



February 16, 2001
NUH61B-TNW0102-03
RMG-01-009

Mr. Timothy Kobetz
Project Manager, Spent Fuel Project Office
U.S. Nuclear Regulatory Commission
11555 Rockville Pike
Rockville, MD 20852

Subject: Supplemental Response to Request for Additional Information and Submittal of Revision 2 of Amendment No. 3 Application for NUHOMS® Certificate of Compliance No. 1004 (TAC No. L23137)

- References:
1. Request for Additional Information (RAI) Regarding Approval of Amendment No. 3 to the NUHOMS® Certificate of Compliance No. 1004 (TAC No. L23137), December 6, 2000.
 2. Response to Request for Additional Information and Submittal of Revision 1 of Amendment No. 3 Application for NUHOMS® Certificate of Compliance No. 1004 (TAC No. L23137), January 22, 2001 (NUH61B-TNW0101-01).

Dear Mr. Kobetz:

Transnuclear West Inc., (TN West) herewith submits supplemental response to specific questions of the RAI (Reference 1) to provide the requested clarification sought by your staff in a telecon on 02/12/01. The information provided in the supplemental response supercedes the corresponding information related to these specific RAI issues submitted previously (Reference 2). In addition, the affected pages of Attachment B and Attachment C of the previous submittal (Reference 2) have been updated and are included on a replacement page basis in this submittal.

Please contact Mr. U. B. Chopra (510-744-6053) or me (510-744-6020) if you require any additional information in support of this submittal.

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NMSSOIPublic

Mr. Timothy Kobetz
U.S. Nuclear Regulatory Commission

NUH61B-TNW0102-03
February 16, 2001

Sincerely,

A handwritten signature in cursive script that reads "Robert M. Grenier".

Robert M. Grenier
President and Chief Operating Officer

Docket 72-1004

- Attachments:
1. Supplemental RAI Response.
 2. Instructions for Updating Revision 1 Submittal (Reference 1).
 3. Ten (10) copies of Attachment B, Suggested Changes to the NUHOMS[®] Certificate of Compliance; Revision 2 (Replacement Pages only).
 4. Ten (10) copies of Attachment C, Revised Subsections of Appendix K to the FSAR; Revision 2 (Replacement Pages only).

cc: File NUH61B.0003.01

**SUPPLEMENTAL RESPONSE TO REQUEST FOR ADDITIONAL INFORMATION
TRANSNUCLEAR WEST INC., TAC NO. L23137**

Chapter 2 Design Criteria

Question 2-2

Revise Section K.2.1 to include a description/definition of damaged fuel assemblies.

The SAR does not define damaged fuel assemblies. This information is necessary for the staff to assess compliance with 10 CFR 72.24(g), 72.26, 72.44(c), and 72.122(l).

Response to Question 2-2

SAR Section K.2.1 is revised to include a definition of damaged fuel assemblies as follows:

“Damaged BWR Fuel Assemblies are assemblies containing fuel rods with known or suspected cladding defects greater than hairline cracks or pinhole leaks or with cracked, bulging, or discolored cladding. Missing cladding and/or crack size in the fuel pins is to be limited such that a fuel pellet is not able to pass through the gap created by the cladding opening during handling and retrievability is assured following Normal/Off-Normal conditions.”

Justification for Assurance of Fuel Assembly Retrievability Under Normal/Off-Normal Conditions:

Damaged BWR fuel retrievability is assured in the NUHOMS[®] -61BT System following Normal/Off-Normal conditions. Retrievability is assured if the fuel assembly structure needed for retrievability remains in the original condition at the time of fuel load following normal or off-normal conditions.

The fuel assembly structure needed for retrievability is assumed to be undamaged and actually demonstrates this condition when the fuel assembly is loaded into the DSC. Following initial fuel assembly loading into the DSC, Normal and Off-normal loading conditions do not significantly challenge the integrity of the fuel assembly structure needed for retrievability.

Normal loading conditions, as described and evaluated in Sections K.3 and K.4 of the SAR, include dead weight, thermal, internal pressure, and handling loads. Of these loads, only the handling loads have any potential for challenging the integrity of the fuel assembly structure needed for retrievability. Handling loads include the following:

- Moving the Cask with a loaded canister from the spent fuel pool to the washdown area
- Moving the loaded cask to the transfer trailer
- Down-ending the loaded cask onto the transfer trailer

- Transfer to the ISFSI
- Insertion of the canister into the HSM

All of these operations are performed and controlled using approved plant procedures. Moving the cask with a loaded canister from the spent fuel pool to the washdown area and then to the transfer trailer is performed in the vertical orientation. Down-ending the DSC from the vertical position to the horizontal position on the transfer trailer (in turn down-ending the fuel assembly to the horizontal position) is performed very slowly with the cask-handling crane.

The remaining transfer operations are performed with the fuel assembly in the horizontal position. The maximum speed during transfer to the ISFSI is limited to less than 5 MPH and any sudden loads which may occur during an emergency stop are transferred from the road bed through 32 rubber tires, the trailer, the support skid, and the DSC prior to reaching the fuel assembly. During insertion of the canister into the HSM, the fuel assembly is supported by the basket structure (fuel compartment) at the spacer grid locations. This insertion of the canister into the HSM is performed at a very slow rate. The typical insertion is completed during a period of 15 to 20 minutes with a maximum load of 80000 lbs on the RAM grapple. The typical load on the canister is less than 40000 lbs since the canister slides on dry-lubricated rails. The weight of the fully loaded canister is approximately 88000 lbs. The grapple load is transferred to the fuel assemblies through the cover plate to the shell and subsequently through the basket rails to the fuel compartments, and finally to the fuel assemblies through friction. A minimal amount bearing of the inner bottom cover plate on the fuel assembly bottom nozzle could be realized. The DSC and internals accelerate slowly to a constant velocity of approximately 0.2 in/sec. The DSC comes to a full stop at the end stops on the HSM rails. At these low velocities, friction will keep the fuel assembly from contacting the top shield plug when the DSC comes to a stop. However, ignoring friction between the fuel assembly and the fuel compartment, the contact force on the fuel assembly for this small velocity is negligible. The maximum force that the fuel assembly would be subjected to is estimated to be less than its dead weight. Therefore, no impact on the fuel assembly structure required for retrievability is expected.

Off-Normal loading conditions include thermal and a jammed canister-handling load. The off-normal thermal load and its impact on fuel cladding is addressed in SAR Sections K.11.1.2 and K.4. The jammed canister load is the only off-normal condition that can challenge the fuel assembly structure needed for retrievability. The constant velocity (approximately .2 in/sec) of the fuel assembly will be the same as for the normal handling load case when the canister becomes jammed. Because the angle imparted due to the jammed condition is less than or equal to 1 degree, the stopping force on the fuel assembly essentially remains the same as for the normal condition loading which is negligible.

Therefore, both normal and off normal handling loads on the fuel assembly are negligible and do not challenge the structural integrity of the fuel assembly structure needed for retrievability.

Chapter 7 Confinement

Question 7-4

Provide additional information regarding the leakage testing described in Section K.7.1.1, for the inner and outer bottom cover plates and the DSC.

Subsection K.7.1.1 states that the inner plate and outer bottom cover plates are tested at the fabricator to meet leak tight criteria. However, it is not clear if the leak tight check includes the 125 percent pressure test of the structural/confinement boundaries.

As required by 10 CFR 72.236(j), the spent fuel storage cask must be inspected to ascertain that there are no cracks, pinholes, uncontrolled voids, or other defects that could significantly reduce its confinement effectiveness.

Response to Question 7-4

Section K.7.1.1 of the SAR is revised to provide additional clarification regarding the leakage testing for the inner bottom cover plates and the DSC. The test program for the DSC top closure welds is developed in accordance with the requirements of the ASME code with exceptions as discussed in SAR Section K.3.1.2.1. The pneumatic pressure test and leak test are performed on the finished shell and inner bottom cover plate during canister fabrication. The outer bottom cover plate provides a redundant confinement boundary. The root and final layer closure welds for this redundant boundary are inspected using dye penetrant inspection methods in accordance with the requirements of the ASME code.

Following closure of the inner top cover plate and installation of the root pass for the shell to outer top cover plate, a vacuum is drawn in the cavity and a helium leak test performed. These tests, coupled with the multi layer welds used in all confinement boundary welds, assure that the confinement effectiveness of the Cask as required by 10CFR72.236(j) is not compromised.

Chapter 9 Acceptance Tests and Maintenance Program

Question 9-1

Provide qualification test data on durability for the Boron Carbide/Aluminum Metal Matrix Composite (MMC). Data should be included for both the isostatic pressing and sintering fabrication process and the vacuum hot pressing fabrication process.

The materials are not produced to a recognized industry standard. Therefore, details on the methods of production, acceptable variations in chemistry, tolerance levels for properties, etc., are unknown. Qualification test data for the proposed materials are required by the staff to: (1) assess whether the proposed conductivity values are bounding; and (2) assess whether the durability of both the borated aluminum and boron carbide metal matrix composite plates is adequate for the thermal and environmental conditions (including radiation) over a 20-year service life of the cask.

This information is required for the staff to assess compliance with 10 CFR 72.122 which requires structures, systems and components (SSCs) important to safety to be designed, fabricated, erected and tested to quality standards commensurate with the importance to safety of the function to be performed, and 10 CFR 72.124(a) and (b) which requires materials used for criticality control functions to be adequate for performance of intended functions.

Response to Question 9-1

Long Term Durability

For long term durability, the materials must demonstrate that they do not sustain measurable physical damage under the thermal and environmental conditions in the NUHOMS[®] -61BT canister. In order to demonstrate the effects of exposure to this environment over an extended period of time, the testing is accelerated by using higher temperatures and higher rates of neutron exposure than actually occur in the canister. The environmental requirements, and the corresponding testing for the various materials are listed in Table 9-1.

Qualification test data for Boralyn were submitted to the Spent Fuel Project Office as part of the TN-68 submittal [1]. Procurement of this material shall require conforming to the essentials of the processing used for the test material, as described in the response to RAI Question 9-5 [5]. Boralyn was produced by hot vacuum pressing, and testing was supervised by Transnuclear.

Test results for Metamic testing [2] were included as Attachment 2 with a previous submittal [5]. Metamic is produced by cold isostatic pressing followed by vacuum sintering. Vacuum sintering results in a billet similar to that produced by vacuum hot pressing. Testing was supervised by Northeast Technology Corp., (NETCO) with input from EPRI.

Eagle Picher and AAR Industries have conducted their own testing for the borated aluminum and Boral[®], respectively. In both cases, the testing focused on irradiation damage and corrosion, without testing for long term exposure at high temperatures. These testing reports for borated aluminum [3] and Boral[®] [4], enclosed with this submittal, show that there no dimensional, weight, or visual changes due to neutron irradiation, and that the corrosion behavior of the materials is comparable to that of the base aluminum.

All of the materials under consideration consist of an inert phase (aluminum or titanium diboride in borated aluminum, or boron carbide in Boral[®] and in both metal matrix composites) in an aluminum matrix. Therefore, the thermal testing performed by Transnuclear and NETCO for the metal matrix composites may be extended to demonstrate the durability of all these materials under the thermal environment in the NUHOMS[®] -61BT.

Thermal conductivity

As stated in SAR Section K.9.1.7, qualification testing will be performed on any of the four candidate materials before that material is used in the NUHOMS[®] 61-BT. This testing will verify that the material can meet or exceed the minimum thermal conductivity requirements established in Section K.4.3.

Furthermore, the same section requires that thermal conductivity acceptance testing must be performed during production.

Transnuclear performed this testing in 1998 on 15% Boralyn over part of the temperature range, with the following results:

Temperature, °C (°F)	20 (68)	100 (212)	200 (482)	300 (571)
requirement W/mK (BTU/hr in °F)	120 (5.78)	145 (6.98)	150 (7.22)	150 (7.22)
test result, W/mK (BTU/hr in °F)	193 (9.30)	203 (9.78)	208 (10.0)	211 (10.2)

Metamic sales literature reports a thermal conductivity of about 150 W/mK (7.22 BTU/hr in °F) for the 15% MMC at 100 °C (212 °F). This is lower than the Boralyn results reported above, and is expected because the matrix of the Metamic product was a 6000 series alloy, while the Boralyn was 1000 series commercially pure aluminum.

Eagle Picher has performed thermal conductivity tests for borated aluminum as documented in the enclosed Report [6]. The results are:

Temperature, °C	20 (68)	100 (212)	200 (482)
requirement W/mK (BTU/hr in °F)	120 (5.78)	145 (6.98)	150 (7.22)
test result, W/mK (BTU/hr in °F)	182 (8.77)	199 (9.59)	202 (9.73)

The Boral[®] core has a thermal conductivity of 85.9 W/mK according to AAR brochures. For the 48 mg B10/cm² areal density, the core would be about 0.125 inch thick, and the cladding total about 0.18 thick. Using a thermal conductivity of 230 W/mK (11.1 BTU/hr in °F) for aluminum, the effective conductivity along the length of the sheet is estimated as:
 $0.305 / (0.18 / 230 + 0.125 / 85.9) = 136 \text{ W/mK at } 20 \text{ °C (68 °F)}$.

These results indicate that all materials are capable of meeting the thermal conductivity requirements for the NUHOMS[®] -61BT, subject to qualification and acceptance testing as described above and in the SAR.

Corrosion/Hydrogen Generation

Transnuclear performed hydrogen generation testing on paired couples of 15% Boralyn and 304 stainless steel in 1998 [1]. The results are reported in SAR Section K.3.4.1. The other candidate materials have been tested for corrosion, but not specifically for hydrogen generation. These tests are reported in the references following Table 9-1, and confirm that the corrosion characteristics are similar to those of the aluminum matrix. The surface characteristics of the materials are compared in the following table:

Material	Surface characteristics
Boralyn-type MMC	Inert boron carbide particles embedded in aluminum 1000 series matrix
Metamic-type MMC	Inert boron carbide particles embedded in aluminum 6000 series matrix
Borated aluminum	Inert aluminum diboride or titanium diboride particles embedded in either 1000 series or 6000 series matrix
Boral [®]	Faces: aluminum 1100 cladding Edges: exposed boron carbide / aluminum matrix

Because the corrosion characteristics of all these materials are governed by the properties of the base aluminum alloy, the differences in hydrogen generation rates between the materials will be insignificant.

Table 9-1
Neutron Absorber Requirements and Testing

Material [Reference]	Thermal damage tests		Fast neutron fluence		Boron content	
	Required	Tested	Required	Tested	Required	Tested
Boralyn-type MMC [1]	Table K.4-1 545 °F normal long term 566 °F off normal and 787 °F accident, short term	20 hr @ 700 °F, tensile test 30 days @ 700 °F, TEM, dimensional and weight inspection	$<10^{15}$ n/cm ² after 40 years	10^{16} n/cm ²	8- 15 vol% B ₄ C (Per SAR Table K.9-2).	15 vol% B ₄ C
Metamic-type MMC [2]	same	48 hr @ 900 °F, tensile test	same	10^{18} n/cm ² <u>see</u> <u>note A</u>	8 - 15 vol% B ₄ C (Per SAR Table K.9-2).	15 and 31 vol% B ₄ C
Borated aluminum [3]	same	none, <u>see note B</u>	same	10^{17} n/cm ²	1 - 5 wt% boron.	4.5 wt% boron
Boral [®] [4]	same	none, <u>see note B</u>	same	10^{20} n/cm ²	not specified; <u>see note C</u>	

Notes:

- A) The Metamic Test Report Table 6-3 lists gamma dose; there is a linear relation to neutron dose indicated in Section 6.2 of the report.
- B) All of the materials under consideration consist of an inert phase (aluminum or titanium diboride in borated aluminum, or boron carbide in Boral[®] and in both metal matrix composites) in an aluminum matrix. Therefore, the thermal testing performed by Transnuclear and NETCO for the metal matrix composites is adequate to demonstrate the durability of all these materials under the thermal environment in the NUHOMS[®] -61BT.
- C) The composition of the Boral[®] core is constant; the areal density is varied by changing the core thickness, not the composition. Therefore, the material tested and the material supplied are the same.

Question 9-2

Provide additional justification for the use of 90 percent credit for the neutron absorbing materials is warranted. The discussion should include both the Boron-Aluminum Alloy Using Enriched Boron material and the Boron Carbide/Aluminum MMC material.

The transmissivity of these materials is a function of their homogeneity. Because accepted consensus standards are not available for this material, qualification test data and statistical analyses are required to demonstrate that, for all heats produced and for all plates within a heat, the methods of production will result in acceptable absorptivity.

The analysis should: (1) determine the uniformity over an entire plate for the composite material; and (2) show with a confidence level of 95 percent that the attenuation results, for thermal neutrons in the range of energy values pertinent to the application, as taken from coupons will equal or exceed the minimum requirements. For the Boron-Aluminum Alloy material the coupon test data and the analyses should be sufficient to support the argument that this product has nearly uniform attenuation characteristics. For the MMC material, the discussion should include the specific level of attenuation required on each coupon taken from production lots to ensure with 95 percent confidence that the product will meet the specified minimum everywhere within the plate materials.

This information is required for the staff to assess compliance with 10 CFR 72.122 which requires structures, systems and components (SSCs) important to safety to be designed, fabricated, erected and tested to quality standards commensurate with the importance to safety of the function to be performed, and 10 CFR 72.124(a) and (b) which requires materials used for criticality control functions to be adequate for performance of intended functions.

Response to Question 9-2

The phenomenon of reduced effectiveness of boron distribution is one that is seen in measurements of thin Boral[®] sheets using collimated neutron beams. The phenomenon is due to the thin boron carbide-containing layer, the large boron carbide particles in Boral[™], and the collimated neutron beam. Because the MMC's are produced with much smaller boron carbide particles, and because we are proposing to use a very thick (0.31 inch) sheet with boron carbide through its full thickness, the physical basis behind the 75% credit restriction does not exist for the MMC or for the boron-aluminum alloy. In practice in a cask, with neutrons traveling in all directions, the effectiveness of even Boral[®] is not reduced by as much as is indicted by the collimated neutron beam experiments. These theoretical arguments are supported by a comparison of the areal density measured by neutron transmission with the nominal areal density. Table 9-2 shows a good correspondence between the nominal boron 10 areal density and that measured by a collimated neutron beam. Furthermore, the results confirm that this conclusion holds even for thin sheets of these materials.

Table 9-2
Nominal B10 Compared to Neutron Transmission Measurements

Material tested	Thickness, inch	B10 areal density, mg/cm ²	
		nominal	avg measured
15% Boralyn	0.305	42.4	43.7
4.5% Borated Aluminum	0.040	12.0	13.4
15% Metamic	0.075	10.4	10.3
31% Metamic	0.075	21.5	20.9

Neutron transmission measurements from production runs of Boralyn (TN-68) and Eagle-Picher borated aluminum (TN-32), and from test coupons of Metamic are statistically analyzed to provide an evaluation of the uniformity of boron distribution over the entire plates of the neutron absorbing material. The data and a summary of the statistical analysis were provided in a previous submittal [5]. The analysis determines the minimum areal density expected for each of the three materials as $x_L = x_{avg} - K\sigma$, where:

x_L is the one-sided lower limit

x_{avg} is the average of the test data

K is the one sided tolerance factors for 95% probability / 95% confidence level, and

σ is the standard deviation of the test data.

The data and analysis are summarized in the following table:

Material	Number of data points	x_{avg}	Std dev σ	95/95 min x_L	Min/Avg, %
Boralyn 15% x 0.305 thick	964	43.720	1.265	41.142	94.1
Borated Aluminum 4.5% x 0.040 thick	846	13.386	0.483	12.399	93.6
Metamic 15% x 0.075 thick	28	10.287	0.202	9.835	95.6
Metamic 31% x 0.075 thick	24	20.943	0.615	19.523	93.2

In all cases, the lower limit (95/95 minimum) is greater than 90% of the average, justifying the use of 90% credit for the boron 10 in these three materials.

Note that the analysis of the Eagle Picher data discards two data points as outliers. The rejection of these data is justified because they are associated with sheets that were rejected in acceptance testing, and therefore would not be used in basket fabrication.

Question 9-3

With regard to the acceptance testing for the Boron Carbide/Aluminum MMC, clarify the statement "In the event...additional measurements may be made to accept the coupon." The intent of this statement is not clear. For example, it could mean count until you like the count you get or do a recount but at a different location, or recheck the counting procedure. The measured values everywhere within a plate of a uniform material are expected to be the true absorptivity, plus or minus the measurement error; additional measurements should not be needed.

This information is required for the staff to assess compliance with 10 CFR 72.124(a) and (b) which requires materials used for criticality control functions to be adequate for performance of intended functions.

Response to Question 9-3

This statement is removed from the SAR.

Chapter 12 Conditions for Cask Use

Question 12-3

Define damaged fuel assemblies in the SAR and in the TS.

Since damaged assemblies are not placed in a canister that can be easily removed from the cask basket, then the assembly should be structurally intact such that it may be grappled. Also, damaged fuel assemblies are usually limited to cladding damage greater than pinhole leaks and hairline cracks, but where pellets won't fall out of the rod. This is needed to show compliance with 10 CFR 72.24(g), 72.26, 72.44(c), and 72.122(l).

Response to Question 12-3

SAR Section K.2.1 and TS 1.2.1 is revised to include a definition of damaged fuel assemblies as follows:

"Damaged BWR Fuel Assemblies are assemblies containing fuel rods with known or suspected cladding defects greater than hairline cracks or pinhole leaks or with cracked, bulging, or discolored cladding. Missing cladding and/or crack size in the fuel pins is to be limited such that a fuel pellet is not able to pass through the gap created by the cladding opening during handling and retrievability is assured following Normal/Off-Normal conditions."

For justification of the revised definition, see RAI 2-2 response provided above.

References:

1. University of Massachusetts Lowell test reports for Boralyn submitted by Transnuclear during TN-68 licensing application submittal.
2. Northeast Technology Corp report NET 152-02, Metamic Qualification Program for Nuclear Fuel Storage Applications, Interim Test Results, 2000.
3. Baratta and Pickering, Evaluation of Dimensional Stability and Corrosion Resistance of Borated Aluminum, Pennsylvania State University, 1991.
4. AAR Brooks and Perkins, Boral® Product Performance Report 624, 1987
5. Response to Request for Additional Information and Submittal of Revision 1 of Amendment No. 3 Application for NUHOMS® Certificate of Compliance No. 1004 (TAC No. L23137), January 22, 2001 (NUH61B-TNW0101-01).
6. R. E. Taylor, H. Groot, and J. Livermore, Thermal Conductivity of Aluminum-Boron Alloy, May 1989.
7. American Society for Mechanical Engineers (ASME) Boiler and Pressure Vessel Code, Section II, Part D, 1998 Edition Including 1999 Addenda.



AAR BROOKS & PERKINS
Advanced Structures Division



BORAL[®]

The Neutron Absorber

Product Performance
Report 624

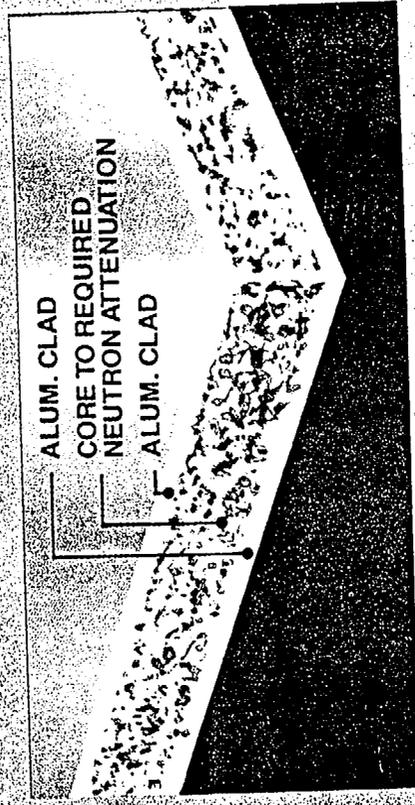


TABLE OF CONTENTS

Item	Page
General	3
Boral Material Characteristics	3
Aluminum	
Boron Carbide	
Materials Compatibility	
Boral Physical Characteristics	4
Dispersion Uniformity	
Corrosion Resistance	4
General Corrosion	
Galvanic Corrosion	
Pitting Corrosion	
Crevice Corrosion	
Intergranular Corrosion	
Stress Corrosion	
Corrosion Monitoring System	
Radiation Resistance	6
Neutron Shielding Performance	7
Boron and Halogen Leachability	
Residual Activity	
Installations Using Boral	7
References	8

BORAL®

NEUTRON ABSORBING/SHIELDING MATERIAL

GENERAL

Boral is a thermal neutron poison material composed of boron carbide and the 1100 alloy aluminum. Boron carbide is a compound having a high boron content in a physically stable and chemically inert form. The 1100 alloy aluminum is a light-weight metal with high tensile strength which is protected from corrosion by a highly resistant oxide film. The two materials, boron carbide and aluminum, are chemically compatible and ideally suited for long-term use in the radiation, thermal and chemical environment of a nuclear reactor or the spent fuel containment.

Boral is an ideal neutron absorbing/shielding material because of the following reasons:

1. The content and placement of boron carbide provides a very high removal cross section for thermal neutrons.
2. Boron carbide, in the form of fine particles, is homogeneously dispersed throughout the central layer of the Boral panels.
3. The boron carbide and aluminum materials in Boral are totally unaffected by long-term exposure to gamma radiation.
4. The neutron absorbing central layer of Boral is clad with permanently attached surfaces of aluminum.
5. Boral is stable, strong, durable, and corrosion resistant.

Boral is manufactured under the control and surveillance of a computer-aided Quality Assurance/Quality Control Program that conforms to the requirements of 10CFR50 Appendix B entitled, "Quality Assurance Criteria for Nuclear Power Plants".

Boral has been licensed by the USNRC for use in BWR and PWR spent fuel storage racks. Boral is also used around the world for spent fuel shipping and storage containers and for many other shielding uses including reactor control blades. For specific applications see later in this report.

Boral panels can be furnished either in the flat panel form or fabricated into a variety of geometrical shapes by standard metalworking methods and techniques. The shielding capability of Boral is assured by wet chemical analysis or neutron attenuation testing and is specified as a minimum of grams of B¹⁰ per square centimeter of

surface area. Boral can be provided at any B¹⁰ loading up to 0.06 gm/sq cm as required.

BORAL MATERIAL CHARACTERISTICS

Aluminum: Aluminum is a silvery-white, ductile metallic element that is the most abundant in the earth's crust. The 1100 alloy aluminum is used extensively in cooking utensils, heat exchangers, pressure and storage tanks, chemical equipment, reflectors and sheet metal work.

It has high resistance to corrosion in industrial and marine atmospheres. Aluminum has atomic number of 13, atomic weight of 26.98, specific gravity of 2.69 and valence of 3. The physical and mechanical properties of the 1100 alloy aluminum are listed in Table 1 and 2.

TABLE 1

1100 Alloy Aluminum Physical Properties⁽¹⁾

Density	0.098 lb/cu. in. 2.713 gm/cc
Melting Range	1190-1215 deg. F 643-657 deg. C
Thermal Conductivity (77 deg. F)	128 BTU/hr/sq ft/ deg. F/ft 0.53 cal/sec/sq cm/ deg. C/cm
Coef. of Thermal Expansion (68-212 deg. F)	13.1 × 10 ⁻⁶ /deg. F 23.6 × 10 ⁻⁶ /deg. C
Specific Heat (221 deg. F)	0.22 BTU/lb/deg. F 0.23 cal/gm/deg. C
Modulus of Elasticity	10 × 10 ⁶ psi
Tensile Strength (75 deg. F)	13,000 psi annealed 18,000 psi as rolled
Yield Strength (75 deg. F)	5,000 psi annealed 17,000 psi as rolled
Elongation (75 deg. F)	35-45% annealed 9-20% as rolled
Hardness (Brinell)	23 annealed 32 as rolled
Annealing Temperature	650 deg. F 343 deg. C

TABLE 2

Chemical Composition — Aluminum (1100 Alloy)⁽³⁾

99.00% min.	Aluminum
1.00% max.	Silicone and Iron
.05-20% max.	Copper
.05% max.	Manganese
.10% max.	Zinc
.15% max.	others each

The excellent corrosion resistance of the 1100 alloy aluminum is provided by the protective oxide film that develops on its surface from exposure to the atmosphere or water. This film prevents the loss of metal from general corrosion or pitting corrosion and the film remains stable between a pH range of 4.5 to 8.5. More detailed corrosion data is provided later in the report.

Boron Carbide: The boron carbide contained in Boral is a fine granulated powder that conforms to ASTM C-750-80 nuclear grade Type III. The particles range in size between 60 and 200 mesh and the material conforms to the chemical composition and properties listed in Table 3.

TABLE 3

Boron Carbide Chemical Composition, Weight %

Total boron	70.0 min.
B ¹⁰ isotopic content in natural boron	18.0
Boric oxide	3.0 max.
Iron	2.0 max.
Total boron plus total carbon	94.0 min

Boron Carbide Physical Properties

Chemical formula	B ₄ C
Boron content (weight)	78.28%
Carbon content (weight)	21.72%
Crystal structure	rhombohedral
Density	2.51 gm./cc-0.0907 lb/cu. in.
Melting point	2450°C-4442°F
Boiling point	3500°C-6332°F
Microscopic capture cross section	600 barn

Materials Compatibility: The materials contained in Boral are compatible with all parts of a spent fuel storage system in either a boiling-water (BWR) or pressurized-water reactor (PWR) including the fuel assemblies, the cooling system, the cleanup system, the pool liner and the structures of the storage racks. This compatibility is evidenced by more than seventeen years of continuous service in both types of pool water ⁽¹⁾⁽³⁾. None of the

following materials are contained in Boral nor do they come in contact with Boral during its manufacture. Therefore Boral can not cause these materials to come in contact with the fuel assemblies:

- a. Any material that contains halogens in amounts exceeding 50 ppm, including chlorinated cleaning compounds.
- b. Lead
- c. Mercury
- d. Sulfur
- e. Phosphorus
- f. Zinc
- g. Copper and Copper alloys
- h. Cadmium
- i. Tin
- j. Antimony
- k. Bismuth
- l. Mischmetal
- m. Carbon steel, e.g., wire brushes
- n. Magnesium oxide, e.g., insulation
- o. Neoprene or other similar gasket materials made of halogen-containing elastomers.
- p. Viton
- q. Saran
- r. Silastic Ls-53
- s. Rubber-bonded asbestos
- t. TFE (Teflon) containing more than 0.75% total chlorine (glass-filled) and TFE films containing more than 0.05% total chlorine.
- u. Nylon containing more than 0.07% total chlorine.
- v. Polyethylene film (colored) with pigments over 50 ppm fluorine, measurable amounts of mercury or halogens, or more than 0.05% lead.
- w. Grinding wheels that have been used on other than stainless steel or Inconel material.
- x. Water containing more than 25 ppm halogens during any cleaning operation.
- y. Any material that forms alloys or deposits on the fuel assembly.

ness may vary from this illustration due to the previously mentioned factors or other customer technical requirements.

Dispersion Uniformity: the aluminum and boron carbide ingredients in the central core of the Boral panel are combined in powder form. The methods used to control the weight and blend the powders as well as the design and construction of the ingots necessary to produce Boral panels are patented and proprietary process of AAR Brooks & Perkins. The manufacturing methods used include a sintering process and hot rolling. The final outcome of the entire manufacturing cycle is Boral panels having boron carbide uniformly dispersed throughout the central core. The amount of boron carbide per unit area is directly related to the panel thickness.

The minimum B¹⁰ content per unit area and the uniformity of dispersion within a panel is verified by wet chemical analysis and/or neutron attenuation testing. For details of the verification methods see AAR Brooks &

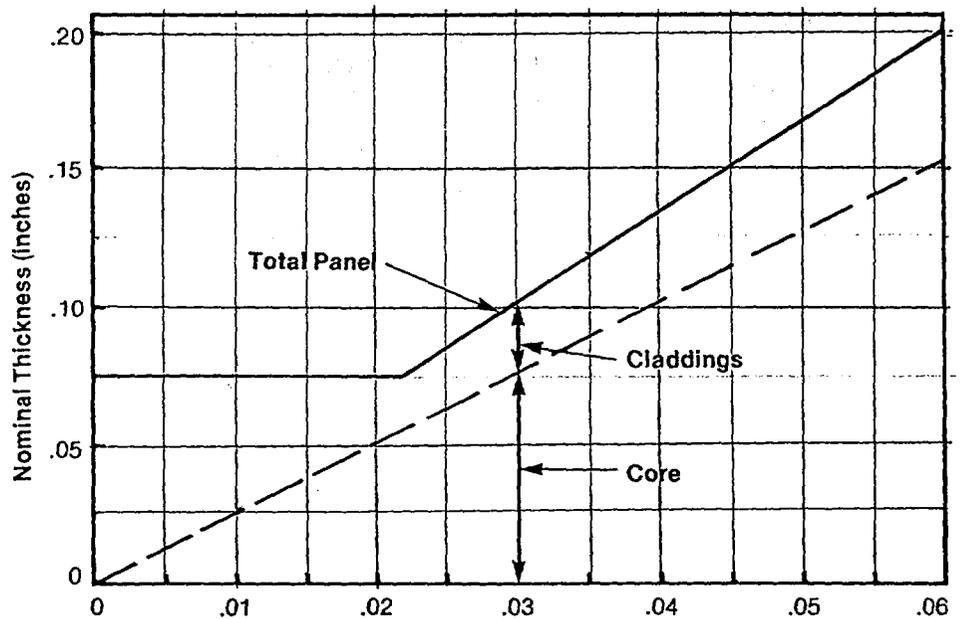
Perkins Quality Assurance Procedures BP-11002-QAP and BP-11004-QAP.

The acceptance standards in these procedures are controlled by statistical data to assure the minimum requirements are achieved with 95/95 confidence level. The maximum variation in the manufacturing processes (statistical tolerance interval) over a significantly large sample size has been determined and is utilized in the establishment of acceptance criteria.

CORROSION RESISTANCE

The useful service life of Boral will exceed 40 years when in contact with the storage pool water of either a boiling-water or pressurized-water reactor. This fact is evident through laboratory testing and is supported by in-service inspections. Boral has the longest continuous, in-pool service of any thermal neutron shielding material. This excellent corrosion resistance is provided

Figure 1: Example of Boral Thickness as Function of B¹⁰ Content



BORAL PHYSICAL CHARACTERISTICS

Boral is a clad composite of aluminum and boron carbide. The Boral panel consists of three distinct layers. The outer layers of cladding are solid 1100 alloy aluminum. The central layer consists of a uniform aggregate of fine boron carbide particles tightly held within an aluminum alloy matrix. The boron carbide particle in the central layer averages 85 microns in diameter. The average spacial separation is 1.25 to 1.50 particle diameters. The overall thickness of Boral will vary with: B¹⁰ content, cladding thickness and weight percent of boron carbide in the core. These factors will also influence the mechanical properties of the sheet. Figure 1 illustrates how thickness can vary with B¹⁰ content, all other parameters being held constant. The actual thick-

B10 Content	Equiv. Boron	Total Thickness Including Cladding			
		Inches	± Tol.	mm	± Tol.
.005	.028	.075	.004	1.91	.10
.010	.056	.075	.004	1.91	.10
.015	.083	.075	.004	1.91	.10
.020	.111	.075	.004	1.91	.10
.025	.139	.085	.004	2.16	.10
.030	.167	.101	.005	2.57	.13
.035	.194	.118	.006	3.00	.15
.040	.222	.134	.006	3.40	.15
.045	.250	.151	.006	3.84	.15
.050	.278	.167	.007	4.24	.18
.055	.306	.185	.007	4.70	.18
.060	.333	.201	.009	5.11	.23

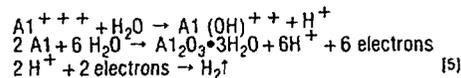
This tabulation is for Boral with thin cladding as used in high density spent fuel racks. Boral with thicker cladding, up to .040", is also available for other applications, and may be required for higher B¹⁰ contents.

ed by the protective film on the aluminum cladding that is an integral facing on the Boral panels. The corrosion of aluminum is negligible in fuel storage pools of either type reactor when the water quality and temperatures are maintained within normal operating limits. Typical spent fuel pool operating ranges are listed in Table 5. The boron content in the Boral will not be reduced below the specified limit during the forty or more years of exposure under those operating conditions.

In order to understand the total corrosion resistance of aluminum within the normal operating conditions of the storage pools. A discussion of that resistance must consider all forms of corrosion. A detailed discussion follows for general, galvanic, pitting, crevice, intergranular, and stress forms of corrosion.

General Corrosion: General corrosion is a uniform attack of the metal over the entire surfaces exposed to the corrosive media. General corrosion is measured by weight loss or decrease in thickness and is generally expressed in mils per year (mpy). The severity of general corrosion of aluminum depends upon the chemical nature and temperature of the electrolyte and can range from superficial etching and staining to dissolution of the metal.

Figure 2 shows a potential-pH diagram for aluminum in high purity water at 25°C (77°F). The potential for aluminum coupled with stainless steel and the limits of pH for BWR and PWR pools are shown on the diagram to be well within the passivation domain. The passivated surface of aluminum (hydrated oxide of aluminum) affords protection against corrosion in the domain shown because the coating is insoluble, non-porous and adherent to the surface of the aluminum. The protective surface formed on the aluminum (gibbsite and bayerite) is known to be stable up to 135°C (275°F)^[5] and in a pH range of 4.5 to 8.5^[6].



The water-aluminum reactions are self-limiting because the surface of the aluminum becomes passive by the formation of a protective and impervious coating making further reaction impossible until that coating is removed by mechanical or chemical means.

Figure 3 is also a potential-pH diagram for the aluminum-water system but at 60°C (140°F) which also shows the potential for the aluminum/stainless steel couple and the BWR and PWR limits for pH at this upper limit of

TABLE 5
Chemistry of Spent Fuel Pool Water

Reactor type	PWR	BWR
Cooling medium	*D-M water	D-M water
Boron content, ppm	0 to 2000	0
pH range	4.5 to 6.0	6.0 to 7.5
Temp range, °F	80 to 140	80 to 125
°C	26 to 60	26 to 52
Conductivity (micro mho/cm) @ 25°C	1 to 30	1
Chloride ions, ppm, max.	0.15	0.20
Fluoride ions, ppm, max.	0.10	—
Total solids, ppm, max.	1.00	0.50
Heavy metals, ppm, max.	—	0.10
Halogens, ppm, max.	0.15	—

*demineralized water

The ability of aluminum to resist corrosion from the boron ions is evident from the wide usage of aluminum in the handling of borax and in the manufacture of boric acid.^[7] Aluminum storage racks with Boral plates in contact with the 800 ppm borated water showed only small amount of pitting after seventeen years in the pool.^[1] These racks maintained their structural integrity and were returned to service.

Galvanic Corrosion: Galvanic corrosion is associated with the current of a galvanic cell consisting of two dissimilar conductors in an electrolyte. The two dissimilar conductors of interest in this discussion are aluminum and stainless steel in an electrolyte similar to the pool water from either a BWR or PWR. There is less galvanic current flow between the aluminum-stainless steel couple than the potential difference would indicate because of the greater than normal resistance at the metal-liquid interface on stainless steel which is known as polarization.^[6] It is because of this polarization characteristic that stainless steel is compatible with aluminum in all but severe marine, or high chloride, environmental conditions. Test data for aluminum coupled with 304 stainless steel in 5.0 pH water at 100°C (212°F) with flow rates ranging from 0.5 fpm to 81 fps show weight losses of 0.1 to 0.2 mpy and randomly spread pits that were not of major consequence.^[8] This performance indicates a projected service life much greater than forty years.

Pitting Corrosion: Pitting corrosion is the forming of small sharp cavities in a metal surface. The first step in the development of corrosion pits is a local destruction of the protective oxide film. Pitting will not occur on commercially pure aluminum when the water is kept sufficiently pure, even when the aluminum is in electrical contact with stainless steel.^[9]

Figure 2
Potential Versus pH Diagram For Aluminum-Water System At 25°C (77°F) ^[10]

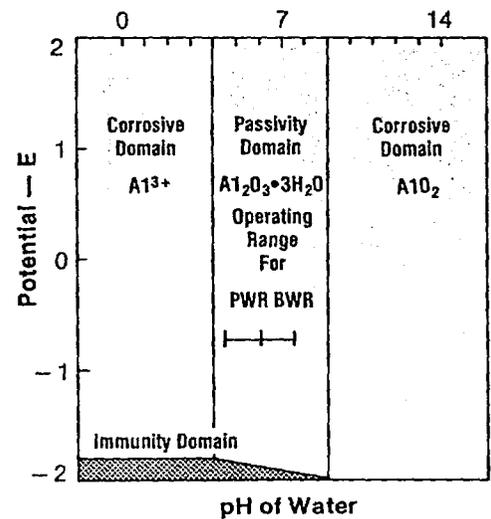
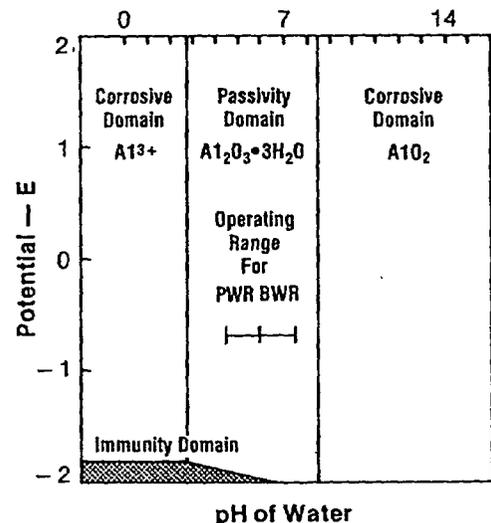


Figure 3
Potential Versus pH Diagram For Aluminum-Water System At 60°C (140°F) ^[5]



Pitting of aluminum has been observed when in contact with stainless steel where the electrolyte can stagnate and the conductivity of the electrolyte increases.

This pitting has not been significant in spent fuel environments and it is not likely that pitting of the aluminum would have any influence on the neutron shielding performance of the Boral.^[4]

Crevice Corrosion: Crevice corrosion is the corrosion of a metal that is caused by the concentration of dissolved salts, metal ions, oxygen or other gases in crevices or pockets remote from the principal fluid stream, with a resultant build-up of differential galvanic cells that ultimately cause pitting. Testing has confirmed that after 2000 hours, under a controlled environment, the Boral and 304 stainless steel combination exhibited little or no corrosion of the aluminum cladding of the Boral. In a separate 2000 hour test at 90° to 180°C the maximum pit depth of corrosion of the Boral surface was reported at less than five mils giving a projected life much greater than forty years.^[6]

Intergranular Corrosion: Intergranular corrosion is corrosion occurring preferentially at grain boundaries or closely adjacent regions without appreciable attack of the grains or crystals of the metal itself. Intergranular corrosion does not occur with the commercially pure aluminum (alloy 1100) and other common work hardening alloys.

Stress Corrosion: Stress corrosion is failure of the metal by cracking under the combined action of corrosion and high stresses approaching the yield stress of the metal. The 1100 alloy used in Boral is not susceptible to stress corrosion and Boral is seldom, if ever, subjected to high stresses when used as a neutron shield in a spent fuel rack.

Corrosion Monitoring System: A corrosion monitoring system is a program whereby a series of surveillance samples are placed in the spent fuel pool radiation and water environment and are periodically examined for physical and chemical changes. It is important the physical configuration of the samples be carefully selected so they are representative of the construction and design of the spent fuel racks and are positioned in the pool to be exposed to representative pool conditions and radiation environment. The physical and chemical characteristics of the samples must be precisely established before insertion into the pool so accurate quantitative com-

parisons can be made after each exposure period. The procedure for the manufacture and testing of surveillance samples recommended by AAR Brooks & Perkins is contained in Procedure No. BPS-454.

RADIATION RESISTANCE

Boral has the ability to absorb thermal neutrons from nuclear fuel assemblies without physical change or degradation of any sort from the accompanying exposure to heat and gamma radiation. This ability is attributable to the fact that Boral contains no organic nor polymeric binders which undergo extensive crosslinking and oxidative scission degradations from heat and radiation exposure. Boral utilizes an all metallic aluminum binder which is stable and unchanged under long-term gamma and neutron irradiation and heat up 540°C (1000°F).

Boral, in addition to having the longest history of use in spent fuel storage applications (since 1965), has been subjected to accelerated irradiation tests which fully support the stability of Boral under these environments. Boral test specimens have been exposed to cumulative doses of 3×10^{11} rads gamma and 16×10^{19} neutrons per sq cm in demineralized and borated water without detectable out-gassing attributable to Boral or any discernible physical changes.

Testing was performed at the Phoenix Memorial Laboratory of the University of Michigan using the Ford Nuclear Reactor.^[11] The purpose of the test was to determine changes to physical and chemical properties of Boral as a result of irradiation under conditions similar to those encountered in PWR and BWR spent fuel storage pools. The data recorded during this testing effort is available upon request and includes the following:

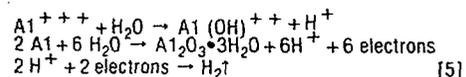
- Total radiation exposure and residual radioactivity
- Dimensions
- Weight
- Specific gravity
- Hardness
- Mechanical strength
- Neutron attenuation
- Solution boron content, pH, conductivity, and leachable halogens

During irradiation -gas evolution rate, total volume of gas evolved, and gas composition were determined. The Boral samples were irradiated in air, demineralized water, and 2000 ppm borated water to simulate both the vented and sealed enclosure of Boral in PWR and BWR spent fuel storage environments.

The test results show conclusively there is no out-gassing from Boral when irradiated in dry air. The same was also true for boron carbide powder in a dry aluminum sample container. This clearly shows that Boral is unaffected by radiation exposure making Boral a neutron absorber that can be safely exposed while being contained in a sealed enclosure.

This characteristic of Boral -no out-gassing from irradiation -shows that the source of the evolved gases when water is in contact with Boral has to be from the water itself. There are two mechanisms by which water will evolve gases under these circumstances and only one of which requires a radiation environment. The one mechanism requiring a radiation field is the hydrolysis of the water. The disassociation of water into its hydrogen and oxygen elements also requires the presence of free radical scavengers. These could well be the boron carbide powder, impurities within the powder, impurities in the water, or surface irregularities on the Boral sample. Gases evolved by hydrolysis would be a hydrogen-oxygen gas mixture in a 2:1 ratio.

The other mechanism by which water will evolve gases is from the chemical reactions between aluminum and water. The surface of the aluminum cladding on the Boral samples is unpassivated and will allow a short term reaction with water. The gas released from the water-aluminum reaction is hydrogen as shown in the following reaction:



The water-aluminum reactions are self-limiting because the surface of the aluminum becomes passive by the formation of a protective and impervious coating making further reaction impossible until that coating is removed by mechanical or chemical means.

The volumes and types of gases collected from the Boral in demineralized and borated water resulted from one or both of the two described mechanisms and did not result from cross linking or oxidative scission of any of the Boral materials.

In summary Boral does not out-gas or change physically or chemically as a result of exposure to gamma radiation. Water in contact with aluminum will release hydrogen chemically until the aluminum surface is passivated and water will disassociate through hydrolysis from gamma radiation. It is only necessary to provide a means for venting the hydrogen and oxygen gases if water

is allowed to come in contact with Boral in spent fuel storage applications.

NEUTRON SHIELDING PERFORMANCE

The thermal neutron shielding capability of Boral is obtained from the B^{10} isotope contained within the boron carbide particles in its core. The efficiency of performance is directly related to the amount of boron carbide provided and the spacial relationship between the particles of boron carbide. Figure 4 shows the actual performance of Boral as compared to a theoretical ideal layer of B^{10} atoms. The shielding performance is measured as a neutron attenuation factor and is plotted against the surface density of B^{10} isotope in grams per square centimeter. The neutron shielding performance of Boral was unaffected after exposure to 3×10^{11} rads gamma and 16×10^{19} thermal neutrons per sq cm.

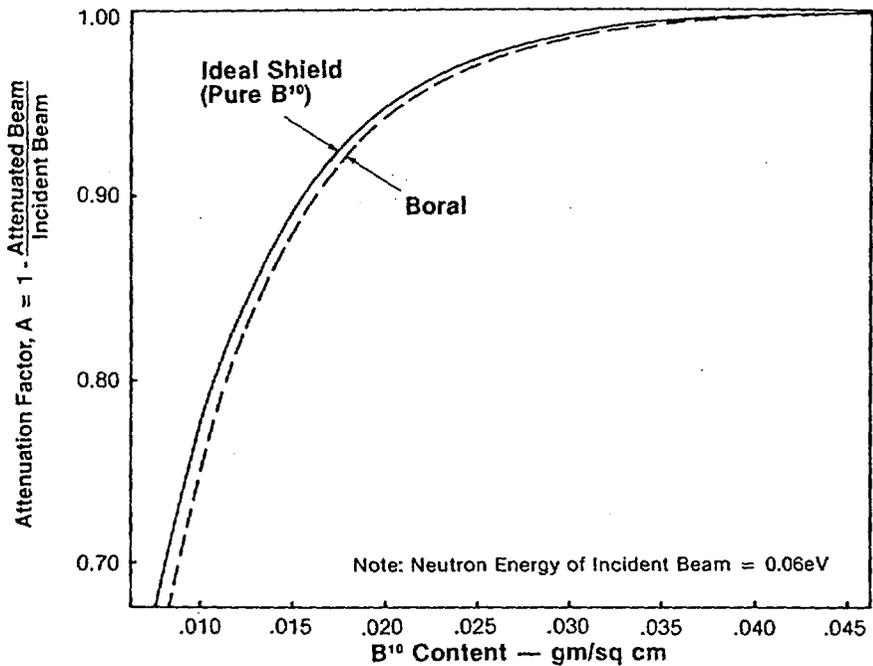
Boron and Halogen Leachability: The boron leachability and the halogen leachability was evaluated for Boral during irradiation testing conducted at the University of Michigan.⁽¹¹⁾ The test solutions were analyzed for boron and halogen contents before and after radiation exposure when sufficient solution was remaining after the test. The analysis of the test solutions showed no increase in boron or halogen that cannot be accounted for by the decrease in test solution volume or pickup of the soluble boron on the external edges of the Boral. The boron carbide is allowed to contain, by the ASTM Specification C750-80, up to a maximum of three percent (3.0%) soluble boron in the form of boric oxide (B_2O_3).

The amount of boron carbide that can come in contact with water is limited to that which is confined to the outer edges of the Boral panel. This wettable amount of boron carbide is of course influenced by the geometrical size and shape of the panel but is less than one percent (1.0%) of the total boron carbide contained therein. In any regard, the total boron content of the panel will remain above the specified minimum content in the event the total soluble boron content were somehow lost through dissolution.

Residual Activity: The residual radioactivity of the Boral was measured following the irradiation testing conducted at the University of Michigan. The activation was limited to trace amounts of impurities contained in the boron carbide and aluminum materials from which Boral is produced. The specific results are available upon request.

Figure 4

Neutron Attenuation Versus B^{10} Content



DOMESTIC INSTALLATIONS USING BORAL [12]

Pressurized Water Reactors

Plant	Utility	Water Contact	Rack Mfg.	Mfg. Year
Bellefonte 1, 2	Tennessee Valley Authority	no	Westinghouse	1981
D. C. Cook 1, 2	Indiana & Michigan Electric	no	Exxon	1979
Indian Point 3	NY Power Authority	yes	U.S. Tool & Die	1987
Maine Yankee	Maine Yankee Atomic Power	yes	PaR	1977
Salem 1, 2	Public Service Elec & Gas	no	Exxon	1980
Seabrook	New Hampshire Yankee	no	PaR	—
Sequoyah 1, 2	Tennessee Valley Authority	no	PaR	1979
Yankee Rowe	Yankee Atomic Electric	yes	B&P/PaR	1964/1983
Zion 1, 2	Commonwealth Edison Co	yes	CECo.	1980

Boiling Water Reactors

Browns Ferry 1, 2, 3	Tennessee Valley Authority	yes	GE	1980
Brunswick 1, 2	Carolina Power & Light	yes	GE	1981
Clinton	Illinois Power	yes	NES	1981
Cooper	Nebraska Public Power	yes	NES	1979
Dresden 2, 3	Commonwealth Edison	yes	CECo.	1981
Duane Arnold	Iowa Elec. Light & Power	no	PaR	1979
J. A. FitzPatrick	NY Power Authority	no	PaR	1978
E. I. Hatch 1, 2	Georgia Power	yes	GE	1981
Hope Creek	Public Service Elec. & Gas	yes	PaR	1985
Humboldt Bay	Pacific Gas & Electric	yes	B&P	1986
LaCrosse	Dairyland Power	yes	PaR	1976
Limerick 1, 2	Philadelphia Electric	no	PaR	1980
Monticello	Northern States Power	yes	GE	1978
Peachbottom 2, 3	Philadelphia Electric	no	PaR	1978
Perry 1, 2	Cleveland Elec. Illuminating	no	PaR	1979
Pilgrim	Boston Edison	no	PaR	1978
Shoreham	Long Island Lighting	yes	PaR	—
Susquehanna 1, 2	Pennsylvania Power & Light	no	PaR	1979
Vermont Yankee	Vermont Yankee Atomic Power	yes	PaR/NES	1978/1986

FOREIGN INSTALLATIONS USING BORAL

Country	Plant	Utility	Manufacturer
Switzerland	Beznau 1, 2		Nordostschweizerische Kraftwerke AG
	Gosgen		Kernkraftwerk Gosgen-Daniken AG
Taiwan	Chin-shan 1, 2		Taiwan Power Co
	Kuosheng 1, 2		Taiwan Power Co
France	12 PWR Plants	Electricite' de France	
South Africa	Koerber 1, 2	ESCOM	

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PROPERTIES RESEARCH LABORATORY

PRL 801

Thermal Conductivity of Aluminum-Boron Alloy

by

R.E. Taylor, H. Groot and J. Larimore

May 1989

West Lafayette, Indiana

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A Report to Eagle-Picher Industries, Inc.

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TABLE OF CONTENTS

	Page
INTRODUCTION	1
RESULTS AND DISCUSSION	2

LIST OF TABLES

1. Specific Heat Results.	3
2. Thermal Diffusivity Results.	4
3. Thermal Conductivity Calculations.	4

LIST OF FIGURES

1. Differential Scanning Calorimeter.	5
2. Digital Data Acquisition System.	6
3. Flash Diffusivity Apparatus.	7
4. Specific Heat.	8
5. Thermal Diffusivity.	9
6. Thermal Conductivity	10

Thermal Conductivity of Aluminum-Boron Alloy

INTRODUCTION

A sample of aluminum-boron alloy was submitted for thermal conductivity determinations. Bulk density (d) values were calculated from the samples geometries and mass. Specific heat (C_p) was measured using differential scanning calorimetry. Thermal diffusivity (α) was determined using the laser flash technique and thermal conductivity (λ) was calculated as a product of these quantities, i.e. $\lambda = \alpha C_p d$.

Specific heat was measured using a standard Perkin-Elmer Model DSC-2 Differential Scanning Calorimeter (Figure 1) using sapphire as a reference material. The standard and sample, both encapsulated in pans, were subjected to the same heat flux and the differential power required to heat the sample at the same rate was recorded using the digital data acquisition system (Figure 2). From the mass of the sapphire standard, pans, the differential power, and the known specific heat of sapphire, the specific heat of the sample is computed. The experimental data is visually displayed as the experiment progresses. All measured quantities are directly traceable to NBS standards.

Thermal diffusivity was determined using the laser flash diffusivity method. The flash method, in which the front face of a small disc-shaped sample is subjected to a short laser burst and the resulting rear face temperature rise is recorded, is used in over 80% of the present thermal diffusivity measurements throughout the world. A highly developed apparatus

exists at PRL (Figure 3) and we have been involved in an extensive program to evaluate the technique and broaden its uses. The apparatus consists of a Korad K2 laser, a high vacuum system including a bell jar with windows for viewing the sample, a tantalum tube heater surrounding a sample holding assembly, a spring-loaded thermocouple or an i.r. detector, appropriate biasing circuits, amplifiers, A-D converters, crystal clocks and a minicomputer based digital data acquisition system (Figure 2) capable of accurately taking data in the 40 microsecond and longer time domain. The computer controls the experiment, collects the data, calculates the results and compares the raw data with the theoretical model.

RESULTS AND DISCUSSION

The same was 0.2304 by 0.4990 by 0.5007 inches and weighed 2.540 grams. Therefore the bulk density was 2.693 gm cm^{-3} .

Specific heat results are given in Table 1 and are plotted in Figure 4. Thermal diffusivity results are given in Table 2 and are shown in Figure 5. Using these data, thermal conductivity values are calculated in Table 3. These results are plotted in Figure 6. Thermal conductivity values increase from 1266 to 1412 BTU/in/hr⁻¹ft⁻²F⁻¹ between 73 and 392F.

TABLE 1

Specific Heat Results

TEMP. (C)	Sp. Heat (Wsgm ⁻¹ K ⁻¹)
23.0	0.868
35.0	0.885
42.0	0.894
52.0	0.905
62.0	0.916
72.0	0.927
82.0	0.935
92.0	0.941
102.0	0.947
112.0	0.954
122.0	0.961
132.0	0.967
142.0	0.971
151.0	0.977
162.0	0.983
172.0	0.988
182.0	0.992
192.0	0.996
202.0	0.999
207.0	1.002

TABLE 2

THERMAL DIFFUSIVITY RESULTS

SAMPLE NO.	TEMP. (C)	DIFFUSIVITY (cm ² sec ⁻¹)
HEAT	23.	0.781
	50.	0.779
	100.	0.790
	150.	0.762
	200.	0.758
COOL	100.	0.772

TABLE 3

Thermal Conductivity Calculations

Temp. (C)	Density (gm cm ⁻³)	Specific Heat (W s gm ⁻¹ K ⁻¹)	Diffusivity (cm ² sec ⁻¹)	Conductivity (W cm ⁻¹ K ⁻¹)	Conductivity (BTU units *)	Temp (F)
23.0	2.693	0.8680	0.78100	1.82561	1265.78	73.4
50.0	2.693	0.9030	0.78200	1.90165	1318.50	122.0
100.0	2.693	0.9460	0.78200	1.99221	1381.29	212.0
150.0	2.693	0.9760	0.77200	2.02910	1406.87	302.0
200.0	2.693	0.9980	0.75800	2.03721	1412.49	392.0

* (BTU in hr ft F⁻¹)

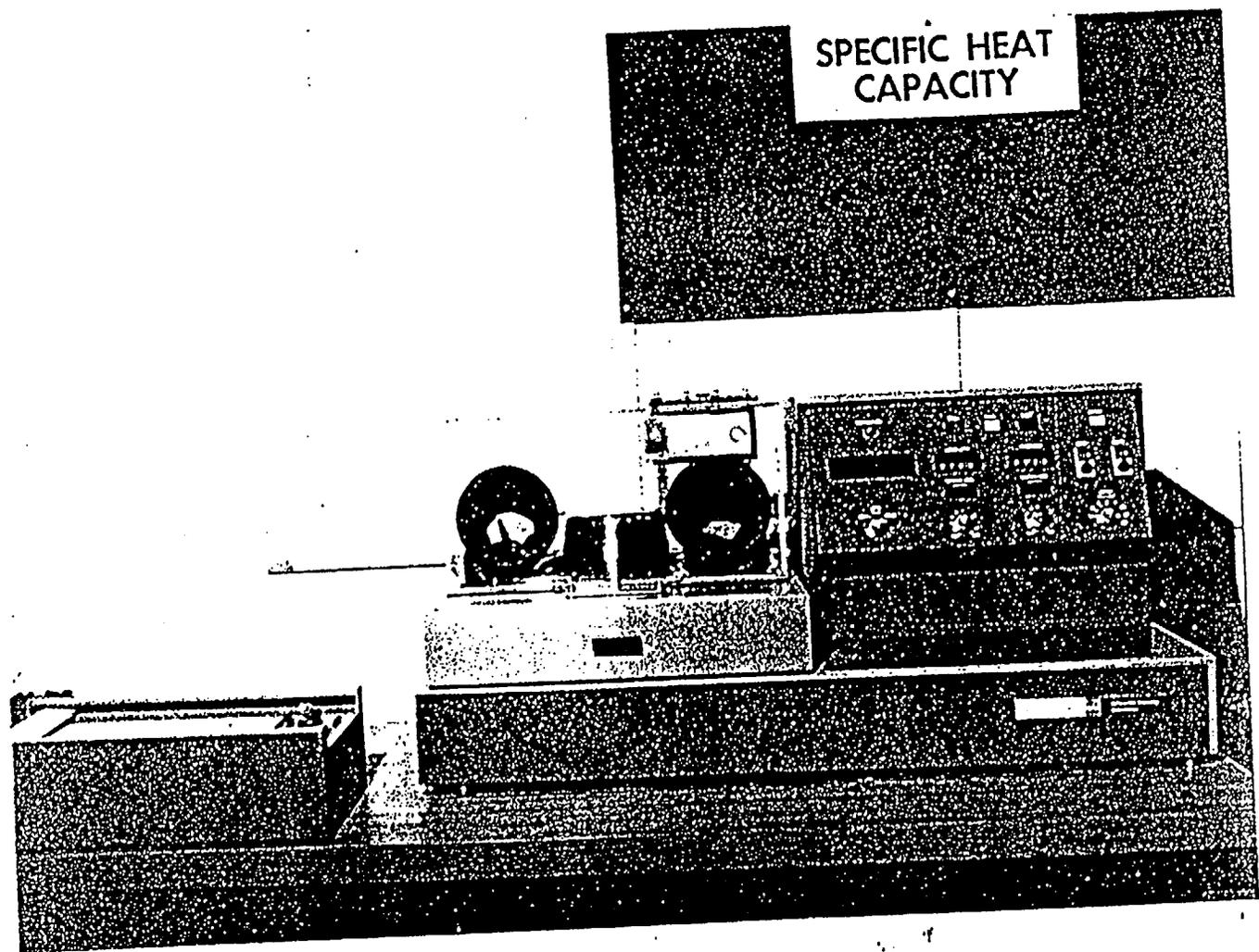


Figure 1. Differential Scanning Calorimeter

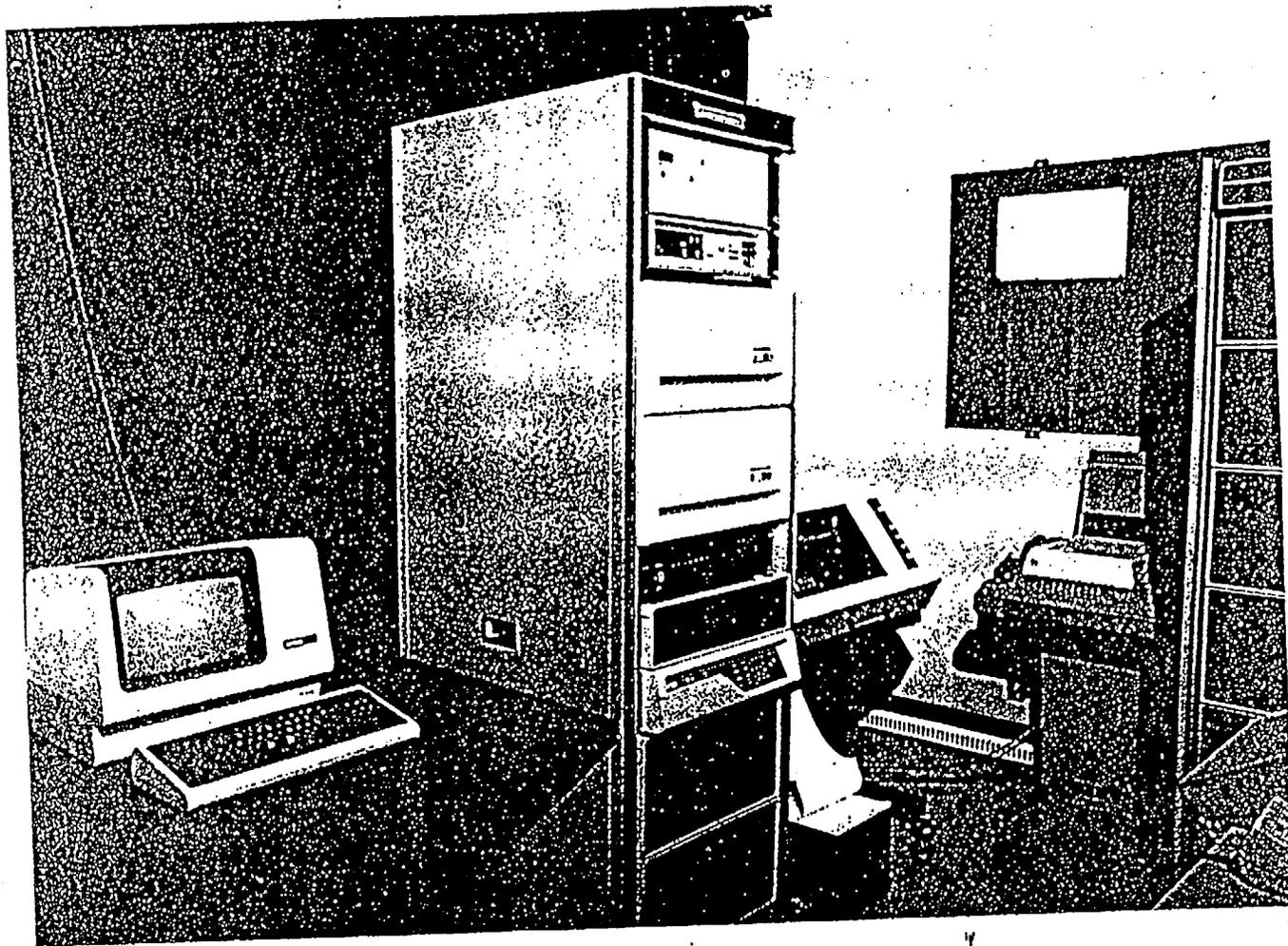


Figure 2. Digital Data Acquisition System

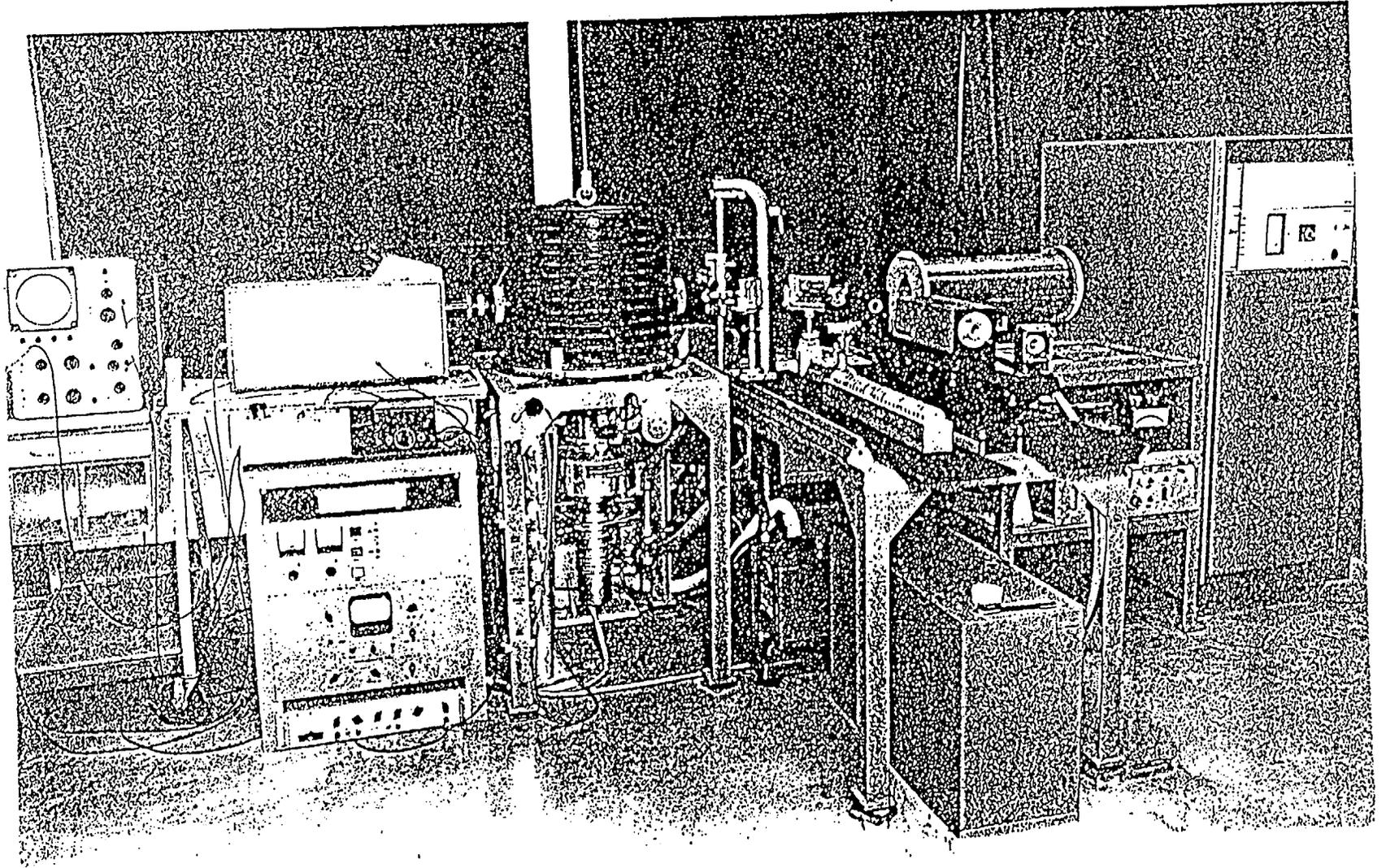


Figure 3. Flash Diffusivity Apparatus

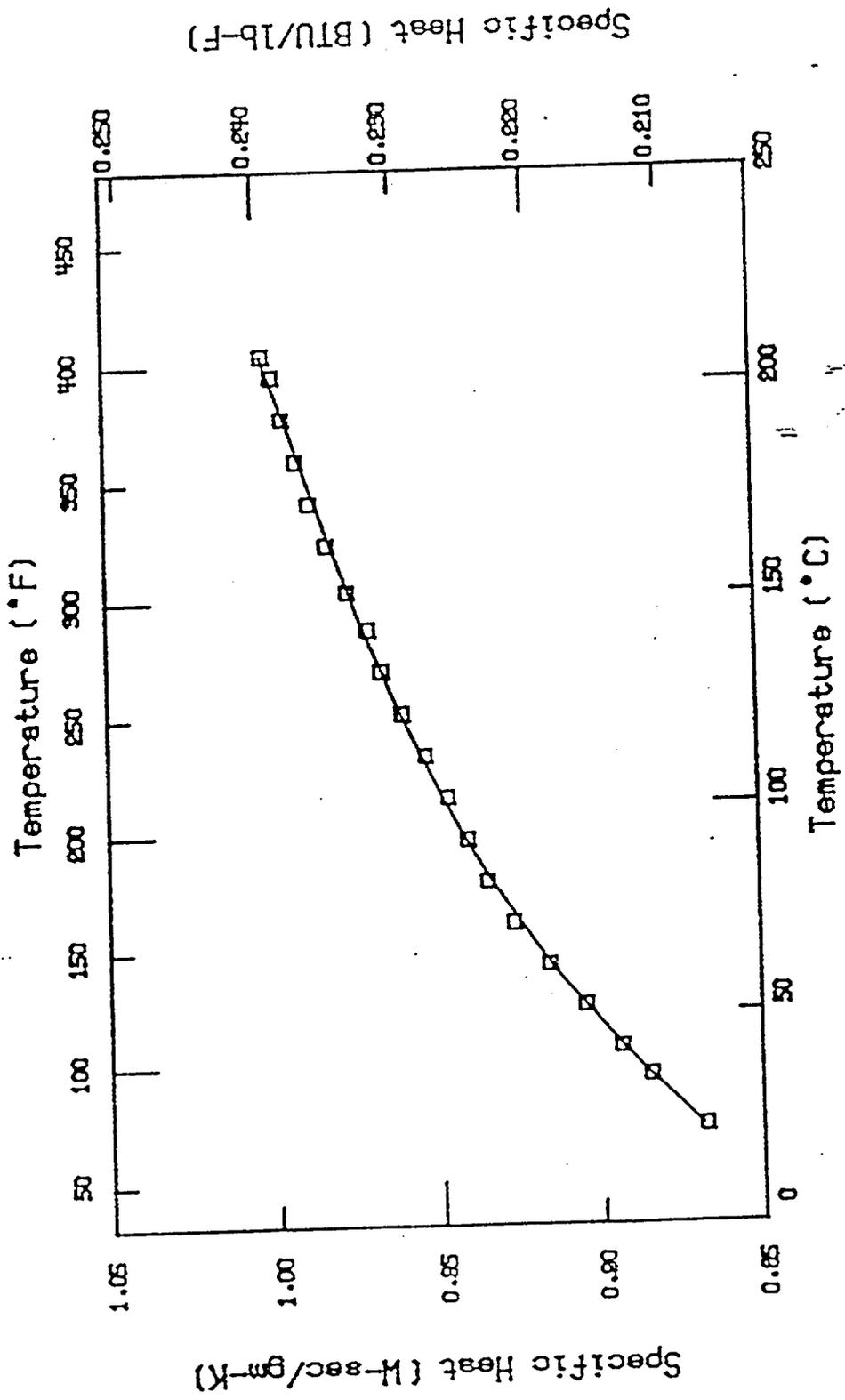
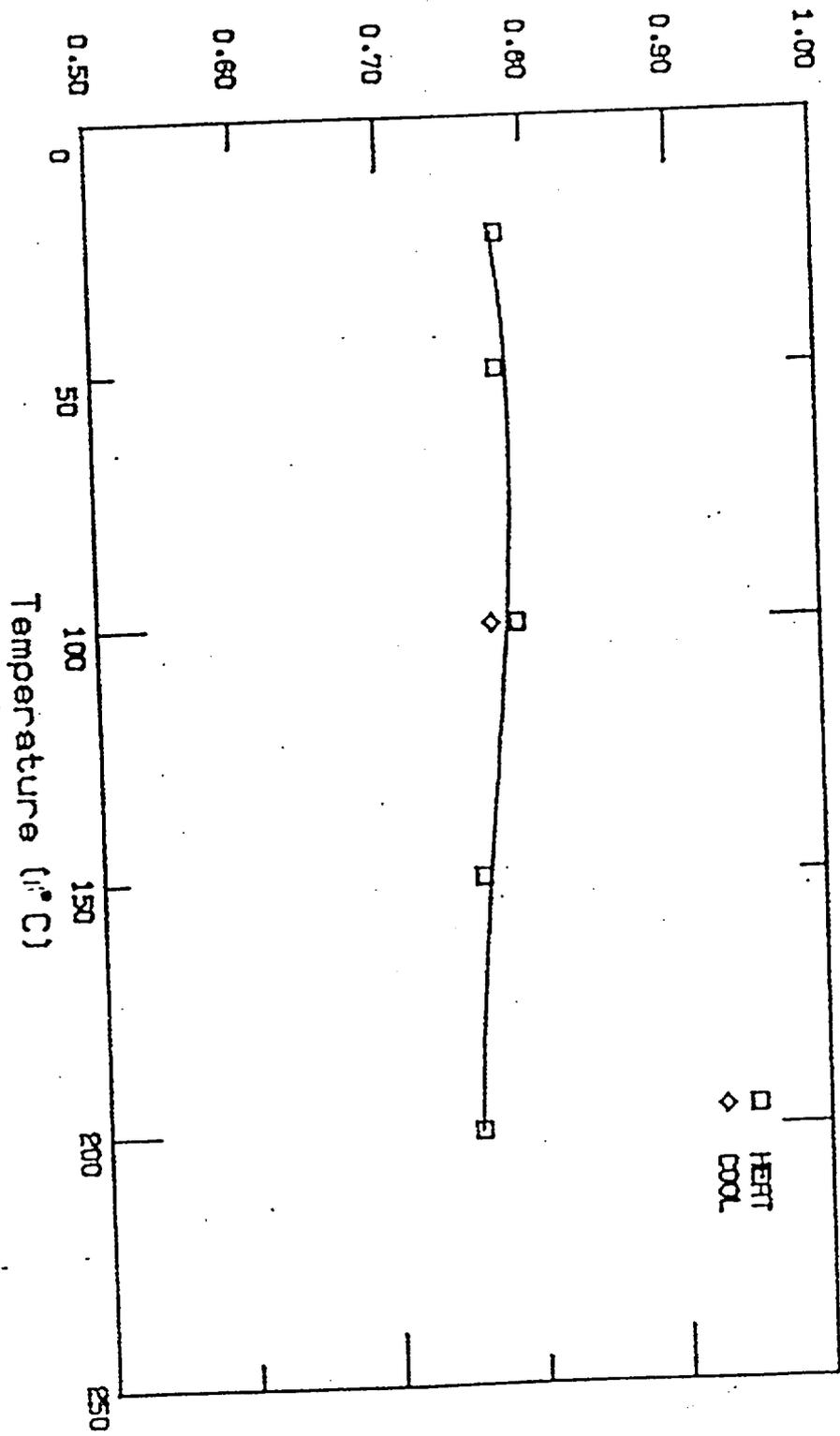


Figure 4. Specific Heat

Thermal Diffusivity (cm^2/sec)



Temperature ($^{\circ}\text{C}$)
Figure 5. Thermal Diffusivity

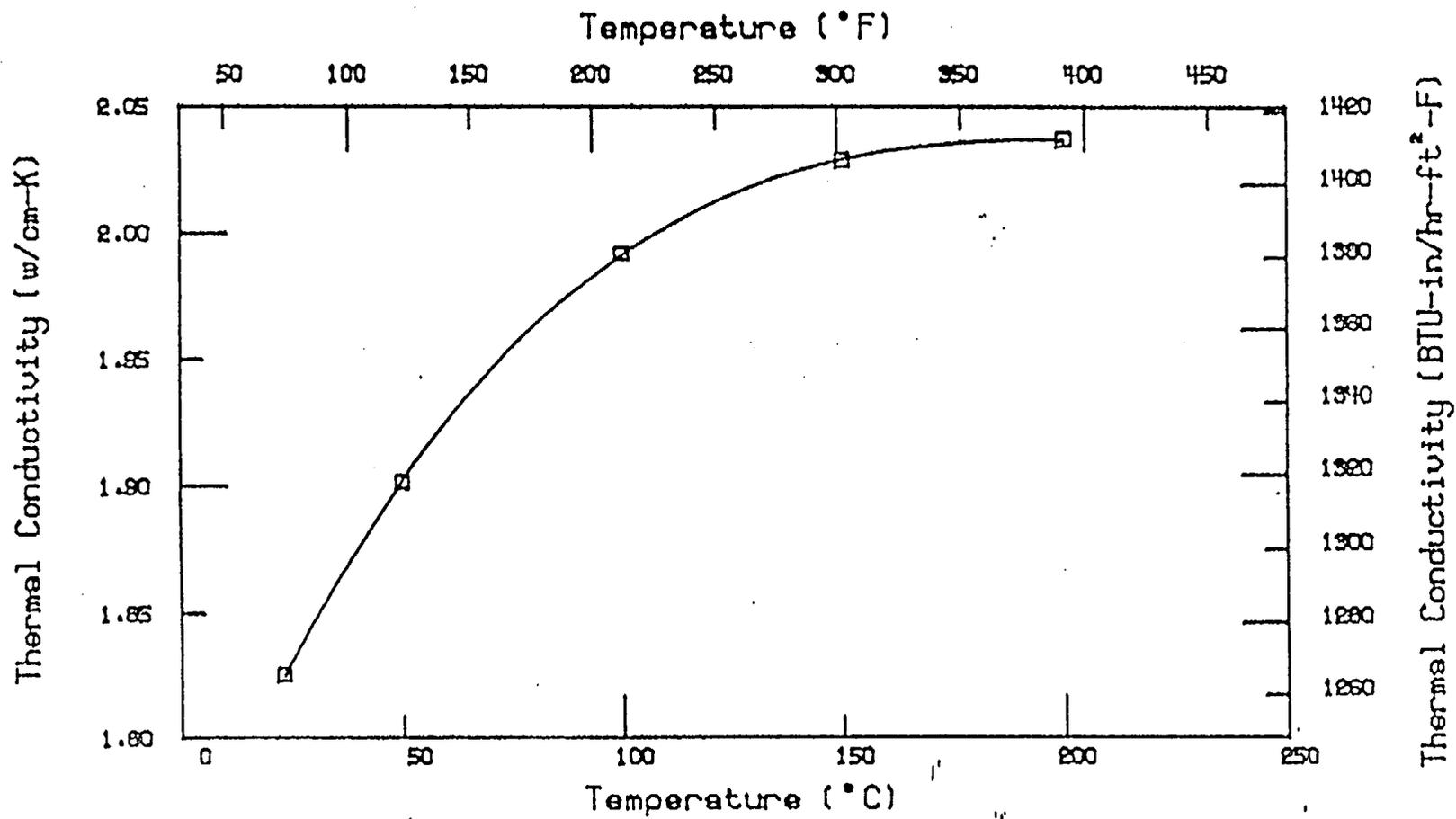


Figure 6. Thermal Conductivity

Evaluation of Dimensional Stability and
Corrosion Resistance of Borated Aluminum

Final Report

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Contents

Abstract.....	I
Introduction	1
Methodology.....	3
Test and Results.....	7
Preliminary Test	8
Irradiation Test	9
Dimensional Stability	9
Neutron Attenuation Measurements	10
Corrosion Test	10
Discussion.....	19
Conclusion.....	24
Reference.....	25
Appendix.I Sample Dimensional Measurement Data.	

ABSTRACT

In this report, research efforts exploring the dimensional stability of borated aluminum and its corrosion resistance are described. It was found that this material has very strong corrosion resistance at room temperature either in reactor grade deionized water or in 2000 ppm borated water. Neutron irradiation up to 10^{17} n/cm² did not cause any measurable macroscopic dimensional changes or any other damage to the material. Local pitting of the material was found when the material was immersed in 2000 ppm borated water and at 80°C.

Introduction:

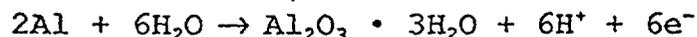
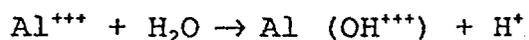
In the spent fuel pool of a nuclear power plant, structural materials are required to have high resistance to the corrosion. Long term exposure to a boric acid solution occurs in the spent fuel pool of a PWR. Since some burnt nuclear fuel may stay inside the pool for forty years, the structural materials should be able to maintain their integrity for forty years or longer. To satisfy these requirements, a new kind of Aluminum was developed, an Aluminum-boron alloy manufactured by Eagle-Picher Boron. The material is composed of #1100 grade Aluminum and enriched Boron. The B¹⁰ enrichment is about 95 wt/°. B¹⁰ atoms have a large thermal neutron absorbing cross section, which make this material a strong neutron absorber ideal for this application. During the neutron absorbing process, however, Alpha particles are released. These helium nuclei may migrate to grain boundaries and form helium bubbles. There is a concern that these helium bubble may alter the metallurgical properties of the material and induce swelling during its service life. To investigate the new material's behavior in a spent fuel pool, tests are needed to evaluate its dimensional stability, corrosion resistance and neutron stopping ability.

Material Characteristics:

The 1100 series aluminum component is a ductile metal having a high resistance to corrosion. Its corrosion resistance is provided by the buildup of a protective oxide film on the metals surface when exposed to a water environment. Once a stable film

develops, the corrosion process is arrested in the bulk metal. The film will remain stable over a pH range of 4.5 to 8.5.

The passivated surface of the aluminum provides an excellent barrier to corrosion of the bulk metal. Its formation is characterized by rapid severe corrosion at the metal surface. The hydrated oxide of aluminum is formed by the process:



Thus the buildup of the passivation film is accompanied by the rapid evolution of hydrogen gas. The evolution is very heavy at first and decreases with increasing coverage of the metal surface by the passivation film.

Boron is non-metallic and brown in color. It is used in very low concentration (<.02 w/o) as an alloying agent in aluminum. At higher concentrations, boron forms an intermetallic precipitate, Al-B₂.

Boron's interest to the nuclear industry originates from its high neutron absorption cross-section. The boron-10 isotope has an absorption cross-section of 3000 b at thermal energies. Because of the 1/v energy dependence of the boron-10 absorption cross-section, boron is effective as a neutron absorber up to about 10 Kev.

General Approach

A total of six different thicknesses of plate provided by Eagle-Picher Industries were tested. The thicknesses are listed in Table 1. These plates were exposed to varying neutron fluence

ranging from 0 to 10^{17} n/cm² and to varying thermal and chemical environments. For comparison, an 1100 series non-borated plate was also exposed to 2000 ppm boric acid solution at 80°C.

Table 1. Thickness of different Boral Plates

B ¹⁰ Areal Density g/cm ²	Thickness	
	(cm)	(in)
0.005	0.044	0.017
0.010	0.087	0.034
0.015	0.131	0.051
0.020	0.174	0.069
0.025	0.218	0.086
0.030	0.261	0.103

~4.5% BORON ALUMINUM, ALL CASES

Density=2.68 g/cm³

Similar tests have been done by AAR Brooks and Perkins Company [1] on another type of borated aluminum; a clad composite of Aluminum and Boron carbide. This type of material consists of three distinct layers. The outer layers of cladding are solid #1100 alloy Aluminum. The central layer consists of a uniform aggregate of fine boron carbide particles tightly held within an Aluminum alloy matrix. The Perkins tests shows that pitting corrosion was not significant when this material was immersed in spent fuel pool water. After their 2000 hour corrosion tests, at room temperature, the material exhibited little or no crevice corrosion and in the test at 90°C to 180°C, the maximum pit depth of corrosion was less than five mils, which gives the material a projected life much greater than forty years. During their tests, they also found that the material was not sensitive to stress

corrosion and there was no sign of intergranular corrosion. To verify the material's radiation resistance ability, they used an accelerated irradiation tests. The Boral test specimens were exposed to cumulative doses of 3×10^{11} rads gamma and 16×10^{19} neutrons/cm² in demineralized and borated water. Even in such a severe environment, there was no detectable out-gassing attributable to the Boral and no discernible physical changes.

For comparison, a series of tests were carried out to evaluate the neutron shielding ability and corrosion resistance of the Eagle Picher Boron Aluminum-boron alloy. The intent was to determine the new material's dimensional stability during irradiation and its corrosion resistance in a manner similar to the tests reported in reference [1].

Methodology:

1. Determination of The Test Matrix

The most significant features of a spent fuel pool environment are neutron/gamma radiation, corrosive boric acid solution and possible temperature changes. The temperature could vary from normal room temperature to boiling (100°C). Therefore, a series of test conditions consisting of different neutron fluences, boric acid concentrations and temperatures were chosen to evaluate the Eagle Picher borated aluminum containing 5 wt% boron. Four neutron irradiation fluences were chosen; 0 n/cm², 10^{13} n/cm², 5×10^{15} n/cm² and 10^{17} n/cm². Either pure water or a 2000 ppm boric acid solution were used. The solution temperatures were set to normal room

temperature, 80°C or 100°C. A detail test matrix is shown in Table 2.

There are, in total four groups of tests samples; group A, group B, group C and group D. Group A tests were carried out at room temperature and in pure water. In group A, there are four sub-groups; AO, AL, AI and AH representing the four neutron fluence levels; AO--0 n/cm², AL--10¹³ n/cm², AI--5x10¹⁵ n/cm² and AH--10¹⁷ n/cm². A boric acid solution at 2000 ppm by weight was used in the group B tests. The temperature was kept at room temperature during the group B tests. Also four sub-groups representing four different neutron fluences, BO--0 n/cm², BL--10¹³ n/cm², BI--5x10¹⁵ n/cm² and BH--10¹⁷ n/cm² were used. Group C consisted of two sub-groups, CL and CO. All of these were under boiling conditions (100°C) and use 2000 ppm boric acid solution. The CL sub-group samples were irradiated to 10¹³ n/cm². The CO sub-group's samples were not irradiated. The D group samples were not exposed to neutron irradiation, but were maintained at 80°C. The Sub-group DB specimens were put into 2000 ppm boric acid solution and sub-group DP were in pure water.

Besides the test samples mentioned above, a 2x2 inch, 0.103 inch thick borated aluminum sample was irradiated to test the materials' neutron stopping ability change. Also, a non-borated 1100 series aluminum plate was exposed to 2000 ppm boric acid solution at 80°C for comparison.

2. Sample Preparation

In each sub-group, there are six borated aluminum samples, each of different thickness. Each sample was marked with a unique sub-group identifier. The length and the width of each specimen was the same; 2 inches in length and 1 inch in width. In each sub-group, the thickest specimen was polished using emery cloth and Al_2O_3 powder, so that the surface can be examined microscopically before and after the irradiation and corrosion test. All specimens were cleaned using an Ultra-sonic cleaner in ethanol solution before any testing.

3. Irradiation Facilities

A TRIGA reactor located at the Radiation Science and Engineering Center was used to irradiate the specimens. Two holders or buckets were designed and used to hold the specimens. One is the boiling bucket. Another is the non-boiling bucket. Simplified drawings can be found in Fig. 1 and Fig. 2 after loading the specimens into the bucket, the bucket was placed into a sealed tube (either round or rectangular). The tube was then located next to the reactor as in Fig. 3.

4. Corrosion test devices

All the irradiated and unirradiated specimens were put into beakers, containing either 2000 ppm boric acid solution or reactor grade demineralized water. Four hot plates were used to heat the

Table 2. Test Matrix

Group Name	Irradiation Level (n/cm ²)	Boric Acid Concentration	Solution Temperature °C
AO	0.	0.	25.
AL	10 ¹³	0.	25.
AI	5x10 ¹⁵	0.	25.
AH	10 ¹⁷	0.	25.
BO	0.	2000 ppm	25.
BL	10 ¹³	2000 ppm	25.
BI	5x10 ¹⁵	2000 ppm	25.
BH	10 ¹⁷	2000 ppm	25.
CO	0.	2000 ppm	100.
CL	10 ¹³	2000 ppm	100.
DB	0.	2000 ppm	80.
DP	0.	0.	80.

beakers, in which 80°C or boiling conditions were maintained. An aluminum frame and plastic wires suspended the specimens in the solution. The corrosion sample' surfaces were examined using a metallograph before and after the corrosion tests.

5. Boron Content Measurement

For the corrosion tests, several liters of 2000 ppm boric acid solution were prepared by dissolving 20.583 g solid boric acid into 1800 ml reactor grade DI water.

To verify the boron content of the solution, a titration test facility was set up. In the test, the main problem was that Boric

acid was too weakly ionized to be titrated directly. In the titration, d-mannitol was added to form a stable complex:



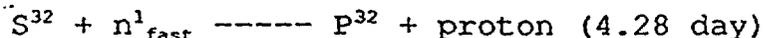
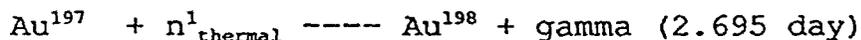
After this, the boric acid was titrated by 0.1N Sodium Hydroxide. The test procedure used was based on GPU's boron titration procedure [2].

6. PH Value and Corrosion Electric Potential Measurement

For the corrosion tests, the PH value and samples' corrosion potentials were measured by using a Calomel pre-filled reference electrode (Fisher. SN1116058), PH electrode (Fisher. SN1058171), PH meter (Leads & Northrup) and Voltmeter.

7. Neutron Fluence Measurement

To accurately measure the neutron fluence, gold foils and sulfur pellets were used for thermal neutron fluence and fast neutron fluence measurements respectively. The related nuclear reaction are:



By measuring the radioactivity of the gold foils and sulphur pellets, the total neutron fluence could be calculated.

This method was used to measure the 10^{13} n/cm² and 5×10^{15} n/cm² irradiation runs. For the 10^{17} n/cm² run, the fluence level was too high to use this method. The fluence was simply calculated based on the 5×10^{15} n/cm² run.

Test and Results:

The whole project was divided into several stages. The first was the preliminary test stage. The second was the irradiation test stage. The long term corrosion testing was the third stage. The fourth stage consisted of pH, electric potential, and Boron content measurements and metallograph analysis.

1. Preliminary Test:

The preliminary testing included the boiling bucket fluence calibration test, the sample material residual radioactivity measurement and the initial examination of the surface of the polished sample. To investigate the neutron flux distribution in the boiling bucket, a 10^{13} n/cm² calibration run was made on the bucket without samples. Three groups of gold foils and sulphur pellets were attached to the sample holder frame and bucket back surface. It turned out that the local neutron flux at the top and the bottom of the frame were the same, but the neutron flux at the back was lower because of the borated water attenuation. By normalizing the flux to one of the dosimeters, a single dosimeter can be used to measure the total fluence seen by all the samples in a bucket.

The initial surface examinations were made using a metallograph. The photomicrographs of the polished samples are shown in Fig. 5, 6. Since boron has a very low solubility in aluminum (0.02 w/o at 600°C), virtually all of the boron can be expected to be in the form of the intermetallic B-Al (β phase) containing approximately 67 at % B (~44 w/o B). The particles seen in the photomicrographics are the β precipitates (B_2Al) in the β

saturated aluminum matrix. Several pits and crevices were found on the polished samples' surface. Some of them are thought to be the defects in the material, but most of them appear to be voids occupied by boron particles, which, during polishing, have been popped out.

2. Irradiation Test

The irradiation testing consisted of the four runs listed below;

Run #	Sample group	Fluence (n/cm ²)	Reactor Power (KW)	Reactor Time (min)
#1	CL	1E+13	5	17
#2	AL & BL	1E+13	5	17
#3	AI & BI	5E+15	500	30
#4	* AH & BH	1E+17	1000	300

* Two split rings and an attenuation sample plate were also irradiated during the #4 Run.

A total of seven groups of corrosion samples were irradiated to the different neutron fluence levels. Only the CL Group samples were immersed in boiling boric acid solution during the irradiation.

3. Dimensional Stability

Before and after the irradiation tests, the thickness of all the samples were measured. Appendix 1 contains data for the before and after dimensional measurements. Dimensional checks of the 2 inch long by 1 inch wide specimens revealed no significant changes in the macroscopic dimension of the pieces. The dimensional checks

of the sample thickness showed typically less than $\pm 1\%$ change. This change is within the scatter of the data.

4. Neutron Attenuation Measurements

A borated aluminum plate (0.103 in thick, 2x2 in in size) was also irradiated with the AH group. The neutron attenuating ability of this sample was tested before and after the irradiation using a highly thermalized neutron beam. The results are shown below.

Table 5. Neutron Attenuation Ability Before And After Irradiation

	Before Irradiation	After Irradiation
Attenuation Factor	7.75	*

* Due to new console installment, the reactor can not be operated to full power now. This data will be given later.

5. Corrosion Tests

As mentioned above, the corrosion tests were carried out to find out whether the Eagle-Picher material would corrode under various environmental conditions, typical of a spent fuel pool. The observed corrosion behavior is discussed below for the twelve groups of corrosion samples.

AO Group

Six unirradiated samples were immersed in demineralized water at normal room temperature for 1008 hours. After 336 hours, gas bubbles were found on the sample surfaces and small blisters began to appear. The gas bubbles are thought to be hydrogen formed as a byproduct of the buildup of a passivation film at the sample surface. The hydrogen bubbles eventually disappeared. At the end

of the test, black corrosion lines and marks were found on parts of the sample surfaces. The final surface condition of these samples is shown in Fig. 7 and 8. In Fig. 7, a new untested sample and a pure 1100 series aluminum piece are included in the figure for comparison. From Fig. 8, we see that some pitting corrosion has occurred, but the depth of the pitting attack is very small. In both figures, a near uniform corrosion film is evident. The film is the result of the passivation process.

Some blistering was noted. The blisters are due to H absorption and formation of H_2 either at the interface of the Al and its passive film or at defects in the Al near the surface. The defects are likely due to the rolling process. The blisters are caused by a buildup of H_2 gas to pressures exceeding the strength of the passive film or the Al matrix.

BO Group

Six unirradiated samples were immersed in 2000 ppm boric acid solution at normal room temperature for 1008 hours. Right after the samples were put into the beaker, gas bubbles were found on the sample surfaces. The bubbles appeared sooner and were more numerous than the A0 group. Because the lower pH (higher H^+ concentration) more rapid corrosion occurred and more H_2 gas was generated. Blisters appeared on the sample surfaces several days after the start of the test. At the end of the test, no gas bubbles were found. The final surface condition of these samples is shown in Fig. 9-11. In Fig. 9, it can be seen that, compared with the new polished sample, the BO group samples do not have any

apparent color changes. In Fig. 10, a blister is shown and several pits are also evident. These pits are likely due to the AlB₂ phase "popping" out of the bare aluminum as corrosion occurred during the passivation process. A more typical surface is shown in Fig. 11. It is estimated that there are 300-400 pits/in².

AL Group

Six samples of different thickness were loaded into demineralized water 24 hours before they were irradiated. The measured fast neutron fluence was 4.0596×10^{12} n/cm². The thermal neutron fluence was 1.33×10^{13} n/cm². Three hours after the irradiation, these samples were taken out of the bucket and loaded into a beaker. Ten days after the irradiation, a total of five gas bubbles were found on the surface indicating that corrosion may have occurred. The total test time was 1152 hours. The final surface examination is shown in Fig. 12-14. In Fig. 12, it is evident that the color of the samples does not change greatly. Fig. 13 shows some pitting corrosion sites. Fig. 14 shows the general surface of the AL06 sample. There is no doubt that corrosion has occurred at certain sites, but not on the whole surface. Similar to the BO group, there are 500-600 pits/in².

BL Group

The BL group samples were loaded into 2000 ppm boric acid solution at the same time as the AL group. The neutron irradiation level was as high as that of AL group. During the irradiation, the samples were immersed in 2000 ppm boric acid solution. Three hours after the irradiation, they were taken out of the bucket and put

into a beaker containing 2000 ppm boric acid solution. The total corrosion test lasted 1152 hours. Fig. 15 shows the final surface examination for the whole group of the samples. Fig. 16 and 17 show the general surface conditions of the polished sample (sample number BL06). Corrosion attack was comparable to the other groups. However, some blisters were found on samples' surfaces.

AI Group

This group of samples experienced a neutron irradiation fluence of 10^{15} n/cm². The samples remained in the deionized water chamber of the non-boiling bucket for 5 days before they were taken out and loaded into a beaker at room temperature. The total corrosion test time was 1092 hours. During the first several days, several gas bubbles and blisters were found on the samples surfaces. The final sample surface condition is shown in Fig. 18 (a)&(b). From Fig. 18(a), one finds that corrosion did occur; but from (b), we can see that the amount is slight. The typical surface appearance of the polished sample (AI06) is shown in Fig. 19. A white corrosion product was found. $Al(OH)_3$ and other hydroxides and oxides of Al are white and have very low solubilities in pure water at room temperature. These bulky solid corrosion products residing on the surface are known to be a favored site for pitting of aluminum. This group had fewer pits than the AL group with approximately 300-400/in². Most of the surface, however, did not corrode severely. In Fig. 20, a blister from sample AI06 is shown.

BI Group

The BI group samples had a corrosion test time of about 1092 hours. They were irradiated with the AI group, but were immersed in the borated water chamber of the non-boiling bucket. After remaining inside the bucket for five days due to high radioactivity, the samples were taken out and loaded into a beaker containing 2000 ppm borated water. A check of the surface right after the irradiation found that there were blisters on the sample surfaces. During the first few days, gas bubbles were found, but after ten days none was evident.

The final surface examination is shown in Fig. 21 (a)&(b). There are some corrosion marks on the BI06 polished surface. Also, in Fig. 22, the general surface appearance is shown. No corrosion beyond the passivation layer was found. The size of the blisters were larger than the AI group, although both were irradiated to the same neutron fluence. Fig. 23 shows part of two blisters. A crevice is shown in Fig. 24. It was found that the edge of the crevice is so sharp that it seems that no corrosion has ever occurred in that area. By checking the inside surface of the crevice, we find that the metal is still shiny. Formation of the crevice could have occurred in two ways, one during rolling the other as the result of a small blister opening after corrosion testing.

CL Group

This group of samples was irradiated to 10^{13} n/cm². They remained inside boiling borated water (100° C, 2000 ppm) contained

in the boiling bucket (see Fig. 1). The sample were boiled for 760 hours. During the corrosion test, no gas bubbles were found. However, a significant amount of insoluble white particles were found at the end of the test (Fig. 25). Further investigations are to be done to analyze the chemical composition of these white particles.

Fig. 26 shows the final surface conditions of the whole group. Blisters were found on the sample surfaces. The color of the samples was found not to be different from the uncorroded samples. The photomicrographs (Fig. 27) show, however, that a large number of pits were formed during the corrosion test. Comparing Fig. 27 with Fig. 4-6, we find that these pits are distributed on the sample surface with the same dispersion as the aluminum diboride phase. Fig. 28 shows that the corrosion occurs near an impurity particle with the particle being unattacked. Fig. 29 shows the surface on top of a blister. Many cracks are evident. Since the passive film on Al is poorly conducting to electrons, the cathodic reaction of the corrosion process is effectively blocked except at discontinuities in the film such as the conducting B_2Al phases. Thus, Al corrodes much faster in the vicinity of the B_2Al phase. This corrosion can eventually cause the AlB_2 phase to "pop out" leaving a hole. The hole then passivates and the corrosion stops. This group had 3-4 times as many such pits as the A and B series, with 1900-2000/in².

CO Group

This group of unirradiated samples were kept in boiling 2000 ppm boric acid solution for 760 hours. A white precipitate was found at the end of the test (Fig. 30) similar to the CL group. No gas bubbles were found. Blisters can be seen, however, on samples surfaces, Fig. 31. The size of these blisters is smaller than that of CL group. Fig. 32 shows pitting. The pit dispersion was found to be the same as Boron Aluminum phases. The corrosion attack appears very similar to the CL group samples. The number of pits/in² numbered 1900-2000.

DB Group

The DB group samples were kept in the 80°C 2000 ppm boric acid solution for 960 hours. This group of samples exhibited the most corrosion of all our corrosion tests. Many gas bubbles formed after the solution was heated to 80°C. Blisters appeared 1.5 hours after the temperature reached 80°C. One day later, yellow black corrosion marks began to appear on the samples' surfaces. These marks expanded with time. Until they covered all of the sample surfaces forming a uniform corrosion layer. This layer looks firm and appeared to protect the samples from further corrosion attack. At a certain number of limited sites, however, significant pitting corrosion was found. As shown in Fig. 33, on sample DB06, white corrosion products circles surround the local pits. At these pitting sites, the corrosion seemed to continue with buildup of the passivation film taking longer than over the remainder of the

sample. This group had the largest number of pits with approximately 2500/in².

1100 Series Al

A comparison corrosion test was made to show the behavior of the pure aluminum pieces in the same solution. It was found that the pure aluminum pieces exhibited the most severe corrosion. Within a few minutes after the sample was put into the solution, gas bubbles nearly covered all of the sample surface. The yellow black corrosion layer was formed in only one day. On the next day, the bubbles disappeared, and a stable corrosion layer formed which appeared to be able to protect the underneath metal from further corrosion. No pitting was evident.

From this comparison, we found that borated aluminum is more resistant to uniform corrosion attack than pure Aluminum, but local pitting can occur, causing localized damage to the borated aluminum. Fig. 34 (a) & (b) shows the general appearance of the surface of the sample DB06. Corrosion products covered much of area of the sample, with pits distributed on the surface having the same area number density of the AlB₂ phase. It is believed that the pits are not corrosion induced pits but represent vacancies left by AlB₂ precipitation that have "popped" out as the base aluminum passivation. Fig. 35 shows part of a white corrosion circle surrounding a local corrosion pit. Both the white and the black material are thought to be the corrosion products. A detail view of the corrosion product at the center of the pit is shown in Fig. 36.

DP Group

The DP group of samples was put in the 80°C deionized water for 672 hours. Eight days later, small blisters were found on the samples surfaces. A check of the surface on the 10th day showed that the sample color had changed to white. The final surface examination further verified this observation (See Fig. 37). A 200X picture is taken of the DP06 polished surface, Fig. 38. It also shows a firm corrosion layer was formed on the sample's surface.

AH Group

This group of samples were irradiated to 10^{17} n/cm² neutron fluence. At the same time, they were immersed in reactor grade deionized water. After remaining inside the holder for three weeks, they were taken out of the holder. Unfortunately, the water inside the holder evaporated. The reason could be that the long irradiation time and environmental temperature had caused the evaporation. A surface check is shown in Fig. 38. A large blister was found on the AH06 polished surface. The length of the blister was about 1cm by 5mm in width. Since the contact dose rate of the samples was still 20 mr/hr, the samples were put into a beaker containing deionized water. Photomicrographs will be taken after the samples' dose rate decreases to an acceptable level and the samples have experienced the corrosion test for enough time.

BH Group

The BH group samples were irradiated to 10^{17} n/cm² at the same time with AH group samples. For the same reason, the 2000ppm boric

acid solution in which the samples were immersed dried out and left white boric acid powder on the samples surface. A surface check is shown in Fig. 40. Small blisters were found on the samples surfaces. After the samples were taken out of the holder, they were immersed into 2000ppm boric acid solution for the further corrosion testing. The metallograph pictures will be taken after the samples' radioactivity decreases.

Corrosion Sample Electrode Potential Measurement

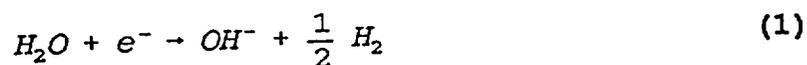
To further investigate the corrosion potential of borated aluminum under different environmental conditions, the corrosion potentials for all groups of samples were measured. During the measurement, a new polished borated aluminum sample and new pure aluminum were used for comparison purposes. The reference electrode used in the test was a Calomel Reference Electrode (Fisher 13-620-52). The measurement results are shown in Table.6. From the results, we found that for most cases, the corrosion potential of the corroded sample was less negative (more noble) than that of the new polished sample. The borated aluminum sample potential was more noble than that of the pure aluminum sample. At higher temperature and in boric acid solution, samples exhibited less noble (more reducing) electrode potentials. E_{corr} of Al is more negative (less noble) and is consistent with a greater polarization of the cathodic reaction during corrosion (because of the poor electronic conductance of the passive film).

Discussion:

In the tests mentioned above, it was found that the borated aluminum exhibited different kinds of behaviors under different environmental conditions. The mechanisms of different environmental effects are discussed below.

Corrosion Mechanisms

In our tests, corrosion was found in both deionized water and boric acid solution. Gas bubbles were found in most of the corrosion test groups. In the deionized water, the evolved gas is undoubtedly hydrogen produced by the cathodic reaction during the corrosion of the aluminum in water:



or in a boric acid solution:

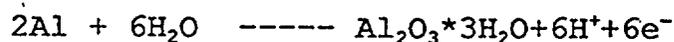


E_{corr} of Aluminum is more negative (less noble) and is consistent with the greater polarization of the cathodic reaction during corrosion (because of the poor electric conduction of the passive film).

The aluminum corrosion reaction forms a self limiting protective and impervious coating on its surface. The reaction, although not known, would be of the form,

Table 6. Electrode Potential Measurement

Group Name.	New Polished Sample EP V, SCE	Old Polished Sample EP V, SCE	Pure Aluminum Sample EP V, SEC
DB	-0.556	-0.562	-0.686
DP	-0.608	-0.517	-0.692
CO	-0.609	-0.527	-0.911
BO	-0.390	-0.336	-0.415
BI	-0.307	-0.272	-0.361
BL	-0.276	-0.186	-0.292
AL	-0.277	-0.323	-0.311
AI	-0.304	-0.324	-0.315
BH	-0.200	-0.155	-0.249
AH	-0.210	-0.183	-0.249
AO	-0.332	-0.437	-0.412
CL	-0.920	-0.567	-1.103



Thus, the corrosion rate decreases with increasing time eventually leveling off at an extremely low (negligible) rate. This could be the reason that in AO, AL, AI, AH group corrosion tests, gas bubble appeared for several days at the beginning of the test, but finally disappeared.

In the boric acid solution the same anodic and cathodic reactions occur although reaction 1a may also occur since the boric acid solution is slightly acidic. Because boric acid is a weak acid, the equilibrium potential of the hydrogen evolution reaction is more positive (more noble) than in the case of neutral water. Thus, the driving force (EMF of the cell formed by Al and the

solution) is increased over that of neutral water. This alone could explain the larger number of the off gas bubbles and rapid corrosion found in the BO, BL, BI and BH groups than in the AO, AL, AI, AH groups consistent with the more noble corrosion potential in the boric acid solution, e.g., $E_{\text{corr}} = -0.437$ vs. -0.336 V, SCE for BO and AO, respectively. However, these corrosion reactions, under room temperature, were found to cease due to the passivation film buildup.

When compared to pure aluminum in the boric acid solution, the corrosion rate was less in the borated alloy groups. In both cases, however, the protective passivation film developed halting the corrosion.

Temperature

Three test temperature were chosen in the corrosion tests, room temperature, 80°C and 100°C. Under different temperatures, the electrode potential measurements show that some materials exhibited quite different corrosion potentials. The higher the temperature, the less noble the corrosion potential.

At room temperature, we found the material exhibited strong corrosion resistance. For all samples in the "A" and "B" groups, only a corrosion passivation film was found. Pitting corrosion also stopped after enough corrosion products were formed. At 80°C, however, in boric acid (DB Group), a more rapid corrosion rate was found. Although the passivation film finally formed on the sample surface and protected the underlying aluminum matrix, this film was not able, initially, to prevent the corrosion from occurring in the

Al matrix next to the β aluminum-boron phase. Here, the inert β phase appears to be functioning as good surfaces for the cathodic hydrogen evolution reaction. This is surely the reason the aluminum matrix near the B_2Al corroded faster than the aluminum matrix elsewhere on the sample surface. Therefore, the pitting corrosion continued on the DB group samples surfaces longer than in the other environments. In the less aggressive pure water, the passivation film quickly protected not only the aluminum matrix, but the boron-aluminum phases as well.

At 100°C, although the corrosion potential was the least noble (most negative). Corrosion was found to be less severe than at 80°C. This is due, possibly, to the lower dissolved oxygen concentration at 100°C (since oxygen can depolarize the cathodic reaction). This effect can be seen from the test results of the CL and CO groups.

Blisters Phenomenon

In all the sample groups, blisters were found along with gas bubble formations. While no scientific study of blister size was made, Table 7 gives a representative size range of the largest blister seen in several of the groups. Since the latter is surely H_2 gas that is the cathodic reaction (Eq. 1) of the Al corrosion process, the blisters can be concluded to be due to some of the H atoms on the surface entering the Al matrix and recombining as H_2 molecules on interior void surfaces to form internal bubbles of H_2 gas at $\gg 1$ atm pressure sufficient to deform the solid Al. They

Table 7

Largest Blister Size Observed

<u>Sample</u>	<u>Fluence</u>	<u>Size Approximate (WxLxH)</u>
B006	0 n/cm ²	1/64" x 1/16" x 0.001"
CL06	10 ¹³ n/cm ²	3/64" x 3/8" x 0.0033"
BI06	10 ¹⁵ n/cm ²	3/64" x 1/2" x 0.0017"
AH06	10 ¹⁷ n/cm ²	1/8" x 5/8" x 0.0041"

were all formed along the plate rolling direction. This phenomenon could be caused by three mechanisms. The first is the original defects formed in the plate rolling process. During the rolling process, the very hard boron-aluminum phases probably were moved along the rolling direction leaving a void track inside the aluminum matrix. During the corrosion process, the reduced H may diffuse into these defects to form H₂, there which in turn produces the blisters. The observation of our tests show that, for those samples immersed inside the boric acid solution, blister sizes were larger than those formed in pure water.

In our tests, we also found that, with higher irradiation levels, the blisters became larger (Shown in Fig. 39). A possible explanation could be that, during the irradiation, due to the B¹⁰ (n, alpha) reaction, helium atoms diffuse into those defects caused by the boron-aluminum phases and accumulate there. The higher the neutron irradiation, the more helium gas diffused into the local defects and the greater the blisters became. Unfortunately, the

Helium diffusion rate at even 100°C is very low; therefore some other phenomenon may be active here.

Radiation Effects

Neutron irradiation in our test (up to 10^{17} n/cm²) did not seem to cause any significant damage or dimensional change to the material. The only irradiation effect appeared to be the enhancement of blister formation.

Dimensional Stability

The corrosion although producing some blistering, appeared to cause essentially no changes in the macroscopic dimensions of the sample. Similarly, the neutron fluence appeared to have no effect on the dimension of the samples.

Future Work

In our tests, the corrosion rates of these samples were not measured quantitatively. This information is needed to further understand the materials corrosion resistance. Also, since the largest amount of corrosion was found in borated water at 80°C, we also suggest that corrosion tests be carried out at different temperatures to better define the materials corrosion resistance at other elevated temperatures.

Conclusion:

With the tests results obtained so far, it can be concluded that the borated aluminum exhibits a strong corrosion resistance at room temperature in either reactor grade deionized water or in 2000 ppm borated water. The behavior is only slightly different than 1100 series aluminum, hence, satisfactory long-term usage in these

environments is expected. The neutron irradiation up to 10^{17} n/cm² level did not cause any measurable dimensional changes or any other negative damage to the material.

At high temperature, the material still exhibits high corrosion resistance in the pure water environment. However, at the most corrosive condition of 80°C, in 2000 ppm borated water, local pitting corrosion was found. At 100°C and room temperature, the, pitting attack is less than at 80°C. In all cases, passivation did occur limiting the pit depth.

From the tests on pure aluminum, we found that borated aluminum is more resistant to uniform corrosion attack than pure Aluminum. Local pitting corrosion can occur, causing localized damage to the borated aluminum. A distinct advantage over other poison materials exists. The boron aluminum material has extremely uniform and small size AlB₂ phase. It is expected that the effectiveness of the boron because of the uniform distribution and particle size will be much greater than in other materials such as boral where particle size is larger and distribution less uniform.

Reference

- [1]. "Boral-neutron absorbing/shielding material." An AAR
Brook & Perkins company.
- [2]. "Boron by titration - chemistry procedure." General
Public Utilities (GPU Nuclear).

Appendix.I Sample Dimensional Measurement Data

Table.I-1 AL Group Samples Dimensional Measurement Data.

Sample Name	Thickness(in) Before Irradiation				Thickness(in) After Test				Size change (%)
	1st	2nd	3rd	Avg.	1st	2nd	3rd	Avg.	
AL1	0.0163	0.0164	0.0163	0.01633	0.0163	0.0163	0.0162	0.01627	-0.367%
AL2	0.0327	0.0327	0.0327	0.03270	0.0327	0.0324	0.0325	0.03253	-0.520%
AL3	0.0500	0.0501	0.0503	0.05013	0.0500	0.0500	0.0500	0.05000	-0.259%
AL4	0.0694	0.0695	0.0694	0.06943	0.0695	0.0694	0.0697	0.06953	+0.144%
AL5	0.0804	0.0803	0.0805	0.08040	0.0806	0.0805	0.0806	0.08067	+0.336%
AL6	0.0996	0.0998	0.0998	0.09973	0.0997	0.0972	0.0973	0.09717	-2.567%

* 10^{13} n/cm² irradiation level.

Table. I-2. BL Group Samples Measurement Results.

Sample Name	Thickness(in) Before Irradiation				Thickness(in) After Irradiation				Size change (%)
	1st	2nd	3rd	Avg.	1st	2nd	3rd	Avg.	
BL1	0.0164	0.0163	0.0163	0.01633	0.0160	0.0164	0.0166	0.01633	0.000%
BL2	0.0327	0.0326	0.0327	0.03263	0.0328	0.0327	0.0327	0.03273	+0.306%
BL3	0.0505	0.0502	0.0504	0.05037	0.0500	0.0500	0.0500	0.05000	-0.734%
BL4	0.0693	0.0694	0.0694	0.06937	0.0693	0.0689	0.0684	0.06989	+0.750%
BL5	0.0803	0.0804	0.0802	0.08030	0.0804	0.0804	0.0807	0.08050	+0.249%
BL6	0.0998	0.0998	0.0998	0.09980	0.0980	0.0967	0.0970	0.09723	-2.575%

* 10^{13} n/cm² irradiation level.

Table.I-3. AI Group Samples Measurements Data.

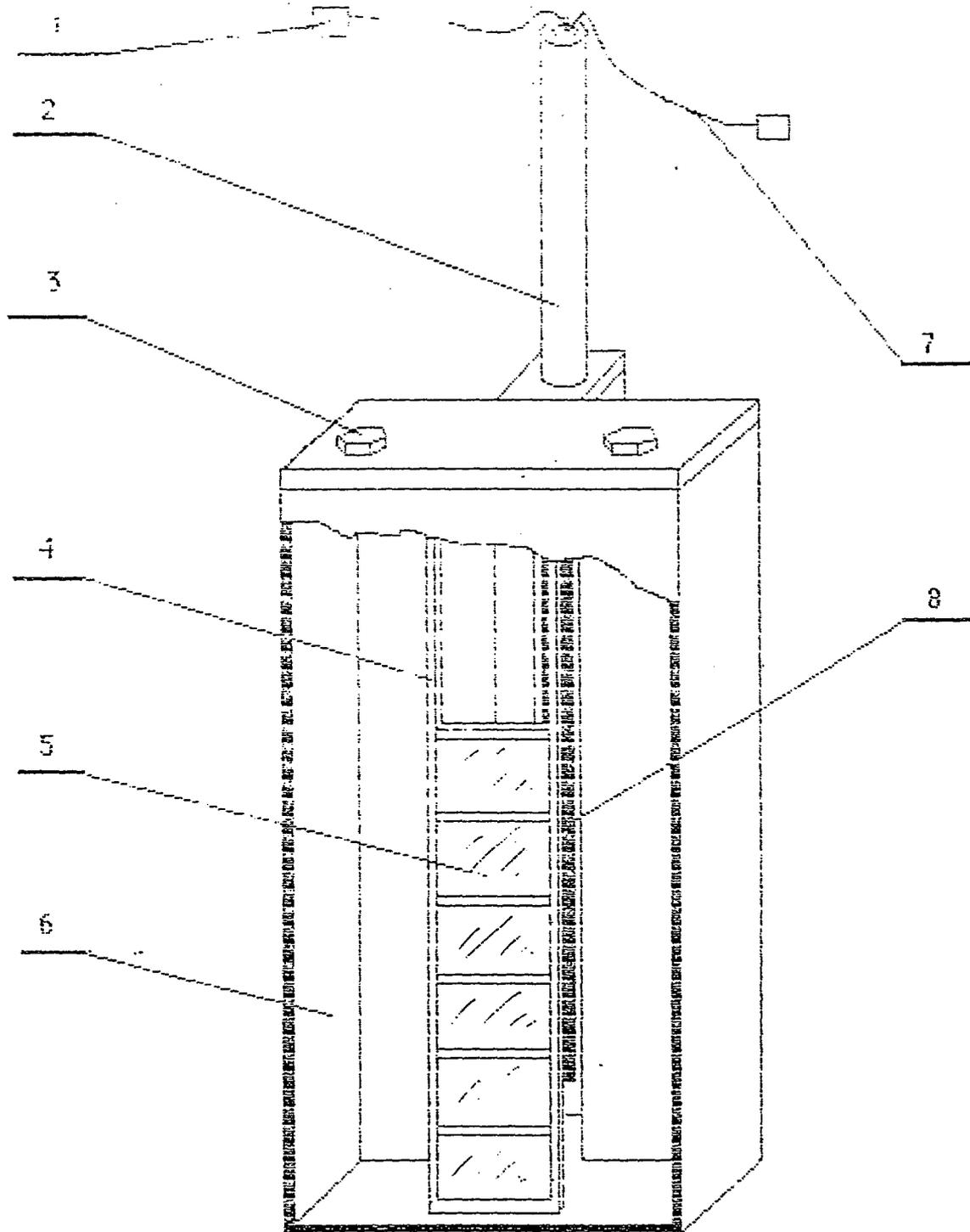
Sample Name	Thickness(in) Before Irradiation				Thickness(in) After Test				Size change (%)
	1st	2nd	3rd	Avg.	1st	2nd	3rd	Avg.	
AI1	0.0164	0.0163	0.0163	0.01633	0.0164	0.0163	0.0164	0.01637	-0.245%
AI2	0.0327	0.0326	0.0323	0.03253	0.0328	0.0328	0.0323	0.03263	+0.307%
AI3	0.0506	0.0505	0.0506	0.05057	0.0509	0.0503	0.0504	0.05053	-0.079%
AI4	0.0694	0.0692	0.0693	0.06930	0.0694	0.0693	0.0693	0.06937	+0.101%
AI5	0.0805	0.0806	0.0806	0.08057	0.0807	0.0806	0.0807	0.08067	+0.124%
AI6	0.0995	0.0995	0.0997	0.09960	0.0990	0.0975	0.0981	0.09820	-1.406%

* 5×10^{13} n/cm² irradiation level.

Table.I-4. BI Group Samples Measurements Data.

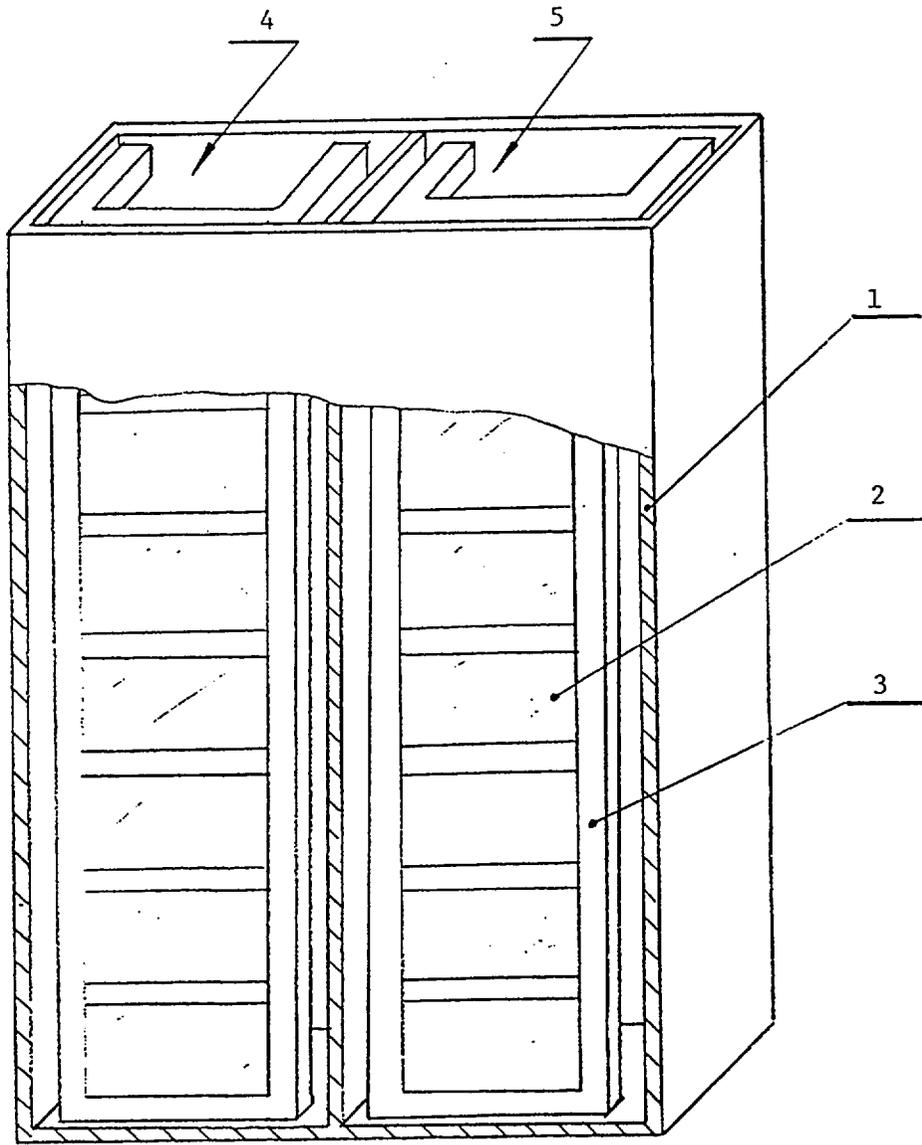
Sample Name	Thickness(in) Before Irradiation				Thickness(in) After Irradiation				Size change (%)
	1st	2nd	3rd	Avg.	1st	2nd	3rd	Avg.	
BI1	0.0163	0.0164	0.0162	0.01630	0.0163	0.0163	0.0161	0.01623	-0.429%
BI2	0.0332	0.0331	0.0330	0.03210	0.0329	0.0328	0.0326	0.03270	+1.869%
BI3	0.0508	0.0509	0.0508	0.05083	0.0508	0.0505	0.0505	0.05050	-0.649%
BI4	0.0696	0.0699	0.0697	0.06973	0.0701	0.0698	0.0695	0.06980	+0.100%
BI5	0.0800	0.0800	0.0800	0.08000	0.0857	0.0855	0.0854	0.08553	+6.910%
BI6	0.0997	0.0982	0.0976	0.09850	0.0989	0.0973	0.0988	0.09833	-0.173%

* 5×10^{13} n/cm² irradiation level.



1. Power Wire. 2. Condensing Tube. 3. Seal & Support Bolts.
4. Samples' Frame. 5. Irradiation Samples. 6. Bucket Body.
7. Thermal Couple Wire. 8. Immersion Heater.

Fig.1 Boiling Bucket.



1. Bucket Body. 2. Irradiation Samples. 3. Sample Holders.
4. Chamber One (Pure Water). 5. Chamber Two (Borated Water)

Fig.2 Non-Boiling Bucket.

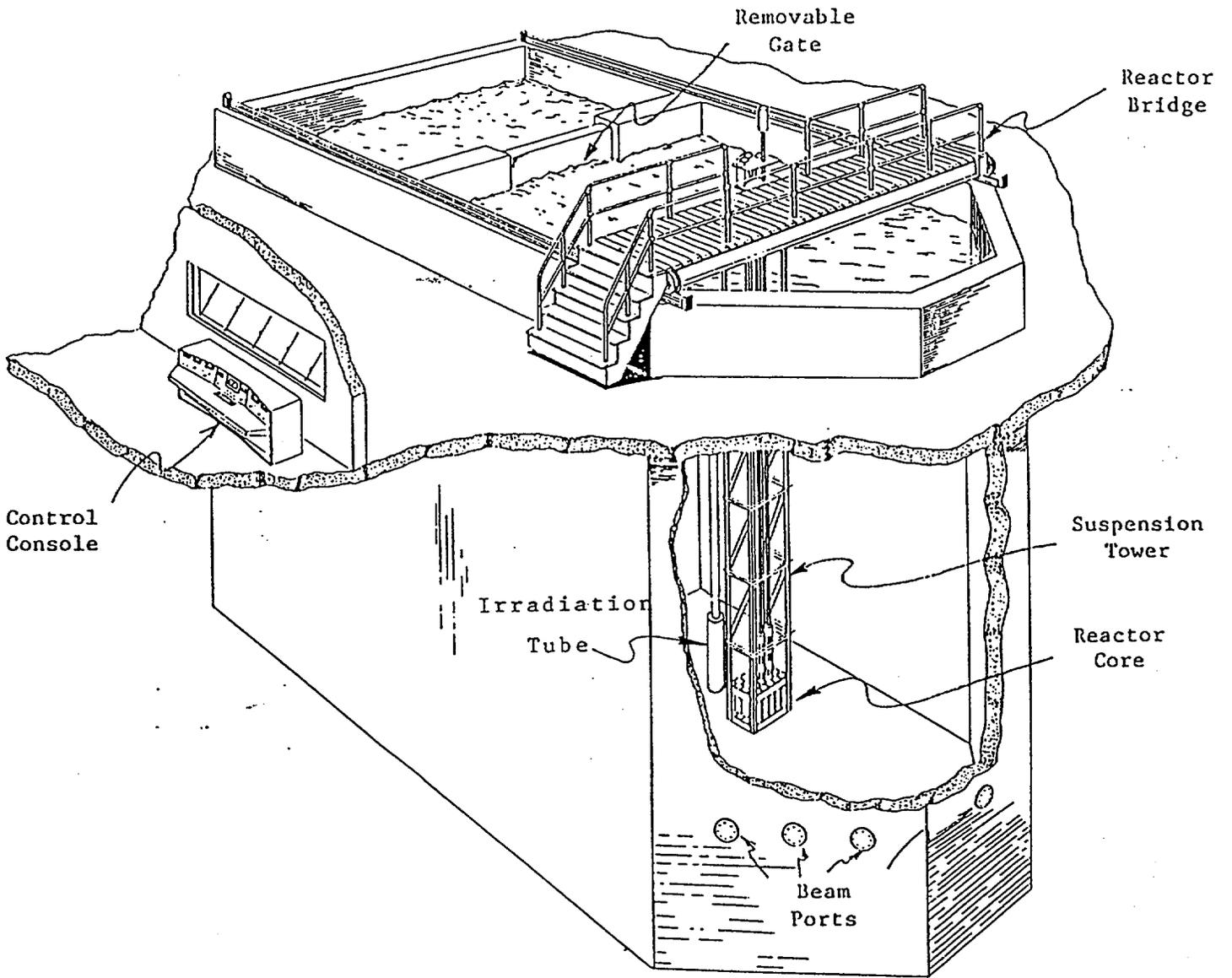


Fig.3 The Reactor Facility and The Irradiation Tube.

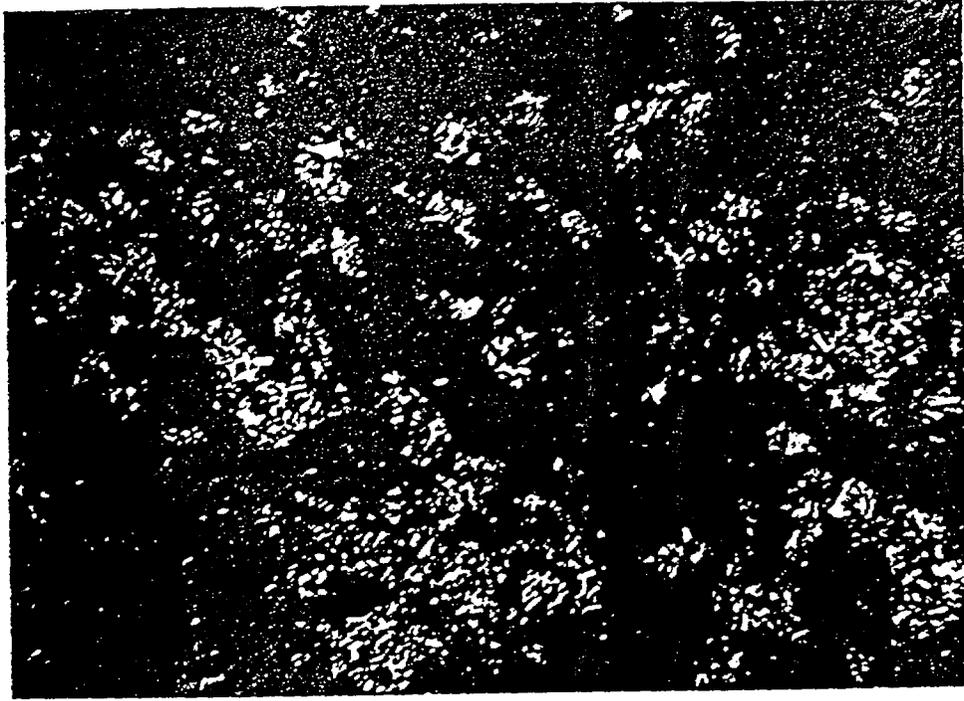


Fig.4 Polished sample surface (AH6 200X). New sample.



Fig.5. Polished Sample Surface (AH6 500x). New sample.

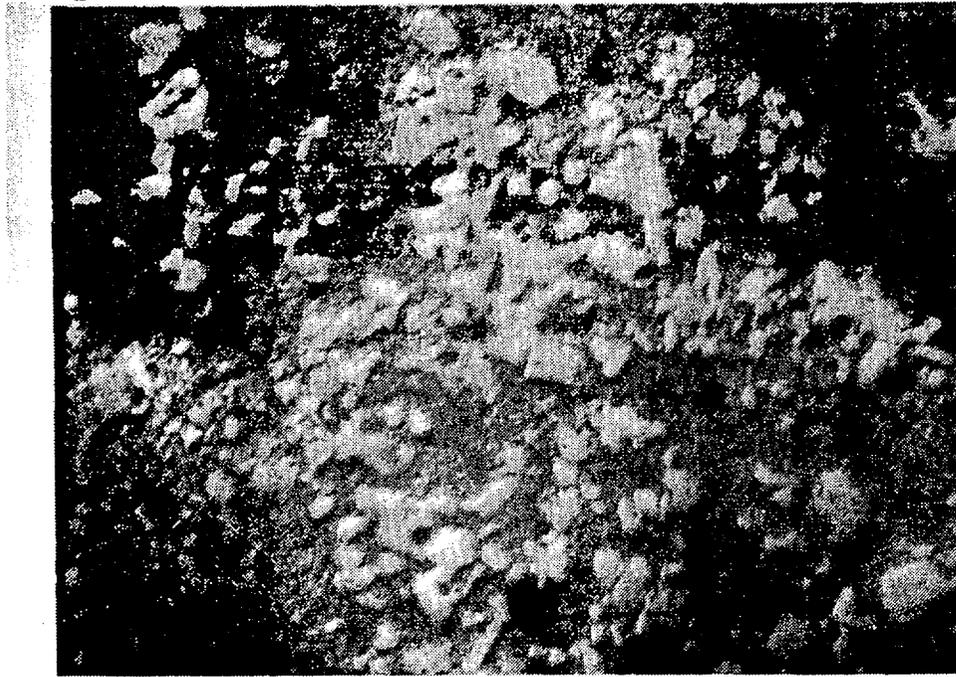


Fig.6. Polished Sample Surface (AH6 1000x). New sample.

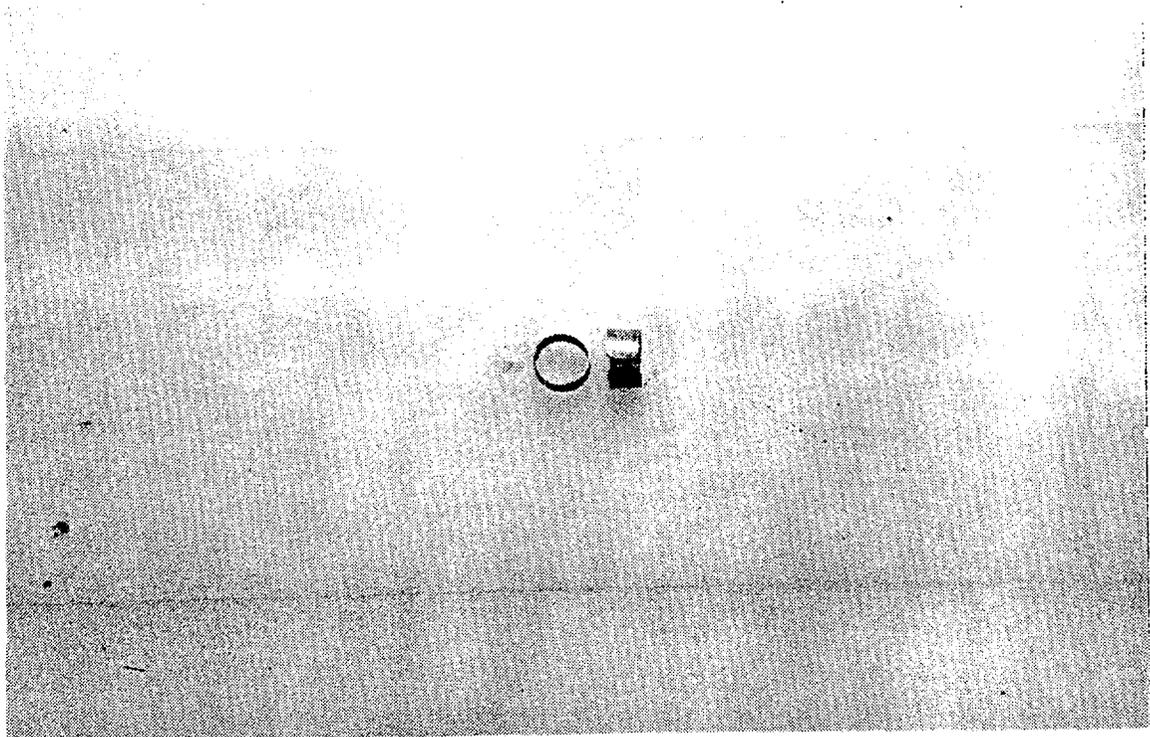


Fig.6(A) Two split rings used for dimensional change measurement.

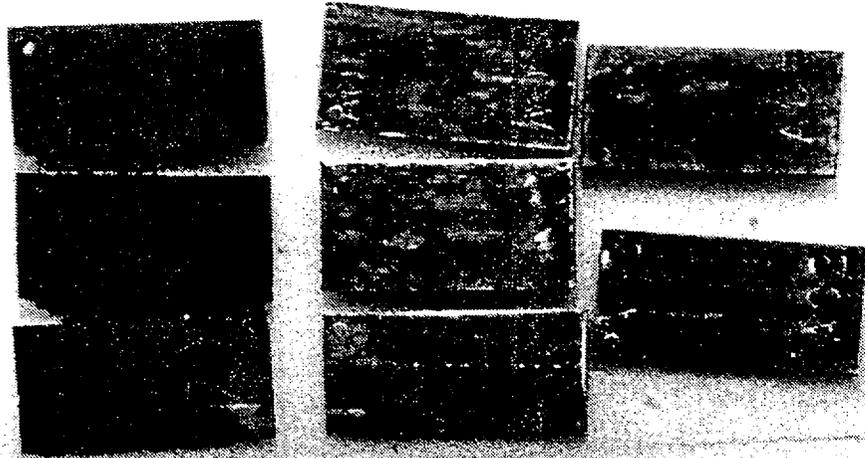


Fig.7. AO group corrosion samples' final examination.
Non-irradiated, pure water.

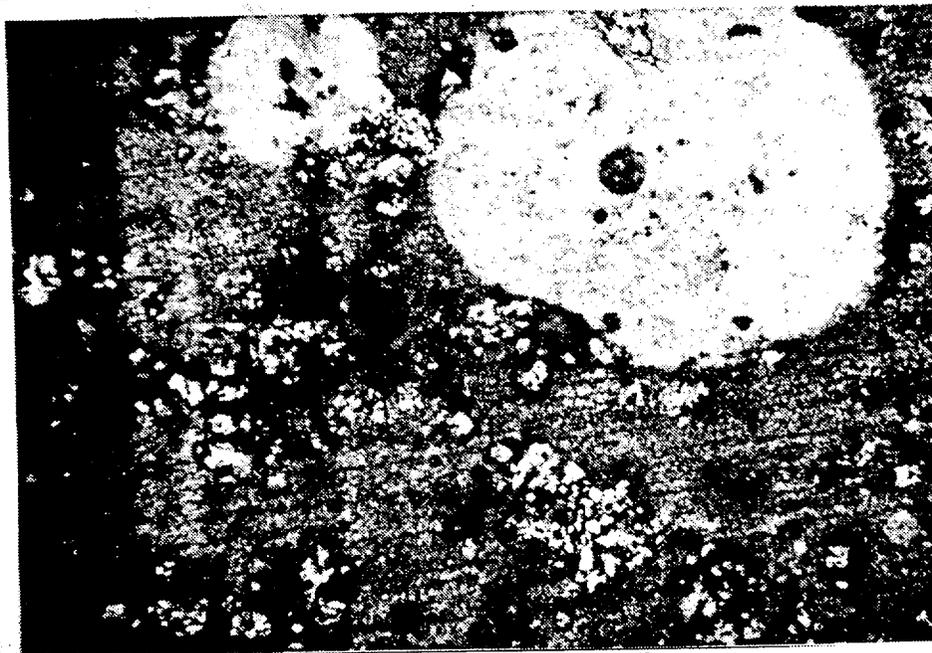


Fig.8. AO06 sample surface. (200X) Final examination.
Non-irradiated, pure water.

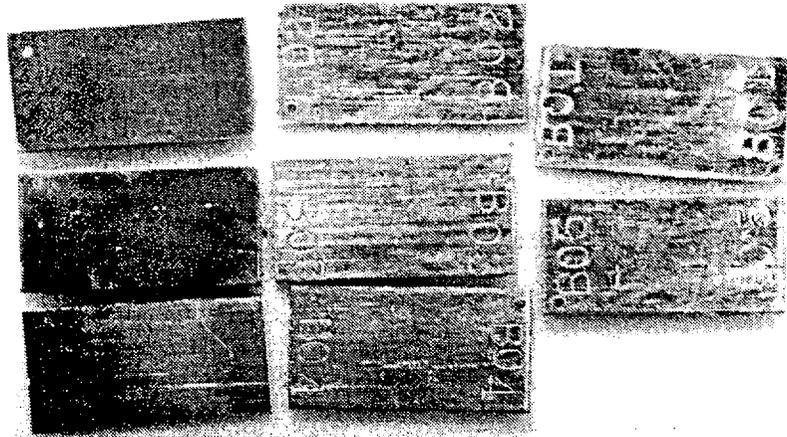


Fig.9. BO group corrosion samples' final examination.
Non-irradiated, 2000 ppm boric acid, room temperature.

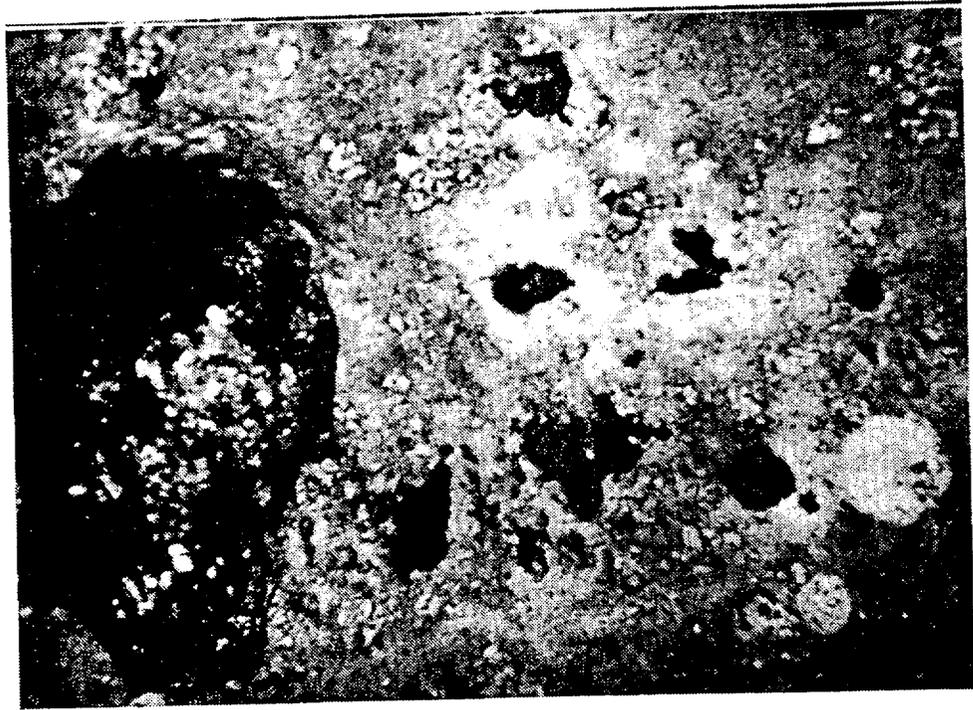


Fig.10. B006 sample surface (200X). (A blister can be found.)
Non-irradiated, 2000 ppm boric solution, normal temperature.

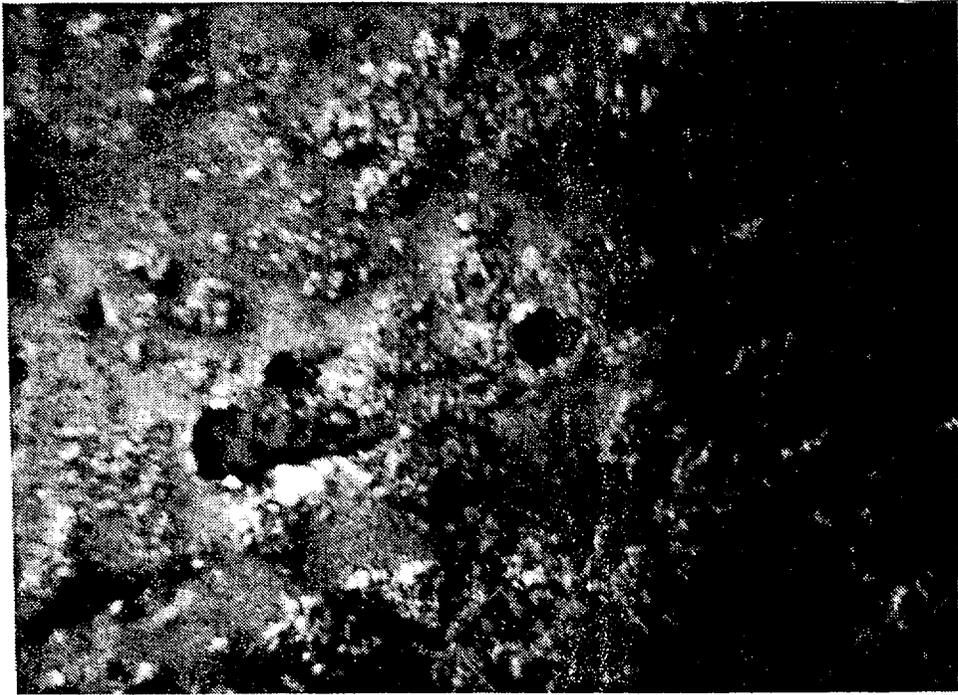


Fig.11. BO06 sample surface (200X). (General)
Non-irradiated, 2000 ppm boric acid, normal temperature.

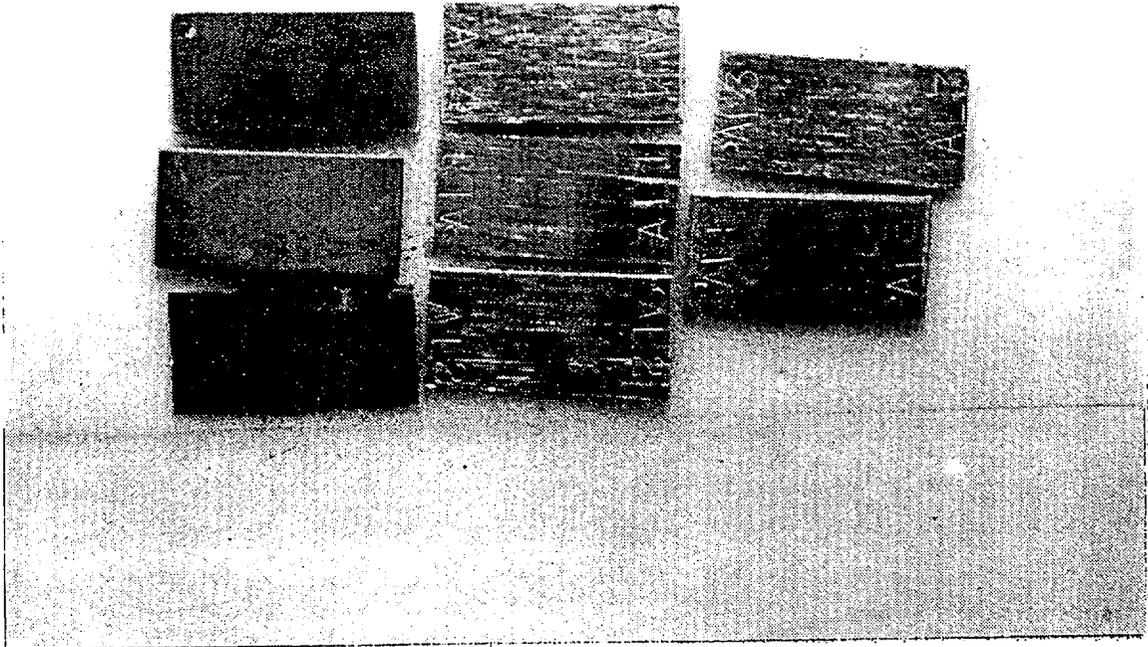


Fig.12. AL group corrosion samples' final examination.
 10^{13} n/cm² irradiation level, pure water, room temp.

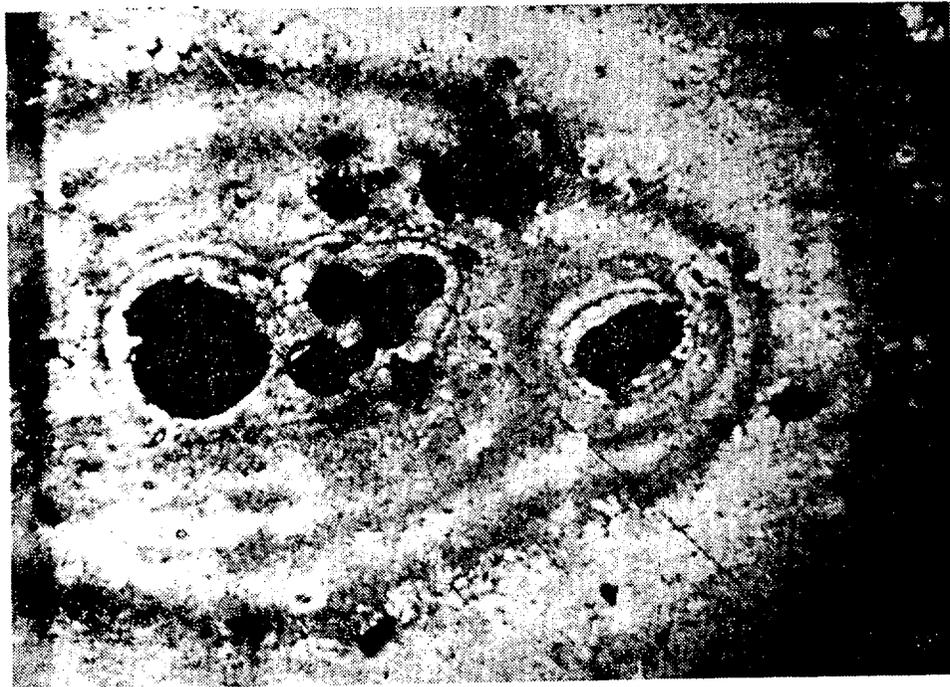


Fig.13. AL06 sample surface (200X). Pitting corrosion sites
 10^{13} n/cm² irradiation level, pure water, room temp.

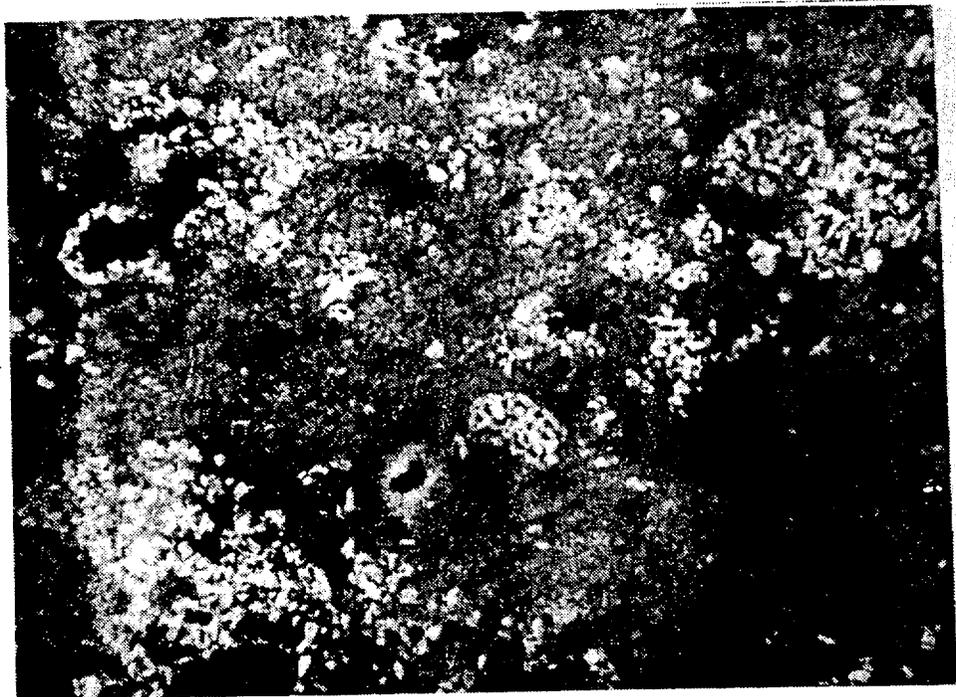


Fig.14. AL06 sample surface (200X). General surface.
 10^{13} n/cm² irradiation level, pure water, room temp.

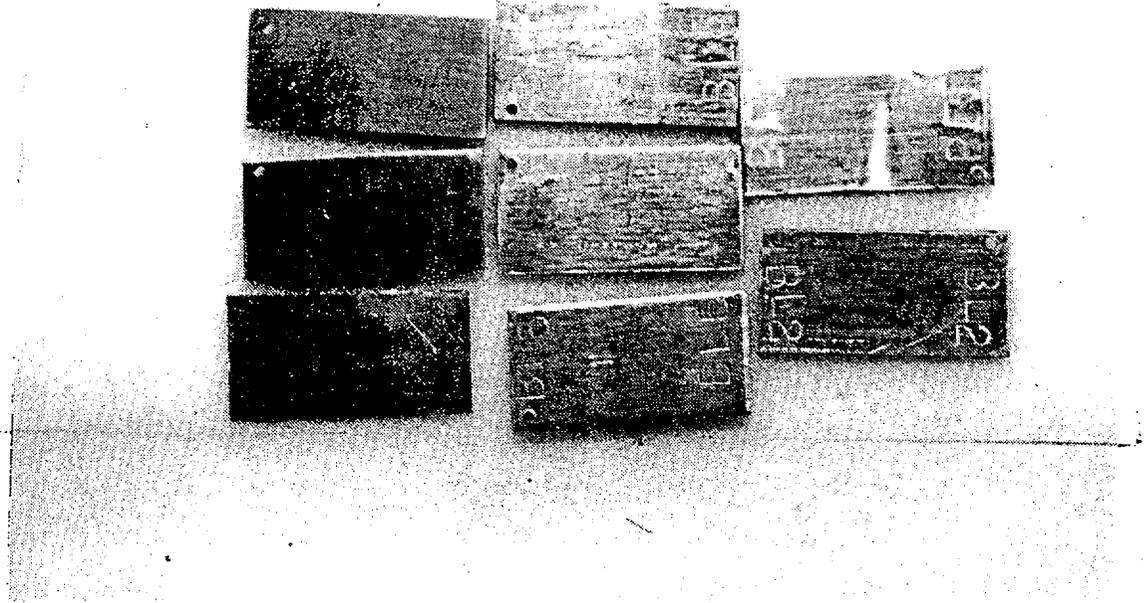


Fig.15. BL group corrosion samples' final examination.
 10^{13} n/cm² irradiation level, boric acid solution, room temp.

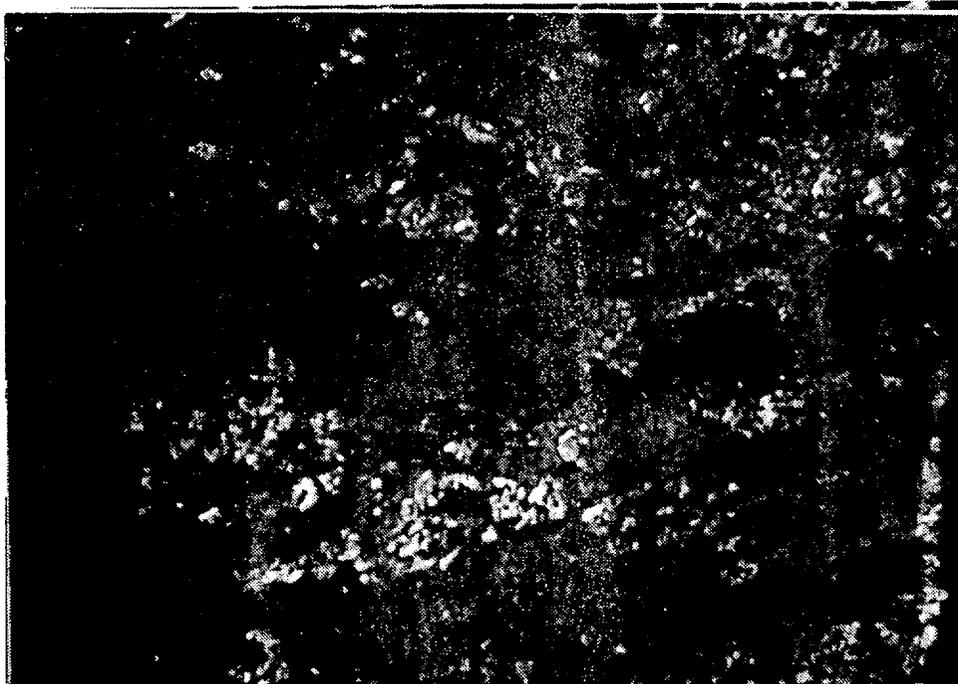
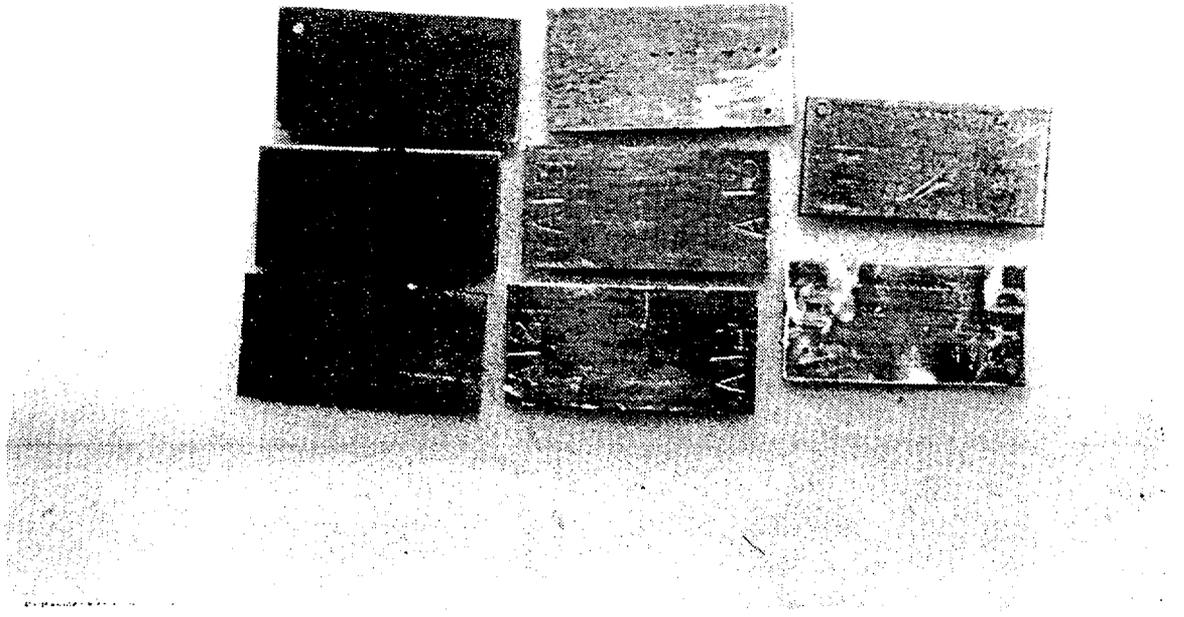


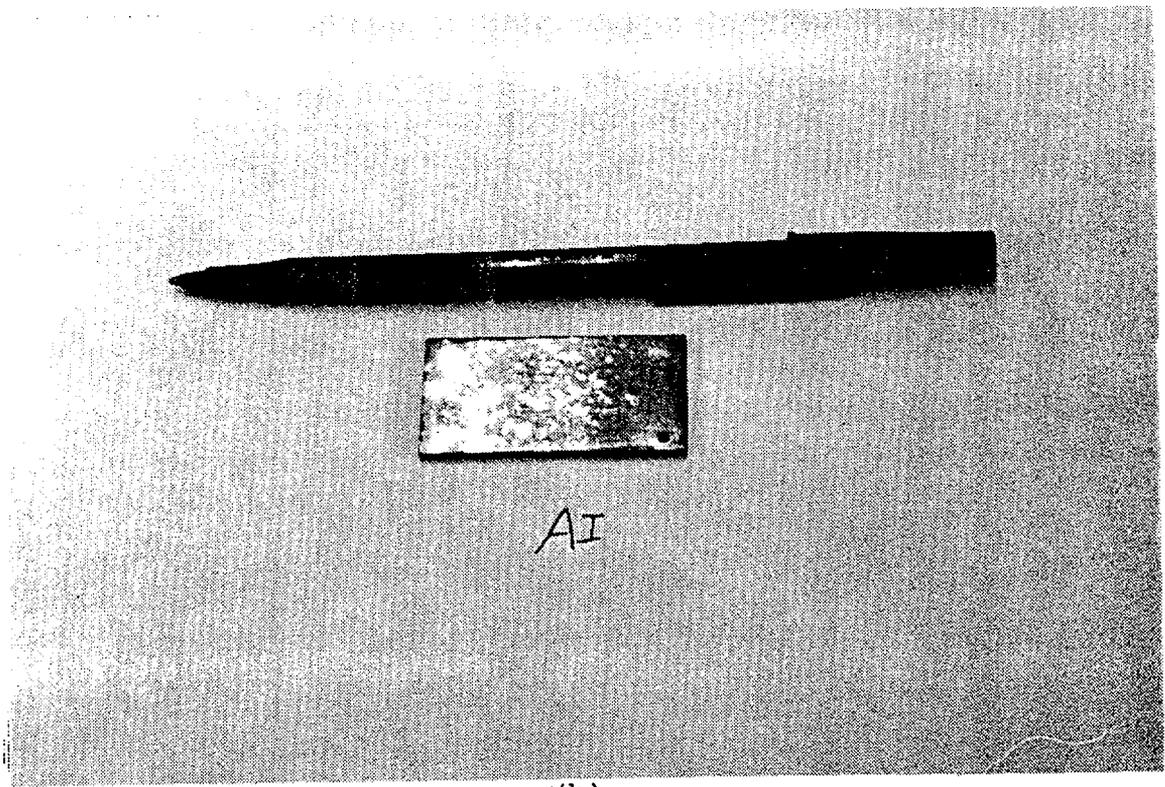
Fig.16. BL06 sample surface (200X). General surface.
 10^{13} n/cm² irradiation level, boric acid solution, room temp.



Fig.17. BL06 sample surface (200X). General surface.
 10^{13} n/cm² irradiation level, boric acid solution, room temp.

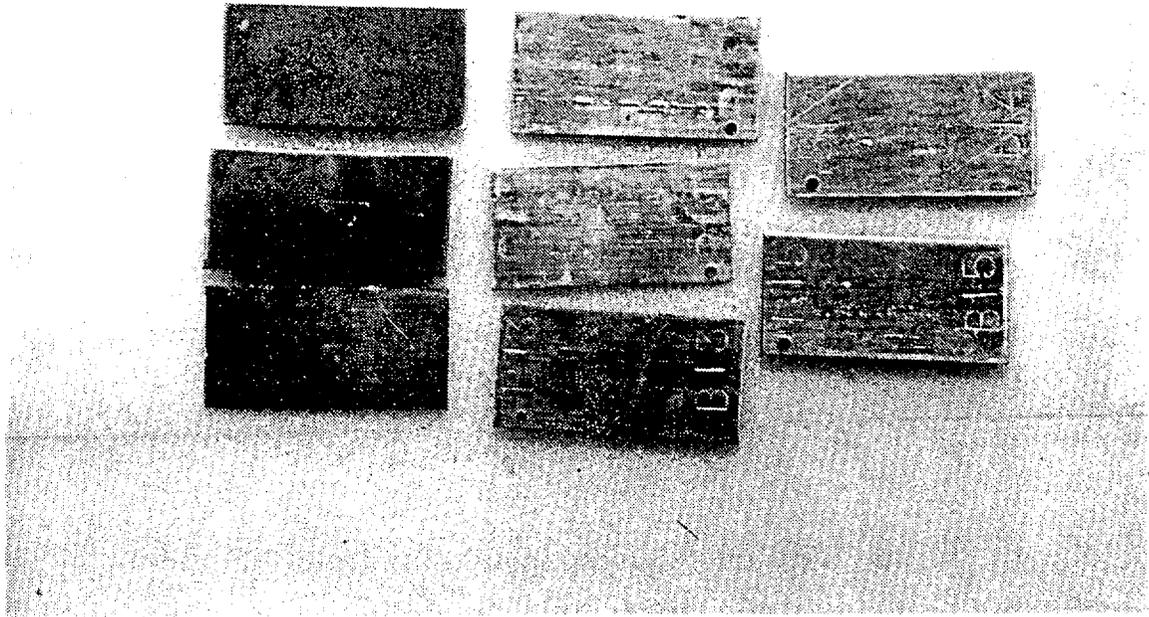


(a) .

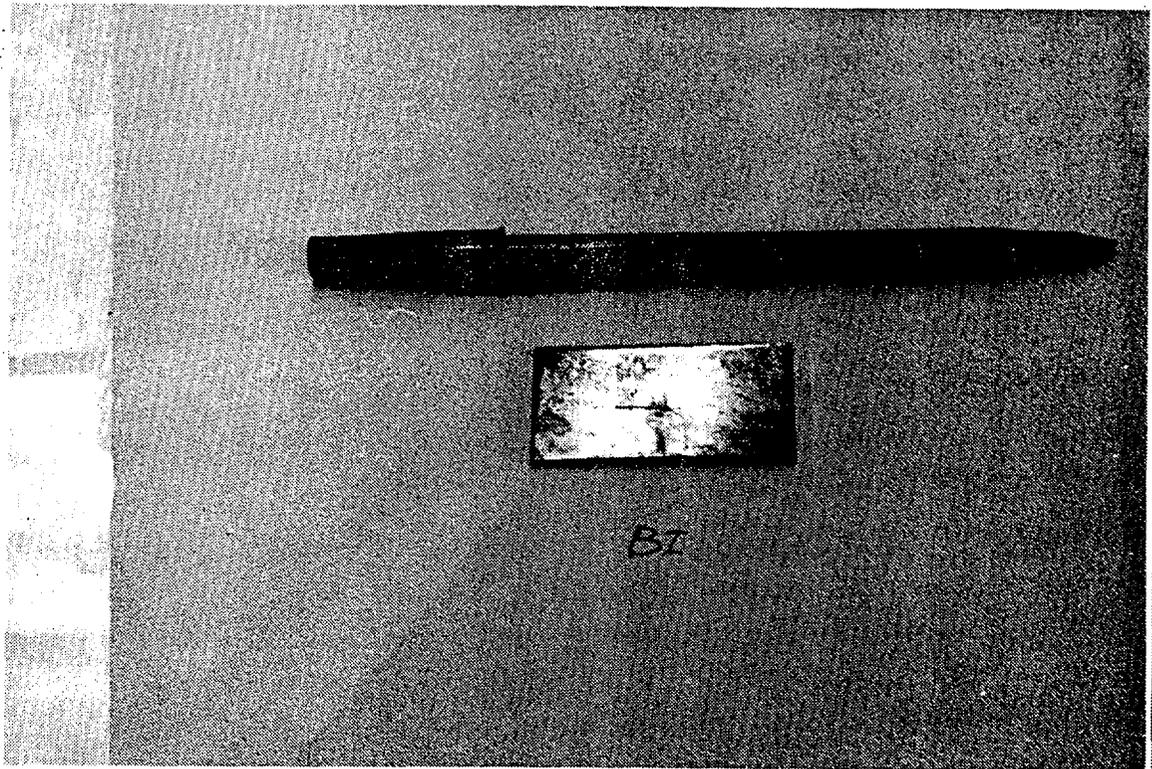


(b) .

(a) . Whole group. (b) AI06 surface.
Fig.18 AI group corrosion samples' final examination.
 10^{15} n/cm² irradiation level, pure water, room temp.



(a).



(b).

(a). The whole group. (b). BI06 sample.
Fig.21 BI group corrosion samples' final examination.
 10^{15} n/cm² irradiation level, boric acid solution, room temp.

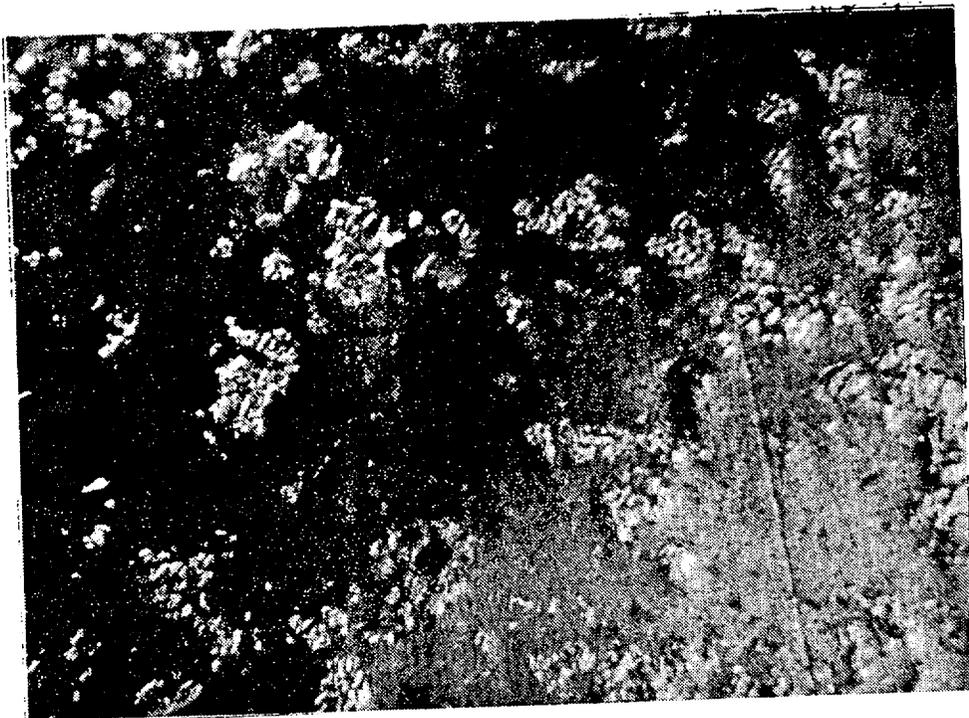


Fig.22 BI06 general surface. (200X)
 10^{15} n/cm² irradiation level, boric acid solution, room temp.

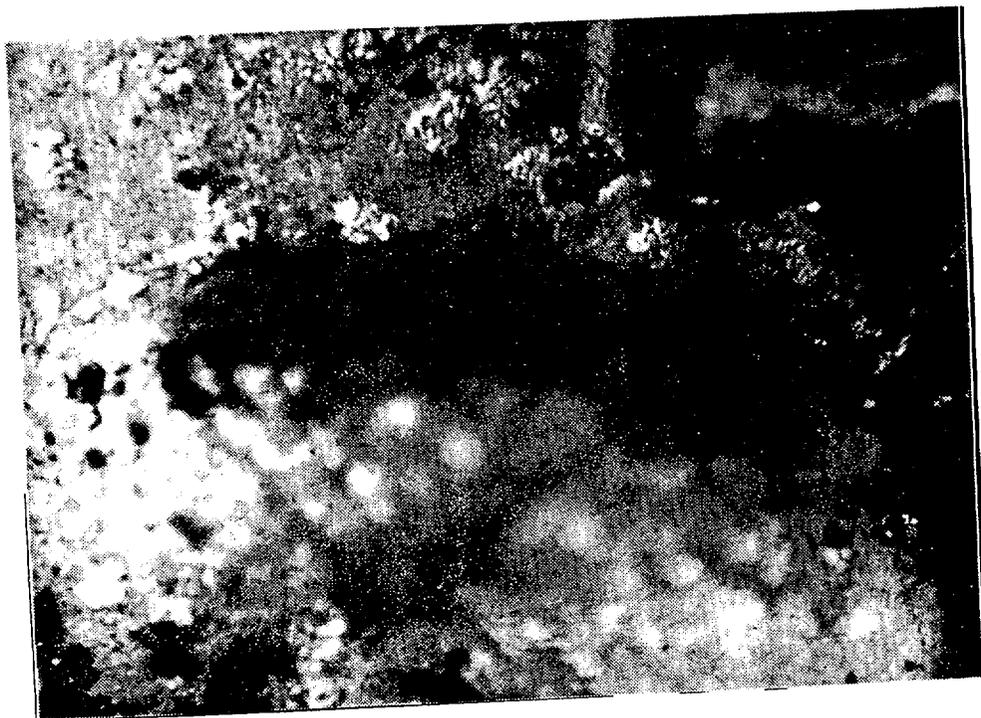


Fig.23 BI06 sample. Two blisters. (200X)
 10^{15} n/cm² irradiation level, boric acid solution, room temp.

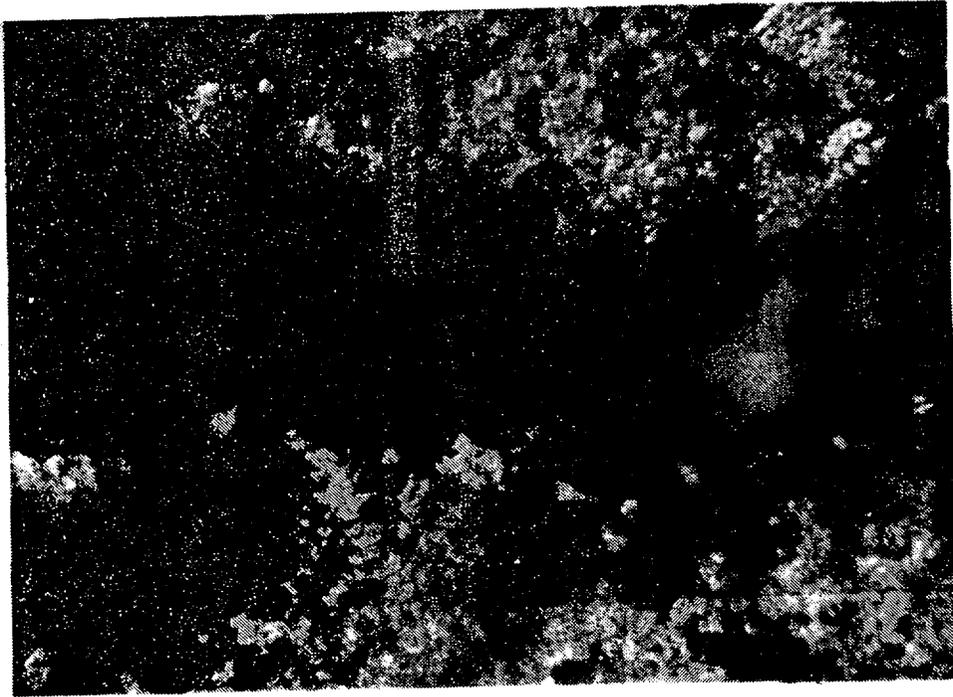


Fig.24 B10 sample . Crevice. (200X)
 10^{15} n/cm² irradiation level, boric acid solution, room temp.

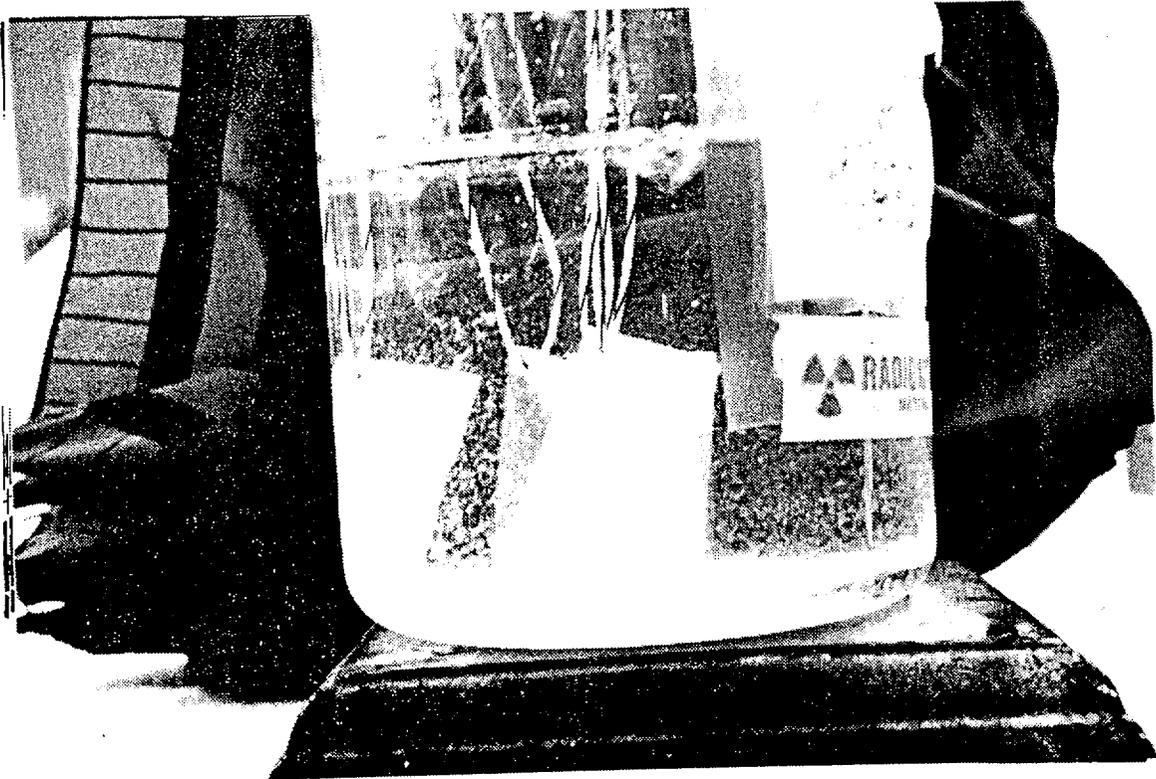


Fig.25 CL group. White particles inside the beaker.
 10^{13} n/cm² irradiation level, boric acid solution, boiling.

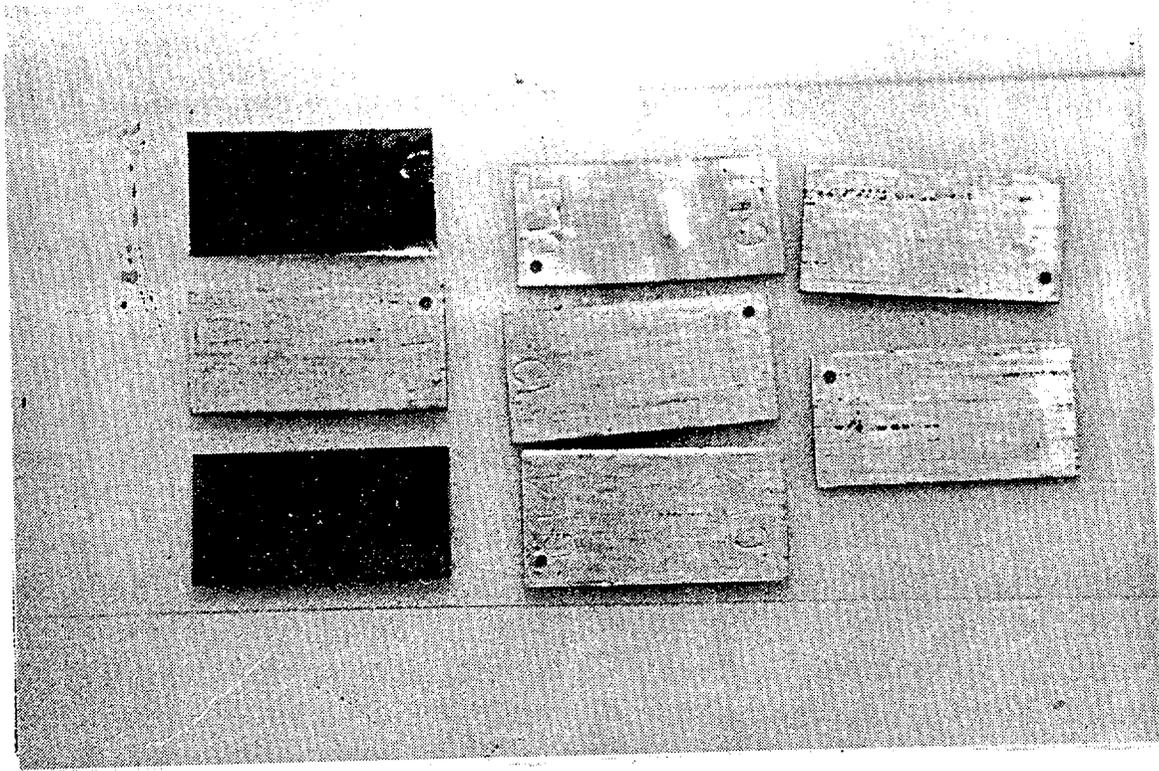
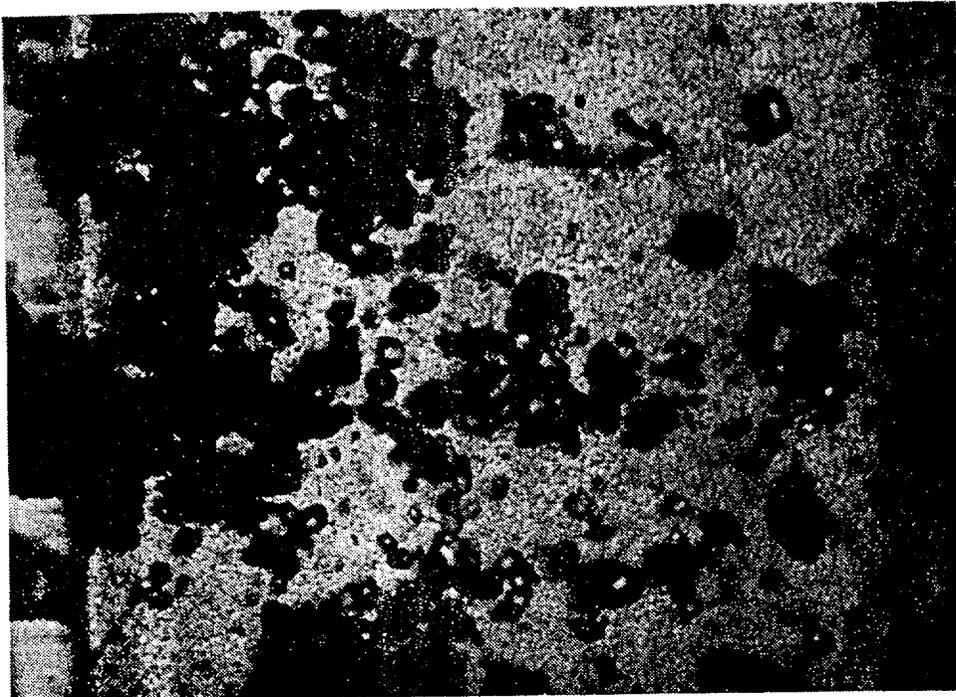
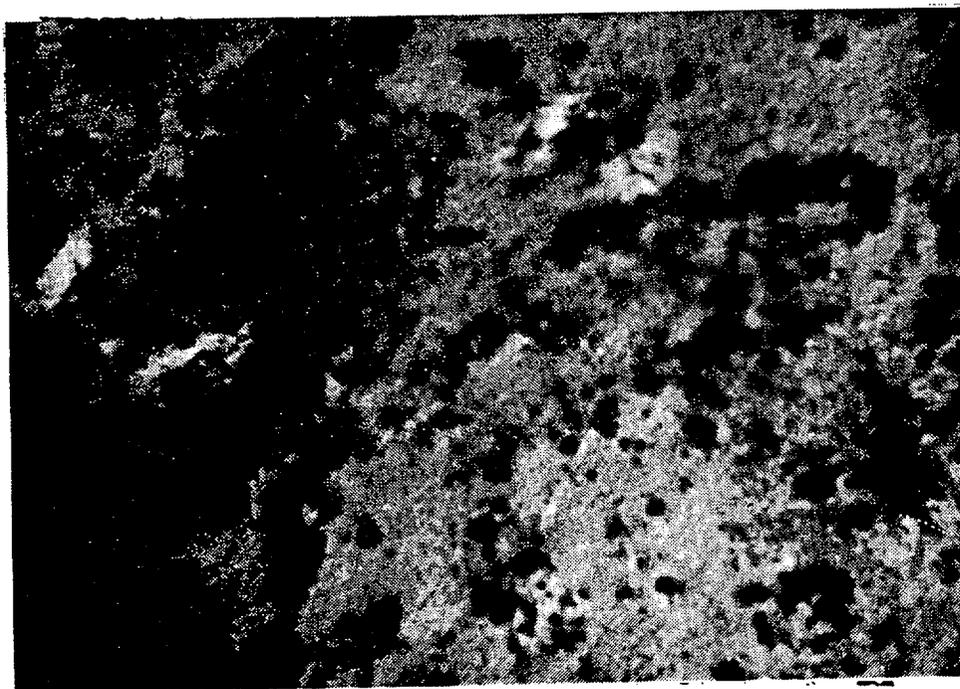


Fig.26 CL group. Final surface examination.
 10^{13} n/cm² irradiation level, boric acid solution, boiling.



(a) 500X



(b) 200X

Fig.27 CL06 sample general surface.
 10^{13} n/cm² irradiation level, boric acid solution, boiling.

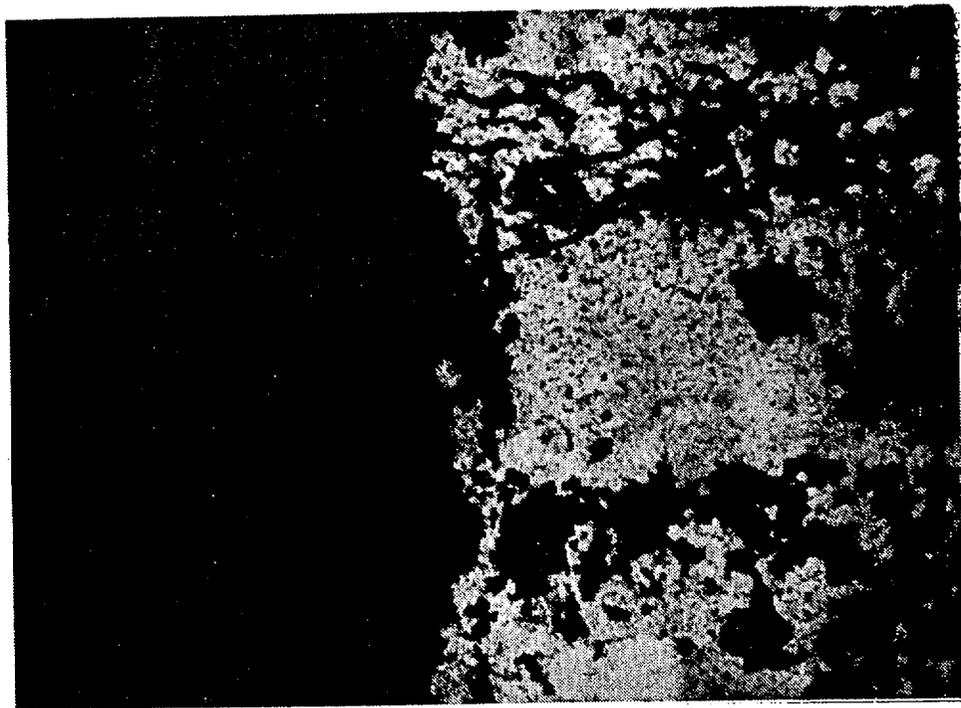


Fig.28 CL06 sample . An Impurity Particle. (200X)
 10^{13} n/cm² irradiation level, boric acid solution, boiling.



Fig.29 CL06 sample. Top of a blister. (200X)
 10^{13} n/cm² irradiation level, boric acid solution, boiling.

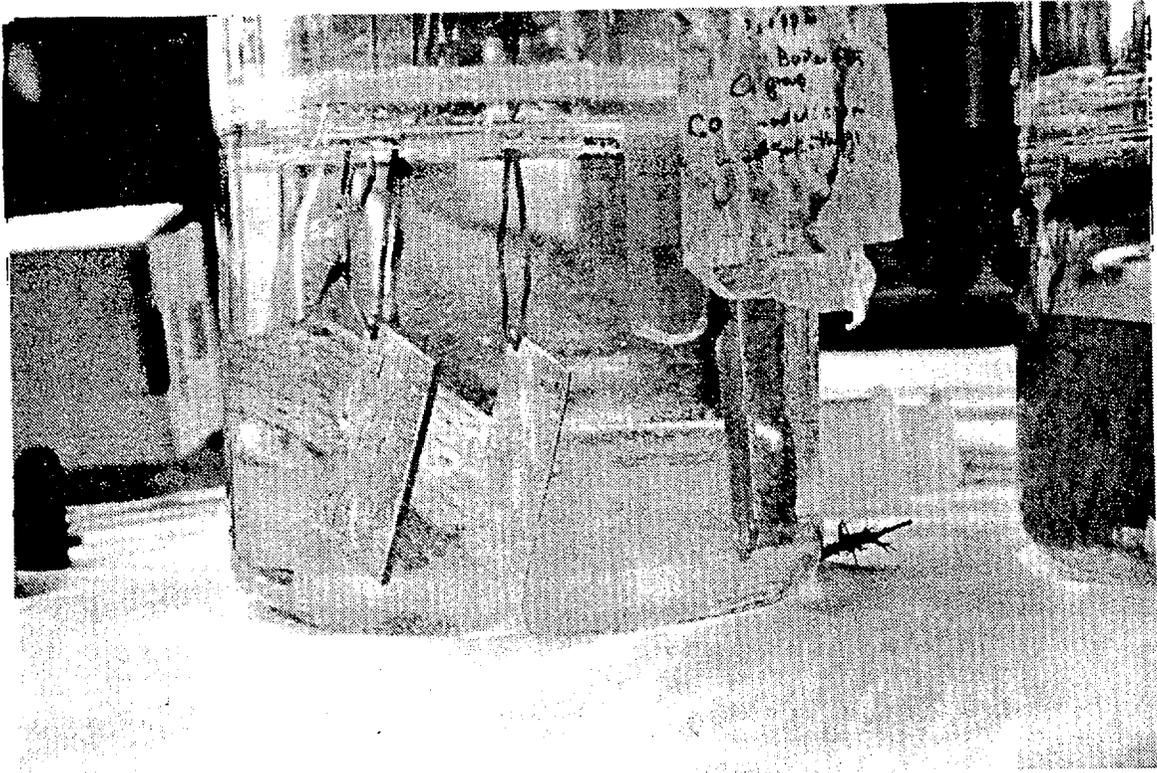


Fig.30 CO group. White insoluble particles.
Non-irradiated, boric acid, boiling.

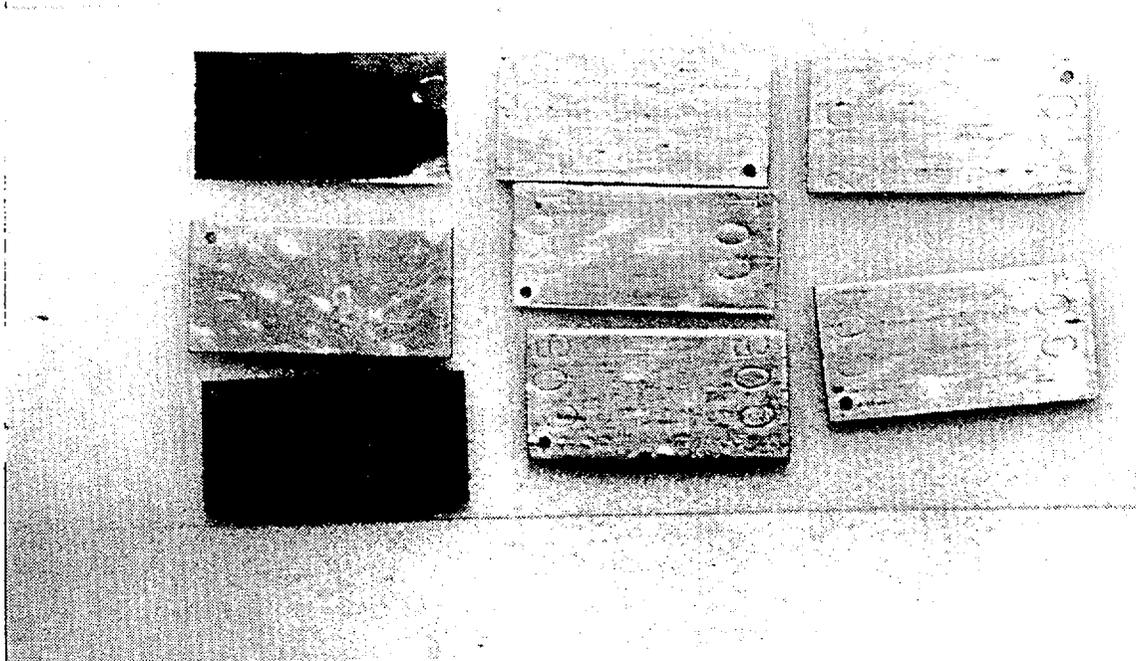


Fig.31 CO group final surface examination.
Non-irradiated, boric acid, boiling.

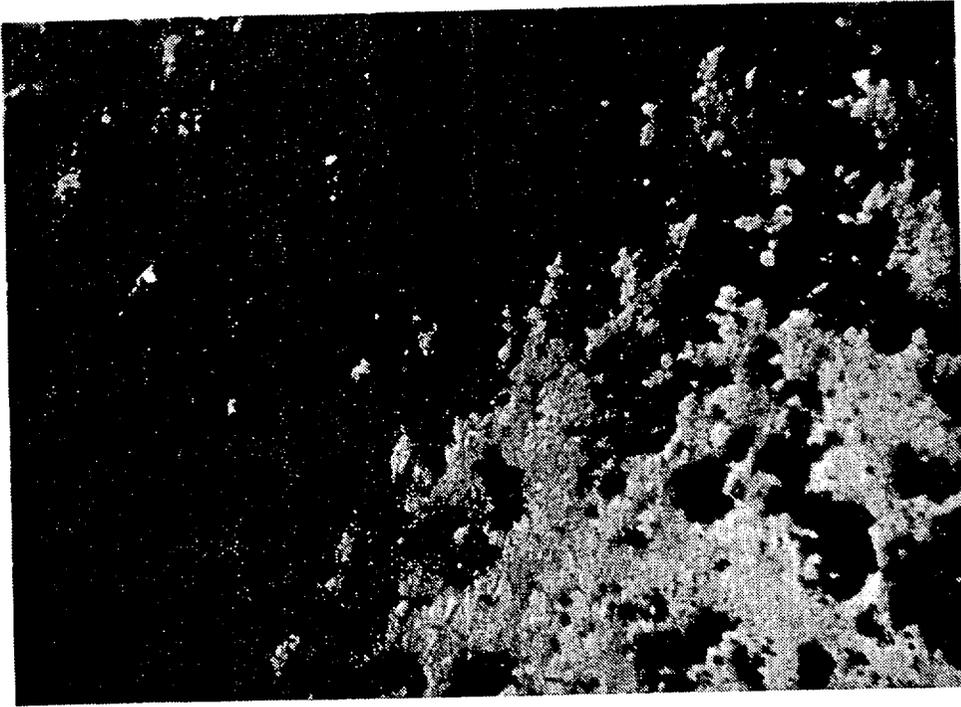


Fig.32 CO06 sample. General surface. (200X)
Non-irradiated, boric acid, boiling.

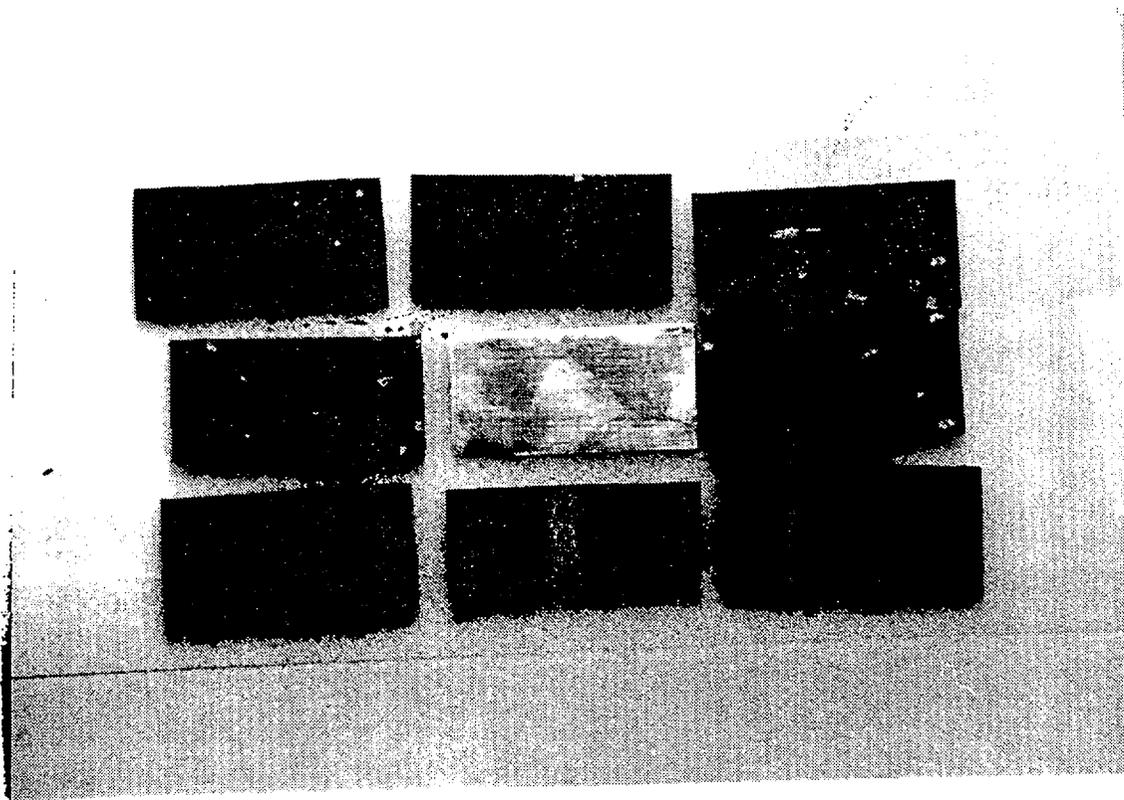
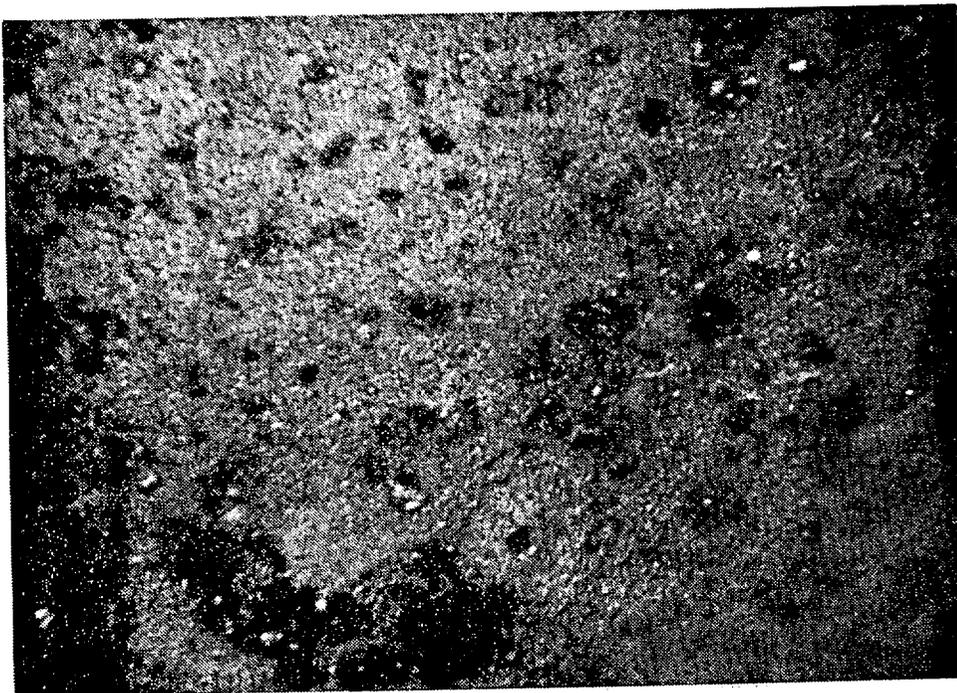


Fig.33 DB Group final surface examination.
Non-irradiated, boric acid, 80°C.

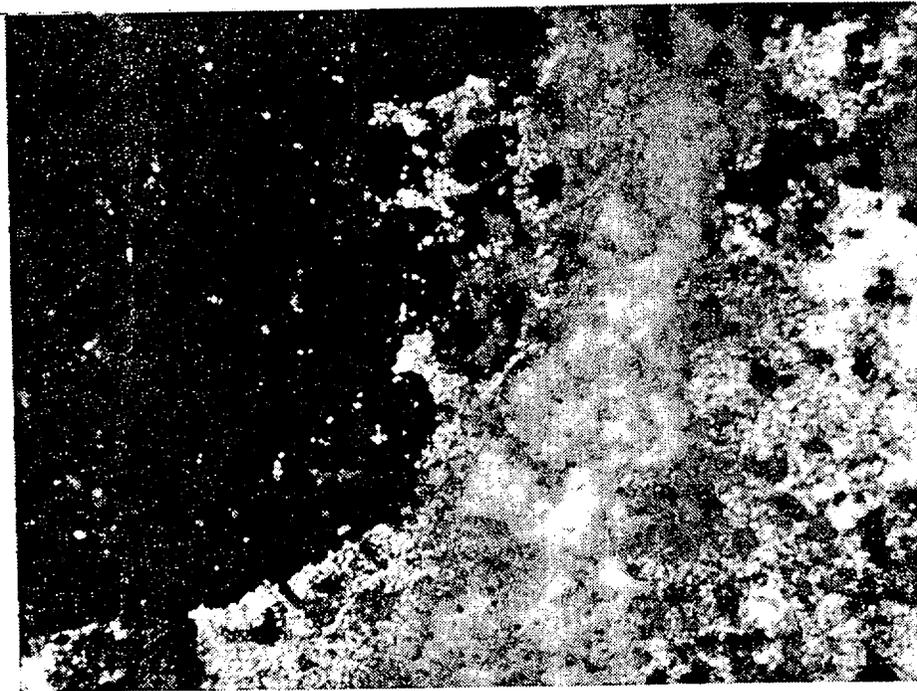


(a) 100X



(b) 200X

Fig.34 DB06 polished sample. General surface.200X
Non-irradiated, boric acid, 80°C.



100X

Fig.35 DB06 polished sample. A local pitting corrosion site.
Non-irradiated, boric acid, 80°C.

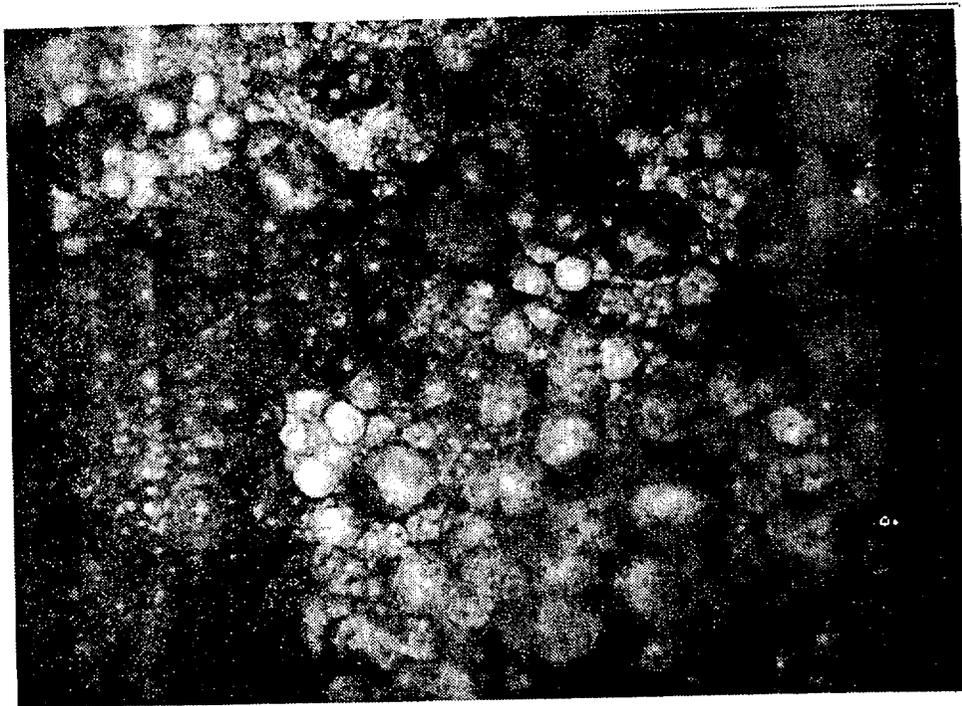


Fig.36 DB06 polished surface. Center of the pitting corrosion
site. (200X). Non-irradiated, boric acid, 80°C.

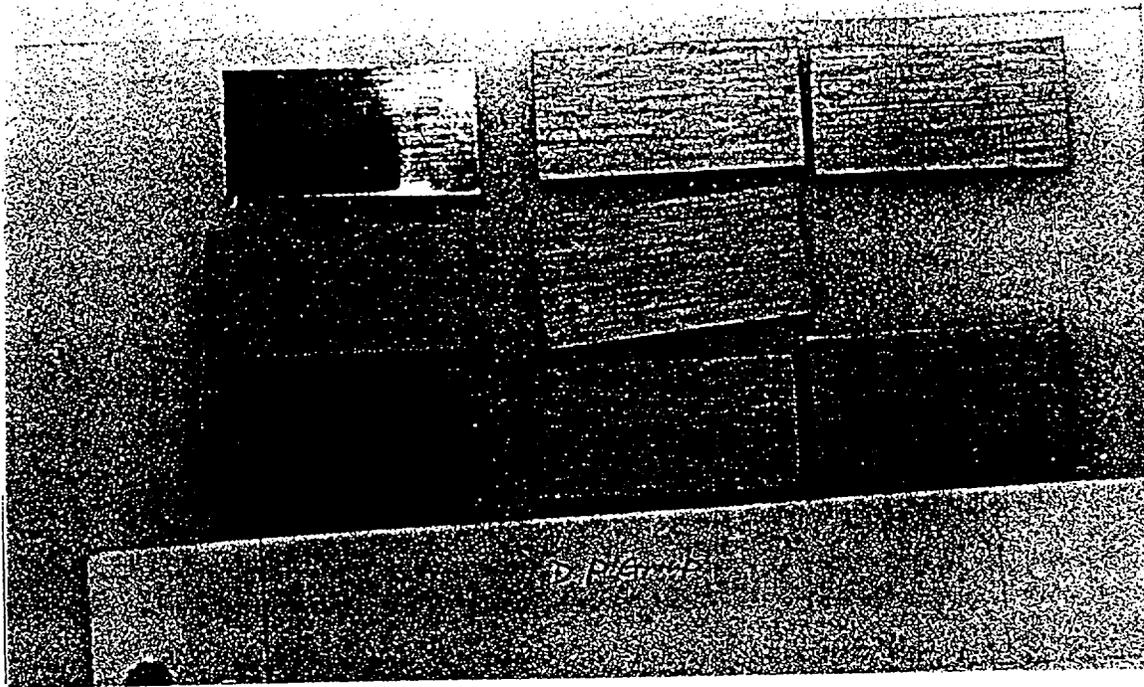


Fig.37 DP group. Final surface examination.
Non-irradiated, pure water, 80°C.



Fig.38 DP06 sample. Polished surface. (200X).
Non-irradiated, pure water, 80°C.

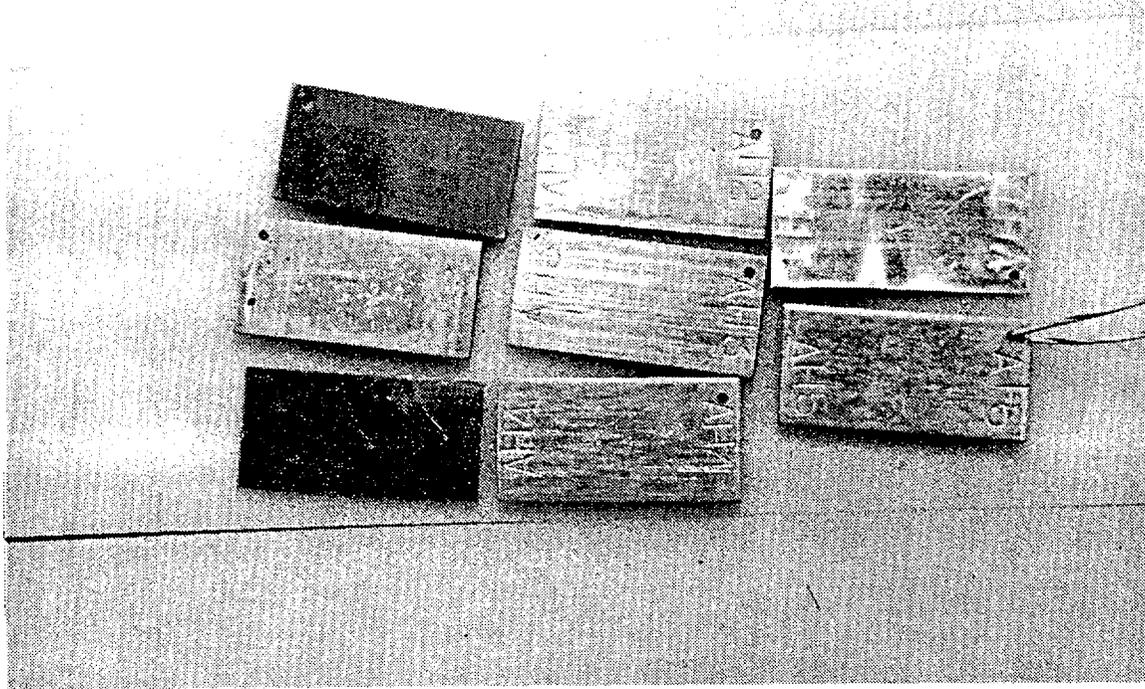


Fig.39 AH group sample surface check. (10^{17} n/cm²) Pure water.

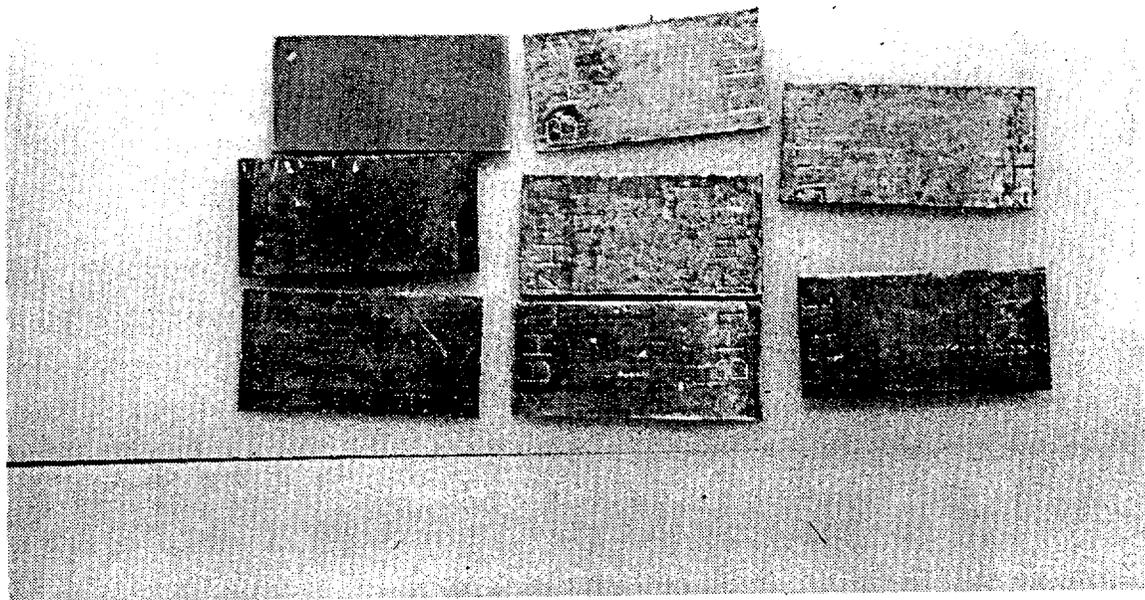


Fig.40 BH group sample surface check. (10^{17} n/cm²). Borated water.

Application for Amendment No. 3 to COC 72-1004, Revision 2

SUBJECT MATERIAL	REMOVE AND DESTROY MATERIAL DATED/REV.	INSERT MATERIAL DATED/REV
Attachment A	January 2001	February 2001
Attachment B	Pages B.1, and B.10, Rev. 1	Pages B.1, and B.10, Rev. 2
Attachment C (Remove and replace pages as noted below)		
TOC	January 2001, Rev. 1	February 2001, Rev. 2
Chapter 2	Page K.2-2, Rev. 1 Page K.2-13, Rev. 1	Page K.2-2, Rev. 2 Page K.2-13, Rev. 2
Chapter 7	Page K.7-2, Rev. 0 Page K.7-3, Rev. 0	Page K.7-2, Rev. 2 Page K.7-3, Rev. 2
Chapter 9	Pages K.9-1 thru K.9-13 Rev. 1	Pages K.9-1 thru K.9-13 Rev. 2
Chapter 10	Page K.10-2, Rev. 1 Page K.10-3, Rev. 1	Page K.10-2, Rev. 2 Page K.10-3, Rev. 2

ATTACHMENT A

Description, Justification, and Evaluation of COC Amendment Changes

ATTACHMENT A

DESCRIPTION, JUSTIFICATION AND EVALUATION OF AMENDMENT CHANGES

1.0 INTRODUCTION

The purpose of this amendment application is to add a third Dry Shielded Canister (DSC), the NUHOMS[®]-61BT DSC, to the authorized contents of the Standardized NUHOMS[®] System.

This section of the application provides (1) a brief description of the changes, (2) justification for the change, and (3) a safety evaluation for this change.

Revision 1 of the application reflects the changes resulting from the responses to the Request for Additional Information (RAI) dated December 6, 2000.

Revision 2 of the application reflects the changes resulting from the supplemental response to the above RAI.

2.0 BRIEF DESCRIPTION OF THE CHANGE

2.1 Significant Changes to NUHOMS[®] COC 72-1004, Revision 2

The changes listed below are relative to COC Revision 2 which is effective September 5, 2000.

- Revise “Limit/Specification” and “Action” sections of Specification 1.2.1, “Fuel Specification”, to add reference to Tables 1-1c, 1-1d, and 1-1e. Table 1-1c, 1-1d and 1-1e show the applicable parameters for each type of BWR fuel allowed to be stored in the NUHOMS[®]-61BT DSC.
- Revise the “Bases” section of Specification 1.2.1, “Fuel Specification”, to provide the supporting basis for storage of BWR fuel in the NUHOMS[®]-61BT DSC.
- Add Table 1-1c to clearly identify the acceptable parameters for each type of Intact BWR fuel allowed to be stored in the NUHOMS[®]-61BT DSC.
- Add Table 1-1d to clearly identify the acceptable parameters for each type of Intact/Damaged BWR fuel allowed to be stored in the NUHOMS[®]-61BT DSC.
- Add Table 1-1e to include BWR fuel assembly design characteristics.
- Revise the title and “Applicability” section of Specification 1.2.3, “Helium Backfill Pressure”, to restrict its applicability to the 24P (standard and long cavity) DSCs, and 52B DSCs.

- Add Specification 1.2.3a, “61BT DSC Helium Backfill Pressure. This specification is identical to 1.2.3 except the allowed tolerance on the helium backfill pressure is reduced from ± 2.5 psig to ± 1.0 psig.
- Revise the title and “Applicability” section of Specification 1.2.4, “Helium Leak Rate of Inner Seal Weld”, to restrict it’s applicability to the 24P, 24P long cavity, and 52B DSCs.
- Add Specification 1.2.4a, “61BT DSC Helium Leak Rate of Inner Seal Weld”. This specification requires that the NUHOMS[®]-61BT top cover plate seal weld be tested to meet the “leak tight” requirements as specified in ANSI N14.5-1997.
- Revise the “Bases” section of Specification 1.2.7, “HSM Dose Rates”, to include a reference to Appendix K where the shielding analysis for 61BT system is located.
- Revise the “Bases” section of Specification 1.2.11, “Transfer Cask Dose Rates to include a reference to Appendix K where the shielding analysis for 61BT system is located.
- Revise the “Applicability” section of Specification 1.2.15, “Boron Concentration in the DSC Cavity Water (24-P Design Only)”, to clearly state that this specification also does not apply to the NUHOMS[®]-61BT system.
- Add Specification 1.2.17, “Vacuum Drying Duration Limit”. This specification places a 96 hour duration limit on Vacuum Drying the NUHOMS[®]-61BT DSC.
- Update Table 1.3.1 for the additional sections added to the specification.

Revision 2 updates the definition of Damaged Fuel in Table 1-1d of Fuel Specification 1.2.1.

2.2 Changes to NUHOMS[®] FSAR, Revision 5

Attachment C of this submittal includes a new FSAR Appendix K, “Evaluation Of Addition Of NUHOMS[®] 61BT DSC To NUHOMS[®] System”. Appendix K has been prepared in a format consistent with the Standard Review Plan for Dry Cask Storage (NUREG 1536). It provides a complete evaluation of the new basket and the revised design features of the DSC. It also documents the changes where applicable to the existing safety analyses provided in the FSAR.

Revision 1 of Appendix K revision reflects the updates to the safety analysis resulting from the responses to the RAI.

Revision 2 of Appendix K reflects updates to the safety analysis report resulting from the supplemental RAI response.

3.0 JUSTIFICATION OF CHANGE

The NUHOMS[®]-61BT System design has been developed based on research and development efforts driven by the commercial nuclear power industry identified needs. TNW believes that the NUHOMS[®]-61BT System is required to optimally support the commercial nuclear industry in

their effort to maintain full core off-load capability and support near term decommissioning activities. TNW is currently having discussions with several nuclear power utilities regarding the near term use of the NUHOMS[®]-61BT at their facilities.

4.0 EVALUATION OF CHANGE

TN West has evaluated the NUHOMS[®]-61BT system for structural, thermal, shielding and criticality adequacy and has concluded that the addition of the new DSC to the standardized NUHOMS[®] System has no significant effect on safety. This evaluation is documented in Appendix K of the FSAR (Attachment C). Supporting calculations are included in Attachment D.

ATTACHMENT B

Suggested Changes to Certificate of Compliance No. 1004 Revision No. 2

Table 1-1d
BWR Fuel Specifications of Intact/Damaged Fuel to be Stored in the
Standardized NUHOMS®-61BT DSC

Physical Parameters:	
<p><i>Fuel Design:</i></p> <p><i>Cladding Material:</i></p> <p><i>Fuel Damage:</i></p> <p><i>Channels:</i></p> <p><i>Maximum Assembly Length</i></p> <p><i>Maximum Assembly Width</i></p> <p><i>Maximum Assembly Weight</i></p>	<p>7x7, 8x8 BWR fuel assemblies manufactured by General Electric or equivalent reload fuel that are enveloped by the Fuel assembly design characteristics listed in Table 1-1e for the 7x7 and 8x8 designs only.</p> <p>Zircaloy</p> <p>Damaged BWR fuel assemblies are fuel assemblies containing fuel rods with known or suspected cladding defects greater than hairline cracks or pinhole leaks or with cracked, bulging, or discolored cladding. Missing cladding and/or crack size in the fuel pins is to be limited such that a fuel pellet is not able to pass through the gap created by the cladding opening during handling and retrievability is assured following Normal/Off-Normal conditions. Damaged fuel shall be stored with Top and Bottom Caps for Failed Fuel. Damaged fuel may only be stored in the 2x2 compartments of the "Type C" NUHOMS®-61B Canister.</p> <p>Fuel may be stored with or without fuel channels</p> <p>176.2 in</p> <p>5.44 in</p> <p>705 lbs</p>
Radiological Parameters: <i>No interpolation of Radiological Parameters is permitted between Groups</i>	
<p><i>Group 1:</i></p> <p><i>Maximum Burnup:</i></p> <p><i>Minimum Cooling Time:</i></p> <p><i>Maximum Initial Lattice Average Enrichment:</i></p> <p><i>Maximum Pellet Enrichment:</i></p> <p><i>Minimum Initial Bundle Average Enrichment:</i></p> <p><i>Maximum Initial Uranium Content:</i></p> <p><i>Maximum Decay Heat:</i></p>	<p>27,000 MWd/MTU</p> <p>5-years</p> <p>4.0 wt. % U-235</p> <p>4.4 wt. % U-235</p> <p>2.0 wt. % U-235</p> <p>198 kg/assembly</p> <p>300 W/assembly</p>
<p><i>Group 2:</i></p> <p><i>Maximum Burnup:</i></p> <p><i>Minimum Cooling Time:</i></p> <p><i>Maximum Initial Lattice Average Enrichment:</i></p> <p><i>Maximum Pellet Enrichment:</i></p> <p><i>Minimum Initial Bundle Average Enrichment:</i></p> <p><i>Maximum Initial Uranium Content:</i></p> <p><i>Maximum Decay Heat:</i></p>	<p>35,000 MWd/MTU</p> <p>8-years</p> <p>4.0 wt. % U-235</p> <p>4.4 wt. % U-235</p> <p>2.65 wt. % U-235</p> <p>198 kg/assembly</p> <p>300 W/assembly</p>
<p><i>Group 3:</i></p> <p><i>Maximum Burnup:</i></p> <p><i>Minimum Cooling Time:</i></p> <p><i>Maximum Initial Lattice Average Enrichment:</i></p> <p><i>Maximum Pellet Enrichment:</i></p> <p><i>Minimum Initial Bundle Average Enrichment:</i></p> <p><i>Maximum Initial Uranium Content:</i></p> <p><i>Maximum Decay Heat:</i></p>	<p>37,200 MWd/MTU</p> <p>6.5-years</p> <p>4.0 wt. % U-235</p> <p>4.4 wt. % U-235</p> <p>3.38 wt. % U-235</p> <p>198 kg/assembly</p> <p>300 W/assembly</p>

ATTACHMENT C

Changed FSAR Pages

TABLE OF CONTENTS

	<u>Page</u>
K.1	General DiscussionK.1-1
K.1.1	Introduction K.1-2
K.1.2	General Description of the NUHOMS®-61BT DSC..... K.1-3
K.1.2.1	NUHOMS®-61BT DSC Characteristics..... K.1-3
K.1.2.2	Operational Features K.1-4
	General Features..... K.1-4
K.1.2.2.2	Sequence of Operations..... K.1-4
K.1.2.2.3	Identification of Subjects for Safety and Reliability Analysis..... K.1-4
K.1.2.3	Cask Contents..... K.1-5
K.1.3	Identification of Agents and Contractors K.1-6
K.1.4	Generic Cask Arrays K.1-7
K.1.5	Supplemental Data K.1-8
K.1.6	References K.1-9
K.2	Principal Design Criteria.....K.2-1
K.2.1	Spent Fuel To Be Stored K.2-2
K.2.1.1	General Operating Functions K.2-3
K.2.2	Design Criteria for Environmental Conditions and Natural Phenomena K.2-4
K.2.2.1	Tornado Wind and Tornado Missiles..... K.2-4
K.2.2.2	Water Level (Flood) Design..... K.2-4
K.2.2.3	Seismic Design..... K.2-4
K.2.2.4	Snow and Ice Loading..... K.2-4
K.2.2.5	Combined Load Criteria..... K.2-4
K.2.2.5.1	NUHOMS®-61BT DSC Structure Design Criteria K.2-4
K.2.3	Safety Protection Systems..... K.2-7
K.2.3.1	General K.2-7
K.2.3.2	Protection By Multiple Confinement Barriers and Systems K.2-7
K.2.3.3	Protection By Equipment and Instrumentation Selection K.2-7
K.2.3.4	Nuclear Criticality Safety..... K.2-7
K.2.3.4.1	Control Methods for Prevention of Criticality K.2-7
K.2.3.4.2	Error Contingency Criteria..... K.2-8
K.2.3.4.3	Verification Analysis-Benchmarking..... K.2-8
K.2.3.5	Radiological Protection..... K.2-8
K.2.3.6	Fire and Explosion Protection..... K.2-8
K.2.4	Decommissioning Considerations..... K.2-9
K.2.5	Summary of NUHOMS®-61BT DSC Design Criteria..... K.2-10
K.2.6	References K.2-11
K.3	Structural EvaluationK.3.1-1
K.3.1	Structural Design..... K.3.1-1
K.3.1.1	Discussion K.3.1-1
K.3.1.2	Design Criteria K.3.1-2
K.3.1.2.1	DSC Confinement Boundary K.3.1-2
K.3.1.2.2	DSC Basket K.3.1-3

K.3.1.2.3	ASME Code Exception for the 61BT DSC.....	K.3.1-4
K.3.2	Weights and Centers of Gravity	K.3.2-1
K.3.3	Mechanical Properties of Materials.....	K.3.3-1
K.3.3.1	Material Properties	K.3.3-1
K.3.3.2	Materials Durability	K.3.3-1
K.4	Thermal Evaluation	K.4-1
K.4.1	Discussion	K.4-1
K.4.2	Summary of Thermal Properties of Materials.....	K.4-3
K.4.3	Specifications for Components	K.4-7
K.4.4	Thermal Evaluation for Normal Conditions of Storage (NCS) and Transfer (NCT).....	K.4-8
K.4.4.1	NUHOMS®-61BT DSC Thermal Models.....	K.4-8
K.4.4.2	Maximum Temperatures	K.4-10
K.4.4.3	Minimum Temperatures	K.4-10
K.4.4.4	Maximum Internal Pressures.....	K.4-10
K.4.4.5	Maximum Thermal Stresses.....	K.4-12
K.4.4.6	Evaluation of Cask Performance for Normal Conditions	K.4-12
K.4.5	Thermal Evaluation for Off-Normal Conditions.....	K.4-13
K.4.5.1	Off-Normal Maximum/Minimum Temperatures during Storage	K.4-13
K.4.5.2	Off-Normal Maximum/Minimum Temperatures during Transfer	K.4-13
K.4.5.3	Off-Normal Maximum Internal Pressure during Storage/Transfer.....	K.4-13
K.4.5.4	Maximum Thermal Stresses.....	K.4-14
K.4.5.5	Evaluation of Cask Performance for Off-Normal Conditions	K.4-14
K.4.6	Thermal Evaluation for Accident Conditions	K.4-15
K.4.6.1	Blocked Vent Accident Evaluation	K.4-15
K.4.6.2	Maximum Internal Pressures.....	K.4-15
K.4.6.3	Maximum Thermal Stresses.....	K.4-15
K.4.6.4	Evaluation of Performance During Accident Conditions	K.4-16
K.4.6.5	Hypothetical Fire Accident Evaluation	K.4-16
K.4.7	Thermal Evaluation for Loading/Unloading Conditions	K.4-17
K.4.7.1	Vacuum Drying Analysis	K.4-17
K.4.7.1.1	Steady State Vacuum Drying Evaluation.....	K.4-17
K.4.7.1.2	Transient Vacuum Drying Evaluation.....	K.4-17
K.4.7.1.3	Reflooding Evaluation.....	K.4-17
K.4.8	References	K.4-19
K.5	Shielding Evaluation	K.5-1
K.5.1	Discussion and Results.....	K.5-2
K.5.2	Source Specification.....	K.5-3
K.5.2.1	Gamma Source	K.5-3
K.5.2.1.1	Energy Group Mapping.....	K.5-3
K.5.2.1.2	Gamma Source Calculations	K.5-4
K.5.2.2	Neutron Source Term	K.5-4
K.5.2.3	Axial Peaking	K.5-5
K.5.3	Model Specification	K.5-6
K.5.3.1	Material Densities	K.5-6
K.5.4	Shielding Evaluation	K.5-7

K.5.4.1	Computer Programs.....	K.5-7
K.5.4.2	Spatial Source Distribution	K.5-7
K.5.4.3	Cross-Section Data.....	K.5-8
K.5.4.4	Flux-to-Dose-Rate Conversion	K.5-8
K.5.4.5	Methodology	K.5-8
K.5.4.5.1	Assumptions.....	K.5-9
K.5.4.6	HSM Dose Rates	K.5-11
K.5.4.7	HSM Roof Model.....	K.5-11
K.5.4.8	HSM Floor Model	K.5-12
K.5.4.9	HSM Side Model.....	K.5-12
K.5.4.10	HSM Lateral Model	K.5-12
K.5.4.11	Data Reduction and Dose Rate Results.....	K.5-12
K.5.4.11.1	Front Surface	K.5-12
K.5.4.11.2	Back Surface	K.5-13
K.5.4.11.3	HSM Roof	K.5-13
K.5.4.11.4	End Shield Wall	K.5-13
K.5.4.12	Cask Dose Rates.....	K.5-14
K.5.4.12.1	Transfer Operations.....	K.5-14
K.5.4.13	Decontamination Operations.....	K.5-14
K.5.4.14	Inner Cover Welding.....	K.5-14
K.5.4.15	Outer Cover Welding	K.5-15
K.5.5	Appendix	K.5-16
K.5.5.1	Sample ORIGEN2 Input File	K.5-16
K.5.5.2	Sample HSM DORT Model (RZ Roof Neutron Model).....	K.5-21
K.5.5.3	Sample Transfer Cask DORT Model (RZ Transfer Configuration)	K.5-27
K.5.6	References	K.5-33
K.6	Criticality Evaluation.....	K.6-1
K.6.1	Discussion and Results.....	K.6-1
K.6.2	Package Fuel Loading	K.6-1
K.6.3	Model Specification	K.6-2
K.6.3.1	Description of Calculational Model	K.6-2
K.6.3.2	Package Regional Densities	K.6-3
K.6.4	Criticality Calculation	K.6-4
K.6.4.1	Calculational Method	K.6-5
K.6.4.1.1	Computer Codes.....	K.6-5
K.6.4.1.2	Physical and Nuclear Data	K.6-5
K.6.4.1.3	Bases and Assumptions.....	K.6-5
K.6.4.1.4	Determination of k_{eff}	K.6-6
K.6.4.2	Fuel Loading Optimization	K.6-7
K.6.4.3	Criticality Results.....	K.6-11
K.6.5	Critical Benchmark Experiments	K.6-12
K.6.5.1	Benchmark Experiments and Applicability	K.6-12
K.6.5.2	Results of the Benchmark Calculations	K.6-13
K.6.6	Appendix	K.6-14
K.6.6.1	References	K.6-14
K.6.6.2	Most Reactive Fuel Analysis.....	K.6-14

K.6.6.3	Damaged Fuel Analysis	K.6-23
K.6.6.4	Example CSAS25 Input Deck.....	K.6-37
K.7	Confinement.....	K.7-1
K.7.1	Confinement Boundary	K.7-2
K.7.1.1	Confinement Vessel	K.7-2
K.7.1.2	Confinement Penetrations	K.7-3
K.7.1.3	Seals and Welds	K.7-3
K.7.1.4	Closure	K.7-3
K.7.2	Requirements for Normal Conditions of Storage.....	K.7-4
K.7.2.1	Release of Radioactive Material	K.7-4
K.7.2.2	Pressurization of Confinement Vessel	K.7-4
K.7.3	Confinement Requirements for Hypothetical Accident Conditions	K.7-5
K.7.3.1	Fission Gas Products	K.7-5
K.7.3.2	Release of Contents.....	K.7-5
K.7.4	References	K.7-6
K.8	Operating Systems.....	K.8-1
K.8.1	Procedures for Loading the Cask	K.8-1
K.8.1.1	Preparation of the Transfer Cask and DSC	K.8-1
K.8.1.2	DSC Fuel Loading.....	K.8-3
K.8.1.3	DSC Drying and Backfilling	K.8-5
K.8.1.4	DSC Sealing Operations.....	K.8-8
K.8.1.5	Transfer Cask Downending and Transport to ISFSI.....	K.8-9
K.8.1.6	DSC Transfer to the HSM.....	K.8-10
K.8.1.7	Monitoring Operations	K.8-11
K.8.2	Procedures for Unloading the Cask.....	K.8-16
K.8.2.1	DSC Retrieval from the HSM	K.8-16
K.8.2.2	Removal of Fuel from the DSC.....	K.8-17
K.8.3	Identification of Subjects for Safety Analysis.....	K.8-26
K.8.4	Fuel Handling Systems.....	K.8-26
K.8.5	Other Operating Systems	K.8-26
K.8.6	Operation Support System	K.8-26
K.8.7	Control Room and/or Control Areas	K.8-26
K.8.8	Analytical Sampling.....	K.8-26
K.8.9	References	K.8-27
K.9	Acceptance Tests and Maintenance Program	K.9-1
K.9.1	Acceptance Tests.....	K.9-1
K.9.1.1	Visual Inspection.....	K.9-1
K.9.1.2	Structural	K.9-1
K.9.1.3	Leak Tests	K.9-1
K.9.1.4	Components.....	K.9-2
K.9.1.5	Shielding Integrity.....	K.9-2
K.9.1.6	Thermal Acceptance.....	K.9-2
K.9.1.7	Poison Acceptance	K.9-2
K.9.2	Maintenance Program	K.9-9
K.9.3	References	K.9-10

K.10	Radiation Protection	K.10-1
K.10.1	Occupational Exposure	K.10-1
K.10.2	Off-Site Dose Calculations.....	K.10-2
K.10.2.1	Activity Calculations.....	K.10-4
K.10.2.2	Dose Rates.....	K.10-4
K.10.3	References	K.10-6
K.11	Accident Analyses.....	K.11-1
K.11.1	Off-Normal Operations	K.11-1
K.11.1.1	Off-Normal Transfer Loads	K.11-1
K.11.1.1.1	Postulated Cause of Event.....	K.11-1
K.11.1.1.2	Detection of Event.....	K.11-1
K.11.1.1.3	Analysis of Effects and Consequences.....	K.11-1
K.11.1.1.4	Corrective Actions.....	K.11-2
K.11.1.2	Extreme Temperatures	K.11-2
K.11.1.2.1	Postulated Cause of Event.....	K.11-2
K.11.1.2.2	Detection of Event.....	K.11-2
K.11.1.2.3	Analysis of Effects and Consequences.....	K.11-2
K.11.1.2.4	Corrective Actions.....	K.11-2
K.11.1.3	Off-Normal Releases of Radionuclides.....	K.11-3
K.11.1.3.1	Postulated Cause of Event.....	K.11-3
K.11.1.3.2	Detection of Event.....	K.11-3
K.11.1.3.3	Analysis of Effects and Consequences.....	K.11-3
K.11.1.3.4	Corrective Actions.....	K.11-3
K.11.1.4	Radiological Impact from Off-Normal Operations.....	K.11-3
K.11.2	Postulated Accidents	K.11-4
K.11.2.1	Reduced HSM Air Inlet and Outlet Shielding	K.11-4
K.11.2.1.1	Cause of Accident	K.11-4
K.11.2.1.2	Accident Analysis	K.11-4
K.11.2.1.3	Accident Dose Calculations	K.11-4
K.11.2.1.4	Corrective Actions.....	K.11-4
K.11.2.2	Earthquake.....	K.11-5
K.11.2.2.1	Cause of Accident	K.11-5
K.11.2.2.2	Accident Analysis	K.11-5
K.11.2.2.3	Accident Dose Calculations	K.11-5
K.11.2.2.4	Corrective Actions.....	K.11-5
K.11.2.3	Extreme Wind and Tornado Missiles.....	K.11-5
K.11.2.3.1	Cause of Accident	K.11-5
K.11.2.3.2	Accident Analysis	K.11-5
K.11.2.3.3	Accident Dose Calculations	K.11-6
K.11.2.3.4	Corrective Actions.....	K.11-6
K.11.2.4	Flood.....	K.11-6
K.11.2.4.1	Cause of Accident	K.11-6
K.11.2.4.2	Accident Analysis	K.11-6
K.11.2.4.3	Accident Dose Calculations	K.11-6
K.11.2.4.4	Corrective Actions.....	K.11-6
K.11.2.5	Accidental Transfer Cask Drop.....	K.11-6

K.11.2.5.1	Cause of Accident	K.11-6
K.11.2.5.2	Accident Analysis	K.11-7
K.11.2.5.3	Accident Dose Calculations for Loss of Neutron Shield	K.11-7
K.11.2.5.4	Corrective Action	K.11-8
K.11.2.6	Lightning	K.11-8
K.11.2.7	Blockage of Air Inlet and Outlet Openings.....	K.11-8
K.11.2.7.1	Cause of Accident	K.11-8
K.11.2.7.2	Accident Analysis	K.11-8
K.11.2.7.3	Accident Dose Calculations	K.11-8
K.11.2.7.4	Corrective Action	K.11-8
K.11.2.8	DSC Leakage.....	K.11-9
K.11.2.9	Accident Pressurization of DSC.....	K.11-9
K.11.2.9.1	Cause of Accident	K.11-9
K.11.2.9.2	Accident Analysis	K.11-9
K.11.2.9.3	Accident Dose Calculations	K.11-9
K.11.2.9.4	Corrective Actions.....	K.11-9
K.11.2.10	Fire and Explosion	K.11-9
K.11.2.10.1	Cause of the Accident	K.11-9
K.11.2.10.2	Accident Analysis	K.11-10
K.11.2.10.3	Accident Dose Calculations	K.11-10
K.11.2.10.4	Corrective Actions.....	K.11-10
K.11.3	References	K.11-11
K.12	Conditions for Cask Use - Operating Controls and Limits or Technical Specifications.....	K.12-1
K.13	Quality Assurance	K.13-1
K.14	Decommissioning.....	K.14-1

LIST OF TABLES

	<u>Page</u>
Table K.1-1 Nominal Dimensions and Weight of the NUHOMS [®] -61BT DSC	K.1-10
Table K.2-1 Intact BWR Fuel Assembly Characteristics	K.2-12
Table K.2-2 Damaged BWR Fuel Assemblies Characteristics.....	K.2-13
Table K.2-3 BWR Fuel Assembly Design Characteristics ⁽¹⁾⁽³⁾⁽⁴⁾	K.2-15
Table K.2-4 BWR Fuel Assembly Poison Material Design Requirements	K.2-16
Table K.2-5 Summary of Canister Load Combinations.....	K.2-17
Table K.2-6 Canister Allowable Stress	K.2-21
Table K.2-7 Basket Stress Limits.....	K.2-22
Table K.2-8 Classification of NUHOMS [®] -DSC Components.....	K.2-23
Table K.2-9 Additional Design Criteria for NUHOMS [®] -61BT DSC.....	K.2-24
Table K.2-10 Summary of NUHOMS [®] -61BT Component Design Loadings ⁽¹⁾	K.2-25
Table K.3.1-1 Numerical Values of Primary Stress Intensity Limits	K.3.1-5
Table K.3.1-2 ASME Code Exceptions for the NUHOMS [®] -61BT DSC Confinement Boundary	K.3.1-6
Table K.3.1-3 ASME Code Exceptions for the NUHOMS [®] -61BT DSC Basket	K.3.1-7
Table K.3.2-1 Summary of the NUHOMS [®] -61BT System Component Weights	K.3.2-2
Table K.4-1 NUHOMS [®] -61BT DSC Component Temperatures During Storage.....	K.4-20
Table K.4-2 NUHOMS [®] -61BT DSC Component Temperatures During Transfer	K.4-21
Table K.4-3 NUHOMS [®] -61BT DSC Component Temperatures During Storage and Transfer (-40 °F Ambient, w/o insolation)	K.4-22
Table K.4-4 Temperature Distribution within the NUHOMS [®] -61BT DSC (After 96 Hours of Vacuum Drying Condition).....	K.4-23
Table K.4-5 NUHOMS [®] -61BT DSC Normal, Off-Normal and Accident Pressures.....	K.4-24
Table K.4-6 Maximum Component Temperatures for the Hypothetical Fire Accident Case for the NUHOMS [®] -61BT DSC in a OS197 Transfer Cask	K.4-25
Table K.5-1 Fuel Assembly Designs Considered	K.5-34
Table K.5-2 Dose Rates Due to the 61 BWR Assemblies	K.5-35
Table K.5-3 Summary of HSM Dose Rates.....	K.5-36
Table K.5-4 Summary of Cask Onsite Transfer Dose Rates.....	K.5-37
Table K.5-5 BWR Fuel Assembly Materials and Masses.....	K.5-38
Table K.5-6 Gamma Energy Group Mapping Functions.....	K.5-39
Table K.5-7 ORIGEN2 Gamma Sources for 27 GWd/MTU, 5-Year Cooled BWR Fuel.....	K.5-40
Table K.5-8 ORIGEN2 Gamma Sources for 35 GWd/MTU, 8-Year Cooled BWR Fuel.....	K.5-41
Table K.5-9 ORIGEN2 Gamma Sources for 37.2 GWd/MTU, 6.5-Year Cooled BWR Fuel.....	K.5-42
Table K.5-10 ORIGEN2 Gamma Sources for 40 GWd/MTU, 10-Year Cooled BWR Fuel.....	K.5-43
Table K.5-11 Gamma Sources for DORT Code Models	K.5-44
Table K.5-12 Total Neutron Source Summary	K.5-45

Table K.5-13 Volumetric Design Basis Neutron Source	K.5-46
Table K.5-14 Source Term Peaking Summary	K.5-47
Table K.5-15 In-Core Region Material	K.5-48
Table K.5-16 In-Core Material Densities (with basket materials, without fuel channels).....	K.5-49
Table K.5-17 Bottom Region Material Densities (without basket materials).....	K.5-50
Table K.5-18 Top Region Material Densities (without basket materials)	K.5-51
Table K.5-19 Summary of Material Densities	K.5-52
Table K.6-1 Minimum B-10 Content in the Neutron Poison Plates	K.6-49
Table K.6-2 Authorized Contents for NUHOMS®-61BT System	K.6-50
Table K.6-3 Parameters for BWR Assemblies.....	K.6-51
Table K.6-4 Axial Layout of the KENO V.a Model of Cask and DSC	K.6-52
Table K.6-5 Material Property Data.....	K.6-53
Table K.6-6 Most Reactive Fuel Type	K.6-54
Table K.6-7 Most Reactive Configuration – Intact Fuel.....	K.6-55
Table K.6-8 Most Reactive 7x7 Configuration – Damaged Fuel	K.6-56
Table K.6-9 Most Reactive 8x8 Configuration – Damaged Fuel	K.6-57
Table K.6-10 Criticality Results.....	K.6-58
Table K.6-11 Benchmarking Results	K.6-59
Table K.6-12 USL-1 Results	K.6-62
Table K.6-13 USL Determination for Criticality Analysis	K.6-63
Table K.9-1 Specified Boron Content	K.9-11
Table K.9-2 Specified Boron Carbide Content	K.9-12
Table K.9-3 Specified B10 Areal Density.....	K.9-13
Table K.10-1 Occupational Exposure Summary.....	K.10-7
Table K.10-2 Total Annual Exposure	K.10-9
Table K.10-3 HSM Gamma-Ray Spectrum Calculation Results.....	K.10-10
Table K.10-4 HSM Neutron Spectrum Calculations	K.10-11
Table K.10-5 Summary of ISFSI Surface Activities.....	K.10-12
Table K.10-6 MCNP Front Detector Dose Rates for 2x10 Array.....	K.10-13
Table K.10-7 MCNP Back Detector Dose Rates for the Two 1x10 Arrays	K.10-14
Table K.10-8 MCNP Side Detector Dose Rates	K.10-15
Table K.11-1 Comparison of Total Dose Rates for HSM with and without Adjacent HSM Shielding Effects	K.11-12
Table K.11-2 Cask Accident Neutron Source	K.11-13
Table K.11-3 Cask Accident Gamma Source	K.11-14
Table K.11-4 Cask Accident Dose Rate Results	K.11-15

LIST OF FIGURES

	<u>Page</u>
Figure K.1-1 NUHOMS [®] -61BT DSC Components.....	K.1-11
Figure K.3.1-1 61BT-DSC Confinement Boundary	K.3.1-8
Figure K.4-1 Applied DSC Temperature Distribution (-40 F Ambient , w/o insolation).....	K.4-26
Figure K.4-2 Applied DSC Temperature Distribution (100 °F ambient w/ insolation).....	K.4-27
Figure K.4-3 Applied DSC Temperature Distribution (125 °F ambient w/ insolation).....	K.4-28
Figure K.4-4 Applied DSC Temperature Distribution (125°F Ambient Blocked Vent Accident Condition)	K.4-29
Figure K.4-5 90° Symmetry Finite Element Model of NUHOMS [®] -61BT DSC.....	K.4-30
Figure K.4-6 Storage Temperature Distribution Within NUHOMS [®] -61BT Basket With a -40 °F Ambient (Hottest Cross-Section).....	K.4-31
Figure K.4-7 Maximum Temperature Distribution Within NUHOMS [®] -61BT Basket During 125°F Ambient, Blocked Vent Accident Condition (Hottest Cross-Section)	K.4-32
Figure K.4-8 Axial Heat Flux Profile for BWR Fuel	K.4-33
Figure K.4-9 NUHOMS [®] -61BT DSC and OS197 Transfer Cask Temperature Response to 15 Minute Fire Accident Conditions	K.4-34
Figure K.5-1 Axial Burnup Profile For Design Basis Fuel.....	K.5-53
Figure K.5-2 HSM Roof Model Geometry	K.5-54
Figure K.5-3 HSM Floor Model Geometry	K.5-55
Figure K.5-4 HSM Side Model Geometry	K.5-56
Figure K.5-5 HSM Lateral Model Geometry.....	K.5-57
Figure K.5-6 HSM Front Wall Dose Rate Distribution	K.5-58
Figure K.5-7 Geometry for Front Wall Average Dose Rate Calculation.....	K.5-59
Figure K.5-8 HSM Back Wall Dose Rate Distribution.....	K.5-60
Figure K.5-9 HSM Roof Dose Rate Distribution.....	K.5-62
Figure K.5-10 Surface Average Calculation Geometry	K.5-63
Figure K.5-11 Cask Model Geometry.....	K.5-64
Figure K.5-12 Cask Normal Operation Dose Rate Distribution	K.5-65
Figure K.5-13 Cask Top-End Dose Rates During Decontamination	K.5-66
Figure K.5-14 Cask Top-End Dose Rates During Inner Cover Welding.....	K.5-67
Figure K.5-15 Cask Top-End Dose Rates During Outer Cover Welding.....	K.5-68
Figure K.6-1 NUHOMS [®] -61BT DSC Axial Cross Section.....	K.6-64
Figure K.6-2 KENO V.a Units and Radial Cross Sections of the Model	K.6-65
Figure K.6-3 Representative KENO V.a Model Cross Section – Most Reactive Fuel.....	K.6-84
Figure K.6-4 Fuel Assembly Layouts	K.6-85
Figure K.6-5 Variable Enrichment Fuel Assembly Layouts.....	K.6-86
Figure K.6-6 Single Break Case – Maximum Separation.....	K.6-87
Figure K.6-7 Double Break Case	K.6-88
Figure K.6-8 Single Break Case – Above Poison Plates.....	K.6-89

Figure K.6-9 Double Break Case – Above Poison Plate..... K.6-90
Figure K.8.1-1 NUHOMS® System Loading Operations Flow Chart K.8-13
Figure K.8.2-1 NUHOMS® System Retrieval Operations Flow Chart..... K.8-23
Figure K.10-1 Annual Exposure from the ISFSI as a Function of Distance..... K.10-16
Figure K.11-1 Cask Accident Dose Rate Distribution..... K.11-16

K.2.1 Spent Fuel To Be Stored

The NUHOMS[®]-61BT DSC is designed to store 61 intact, or up to 16 damaged and the remainder intact, for a total of 61, standard BWR fuel assemblies with or without fuel channels. The NUHOMS[®]-61BT DSC can store intact BWR fuel assemblies with the characteristics described in Table K.2-1, or damaged and intact BWR fuel assemblies with the characteristics described in Table K.2-2, which include a variety of cooling times, enrichment and maximum bundle average burnup. Damaged BWT fuel assemblies are fuel assemblies containing fuel rods with known or suspected cladding defects greater than hairline cracks or pinhole leaks or with cracked, bulging, or discolored cladding. Missing cladding and/or crack size in the fuel pins is to be limited such that a fuel pellet is not able to pass through the gap created opening during handling *and retrievability is assured following Normal/Off-Normal conditions*. The NUHOMS[®]-61BT DSC may store BWR fuel assemblies with a maximum decay heat of 300 watts/assembly, or a total of 18.3 kW. The NUHOMS[®]-61BT DSC is inserted and backfilled with helium at the time of loading. The maximum fuel assembly weight with channel is 705 lbs.

Calculations were performed to determine the fuel assembly type which was most limiting for each of the analyses including shielding, criticality, heat load and confinement. The fuel assemblies considered are listed in Table K.2-3. It was determined that the GE 7x7 is the enveloping fuel design for the shielding source term calculation. However, for criticality safety, the GE 10x10 assembly is the most reactive, and is evaluated for configurations that bound all normal, off-normal and accident conditions.

The NUHOMS[®]-61BT DSC has three basket configurations, based on the boron content in the poison plates. The maximum lattice average enrichment authorized for Type A, B and C NUHOMS[®]-61BT DSCs is 3.7, 4.1 and 4.4 weight percent (wt. %) U-235, respectively.

Intact BWR fuel assemblies may be stored in any of the three NUHOMS[®]-61BT DSC Types provided the loading meets the maximum lattice average enrichment limit for the NUHOMS[®]-61BT DSC type, as given on Table K.2-4. Damaged BWR fuel assemblies may only be stored in Type C NUHOMS[®]-61BT DSCs with endcaps installed on each four compartment assembly where a damaged fuel assembly is stored.

Fuel assemblies with various combinations of burnup, enrichment and cooling time can be stored in the NUHOMS[®]-61BT DSC as long as the fuel assembly parameters fall within the design limits specified in Table K.2-1 or Table K.2-2, and Table K.2-4.

For calculating the maximum internal pressure in the NUHOMS[®]-61BT DSC, it is assumed that 1% of the fuel rods are damaged for normal conditions, up to 10% of the fuel rods are damaged for off normal conditions, and 100% of the fuel rods will be damaged following a design basis accident event. A minimum of 100% of the fill gas and 30% of the fission gases (e.g., H-3, Kr and Xe) within the ruptured fuel rods are assumed to be available for release into the DSC cavity, consistent with NUREG-1536 [2.1].

**Table K.2-2
Damaged BWR Fuel Assemblies Characteristics**

<u>PHYSICAL PARAMETERS:</u>	
Fuel Design:	7x7, 8x8 BWR damaged fuel assemblies manufactured by General Electric or equivalent reload fuel that are enveloped by the Fuel assembly design characteristics listed in Table K.2-3 for the 7x7 and 8x8 designs only.
Cladding Material:	Zircaloy
Fuel Damage:	Damaged BWR fuel assemblies are fuel assemblies containing fuel rods with known or suspected cladding defects greater than hairline cracks or pinhole leaks or with cracked, bulging, or discolored cladding. Missing cladding and/or crack size in the fuel pins is to be limited such that a fuel pellet is not able to pass through the gap created by the cladding opening during handling and retrievability is assured following Normal/Off-Normal conditions. Damaged fuel shall be stored with Top and Bottom Caps for Failed Fuel. Damaged fuel may only be stored in the 2x2 compartments of the "Type C" NUHOMS [®] -61B Canister.
Channels:	Fuel may be stored with or without fuel channels
<u>RADIOLOGICAL PARAMETERS²:</u>	
Group 1:	
Maximum Burnup:	27,000 MWd/MTU
Minimum Cooling Time:	5-years
Maximum Initial Lattice Average Enrichment:	4.0 wt. % U-235
Maximum Pellet Enrichment:	4.4 wt. % U-235
Minimum Initial Bundle Average Enrichment:	2.0 wt. % U-235
Maximum Initial Uranium Content:	198 kg/assembly
Maximum Decay Heat:	300 W/assembly
Group 2:	
Maximum Burnup:	35,000 MWd/MTU
Minimum Cooling Time:	8-years
Maximum Initial Lattice Average Enrichment:	4.0 wt. % U-235
Maximum Pellet Enrichment:	4.4 wt. % U-235
Minimum Initial Bundle Average Enrichment:	2.65 wt. % U-235
Maximum Initial Uranium Content:	198 kg/assembly
Maximum Decay Heat:	300 W/assembly
Group 3:	
Maximum Burnup:	37,200 MWd/MTU
Minimum Cooling Time:	6.5-years
Maximum Initial Lattice Average Enrichment:	4.0 wt. % U-235
Maximum Pellet Enrichment:	4.4 wt. % U-235
Minimum Initial Bundle Average Enrichment:	3.38 wt. % U-235
Maximum Initial Uranium Content:	198 kg/assembly
Maximum Decay Heat:	300 W/assembly

² Fuel assemblies fully complying with any of the following groups of parameters are suitable for storage in the NUHOMS[®]-61BT DSC. No interpolation of Radiological Parameters is permitted between Groups.

K.7.1 Confinement Boundary

Once inside the DSC, the SFAs are confined by the DSC shell and by multiple barriers at each end of the DSC. For intact fuel, the fuel cladding is the first barrier for confinement of radioactive materials. The fuel cladding is protected by maintaining the cladding temperatures during storage below those levels, which may cause degradation of the cladding. In addition, the SFAs are stored in an inert atmosphere to prevent degradation of the fuel, specifically cladding rupture due to oxidation and its resulting volumetric expansion of the fuel. Thus, a helium atmosphere for the DSC is incorporated in the design to protect the fuel cladding integrity by inhibiting the ingress of oxygen into the DSC cavity.

Helium is known to leak through valves, mechanical seals, and escape through very small passages because of its small atomic diameter and because it is an inert element and exists in a monatomic species. Negligible leakage rates can be achieved with careful design of vessel closures. Helium will not, to any practical extent, diffuse through stainless steel. For this reason, the DSC has been designed as a redundant weld-sealed containment pressure vessel with no mechanical or electrical penetrations.

For damaged fuel assemblies, top and bottom caps are provided to contain fuel debris such as broken rods, loose pellets and/or pieces of cladding in the fuel compartment. The end caps fit snugly into the top and bottom of the fuel compartment. They are held in place by the fuel compartments and the inner bottom cover plate and the top shield plug during transfer and storage. The end caps have multiple 1/8-inch through holes to permit unrestricted flooding and draining of the fuel cells.

K.7.1.1 Confinement Vessel

The confinement vessel is provided by the NUHOMS[®]-61BT DSC. The DSC is designed to provide confinement of all radionuclides under normal and accident conditions. The DSC is designed, fabricated and tested in accordance with the applicable requirements of the ASME Boiler and Pressure Vessel Code, Division 1, Section III, Subsection NB [7.2] *with exceptions as discussed in Section K.3.1.2.3*. The shell and inner and outer bottom cover plates are delivered to the site as an assembly. The shell and the inner bottom cover plate, which provide the confinement boundary as shown in Figure K.3-1, are tested to meet the leak tight criteria as defined in Reference 7.1 at the fabricator. The pneumatic pressure test and leak test are performed on the finished shell and the inner cover plate during fabrication. The outer bottom cover plate provides redundant confinement boundary. The root and final layer closure welds for this redundant boundary are inspected using dye penetrant inspection methods in accordance with requirements of the ASME code[7.2].

Once the fuel assemblies are loaded in the DSC, the heavy shield plug is installed to provide radiation shielding to minimize radiation exposure to workers during DSC closure operations. The inner top cover plate is welded into place along with the vent and siphon port cover plates. These welds represent the first level of closure for the DSC. Finally, the outer top cover plate is welded into place to form the redundant confinement boundary of the DSC. The inner plate is

tested using the test port in the outer top cover plate to meet the leak tight criteria [7.1]. The test port *is then threaded into the outer top cover plate and seal welded in place*. The root, mid and final layer closure welds for this redundant boundary are inspected using dye penetrant inspection methods in accordance with requirements of the ASME code [7.2].

K.7.1.2 Confinement Penetrations

The DSC pressure boundary contains two penetrations (vent and siphon ports) for draining, vacuum drying and backfilling the DSC cavity. The vent and siphon ports are closed with welded cover plates and the outer top cover plate provides the redundant closure. The outer coverplate has a single penetration used for leak testing the closure welds. This test port is *threaded into the outer top cover plate and seal welded in place* after testing to complete the redundant closure. The DSC has no bolted closures or mechanical seals. The final confinement boundary contains no external penetrations.

K.7.1.3 Seals and Welds

The DSC cylindrical shell is fabricated from rolled ASME stainless steel plate that is joined with full penetration 100% radiographed welds. All top and bottom end closure welds are multiple-layer welds. This effectively eliminates a pinhole leak which might occur in a single pass weld, since the chance of pinholes being in alignment on successive weld passes is not credible. Furthermore, the DSC cover plates are sealed by separate, redundant closure welds. All the DSC pressure boundary welds are inspected according to the appropriate articles of the ASME Boiler and Pressure Vessel Code, Section III, Division 1, Subsection NB. These criteria insure that the weld filler metal is as sound as the parent metal of the pressure vessel. There are no bolted closures or mechanical seals.

K.7.1.4 Closure

All top end closure welds are multiple-layer welds. This effectively eliminates a pinhole leak which might occur in a single pass weld, since the chance of pinholes being in alignment on successive weld passes is not credible. Furthermore, the DSC cover plates are sealed by separate, redundant closure welds. Finally, the inner closure welds are tested to the leak tight criteria [7.1]. There are no bolted closures or mechanical seals.

K.9 Acceptance Tests and Maintenance Program

K.9.1 Acceptance Tests

The acceptance requirements for the NUHOMS[®]-61BT System are given in the existing FSAR with the exceptions described in the following sections. The NUHOMS[®]-61BT DSC has been enhanced to provide leaktight confinement and the basket includes an updated poison plate design. Additional acceptance testing of the NUHOMS[®]-61BT DSC welds and of the poison plates are described.

K.9.1.1 Visual Inspection

There are no changes associated with this amendment.

K.9.1.2 Structural

The NUHOMS[®]-61BT DSC confinement welds are designed, fabricated, tested and inspected in accordance with ASME B&PV Code Subsection NB [9.1] with exceptions as listed in Section K.3.1. The following requirements are unique to the NUHOMS[®]-61BT DSC:

- The inner bottom cover weld is inspected in accordance with Article NB-5231.
- The outer bottom cover weld root and cover are penetrant tested.
- The canister shell longitudinal and circumferential welds are 100% radiographically inspected.
- The outer top cover plate weld root, middle and cover are penetrant tested.

The NUHOMS[®]-61BT DSC basket is designed, fabricated, and inspected in accordance with ASME B&PV Code Subsection NG [9.1] with exceptions as listed in Section K.3.1. The following requirements are unique to the NUHOMS[®]-61BT DSC:

- The fuel compartment wrapper welds are inspected in accordance with Article NG-5231.
- The fuel compartment welds are inspected in accordance with Article NG-5231.

K.9.1.3 Leak Tests

The NUHOMS[®]-61BT DSC confinement is leak tested to verify it is leaktight in accordance with ANSI N14.5 [9.2].

The leak tests are typically performed using the helium mass spectrometer method. Alternative methods are acceptable, provided that the required sensitivity is achieved.

K.9.1.4 Components

No changes associated with this amendment.

K.9.1.5 Shielding Integrity

No changes associated with this amendment.

K.9.1.6 Thermal Acceptance

The analyses to ensure that the NUHOMS[®]-61BT DSCs are capable of performing their heat transfer function are presented in Section K.4.

K.9.1.7 Poison Acceptance

Functional Requirements of Poison Plates

The poison plates only serve as a neutron absorber for criticality control and as a heat conduction path; the NUHOMS[®]-61BT DSC safety analyses do not rely upon their mechanical strength. The basket structural components surround the plates on all sides. The radiation and temperature environment in the cask is not sufficiently severe to damage the aluminum matrix that retains the boron-containing particles. To assure performance of the plates' Important-to-Safety function, the only critical variables that need to be verified are thermal conductivity and B10 areal density as discussed in the following paragraphs.

Thermal Conductivity Testing

The poison plate material will be qualification tested to verify that the thermal conductivity equals or exceeds the values listed in Section K.4.3. Acceptance testing of the material in production may be done at only one temperature in that range to verify that the conductivity equals or exceeds the corresponding value in Section K.4.3.

Testing may be by ASTM E1225 [9.3], ASTM E1461 [9.4], or equivalent method, performed on a sample of specimens removed from coupons adjacent to the final plates (see Section K.9.1.7 for more detail on coupons).

B10 Aerial Density Testing

There are three types of NUHOMS[®]-61BT DSC baskets (Type A, B, and C), each identical with the exception of the minimum B10 content in the poison plates, as described in Table K.6-1. Only one type of poison plate is used in a specific NUHOMS[®]-61BT DSC, based on the maximum enrichment of the fuel that will be placed in the NUHOMS[®]-61BT DSC. There are three acceptable poison materials, Boral[®], Borated Aluminum and Boron Carbide/Aluminum Metal Matrix Composite (MMC). There are two variations on the MMC, one with billets produced by vacuum hot pressing, and the second produced by cold isostatic pressing followed

by vacuum sintering. All materials shall be subject to thermal conductivity, dimensional, and visual acceptance testing. The B10 areal density and uniformity of the poison plates shall be verified, based on type, using approved procedures, as follows.

A. Borated Aluminum Using Enriched Boron, 90% B10 Credit

Material Description

The poison consists of borated aluminum containing a specified weight percent (wt. %) boron, depending on the NUHOMS®-61BT DSC Type, which is isotopically enriched to 95 wt. % B10. Because of the negligibly low solubility of boron in solid aluminum, the boron appears entirely as discrete second phase particles of AlB₂ in the aluminum matrix. The matrix is limited to any 1000 series aluminum, aluminum alloy 6063, or aluminum alloy 6351 so that no boron-containing phases other than AlB₂ are formed. Titanium may also be added to form TiB₂ particles, which are finer. The effect on the properties of the matrix aluminum alloy are those typically associated with a uniform fine (1-10 micron) dispersion of an inert equiaxed second phase.

The cast ingot may be rolled, extruded, or both to the final plate dimensions.

The specified wt. % boron for full thickness (0.305 inch) plates, by NUHOMS®-61BT DSC Type is given in Table K.9-1. For example, the 2.1 wt. % converts to a nominal areal density of B10 as follows: $(2.69 \text{ g BAl/cm}^3)(2.1 \text{ wt. \% B})(95 \text{ wt. \% B10})(0.305 \text{ inch})(2.54 \text{ cm/inch}) = 0.0416 \text{ g B10/cm}^2$, which is intentionally 4% above the design minimum of 0.040 g B10/cm². If thinner poison sheets are paired with aluminum sheets (see drawing NUH-61B-1065), the boron content shall be proportionately higher, up to that needed to maintain the minimum required B10 areal density.

Test Coupons

The poison plates are manufactured in a variety of sizes. Coupons will be removed between every other plate or at the end of the plate so that there is at least one coupon contiguous with each plate. Coupons will generally be the full width of the plate. Thermal conductivity coupons may be removed from the full width coupon. The minimum dimension of the coupon shall be as required for acceptance test specimens; 1 to 2 inches is generally adequate.

Acceptance Testing, Neutronic

Effective B10 content is verified by neutron transmission testing of these coupons. The transmission through the coupons is compared with transmission through calibrated standards composed of a homogeneous boron compound without other significant poisons, for example zirconium diboride or titanium diboride. These standards are paired with aluminum shims sized to match the scattering by aluminum in the poison plates. Uniform but non-homogeneous materials such as metal matrix composites may be used for standards, provided that testing shows them to be equivalent to a homogeneous standard. The effective B10 content of each

coupon, minus 3σ based on the number of neutrons counted for that coupon, must be greater than or equal to the minimum value given in Table K.9-1.

Macroscopic uniformity of B10 distribution is verified by neutron radioscopy or radiography of the coupons. The acceptance criterion is that there be uniform luminance across the coupon. This inspection shall cover the entire coupon. Alternatively, a statistical analysis of the neutron transmission results for all accepted plates in a lot may be used to demonstrate that applying the one-sided tolerance factors for a 95% probability / 95% confidence level results in a minimum areal density greater than 90% of the average.

Initial sampling of coupons for neutron transmission measurements and radiography/radioscopy shall be 100%. Rejection of a given coupon shall result in rejection of its associated plate. Reduced sampling may be introduced.

Justification for Acceptance Test Requirements, Borated Aluminum

According to NUREG/CR-5661 [9.5]

“Limiting added poison material credit to 75% without comprehensive tests is based on concerns for potential ‘streaming’ of neutrons due to nonuniformities. It has been shown that boron carbide granules embedded in aluminum permit channeling of a beam of neutrons between the grains and reduce the effectiveness for neutron absorption.”

Furthermore

“A percentage of poison material greater than 75% may be considered in the analysis only if comprehensive tests, capable of verifying the presence *and uniformity* of the poison, are implemented.” [emphasis added]

The calculations in Section K.6 use boron areal densities that are 90% of the minimum values given in Table K.9-1. This is justified by the following considerations.

- a) The coupons for neutronic inspection are removed between every other finished plate. As such, they are taken from locations that are representative of the finished product. Coupons are also removed at the ends of the “stock plate”, where under thickness of the plates or defects propagated from the pre-roll ingot would be most likely. The use of representative coupons for inspection is analogous to the removal of specimens from structural materials for mechanical testing.
- b) Neutron radiography/radioscopy of coupons across the full width of the plate will detect macroscopic non-uniformities in the B10 distribution such as could be introduced by the fabrication process.
- c) Neutron transmission measures effective B10 content directly. The term “effective” is used here because if there are any of the effects noted in NUREG/CR-5661, the neutron transmission technique will measure not the physical B10 areal density, but a lower value.

Thus, this technique by its nature screens out the microscopic non-uniformities which have been the source of the recommended 75% credit for B10 in criticality evaluations.

d) The use of neutron transmission and radiography/radioscopy satisfies the “and uniformity” requirement emphasized in NUREG/CR-5661 on both the microscopic and macroscopic scales.

e) The recommendations of NUREG/CR-5661 are based upon testing of a poison with boron carbide particles averaging 85 microns. The boride particles in the borated aluminum are much finer (5-10 microns). Both the manufacturing process and the neutron radioscopy assure that they are uniformly distributed. For a given degree of uniformity, fine particles will be less subject to neutron streaming than coarse particles. Furthermore, because the material reviewed in the NUREG was a sandwich panel, the thickness of the boron carbide containing center could not be directly verified by thickness measurement. The alloy specified here is uniform throughout its thickness.

B. Boron Carbide/Aluminum Metal Matrix Composite (MMC), 90% B10 credit

Material Description

The poison plates consist of a composite of aluminum with a specified volume % boron carbide particulate reinforcement, depending on the NUHOMS[®]-61BT DSC Type. The material is formed into a billet by powder metallurgical processes and either extruded, rolled, or both to final dimensions. The finished product has near-theoretical density and metallurgical bonding of the aluminum matrix particles. It is “uniform” blend of powder particles from face to face, i.e.; it is not a “sandwich” panel.

The specified volume % boron carbide, by NUHOMS[®]-61BT DSC Type, is given in Table K.9-2. For example, 15 volume % boron carbide corresponds to a B10 areal density of $0.15(2.52 \text{ g/cm}^3 \text{ B}_4\text{C})(0.782 \text{ gB/gB}_4\text{C})(0.185 \text{ g B10/gB})(0.305 \text{ in})(2.54 \text{ cm/in}) = 0.0424 \text{ g B10/cm}^2$, which is intentionally 6% above the design minimum of 0.040 g B10/cm^2 .

The process specifications for the material shall be subject to qualification testing to demonstrate that the process results in a material that:

- has a uniform distribution of boron carbide particles in an aluminum alloy with few or none of the following: voids, oxide-coated aluminum particles, B₄C fracturing, or B₄C/aluminum reaction products,
- meets the requirements for B10 areal density and thermal conductivity, and
- will be capable of performing its Important-to-Safety functions under the thermal and radiological environment of the NUHOMS[®]-61BT DSC over its 40-year lifetime.

The production of plates for use in the NUHOMS[®]-61BT DSC is consistent with the process used to produce the qualification test material. Processing changes may be incorporated into the production process, only if they are reviewed and approved by the holder of an NRC-approved QA plan who is supervising fabrication. The basis for acceptance shall be that the

changes do not have an adverse effect on either the microstructure or the uniformity of the boron carbide distribution, because these are the characteristics that determine the durability and neutron absorption effectiveness of the material. The evaluation may consist of an engineering review, or it may consist of additional testing. In general, changes in key billet forming variables such as the temperature or pressure would require testing, while changes in mechanical processing variables, such as extrusion speed, would not have to be evaluated. Increasing the boron carbide content would require testing, while decreasing it would not.

Typical processing consists of:

- blending of boron carbide powder with aluminum alloy powder,
- billet formed by cold isostatic pressing + sintering or by vacuum hot pressing,
- billet extruded to intermediate or to final size,
- hot roll, cold roll and flatten as required, and
- anneal.

Test Coupons

The poison plates are manufactured in a variety of sizes. Coupons will be removed between every other plate or at the end of the plate so that there is at least one coupon contiguous with each plate. Coupons will generally be the full width of the plate. Thermal conductivity coupons may be removed from the full width coupon. The minimum dimension of the coupon shall be as required for acceptance test specimens; 1 to 2 inches is generally adequate.

Acceptance Testing, B10 Density

Effective B10 content is verified by neutron transmission testing of these coupons, or by chemical, spectrometric, and dimensional inspection.

In the first method, the transmission through the coupons is compared with transmission through calibrated standards containing a uniform distribution of boron without other significant poisons, for example zirconium diboride, titanium diboride, or boron carbide metal matrix composites. These standards are paired with aluminum shims sized to match the scattering by aluminum in the poison plates. Uniform but non-homogeneous materials such as metal matrix composites may be used for standards, provided that testing shows them to be equivalent to a homogeneous standard. The effective B10 content of each coupon, minus 3σ based on the number of neutrons counted for that coupon, must be greater than or equal to the minimum value given in Table K.9-2.

In the second method, the grams B10 per gram of total boron and the grams of total boron per grams of boron carbide are determined by spectrometric and chemical analysis of each lot of boron carbide feed powder (ASTM-C791 [9.6] or equal). The grams of boron carbide per gram of finished composite is then determined by chemical analysis of a specimen selected from a random location on the finished coupon (ASTM D-3553 [9.7] or equal). These three values are multiplied by the composite density and the minimum allowable plate thickness:

$$(gB_{10}/g B) * (g B/g B_4C) * (g B_4C/g MMC) * (g MMC/cm^3) * (\text{min thickness, cm}) = g B_{10}/cm^2.$$

The value for each coupon must be greater than or equal to the minimum value given in Table K.9-2.

Macroscopic uniformity of B10 distribution is verified by the qualification testing and need not be verified in production because of the high reproducibility of powder metallurgical techniques and the fineness of the boron carbide particles used.

Initial sampling of B10 density measurement shall be 100%. Rejection of a given coupon shall result in rejection of its associated plate. Reduced sampling may be introduced.

Justification for Acceptance Test Requirements, Metal Matrix Composite

According to NUREG/CR-5661

“...Limiting added poison material credit to 75% without comprehensive tests is based on concerns for potential ‘streaming’ of neutrons due to nonuniformities. It has been shown that boron carbide granules embedded in aluminum permit channeling of a beam of neutrons between the grains and reduce the effectiveness for neutron absorption.”

Furthermore

“A percentage of poison material greater than 75% may be considered in the analysis only if comprehensive tests, capable of verifying the presence *and uniformity* of the poison, are implemented.” [emphasis added]

The calculations in Section K.6 use boron areal densities that are 90% of the minimum values given in Table K.9-2. This is justified by the following considerations.

- a) The coupons for neutronic inspection are removed between every other finished plate. As such, they are taken from locations that are truly representative of the finished product, and every plate is represented by a contiguous coupon. Coupons are also removed at the ends of the “stock plate”, where under thickness of the plates or defects propagated from the pre-roll ingot would be most likely. The use of representative coupons for inspection is analogous to the removal of specimens from structural materials for mechanical testing.
- b) Macroscopic uniformity of B10 distribution is verified as part of qualification testing. Thereafter it is assured by controls over the powder metallurgical process.
- c) Neutron transmission measures effective B10 content directly. The term “effective” is used here because if there are any of the effects noted in NUREG/CR-5661, the neutron transmission technique will measure not the physical B10 areal density, but a lower value. Thus, this technique by its nature screens out the microscopic non-uniformities which have been the source of the recommended 75% credit for B10 in criticality evaluations.

d) The use of neutron transmission and powder metallurgical processing satisfies the “and uniformity” requirement emphasized in NUREG/CR-5661 on both the microscopic and macroscopic scales.

e) The recommendations of NUREG/CR-5661 are based upon testing of a poison with boron carbide particles on the order of 80-100 microns. The boron carbide particles in a typical metal matrix composite are much finer (1-25 microns). The powder metal manufacturing process controls and the qualification testing assure that they are uniformly distributed. For a given degree of uniformity, fine particles will be less subject to neutron streaming than coarse particles. Furthermore, because the material reviewed in the NUREG was a sandwich panel, the thickness of the boron carbide containing center could not be directly verified by thickness measurement. The metal matrix composite specified here is uniform throughout its thickness.

C. Boral[®], 75% B10 Credit

Material Description

Boral[®] consists of a core of mechanically bonded aluminum and boron carbide powders sandwiched between two outer layers of aluminum 1100, which is mechanically bonded to the core. The boron carbide particles average approximately 85 microns in diameter. The sheet is formed by filling an aluminum 1100 box with the boron carbide/aluminum powder mixture, and then hot-rolling the box. The walls of the box form the cladding, while the powder mixture forms the core of the Boral[®]. Additional information on the fabrication, specification, and performance of Boral[®] may be found in References [9.8] and [9.9].

Acceptance Testing, Neutronic

Boral[®] will be procured using AAR Advance Structures' standard specification for guidance [9.8]. In accordance with Section 7.3 of that specification, B 10 areal density will be verified by chemical analysis or by neutron attenuation testing, using a sampling plan that will verify conformance to the appropriate requirement of Table K.9-3 with 95% probability at the 95% confidence level.

K.9.2 Maintenance Program

NUHOMS®-61B system is a totally passive system and therefore will require little, if any, maintenance over the lifetime of the ISFSI. Typical NUHOMS®-61BT System maintenance tasks will be performed in accordance with the existing FSAR.

K.9.3 References

- 9.1 ASME Boiler and Pressure Vessel Code, Section III, 1998 Edition including 1999 addenda.
- 9.2 ANSI N14.5-1997, "American National Standard for Leakage Tests on Packages for Shipment of Radioactive Materials", February 1998.
- 9.3 ASTM E1225, "Thermal Conductivity of Solids by Means of the Guarded-Comparative-Longitudinal Heat Flow Technique."
- 9.4 ASTM E1461, "Thermal Diffusivity of Solids by the Flash Method."
- 9.5 NUREG/CR-5661, "Recommendations for Preparing the Criticality Safety Evaluation of Transportation Packages," 1997.
- 9.6 ASTM C 791, "Standard Methods for Chemical, Mass Spectrometric, and Spectrochemical Analysis of Nuclear-Grade Boron Carbide."
- 9.7 ASTM D 3553, "Fiber Content by Digestion of Reinforced Metal Matrix Composites."
- 9.8 AAR Advanced Structures, "Boral[®], The Proven Neutron Absorber".
- 9.9 AAR Advanced Structures, Boral[®] Product Performance Report 624.

Table K.9-1
Specified Boron Content
Borated Aluminum (90% B10 Credit)

Reference	Section K.6 Analysis	Specified Minimum
Boron Content (wt. % Boron)	B10 Content (g/cm ²)	B10 Content (g/cm ²)
1.1	0.019	0.021
1.6	0.029	0.032
2.1	0.036	0.040
For Damaged Fuel		
2.1	0.036	0.040

Table K.9-2
Specified Boron Carbide Content
Metal Matrix Composites (90% B10 Credit)

Reference	Section K.6 Analysis	Specified Minimum
Boron Carbide Content (volume %)	B10 Content (g/cm²)	B10 Content (g/cm²)
8	0.019	0.021
12	0.029	0.032
15	0.036	0.040
For Damaged Fuel		
15	0.036	0.040

Table K.9-3
Specified B10 Areal Density
Boral[®] (75% B10 credit)

Section K.6 Analysis	Specified Minimum
B10 Content (g/cm²)	B10 Content (g/cm²)
0.019	0.025
0.029	0.039
0.036	0.048
For Failed Fuel	
0.036	0.048

K.10.2 Off-Site Dose Calculations

Calculated dose rates in the immediate vicinity of the NUHOMS[®]-61BT System are presented in Section K.5 which provides a detailed description of source term configuration, analysis models and bounding dose rates. Dose rates at longer distances (off-site dose rates and doses) are presented in this section. This evaluation determines the neutron and gamma-ray off-site dose rates *including skyshine* in the vicinity of the two generic Independent Spent Fuel Storage Installations (ISFSI) layouts containing design basis fuel in the NUHOMS[®]-61BT DSCs. The first generic ISFSI evaluated is a 2x10 array (back-to-back) of Horizontal Storage Modules (HSMs) loaded with design basis fuel, including fuel channels, in NUHOMS[®]-61BT DSCs. The second generic layout evaluated is two 1x10 arrays (front-to-front) of Horizontal Storage Modules (HSMs) loaded with design basis fuel, including fuel channels, in NUHOMS[®]-61BT DSCs. This calculation provides results for distances ranging from 6.1 to 600 meters from each face of the two arrays of HSMs.

The total annual exposure for each ISFSI layout as a function of distance from each face is given in Table K.10-2 and plotted in Figure K.10-1. The total annual exposure assumes 100% occupancy for 365 days.

The Monte Carlo computer code MCNP [10.1] calculated the dose rates at the specified locations around the arrays of HSMs. The results of this calculation provide an example of how to demonstrate compliance with the relevant radiological requirements of 10CFR20 [10.2], 10CFR72 [10.3], and 40CFR190 [10.4] for a specific site. Each site must perform specific site calculations to account for the actual layout of the HSMs and fuel source.

The assumptions used to generate the geometry of the two ISFSIs for the MCNP analysis are summarized below.

- The 20 HSMs in the 2x10 back-to-back array are modeled as a box enveloping the 2x10 array of HSMs including the six inch vents between modules and the 2-foot shield walls on the two sides of the array. MCNP starts the source particles on the surfaces of the box.
- The 20 HSMs in the two 1x10 face-to-face arrays are modeled as two boxes which envelope each 1x10 array of HSMs including the six inch vents between modules and the 2-foot shield walls on the two sides of each array. MCNP starts the source particles on the surfaces of one of the boxes.
- The ISFSI approach slab is modeled as concrete. Because the ground composition has, at best, only a secondary impact on the dose rates at the detectors, any differences between this assumed layout and the actual layout would not have a significant affect on the site dose rates.
- For the 2x10 array, the interiors of the HSMs and shield walls are modeled as air. Most particles that enter the interiors of the HSMs and shield walls will therefore pass through unhindered.
- For the two 1x10 arrays, the interiors of the HSMs and shield walls modeled the 1x10 array in which the source is as air. Most particles that enter the interiors of these HSMs and shield walls will therefore pass through unhindered. Model the other 1x10 array as concrete to simulate the shielding

provided by the second array of HSMs for the direct radiation from the front of the opposing 1x10 array.

- The "universe" is a sphere surrounding the ISFSI. *To account for skyshine* radius of this sphere ($r=500,000$ cm) is more than 10 mean free paths for gammas and 50 mean free paths for neutrons greater than that of the outermost surface, thus ensuring that the model is of a sufficient size to include all interactions, *including skyshine*, affecting the dose rate at the detectors.

The assumption used to generate the HSM surface sources for the MCNP analysis is summarized below.

- The HSM surface sources are bootstrapped (input to provide an equivalent boundary condition) using the HSM surface average dose rates calculated in Section K.5.4.

The assumptions used for the MCNP analysis are summarized below.

MCNP starts the source particles on the ISFSI array surface with initial directions following a cosine distribution. Radiation fluxes outside thick shields such as the HSM walls and roof tend to have forward peaked angular distributions; therefore, a cosine function is a reasonable approximation for the starting direction distribution. Vents through shielding regions such as the HSM vents tend to collimate particles such that a semi-isotropic assumption would not be appropriate.

Point detectors determine the dose rates on the four sides of the ISFSI as a function of distance from the ISFSI. All detectors represent the dose rate at three feet above ground level.

Source information required by MCNP includes gamma-ray and neutron spectra for the HSM array surfaces, total gamma-ray and neutron activities for each HSM array face and total gamma-ray and neutron activities for the entire ISFSI. The neutron and gamma-ray spectra are determined using a 1-D ANISN[10.6] run through the HSM roof using the design basis In-core neutron and gamma fuel sources. Use of the roof is conservative because it represents the thickest cross section of the HSM shield. The thicker shield increases the dose rate importance of the higher energy neutrons and gamma-rays from the fuel because the thicker shield filters out the lower energy particles. Therefore, use of the thickest part of the shield results in a harder spectrum for all of the other surfaces. The HSM spectra as determined from ANISN are normalized to a one mrem/hour source using the flux-to-dose-factors from Reference [10.5]. These normalized spectra are then input in the MCNP ERG source variable.

The probability of a particle being born on a given surface is proportional to the total activity of that surface. The activity of each surface is determined by multiplying the sum of the normalized group fluxes, calculated above, by the average surface dose rate and by the area of the surface. This calculation is performed for the roof, sides, back and front of the HSM. The sum of the surface activities is then input as the tally multiplier for each of the MCNP tallies to convert the tally results to fluxes (particles per second per square centimeter).