Fracture Toughness and Required Testing of Borated Stainless Steels

Structural Integrity Associates, Inc.

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Fracture Toughness and Required Testing of Borated Stainless Steels

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EXECUTIVE SUMMARY

There is a fairly large quantity of information available on the physical metallurgy and mechanical properties of borated stainless steel. In general, tensile strength increases with increasing boron concentration; tensile ductility and impact properties are reduced.

The primary influence of the boron concentration on the mechanical properties is the result of hard, brittle $(Cr,Fe)_2B$ boride particles in the ductile and tough austenite matrix. The size and shape of the boride particles and the boride particle distribution is a critical parameter. Smaller, more spherical, and uniformly distributed boride particles have the least detrimental effect on ductility and impact strength.

The ductility and toughness of borated stainless steels produced by Powder Metallurgy (PM) techniques are clearly better superior to those from the ingot cast and wrought material at all boron levels.

The fuel basket for the Transnuclear TNI-REG is a PM product with approximately 2.2 weight per cent boron, produced by Carpenter Technology. The TNI-BRP basket material is a conventionally produced ingot metallurgy product with approximately 1.45% boron.

Since the TNI-REG and TNI-BRP casks were produced in themid-1980s, an ASTM materials standard for borated stainless steels, A-887, has been approved. That standard includes 16 material types – 8 different boron levels from 0.20% to 2.25%, and two grades (Grade A and Grade B) that exhibit significantly different ductility and toughness properties. In general, the Grade A material, which has superior ductility and toughness is produced by PM methods.

ASME Section III Code Case N-510-1, prepared to permit the use of borated stainless steels for Core Support Structures in water cooled reactors has been approved. That Code Case includes ASTM A-887 Grades 304BA through 304B6A. It does not include the 304B7A grade nor any of the Grade B materials.

Section III, Division 3 of the ASME Code has also been issued specifically for the design and construction of spent fuel storage and transport containers.

Temperature appears to exert only a minor effect on tensile strength and ductility. Temperature effects are less for the borated stainless steels than for standard grades such as Type 304L.

The impact properties of the borated stainless steels do not appear to affected by temperature at all over the range of –29°C to 350°C.

Neutron irradiation to fast fluences of $1x10^{13}$, $5x10^{15}$, and $1x10^{17}$ n/cm^2 also appeared to have little or no effect on mechanical properties of borated stainless steels, both A and B Grades, containing 0.25 to 2.01% boron.

Charpy impact tests are required by ASTM A-887. For the highest boron content materials, the required Charpy impact energy is not very high (10 ft-lbs at room temperature) but the material must have some toughness to be accepted. The level of toughness is roughly comparable to that for very high strength materials used for bolting or shafting (e.g., Type 410 stainless steel or 17-4PH stainless steel in the H900 temper).

Using Charpy impact energy values and correlations between impact energy and K_{Ic} developed for other materials (e.g., pressure vessel steels) suggests that the K_{Ic} for PM 304 with 2% boron (i.e., equivalent to ASTM A-887, Grade 304B7A) is of the order of 30 to 70 ksi√in.

No data were located on fracture toughness parameters such as K_{Ic} or K_{ID} for the borated stainless steels. Values of those parameters will be required for design analyses. Limited information on J found (associated K_{Ic}'s range from about 65 to 200 ksi√in.

All of these measured values or estimates of toughness indicate that a reasonable level of toughness would be expected for both the ingot metallurgy material with 1.45% boron (TNI-BRP basket0 and for the PM material with 2.2% boron (TNI-REG)

The key factor in defining the expected fracture toughness of the borated stainless steel materials used in the Transnuclear TN-REG and TN-BRP casks is demonstrating that those materials represent a sample from the same population as that used to generate the existing tensile and Charpy impact toughness properties.

Limited tensile and fracture toughness testing of TN-REG and TN-BRP materials, combined with impact data in hand, is considered viable for qualification of existing materials.

The test program required to quantify and bound the actual fracture toughness of the basket materials is expected to include Charpy V-notch tests, tensile tests, and J-integral tests (e.g., small pre-notched and fatigue pre-cracked bent beams). The Charpy testing is expected to demonstrate that the material properties are consistent with the requirements of ASTM A-887 and that the expected fracture toughness is too great to permit a valid direct measurement of K_{Ic}. Instead, multiple specimen J vs. a (Δa) curve will be determined as outlined in ASTM E-813 and E-1737 such that a limiting J value (J_{Ic}) can be determined.

From that measured J_{Ic}, a K_{Ic} value can be calculated for comparison to the applied stress intensity factor in the design analyses. Analytical demonstration that conservatively calculated applied K's are less than K_{Ic} for all loading conditions provides the assurance that brittle fracture will be avoided.

The recommended test program will also include limited optical metallographic examination of the TNI-REG and TNI-BRP basket materials to confirm that the desired boride sizes and distributions, consistent with those reported in the literature, have been achieved.

1.0 BACKGROUND

The TN-REG and TN-BRP are large rail casks for the one-time transport of commercial spent nuclear fuel from West Valley, NY to INEEL, Idaho. The casks and their baskets were built in 1984, but have not been used fully loaded yet; in part due to questions regarding the toughness of the basket materials.

Both casks are thick-walled, forged carbon steel shells with welded forged steel bottoms and bolted forged steel tops [24] (Figure 1-1). Each cask weighs about 100 tons.

Baskets are egg crate type assemblies made from interlocking flat plates to produce square fuel compartments that run the full length of the cask. Both casks used borated stainless steel for criticality control and structural functions. In both baskets and both casks, the plates are about 7mm (≈ 0.276") thick. Some of the plates have a 0.5 mm layer of copper electroplated on both sides to enhance heat transfer. None of the plates are welded. Instead, the plates are slotted to one quarter width and interlocked with the adjacent plates. The baskets in both plates are annealed. A stainless steel tie rod at the center of each basket provides axial restraint.

The TNI-BRP cask holds 85 fuel assemblies from Big Rock Point. The TN-BRP plates are a cast and rolled product containing about 1.5% boron. All BRP plates were produced from a single heat. TNI-BRP has 44 6.80 in^2 compartments (2 fuel assemblies each. Basket plates are 17 inches high, nominally 1.3 weight percent boron (actual = 1.4%). The BRP basket weighs 14,300 pounds

The TNI-REG cask holds 40 assemblies from Ginna. The fuel basket (borated stainless steel) maintains position of the fuel inside the cask (Figure 1-2). The TNI-REG plates are a powder metallurgical product with about 2.2 wt % boron. TNI-REG has 20 8.05 in^2 compartments (1 fuel assembly). Basket plates are 18 inches high, nominally 1.7 weight percent boron (actual = 2.2%). The BRP basket weighs 14,100 pounds.

The operating temperature range of the baskets is –20 to 400 °F.

Estimated fast neutron fluence over a 40 year life is of the order of 10^{14} n/cm^2, E>1 MeV.

The different casks use borated stainless steel plates from different vendors, fabricated by different techniques (Table 1-1).

Safety Analysis Reports for the TNI-REG and TNI-BRP casks were submitted to NRC in 11-85 for certification as Type B containers. Primary NRC concerns were:

1. Borated stainless steel had no established materials standard (e.g., ASTM)
2. No accepted codes or standards for acceptance of borated stainless steel as a structural material for loading conditions that include a 30 foot drop (per 10CFR71)
3. Analysis by Lawrence Livermore calculated basket stresses beyond specified yield stresses for the same conditions (some of which were not in the SAR)
4. LLNL analysis indicated susceptibility to buckling under some side drop conditions
5. No fatigue evaluation submitted.

NRC judged the borated stainless steel, used for these original cask designs in the cask demonstration project, to be unacceptable as a structural material.

The basket design was altered so that payload would be kept subcritical without using the borated stainless steel as a structural material – ship half full of fuel with inserts in the empty slots in a checkerboard pattern and along the periphery (Figure 1-2). Structural inserts are full length, diagonally braced box beams (SA-240, XM-19). Each insert is constructed from 5 individual segments jointed by pinned adapters/flexible joints. For the TNI-BRP cask, there are 22 inserts (6.47 in^2, 0.375 inch wall). For the TNI-REG cask, there are 20 inserts (8.05 in^2, 0.5 inch wall). Peripheral inserts fit in the spaces between the basket and the cask wall (full length).

TNI-BRP was certified for half-loads in July 1989; certification of TNI-REG was anticipated in early 1990.

The NRC's rejection noted that the following future work would be required:

1. Borated stainless steel must be covered by an ASTM specification
2. Allowable stresses for borated stainless steel under normal and accident conditions must be defined in a consensus code standard
3. Fatigue and fracture must be addressed by the standard. Brittle fracture must be avoided by sufficiently ductile and tough material.
4. Analysis or testing must demonstrate that stresses are within specified limits for all loadings and orientations.

Since then, materials specification ASTM A-887-88 was issued (August 26, 1988). It includes 8 types of borated stainless steel based on the amount of boron (from Type 304B with 0.2% to 0.3%) to Type 304B7 (1.75% to 2.25%). For each Type, there are two Grades (A and B), defined by tensile elongation. In practice, Type A is produced by powder metallurgy techniques; Type B is a wrought, product produced by conventional ingot metallurgy.

Tensile testing of the plate material was done at room temperature and at elevated temperatures. Elevated temperature test results are included in Table 1-1. There was no fracture toughness testing. There are no photomicrographs available.

In order to certify the TNI-BRP and TNI-REG casks, the NRC has requested that Transnuclear provide:

1. Test data demonstrating how the tensile properties vary with temperature. This could either be by new testing of the material in hand, or by reference to existing test literature for borated stainless steel.
2. Statistically significant fracture toughness data over the range of operating temperatures.

Transnuclear intends to submit a license application to the NRC by the beginning of March, 2000.

The current guidance from the Nuclear Regulatory Commission recommends designing baskets for spent fuel transport in accordance with ASME Boiler and Pressure Vessel Code Section III,

Division 1, Subsection NG (Core Support Structures). Section NG-2300 requires ferritic materials, such as reactor pressure vessel steels, to be subjected to drop weight testing and Charpy V notch testing. At the minimum service temperature, the Charpy test acceptance criteria for materials over 2 inches thick are at least 35 mils lateral expansion and 50 ft-lb of absorbed energy. For materials less than 2 inches thick, there are only lateral expansion criteria varying from 20 mils at 5/8 inch to 40 mils at 2 inches. No test is required under 5/8 inch.

Code Case-N-510-1 was approved for the use of borated SS for Core Supports. That Code Case includes only the Grade A material and only for boron concentrations up to 1.75% (304B6A).

Further, Section III, Division 3 of the ASME Code [33] provides criteria for the design and construction of containment systems and transport packaging of spent nuclear fuel and high level radioactive waste.

Per Transnuclear, no material from the original lot is available for testing, other than what is actually in the basket. Some material could be removed from the basket for testing and for metallurgical examination, but probably not more than one or two plates from each basket. Therefore, it will not be possible to get a "statistically significant" sampling, nor, in fact, will it be possible to get a test coupon that is representative of each "master" plate.

The alternative that Transnuclear is considering is to provide as much data as possible from published and unpublished sources, and provide only as much testing of the TN-REG and TN-BRP materials as is required to demonstrate that this material behaves consistently with other materials of its type.

Table 1-1
Composition and Mechanical Properties of TNI-REG and TNI-BRP Basket Materials

TNI-REG Basket Material

Heat	Can	Length Group	Plates
B260	C1592	L6	1B, 1C, 1D, 1E, 1F, 1G, 1H, 1I, 1J, 1K, 1L, 1M, 1N, 1O, 1P, 1X, 1A1
	C1592	LN5	1A1, 1A2
B261	C1958	L2	6A, 6B, 6C, 6D, 6E, 6F, 6J
	C1958	L6	6K, 6L, 6M, 6N, 6X
	C1959	L1	12B, 12C, 12D, 12E, 12F, 12G, 12H, 12J, 12K, 12L, 12M, 12N
	C1959	L5	12A1, 12A2
	C1960	LN2	8E1, 8E2
	C1960	LN3	8G
	C1960	LN4	8A, 8N2
	C1960	L3	8C, 8F
	C1960	L7	8B, 8D, 8H, 8M
	C1960	L10	8N1
	C1961	LN1	9C, 9J
	C1961	LN2	9H
	C1961	L3	9E, 9N, 9P
	C1961	L5	9A1, 9A2, 9K1, 9K2, 9M3
	C1961	L7	PB
	C1961	L10	9L1, 9L2, 9L3, 9L4, 9M1, 9M2, 9X1, 9X2
	C1962	L2	5F, 5G, 5H, 5J, 5K, 5L, 5M, 5N, 5X
	C1962	L3	5P1
	C1962	L10	5P2
B262	C1963	L1	11K, 11L
	C1963	LN1	11F1, 11F2
	C1963	L3	11A, 11AA, 11B1, 11C, 11D, 11E, 11M, 11X
	C1963	L5	11G1, 11G2, 11H1, 11H2, 11J1, 11J2
	C1963	L7	11N
	C1963	L10	11B2
	C1964	L7	10J, 10K, 10L, 10M, 10X
	C1964	L9	10A1, 10A2, 10B1, 10B2, 10C1, 10C2, 10G1, 10D1, 10D2, 10E1, 10E2, 10F1, 10F2, 10G2
	C1964	L7	10H1, 10H2
	C1965	LN2	7C
	C1965	L3	7H, 7N
	C1965	L5	7X1, 7X2
	C1965	L7	7D, 7E, 7F, 7K, 7L, 7M
	C1965	L9	7G1, 7G2
	C1965	LN3	7J1, 7J2
	C1965	L6	7B
	C1966	LN3	2D2
	C1966	LN4	2C1, 2C2
	C1966	LN5	2X1, 2X2
	C1966	L5	2X2A
	C1966	L8	2A1, 2A2, 2B1, 2B2, 2D1, 2F1, 2F2, 2G1, 2G2, 2H1, 2H2, 2I2, 2I2
	C1966	L9	2E1, 2E2
	C1967	L4	4A1
	C1967	L7	4G
	C1967	L10	4A2, 4F1, 4F3
	C1968	L4	3C1, 3D1, 3D2, 3E1, 3E2, 3F1, 3F2, 3G1, 3G2, 3H1, 3H2, 3I1, 3I2, 3X1, 3X2
	C1968	L8	3A1, EA2, 3B1, 3B2, 3C2

Table 1-1 (continued)

TNI-REG Basket Material

Can	C	Mn	Si	P	S	Cr	Ni	Mo	Cu	Fe
Heat #B261										
C1958	0.039	1.82	0.48	0.017	0.005	18.41	13.04	0.22	0.12	Bal.
C1959	0.040	1.83	0.45	0.017	0.004	18.37	12.88	0.22	0.12	Bal.
C1960	0.040	1.81	0.48	0.017	0.005	18.32	13.00	0.22	0.12	Bal.
C1961	0.041	1.81	0.46	0.016	0.005	18.40	12.93	0.22	0.12	Bal.
C1962	0.040	1.86	0.46	0.016	0.004	18.38	12.88	0.22	0.12	Bal.
Heat #B262										
C1963	0.042	1.82	0.47	0.016	0.004	18.37	13.07	0.21	0.12	Bal.
C1964	0.041	1.84	0.45	0.016	0.005	18.43	12.93	0.21	0.12	Bal.
C1965	0.042	1.85	0.46	0.017	0.005	18.34	12.99	0.21	0.11	Bal.
C1966	0.042	1.86	0.56	0.019	0.006	18.46	13.40	0.18	0.14	Bal.
C1967	0.042	1.84	0.50	0.016	0.004	18.43	13.19	0.20	0.12	Bal.

Table 1-1 (continued)

TNI-REG Basket Material

				Mechanical Properties					
				Room Temperature			650F		
Heat	Can	Sample	Boron, w/o	Yield Strength, ksi	Ultimate Strength, ksi	Elongation (4D), %	Yield Strength, ksi	Ultimate Strength, ksi	Elongation (4D), %
B260	C1592	1A	2.194						
		1C	2.18	55	110	17.5	48.5	92	17.5
		1K	2.188	53	111	19	48.5	92	12
		1N	2.186						
		1X	2.188						
B261	C1958	6L	2.20				46	99	20
	C1958	6F		52	107	20			
	C1959	12N	2.21						
	C1959	12A		53	108	22	68	96	11
	C1960	8E	2.20	55	112	23	52	99	20
	C1961	9N	2.20						
	C1961	9B		54	109	22	42	89.5	10
	C1962	5X	2.20	51	109	22	45	106	17
B262	C1963	11A	2.22	58	113	21	45.5	97	17
	C1964	10L	2.22	58	110	22	45	98	21
	C1965	7B	2.22	51	111	23	44.5	100	18
	C1966	2A	2.24	56	112	19.8	47	100	18
		2H	2.24						
	C1967	4F	2.22						
		4G		53	109	22	48	101	18
	C1968	3F	2.25						
		3X	2.24						
		3X-1	2.24						

Table 1-1 (continued)

TNI-BRP Basket Material

Heat N63002

Length Group	Plates
L1	101/2, 101/1, 102/2, 102/1
L1	14/2, 17/2, 17/1, 22/2, 8/2, 12/2
LN3	116/1, 116/2, 116/3, 116/4
LN2	20/2, 3/2, 3/1, 13/2
L4	114/2
L1	93/1, 93/2, 96/1, 97/1, 96/2, 98/1, 98/2, 99/1, 99/2, 100/1, 100/2, 103/1, 103/2, 97/2
L3	115/1, 104/2, 105/1, 105/2, 106/1, 106/2, 107/1, 107/2, 108/1, 108/2, 109/1, 109/2, 110/2, 111/1, 111/2, 112/1, 112/2, 113/1, 113/2, 114/1, 110/1
L3	91/2, 90/1, 90/2, 55/1, 72/1
L2	74/2, 75/2, 75/1, 73/2, 30/2, 40/1, 35/2, 28/2, 39/1, 36/2, 38/2, 39/2, 25/1, 28/1, 36/1, 37/1, 38/1, 24/2, 25/2, 27/2, 29/2, 37/2, 40/2, 27/1, 29/1, 79/2

Length Group	Plates
L4	60/2, 61/2, 65/2, 69/2, 62/2, 66/1, 65/1, 60/1, 64/1, 64/2, 63/2, 63/1, 66/2, 68/2, 62/1, 68/1, 61/1
LN1	2/4, 2/2, 2/3, 2/1
L4	80/1, 92/1, 85/1, 81/1, 82/1, 88/1, 92/2, 85/2, 82/2, 88/2, 80/2, 87/1, 87/2, 86/1, 86/2, 83/1, 84/1, 83/2, 81/2, 84/2
LN5	78/2, 78/3, 78/4, 78/1
L5	81/3, 92/3, 88/3, 88/4, 81/4, 92/4, 80/3, 82/3, 85/3, 87/4, 80/4, 82/4, 87/3, 85/4, 86/4, 86/3, 83/4, 84/4, 83/3, 84/3, 69/3, 66/3, 60/3, 64/3, 66/4, 69/4, 60/4, 64/4, 63/4, 62/3, 68/3, 65/4, 65/3, 61/3, 68/4, 62/4, 61/4, 63/3
LN4	78/8, 78/7, 78/6, 78/5
L3	89/2, 89/1, 91/1, 42/1, 42/2, 50/2, 50/1, 43/1, 44/2, 56/1, 53/2, 53/1
L2	1/1, 1/2
L1	11/1, 11/2, 10/1, 6/1, 6/2, 8/1, 7/1, 5/1, 5/2, 4/1, 4/2, 21/1, 21/2, 18/1, 18/2, 15/1, 15/2, 14/1, 13/1, 9/1, 9/2, 23/2, 23/1, 19/1, 19/2, 10/2, 7/2, 20/1
L4	94/2, 115/2

Table 1-1 (concluded)

TNI-BRP Basket Material

Heat #N63002

C	Mn	Si	P	S	Cr	Ni	Mo	Cu	Co	Fe	Boron
0.036	1.28	0.53	0.02	0.002	19.15	12.75	0.07	0.04	0.16	Bal.	1.43
0.037	1.28	0.53	0.02	0.002	19.09	12.83	0.07	0.02	0.15	Bal.	1.41

Mechanical Properties

Room Temperature			650F		
YS, ksi	UTS, ksi	El'n (4D), %	YS, ksi	UTS, ksi	El'n (4D), %
47.1	89.2	15.6	40.6	78.5	12.0
47.0	93.8	16.0			

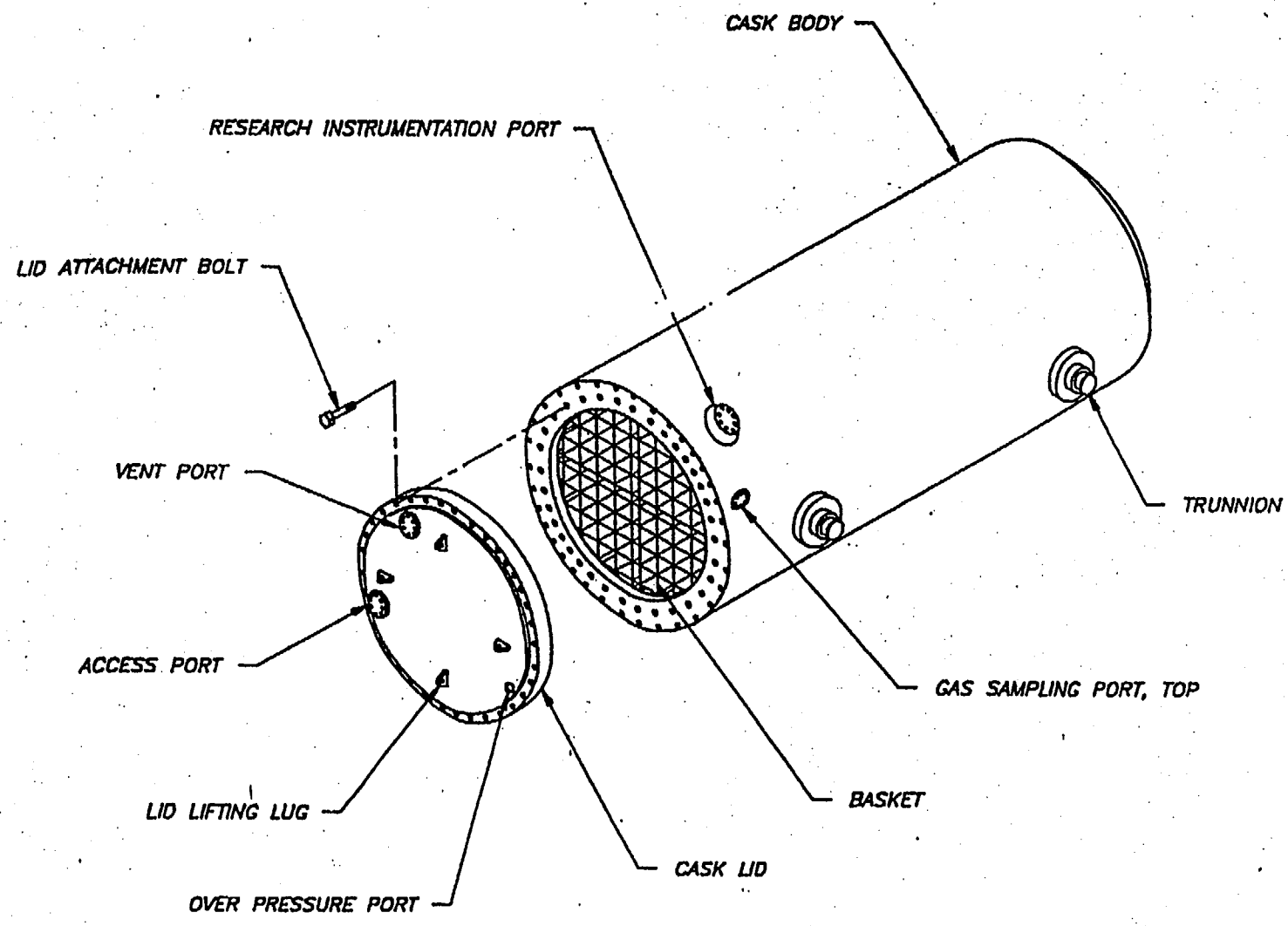

FIGURE 1. SCHEMATIC OF TN-BRP CASK

Figure 1-1. TNI-REG and TNI-BRP Casks (from [24])

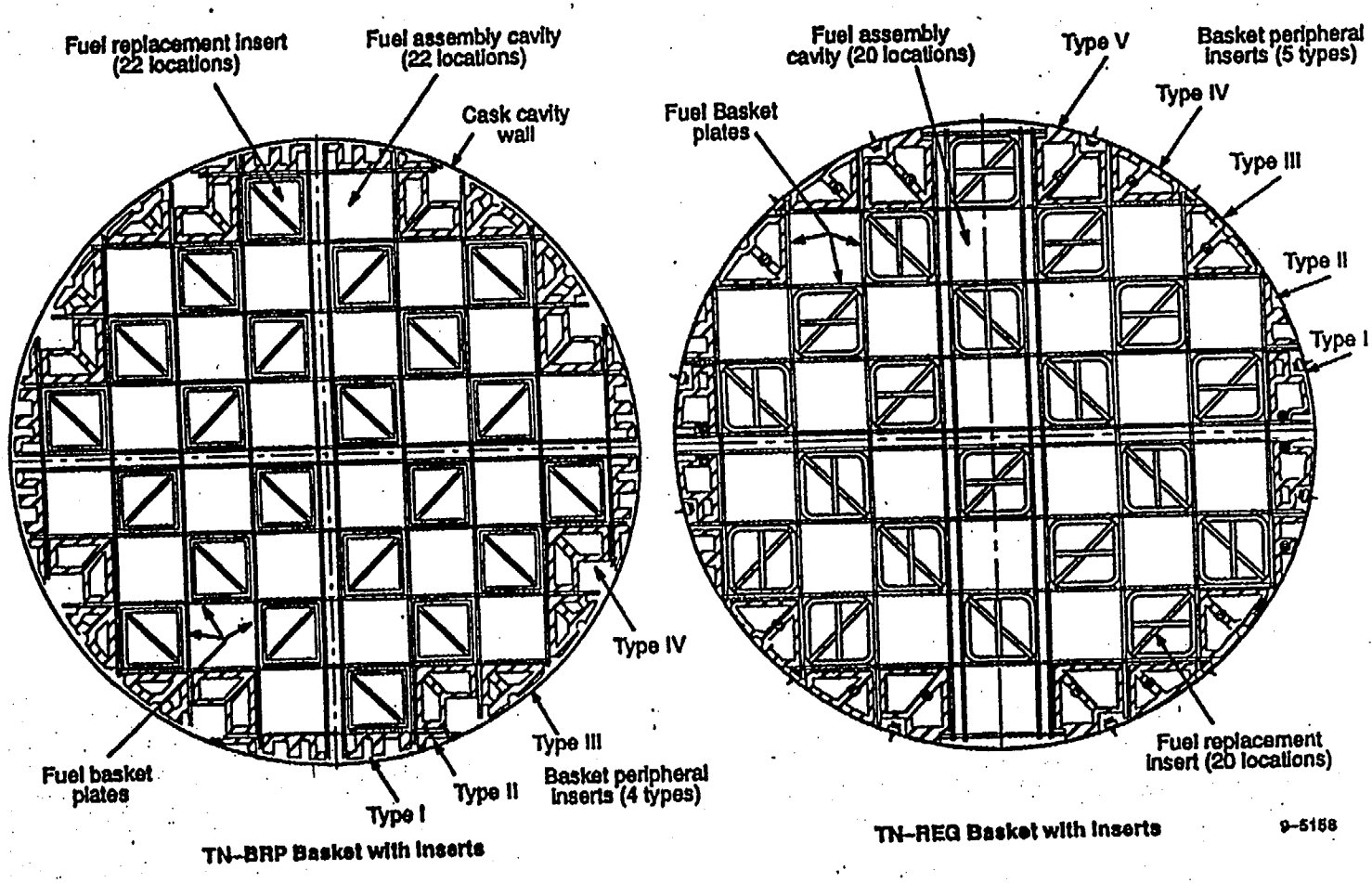

Figure 1-2. Fuel Baskets with Inserts for TNI-REG and TNI-BRP Casks (from [24])

2.0 OBJECTIVES

The primary objective of this work was to define the fracture toughness of the borated stainless steels in the TN-REG and TN-BRP casks. A secondary objective was to define the completeness and applicability of the fracture toughness data available in the literature to the TN-REG and TN-BRP casks and evaluate the feasibility and validity of providing limited test data supported by the literature rather than providing a statistically significant amount of test data from the actual material lots. Finally, where testing was identified as required, recommend test procedures for fracture toughness testing.

3.0 APPROACH

Pertinent reports were reviewed from Carpenter Technology and Bohler Bleche, formerly Vereinigte Edelstahl Werke, the respective producers of the TN-REG and TN–BRP basket materials; from national laboratories participating in United States Department of Energy (USDOE) efforts to develop and qualify materials for transport and storage casks; and articles in the open literature. That literature was reviewed for mechanical properties data and for descriptions of the physical metallurgy of borated stainless steels that were pertinent to the resulting properties. Data from those literature citations was compared to the actual heats and lots of material used for the TN-REG and TN-BRP casks.

4.0 RESULTS

4.1 Metallurgy of Boron Stainless Steels

Boron is essentially insoluble in austenite at virtually all temperatures, which means that borides will basically form from the melt. In any steelmaking operation, boron will be in some form of precipitate at all times. For well-deoxidized steel, boron first reacts with available nitrogen (BN), then with carbon to form carbides and borides. At low B/C ratios, boron dissolves in the normal carbides. At intermediate B/C, mixed borides-carbides (e.g., $M_{23}(B,C)_6$ and $M_2(B,C)$) form. At high B/C, the predominant precipitate is M_2B. Maximum solubility of boron in the three stainless steels studied by Goldschmidt were 58 ppm, 95 ppm, 158 ppm [9, 10]. In all cases, the precipitating phase was $(Fe,Cr)_2B$ which formed a low melting point eutectic between 1150°C and 1225°C. Whenever there is excess boron, which is almost all the time since solubility is so low, a boride, either a $Cr_{23}C_6$ type at low contents or $(Fe, Ni, Cr)_xB$ where $x \approx 2$, will precipitate. Goldschmidt found that in the 20%Cr-25% Ni alloy that borides were of a M_2B composition [9]. For 18%Cr-15%Ni, the basic composition was $M_{2.3}B$ [10]. In the M_2B type of boride, the ratio of Fe:Cr:Ni is about 11:11:1. Borides appear at grain boundaries as very small, discontinuous particles. At higher boron levels, a nearly continuos network of austenite-boride eutectic forms, enclosing the austenite grains. At 4.63 atomic% B, austenite+massive boride + globular eutectic regions appear. [9].

The first hurdle in the development of the boron stainless steels from which useful products could be made was to define fabrication processes that permitted hot rolling, etc. to even make plate, strip, or other shapes. Boron precipitates form a continuous network in as-cast ingots. Continued working (i.e., if the boron is dispersed without failing the product) yields dispersed, compact precipitates which strengthen the matrix while some ductility remain. Some of that history is described in [17]. In a 1980 reference, Loria and Isaacs [17] note that "Type 304 stainless steel with 1 to 2 wt% boron has been used for control rods and spent fuel racks for many years." They evaluated the hot workability of a 0.53%B Type 304. The current interest that prompted the paper [17] is in 304 with 0.5% to 0.7% boron. They focus on a 0.53%B alloy

looking at hot ductility (Gleeble) and microstructural studies. The boron stainless steel is known to have reduced ductility in the 900-1180°C range.

The borides that potentially affect primary processing still persist to room temperature and affect ductility and toughness dramatically. The next step in the development of the borated stainless steels was to control the distribution, size, and shape of the borides so that the useful products would have useful and usable properties. The size of the M_2B precipitates (1 or; 6μm; as discrete precipitates) does not change when as-hot rolled and air cooled bar is reheated to 1090°C. One characteristic of boron in stainless steel is to produce very fine grain sizes, as grain boundaries are pinned by the presence of a fine dispersion of those particles. The final particle size is set by the as-cast boride size and by the amount of work put into the metal during processing. Chromium content of borides is close to 50%; iron and nickel are about 40% and 1%; consistent with the 11:11:1 ratio of chromium, iron, and nickel reported for a 25%Cr-20%Ni stainless steel by Goldschmidt [9].

In the borated stainless steels, the boron will be present as the finely dispersed chromium-rich boride precipitate discussed above. That boride will tie up a significant concentration of chromium. For example, a 0.5% B alloy can tie up as much as 2% Cr [17], producing chromium-depleted zones; akin to the sensitization observed in the normal stainless steel grades. The borides appear at a relatively uniform density and concentration of 1 to 6μm particles at grain boundaries that contain ~50% chromium. Loria and Isaacs [17] showed via electrochemical testing (an electrochemical potentiokinetic reactivation type test in deaerated 1.0N or 2.5N sulfuric acid) that the 0.53% B showed similar features as that for a boron-free sensitized 304.

4.2 Mechanical Properties

Three objectives for the nuclear power industry for spent fuel cask design are 1) economy of space; 2) safe transport and storage, including the capability to withstand severe impact; and 3) assure sufficient shielding of thermal neutrons. Borated stainless steels allow those objectives to be

achieved with a single material. In the UK, "fuel skips", the British equivalent of the fuel basket in the United States, (Figure 4-1) have been fabricated from boronated stainless steel since 1972.

There is a fairly large quantity of information available on the mechanical properties of borated stainless steel. In general, tensile strength increases with increasing boron concentration; tensile ductility and impact properties are reduced. The influence of boron concentration on mechanical properties is a result of the dispersion of the hard boride particles through the microstructure. The size and distribution of those particles exerts a profound influence on the mechanical properties, especially the ductility and toughness.

The majority of the development activity related to the borated stainless steels has been devoted to producing finer boride particles and more uniform distributions that result in ductility and toughness values that approach those of the conventional stainless steel grades. The ductility and toughness of the borated stainless steels produced by Powder Metallurgy (PM) techniques produce a product that is clearly better relative to ductility and toughness than the ingot cast and wrought material at all boron levels (Figures 4-2, 4-3, and 4-4, from [2]).

The one set of structural criteria published for cask design is USNRC Reg. Guide 7.6 which requires that ASTM/ASME materials be used, among its other requirements. A joint effort between EPRI and Carpenter resulted in the development and approval of ASTM A-887. [23]

The higher boron grades, B4, B5, B6, and B7, are most useful for criticality control At these high boron levels, only the Grade A material was considered by ASME to have adequate impact properties to permit to its inclusion in the ASME Code Case Inquiry. For example, 304B2B (0.50%-0.70%) has a required minimum CVN energy of 22J (16 ft-lbs). All of the heats evaluated in [20] (304B5A&B, 304B7A&B) were produced by Carpenter. As shown in Table 4-1, 304B5A material had 1.41%B, 304B5B had 1.38% B, 304B7A had 2.19% B, and B7B had 1.90% B. Tensile tests for B5 grades used round tensiles (1/4" gage); for B7 flat plate tensiles ½" wide by 0.200" thick. Most specimens tested were in the transverse orientation.

Boride phase was consistently finer in the PM processed Grade material vs. the IM processed Grade B. Some of the boride particles in the Grade B showed cracks within the particles. Area size distribution is described well by a log-normal distribution. For Grade A, average particle area and maximum particle area are finer than for Grade B. [20]

NeutroSorb™ and NeutroSorb PLUS™, formulated by Carpenter Technology for spent fuel casks and racks that require high thermal neutron capture cross sections, are modified Type 304 stainless steels with boron additions up to 2% (and above if required). NeutroSorb PLUS provides improved properties over Carpenter's conventional boron stainless steel, NeutroSorb. Cask fuel baskets must be capable of safe transport and storage and withstand severe impact without fracturing. The primary goal in the development of NeutroSorb PLUS was to provide higher ductility, higher boron levels, and greater flexibility in material thickness [1].

Effects of boron content on strength are about the same for NeutroSorb and NeutroSorb PLUS. Detrimental ductility effects, especially at the higher boron contents (i.e., to about 2%), are far less for NeutroSorb PLUS [1].

NeutroSorb PLUS was developed to provide significantly improved impact strength and tensile ductility. Requirements for borated stainless steel flat rolled products have been established in ASTM A-887 [8]. NeutroSorb steels are conventionally manufactured boron modified Type 304 stainless steel with up 2.0% boron. They have been used in the nuclear industry since about 1960 for storage racks, spent fuel storage and transportation casks, control rods, and other applications where high thermal neutron absorption is required. The conventionally manufactured materials have not been used widely as structural components due to toughness and ductility limitations, especially when the boron level exceeds about 1%. [2]

Figures 4-2 through 4-4 compare two series of boron modified Type 304 heats – one manufactured by conventional ingot metallurgy (VIM) ; the other by powder metallurgy methods from gas atomized alloy powders consolidated to full density by hot isostatic pressing (HIP). Nominal boron contents of ½, ¾, 1, 1¼, 1½, 1¾, and 2% boron (by weight) were produced for each heat. Properties compared were hardness, tensile strength and ductility (22°C and 350°C),

Charpy impact strength at –29°C , 22°C , and 350°C , and bend bar fracture toughness (most often on transverse specimens). Microstructural analysis and X-ray diffraction analysis were also done [2]. Those figures show that strengths increase with boron content for both NeutroSorb (A-887, Grade B) and NeutroSorb PLUS (A-887, Grade A). Differences between the Grades are only for ultimate strength (slightly lower for NeutroSorb, increasing with boron content). Ductilities of NeutroSorb PLUS are better at all boron contents; much better at 2% boron (e.g., ~10%vs. ~20% elongation; ~15% vs. 30% reduction of area).

Room temperature Charpy impact energy more than doubled for NeutroSorb PLUS vs. NeutroSorb at 2% boron (16 ft–lbs vs. 5 ft-lbs); slightly less than double at 0.5% boron. At about 1.5% boron, the impact energy for NeutroSorb ranged from 8 to 10 ft-lbs over the full temperature range vs. 29-30 ft-lbs for NeutroSorb PLUS. There was no effect of impact test temperature between –29°C and 350°C for NeutroSorb PLUS [2].

The microstructure of NeutroSorb contained larger, and more segregated and more flattened islands of Cr_2B. The Cr_2B in the NeutroSorb PLUS was essentially spherical at all boron contents and distributed much more uniformly. [2]

The B4A grade was the only material which exhibited a significant difference in strength and ductility values between longitudinal and transverse orientations. All grades exhibit a slight decrease in tensile property as temperature increases. [4]

For all of the grades, natural boron[1] can be replaced with enriched (in ^{10}B) boron. The absorption cross section of a boron stainless steel with about 0.4% ^{10}B is about the same as that of alloy with 2.0% natural boron. [1]

Borated stainless steel produced by conventional ingot metallurgy with 2% boron would have a room temperature Charpy impact strength of approximately 6 ft-lbs vs. about 20 ft-lbs for

[1] Natural boron is typically about 19.6% ^{10}B

NeutroSorb PLUS alloy with the same 2% boron. For NeutroSorb PLUS with 0.4% enriched boron, Charpy impact energy would be about 65 ft-lbs (Figure 4-4).

Bohler Bleche also produces several grades of borated stainless steels. Reference 6 includes much of the background on typical uses of borated stainless steels, the use of provides some typical micrographs of the boride distribution in "Neutronit 976" at 0.84%B, 1.22%B, 1.58%B, and 1.85%B grade (plates). Those distributions appear to be consistent with a conventional ingot metallurgy product. Specification minimum values for elongation for those boron contents are 19%, 16%, 13%, and 6%. The 1.75% (nominal) boron material has an impact energy of approximately 20J/cm^2 from a sub-size specimen (about 7 ft-lbs for a half-size Charpy); the 1.5% B material has about the same Charpy impact toughness. Those data also indicate that there is no temperature dependence for the toughness properties. The material is considered to be weldable and laser cut material is offered. A laser cut edge for a 1.45% boron material is shown with no obvious discontinuity or agglomeration of borides at or near the cut. Bohler Bleche consider the practical upper limit for boron is 1.9% "because of the tendency of boron to produce low melting point eutectic . . . makes it impossible to roll the material to a sheet". They also increase nickel to 13% to improve formability. [6]

Bohler Bleche produces A976 grades (0.80% B, 1.20% B, 1.50% B) and A978 (with 2.2% Mo; 0.80% B, 1.20% B, and 1.40% B). Those materials exhibit the same trend of decreasing impact strength with increasing boron content to the presence of the boride particles. Both grades are considered be weldable, using boron free filler. [29]

British Stainless (BSC) has produced a grade called 304 Boron for criticality control and safe handling, transportation and long term storage of spent nuclear fuel (e.g., Figure 4-1). Traditionally, companies like UKAEA and BNFL have used Boral[2] linings for criticality control. Boral is very brittle and prone to mechanical damage, corrosion, and disintegration. BSC clients such as CEGB and Jordan Engineering have opted to design such structures with 304 stainless steel with up to 2%B rather than Boral [16].

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[2] Boral™ is a sintered boron carbide/aluminum sandwiched between aluminum sheets

The BSC Boron 304 has a boron range from 0.6% to 1.0%, YS : 265-310N/mm^2 (38-45 ksi), UTS 550-590N/mm^2 (80-86 ksi), elongation of 20-35%, and U-notch impact toughness (2 mm U-notch) of 20-30J. [16]

The BSC 304 Boron is a version of 304L with up to 1% boron. Boron can/does lead to hot shortness requiring testing and development to determine adequate hot ductility. The key factors in production that are cited are stringent temperature controls of ingots during slab rolling and the introduction of a 3-cycle rolling program. Like the Carpenter and Bohler Bleche products, the BSC material exhibits discrete, finely distributed chromium-rich borides. The addition of up to 2% B will increase yield strength, tensile, strength, and hardness, and decrease elongation, reduction of area, and impact strength. [16]

Figures 4-5 through 4-7 are based upon mechanical properties characterization work performed by Sandia in support of an ASME Section III Code case on borated stainless steel (ASTM A-887) for all 16 grades of material (boron contents from 0.20% to 2.25%) [4]. Like Reference 2, this work showed that tensile strengths increase with boron content and ductilities decrease with increasing boron content. The Grade A material (PM) has significantly better impact properties than the B grades. Driving forces for use of the borated stainless steel as an alternate material for transport casks are decreased weight, improved thermal efficiency, coupling of structural and neutron absorption functions (earlier designs used stainless steel structural members with borated materials attached for neutron absorption). Regulatory Guide 7.6 provides structural design criteria for the casks. The initial Code inquiry covered 304B3B (0.75%-0.99%B), B4A (1.00%-1.24%B), B5A (1.25%-1.49%B), B6A (1.50%-1.74%B) and B7A (1.75%-2.25%B). Grade B3B was included because it has been the most commonly used grade. Material tested was obtained from Carpenter. All material was solution annealed (B6A also had a light finish cold roll). Most specimens were tested in a transverse orientation. [4]

Specific tensile property and microstructural comparisons were made of Grades B5A and B5B and B7A and B7B [5]. The boride precipitates, Cr_2B or $(Cr,Fe)_2B$, were consistently finer and more uniformly dispersed in the Grade A material as opposed to that in the Grade B. Detailed statistical

analysis of metallographic images showed that the precipitates were finer and more uniformly distributed based upon numerous measures of size and distribution (e.g., area, longest particle, etc.). At these high boron concentrations, the differences were very dramatic in back scattered electron images. For the B5 material, differences in particle size were more dramatic than for the B7 material. For both grades, the strain to fracture was significantly larger for the Grade A material at all temperatures. There was essentially no temperature dependence of that difference between room temperature and 400°C. The paper also describes the inquiry to the ASME Code for acceptance of the material for Section III applications. That inquiry was accepted, resulting in Code Case N-510 [7]. [5]

Ingot metallurgy borated 304 has been used for a number of years in spent fuel storage applications for combination of structural integrity and criticality control. However, at high boron contents (>1.0 wt%), conventionally processed material has low ductility and low impact toughness due to relatively coarse boride particles that act as crack initiation sites. The "premium" grade of borated 304 produced by Powder Metallurgy (they reference Strobel and Smith [14]) has greatly improved ductility and impact properties vs. conventional metallurgy material. ASTM A887 was developed that contains 8 different boron contents (e.g., B7 has boron from 1.75% to 2.25%) and two Grades based tensile and impact properties. The ASTM specification is properties-based, however, only the PM materials qualify as Grade A materials while the Ingot Metallurgy material generally qualifies as Grade B. [20]

Stephens and Sorenson [23] also reported on a program regarding the Code Case Inquiry (submitted to Section on 2-5-90) for use of borated stainless steel for ASME Section III structural applications. (ASTM A887, Grades A and B, boron from 0.20% to 2.25%). Tensile strength properties increase with increasing boron content (always greater than ASME minimum properties for SA-2440, Grade 304). Ductilities decrease with increasing boron. This paper has results on 304B3B (0.80%B), B4A (1.17%B), B5A (1.41%B), B6A (1.75%B), and B7A (2.19%B) for temperatures to 750°F. Ductility of the various grades exhibit a slight decrease with increasing temperature.

Results of J-integral (of J_Q or J_{Ic} were reported) vs. boron content to 1.97% boron were reported in reference 27. That reference also included impact properties for NeutroSorb PLUS to a little over 2.0% B (Figure 4-8). Table 4-2 includes determinations of K_{Ic} from values of J_{Ic} [27] using the expression

$$J_{Ic} = \frac{K_{Ic}^2(1-\nu^2)}{E}$$

Bending tests of welds (as-welded and welded plus annealed material) showed cracking along the fusion line except for material annealed at 1200°C. Tensile elongations of as-welded and annealed welds at up to 1000°C were only about half the values in base metal. Annealing at 1200°C recovered properties fully. Charpy test showed the same tendency. Elongated and acicular austenite/$(Cr,Fe)_2B$ eutectic at the Partially Melted Heat Affected Zone was shown to be responsible for the poor ductility. Tests were on AISI 304-B3 (1.1 wt % B). $(Fe,Cr)_2B$ is know to adversely affect ductility at ambient and elevated temperature. Recent developments employing hot sintering have produced commercial borated stainless steel with better ductility and other properties. Mechanical properties of the as-welded and annealed GTA weldments were made from tensile tests, 3 point 90° face bends with a 4T mandrel and sub-size Charpy impact specimens (55 x 10 x 3 mm). [15]

In bend tests, as-welded material and welds annealed at 700 to 1100°C for 1 hour showed cracks propagating along the fusion line [15]. Specimen welds annealed for 3 hours at 1200°C had no cracks. Table 4-3 shows that as-welded material or material welded plus annealed at 700°C through 1000°C fractured, 1100°C annealed material had some cracks, and 1200°C annealed material had no cracks (Figure 4-9). Elongations of annealed welds did not increase from about 8% (vs. 16% for base metal), until the annealing temperature exceeded 900°C. Then elongation increased steadily with annealing temperature: 13.2% after 1000°C treatment; 16% for 1200°C annealing. Charpy impact tests showed a similar trend. Properties for welded samples averaged 15J for annealing temperatures to 1000°C. Welds annealed at 1100°C averaged 22J, slightly higher than the 20J specified by ASME Code, as discussed in [18]. [15]

Microstructurally, all of the properties effects were shown to be related to the size and distribution of the boride phase. No coarsening of the borides was seen in the unmelted regions of the HAZ;

but elongated and acicular austenite-(Cr,Fe)2B eutectic was seen in the Partially Melted Heat Affected Zone for welds annealed for 1 hour at 700°C to 1000°C. Increasing time at 1100°C (e.g., 3, 5, 7 hours) didn't change the results. The well dispersed, spheroidized borides as in the base metal were the goal of the PWHT for the PMHAZ. Fractography showed that the brittle, elongated eutectic phase gave an easy fracture path while the amount of fully spheroidized eutectic in the PMHAZ welds annealed at 1200°C increased with annealing time (1, 3, 5, 7 hours). They included some shape factor evaluation that also correlated with a return to base metal properties. Welds annealed at 1200°C had fully recovered the base metal properties. [15]

Impact results of welded NeutroSorb PLUS decreased to values comparable to those of annealed NeutroSorb, apparently influenced by the formation of a dendritic austenite/boride structure, a boride eutectic phase, and agglomeration of the boride precipitates. Consistent with the data from Park et al., and Robino and Cieslak, post weld heat treatment appeared to restore the ductility. [2]

Impact testing of material aged at temperatures near the solidus indicated only moderate reductions in toughness. Particle shape measurements showed that the boride particles were initially nearly spherical and remained that way during elevated temperature exposure. Only minor faceting and agglomeration occurred. Consistent with other mechanical properties, the loss in toughness of borated stainless steel welds is not associated with solid state reactions in the heat affected zone. Fracture surfaces of impact specimens that were isothermally treated was ductile and identical to that of as-received material. [28]

Impact properties (and tensile ductility) of as-welded borated stainless steel was poor (7.4 ft-lb). Fracture occurred along the partially melted region of the HAZ. Post-weld heat treatments at high temperatures (~1150°C) restored weld impact properties (to about 30 ft-lb). PWHTs spheroidized the borides, producing a similar structure to the as-received material (and similar fracture surfaces). [28]

4.2.1 *Temperature Effects*

Temperature appears to exert only a minor effect on tensile properties (Figures 4-5 through 4-7; 4-10, and 4-11) and essentially no effect on impact properties (Figure 4-12).

The effect of temperature on tensile properties was evaluated as part of the ASME Code Inquiry qualification [23]. Tests included B5A, B6A, and B7A plates 0.625", 0.130", and 0.271" thick from Carpenter. The 304BA was rectangular bar 0.625" thick x 4" wide. The 304B3B was obtained from British Steel as 0.196" thick plate. The majority of the samples machined in transverse direction; some comparison samples made in longitudinal direction. Elevated temperature tensile properties were reported at 100, 200, 300, 400, 500, 600, 700, and 743 or 752°F (Table 4-4). The elevated temperature properties results were reported as a fraction of room temperature yield strength retained at each temperature plus plots of ultimate strength, yield strength, and, and engineering strain at fracture vs. temperature (Figures 4-5 through 4-7). Ductilities exhibit a slight decrease as temperature increases. [23]. The temperature effect is most pronounced for B7A. Temperature trend for B5 is quite flat (average ductility of B5A = 1.51xB5B at room temperature; 1.53 at 400°C). For B7, ductility of B7A = 3.19xB7B at room temperature and 2.93X at 400°C. "No plastic strain was observed in the 304B7B samples past the point of uniform strain , 304B7A always exhibited . . necking". For 304B5, both grades showed necking. At a given temperature, the Grade A (PM processed) material exhibited a higher yield strength than the Grade B material, due at least in part to finely dispersed borides, and, possibly, to the grain refinement in the PM product. [20]

4.2.2 *Irradiation Effects*

When ^{10}B absorbs a neutron, it transmutes to lithium and helium. Helium bubbles can disrupt grain boundaries and reduce ductility [9]. As a result, there is a concern for the effects of irradiation on tensile properties of borated stainless steels.

Neutron effects on the mechanical properties (tensile, Charpy, and metallography) of borated stainless steel were studied at fluences from $1x10^{13}$ $5x10^{15}$, and $1x10^{17}$ n/cm^2 for steels from 0.25

to 2.01 wt% produced by conventional metallurgy and by PM (A887 Grades A and B). Mechanical properties showed almost no change in mechanical properties with fluence. No evidence of helium effects was found. Materials were produced by Carpenter and irradiated at Penn State. Irradiations were at 22°C in a pool type reactor. Approximately 20% of the flux had energy >0.1 MeV. Fluence levels at the low fluence are considered comparable to spent fuel applications. Intermediate and high fluence were selected to provide comparisons to other literature data. [22]

For the NeutroSorb PLUS material, a minor increase in ultimate strength and yield strength for the material irradiated to the highest fluence (Figure 4-13) was reported although those reported increases certainly appear to be very small. Impact strengths exhibit slight differences for the low boron samples in the high fluence but no differences in the low and medium fluences materials (Figure 4-14). [22]

For the NeutroSorb material, radiation produced a slight increase in the ultimate strength for samples from the low fluence irradiation at 0.24%. No other grades appear to exhibit any change. (Figure 4-15b). Figure 4-15a shows no significant change in yield strength for irradiated samples at up to 1.06 wt% B. Samples with 2.01 wt% B from the low and medium fluence irradiations had yield strengths that were lower than the unirradiated material. Yield strength of the 2.01% B material at high fluence was the same as the unirradiated material. Impact strengths did not change (Figure 4-16).

There were no significant differences in microstructure for either alloy per optical metallography. [22]

4.2.3 TNI-REG and TNI-BRP Basket Materials

The chemical composition and mechanical properties for the TNI-REG and TNI-BRP materials are reported in Table 1-1. The mechanical properties are compared with measured mechanical properties from the literature in Figures 4-17 through 4-19. Those plots illustrate where the properties of those materials fall with respect to other data used to characterize the borated stainless

steel. Although the TNI-REG and TNI-BRP materials pre-date the ASTM specification, the properties of the TNI-REG material (powder metallurgy product) and the TNI-BRP plates (conventional ingot metallurgy) are consistent with properties for ASTM A-887 Grades A and B, respectively.

4.3 Design Criteria

As noted previously, the NRC has recommended the use of ASME Section III, Div. 1 rules for the transport casks.

The ASME issued Section III, Div. 3, Containment Systems and Transport Packagings for Spent Nuclear Fuel and High Level Radioactive Waste, in 1997. That section of the Code includes rules for design and construction of spent fuel transport and storage casks.

Reference 12 describes IAEA activities toward establishing criteria for radioactive material shipments (Type B(U) certification). The Type B(U) certification is a verification that the cask has met all IAEA rules and regulations. The results of actions toward developing a consensus brittle fracture evaluation criterion are reported. New candidate materials for such casks, which include ferritic steel, ductile iron, borated stainless steel, titanium, and depleted uranium, are mentioned in the discussion. The motivation for the use of the new materials over more traditional metals such as austenitic stainless steel are lower costs and greater ease of fabrication. [12]

The main problem in establishing such standards is that existing brittle fracture criteria cannot be applied to a wide range of structural materials easily and are not accepted internationally. For example, there is USNRC Reg. Guide 7.12 on Fracture Toughness Criteria for Ferritic Steels (4"<t<12"). That Regulatory Guide used empirically-based fracture criteria. As such, it will only be directly applicable to ferritic steels. The goal of the IAEA effort was to apply advances in fracture mechanics analysis to provide criteria applicable to a wide range of materials.[12]

IAEA committed to US DOT to:

- A proposal by Sorenson, et al., for an International Brittle Fracture Acceptance Criterion for Nuclear Transport Cask Applications (Int. J. of Radioactive Materials Transport, Vol. 1, pp. 33-40, 1990), .
- Consider all packaging materials with "brittle characteristics"
- Address issues of catastrophic flaw, failure prediction and NDT methods for significant flaws [12]

Technical consensus was achieved in those efforts, assuming an existing flaw at the location of highest stress and in the most damaging orientation. The sizes of those types of limiting flaws were not discussed, however. [12]

Appendix IX to IAEA Safety Series #37 includes 3 approaches (Figure 4-20):

1. Actual fracture toughness must be determined for the most severe loading and environmental conditions (e.g., rapid loading at -40°C). This approach is the most empirical and requires the least conservatism (rigorously determined and statistically significant fracture toughness is measured and applied). It is potentially the least conservative.
2. Lower bound K_{Ic} for the material is determined from a statistically significant set of data for a specific class of materials. The most important characteristic of the data is that they must be demonstrated to envelope the fracture behavior of the material. This data may be pre-existing or may need to be generated. Selected values must be lowest bound toughness values at (e.g., -40°C) design temperature. Main benefit of this approach is the potentially reduced requirements for fracture toughness testing.
3. Lower shelf values, fully linear-elastic brittle behavior, usually determined at a temperature below –40°C . This gives the greatest actual margin of safety (but that increase in margin cannot be quantified). Primary incentive for this approach is that the test procedure for measuring a lower shelf fracture toughness value is straightforward. [12]

Salzbrenner, et al. [13] described laboratory testing done to support the MOSAIK Drop Test Program. That program focused on fracture toughness approaches. A description of the general fracture mechanics approach and its application to the specific cask designs are described by reference to other papers by Salzbrenner and papers by Sorenson, et al. A thorough mapping of the mechanical properties is required to apply fracture mechanics to a particular prototype but "is not sufficient for qualifying serially produced casks".

The test program described in Reference 13 includes specifics of the MOSAIK KfK case (ductile iron). All of the testing was done at –29°C to match the limiting accident conditions per 10CFR71, 1984.

Static fracture toughness measurements were determined using a single specimen (compact specimens; B=2.29 cm) J_{Ic} method per ASTM E813. The recognized accuracy of the J-integral method is ±15%; resulting K_{Ic} accuracy will be ±4%. [13]

A key item was selection of properties for finite element modeling. The major item noted was the variation in the high rate fracture toughness and uncertainty in its measurement. That uncertainty was far greater than the uncertainty in the modulus or tensile measurements. Still, the measured values provided a valuable estimation for the finite element work [13].

High rate fracture toughness measurements used the same type of compact specimens, -29°C with a multiple specimen approach. Extension rate was 125 cm/sec., yielding a stress intensity rate of 10^5 MPa√m/sec. That rate is faster than the loading the cask sees from a 9 meter drop. [13]

Charpy V-notch tests were also done to cover the temperature range –130°C to +100°C. As noted in this paper, "Charpy values are not inherent materials properties and cannot be used to quantify the mechanical performance". The paper includes plots of the tensile strength, elongation, reduction of area, and J-integral for each plane of the ductile iron used in the cask (NOTE: For

static tests, J for all planes is about 55kJ/m^2; for the high loading rate tests it ranges from about 20 to about 35kJ/m^2). [13]

A key item was the selection of properties for finite element modeling. The major item noted was the variation in the high rate fracture toughness and uncertainty in it measurement. That was far greater than the modulus or tensile measurements. Still, the measured values provided a valuable estimation for the finite element work. [13]

Two ductile iron casks, as are used in Europe, were dropped from 9 m onto an unyielding surface (per 10CFR71, 1984) at temperature of –29°C . An artificial flaw was placed into the cask to encourage linear elastic behavior. Post-drop evaluations of the casks showed that the LEFM* values (K_{Ic} = 87ksi√in; K_{Id} = 68ksi√in) were not exceeded; that is, the casks did not fail in a brittle manner, even though the calculated values for K predicted brittle fracture. Some of the tests did show evidence of stable crack growth. A drop from 18 meters (1150 g vs. 900 g for the 9 meter drop) produced a small amount of crack growth by stable, ductile tearing. [3]

Only the Grade A materials are included in Code Case N-510-1 (Borated Stainless Steel for Class CS Core Support Structures and Class 1 Component Supports) [7]. The maximum boron content included in the Code Case is 1.74%; Grade B6A. Charpy V-notch test are required for all grades. Standard size impact specimens are required whenever thicknesses permit; the required test temperature must be the lowest service temperature or lower. The applicable requirements for impact energy and lateral expansions given by ASTM A-887 are required. Welding of the material is not permitted and scarf from thermal cutting must be removed. Design stress intensity allowables are 20 ksi for all seven grades (Grades BA, and B1A through B6A) at room temperature through 650°F. For 304BA, 304B1A-304B3A, the allowable decreases slightly at higher temperatures. [7]

4.4 Materials Standards

ASTM A-887, first issued in 1988, covers borated stainless steel plate, sheet and strip for nuclear applications (A480 is the parent specification). [8]

The standard has no requirements on melting practice and defines Grade A material vs. Grade B materials based solely on mechanical properties. Grade A is for a "near-optimal dispersion" of boron; Grade B is less than optimal. "Conventional wrought metallurgical practice conforms to Grade B properties". Impact test requirements are given but Charpy V-notch impact testing is not required unless specified on the purchase order. Full size impact specimens are required when material thickness permits; when full size specimens cannot be used, the largest sub-size specimens possible shall be. Solution annealing at 1900°F is required. [8]

The tensile test data for selected Types of Grade A material were used to initiate an ASME Code Case Inquiries for borated stainless steel for " the construction of component supports for storage or transport of new or spent fuel assemblies". Types 304B4A, 304B5A, 304B6A are included. Type 304B7A material was not included in the code case "because its required minimum impact energy (14 J = 10 ft-lbs) was not deemed adequate: a value of 21 J (15 ft-lbs) is considered necessary for consideration in a code case." [20]

Table 4-1

Chemical Composition of Materials Characterized in [20]

Element	304B5, Grade A ("304B5A")	304B5, Grade B ("304B5B")	304B7, Grade A ("304B7A")	304B7, Grade B ("304B7B")
Carbon	0.032	0.034	0.027	0.034
Manganese	1.83	1.93	1.74	1.79
Phosphorus	0.014	0.014	0.024	0.022
Sulfur	0.002	0.001	0.004	0.004
Molybdenum	0.02	0.03	0.29	0.28
Copper	0.04	0.04	0.10	0.12
Cobalt	0.06	0.06	--	0.22*
Silicon	0.73	0.71	0.58	0.67
Chromium	18.39	18.22	18.40	18.00
Nickel	12.98	13.03	13.01	13.42
Boron	1.41	1.38	2.19	1.90
Iron	Balance	Balance	Balance	Balance
Heat#	C1835	11666	C1592	94480
Required Min.				
Elongation (%)	24.0	13.0	17.0	6.0
Required Min. Charpy V-Notch Energy – J(ft-lbs)	31(23)	--	14(10)	--

Table 4-2

Measured J-Integral Values from [27]

Alloy	%B	LT Orientation		TL Orientation	
		J_{IC}, in-lb/in^2	K_{IC}, ksi-sqrt(in)	J_{IC}, in-lb/in^2	K_{IC}, ksi-sqrt(in)
NeutroSorbPLUS	0.28	1945	255	1584	230
NeutroSorbPLUS	0.83	754	158	699	153
NeutroSorbPLUS	1.43	534	133	485	127
NeutroSorbPLUS	1.86	439	121	212	84
ASTM A887 Gr. B	1.07	344	107	277	96

All reported J_Q or J_{IC} values are assumed = J_{IC}

Table 4-3

Results of 90° Face Bends with 4T Former – ASTM A887 304B3B (from [15])

Condition	Result
As-welded	Fracture
700°C/1hr	Fracture
800°C/1hr	Fracture
900°C/1hr	Fracture
1000°C/1hr	Fracture
1100°C/1hr	Cracks observed
1100°C/3hr	No cracks observed

Table 4-4

Yield Strength Temperature Factors (from [23])

$$\left(\frac{\text{Yield Strength at Temperature}}{\text{Room Temperature Yield Strength}}\right)$$

At 752°F

Grade	Yield Strength Factor, %		
	Min.	Avg.	Max.
304B3B	63.5	65.9	68.0
304B4A	70.4	75.2	83.8
304B5A	74.4	77.6	83.5
304B6A	69.2	77.3	81.2
304B7A	79.2	80.2	81.3
304L	- ~53 -		

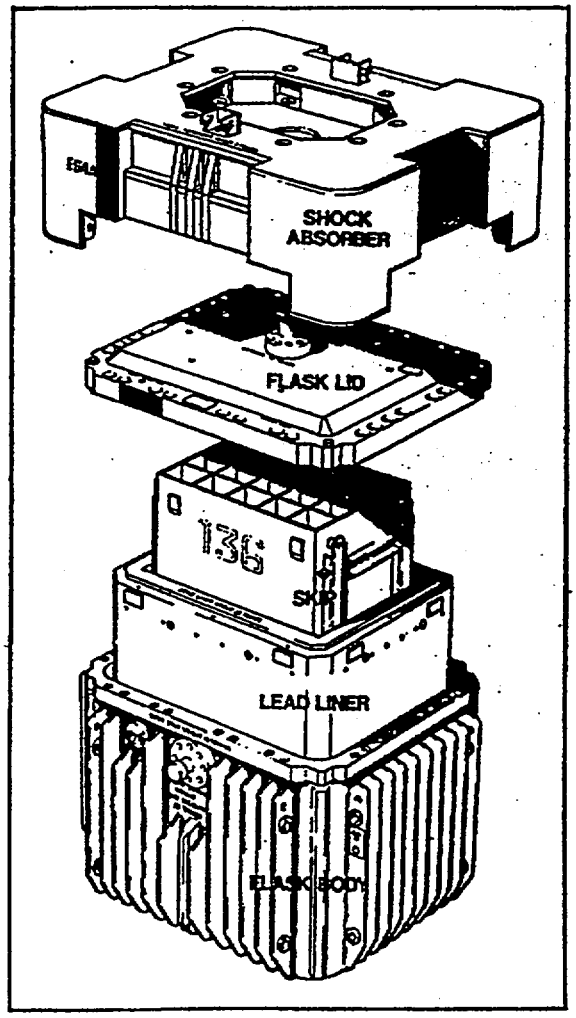


Figure 4-1. Spent Nuclear Fuel Transport Container (UK; from [16])

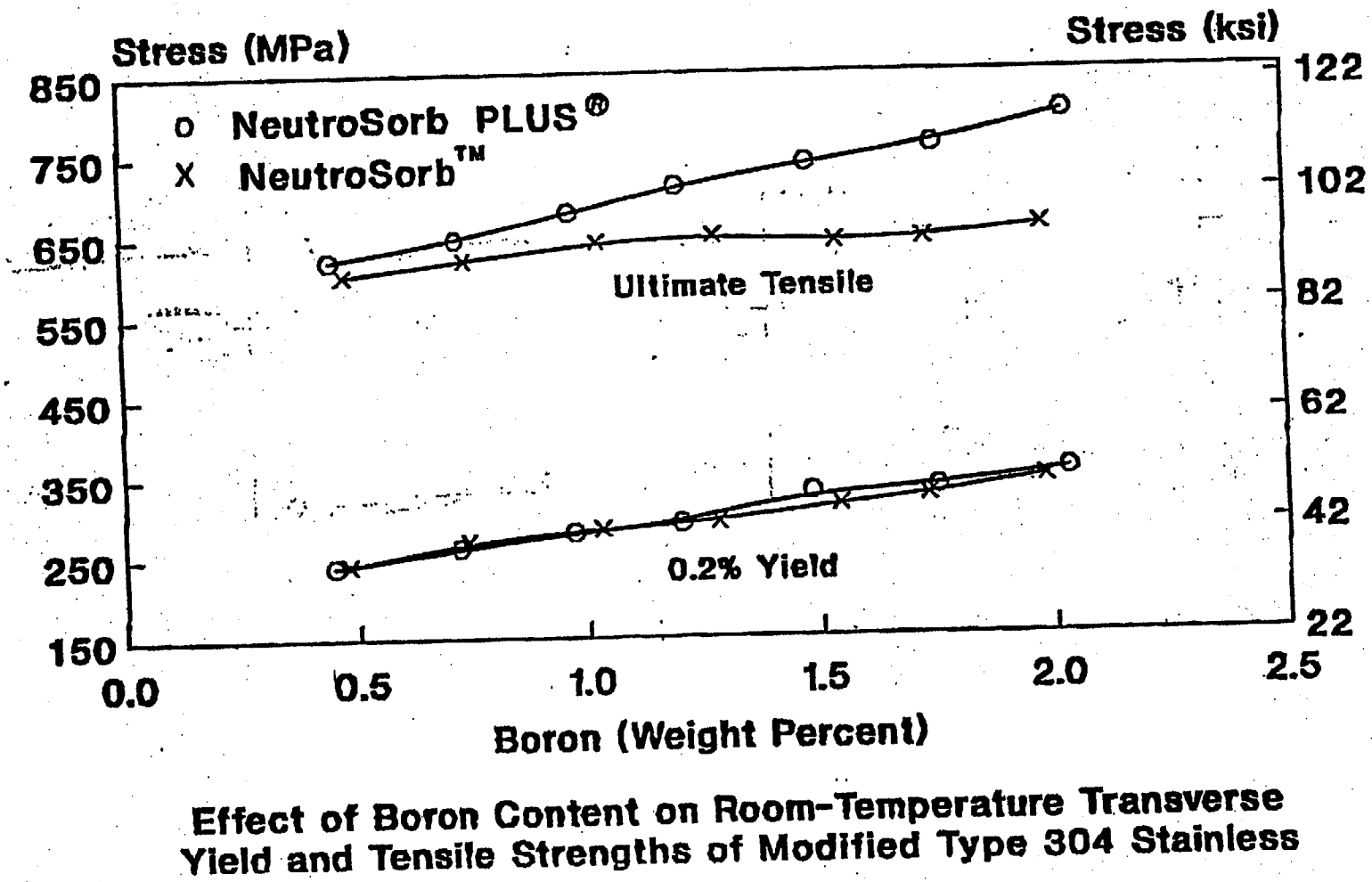
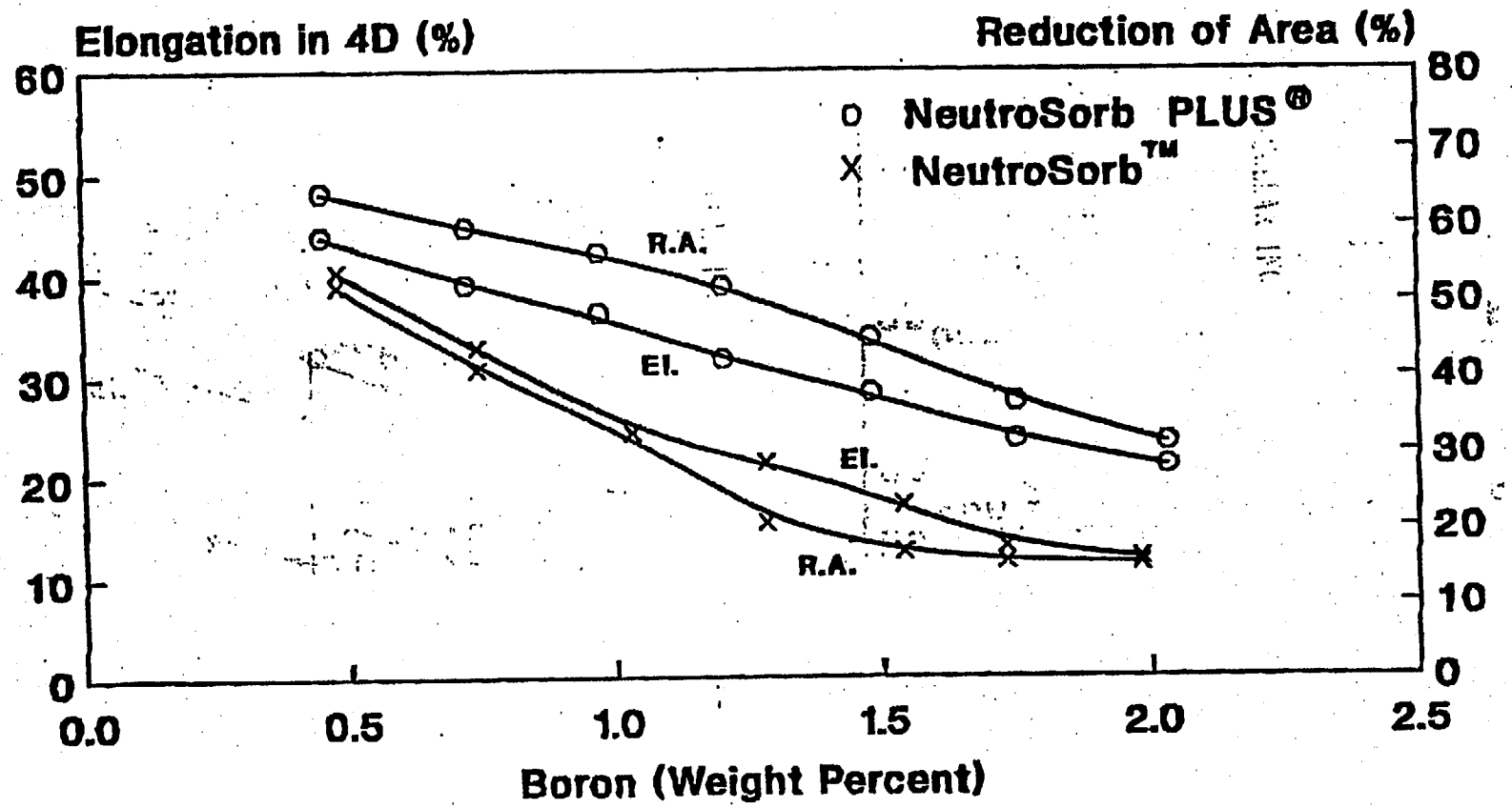


Figure 4-2. Room Temperature Yield Strength and Ultimate Tensile Strength of Borated Stainless Steels (from [2])



Effect of Boron Content on Room-Temperature Transverse Tensile Ductility of Modified Type 304 Stainless

Figure 4-3. Room Temperature Transverse Ductility of Borated Stainless Steels (from [2])

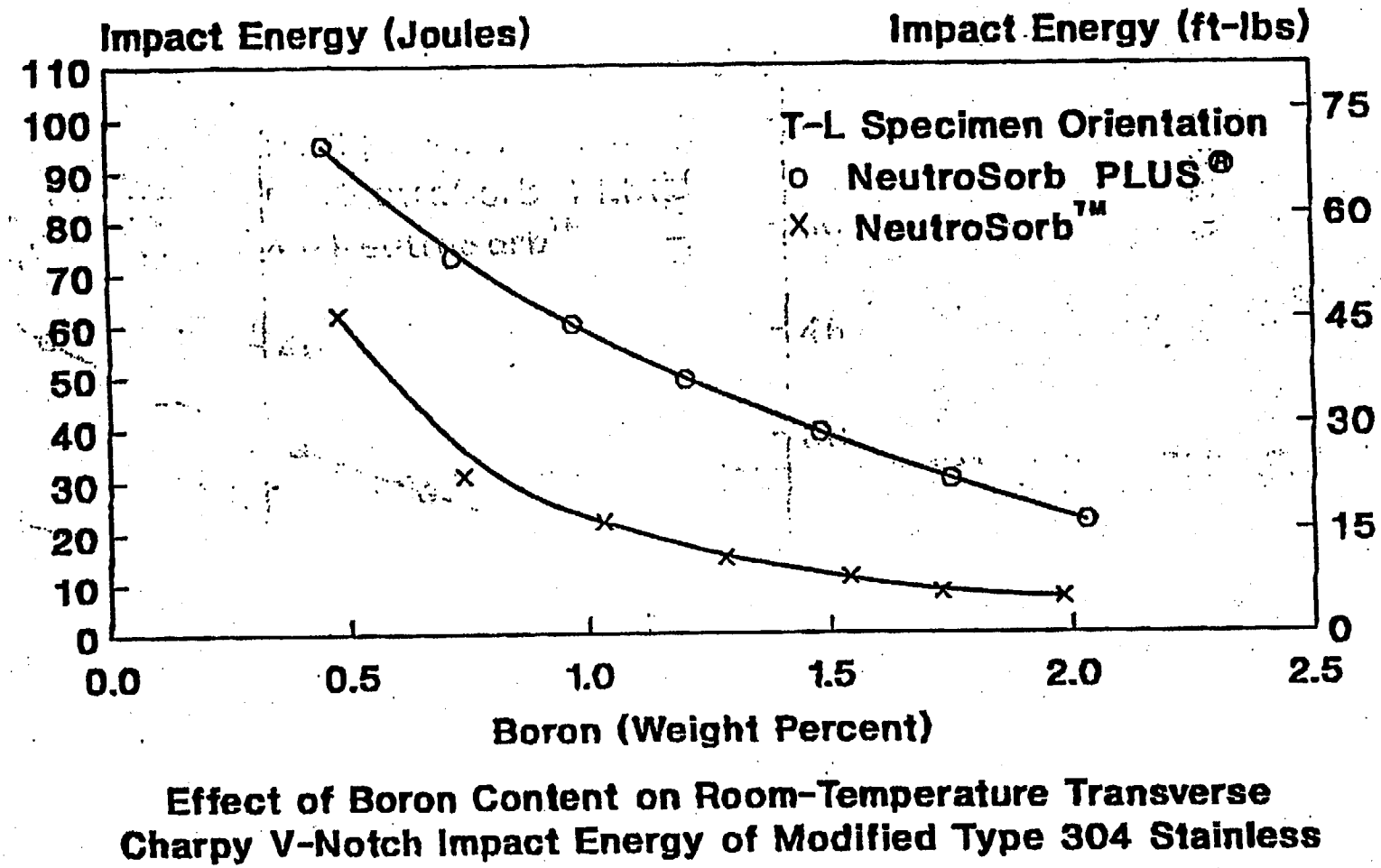


Figure 4-4. Charpy V-Notch Impact Energy (Room Temperature) of Borated Stainless Steels (from [2])

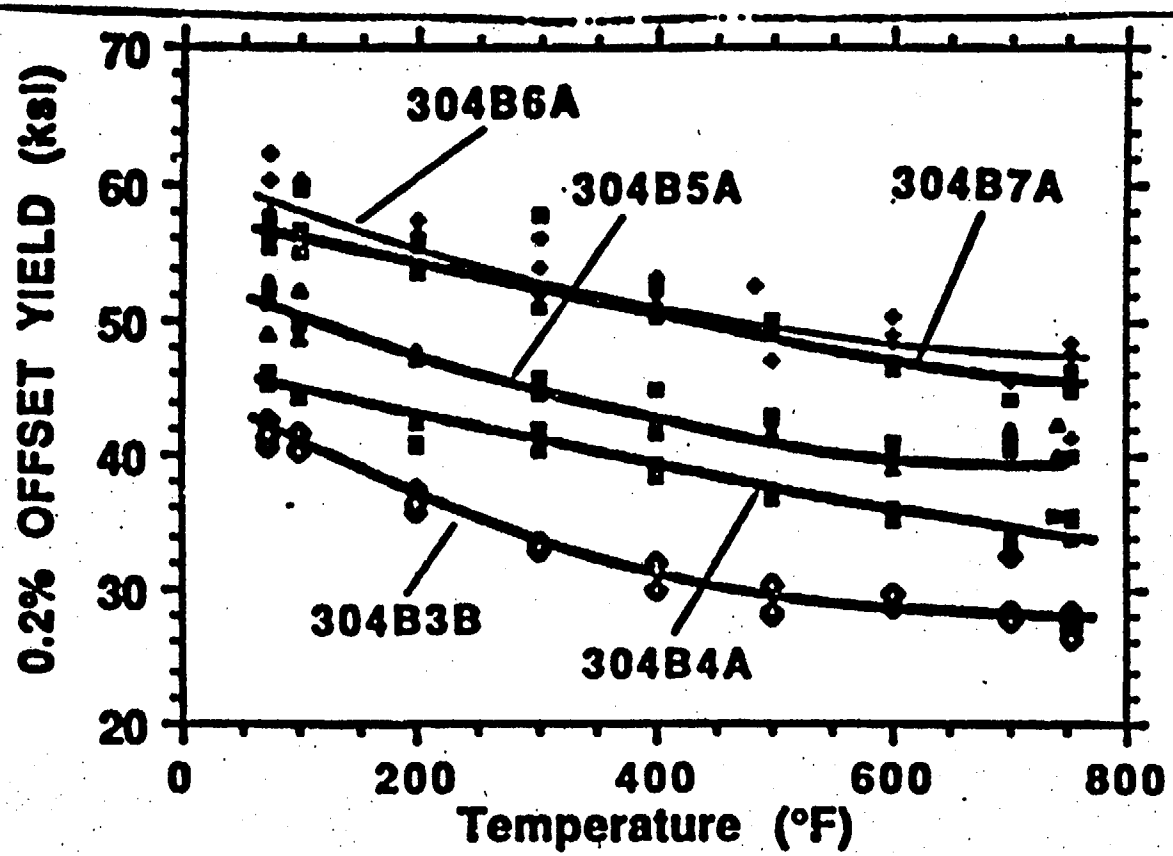


Figure 1. 0.2% offset yield stress as a function of temperature for the various borated 304 stainless steel grades tested to date. All grades are in solution annealed condition, except for B6A which was solution annealed plus lightly rolled to finish dimensions at room temperature.

Figure 4-5. Effect of Temperature on Yield Strength of Borated Stainless Steels (from [4])

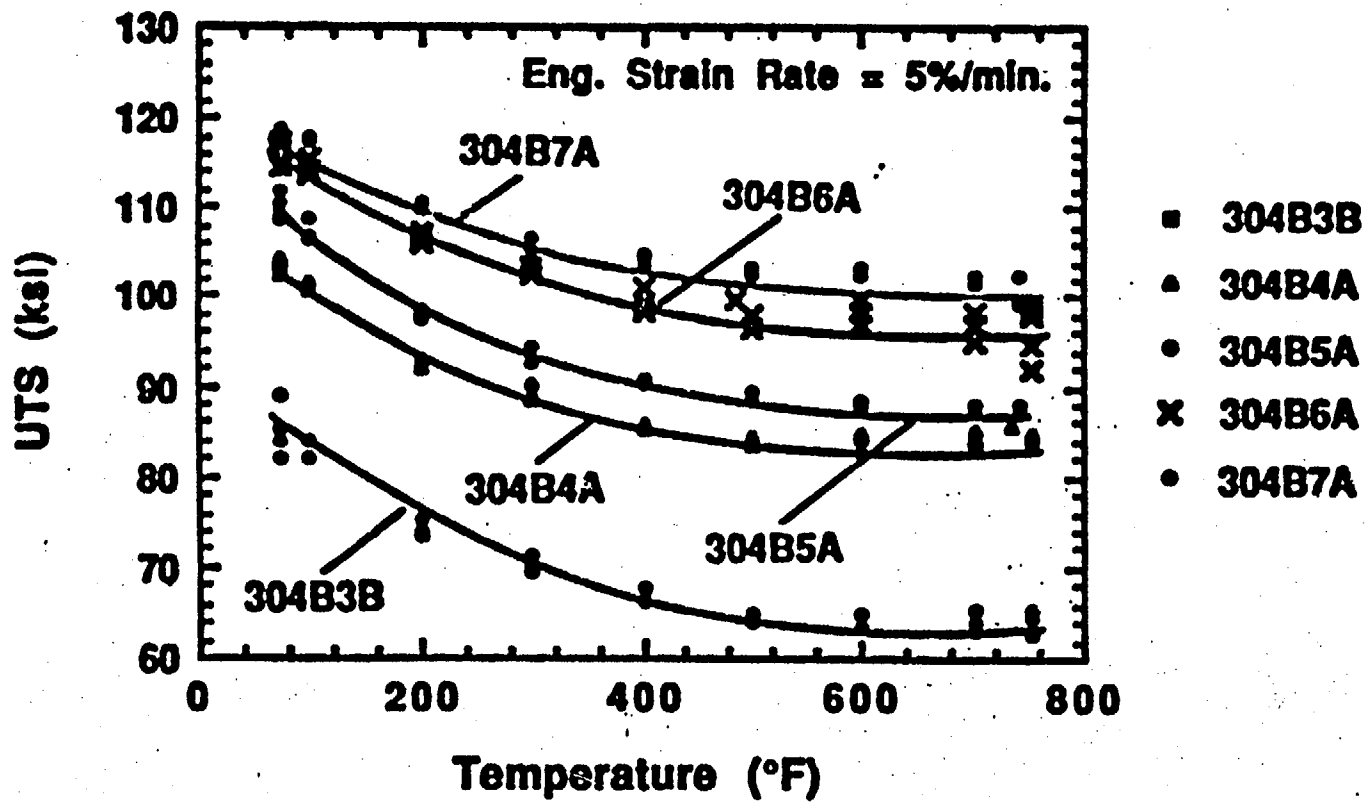


Figure 2. Ultimate tensile strength (UTS) as a function of temperature for the various borated 304 stainless steel grades tested to date.

Figure 4-6. Effect of Temperature on Ultimate Tensile Strength of Borated Stainless Steels (from [4])

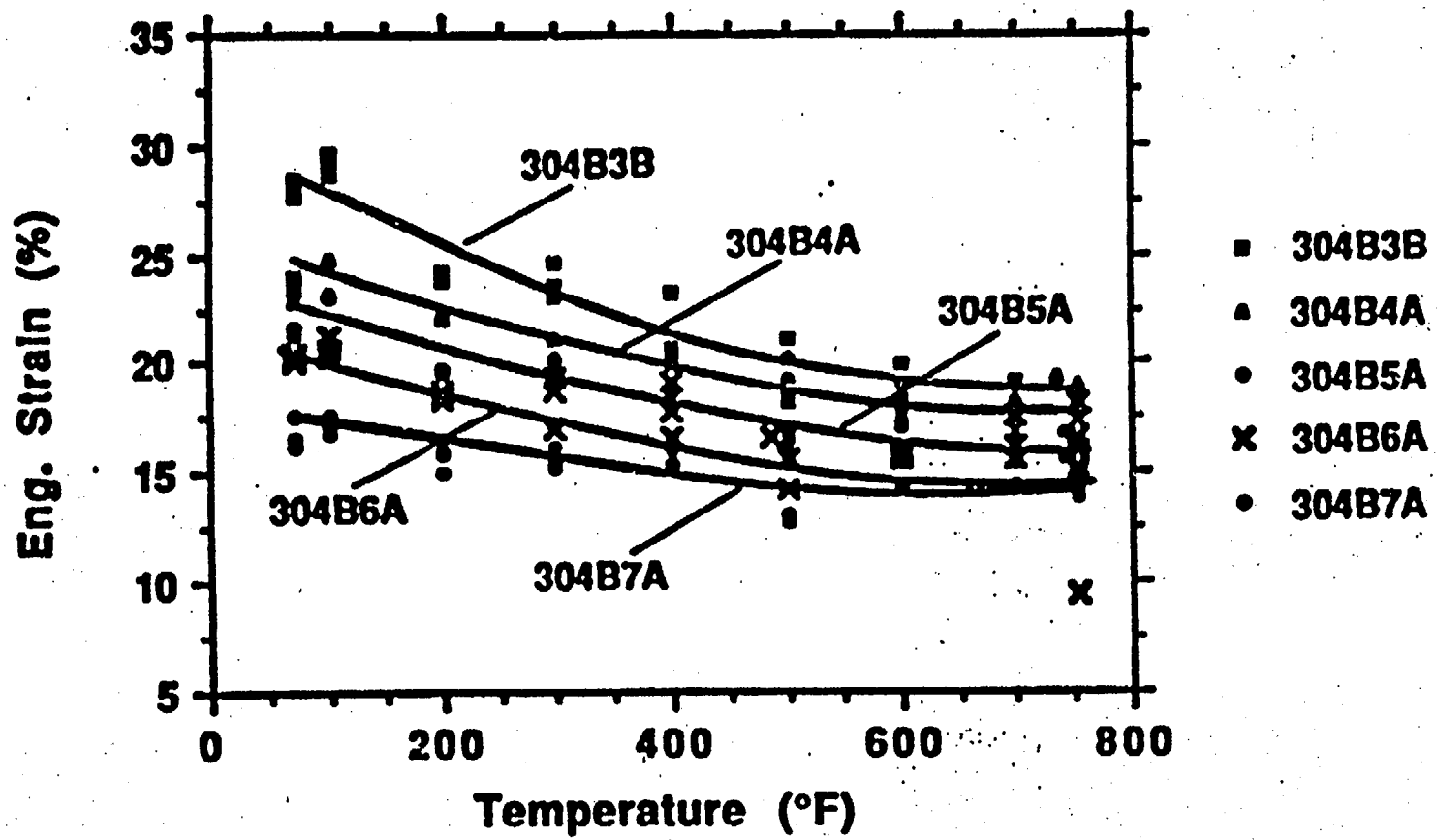


Figure 3. Uniform plastic strain data as a function of temperature for the various borated 304 stainless steel grades tested to date.

Figure 4-7. Effect of Temperature on Uniform Plastic Strain for Borated Stainless Steels (from [4])

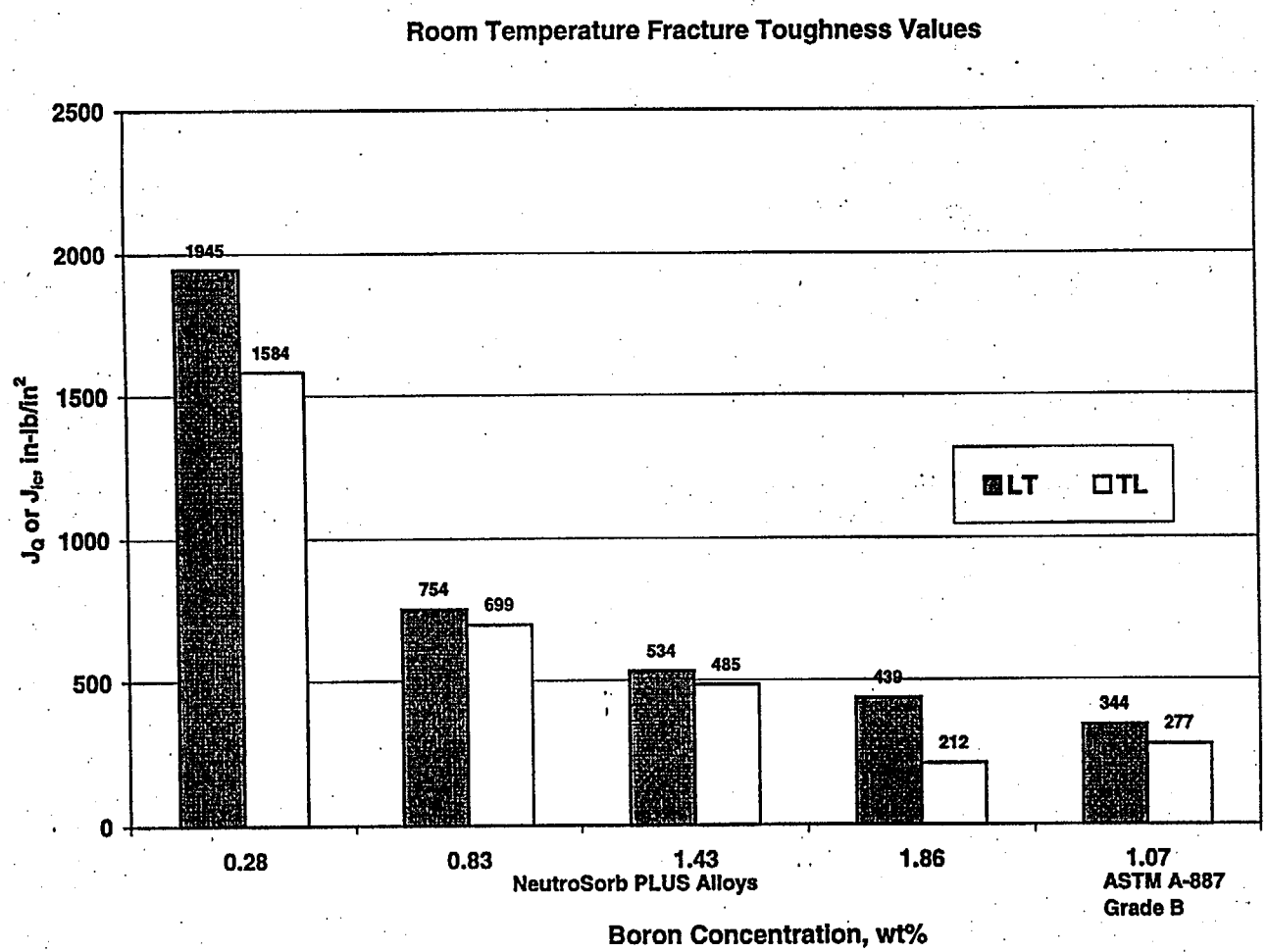


Figure 4-8. Room Temperature Fracture Toughness Values – Borated Stainless Steels (From [27])

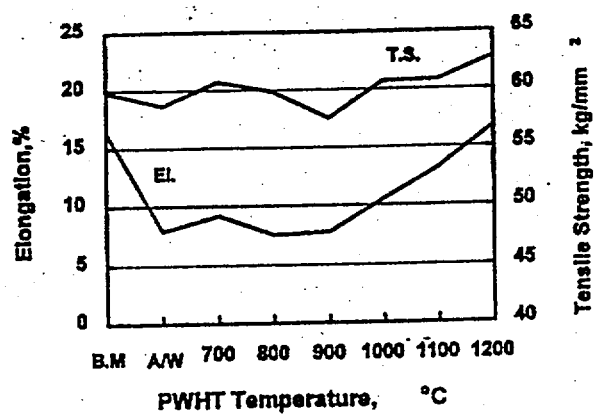


Figure 4-9. Tensile Properties of Welds in Borated Stainless Steels with Various Annealing Treatments (from [15])

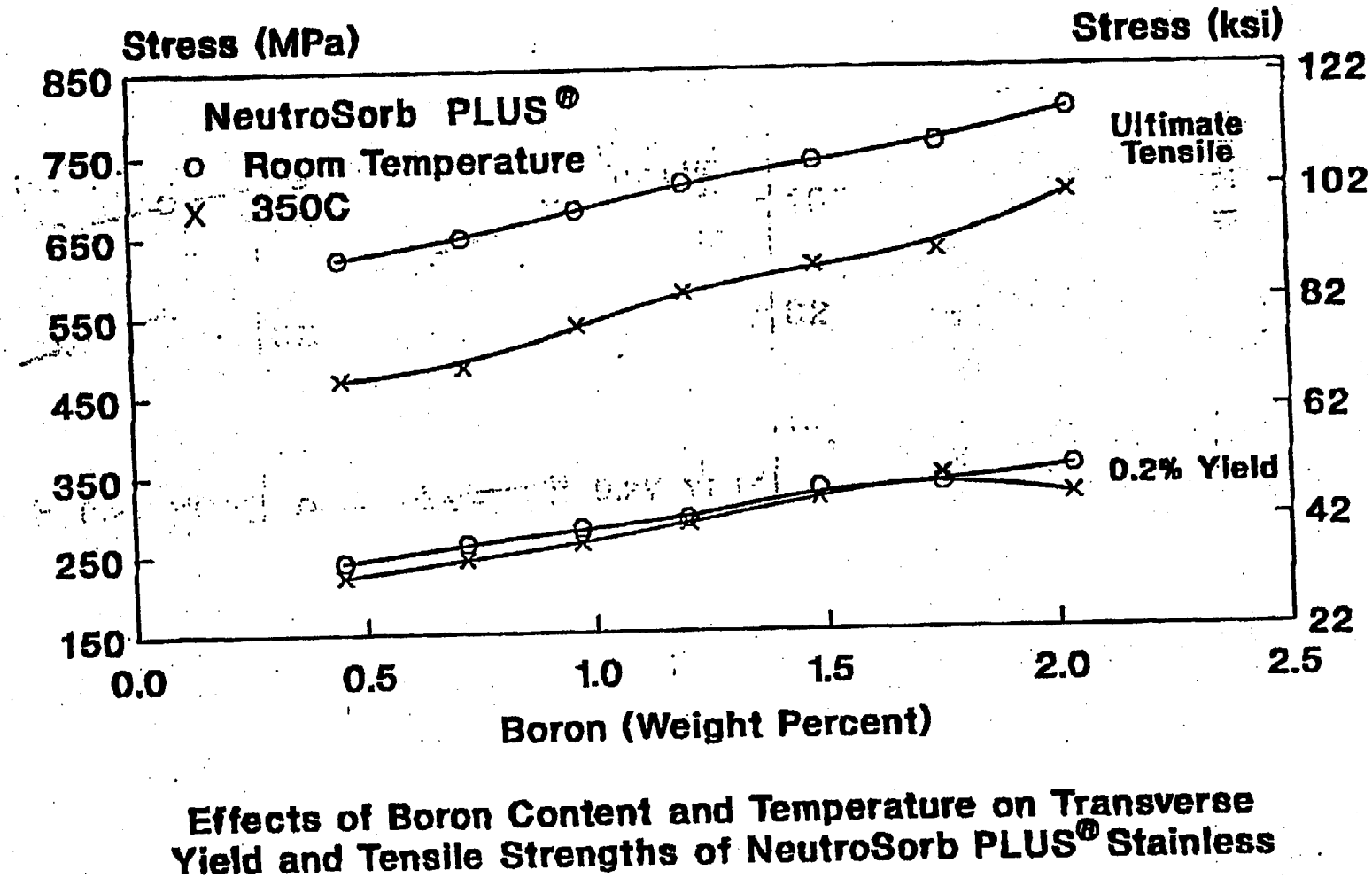
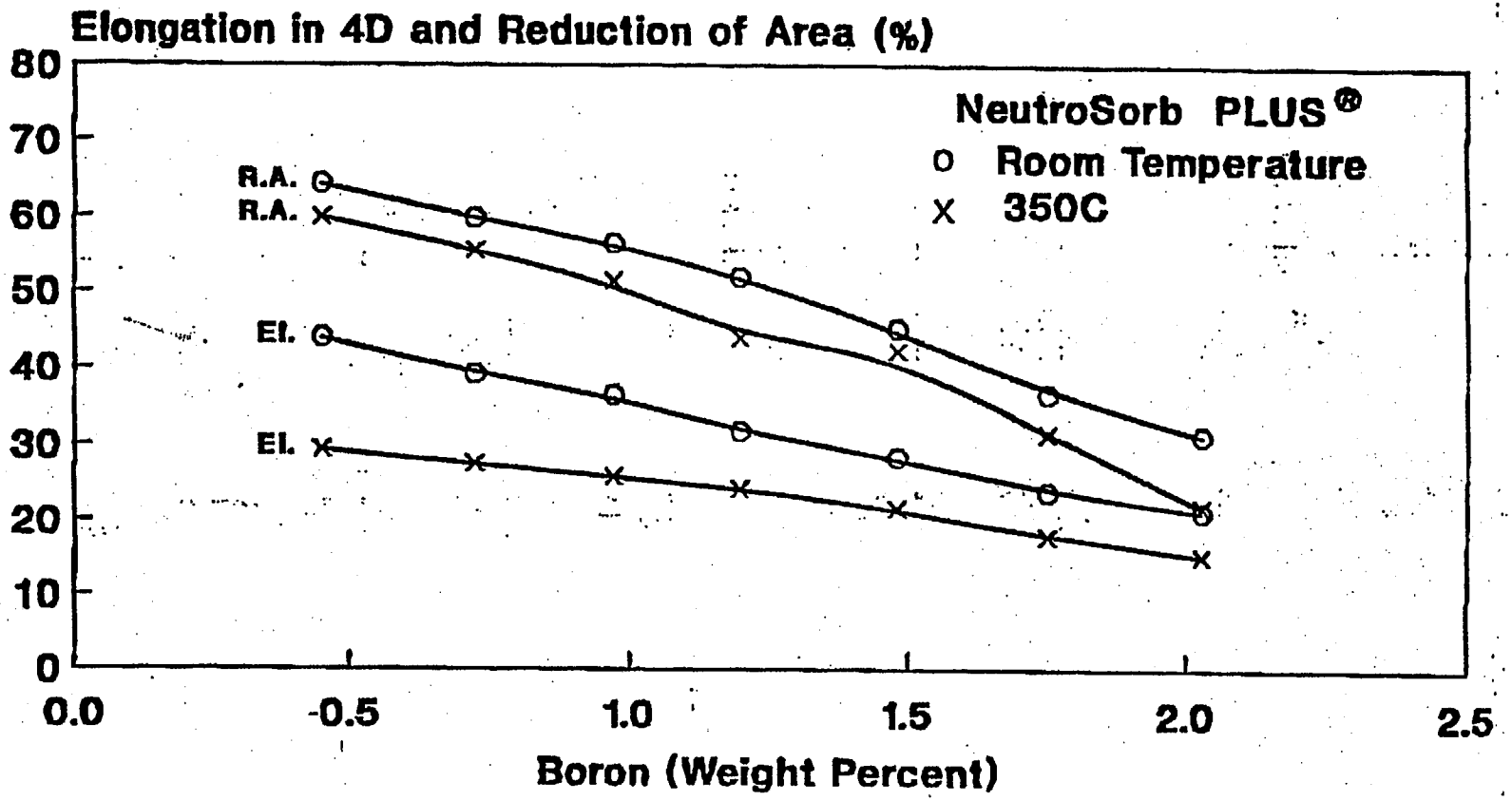
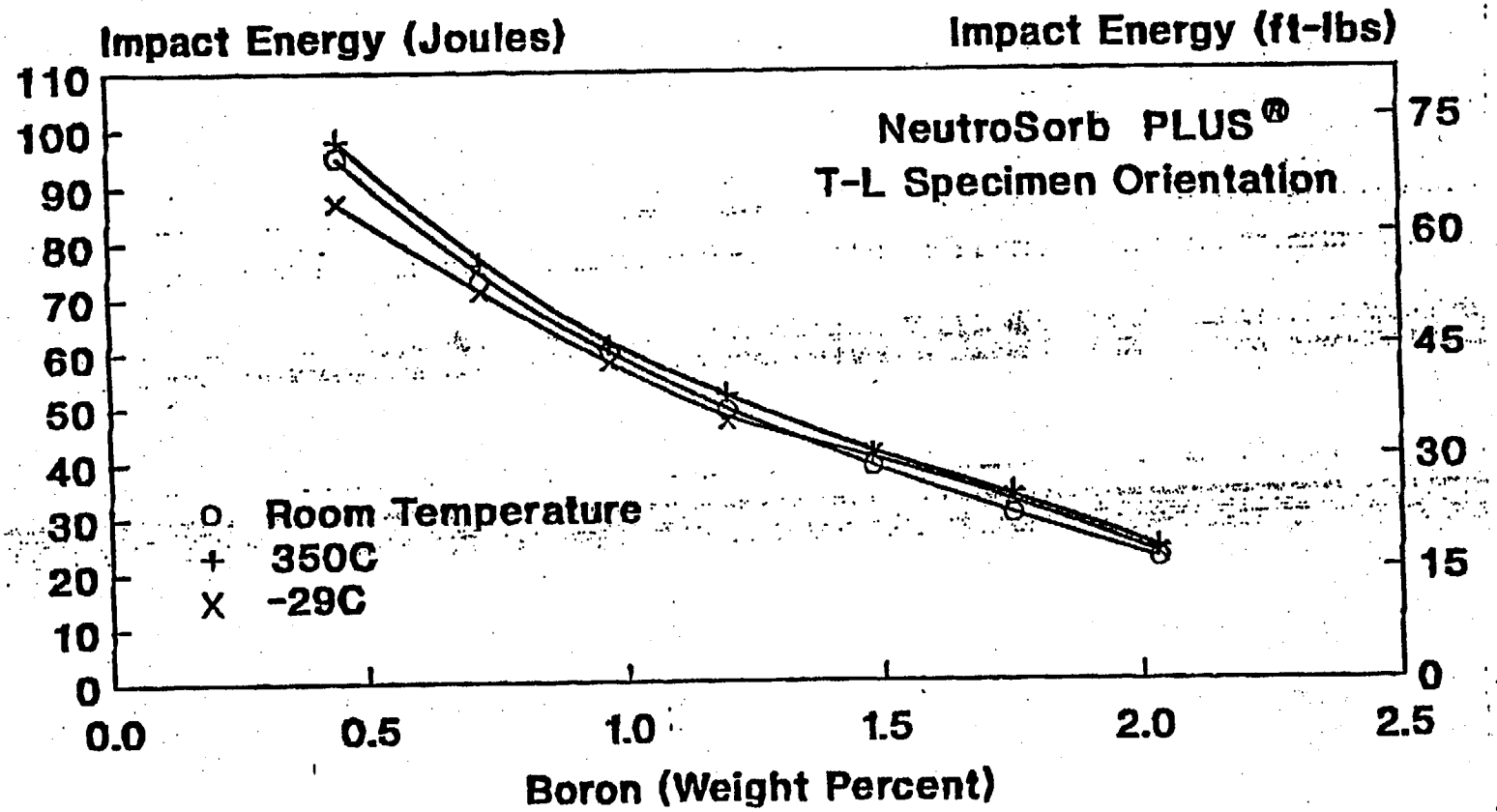


Figure 4-10. Effects of Boron Content and Temperature on Transverse Yield and Ultimate Tensile Strengths of NeutroSorb PLUS Stainless Steel (from [2])



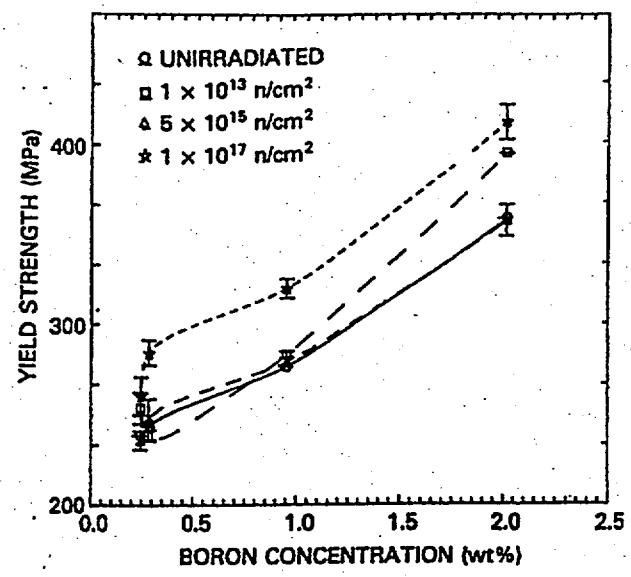
Effects of Boron Content and Temperature on Transverse Tensile Ductility of NeutroSorb PLUS® Stainless

Figure 4-11. Effects of Boron Content and Temperature on Transverse Ductility of NeutroSorb PLUS Stainless Steel (from [2])

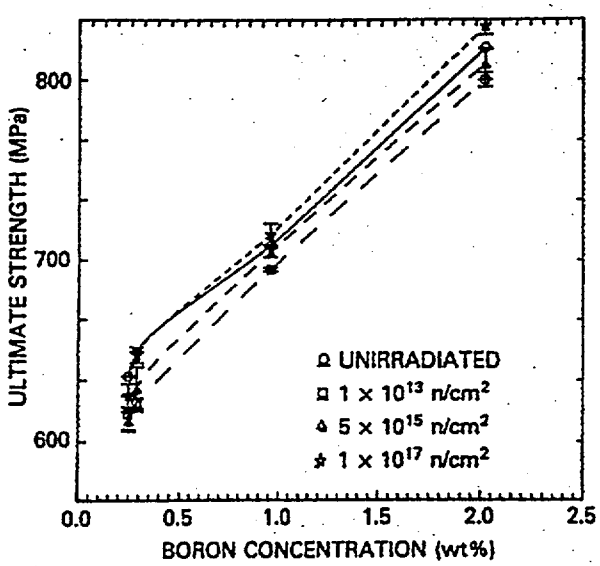


Effects of Boron Content and Temperature on Transverse Charpy V-Notch Impact Energy of NeutroSorb PLUS® Stainless

Figure 4-12. Effectsof Boron Content and Temperature on Transverse Charpy V-Notch Impact Energy of NeutroSorb PLUS Stainless Steel (from [2])



a. Yield Strength



b. Ultimate Tensile Strength

Figure 4-13. Effects of Irradiation on Strength of NeutroSorb PLUS at Varying Boron Levels (from [22])

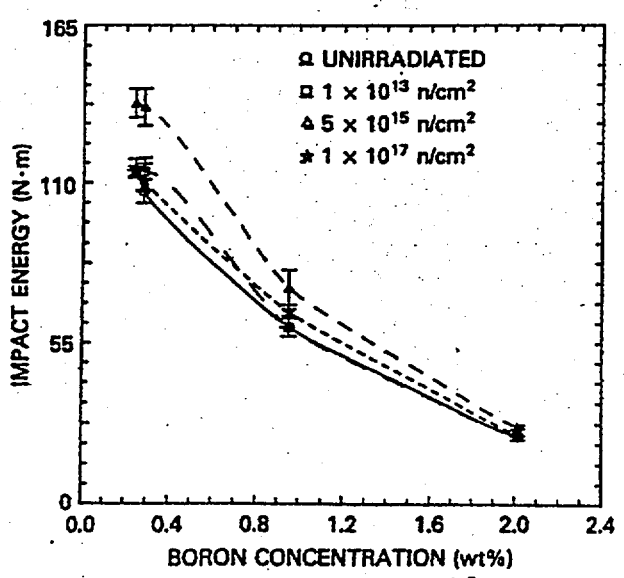
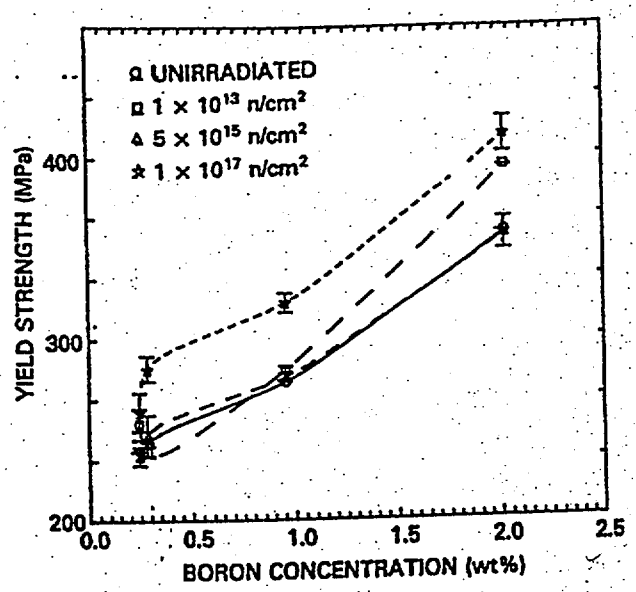
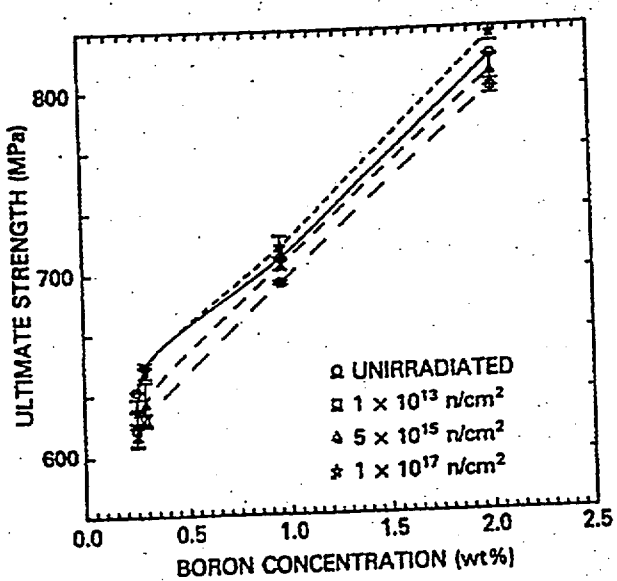


Figure 4-14. Effects of Irradiation on Charpy V-Notch Impact Energy of NeutroSorb PLUS at Varying Boron Levels (from [22])



a. Yield Strength



b. Ultimate Tensile Strength

Figure 4-15. Effects of Irradiation on Strength of NeutroSorb at Varying Boron Levels (from [22])

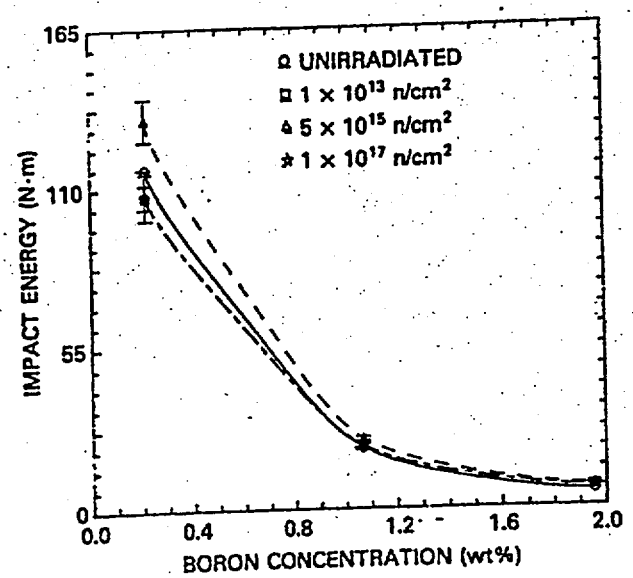


Figure 4-16. Effects of Irradiation on Charpy V-Notch Impact Energy of NeutroSorb at Varying Boron Levels (from [22])

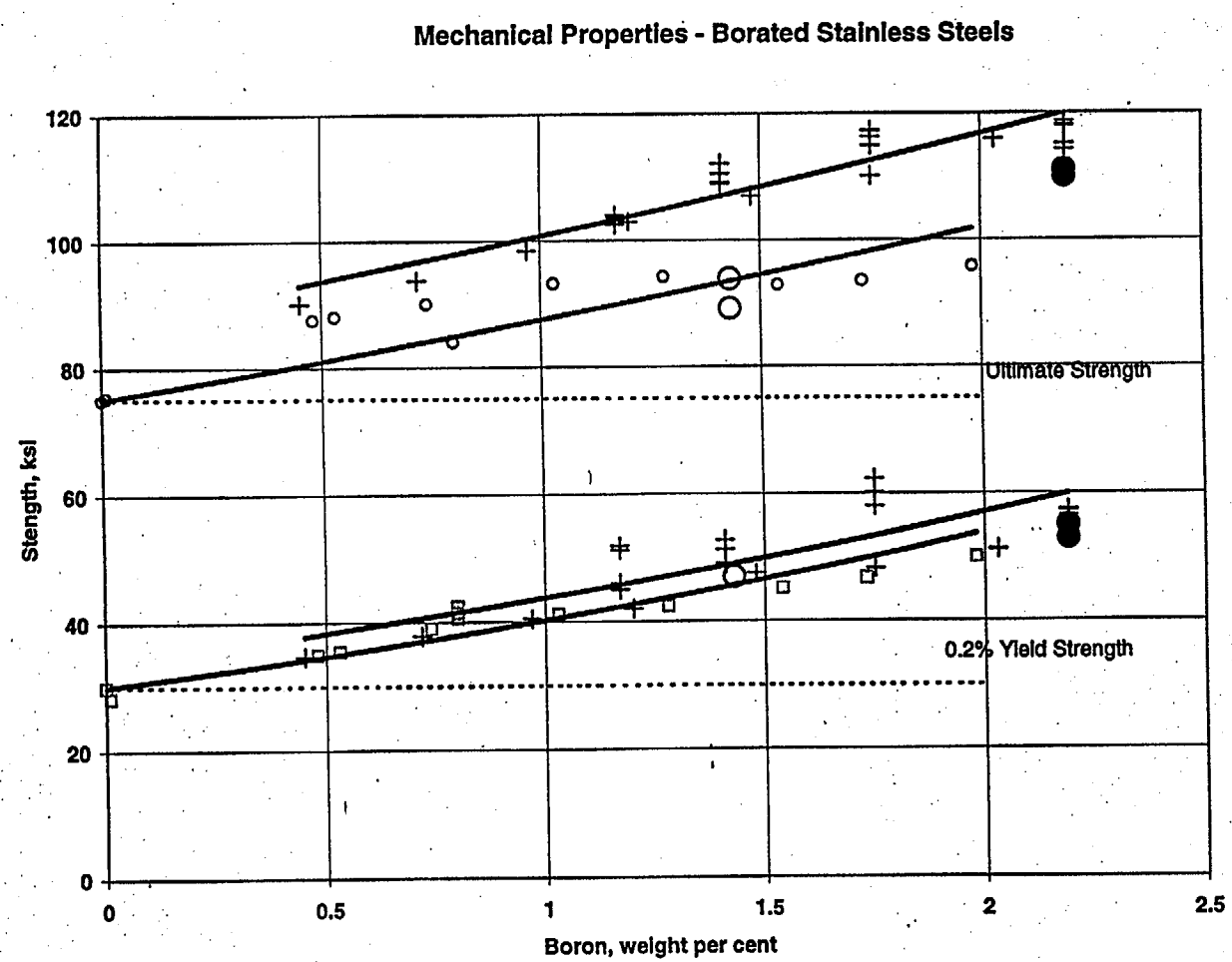


Figure 4-17. Influence of Boron Concentration on the Strength of Borated Stainless Steels

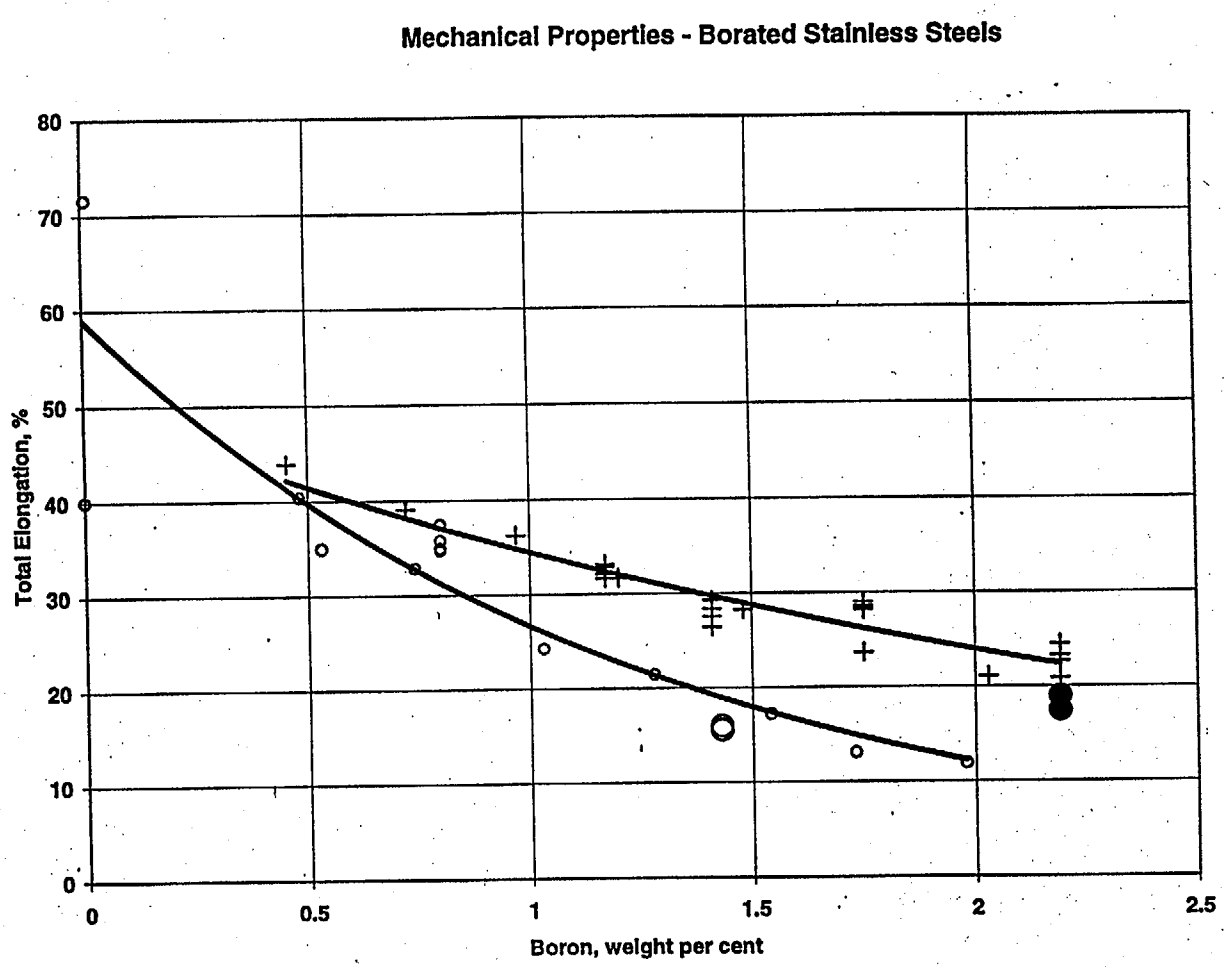


Figure 4-18. Influence of Boron Concentration on the Tensile Elongation of Borated Stainless Steels

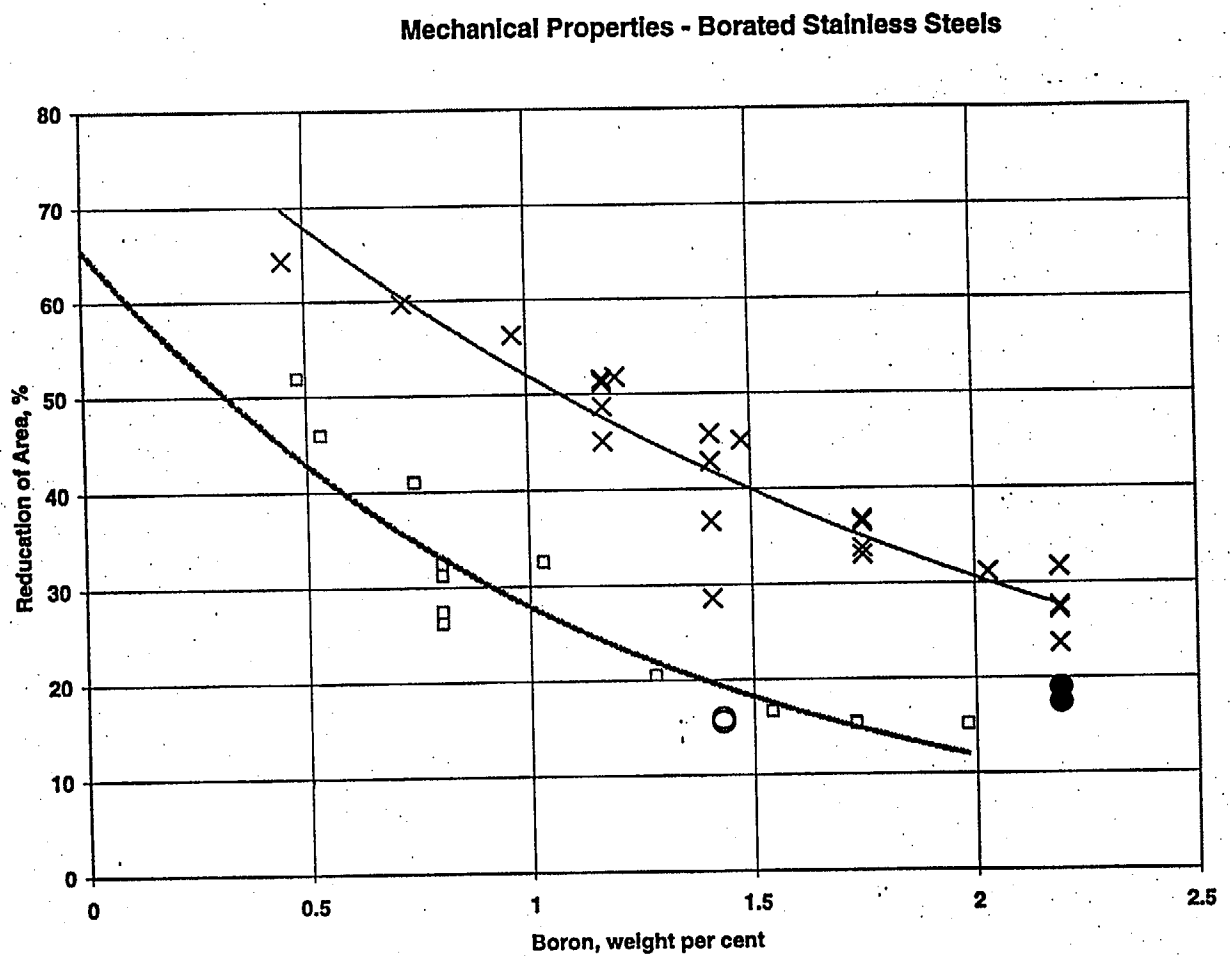


Figure 4-19. Influence of Boron Concentration on the Reduction of Area of Borated Stainless Steels

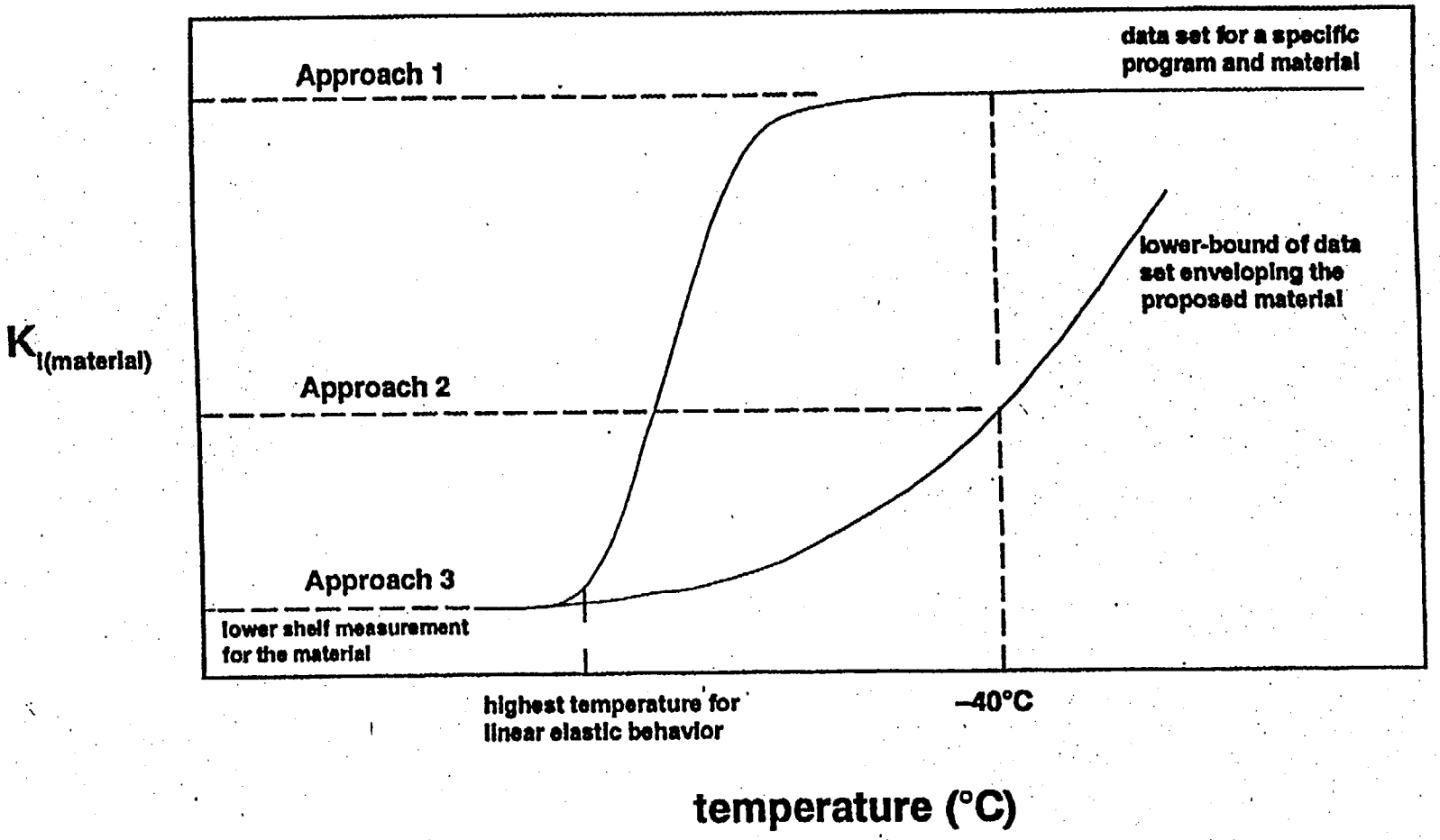


Figure 4-20. IAEA Safety Series #37 Appendix IX Approaches for $K_{allowable}$

5.0 DISCUSSION

This detailed review of the available literature has demonstrated that

- There is a considerable amount of published information available on the physical metallurgy and mechanical properties of borated stainless steel
- That information is not terribly complete, especially with respect to fracture toughness
- Since the TNI-REG and TNI-BRP casks were built and the original certification application was filed, the approach to design with borated stainless steel has become much more codified. Unfortunately, the grades of material that have been accepted for use in Core Support Structures, CC-N-510-1, [9], do not include the grades that were used in the absorber baskets of the TNI-BRP and TNI-REG casks

In general, tensile strength increases with increasing boron concentration; tensile ductility and impact properties are reduced.

The ductility and toughness of the borated stainless steels produced by Powder Metallurgy (PM) techniques are clearly superior to those of the ingot cast and wrought material at all boron levels.

Charpy impact tests are required by ASTM A-887. For the highest boron content materials, the required Charpy impact energy is not very high (10 ft-lbs at room temperature) but the material still must have some toughness to be accepted. The level of toughness is roughly comparable to that for very high strength materials used for bolting or shafting (e.g., Type 410 stainless steel or 17-4PH stainless steel in the H900 temper).

Impact energy requirements are not included in A-887 for 304B4B or 304B5B (ingot metallurgy borated 304 with approximately 1.5% boron), however, values less than 6 ft-lbs would be expected.

Welding Research Council Bulletin 265 [36] shows numerous correlations between K_{Ic} and CVN impact and pre-cracked slow bend data; most of them for steels (Figure 5-1). These provide a useful indication of the trends between results from inexpensive impact tests and fracture

toughness. Most correlations show that $(K_{Ic})^2$ is proportional to the impact energy. The correlations have a significant scatter, even for alloys for which a considerable data base exists. Using such correlations to make **quantitative** predictions of fracture toughness for alloys such as the borated stainless steels is not recommended. Those correlations are most useful and accurate when there is large quantity of fracture toughness-related data; clearly not the case for the borated stainless steels.

Using Charpy impact energy values and correlations between impact energy and K_{Ic} developed for other materials (e.g., pressure vessel steels and other iron-based alloys [36]), where K_{Ic} and K_{ID} are proportional to the square root of the Charpy V-notch impact energy, **suggests** that the K_{Ic} for PM 304 with 2% boron (i.e., equivalent to ASTM A-887, Grade 304B7A) is of the order of 30 to 70 ksi√in. No data have been located to date on fracture toughness parameters such as K_{Ic} or K_{ID} for the borated stainless steels. Values of those parameters will be required for design analyses. Limited information found for J indicates that the associated K_{Ic}'s range from about 65 to 200 ksi√in (Table 4-2).

Evaluation of stress-strain curves, including estimated constructions of those curves based on the yield and ultimate tensile strength and total elongation can also be used to provide a crude approximation of the energy absorbed (i.e., the area under the curve), a very rough estimate of the fracture toughness under tensile loading. For the 2% boron PM alloy (Grade 304B7A), that area is about 42% of that of standard Type 304 stainless steel. For Grade 304B7B, the relative area is reduced to about 15% that of the standard Type 304. Note that the standard 304 is much too tough for valid determinations of K_{Ic}. Elastic-plastic methods are required to determine a J_{Ic} from which a K_{Ic} can be estimated.

The key factor in defining the expected fracture toughness of the borated stainless steel materials used in the Transnuclear TN-REG and TN-BRP casks is demonstrating that those materials represent a sample from the same population as that used to generate the existing tensile and Charpy impact toughness properties.

Limited tensile and fracture toughness testing of TN-REG and TN-BRP materials, combined with impact data in hand, is considered viable for qualification of existing materials.

The test program required to quantify and bound the actual fracture toughness of the basket materials is expected to include Charpy V-notch tests, tensile tests, and J-integral tests (e.g., small pre-notched and fatigue pre-cracked bent beams). The Charpy testing is expected to demonstrate that the material properties are consistent with the requirements of ASTM A-887 and that the expected fracture toughness is too great to permit a valid direct measurement of K_{Ic}. Instead, multiple specimen J vs. a (Δa) curve will be determined as outlined in ASTM E-813 [34] and E-1737 [35] such that a limiting J value (J_{Ic}) can be determined.

From that measured J_{Ic}, a K_{Ic} value can be calculated for comparison to the applied stress intensity factor in the design analyses. Analytical demonstration that conservatively calculated applied K's are less than K_{Ic} for all loading conditions provides the assurance that brittle fracture will be avoided.

The various test programs that have been performed on the borated stainless steels have shown that the properties of materials prepared by either standard ingot metallurgy or by powder metallurgy are affected by the boron content. The ductility and the toughness are definitely degraded as boron content increases. The powder metallurgy product appears to be far less affected by boron additions than the material made by standard ingot metallurgy. Much of the data were collected to support an ASTM standard on borated stainless steel (ASTM A-887) and appear to have been collected some time after the TN-REG and TN-BRP casks were manufactured.

This review noted that fracture toughness properties for Grade A material (or Grade B with 1.07% B for that matter) have only a minimal directionality component to them. That is, LT and TL properties were comparable. The same observation holds true for the tensile properties in hand, although the vast majority of those properties are for the transverse orientation.

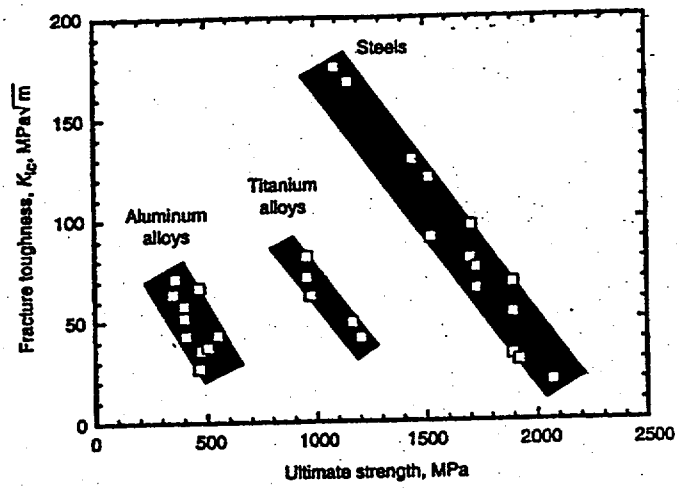
Metallographic observations also confirm that the processing of Grade A and B material seems to do a good job of removing anisotropy. Boride dispersions are generally pretty uniform, particles are fine and nearly spherical (Figure 5-2).

The characterization program for the TNI basket materials will require that optical metallography be performed to demonstrate that the basket materials have similarly uniform dispersions of fine, spherical particles. The metallographic evidence will provide the final demonstration that the TNI-BRP and TNI-REG basket materials are from the same populations as the materials that were tested in the mechanical properties characterization effort.

Note that CC-N-510-1 considers the PM product (ASTM A-887 Grade A), at least up through B6A, acceptable for core support structures. The Grade B material is not included as an acceptable material at any boron concentration.

The purpose of the mechanical properties testing and metallographic characterizations for the TNI basket materials is to demonstrate the properties of the basket materials are adequately described by the large body of data reviewed in this report. The testing of those materials must also consider the typicality of the plates used to construct the various test samples.

The laboratory testing done by Salzbrenner, et al. [13] described in Section 4.3 provides a useful perspective on the application of fracture mechanics data to full scale tests. A drop test, from 9 meters, of a pre-cracked ductile iron cask at –29°C showed that the cask did not fail in a brittle manner and showed evidence of stable crack growth.



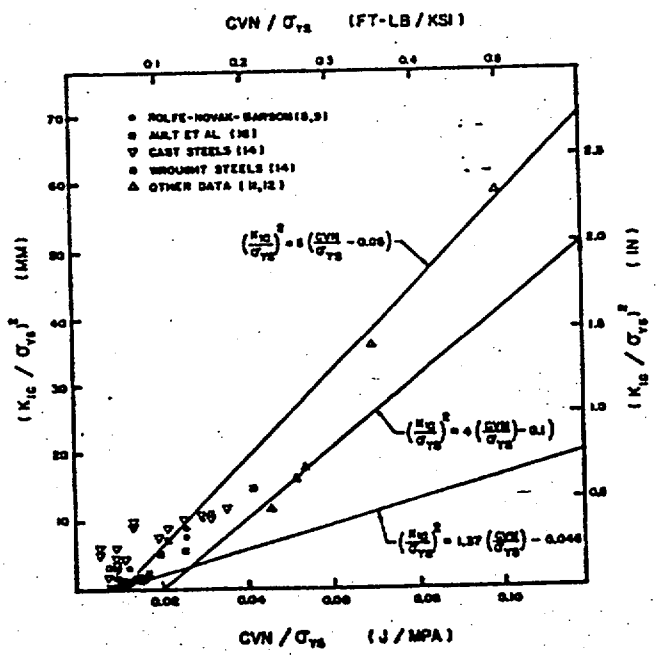


Figure 5-1. Example of Correlations Between K_{Ic} and Charpy Impact Energy (from [36])

6.0 CONCLUSIONS AND RECOMMENDATIONS

The detailed literature review performed for this project revealed that there is a fairly large quantity of information available on the physical metallurgy and mechanical properties of borated stainless steel. Tensile properties and Charpy impact energy make up the vast majority of the properties were available.

In general, tensile strength increases with increasing boron concentration; tensile ductility and impact properties are reduced.

The primary influence of boron on the mechanical properties is the result of hard, brittle $(Cr,Fe)_2B$ boride particles in the ductile and tough austenite matrix. The size and shape of the boride particles and the boride particle distribution is a critical parameter. Smaller, more spherical, and uniformly distributed boride particles have the least detrimental effect on ductility and impact strength.

The ductility and toughness of borated stainless steels produced by Powder Metallurgy (PM) techniques are clearly better superior to those from the ingot cast and wrought material at all boron levels.

The fuel basket for the Transnuclear TNI-REG is a PM product with approximately 2.2 weight per cent boron, produced by Carpenter Technology. The TNI-BRP basket material is a conventionally produced ingot metallurgy product with approximately 1.42% boron.

Since the TNI-REG and TNI-BRP casks were produced in the mid-1980s, an ASTM materials standard for borated stainless steels, A-887, has been approved. That standard includes 16 material types – 8 different boron levels from 0.20% to 2.25%, and two grades (Grade A and Grade B) that exhibit significantly different ductility and toughness properties. In general, the Grade A material, which has superior ductility and toughness is produced by PM methods.

ASME Section III Code Case N-510-1, prepared to permit the use of borated stainless steels for Core Support Structures in water cooled reactors, has been approved. That Code Case includes ASTM A-887 Grades 304BA through 304B6A. It does not include the 304B7A grade nor any of the Grade B materials.

Section III, Division 3 of the ASME Code has also been issued specifically for the design and construction of spent fuel storage and transport containers.

Temperature appears to exert only a minor effect on tensile strength and ductility. Temperature effects are less for the borated stainless steels than for standard grades such as Type 304L.

The impact properties of the borated stainless steels do not appear to affected by temperature at all over the range of –29°C to 350°C.

Neutron irradiation to fast fluences of $1x10^{13}$, $5x10^{15}$, and $1x10^{17}$ n/cm^2 also appeared to have little or no effect on mechanical properties of borated stainless steels, both A and B Grades, containing 0.25 to 2.01% boron.

Charpy impact tests are required by ASTM A-887. For the highest boron content materials, the required Charpy impact energy is not very high (10 ft-lbs at room temperature) but the material must have some toughness to be accepted. The level of toughness is roughly comparable to that for very high strength materials used for bolting or shafting (e.g., Type 410 stainless steel or 17-4PH stainless steel in the H900 temper).

Using Charpy impact energy values and correlations between impact energy and K_{Ic} developed for other materials (e.g., pressure vessel steels) suggests that the K_{Ic} for PM 304 with 2% boron (i.e., equivalent to ASTM A-887, Grade 304B7A) is of the order of 30 to 70 ksi√in.

No data were located on fracture toughness parameters such as K_{Ic} or K_{ID} for the borated stainless steels. Values of those parameters will be required for design analyses. Limited information on J indicates that K_{Ic}'s should range from about 65 to 200 ksi√in.

All of these measured values or estimates of toughness indicate that a reasonable level of toughness would be expected for both the ingot metallurgy material with 1.45% boron (TNI-BRP basket0 and for the PM material with 2.2% boron (TNI-REG)

The key factor in defining the expected fracture toughness of the borated stainless steel materials used in the Transnuclear TN-REG and TN-BRP casks is demonstrating that those materials represent a sample from the same population as that used to generate the existing tensile and Charpy impact toughness properties.

Limited tensile and fracture toughness testing of TN-REG and TN-BRP materials, combined with impact data in hand, is considered viable for qualification of existing materials.

The test program required to quantify and bound the actual fracture toughness of the basket materials is expected to include Charpy V-notch tests, tensile tests, and J-integral tests (e.g., small pre-notched and fatigue pre-cracked bent beams). The Charpy testing is expected to demonstrate that the material properties are consistent with the requirements of ASTM A-887 and that the expected fracture toughness is too great to permit a valid direct measurement of K_{Ic}. Instead, multiple specimen J vs. a (Δa) curve will be determined as outlined in ASTM E-813 and E-1737 such that a limiting J value (J_{Ic}) can be determined.

From that measured J_{Ic}, a K_{Ic} value can be calculated for comparison to the applied stress intensity factor in the design analyses. Analytical demonstration that conservatively calculated applied K's are less than K_{Ic} for all loading conditions provides the assurance that brittle fracture will be avoided.

The recommended test program will also include limited optical metallographic examination of the TNI-REG and TNI-BRP basket materials to confirm that the desired boride sizes and distributions, consistent with those reported in the literature, have been achieved.

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