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Report 554

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Brooks & Perkins Inc.
Spent Fuel Storage
Module Corrosion
Report

Brooks & Perkins, Incorporated

ABSTRACT

Brooks & Perkins, Inc. Spent Fuel Storage
Module Corrosion Report No. 554

A determination is made from published data of the expected life of a storage module following a rupture in the water barrier covering. The environmental conditions external and internal to the module are defined. The various types of corrosion which can occur are also defined and their experimentally determined corrosion rates are listed. Results show an expected life to be at least greater than fifty three (53) years and probably greater than sixty (60) years following the occurrence of the rupture to the water barrier covering.

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BROOKS & PERKINS, INC. SPENT FUEL STORAGE MODULE CORROSION REPORT

PURPOSE: The purpose of this report is to determine from published data the extent of any deterioration that is likely to occur over a forty year period to the shielding capability of a Brooks & Perkins, Inc. spent fuel storage module following a water leak in the stainless steel covering.

BACKGROUND: The spent fuel storage module (SFSM) is a slender square-shaped tube with open ends that is used for the storing and the shielding of one spent fuel assembly in a light water nuclear reactor storage pool. The tube is constructed with the inside and outside coverings being made of type 304 stainless steel. These two stainless steel surfaces are welded together at the top and bottom of the tube over an inner layer of a thermal neutron shielding material called BORAL™.

A group of SFSM's are assembled into a tightly packed array called a high-density storage rack. A network of horizontal and diagonal members separate the modules within the rack and provide the necessary lateral support. The racks stand in a vertical position on the bottom of a forty foot deep storage pool.

The water in the storage pools is constantly circulated through a series of filters which causes a constant water flow within the pool. The water is monitored and controlled for pH and temperature within specific limits depending on the type of nuclear reactor.

The quality of the water in the storage pool of the two types of reactors is controlled within the following ranges:

Pressurized Water Reactor (PWR)

water type	demineralized
water temperature	70° to 150°F (21° to 66° C)
pH at 77°F (25°C)	4.0 to 8.0*
boron, ppm	1800 to 2200
chloride ion, ppm, max.	0.1

* (4.5 to 10.6 at Combustion Engineering Reactors)

fluoride ion, ppm, max.	0.1
total suspended solids, ppm, max.	1.0
solids filtration, microns, max.	25

Boiling Water Reactor (BWR)

water type	demineralized
water temperature	70° to 150°F (21° to 66°C)
pH at 77°F (25°C)	5.8 to 7.5
chloride ion, ppm, max.	0.5
total heavy element, ppm, max.	0.1
total suspended solids, ppm, max.	1.0
solids filtration, microns, max.	25

The thermal neutron absorbing material BORAL™ is a sandwich type panel that has outer surfaces of type 1100 aluminum and a core of boron carbide uniformly dispersed in a matrix of type 1100 aluminum.

DISCUSSION: The shielding capability of a BORAL panel is due to its ability to capture thermal neutrons. The capture of thermal neutrons is accomplished by the B^{10} (boron-ten) isotopes that are contained within the boron carbide particles. These boron carbide particles are chemically inert (unreactive), heat resistant, highly crystalline and nearly equivalent to diamond in hardness.

In order for corrosion to cause a reduction in the shielding capability of a BORAL panel, the boron carbide particles have to be physically displaced from the panel. A displacement of the boron carbide particles to occur would require the following sequence of events.

(1) the complete removal of the outer protective aluminum surfaces on the BORAL panel.

(2) the complete removal of the aluminum matrix surrounding each boron carbide particle.

(3) the physical displacement of the boron carbide particles.

It is interesting to note that BORAL has been used in fuel storage pools [1] [2] since 1964 and samples have been subjected to many corrosion studies [3] [4] for long periods of time. In none of these exposures has it been reported that any boron carbide particles were displaced.

The progression of corrosion to the outer surface is directly dependent upon the area in contact with the water. The outer surface will reduce in thickness at the same rate in mils per year as the edge will be attacked if the entire panel is in contact with the water. If only the edges of the BORAL are exposed to the water, the corrosion rate would be the same but a much longer period of time would be required for the total failure of the panel to occur.

In order to effectively extrapolate from previous test results, it is often necessary to make reasonable interpolations or projections from the published data because of differences between test and actual conditions. It must also be kept in mind that most, if not all, tests are conducted with constant or precisely controlled conditions throughout the test period which would not be the case in an actual leak.

Alwitt et al [5] states, "Aluminum reacts readily with water to form a hydrous oxide film. Depending upon the conditions of film formation, the film is more or less protective against subsequent corrosion. Growth occurs in two states: a pseudoboehmite film is produced initially and then is covered with a layer of bayerite crystals. By analogy with the aging mechanism in a colloidal suspension, it is thought that the pseudoboehmite dissolves and re-precipitates as bayerite crystals. The growth of bayerite is inhibited at higher temperatures (80°-100°C), presumably because the pseudoboehmite is better crystalized and dissolves more slowly."

"The growth kinetics and properties of the pseudoboehmite film produced at 100°C have been studied extensively. Less is known about the layers produced at low temperatures, but Hart has reported the weight gain and electron diffraction analyses for aluminum samples immersed in water at temperatures between 20° and 80°C."

There are at least four significant changes that will occur immediately to the water that enters into the internal voids in the storage module. Those changes are as follows:

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1. Flow Rate. The pool water surrounding the storage module is constantly flowing and therefore its chemistry, purity and temperature can be controlled within precise limits. The water entering through a hole into the internal voids of the storage module will cease flowing and will become stagnant once the voids are filled. The internal water will change from the external water and will be the corrodent media to consider for the long term affects of corrosion. As pointed out by Godard, [6] "Movement of the corrosive liquid usually accelerates the rate of corrosion."

2. Shift in pH. The internal water will react with the aluminum upon contact and cause the pH to change. The pH will increase or decrease towards a steady pH near neutral depending on whether the initial condition is acidic or alkaline. This change in pH is reported by the following:

   A. Sedriks et al [7] "The change of pH with time for initially acidic solutions (i.e., pH <2) in the presence of dissolving aluminum is shown in Figures 1 and 2. (The curves shown could be reproduced within $\pm$ 0.05 of a pH unit.) In general, the change can be characterized by (1) an initial increase in pH, and (2) the subsequent attainment of a steady pH value."

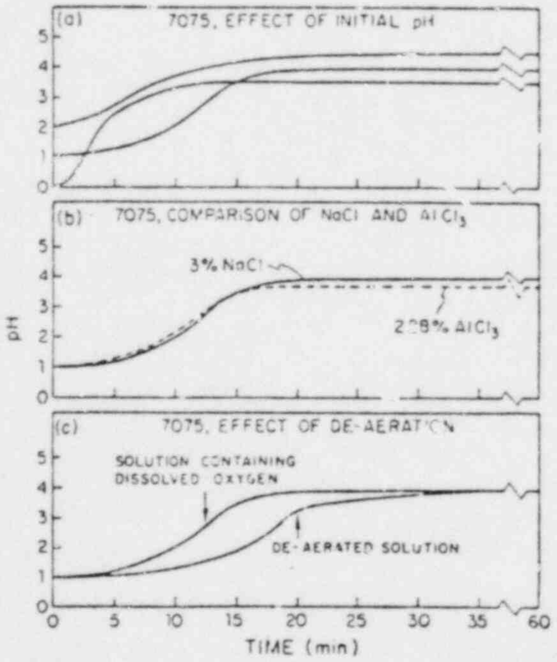

FIGURE 1 — The change of pH with time as a function of (a) initial pH of solution, (b) presence of aluminum ions, and (c) effect of oxygen.

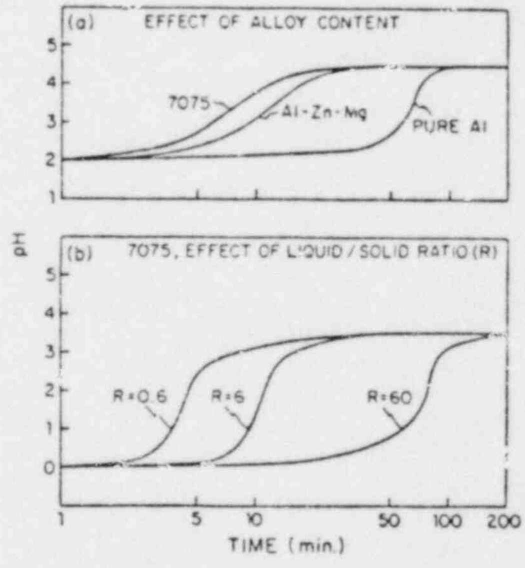

FIGURE 2 — The change of pH with time as a function of (a) alloy content, and (b) liquid/solid ratio.

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"The steady pH value is related to the concentration of aluminum ions in solution.... and is associated with the onset of precipitation of aluminum hydroxide, AL $(OH)_3$."

B. "Peterson et al [8] report that in sea water (pH 8.2) the corrodent in crevices in Type 304 stainless steel was less than 2(pH). The pH at the growing front of exfoliation crevices in aluminum alloys does not appear to have been reported, but it is postulated to be acid, having a pH of possibly as low as 3.2 based upon measurements of pH at the tips of stress corrosion cracks in aluminum alloys."

C. B. F. Brown. [9] "The acidity is caused by hydrolysis of one or more components of the metal or alloy, and the acidity persists because of the restricted interchange between the corrosion cell and the bulk environment."

D. Peterson et al [10] "Figures 3 and 4 show that regardless of the initial potential and pH, the crevices on stainless steel polarized the pH shifted in the alkaline direction to the domain where water is unstable and hydrogen discharge would be expected. One would therefore expect that cathodic protection has been achieved, since the potential of the surface has been shifted into a region where stainless steel is known to be cathodically protected. In addition, the pH has shifted to a value which indicates that the solution within the crevice is benign to stainless steel."

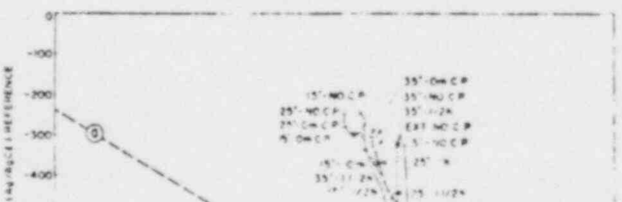

FIGURE 3 – Type 304 stainless steel, crevice polarization and pH data at various distances from the crevice opening and at various times. Shown on a partial Pourbaix diagram. The 0.6 M NaCl solution had an initial pH of 7.6

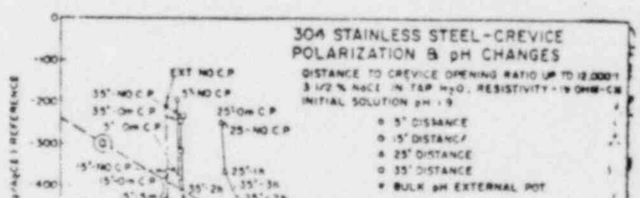

FIGURE 4 – Type 304 stainless steel, crevice polarization and pH data at various distances from the crevice opening and at various times. Shown on a partial Pourbaix diagram. The 0.6 M NaCl solution had an initial pH of 1.9.

E. B&P Report No. 553 [11]

Samples of the SFSM were placed in water baths having a pH of 4.5 and 10.5. Within a few hours the pH of the water that entered the SFSM had changed and was steady at 7.1 and 7.7 respectively.

3. Oxygen Content. The content of dissolved oxygen in the internal water will be depleted by the oxidation of the metal surfaces. The decelerating effect on the reactivity of the solution by this de-aeration can be seen in Figure 1(c) [1]. The de-aerated solution required 38% more time to change pH from 1.0 to 3.0 and 80% more time to change from 1.0 to 4.0 than the solution containing dissolved oxygen. This delay in reaction time is also caused by the development of a protective oxide film on the surface of the aluminum which tends to arrest further corrosion action.

4. Ion Concentration. The volume of the internal water will be small compared to the surface area of the metal faces and will therefore become saturated with ions very quickly. The further ionization of the aluminum surfaces can proceed only to the extent that aluminum ions precipitate out of solution in the form of an insoluble compound. A study of a potential-pH diagram (Pourbaix) for the aluminum-water system (see Figures 5 and 6 of MacDonald [12] et al) discloses the following reaction will occur within a pH range of 3 to 8.5 and a temperature range of 77° to 140°F.

$$2\,Al + 6\,H_2O \rightarrow Al_2O_3 3H_2O \downarrow + 6H^+ + 6\text{ electrons}$$

A dissolved aluminum atom will react directly with water to form the precipitate gibbsite and bayerite ($Al_2O_3\ 3H_2O$).

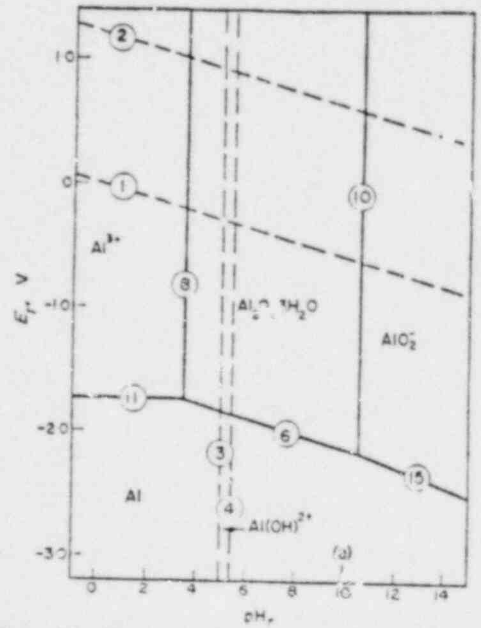

FIG. 5 Potential-pH diagram for the aluminium-water system at 25°C.
(a) refers to the pH_T of a 10^{-4}m OH^- solution.

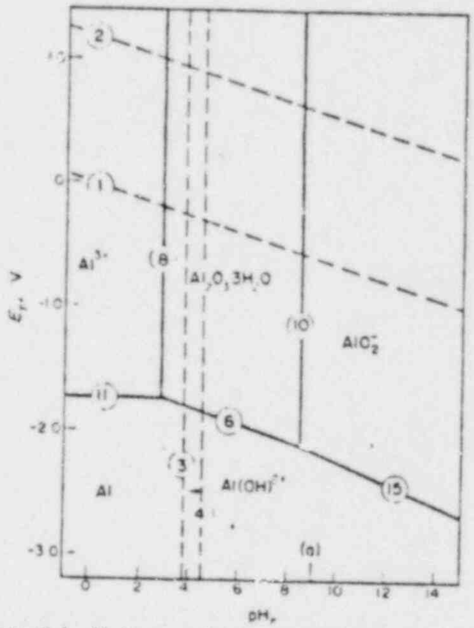

FIG. 6 Potential-pH diagram for the aluminium-water system at 60°C.
(a) refers to the pH_T of a 10^{-4}m OH solution.

The precipitate is a hydrated oxide of aluminum which is stable up to 135°C (275°F). The entrapped water will become saturated by the forming of the gibbsite and bayerite, and therefore would be a self-limiting influence to the corrosion.

CORROSION DATA

BORAL

1. One year test results [3]

water type	BWR
pH	5.6 to 7.7
temp.	68° to 78°F (20° to 26° C)
corrosion rate, mpy	0.28
expected life (at 15 mils thickness)*	> 53 years

*10 Mils of Clad Plus 5 Mils of Matrix Holding Boundary Layers of B_4C.

2. 2000 hour test results [4]

water type	BWR
pH	7.0
temp.	190°F (88°C)
corrosion rate, mpy	1.2 to 2.1
estimated corrosion rate @ 70° to 150°F., mpy	.18 to .32
expected life (at 15 mils thickness)*	> 45 years

3. Twelve years of service [1]

water type	PWR
boron	nil
pH	4.0 to 8.0 (est.)
temp.	70° to 150°F (21° to 66°C) (est.)
corrosion rate, mpy	nil
expected life (at 15 mils thickness)*	> 60 years

STAINLESS STEEL - type 304

1. General Corrosion [13]

water type	BWR or PWR
pH	7.0 to 11
temp.	572°F (300°C)
oxygen, ppm	< .01 to 2
chlorides, ppm	< .1
corrosion rate, mpy	< 2
estimated corrosion rate @ 150°F, mpy	< .6
expected life (at 60 mils thickness)	> 60 years

* 10 mils of Clad plus 5 mils of Matrix Holding Boundary Layers of B_4C.

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2. General Corrosion after 3000 hours [14]

water type	high purity, demineralized
hydrazine, ppm	.01 to .07
oxygen, ppm	< .005
chlorine, ppm	< .05
pH	6.95 to 9.58
flow rate, gal/hr.	3.5
temp.	320°F (160°C)
corrosion rate, mpy	.01
expected life (at 60 mils thickness)	> 60 years

3. Stress-Corrosion-Cracking after 3000 hours [14]

water quality same as 2 above	
stress % of .2% yield	120
results	"Metallographic examination of selected samples also failed to reveal any cracking."
expected life (at 60 mils thickness)	> 60 years

ALUMINUM - type 1100F

1. General Corrosion after 14,200 hours [15]

water type	high purity, demineralized
oxygen, ppm	4 to 5
pH	5.0 to 6.0
flow rate, fps	7.6
temp.	194° to 356°F (90° to 180°C)
corrosion rate, mpy	0.16
expected life (at 15 mils thickness)	> 60 years

STAINLESS STEEL (type 304) coupled with ALUMINUM (type 1100F)

1. Crevice and Galvanic Corrosion [15]

water type	high [illegible]ity, demineralized		
oxygen, ppm	4 to 5		
pH	5.0 to 6.0		
flow rate, fpm	0.5		
temp.	194° to 356°F (90° to 180°C)		
time, hrs.	1100	1775	2000
Al max. pit depth, mils	2	< 3	< 5
Al corrosion rate, mpy	0.[illegible]	0.1	0.1
S.S. Corrosion rate, mpy	0	0	0
expected life (at 15 mils thickness of Al)	>60 yrs	>60 yrs	>60 yrs

CONCLUSION: A thorough review of the published test data indicates the materials used in the Brooks and Perkins Inc. spent fuel storage module (namely 304 Stainless Steel and 1100F Aluminum) provide adequate corrosion resistance to achieve a life expectancy of forty years without a reduction of neutron absorbing capability when used in a BWR or PWR storage pool with a rupture in the stainless steel covering.

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[2] Dai. land Power Cooperative, LaCrosse Plant, BWR, Mar,1975

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[6] H. P. Godard, The Corrosion Behavior of Aluminum, NACE-Corrosion, Vol. 11, Dec. 1955, pg. 55

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[8] M. H. Peterson, T. J. Lennox, Jr., and R. E. Groover, A Study of Crevice Corrosion in Type 304 Stainless Steel, Proceedings of 25th NACE Conference, 314-317, National Association of Corrosion Engineers, Houston (1970). Quotation from [9].

[9] B. F. Brown. Concept of the Occluded Corrosion Cell. NACE-Corrosion, Vol. 26, No. 8, Aug. 70, pg. 249

[10] M. H. Peterson and T. J. Lennox, Jr. A Study of Cathodic Polarization and pH Changes in Metal Crevices NACE-Corrosion, Vol. 29, No. 10, Oct. 73 Pg 409

[11] B&P Report No. 553, pH Shift of Water Inside Spent Fuel Storage Module, Feb., 77.

[12] D. D. MacDonald and P. Butler, The Thermodynamics of the Aluminum-Water System at Elevated Temperatures. Corrosion Science 1973, Vol. 13, pg. 265

[13] National Assoc. of Corrosion Engineers, Corrosion Data Survey, 1974, pp. 34 & 252

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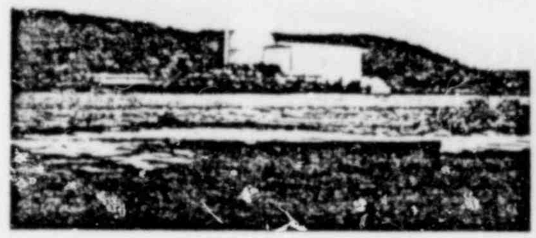
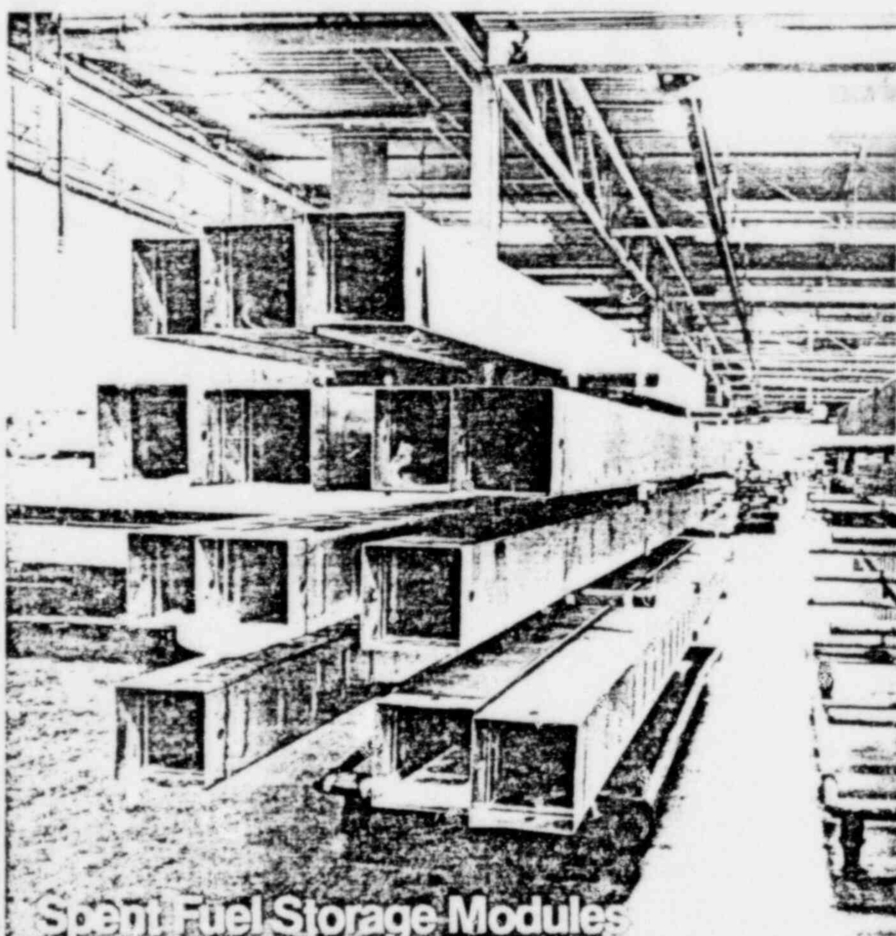


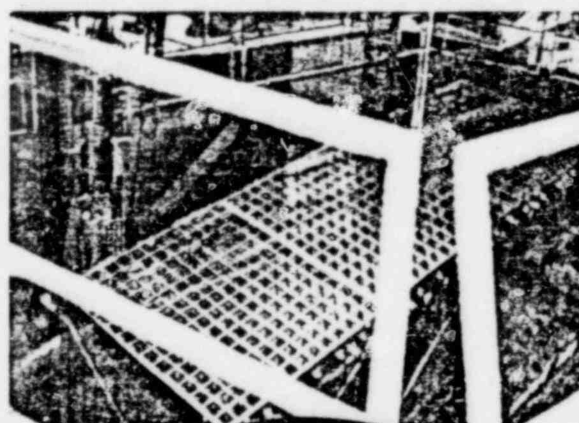
HIGH DENSITY fuel storage products

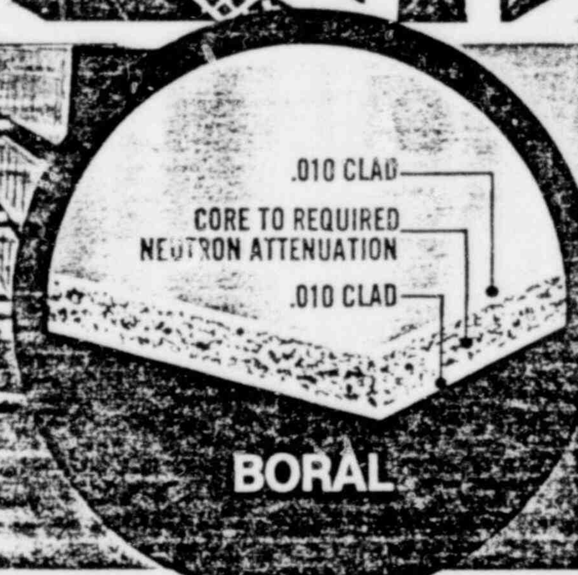
Spent fuel storage expansion of on site and central storage pools are most cost effective with maximum densification of fuel elements. The key to this concept is the Brooks & Perkins's Spend Fuel Storage Module which incorporates Brooks & Perkins' Boral—the most widely used neutron absorber for fuel storage applications, as well as for a wide range of other applications.

Featuring Boral™ neutron absorbing/shielding material and spent fuel storage modules.

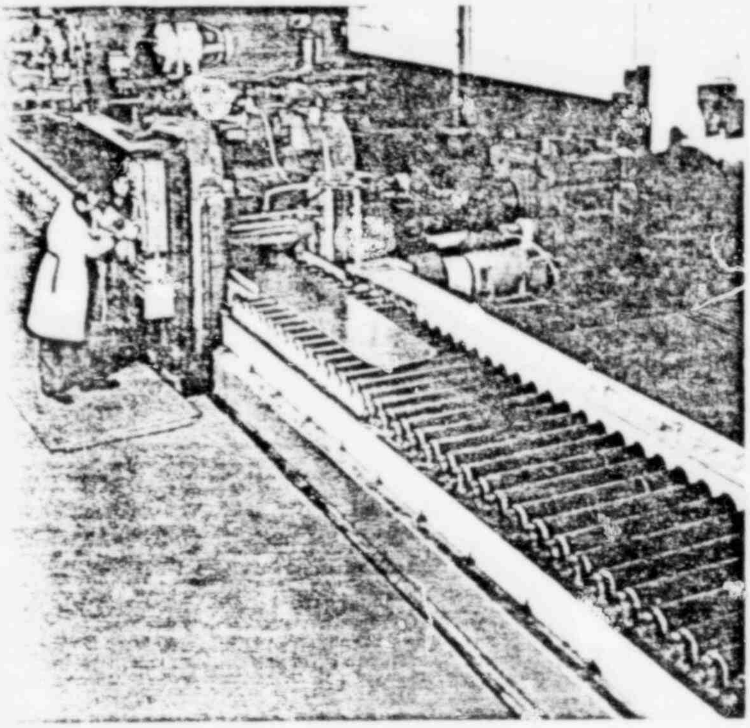


Spent Fuel Storage Modules

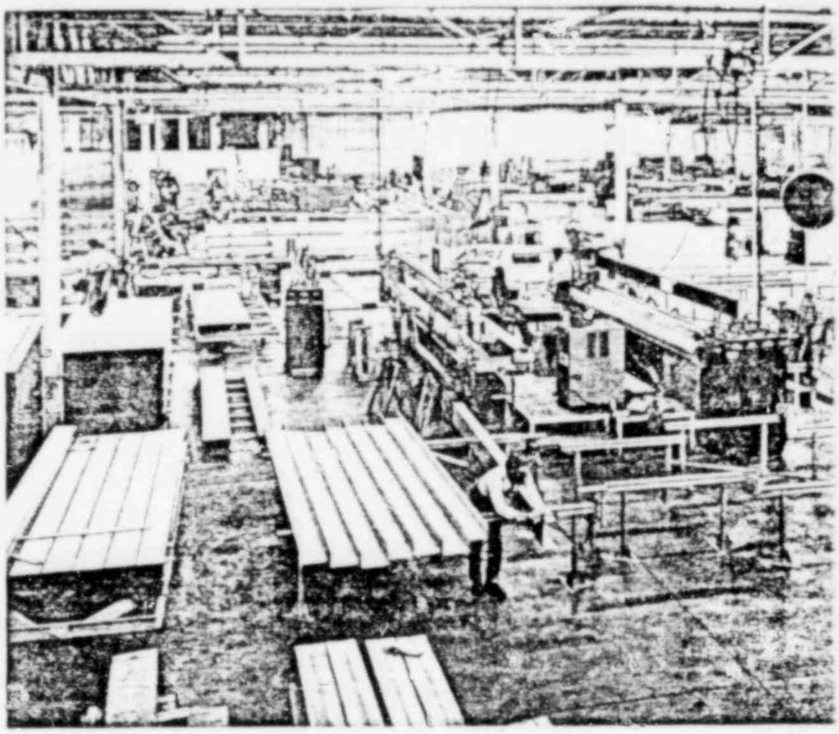




BORAL



The rolling mill for producing Boral panels.



Part of the spent fuel storage module assembly area.

BORAL™ Neutron Absorbing/Shielding Material

Radioactive materials produced by the nuclear industr... ...ay create a variety of radiation including alpha particles, beta particles, gamma rays, neutrinos and neutrons. Alpha and beta particles are easily shielded by relatively thin sheets of metals. Neutrinos, although highly penetrating, appear to have little physiological importance. Only gamma rays and neutrons require special shielding consideration, with appreciable thickness of shielding materials to provide radiation protection. Gamma radiation is most effectively absorbed by high-density materials such as lead, steel and concrete. The best elements for neutron attenuation are boron, hydrogen, lithium, along with water and polyethylene.

Most shielding materials will readily absorb neutrons, but in doing so they induce secondary gamma rays in the 5 to 10 MeV range. This, in turn, requires further shielding and heat dissipation. Boron is unique in its ability to shield the thermal neutron without leaving any significant residual radioactivity. Each attenuated neutron produces only one soft gamma ray (0.42 MeV) and an easily absorbed alpha particle in the process. By contrast, cadmium shielding emits a 6 MeV gamma ray and leaves a residue of four radioactive isotopes.

BORAL is a composite material consisting of boron carbide evenly dispersed within a matrix of aluminum and clad with aluminum. As used in the Spent Fuel Storage Modules, the panels are identified by the nominal overall thickness of the panel and the minimum weight of the boron-10 per unit area of panel surface. Boral panels are produced with a thickness and boron-10 content to provide the neutron attenuation characteristics necessary for the specific application. It is produced in standard sizes up to 48 x 120 inches and in standard mill thicknesses of .177 (± .012) and .265 (± .015) inches. These sizes are in stock for immediate delivery. Typical thicknesses also available for use in spent fuel storage modules or other applications are:

Overall Panel Thickness		Reference B^{10} Content per unit area
(Inches)	(Millimeters)	(Grams/sq. cm.)
.075	1.91	.010
.085	2.16	.020
.110	2.79	.030
.142	3.61	.040
.178	4.52	.050
.215	5.46	.060

Besides use in the manufacture of spent fuel storage modules, Boral has also been used on the inner sections of reactor shields, shutdown control rods and as neutron curtains and shutters for thermal columns. In addition, it has been fabricated into housings to shield sensitive electronic and avionic equipment and as shipping and storage containers for radioactive materials.

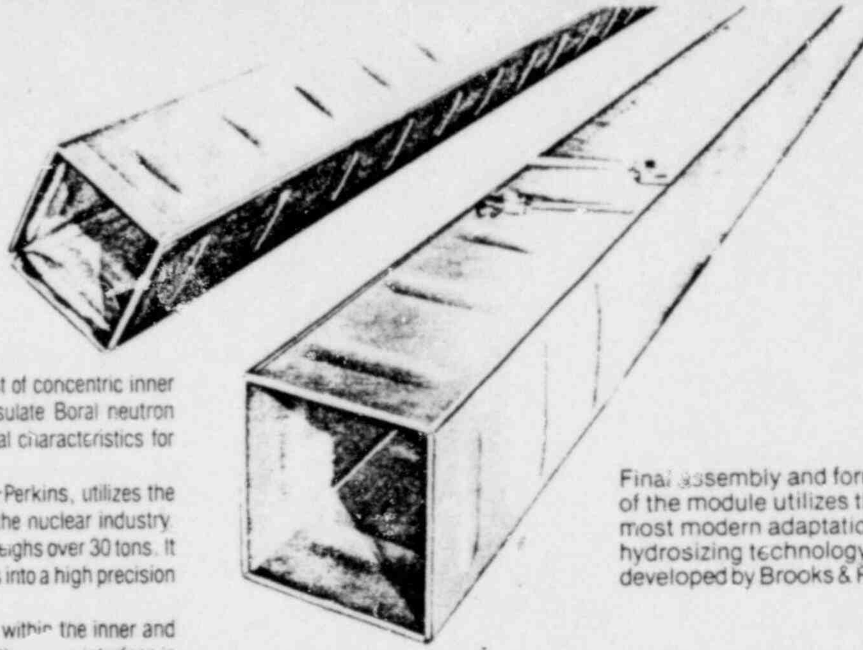
MECHANICAL PROPERTIES OF BORAL MATERIALS

Property	Units	Aluminum	Boron Carbide
Modulus of Elasticity (tension)	(psi)	10×10^6	64×10^6
Percent Elongation (in 2")	(75°F)	35	N/A
Tensile Strength — Ultimate	(psi @ 75°F)	13,000 (annealed)	N/A
Shear Strength	(psi @ 75°F)	9,000 (annealed)	N/A
Tensile Strength — Yield	(psi @ 75°F)	5,000 (annealed)	N/A
Compression Strength	(psi @ 75°F)	5,000 (annealed)	398-414,000

MECHANICAL STRENGTHS OF BORAL PANELS (Min. 35%)

Property	Units	Th. .177	Th. .265
Weight — Typical	(lbs./sq. ft.)	2.46 / 2.45	3.67 / 3.65
Compression Strength — Compression Failure	(lbs/inch of width)	1140	2140
Tensile Strength — Ultimate	(lbs/inch of width)	1230	1530
Compression Strength — Buckling Failure	(lbs/inch of width)	,00	560
Tensile Strength — Yield	(lbs/inch of width)	1140	,510
Flexural Strength — Max. Bending Moment	(in-lbs/in. of width)	95	145
Percent Elongation (in 2")	(75°F)	7.0	4.5
Modulus of Elasticity	(lbs/sq. in.)	5.8×10^6	4.4×10^6
Shear Strength	(lbs/inch of width)	1142	1386
Water Absorption (%)	(24 hrs @ 0 psi)	0.295	1.940
Water Absorption (%)	(5 mins. @ 2200 psi)	0.429	0.620

(For more information on Boral panels concerning additional product performance and technical data and quality assurance, contact us.)



Final assembly and forming of the module utilizes the most modern adaptation of hydrosizing technology... developed by Brooks & Perkins.

Spent Fuel Storage Modules

patented

Brooks & Perkins' Spent Fuel Storage Modules consist of concentric inner and outer square "shrouds" which integrally encapsulate Boral neutron absorber plates...also providing the required structural characteristics for use in spent fuel storage racks.

The manufacturing process, developed by Brooks & Perkins, utilizes the most modern adaptation of hydrosizing technology in the nuclear industry. The fixture, designed by B&P, is over 25 feet long and weighs over 30 tons. It uses extreme pressures to form the module components into a high precision sandwich-type structure.

The Boral neutron absorber plates are encapsulated within the inner and outer shrouds with the ends of the shrouds formed together. This interface is then welded at each end. The structural design is further enhanced by the forming of convex stiffening beads on the sides of the module.

Rigid inspection is performed on each finished module, subsequent to the quality controls implemented during the production procedure, to see that variations do not exceed the allowable tolerances for the entire length. Modules are also selected at random and subjected to various types of NDE testing, as specified, to assure the adequacy of the welds and structure. All inspection follows the schedules and procedures as prescribed by Brooks & Perkins Quality Assurance Program.

HIGH DENSITY SPENT FUEL STORAGE RACKS USING BROOKS & PERKINS' SPENT FUEL STORAGE MODULES PERMIT...

Increased Storage Capacity. The Boral neutron absorber in the module permits closer spacing of spent fuel elements within a rack.

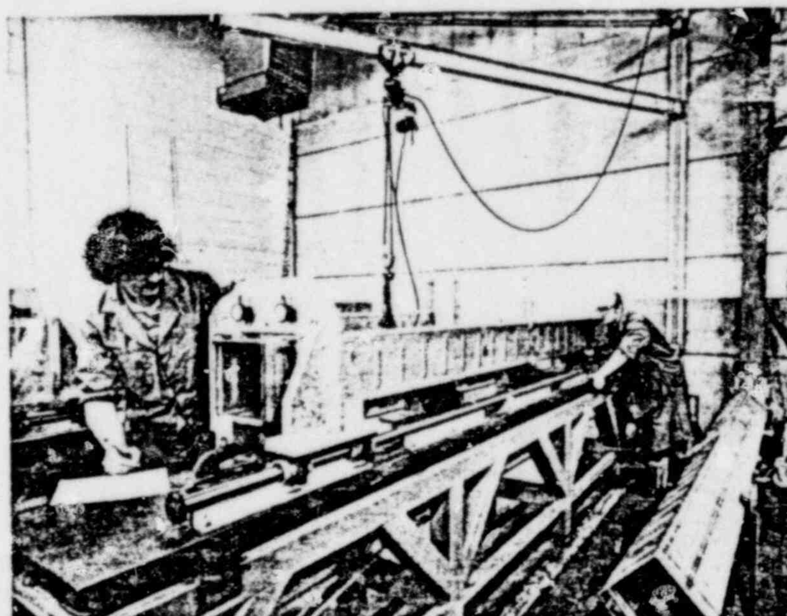
High Strength and Rigidity. Sandwich construction of the module offers the highest strength-to-weight ratio available.

Simple Design and Fabrication. The sandwich structure module can be readily designed to meet the structural and shielding requirements at each storage site and can be easily and quickly assembled into a rack with a minimum of welding.

Low Costs. Manufacturing costs are reduced as a result of the efficient forming of the modules and simplified rack assembly of the high precision components.

The inner and outer shrouds o the module are welded int tube configurations on Brooks & Perkins-designed custom-made 20-foot long tudinal seam welder. Each fu penetration weld is 100 visually inspected and per odically examined by ND methods.

Each module is fully inspecte following the procedures pr scribed by Brooks & Perkin rigid Quality Assurance Pr gram.



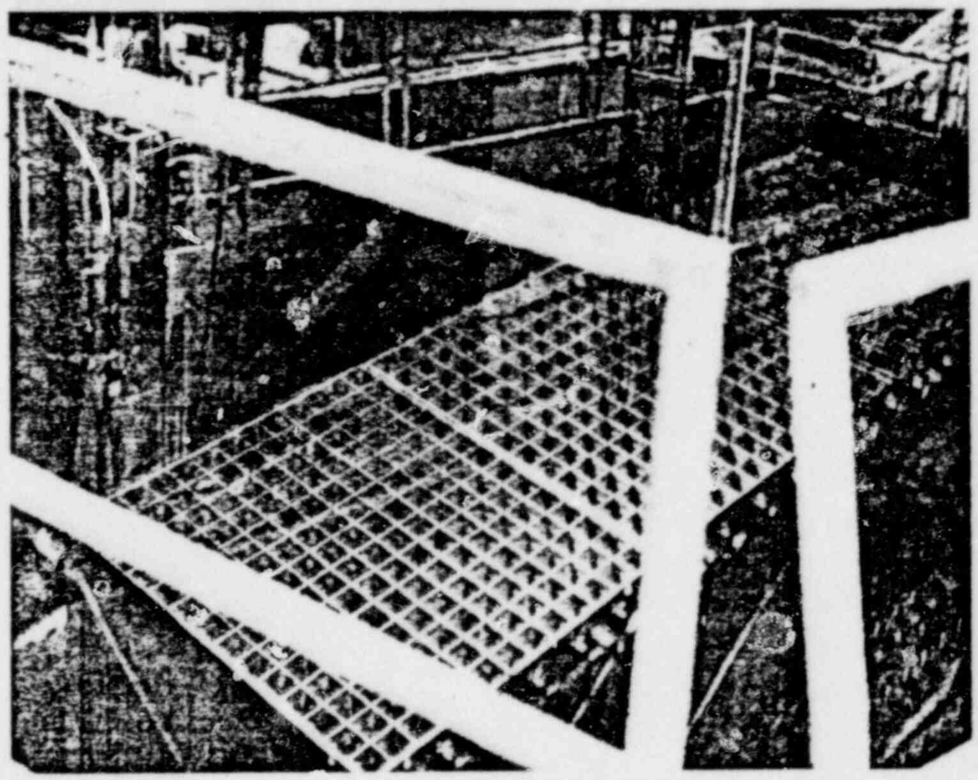
Spent Fuel Storage Module Specifications

Shroud Materials— (Choice of)	Type 304 Stainless Steel Type 6061 Aluminum Type 5083 Aluminum	
Core Material—	Boral	
Dimensions—		
Length:	120 to 192 in./3048.0 to 4876.8 mm.	
Inner Shroud:	.030 to .060 in./0.52 mm.	
Outer Shroud:	.030 to .110 in./2.54 mm.	
Boral Thickness:	.075 to .215 in./1.91 to 5.46 mm.	
Inside Dimension:	5.5 to 10.5 in./139.7 to 266.7 mm.	
Inside Corner Radius:	Typ. .25 in./6.35 mm.	
Stiffening Bead Protrusion:	Typ. .125 in./3.18 mm.	
End Configurations—	Straight Flared	Reinforced Capped

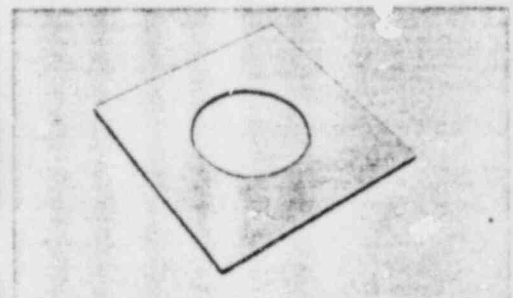
BROOKS & PERKINS *provides a complete fabrication/consultation service for producing* BORAL™ *components...*

Fabricating Boral plate into neutron shielding components requires special knowledge as to its properties and experience in working with this composite material. Brooks & Perkins has developed unique capabilities in working with Boral fabrication problems and offers a complete service to Boral customers. These include welding, cutting, shearing, punching, drilling, sawing, forming and countersinking.

Illustrated here are a few of the Boral components produced by Brooks & Perkins or Brooks & Perkins customers. Whatever your needs, this expertise and experience is available to you. Call or write, outlining your specific requirements.



A typical spent fuel storage pool with storage racks featuring Boral panel construction.



This ¼" thick Boral plate was completely cut by plasma arc method, both on outer edges and the circular hole.

This Boral-lined neutron shielding jacket was produced by forming and welding Boral components.

You can tell the leader by the facilities it serves:

Zion 1 + 2	Yellow Creek 1 + 2	Dresden 2 + 3	Susquehanna 1 + 2	Hartsville 1 + 2
Cook 1 + 2	Sequoyah 1 + 2	Duane Arnold 1	Peachbottom 2 + 3	Phipps Bend 1 + 2
Maine Yankee	Belefonte 1 + 2	Cooper	Browns Ferry 1, 2 + 3	Hatch 1 + 2
Salem 1 + 2	Pilgrim 1	Fitzpatrick	Vermont Yankee	Limerick 1 + 2
Yankee Rowe	Perry 1 + 2	Monticello	LaCrosse	Plus overseas facilities

Brooks & Perkins
INCORPORATED

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TW4 6BL, England
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b+p

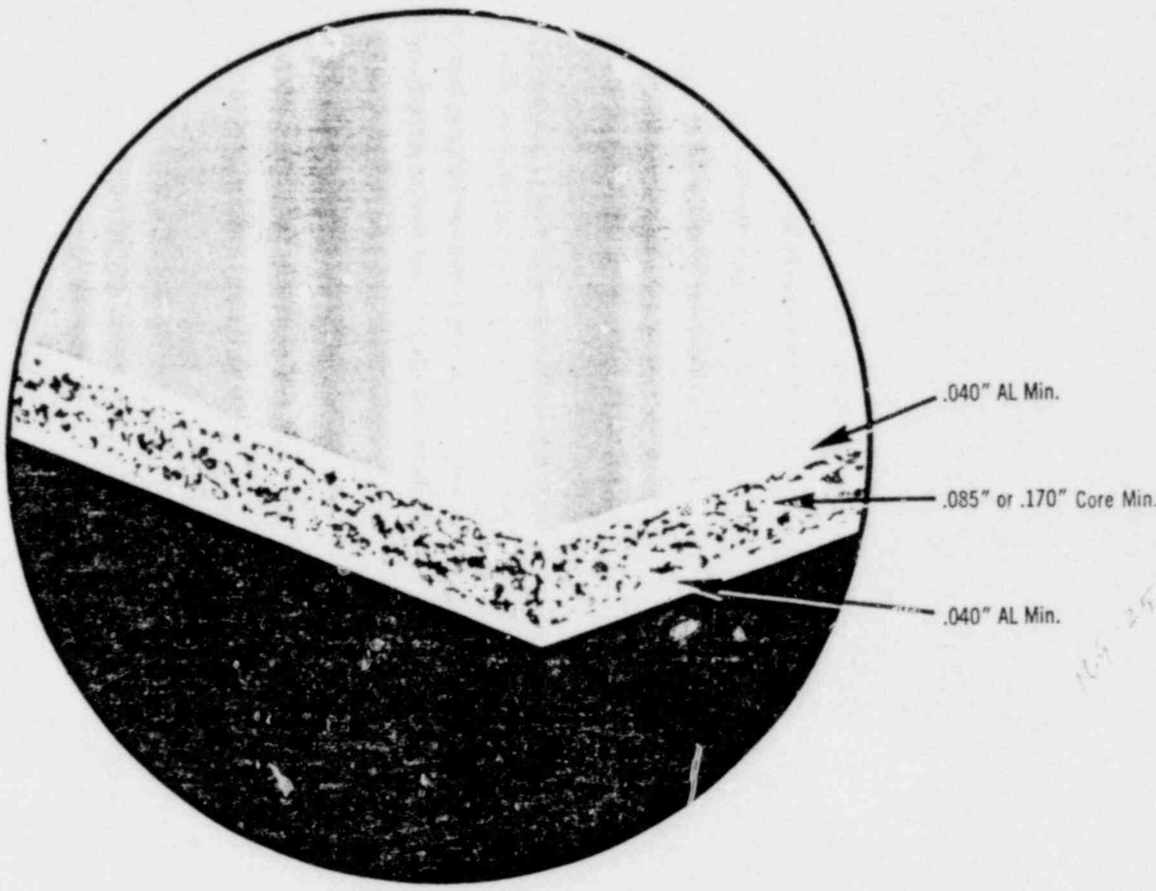
technical bulletin

NOVEMBER, 1975

BORAL

Neutron Shielding Material*

RADIATION



BORAL PLATE SHIELDS NEUTRONS WITHOUT INCLUDING GAMMA RADIATION

Boral shielding material offers the unique ability to absorb thermal neutrons without producing hard gamma radiation. A dispersion of boron carbide in aluminum that is clad in 1100 aluminum sheets, Boral is a sandwich material produced in standard sizes up to 48" x 120", and in standard mill thicknesses of .177" (±.012) and .265" (±.015).

These sizes are in stock for immediate delivery. Other sizes up to 168" in length can be specified subject to special inquiry.

Boral absorbs slow neutrons with a minimum of secondary radiation being induced. With each neutron absorbed, only a soft gamma ray (0.42MeV) and an easily absorbed alpha particle are emitted.

Boral offers excellent neutron shielding capabilities for a wide range of applications. It is being used extensively as a shield in spent fuel storage racks. It has also been used on inner section of reactor shields, shutdown control rods, as neutron curtains and shutters for thermal columns. In addition, it has been fabricated into housings to shield sensitive electronic and avionic equipment and as shipping and storage containers for radioactive materials.

Boral plate is also available in several forms including: Stainless Steel Clad/Encapsulated . . . and with aluminum edge cladding/sealing.

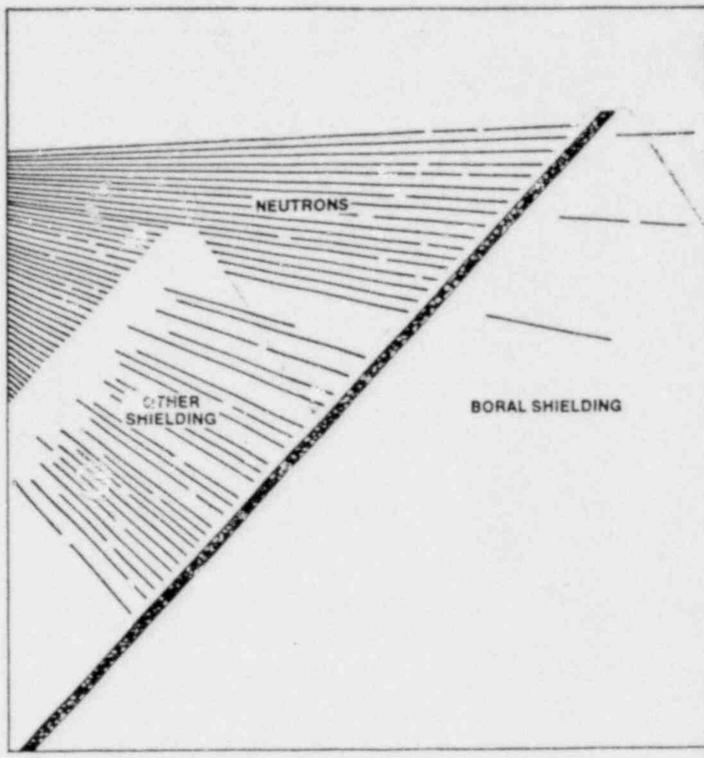
*Patent applied for.

SHIELDING CONSIDERATIONS FOR THE THERMAL NEUTRON

Radioactive materials produced by the nuclear industry today create a variety of radiation, including alpha particles, beta particles, gamma rays, neutrinos and neutrons. Alpha and beta particles are easily shielded by relatively thin sheets of metals. Neutrinos, although highly penetrating, appear to have little physiological importance. Only gamma rays and neutrons require special shielding consideration, with appreciable thickness of shielding materials to provide radiation protection. Gamma radiation is most effectively absorbed by high-density materials such as lead, steel and concrete. The best elements for neutron attenuation are boron, hydrogen, lithium, along with water and polyethylene.

Most shielding materials will readily absorb neutrons, but in doing so they ir... secondary gamma rays in the 5 to 10 MeV range. This, in turn, requires further shielding and heat dissipation. Boron is unique in its ability to shield the thermal neutron without leaving any significant residual radioactivity. Each attenuated neutron produces only one soft gamma ray (0.42 MeV) and an easily absorbed alpha particle in the process. By contrast, cadmium shielding emits a 6 MeV gamma ray and leaves a residue of four radioactive isotopes.

Boron is available in several forms: crystalline, amorphous and boron carbide. Boron carbide offers the least expensive form of highly concentrated boron. It is extremely hard, atomically dense, light weight, chemically inert, with a high melting point and high compressive strength.



Properties and Characteristics of BORAL

The boron carbide in the core of the sandwich panel is evenly dispersed throughout a matrix of aluminum. The outer cladding or "skins" of the sandwich panel is aluminum. BORAL™ panels are identified by the nominal thickness of the total sandwich panel and the minimum percentage content of boron carbide in the core.

Chemical Composition

Aluminum (1100 Alloy)	99.00% min. — aluminum
	1.00% max. — silicon and iron
	.05-.20% max. — copper
	.05% max. — manganese
	.10% max. — zinc
	.15% max. — others
	.05% max. — others each

Boron Carbide (type 2, ASTM C750-73T)	97.00% min. — Total boron and carbon
	77.00% max. — boron
	70.00% min. — boron
	3.00% max. — boron oxide
	2.00% max. — iron
	19.75% ±.3% isotope B^{10}

Corrosion Resistance

BORAL™ offers the same excellent corrosion resistance as 1100 alloy aluminum. It provides unlimited service in boric acid solutions when the pH is controlled between 0 and 8.5. Corrosive attack to the aluminum cladding will occur in strong alkaline solutions (pH 9.5) and at a temperature near boiling (212°F). For unlimited service in these environments, we recommend capsulating the BORAL™ in stainless steel sheathing.

Physical Properties of Base Materials

Density

	(gm/cc)
Aluminum	2.71
Boron Carbide	2.51
Core (35% B_4C)	2.64

Melting Temperature Range

	(°F)
Aluminum	1190 to 1215
Boron Carbide	4440

Thermal Conductivity

	(cal/cm²/cm/°C/sec)	
Aluminum	(77° F)	0.53
Boron Carbide	(77° F)	0.065

Coefficient Of Thermal Expansion

	(per °F)	
Aluminum	13.1×10^{-6}	(68-212° F)
Boron Carbide	2.5×10^{-6}	(68-1400° F)

Specific Heat

	(cal/gm/°C)
Aluminum	0.23
Boron Carbide	12.36

Mechanical Properties of Base Materials

Modulus of Elasticity (tension)

	(psi)
Aluminum	10×10^6
Boron Carbide	64×10^6

Tensile Strength — Ultimate

	(psi @ 75° F)
Aluminum	13,000 (annealed)
Boron Carbide	N/A

Tensile Strength — Yield

	(psi @ 75° F)
Aluminum	5 000 (annealed)
Boron Carbide	N/A

Percent Elongation (in 2")

	(75° F)
Aluminum	35
Boron Carbide	N/A

Shear Strength

	(psi @ 75° F)
Aluminum	9,000 (annealed)
Boron Carbide	N/A

Compression Strength

	(psi @ 75° F)
Aluminum	5,000 (annealed)
Boron Carbide	398 - 414,000

Mechanical Strengths Of BORAL™ Panels (Min. 35% B_4C Core)

Weight-Typical

	(lbs/sq. ft.)	
Th. .177	2.46	2.45
Th. .265	3.67	3.65

Tensile Strength — Ultimate

	(lbs/inch of width)
Th. .177	1230
Th. .265	1530

Tensile Strength — Yield

	(lbs/inch of width)
Th. .177	1140
Th. .265	1510

Percent Elongation (in 2")

	(75° F)
Th. .177	7.0
Th. .265	4.5

Shear Strength

	(lbs/inch of width)
Th. .177	1142
Th. .265	1386

Compression Strength — Compression Failure

	(lbs/inch of width)
Th. .177	1140
Th. .265	2140

Compression Strength — Buckling Failure

	(lbs/inch of width)
Th. .177	300
Th. .265	560

Flexural Strength — Max. Bending Moment

	(in-lbs/inch of width)
Th. .177	95
Th. .265	145

Modulus of Elasticity

	(lbs/sq. in.)
Th. .177	5.8×10^6
Th. .265	4.4×10^6

Water Absorption

	(%)	
	(24 hrs @ 0 psi)	(5 mins. @ 2200 psi)
Th. .177	0.295	0.429
Th. .265	1.940	0.620

Shielding Properties of BORAL™ Panels (Min. 35% B_4C Core)

Neutron Transmission Factor

	(Theoretical)
Th. .177	1.74×10^{-1}
Th. .265	2.30×10^{-2}

Neutron Transmission Factor

	(Experimental)	
	min.	nom.
Th. .177	3.5×10^{-2}	1.7×10^{-2}
Th. .265	11.5×10^{-4}	3.5×10^{-4}

Removal Cross Section

	(Theoretical)
Th. .177	14.0 IN^{-1}
Th. .265	21.6 IN^{-1}

Removal Cross Section

	(Experimental)	
	min.	nom.
Th. .177	20.4 IN^{-1}	23.2 IN^{-1}
Th. .265	26.0 IN^{-1}	31.4 IN^{-1}

Heat Generation From Neutron — Alpha Reaction
7.4×10^{-10} watts/sq. ft. x unit thermal neutron flux.

"Corrosion of Aluminum Alloys in an Aqueous Solution of Boric Acid and Sodium Hydroxide."
Dr. E. H. Hollingsworth; Aluminum Company of America

"A Handbook on Boron Carbide and Elemental Boron."
Norton Company

"Aluminum Standards and Data." The Aluminum Association

"Boron Carbide Production Properties, Application."
Dr. Alfred Lipp; Reprint from "Technische Rundschau" Nos. 14, 28, 33 (1965) and 7 (1966).

The data presented in this bulletin is, to the best of our knowledge, correct and up-to-date based on the above references and our own independent laboratory tests.

Fabricating with BORAL™ Plate

In fabricating Boral plate, it is recommended that forming operations be limited because of the nature of the sandwich material of the plate. Generally, a 1/4" plate may be formed at 90° right angles providing a 3/4" radius is held. In forming cylinders, 2½" to 8" OD sizes may be made with tolerances of ±1/32"; over 8" the tolerance is ±1/16". When forming small diameters, the sheet must be annealed during forming to prevent parting of the sandwich.

Welding of Boral plate is not recommended if maximum strength is required. In most applications, arc welding is done to butt plates together when widths over 48" are needed, or when special clips are required. For the best welds, clean the clad surfaces with a fine wire brush, then butt all joints as tight as possible. For large areas, pre-heat Boral plate to 400°F. in an oven or on a hotplate; a torch should not be used. The welding arc must be held as close as possible to the Boral plate, use

Amperage settings for welders must be determined by trial.

Other recommendations in fabrication of Boral plate.

Drilling — Use carbide tip drills, slow speeds, high feed pressures. Drilling is recommended only when holes cannot be punched.

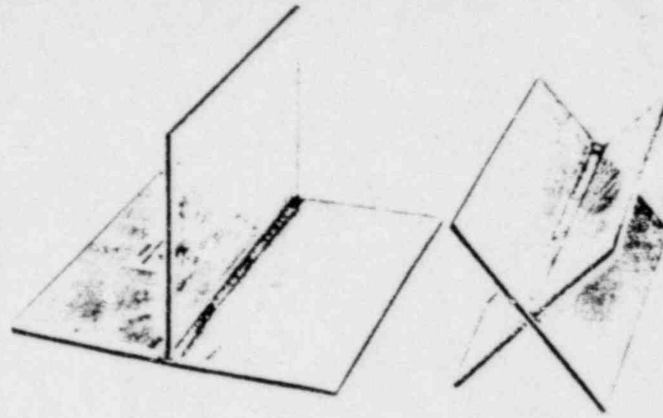
Countersinking — Use 4-flute carbide tip type at low speeds, high feed pressures.

Punching — Use carbide tip punch and die of hardened tool steel. Punch and die must be kept sharp to maintain hole sizes to tolerances of ±.005".

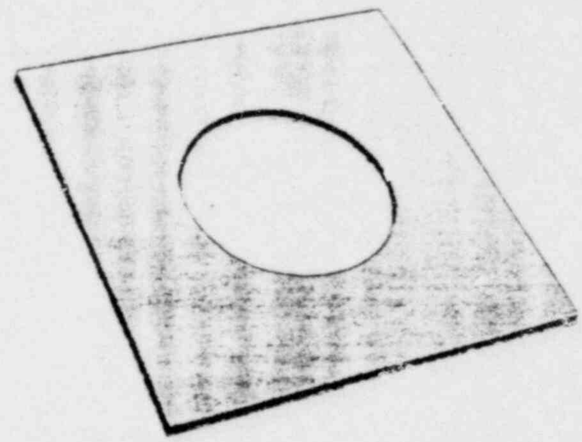
Sawing — Use a 10 to 14-tooth blade, cutting at 75 feet per minute. If a 111-inch blade is used, allow 24" per blade for 1/4" Boral and 36" for 1/8" Boral plate. Tolerance for saw cuts is ±.015".

Shearing — Boral can be sheared on 8-foot-length tolerances of ±1/32". Sharpen shear blades frequently.

Plasma arc cutting — Boral plate can be cut to special shapes or sizes by plasma arc.



Boral plate can be welded by the heliarc process, as shown in these fabricated samples. Care should be used to butt weld joints as close as possible.



This 1/4" thick Boral plate was completely cut by plasma arc method, both on outer edges and circular hole in the center.

BROOKS & PERKINS Provides A Complete Fabrication Service For BORAL Components

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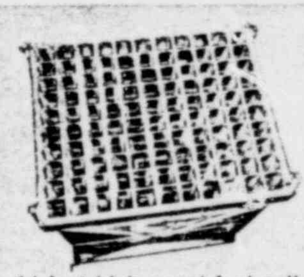
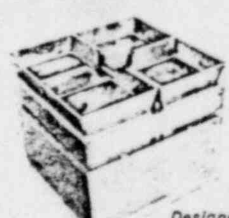
Illustrated here are a few of the Boral components produced by Brooks & Perkins. Whatever your needs, this expertise and experience can be of benefit to you. Call or write, outlining your specific requirements.

This Boral-lined neutron shielding jacket was produced by welding Boral components at Brooks & Perkins.



This 14 foot high spent fuel cell storage rack was built by Brooks & Perkins of Boral and Aluminum.



Designed by NUS

Designed by Nuclear Services Corp.

Two different configurations of Boral and aluminum spent fuel storage racks (sample sections) for BWR fuel assemblies.

b+p Brooks & Perkins Inc.
NUCLEAR PRODUCTS
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Fabrication: Ext. 224 Boral Panels: Ext. 256