WANL-TME- 1956
October, 1969

Westinghouse Astronuclear Laboratory

MATERIAL SELECTION FOR SUPPORT PLATE:

Al 2219 - T852 vs. Al 6061 - T652

MASTER

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

WANL-TME- 1956
October, 1969

MATERIAL SELECTION FOR SUPPORT PLATE:

Al 2219 - T852 vs. Al 6061 - T652

Prepared by:

J. B. McAndrew
Materials Department

Approved by:

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Atomic Energy Commission, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

E. L. Layland, Manager
Materials Engineering and
Specifications

INFORMATION CATEGORY

Unclassified

D. E. Thomas,
Engineering Manager
Systems and Technology

10/15/69
Authorized Classifier Date

A. N. Holden, Manager
NERVA Materials & Fuel Control

DISTRIBUTION

SW

TABLE OF CONTENTS

	<u>Page No.</u>
I. INTRODUCTION	1
II. BASIS FOR COMPARISON OF 2219 and 6061	3
III. PERTINENT PROPERTIES	5
IV. PHYSICAL PROPERTIES	6
V. NUCLEAR CHARACTERISTICS	8
VI. MECHANICAL PROPERTIES	9
VII. RADIATION EFFECTS	22
VIII. SUMMARY	24
IX. CONCLUSIONS AND RECOMMENDATION	25

I. INTRODUCTION

The reasons for selection of an aluminum alloy for the R-1 support plate are rather obvious, and will not be reviewed here. The only reason for selecting a different type of material would have to arise from some unforeseen design evolution that permitted much higher temperature in the support plate region coupled with a large advantage from the increased allowable temperature.

The reasons for selection of 2219 as the particular alloy to be used in the support plate are less obvious, are more complex, and need to be stated in terms that are as simple as the complexity of the factors involved will permit. To achieve this simplicity of presentation, this review will be limited to a comparison of the relative merits of 2219 and 6061. However, it should be understood that the rejection of other candidate alloys is based on equally valid and often similar reasons.

Before proceeding to examination of the available experimental data, the general basis for materials selection should be considered briefly. In the great majority of instances the designer can employ any of a number of materials for a given component. The properties of a material interact with the design features to determine service performance of the component. That is to say, material deficiencies can be compensated by appropriate design modifications, within some limits. Likewise, selection of a particular material can often solve an otherwise troublesome design problem. But more often the design is not so difficult or critical that the selection of a specific alloy is mandatory. Rather, it will commonly be found that each candidate material offers some unique combination of advantages and disadvantages within the envelope of design alternatives. Proper materials selections require analysis of combinatorial matrices comprising materials properties, design variables, and performance criteria. This analysis can be, and generally is, very difficult - particularly when all of the needed facts are not known. When a high degree of optimization is not important, an informal analysis by judgment, intuition, and past experience may be entirely

adequate. In more sophisticated endeavors, extensive experimental reiteration may be the only feasible approach. Often, it is very tempting to scan a matrix and make a selection without adequately verifying that the matrix is complete, the factors listed are correct, and the weighting of performance criteria is based on acceptable value judgments. That error should be avoided.

Another shortcut that frequently compromises optimum selection of materials is the application of general rules to specific cases. Optimum selection cannot be achieved without detailed consideration of each problem. The same applies to design; designing by rule is often expedient, often adequate, but by no means does it always produce optimum results. This follows naturally from the fact that general rules must be highly conservative to safely accommodate worst cases; for other cases, the conservatism may be unnecessary and unreasonable.

II. BASIS FOR COMPARISON OF 2219 and 6061

It is important when evaluating the mechanical properties of heat treatable aluminum alloys to ensure that test data considered were obtained from samples that properly represent the desired application with respect to production and processing variables. In forgings like those from which core support plates are made, the mechanical properties observed will depend on thickness of the forging, ratio of reduction during forging, location of sample within the forging, sample orientation with respect to forging direction, as well as the usual variables of chemistry, heat treatment, and environmental exposure during and prior to test. Some alloys are more sensitive to these variables than are others; even the same alloy may respond differently to such variations in different heat treated tempers. The two alloys under discussion - 2219 and 6061 - differ in that 6061 is generally considered among the least sensitive of the heat treatable alloys with respect to processing variables, while 2219 requires closer attention to such considerations. However, the difference is only relative, and the factors mentioned above should not be ignored for either alloy; this is particularly true when the environmental exposure effects are strongly structure-dependent, as is the case with nuclear radiation or cryogenic temperature. For these reasons, a valid and meaningful comparison with respect to mechanical properties can only be made on the basis of data obtained from material stock of the dimensions and processing history appropriate to the application. If the attempt must be made to extrapolate data obtained on other forms of the alloys, it should be done with caution and on the basis of a thorough appreciation of the fundamental metallurgy involved.

For substantiation of the important effect of thermo-mechanical history on aluminum alloys, an excellent reference is a recent paper by H. Y. Hunsicker, who is Chief, Physical Metallurgy Division, ALCOA Research Laboratories, New Kensington, Pa.* Further references

*Hunsicker, H. Y., New Graphic Method for Analysis of Hot Deformation and Effects on Directional Properties, Trans. Met. Soc. AIME, 245, p. 29, Jan., 1969.

are given in that paper. An interesting treatment of the theory of interaction between metallurgical structure and mechanical properties has been presented by D. McLean* in the 1968 Institute of Metals Lecture. The view which he presents will be helpful to understanding why neutron irradiation effects on mechanical properties of metals are strongly dependent on metallurgical microstructure, which in turn is determined by thermomechanical processing history.

* McLean, D., Resistance to Hot Deformation, Trans. Met. Soc. AIME, 242, p. 1193, July, 1968.

III. PERTINENT PROPERTIES

The properties that must be determined for the support plate material are listed as follows in Scope of Test 61 DM - 257 - 0:

1. Stress vs. Strain
2. Ultimate Tensile Strength
3. Tensile Yield Strength
4. Young's Modulus
5. Poisson's Ratio
6. Tensile Elongation
7. Reduction of Area
8. Fatigue Strength
9. Thermal Expansivity
10. Thermal Conductivity
11. Specific Heat
12. Density
13. Goodman Fatigue Diagrams
14. Creep Strength
15. Rupture Strength
16. Strain Rate Sensitivity

The temperature range over which these properties are to be determined is 140 to 1000°R. With the exception of stress-strain curves, reduction of area, thermal expansivity, specific heat, density, creep, and rupture, the same properties must be obtained both in the unirradiated condition and after exposure to 2×10^{18} thermal neutron fluence plus 2.3×10^{18} fast neutron fluence. The properties dependent on directionality are to be determined in both the axial and transverse directions with respect to forging direction. With the exception of stress-strain curves, a statistical evaluation of the data variability is required.

IV. PHYSICAL PROPERTIES

It is apparent that a great amount of information concerning material properties is pertinent to performance of the support plate. Even for 2219, most of this information remains to be obtained through experimental effort. For 6061 forgings of the size required, much less is available. Fortunately, not all of this information is needed to select between 2219 and 6061. In some instances, the properties are essentially identical in the two alloys, and in others, the properties are not of critical importance. Examples of properties which have been considered to be sufficiently equivalent in the two alloys to be disregarded are Young's modulus, Poisson's ratio, thermal expansivity, fatigue strength, specific heat, and density. With respect to these properties, typical values have been used to obtain the following comparisons, which should be considered approximations:

Young's Modulus;	2219	6%>	6061
Poisson's Ratio;	2219	=	6061
Thermal Expansivity;	2219	3.5%>	6061
Fatigue Strength;	2219	7%>	6061 (endurance limit)
Specific Heat;	2219	=	6061
Density;	2219	5%>	6061

It may be seen that the slight advantages are about evenly divided, with Young's modulus and fatigue strength favoring 2219, and density and thermal expansivity favoring 6061.

Thermal conductivity comparison is much more difficult to make on the basis of available data. In theory, however, 6061 should have higher conductivity, and this is supported by the experimental evidence that has been obtained. In the T - 652 and T - 852 conditions, respectively, it is estimated that the thermal conductivity of 6061 will be 20 to 30% higher than that of 2219 in the expected service temperature range. If verified, this

difference would favor 6061; however, the thermal conductivity of both alloys is quite good, so that the relative advantage in this respect is not great.

Another difference between the two alloys which should be noted, although it is not very important, is that the melting point (solidus) of 2219 is 70°F lower than that of 6061 (1010 vs. 1080°F). The higher melting point is more desirable.

V. NUCLEAR CHARACTERISTICS

Still another secondary factor that constitutes a difference in the two alloys is the manner in which they absorb neutrons, become radioactive, and subsequently decay. A readily available source of information on this subject is Van Horn*. The magnesium and silicon in 6061 activate less easily on an equal-weight basis and have shorter decay half-lives than does the copper in 2219, and the alloy content in 2219 is also higher. Difference in trace elements could also be a factor, but the advantage should be expected to remain with 6061 in this respect. Absorption and activation are not of much importance within the range of these two alloys for the core support plate, which lies adjacent to the core and below the internal shield. They would be somewhat more important in the shield or reflector regions.

* Van Horn, Kent R., ed., Aluminum Vol.I, p. 164, Am. Soc. for Met., Metals Park, Ohio, 1967.

VI. MECHANICAL PROPERTIES

The sensitivity of flow stress to strain rate should be similar for the two alloys provided that creep and rupture characteristics are set aside for separate consideration. D' Antonio et al* cite experiments by Holt et al (1967) showing that at room temperature, strain rate sensitivity in aluminum alloys was significant in the "O" (annealed) condition only. Creep effects should be considered at temperatures approaching $T_m=0.5$, or 700-750°R, where the rate-controlling mechanism of deformation changes from cross-slip or breakdown of Cottrell-Lomer barriers to climb of dislocations or nonconservative motion of jogs.**

Having considered a number of properties which do not provide a basis for discrimination between the two alloys for the present application, it remains to consider in somewhat more detail those mechanical properties in which greater differences would be expected. A few words considering the general nature of the two alloys may be helpful as a preface. Nominal composition of 6061 in wt. % is 1 Mg, 0.6 Si, 0.25 Cu, 0.20 Cr, bal. Al. This is a balanced alloy with respect to magnesium and silicon, i.e., there is just enough of each to form the compound Mg_2Si , which constitutes 1.5% of the alloy. The copper and chromium contribute to the strength, and the chromium also acts to control grain size. The principle strengthener, however is Mg_2Si . At solution treating temperature, the magnesium and silicon are nearly all in solution and are retained (metastable) on quenching. On aging to the T6 condition, the Mg_2Si compound precipitates as well dispersed, very fine needles (60 by 200 - 1000 Å) which are evidently non-coherent with the matrix and are oriented in the $\langle 001 \rangle$ direction of the matrix. Overaging causes coarsening of these needles by 3-dimensional growth, with a consequent reduction in strengthening effectiveness. The matrix is always rather low in solute, and becomes further depleted as aging and overaging progress.

* D' Antonio, C. R., Maciag, R. J., Mukherjee, K., and Fisher, G. J., "The Effect of Strain Rate and Temperature on the Flow Stress of 7075 Aluminum", Trans. Met. Soc. AIME, 242, p. 2295, Nov., 1968.

** Conrad, H., "Thermally Activated Deformation of Metals" Jnl. of Metals, July, 1964, p. 852.

The phase relationships on which the properties of 2219 depend are quite different. Nominal composition of this alloy is 6 Cu, 0.3 Mn, 0.2 Zr, 0.1 V, bal. Al. The manganese contributes a small increment of strength and modifies the precipitation kinetics; zirconium and vanadium help control grain growth and hot shortness. Copper imparts strength in two ways. First, with suitable heat treatment, it forms coherent precipitate, with the composition Cu Al_2 ; second, it remains in large amount as a solute in the matrix. Not only is the precipitate coherent with the matrix, in contrast to that in 6061, but it has a platelike morphology rather than acicular, and it forms by a more complicated 3-step series of transitions. The metallurgy of 6061 and that of 2219 are thus basically different, and the properties are correspondingly affected.

The more complex precipitation processes in 2219, and the presence of coherency lattice strains which interact with dislocations and point defects, mean that the mechanical properties can be extended beyond those of 6061, but it also follows that more careful control must be maintained during processing, because 2219 properties are more sensitive to processing variables. An illustration of this is the effect of cold working the two alloys after solution treatment and prior to aging. In 6061, the effect of the intermediate cold work is so slight that it is generally disregarded except for stress relief purposes; in 2219, such cold work can increase the ultimate tensile strength 15% and the yield strength 35%, while elongation values remain the same (typical values at room temperature). The interaction of cryogenic temperature is shown by data of Schwartzberg, Kiefer, and Keys* as reported by DMIC. The samples without intermediate cold work (T62) had 3% lower ultimate strength, 20% lower yield strength, but twice the elongation (28% vs. 14%) of the alloy with cold work (T87) when tested at -423°F .

*Schwartzberg, F. R., Kiefer, T. F., and Keys, R. D., "Determination of Low-Temperature Properties of Structural Metal Alloys", Martin CR-64-74, The Martin Co., Denver, Colo., Contract NAS8-2631 (Oct. 1961), DMIC No. 58024.

It might be anticipated that the toughness of the lower ductility (T87) samples would also be lower; however this was not the case. Notched tensile strength of the T87 samples was 6% higher than that of the T62 samples, as was the unnotched fatigue strength (10^6 cycles), and the notched fatigue strengths were the same. More sophisticated measurements of cryogenic toughness of 2219 - T87 have verified that the material does indeed have good toughness despite a relatively low elongation and high yield strength. See for example the work of Carman, Forney, and Kaltin*, who found K_{Ic} values in 1-inch plate at -423°F to be from 35 to 55 ksi $\sqrt{\text{in.}}$ depending on orientation; the yield strength was 70 ksi and the elongation about 16 to 22%. Thus it may be seen that rule-of-thumb generalities, if used at all, must be applied with caution.

A good starting point for comparing the tensile properties of 6061 and 2219 is the design allowables (0.99 probability at 0.95 confidence level) for the two alloys as shown in MIL-HDBK-5A**. For 6061-T652 forgings of 4 - 8" thickness and cross-sectional area $\leq 256 \text{ in.}^2$, the room temperature values in the longitudinal (L), long transverse (LT), and short transverse (ST) directions are as follows:

Property	Direction		
	L	LT	ST
UTS, ksi	37	37	35
TYS, ksi	34	34	32
Elongation, %	8	6	4

* Carman, C.M., Forney, J.W., and Katlin, J.M., "Plane Strain Fracture Toughness of 2219 T-87 Aluminum Alloy at Room and Cryogenic Temperatures", NASA CR-54297, Frankford Arsenal, Phila., Pa., (August, 1966) DMIC No. 66167.

** "Metallic Materials and Elements for Aerospace Vehicle Structures", Department of Defense, Washington., D.C., 1966.

Comparable data on 2219 forgings are not given in MIL-HDBK-5A. Allowables for T851 plate in 5 - to 6 - in. thickness are given as follows:

Property	Direction		
	L	LT	ST
UTS, ksi	--	57	--
TYS, ksi	--	42	--
Elongation, %	--	4	--

WANL data on 2219 - T852 support plate forgings 9" thick by 44" diameter show the following properties at peripheral sampling locations (note that these are average values, not design allowables; radial and tangential values did not differ significantly):

Radial and Tangential UTS, ksi	63	} 41 spec.
Radial and Tangential TYS, ksi	50	
Radial and Tangential elongation, %	7.7	

WANL TME 1901 reported the following values (average of 3 specimens) for axial properties near the center of a 7" thick x 24" diam. forging of T2219 - T852:

Axial UTS, ksi	61
Axial TYS, ksi	48
Elongation, %	8.8

For purpose of comparison, the effect of elevated temperature on strength of the two alloys must be made on the basis of assumptions that percentage reductions from room temperature strength will be the same for 2219 - T852 as for 2219 - T81, and the same for forgings as for plate, in T852 and T851 tempers respectively. The strengths at temperature after various (unstressed) exposure times are shown below as percentages of original room temperature strengths. (MIL-HDBK-5A).

6061 - T6

Temp., °F	250	350	450	550
UTS, % 1/2 - hr. exp.	86	71	54	31
10 - hr. exp.	86	70	49	27
100 - hr. exp.	86	69	42	19
TYS, % 1/2 - hr. exp.	88	79	58	31
10 - hr. exp.	88	74	53	28
100 - hr. exp.	88	74	45	17

2219 - T81

Temp., °F	250	350	450	550
UTS, % 1/2 - hr. exp.	88	75	54	37
10 - hr. exp.	88	74	52	37
100 - hr. exp.	88	70	50	37
TYS, % 1/2 - hr. exp.	90	79	58	42
10 - hr. exp.	90	77	53	40
100 - hr. exp.	90	73	53	39

Applying these percentages to the MIL-HDBK-5A room temperature allowables for the long transverse direction in 5" - 6" thick 2219 - T851 and 4" - 8" thick forgings of 6061 - T6 gives the following strengths:

6061 - T6 (LT)

Temp., °F	250	350	450	550
UTS, ksi 1/2 hr- exp.	32	26	20	11.5
10 hr- exp.	32	26	18	10
100 hr- exp.	32	25.5	15.5	7
TYS, ksi 1/2 hr- exp.	30	27	20	10.5
10 hr- exp.	30	25	18	9.5
100 hr- exp.	30	25	15	6

2219 - T851 (LT)

Temp., °F	250	350	450	550
UTS, ksi 1/2 hr- exp.	50	43	31	21
10 hr- exp.	50	42	30	21
100 hr- exp.	50	40	28.5	21
TYS, ksi 1/2 hr- exp.	38	33	24	18
10 hr- exp.	38	32	22	17
100 hr- exp.	38	31	22	16

It is apparent that the strength advantage of 2219 at room temperature not only persists at elevated temperatures, but increases as a direct function of temperature and time of exposure prior to test. When tested at 550°F (1010°R) after holding at temperature for 100 hours, the 2219 has three times the ultimate strength and two and a half times the yield strength of 6061. The 550°F ultimate strength of the 2219 is higher than the 450°F ultimate strength of 6061 for all three times, but is about 20% lower than the 350° ultimate strength of 6061. The 550°F yield strength of the 2219 is slightly less than the 450° yield strength of 6061 after 1/2 hr., but is slightly more than the 450° yield strength of 6061 after 100 hr.

Another measure of the high temperature capability of an alloy is the degradation of strength at room temperature after exposure to elevated temperature. MIL-HDBK-5A gives the following percentages of room temperature strength retained after the exposures shown:

6061 - T6 (All products)

Exposure Temp., °F	400	500	600
R. T. UTS, % 1/2-hr exp.	96	76	61
10-hr exp.	88	64	52
100-hr exp.	81	54	44
R. T. TYS, % 1/2-hr exp.	95	72	43
10-hr exp.	88	50	30
100-hr exp.	80	37	22

MIL-HDBK-5A does not have the same information for 2219, but it may be found in the Aerospace Structural Metals Handbook* for T81 - T851 sheet and plate, as follows:

2219 - T81, -T851

Exposure Temp., °F	400	500	600
R. T. UTS, % 1/2-hr exp.	100	94	83
10-hr exp.	---	--	--
100-hr exp.	91	82	71
R. T. TYS, % 1/2-hr exp.	96	81	64
10-hr exp.	---	--	--
100-hr exp.	80	68	53

* Aerospace Structural Metals Handbook, Mechanical Properties Data Center, Belfour Stulen, Inc., Traverse City, Mich., 1969. (AFML-TR-68-115)

When these percentages are applied, as above, to the design allowables in MIL-HDBK-5A, the results are these:

6061 - T6 (LT)

Exposure Temp., °F			400	500	600
R. T. UTS, ksi	1/2-hr. exp.		35.5	28	22.5
	10-hr. exp.		32.5	24	19
	100-hr. exp.		30	20	16
R. T. TYS, ksi	1/2-hr. exp.		32	24.5	14.5
	10-hr. exp.		30	17	10
	100-hr. exp.		27	12.5	7.5

2219 - T851 (LT)

Exposure Temp., °F			400	500	600
R. T. UTS, ksi	1/2-hr. exp.		57	53.5	47
	10-hr. exp.		--	--	--
	100-hr. exp.		52	46.5	40.5
R. T. TYS, ksi	1/2-hr. exp.		40	34	27
	10-hr. exp.		--	--	--
	100-hr. exp.		33.5	28.5	22

Again, the strength advantage of 2219 after high temperature exposure is large, ranging from about 60% to 190% increments.

Still other measures of high temperature performance are creep strength and stress rupture life. The best data available for this comparison are those shown in the Aerospace

Structural Metals Handbook as revised in 1966 and 1967 for 6061 and 2219, respectively. The following table will facilitate comparison. (The figures were interpolated from a curve on logarithmic coordinates, and are approximate).

Temp., °F	Time, hr.	0.2% Creep Stress, ksi		Rupture Stress, ksi	
		6061-T6	2219-T852	6061-T6	2219-T852
300	1	33	38	35	45
	10	30	34	34	42
	100	25	30	32	39
400	1	23	22	28	32
	10	16	20	25	27
	100	13	17	20	24
500	1	12	18	15	24
	10	--	15	12	21
	100	--	11	8.5	18
600	1	--	12	--	17
	10	--	8	--	14
	100	--	5	--	10

It is apparent that at the higher temperatures and longer times, the 2219 has about 100°F advantage in either creep or rupture, or at the same temperature has about 100 times the rupture life and requires about 100 times as long for 0.2% creep deformation.

In summary, 2219 has much better strength at elevated temperatures than does 6061, and it better withstands degradation of its low temperature properties by exposure

to elevated temperatures. Although the data shown are for tensile strength, it can safely be assumed that similar behavior would be found for compressive strength or other strength parameters.

The next subject to be considered is that of cryogenic properties. The MIL-HDBK-5A strength curves for 2219 extend to cryogenic temperatures, but those for 6061 do not, and in fact, published data on cryogenic properties of 6061 are rather sparse. The best available for present purposes appear to be those of Kaufman*, as presented in the Cryogenic Materials Data Handbook.

The material tested was 6061 - T651 in 1.250-in. plate; longitudinal and transverse properties were obtained. For comparison on an equivalent basis, data are available from the same reference for 2219 - T851 in 1.00-in. plate. The following table shows tensile ultimate, yield, and elongation at several temperatures for the two materials.

Property	Test Temperature, °F							
	-100		-200		-300		-400	
(Longitudinal)	6061	2219	6061	2219	6061	2219	6061	2219
UTS, ksi	49	71	52	75	57	81	65	93
TYS, ksi	44	57	46	59	48	62	52	67
Elong. %	19	11	20	12	23	13	25	15
(Transverse)								
UTS, ksi	49	70	52	74	57	81	65	93
TYS, ksi	42	55	43	57	46	60	50	66
Elong. %	17	10	18	11	20	12	22	15

Examination of these data show that 2219 has 40% higher ultimate strength and 30%

* Kaufman, J. G., et. al., "Tensile Properties and Notch Toughness of Aluminum Alloys at -452°F in Liquid Helium", Advances in Cryogenic Engineering, Plenum Press, N. Y., Vol. 13, 1967.

higher yield strength, while 6061 has from 46 to 73% higher elongation. To see whether the higher ductility of 6061 is of any value so that it should be balanced against the higher strength of 2219, it is necessary to see whether toughness of the less ductile material is adequate, since ductility is of no direct use in design, but is important insofar as it may limit toughness.

One method of comparing the toughness of two materials is to measure the tensile strength of specimens with sharp notches. In tough materials, such notches increase the net fracture strength (although the gross fracture strength, based on the unnotched cross-sectional area, decreases). Such tests were also reported in the reference cited above, with the same materials. They showed that for both 2219 and 6061 in both directions and at all test temperatures, there was an increase in net fracture strength with notches of high acuity ($K_t=16$). The notch tensile strengths were as follows:

Property	Test Temperature, °F							
	-100		-200		-300		-400	
	6061	2219	6061	2219	6061	2219	6061	2219
Long. NTS, ksi	74	83	78	87	83	93	88	101
Trans. NTS, ksi	72	81	75	85	79	89	85	95

The data show that in the sharply notched condition, the advantage of 2219 is reduced, but still remains in the amount of 11 to 14%.

The cryogenic plane strain fracture toughness of a 2219-T852 forging 2.5 in. thick by 26.8 in. diameter is also reported in the Cryogenic Materials Data Handbook, although it appears that data may have been taken only at room temperature and -320°F. The values of K_{Ic} (ksi $\sqrt{\text{in.}}$) in the short transverse direction were 23 at R. T. and -320°F; in the radial direction they were 41 at R. T. and 49 at -320°F; and in the tangential direction they were 43 at R. T. and 52 at -320°F. Comparable data for 6061 were not found.

McClaren and Foreman* performed cryogenic tests of 2219 - T81, cold rolled type 310 stainless steel, and Ti-5Al-2.5 Sn ELI in 0.125 - in. sheet form. On the basis of fracture ratio (K_c/UTS), they rated 2219 superior to the 310 stainless at temperatures down to -320°F , but not at -423°F . The Ti-5Al-2.5 Sn was rated higher than either down to -320°F .

It should be noted, in connection with the fracture toughness tests, that a minimum specimen thickness of $1\frac{3}{8}$ " is required in 2219 - T851 to obtain plane strain fractures at room temperature**. Since the toughness is as high or higher at low temperatures, the section thickness required to allow plane strain conditions to prevail cryogenically should be comparable. In thinner sections, failure should be by some mixed mode in which the fracture strength is higher. The plane stress fracture toughness, K_c ($\text{ksi}\sqrt{\text{in.}}$), for 0.060 - in. 2219 - T87 (trans.) is shown in the Cryogenic Materials Data Handbook as 81 at room temperature, and 111 at -320°F . Tear tests of 2219 - T81 and -T87 sheet reported by Kaufman, Nelson, and Johnson*** indicate that the plane stress toughness of 2219 - T81 should be similar to that of 2219 - T87. It must be remembered that the toughness values for 2219 - T852 will not be the same as those for 2219 - T81; however, the trends should be similar.

* McLaren, S.W., and Foreman, C.R., "Cryogenic Design Data and Criteria of Aerospace Materials Subjected to Uniaxial and Biaxial Stress States", LTV Aerospace Corp., Dallas, Tex., presented at the Cryogenic Engineering Conference, Rice University, Houston, Texas. (Aug. 23-25, 1965). Reported by DMIC.

** MIL-HDBK-5A, *ibid*.

*** Kaufman, J.G., Nelson, F.G., and Johnson, E.W., "The Properties of Aluminum Alloy 2219 Sheet, Plate, and Welded Joints at Low Temperatures", presented at the Cryogenic Engineering Conference, Los Angeles, Calif., Aug. 1962. (Available from ALCO A).

Notch toughness of axial specimens from the center of a 7 in. thick by 24 in. diameter 2219 - T852 forging at temperatures from -320°F to room temperature may be estimated from data reported in WANL-TME-1901 - Rev. A (June, 1969). Throughout the temperature range, the ratio of notched to unnotched tensile strength varied between 1.15 and 1.19. The notched tensile strength varied from 72 ksi at room temperature to 88 ksi at -320°F . The stress concentration factor, K_t , was 4.8 in these specimens, and the diameter at the notch root was 0.200 in. The data indicate good cryogenic toughness.

One other parameter that is sometimes used to judge toughness of a material is impact strength. Kaufman et. al.* found that the notched Izod impact strength of 1.00 in. thick 2219 - T81 plate was somewhat higher at -320°F than at room temperature, the values being about 7 and 6 ft.-lb. respectively in the longitudinal direction, and 5 and 5.5 ft.-lb. in the transverse.

In the light of the above information on cryogenic toughness of 2219, it is evident that the alloy has adequate low temperature ductility and that the higher ductility of 6061 does not constitute an advantage that should be weighed against the higher strength of 2219.

* Kaufman, J.G., Nelson, F.G., and Johnson, E.W., *ibid.*

VII RADIATION EFFECTS

The subject of radiation effects remains to be considered. Aluminum alloys in general are considered so highly resistant to radiation damage at the NERVA levels of fluence that this criterion could be ignored. The subject merits attention, however, because the radiation exposure is cryogenic as well. At cryogenic conditions, radiation effects can accumulate which would be continually removed by annealing if the irradiation were done at room temperature. Data for 6061 under the appropriate conditions are almost nil. The most nearly applicable data are for 8 specimens reported in REON Report 2275. These were from 1/4-in. 6061 -T6 sheet, and received a fluence of 4×10^{17} integrated flux (neutrons/cm²). Four specimens were exposed and tested at -423°F, and four were exposed and tested at -320°F, presumably without intermediate warmup. The -423°F specimens lost 31% in cryogenic ductility, and the -320°F specimens lost 21%. However, this fluence is rather low, and the material is not representative of a large forging, particularly in that short transverse properties are not represented. Radiation effects at low temperatures are sensitive to microstructure, and the microstructure of large aluminum forgings is quite different from that of sheet.

Also reported in REON Report 2275 was a test of 3 specimens of 2219 -T6 sheet exposed to a fluence of 7.5×10^{17} nvt at -320°F and tested at -320°F. The elongation at fracture decreased 7% as a result of the irradiation. However, specimens of a 2219 -T6 forging (axial direction) similarly exposed and tested decreased 70% in elongation at fracture. Elongations of the sheet and forging control (unirradiated) specimens were nearly identical, yet the response to irradiation was quite different. This example is cited to show the hazard of trying to estimate the irradiated properties of 6061 forgings from available data on sheet or plate material. (Elongation is cited as the parameter of interest, because the effect of cryogenic irradiation on the yield strength of aluminum alloys in general is to increase it, while the ultimate strength remains little affected). Thus it is doubly difficult to predict the properties of 6061 -T652 forgings of support plate dimensions after cryogenic irradiation: the

mechanical properties of such forgings at cryogenic conditions are not available, and it is not known quantitatively how they would be affected by irradiation.

For 2219 - T852, however, data are reported in WANL-TME-1901 Rev. A (June, 1969). The data show that after 8×10^{17} N/cm² ($E > 1$ Mev.) fluence at -320°F, the properties in the axial direction near the center of a 7" x 24" diameter forging were (no warmup): UTS, 80.5 ksi; TYS, 72.0 ksi; elongation, 7.2% ; NTS, 92.4 ksi; and notched-to-unnotched tensile ratio, 1.14. It may be seen that the strength values are very high and the ductility is high enough to maintain high notch toughness. Furthermore, if design evolution calls for longer reactor operating times that would increase the integrated fluence, the 2219 - T852 properties will remain adequate, because propellant supplies will limit run times, and intermediate warmup will restore the alloy to approximately pre-irradiation condition by annealing the radiation effects, as is also shown by experiments reported in WANL-TME-1901.

VIII SUMMARY

The significant differences between 6061 - T652 and 2219 - T852 for the support plate application are in mechanical properties. Precise quantitative comparisons are limited by lack of data on 6061 - T652 forgings of the required size, particularly at cryogenic temperatures and after irradiation. Therefore it has been necessary in part to compare data for the two materials in comparable thicknesses in plate form, in which the temper designation for 2219 is T851 or T81.

The comparisons show that at elevated temperature the 2219 is much stronger and less subject to degradation of strength. The margin is from 25% to 200% increase over 6061 strength, depending on the particular temperature and time. Stated another way: the strength advantage of 2219 offers the possibility of increasing the temperature of the component from 100 - 200°F depending on the exposure time and on which strength parameter is limiting in the design.

At cryogenic temperatures, the strength advantage of 2219 is 30% to 40%. The lower strength of 6061 is accompanied by higher ductility; however the ductility and toughness of 2219 are adequate, so that no benefit is gained from the excess ductility in 6061.

The radiation resistance of 6061 forgings cannot be properly assessed because the data required are not available. However, the radiation resistance of 2219 forgings has been shown to be adequate, so that even if 6061 should prove better in this respect, the greater resistance to damage would not be useful.

IX. CONCLUSIONS AND RECOMMENDATIONS

All of the significant advantages in material properties that can be identified for the support plate application are found in 2219 - T852 rather than 6061 - T652. The advantages are in higher strength, particularly at elevated temperature, but also throughout the possible range of temperatures to which it will be or may be exposed. This higher strength and better temperature tolerance can be utilized to provide more efficient or more reliable designs, or both. Greater flexibility for future design evolution is also a substantial benefit. The past record of performance of 2219 - T852 in reactor core support plates, and the greater amount of materials testing which has been done to qualify the material should also be considered advantages, though secondary ones.

It is recommended that the R-1 core support plate material be Al 2219 - T852.