The RACKLIFE Boraflex Rack Life Extensin Computer Code: Theory and Numerics

TR-107333
3097

Final Report, August 1997

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ABSTRACT

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.

ACKNOWLEDGMENTS

In the course of this project, Northeast Technology Corp (NETCO) has requested and received data from many utilities. The data provided were invaluable to this project and NETCO hereby acknowledges and expresses appreciation for the data contributed.

In particular, some utilities provided data and/or users for beta testing RACKLIFE. The beta testers include Niel Jones of Pacific Gas and Electric; Dave Hoppes, Brian Handley, and Steve Nance of Houston Lighting and Power; and Brad Kranz of Niagara Mohawk. Pacific Gas and Electric and PECO Energy provided extensive plant data which were used to test the code. Further development and release testing of RACKLIFE was supported very generously by Mark Brossart of Northern States Power.

The continued support of the Electric Power Research Institute staff on behalf of the EPRI Boraflex User's Group is sincerely appreciated. In particular, the assistance and valuable comments provided by Odelli Ozer and Ray Lambert are greatly appreciated.

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INTRODUCTION

RACKLIFE, the Boraflex RACK LIFe Extension software package, was developed by Northeast Technology Corp. (NETCO) for the Electric Power Research Institute (EPRI) under research project WO-3901-01. The development of RACKLIFE was prompted by the observed in-service deterioration of one neutron absorber material, Boraflex™[*], used for reactivity control in spent fuel racks. In its as-manufactured condition Boraflex is polydimethyl siloxane (silicon rubber) which serves as a matrix to retain a finely divided powder of boron carbide. The supplier of the polymer component of Boraflex adds fine ground quartz (crystalline silica) as a filler to serve as an extender. As the material ages in the spent fuel pool environment, the polymer matrix is converted to a silica dominated material as a result of exposure to gamma radiation and the pool water.[1,2,3] The silica converted from the polymer matrix of Boraflex is amorphous silica.

The boron-10 atoms in boron carbide effect reactivity control via their very large nuclear cross section for thermal neutrons; loss of boron-carbide results in loss of reactivity margin. After modest periods of service, the boron-carbide and crystalline silica fillers are encapsulated in a matrix of amorphous silica, which is somewhat soluble in the aqueous pool environment at increasing rates with absorbed dose, temperature, and residence time. Thus the solubilization of the silica matrix of Boraflex is the physical mechanism that leads to increased soluble silica levels in the spent fuel pool and loss of boron-carbide. The silica component from converted polydimethyl siloxane is amorphous and can be relatively soluble in water. Compared to amorphous silica, the fine ground quartz component is effectively insoluble.

Almost all spent fuel pools with fuel storage racks containing Boraflex have experienced elevated levels of reactive silica in the pool water.[4] The silica level in a given pool depends on a number of factors including the design features of the storage racks, quantity of spent fuel in storage, age of the racks, type of pool water cleanup system, and cleanup system utilization and maintenance practices. In PWR pools, silica levels higher than 100 ppm have been experienced. In BWR pools the levels are generally lower owing to the absence of boric acid in the pool water and the effectiveness of the demineralizers in removing silica. However, silica levels approaching 10 ppm have been observed in some BWR pools. These silica

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[*] Boraflex™ – Boraflex is a trademark of BISCO

concentrations can be compared with the pool water in LWRs without Boraflex-bearing storage racks: in BWR pools silica at a level of 100 to 200 ppb are common, whereas in PWR pools 1 to 3 ppm are typical.

RACKLIFE is a stand-alone PC/DOS executable program which computes the loss of boron-carbide from Boraflex panels in fuel storage racks in spent fuel pools. The RACKLIFE model is based on first principles. It contains a mass balance calculation of silica in the pool, from its source (solubilization of the Boraflex matrix), subsequent transit into the bulk pool volume, and removal via the pool cleanup system. RACKLIFE performs this mass balance for each of the several thousands of Boraflex panels present in a typical fuel storage rack configuration.

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 results can be displayed graphically to facilitate rack management activities, and written to ASCII files for documentation and/or imported into other user software packages (such as a spreadsheet). A RACKLIFE model of the spent fuel pool and racks can also be used to identify those storage cells and specific Boraflex panels which have been subjected to the most severe service histories in terms of integrated gamma exposure and boron-carbide loss. This information can be used to identify specific panels for in-situ testing with equipment such as the EPRI BADGER system.[5]

The purpose of this report is to document the theory and numerics behind the RACKLIFE code, including the laboratory tests which were used to develop parameters for many of the models. Section 2 contains some of the background information which identified the need for a predictive model for boron carbide loss from Boraflex panels, as well as some of the approaches that evolved into the RACKLIFE program. Section 3 presents Boraflex in-service performance models which are solved to track the dissolution of each Boraflex panel in the spent fuel pool. This section refers often to Appendix A which describes a series of laboratory tests. Data from these tests provide the dissolution rates of irradiated Boraflex as a function of radiation dose and water temperature. As background, Section 3 also reviews the mechanism of silica dissolution in water. Section 4 details the design of the software and Section 5 describes the expression of the models into program code. In Section 6, the test suites used to test the implementation of the software are outlined. A User's Manual that includes a tutorial is contained in Appendix B.

2

BACKGROUND

Prior publications have demonstrated that elevated spent fuel pool silica levels can be traced to Boraflex in spent fuel racks.[1,2,3] As the presence of silica in the spent fuel pool water is direct evidence of the dissolution of the matrix in Boraflex, it was thought that historical or trend data on pool silica may provide a means to assess the in-service condition of this material. That is, the rate at which the silica concentration in a specific pool is increasing should be related to the rate at which boron carbide is being lost from the Boraflex. Based on projected use patterns of the spent fuel racks, the future conditions of the Boraflex could then be predicted. This information, when used in conjunction with parallel reactivity calculations of the fuel/rack configuration, could be used to assess the useful service life of the Boraflex in the fuel racks.

Accordingly, a kinetic model describing the dissolution and subsequent transport of silica into the pool water was developed and applied. The basis for this model is presented in Section 3, subsequent to some review of the mechanism of silica dissolution in water. The first attempt to solve this model was an electronic spreadsheet solution of the kinetics equations with many simplifying assumptions. The results of this analysis were presented previously.[3] This solution suffered from four serious limitations:

- the model gave only spent fuel rack average results (not panel specific);
- the spreadsheet recomputation time was excessively long;
- the spreadsheet format was not well suited to the types of user input required;
- the degree of conservatism or non-conservatism of the assumptions was highly dependent on which pool was being modeled and so was difficult to assess.

These limitations were overcome by moving to a programmed solution to the models. As work progressed it became clear that a user-friendly software package, complete with a user interface for data I/O and interpretation, was needed to minimize the complex task of data collection and input and to maximize the usefulness of the results in managing spent fuel racks to obtain maximum useful service life of the Boraflex.

It is noted that some of the calculational models used in the present work are based on models presented in Reference 2. Section 5 of this reference details simplified gamma dose calculation procedures for gamma energy deposition to Boraflex, and their implementation in a spreadsheet template. Appendix A of the same reference is the User's Manual for the template. While very simple to use, it can become time consuming if the dose to many panels is desired. The present work incorporates these models and greatly simplifies their application to an entire pool of Boraflex panels.

3

BORAFLEX IN-SERVICE PERFORMANCE MODEL

This section describes the theoretical background and analytical models of silica dissolution in water leading to boron carbide loss from Boraflex panels. The basis for calculating unknown model parameters using the laboratory data described in Appendix A is also covered.

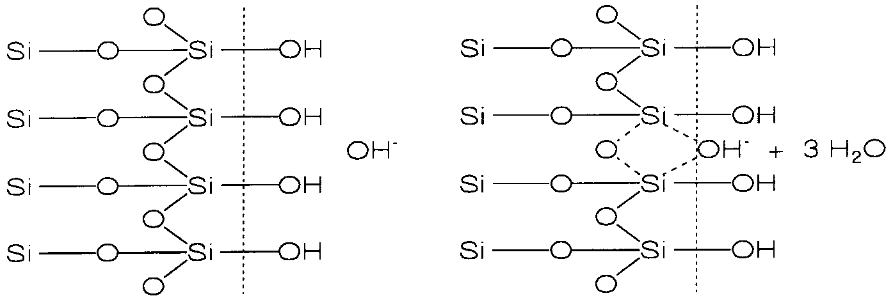
3.1 Mechanisms of Silica Dissolution in Water

3.1.1 The Formation of Reactive Silica in Solution

Silica is by far the most abundant constituent of the earth's crust. In spite of its abundance, the chemistry of silica and, in particular, its solubility in water is not fully understood.[6] The dissolution of silica is via the following chemical reaction:

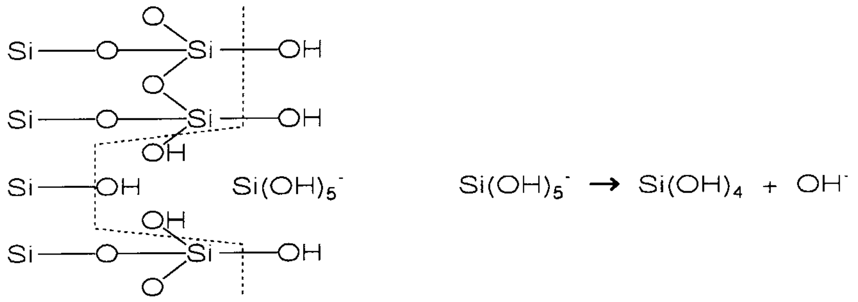
$$(SiO_2)_x + 2H_2O \Leftrightarrow (SiO_2)_{x-1} + Si(OH)_4 \qquad \text{(eq. 3-1)}$$

This process is believed to occur as a series of steps as shown in Figure 3-1. An ambient hydroxyl radical near the surface of silica (a) is adsorbed and coordinated to two silica atoms at the surface of the silica (b). This weakens the Si-O bonds and a silica atom goes into solution as a silicate ion (c). The silicate ion then hydrolyzes to form soluble silica and a free hydroxyl ion. The soluble form of silica is $Si(OH)_4$ or monosilicic acid, which is also referred to as reactive silica. This form of silica is traditionally monitored in spent fuel pools. In water, silica only undergoes dissolution to monosilicic acid. The other form of aqueous silica, referred to as polymerized or colloidal silica, may form subsequently in the solution but not as a direct product of the dissolution of SiO_2.



(a) Ambient hydroxyl ion near silica surface

(b) Ion adsorbed, coordinated to silicons, weakening oxygen bonds



(c) Silicon atom goes into solution as a silicate ion

(d) Silicate ion hydrolizes to soluble silica and a free hydroxyl ion

Figure 3-1
Mechanism of Dissolution of Silica in Water catalyzed by OH^- ions

The dissolution reaction is reversible and redeposition of SiO_2 back on the surface of the silica may occur. This involves hydration and dehydration reactions which are shown in Equation 3-2:

$$(SiO_2) + 2H_2O \Leftrightarrow (SiO_2)_{x-1} + Si(OH)_4 \qquad \text{(eq. 3-2)}$$

The rate of hydration (dissolution) is a relatively strong function of temperature. The rate of dehydration (deposition) depends primarily on the concentration of monosilicic acid in solution. The rates are strongly dependent on the form of the silica. Crystalline silica has an extremely small rate of dissolution; this is clear from the fact that sand is not readily dissolved by rain water. Amorphous silica, however, is approximately 10^6 times more soluble than crystalline silica. In subsequent discussions the term "silica" will refer to the relatively soluble amorphous silica.

3.1.2 Reactive Silica Equilibrium Solubility

As discussed in Appendix A, at sufficiently high concentrations the reactive silica in solution reaches an equilibrium saturation condition which depends on temperature and pH. At this condition the rates of dissolution and deposition are equal and, in the absence of polymerization, there is no further net loss of silica from the surface. If, on the other hand, reactive silica is undergoing polymerization, the reaction in Equation 3-1 will favor hydration. The equilibrium of a silica solution is established relatively slowly, on the order of days. The approach to equilibrium can be erratic, with more acidic solutions tending to be overdamped (monotonically asymptotic) and more basic solutions tending to be underdamped (oscillatory in its approach to equilibrium).

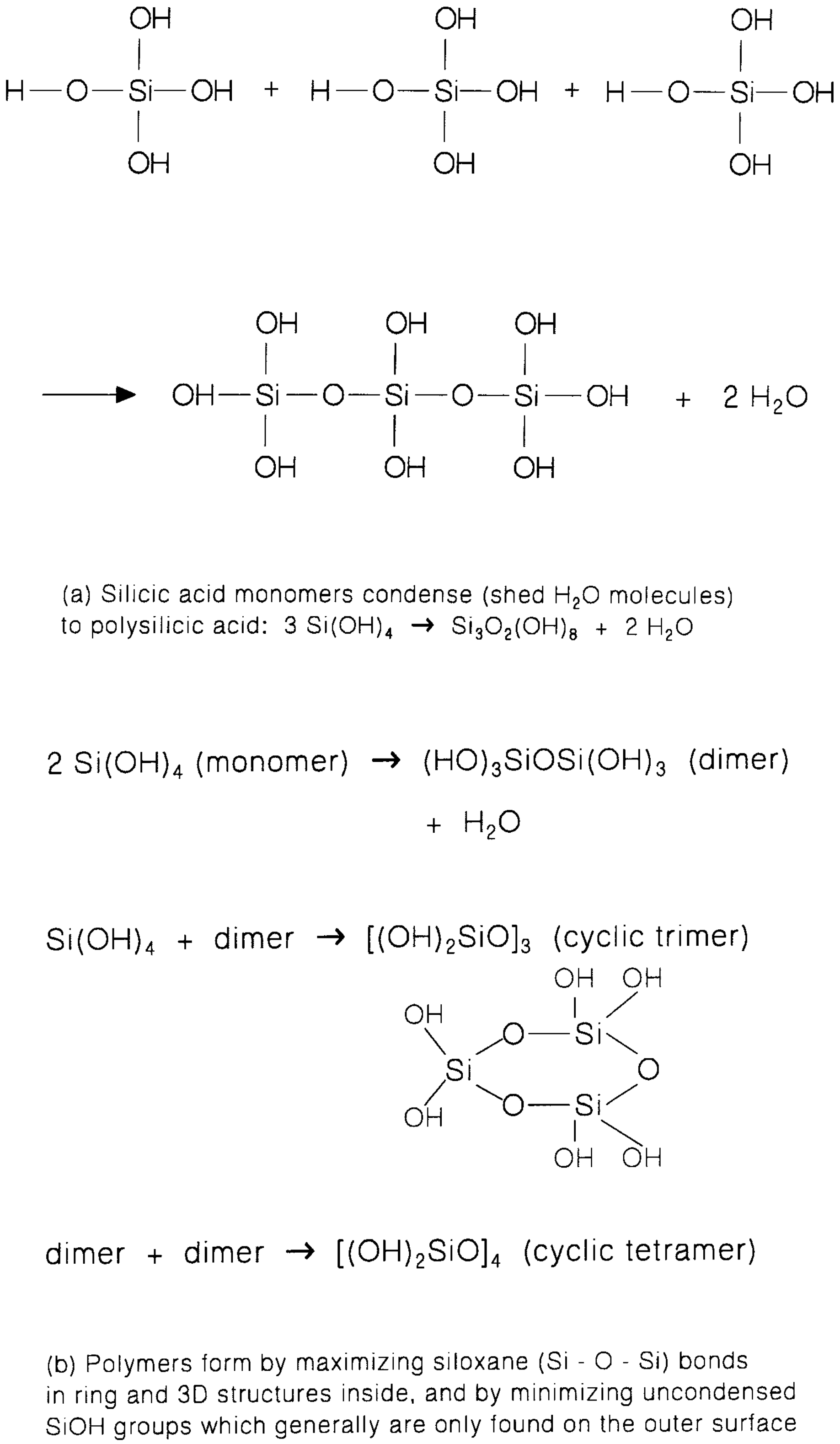
The reactive silica equilibrium concentration is a strong function of temperature. A quick rule of thumb for solutions at pH 5 between 85°F and 150°F is that the equilibrium concentration is approximately the temperature of the solution in degrees Fahrenheit. Between pH 3 and pH 7 the equilibrium concentration decreases slowly, and then is nearly constant between pH 7 and pH 8. Above pH 8, the equilibrium concentration rises very rapidly to become theoretically infinite around pH 10.5.

3.1.3 Polymerization of Reactive Silica

Colloidal silica is formed when the reactive silica concentration in solution becomes large. Reactive silica undergoes a three stage process to form colloidal silica, as described below.

1. Condensation of silanol groups until particles form.

This polymerization process is illustrated in Figures 3-2a and 3-2b. In this process silicic acid monomers condense (shed) H_2O molecules to form polysilicic acid, as shown in Figure 3-2a. Further polymerization can result in very large molecules with a cyclic structure as shown in Figure 3-2b. In this process the number of siloxane bonds (Si-O-Si) is maximized in a ring, forming a three dimensional structure. As polymerization continues and larger and larger molecules are formed the polymer can appear as a spherical particle.



(a) Silicic acid monomers condense (shed H_2O molecules) to polysilicic acid: $3\ Si(OH)_4 \rightarrow Si_3O_2(OH)_8 + 2\ H_2O$

$2\ Si(OH)_4$ (monomer) $\rightarrow (HO)_3SiOSi(OH)_3$ (dimer) $+ H_2O$

$Si(OH)_4$ + dimer $\rightarrow [(OH)_2SiO]_3$ (cyclic trimer)

dimer + dimer $\rightarrow [(OH)_2SiO]_4$ (cyclic tetramer)

(b) Polymers form by maximizing siloxane (Si - O - Si) bonds in ring and 3D structures inside, and by minimizing uncondensed SiOH groups which generally are only found on the outer surface

Figure 3-2
Polymerization of Silicic Acid

2. Particle growth

A particle acts as a nucleus for growth. The solubility of a particle depends on its radius of curvature: small particles are more soluble than larger ones. Thus the growth of particles is typically accompanied by a reduction in the number of particles (neglecting any source term) as some smaller particles return to solution and then deposit on the larger particles. Beyond a size which is dependent on temperature and pH, however, particle growth slows considerably to become negligible.

3. Formation of siloxane bridges between particles to form colloids.

What happens next is a complex function of pH, temperature, and the electrolyte concentration (e.g., sodium chloride, sodium sulfate, other flocculating salts) in the aqueous solution. In general, the polymer particles will randomly collide. The contact point of two spherical particles has an infinitesimal negative radius of curvature, which theoretically gives a region of zero solubility. Thus any monomers locally in solution will theoretically deposit instantly at that point, forming siloxane bond bridges that thicken rapidly between the particles. In this way particles go on to form chains, and chains branch and join to form networks. If this continues and the silica concentration is high, the formerly aqueous system will "gel", characterized by a rapid increase in viscosity, and the networks will continue to solidify.

Above about pH 6 the particles have a negative ionic charge and so are unlikely to collide because of mutual repulsion; they simply continue to grow. Higher temperatures favor more rapid growth so that particles may grow in size and decrease in number, decreasing the probability of a collision. The presence of electrolytes can decrease the ionic charge of the particles, increasing the probability of collision even at higher pH. Colloid, chain, and network formation is virtually impossible to observe visually because the refractive index and density of the system remains uniform; that is, the colloids retain the same ratio of water to silica as the ambient solution.

Note that siloxane bond formation is a reversible reaction: the ambient hydroxyl ions that promote condensation also promote hydrolysis equally. The only mechanism to retard depolymerization is the approach of the reactive silica concentration to its equilibrium concentration, thereby resisting depolymerization that would otherwise bring the reactive silica to a supersaturated state. In a solution containing silica both the reactive and colloidal forms of silica may be present at the same time. Data presented in Appendix A would indicate that at concentrations of reactive silica of less than 50 ppm the amount of colloidal silica is very low. Above 50 ppm the colloidal component increases and has been determined to represent a significant fraction of the total silica in some tests.

3.2 The Kinetics of Dissolution of Boraflex

The kinetics of silica dissolution and subsequent polymerization have a strong influence on the rate at which the silica matrix of irradiated Boraflex dissolves. In a spent fuel storage rack the Boraflex is housed between two sheets of stainless steel. The cavity between these two sheets of stainless steel containing the Boraflex is vented to the pool to allow off-gas to escape. When the racks are first installed the cavities will fill with pool water such that the water surrounds the Boraflex. After the Boraflex has been exposed to large amounts of gamma radiation, the silica matrix of the Boraflex will begin to undergo significant dissolution.

If the water exchange rate between the Boraflex cavity and the pool is low, the volume of water in the cavity will come to saturation equilibrium with respect to reactive silica. At this stage, the silica dissolution rate from the Boraflex and the deposition rate back onto the Boraflex will be in equilibrium and there will be little further loss of silica from the surface. As reactive silica in the cavity diffuses from the cavity into the pool or as the reactive silica polymerizes, the concentration of reactive silica in the cavity will theoretically be reduced. This will promote further dissolution from the surface of the Boraflex in an attempt to bring the cavity water back to its equilibrium saturation. Accordingly, the dissolution rate of silica from the Boraflex matrix will be limited by either its polymerization to colloidal silica or the diffusion of reactive silica (and for that matter colloidal as well) out of the cavity.

If, on the other hand, the volume exchange rate between the Boraflex cavity and pool is large, the equilibrium condition for reactive silica will never be established. In this case the dissolution of silica from the Boraflex can be fairly rapid, approaching the initial rates of silica release from unclad specimens as presented in Appendix A. If the rack design is such that flow, due to natural circulation cooling, is present in the Boraflex cavity, the rate of dissolution will be accelerated. The flow will continuously bring the bulk pool water with relatively low reactive silica concentration in contact with the Boraflex.

The rate of silica dissolution from Boraflex in spent fuel racks is likely to vary from rack to rack and among racks from various manufacturers. For some rack designs, relatively low pool silica levels, in the absence of cleanup systems, would indicate a low rate of water exchange between the Boraflex cavities and the bulk pool water volume, even after the racks have been in service for some time. In other rack designs, high pool silica levels may indicate a large rate of volume exchange between rack cavities and the bulk pool volume.

3.2.1 Kinetics Model of Silica in Spent Fuel Pools

A model has been developed which describes the formation of reactive silica within the rack cavity due to the dissolution of silica in Boraflex and its subsequent transport to the bulk pool volume. The overall model is depicted graphically in Figure 3-3. As reactive silica is produced in the rack cavities and its concentration within the cavity increases, some of the silicic acid will polymerize, some will redeposit on the Boraflex and may deposit on other cavity surfaces, and some will leave the cavity and enter the bulk pool volume. The rate at which the reactive and polymerized silica leaves the rack cavities is characterized by a volume exchange rate. The volume exchange rate is the number of times the cavity volume is replaced with pool water per unit time.

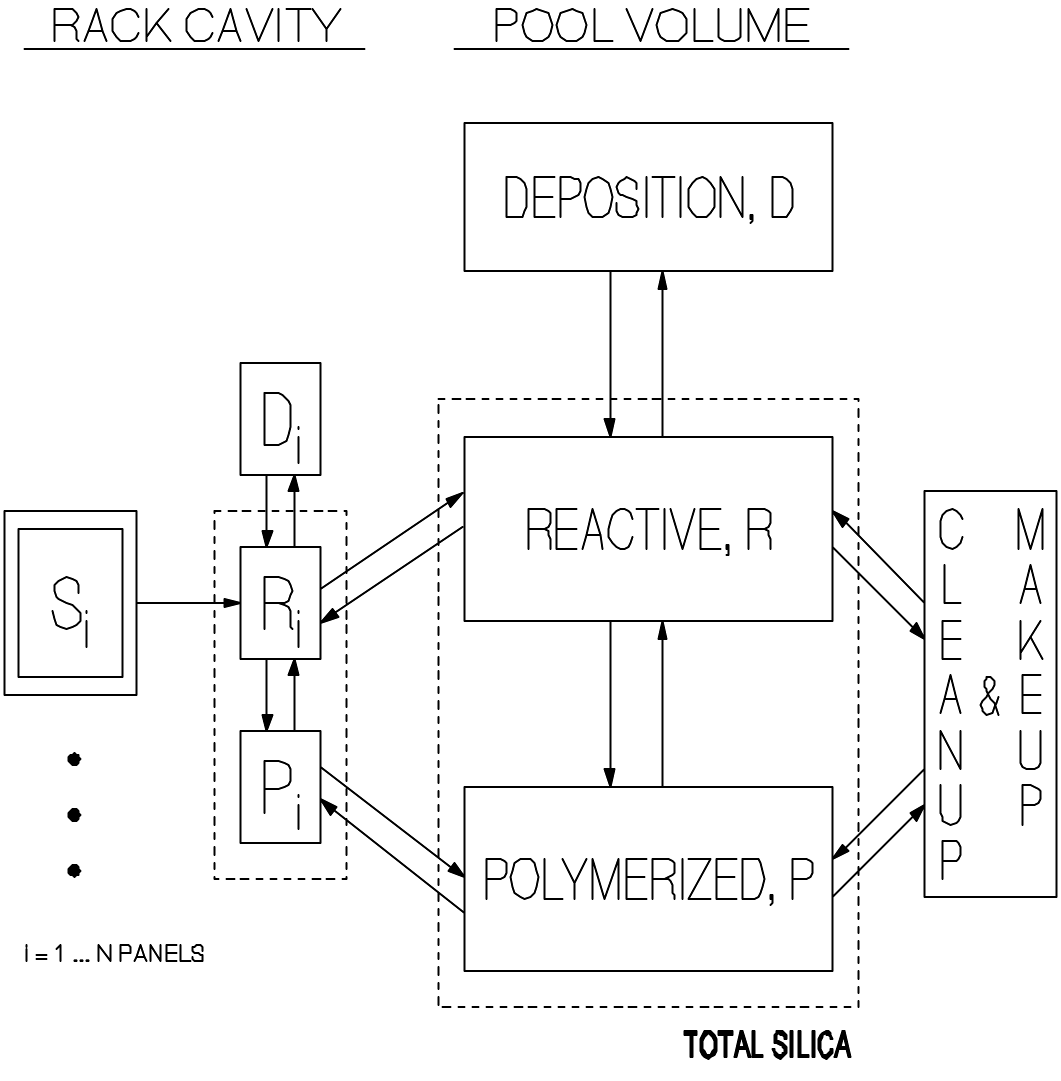


Figure 3-3
Kinetics Model of Silica in Spent Fuel Pools

In the pool volume a similar situation prevails. The silica source term for the pool volume is the reactive and polymerized silica which is exiting the rack cavities. Once in the pool volume the reactive silica can polymerize, deposit on surfaces in the pool, and be removed by the spent fuel pool cleanup system. The makeup system is modeled to account for water makeup due to leakage and evaporative losses. The makeup system model can also be used to account for dilution effects during refueling outages. Once polymerized silica is present in the pool it may be subject to depolymerization or complete or partial removal by the cleanup system.

Each rack cavity containing Boraflex can be treated as a single volume, independent of each other but communicating directly with the bulk pool water volume via the volume exchange rate. For a particular panel cavity I out of N panels the source term for reactive silica is given by:

$$S_i = \lambda_i (1 - R_i / R_{eq_i}) \qquad \text{(eq. 3-3)}$$

where

λ_i = *dissolution rate into water with* 0 *ppm silica [mg/d]*
R_i = *reactive silica concentration [ppm]*
R_{eq_i} = *reactive silica equilibrium concentration [ppm]*

The expression $(1 - R / R_{eq})$ can be considered a "proximity to equilibrium term": as R increases from zero to R_{eq} the expression goes from one to zero. Since many processes are affected by the proximity of the reactive silica concentration to its equilibrium value, such as the source term, depolymerization, etc., this term appears often. (Note that in Reference 3 this expression was often implicit in reaction rate coefficients but is made explicit here for clarity.) As noted previously, in the absence of any reactive silica loss mechanisms the source term would go to zero as the reactive silica approached equilibrium.

In the following discussion, these variables are used in writing the kinetics equations:

t — time [days]
R — mass of reactive silica in solution [mg]
P — mass of polymerized/colloidal silica in solution [mg]
D — mass of silica deposited on non-Boraflex surfaces [mg]
k — rate constant for a process, defined by its subscripts; e.g.: k_{RP} is the rate constant for the polymerization of reactive silica ($R \rightarrow P$) [days^{-1}].
I — subscript indicating a particular Boraflex panel cavity, I=1...N panels. The absence of a subscript I denotes a bulk pool volume variable; e.g.: R_i is the mass of reactive silica in rack panel cavity I, while R is the mass of reactive silica in the bulk pool.

In general, time is measured in days (or fractions thereof) and quantities are expressed as masses in milligrams. Thus the kinetics equations given below are essentially mass conservation equations. Volumes are measured in liters; this allows an easy conversion from mass to concentration in water as, for example:

$$C_R\ [\text{ppm} \equiv \text{mg/liter}] = R\ [\text{mg}]\ /\ V\ [\text{liters}]$$

For a particular rack cavity I, the time rate of change of the reactive silica concentration is given by a mass balance over the rack cavity fluid volume (illustrated in Figure 3-3):

$$\begin{aligned} \frac{dR_i}{dt} &= S_i && \text{source term} \\ &\quad -[k_{R_iR}\, R_i(1-R/R_{eq}) - k_{RR_i} R(1-R_i/R_{eq_i})] && \text{net leakage of reactive} \\ &\quad -[k_{R_iP_i} R_i - k_{P_iR_i} P_i\ (1-R_i/R_{eq_i})] && \text{net polymerization} \\ &\quad -[k_{R_iD_i}\ R_i - k_{D_iR_i} D_i (1-R_i/R_{eq_i})] && \text{net deposition} \end{aligned} \qquad \text{(eq. 3-4)}$$

The time rate of change in pool reactive silica due to the reactive silica flowing from all of the groups of cavities is given by:

$$\begin{aligned} \frac{dR}{dt} &= \sum_{i=1}^{N} [k_{R_iR} R_i(1-R/R_{eq}) - k_{RR_i} R(1-R_i/R_{eq_i})] && \text{net leakage into pool from all N panel cavities} \\ &\quad -[k_{RP} R - k_{PR} P(1-R/R_{eq})] && \text{net polymerization} \\ &\quad -[k_{RD} R + k_{DR} D(1-R/R_{eq})] && \text{net deposition} \\ &\quad + \textit{cleanup terms} \\ &\quad\ \ \textit{(see Equations 3-27 et seq.)} \end{aligned} \qquad \text{(eq. 3-5)}$$

Similarly, the time rate of change of the polymerized (colloidal) silica concentration is given by:

$$\begin{aligned} \frac{dP_i}{dt} &= [k_{R_iP_i} R_i - k_{P_iR_i} P_i (1-R_i/R_{eq_i})] \\ &\quad -[k_{P_iP} P_i - k_{PP_i} P] \end{aligned} \qquad \text{(eq. 3-6)}$$

and the time rate of change in pool polymerized silica is given by:

$$\begin{aligned}\frac{dP}{dt} &= [k_{RP}R - k_{PR}P(1 - R/R_{eq})] \\ &\quad + \sum_{i=1}^{N}[k_{P_iP}P_i - k_{PP_i}P] \\ &\quad + \textit{cleanup terms (see Equations 3-27 et seq.)}\end{aligned} \qquad \text{(eq. 3-7)}$$

The solution of Equations 3-4 through 3-7 provides $R_i(t)$, R(t), $P_i(t)$, and P(t), which all vary with time. Total silica is the sum of reactive and polymer in a given volume; e.g.:

$$\text{Pool Total Silica (t)} = \text{R(t)} + \text{P(t)} \qquad \text{(eq. 3-8)}$$

3.2.2 Determination of Boron Carbide Loss

To determine the total mass of silica lost from a particular panel i over a time interval [t_1, t_2], its source term is integrated over time:

$$\begin{aligned}\textit{Silica Mass Lost}\Big|_{t_1}^{t_2} &= \int_{t_1}^{t_2} S_i(t)dt \\ &= \int_{t_1}^{t_2} \lambda_i(t)(1 - R_i(t)/R_{eq_i}(t))\,dt\end{aligned} \qquad \text{(eq. 3-9)}$$

Multiplying the result of Equation 3-9 by the ratio of the mass of boron carbide to the mass of silica in the panel yields the total mass of boron carbide lost from the panel over the time interval [t_1, t_2]; or, as a percent of the initial mass of boron carbide present in the panel:

$$\%\ B_4C\ lost\Big|_{t_1}^{t_2} = \frac{\textit{silica mass lost}\Big|_{t_1}^{t_2} \cdot \dfrac{w/oB_4C \textit{ in Boraflex}}{w/oSiO_2 \textit{ in Boraflex}}}{\textit{initial mass of } B_4C} \qquad \text{(eq. 3-10)}$$

Recall that "silica" here means the amorphous silica component of Boraflex only; the relatively insoluble quartz filler component does not enter into these calculations.

The following sections detail the constitutive equations that model the release rate, equilibrium, reaction rate, and removal rate coefficients in the kinetics model defined by Equations 3-4 through 3-7. In general, the coefficients have been developed based on the long-term laboratory tests described in Appendix A except for k_{RiR}, k_{RRi}, k_{PiP}, and k_{PPi}. These parameters are the rate coefficients for silica transfer in and out of the Boraflex panel cavities. These will depend on specific design and manufacturing features of each rack design and are generally not known. As will be discussed, these coefficients are adjusted by the user during a RACKLIFE simulation until the calculated rate of pool reactive silica increase matches the rate from plant pool silica measurements.

3.3 The Silica Source Term

This section develops constitutive equations for the release rate and equilibrium concentration coefficients in Equation 3-3 based on the experimental data discussed in Appendix A and analytical models from the literature.

3.3.1 Reactive Silica Dissolution Rate

As discussed in Appendix A, the silica dissolution rate is primarily a function of temperature and absorbed gamma dose. The dependence of silica dissolution rate on temperature is postulated to be an Arrhenius function of the form:

$$f(T) = ke^{-q/T} \qquad \text{(eq. 3-11)}$$

where

T = temperature [K]

This form of dependence is used to calculate fit coefficients that depend on temperature for a fit of release rate versus dose.

Based on the data illustrated in Figure A-12 of Appendix A, the dependence on dose is divided into three intervals:

Interval	Fit type
$0 \leq I \leq I_L$	Constant
$I_L < I \leq I_U$	Quadratic log-log regression
$I_U < I$	Extrapolation of regression fit

where

I = the absorbed gamma dose [rads]
$I_L = 5.0 \cdot 10^8$ rads
$I_U = 1.0 \cdot 10^{10}$ rads

As can be seen in Appendix A, silica release rates per unit area, λ'', below about $1.0 \cdot 10^{-3}$ mg/cm^2·day show significant scatter, in part due to the inherent uncertainty in the measurement techniques at such low levels of silica. The exact release rate is not important at these very low levels, however, since the Boraflex would last thousands of years at these dissolution rates. Thus, below I_L the release rate is assigned the value at I_L based on the regression of the data from I_L to I_U.

The log-log multivariate regression of the data from I_L to I_U has the form:

$$\log(\lambda'') = a(T) + b(T)[\log(I)] + c(T)[\log(I)]^2 \tag{eq. 3-12}$$

where the coefficients a, b, and c are Arrhenius functions of temperature as in Equation 3-11. As discussed in Appendix A, data above $1.0 \cdot 10^{10}$ rads was not practicable. While some data suggests a saturation effect at about $1.0 \cdot 10^{10}$ rads (e.g., dimensional data and density data), porosity data, which is related to the surface area available for dissolution, shows no such saturation.[7] Preliminary application of RACKLIFE to a high absorbed dose spent fuel pool also suggests that the release rate does not have a saturation dose. Thus for absorbed gamma doses beyond I_U the regression is extrapolated. The fits versus dose at three temperatures are illustrated in Figure 3-4 along with the data from Appendix A for comparison.

Equation 3-12 gives the silica source term in units of mg/cm^2·day. Multiplying this by the surface area of a given panel yields the source term for that panel in mg/day:

$$\lambda_i = \lambda''(T_i, I_i) \cdot A_i \tag{eq. 3-13}$$

The coefficients of Equation 3-11 for a, b, and c in Equation 3-12 are given in Table 3-1.

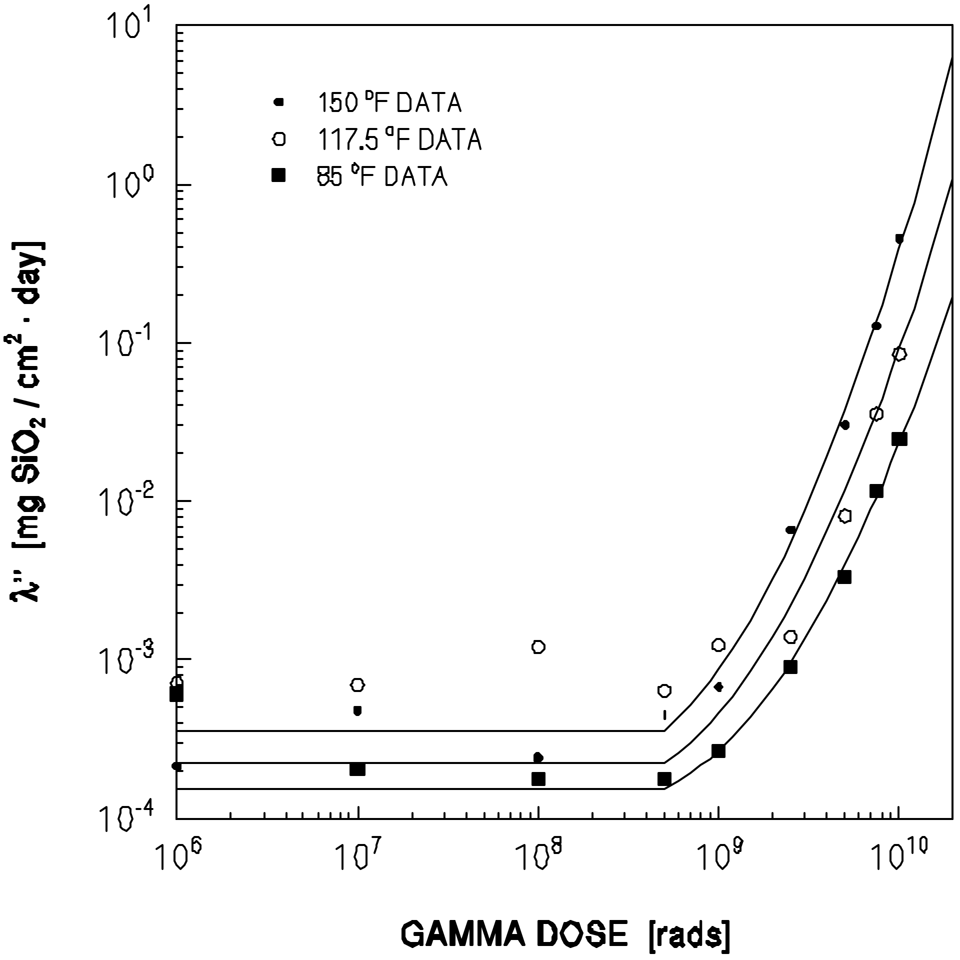


Figure 3-4
Silica Release Rate per Unit Area—Fit versus Data

Table 3-1
Coefficients of Constitutive Equation for Dissolution Rate

Coefficient in Equation 3-11	Coefficients of Equation 3-12		
	a	b	c
k	224.479	-61.7363	4.42505
q	402.684	427.683	484.437

3.3.2 Reactive Silica Equilibrium Concentration

The reactive silica equilibrium concentration as a function of temperature is modeled using a fit of the form suggested by Reference 6:

$$R_{eq}(T) = 10^{-\frac{a}{T}+b} \qquad \text{(eq. 3-14)}$$

where

T = temperature [K]

The coefficients of this fit are determined by regression of the equilibrium concentrations observed in the data in Appendix A.

The data used from Appendix A is for water at pH 5. A correction to Equation 3-14 for pH is based on a fit of data presented in Reference 6; it is formed over three intervals:

Interval	Form of fit	Equation
$3 < pH \le 7$	Log-Linear, slowly decreasing	3-15a
$7 < pH \le 8$	Constant	3-15b
$8 < pH \le 10$	Power, rapidly increasing	3-15c

The fits with respect to pH take the form:

$$R_{eq}(T,pH) = R_{eq}(T) \cdot 10^{-g(pH-pH_1)} \qquad 3 \le pH \le 7 \qquad \text{(eq. 3-15a)}$$

$$R_{eq}(T,pH) = R_{eq}(T) \cdot f \qquad 7 < pH \le 8 \qquad \text{(eq. 3-15b)}$$

$$R_{eq}(T,pH) = R_{eq}(T) \cdot (c + d(pH - pH_2)^5)/e \qquad 8 < pH \le 10 \qquad \text{(eq. 3-15c)}$$

The coefficients for Equations 3-14 and 3-15 are given in Table 3-2 and the fit versus temperature for various pH is illustrated in Figure 3-5.

Table 3-2
Coefficients for the Equilibrium Concentration Constitutive Model

Equation	Coefficient	Value
3-14	a	701.4
3-14	b	4.253
3-15c	c	72.6192
3-15c	d	6.295
3-15c	e	88.94
3-15b	f	0.816497
3-15a	g	0.0440228
3-15c	pH_1	5.0
3-15a	pH_2	8.0

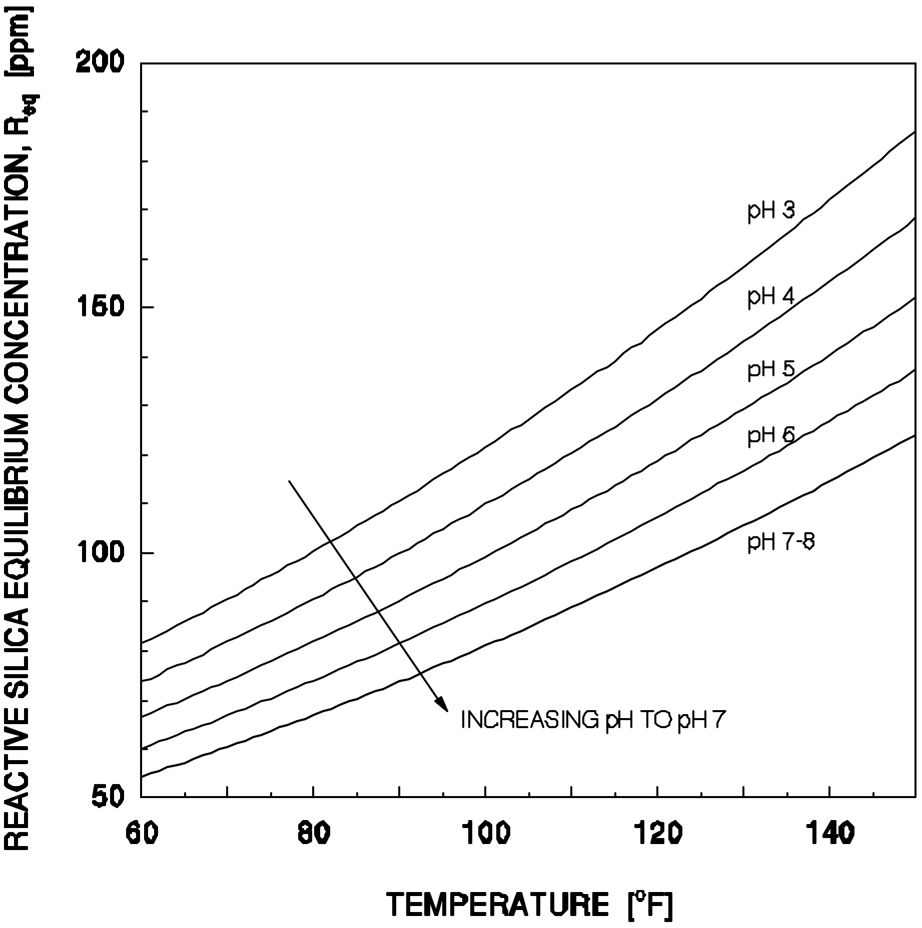


Figure 3-5
Fits of Reactive Silica Equilibrium Concentration

3.4 Polymerization of Silica

The kinetics of the laboratory tests for total silica described in Appendix A can be modeled as a single-volume system comprised of source, polymerization, and depolymerization terms:

$$\frac{dR}{dt} = \lambda(1 - R/R_{eq}) - k_{RP}R + k_{PR}P\,(1 - R/R_{eq}) \qquad \text{(eq. 3-16a)}$$

$$\frac{dP}{dt} = \qquad + k_{RP}R - k_{PR}P(1 - R/R_{eq}) \qquad \text{(eq. 3-16b)}$$

where

$k_{RP} = \text{rate of polymerization} \, (\text{R} \rightarrow \text{P}), [\text{d}^{-1}]$
$k_{RP} = \text{rate of depolymerization} \, (\text{P} \rightarrow \text{R}), [\text{d}^{-1}]$

The rate of polymerization was noted previously to generally be equal to the rate of depolymerization; thus it is assumed that:

$$k_{RP} = k_{PR} \; (= k_{RiPi} = k_{PiRi} \text{ for panel cavity volumes}) \qquad \text{(eq. 3-17)}$$

As noted previously, differences between the polymerization and depolymerization terms come about by the proximity to equilibrium term, $(1 - R / R_{eq})$, that retards depolymerization as the reactive silica concentration approaches equilibrium. As the Boraflex sample dissolution experiments progress in time:

$$\lim_{t \rightarrow \infty} R = R_{eq} \qquad \text{(eq. 3-18)}$$

and equation 3-16b can be approximated as:

$$\lim_{t \rightarrow \infty} \frac{dP}{dt} = k_{RP} \cdot R_{eq} \qquad \text{(eq. 3-19)}$$

Thus, given R_{eq} for the experimental conditions of temperature and pH, the slope of the P(t) curve as $t \rightarrow \infty$ can be used to compute k_{RP} as:

$$k_{RP} = \lim_{t \rightarrow \infty} \left(\frac{1}{R} \frac{dP}{dt} \right) = \frac{1}{R_{eq}} \frac{dP}{dt} \bigg|_{t \rightarrow \infty} \qquad \text{(eq. 3-20)}$$

and hence, by Equation 3-17, k_{PR} is known. Table 3-3 gives the computed value for the polymerization/depolymerization rate coefficients.

Table 3-3
Rate Constants for Polymerization/Depolymerization Terms

Coefficients for Equations 3-4 to 3-7	Value $[\text{d}^{-1}]$
k_{RP}, k_{PR}, k_{RiPi}, k_{PiRi}	$1.644 \cdot 10^{-3}$

3.5 Deposition of Silica

The mechanism of redeposition of silica onto the silica matrix of Boraflex is implicit in the use of the reactive silica equilibrium concentration. Silica deposition onto other spent fuel pool surfaces is neglected in this model so that, from Equations 3-4 to 3-7:

$$k_{RD} = k_{DR} = k_{RiDi} = k_{DiRi} = 0 \qquad \text{(eq. 3-21)}$$

is assumed. The most likely “deposition” mechanism is the aggregation of silica, metal ions, organic molecules, etc., into so-called “universal colloids” that can make pool water cloudy. As most spent fuel pool cleanup systems will keep other universal colloid constituents low this mechanism is also neglected.

3.6 Panel Cavity and Pool Volume Exchange Rate

The previous discussion on the kinetics of dissolution of Boraflex details the importance of the volume exchange rate and the difficulty in making a priori estimates of it. Mass conservation requires that the rate of flow into and out of a Boraflex panel cavity be equal. It is assumed that this flow will transport polymerized silica in proportion to its concentration, just as for reactive silica. Thus, from Equations 3-4 to 3-7:

$$k_{RiR} = k_{RRi} = k_{PiP} = k_{PPi} = \varepsilon \qquad \text{(eq. 3-22)}$$

where ε is referred to as an “escape coefficient”. Physically, the escape coefficient represents the number of panel cavity fluid volume exchanges per day. That is, if ε = 1.0 and the panel cavity volume were 0.2 liters, then 0.2 liters of fluid would be assumed to flow into and out of the panel cavity each day. A very low escape coefficient implies a “tight” rack, with little opportunity for fluid ingress. A high escape coefficient implies a more “open” rack design, permitting greater flow across the Boraflex surface.

In order to solve for the escape coefficient, it must be assumed that ε is constant for all panel cavities throughout the pool. Manufacturing tolerances dictate that this is not so, but an acceptable average can be formulated and sensitivity studies used to explore local effects. The user solves for the escape coefficient by repeatedly running the program to solve the kinetics equations and comparing the results with historical spent fuel pool reactive silica measurements. If the spent fuel pool reactive silica concentration is under predicted, a larger escape coefficient must be selected.

Because of the small volume of a rack panel cavity, the cavity reactive silica concentration can become large, leading to a significant amount of polymerization. When some of this polymer escapes to the bulk pool water, it generally will encounter a lower pool reactive silica concentration, causing depolymerization. Because the pool kinetics equations treat the pool volume as a bulk volume with instantaneous mixing, the model could direct a large amount of this polymer directly to a cleanup system. Physically, much of the polymer could significantly depolymerize during its transport through the pool, depending on the pool reactive silica concentration. In implementing the escape coefficient model, it is assumed that 90% of the escaping cavity polymer is converted to reactive silica in a zero silica pool. This value is scaled by the proximity to equilibrium so that polymer escaping to a pool at the reactive silica equilibrium concentration would remain as polymer.

3.7 Cleanup Systems and Pool Silica

Spent fuel pool cleanup systems serve to reduce silica levels, reducing the proximity to the reactive silica equilibrium concentration, and thereby accelerating the rate of silica dissolution. For example, increased silica loss has been observed at several plants where reverse osmosis (RO) filtration has been implemented. After RO cleanup, pool silica levels have been observed to rise at an accelerated rate.[3] The enormous variety of cleanup systems precludes formulating exact models of their performance at removing silica from the spent fuel pool. However, general models of five types of cleanup systems and events have been developed. These are:

- continuously operated filters
- continuously operated demineralizers
- continuously operated precoat filters
- reverse osmosis cleanup campaigns
- dilution events (not necessarily for cleanup purposes)

Models for each were generally developed in concert with cleanup system vendor chemists, plant chemists, and the literature.[8–16] Each model is detailed in turn below.

3.8 Filters

Spent fuel pool filter media are generally made of glass fiber, nylon, or cellulosic in a large variety of shapes and sizes. The filter media can be positively charged, which is advantageous for silica removal, neutral, or negatively charged to retard silica uptake. Filters are also rated based on their ability to remove particles of a given diameter from the influent. A “6 µm absolute” rating will filter 100% of all particles ≥6 µm, and will also filter some percentage of all smaller particles. Its ability to filter particles with smaller diameters is quantified by “beta” values. Typically, vendor specifications for a filter will cite particle diameters for three beta values: beta-5000, beta-1000, and beta-

100. Table 3-4 gives the corresponding efficiency of removal for these beta values. As an example, a beta-100 of 1 μm indicates that the filter will remove 99.0% of all 1 μm particles from the influent stream. Some filter vendors use colloidal silica as part of their rating system, but in general the data is proprietary. To formulate efficiencies for every type of filter is not practical, but the filter rating can be used to formulate an approximate efficiency for removing colloidal silica.[8, 9]

With particle diameters for the three beta values listed in Table 3-4, a fit of beta versus particle size can be made. Based on discussions with vendor chemists[9], this fit takes the form:

$$\beta = a\left(\frac{\phi}{1-\phi/\phi_0}\right) \qquad \text{(eq. 3-23a)}$$

where

ϕ = particle diameter [μm]
ϕ_0 = absolute particle diameter filtered [μm]
a = fit coefficient

The filter efficiency can then be calculated as:

$$efficiency = \frac{\beta - 1}{\beta} \qquad \text{(eq. 3-23b)}$$

Table 3-4
Relationship between beta and filter efficiency

beta	probability that a particle of given diameter will be filtered
absolute	100%
5000	99.98%
1000	99.90%
100	99.00%

Vendor studies[9] show that silica colloids are typically 0.05 μm in diameter. After regressing the beta versus diameter vendor data to obtain the coefficient a in Equation

3-23a, $\phi = 0.05\ \mu m$ is substituted into Equation 3-23a to obtain a beta value for colloidal silica.

Given an average volumetric flow rate through the filter system, the cleanup system can then be modeled in Equation 3-7 as:

$$-\left(\frac{\beta-1}{\beta}\right)\frac{\dot{V}}{V}P \qquad \text{(eq. 3-24)}$$

where

$\dot{V} = cleanup\ system\ \ flow\ rate\ [liters/day]$
$V = pool\ volume\ [liters]$

Depending on the ambient concentration of reactive silica in the pool water, a large concentration of trapped colloidal silica on the filter may depolymerize, reintroducing reactive silica into the effluent stream. The quantity reintroduced is a function of the quantity of colloidal silica plugging the filter. This in turn is a function of the effective filter area and the frequency that the filter is changed out. Because filters are assumed to operate continuously if present, this frequency, like the filter flow rate, is input as a constant; thus averages over time are used.

3.8.1 Demineralizers

Typical deep-bed demineralizers are large vessels containing a “mixed-bed” of cation and anion resins that clean influent water by ion exchange. Cation resins remove cations such as cobalt and calcium, while anion resins remove anions such as sulfates, reactive silica, and colloidal silica above pH 6. Demineralizer resins have many different types of physical and chemical structures that can be optimized to many different types of plant-specific demineralization concerns. In particular, resins for PWRs are optimized to not remove boric acid. As with filters, this variety makes specific models for efficiency impractical. Thus general characteristics are modeled and applied to the removal of silica from spent fuel pool water.[8,10–15]

The affinity of a resin to take up an ion is a function of the resin’s “selectivity” for that particular ion. Selectivity is measured on a scale with hydrogen ions at 1.0 for cation resins and hydroxyl ions at 1.0 for anion resins. An ion with a higher selectivity will undergo ion exchange with a resin more quickly than an ion with a lower selectivity. This also means that higher selectivity ions can displace lower selectivity ions on a resin. For example, a resin with a selectivity for chloride ions of 22 will readily shed a hydroxyl to take up the chloride (i.e., ion exchange). It may subsequently shed the chloride ion in favor of a sulfate with a selectivity of 85. Silica has a selectivity less than

1.0, such that it may not be taken up at all, and will readily be shed in favor of almost any other ion.

Silica removal and retention rates are a strong and complex function of spent fuel pool anion chemistry and resin type. To preclude excessive data input requirements for uncertain models an average efficiency of 45% for reactive silica is used for unborated (BWR) pools. Pools (PWR) with dissolved boric acid have resins that do not take up boric acid, and take up very little silica as a side effect; an average efficiency of 1% for reactive silica is used for these demineralizers. Demineralizers are typically in a cleanup train after filters, so unless a large absolute diameter filter is in use very little polymerized silica will enter the demineralizers. Below pH 6 what polymerized silica does enter the resin bed will pass through; above pH 6 the above efficiencies are assumed.

Thus for unborated pools the demineralizer cleanup system kinetics terms take the form:

$$-0.45\frac{\dot{V}}{V}R \qquad \text{(eq. 3-25a)}$$

for the pool reactive silica kinetics Equation 3-5. For borated pools the term is:

$$-\ 0.01\frac{\dot{V}}{V}R \qquad \text{(eq. 3-25b)}$$

If the pH is greater than 6 these same terms are applied in Equation 3-7 with P substituted for R.

3.8.2 Precoat Filters

Precoat filters utilize a floc of fibers and demineralizer resin powders to perform filtration and ion-exchange polishing simultaneously. The filter media is about as effective at removing colloidal silica as conventional 20µm-absolute filters.[16] Thus the same model as for conventional filters described above by Equation 3-24 can be used. The demineralizer resins are as effective at reactive silica removal as deep-bed demineralizers, but their very small capacity relative to deep bed demineralizers only allows a limited quantity of reactive silica to be taken up. When the silica concentration saturates additional influent silica is passed through. Further, as higher selectivity ions are taken up the previously adsorbed silica is released back into the effluent stream. A review of spent fuel pool precoat filter operating influent and effluent silica concentration data shows that precoat filters can saturate in only a day or two and then begin to discharge what little silica has been taken up by ion-exchange.

3.8.3 Reverse Osmosis Units

Reverse osmosis (RO) units are only run for the duration of an RO cleanup effort; they are not considered a continuously operating system. Colloidal silica is removed with at least 99% efficiency and reactive silica is typically removed with about 90% efficiency.[8] Thus the RO unit cleanup system kinetics terms take the form:

$$-\ 0.90\frac{\dot{V}}{V}R \qquad \text{(eq. 3-26a)}$$

for the pool reactive silica kinetics Equation 3-5, and

$$-\ 0.99\frac{\dot{V}}{V}P \qquad \text{(eq. 3-26b)}$$

for the pool polymer silica kinetics Equation 3-7.

3.8.4 Pool Dilutions

During outages the spent fuel pool fluid volume is allowed to mix to some extent with the reactor water. This mixing may be significant and can be observed in plots of silica versus time as a sudden decrease in spent fuel pool silica concentration at the start of an outage.[4] This can be modeled as an instantaneous exchange of spent fuel pool fluid volume for another at a different (usually lower) silica concentration. It is assumed that the polymer silica concentration in the makeup fluid volume is negligible. As an instantaneous event this model is not invoked in the solution of the kinetics equations. Instead, prior to a kinetics solution step, the reactive and polymer silica levels are adjusted to reflect the dilution as:

$$R(t')=R(t')\left(1-\frac{V_L}{V}\right)+R_L\,\frac{V_L}{V} \qquad \text{(eq. 3-27a)}$$

and

$$P(t')=P(t')\left(1-\frac{V_L}{V}\right) \qquad \text{(eq. 3-27b)}$$

where

t' = a time infinitesimally later than t
V_L = volume of the dilution [liters]
V = volume of the pool [liters]
R_L = mass of reactive silica in the dilution [mg]

As an example, suppose a user's spent fuel pool silica data indicated a drop from 10 ppm to 5 ppm in a $1 \cdot 10^6$ liter pool during an outage when the pool water was allowed to mix with the reactor water and be cleaned up by the reactor water cleanup systems. The user could model this as an instantaneous dilution with clean (0 ppm) water. Solving Equation 3-28 for the dilution volume V_L given $R_L = 0$ gives:

$$V_L = V\,(1 - R(t') / R(t)) = 1 \cdot 10^6\,(1 - 5 \text{ ppm} / 10 \text{ ppm}) = 5 \cdot 10^5 \text{ liters}$$

Note that the units for the term $R(t') / R(t)$ cancel (the pool volume remains constant) so that conversion from ppm to mg is not necessary.

3.9 Absorbed Gamma Dose to Boraflex

The silica release rate from a Boraflex panel, modeled by Equation 3-13, was noted to be a very strong function of the absorbed gamma dose. Computing the gamma energy deposition to a Boraflex panel from a spent fuel assembly is a two step process:

1. Compute the gamma source term for the particular type of spent fuel assembly; then,

2. Compute the gamma energy deposition from the fuel assembly to each neighboring Boraflex panel in the spent fuel rack geometry.

It is impossible to perform these calculations for every panel of Boraflex in a spent fuel pool that is irradiated by any number of neighboring spent fuel assemblies in a reasonable amount of time. Thus, as described subsequently, a simplified and streamlined calculational procedure was developed by calculating fits with respect to variables of interest based on a large series of parametric calculations.

3.9.1 Methodology

The models used are based on

- correlations of fuel gamma source strength versus fuel operational parameters and cooling times for both PWRs and BWRs,

- correlations of gamma energy deposition rates with water and stainless steel thickness between the fuel and the dose point, and

- an analytical integration routine to compute the cumulative gamma dose as a function of fuel residency time in the racks.

ORIGEN[17] was used to develop multigroup gamma sources, principally as functions of

- reactor spectrum (e.g., BWR, PWR),
- discharge burnup (6 GWD/MTU to 62 GWD/MTU),
- power density (30% to 150% of nominal), and
- cooling time (1 day to 40 years).

All results were normalized to 1 MTU of fuel such that they are generally applicable to all fuel types for a given reactor spectrum. Fuel fission products are the dominant source for gammas, with these and fuel actinides and daughters contributing well over two orders of magnitude more to energy deposition to Boraflex panels than all other sources combined. Thus differences in clad and non-fuel-bearing-components between assembly types were neglected in generating the source terms. Additional sensitivity studies were performed to verify that other parameters, such as fuel impurity concentrations, etc., were negligible.

Next Microshield[18], a shielding code applying a point kernel approximation to gamma transport, was used to develop combined geometric/material attenuation factors. The output from Microshield is the dose rate at a point in rads/hour from a three-dimensional multigroup gamma source in photons/second separated by shields of given composition and geometry. Note that the dose rate as discussed in this report is the actual energy deposited to a point at the center of a Boraflex panel, not a detector response rate. Gamma energy deposition rates were computed for a variety of spent fuel rack geometries, principally as functions of

- water thickness between assembly source and Boraflex center (0cm–100cm), and
- stainless steel thickness between assembly source and Boraflex center (0cm–10cm).

It was found that Boraflex panels and identical thicknesses of water have sufficiently similar spent fuel gamma spectrum attenuation characteristics to use the water fits to model attenuation through Boraflex panels.

The spent fuel rack geometries modeled only include “face-on” contributions of assembly source to Boraflex panels. That is, only immediately neighboring assemblies with source faces that are parallel to the Boraflex panel are assumed to have a significant contribution. This is illustrated in Figure 3-6 for BWR assemblies in an egg-crate type rack; the center horizontal Boraflex panel is assumed to be irradiated only by assemblies in the cells above and below it. This assumption significantly reduces computation time and storage requirements and is valid for most typical spent fuel pool applications.

In the course of developing these attenuation factors it was noted that, for a given source energy group from a given source spectrum, the conversion factor from source strength to dose rate is approximately invariant. That is, the conversion factor for a given spectrum is independent of source assembly burnup, relative power, cooling time, etc. Thus a nominal set of energy group dependent conversion factors for each source spectrum is used. These convert an assembly source strength in photons/second to an energy deposition rate in rads/hour to Boraflex panels in a nominal rack. Subsequently, corrections to the dose rate for source characteristics (e.g., burnup, etc.) are applied. Finally, the dose rate is attenuated for specific rack geometric/material characteristics (e.g., specified thicknesses of water and stainless steel).

The final step in computing the absorbed dose is to integrate the dose rate with respect to time. The energy deposition decay curve was developed by using ORIGEN to calculate decayed source terms and applying those source terms to various rack models. As noted above, the source strength to dose rate conversion factors were found to be approximately invariant with respect to cooling time and rack geometry. Thus, for a given source spectrum, a single fit of the dose rate decay curve can be used for any source/rack combination. The fit was generated as a function of cooling time for nominal source characteristics and nominal rack geometry. This function was then integrated analytically and is scaled by applying the appropriate source and attenuation correction factors.

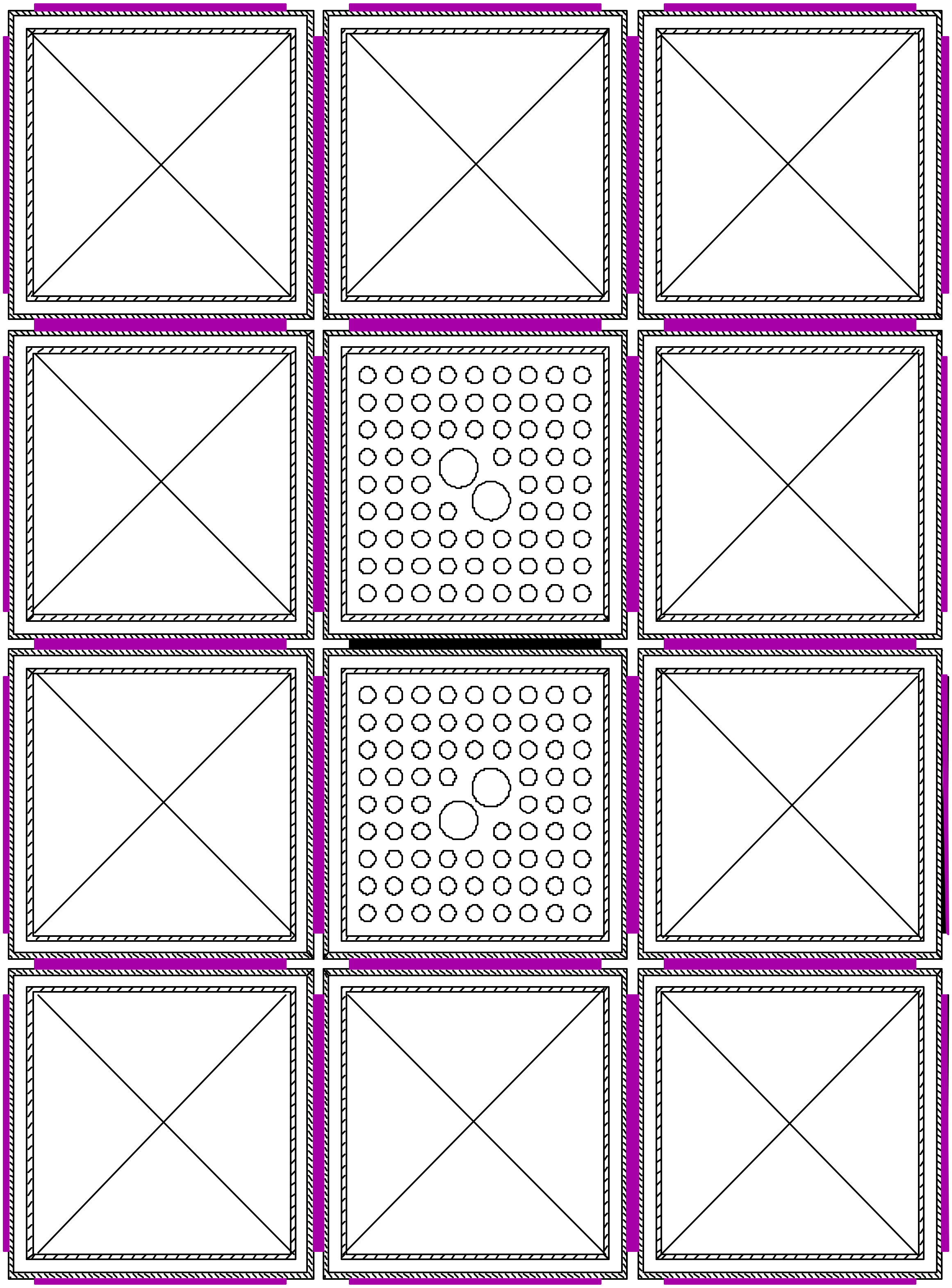


Figure 3-6
Illustration of Assemblies Contributing to Boraflex Panel Absorbed Dose

3.9.2 Implementation

This section details the numerical fits identified above and includes a discussion of ranges of applicability and relative importance. To begin, Table 3-5 lists the energy dependent factors for converting nominal assembly source strength in [photons/ second] to energy deposition rates to a Boraflex panel in a nominal rack in [rads/ hour] for both PWRs and BWRs. The nominal PWR and BWR spent fuel assembly source characteristics are given in Table 3-6. The dose rate is then scaled linearly according to the source density and relative power of the actual assembly type being considered. For example, in a different PWR core the dose rate scales as:

$$I' = I * (\text{rated power [MWth]} / \text{\# assemblies in core}) * (2727\ \text{MWth} / 157)$$

where

I = nominal energy deposition rate [rads/hr]
I′ = core assembly power adjusted energy deposition rate [rads/hr]

Sequences of calculations from 30% to 150% of nominal power confirm the linearity of the correction and it is assumed to be valid for all power levels. Because of the strong effect of this dependence, knowing the assembly end of cycle power sharing is very important to computing the dose rate correctly. Note that the end of cycle power sharing may be significantly different from the cycle average power sharing.

A linear burnup scaling factor is then applied as:

$$I' = I * (1.01316 - 3.44390\text{E-}7 * (\text{burnup in MWD/MTU}))$$

over a range of 6,000 MWD/MTU to 62,000 MWD/MTU. Limitations of ORIGEN prevented accurate simulations of low burnup fuel. Nominally the linear fit is extrapolated back; this is not valid for low burnup fuel, however, as the fission product inventory will not have built up to a quasi-equilibrium. The decrease with respect to burnup is believed to be due to changes in the gamma energy spectrum as fuel species (and hence fission product) inventories change as depletion and breeding occur. It is noted that the absorbed dose rate is a very weak decreasing function of burnup. This is due to a hardening of the gamma source spectrum with burnup and a decrease in the mass absorption coefficients for Boraflex with higher energy gamma photons.

Table 3-5
Gamma Source Strength to Boraflex Energy Deposition Rates for a Nominal Rack

Energy	**[(rads/hr/assembly) / (λ/second/MTU)]**	
[MeV]	**PWR**	**BWR**
9.5	1.363E-10	2.607E-10
7.0	1.180E-10	2.222E-10
5.0	9.875E-11	1.838E-10
3.5	8.086E-11	1.499E-10
2.75	6.856E-11	1.275E-10
2.25	5.899E-11	1.103E-10
1.75	4.792E-11	9.062E-11
1.25	3.337E-11	6.510E-11
0.85	2.107E-11	4.277E-11
0.575	1.149E-11	2.448E-11
0.375	4.779E-12	1.044E-11
0.225	1.701E-12	3.073E-12
0.125	5.676E-13	7.891E-13

Table 3-6
Nominal Source Assembly Characteristics

	PWR	**BWR**
Reactor Rated Thermal Power (MW_{th})	2727.0	2511.0
Number of Assemblies in Core	157.0	724.0
Fuel Loading (MTU/assembly)	0.426	0.1765
Active Fuel Length (in)	144.0	159.0
Assembly Width (in)	8.296	4.963
EOC Power Sharing	1.0	1.0
Burnup (MWD/MTU)	38,200	38,200

Finally, a correction for the reactor operating power versus time prior to shutdown at end of cycle is applied. Limitations of ORIGEN allowed only a few operating power scenarios to be considered; actual operating conditions must be approximated by one of these scenarios as closely as possible. The scenarios are

1. Instantaneous shutdown from a fraction of rated power;
2. A step reduction from one fraction of rated power to another, operation at this new power level for a given number of days, and then an instantaneous shutdown; and
3. Coast-down in power from one fraction of rated power to another over a given number of days, and then an instantaneous shutdown.

The equivalent operating power, P_{eq}, of the reactor at end of cycle is computed according to the scenario selected:

1. $P_{eq} = f_1 \cdot P_{rated} = P_1$
2. $P_{eq} = P_2 + D(T) \cdot (P_1 - P_2)$
3. $P_{eq} = P_2 + D^{0.8}(T) \cdot (P_1 - P_2)$

where

f = the fraction of rated power the reactor is shutdown from
P_1 = the initial reactor power
P_2 = the reactor power T days after P_1
D = a scaled decay curve that reduces the source term from P_1 toward P_2 by the decay over time T of the source
P_{eq} = the constant reactor operating power that yields a source term upon shutdown equivalent to that of the shutdown scenario.

This equivalent operating power is used to scale the source strength with respect to the rated operating power.

3.9.3 Gamma Attenuation

The standard monoenergetic narrow-beam attenuation formula is given by:

$$I = I_0 e^{-\mu x}$$

where

I = attenuated gamma flux
I_0 = unattenuated gamma flux
u = attenuation coefficient
x = thickness of water to attenuate across

An extension to this formula is used to fit calculated attenuations of a spent fuel gamma spectrum through water. The fit takes the form:

$$I = I_0 \left(\frac{C_{0i}}{C_{01}} \right) \left(C_{1_i} e^{-C_{2i}\,(x - x_{0_i})} + C_{3_i} e^{-C_{4i}\,(x - x_{0_i})} \right) / 2K$$

where

I = attenuated gamma flux
I_0 = unattenuated gamma flux
I = fit number
C_{ji} = fit coefficient number j for fit number i
K = fit coefficient
x = thickness of water to attenuate across
x_0 = nominal thickness in fit

Table 3-7 gives the fit coefficients.

Table 3-7
Coefficients for the Fit of Attenuation through Water

Coefficient	fit-1	fit-2	fit-3	fit-4
C_0	39280000	12948007	2161377	496918.1
C_1	1.80834	1.34500	1.43436	1.04778
C_2	0.11211	0.07312	0.06271	0.05148
C_3	0.19127	0.66762	0.56703	0.95200
C_4	1.17736	0.17007	0.12083	0.08778
X_0	1	10	30	50
K	1.08770			

The attenuation through stainless steel takes a somewhat different form:

$$I = I_0 \, e^{-C_1(x-x_0)} e^{-C_2(x-x_0)}$$

where

I = attenuated gamma flux
I_0 = unattenuated gamma flux
C_i = fit coefficients, i = 1, 2
x = thickness of stainless steel to attenuate across
x_0 = nominal thickness in fit

Table 3-8 gives the fit coefficients.

Table 3-8
Coefficients for the Fit of Attenuation through Stainless Steel

Coefficient	Value
C_1	0.485096
C_2	0.005053
X_0	0.2286

3.9.4 Energy Deposition to Boraflex

For calculating absorbed dose rates to Boraflex the "energy absorption coefficient", μ_{en}, is the factor to use. It represents the probability of energy being transferred to a given absorbing material as a given energy gamma interacts along its path through the material. As gammas pass through a material, their interaction with the material produce electrons which lose energy by creating ion pairs; it is assumed that all of the energy of interaction goes into creating ion pairs. This leads to an absorbed dose rate given by the equation:

$$\begin{aligned} \mathrm{DR\ rad/hr} &= \phi \ \mathrm{gammas/cm^{2}\cdot sec} \cdot \mathrm{E\ MeV/gamma} \\ &\quad \cdot (\mu_{en}\ \mathrm{cm^{-1}} \ / \ \rho\ \mathrm{g/cm^{3}}) \cdot 1.6 \cdot 10^{-13}\ \mathrm{J/MeV} \cdot 1\ \mathrm{Gy \cdot kg/J} \\ &\quad \cdot 100\ \mathrm{rads/Gy} \cdot 3600\ \mathrm{sec/hr} \cdot 1000\ \mathrm{g/kg} \end{aligned}$$

Attenuation and absorption coefficient data was obtained from Reference 21. Linear interpolation was used to calculate coefficients at energies other than those given in the handbook. Typically the coefficients are reported as mass energy-absorption coefficients, given by (μ_{en}/ρ) cm^2/g where ρ is the material density in g/cm^3. The following formula was used to calculate coefficients for material compositions made up of N elements, with w_i weight percent of element i:

$$(\mu/\rho) = \sum_{i=1}^{N} [(\mu/\rho)_i w_i]$$

For Boraflex, the compositions are given Reference 2, and the computed mass energy-absorption coefficients are presented in Table 3-9.

Table 3-9
Mass Energy-Absorption Coefficients for Boraflex.

Gamma Energy (MeV)	Absorption μ_{en}/ρ (cm^2/g)
9.5000	0.0149
7.0000	0.0160
5.0000	0.0175
3.5000	0.0198
2.7500	0.0214
2.2500	0.0228
1.7500	0.0246
1.2500	0.0268
0.8500	0.0288
0.5750	0.0298
0.3750	0.0296
0.2250	0.0278
0.1250	0.0271

4

PROGRAM DESIGN

This section describes the RACKLIFE program design specifications, including:

- objectives—against which the final program is requirements tested;
- syntax—the language the program is coded in;
- environment—the computer hardware and system software requirements for developing and running the program
- human factors—how the user will interface with the program
- performance—performance goals and how they are achieved
- maintenance—program design for fixes, enhancements, and upgrades while maintaining configuration control.

Each subsequent section addresses one of these areas of specification.

4.1 Software Objectives

The objective of the RACKLIFE program is to solve the Boraflex dissolution kinetics models discussed in Section 3 in a user defined spent fuel pool. Specifically, RACKLIFE will compute the irradiation and dissolution of Boraflex neutron absorber panels as used in spent fuel pool storage racks. The effects of spent fuel pool environment and cleanup systems on Boraflex integrity are included in the model, as are geometric characteristics particular to specific spent fuel rack cells and LWR fuel designs. The output data can be presented graphically in a format to facilitate decision making on the optimal shuffling of discharged fuel in the pool and desirable pool operating characteristics to preserve Boraflex integrity. ASCII output files can be generated for use by spreadsheet, wordprocessor, database, and other external user software.

4.2 Syntax

RACKLIFE is programmed using ANSI/ISO standard Fortran 90 and a third party input/output library. It was developed under IBM OS/2 3.0 (Warp). Lahey Computer Systems developed LF90[19], a complete implementation of the ANSI and ISO Fortran 90 standards. The compiler uses processor-specific microcode for faster execution speeds on Intel 486, Pentium, and Pentium Pro CPUs. LF90 uses a 32 bit memory manager developed by Phar Lap that takes full advantage of 32 bit CPUs for maximum performance. Lahey compilers have been successfully used throughout the nuclear industry, including, for example, the SCALE software package which uses KENO for criticality safety.

Interactive Software Services developed INTERACTER, a "portable Fortran user-interface development system".[20] This set of Fortran libraries has extensive cross-platform support, allowing applications to be recompiled and run on a large variety of computers (PCS, workstations, mainframes) under many different operating systems without modification. At this time RACKLIFE has only used the PC/DOS INTERACTER libraries.

With only one exception RACKLIFE has been coded using standard conforming Fortran 90 syntax. The exception is in subroutine IOSTAT_Error (described in Section 5); this subroutine displays text descriptions of operating system errors specific to DOS/Intel PCS. Additional code, currently commented out, is included to bypass the non-standard-conforming code should the need arise.

4.3 System Environment

RACKLIFE is intended for use on IBM-compatible Intel 386/387, Intel 486DX, Intel Pentium, or Intel Pentium Pro PCS running IBM or MS-DOS 5.x or 6.x. An Intel math co-processor is required. RACKLIFE has not been tested with other vendor's CPUs or math co-processors. RACKLIFE was developed under OS/2 3.0 and is known to work in an OS/2 DOS Full Screen Session with the DPMI_MEMORY_ LIMIT setting set to 16 or higher. RACKLIFE has not been tested in a Windows 3.x DOS box or on a network. Limited usage under Windows 95 and Windows NT DOS boxes have been successful.

The PC monitor and graphics card must support color VGA (640 x 480 x 16 colors mode). The system must have 16 MB of usable RAM available to DOS and the program. RACKLIFE and its associated program files occupy less than 2 MB of hard drive space; however, a typical set of input files occupies 4 MB and just one typical state point (results) file can occupy upwards of 4 MB. It is thus recommended that the system have at least 40 MB of free hard drive space. RACKLIFE has not been tested with compressed drives.

4.4 Human Factors

RACKLIFE is navigated by sequences of menus. The use of menus allows users to familiarize themselves with the program using a “flow chart” paradigm. Menu selections lead to either a sub-menu or a new screen specifically oriented to the menu operation selected by the user. Operations are generally associated with input, execution, or output, though some execution operations involve all three.

Input operations are performed under nearly identical interface conditions. The input forms generally have the same appearance and use the same keys for navigation, help, input, saving, and exiting. The key assignments are detailed in the User’s Manual (in Appendix B) and appear at the bottom of every input screen. Input is performed in an input form the user can edit, where labeled input fields and field specific help windows guide the user. The input forms also perform checks for validity of input and, if applicable, cross checks with other input fields.

Execution operations are either quick or very long in duration. Quick operations are indicated by a “Wait” window, a message displayed indicating that RACKLIFE is actively performing the operation and has not simply “hung up”. Creating pool geometry files and dose-only calculations are examples of quick operations that should take less than a minute or so. State point calculations are very long in duration (on the order of hours); activity is tracked in a low-intensity text window on a black screen to avoid screen “burn-in” and so as not to distract the user from other work.

Output operations include:

- displays of qualitative and quantitative data in pool and module maps;
- plots of time dependent (pool state) data; and
- ASCII files of quantitative data written to the hard drive.

The displays look identical to the displays used for pool geometry input so the spent fuel pool orientation and “look” is familiar to the user. The use of graphics of pool module layouts facilitates decision making on the optimal shuffling of discharged fuel in the pool to preserve Boraflex integrity. Summary results are also provided with the displays for comparison. The ASCII files, referred to as “print” files are not actually output to a printer for two reasons. First, most users will import the data into another software package (e.g., a spreadsheet or wordprocessor) for annotating before printing. Second, this precludes having to provide and install printer drivers for the myriad printers that users may have.

User help in RACKLIFE comes in three forms: program help, action help, and procedure help. The program has a help system that contains much of the User’s Manual organized by menu selections and tasks to perform. This system is accessible from the title screen (so that help may be viewed without being required to formally enter the program with a scenario name), as well as from the main menu. Action help is available for any user action by pressing the <F1> function key before committing to the action. For example, when about to input data into an input form data field, pressing <F1> will display a help window with information specific to that input field. Procedure help is available from the "File / Start" menu selection. It assesses the files created under the current scenario name and advises the user on how to proceed to the final goal of executing a state point calculation.

4.5 Performance

The amount of data that RACKLIFE can generate is potentially enormous. Consider the largest pool of 5,000 rack storage cells with around 10,000 panels of Boraflex. Data on silica (reactive, colloidal, deposited), environment (temperature, pH, etc.), irradiation, boron-carbide loss, etc., must be saved 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 panels and the pool. Thus RACKLIFE has been organized to be selective in its output of all of this data. (It has also been organized to achieve a balance between computational speed and memory requirements, but this should be transparent to the user.)

In general users may have as many data records in a data file as their hard drive will permit. The memory RACKLIFE uses is dynamically allocated, which means that storage arrays are allocated and deallocated as they are needed—they are not stored permanently. This adds some overhead to execution time but greatly reduces the amount of memory that is required at any particular point-in-time.

In the event that users generate so much data that they exceed the available memory (RAM) of their system, RACKLIFE will use their hard drive as if it were additional memory. This will slow down computations significantly but guarantees that the desired computations can be performed.

The RACKLIFE executable occupies approximately 1.5 MB of hard drive space and expands in RAM even larger. A number of factors contribute to the large size; some of the major factors are:

- the INTERACTER libraries linked for user-interface development produce very large amounts of code.
- The Phar Lap memory manager is bound into the executable for easy distribution.
- There is some redundancy in coding computation-intensive parts of the program if it significantly increases the rate of computation.
- The program has a large number of error-checking and memory allocation routines.

- Most of the supporting files have been compiled into the program. This includes help text files which take up a large amount of space. By integrating these files memory usage can be tracked more easily.

4.6 Maintenance

RACKLIFE is developed and distributed by Northeast Technology Corp (NETCO) for EPRI. The program, supporting files, and limited technical support are free to all members of the EPRI Boraflex User's Group. NETCO can be contacted at:

Northeast Technology Corp.
UPO Box 4178 (Street Address: 26 Pearl Street, zip code: 12401)
Kingston NY 12402
Phone: 914-331-8511 (USA, Eastern Time)
Fax: 914-331-8521

New copies of RACKLIFE are sent with a copy of the "User's Manual", which is also appears as Appendix B of this report. In subsequent releases of RACKLIFE after 1.00, "User Notes" will be distributed with installation instructions, bugs fixed (and their impact on users), enhancements added, and a "Questions and Answers" section which includes some of the questions received by Technical Support deemed relevant to the RACKLIFE user community.

The project managers for the EPRI Boraflex User's Group are Dr. Odelli Ozer and Mr. Ray Lambert. They can be contacted at:

Electric Power Research Institute
3412 Hillview Avenue (PO Box 10412)
Palo Alto CA 94304
Phone: 415-855-2089 (USA, Pacific Time)
Fax: 415-855-2774

5

PROGRAM EXPRESSION

This section describes the program structures and data utilized to achieve the software objectives described in Section 4. The structures (subroutines, functions, etc.) used to effect the program logic are grouped into quasi-object-oriented modules and groups of subroutines. The modules and groups are summarized first. Next the control of interfaces between the modules and groups are reviewed. Then the input and output aspects of the various groups are covered. Finally, program parameters are detailed.

When referring to a RACKLIFE data file, the term “scenario” will be used to denote any valid scenario name as selected by the user. Thus “scenario.GEO” refers to any pool geometry data file.

5.1 Structures

This section summarizes the modules and subroutine groups that are compiled and linked to make the RACKLIFE executable.

The RACKLIFE Subroutine Group

The program starts with the RACKLIFE.F90 subroutine group. This contains the main program structure, Racklife, and the primary user interface subroutine, Menu. Auxiliary structures associated with Menu are also in this group.

Racklife is simply a sequence of initialization routines and followed by a call to Menu. The initialization routines include:

- initializing the interface to the INTERACTER library,
- accessing the embedded program version and serial numbers,
- displaying the title screen with the option to enter the program help system,
- verifying that all required program files are present, and
- user input of the scenario directory and name.

Once Menu is executed the program will continue to run until the user selects the menu option to exit the program. When this occurs INTERACTER's control of the keyboard and screen input/output is terminated and the program stops, returning the user to the DOS prompt. The only exception is the "Restart" menu option which returns to subroutine RACKLIFE and begins execution from where it verifies that all required program files are present.

The Common_Variables Module

This module makes program variables commonly available by use association. (For those familiar with Fortran 77 constructs this module essentially acts as a common block.) It also establishes program parameters, such as maximum array bounds. All initialization data is covered at the end of this section.

The Calendar Module

This program independent module provides a set of calendar routines for basic date and time manipulation and tracking. It is based on storing the date/time as a double precision real number of days since 1900/01/01 at 00:00:00. This method of tracking time is accurate to much better than a millisecond so computational round-off can be ignored in this application.

The Text_Window_Control Module

This program independent module acts as an interface with the INTERACTER I/O library routines, providing a simplified method for controlling screen initialization, display attributes, and some error control. This module also controls many aspects of text window control that are generic across the program. Such text windows are often used for introduction, help, error/warning, and wait instructions. Help windows are black text on cyan background and provide help on the currently displayed input form and/or the currently active input field in an input form. Help windows are separate from the "help system", which is discussed below under "The Help Module". Error, warning, and wait windows are red text on grey background. Error windows indicate that the current operation initiated by the user can not continue. Warning windows allow the current operation to continue, optionally with a required Yes/No response. Wait windows are only displayed as long as the user must wait for an operation to be completed.

Error control is facilitated by subroutine IOSTAT_Error. If an operating system error occurs during an external file operation (e.g., opening, reading from, or writing to a RACKLIFE data file on a hard drive), this subroutine will display an error message specific to the operating system (DOS) and/or processor (i486, Pentium, etc.). Because this message is specific to the operating system and processor, part of the routine is necessarily non-standard-conforming Fortran 90. To maintain standard conformance an alternate code fragment is provided that can be un-commented to circumvent the call to the Lahey Fortran 90 extension subroutine that retrieves the error message.

The FMUSER Module

Each subroutine in this module acts as a powerful hook into the form editor capabilities provided by the INTERACTER I/O library routines. Each is tailored to a particular type of input form presented in RACKLIFE. Each time a user moves to another input field or presses an action key, these routines can perform special processing “on the fly” rather than waiting until the user is finished filling out an input form. This allows input fields to be cross checked, warning and/or error messages to be displayed, and time-saving actions to be performed (such as automatically issuing a “next-line” command when the user “tabs” off the end of a previous input line).

The Common_Geometry Module

This module establishes a common I/O interface to the pool geometry files and graphics routines to display the pool and racks, including selecting a rack module to display. This includes subroutines to read data from a geometry data file (scenario.GEO), select a module (e.g., for detailed display), and draw the pool.

This module also defines derived types `module_data`, `cell_data`, and `panel_data`, which are made available by use association. These contain the necessary geometry data to orient and display rack modules, rack cells, and Boraflex panels, respectively. Orientation includes position (x, y coordinates) and facing (north, east, south, west), identification of neighboring cells or panels, and quantity of intervening material (stainless steel, water).

The Common_Silica Module

This module establishes a common I/O interface to the state point and pool state data files. It also defines derived types associated with state point and pool state data which are made available by use association. The derived type definitions are

• type_silica	silica components (polymer, reactive), release rates (λ), and equilibrium concentration (R_{eq}) for each panel and the pool;
• type_environment	temperature, pH, inhibitor concentration, and water volume in each panel cavity and the pool;

type_panel_state	absorbed gamma dose, surface area, and fraction of boron carbide lost for each panel; and
type_rate_constants	kinetics equations rate constants

Variables silica, environment, panel_state, and rate_constant are typed using the above respective derived type definitions, are made available by use association, and are specified as allocatable arrays for memory optimization.

The Compute_Silica_Source_Term Module

This module embodies the Boraflex silica source term equations as described in Section 3, Equation 3-3 et seq. The subroutine Compute_Lambda computes the silica dissolution rate in mg/day as an array operation for all Boraflex panels in the pool. The subroutine Compute_Req computes the reactive silica equilibrium concentration for the pool and all panel cavities in ppm SiO2, also as an array operation for all Boraflex panels in the pool.

The Initialize_Files Module

The subroutines in this module are involved with initializing RACKLIFE, selecting files, viewing files, and providing a common I/O interface to the scenario data file (scenario.DAT).

The Pool_History Module

This module establishes a standard structure for the input, storage, and editing of pool history data. It includes derived type definition pool_history_data and makes it available by use association. Input includes field by field input into a standard form and import from an external ASCII file. Editing includes both altering and deleting data already input. Because the same standard input form is used to enter initial conditions, additional subroutines are included to introduce and provide input field specific help for entering initial conditions, as well as to write the initial conditions to the pool history data file (scenario.HIS).

The Input_Pool_Geometry Module

This module controls the creation of a pool geometry data file (scenario.GEO). This is effected from subroutine Pool_Geometry_Menu, which presents a menu of sequential creation options to build the geometry of a spent fuel pool and its associated spent fuel storage racks.

The Assembly_Types_Database Module

This module provides the interface between RACKLIFE and the program independent assembly types database, ASBLYTYP.DB. This database is discussed in Appendix B of this report, the RACKLIFE User's Manual.

The Module_Cycle_Data Module

This module controls the input of cycle data to a reactor data file (REACTOR.Rnn). It includes derived type definition `reactor_cycle_data`, available by use association. The module also provides function `Decay_Factor` which computes the reduction in spent fuel gamma source strength due to decay (over time).

The Module_Reactor_Data Module

This module controls the creation and selection of a reactor data file (REACTOR.Rnn) and the input of reactor data to the file. It includes derived type definition `reactor_data`, available by use association.

The Assembly_Database Module

This module establishes a standard structure for the input, storage, and editing of assembly database data. It includes derived type definition `assembly_data` and makes it available by use association. Input includes field by field input into a standard form and import from an external ASCII file. Editing includes both altering and deleting data already input. Subroutine `Calculate_Assembly_Source` is used to compute the unattenuated gamma source from an assembly, corrected for assembly data such as power sharing and burnup.

The Shuffle_Assemblies Module

This module establishes a standard structure for the input, storage, and editing of assembly shuffle data. It includes derived type definition `shuffle_data` and makes it available by use association. Input includes field by field input into a standard form and import from an external ASCII file. Editing includes both altering and deleting data already input.

The Cleanup_System Module

This module establishes a standard structure for the input and storage of cleanup system data, as well as the computation of coefficients for the cleanup models.

The Output_Data Module

This module establishes a standard structure for the output of state point, pool state, and dose-only data, as well as pool geometry data and shuffle data for the purpose of verifying input.

The Dose_Calculation Module

The subroutines in this module provide a sequence of steps to calculate the integrated absorbed dose to a Boraflex panel from spent fuel assemblies. Subroutine Compute_Dose computes the dose to all of the panels in the pool as a dose-only calculation. Dose computations during state point calculations are in-lined in subroutine Compute_State_Point (in module Compute, described below) to increase computation speed. Subroutine Attenuate_Water attenuates the assembly source calculated in subroutine Calculate_Assembly_Source (in module Assembly_Database, described above) through a given thickness of water shield. Subroutine Attenuate_SS continues the attenuation through a given thickness of stainless steel. Finally, the dose is integrated with respect to time in subroutine Integrate_Dose_Rate.

The Escape_Coefficient_Calc Module

This module is devoted to computing a best estimate of the escape coefficient. It scans the scenario files to determine that the user has all of the necessary files to perform a state point calculation and that there is sufficient historical silica data in the pool history file. From this data it calculates a best estimate of the escape coefficient.

The Compute Module

This module is devoted to performing a state point calculation. The principal subroutine is Compute_State_Point, which performs the computations and displays a window tracking progress toward the result. A considerable amount of computational code is inlined into this subroutine (parts of the dose calculations, for example) to increase computation speed. Subroutine Input_New_State_Point displays an input form to commence a state point calculation. The remaining subroutines perform checks and routine array operations such as interpolations and sorts to support the computation process.

The Help_System Module

This module establishes a standard help system for the RACKLIFE program. This is different from help windows which are context sensitive; the help system is accessible only from the title screen and the main menu. It contains menu screens with selectable menu buttons for navigating help topics, and text screens with multiple pages of information.

The Embed_Serial_Number Subroutine Group

This subroutine group contains only one subroutine: Embed_Serial_Number. This subroutine contains user serial number and program version number information which is easily modified, recompiled, and linked with the rest of the program module library and object files to customize each program for unique and configuration controlled distribution.

5.2 Input and Output

Two modes of input are used in RACKLIFE: graphical and text. Graphical input is only used to draw the spent fuel pool perimeter and the location of modules in the pool in creating the pool geometry data file. Dimensional data is prompted for as text during the drawing process. The rest of the data input is handled as text, either by direct entry to prepared input forms, or by importing an ASCII file created outside the RACKLIFE program.

Input forms are specific to the following types of data:

- reactor data
- cycle data
- assembly data
- assembly shuffle data
- pool history data
- cleanup data
- scenario data

Program limits and requirements on the data prompted for are summarized at the end of this section, and are described in Appendix B, the User's Manual. If user input conflicts with previously input data an error message is displayed. If the input is not within the limits the input is rejected and the program will not continue until acceptable input is provided or the user exits the input form. In general, the <F1> key will bring up help information, including valid input ranges, specific to the current input field.

The formats for import files are covered in detail in the User's Manual, included as Appendix B of this report. If the user has a large amount of data to input and can put it in electronic form (e.g., on diskette), import is the most effective approach. The file import routine reads lines of data from an ASCII text file you created outside RACKLIFE and loads each one into an input form just as if it had been typed into the form by hand. Each import line is editable as it is displayed. When the user is satisfied that the line of data is correct, the <F10> key enters the line just as for hand entry of the data. Thus, if no editing is needed, one can import a file by holding down the <F10> key until the import is completed, causing an immediate return to the main menu.

By processing each line of the import file in the input form all of the usual error checking is performed: individual lines can be rejected without rejecting the rest of the file. When a line is rejected (or if the user chooses not to import a line), pressing the <F9> function key will "skip" that line and continue. One can also press <Escape> to skip all of the remaining lines in the import file. All skipped lines are copied to an error file with the name "scenario.ERR". This file has the same format as the import file, allowing the user to correct it outside of RACKLIFE, rename it with an ".ADD" extension, and treat it as additional import data.

5.3 Program Data

As noted above, module Common_Variables is used to initialize the maximum permissible size of arrays. This allows for easy modification if the array bounds are insufficient for a specialized application. Table 5-1 lists the internal limits on various data arrays.

The number of entries in the assembly database, assembly shuffle, and pool history files is not limited. It is possible that one could have enough assemblies or shuffles or history points defined to exceed the 16 MB of memory suggested to run the program. If this occurs, RACKLIFE will use a virtual memory manager to use the hard drive as additional memory. While this will allow computations to continue, it will cause a significant slowdown of the rate of progress.

Table 5-1
Program Array Dimensions

Maximum number of files in a directory	300
Maximum length of data cards in import files	180
Maximum length of data cards in all non-import files	512
Maximum number of reactor data files	99
Maximum number of pool walls in drawing the pool perimeter	99
Maximum number of moves to locate a rack module	50
Maximum number of rack modules in the spent fuel pool	30
Maximum number of rows in a rack module	120
Maximum number of columns in a rack module	120
Maximum number of rack cells in the spent fuel pool	5,000
Maximum number of Boraflex panels in the spent fuel pool	10,000

Tables 5-2 to 5-7 review the data that can be input to RACKLIFE, identify the ranges of valid input, and summarize what data is required, optional, and recommended.

Table 5-2
Reactor Data Summary

Data	Valid Range	Required?
Reactor number	1-99	yes
Reactor type	from menu	yes
Number of assemblies in core	1–999	yes
Name or description	50 characters	no, recommended

Table 5-3
Cycle Data Summary

Data	Valid Range	Required?
Cycle number	1–99	yes, starting cycle only
Rated thermal power [MWth]	>0	yes
EOC shutdown day	1–31	yes
EOC shutdown month	1–12	yes
EOC shutdown year	(19)51–(20)50	yes
Shutdown power profile number	0–3	yes
Profile 1 P1%	0–150	yes
Profile 2 P1%	0–150	yes
Profile 2 P2%	0–150, <P1	yes
Profile 2 T2 [days]	>0	yes
Profile 3 P1%	0–150	yes
Profile 3 P2%	0–150, <P1	yes
Profile 3 T2 [days]	>0	yes

Table 5-4
Fuel Data Summary

Data	Valid Range	Required?
Assembly ID	8 characters	yes
Fuel assembly type	from menu	yes
Fuel loading [MTU]	0–9.9	no
Enrichment [w/o 235U]	0–9.9	no
Burnup [MWD/MTU]	6,000–62,000	no
EOC power sharing	0–9.9	no, recommended
Discharge cycle number	1–99	yes

Table 5-5
Fuel Shuffle Data Summary

Data	Valid Range	Required?
Pool ID	2 characters	yes, if used
Region ID	2 characters	yes, if used
Row ID	2 characters	yes
Column ID	2 characters	yes
Assembly ID	8 characters	yes
Placement day	1–31	yes
Placement month	1–12	yes
Placement year	(19)51 – (20)50	yes
Removal day	1–31	yes
Removal month	1–12	yes
Removal year	(19)51 – (20)50	yes

Table 5-6
Pool History Data

Data	Valid Range	Required?
Measurement day	1–31	yes
Measurement month	1–12	yes
Measurement year	(19)51 – (20)50	yes
Reactive silica [ppm]	0–999.9	no*, recommended
Total silica [ppm]	0–999.9	no
Bulk pool temperature [°F]	60–150	no*, recommended
pH	3–10	no*
solubility inhibitor [ppm]	0–99.9 [ppm]	no

* input is required for initial conditions

Table 5-7
Other Input Data Limitations

Data	Valid Range
Cleanup system flow rate [gpm]	0–1500

6

SOFTWARE IMPLEMENTATION TESTING

This section reviews the methods by which the RACKLIFE software is tested. Testing is divided into four categories; as described below along with the objectives of each test category.

- Unit Tests

Does the program unit (subroutine, function, or module) do what it is coded to do. For example, does the computed reactive silica equilibrium concentration match the laboratory data taken at 85°F and 150°F to within model accuracy.

- Algorithm Tests

Can the program code be relied on outside of the test domains. For example, while the computed reactive silica equilibrium concentration may match the laboratory data at two temperatures, does it smoothly and accurately interpolate and extrapolate to all temperatures that a user may input.

- Integration Tests

Does the program as a whole do what it is supposed to do when all of the program units are put together. For example, does the silica source term, which depends on the reactive silica equilibrium concentration, properly reference and interface with the subroutine that computes the reactive silica equilibrium concentration. Essentially, these tests involve interface checking between program units.

- Requirements Test

Does the program satisfy the software objectives detailed in Section 4.

6.1 Unit Tests

All subroutines, functions, and modules were tested periodically during the development process. The Lahey Fortran 90 compiler comes with a run-time debugger that can be used on a line-by-line basis to set variables and compute results. While this allows great flexibility in testing individual lines of code, it is a slow process and it is impossible to test every possible execution path with even a few combinations of input data in this manner. While not specifically unit tests, debug testing of key execution paths with specific input data sets of interest during development lends confidence to the unit testing process. The testing of groups of important computation units is covered below.

Units that Track Time

As noted above, module Calendar contains all of the subroutines and data for tracking time in RACKLIFE. The two main units, function Datetime_To_Days and subroutine Days_To_Datetime, can be used to test each other. A test program was developed to cycle through all calender dates and selected times from 1 January 1951 through 31 December 2050. These dates were first passed to Datetime_To_Days to be converted to an elapsed number of days from 1900/01/01 0:00:00, and then converted back to a date and time using Days_To_Datetime. The result was checked against the input to verify that the routines were accurate. The times tested included one second after and before midnight to insure precision. Leap days (29 February) were confirmed using published calendars.

Other calendar routines, such as for computing the day of the week, do not impact RACKLIFE's calculations and were only verified for a selection of dates using published calendars.

Units that Compute Geometry

RACKLIFE beta testers provided spent fuel pool geometry data that was input to RACKLIFE. The results (from the scenario.GEO file) were then compared by hand with the data to insure that the geometry was being interpreted correctly. In addition, a number of fictitious pool and rack geometries were created to exercise each geometry option combination and again verified by hand. The only discrepancies noted were due to round off of the single precision variables used to store geometry data, typically because of conversions from inches to fractions of a foot; all of these were negligible.

Units that Compute Absorbed Dose

As discussed in Section 2, prior to the development of RACKLIFE the spreadsheet applications PWRDOSE and BWRDOSE were developed to compute the dose from an assembly to a Boraflex panel. These spreadsheets were tested prior to distribution as part of Reference 2; verification and validation information for the spreadsheet is included in the same reference. The RACKLIFE code uses the same algorithms and data used to develop the fits in the spreadsheets. To facilitate computation and extend the range of applicability the fits were redeveloped for RACKLIFE, resulting in differences of no more than about 3% in absorbed dose calculations, well within the uncertainty of the fits. Consequently, the dose calculations were tested by comparing RACKLIFE results to the spreadsheet results for a variety of input data.

Units that Compute the Silica Source Term

As discussed in Section 3, parameters for the silica source term models are based on laboratory data presented in Appendix A. A special test program was written to verify that the subroutines `Compute_Lambda` and `Compute_Req` returned the correct Boraflex silica release rate and reactive silica equilibrium concentration, respectively, for a variety of input data, as predicted by the laboratory testing. The RACKLIFE program can not easily be used to directly simulate the laboratory data. This is because the laboratory tests were performed by immersing a Boraflex sample into a single volume of fluid; the RACKLIFE kinetics model is a two volume model, representing each Boraflex cavity in the racks as a volume in communication with the bulk pool water volume via the escape coefficient.

Units that Compute the Cleanup System Performance

The models discussed in Section 3 for the cleanup system are based on analytical and heuristic cleanup system performance models. As noted in Section 3, vendor data is both scarce and proprietary, and there is no laboratory data to compare results with. For this reason the cleanup system subroutines are tested using a special test program that exercises all cleanup system options for a variety of input data and compares the results with those obtained by hand calculations using the same models.

Units that Solve the Silica Kinetics Equations

The `Compute_State_Point` subroutine and its associated subroutines in module `Compute` are critical to solving the silica kinetics equations and so are rigorously tested. Testing includes prescribed debug sessions to test certain sections on a line-by-line basis, as discussed above. Special test computations are also used to insure that, for select input data sets, the solution scheme maintains precision and accuracy throughout computation.

6.2 Algorithm Tests

As discussed in Section 3, all fits were developed such that they would be continuous in the domain of all acceptable input data. This does not mean that there are no discontinuities in the slope of the fits; some fits are prescribed over subintervals and do not necessarily match slope at the subinterval boundaries. However, continuity of the fit guarantees that the solution output will vary continuously with continuous input data. Thus the fits can be relied on over all acceptable input domains.

The various fits are only used to determine parameters in the silica kinetics equations. As discussed in section 3, to solve these equations over time a finite difference scheme is applied. This discontinuous solution scheme, by its very nature, introduces discontinuities into the results. These discontinuities become relatively smooth as the finite difference step size is reduced so that, for smooth input data, any major discontinuities observed in output would be indicative of coding errors that are otherwise trapped in the unit tests. Running tests with a reduced step size also serve to confirm that the original step size selected is sufficient to maintain acceptable accuracy of the solution.

6.3 Integration Tests

As noted above, program integration testing is essentially a test of program unit interfaces to insure that units call each other and pass data in appropriate formats. This is greatly facilitated by the use of Fortran 90 as a programming language (as discussed in Section 4). Fortran 90 contains provisions for explicit data type declaration, variable passing intent, and explicit interface requirements, with all checks performed at compile time. Thus all syntactic interface problems can be handled during the software development phase.

Dose-only calculations provide additional means of integration testing. As discussed above, dose calculation program units were tested by comparing RACKLIFE results with results from a spreadsheet template, described in Section 2. Using data provided by beta testers, RACKLIFE models were developed and executed for dose-only calculations and compared with results obtained by the beta testers from the spreadsheet template. This tested much of the integrated program code, including calendar, geometry, data IO, and dose calculation routines. The comparisons were generally acceptable. Major differences were attributable to simplifying assumptions made by users to save time in developing input data for the spreadsheet template. The spreadsheet template was designed to calculate the dose to one panel at a time and so was time consuming when used repeatedly for a large number of panels. Because the amount of calculational effort using RACKLIFE to perform a dose calculation for all panels in the pool is almost negligible, users tended to spend the time saved collecting more accurate input data.

Finally, the code has been and continues to be compared with results generated by EPRI's BADGER (discussed in Section 2). When this report was written, BADGER had been used in an EPRI sponsored demonstration program.[5] The data compared well with the RACKLIFE predictions for boron carbide loss; however, only a small number of panels were tested and, of those available for testing, the highest dose was only $4.3 \cdot 10^9$ rads. RACKLIFE will continue to be compared to BADGER test results in the future.

6.4 Requirements Test

The objective of the RACKLIFE program was discussed in Section 4: to solve the Boraflex dissolution kinetics models in a user defined spent fuel pool. Section 3 detailed the kinetics models as well as additional models to convert user input data to the coefficients and parameters of the kinetics models. For example, a model to convert temperature and pH input data to a reactive silica equilibrium concentration was discussed. These models are generally based on

- experimental models specific to Boraflex dissolution in water,
- analytical models developed in the literature,
- quantitative heuristic models developed with industry experts (such as the cleanup models), and
- regression fits of numerical simulations with respect to critical variables (such as for the absorbed gamma dose models).

These models account for the effects of spent fuel pool environment and cleanup systems on Boraflex integrity, the geometric characteristics particular to specific spent fuel rack cells, and LWR fuel designs.

Section 4 described how the output routines were designed to present the data graphically in a format to facilitate decision making on the optimal shuffling of discharged fuel in the pool. “What-if” types of calculations can be formulated by adjusting input data in order to study desirable pool operating characteristics to preserve Boraflex integrity. Output data can be written to ASCII files for use by spreadsheet, wordprocessor, database, and other external user software.

Thus the RACKLIFE software satisfies its computational, performance, and IO objectives.

7

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A

SILICA RELEASE FROM IRRADIATED BORAFLEX

Introduction

Boraflex has been identified as the major source of reactive silica contamination in spent fuel pools. This conclusion is based on chemical analysis of irradiated Boraflex and some preliminary testing of irradiated Boraflex samples prepared from panel sections taken from destructively examined spent fuel racks and from Boraflex surveillance coupons.[1] In these tests the Boraflex specimens were placed in special aging baths containing either boric acid solutions (with 2000 ppm boron) or demineralized water. The baths were maintained at 85°F and 150°F and the solutions were periodically monitored for silica using standard colormetric methods. Some of the aging baths were sampled for total silica using inductively coupled plasma spectrophotometry (ICPS).

The data presented previously lead to some significant conclusions with respect to the release of silica from Boraflex in an aqueous environment. These conclusions include:

Reactive Silica Test Results

- The initial rate of reactive silica release from Boraflex appears to be independent of whether soluble boron is present in the immersion fluid. Testing in demineralized water and a boric acid solution with 2000 ppm soluble boron at 85°F and 150°F confirms this conclusion.

- The equilibrium concentration of reactive silica is relatively insensitive to the solute (water with and without soluble boron) but is sensitive to the temperature. If, as suggested, the release of silica into the immersion fluid is primarily governed by solubilization of silica, a strong temperature dependence is expected.

- The dissolution rate of silica from Boraflex depends on the level of reactive silica in the solute. The lower the reactive silica in solution, the greater the dissolution rate of silica from Boraflex.

- At low integrated gamma exposures ($\leq 1 \times 10^9$ rads) the release rate is a weak function of dose, but is greater than the release rate for unirradiated Boraflex. At higher doses (1 x 10^{10} rads) the rate of release increases significantly relative to low doses.

- The degree of aging (grey versus black Boraflex) is perhaps the single most significant factor influencing silica release. The degree of aging is a function of dose and the length of time the Boraflex has been exposed to the pool water. The rate of silica release is five times greater once the material has greyed.
- Encapsulation of Boraflex in non-sealed capsules, simulating the condition in some spent fuel racks, greatly retards the rate of silica transport to the bulk fluid volume. This has significant implications on the performance of Boraflex in spent fuel racks. In cases where the water exchange rate between the rack enclosure and the pool is low, silica release is likely to be low. This will vary among fuel rack designs and manufacturers.
- At the temperatures and flow velocities expected in the spent fuel pool, flowing fluid around the Boraflex does not appear to result in physical erosion. It does, however, provide a continuous source of water with relatively low reactive silica levels which increases the dissolution rate of the silica in Boraflex.

Total versus Reactive Silica

- Measurement data from either laboratory tests or pool water samples based on reactive silica alone would suggest that silica release from Boraflex saturates at a concentration which depends on temperature.
- Test data for total silica demonstrates that release continues in spite of unchanged reactive silica concentration.

In order to more precisely define the relationship between Boraflex service variables including cumulative gamma exposure and temperature, a second series of tests was performed. The objective of these tests was to accurately determine reactive silica release rates from Boraflex samples irradiated over a range of exposures and at three temperatures. These data serve as the basis for the source term correlations in RACKLIFE. In addition, it had been previously reported[1] that the presence of certain bi- and trivalent ions in dilute concentrations in water greatly reduce the dissolution rate of silica, the primary constituent of the residual matrix of irradiated Boraflex. Tests were performed to determine the effect of trace concentrations of one such ion, zinc, on the dissolution rate of irradiated Boraflex. Test data reported in this Appendix provide Boraflex dissolution rates as a function of radiation dose, water temperature, and zinc concentration.

In addition to the testing described above, the relationship between reactive silica and colloidal silica was examined experimentally in further detail. In this investigation both the reactive silica as well as the total silica (reactive plus colloidal) released from irradiated Boraflex specimens were measured as a function of time and temperature. The data from these tests provide the relationship between reactive and colloidal silica used in the RACKLIFE model. The initial results of these tests were described previously[1]; the final test results are given here.

Experimental METHOD

Boraflex Specimens

Silica Release versus Temperature, Gamma Exposure, and Zinc Concentration

A series of small specimens of Boraflex were irradiated in a Cobalt-60 facility at the Armed Forces Radiobiology Research Institute (AFRRI) over a range of gamma exposures from 1×10^7 rads to 1×10^{10} rads. The original objective of these tests was to develop a detailed characterization of the physical changes in Boraflex in an accurately known gamma field.[2,3] The specimens were archived after the initial tests and were available for subsequent dissolution testing.

The original AFRRI specimens were one inch wide by seven inches long by 0.075 inches thick. The minimum certified areal density of the batch of Boraflex from which these samples were prepared was 0.020 gms boron-10/cm^2 and the actual areal density, as determined by chemical analysis, was 0.0235 gms boron-10/cm^2. During irradiation, the specimens were clad in thin wall stainless steel with the edges of the Boraflex exposed to the pool water. At periodic intervals two specimens were removed from the irradiation facility and shipped to a laboratory for testing.

For the purpose of dissolution testing, the AFRRI specimens were cut into two pieces of equal size, 1″ x 3.5″ x 0.075 inches, each weighing approximately 7.5 grams. Two of the original AFFRI specimens were irradiated to each of the intermediate gamma doses over the range of 1×10^7 rads to 7.5×10^9 rads, so that a total of four half specimens were available for dissolution testing at each dose. Five of the AFFRI specimens were irradiated to a dose of 1×10^{10} rads so that a total of ten half size specimens were available for dissolution testing. Prior to testing, each sample was dried in a desiccator for 48 hours and weighed.

Reactive and Total Silica Release

The specimens used for the reactive versus total release tests were prepared from pieces of Boraflex removed from the Point Beach spent fuel racks during a destructive examination of a poison insert assembly.[4] The specimen Boraflex had received an estimated exposure of 1×10^{10} rads. The specimens were prepared from material which had completely turned a light grey color. The specimens were irregular in shape. The initial weight of the specimen tested at 85°F was 12.7 grams. The 150°F sample initially weighed 9.6 grams.

Test Method

The aging baths were standard stainless steel laboratory ware with a fluid capacity of more than one liter. Each of the baths were fitted with a tight fitting lid to minimize evaporative losses. At the beginning of the tests each bath was filled with 1 liter of demineralized and distilled water. The initial silica concentration of the aging fluid was in all cases <50 ppb. Periodically, low silica makeup water was added to each bath to maintain a volume of 1 liter and compensate for evaporative losses.

During the tests the baths were maintained at constant temperature in large ovens, maintained at 85°F,117.5°F, and 150°F. At regular intervals the baths were removed and cooled. A small sample of water was then withdrawn from each bath and analyzed for reactive silica using a colormetric method. Depending on the anticipated silica level of an aging bath solution, one of two methods was used. For the baths with low silica (0 to 1.6 ppm), the heteropoly blue method was used. For the baths with high silica (0 to 100 ppm), the silico-molybdate method was used. For samples with silica concentrations greater than 100 ppm, the withdrawn fluid was first diluted and then analyzed. Following sampling and testing the aging baths were returned to the constant temperature ovens. At the completion of the tests the Boraflex samples were dried in air, desiccated for 48 hours, and weighed. This served as gravimetric verification of the silica release data determined from analyses of the aging bath solutions.

For the total silica determinations, inductively coupled plasma spectrophotometry was used. A two milliliter fluid sample was evaporated to dryness in a platinum crucible. The residue was fused with 1.0 gram of lithium borate ($LiBO_2$) and the melt dissolved in dilute nitric acid. A Leeman Labs PS 3000 uv was used for the ICPS measurements.

Experimental Results

Silica Release as a Function of Gamma Exposure and Temperature

Three specimens each were prepared from the AFRRI irradiated coupons at eight different gamma exposures over the range of 1×10^7 rads to 1×10^{10} rads. Three unirradiated control samples were also included in the test matrix. A third of the samples were immersed in aging baths maintained at 85°F, a third in baths at 117.5°F, and a third in baths at 150°F. In total there were nine Boraflex samples at each of the three temperatures. Figure A-1 contains a plot of silica release versus time for the samples maintained at 85°F. The release has been converted from the raw data, which is in units of parts per million (ppm) silica, and is reported in units of mg SiO_2 per unit surface area of the sample. The dependence of the release on integrated gamma exposure is clearly evident with the slope of the release curves increasing with increasing exposure.

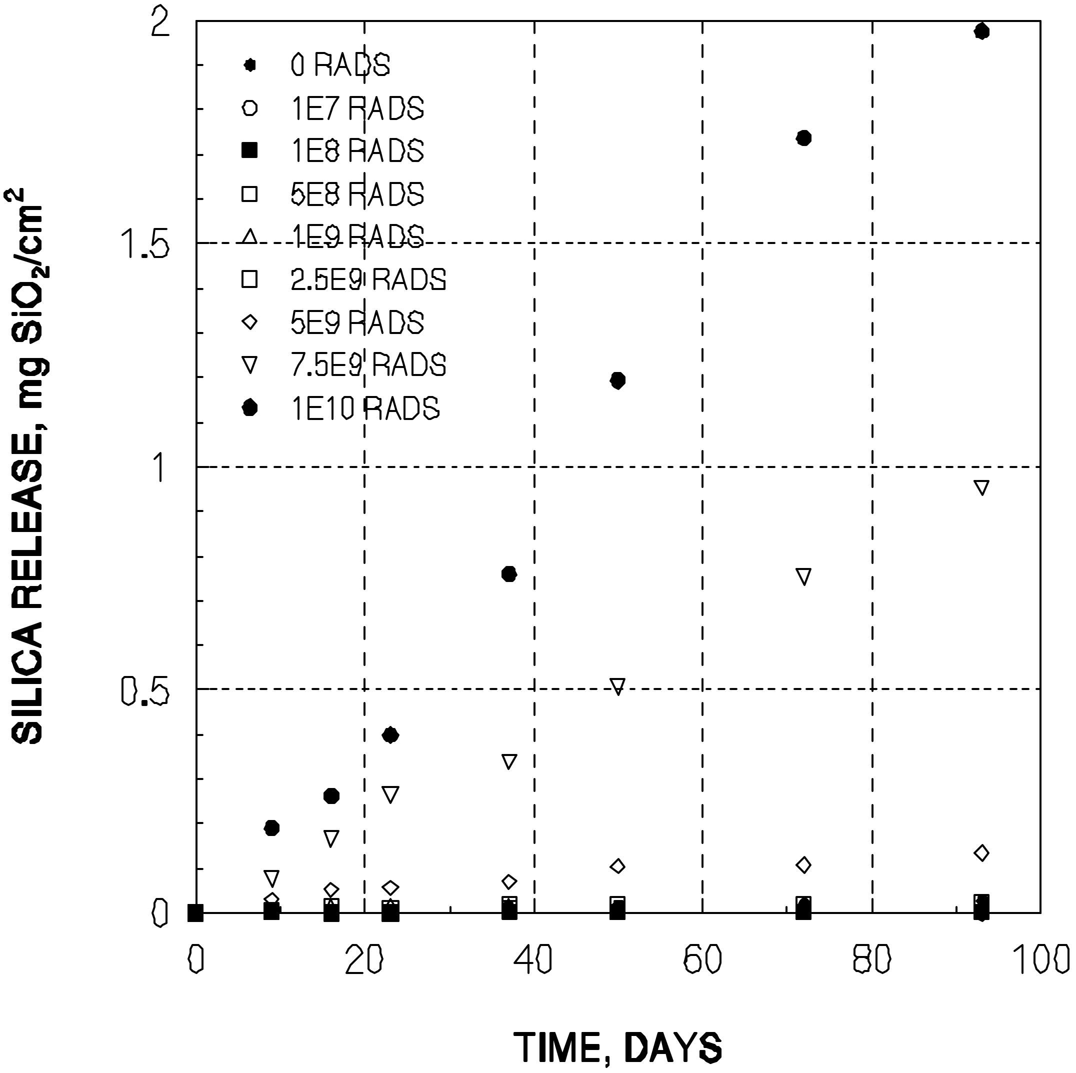


Figure A-1
Silica Release from Irradiated Boraflex at 85°F

Figure A-2 contains plots of the release from the nine specimens maintained at 117.5°F. As for the specimens aged at 85°F, the rate of release increases with increasing gamma exposure. For the two specimens with highest exposure (7.5 x 10^9 rads and 1 x 10^{10} rads), the reactive silica in aging baths reaches an equilibrium value after 40 days to 60 days of ~120 ppm. At this condition the rate of dissolution of silica from the Boraflex is governed by the rate of polymerization of monosilicic acid molecules to form colloidal silica. Previous tests[1] have demonstrated that while the reactive silica concentrations remain more or less constant when this equilibrium is attained, the colloidal component and hence the total silica in the solution continues to increase.

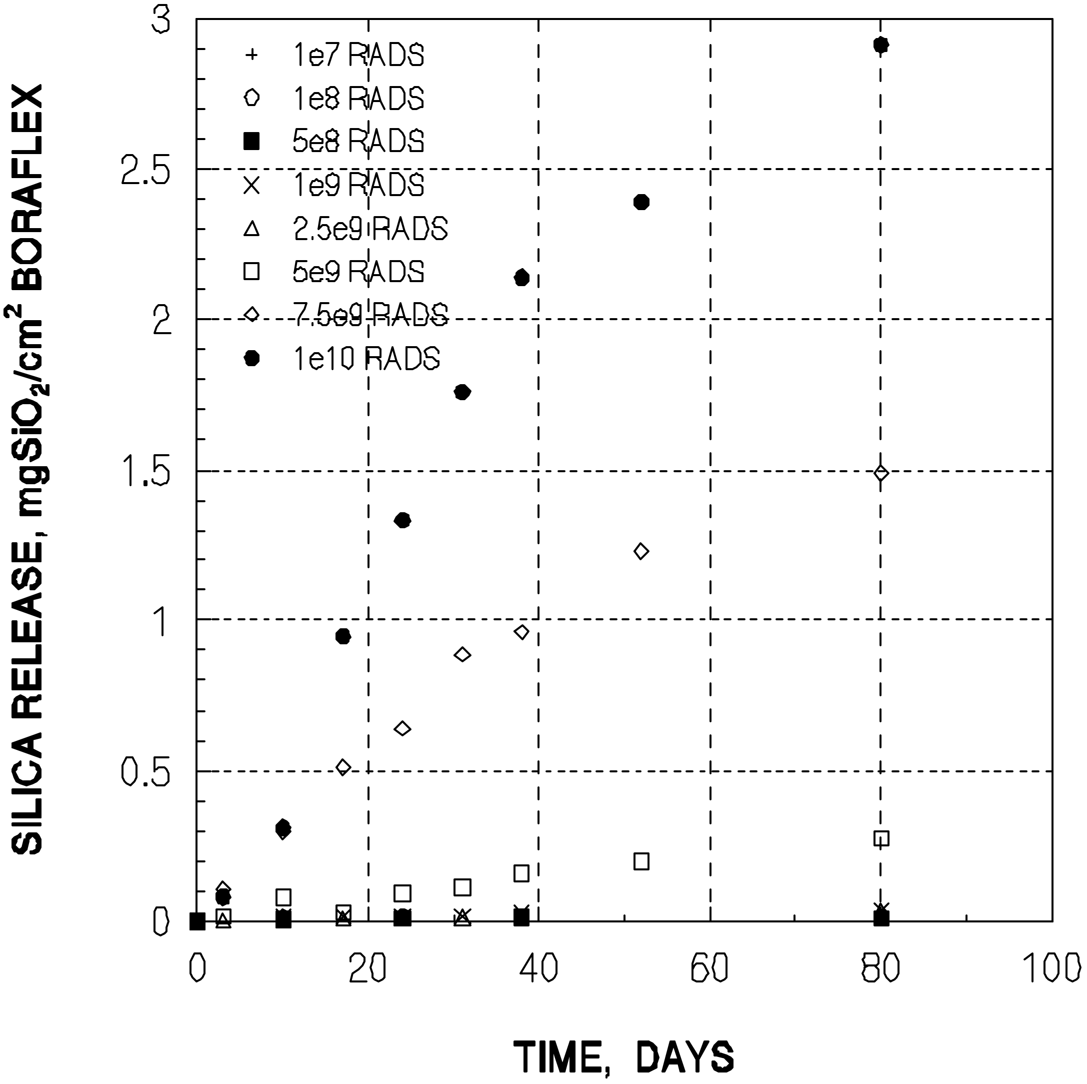


Figure A-2
Silica Release from Irradiated Boraflex at 117.5°F

Figure A-3 contains the silica release data for the samples aged at 150°F. The same trend with increasing exposure is observed for these samples as for the samples aged at the lower temperatures. At the elevated temperature, the silica release rates increase relative to the lower temperature samples as one might expect. As discussed subsequently, the data presented in Figures A-1, A-2, and A-3 have been used to develop the silica release rates as a function of dose and temperature for use in RACKLIFE.

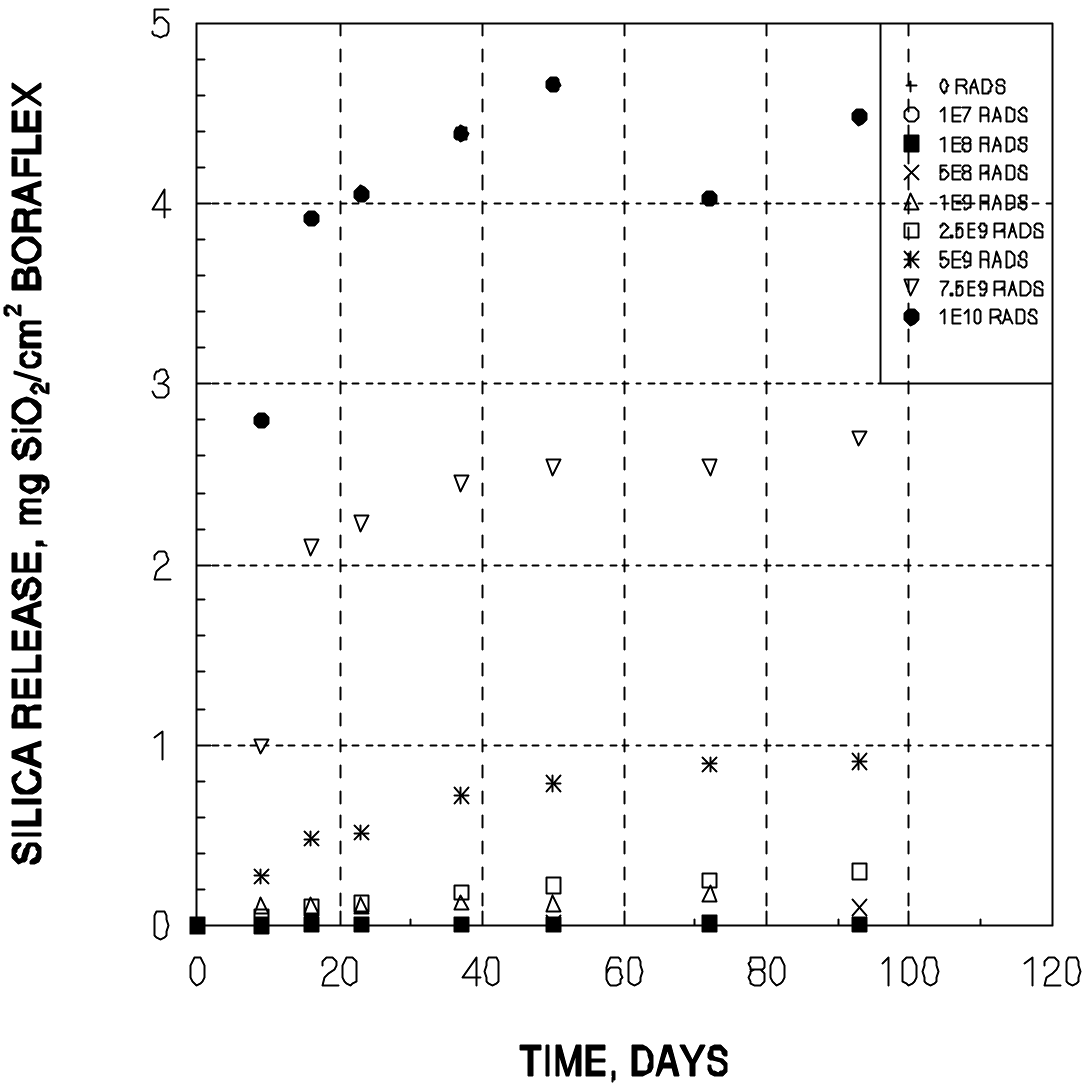


Figure A-3
Silica Release from Irradiated Boraflex at 150°F

Total and Reactive Silica Release versus Time

Two series of tests were conducted with Boraflex samples prepared from material removed from a poison insert from the Point Beach spent fuel racks. These samples were prepared from Boraflex which was at an advanced stage of aging as evidenced by its light grey color. In the first series of tests, the samples were aged at 85°F and 150°F and the aging bath solutions were sampled for reactive silica only. In the second series of tests, the same two samples were aged at the same temperatures in new demineralized water initially containing <50 ppb silica. During the second series of tests the aging fluid was sampled for both reactive and total silica. The duration of these tests was ~260 days each.

Figures A-4 and A-5 show the results of the two series of tests at 85°F and 150°F, respectively. The scale of the ordinate in both figures is the same to illustrate the strong influence of temperature. The release data reported for these tests is in units of mg SiO_2/gm Boraflex. These samples were irregular in shape making measurement of their surface areas difficult.

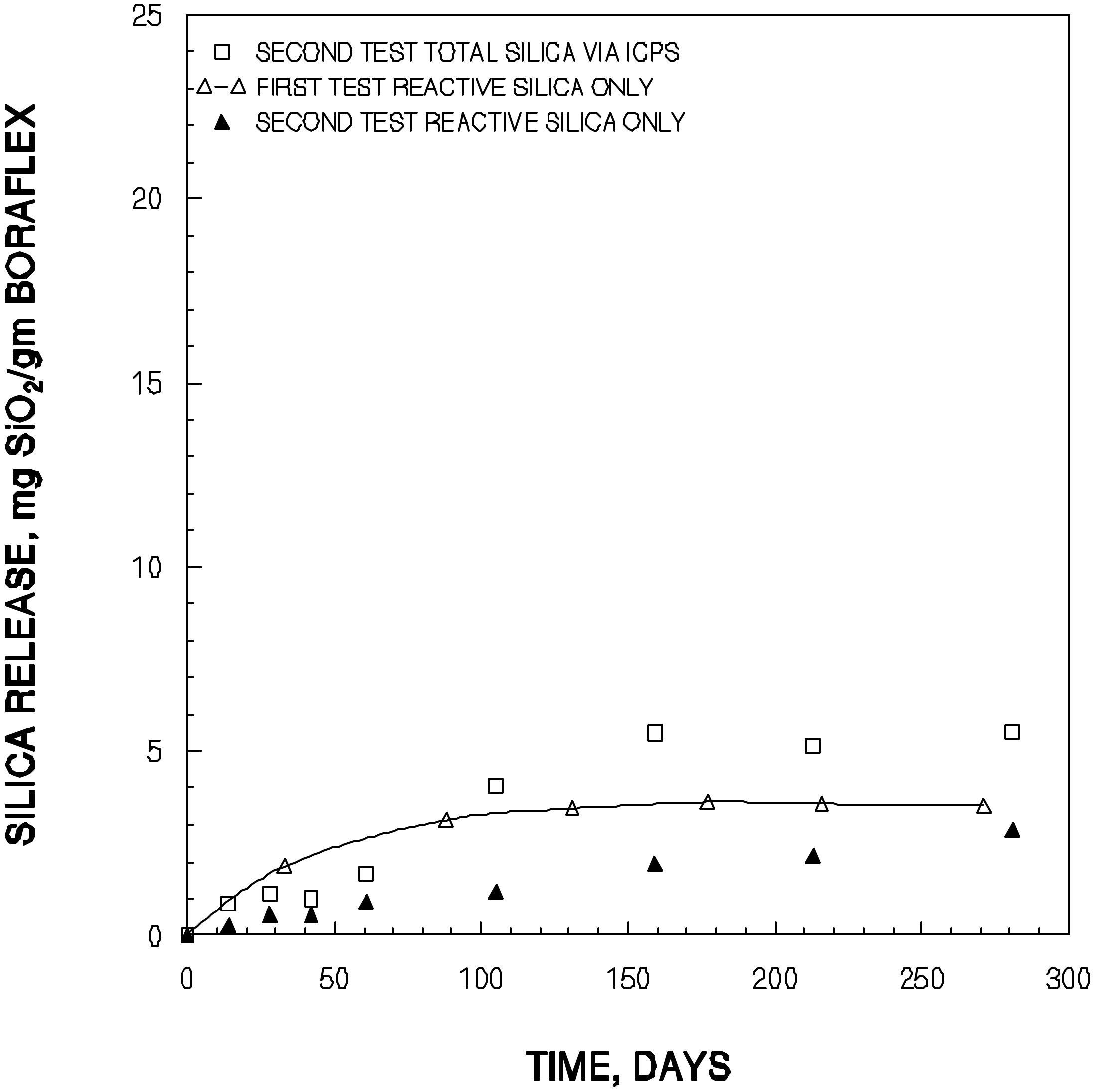


Figure A-4
Total and Reactive Silica Release from Boraflex at 85°F

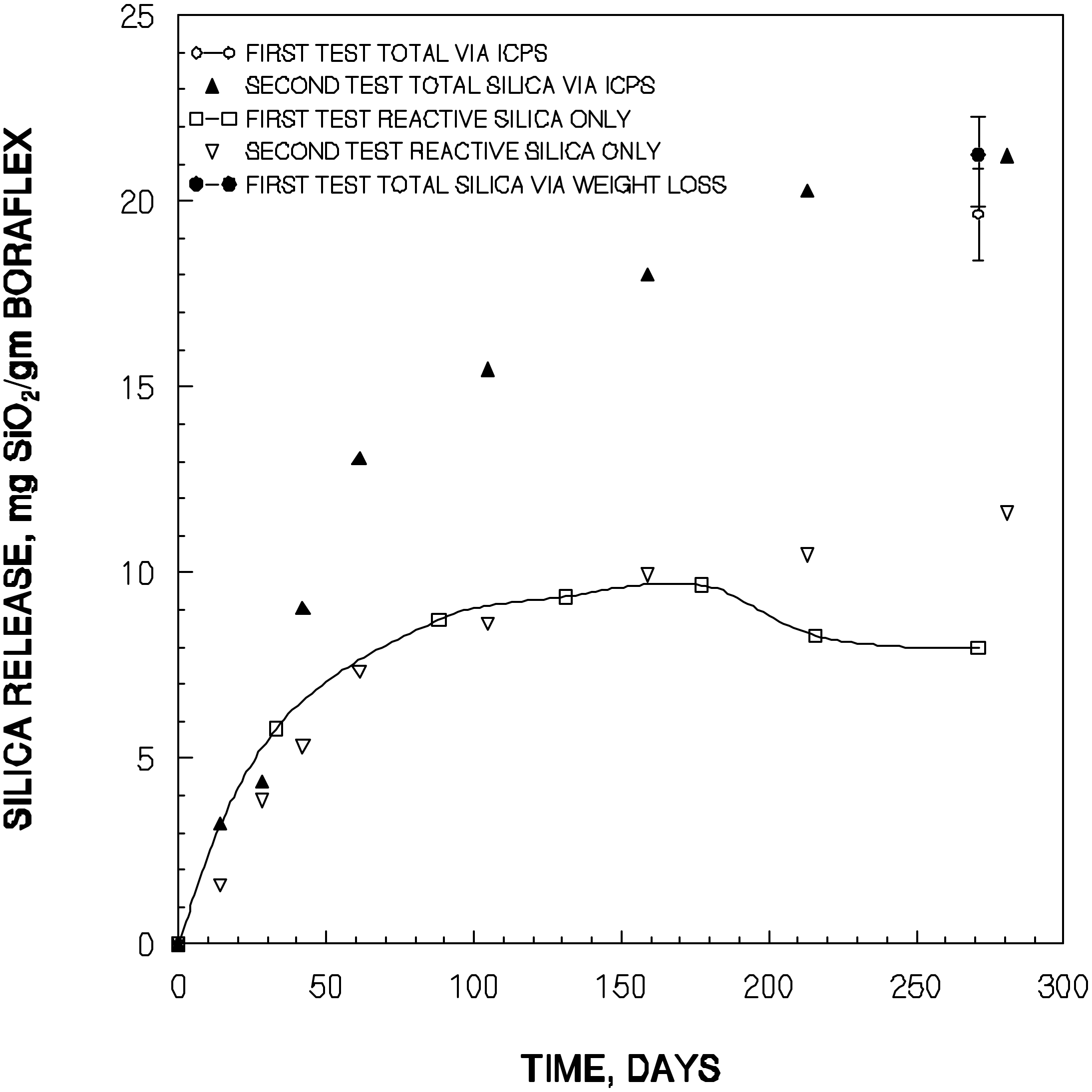


Figure A-5
Total and Reactive Silica Release from Boraflex at 150°F

Referring to Figure A-4, it is noted that the initial rate of reactive silica release is somewhat less in the second test then in the first test, although after ~250 days the total reactive silica levels are about the same in both tests. This may be due to the presence of a greater amount of surface silica available for solubilization during the first test. In any case, the silica release as determined via the total silica measured in the second test is about twice as great as the release determined from the reactive silica measurements in either test after ~250 days. The difference between the total and reactive silica is the colloidal silica component—the monosilicic acid molecules which have polymerized forming dimers, trimers and larger multi-molecular agglomerations.

The distinction between total and reactive silica is more pronounced in the testing conducted at 150°F as shown in Figure A-5. In this case, the reactive silica in both the first and second series of tests reaches an equilibrium level after about 100 days while the total silica released in the second test continues to increase. Also shown in this figure are the total silica measurements made during the first test after 250 days at temperature. The total silica was determined via ICPS and by sample weight loss. The total silica by both methods are consistent and compare favorably with the total silica measured during the second tests.

Effect of Zinc on the Dissolution Rate of Irradiated Boraflex

The presence of bi- or trivalent metal ions in water has been observed to greatly reduce the dissolution rate of silica beverage and food containers.[5] NETCO completed a review of the literature and identified zinc as being one of the bivalent ions which had the greatest effect. Of all such ions which include aluminum, magnesium, beryllium, etc., zinc was believed to be the most benign, should one of these be added to the spent fuel pool water. Additionally, zinc is currently in use in the reactor coolant systems of several BWRs to immobilize corrosion products.[6]

To determine the effect of zinc on the dissolution rate of irradiated Boraflex, a special series of tests were conducted. A series samples were prepared from the AFRRI coupons which were irradiated to 1 x 10^{10} rads. In addition, two samples of approximately the same size were prepared from Boraflex removed from the spent fuel racks at Fort Calhoun.[7] These samples were cut to be approximately the same size as the AFRRI samples and had received an estimated exposure of 2 x 10^{10} rads. The test matrix included two test temperatures (85°F and 150°F) and three levels of zinc concentration, 0.1 ppm, 1.0 ppm, and 10.0 ppm. The zinc used for these tests was a standard solution of Zn^{+2} diluted with demineralized water to achieve the three bath concentrations. The zinc was added to each bath prior to placing the Boraflex in the vessels. The zinc concentrations of the aging baths were measured using the zincon colormetric method.

Figure A-6 contains the results of the tests at 85°F with the AFRRI samples. Zinc at the higher concentrations has a dramatic effect on the silica released from irradiated Boraflex. With 1.0 ppm and 10.0 ppm of zinc in the aging baths, the silica release rates are reduced by a factor of 4 to 5 relative to the bath without zinc. It is further noted that the difference between the 1.0 ppm and 10.0 ppm tests is small, perhaps indicating that the effect of zinc on the dissolution rate saturates. Figure A-7 contains the data from the tests conducted at 150°F. The same trend is evident as for the 85°F tests, although there appears to be a somewhat larger difference between the 1.0 ppm and 10.0 ppm tests. Similar results were obtained with the samples prepared from the Boraflex removed from the Fort Calhoun fuel racks as shown in Figure A-8.

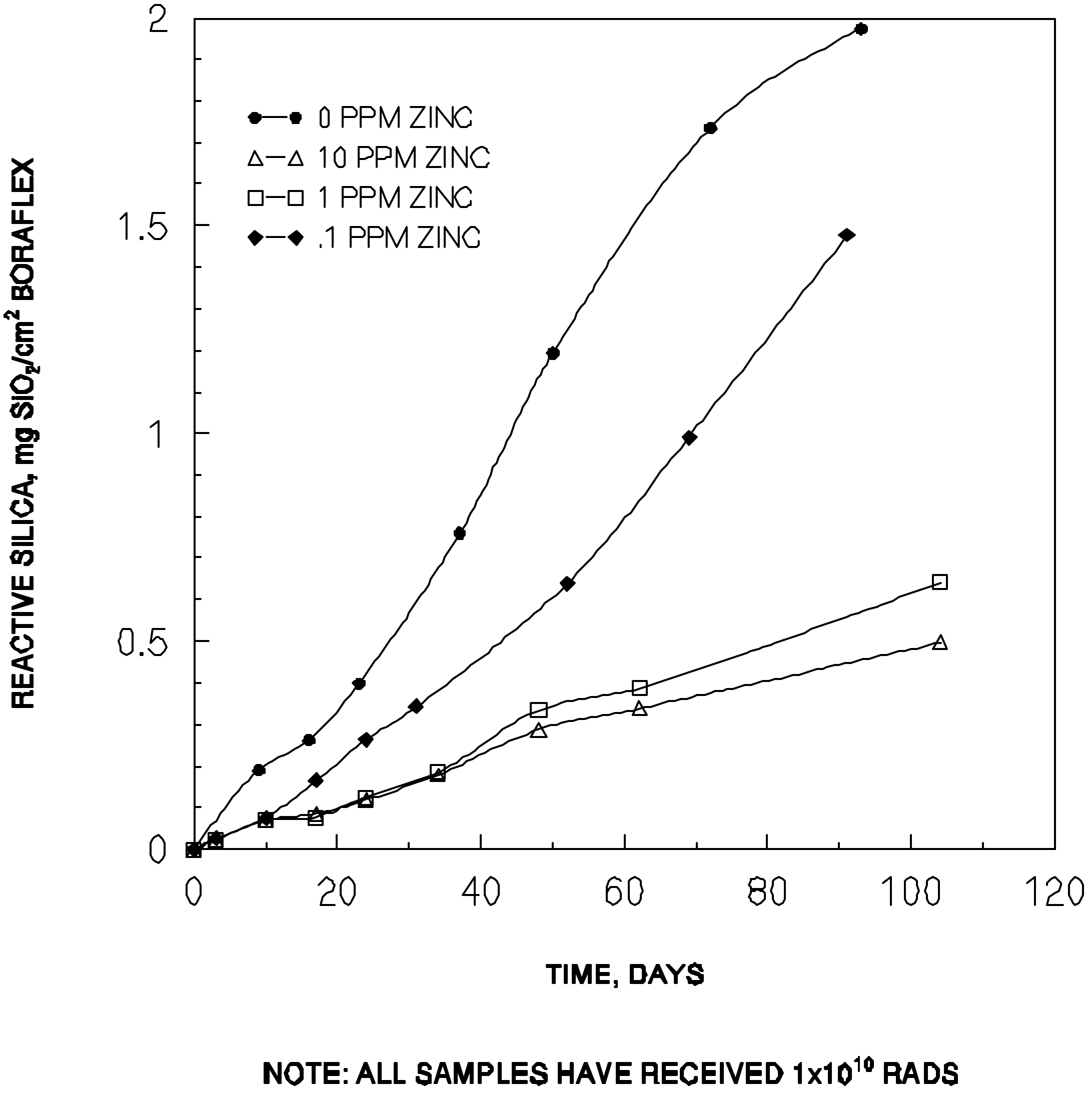


Figure A-6
Boraflex Dissolution Tests—Effect of Zinc at 85°F

After the completion of the tests, the AFRRI specimens were suspended in air until all fluid droplets had drained away. They were then placed in new baths containing deionized water with neither zinc nor silica in the water. These samples have been referred to as having been "pre-treated" with zinc. The silica release tests were then rerun. Figure A-9 contains the results of the second series of tests at 85°F and the silica release characteristics are compared with the results from the first test. It would appear that the zinc attached to the Boraflex surface during pretreatment has a lasting effect on the dissolution rate of Boraflex, although the release rates are somewhat higher in the second test.

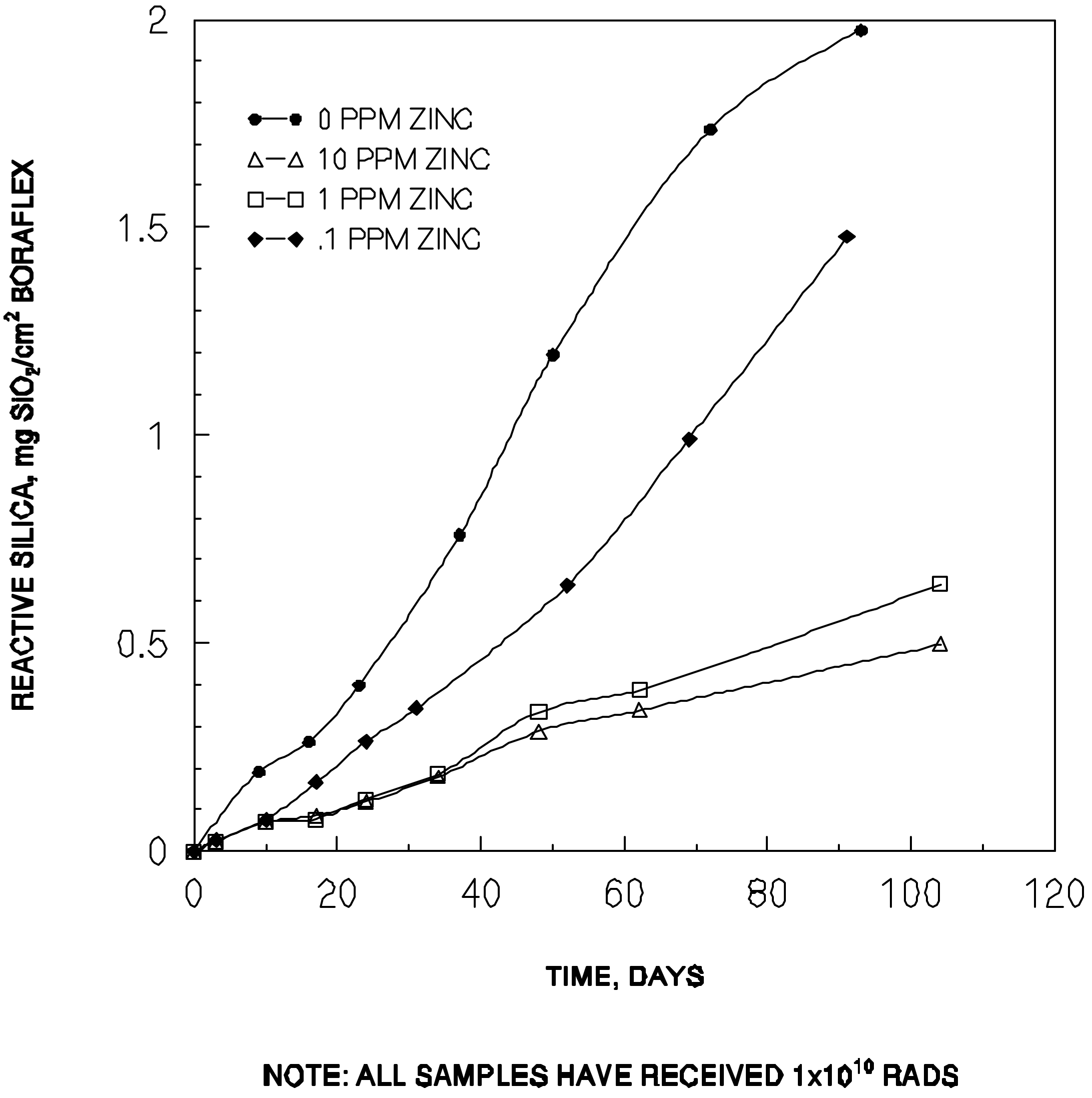


Figure A-7
Boraflex Dissolution Tests—Effect of Zinc at 150°F

Figure A-10 contains the results of the second test conducted at 150°F. Again, the effect of zinc appears to persist on the pre-treated samples even though the aging baths fluids did not contain zinc. In this case, as opposed to the tests at 85°F, the pre-treated specimens actually had lower silica releases in the second test than in the first series of tests. It is speculated that the silica release rates at 150°F are so rapid that considerable silica was released in the first test when the samples were initially placed in the baths. This rapid initial release, before the zinc had attached to the Boraflex surface, is thought to account for the higher release in the first tests. This was not observed in the tests at 85°F as the initial silica release rates were much lower.

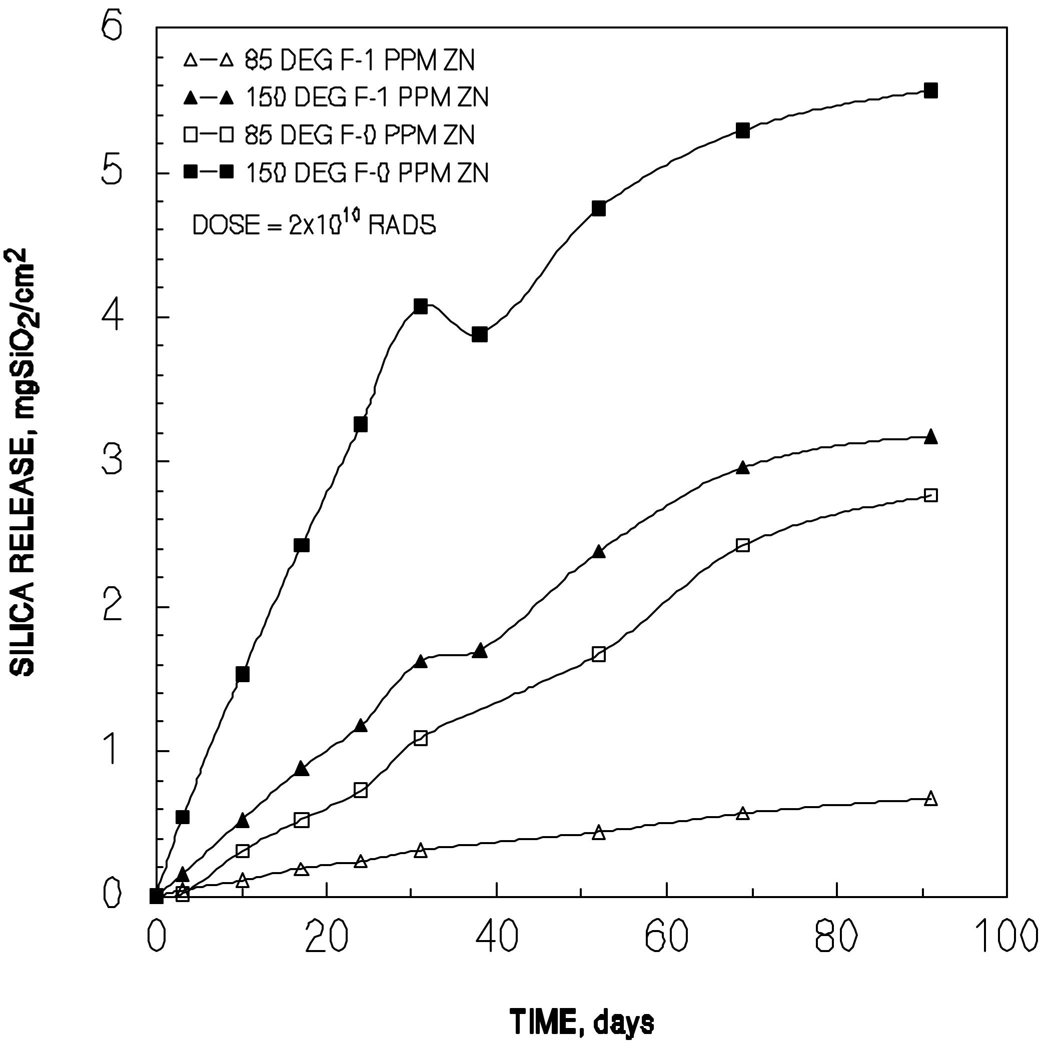


Figure A-8
Boraflex Dissolution Tests—Effect of Zinc on the Fort Calhoun Samples at 85°F and 150°F

After each of the tests was completed, the Boraflex samples were dried in a desiccator and weighed. As an independent check of the dissolution test data, the expected sample weight loss based on the quantity of silica released to the aging baths was calculated. This calculation utilized a composition of irradiated Boraflex which had been determined previously by chemical analyses and the measured concentration of reactive silica in the baths.[1] Figure A-11 contains a plot of this expected sample weight loss versus the actual measured weight loss determined gravimetrically. The data are well represented by a straight line with a slope very nearly equal to one. The one outlier data point which had a measured weight loss of ~250 mg had a small chip break off one corner while in the aging bath. The data in Figure A-11 provides independent confirmation of the effect of zinc on the dissolution rate of irradiated Boraflex.

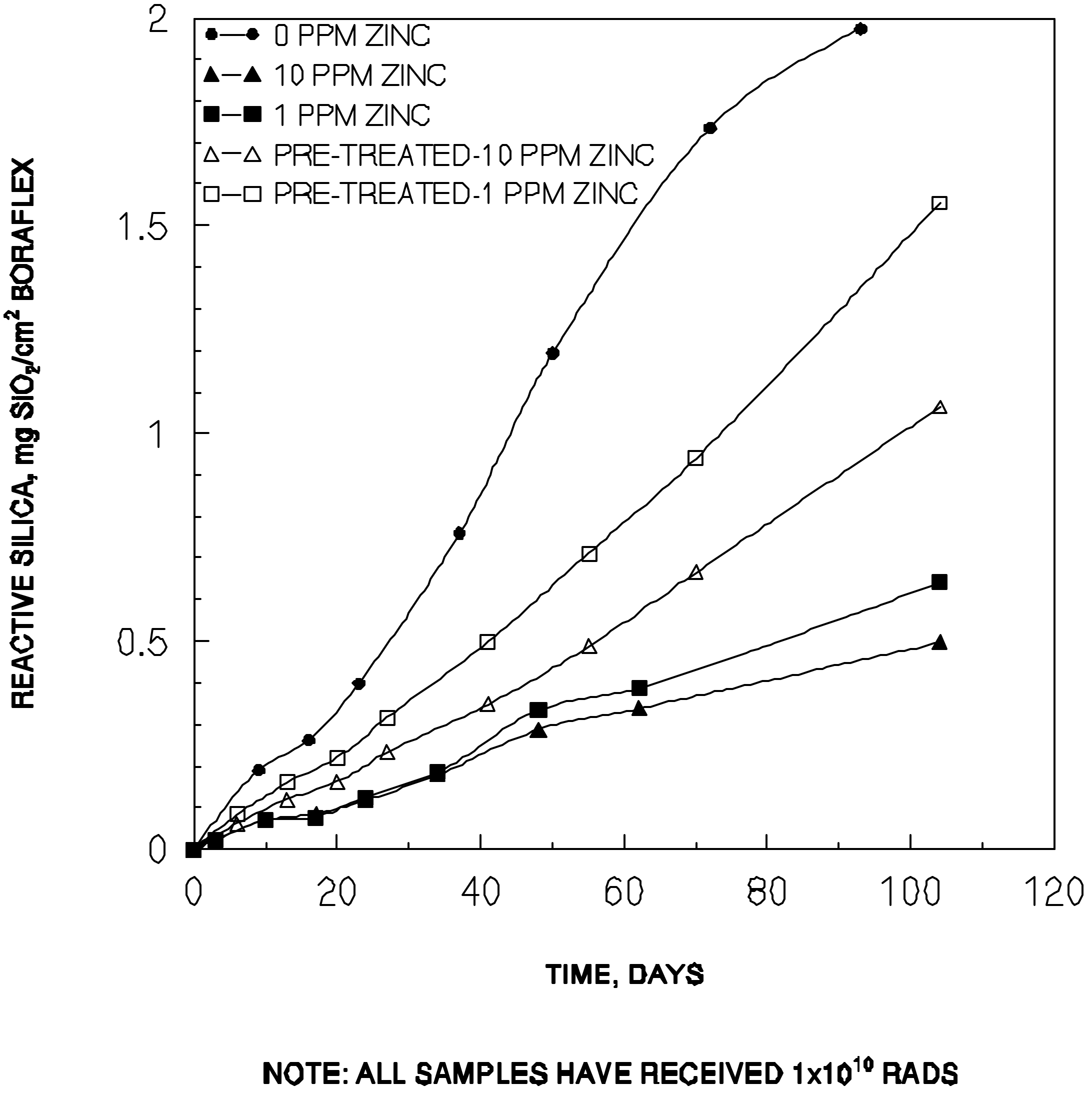
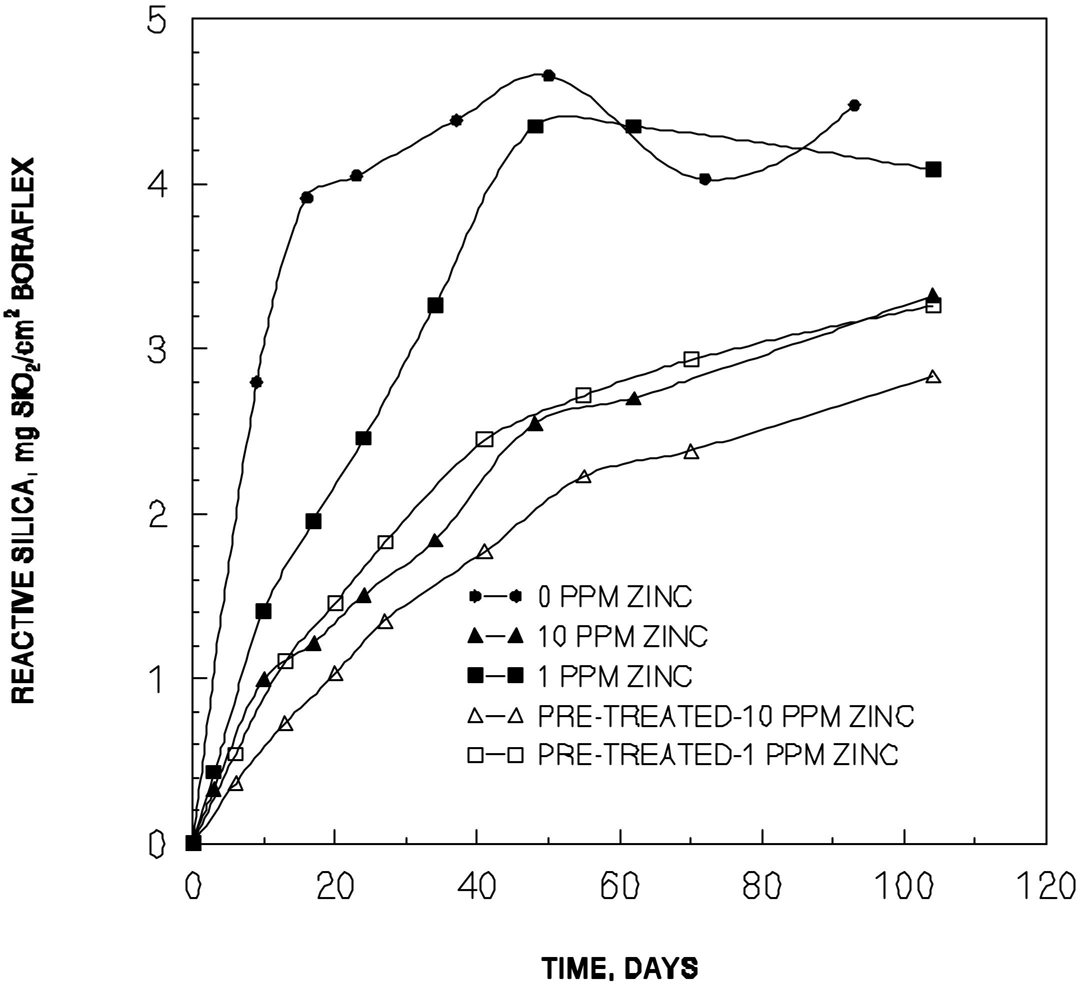


Figure A-9
Boraflex Dissolution Tests at 85° F—Effect of Zinc Pretreatment



NOTE: ALL SAMPLES HAVE RECEIVED 1×10^{10} RADS

Figure A-10
Boraflex Dissolution Tests at 150°F—Effect of Zinc Pretreatment

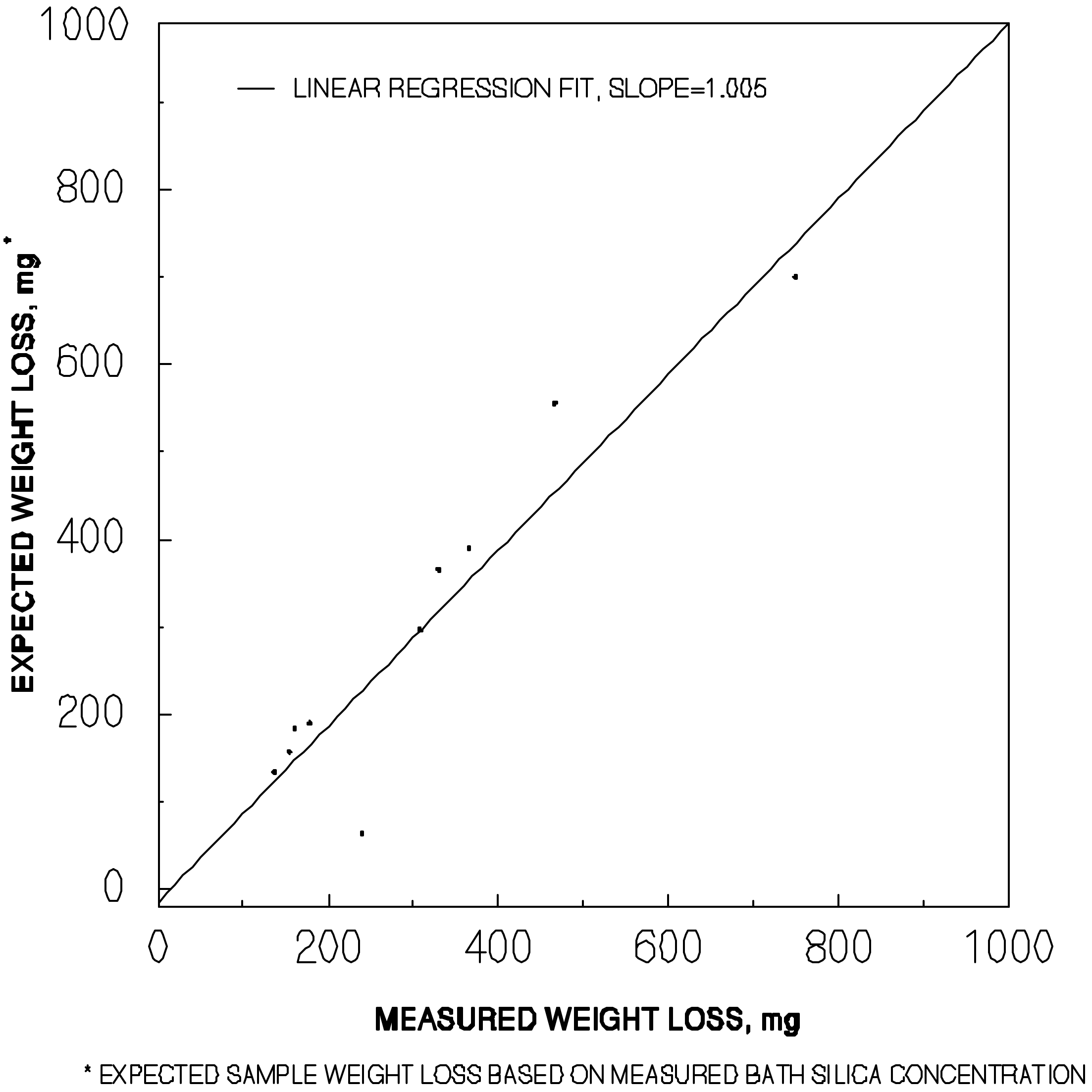


Figure A-11
Boraflex Dissolution Tests with Zinc -Expected versus Measured Sample Weight Loss

Discussion

Silica Release Rate as a Function of Dose and Temperature

The data contained in Figures A-1, A-2, and A-3 were used to develop release rate data for the RACKLIFE correlations. The release data in these figures was fit to a straight line using regression techniques and the slope of the line determined. For the high release samples (those with high exposure and in the higher temperature baths) only the initial data points prior to establishment of reactive silica equilibrium were used.

This is representative of the rate expected in spent fuel pools where the bath fluid is generally well below the concentration for reactive silica equilibrium. The rates so determined are plotted in Figure A-12. It is noted that the ordinate and abscissa scales in Figure A-12 are logarithmic and the release rates for which data are available span four orders of magnitude. Examination of these data reveals some interesting features of the kinetics of silica release from irradiated Boraflex. First, at exposures of less than ~1.0 x 10^9 rads, the release rates are in the range of 10^{-4} mg $SiO_2/cm^2 \cdot$ day to 10^{-3} mg $SiO_2/cm^2 \cdot$ day and are more or less invariant with respect to gamma dose. Also, at these low exposures the release rates do not appear to have a strong dependence on temperature. Second, at a threshold dose of about 2.5 x 10^9 rads the release rates increase dramatically and at these higher dose levels the release rates are a strong function of temperature.

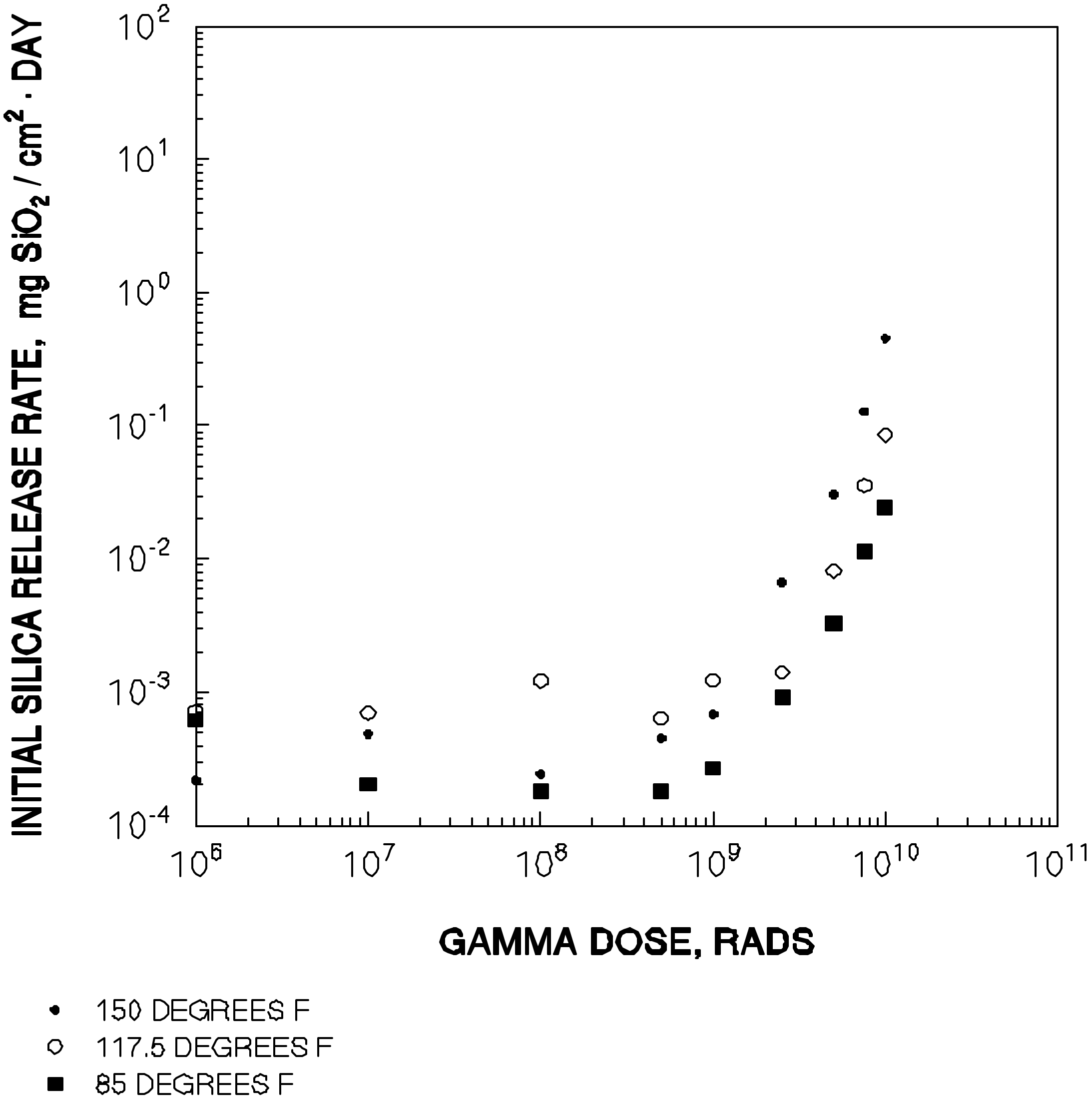


Figure A-12
Initial Silica Release Rate versus Gamma Dose

It is also noted that the data from the AFFRI coupons is limited to a maximum dose of 1 x 10^{10} rads, while the dose to Boraflex in fuel racks will exceed this value after several years of service. The dose to the AFFRI samples were limited to 1 x 10^{10} rads by practical considerations. These samples required some three calendar years of irradiation to complete and further irradiation to 2 x 10^{10} rads would have required six years. For the purpose of the RACKLIFE model, the release rates for panel exposures in excess of 1 x 10^{10} rads is estimated by extrapolation of the data.

Total and Reactive Silica

In the tests described previously[1] in which reactive silica only was measured, the data would indicate that silica release from Boraflex ceases when the aging bath silica concentration reaches an equilibrium value which depends on temperature. If it were not for the polymerization of monosilicic acid molecules (reactive silica) forming colloidal silica, the equilibrium condition would suggest that no further net release of silica from Boraflex occurs. At this condition, the rate of dissolution at the surface of silica would be equal to the rate of re-deposition of monosilicic acid molecules on the surface. However, the data presented in Section 3 indicates that as the reactive silica concentrations in solution increases, polymerization of reactive silica to colloidal silica occurs. The rate of polymerization to colloidal increases with increasing concentration of reactive silica. Under these conditions, the rate of silica release from the Boraflex surface is governed by the rate at which polymerization occurs. As polymerization proceeds, the reactive silica level in the solute is reduced, thus allowing further solubilization of silica from the Boraflex surface as reactive silica.

The equilibrium concentration of reactive silica depends on the temperature of the solution. From the test data the equilibrium concentration ranges from 85 ppm–90 ppm at 85°F, to 165 ppm–175 ppm at 150°F. Figure A-13 contains an Arrhenius plot of the equilibrium reactive silica concentration versus the reciprocal temperature. It is noted that the test data are represented by a linear plot in this figure as one might expect. The slope of this curve is the heat of dissolution which is calculated to be 1.78 kcal/mole. Also shown on this plot are typical ranges of equilibrium concentrations of reactive silica from solutions containing amorphous and crystalline silica. These latter ranges of values have been taken from Reference 5. It is noted that the Arrhenius plot for irradiated Boraflex lies between the range of plots for amorphous and crystalline silica. The reported[5] heats of dissolution for silica range from 5.3 kcal/mole for crystalline silica (quartz) to ~1.5 kcal/mole for amorphous silica. Investigation of the constituents that make up Boraflex has shown that the polymer manufacturer (Dow-Corning) adds as a filler of finely ground quartz, a crystalline form of silica as an extender. The polydimethyl siloxane polymer component, under irradiation, transforms to an amorphous silica dominated material. After being exposed to irradiation, Boraflex consists of ~50 w/o boron carbide, 25 w/o crystalline silica and 20 to 25 w/o amorphous silica.

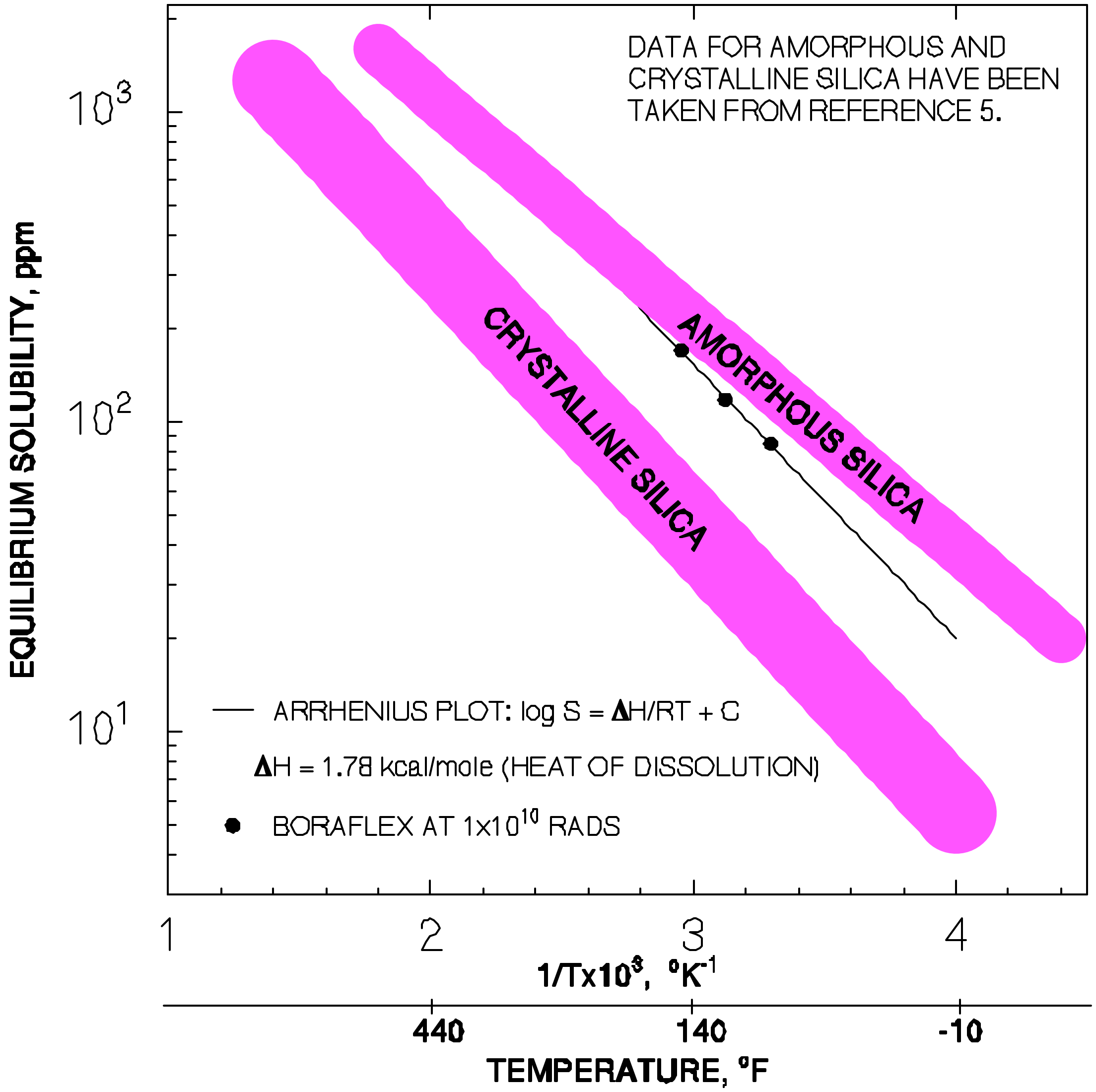


Figure A-13
Equilibrium Solubility of Silica versus Reciprocal Temperature

Effect of Zinc on the Solubility of Irradiated Boraflex

The data presented in Section 3 illustrates the dramatic effect of small quantities of zinc on the dissolution rate of irradiated Boraflex. The initial release data contained in Figures A-6 and A-7 have been fit by linear functions using regression techniques and the slope (release rate) regressed as a function of zinc concentration and temperature. Figure A-14 contains a logarithmic plot of silica release rate as a function of bath zinc concentration at 85°F and 150°F. Both plots exhibit the same trend. There is a factor of four to five reduction in release rate going from 0 ppm to 1 ppm zinc. At a zinc concentration of 1 ppm and greater the release rate is almost independent of zinc concentrations up to the maximum level of 10 ppm tested. This suggests that at bath concentrations greater than 1 ppm zinc, the beneficial effect of zinc saturates. A possible explanation for this observed phenomenon is discussed subsequently.

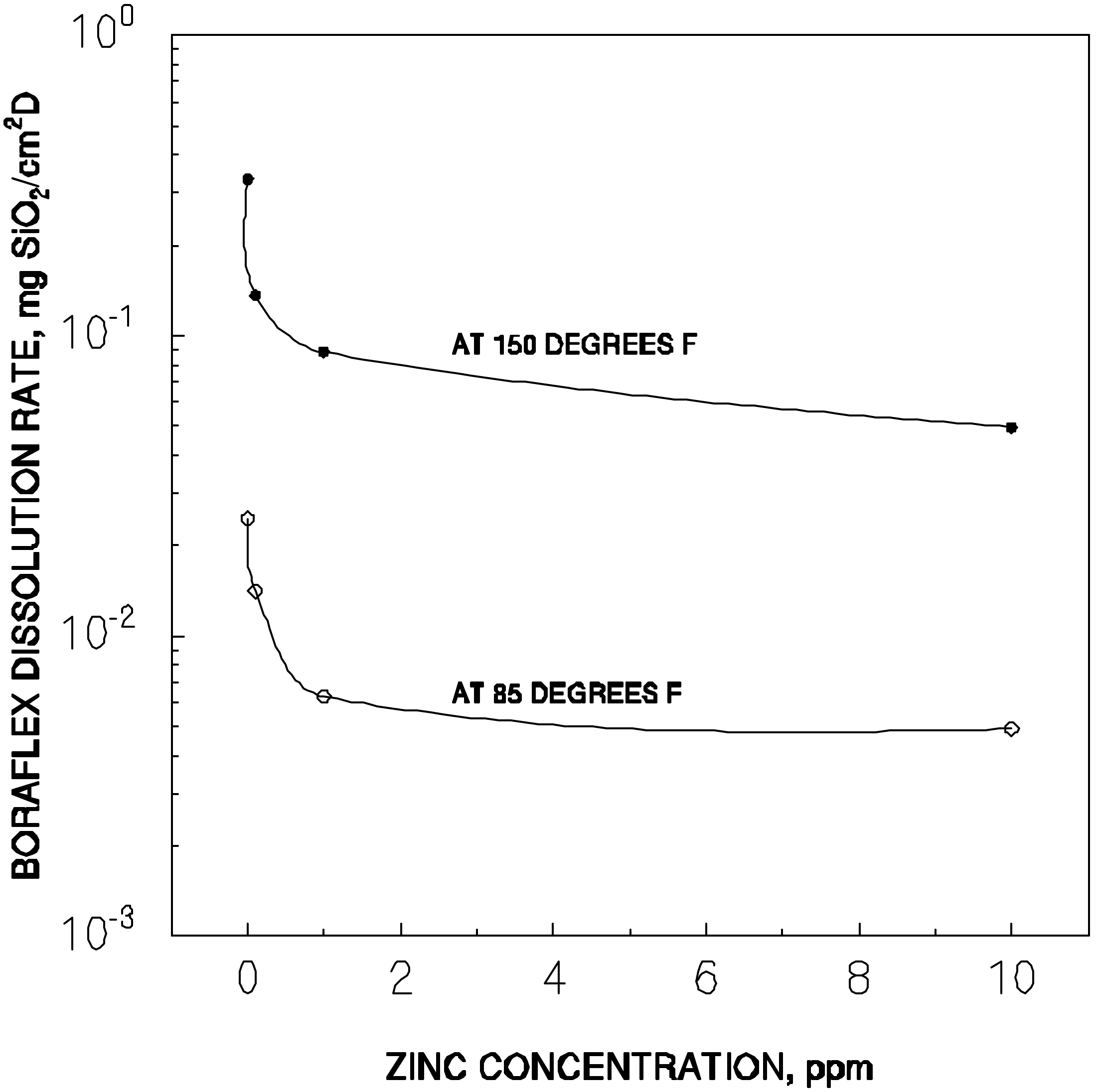


Figure A-14
Boraflex Dissolution Rate versus Zinc Concentration

In Figure A-15, the normalized silica release rates at 85°F and 150°F are plotted versus zinc concentration. The normalized release rate is defined as the release rate with zinc present divided by the release rate in the baths without zinc. It is interesting to note that the curves at 85°F and 150°F coincide nearly exactly and a possible explanation for this is discussed subsequently.

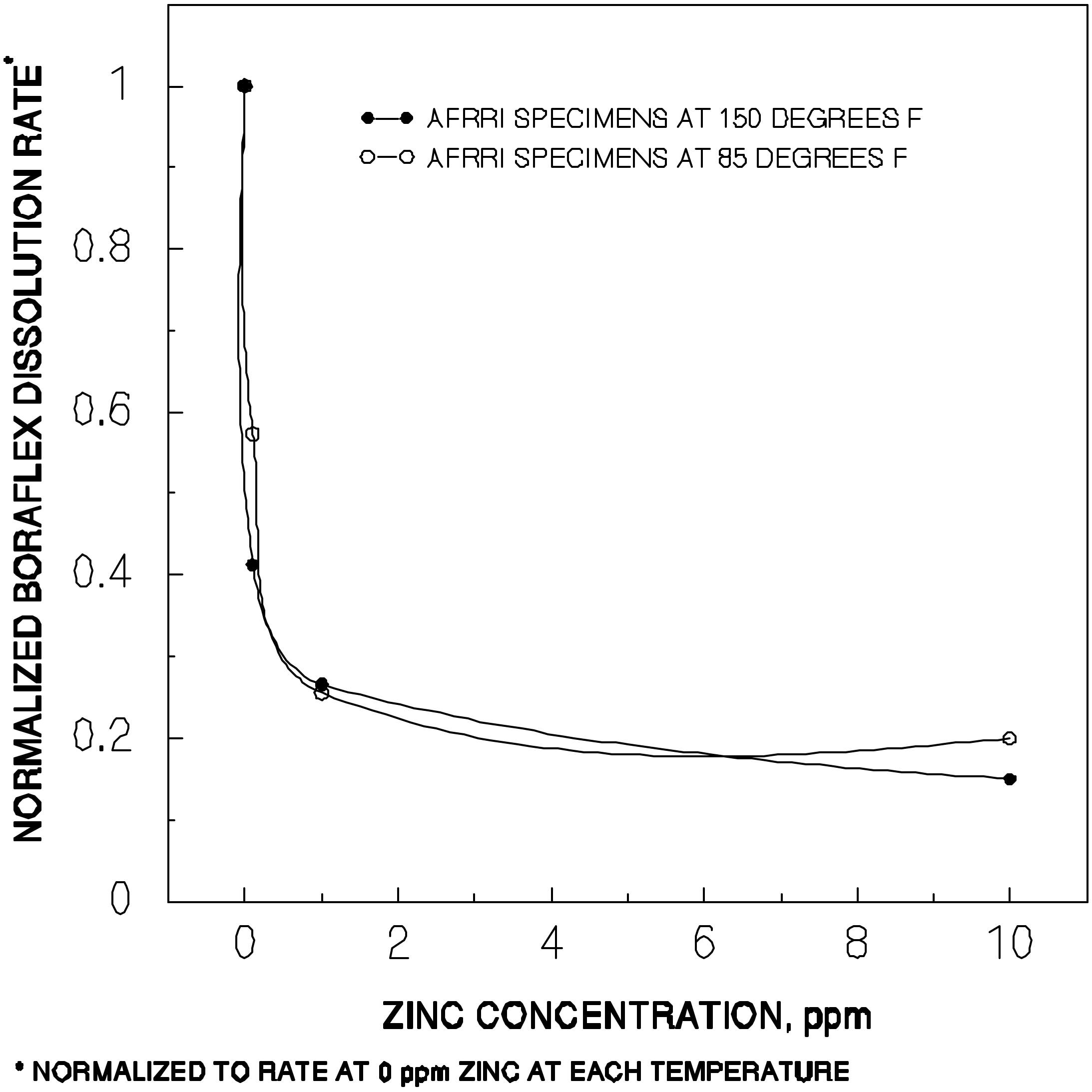


Figure A-15
Normalized Boraflex Dissolution Rate versus Zinc Concentration

Figure A-16 illustrates schematically how the initial dissolution of a silicon atom from the Boraflex surface forms a site for preferential attachment of a zinc ion with +2 valence state. Initially, a free hydroxyl ion in the water attacks a silicon atom on the surface of the Boraflex (see Figure A-1 in the main body of this report). The silicon atom and hydroxyl ion form the intermediate $Si(OH)_5^-$ silicate ion which subsequently disassociates to form monosilicic acid ($Si(OH)_4$, or reactive silica). This leaves a vacant silicon atom site on the surface of the silica as shown in Figure A-16a. A zinc ion migrates to the site vacated by the silicon atom and coordinates with three or four oxygen atoms creating a net minus one or minus two charged site on the surface of the Boraflex as shown in Figure A-16b. This negatively charged zinc silicate site repels free OH^- radicals in the water thereby precluding further attack of the silica-rich Boraflex surface. Accordingly, the solubilization of the silica dominated matrix of irradiated Boraflex by OH^- ions is reduced. The influence of this negatively charged zinc silicate site is believed to extend over several SiO_2 molecules on the surface with one surface zinc ion protecting several surface molecules of SiO_2. The test data shown in Figure A-14 indicated that at bath solutions of 1 ppm the effect tends to saturate. It would appear that at about 1 ppm zinc there are a sufficient number of zinc ions deposited on the surface of the Boraflex and that the presence of additional zinc ions does not have a significant effect on the solubilization rate. Referring again to Figure A-15, and considering the hypothesized mechanisms at play, one might expect the normalized release rate versus zinc concentrations to be independent of temperature. That is, if each surface zinc ion protects several SiO_2 molecules, then the effect on solubilization rate should be the same independent of temperature.

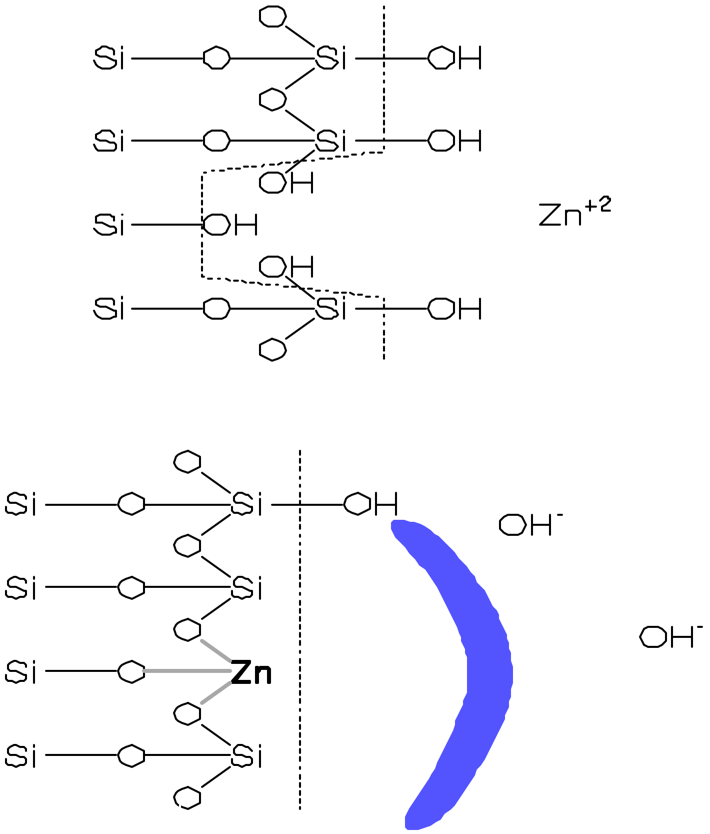


Figure A-16
(a) Zinc +2 Ion Mitigation to Silicon Atom Vacancy. (b) Surface Zinc Repels OH^- Ions in Solution

Iler[8] has studied the effect of aluminum ions on the solubility of amorphous silica particles. He concluded that a certain minimum number of aluminum atoms are irreversibly adsorbed on the surface of the amorphous silica particles. In the case of the aluminum/silica system, about 9 ppm Al_2O_3 in solution (4.5 ppm Al^{+3}) or about 0.43 Al atoms/nm^2 is irreversibly absorbed on the surface. This corresponds to about one aluminum atom per 18 potential silicate sites and the equilibrium solubility of silica was reduced from 100 ppm at 25°C to about 30 ppm. The addition of further Al^{+3} ions to the solution resulted in additional, but reversible, adsorption of Al on the surface. The maximum adsorbed aluminum concentration occurred with 30 ppm Al_2O_3 in solution (15 ppm Al^{+3}) or about three aluminum atoms per 18 potential silicate surface sites. At this concentration of Al_2O_3, the equilibrium solubility of silica was reduced from 100 ppm to 10 ppm at 25°C. While there are differences in the systems studied by Iler and the zinc/silica system in the present work, the mechanism of bi- and trivalent metal ions forming protective silicate sites appear similar. As part of a plant demonstration of zinc addition to a BWR spent fuel pool, some additional laboratory tests are planned. These tests will include dot mapping the surface of zinc treated Boraflex samples with energy dispersive microscopy to estimate the number of zinc silicate sites as a function of zinc concentration in solution.

Summary and Conclusions

The results of a series of experimental aging tests with irradiated Boraflex have been described. The test data provides, in addition to a basic understanding of the dissolution mechanisms of irradiated Boraflex in warm water, the silica source term models for the RACKLIFE program. These source term models relate silica release to integrated gamma exposure and pool water temperature.

Aging tests in which both the reactive silica and total silica concentrations were measured in the baths provide the relationship between reactive silica and total silica as a function of temperature. These relationships have been used in the RACKLIFE model of silica dissolution and transport to define the rates of dissolution in the small volume of water surrounding each Boraflex panel within the fuel racks. Measurements of the equilibrium reactive silica concentration versus temperature are consistent with data reported in the literature for amorphous and crystalline silica. This further confirms chemical tests which show the residual matrix of irradiated Boraflex to be silica or a silica dominated material.

The addition of small concentrations of zinc ions (+2 valance state) to the aging bath solutions was shown to reduce the dissolution rate of Boraflex by a factor of four to five. Mechanisms have been proposed to describe the effect of surface zinc on reducing the solubilization rate. The results of these tests have provided the basis for evaluating and implementing a demonstration program in which low levels (1 ppm) of zinc are introduced into the spent fuel pool specifically to reduce the dissolution rate of irradiated Boraflex. This demonstration program is currently being carried out under EPRI sponsorship. Previous calculations with a simplified RACKLIFE model have been reported which demonstrate that solubility inhibitors, such as zinc, have the potential to restore the useful service life to the originally intended 30 to 40 year duration.[1]

References for Appendix A

1. "Guidelines for Boraflex Use in Spent-Fuel Storage Racks", TR-103300, Electric Power Research institute, Palo Alto, CA; December 1993.

2. "Boraflex Test Results and Evaluation", TR-101986, Electric Power Research Institute, Palo Alto, CA; February 1993.

3. Lindquist, K., D. E. Kline, and R. Lambert. "Radiation Induced Changes in the Physical Properties of Boraflex™, a Neutron Absorber Material for Nuclear Applications", J. Nucl. Mat., Vol. 217, pp 223-228; 1994.

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6. "Zinc Injection to Control Radiation Buildup at BWRs: Plant Demonstrations", NP-6168, Electric Power Research Institute, Palo Alto, CA; January 1989.

7. "Inspection and Testing of Boraflex from the Fort Calhoun Spent Fuel Racks", NET-092-02. Northeast Technology Corp., Kingston, NY; March 1995.

8. Iler, R. K. "Effect of Adsorbed Aluminum as the Solubility of Amorphous Silica in Water", J. Colloid and Interface Sci., Vol 43, No. 2, pp 399; May 1973.

B

RACKLIFE USER’S MANUAL

Report No. NET-092-04 Rev. 0

RACKLIFE

Nuclear Spent Fuel Pool
Boraflex Rack Life Extension
Rack Management Tool

User’s Manual

March 1996

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Requests for copies of this report should be directed to Northeast Technology Corp. (NETCO) UPO Box 4178, Kingston, New York 12401. There is no charge for reports requested by members of the EPRI Enhanced Boraflex R&D Program. The software described herein is also available to members at no charge through NETCO.

NOTICE

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Abstract

RACKLIFE computes 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 to RACKLIFE: both how to run it and how to use it. 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 all of the features and functions of RACKLIFE.

RACKLIFE is designed for Intel (386 & 387, 486DX, Pentium)/DOS PC platforms.

Acknowledgments

Some of the algorithms in RACKLIFE are direct descendants of algorithms used in the BWRDOSE.wk1 and PWRDOSE.wk1 Lotus 1-2-3 templates for computing the dose to Boraflex coupons and panels in spent fuel pools. This was described in "Boraflex Test Results and Evaluations," TR-101986 (Electric Power Research Institute: Palo Alto, CA; February 1993).

Portions of the beta testing for RACKLIFE were performed by Niel Jones of Pacific Gas and Electric, Dave Hoppes and Brian Handley of Houston Lighting and Power, and Brad Kranz of Niagara Mohawk. In addition, Pacific Gas and Electric and Philadelphia Electric Company provided extensive plant data to test the code with.

1.0 Introduction

Welcome to EPRI's RACKLIFE, the **RACK** **LIF**e **E**xtension rack management tool. RACKLIFE computes the behavior 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.

1.1 Overview of RACKLIFE's Organization

The amount of data that RACKLIFE can generate is potentially enormous. Consider a large BWR pool with 4000 rack storage cells with about 8,000 panels of Boraflex. Data on silica (reactive, polymer, deposited), environment (temperature, pH, etc.), irradiation history, boron loss, etc., must be saved for each of these panels at each time step. In addition, the numerical solution of the silica kinetics equations must be executed simultaneously for the panels and the pool. 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.)

When it is desirable to know the state of the entire pool—the silica levels, panel irradiation levels, etc.,—for every panel and the pool as a whole, RACKLIFE uses a ***state point*** file. 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 boron-10 density. This would serve as the initial conditions for computing a subsequent state point in the future. Subsequent state points could be computed at the time of each refueling outage, just before another batch of spent fuel is loaded into the pool. In simulating a typical reactor lifetime of 40 years, then, you may only generate 30 to 40 state point files.

In simulating ***historical*** state points, those that have already occurred and for which some data is known from pool chemistry records, the 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 data*** (pool silica levels, pool environment) is saved daily during the computation. This allows a more accurate comparison of pool data results with recorded pool chemistry data.

An example of a difficult to measure parameter is the ***escape coefficient*** for the racks. The escape coefficient represents the rate at which pool water is exchanged between a panel cavity (that contains a Boraflex panel) and the bulk pool. "High escape" racks are typically those with stainless steel cover plates that are loose fitting and tack welded in only a few locations. An example of "low escape" racks may have stainless steel enclosure plates which press tightly against the Boraflex thereby exposing only the edges of the panels to the pool water.

In the RACKLIFE model a ***panel cavity*** is considered a distinct pool water volume, independent of any other panel cavity and connected to the bulk pool via the escape coefficient. It is the small volume of water that surrounds the Boraflex between the rack cell walls or between a cell wall and a retainer. To further illustrate the concept, consider two extremes. An infinite escape rack would have the Boraflex unclad, just sitting in the pool releasing silica directly into the bulk pool volume. A zero escape rack would have the Boraflex fully seal welded into an enclosure, releasing silica into the small volume of water around it but without any escaping into the bulk pool.

The input data required to run RACKLIFE is initially large, but there after is moderate. The following input files identified by a file name extension are created and used by RACKLIFE.

".GEO" — pool and rack geometry
".Rnn" — reactor cycle data for reactor "nn"
".ASB" — assembly database; data on all assemblies in pool
".MOV" — assembly placement; fuel shuffled into and out of racks
".CLE" — cleanup system operating parameters and history
".HIS" — historical pool chemistry data
".Snn" — state point file number "nn", "00" contains the initial conditions

The filename associated with these files is called a ***scenario***. 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.) Note that 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.

Input to these files generally progresses in the order they are listed above. First you must fully define the ***pool geometry*** and the rack modules in it. This includes creating a scale drawing of the pool perimeter using horizontal and vertical lines, and providing dimensions of rack module elements: cell pitch, cell wall thickness, Boraflex panel width, etc. For this you will need dimensioned drawings of the pool perimeter, as-built drawings of the rack modules, and the location of some point on each module in the pool as installed. In addition, if you do not enter a pool water volume directly, you will be prompted for a nominal pool water depth to calculate the pool water volume from. You may adjust this volume up or down to account for cleanup system resident fluid volumes, irregular pool shape, the racks and equipment in the pool, etc. Only volumes that combine to greater than 2% of the pool volume need be considered. Finally, you must label rows and columns of cells in each rack module as identifiers for placing fuel assemblies. Depending on how you index the cells in your pool, you may also have a pool ID and/or a region/module ID to uniquely locate a cell.

Next you must provide ***reactor data***. You can have more than one reactor data file for cases where fuel from more than one reactor is discharged into a given pool (such as at multiple unit / single pool plants). Reactor data includes:

- type of reactor (PWR or BWR, NSSS supplier)
- number of assemblies in the core

and, for each cycle,

- rated power during the cycle
- shutdown date
- power profile at end of cycle (shutdown from rated, shutdown from reduced power, step reduction in power before shutdown, orramp reduction in power before shutdown)

Simulations into the future assume shutdowns from rated at the last rated power level; this conservatively maximizes the radiation damage to the Boraflex.

The ***assembly database*** stores data on all assemblies that are ever resident in the pool. This includes:

- an assembly ID of up to 8 characters
- the assembly type, chosen from a list appropriate for the reactor type from which they came
- the fuel loading in metric tons of uranium (optional)
- the bundle average enrichment in weight percent U-235 (optional)
- the assembly burnup in MWD/MTU (optional)
- the assembly power sharing at end of cycle
- the reactor operating cycle the assembly was discharged from

A unique data entry is identified by three input items: the assembly ID, the reactor it was discharged from, and the cycle it was last depleted in. Thus a typical assembly will appear in the database three times: once for each of the cycles it is burned. The optional items are recommended but have only a secondary effect on calculations (internal defaults appropriate to the assembly type are used if these values are not included).

An assembly from the database is moved into and out of rack cells in the ***assembly placement*** file. This stores the assembly ID and the reactor it was discharged from, the date it was placed in a cell, the row and column IDs of the cell (and pool and/or region/module IDs if used), and the date it was removed from the cell (if ever).

Input data on ***cleanup systems*** is not required for a simulation but is necessary for an accurate simulation, particularly for BWRs which maintain low levels of pool silica via their cleanup systems. By removing silica from the pool water, cleanup systems increase the rate at which silica dissolves as it tries to reach equilibrium concentrations. Thus neglecting cleanup systems is non-conservative. Three types of cleanup systems are modeled: filters, demineralizers, and reverse osmosis systems. For each of these systems the nominal flow rate in gallons per minute is required. Filters require data from the filter spec sheet provided by the filter vendor, including:

- effective filtration area, in square feet
- pressure drop coefficient (permeability factor)
- particle sizes filtered absolutely (100% filtration), beta-5000 (99.98% filtration), beta-1000 (99.9% filtration), and beta-100 (99% filtration)
- nominal days to filter changeout

Demineralizers require vendor spec data on:

- bed depth, in feet
- bed area, in square feet

In addition, you must also provide:

- the nominal time between bed regenerations, in days
- the nominal time between bed resin exchanges, in days

This latter data must be prior to installing Boraflex racks in the pool. That is, you must estimate the average time between regenerations and resin exchanges before you had a significant silica problem as a result of having Boraflex in the spent fuel pool. Finally, reverse osmosis systems only require the nominal flow rate in gallons per minute and dates of operation. It is assumed that the filter/demineralizer train operates continuously while reverse osmosis equipment operates only when specified (for special pool cleanup operations).

Historical data is required to make accurate predictions of the escape coefficient, as discussed above. Only reactive silica data is necessary but the optional data is recommended for accurate simulations. The data includes:

- pool reactive silica concentration, in ppm
- pool colloidal silica concentration, in ppm
- bulk pool temperature and pH
- date of measurement

Finally, initial conditions are required. This is the state of the pool when the Boraflex racks are first put into service. The data is saved in a state point file with file name extension ".S00". This data is input immediately after defining the pool geometry and includes data similar to the historical data:

- pool reactive silica concentration, in ppm
- bulk pool temperature and pH

One last file of interest is the ***assembly types database***, "ASBLYTYP.DB". This is an application independent file containing data on assemblies specific to a given reactor. The formats used to store the data are given in the file and you may feel free to update the file to include more recent fuel assembly types that may appear in your spent fuel pool. Alternatively, you may define your reactor specifically and include only the assembly types that you have utilized during reactor operations.

This concludes the introduction to RACKLIFE's organization.

2.0 How to Run RACKLIFE

a. change to the directory RACKLIFE was installed to;

b. type "RACKLIFE" at the DOS prompt.

You must run RACKLIFE from the directory it was installed to. In particular, do not put the directory in a DOS "PATH" statement and try to run the program from another directory. The following files must appear in the RACKLIFE directory:

RACKLIFE.EXE	—	main program
MODULES.PCX	—	graphics file used in RACKLIFE
CELINOUT.PCX	—	graphics file used in RACKLIFE
CELLDIM.PCX	—	graphics file used in RACKLIFE
ASBLYTYP.DB	—	assembly type database (see Section 2.4)

2.1 Before You Start

RACKLIFE data files must be stored in a directory on your hard drive. In general this will be a subdirectory of the directory RACKLIFE was installed to. You must create this directory before you do anything more than use the Help System from the title screen in RACKLIFE. To create a subdirectory,

a. from the DOS prompt change to the directory RACKLIFE was installed to.

b. type "MD subdir" where "subdir" is a valid DOS subdirectory name of up to eight characters.

If you plan on keeping all of your data files in this directory you could call it "DATA". If you have more than one spent fuel pool to model you could name it for the plant or pool, and make other subdirectories for other pools.

Be sure to remember the directory name; you will need to supply it as input to RACKLIFE.

RACKLIFE data files are given a ***scenario*** name. All of the files you create during a RACKLIFE session will be given this name. Essentially, each spent fuel pool you simulate will have a different scenario name. ("What if" simulations for a given pool will generally be done under a different scenario name as well.)

Be sure to remember the scenario name you want to work with as you will need to supply it as input to RACKLIFE.

2.2 Entering the Program

Note your serial number and the program version number at the top of the title screen.

From the title screen you may press the <F1> function key to enter the help system, <Esc> to exit RACKLIFE, or any other key to continue.

If you continue, you are first prompted to toggle the <Num Lock> key "on". This is so the numeric keypad on extended keyboards will function properly. You will generally find that <Num Lock> is already on.

Next input a working directory. The input is initialized to the directory RACKLIFE was installed to; in general you will work in a subdirectory from this.

Finally input a scenario name. All files you create this session will bear this name. The program will automatically search for data files that already exist with this name.

You are now at the **top line menu** of the **main menu**.

2.3 Using the Help System

The RACKLIFE Help System can be accessed two ways. You can press <F1> from the title screen. This allows you access to the Help System without having to input a scenario directory or name. Alternatively, once you have entered RACKLIFE, you can press <F1> while the main menu screen is displayed.

Pressing<F1> displays a list of help topics. Use the arrow keys to highlight the topic of interest and press <Enter>. "Introduction" is simply the introduction to this User's Manual. "Getting Started" presents another list of topics designed to help walk you through the input process. "Menu Hierarchy" presents an expanded view of the main menu structure. Selecting a menu option gives help specific to that selection. "Tutorial" refers you to Section 3.0 in this User's Manual. "Technical Support" repeats the information in Appendix D of this User's Manual so that it is available to you on-line. "About EPRI RACKLIFE" documents the program's origins and development environment. Finally, "How to Exit" gives instructions on how to exit RACKLIFE and return to the DOS prompt for novices or those who stumble into the program inadvertently.

2.4 The Assembly Types Database

The file is stored in the directory RACKLIFE was installed to under the name ASBLYTYP.DB. It contains reactor type cards with data on the reactor. Under each reactor type card are assembly type cards for assemblies appropriate to the reactor type. These cards contain assembly data such as rod pitch, nominal fuel loading, active fuel length, etc. This data is used to create menus to select reactor and assembly types from. It is also used to get default data for values that the user does not enter (such as fuel loading).

ASBLYTYP.DB is an ASCII file and can be viewed with any ASCII viewer or editor. You can view it from RACKLIFE by selecting "Data / View / Other File" from the top line menu. Enter the drive and directory RACKLIFE was installed to, set the search criteria to "*.DB", and select the file to view.

Details on the structure of this file and how to add records to it can be found in Appendix C.

3.0 Tutorial

The following tutorial will demonstrate how to create scenario data files as summarized in Section 1.0, and how to execute simulations to calculate new state points. Before beginning, it must be emphasized that the following example is in no way representative of a real spent fuel pool. It is a simple fictitious "pool-like" example that will allow you to become familiar with RACKLIFE, its input requirements, its computational abilities, and its output options. Carefully going through this tutorial will prepare you to use RACKLIFE to simulate your own spent fuel pool or pools without further assistance.

3.1 Introductory Screens

Begin the tutorial by running RACKLIFE as described in Section 2.2 above. The first thing you see is a title screen. Note the white-on-blue text at the bottom of the screen. This is where you will generally find information on what keyboard keys you can use in the current screen. Press the <F1> function key. This brings up the Help Topics menu. From here you can view instructions and suggestions on how to use RACKLIFE. The "Introduction" and "Technical Support" sections from this User's Manual can also be viewed from here. Since you have already read the introductory text press <Escape> as noted on the bottom line to exit the help system. Press the <Space bar> to enter RACKLIFE.

The next screen requests that you toggle your <Num Lock> key on if it is not already on. (There should be an indicator lamp on your keyboard that lights when <Num Lock> is on; in general you will find <Num Lock> on.) This is necessary for the program to utilize the numeric keypad and cursor control keys correctly. Press any key to continue. You are now prompted for the drive and directory your scenario data files are (and/or will be) stored in. If the directory path you specify can not be accessed an error message will appear. Change the directory to the tutorial directory. This should be something like:

```
c:\racklife\tutorial
```

(Upper or lower case is acceptable; the result is converted to upper case.) Press <Enter> to input the directory. Next you are prompted for the scenario name you wish to use during this RACKLIFE session. Any valid DOS file name of one to eight characters can be used. If the file name is not valid an error message will be displayed. For this tutorial type "tutor" and press <Enter>. (From now on the <Enter> to input what has been typed will be assumed.)

3.2 The Main Menu

You are now at RACKLIFE's ***main menu***. The top of the screen displays a series of menu options on the first line and descriptions of each on the second. The following keys utilize the menu:

movement: right and left arrow keys

selection: <Enter>, down arrow,

retreat: <Escape>, up arrow

The bottom of the screen displays a list of the data files that are used to calculate new state points. When starting a new scenario all of these would be gray. For this tutorial the assembly database and assembly shuffle files are "Defined" and appear white in color. This means that the program has found files "TUTOR.ASB" and "TUTOR.MOV" in the scenario directory and has successfully loaded some data from them. When RACKLIFE is started it will always attempt to load all of the files listed except the state point file. Note that you can also access the help system from the menu by pressing <F1>.

The menu choices displayed are collectively called the ***top line menu.*** Pressing <Escape> repeatedly from anywhere in the main menu will return you to the top line menu.

The "File" menu governs entire files of data, while the "Data" menu governs individual data elements in a given file. When calculations are run under the "Execute" menu the data in these files is used to generate results. The display of these results is governed by "Output". To execute a calculation certain data files must exist and others are optional. The display at the bottom charts your progress toward providing those files.

3.3 The "File" Menu

Begin by exploring the "File" menu. Use the arrow keys to highlight "File" and press <Enter>. The first new menu choice is "Start". For your own simulations you can select "File/Start" to be sequentially prompted for input leading up to the calculation of a new state point. This is an easy way to navigate the program when first starting. Select "Start" to see the opening screen, and then press <Escape> to return to the top line menu. Select "File" again.

"Load" allows data files that do not use the scenario name to be loaded for use by the program. Highlight "Load" and press <Enter>. The two data files automatically found are displayed while the others show "No file yet". Note the keys defined on the bottom line. Press <F1> to read the help screen. When done, press any key to return to the input form. Use the <Tab> and <Shift>&<Tab> keys to move from field to field. (Note that the <Enter> key will also move to the next field like <Tab>; this is true in most input forms.) Move to the "assembly shuffle" field. As described in the help screen, use the left and right arrow keys to cycle the assembly shuffle selection between all files in the scenario directory with a ".MOV" extension. Now press <F2> to show the same choices in a vertical menu. Use the up and down arrow keys to highlight "TUTOR.MOV" and press <Enter>. The highlight automatically jumps to the next input field. Make sure that "TUTOR.ASB" and "TUTOR.MOV" are displayed and that the rest of the fields display "No file yet". Now press the <F10> function key to save your selections and exit the input form.

- in most forms the <F10> key is used to save an input set and in some cases it then exits the input form.

Remember to check the line at the bottom of the screen to see the current key associations for an input form. Select "File" again.

The third menu selection, "Import", allows pre-prepared data files to be used for input. The formats for these files are given in Appendix B of this User's Manual. More information can also be found in the help system. The fourth menu selection is "State". It allows you to select a state point file to act as the initial conditions for computing a new state point. The fifth menu selection, "Exit", allows you to return to DOS. You will return to these later in the tutorial. For now press <Escape> to backtrack to the top line menu.

The next few sections of the tutorial will explore the "Data" menu selection. You will see examples of input to each of the different data files, as well as how to edit and delete entries, by proceeding in the order you would follow to start a new scenario.

3.4 Pool Geometry

Begin by defining the spent fuel pool and rack module geometry. This sets the ground work for the rest of the data input and is the first data file that must be created. (This tutorial pre-loaded some files out of order for sake of example; recall that selecting "File/Start" directed you here first.)

1. Select "Data" from the top line menu.

2. Select "Input"

3. Note the three dots at the right side of the menu. This indicates that there are more menu items than are displayed. Use the "→" key to move beyond the displayed items to "Pool Geometry", and select it.

4. First you see a summary of your progress in creating a pool geometry file; it directs you to begin by defining the pool perimeter. Press any key to continue. Next the pool geometry menu is displayed. Press <F1> for an introduction. Pressing any key now redisplays the summary page. Pressing any key again returns you to the pool geometry menu. Select menu item 1, "Define the pool perimeter".

5. First you see a set of instructions on how to draw the pool walls. The pool you will draw is illustrated in Figure B-1. When you have carefully read the instructions

press any key to continue. You do not need to memorize or take notes on the instructions; pressing the <F1> function key will redisplay them.

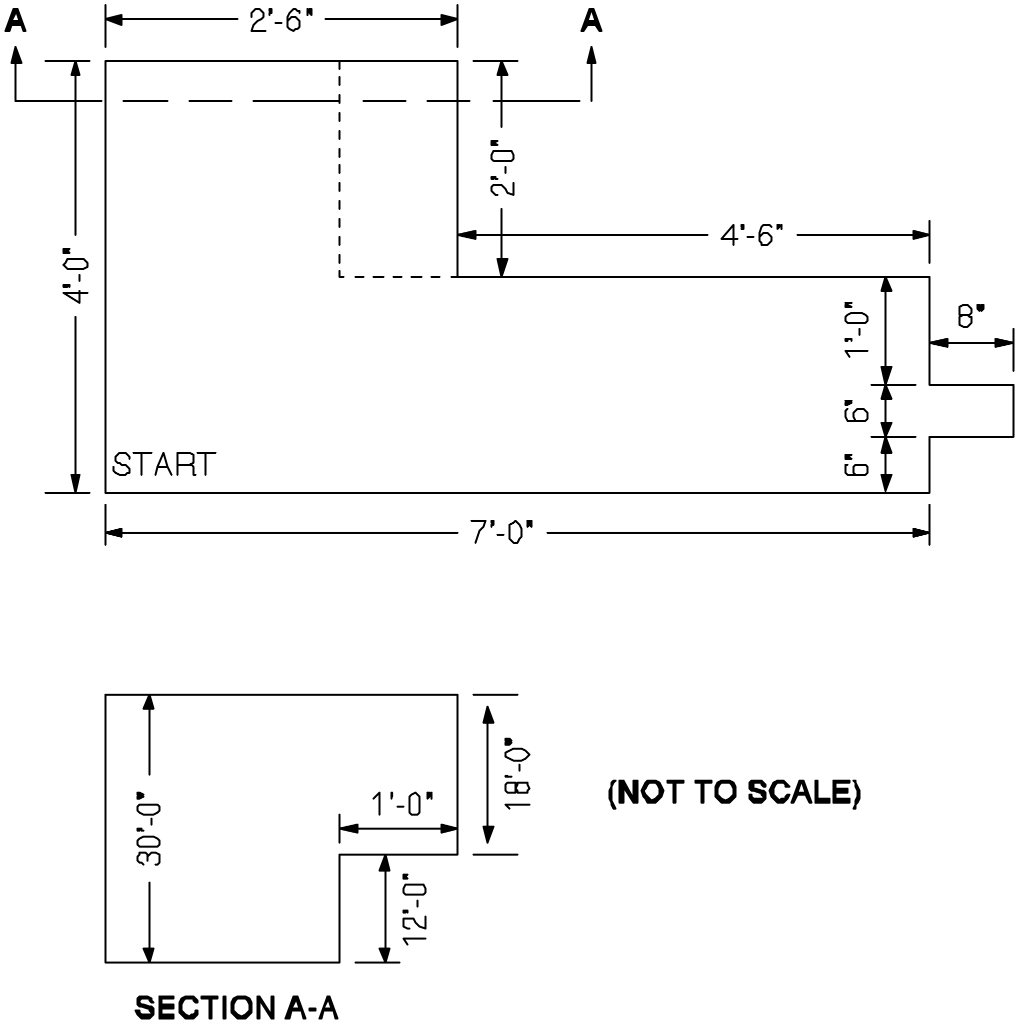


Figure B-1
Tutorial Pool Wall Geometry

6. Begin the drawing from the lower left corner marked "Start". Type "U" for up and "4" for the wall length in feet to draw in this direction. Press <Enter> to input the "4". Input is not case sensitive, so "U" and "u" have the same effect. The value could have been entered as "4", "4.", or "4.0"; trailing decimal points and zeros and leading zeros before decimal points are not required.

7. Type "R" and "2-6" to continue the outside perimeter.

— When you input dimensions in feet, the form of the syntax is feet[-inches][-numerator/denominator]

where items in brackets are optional. For example, to enter a length of 7′-6½″, you could enter any of

7.5417 or 7-6.5 or 7-6-1/2

If inches is present, the fraction is in inches. If inches is not present then any fraction is in feet. Thus 7-6 and 7-1/2 are equivalent. To enter a value in inches, for example 8 inches, when input in feet is required, type 0-8.

8. For subsequent lines, use the arrow keys to select a direction. In sequence, type "↓", "2", "→", "4-6", "↓", "1". Note that the drawing is automatically rescaled as necessary.

9. In a real pool this subsequent small water recess would probably be negligible. Any volumes that total to less than a few percent of the volume of the pool can be neglected. Here it is used to show a possible source of input error and, later, how that error can be handled. First the 8 inches will be represented as "0.66", and then as "0.67". In sequence, type "→", "0.66", "↓", "1/2", "←", "0.67".

10. Using an incorrect dimension, now type "↓", "2", "←", "7". To recover from this error tap the <Escape> key twice to erase the last two lines (alternatively, you could have typed "E" or "e").

11. Now type "↓", "1/2", "←", "7".

12. The perimeter has been completely specified back to the original corner, so type "F" for finished. (The screen image may not look exactly like Figure B-1, depending on the aspect ratio of your monitor.) While the perimeter appears complete on screen, the difference between 0.66 and 0.67 in step (9) is now detected. If the magnitude of the error had been larger than about 2 inches you would have been given no choice but to redraw the entire pool. Because the error is small, you may choose to have a small adjustment made to make the end points coincide. Type "1"; the adjustment is made automatically. You are then returned to the pool geometry, ready to add a module to the pool.

13. Select the highlighted menu option "Add a module to the pool". Because this is the first module you have defined, a special instruction screen appears on the use of pool and region/module IDs. Read the introduction carefully and then press any key to continue. For this tutorial press "N" twice to not use pool or region/module IDs. An introduction screen for creating a module now appears. Review the text and press any key to continue.

14. Each rack module is located by the center of its upper left cell. You must somehow trace a dimensioned path from some pool corner to this point. Dimensions can be found on drawings of the pool that include dimensions to the rack module feet (which are generally in the four corners). These dimensions can be used to trace a path from a pool corner to the cell center. If these dimensions are unavailable, you could chain a series of dimensions together from rack walls, as illustrated in Figure B-2. Pool wall to rack wall dimensions are typically found on "as-built" drawings of the racks in the pool. For this tutorial press <Tab> twice and enter "→", "0.7066", "↓", "0.6266".

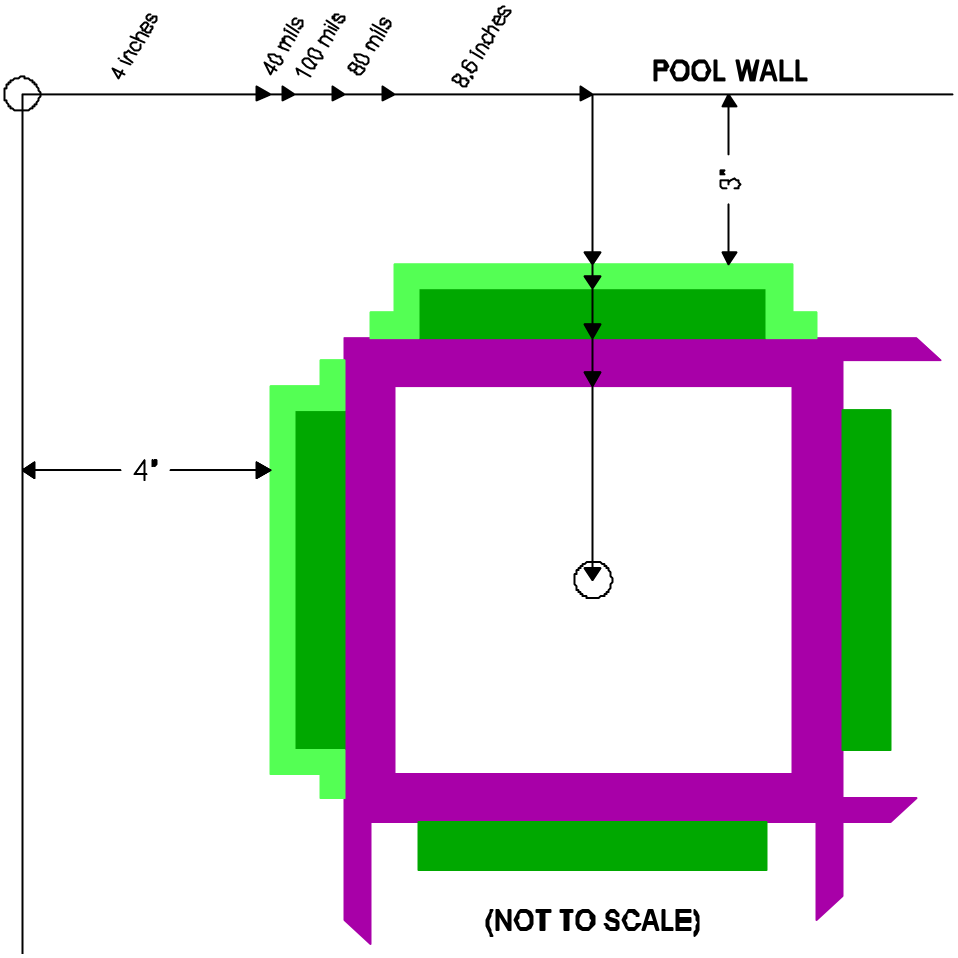


Figure B-2
Locating Tutorial Module Number 1

15. Four different types of racks are now illustrated. Choose the illustration by number that most closely corresponds to the type of rack module you are defining. For this tutorial enter "2" for flux trap.

16. Next the face of a rack module is illustrated. Input the specified dimensions as prompted.

— Note that when input in inches is requested, you can enter values in the form:

inches [-numerator/denominator] such as 6.5 or 6-1/2.

Type "10", "10", "8.6", "0.08", "0.04", "0.04", "0.1", "8.4", "144". These dimensions in inches are echoed at right. Note that the retainer on the outside of a module can have a different width from those on the interior. This is particularly important in egg crate designs that trap Boraflex between two cell walls. In that case the "retainer" thickness is the same as the rack thickness, but outside panels may have a retainer of a different thickness. It is assumed that the Boraflex is centered on the face of the rack cell and is of equal width on all sides. If this is not correct for your rack type, input the average Boraflex width such that the perimeter of Boraflex around a cell is conserved.

17. With all cell dimensions specified, the size of the module in rows and columns is prompted for. Type "2" and "2". All of this data is displayed at right and you are prompted to confirm that it is correct. Press "y" to accept the data.

18. Next the row and column identifiers are specified. If you had answered "Yes" to pool and/or module/region IDs they would be prompted for as well. Pressing any key to continue, type "a", "b" for the row IDs, press any key to continue, and type "1", "2" for the column IDs. The IDs may be one or two characters long and are automatically converted to upper case and right justified. If you make a mistake press <Escape>.

19. Finally, instructions for deleting panels are displayed for modules at the pool edge which often do not have Boraflex next to the wall. After reading the instructions press any key to continue. The rack module is now displayed with existing panels in blue and deleted panels in grey. Use the arrow keys to move the red spot around the module. Move it to cell A-1 and press <Enter> to make that cell active, indicated by a yellow spot. Now press "↑" and "←" to delete these two panels next to the wall. Press <Enter> to deactivate the cell. Use the arrow keys to move to cell A-2. Again press <Enter> to activate the cell, tap "↑" to delete that panel, and press <Enter>. Do the same thing using "←" to delete the left panel in cell B-1. This deletes all of the panels directly next to the pool wall. Press <Escape> to return to the pool geometry menu.

20. Select "Show pool drawing so far". This displays your current progress toward building a pool geometry file. Each module is numbered in the order that you input it. Press <Escape> to return to the pool geometry menu.

21. Select "Add a module to the pool" again. Simply type the following as prompted: <Tab> and then <Enter> to select the lower left corner; "↑", "1.3", "→", "0.5", "F". This will be a completely new module so type "N" for No. Now select module type "1" for egg crate.

22. In some egg crate designs the Boraflex is sandwiched between equally thick cell walls, making the following geometric distinction immaterial. In others, like the one illustrated, assemblies in some cells are surrounded by cell walls while others are surrounded by Boraflex cover plates (retainers) that are generally thinner than cell walls. Press any key to continue. For the upper left corner cell in the module, identify what an assembly placed there would face: a wall or a cover plate. For this example type "W". (If for your racks the choice is immaterial just type "W".)

23. Again dimension the cell. Type "8.82", "8.82", "8.6", "0.08", "0.04", "0.04", "0.1", "7.5", "146". Type "2", "2", "Y", press any key, "C", "D", press any key, "1", "2".

24. Press any key to clear the instruction display. The egg-crate module displayed automatically has some peripheral panels deleted as is typical of this rack type. You could add some panels back in the same way that they were deleted for the last module if necessary. For this example, just press <Escape>.

25. Select "Add a module to the pool" again to define a third module and press any key to skip the introduction. Press <Tab> and then <Enter> to select the lower left corner, "↑", "1.3", "→", "2", and "F" for finished. This is going to be identical in manufacture to module number 2 so type "Y" for yes. Enter "2" to select module 2. Note that the geometry data from the previous module is displayed for this one at right. Type "2", "3", "Y", press any key, "C", "D", press any key, "3", "4", "5". Press <Enter> to clear the help screen and <Escape> to accept the panel layout.

26. Finally, define one more module by selecting "Add a module to the pool", press any key, <Tab> and <Enter> again to select the lower left corner, "↑", "1.3", "→", "4.5", "F" for finished, "N" for no, and "4" for an unpoisoned rack. These are useful in the following ways: when importing assembly shuffle data you do not have to segregate out non-Boraflex rack assemblies; and the dose from assemblies in these racks to Boraflex in adjacent racks is included. On the other hand, input and computation time is increased.

27. Dimension the non-Boraflex cells by typing "8.7", "8.7", "8.6", and finally "0.1" for the thickness of stainless steel between cells in the non-Boraflex rack. (Do not include the thickness of any other materials such as boron or aluminum.) No other dimensions are prompted for. Type "2", "3", "Y", press any key, "AA", "BB", press any key, "11", "22", "33".

28. Select "Show pool drawing so far" to display the completed pool, then press any key. Now select "specify pool water volume". If you were to select "Input water volume directly" you could input a known value in liters, gallons, or cubic feet. Instead, select "RACKLIFE calculated volume". Enter "32-6" for the depth. Subsequently, you can add and subtract volumes in cubic feet from the calculated total. Since the shelf in Figure B-1 occupies 1′ x 2′ x 12′ = 24 cubic feet, enter -24. To

account for heat exchanger and cleanup system volumes, enter 50. Finally, enter 0 to exit.

29. Select "Create pool geometry file". In a few seconds a summary page will appear, indicating that the pool geometry file TUTOR.GEO has been created. Press any key and then select "Create initial conditions". This requires that you have data on your pool conditions around the time that the Boraflex was installed. Read the introduction and press any key to continue.

30. The input form you see is typical of all input forms in RACKLIFE. The form is made up of a sequence of input fields that each hold an element of input data. Keyboard keys that are important to the form are listed at the bottom of the screen. More details on using input forms will be given later. Type "1", <Tab>, "1", <Tab>, "90", <Tab>, to input a day about when the Boraflex racks were installed. This should be a day before the Boraflex racks had any exposure to spent fuel.

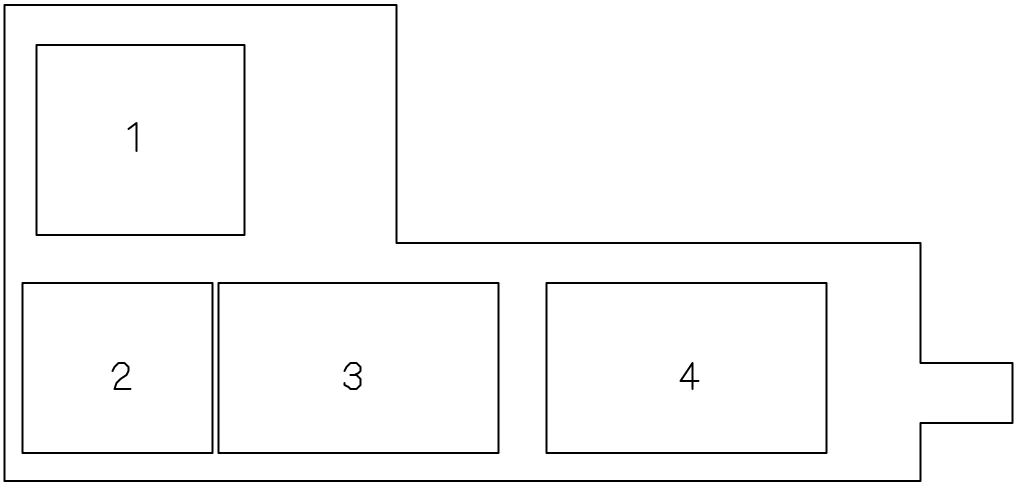


Figure B-3
The Final Tutorial Pool Layout

31. Enter 1 , <Tab> to input the initial reactive silica concentration in the pool. Press <Tab> again to leave the total silica input field blank. Only this field can be left bland in this form; a suitable approximation is used if no total silica data is available.

32. Enter "85", <Tab>, "5", <Tab> and "0". A final <Tab> will exit the input form, create an initial conditions file, and return you to the pool geometry menu. Select "Return to the main menu". Note that the bottom of the screen shows that the Pool Geometry, Pool History, and State Point files have been defined. Press <Escape> repeatedly to return to the top line menu.

3.5 Reactor Data

Next the reactor or reactors that discharge fuel assemblies to the pool must be defined. Reactor data files are not explicitly required and their presence is not indicated at the bottom of the main menu screen. The data in them is required, however, to add assemblies to the assembly database.

1. Select "Data" from the top line menu.

2. Select "Input"

3. Select "Reactor Data" and then "Define New Reactor". This will create a completely new reactor data file. Once created, "Append Cycle Data" can be used to add future cycle data as it becomes available.

4. First an instruction screen is displayed. In reading it you will note that there are two sets of data to provide: data on the reactor itself, and data on each of its operating cycles. Press any key to continue.

5. The input form is now displayed with key definitions at the bottom. When text input is requested, you may use both upper and lower case. For labels, identifiers, and file names all input is converted to upper case to avoid any confusion. Comments and descriptions like the reactor name are left in mixed case. For numerical input the numeric key pad can be used as well as the numbers above the main keyboard. When editing data the <Home> and <End> keys move to the beginning and end of the field, respectively. <Insert>, <Delete>, <Backspace> and the left and right arrow keys have their usual meanings. The <F3> function key will clear from the cursor position to the start of a field and the <F4> function key will clear from the cursor position to the end of a field. In general, the <F1> key brings up a help screen specific to the current input field.

6. Input "70" for the reactor number and press <Tab> to move to the next field.

7. Press <F2> to select from a menu of available reactor types. This list comes from the "ASBLYTYP.DB" assembly types database that you can modify to suit your particular needs. Note the gray help string under the input form showing keys specific to this field. Select "W PWR" from the list.

8. Enter "193" for the number of assemblies in the core. Finally, enter a description of the reactor to distinguish it from any other reactors defined. Type anything like "Tutorial Unit 1" but do not exit the field.

9. There are now a variety of keys that can be pressed. The edit keys noted in step 5 can be used to edit this field. <Shift>&<Tab> can be used to move to a previous field to edit it. A "safe" key to use in these multiple field input line forms is the <Enter> key. It moves to the next field in order, wrapping around from the last field

to the first. If you want to be cautious in your input habits use the <Enter> and <Shift>&<Tab> keys to move from field to field. Then, when you are satisfied with the input line, use the <F10> key to save the data. The <Tab> key works just like the <Enter> key except that when you Tab out of the right most field the program executes an automatic <F10> to save the line of data and move to the next line. This is useful when you are familiar with the input forms and want to enter data quickly. Try using the keys; when you are ready press <F10> or Tab off the right side of the form.

10. In this particular form saving a line of data automatically takes you to a second data input form. As the introduction screen says, data for each operating cycle must be input. Press any key to continue.

11. Input the following data: "1" for cycle number; "3400" for the rated power; "1", "1", "91" for the day/month/year of shutdown of cycle 1. Valid years include 51-99 for 1951 through 1999, and 00-50 for 2000 through 2050. The first line is the only time you will be prompted for a cycle number; subsequent cycles are assumed to be in ascending order after this one. If you knew, for example, that no assemblies prior to cycle 5 would ever be placed in Boraflex racks (and would also not be included in any fuel shuffle input data) you could start the file with cycle 5.

12. Move into the "shutdown power profile" input field and press <F1> for help. This describes what is being input here. Press any key to clear the help window. Enter a "1" for the shutdown profile number and press <F10> or Tab off the right to save the line.

13. Because you selected profile 1 you are automatically prompted for data specific to that profile. Profile 1 is a shutdown from some percentage of the rated power input in field 2. Profile 0 is just like profile 1 except that the shutdown is assumed to be from 100% of rated power and no profile-specific input is required. Input "90" for the percent of rated and press <Tab>.

14. A new line of input is automatically prompted for, complete with default values based on the previous line. Note that the next cycle number is automatically displayed in a protected (unalterable) field and the previous rated power is assumed as a default. Profile 0 is always assumed as a default. Enter "2", "2", "92" for the shutdown date, "2" for the profile, and <F10> or <Tab> to save the line.

15. Again you are prompted for profile specific data. Input "100", "85", "10" and <Tab> out or press <F10>. Profile 3 input is identical to profile 2 input; only the shape of the profile is different.

16. For cycle 3 enter "3", "3", "93", for the shutdown date and accept the default of "0" for the profile number.

17. Cycle 4 is automatically prompted for, but you only want to enter 3 cycles worth of data for this tutorial. Recall that data is not saved until <F10> has been pressed (or its equivalent by Tabbing off the right side). Press <Escape> to exit. The pop-up line correctly shows that cycle 3 was the last data set input. Highlight "Yes" and press <Enter>.

18. You now return to the reactor definition window. Since this is the only reactor you will define press <Escape> again and select "Yes". This returns you to the main menu. When cycle 4 data becomes available you could select "Append Cycle Data" to bring up the same input form and add the data.

3.6 Assembly Database Input

Having defined a reactor that will be discharging assemblies you must now provide data for each of those assemblies. For this tutorial a number of assemblies have already been defined. When input is selected the program checks if a data file exists or not. If not, it is created and data is input to it. If it already exists the input data is appended to the file. The program does check for conflicting input.

1. Select "Data/Input/Assembly Data".

2. Read the introduction screen and press any key to continue.

3. Select reactor number 70 with the description you typed in previously

4. The assembly database input form is now displayed with the reactor description above it. Enter an assembly ID of "tut01" (which is converted to upper case) and <Tab> or <Enter> to the next field.

5. As the gray help field indicates, press <F2> to get a menu of fuel assemblies defined in the "ASBLYTYP.DB" assembly types database as appropriate for the reactor type selected. If you do not find the assembly you need in this list you would have to <Escape>, exit the program, and update the assembly types database file to suit your needs. This file will be examined in more detail later.

6. Select the first on the list, "W 14 x 14 STD".

7. Now Tab all the way across to the discharge cycle number, enter "1", and <F10> to save the input. What you have entered is the minimum required data to define an assembly. The missing data is handled as follows: the fuel loading is taken as the value typical for the assembly type; the enrichment is taken as 3.0 weight percent; the burnup is assumed to be 33,000 MWD/MTU; and the power sharing is assumed to be 1.0. The first three approximations have a small or secondary effect on the results and are acceptable. The power sharing is very important to an accurate solution, however, and is strongly recommended as an input.

8. The new input line defaults to the assembly type input on the previous line. Enter "TUT01" for the ID and "0.43", "2.9", and "22000", and "1.1" for the loading, enrichment, burnup and power sharing respectively. Enter "1" for the discharge cycle number and press <F10>. The program indicates an error because this assembly is multiply defined. Change the discharge cycle to "2" and press <F10>.

9. Again a new input line is generated with the default assembly type from the previous line. Enter "TUT01", "33000" for the burnup, "0.9" for the power sharing, and "3" for the discharge cycle. Press <F10> to save this line. Press <Escape> and select "Yes" to end this input session.

3.7 Assembly Shuffle (Movement) Data

The assemblies just defined can now be placed into the racks for specified time intervals.

1. Select "Asbly Shuffle", read the introduction screen, and press any key to continue.

2. Select reactor number 70 with the description you gave it as the source of these assemblies.

3. In this case when the input form is displayed the first two fields are protected. This is because when defining the pool geometry you indicated that pool and region/module IDs were not necessary to locate a rack cell. If they were necessary one or both of these would be accessible for data input as well.

4. Input the following data: "A", "1" for the cell location, "TUT01" for the assembly ID, "8", "1", "91" for the placement date and "9", "2", "92" for the removal date. Press <F10> to save the data. The "A" and "1" are automatically capitalized and right justified.

5. The next line defaults to what was entered on the previous line. Change the placement and removal dates to "9", "2", "92", and "10", "3", "93", respectively, and press <F10>.

6. For the third line change the row and column IDs to "B" and "1" and the placement date to "10", "3", "93". Enter a "0" for the removal day and press <F10> or Tab out of it. This automatically places the assembly in the cell "in perpetuity" (forever). If, at some later date, this assembly is moved, simply input the new data. You will be cautioned that you are moving a formerly permanent assembly but selecting "OK" will alter the old date accordingly.

7. Press <Escape> to exit and select "Yes" to return to the main menu.

3.8 Cleanup Systems Data

Cleanup system data is not required to execute a simulation, but because cleanup systems may have a significant impact on silica release rates it is strongly recommended.

1. Select "Cleanup Data" / "Define"

2. There are three types of cleanup systems that can be modeled in RACKLIFE: filters, demineralizers, and reverse osmosis cleanup units. Filters and demineralizers are assumed to be parts of a cleanup system train that operates continuously (except for filter changeouts, demineralizer resin exchanges, etc.). Because of the large variety of filter and demineralizer media and configurations some model idealizations were required; a limited subset of vendor data on the media is prompted for. Reverse osmosis units, if used, are generally infrequently operated and then only for a short period of time. Reverse osmosis units are much easier to model and are much more predictable; no vendor data is required.

3. Select "Filter"

4. The data table displayed must be completely filled out using vendor data for the filter media and system nominal flow rates for a clean filter. Input "120" gpm for the flow rate.

5. Use the data in Figure 4, a typical vendor data sheet, to fill in subsequent data fields: "54.5" square feet effective filtration area, "0.420" 'K factor in water' (pressure loss coefficient), "20" µm absolute, "16.5", "14.1", "9.3" µm particle size. These particle sizes are filtered with the efficiency given in parenthesis. Some filters are so fine that the particle size is given as '<1 µm'. For these cases enter "0" and the program will make an appropriate approximation.

6. Finally enter the median number of days between filter changeouts. This data must be from a period of time after the Boraflex racks were installed but before a significant pool silica problem was encountered. Enter "90" for this example.

Filter:	Pall U200Z (20 µm absolute)	
Element:	6″ diameter x 30″ high	
Effective Filtration Area:	54.5 square feet	
"K" factor (in water):	0.420	
Efficiency:	β_{5000} (99.8%)	16.5 µm
	β_{1000} (99.9%)	14.1 µm
	β_{100} (99.0%)	9.3 µm

Figure B-4
Typical Vendor Data for Filter

7. When finished press <F10> to save the filter data.

8. Select "Define", and then "Demineralizer".

9. Enter a flow rate of "120" gpm.

10. From demineralizer spec sheets enter the bed depth and area as "4" feet and "6" square feet.

11. The next two items will again have to be culled from historical pool chemistry data. The average time between regenerations and the average time between resin exchanges must be over a period of time just after the Boraflex racks were installed. That is, the regenerations and exchanges should be due to pool contaminants without including the additional silica burden caused by its dissolution from the Boraflex. For this tutorial enter "30" and "150" days.

12. Finally, select "borated" to indicate that boric acid is dissolved in the pool water. Press <F10> to save the data.

13. Select "Define" and "Reverse Osmosis".

14. Note that only the flow rate and dates of operation are required. For this tutorial press <Escape> to exit without entering any values.

    The program assumes that the filter demineralizer train operates continuously and that the reverse osmosis unit operates only between the dates entered. If any of the data changes (for example, if a new type of filter is installed), simply execute a state point calculation to the changeout date, enter the new data, and then begin subsequent state point calculations from that state point. If the cleanup system is off-line for a significant length of time the flow rate can be set to zero and a state point calculation performed for the duration of the outage.

15. Finally, select "Data/Input/Cleanup Data/Letdown". This form can be used to model discrete water-volume changeouts. The volume of makeup/letdown, the silica concentration in the makeup water, and the dates are required. For this tutorial simply press <Escape> to exit.

3.9 Pool History Data

Pool history data is not required to calculate a new state point but can be important for accurate simulations. Of greatest importance is the bulk pool temperature over time, as this has a significant effect on the silica release rate. Silica data is vital for computing the escape coefficient.

1. Select "Data"/"Input"/"Pool History", read the introduction screen, and press any key to continue.

2. The input form you see is the same as that used to input the pool initial conditions after defining the pool geometry, so no more time will be spent in it here.

3. Press <Escape> to exit.

4. Note that, since you have not input any data (by using <F10>), the 'last pool history date' is blank. Select "Yes".

5. Press <Escape> until you are at the top line menu ready to select "Data".

3.10 Editing Data

Editing input data uses the same forms as shown above for input. When you first enter the form you must fill in certain "search" fields, such as the assembly ID and discharge cycle to identify a single assembly in the assembly database. The other fields are "protected" and can not be filled. If matching input is found, the data is displayed in unprotected fields that can be edited. As an example,

1. Select "Data" / "Edit" / "Assembly Data". Press any key to clear the introduction screen.

2. Select reactor number 70 with the description you gave it.

3. Enter "TUT01" for the assembly ID and press <Tab>. Note that you jump directly to the discharge cycle field.

4. Enter "3" for the discharge cycle number and press <Tab>. This generates an <F10> to call up the data for this assembly

5. You can now edit the data just called up (but not the ID or discharge cycle, which are now in protected fields). Change the burnup to "34000" and press <F10> to save the edited data.

6. Press <Escape> to exit. The exit from the editor is always automatic; no confirmation is requested.

3.11 Deleting Data

Deleting input is just like editing except that, instead of bringing up data to edit, the searched for data line is deleted and another deletion search set is prompted for.

3.12 Viewing File Data

All of the data used in RACKLIFE is stored in ASCII files to allow easy viewing. To illustrate the data viewer you will look at the assembly types database, "ASBLYTYP.DB".

1. Select "Data"/"View".

2. Note the three dots at the right side of the menu indicating more selection are available. The first five menu options allow you to look at data files defined in the current scenario, while the sixth allows you to view any reactor file. "ADD File" displays a list of import data files to choose from. "Print File" lets you view a results file created under "Output/Print".

   The "Scenario" menu selection displays a list of all files with the scenario name for a filename. The last menu selection, "Other File", lets you specify a directory and search criteria to generate a list of files from. (If there were more files than would fit on the page the menu would scroll up and down and you could use "Page Up/Page Down" and "Home/End" to navigate it quickly.) Select "Other File", enter "c:\racklife" (or whatever path RACKLIFE was installed to), and then enter "*.DB" for the search criterion. Select the "ASBLYTYP.DB" file highlighted.

3. The ASCII file is displayed with a number of buttons across the bottom. Press "H" for help to see what the buttons and other keys do. Select "I" for "Info" to see the time and date that the file was created, as well as the file size.

4. Move around the file to examine its contents. As long as you use the format conventions specified in the file you can add assemblies specific to your reactor and even create your own reactor type with only the assembly types you use in it. This is described in Appendix C.

5. When done press "Q" for 'Quit' or <Escape>.

6. Press <Escape> again to get to the top line menu.

3.13 Importing Files

Select "File/Import". "Import" is used to bring in files of input data that you have created outside of the RACKLIFE program. The ability to import allows you to use existing data files on the computer, manipulate them to meet the file format requirements (given in Appendix B), and input the data more easily than typing it all in by hand. You still must go through the input forms for error checking but the data is automatically entered so you need only press <F10> to load it into the file. As an example, you will now import some assembly placement data. Select "Asbly Shuffle". All of the files with ".ADD" for an extension are displayed. When you create a file to import you must give it a ".ADD" extension so it is recognized here. Select "TUTORMOV.ADD" by using the keys noted on the bottom line. You are now at the instructions page of the pool history input form; press any key to continue. The data you see displayed in the input form is directly from the ".ADD" file. Press <F10> to save the current line of data and display the next line. Continue to press <F10> until you suddenly return to the main menu. All of the data in the "TUTORMOV.ADD" file has been appended to the pool history file previously input.

3.14 Select a State Point File

The input of data is now complete. The only remaining tasks are to select a state point file to compute from and a state point to compute to. Select "File/State" to get a menu of state point selection possibilities. The first option is to select the last defined state point in the sequence "scenario_name.Snn" where "nn" ranges from "00" to "99". The second lists all "scenario_name.Snn" files in a list to choose from. The third option lists state points from any other scenario in the directory (for "what if?" scenarios, for example). The last option simply lists all of the files in the scenario directory to choose from. Select the first option to use "TUTOR.S00" as the initial conditions state point. This file was created when the initial conditions were input after defining the pool geometry. Returning automatically to the main menu, note that the state point file is now defined.

3.15 Verifying Your Input

In general, you will need to review the ASCII data files to verify your input. To assist you, two displays under "Output/Display" give pool geometry and pool shuffle information.

1. Select "Output/Display/Pool Geometry". The pool and modules are displayed.

2. Enter "0" and then continue to press <Enter>. This will highlight successive pool walls in yellow and report their length in feet. If the pool perimeter needed to be

corrected (so the beginning and end corners coincided), then you will note a slight adjustment in one or two dimensions. In this case wall number 10 reports a length of 6.99 feet when the input dimension was 7 feet. Finally, the pool water volume and surface area are reported.

3. Next enter "1" to view module 1. The deleted panels are in grey and dimension data is displayed. Press <Escape> twice to return to the main menu.

4. Next select "Display/Pool Utilization".

5. Enter "10", "1", "91" and press <F10>.

6. Enter "2" to view module 2. What you see is a map of assemblies in module 2 at the end of the day entered. Cell D1 does not contain an assembly and so is shown with a dotted line. The occupied cells are highlighted in yellow. Moving the red cursor to a cell and pressing enter displays the assembly ID of the assembly in that cell. Press <Escape> twice to exit the main menu.

3.16 Performing Dose-Only Calculations

This calculation requires no cleanup, pool history, or escape coefficient data. It calculates only the dose to the Boraflex panels on a given day.

1. From the top line menu select "Execute/Dose Only".

2. Enter the data "1", "1", "92" and press <F10>. In a few seconds a message will appear noting that a print file has been created and saved in the scenario directory. During your own calculations you may wish to write down the name of the file to look at later. Press any key.

3. Enter "0" to view the entire pool. An input form first appears to allow you to change the bounds on the colors the panels are displayed in. Press <F10> to accept the defaults. The pool is now displayed with a coarse view of how panel doses are distributed in the pool. Press <Escape> to exit.

4. Next enter "2" and again press <F10> to accept the default bounds. This gives a detailed view of the module. Moving the red cursor to a cell and pressing <Enter> will display the cumulative dose to each panel on the date input. Press <Escape> twice to return to the main menu.

3.17 Adjusting Default Program Data

The color flag bounds observed in the dose-only calculation can be adjusted, as can the methodology for performing the dose estimates.

1. From the top line menu select "Date/Edit/Scenario Data".

2. Press <F1> to view a description of the input form. Changing the bounds here will change the defaults offered when displaying boron carbide loss or dose. Changing the calculation methodology determines whether you use a conservative or best estimate approach. Press <Escape> to return to the main menu.

3.18 Estimating the Escape Coefficient

From the top line menu select "Execute/Escape Coef". If you were to select "Compute", RACKLIFE will perform a long series of calculations to make a best estimate of the escape coefficient based on the silica data in your pool history file. The more data you provide a better estimate that RACKLIFE will make. Alternatively, you can input a value directly by selecting "Input". Press <Escape> until you return to the top line menu.

3.19 Performing a State Point Calculation

Once an escape coefficient is estimated or input you could then select "Execute/State Point". After entering a date to compute to, a lengthy calculation is performed to compute the state of the pool and Boraflex panels on that date. When the calculations are completed, you could then select "Output" and "Display", "Plot", or "Print" to view silica concentrations in the pool and boron carbide loss from the panels. At any time in the future you can recall this data for output by loading the appropriate state point.

Appendix A: Installing Racklife

System Requirements

CPU:	Intel 386 & 387, 486DX, Pentium
RAM:	16 MB (If more than 16 MB is available, allocating some to a disk cache will improve performance.)
Hard Drive:	50 MB free space
Video:	VGA at 640 x 480 x 16 colors
Operating System:	PC-DOS or MS-DOS 5.x or 6.x (RACKLIFE has not been tested in a Window's DOS box.

RACKLIFE will run in an OS/2 3.0 (Warp) DOS full screen session with DPMI_MEMORY_LIMIT set to 16 or greater.)

Distribution Diskettes

RACKLIFE is distributed on a 3.5″ High Density diskette in a compressed form. You will find four files on the diskette:

RACFILES.EXE
TUTORIAL.EXE
INSTALL.BAT
DISK_ID.TXT

RACFILES.EXE

This is a self-extracting compressed file that contains the RACKLIFE.EXE executable and all associated data files.

TUTORIAL.EXE

This is a self-extracting compressed file that contains the files used in the tutorial.

INSTALL.BAT

This batch file will install RACKLIFE from the diskette to your hard drive.

DISK_ID.TXT

This file is created in the diskette transmittal process. It confirms distribution data, filename and serial number data, that a diskette surface scan was completed successfully, and that a virus scan was completed successfully.

Running the Installation Batch File

The following assumes that you will install RACKLIFE from the diskette in drive A to your hard drive C. If you are installing from drive B and/or to hard drive D, E, etc., substitute the appropriate drive letters below.

1. Put the diskette in the drive.

   Type

   ```
   "A:INSTALL A: C:"
   ```

where A is the diskette drive (usually A or B) and C is the hard drive to install RACKLIFE to. The program will be installed to C:\RACKLIFE. If you want the program in a subdirectory, enter

```
"A: INSTALL A: C:\subdir"
```

Do not include a trailing backslash.

Note: You can not install RACKLIFE to a root directory.

2. Wait for a message to appear on the screen confirming that RACKLIFE has been installed successfully. Installation is now complete.

Appendix B: Import File Formats and Input Data Forms

Racklife Input File Formats

File types that data can be imported to via "File/Import":

- Assembly database entries
- Assembly placement (shuffle) data
- Pool history data

All import files must have the extension ".ADD". They may have any valid DOS one to eight character filename.

If a data file already exists, the import file data is appended to the existing data. If you wish to replace the existing file with the import file, select "File/Load" from the top line menu and select "No File Yet" for that file type. When you then import the data you will be asked whether the existing data file is to be deleted.

Comment Cards

A common feature of each of these files is the use of comment cards. By placing an exclamation point, "!", in column 1, the line becomes a comment card. Comment cards can be placed anywhere in these files. Data cards must have a blank in column 1 and may not have comments embedded in them. You may place comments to the right of a line of input data, but future RACKLIFE upgrades may make files with these types of comments unusable.

Data Alignment and Format

- Alphanumeric text is generally left justified.
- Values may fit anywhere in the input field but are generally right justified.
- Leading and trailing zeros are ignored.
- Decimal points are only required to set off decimal fractions.
- Alphabetical characters may be entered in either case but are converted to upper case when imported.

Assembly Data

Example:

```
!        1         2         3         4         5         6
!234567890123456789012345678901234567890123456789012345678901234567890
!
 A0000001 B&W 15x15 B5  1  0.4635  3.0500 33000.0  1.0010  1
!
```

Columns	Description
1	blank
2–9	assembly ID, left justified, 1–8 alphanumeric characters
11–22	fuel assembly type as given in the assembly types database, ASBLYTYP.DB, or leave blank to be prompted for the type during import.
24–25	reactor number assembly was depleted in
27–33	assembly fuel loading [MTU]
35–41	assembly average U-235 enrichment [weight–percent]
43–49	assembly total burnup when discharged [MWD/MTU]
51–57	assembly end of cycle power sharing
59–60	cycle number assembly was discharged from

Assembly Shuffle

Example:

```
!        1         2         3         4         5         6
!23456789012345678901234567890123456789012345678901234567890
!
  1  1  A  1 A0000001     1 91/01/05 12:00 91/02/05 12:00
!
```

Columns	Description
1	blank
2 3	spent fuel pool ID of rack cell (1 if not applicable)
5 6	region/module ID of rack cell (1 if not applicable)
8 9	rack cell row ID
11–12	rack cell column ID
14–21	assembly ID, left justified, as entered in assembly database
23–24	reactor number assembly was discharged from
26–27	blank
29–30	year assembly placed in cell ("51" to "50" for 1951–2050)
31	"/" or blank
32–33	month assembly placed in cell
34	"/" or blank
35–36	day assembly placed in cell
38–39	hour assembly placed in cell (__ if not applicable)
40	":" or blank
41–42	minute assembly placed in cell (__ if not applicable)
44–45	year assembly removed from (0 if permanent)
46	"/" or blank
47–48	month assembly removed from cell (0 if permanent)
49	"/" or blank
50–51	day assembly removed from cell (0 if permanent)
53–54	hour assembly removed from (__ if not applicable)
55	":" or blank
56–57	minute assembly removed from ("00" if not applicable)

Pool History

Example:

```
!        1         2         3         4         5         6
!23456789012345678901234567890123456789012345678901234567890
!
 94/01/01 12:00  40.00000  74.30000 113.540  5.54 0.0
!
```

Columns	Description
1	blank
2-3	year measurement was taken ("51" to "50" for 1951-2050)
4	"/" or blank
5-6	month measurement was taken
7	"/" or blank
8-9	day measurement was taken
11-12	hour measurement was taken ("12" if not applicable)
13	":" or blank
14-15	minute measurement was taken ("00" if not applicable)
17-25	* bulk pool reactive silica concentration [ppm]
27-35	* bulk pool total silica concentration [ppm]
37-43	* bulk pool temperature [degrees Fahrenheit]
45-49	* bulk pool pH
51-56	* concentration of solubility inhibitor [ppm]

*Between one and all of these fields must contain data; leave the field or fields blank if no data is available for that quantity at the given date and time.

INPUT DATA FORM: POOL GEOMETRY

Wall Number	Direction (U,D,R,L)	Dimension [feet]
1		
2		
3		
4		
5		
6		
7		
8		
9		
10		
11		
12		
13		
14		
15		
16		
17		

Sketch Pool Perimeter, labeling walls and corners in order.

× indicates corner to start from

Nominal Pool Water Depth [ft]: ___________Volume corrections [ft^3]:
(7.4805 gal/ft^3)

Do you use a pool ID to locate cells?: Yes/No
Do you use a region/module ID to locate cells: Yes/No

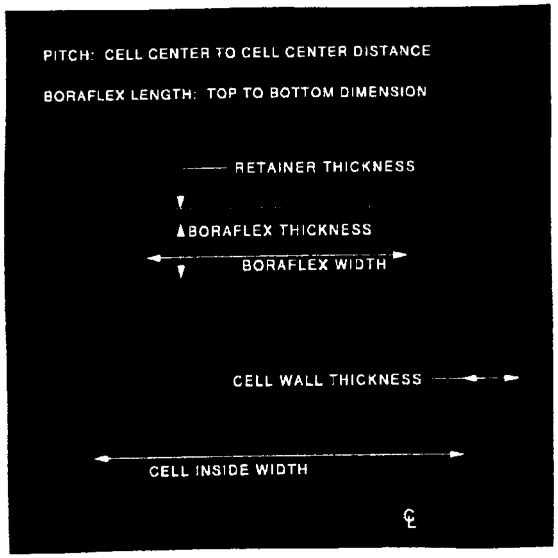
INPUT DATA FORM: MODULE GEOMETRY
MODULE NUMBER _____ OF _____

Starting Corner: ____________________

Move Direction (U,D,R,L)	Move Dimension

Module Type: 1⇦Egg Crate 2⇦Flux Trap 3⇦Mixed
4⇦Unpoisoned

(If Egg Crate, is the upper left corner assembly next to [w]all or [r]etainer _____)



cell pitch in x: ☐

cell pitch in y: ☐

cell inside width: ☐

cell wall SS thick t_w: ☐

retainer SS thick t_r: ☐

outside retainer SS t_o: ☐

Boraflex thicknessT_B: ☐

Boraflex width W_B: ☐

Boraflex length L_B: ☐

Module Rows: ☐

Module Columns: ☐

Input Data Form: Reactor Data

	<u>Options</u>
Reactor Number: ____________	1-99
Reactor Type: ____________	B&W PWR; CE PWR; GE BWR/2,3; GE BWR/4,5,6; W PWR
#Assemblies in Core: ____________	
Name or Description: ______________________________	(50 CHARACTERS MAX)

Cycle Data for this Reactor

Cycle Number	Rated Thermal Power [MW_{th}]	End of Cycle Shutdown			Shutdown Power Profile Number*	% of rated		Time T_2 [days]
		Day	Month	Year		P_1	P_2	
(1-99)		(1-31)	(1-12)	(51-50)	(0-3)			

* 0⇒shutdown from rated; 1⇒shutdown from P_1; 2⇒step reduction from P_1 to P_2, holding at P_2 for T_2 days, and shutdown; 3⇒ramp reduction from P_1 to P_2 over T_2 days, then shutdown.

Cycle Data for Reactor Number: ________

Cycle Number	Rated Thermal Power [MW_{th}]	End of Cycle Shutdown			Shutdown Power Profile Number*	% of rated		Time T_2 [days]
		Day	Month	Year		P_1	P_2	

(1-99) (1-31) (1-12) (51-50) (0-3)

* 0⇨shutdown from rated; 1⇨shutdown from P_1; 2⇨step reduction from P_1 to P_2, holding at P_2 for T_2 days, and shutdown; 3⇨ramp reduction from P_1 to P_2 over T_2 days, then shutdown.

Input Data Form: Assembly Data (for reactor number: ______)

Assembly ID	Fuel Assembly Type	Fuel Loading [MTU]	U-235 Enrichment [w/o]	Total Burnup [MWD/MTU]	EOC Power Sharing	Discharge Cycle Number
8 characters maximum	Select from ASBLYTYP.DB	optional	optional	optional	optional, recommended	must be in cycle data

Input Data Form: Assembly Placement Data (for reactor number: ______)

Pool *	Region/ Module*	Cell Row	Cell Column	Assembly ID	Placed in Cell			Removed from Cell		
					Day	Month	Year	Day**	Month	Year
-------------------- 2 character IDs-------------------------				from assembly database	(1-31)	(1-12)	(51-50)	(0-31)	(1-12)	(51-50)

* if used

**0 for permanent placement

Input Data Form: Pool History Data

Measurement Taken			Reactive Silica [ppm]	Total Silica [ppm]	Bulk Pool Temperature [°F]	pH	Dissolved Boron [ppm]
Day	Month	Year					
(1-31)	(1-12)	(51-50)	req. for escape coeff.	optional	optional, recommended	optional	optional

INPUT DATA FORM: CLEANUP SYSTEMS

FILTER:

Nominal flow rate [gpm]: ________________
Effective filtration area [ft^2]: ________________
Pressure drop coefficient k: ________________
(permeability factor)

Efficiency

absolute: ________________ micrometers
BETA-5000 (99.98%): ________________ micrometers
BETA-1000 (99.98%): ________________ micrometers
BETA-100 (99.8%): ________________ micrometers

Nominal days to filter changeout: ________________

DEMINERALIZER:

Nominal flow rate [gpm]: ________________
Bed depth [feet]: ________________
Nominal time to regeneration [days]: ________________
Nominal time to resin exchange [days]: ________________
Is the pool water borated? (Y/N): ________________

REVERSE OSMOSIS:

Nominal flow rate [gpm]: ________________
Dates of operation - from (DD/MM/YY): ________________
To (DD/MM/YY): ________________

Appendix C: Modifying the Assembly Types Database

The assembly types database is an application independent file containing data on assemblies specific to a given type of reactor. You are encouraged to modify this file to suit your needs. These modifications typically take two forms:

- add new assembly types for a given reactor, or
- define a new reactor and all of its associated assembly types.

Examples of both are given below. Changes can be made using any ASCII editor.

Example of a new assembly type data card for the “W POOR” reactor.

```
!        1         2         3         4         5         6         7
!23456789012345678901234567890123456789012345678901234567890123456789012345
!
 W 17 x 17 XLR WST17W    17 0.542  0.4632 289 0.374  168.0   0.0225 0.332
!
```

Columns	Description
I	blank
2- 13	assembly type name
15-23	EIA (Energy Information Agency) assembly type code (optional)
25-26	rod array size (number of rods across one side of assembly array)
28-33	rod pitch [inches]
35-40	fuel loading (metric tonnes of uranium) [MTU]
42-44	number of fuel rods in assembly (not including water rods)
46-51	fuel rod clad outside diameter [inches]
53-59	active fuel length of enriched fuel [inches]
61-66	clad thickness [inches]
68-73	fuel pellet diameter [inches]

Example of a new reactor type card and an associated assembly.

```
!        1         2         3         4         5         6         7
!23456789012345678901234567890123456789012345678901234567890123456789012345
!
$ 1 'ABC Unit 1   '
!
 W 17 x 17 XLR WST17W    17 0.542  0.4632 289 0.374  168.0   0.0225 0.332
!
```

Reactor Type Card

Columns	Description
1	dollar sign ($)
3	reactor type (1 => POOR, 2 =>BWR)
6-18	reactor or plant name. Note that the apostrophes are optional and are only used for improved readability.

Assembly Type Data Card

This is identical to the assembly added in the preceding example.

End of File Card

Note the "E" in column 1 of the last card in the example. This indicates that this is the last card in the assembly types database. Do not forget to include this card (the dashes are optional) at the end of your modified file, and make sure it only appears at the end.

Note that you can include comment cards anywhere in the database.

Appendix D: Technical Support

RACKLIFE is developed and distributed by NETCO (Northeast Technology Corp.) for EPRI; NETCO is solely responsible for technical support.

TO CONTACT TECHNICAL SUPPORT:

Northeast Technology Corp.
UPO Box 4178, 26 Pearl Street
Kingston, New York 12402 USA

Voice: 914-331-8511
Fax: 914-331-8521

NETCO's Business Hours: 9:00 a.m. to 5:00 p.m. Eastern Time, Monday -Friday. When calling please ask for RACKLIFE support and give your serial number.

NETCO provides limited free technical support to members of the EPRI Enhanced Boraflex R&D Program. This support includes assistance in the installation and use of RACKLIFE and fixing any bugs you report. It does not include data preparation or input, running calculations, or results evaluation except to support installation, use, or fixing bugs.

BEFORE CONTACTING NETCO SUPPORT: INFORMATION WE MAY NEED:

YOUR SERIAL NUMBER:

You can find you serial number in three places.

- At the top of the RACKLIFE title screen;
- On the label of the RACKLIFE diskette sent to you, and;
- As the volume serial number of the distributed RACKLIFE diskette when you type "dir" at the DOS prompt. The serial number takes the form"xxxx-xxxx" where "x" is an alpha-numeric character. The last digit is used to number the transmitted distribution diskettes; as a serial number "0" is used.

YOUR SYSTEM:

You can obtain a wealth of information about your PC system by running the program TELLME.EXE. We may ask you to print and send us its output; this is covered in detail below.

PHAR LAP'S TELLME.EXE UTILITY:

TELLME.EXE is installed in the "TUTORIAL" directory. From the DOS prompt change to the RACKLIFE directory and then type:

```
cd tutorial <ENTER>
```

```
tellme | more <ENTER>
```

where "|" is the vertical bar, or "pipe" symbol, typically above the backslash on PC keyboards. Press any key to display subsequent screens. To copy what you see to an ASCII test file type:

```
tellme > filename.txt <ENTER> [choose your own filename]
```

To copy what you see to an ASCII-capable printer type:

```
tellme > prn <ENTER>
```

TELLME.EXE is licensed from Phar Lap through Lahey Computer Systems. You may only use TELLME.EXE to help in diagnosing problems you may be having with RACKLIFE. In particular, you may not redistribute TELLME.EXE.

BEFORE CONTACTING NETCO SUPPORT: HARDWARE/ OS VERIFICATION

We recommend you verify your hardware and operating system before contacting NETCO technical support:

If you are running RACKLIFE in a Windows DOS box, on a network, or under any kind of memory manager, try running it stand-alone (off the network) under IBM or MS-DOS 5.x or 6.x with all memory managers disabled, and see if the problem persists. RACKLIFE is intended for use only under these conditions. RACKLIFE was developed under OS/2 3.0 and is known to work in an OS/2 DOS Full Screen Session with the DPMI_MEMORY_LIMIT setting set to 16 or higher. Make sure you are using an Intel 386 with 387, 486DX, or Pentium CPU. RACKLIFE has not been tested with other vendor's CPUs. Make sure your monitor and graphics card support color VGA, you have at least 16 Megabytes of RAM, and at least 50 Megabytes of free hard drive space. RACKLIFE has not been tested with compressed drives.