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Advanced Neutron Source Materials Surveillance Program

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MASTER

Advanced Neutron Source

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DEPARTMENT OF ENERGY

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ADVANCED NEUTRON SOURCE MATERIALS SURVEILLANCE PROGRAM

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ACRONYMS

ANS	Advanced Neutron Source
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
CPBT	core pressure boundary tube
HAZ	heat affected zone
HFIR	High Flux Isotope Reactor
INEL	Idaho National Engineering Laboratory

1. INTRODUCTION

The Advanced Neutron Source (ANS) will be composed of several different materials, one of which is 6061-T6 aluminum. Among other components, the reflector vessel and the core pressure boundary tube (CPBT), seen in Fig. 1, are to be made of 6061-T6 aluminum. These components will be subjected to high thermal neutron fluences and will require a surveillance program to monitor the strength and fracture toughness of the 6061-T6 aluminum over their lifetimes.

2. OBJECTIVE

The purpose of this paper is to explain the steps that were taken in the summer of 1994 toward developing the surveillance program. The first goal was to decide upon standard specimens to use in the fracture toughness and tensile testing. Second, facilities had to be chosen for specimens representing the CPBT and the reflector vessel base, weld, and heat-affected-zone (HAZ) metals. Third, a timetable had to be defined to determine when to remove the specimens for testing.

3. BACKGROUND

Neutron irradiation is known to cause embrittlement and loss of ductility in 6061-T6 aluminum. Therefore, code case N-519[1] (Attachment 1) requires that a surveillance program be developed to allow use of this material in welded pressure vessels. The guideline for this surveillance program is the procedure for surveillance of light-water cooled reactor vessels, which is given in the American Society for Testing and Materials (ASTM) Std. E185-82[2]. This standard is defined for steel pressure vessels and will have to be modified appropriately because the ANS will be using an aluminum pressure vessel.

ASTM Std. E185-82 defines the minimum number of capsules (irradiation exposure sets) needed for the surveillance program by the predicted transition temperature shift that the reactor vessel will undergo. The transition temperature shift is the difference in the index temperatures from the average Charpy curves measured before and after irradiation.[2] Three different sets of specifications are given for the defined small, medium, and large temperature shifts.[2] Note that unlike steels, aluminum does not exhibit a transition temperature. For the ANS surveillance program, it was decided to be on the safe side and follow the most stringent of these requirements as the guideline. In this case, the ASTM standard requires at least five surveillance capsules. Each of these capsules must contain 42 specimens. Of these specimens, 36 are to be Charpy impact specimens, and the remaining 6 are to be tensile specimens. Twelve Charpy specimens are required from base metal, weld metal, and HAZ metal, and three tensile specimens each from base and weld metal. Each capsule is to be removed after a predetermined amount of time and the specimens tested to see that the material is behaving as expected with respect to fracture toughness and tensile strength.

The ASTM standard defines the periods of time between removal of the capsules. These intervals correspond to 5%, 10%, 20%, 50%, and 100% of the effective power years of the reactor. These same percentages will be used as a basis to determine the removal times of the specimens for the CPBT and the reflector vessel, based upon their respective expected lifetimes. However, the percentages cannot be followed exactly, since samples can be removed only when the reactor is shut down. These ASTM standard requirements will form the guideline for the ANS surveillance program, but they will be modified for the use of aluminum instead of steel for the pressure vessel.

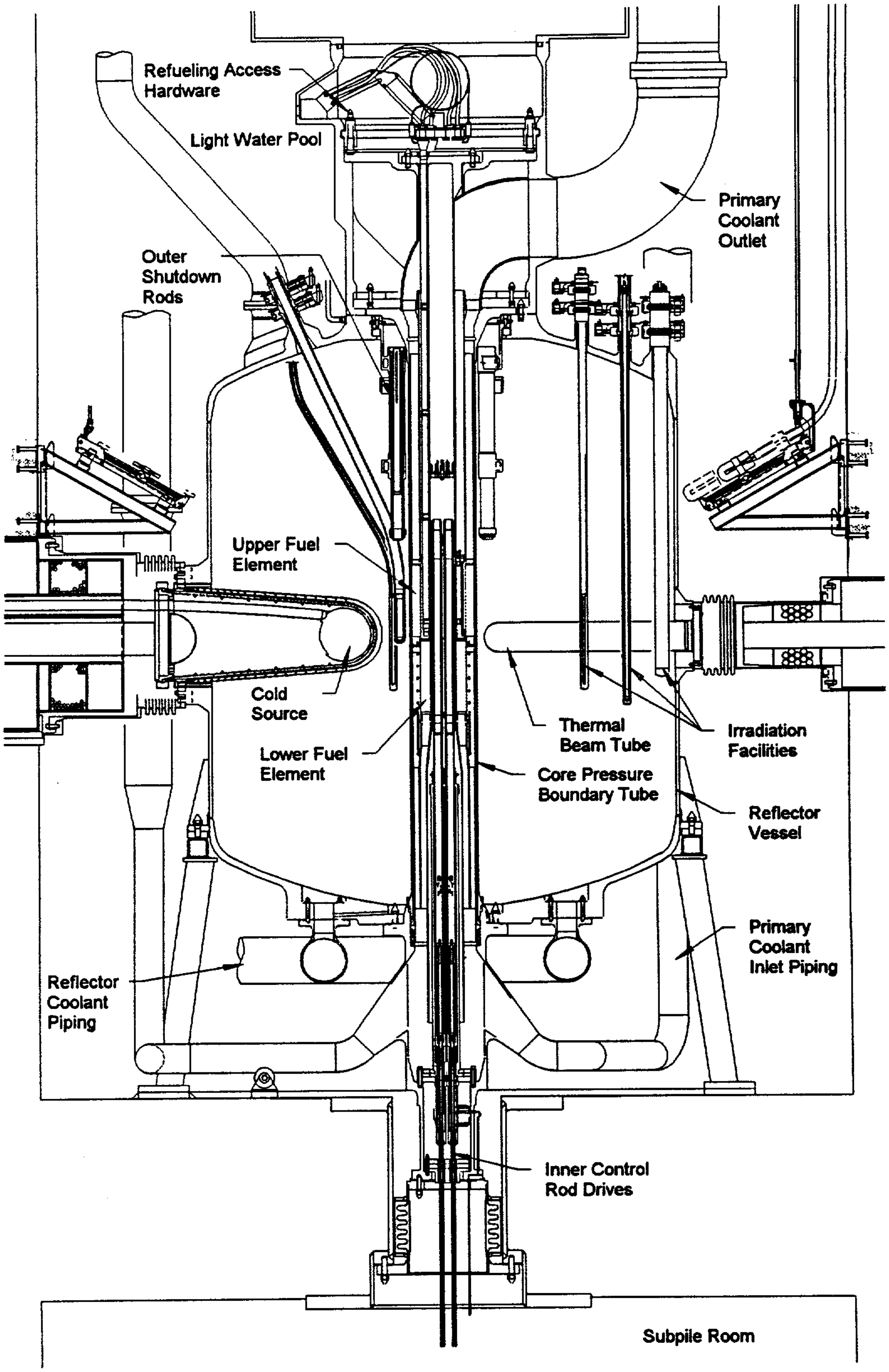


Fig. 1. Section through the reactor assembly.

4. HANSAL-T TESTING

To assess the effects irradiation has on 6061-T6 aluminum, a testing program has been in place using capsules placed into the High Flux Isotope Reactor (HFIR) target positions. These HANSAL-T capsules have contained both tensile specimens and compact tension fracture toughness specimens. The first capsule, HANSAL-T1,[3] was irradiated to a fluence of 1×10^{26} m^{-2} ($E < 0.625$ eV). The second capsule, HANSAL-T2,[4] was irradiated to a fluence of 8×10^{26} m^{-2} ($E < 0.625$ eV). These capsules contained base metal 6061-T651 specimens.

The testing of the specimens in these two capsules has shown no large loss of fracture toughness, except at a test temperature of 150°C, which is a higher temperature than is expected in the ANS. The yield and ultimate strengths of the material increased significantly with irradiation, as was expected.[3,4] These are favorable results.

The HANSAL-T3 capsule, containing weld metal specimens, is currently scheduled to be removed from HFIR. It is being removed earlier than planned because it contains a screen similar to the one in HANSAL-T2 that was partially clogged upon removal.[4] Removal of HANSAL-T3 at this early date is not a problem; it has already seen more fluence than the CPBT welds will be exposed to in their lifetime.[5]

5. COMPACT vs SHORT ROD SPECIMENS

The surveillance program for light-water cooled reactors in ASTM Std. E185-82 uses Charpy impact specimens to determine the shift in the nil-ductility temperature caused by reactor operation. Unlike the low-alloy steels, aluminum does not exhibit a nil-ductility temperature. The change in the plane-strain fracture toughness caused by reactor operation will be used to evaluate radiation damage. The plane-strain fracture toughness can then be used directly in analyses to determine when the vessel must be replaced to ensure that a non-ductility rupture will not occur.

The compact specimen used in the HANSAL-T capsules (Fig. 2) is used to evaluate plane-strain fracture toughness. However, there is an alternate fracture toughness specimen to this compact specimen. ASTM Std. E1304-89[6] outlines the use of a short rod specimen (Fig. 3) to measure the fracture toughness of metallic materials. This specimen has been used previously in the testing of 6061-T651 aluminum specimens[7] and may be the best choice for the surveillance of the ANS.

ASTM fracture toughness standards require that the specimen size meet requirements that are based upon the ratio of the toughness to the yield strength squared $(K_Q/\sigma_{YS})^2$ (Table 1). ASTM Std. E399-90[8] requires that the width (B) of the fracture toughness specimen be two and a half times this ratio for aluminum alloys (Table 1). However if the short rod specimen is used, the width need only be one and a quarter times this ratio.[6] The overall dimensions of the compact specimen required by E399-90[8] for the unirradiated material are $28 \times 67.2 \times 70$ mm, whereas the required dimensions of the short rod specimen are 14 mm diam. by 21 mm length. Therefore, the short rod specimen has one-fortieth of the volume of the compact specimen. Since there is little extra room in the ANS reflector vessel irradiation facilities, the short rod specimen seems to be a better choice than the compact specimen.

Typical values for K_Q and σ_{YS} (Table 1) were used to determine the minimum required value for the diameter of the short rod specimen. The height of the short rod specimen is defined as 1.6 times the diameter, including the loading flats. The minimum diameter for unirradiated 6061-T6 aluminum is 14.0 mm and the minimum diameter for highly irradiated 6061-T6 aluminum was calculated to be 5.0 mm. The first specimen size chosen was 20.0 mm in diameter and 32.0 mm in length (Fig. 4).

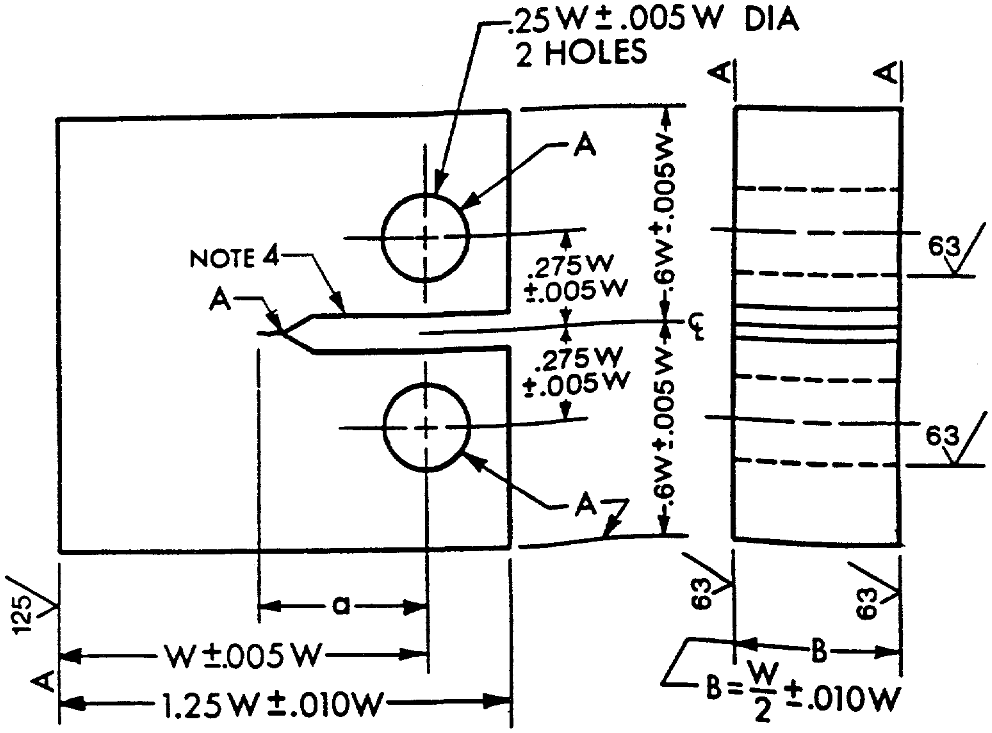


Fig. 2. Compact specimen C(T) standard proportions and tolerances.

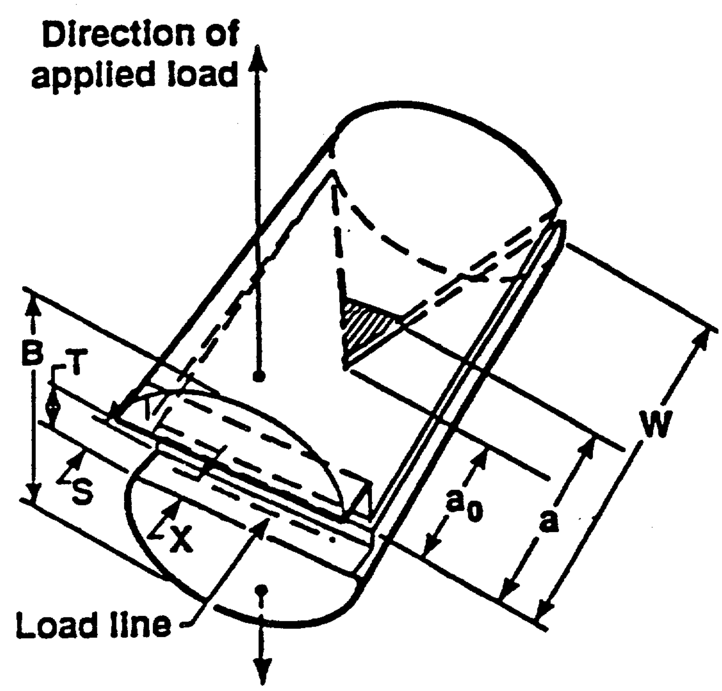


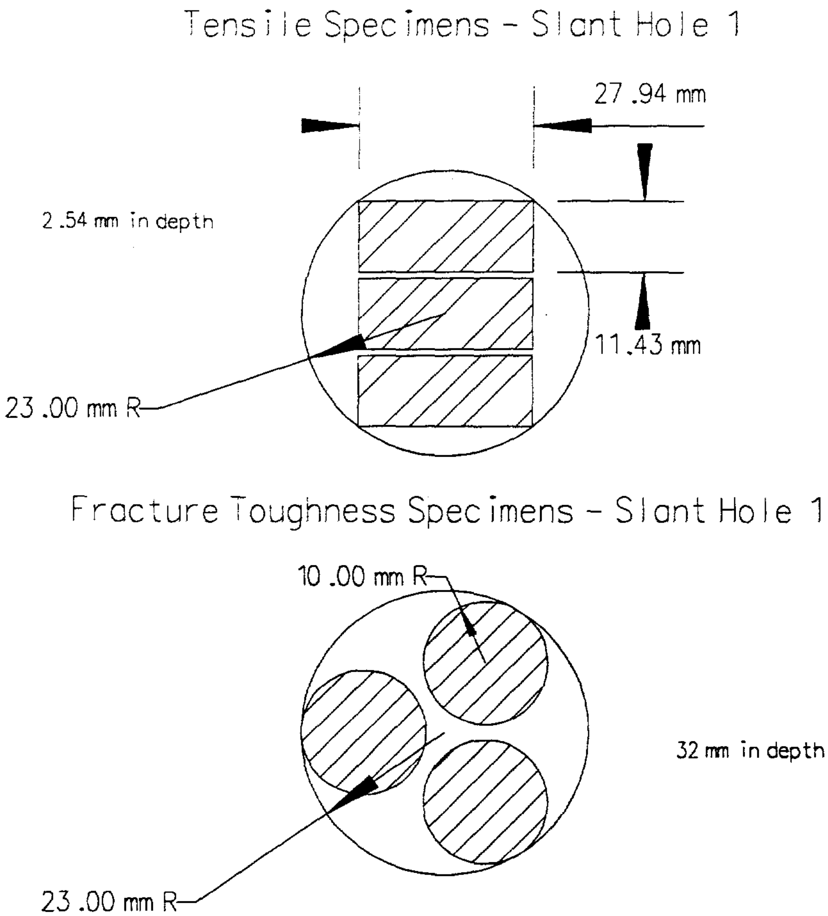
Fig. 3. Schematic drawing of chevron-notched short rod specimen.

Table. 1. Compact width vs short rod diameter calculations

B = width/diameter of specimen

	Unirradiated	Irradiated to 8×10^{26} n/m^2
Toughness	$K_Q = 27.5$ MPa$\sqrt{m}$	$K_Q = 20$ MPa$\sqrt{m}$
Yield strength	$\sigma_{YS} = 260$ MPa	$\sigma_{YS} = 400$ MPa

ASTM standard	Formula	B unirradiated	B irradiated
E 399 test method for plane-strain fracture toughness of metallic materials—compact specimen	$B \geq 2.5(K_{Ic}/\sigma_{YS})^2$	$B \geq 28$ mm	$B \geq 6.25$ mm
E 1304 test method for plane-strain (chevron-notch) fracture toughness of metallic materials—short rod specimen	$B \geq 1.25(K_{Iv}/\sigma_{YS})^2$	$B \geq 14$ mm	$B \geq 3.125$ mm



Slant Hole 1- Vertical View

21 tensile
21 fr. tough
241.8 mm tall

	Remove after:
3 fr. tough	1 fuel cycle
3 tensile	
3 fr. tough	2 fuel cycles
3 tensile	
3 fr. tough	4 fuel cycles
3 tensile	
3 fr. tough	8 fuel cycles
3 tensile	
3 fr. tough	12 fuel cycles
3 tensile	
3 fr. tough	16 fuel cycles
3 tensile	
3 fr. tough	extra
3 tensile	

Fig. 4. Core pressure boundary tube short rod and tensile surveillance specimens—version 1.

This was later changed to 12.0 mm in diameter and 19.2 mm in length to allow space for more specimens in the available facility (Figs. 5–10). See Sect. 6 for a discussion of this facility. The nine fracture toughness specimens included in Figs. 6–10 account for the CPBT base, weld, and HAZ metals, with three specimens from each of these metals.

The compact specimen used in the HANSAL-T experiments (B = 11.4 mm) (Fig. 11) was then placed into the facility. Three specimens each are needed for the CPBT base, weld, and HAZ metals. One layer of tensile specimens is also needed. To have enough capsules to cover the 6-month lifetime of the CPBT and do the additional testing to see if it is possible to extend this lifetime, the overall facility would have to be 620 mm tall, compared with less than 300 mm for the short rod specimen (Fig. 10).

Finally, 16.0 mm was chosen as the standard specimen diameter to facilitate the testing process (Fig. 12), and this choice determined that the height of each specimen would be 25.6 mm. It was then determined that these six specimens would be representative only of the CPBT base metal. The timetable decided upon (Fig. 12) corresponds approximately to 10%, 20%, 50%, 100%, 150%, and 200% of the lifetime of the CPBT, which is similar to the guideline.[2] Keeping six samples when only three are needed for the CPBT base metal will provide some extra specimens. It was decided to move the specimens for the CPBT weld and HAZ metals to locations that would better reflect their respective fluences and softer spectrums. These locations have not been determined yet, but the use of an existing isotope production facility looks promising.

6. FACILITIES

In addition to choosing a specimen size, it was also necessary to choose a facility in which to irradiate the specimens. The facility must have a flux similar to or higher than that of the component that it represents. In addition, the facility should be in a similar spectrum and be able to cool the specimens adequately. Because the 6-month lifetime of the CPBT is relatively short, it would be desirable to use an existing experimental facility to do the surveillance for the first year or two. Testing will be continued after the lifetime of the CPBT to see if it would be feasible to extend this lifetime. After this time, there will be no need to continue the surveillance, and the facility can be transferred to its original intended use. The reflector vessel, however, must be under surveillance for the lifetime of the reactor, so a new facility will have to be developed for its surveillance capsules.

After looking at the existing experimental facilities, the slant holes (Fig. 13) were chosen as possible facilities for the CPBT base metal samples. There are two slant hole experimental facilities, SH-1 and SH-2. The irradiation region for each is 46 mm in diameter and 300 mm tall. The thermal-to-fast ratio in the slant holes corresponds relatively well to the expected thermal-to-fast ratio at the location of peak thermal fluence, so the samples should be representative of the irradiation that the CPBT is experiencing.

Figure 14 shows the thermal-to-fast ratio vs fluence from the top to the bottom of the CPBT after seven fuel cycles. The figure also shows the conditions at the location of the slant holes, as well as the conditions for the HANSAL-T testing. Two results for the slant holes are shown. One is the unperturbed value in the reflector vessel at the slant hole locations. The other is the Idaho Nuclear Engineering Laboratory (INEL) perturbed calculation with 13% stainless steel/87% aluminum targets in place at the beginning of the cycle. For the anticipated life of seven fuel cycles, the peak thermal fluence on the CPBT is 5.1×10^{26} n/m with a thermal-to-fast ratio of 7. The slant hole with only aluminum specimens in it may a good match for the region of the CPBT with the highest fluence, because the fluence and spectrum should be somewhere between the slant hole unperturbed value and the perturbed value. However, these are preliminary figures. The CPBT data are taken from an INEL

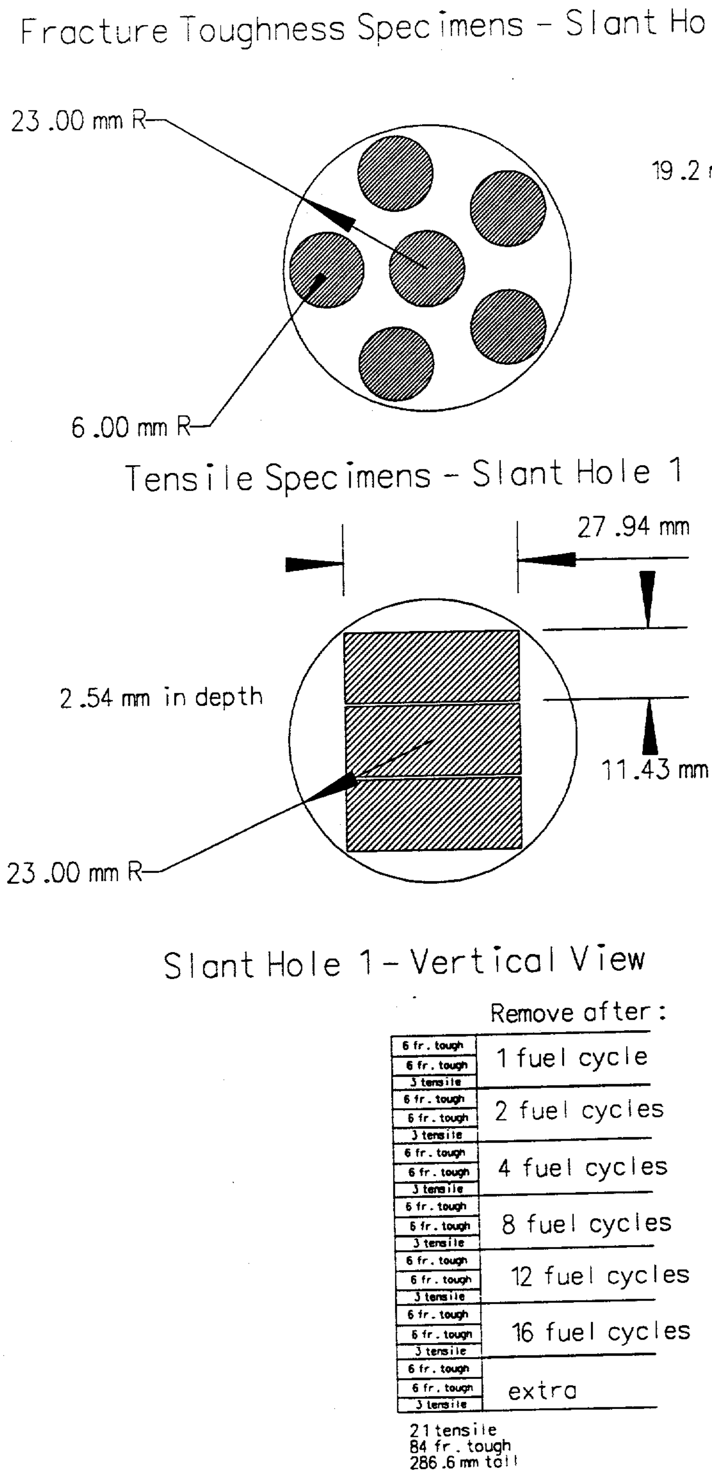


Fig. 5. Core pressure boundary tube short rod and tensile surveillance specimens—version 2.

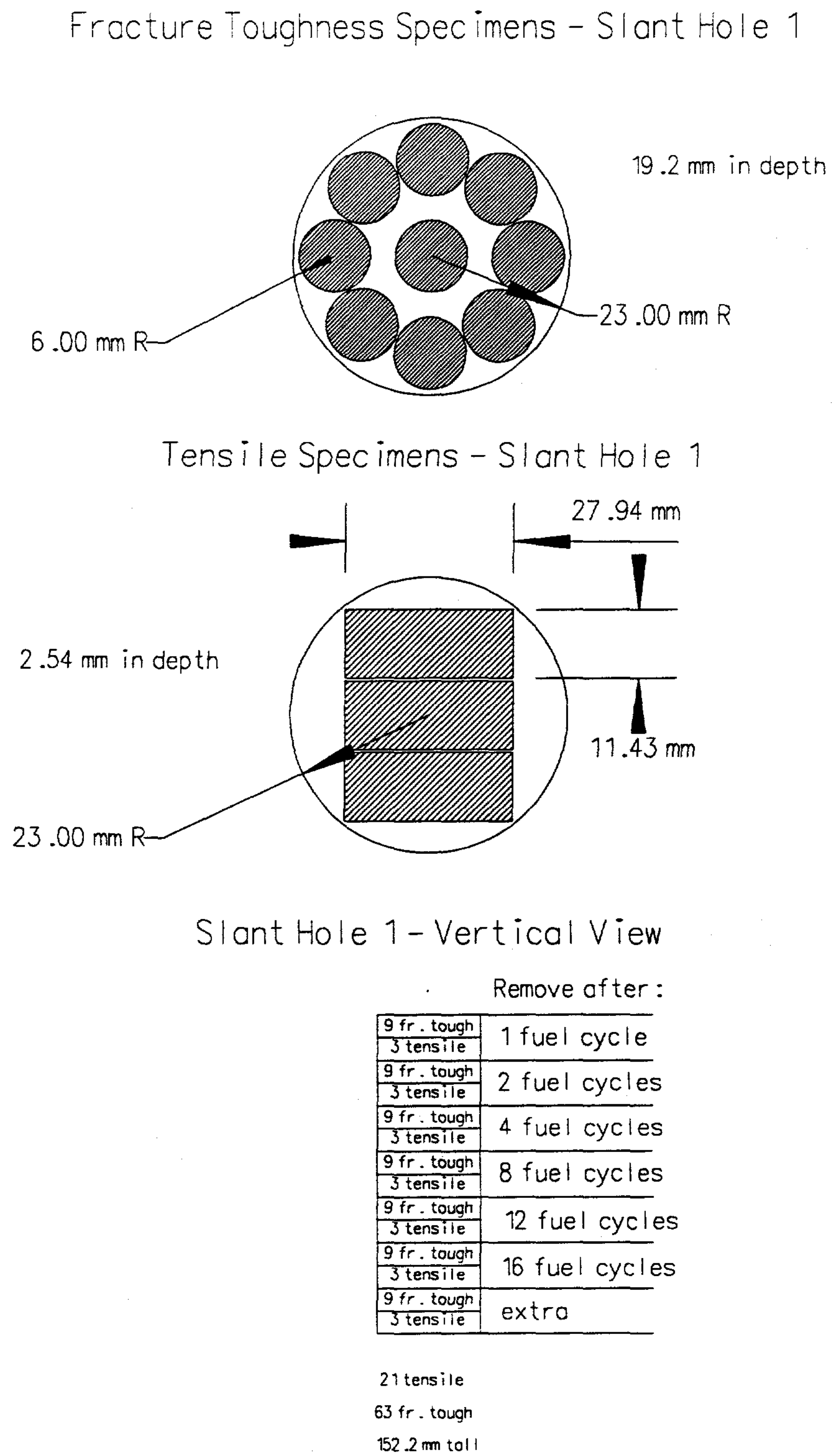


Fig. 6. Core pressure boundary tube short rod and tensile surveillance specimens—version 3.

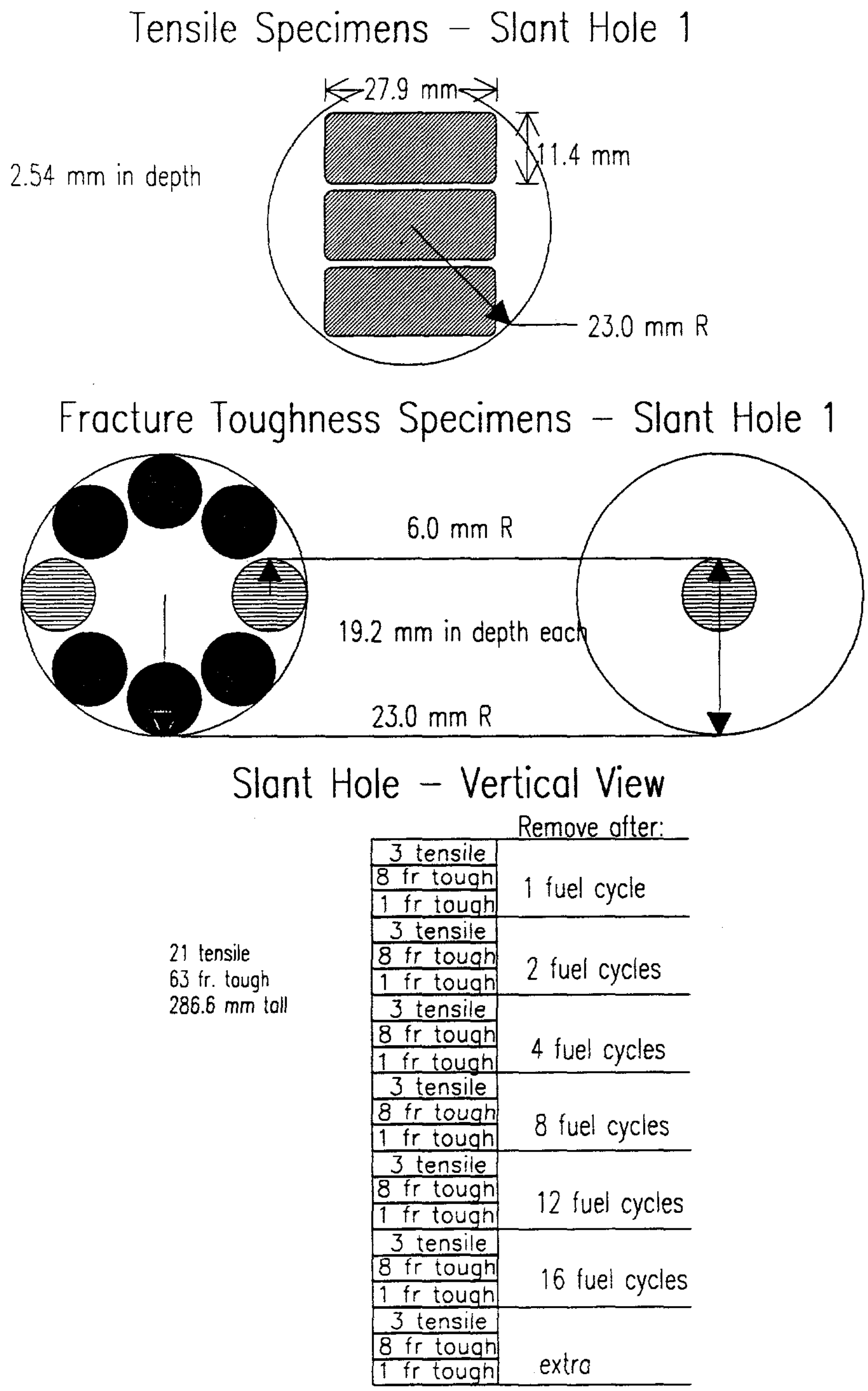
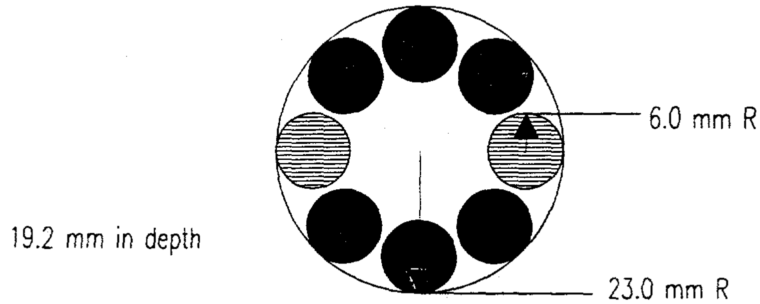
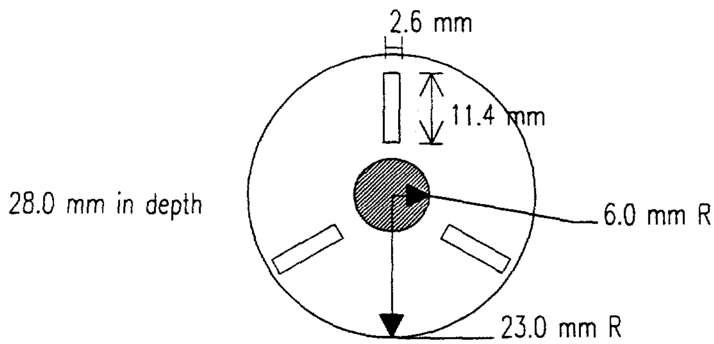


Fig. 7. Core pressure boundary tube short rod and tensile surveillance specimens—version 4.

Fracture Toughness Specimens – Slant Hole 1



Fracture Toughness and Tensile Specimens – Slant Hole 1



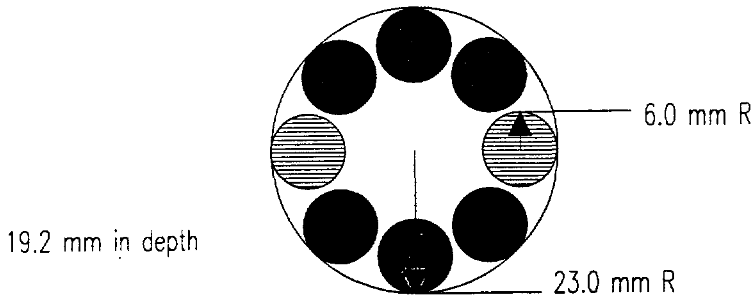
Slant Hole – Vertical View

	Remove after:
8 fr. tough	1 fuel cycle
3 tensile & 1 fr. tough	
8 fr. tough	2 fuel cycles
3 tensile & 1 fr. tough	
8 fr. tough	4 fuel cycles
3 tensile & 1 fr. tough	
8 fr. tough	8 fuel cycles
3 tensile & 1 fr. tough	
8 fr. tough	12 fuel cycles
3 tensile & 1 fr. tough	
8 fr. tough	16 fuel cycles
3 tensile & 1 fr. tough	
8 fr. tough	extra
3 tensile & 1 fr. tough	

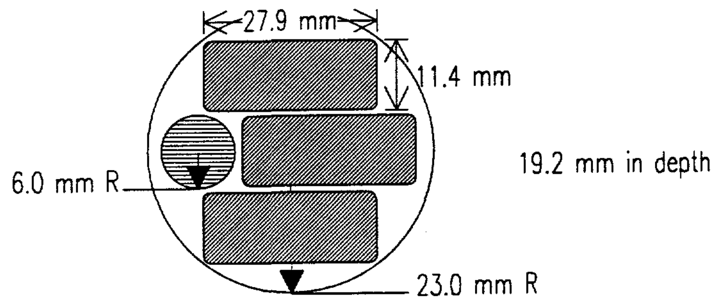
21 tensile
63 fr. tough
330.4 mm tall

Fig. 8. Core pressure boundary tube short rod and tensile surveillance specimens—version 5.

Fracture Toughness Specimens – Slant Hole 1



Tensile Specimens – Slant Hole 1



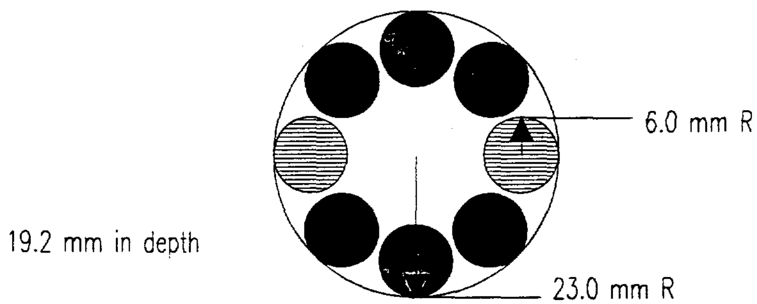
Slant Hole – Vertical View

	Remove after:
8 fr. tough	1 fuel cycle
3 tensile & 1 fr. tough	
8 fr. tough	2 fuel cycles
3 tensile & 1 fr. tough	
8 fr. tough	4 fuel cycles
3 tensile & 1 fr. tough	
8 fr. tough	8 fuel cycles
3 tensile & 1 fr. tough	
8 fr. tough	12 fuel cycles
3 tensile & 1 fr. tough	
8 fr. tough	16 fuel cycles
3 tensile & 1 fr. tough	
8 fr. tough	extra
3 tensile & 1 fr. tough	

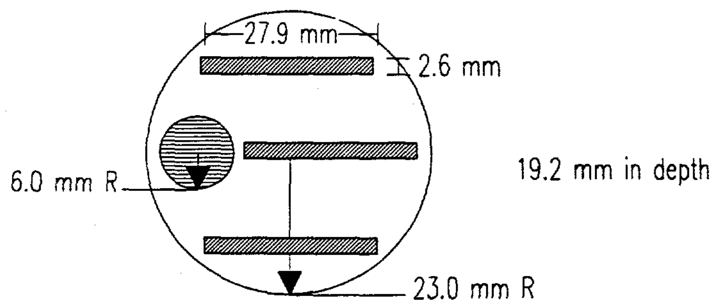
21 tensile
63 fr. tough
268.8 mm tall

Fig. 9. Core pressure boundary tube short rod and tensile surveillance specimens—version 6.

Fracture Toughness Specimens – Slant Hole 1



Tensile Specimens – Slant Hole 1



Slant Hole – Vertical View

	Remove after:
8 fr. tough	1 fuel cycle
3 tensile & 1 fr. tough	
8 fr. tough	2 fuel cycles
3 tensile & 1 fr. tough	
8 fr. tough	4 fuel cycles
3 tensile & 1 fr. tough	
8 fr. tough	8 fuel cycles
3 tensile & 1 fr. tough	
8 fr. tough	12 fuel cycles
3 tensile & 1 fr. tough	
8 fr. tough	16 fuel cycles
3 tensile & 1 fr. tough	
8 fr. tough	extra
3 tensile & 1 fr. tough	

21 tensile
63 fr. tough
268.8 mm tall

Fig. 10. Core pressure boundary tube short rod and tensile surveillance specimens—version 7.

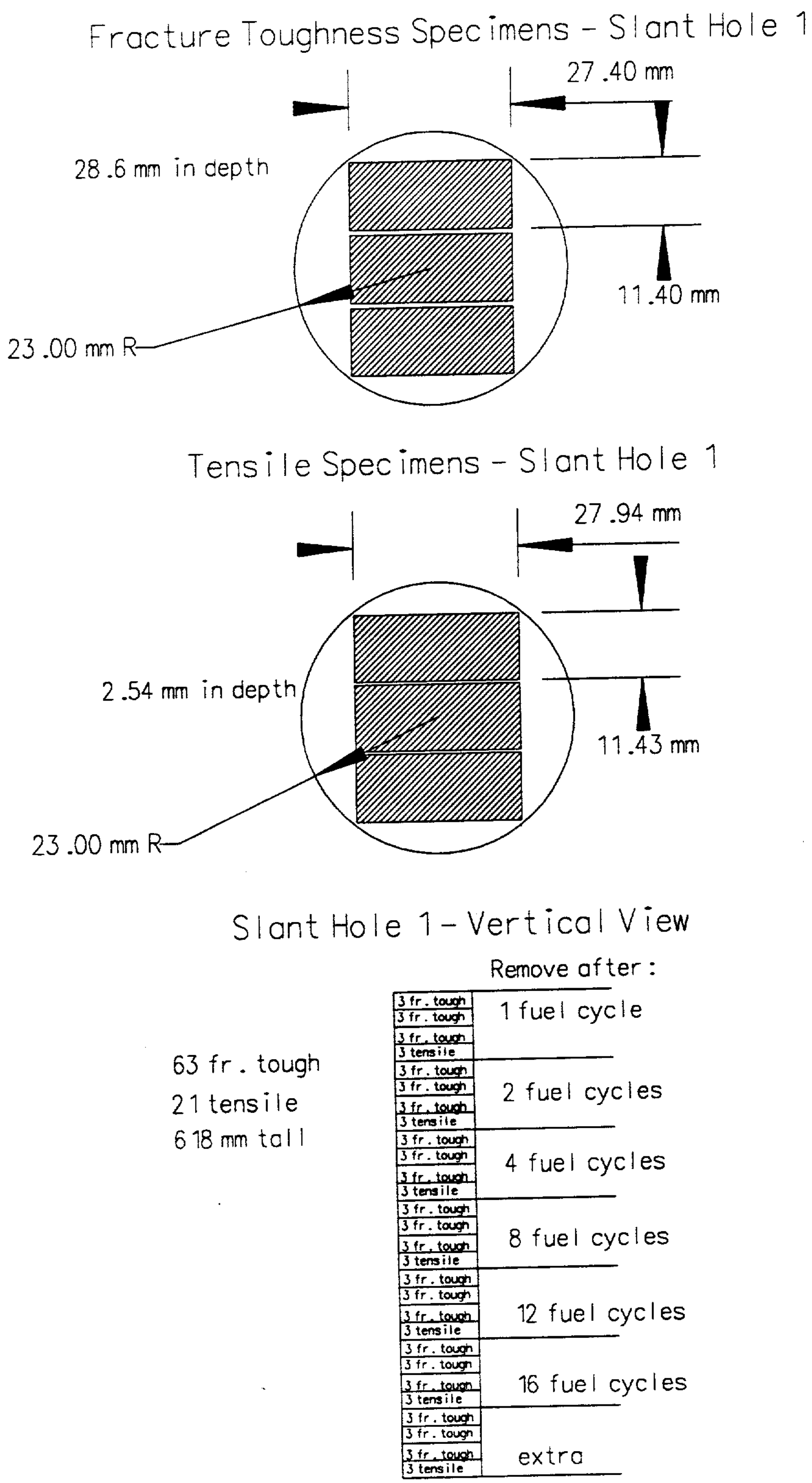


Fig. 11. Core pressure boundary tube compact and tensile surveillance specimens.

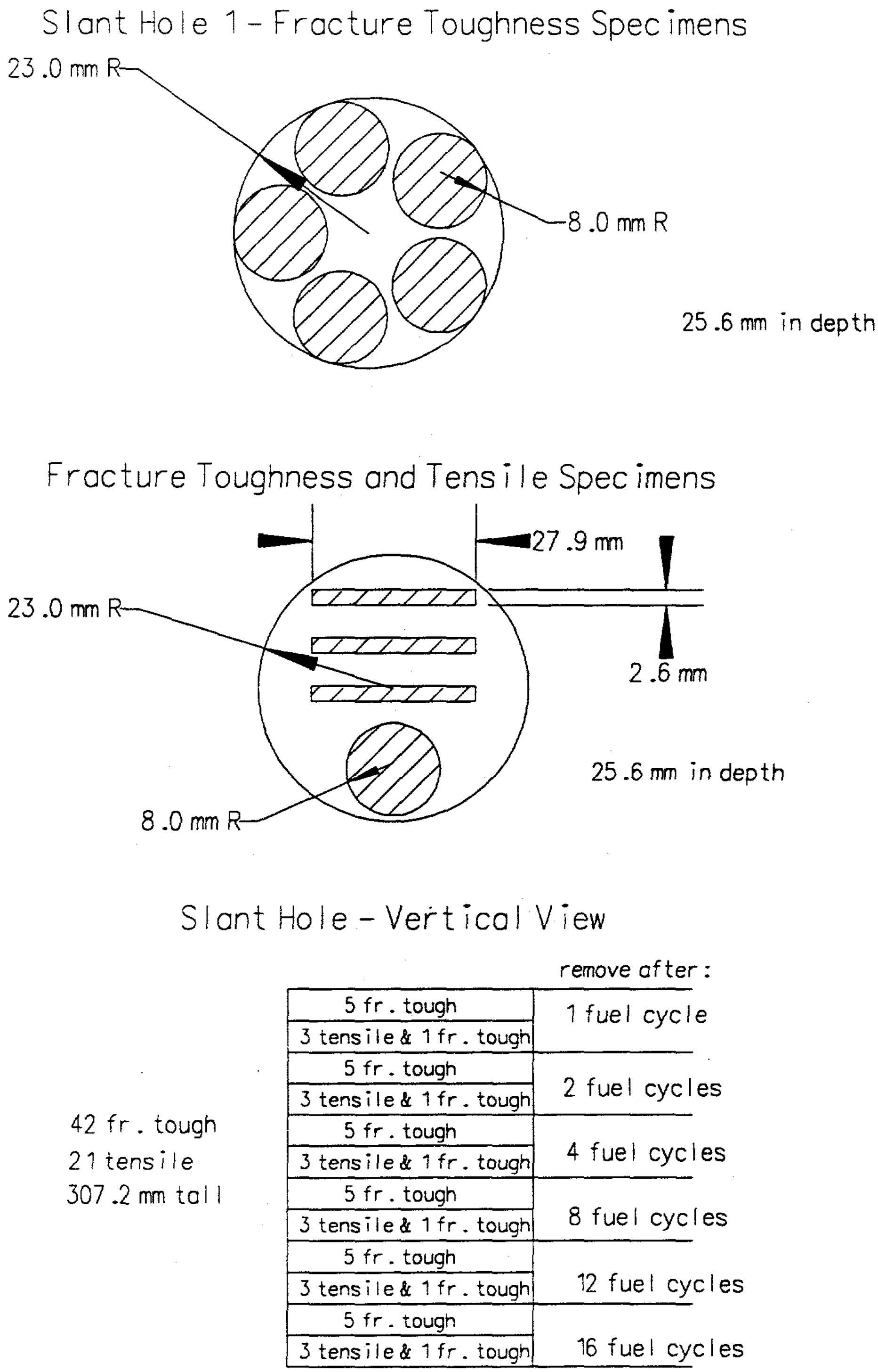


Fig. 12. Core pressure boundary tube base metal surveillance specimens—final version.

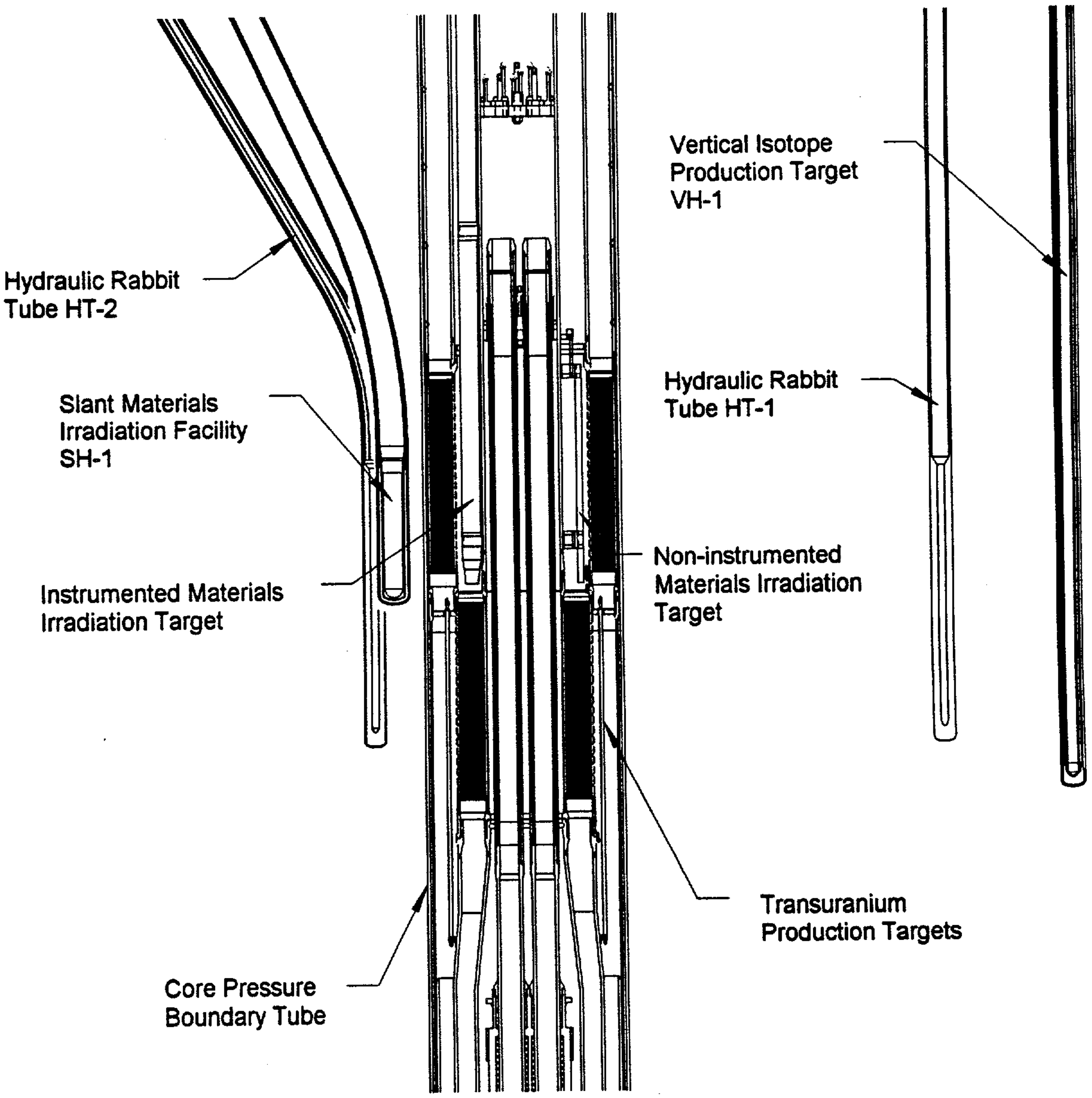


Fig. 13. Irradiation facilities in the Advanced Neutron Source reactor.

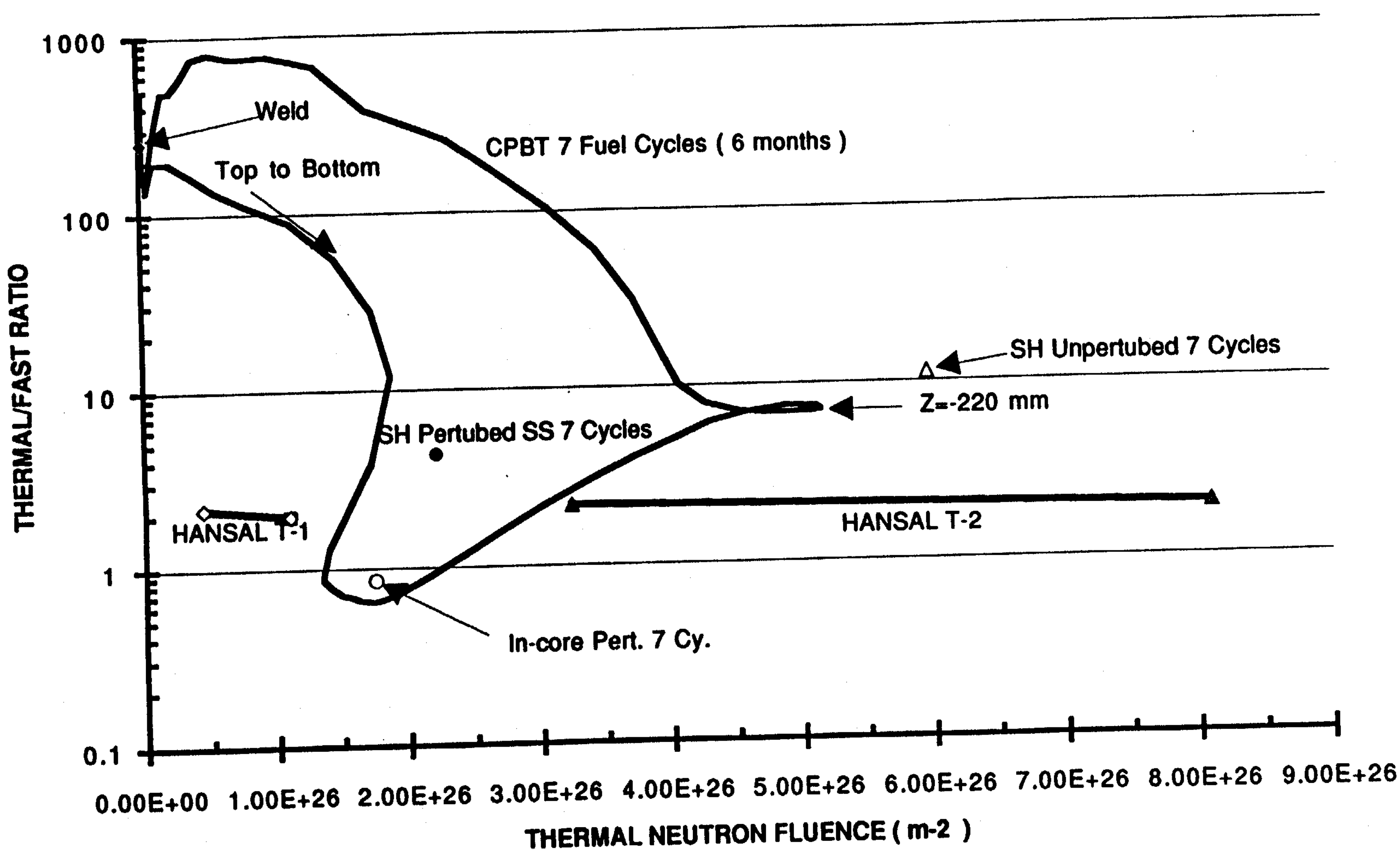


Fig. 14. Thermal/fast ratio vs fluence.

Monte Carlo calculation of the flux profile along the CPBT at beginning of cycle.[9] The figure was drawn assuming that the flux remains constant for the duration of the fuel cycle, which is an approximation. In addition to having a similar thermal-to-fast ratio, the slant holes are cooled by a heavy-water flow of 10 kg/s that uses a supply pressure of 1 MPa. It is believed that this flow will cool the surveillance specimens adequately.

After the sample size and the facility size were determined, the layout of the samples could be investigated. All of the necessary fracture toughness and tensile samples for the CPBT base metal will fit into one of the slant holes, leaving the other slant hole to perform its intended function. In contrast, if the HANSAL-T compact specimen had been chosen, there would not have been enough room in both of the slant hole facilities (Fig. 11) for all of the specimens.

The facilities for the CPBT weld and HAZ metals have not been determined yet. It is uncertain at this point whether there are adequate existing facilities, or if new facilities must be designed; use of an existing isotope production facility is a likely possibility, and one preliminary drawing has been done using a vertical hole as this facility (Fig. 15).

The facility for the reflector vessel surveillance samples will have to be a new facility because it will be used for the life of the reactor. The facility should be placed near the surface of the reflector vessel near the midplane. If possible, the specimen size will be kept the same. Some preliminary drawings have been done, giving different options for this facility (Figs. 16–18). This facility must be accessible so that the surveillance specimens can be removed for testing, and it must be capable of cooling the specimens adequately.

7. SUGGESTED FURTHER STUDY

Although the surveillance specimens and facilities have been determined for the CPBT base metal (Table 2), the facilities that will be used for the CPBT weld and HAZ metals must be finalized, as must the design of the reflector vessel facilities. In addition, there may be other components of the reactor that need to have surveillance programs, such as the core support system. These additional surveillance programs will have to be determined separately, but similarly to the CPBT program.

The baskets for holding the specimens inside the CPBT base metal capsules still must be completed. Three-dimensional drawings of the specimens placed in their initial baskets are included as Figs. 19 and 20.

In addition, tests should be performed on 6061-T6 aluminum samples to compare fracture toughness results using the short rod specimen with results using the compact fracture toughness specimen. These tests are needed to confirm that the short rod specimen will be able to monitor the fracture toughness of the 6061-T6 aluminum as well as the compact specimen can.

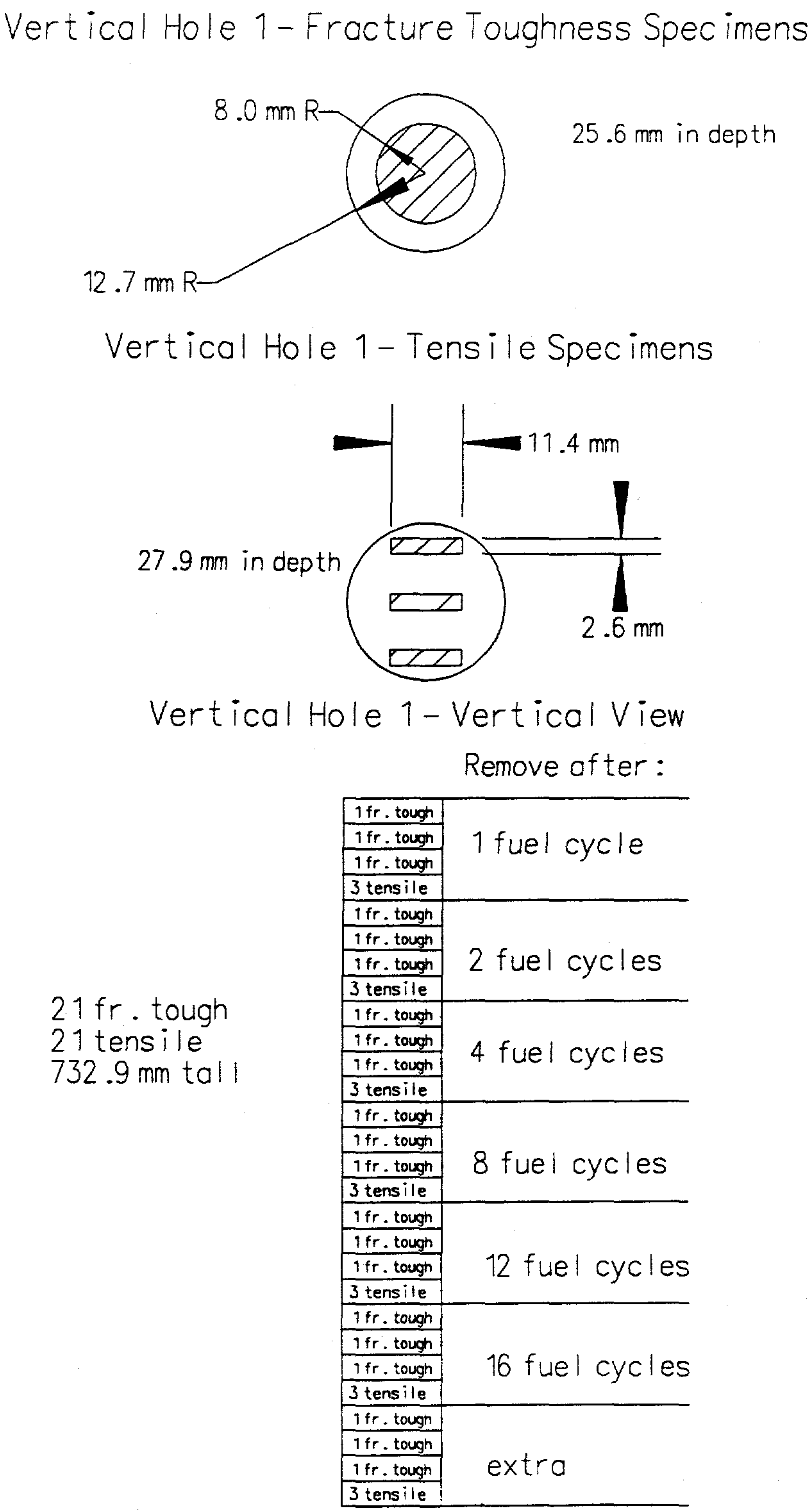
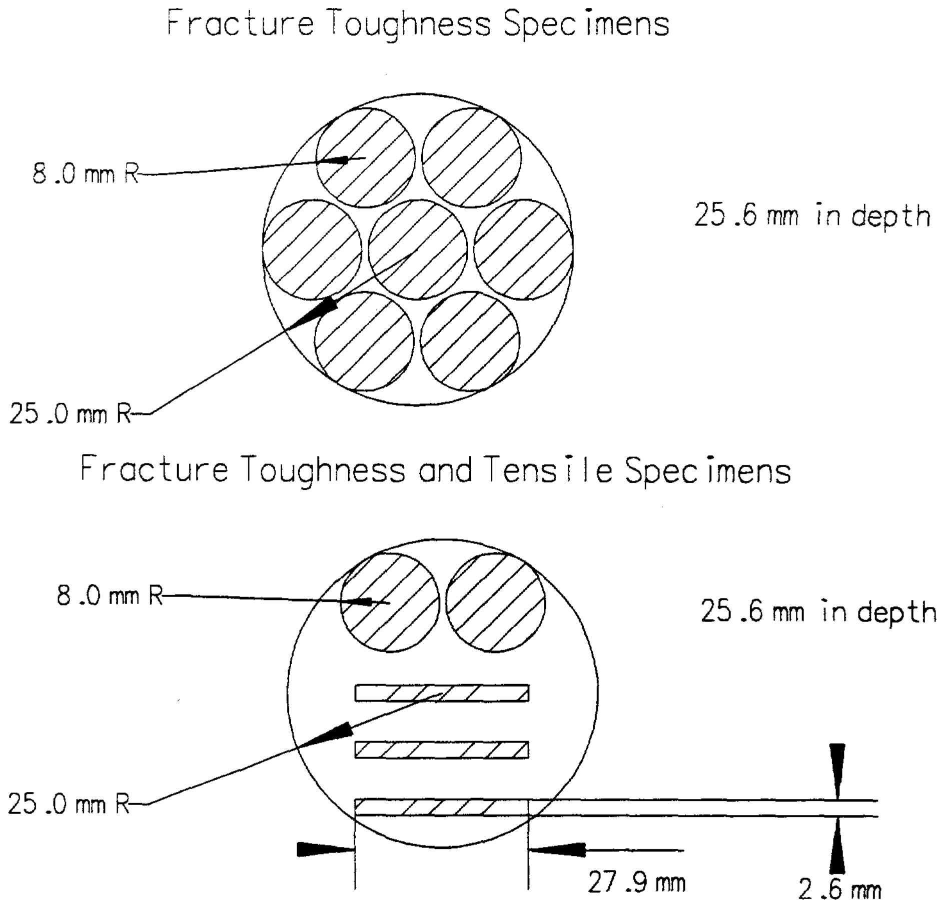


Fig. 15. Core pressure boundary tube weld metal surveillance specimens—preliminary version.



Vertical View

	Remove after:
7 fr. tough 3 tensile & 2 fr. tough	1.5 yrs
7 fr. tough 3 tensile & 2 fr. tough	3 yrs
7 fr. tough 3 tensile & 2 fr. tough	6 yrs
7 fr. tough 3 tensile & 2 fr. tough	15 yrs
7 fr. tough 3 tensile & 2 fr. tough	20 yrs
7 fr. tough 3 tensile & 2 fr. tough	30 yrs
7 fr. tough 3 tensile & 2 fr. tough	40 yrs
7 fr. tough 3 tensile & 2 fr. tough	extra

72 fr. tough
24 tensile
409.6 mm tall
8.0 x 10^5 cubic mm in volume

Fig. 16. Reflector vessel facility for base, weld, and heat-affected-zone metals—preliminary version.

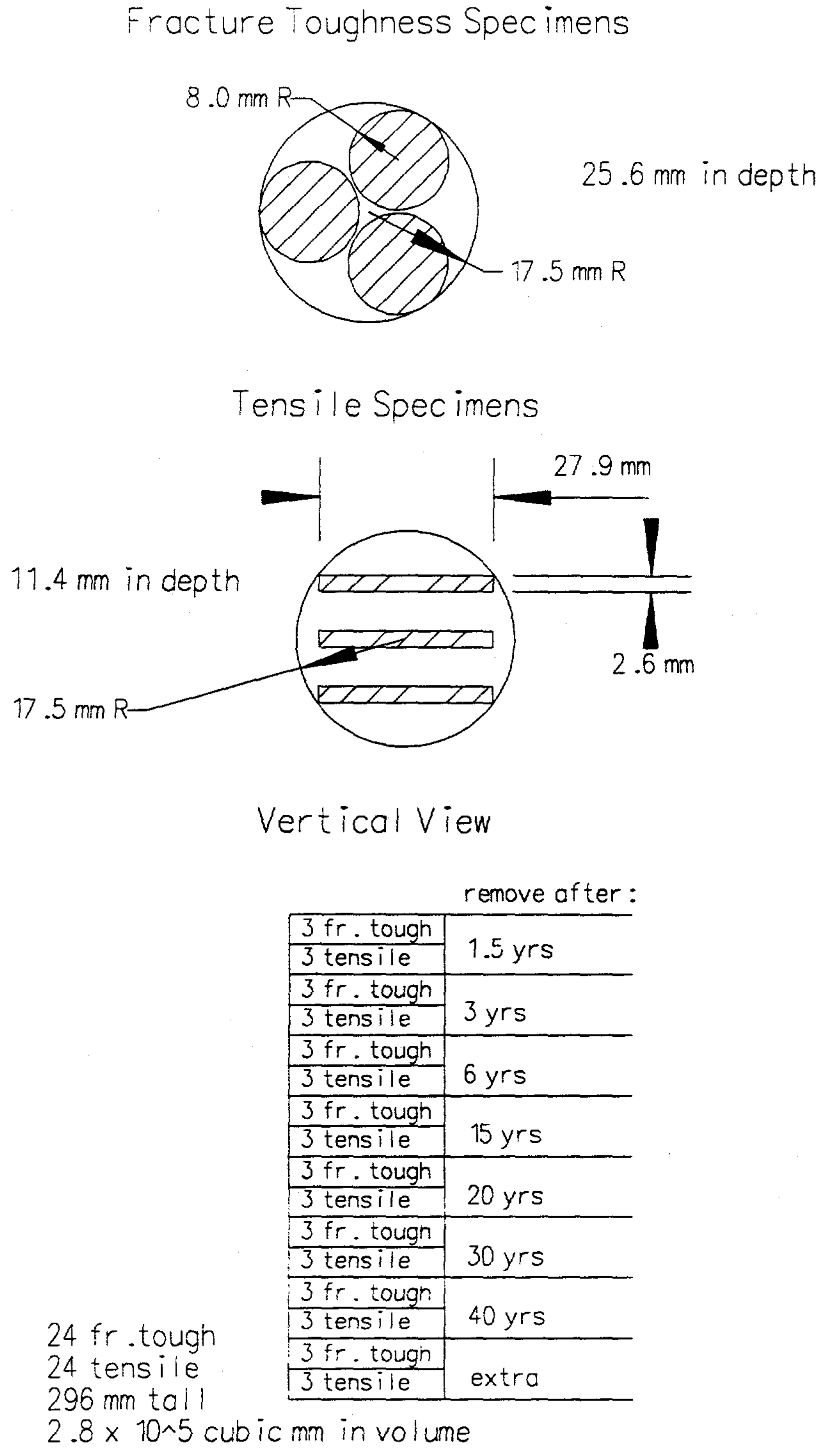
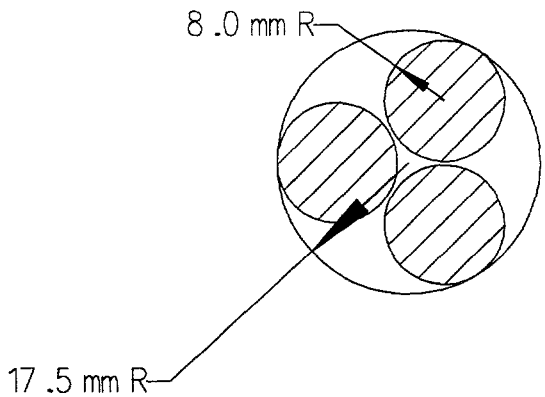


Fig. 17. Reflector vessel facility for base or weld metals—preliminary version.

Fracture Toughness Specimens



25.6 mm in depth

Vertical View

	remove after:
3 fr. tough	1.5 yrs
3 fr. tough	3 yrs
3 fr. tough	6 yrs
3 fr. tough	15 yrs
3 fr. tough	20 yrs
3 fr. tough	30 yrs
3 fr. tough	40 yrs
3 fr. tough	extra

24 fr. tough
204.8 mm tall
2.0 x 10^5 cubic mm in volume

Fig. 18. Reflector vessel facility for heat-affected-zone metals—preliminary version.

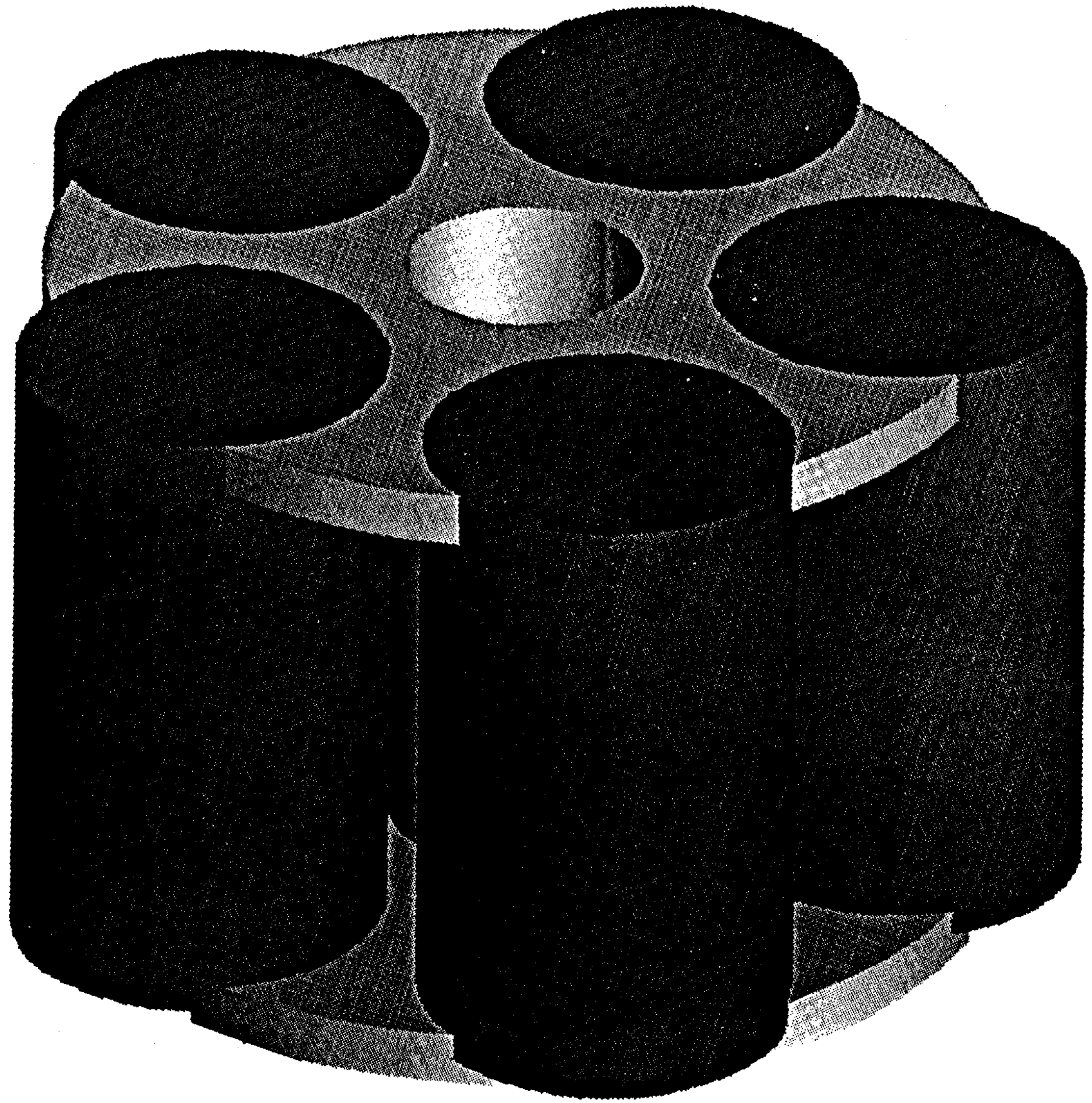


Fig. 19. Core pressure boundary tube metal short rod specimens.

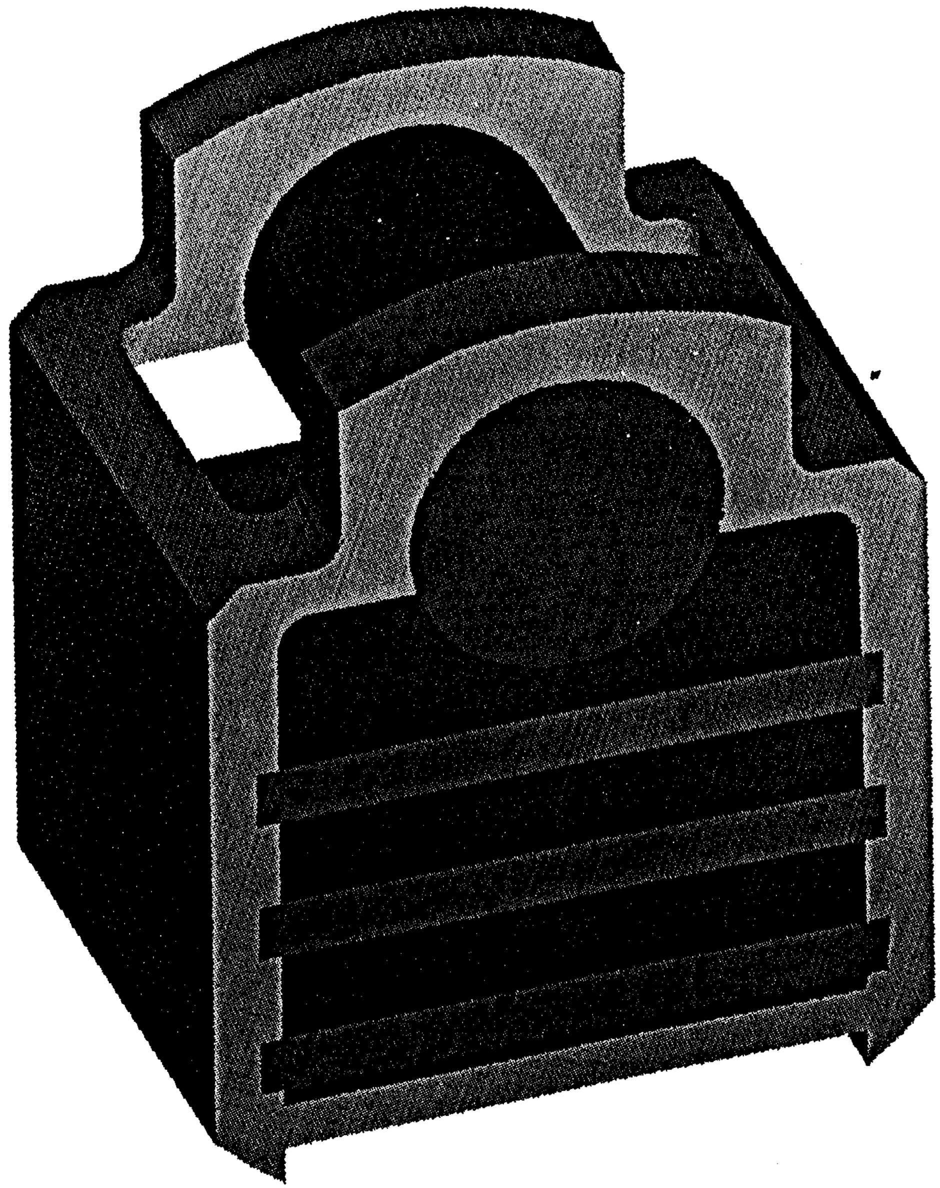


Fig. 20. Core pressure boundary tube metal short rod and tensile specimens.

Table 2. Core pressure boundary tube and reflector vessel surveillance summary

Metal	Capsule size	Coupon size	Number of capsules	Number of coupons per capsule	Testing temp	Capsule location
CPBT base metal	46 mm diam.	16 mm diam. × 24 mm height short rod 27.9 × 11.4 × 2.6 mm tensile	6: 1 mo 2 mo 4 mo 8 mo 12 mo 16 mo	6 fracture toughness 3 tensile		Slant hole 1
CPBT weld metal		16 mm diam. × 24 mm height short rod 27.9 × 11.4 × 2.6 mm tensile	7: 1 mo 2 mo 4 mo 8 mo 12 mo 16 mo extra			
CPBT HAZ metal		16 mm diam. × 24 mm height short rod 27.9 × 11.4 × 2.6 mm tensile	7: 1 mo 2 mo 4 mo 8 mo 12 mo 16 mo extra			
Reflector vessel base metal		16 mm diam. × 24 mm height short rod 27.9 × 11.4 × 2.6 mm tensile	8: 1.5 years 3 years 6 years 15 years 20 years 30 years 40 years extra			
Reflector vessel weld metal		16 mm diam. × 24 mm height short rod 27.9 × 11.4 × 2.6 mm tensile	8: 1.5 years 3 years 6 years 15 years 20 years 30 years 40 years extra			
Reflector vessel HAZ metal		16 mm diam. × 24 mm height short rod 27.9 × 11.4 × 2.6 mm tensile	8: 1.5 years 3 years 6 years 15 years 20 years 30 years 40 years extra			

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ATTACHMENT 1

Code Case N-519: Use of 6061-T6 and 6061-T651 Aluminum for Class 1 Nuclear Components Section III, Division I

Attachment 1

Case N-519

Use of 6061-T6 and 6061-T651 Aluminum for Class 1 Nuclear Components, Section III, Division I

Inquiry:

Under what conditions may 6061-T6 and 6061-T651 aluminum be used in the construction of Section III, Division 1, Class 1 welded pressure vessels at temperatures not exceeding 300°F?

Reply:

It is the opinion of the Committee that 6061-T6 and 6061-T651 aluminum may be used at temperatures not exceeding 300°F for the construction of Section III, Division 1, Class 1 welded vessels provided the following requirements are met:

1. Materials shall conform to the specifications listed in Table 1 for the various product forms. Chemical composition requirements of Table 2 shall be met.

2. Fabrication shall conform to the applicable requirements of Section III.

3. Design stress intensity values and specified minimum strength values given in Table 3 shall be used.

4. Yield strength values given in Table 4 and tensile strength values given in Table 5 shall be used.

5. The charts in Figs. NFA-12 and NFA-13 in Section II, Part D, Subpart 3 shall be used for external pressure design (NB-3133) at temperatures at/or below the maximum temperature for which design stress intensity values are listed in Table 3. Tabular values are given in Tables NFA-12 and NFA-13 in Section II, Part D, Subpart 3.

6. The fatigue design curves shown in Fig. 1 shall be used for fatigue evaluation. Tabular values are given in Table 6. The allowable stress values, S_a, shall be reduced to one-half the values given in Fig. 1 and Table 6 within 1.0 inch of a weld.

7. Post weld heat-treatment is not permitted

8. When the Design Specification stipulates more than ten thousand cycles, the quantity used instead of S_y for evaluating thermal ratcheting in the ratcheting rules of NB-3222.5(b) shall be 14 ksi for base metal and 7 ksi within 1.0 inch of a weld.

9. Simplified elastic-plastic analysis rules of NB-3228.5 are not applicable. The 3 S_m limit on the range of primary plus secondary stress intensity (NB-3222.2) shall not be exceeded.

10. Protection against non-ductile fracture shall be provided. The procedure for evaluating non-ductile fracture shall be the same as Appendix G except that a value of 23 ksi$\sqrt{in}$ shall be used for the critical, or reference, stress intensity factor, K_{IR} (G-2110) for both base metal and welds.

11. This material is known to be susceptible to embrittlement as a result of neutron irradiation. When the component will be subjected to neutron irradiation during service, the Design Specification shall include requirements for consideration of the effects of neutron irradiation on the fracture toughness and requirements for replacement of components before they pose a hazard for brittle fracture. The designer shall establish the irradiated K_{IR} value. That value shall be used to determine when components must be replaced. An in-service surveillance program similar to the one given in ASTM E185-82 for light-water cooled nuclear power reactor vessels shall be established to monitor the embrittlement of the reactor vessel material. If data from surveillance tests indicate that the established K_{IR} value is unconservative, the component replacement schedule must be modified appropriately. The designer shall ensure that loss of ductility in-service does not invalidate the 3 S_m limit on the range of primary plus secondary stress.

12. All other requirements of Section III, Division 1, for Class 1 construction, as applicable, shall be met.

13. This Code Case shall be identified on the Materials Manufacturer's certification for the material and on the applicable Data Report Form furnished by the N—Type Certificate Holder.

14. The designer shall evaluate potential chemical reactions with the environment for both normal and design basis accident conditions and ensure that significant loss of strength or significant hydrogen generation will not occur.

TABLE 1. SPECIFICATIONS

SB-209	Sheet and Plate
SB-210	Drawn Seamless Tube
SB-241/SB-241M	Seamless Pipe and Seamless Extruded Tube
SB-221	Extruded Bar, Rod, and Shape
SB-247	Die and Hand Forgings

TABLE 2. CHEMICAL COMPOSITION LIMITS[1,2,3]

Alloy 6061	Composition, %
Silicon	0.40-0.80
Iron	0.70
Copper	0.15-0.40
Manganese	0.15
Magnesium	0.80-1.20
Chromium	0.04-0.35
Zinc	0.25
Titanium	0.15
Other elements each	0.05
Other elements, total[4]	0.15
Aluminum	remainder

[1]Where single units are shown, these indicate the maximum amounts permitted.

[2]Analysis shall regularly be made only for the elements specified in this table. If, however, the presence of other elements is suspected or indicated in the course of routine analysis, further analysis shall be made to determine that these elements are not in excess of the amount specified.

[3]For purposes of determining conformance to these limits, an observed value or a calculated value obtained from analysis shall be rounded to the nearest unit in the last right-hand place of figures used in expressing the specified limit, in accordance with the rounding method of Recommended Practice E 29.

[4]Other Elements—Total shall be the sum of unspecified metallic elements 0.010% or more, rounded to the second decimal before determining the sum.

Attachment 1 (continued)

TABLE 3. DESIGN STRESS INTENSITY VALUES, S_m, FOR 6061-T6 AND 6061-T651 ALUMINUM

Spec. No.	Temper	Size or thickness (in)	Specified Min. Tensile Strength (ksi)	Specified Min. Yield Strength (ksi)	Notes	Allowable Stress, ksi, for Metal Temp., °F, Not Exceeding 100	150	200	250	300
Sheet and Plate										
SB-209	T6	0.051-0.249	42	35	(1)(2)	14.0	14.0	14.0	13.4	11.3
	T651	0.250-4.000	42	35	(1)(2)	14.0	14.0	14.0	13.4	11.3
	T651	4.001-6.000	40	35	(1)(2)	13.3	13.3	13.3	13.0	11.1
	T6,T651 Wld.	All	24		(1)	8.0	8.0	8.0	7.9	7.3
Rod, Bar, and Shape										
SB-221	T6	All	38	35	(1)(2)	12.7	12.7	12.7	12.3	10.5
	T6 Wld.	All	24		(1)	8.0	8.0	8.0	7.9	7.3
Drawn Seamless Tube										
SB-210	T6	0.025-0.500	42	35	(1)(2)	14.0	14.0	14.0	13.4	11.3
	T6 Wld.	All	24		(1)	8.0	8.0	8.0	7.9	7.3
Seamless Pipe										
SB-241	T6	<1	42	35	(1)(2)	14.0	14.0	14.0	13.4	11.3
	T6	≥1	38	35	(1)(2)	12.7	12.7	12.7	12.3	10.5
	T6 Wld.	All	24		(1)	8.0	8.0	8.0	7.9	7.3
Seamless Extruded Tube										
SB-241	T6	All	38	35	(1)(2)	12.7	12.7	12.7	12.3	10.5
	T6 Wld.	All	24		(1)	8.0	8.0	8.0	7.9	7.3
Die and Hand Forgings										
SB-247	Die T6	Up thru 4.000	38	35	(1)(2)	12.7	12.7	12.7	12.1	10.5
	Hand T6	Up thru 4.000	37	33	(1)(2)	12.3	12.3	12.3	11.7	10.3
	Hand T6	4.000-8.000	35	32	(1)(2)	11.7	11.7	11.7	11.2	9.9
	T6 Wld.	Up thru 8.000	24		(1)	8.0	8.0	8.0	7.9	7.3

Notes:
1. Design stress intensity values for 100°F may be used at temperatures down to -452°F without additional specification requirements.
2. The stress values given for this material are not applicable when either welding or thermal cutting is employed.

TABLE 4. VALUES OF YIELD STRENGTH S_y FOR 6061-T6 AND 6061-T651 ALUMINUM

Spec. No.	Temper	Thickness, in.	Specified Minimum Yield, ksi	Notes	Yield Strength, ksi (Multiply by 1000 to Obtain psi), for Metal Temp., °F, Not Exceeding				
					100	150	200	250	300
Sheet and Plate SB-209	T6	0.051-0.249	35	. . .	35.0	34.6	33.7	32.4	27.4
	T651	0.250-6.000	35		35.0	34.6	33.7	32.4	27.4
Rod, Bar, and Shape SB-221	T6	All	35	(1)	35.0	34.6	33.7	32.4	27.4
Drawn Seamless Tube SB-210	T6	0.025-0.500	35	. . .	35.0	34.6	33.7	32.4	27.4
Seamless Pipe SB-241	T6	All	35	(2)	35.0	34.6	33.7	32.4	27.4
Seamless Extruded Tube SB-241	T6	All	35	(1)	35.0	34.6	33.7	32.4	27.4
Die and Hand Forgings SB-247	Die-T6	≤4.000	35		35.0	34.6	33.7	32.4	27.4
	Hand-T6	≤4.000	33		33.0	32.6	31.8	30.5	25.8
	Hand-T6	4.001-8.000	32		32.0	31.6	30.8	29.6	25.1
Welds		≤0.375			20.0	19.8	19.3	18.5	15.7
		≥0.375			15.0	14.8	14.4	13.9	11.7

Notes:

(1) For stress-relieved temper (T-651), stress values for material in the basic temper shall be used.

(2) All standard pipe sizes.

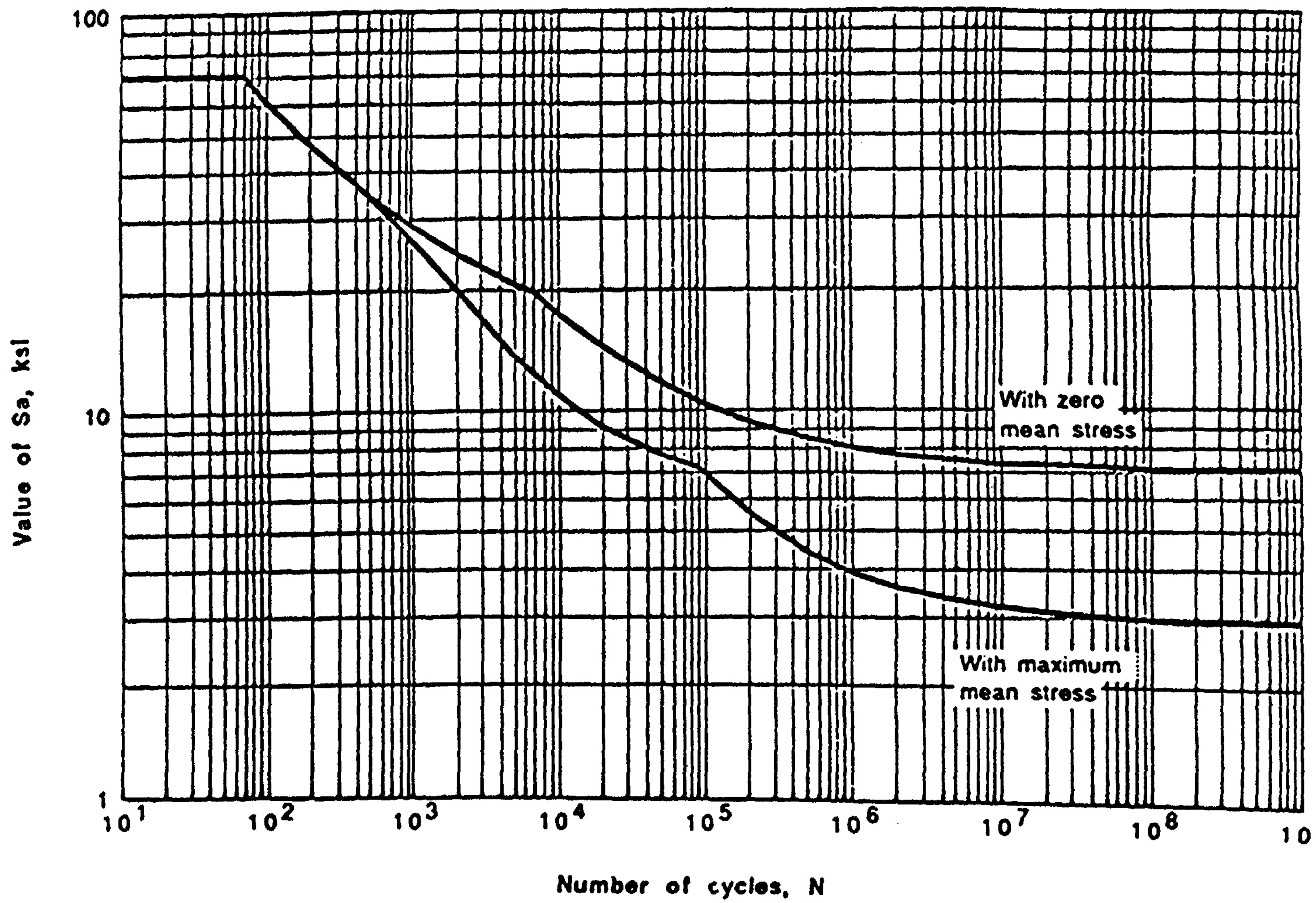
TABLE 5. TENSILE STRENGTH VALUES, S_u, FOR 6061-T6 AND 6061-T651 ALUMINUM

Spec. No.	Temper	Size or thickness (in)	Specified Min. Tensile Strength (ksi)	Tensile Strength, ksi, for Metal Temp., °F, Not Exceeding 100	150	200	250	300
Sheet and Plate								
SB-209	T6	0.051-0.249	42	42.0	42.0	42.0	40.2	33.9
	T651	0.250-4.000	42	42.0	42.0	42.0	40.2	33.9
	T651	4.001-6.000	40	40.0	40.0	40.0	39.0	33.3
	T6,T651 Wld.	All	24	24.0	24.0	24.0	23.7	21.9
Rod, Bar, and Shape								
SB-221	T6	All	38	38.0	38.0	38.0	36.9	31.5
	T6 Wld.	All	24	24.0	24.0	24.0	23.7	21.9
Drawn Seamless Tube								
SB-210	T6	0.025-0.500	42	42.0	42.0	42.0	40.2	33.9
	T6 Wld.	All	24	24.0	24.0	24.0	23.7	21.9
Seamless Pipe								
SB-241	T6	<1	42	42.0	42.0	42.0	40.2	33.9
	T6	≥ 1	38	38.0	38.0	38.0	36.9	31.5
	T6 Wld.	All	24	24.0	24.0	24.0	23.7	21.9
Seamless Extruded Tube								
SB-241	T6	All	38	38.0	38.0	38.0	36.3	31.5
	T6 Wld.	All	24	24.0	24.0	24.0	23.7	21.9
Die and Hand Forgings								
SB-247	Die T6	Up thru 4.000	38	38.0	38.0	38.0	36.3	31.5
	Hand T6	Up thru 4.000	37	37.0	37.0	37.0	35.1	30.9
	Hand T6	4.000-8.000	35	35.0	35.0	35.0	33.6	29.7
	T6 Wld.	Up thru 8.000	24	24.0	24.0	24.0	23.7	21.9

TABLE 6. TABULATED VALUES OF S_a, ksi, FROM FIG. 1

Number of Cycles [Note (2)]	Zero Mean Stress	Maximum Mean Stress
1.0E1	70.00	70.00
2.0E1	70.00	70.00
5.0E1	70.00	70.00
7.0E1	70.00	70.00
1.0E2	60.96	60.96
2.0E2	47.20	47.20
5.0E2	35.00	34.80
1.0E3	28.85	26.79
2.0E3	24.50	20.00
5.0E3	20.64	13.78
7.0E3	19.70	12.40
1.0E4	17.50	10.93
2.0E4	14.43	9.14
5.0E4	11.70	7.74
9.0E4	10.53	7.18
1.0E5	10.32	6.89
2.0E5	9.35	5.47
5.0E5	8.49	4.36
1.0E6	8.05	3.87
2.0E6	7.74	3.55
5.0E6	7.47	3.29
1.0E7	7.33	3.16
2.0E7	7.24	3.07
5.0E7	7.15	3.00
1.0E8	7.11	2.96
2.0E8	7.07	2.93
5.0E8	7.05	2.91
1.0E9	7.03	2.90

Notes:
(1) Interpolation between tabular values is permissible based upon data representation by straight lines on a log-log plot. See Table I-9.1, Note (2).
(2) The number of cycles indicated shall be read as follows: $IEJ = I \times 10^J$, e.g., $5E6 = 5 \times 10^6$ or 5,000,000



Note: $E = 10.0 \times 10^6$ psi

FIG. 1. DESIGN FATIGUE CURVE FOR 6061-T6 ALUMINUM FOR TEMPERATURES NOT EXCEEDING 300°F

Internal Distribution

1. C. W. Alexander
2. D. J. Alexander
3. R. R. Allen
4. E. E. Alston
5. B. R. Appleton
6. R. E. Battle
7. R. S. Booth
8. W. W. Bowman
9. R. A. Brown
10. G. J. Bunick
11-15. J. H. Campbell
16. P. F. Cento
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20. J. T. Cleveland
21. G. L. Copeland
22. J. R. Dixon
23. K. Farrell
24. D. K. Felde
25. R. E. Fenstermaker
26. M. L. Gildner
27. H. A. Glovier
28. D. C. Haberkost
29. R. M. Harrington
30. J. B. Hayter
31. M. P. Hechler
32. W. E. Hill
33. S. E. Holliman
34. M. M. Houser
35. R. O. Hussung
36. D. T. Ingersoll
37-40. R. L. Johnson
41. J. R. Joplin
42. R. M. Leitch
43. R. A. Lillie
44. M. A. Linn
45. A. T. Lucas
46. J. A. March-Leuba
47. G. T. Mays
48. S. V. McGrath
49. T. J. McManamy
50. G. R. McNutt
51. J. T. Mihalczo
52. R. M. Moon
53. D. G. Morris
54. D. L. Moses
55. J. A. Novak
56. L. C. Oakes
57. R. E. Pawel
58. F. J. Peretz
59. G. M. Powers
60. C. C. Queen
61. S. Raman
62. C. T. Ramsey
63. J. S. Rayside
64. J. P. Renier
65. J. B. Roberto
66. L. R. Robinson
67. R. B. Rothrock
68. T. L. Ryan
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85. ORNL Patent Office
86 Document Research Library (2)
87. Y-12 Technical Library
88. Laboratory Records (2)
89. Laboratory Records (RC)

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