Presentation Material

Duke/USNRC Meeting

February 5, 2002

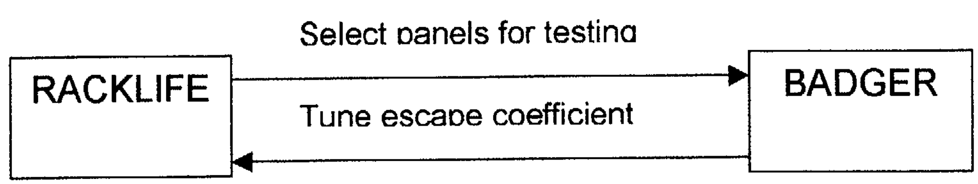
White Flint N.

BADGER and RACKLIFE

K. Lindquist
Northeast Technology Corp.

RACKLIFE/BADGER

- Designed and developed to be used hand in hand.
- RACKLIFE is used to select Boraflex panels for BADGER testing.
  - Assures panels with highest service history (gamma dose and time of dose) are tested.
  - Allows testing over a spectrum of service histories to determine if a threshold exists.
  - Reduces the number of panels to be tested to a manageable population without compromising confidence level of the BADGER measurements.
- Comparison of BADGER test results with RACKLIFE projections provides a rationale for "tuning" the RACKLIFE escape coefficient(s).
  - Assures accuracy of RACKLIFE projections to the next BADGER test.



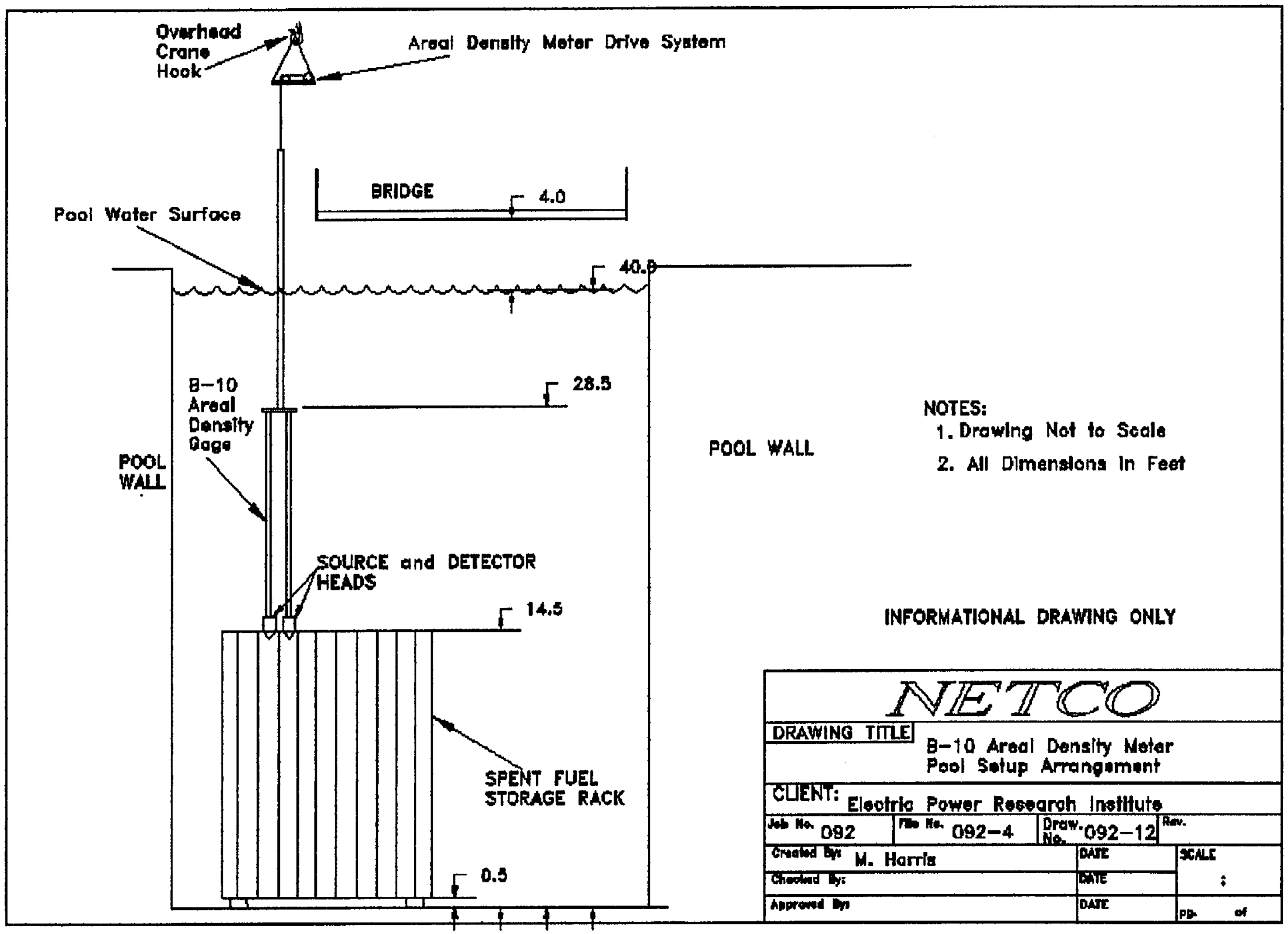
BADGER

Boron-10 Areal Density Gage for Evaluating Racks

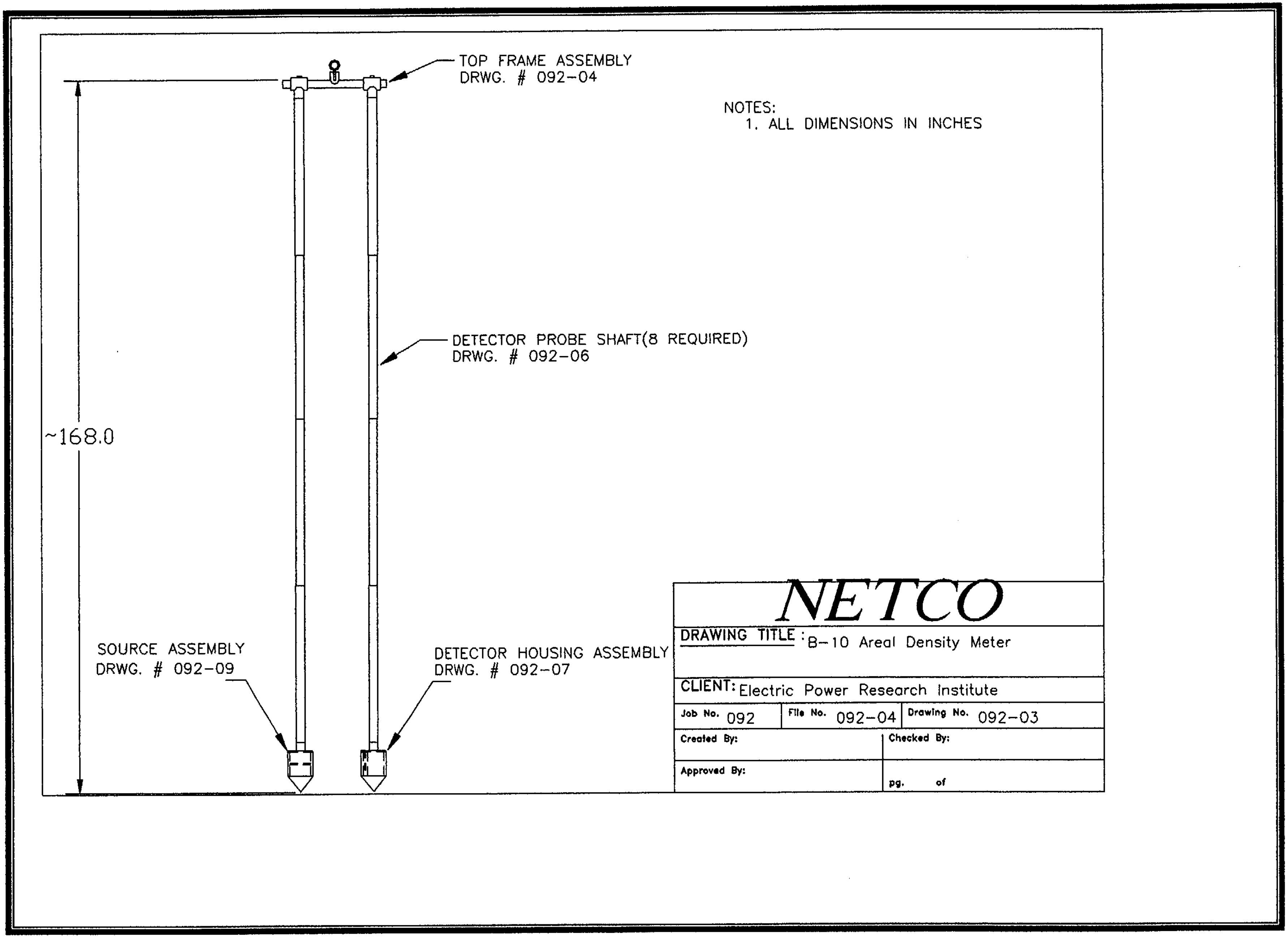
- In most racks Boraflex is encapsulated within rack structures. Direct inspection requires destructive techniques.
- Rack modules rest on the bottom of a water filled pool forty feet deep.
- Inspection/testing of Boraflex was recognized as a challenging task.
- BADGER concept devised based on neutron transmission measurements.

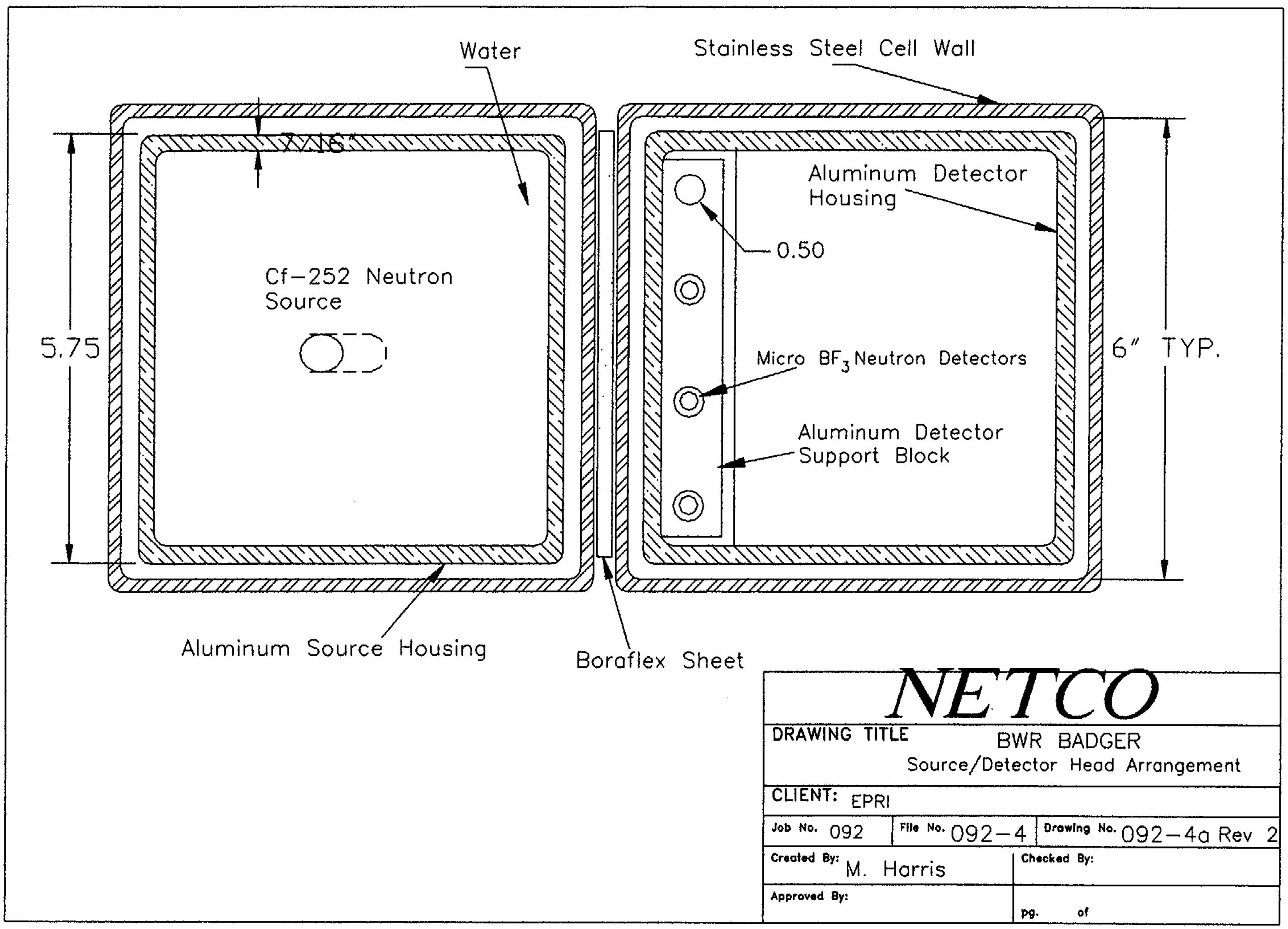
BADGER Chronology

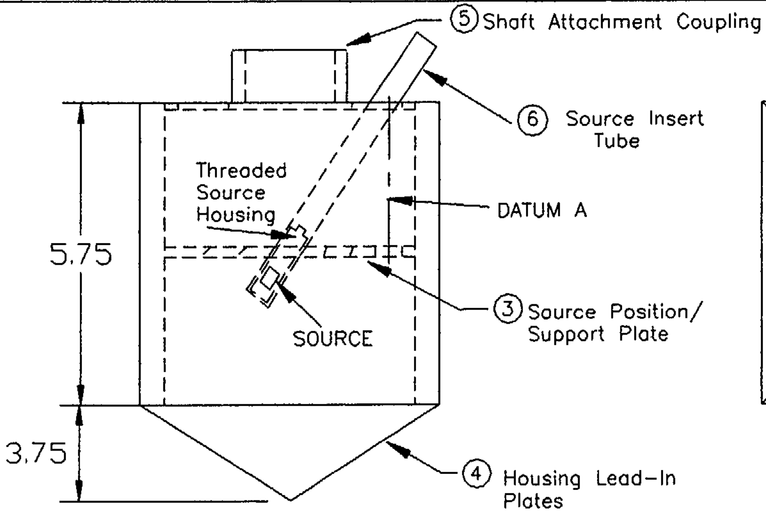
- Proof-of-principle testing (1993) conducted in the beam hole laboratory of the Penn State Reactor with mock-up sections of fuel racks:
  - Single sheets of Boraflex with stainless cladding.
  - Double sheets of Boraflex with water filled (2000 ppm soluble boron) flux trap.
- Proof-of-principle test results were positive and a proto-type BWR BADGER designed and fabricated (1994).
- Clean testing in the Co-60 pool at Penn State - May through August of 1995.
- Plant demo at Peach Bottom 2 April 1996.
- PWR BADGER designed and fabricated 1996.
- Clean testing fall of 1996.
- PWR demo at McGuire 2 January 1997.
- To date 7 campaigns at BWRs and 4 campaigns at PWRs.
- Crew departs today for second campaign at Peach Bottom 2.



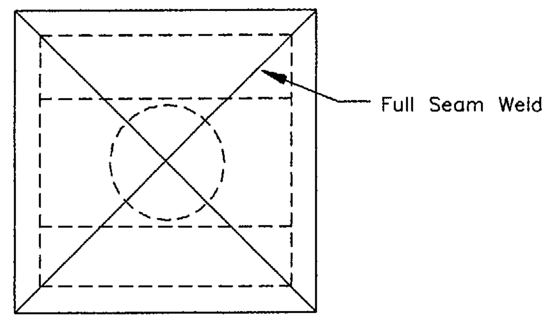
Overhead
Crane
Hook
Areal Density Meter Drive System
BRIDGE
4.0
Pool Water Surface
40.0
28.5
B-10
Areal
Density
Gage
POOL
WALL
POOL WALL
SOURCE and DETECTOR
HEADS
14.5
SPENT FUEL
STORAGE RACK
0.5
NOTES:
1. Drawing Not to Scale
2. All Dimensions In Feet
INFORMATIONAL DRAWING ONLY
NETCO
DRAWING TITLE
B-10 Areal Density Meter
Pool Setup Arrangement
CLIENT: Electric Power Research Institute
Job No. 092
File No. 092-4
Draw. No. 092-12
Rev.
Created By: M. Harris
DATE
SCALE
Checked By:
DATE
Approved By:
DATE
pg. of


TOP FRAME ASSEMBLY
DRWG. # 092-04
NOTES:
1. ALL DIMENSIONS IN INCHES
DETECTOR PROBE SHAFT(8 REQUIRED)
DRWG. # 092-06
~168.0
SOURCE ASSEMBLY
DRWG. # 092-09
DETECTOR HOUSING ASSEMBLY
DRWG. # 092-07
NETCO
DRAWING TITLE : B-10 Areal Density Meter
CLIENT: Electric Power Research Institute
Job No. 092
File No. 092-04
Drawing No. 092-03
Created By:
Checked By:
Approved By:
pg. of


Water
Stainless Steel Cell Wall
7/16"
5.75
Cf-252 Neutron Source
Aluminum Detector Housing
0.50
Micro BF_3 Neutron Detectors
Aluminum Detector Support Block
6" TYP.
Aluminum Source Housing
Boraflex Sheet
NETCO
DRAWING TITLE
BWR BADGER
Source/Detector Head Arrangement
CLIENT: EPRI
Job No. 092
File No. 092-4
Drawing No. 092-4a Rev 2
Created By: M. Harris
Checked By:
Approved By:
pg. of

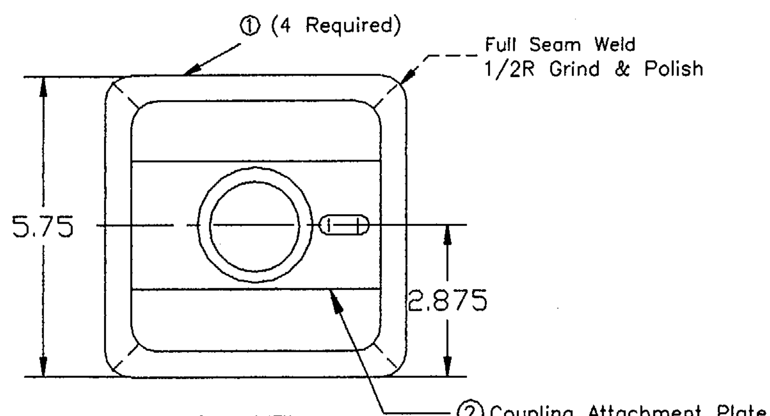


ELEVATION VIEW



BOTTOM VIEW

NOTES:
1. ALL DIMENSIONS IN INCHES
2. ALL WELDS– IN CASE OF OVERPENETRATION, GRIND & POLISH
3. ITEMS 3 & 6 – WELD IN POSITION @ HORIZONTAL MIDPLANE
4. ITEM 3 – POSITION @ VERTICAL MIDPLANE DRILL HOLES @ 0°,17.9°,33.7°, & 46.5° with respect to DATUM A



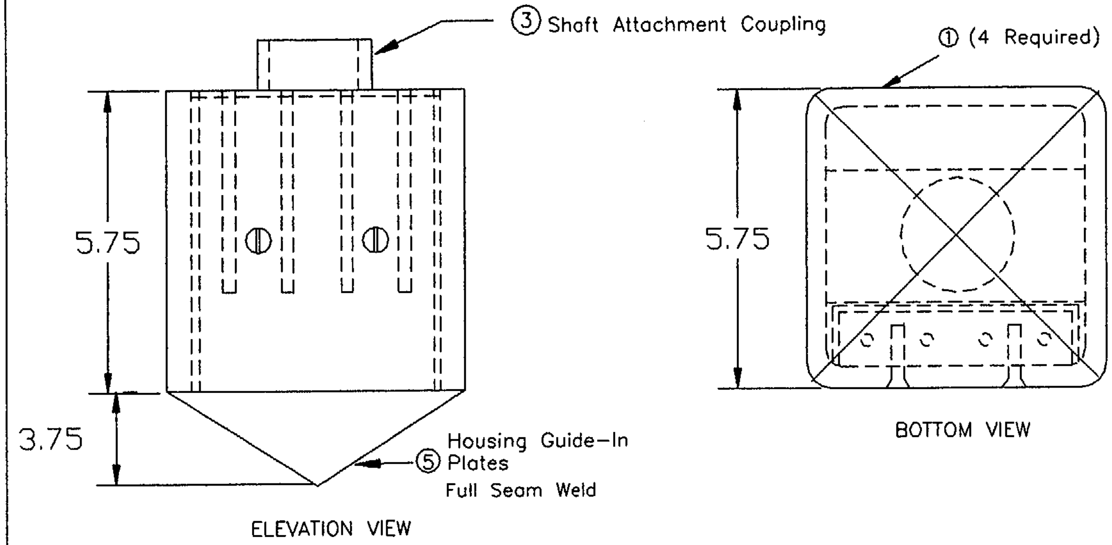
PLAN VIEW

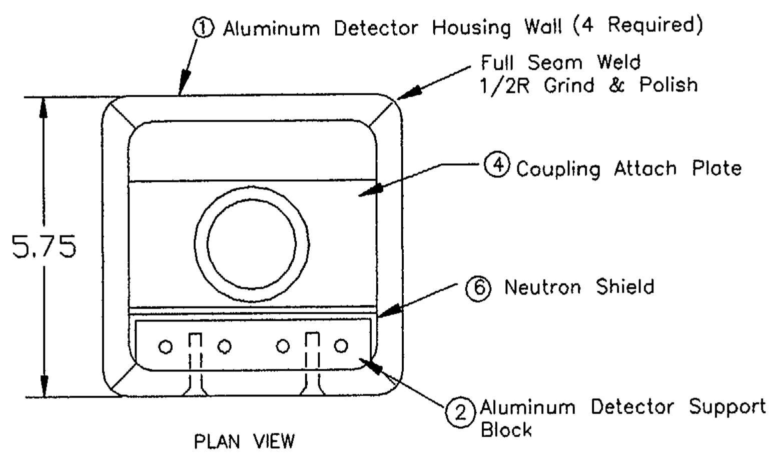
NETCO

DRAWING TITLE: B-10 Areal Density Meter Source Head Assembly

CLIENT: Electric Power Research Institute

Job No. 092	File No. 092 -04	Drawing No. 0909S	Rev.1
Created By:		Checked By:	
Approved By:		pg. of	



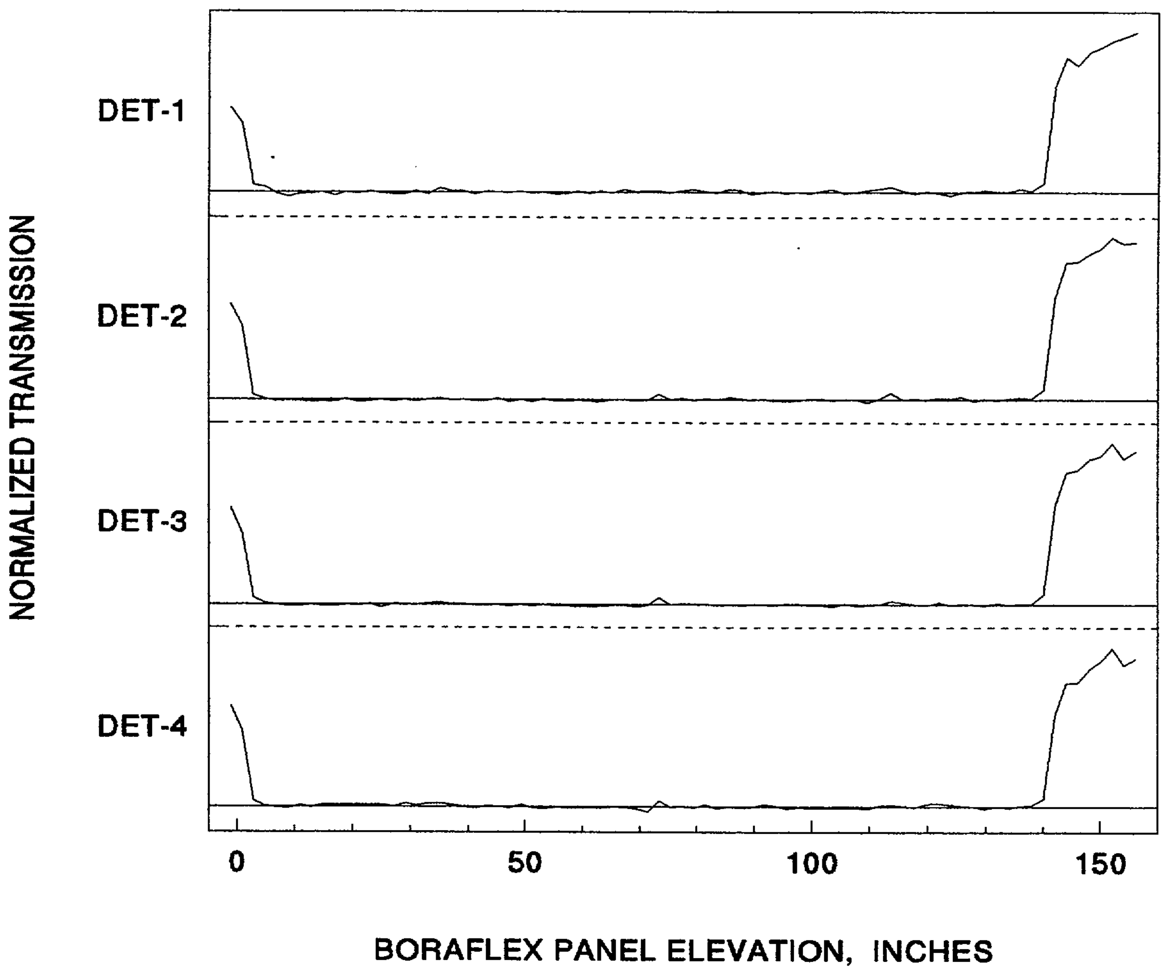


NOTES:
1. ALL DIMENSIONS IN INCHES
2. Item 2– Machine Aluminum to Fit
3. Item 5– In Case of OverPenetration
Grind & Polish

NETCO

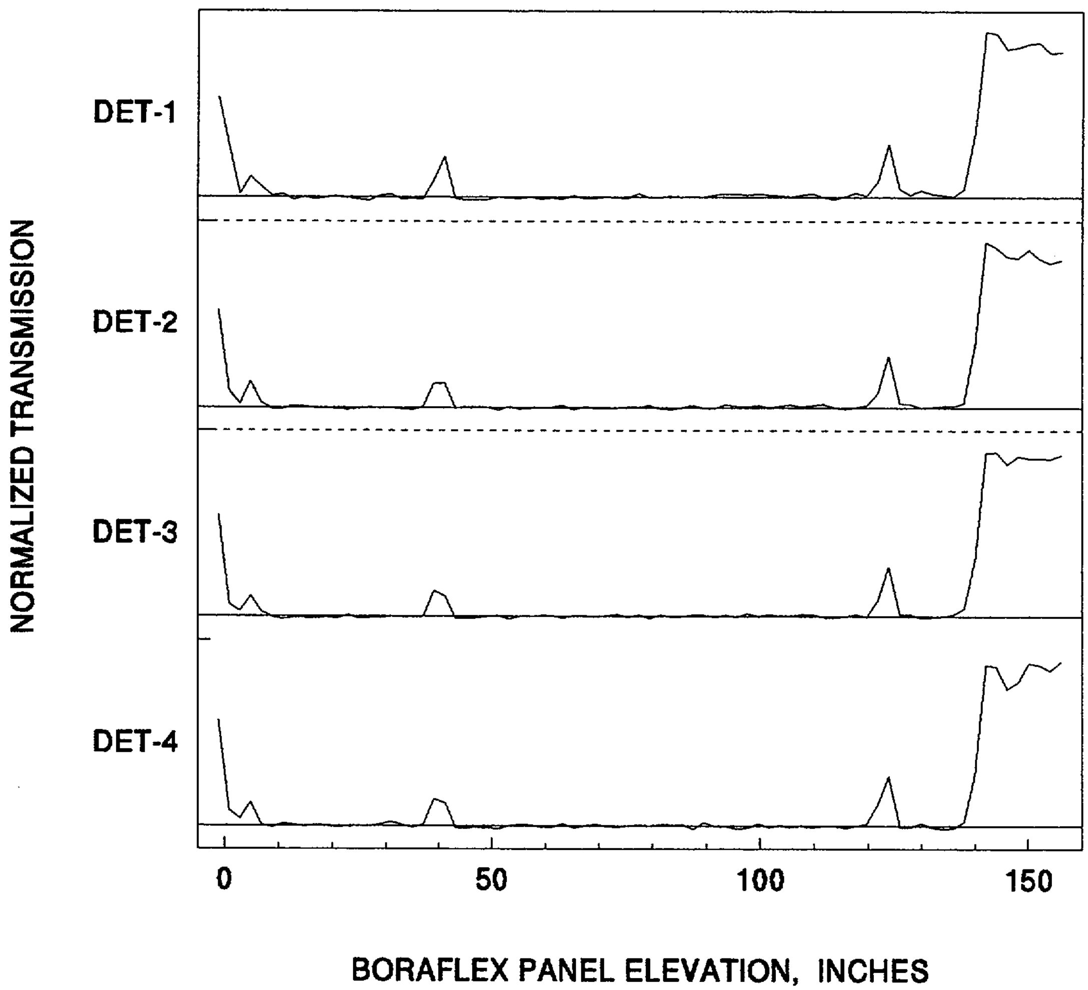
DRAWING TITLE : BWR BADGER Detector Head Assembly		
CLIENT: Electric Power Research Institute		
Job No. 092	File No. 092 –04	Drawing No. 092–07
Created By: M. Harris	Checked By:	
Approved By:	pg. of	

A23S Data



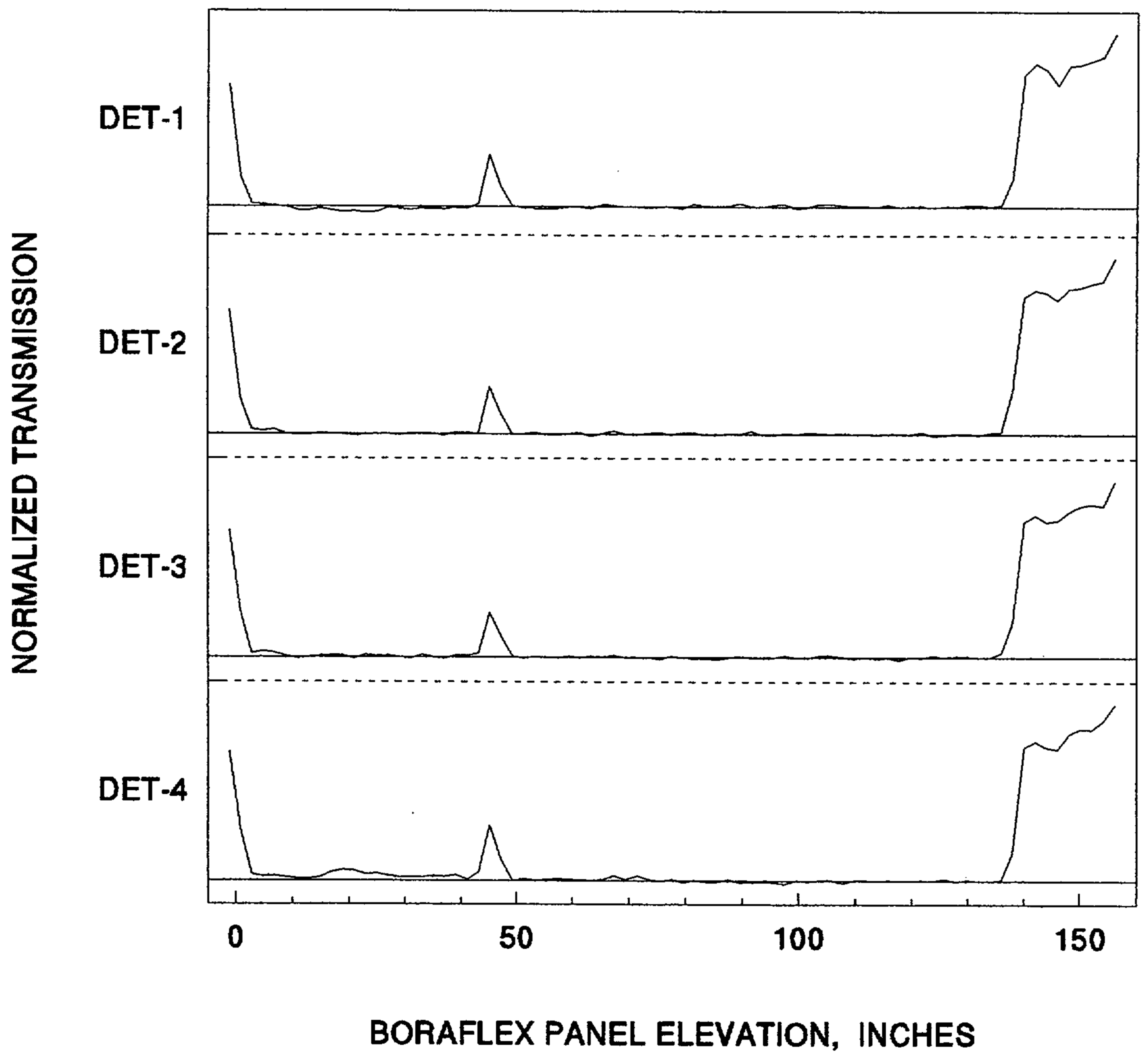
Low Dose Panel

E13E Data



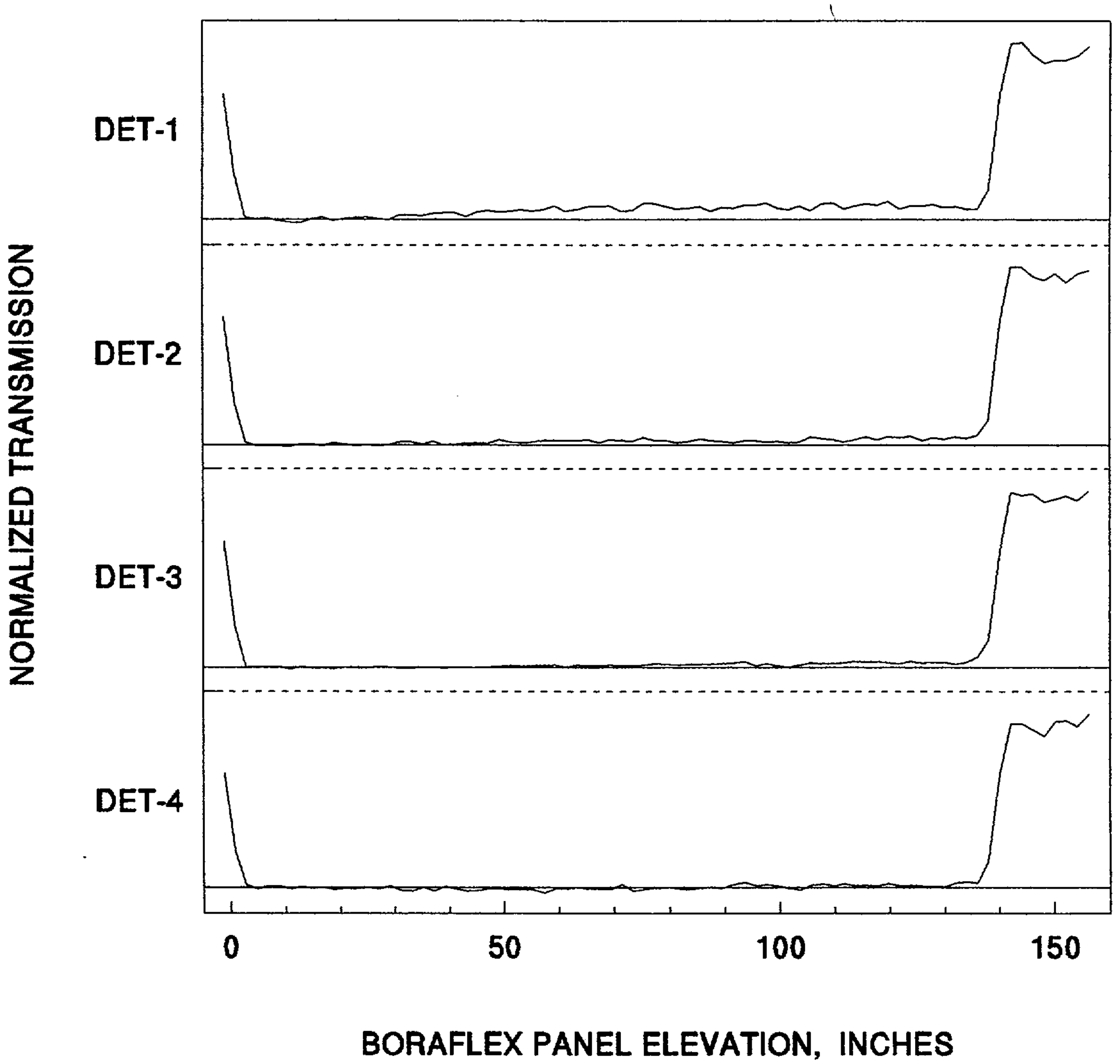
High Dose Panel with Three Gaps

F12W Data

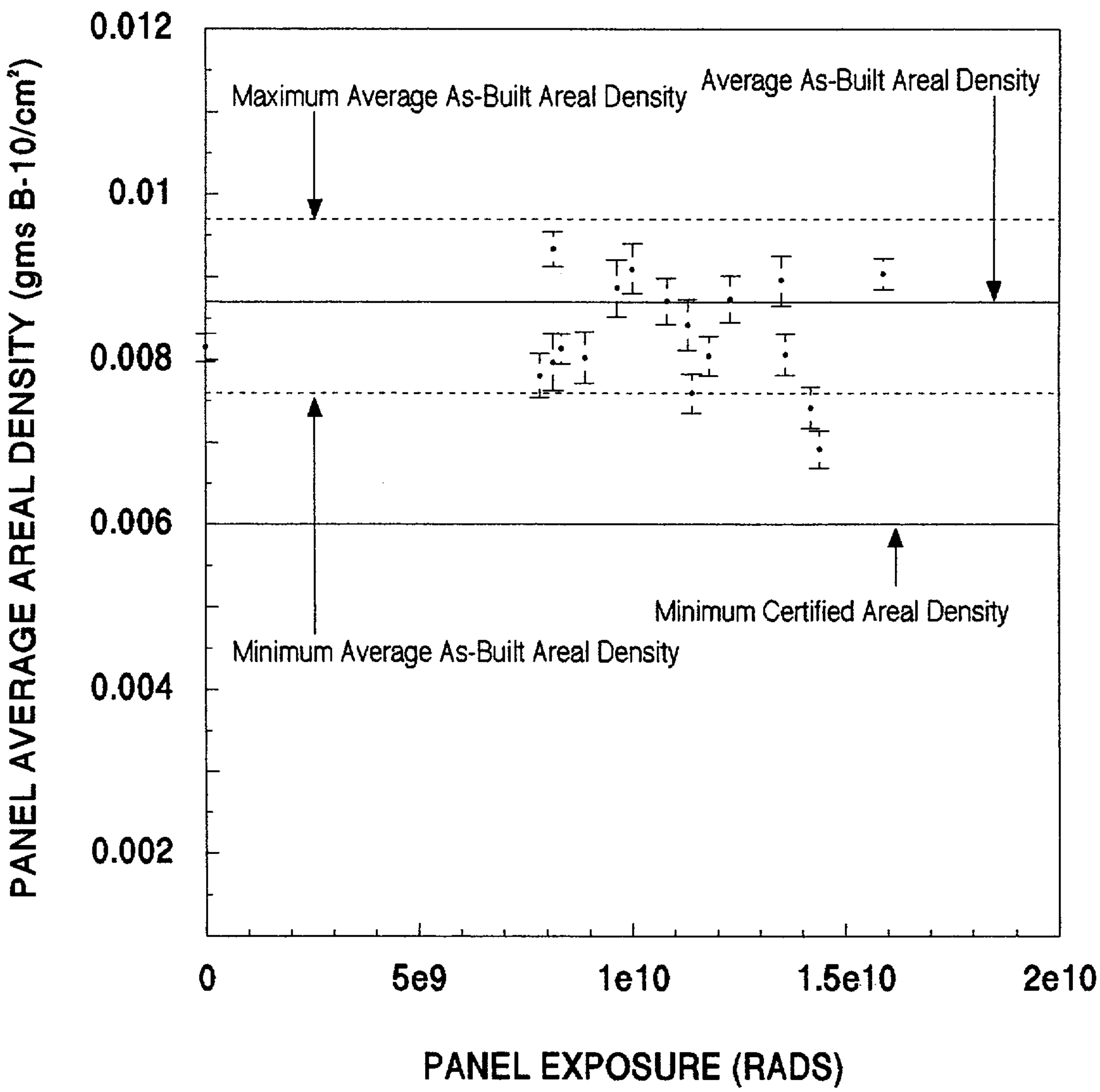


High Dose Panel with Thinning and One Gap

F2E Data



High Dose Panel with Edge Thinning



PWR-A Region 2 Panel Average Areal Density versus Gamma Exposure

RACKLIFE

- RACKLIFE model objectives
- RACKLIFE chronology
- Radiation transformation of Boraflex matrix
- Composition of Boraflex (pre and post irradiation)
- Mechanisms of silica dissolution and polymerization
- Silica mass balance in spent fuel pool
- Examples of RACKLIFE results
- Comparison of BADGER measurement and RACKLIFE predictions

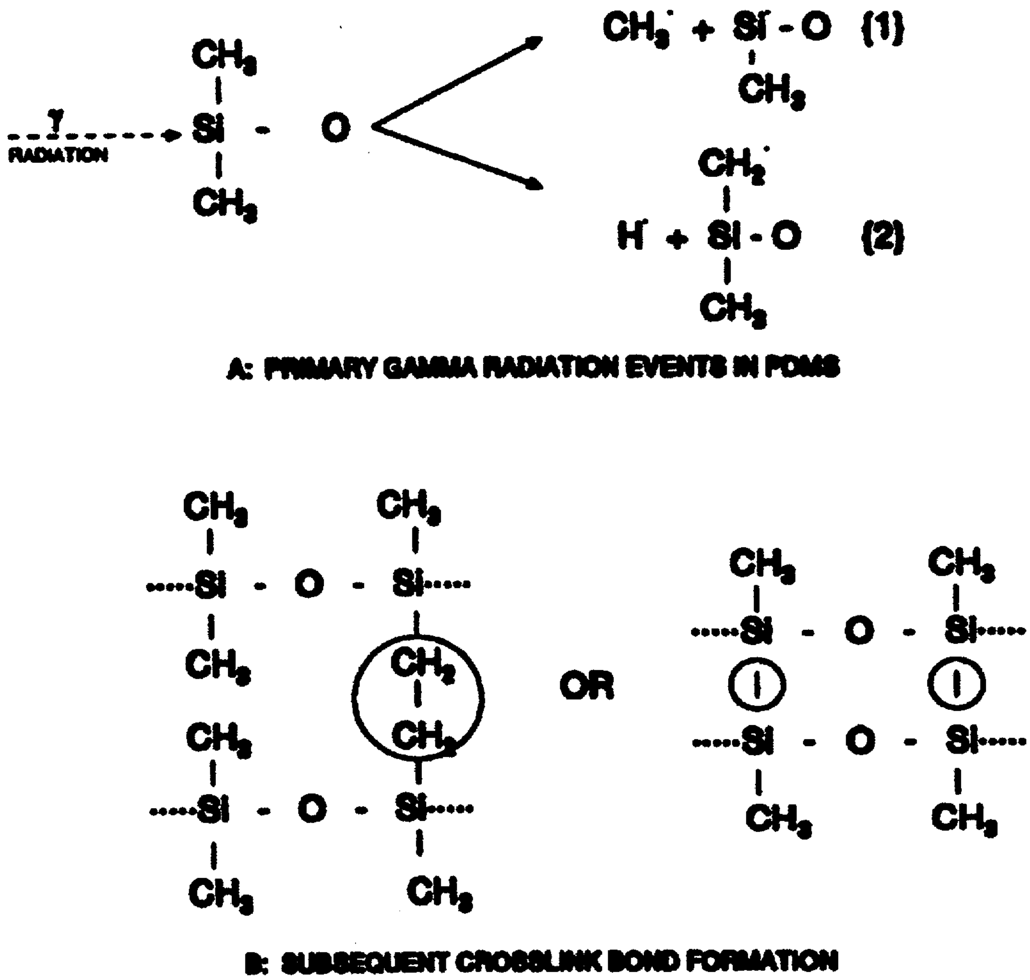
RACKLIFE MODEL OBJECTIVES

- Provide a management tool to extend the useful service life of Boraflex spent fuel storage racks.

- Predict Boraflex degradation in spent fuel pools for user-specified fuel discharge and pool cleanup scenarios:
  - Compute gamma dose to Boraflex panels.
  - Compute total (reactive and polymerized) silica in the bulk pool and in Boraflex panel cavities.
  - Compute boron carbide loss from Boraflex.

RACKLIFE Chronology

- Need for a model to assess rack use strategies on Boraflex performance identified in early 1990s.
- Spreadsheet solutions to silica mass balance in spent fuel pools developed:
  - Demonstrated feasibility of modeling each of the several thousand Boraflex panels in a spent fuel rack.
  - Files became large and unmanageable.
- Fortran version of RACKLIFE initiated 1994.
- Beta version released in 1995.
- Version 1.0 released in 1996.
- V/V of Version 1.0 3/99.
- Version 1.10 released 2001.
- Windows Version under development 2002 – 2003.



Gamma Radiation Reactions and Cross-Link Bond Formations in PDMS

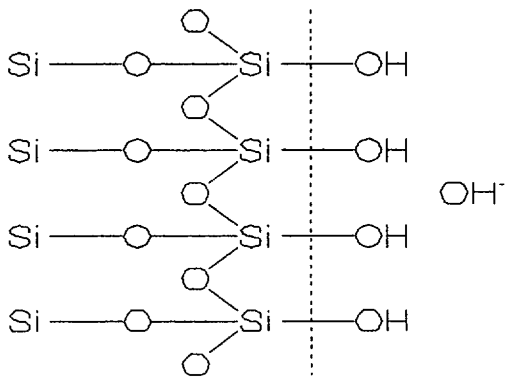
Composition of Boraflex

Unirradiated:	Early Boraflex	Later Boraflex
Boron Carbide	40 W/O	50 W/O
SiO_2 Filler	30 W/O	25 W/O
Polymer Matrix	30 W/O	25 W/O

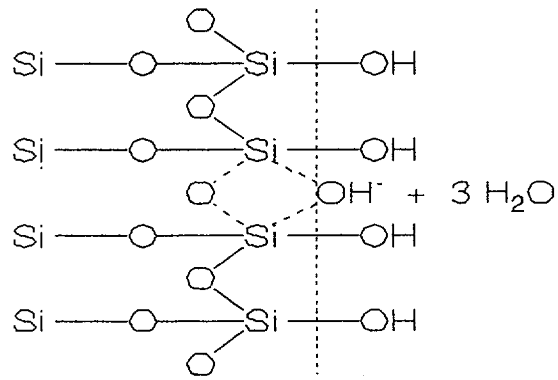
After Irradiation:

Boron Carbide	40 W/O	50 W/O
SiO_2 Filler	30 W/O	25 W/O
Amorphous Silica	23 W/O	21 W/O
Residual Polymer	7 W/O	4 W/O

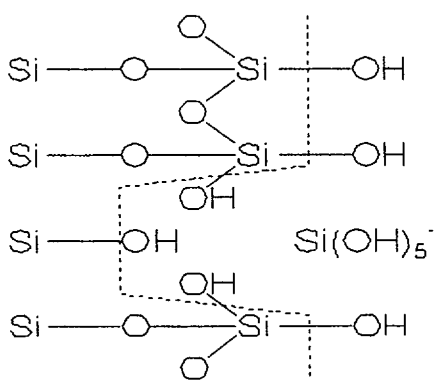
Mechanism of Dissolution of Silica in Water



(a) Ambient hydroxyl ion near silica surface



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

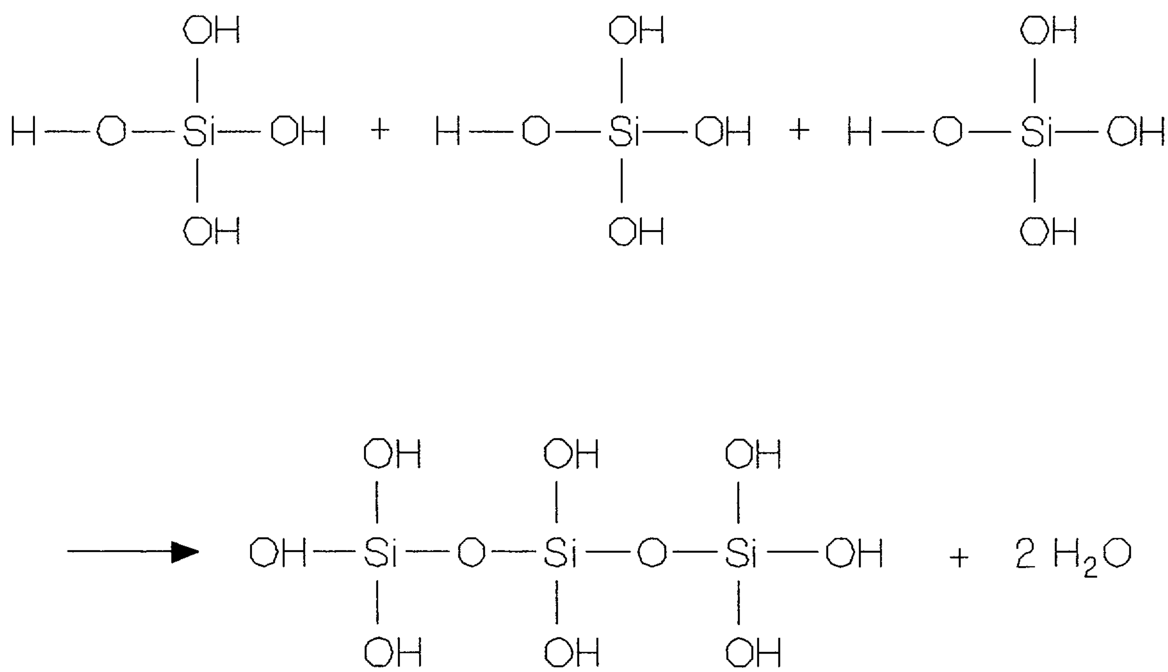


(c) Silicon atom goes into solution as a silicate ion

$Si(OH)_5^- \Rightarrow Si(OH)_4 + OH^-$

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

Polymerization of Silica Acid



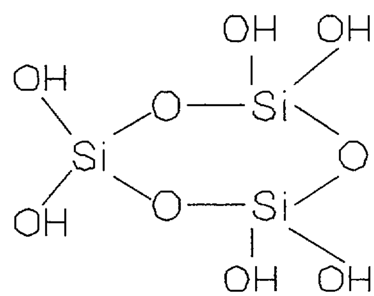
(a) Silicic acid monomers condense (shed H_2O molecules) to polysilicic acid: 3 $Si(OH)_4$ ⇒ $Si_3O_2(OH)_8$ + 2 H_2O

Polymerization of Silica Acid (continued)

$2\ Si(OH)_4$ (monomer) → $(HO)_3SiOSi(OH)_3$ (dimer)

+ H_2O

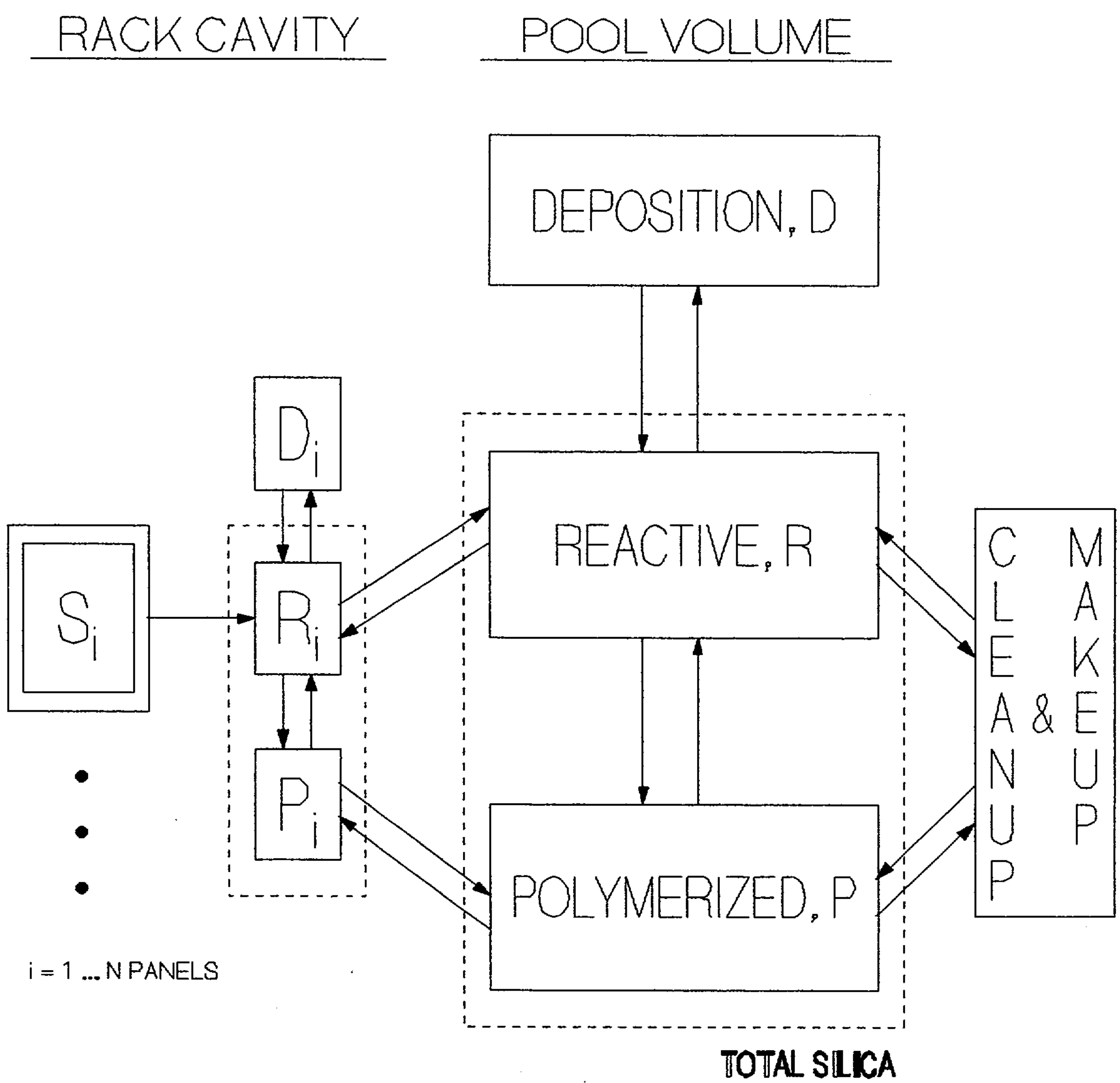
$Si(OH)_4$ + dimer → $[(OH)_2SiO]_3$ (cyclic trimer)



dimer + dimer → $[(OH)_2SiO]_4$ (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

Silica Mass Balance in Spent Fuel Pools

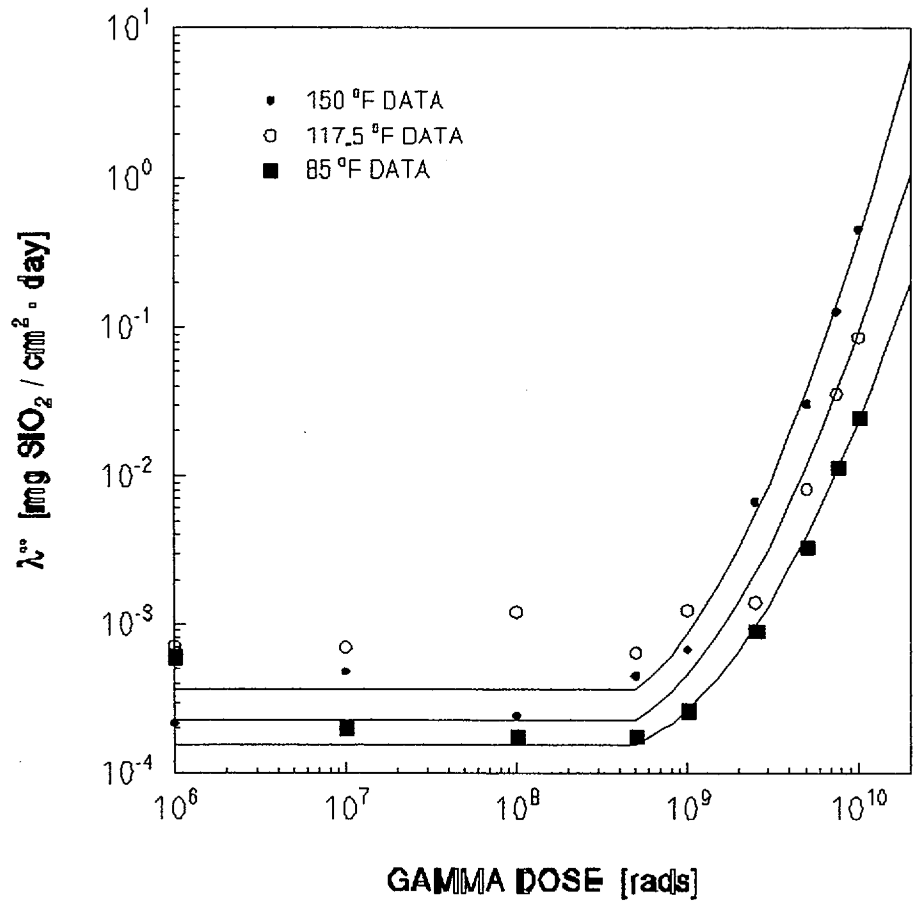


Source Term for Reactive Silica in Panel Chambers

$S_i = \lambda\ (1 - R_i/R_{eqi}\ )$

$\lambda = \lambda$ (Temperature, Irradiation)

$R_{eqi} = R_{eqi}$ (Temperature, pH)



Silica Release Rate per Unit Area – Fit versus Data

Kinetics Equations for Pool Silica

Reactive Quantity of Total Silica, R

$\frac{dR}{dt} = +\Sigma\,[K_{RiR}R_i - K_{RRi}R]$ Escape (Re-entry)

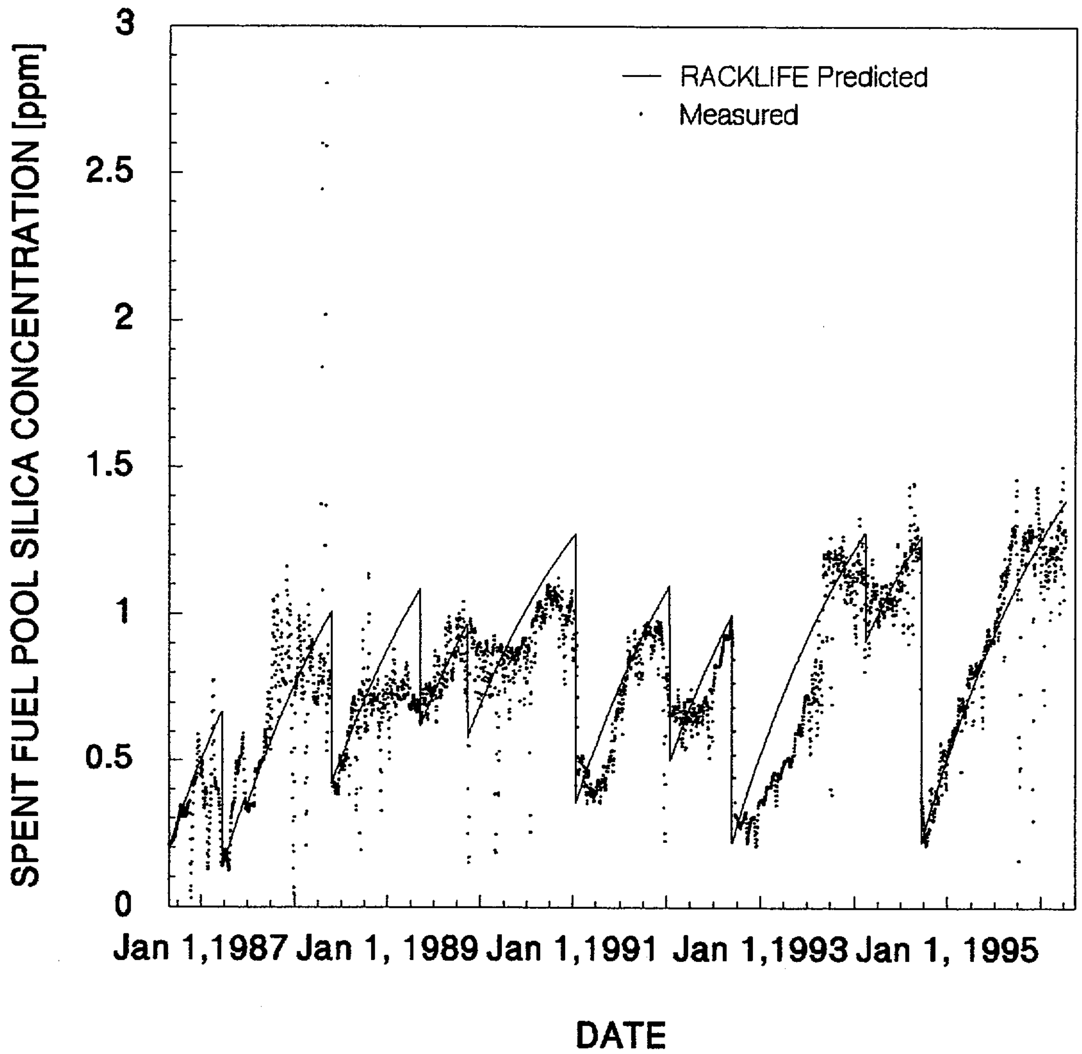
$- K_{RP}R + K_{PR}P$	Polymerization (Depolymerization)
$- K_{RD}R + KD_{RD}$	Deposition (Re-Solution)
$- k_{RC}R$	Cleanup
$- k_{RM}\,(R\text{-}M)$	Makeup (Conc. M)
$+ k_{ER}M$	Evaporation

RACKLIFE Input

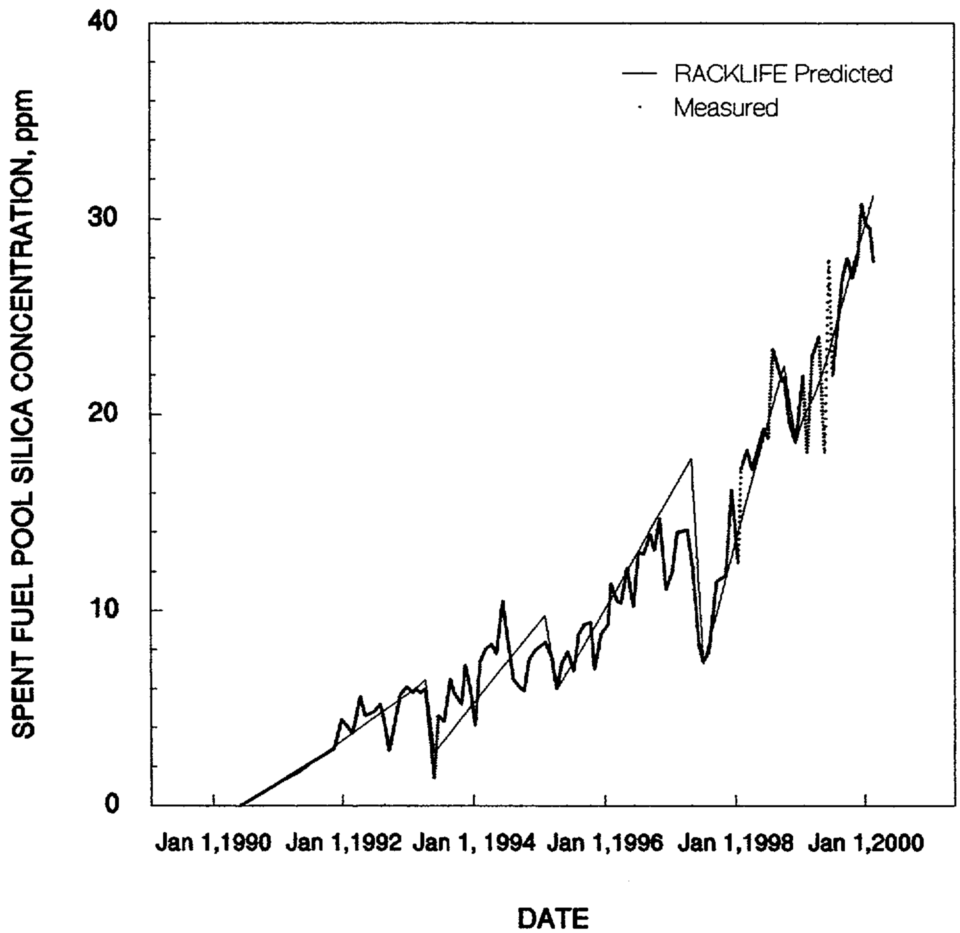
- Pool design data
  - Pool water volume and layout
- Rack design data
  - Module / cell design data
  - Module layout data
- Boraflex as-built properties
- Fuel design and operating history data
  - Initial U-235 enrichment and loading (MTU)
  - Discharge burnup
  - Reactor shutdown time and date
  - Date, time and location to which fuel assembly moved to rack
  - Date, time and location of subsequent fuel moves for each assembly in the pool
  - End of cycle assembly average power
- Pool water condition
  - pH
  - Temperature
  - Soluble silica versus time
- Pool cleanup system design data
- Escape coefficient

RACKLIFE Output

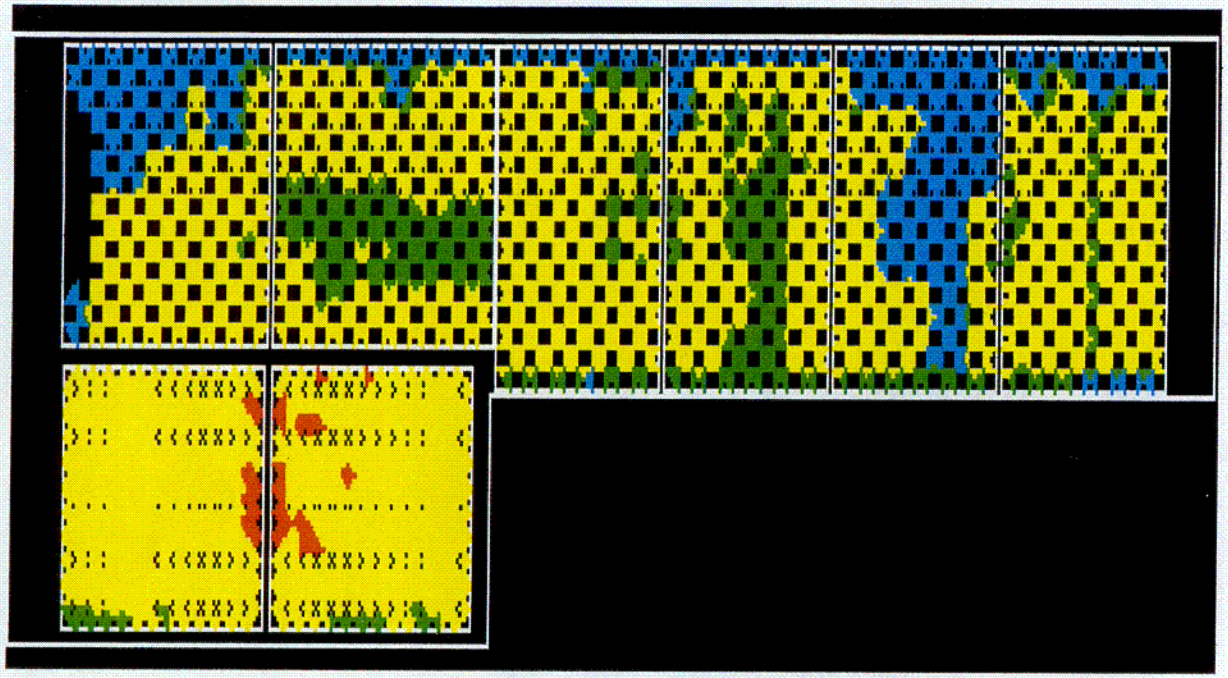
- Predicted and measured soluble silica versus time
- Pool wide distribution of exposure
- Pool wide distribution of boron carbide loss
- Module and panel by panel exposure
- Module and panel by panel boron carbide loss



Measured versus Predicted Pool Silica Levels for BWR-A



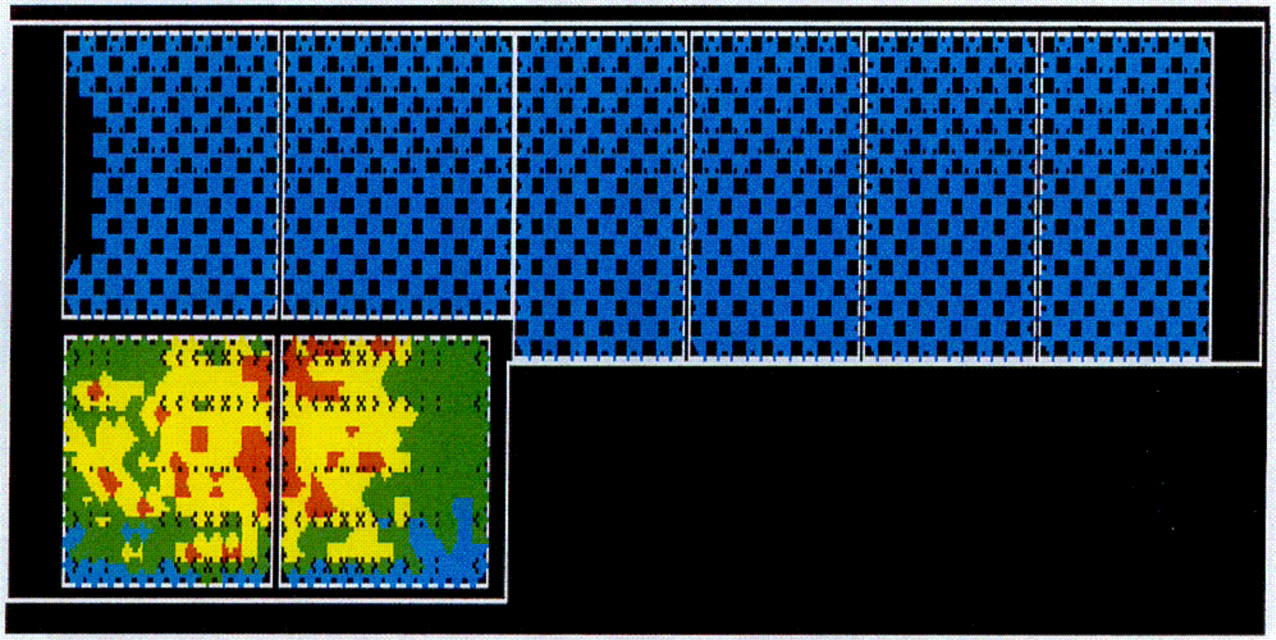
Measured versus Predicted Pool Silica Levels for PWR-C



Poolwide Distribution of Panel Absorbed Dose

Red $\geq 1.0 \cdot 10^{10}$ rads (peak is $2.7 \cdot 10^{10}$ rads)
Yellow $\geq 2.0 \cdot 10^{9}$ rads
Green $\geq 5.0 \cdot 10^{8}$ rads
Blue ≥ 0.0 rads

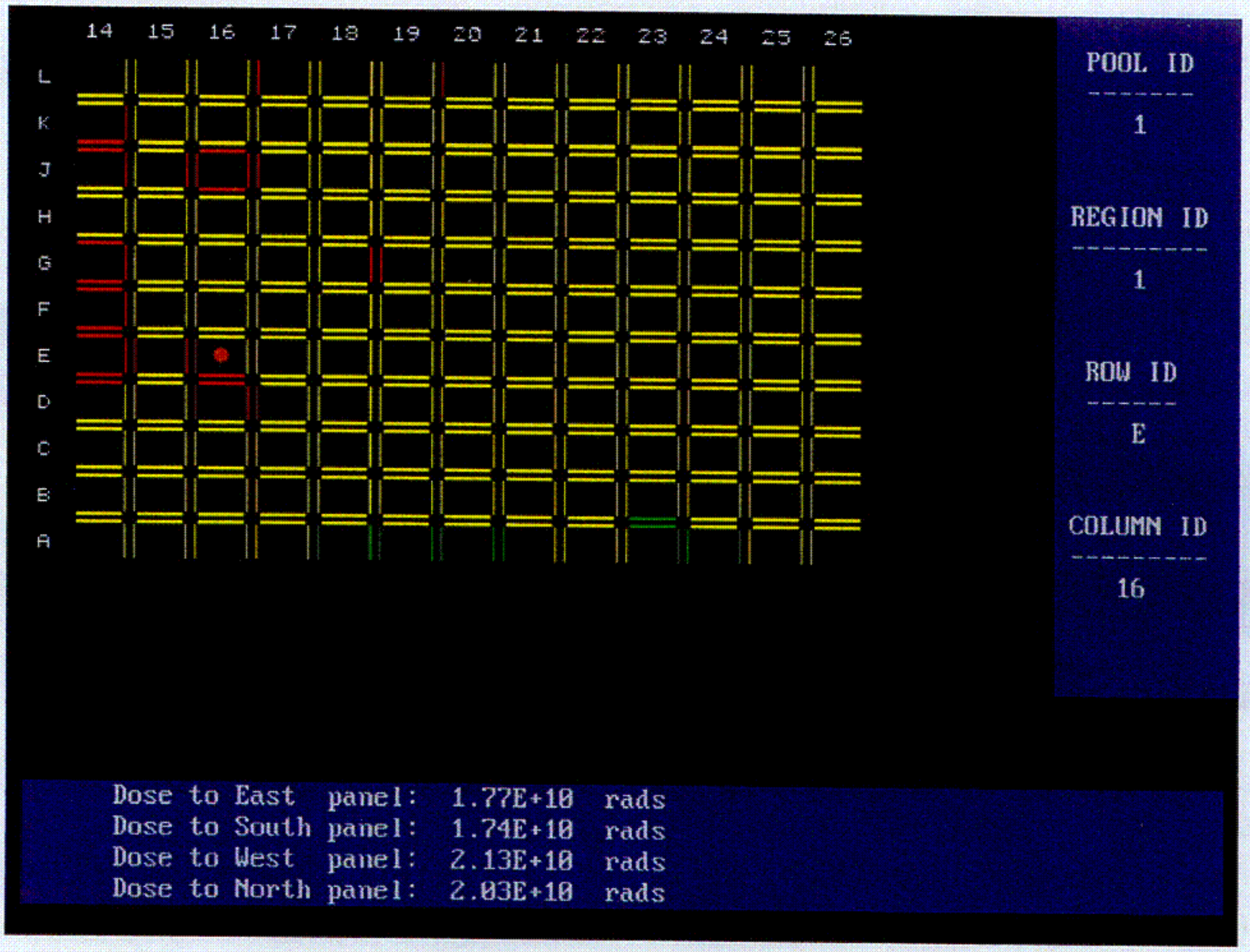
C01



Poolwide Distribution of Panel Boron Carbide Loss

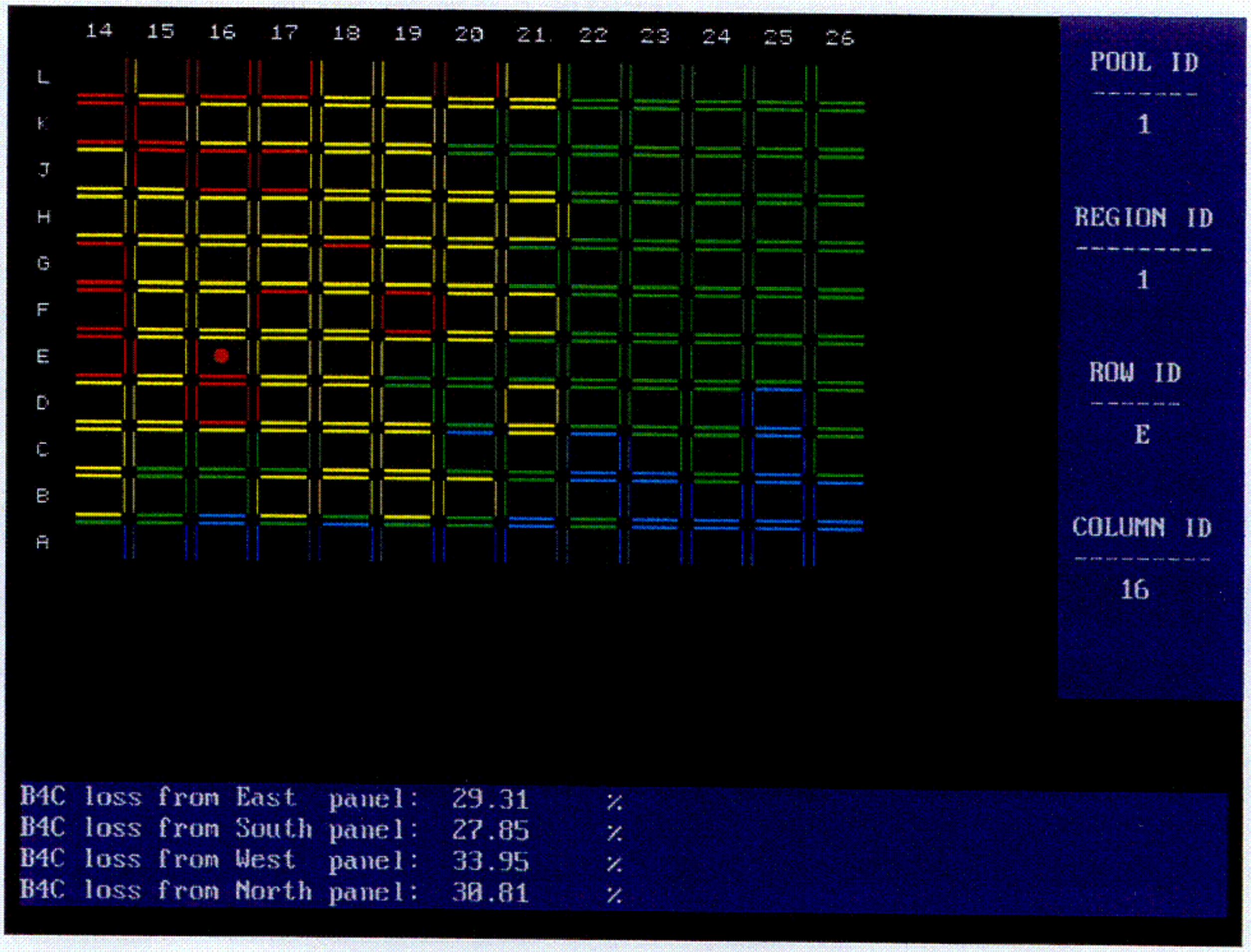
Red $\geq$ 30% loss (peak is 36.6% loss)
Yellow $\geq$ 20% loss
Green $\geq$ 10% loss
Blue $\geq$ 0% loss

C02

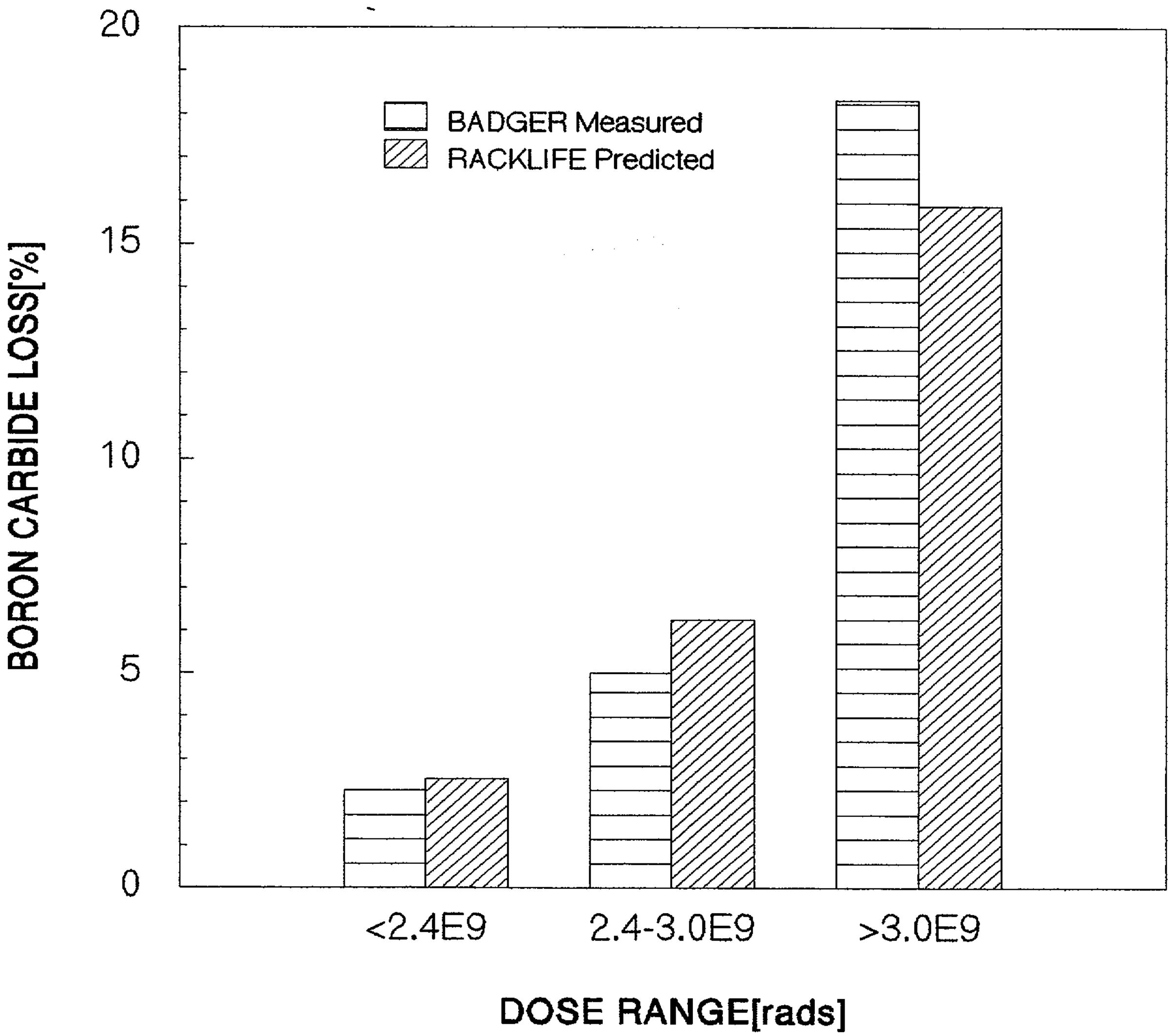


Module Distribution of Exposure

C03



Module Distribution of Boron Carbide Loss



PWR-B Measured and Predicted Boron Carbide Loss Averaged by Dose

PWR A Region 1 Measured and Predicted Boron Carbide Loss

Panel	Dose	Boron Carbide Loss, %	
		BADGER Measured	RACKLIFE
A23S	0.0E+00	0±9	-2
D13E	1.1E+10	-27±15	-16
C13E	1.2E+10	-17±10	-18
C13N	1.2E+10	-27±11	-18
E2W	1.2E+10	-10±9	-11
F2E	1.2E+10	-15±9	-13
H13W	1.9E+10	-23±10	-18
G12E	2.0E+10	-25±10	-21
F12W	2.0E+10	-20±10	-22
E13E	2.4E+10	-22±11	-23
E13N	2.6E+10	-33±13	-23
F13N	3.0E+10	-29±11	-24
E13W	3.3E+10	-31±13	-24
F14E	3.4E+10	-26±-12	-24
F13E	3.4E+10	-26±11	-24

Conclusions

- RACKLIFE models when used in tandem with BADGER testing provide a reliable means to project future Boraflex performance.
- The approach utilizes a predictive model coupled with measurement technique to monitor the slow deterioration of a plant component.
- The approach is analogous to that used in many PWRs to monitor steam generation tube wastage.

NRC Boraflex Information Meeting

February 5, 2002
Washington D.C

Ray W. Lambert
EPRI

Early History of Boraflex

Commercial History

- Introduced in late 1970's
- Dominated market through 1980's
- Cost and ease of fabrication were main advantages
- About 75 pools world wide installed Boraflex

Early History of Boraflex

Commercial History (cont'd)

- After a few years in service performance problems began to emerge
- Coupons gave first indications
- Embrittlement at relatively low doses was noted
- Blackness testing indicated shrinkage and some cracking of the Boraflex

EPRI

Early History of Boraflex

Commercial History (cont'd)

- Technical support for product was minimal
- Manufacturer was unwilling and unable to assist
- Vendors claimed no responsibility
- Background material qualification information was minimal and inconsistent
- Technical data was insufficient for utilities to perform root-cause analyses

EPRI's Involvement with Boraflex

Utilities requested EPRI's help in 1986

- High priority project started using base budget dollars
- NETCO selected as primary contractor based on experience with:
  - Pool criticality analyses
  - Fuel designs and performance
  - Materials expertise
- As scope of work expanded, a Boraflex Working Group (BWG) was organized with responsibility to:
  - Oversee EPRI's R&D work
  - Fund activities
- The BWG is now approaching its end of life

EPRI

EPRI's Involvement with Boraflex

EPRI R&D Objectives

- Develop fundamental understanding of Boraflex degradation mechanisms
- Develop techniques to measure and manage degradation
  - There was early recognition that there would be no silver bullet

EPRI's Involvement with Boraflex

Utilities were highly motivated to support Boraflex R&D

- Ensure pools maintain adequate safety margins
- Pools were filling fast and loss of storage could lead to reactor shutdown
- Dry storage option required long lead time and high cost
  - Pools already had been reracked and a second round was difficult and often exceeded $10M

EPRI

EPRI's Involvement with Boraflex

Early priorities for EPRI's R&D

- Understand the fundamental composition of Boraflex
- Understand the shrinkage mechanism and determine the limits
- Analyze the impact of gap formation and pull back effects
- Perform laboratory tests to determine the impact of variables
  - Radiation dose
  - Pool chemistry and pH
  - Temperature
  - Variety of Boraflex compositions

EPRI's Involvement with Boraflex

Crash effort resulted in the following conclusions and activities:

- Chemical makeup of Boraflex was defined
- Radiation effects on the polymer cross linking creates hardening and shrinkage
- Theoretical model developed that suggested a maximum shrinkage of about 3% at doses of about 1 x 10^{10}R
- Tests were started ASAP
  - Material stability tests at Penn State
  - Irradiation tests at AFRRI
  - Full scale panel tests at Beaver Valley 2
  - Assembly of data base from blackness testing

The NRC/EPRI Interface

NRC also became aware of the Boraflex issue in the mid 1980's

NRC issued its first Information Notice in September 1987

Status in 1987

- Boraflex manufacturer was beginning to exit the business
- Fabricators were not offering technical help
- NRC did not have any Boraflex R&D underway
- EPRI program was up and running

The NRC/EPRI Interface

BWG made a conscience decision to voluntarily share R&D data with the NRC

- NRC representative attended portions of EPRI workshops
- EPRI information was made available to the NRC

The NRC/EPRI Interface

Open interchange continued on topics such as:

- EPRI test data, current results and future R&D plans
- NRC's areas of concern or data needs
- Information Notices and Generic Letters

Status of Technology by 1994

EPRI shrinkage model had been confirmed by data

Recognition that shrinkage and gaps were only one part of the degradation mechanism

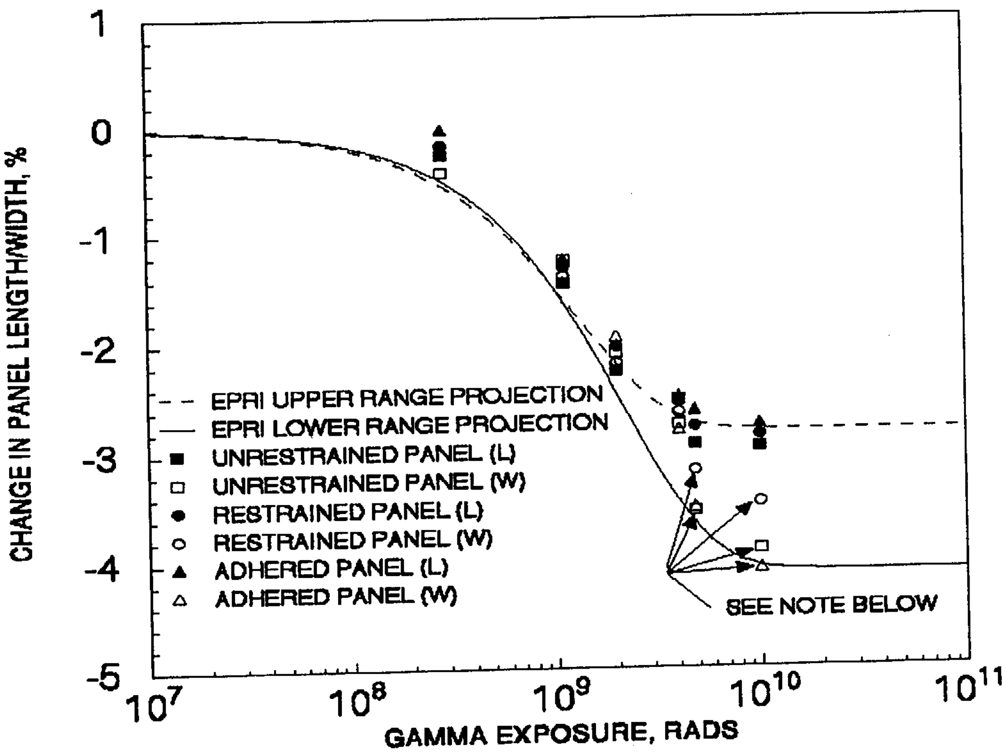
Long-term environmental effects determined to play a major role in the degradation process

- Gradual dissolution process was modeled for irradiated Boraflex
- Key variables were identified that included:
  - Gamma dose
  - Rack design
  - Access to pool water (called water escape coefficient)
  - Temperature of pool
  - Reactor and/or pool water treatment designs

EPRI

BORAFLEX SHRINKAGE DATA

FULL SIZE PANELS-EPRI/BVPS SURVEILLANCE ASSEMBLY



NOTE: THESE ARE THE AVERAGE OF THREE WIDTH MEASUREMENTS. EDGE DISSOLUTION HAS CONTRIBUTED TO THE APPARENT CHANGE IN PANEL WIDTH.

Status of Technology by 1994

Understanding increased to the point that it was practical to model the Boraflex performance

- BWG authorized a project to build a DOS code for modeling performance (start of RACKLIFE)
- Concept was that code would be a tool to help manage the Boraflex issue
- As code developed, its capability exceeded expectations

Status of Technology by 1994

It was concluded that to take full advantage of RACKLIFE that there would need to be a way to take measurements to confirm its efficacy

- Blackness testing was inadequate
- Development of BADGER was begun to directly measure B-10 areal density

Summary of EPRI Boraflex Activities

- Over $3M has been spent on R&D
- Utilities have committed major resources to the running of RACKLIFE and doing BADGER measurements
- An in-depth understanding of Boraflex has been developed that:
  - Permits degradation to be managed
  - Maintains adequate safety margins in pools
  - Has kept reactors operating
  - Allows time for utilities to seek and select long term solutions

Summary of EPRI Boraflex Activities

Other specific EPRI Boraflex products have included:

- 17 utility workshops
- Full documentation of Boraflex performance data base
- Completion of a 12 year full scale panel test at Beaver Valley 2
- Participation with W in the original Boron credit project
- Special coupon testing at Millstone
- Destructive inspection and testing of the Ft. Calhoun Boraflex racks
- Special coupon tests at Palisades
- Testing of zinc as a method to reduce Boraflex solubility
- Partner in the RACKSAVER demonstration
- Evaluated the performance of Boraflex during seismic events
- Devising technologies for managing silicon levels in pools
- Supported the METAMIC qualification program