Non-Concurrence Process Record for NCP-2012-004

The U.S. Nuclear Regulatory Commission (NRC) strives to establish and maintain an environment that encourages all employees to promptly raise concerns and differing views without fear of reprisal and to promote methods for raising concerns that will enhance a strong safety culture and support the agency's mission.

Individuals are expected to discuss their views and concerns with their immediate supervisors on a regular, ongoing basis. If informal discussions do not resolve concerns, individuals have various mechanisms for expressing and having their concerns and differing views heard and considered by management.

Management Directive MD 10.158, "NRC Non-Concurrence Process," describes the Non-Concurrence Process (NCP). http://pbadupws.nrc.gov/docs/ML0706/ML070660506.pdf

The NCP allows employees to document their differing views and concerns early in the decision-making process, have them responded to, and attach them to proposed documents moving through the management approval chain.

NRC Form 757, Non-Concurrence Process is used to document the process.

Section A of the form includes the personal opinions, views, and concerns of an NRC employee.

Section B of the form includes the personal opinions and views of the NRC employee's immediate supervisor.

Section C of the form includes the agency's evaluation of the concerns and the agency's final position and outcome.

NOTE: Content in Sections A and B reflects personal opinions and views and does not represent official factual representation of the issues, nor official rationale for the agency decision. Section C includes the agency's official position on the facts, issues, and rationale for the final decision.

The agency's official position (i.e., the document that was the subject of the non-concurrence) is included in ADAMS Accession Number ML12151A156.

This record has been redacted prior to discretionary release to the public.

NRC FORM 757 NRC MD 10.158 (7-2011)	NON-CONCURRENCE PROCESS	U.S. NUCLEAR REGULATORY COMMISSION NCP TRACKING NUMBER NCP-2012-004

SECTION A - TO BE COMPLETED BY NON-CONCURRING INDIVIDUAL

TITLE OF SUBJECT DOCUMENT NUREG/CR 7130 Assessment of Uncertainties Associated with the BADGER Methodology		ADAMS ACCESSION NO. ML12151A156
DOCUMENT SIGNER Michael Case		SIGNER PHONE NO. (301) 251-7619
TITLE Director	ORGANIZATION RES/DE	
NAME OF NON-CONCURRING INDIVIDUAL(S) Charles Harris		PHONE NO. (301) 251-7637
TITLE Materials Engineer	ORGANIZATION RES/DE/CMB	

☐ DOCUMENT AUTHOR ☐ DOCUMENT CONTRIBUTOR ☐ DOCUMENT REVIEWER ☑ ON CONCURRENCE

REASONS FOR NON-CONCURRENCE AND PROPOSED ALTERNATIVES

See the eight page appendix added to this form, explaining that it is impractical to use radiation detectors to report boron-10 content in degraded spent fuel pool neutron absorber panels. Therefore, criticality calculations in spent fuel pools are unreliable.

☑ CONTINUED IN SECTION D

SIGNATURE Charles Harris | DATE June 12, 2012

SEE SECTION E FOR IMPLEMNATION GUIDANCE

NRC FORM 757
NRC MD 10.158
(7-2011)

U.S. NUCLEAR REGULATORY COMMISSION

NON-CONCURRENCE PROCESS

NCP TRACKING NUMBER
NCP-2012-004

TITLE OF SUBJECT DOCUMENT	ADAMS ACCESSION NO.
Draft NUREG/CR 7130 Assessment of Uncertainties Associated with the BADGER Methodology	ML12151A156

SECTION B - TO BE COMPLETED BY NON-CONCURRING INDIVIDUAL'S SUPERVISOR

NAME
Mirela Gavrilas

TITLE	PHONE NO.
Branch Chief	(301) 251-7556

ORGANIZATION
RES/DE/CMB

COMMENTS FOR THE NCP REVIEWER TO CONSIDER

The technical staff in both NRR and RES share Charles Harris's concern regarding the degradation of neutron absorbing materials. This concern was the impetus for the 2010 NRR request for assistance under NRR-2010-015, "User Need Request to Develop the Technical Bases for the Evaluation of Neutron-absorbing Materials in Spent Nuclear Fuel Pools." (ADAMS accession number ML101720572). The assessment of uncertainties associated with BADGER measurements is one of the research activities initiated in response to this user need. Note, that technical staff in NRR have placed a high priority on this work. The draft report has benefitted from extensive staff review throughout its development. Charles was invited to provide comments throughout the development of the report and to participate in the meetings of the technical group who reviewed and commented on earlier drafts of this report. Some sections of the report were bolstered to address comments from Charles regarding detector size and wall effect.

To the best of my knowledge, the draft report does not, at any point, find the BADGER methodology acceptable. In email exchanges with me after the NCP was initiated, Charles provided examples of statements in the draft report, which Charles considers support his concern that "The document concludes that the current industry method, BADGER (explained below), is acceptable, with proper allowances regarding uncertainties in measurements." (Form 757, appendix, pg. 5) His examples from the draft report are:

- "Approximate adjustments or correction factors could be developed to ensure that the physical measurement distortions are accounted for when developing calibration model uncertainties. Alternatively, if like-for-like characteristics are not available, computational assessments and bounding system performance studies could be conducted to estimate TMU introduced by the physical differences between the calibration panel, reference panel, and actual panel under test."
- "For on-site calibration, a standard calibration panel that is identical in all physical properties and characteristics as the test panel(s) (i.e., rack designs with corresponding matching "representative" calibration panels) is likely to generate the lowest uncertainty. In situ neutron transmission measurements are very sensitive to variation in measurement geometry. If "representative" calibration panels for reference panels are not available, then uncertainties can be addressed and mitigated by developing a technical basis document which includes radiation transport-based calculations which can be used to supplement the detector response functions."
- "When a more rigorous evaluation of the influence factors has been performed and made available, subsequent corrections to the algorithms made, and all deployment issues proven acceptable, a technically defensible estimate of TMU can be calculated and represented."

All these statement refer to calibration as a contributor to uncertainty, which is how it is treated throughout the draft report. The draft report recognizes that calibration, among others, can render BADGER measurements invalid; see, for example, the Foreword which states: "Secondly, although the Type B analysis did not provide quantitative estimates for each contributor to overall uncertainty, several contributors to uncertainty were identified that can potentially invalidate measurement results. Examples of such errors are use of the instrument in a very high gamma field, the improper adjustment of low-level pulse discrimination, inconsistency in operator interpretation of data, and material mismatch between calibration and test panel."

The statement by Charles that "I think many US power plant licensees can not ensure subcriticality in spent fuel pools because, given the uncertain condition of the neutron absorber materials, such as in Figures 1 through 6 above,..." goes beyond the scope of the draft NUREG/CR covered by the non-concurrence. Charles has expressed this on earlier occasions and I have shared Charles' concern at that time with the cognizant branch chiefs and team leaders in NRR: Tony Ulses and Kent Wood of NRR/DSA, and Gloria Kulesa of NRR/DE.

☐ CONTINUED IN SECTION D

SIGNATURE	DATE
MGav	6/28/2012

SEE SECTION E FOR IMPLEMENTATION GUIDANCE

NRC FORM 757
NRC MD 10.158
(7-2011)

U.S. NUCLEAR REGULATORY COMMISSION

NON-CONCURRENCE PROCESS

NCP TRACKING NUMBER
NCP-2012-004

TITLE OF SUBJECT DOCUMENT
Draft NUREG/CR 7130 Assessment of Uncertainties Associated with the BADGER Methodology

ADAMS ACCESSION NO.
ML12151A156

SECTION C - TO BE COMPLETED BY DOCUMENT SPONSOR

NAME
Stuart Richards

TITLE
Deputy Director

PHONE NO.
(301) 251-7616

ORGANIZATION
Division of Engineering (DE), Office of Nuclear Regulatory Research (RES)

SUMMARY OF ISSUES
See attached Summary of Issues.

ACTIONS TAKEN TO ADDRESS NON-CONCURRENCE

Mr. Harris and I discussed his concerns, as documented in his non-concurrence. We agreed on a Summary of Issues, which is attached.

Mr. Harris proposed revisions to the document. A copy of his proposed revisions is attached.

I then proposed some changes to the revisions suggested by Mr. Harris, which is also attached.

Mr. Harris considered this write-up to be acceptable.

Note that as part of our discussions, Mr. Harris proposed to include photographs of actual neutron absorber degradation in order to illustrate the degree of degradation which has occurred in some instances. I agreed that including photographs was appropriate.

Mr. Harris agreed that we need to ensure that the photographs which are used are acceptable to be placed in the public domain (not proprietary or copy-righted for example). Mr. Harris and I agreed to allow other staff in the division to work on identifying these photographs.

SIGNATURE--DOCUMENT SPONSOR (signature)	TITLE Deputy Director
ORGANIZATION Division of Engineering/RES	DATE 8/1/12
SIGNATURE--NCP REVIEWER (signature)	TITLE Director, DE
ORGANIZATION CMB/DE/RES	DATE 08/03/2012

NCP OUTCOME

Non--Concurring Individual: ☐ CONCURS ☒ NON-CONCURS ☐ WITHDRAWS NON-CONCURRENCE (i.e., discontinues process)

AVAILABILTY OF NCP FORM

Non--Concurring Individual: ☒ WANTS NCP FORM PUBLIC ☐ WANTS NCP FORM NON-PUBLIC

☐ CONTINUED IN SECTION D

SEE SECTION E FOR IMPLEMENTATION GUIDANCE

<u>Non-concurrence issue</u>:

Unlike the conclusions stated in NUREG/CR-7130, I believe that it is impractical to use radiation detectors to report boron-10 content in degraded spent fuel pool neutron absorber panels. The method is based on a flawed application of a basic scientific principle. Therefore, many criticality calculations in spent fuel pools may be unreliable.

<u>A possible radiation safety issue</u> is depicted in following photographs of neutron absorber materials used in spent fuel pools (SFPs) at many United States nuclear power facilities [Refs. 1, 2, 3]:

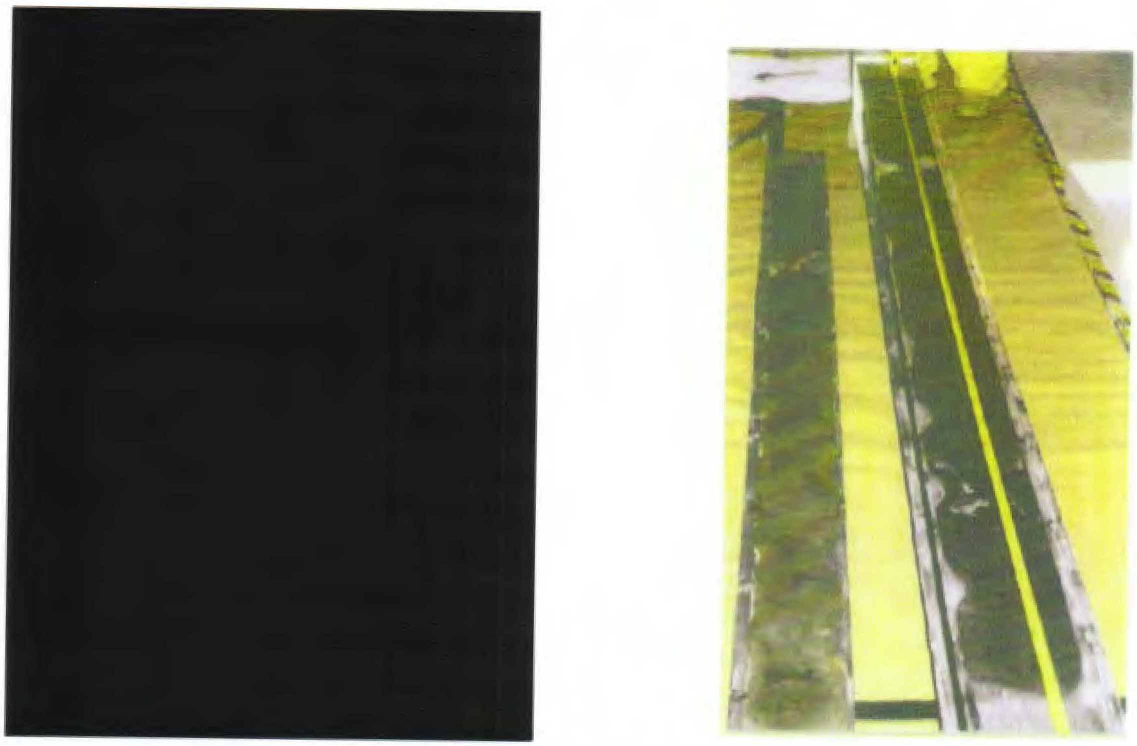


Figure 1. Irradiated Boraflex. [Refs. 1, 2]. **<u>NOTE</u>**: Disintegrated, eroded, material, holes, delamination, edge scallops (in the right photo). faded color from the original opaque black. {Rulers mark the scale, in addition to a person's feet in the right photo.}

Figure 2. Boral coupon corrosion. [Ref. 2] **NOTE**: This was originally a bright, glossy aluminum surface. Note the discolored, uneven, corrosion products of unknown composition.

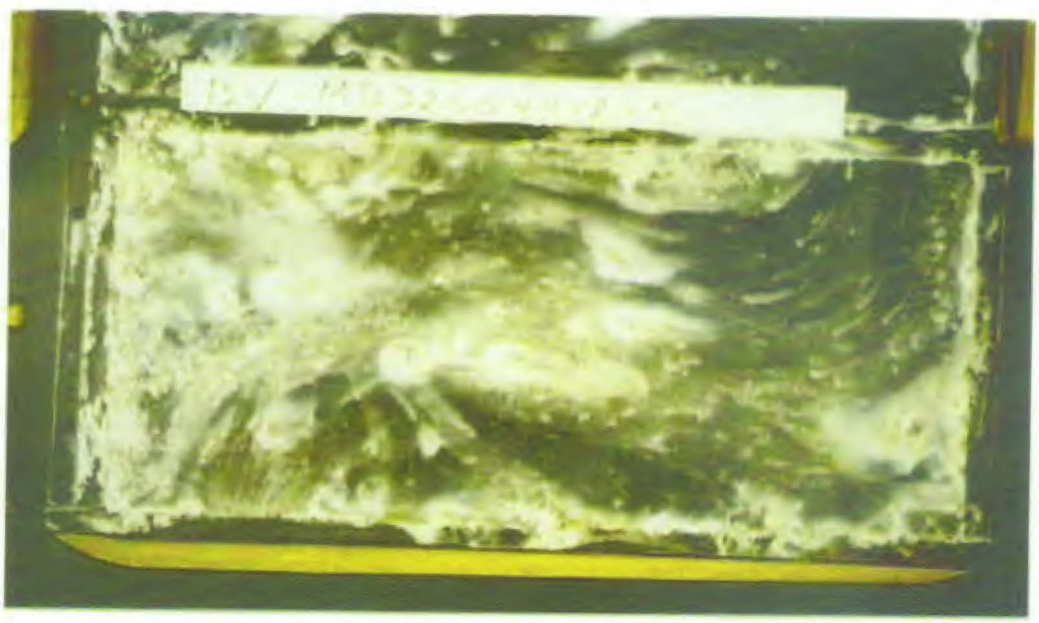


Figure 3. Boral coupon corrosion. [Ref. 2] **NOTE**: This was originally a bright, glossy aluminum surface. Note the discolored, uneven, corrosion products of unknown composition. There is pitting (holes) in the centers of the lightest color areas.

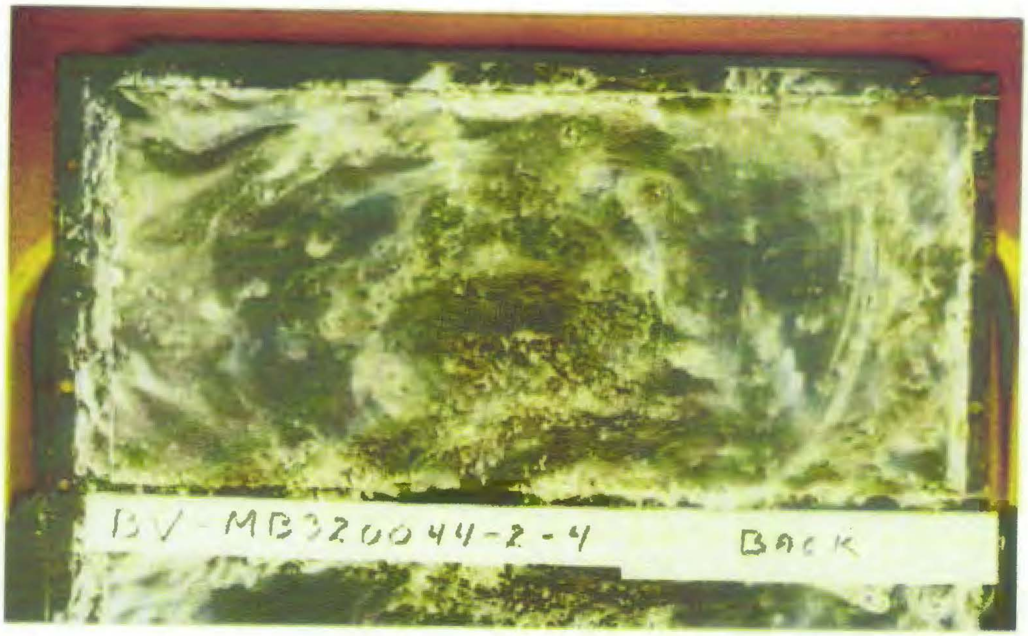


Figure 4. Boral coupon corrosion. [Ref. 2] **NOTE**: Excessive pitting (holes) in the center, and botton center, light and dark corrosion products of unknown composition.

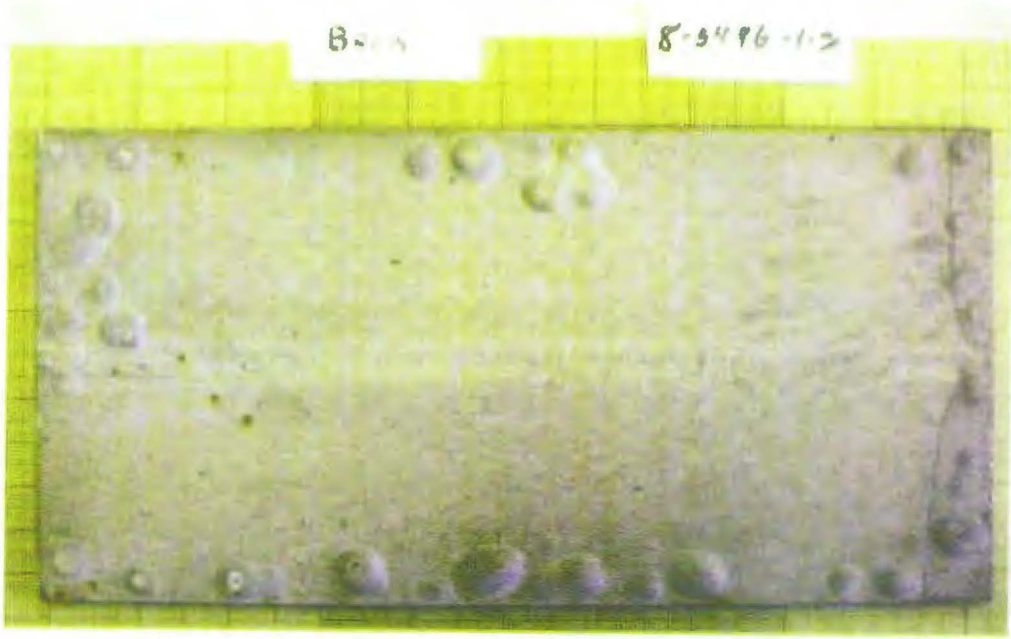


Figure 5. Boral blisters. [Refs. 2, 3]. **NOTE**: Edge blisters, uneven surface colors, white spots on two blisters with small center pits or other corrosion.

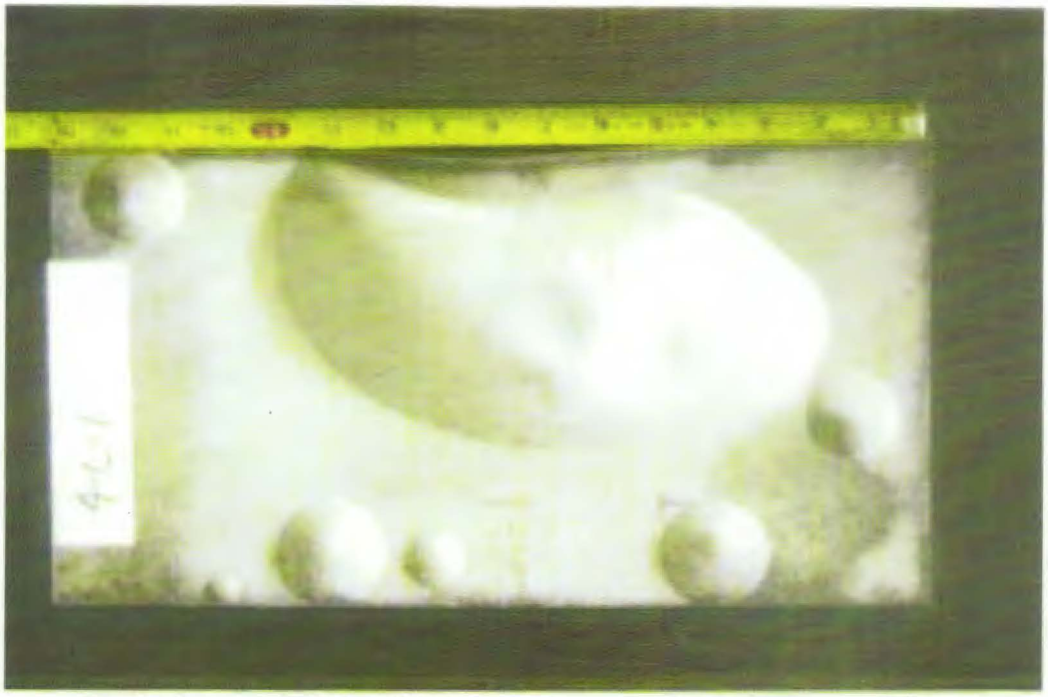


Figure 6. Boral blisters. [Ref. 3]. **NOTE**: Blisters up to 10 inches long. Contents of the blister bubbles are unknown, possibly borated water, hydrogen gas, vacuum, or other unknown corrosion byproduct.

Such degradation has been highlighted by the NRC in the past, such as in information notice IN-2009-26.

Boraflex is a polymer and boron carbide composite (Figure 1). It is still credited for SFP subcriticality at several U.S. locations. Degradation of Boraflex in the 1970s and 1980s lead to NRC information notices, IN 87-83, IN 93-70, and IN 95-38. [Ref 4].

An aluminum boron carbide composite, Boral, experienced several much more recent degradation events, including blistering at Seabrook in 2003, Beaver Valley in 2007, and Three Mile Island in 2008. Additionally, in 2009, Susquehanna experienced Boral bulging in the spent fuel pool [Ref. 4].

Differing Opinion:

I think many US power plant licensees can not ensure subcriticality in spent fuel pools because, given the uncertain condition of the neutron absorber materials, such as in Figures 1 through 6 above, I do not believe it is practical for licensees to use their current method (via radiation detectors) of reporting boron-10 content in those materials.

I have a differing opinion on the validity of the method used to verify the boron-10 content of these neutron absorber panels. It is that boron-10 content which is credited for maintaining subcriticality in many U.S. spent fuel pools. The Office of Nuclear Regulatory Research (RES) intends to publish NUREG/CR-7130, contracted with Oak Ridge National Laboratory (ORNL). The document concludes that the current industry method, BADGER (explained below), is acceptable, with proper allowances regarding uncertainties in measurements. I disagree, and conted that the entire concept is based on a flawed application of a fundamental scientific principle. I do not think the method is valid, and I do not think NRC should publish a NUREG/CR which states that it is valid.

Industry method:

BADGER is the Boron Areal Density Gauge for Evaluating Racks [Refs 5, 6]. The concept is simple:

a) Use a radiation source and detector to measure neutron attenuation through a set of calibration standards (of known boron-10 content) to plot a calibration curve of boron-10 content vs. attenuation.
b) Next, measure the neutron attenuation of selected (unknown) neutron absorber panels in the spent fuel pool.
c) Then compare the unknown panels to the calibration curve, thus reporting the boron-10 content of the unknowns. The boron-10 content of the fuel pool panels is reported as boron-10 areal density, which can be compared to the as-manufactured state, to estimate degradation.
d) The fuel pool panels' boron-10 content is then used in criticality calculations to ensure subcriticality in the fuel pool.

Problem:

I contend that there is a fundamental problem:

Once neutron absorber panel degradation begins (up to and including the conditions in the photographs of Figures 1 through 6) then the calibration standards are no longer representative of the unknown materials being measured in the fuel pools.

I contend that after degradation of panels occurs, the BADGER method is no longer valid as a way to measure boron-10 content in the panels of the pool. Therefore, criticality calculations, which take credit for boron-10 panel content, are not reliable.

Theory:

The boron-10 isotope has a high likelihood of interacting with neutrons of thermal energy. That likelihood is called the cross section, Σ. In the fuel pools, boron-10 may be contained in panels and placed between fuel assemblies. The boron-10 may be credited with absorbing thermal neutrons from the fuel, thus preventing criticality.

Considering a panel of a certain thickness, BADGER neutron attenuation testing follows the Beer-Lambert law (equation 1) for neutron attenuation through all of the materials comprising the thickness of the panel [Ref. 7]

$$I/I_o = \exp([-\Sigma_a/\rho]\cdot\rho x) \qquad \text{(equation 1)}$$

where

I_o = initial neutron intensity, incident on the panel
I = transmitted neutron intensity, after passing through the panel
ρ = the densities of all materials within the panel
x = the thickness of the panel
Σ_a = the integral macroscopic absorption cross section of all materials comprising the panel.

It is an acceptable practice to use calibration standards having properties similar to the unknowns. These properties include composition, geometry, and homogeneity, among others.

Theory Related to the Problem:

The macroscopic cross section, Σ_a, is the variable with which I say there is a problem for BADGER. The macroscopic cross section Σ, for any volume of a material is the number of atoms (N) in the volume, multiplied by the microscopic cross section for the particular material (σ):

$$\Sigma = N\sigma \qquad \text{(equation 2)}$$

{The subscript "a" in Σ_a denotes the absorption cross section, since there are different cross sections for different possible nuclear reactions, such as absorption.}

For a panel made of two, three, or n materials, such as those in the fuel pools, the total macroscopic cross section (Σ_{total}) is made up of the sum of the cross sections for all of the panel's component materials:

$$\Sigma_{total} = \Sigma_1 + \Sigma_2 + \ldots \Sigma_n \qquad \text{(equation 3)}$$

- It is that Σ_{total}, the total macroscopic cross section, which I contend is the problem. The calibration standards are as-manufactured, non-degraded materials of known compositions (within error limits) and geometries. The macroscopic cross section may be measured or calculated. For the standards, neutron attenuation between a source and a detector may be measured, and related to boron-10 content.

- Once fuel pool panels undergo degradation, the degraded materials can not be reliably compared to the calibration standards. The degraded panel composition is unknown; there may be significant corrosion of unknown degree and unknown chemical content. Material may be completely missing from the panel. Material may be adhered to or added to the panel. The density is unknown. The geometry is unknown. The homogeneity has changed. For equation 2, the numbers of atoms has changed and, if corroded, the materials and the microscopic cross sections have changed. If blistered or bulged, there may be materials of unknown quantity and composition within the deformities. Therefore the macroscopic cross section has changed and the unknown panels can not be properly compared to calibration standards.

- Calibration materials and degraded panel materials are not similar, so reporting a boron-10 content via the calibration curve is not a valid method.

<u>**Summary**</u>:

Given the uncertain condition of SFP neutron absorber materials, I do not believe it is practical for licensees to use their current method of reporting boron-10 content in those materials via radiation detectors; sub-criticality can not be ensured.

The BADGER method compares neutron attenuation of calibration standards to neutron attenuation measurements of fuel pool neutron absorber panels. A calibration curve from a set of calibration standards is used to report boron-10 content in all the fuel pool panels after some sample measurements have been made of unknown sample panels in the fuel pool.

RES plans to publish NUREG/CR-7130, which concludes that the BADGER method is acceptable. ORNL concludes, based on limited industry information, that a measurement uncertainty of ~40% may exist, and that with additional industry information, the BADGER method should be acceptable within a smaller maximum error (<15% is the number extimated by ORNL).

My opinion differs from the RES and ORNL conclusion stated in the preceding paragraph. My contention is that the BADGER method is fundamentally in error, when comparing undegraded calibration standards to panels which have undergone degradation.

References:

1. Sixth Inspection—EPRI Boraflex, Surveillance Assembly Technical Report #1003414, Electric Power Research Institute, Palo Alto, CA , July 2002.
2. Handbook of Neutron Absorber Materials for Spent Nuclear Fuel transportation and Storage Applications, 2009 ed., report #1019110, Electric Power Research Institute, Palo Alto, CA, 2009.
3. "Underappreciated Materials": Used Fuel Storage J. Kessler Manager, Used Fuel & HLW Management Program Life Beyond 60 Workshop, Electric Power Research Institute, 23 February 2011.
4. Spent Fuel Criticality: Neutron Absorbing Material Degradation Issues, Emma Wong, Nuclear Regulatory Commission, Regulatory Information Conference Presentation, March 11, 2010.
5. BADGER, a Probe for Nondestructive Testing of Residual Boron-10 Absorber Density in Spent-Fuel Storage Racks: Development and Demonstration, EPRI TR-107335, Topical Report, Electric Power Research Institute, Palo Alto, CA, October 1997.
6. MCNP Validation of BADGER, GC-110539, Electric Power Research Institute, Palo Alto, CA, May 1998.
7. Introduction to Nuclear Engineering, Lamarsh, John R., Baratta, Anthonty J., 3rd ed., Prentice Hall, 2001.

Summary of Issues
NCP-2012-004

Background: Spent nuclear fuel is stored in spent fuel pools (SFPs), either for long-term storage, or until the spent fuel can be moved to dry storage casks. To increase the storage capacity of spent fuel pools, some licensees use neutron absorbing panels to ensure that the fuel remains sub-critical, in accordance with NRC requirements. Some of these neutron absorbing panels have physically degraded over time. Some licensees use the BADGER testing system to evaluate the degree of neutron absorbing panel degradation. Although the NRC has not endorsed the use of BADGER testing, the NRC recognizes that the BADGER system is in use by some licensees, and that those licensees may possibly be using the results of BADGER testing to determine compliance with NRC sub-criticality requirements.

The NRC Office of Nuclear Reactor Regulation (NRR) requested in NRR User Need Request (UNR) 2010-015, "User Need Request to develop the Technical Bases for the Evaluation of Neutron Absorbing Materials in Spent Fuel Pools," that the Office of Nuclear Regulatory Research (RES) review the accuracy on in-situ surveillance testing of neutron absorber panels in SFPs. The BADGER testing system is such a system to perform in-situ surveillance testing.

In response to the UNR, RES contracted for associated work to be carried out by the Oak Ridge National Laboratory (ORNL). ORNL subsequently produced NUREG/CR-7130, "Assessment of Uncertainties Associated with BADGER Methodology." This NUREG/CR is the subject of the non-concurrence.

Summary of Issues:

- Some neutron absorbing panels are significantly physically degraded. Pictures of degraded panels are included in the non-concurrence package.

- The BADGER system is calibrated using neutron absorbing panels that are not physically degraded.

- Because the BADGER system is sometimes utilized to evaluate panels which are significantly physically degraded, the system is not properly calibrated for this purpose.

- The NUREG/CR should not be published because by its publication, with the current conclusions, it will appear that the NRC endorses the use of BADGER if the measurement uncertainties are assessed. The BADGER system is fundamentally in error by comparing degraded panels to un-degraded calibration standards.

- If BADGER testing is used as the basis for criticality calculations, licensees cannot ensure fuel sub-criticality in SFPs due to the uncertain degree of degradation of neutron absorbing panels.

Richards, Stuart

From: Harris, Charles
Sent: Thursday, July 19, 2012 10:09 AM
To: Richards, Stuart
Subject: Non-concurrence edits
Attachments: Non-concurrence edits.docx

Stu,

If the attached changes and additions were made to the document, I believe I would concur. I still do not think this document has enough "necessary background information provided" for it to be published as an authoritative NUREG; I believe a technical letter report designation is more appropriate.

Thank you,

Charlie

Charles Harris

Materials Engineer
Office of Research
Division of Engineering
Corrosion and Metallurgy Branch
(301) 251-7637

1. Add as the first sentence of the introduction:

To fully appreciate the issues herein, one must pay special attention to Chapter 5 of this document , especially regarding calibration methods.

2. Add as the first paragraph and 5 figures of Chapter 4, "BADGER System Description."

Before describing the BADGER measurement system, it is appropriate to have a sense of the types of material degradations which have necessitated the use of some method to confirm neutron absorber integrity. The following five figures from EPRI documents [ref. 1,2,3, {must adjust reference numbers}] illustrate instances of degraded Boraflex and Boral from spent fuel pools. It is essential to account for any dimensional changes, material losses, corrosion products, or other compositional changes, if BADGER measurements will be employed using calibration curves based on a set of undegraded standards.

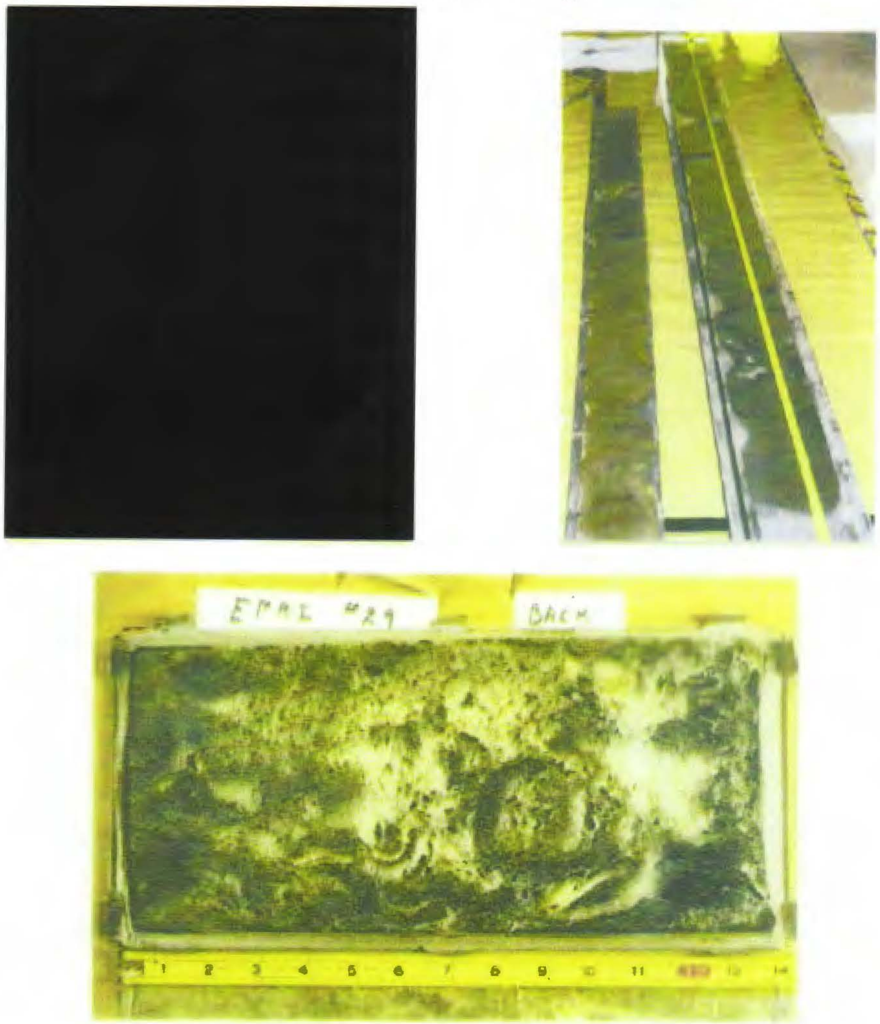


Figure ??. Irradiated Boraflex. [Refs. 1, 2] Note the Disintegrated, eroded, material, holes, delamination, edge scallops (in the right photo). faded color from the original opaque black. {Rulers mark the scale, in addition to a person's feet in the right photo.}

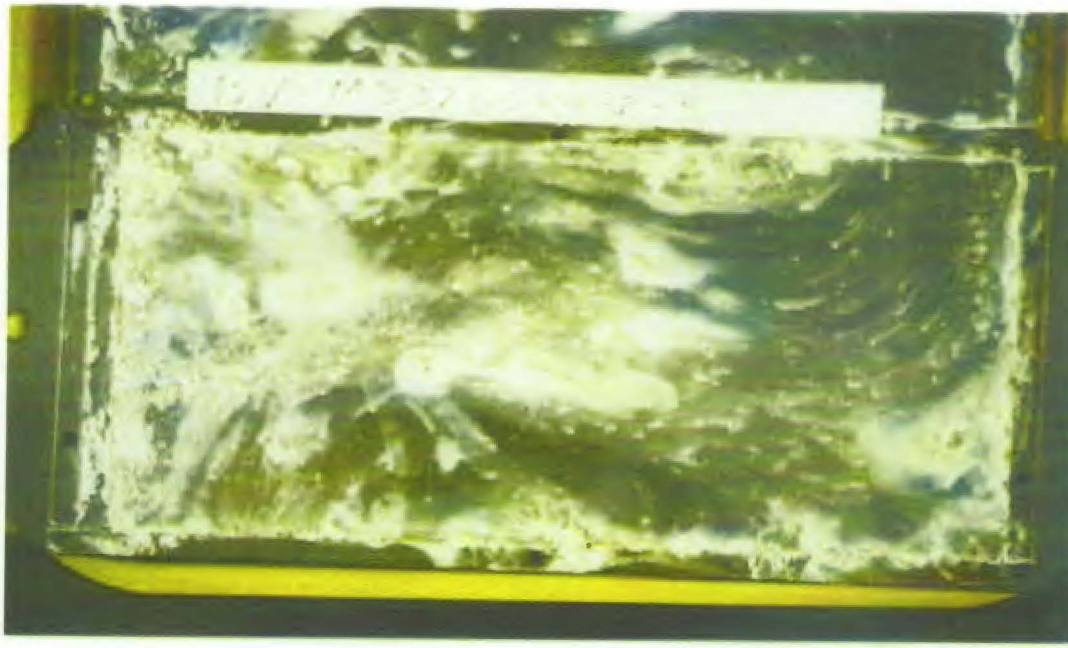


Figure ??. Boral coupon corrosion. [Ref. 2] Note: This was originally a bright, glossy aluminum surface. Note the discolored, uneven, corrosion products of unknown composition.

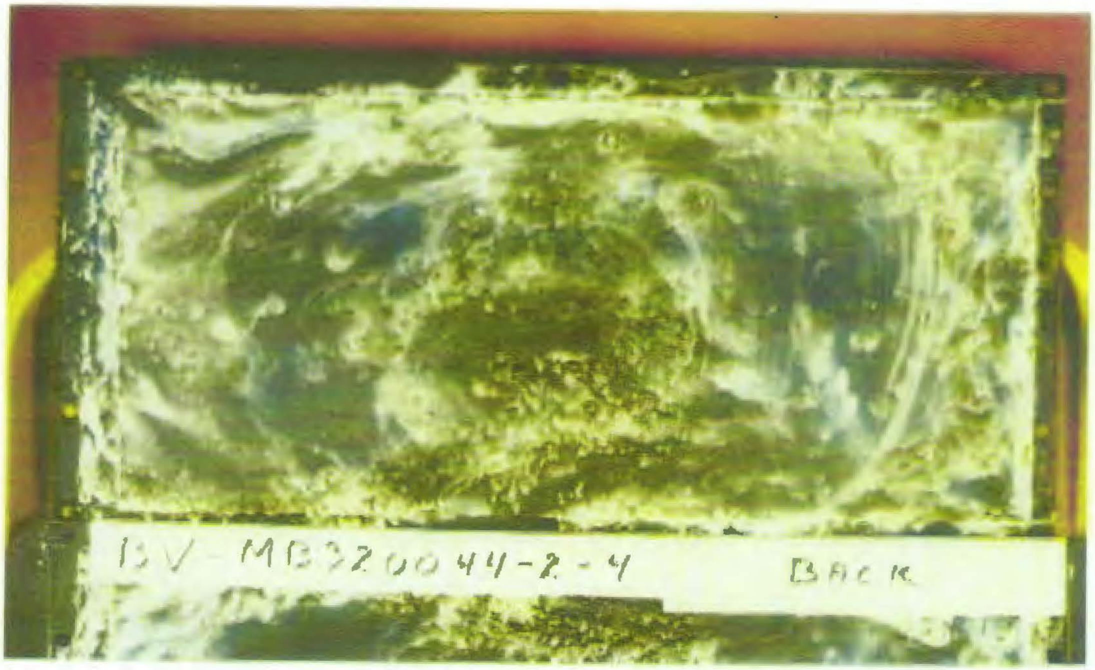
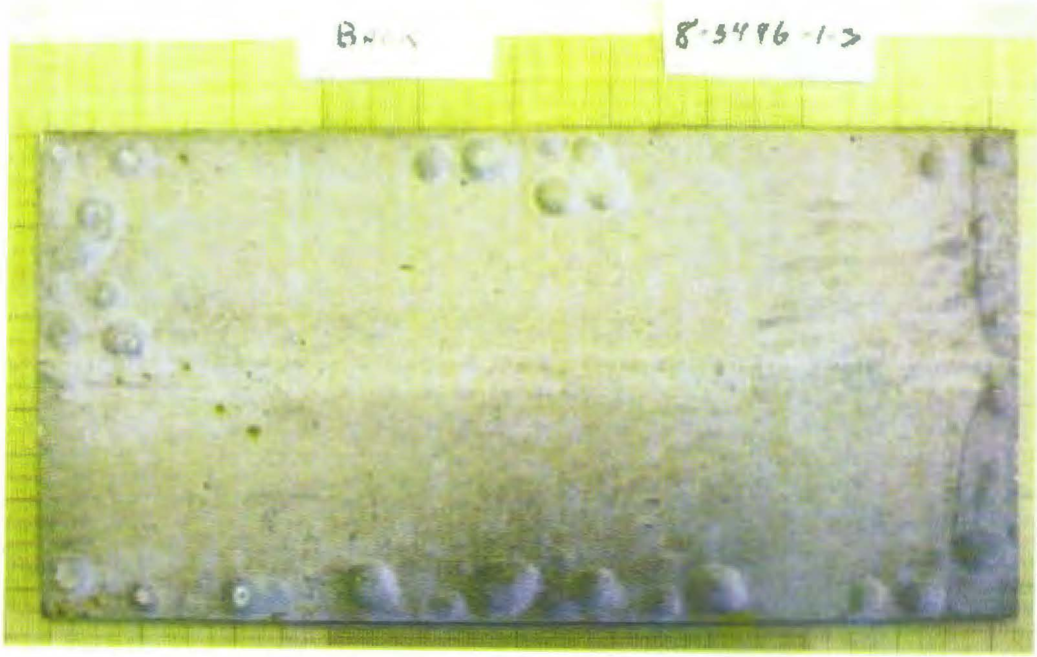


Figure ??. Boral coupon corrosion. [Ref. 2] Note: Excessive pitting (holes) in the center, and botton center, light and dark corrosion products of unknown composition.



Figure??. Boral blisters. [Ref. 2] Note: Edge blisters, uneven surface colors, white spots on two blisters with small center pits or other corrosion.

Figure ??. Boral blisters. [Ref. 2] Note: Blisters up to 10 inches long. Contents of the blister bubbles are unknown, possibly borated water, hydrogen gas, vacuum, or other unknown corrosion byproduct.

Modify section 5.6.4 as follows (in red):

5.6.4 Relevance of Standard Panel Material to Rack Panel Material

The effects of self-shielding, streaming, and channeling of neutrons between absorber particles can vary significantly for different materials. Neutron channeling and streaming occur when the distribution of boron in the absorber panel matrix is heterogeneously distributed such that a path between boron particles exists that allows neutrons to penetrate the absorber sheet without attenuation. Self-shielding is in reference to the neutron absorber particles at the surface absorbing neutrons before they can penetrate deeper into the absorber material. The materials' heterogeneity parameters (e.g., particle composition, size, dispersion) of the calibration cell and test panels must be similar for accurate calibration. The effect of heterogeneity of composition is more pronounced in soluble boron environments. For example, consider a PWR spent fuel pool that contains soluble boron in the moderator and test panels with different levels of degradation. The test panels that have exhibited degradation may have void regions within the panels with different porosity levels. In addition to water moderator, these pores could also contain soluble boron that would not be captured in scans of the calibration standards or the reference panel but will affect the thermal neutron attenuation rates. The impact of this difference in heterogeneous properties depends upon the amount of degradation, the areal density of the test panel, and the amount of soluble boron present in the pores. In addition, neutron in-scatter will be dependent on local measurement perturbations from scallops, warp, and geometric effects.

If one wished to make approximate adjustments or correction factors ~~could be developed~~ to ensure that the physical measurement distortions are accounted for when developing calibration model uncertainties, it would be necessary to fully account for all differences between standards and the unknown fuel pool materials, including all inhomogeneities, compostion changes,, material losses, and dimensional changes~~.~~ Alternatively, if like-for-like characteristics are not available, and computational assessments and bounding system performance studies ~~could~~ wished to be conducted to estimate TMU introduced by the physical differences between the calibration panel, reference panel, and actual panel under test, then again, all physical differences between standards and unknown materials would have to be satisfactorily accounted for and explained.~~.~~

As discussed in Reference [i], experimental and calculational results have indicated that neutron channeling effects diminish as the thickness of the neutron absorber increases. Hence, at high areal densities and thicknesses, the impact of different materials should be small. However, the rate of change in areal density as a function of neutron transmission will be different for different materials (Reference [ii]), resulting in a calibration curve that is not representative of the material of interest. Accuracy of neutron transmission measurements is very susceptible to the physical properties of the calibration cell standards matching the test panels. Based on the limited documentation reviewed, the estimated relative uncertainty associated with using different calibration standard materials from the rack cell materials (provided ^{10}B is the primary neutron absorber isotope) is estimated to be ±30 percent which takes into consideration existing guidance for spent fuel storage and transportation applications regarding credited neutron absorber (Reference [iii]). If a different absorber (e.g., gadolinium) is used, no estimate can be made without detailed experimental data.

For on-site calibration, a standard calibration panel that is identical in all physical properties and characteristics as the test panel(s) (i.e., rack designs with corresponding matching "representative" calibration panels) is likely to generate the lowest uncertainty. In situ neutron transmission measurements are very sensitive to variation in measurement geometry. If "representative" calibration panels for reference panels are not available, ~~then~~ and uncertainties ~~can~~ were to be addressed ~~and~~ in an attempt to mitigate~~d~~ the unavailability by developing a technical basis document, then that document would need to ~~which~~ include~~s~~ radiation transport-based calculations which can be used to supplement the detector response functions. Such calculations would need to address all geometric variations, compositional changes, loss of material, and other factors which may affect neutron attenuation, which are caused by degradation of the unknown absorber panels being examined.

Add to the last sentence of the Conclusion, Chapter 7.

For any BADGER measurement employing calibration standards to measure degraded panels, it would be necessary to fully account for all differences between calibration standards and the unknown fuel pool materials, including all inhomogeneities, compostion changes, material losses, and dimensional changes.

References:

1. Sixth Inspection—EPRI Boraflex, Surveillance Assembly Technical Report #1003414, Electric Power Research Institute, Palo Alto, CA , July 2002.

2. Handbook of Neutron Absorber Materials for Spent Nuclear Fuel transportation and Storage Applications, 2009 ed., report #1019110, Electric Power Research Institute, Palo Alto, CA, 2009.

3. "Underappreciated Materials": Used Fuel Storage J. Kessler Manager, Used Fuel & HLW Management Program Life Beyond 60 Workshop, Electric Power Research Institute, 23 February 2011.

i. EPRI, "Neutron Transmission Through Boral®: Impact of Channeling on Criticality," TR 1011819, EPRI, Palo Alto, California, June 2005.

ii. S. E. Turner, "Reactivity Effects of Streaming Between Discrete Boron Carbide Particles in Neutron Absorber Panels for Storage or Transport of Spent Nuclear Fuel," *Nucl. Sci. Eng.* **151**, 344–347 (2005).

iii. U.S. Nuclear Regulatory Commission, "Application of ASTM Standard Practice C1671-07 when perfofming technical reviews of spent fuel storage and transportation packaging licensing actions," *Division of Spent Fuel Storage and Transportation Interim Staff Guidance – 23*, January 18, 2011.

Richards, Stuart

From: Richards, Stuart
Sent: Friday, July 20, 2012 1:33 PM
To: Harris, Charles
Subject: BADGER Revision
Attachments: BADGER REV - Stu (2).docx

Charlie

Thanks for providing me the recommended changes.

Based on your recommended changes, attached is my mark-up. I propose to incorporate most of your material, with some revisions.

Text in blue indicates existing text which already supports some of the points you want to emphasize.

Text in red are changes.

In the introduction section, I would make a change further into the section, as I believe it would flow better with the general discussion.

Rather than add the pictures to section 5, I propose to add pictures to section 2, which is the background section. I would only add the pictures on the Boraflex material as it is the focus of the discussion.

I propose changes to section 5.6.4, but I reworded your changes to a certain degree.

I would not make any changes to the conclusion section. The conclusion section is written at a high level, which I think is appropriate. The points you suggest be added appear to me to have been fully described in the preceding sections with the revised text.

Take a look and let me know what you think.

Stu

FOREWORD

The degradation of neutron absorbing materials in spent fuel pools has prompted the staff to undertake a review of the tools and methods used by the industry to ascertain the condition of panels. Boraflex and Carborundum have degraded severely through chemically-induced changes and dissolution. Boral degraded by corrosion and deformation. Consequently, the subcriticality margins that existed when neutron absorbers were first installed have eroded. As margins erode, one must have confidence in the neutron absorber data used in criticality analyses to demonstrate compliance with the subcriticality requirements specified by Title 10 of the Code of Federal Regulations Section 50.68 (10 CFR 50.68) or General Design Criteria (GDC) 62. Therefore, when using surveillance methods to determine the areal density of neutron absorbers in spent fuel pools, it is necessary that associated uncertainties be catalogued in a systematic manner.

The staff has focused on the surveillance methods for neutron absorber panels. Specifically, the staff has undertaken a review of the RACKLIFE computational tool and the Boron Areal Density Gauge for Evaluating Racks (BADGER) in-situ measurement technique. The primary focus of the current NUREG/CR is the uncertainty associated with the BADGER in-situ instrument. The uncertainty associated with RACKLIFE is discussed in the companion report NUREG/CR 7129: Boraflex, RACKLIFE, and BADGER: Description and Uncertainties (T.C. Haley).

The BADGER system was originally designed, assembled, and tested in the early-to-mid 1990s by Northeast Technologies Company (NETCO, now a subsidiary of Curtiss-Wright), as a nondestructive scoping tool to evaluate neutron absorbers placed in spent fuel racks. While BADGER is employed primarily to measure the degradation of Boraflex neutron absorbing material, it is theoretically applicable to any neutron absorber and has, in fact, been used for Carborundum.

BADGER uses BF_3 gas-filled detectors. Gas-filled detectors were among the first devices used for radiation detection. BF_3 detectors tend to be reliable, offering good neutron/gamma-ray discrimination at a reasonable efficiency. While BF_3 tubes have been used in many neutron detection applications, their use for measuring areal density of ^{10}B in spent fuel pool neutron absorber panels can be challenging.

The BADGER instrument comprises a neutron source head and a detector head, which are lowered into neighboring cells of a spent fuel rack. The source and detector heads are drawn upwards along the cell in a stepwise fashion, producing two-dimensional spatial data about the neutron absorbing capabilities of the panel in between the cells. The BADGER trace raw data is converted to ^{10}B areal density by means of a calibration curve.

The analysis and assessment of the BADGER instrument and the associated measurement methodology yielded three principal findings. First, detailed documentation is required in order to conduct a rigorous quantitative uncertainty analysis. This includes technical specifications and/or quality control test reports. For BADGER, such documentation is not publicly available nor was it available to the authors of this report. Therefore, a Type B analysis, as defined by National Institute for Standards and Testing for use in cases where supporting measurement data is not available, was conducted. Estimates of uncertainty that appear in this report are a combination of data, analytical estimates and expert opinions.

Secondly, although the Type B analysis did not provide quantitative estimates for each contributor to overall uncertainty, several contributors to uncertainty were identified that can potentially invalidate measurement results. Examples of such errors are use of the instrument in a very high gamma field, the improper adjustment of low-level pulse discrimination, inconsistency in operator interpretation of data, and material mismatch between calibration and test panel. Flux-trap racks, a configuration where two neutron absorber panels are interposed between spent fuel assemblies, are especially susceptible to high error because neutrons must travel through two panels to the detector.

Lastly, head misalignment contributes an estimated uncertainty of ±40 percent to the overall BADGER results. The uncertainty resulting when the source and detector head are not properly aligned was estimated using the MAVRIC neutron radiation transport sequence in the SCALE criticality package. This 40 percent error may be significantly higher if the rack cell walls are warped or deformed.

Uncertainties associated with over 40 different factors affecting the measurement accuracy of the BADGER system were assessed, but documented information was available for less than five. In addition to discussing contributors to uncertainty, this NUREG/CR provides examples of the types of data and information necessary for a more rigorous calculation of uncertainty. The report illustrates the need to more closely scrutinize actual information and data associated with BADGER campaigns, and quantify uncertainties that propagate in criticality calculations. The report illustrates the need to more closely scrutinize actual information and data associated with BADGER campaigns, and quantify uncertainties that propagate in criticality calculations.

Michael Case, Director
Division of Engineering
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission

1 INTRODUCTION

Criticality safety analyses are performed to demonstrate that a proposed fuel storage configuration meets the applicable requirements of Title 10 of the Code of Federal Regulations (CFR) Part 50.68, "Criticality accident requirements," (Reference) and Part 50 Appendix A General Design Criterion (GDC) 62, "Prevention of criticality in fuel storage and handling" (Reference). Several options for criticality control are available to licensees including use of a geometrically safe configuration, soluble boron, and interstitial neutron absorber panels. As spent fuel pool strategies shift to maximizing storage density, reliance on neutron absorber panel reactivity control has increased. Utilities have typically used neutron absorbers such as Boraflex, Boral®, Metamic™, and Carborundum in spent-fuel storage racks to control reactivity where boron 10 (10B) is the principal neutron-absorbing material contained in the plate. Neutron-absorbing materials used in spent fuel pools and credited to demonstrate compliance with NRC regulations are exhibiting degradation, as documented in Information Notices (INs) 87-43, 93-70, 95-38, and 2009-26 and Generic Letter (GL) 96-04 (References , , , , and). As discussed in Reference 6, a position has been taken that the degradation mechanisms and deformation rates of any of the neutron-absorbing materials in the spent fuel pool are not well understood. Therefore, licensees that credit the use of a neutron-absorbing material to maintain subcriticality in their spent fuel pool must monitor it for any indications that degradation of the material may be occurring that can result in noncompliance with criticality requirements for spent fuel pools.

A nondestructive measurement system was developed by Northeast Technology Corp. for the Electric Power Research Institute (EPRI), named BADGER (Boron-10 Areal Density Gage for Evaluating Racks) (Reference). The BADGER system is being used by utilities to monitor and estimate the extent of degradation of the neutron absorber panels to determine whether sufficient absorber remains to meet subcriticality margin requirements. BADGER is used to measure neutron transmission in 2-inch increments up the vertical length of a rack cell wall in a spent fuel pool. Through calibration and the use of various algorithms, the neutron transmission measurement is converted to a 10B areal density estimate.

The purpose of this report is to provide a technical assessment of the BADGER system surveillance tool, for both pressurized water reactor (PWR) and boiling water reactor (BWR) rack designs, in an effort to understand the magnitude of the uncertainties as well as any limitations in its methodology and application. In particular, this report reviews the implementation of the BADGER system in measuring neutron transmission, correlating neutron count rates to absorber areal density, and determining how this information is applied to criticality evaluations of spent fuel pools, and identifies parameters that contribute most to uncertainty. Uncertainties considered include the use of the instrument in a very high gamma field, the improper adjustment of low-level pulse discrimination, inconsistency in operator interpretation of data, and material mismatch between calibration and test panel.

Though most of the test data information reviewed and examples provided are from Boraflex evaluations, the overall assessment is being conducted in terms of general applicability independent of the specific neutron absorber material used in the spent fuel pool rack.

2 BACKGROUND

Neutron absorbers for spent fuel pool racks are typically composed of a neutron absorber nuclide within a matrix that maintains the distribution of the absorber material. Both metal matrix and non-metal-matrix neutron absorber materials have been produced and are currently being used for spent fuel pool applications. The Handbook of Neutron Absorber Materials for Spent Nuclear Fuel Transportation and Storage Applications (Reference) provides a listing of data and product information for a number of metal matrix neutron absorbers that are commercially available and have had the most widespread use in spent fuel storage and transportation applications, as well as information on non-metal-matrix absorbers, newly proposed aluminum matrix composites, and emerging materials. The primary function of the neutron absorber is to provide sufficient thermal neutron removal along the active fuel region between adjacent fuel assemblies.

Spent fuel pools that employ absorber panels may consist of one of two types of rack systems (or a combination of the two)—(1) flux trap or Region I systems, which contain two absorber panels separated by a water gap between panels, and (2) higher-density, egg-crate or Region II systems, where only a single absorber panel is interstitial to the spent fuel assemblies. A photograph of a typical spent fuel pool with racks is shown in Figure 2.1, and example Region I and Region II rack configurations taken from Reference 9 are illustrated in Figure 2.2 and Figure 2.3, respectively. The focus of this evaluation is based on the application of BADGER to Region I and Region II spent fuel pool rack configurations. The different rack configurations are designed to account for different levels of fuel assembly reactivity and for more effective space utilization. Some variability exists within the rack designs themselves, including fabrication and material specifications in addition to design and dimensional differences. Materials susceptible to expansion or blistering, such as Carborundum or BORAL®, can prevent fuel assemblies from being inserted or removed, as well as change the criticality control conditions.

Figure 2.1. Typical spent fuel pool for U.S. nuclear power plant (NRC file photo).

Figure 2.2. Typical Region I spent fuel pool rack configuration.
Adapted from Reference 9 with permission of Electric Power Research Institute.

Figure 2.3. Typical Region II spent fuel pool rack configuration Adapted from Reference 9 with permission of Electric Power Research Institute.

As an outcome of the observed in-service deterioration of Boraflex, the BADGER system was developed as a nondestructive in situ means to estimate the 10B areal density remaining in neutron absorber materials installed in spent fuel racks for the purpose of reactivity control. Examples of the material degradation experienced with Boraflex are illustrated in Figure XX below, which indicate the potential for dimensional changes and compositional changes.

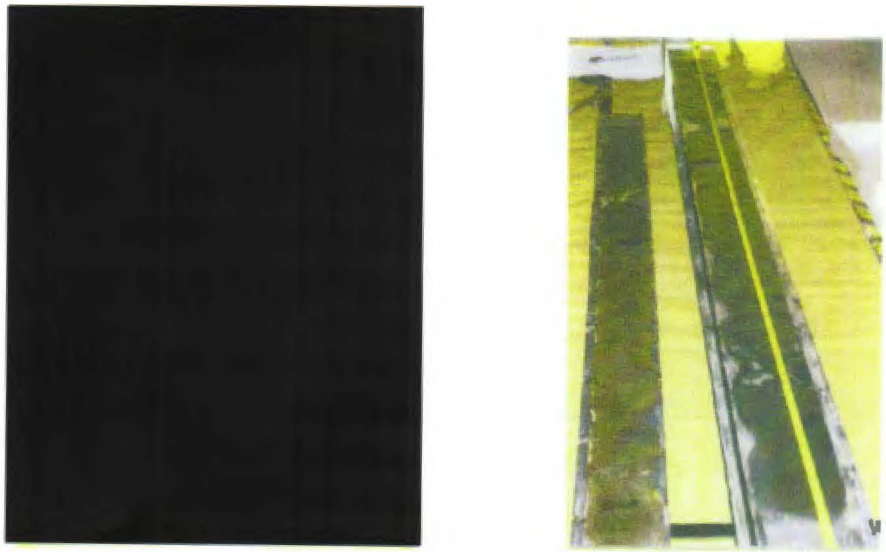


Figure XX. Degraded Boraflex. [Refs. 1, 2]

BADGER employs a well-understood physics method of measuring the attenuation of thermal neutrons through an absorber panel between the neutron source and the detectors. American Society of Testing and Materials (ASTM) C1671 (Reference) discusses neutron attenuation, converting measured count rates to areal density through the use of calibration standards, and provides the following definition:

5.6.4 Relevance of Standard Panel Material to Rack Panel Material

The effects of self-shielding, streaming, and channeling of neutrons between absorber particles can vary significantly for different materials. Neutron channeling and streaming occur when the distribution of boron in the absorber panel matrix is heterogeneously distributed such that a path between boron particles exists that allows neutrons to penetrate the absorber sheet without attenuation. Self-shielding is in reference to the neutron absorber particles at the surface absorbing neutrons before they can penetrate deeper into the absorber material. The materials' heterogeneity parameters (e.g., particle composition, size, dispersion) of the calibration cell and test panels must be similar for accurate calibration. The effect of heterogeneity of composition is more pronounced in soluble boron environments. For example, consider a PWR spent fuel pool that contains soluble boron in the moderator and test panels with different levels of degradation. The test panels that have exhibited degradation may have void regions within the panels with different porosity levels. In addition to water moderator, these pores could also contain soluble boron that would not be captured in scans of the calibration standards or the reference panel but will affect the thermal neutron attenuation rates. The impact of this difference in heterogeneous properties depends upon the amount of degradation, the areal density of the test panel, and the amount of soluble boron present in the pores. In addition, neutron in-scatter will be dependent on local measurement perturbations from scallops, warp, and geometric effects.

To account for differences between the standard panel material and the rack panel material, including inhomogeneities, compostion changes, material losses, and dimensional changes, approximate adjustments or correction factors would be needed to ensure that the physical measurement distortions are accounted for when developing calibration model uncertainties. Alternatively, if like-for-like characteristics are not available, computational assessments and bounding system performance studies could be conducted to estimate TMU introduced by the physical differences between the calibration panel, reference panel, and actual panel under test. These assessments and studies would need to account for all physical differences between the standard panels and the rack panels.

As discussed in Reference , experimental and calculational results have indicated that neutron channeling effects diminish as the thickness of the neutron absorber increases. Hence, at high areal densities and thicknesses, the impact of different materials should be small. However, the rate of change in areal density as a function of neutron transmission will be different for different materials (Reference), resulting in a calibration curve that is not representative of the material of interest. Accuracy of neutron transmission measurements is very susceptible to the physical properties of the calibration cell standards matching the test panels. Based on the limited documentation reviewed, the estimated relative uncertainty associated with using different calibration standard materials from the rack cell materials (provided 10B is the primary neutron absorber isotope) is estimated to be ±30 percent which takes into consideration existing guidance for spent fuel storage and transportation applications regarding credited neutron absorber (Reference). If a different absorber (e.g., gadolinium) is used, no estimate can be made without detailed experimental data.

For on-site calibration, a standard calibration panel that is identical in all physical properties and characteristics as the test panel(s) (i.e., rack designs with corresponding matching "representative" calibration panels) is likely to generate the lowest uncertainty. In situ neutron transmission measurements are very sensitive to variation in measurement geometry. If "representative" calibration panels for reference panels are not available, then uncertainties might be addressed by developing a technical basis document which includes radiation transport-based calculations which can be used to supplement the detector response functions to get a better estimate of the bounds.