Aging Optimization of Aluminum-Lithium Alloy C458 for Application to Cryotank Structures

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Outline

- Aluminum-Lithium Alloys
- Cryogenic Fracture Toughness (CFT) of Al-Li Alloys
  - Mechanisms of toughness improvements
- Design of Experiments (DOE) for Aging Optimization of C458
  - Effects of Two-Step Aging on Strength/Toughness
  - Aging Cycle Recommendations
- Summary

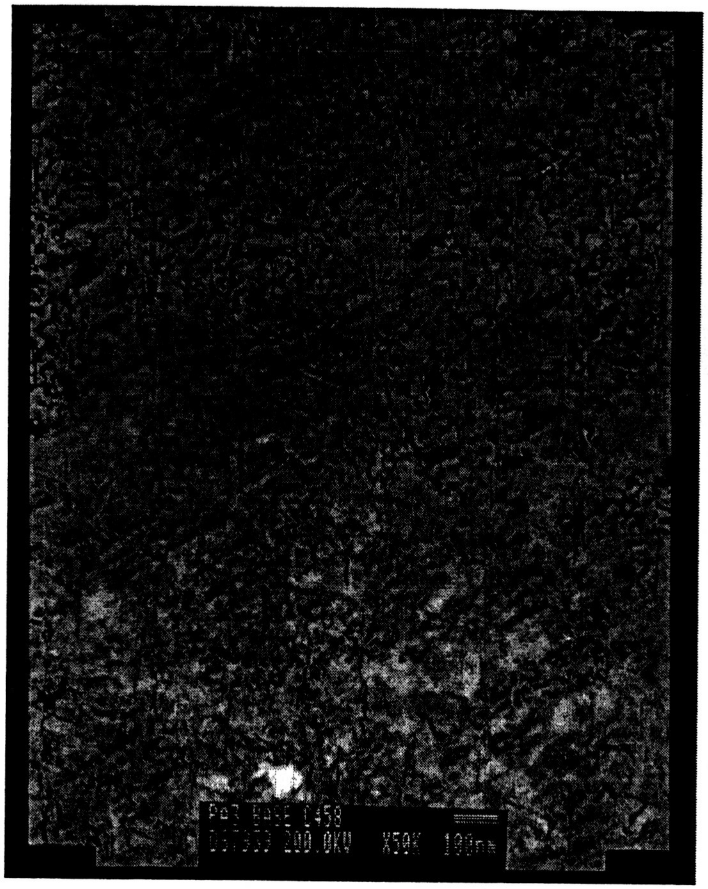
Alloy Compositions (wt. %)

Alloy	Density (lb/in.^{3})	Cu	Li	Mg	Zn	Mn	Zr	Ag
2195	0.0975	4.0	1.0	0.4			0.11	0.4
L277	0.0975	3.5	1.0	0.4		0.35	0.10	0.4
C458	0.0945	2.7	1.8	0.3	0.6	0.25	0.08	
2090	0.093	2.7	2.2				0.12	
8090	0.092	1.2	2.4	0.95			0.11	
2219	0.103	6.3				0.30	0.18	

Strengthening Precipitates in C458

Plate-like $T_1(Al_2CuLi)$ and Spherical δ' (Al_3Li)

Bright Field



100 nm

Dark Field

100 nm

Cryogenic Fracture Toughness Improvements

- **Extrinsic Mechanism (Rao and Ritchie, UC Berkeley, Ca. 1990)**
  - –Certain Al-Li Alloys (2090-T81, 8090-T8 Etc.) Exhibit a Significant Increase in L-T and T-L Cryogenic Fracture Toughness
  - –Attributed to Delamination Toughening
  - –Accompanied by a Slight Decrease in S-L and S-T Toughness
  - –Transgranular Microvoid Coalescence Remains As the Fracture Mechanism With Decreasing Temperature
- **Intrinsic Mechanism (Chen and Stanton, NASA MSFC, 1996)**
  - –Suppression of Sub-grain Boundary Precipitation of T_1
    - ✓Increase Driving Force for Homogeneous Nucleation in the Grains by Decreasing Aging Temperature. Second Step Aging in the "Peak Aging" Range Results in Precipitate Growth to the Optimum Size.
  - –General Increase of Ductility and Strain Hardening Rate With Decreasing Temperature.

DOE for Aging Optimization of C458 Plate

- 2^4 Full Factorial Experiment With Center Point
  - 16 Aging Trials and Center Point (205°F/48 hrs + 300°F/24 hrs)
  - Solution Heat Treat and Stretch to be Held Constant
  - Smaller Test Plan Used for –T6 Validation

- Temperature Selection Rationale
  - First Step Aging Treatment at Temperatures Between 175°F and 250°F to Promote Homogeneous Nucleation of T_1 Which Improves Toughness at Cryogenic Temperature, While Not Impacting Other Properties
  - Second Step Aging Treatment Is Necessary to Obtain the Optimum Combination of Strength and Toughness Within Practical Aging Times
    - ✓ Temperatures From 275°F and 325°F for –T8
    - ✓ Temperatures From 300°F to 325°F for –T62

DOE Details for C458 Plate

- **Materials**
  - All Specimens Came From a Single Lot of C458 Material Rolled to 0.75 Inch Thickness and Subsequently Milled to 0.375 Inch Thickness
  - Specimen Orientation of All Tensile Specimens Believed to be LT Orientation and All Toughness Specimens Believed to be T-L Orientation; Consistent Orientation Used for All Tensile and Toughness Specimens
- **Processing**
  - T8 Temper (Panels P01 through P17 and P20)
    - ✓ Solution Heat Treat (1020°F/0.5 hr), 6%, Stretch, hold at RT/48 hours, age
  - T62 Temper (Panels P30 through P33)
    - ✓ Solution Heat Treat (1020°F/0.5 hr), hold at RT/48 hours, age
- **Testing**
  - Tests Conducted at Room and Cryogenic (-320°F) Temperatures
  - Tensile Tests Performed in Triplicate (ASTM E8)
  - Toughness Tests Performed in Duplicate (ASTM E1820)

Effects of Aging on Properties of C458-T8 Plate

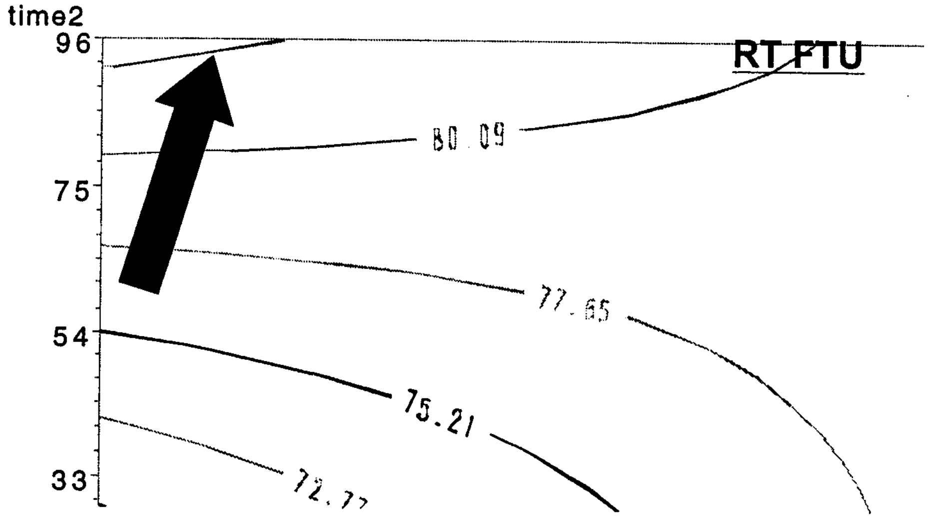
	Plate	Aging Parameters				Tensile Properties (Average of Three Tests)								Toughness			
		First Step		Second Step		Room Temperature				-320°F				RT		-320°F	
						Average				Average				Average		Average	
		Temp, °F	Time, hrs	Temp, °F	Time, hrs	FTU	FTY	%e	%RA	FTU	FTY	%e	%RA	K_{JC}	K_{JQ}	K_{JC}	K_{JQ}
Design of Experiments Two Step Aging	P01	175	12	275	12	64.8	52.6	10.9	16.7	83.3	57.0	14.7	13.0				
	P02	175	12	275	96	83.5	75.4	8.7	19.7	102.5	83.4	11.3	20.7			46.9	
	P03	175	12	325	12	79.9	72.9	9.7	23.3	98.8	81.1	13.7	19.7			33.5	
	P04	175	12	325	96	78.6	72.3	10.0	22.7	97.9	82.6	9.0	12.7			29.2	
	P05	175	192	275	12	67.8	54.7	10.7	17.0	87.4	61.0	14.7	19.7				
	P06	175	192	275	96	83.6	74.2	10.0	19.3	102.4	81.6	14.7	18.3			51.9	
	P07	175	192	325	12	80.0	72.9	10.0	23.3	98.4	81.4	11.3	19.7				
	P08	175	192	325	96	78.9	72.9	10.3	26.0	99.2	84.3	9.0	12.7				
	P09	250	12	275	12	66.0	53.5	10.7	17.3	85.6	59.3	14.3	15.0				
	P10	250	12	275	96	83.2	75.5	9.7	21.3	101.8	82.6	12.7	21.7			49.2	
	P11	250	12	325	12	80.0	73.1	9.0	23.7	98.3	81.4	13.0	19.7			34.6	
	P12	250	12	325	96	78.7	72.6	10.0	25.3	98.3	83.1	10.7	14.3				
	P13	250	192	275	12	81.4	70.4	10.0	14.7	98.4	76.6	15.7	22.3				
	P14	250	192	275	96	83.1	75.5	10.0	21.0	102.2	83.4	11.7	18.0			46.4	
	P15	250	192	325	12	80.3	73.3	10.7	24.3	98.1	81.2	12.0	20.0			38.8	
	P16	250	192	325	96	78.2	71.9	10.0	23.0	97.5	82.0	11.7	16.7			25.7	
	P17	205	48	300	24	81.2	72.2	9.7	18.0	99.7	80.1	13.7	22.3		48.2	54.1	
Baseline Single Step Aging	P20	300	24	n/a	n/a	81.8	73.3	10.7	20.7	99.2	80.5	13.3	22.0		47.6	41.6	

Discussion of Aging Effects for C458-T8 Plate

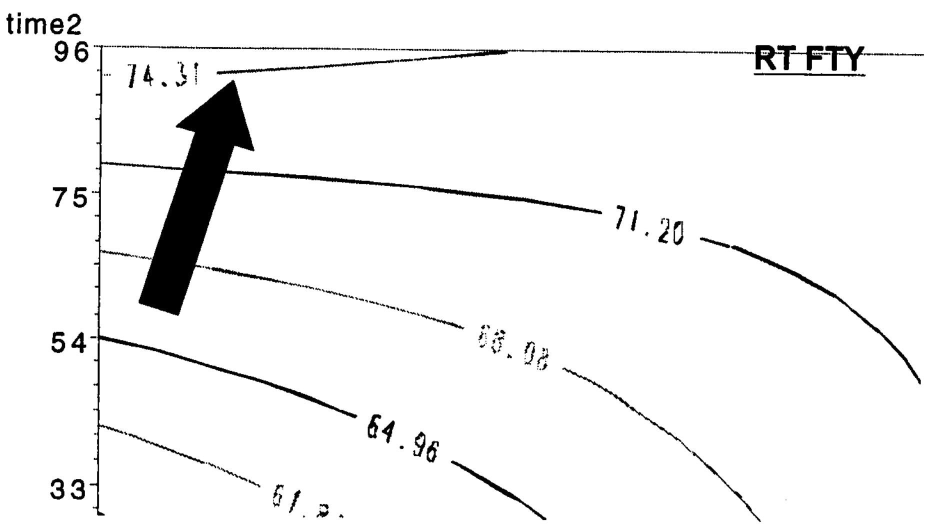
- **For a Specific Second Step Aging Practice, Varying the First Step Aging Practice Did Not Affect the Resulting Room or Cryogenic Temperature Tensile Properties (P13 Appears to Be an Anomaly)**

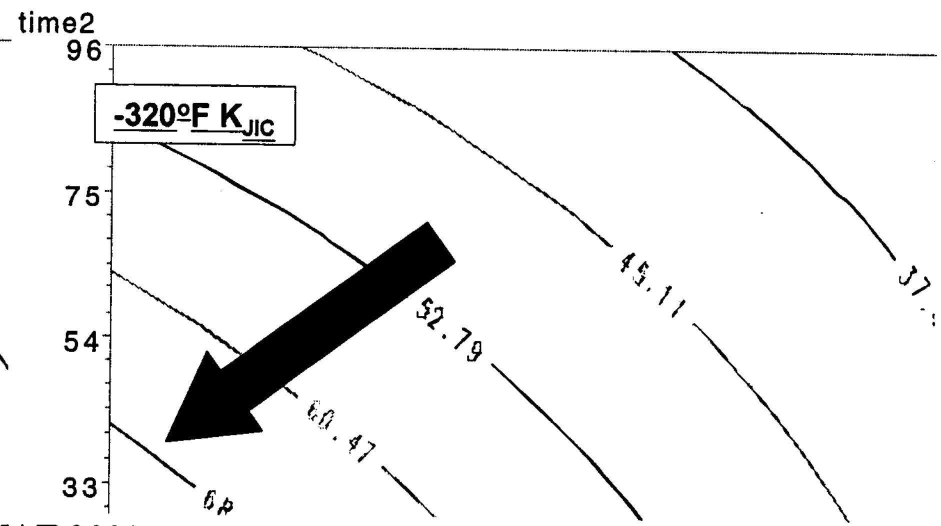
Plate	Aging Parameters				Tensile Properties							
	First Step		Second Step		Room Temperature				-320°F			
					Average				Average			
	Temp, °F	Time, hrs	Temp, °F	Time, hrs	FTU, ksi	FTY, ksi	%e	%RA	FTU, ksi	FTY, ksi	%e	%RA
P01	175	12	275	12	64.8	52.6	10.9	16.7	83.3	57.0	14.7	13.0
P05	175	192	275	12	67.8	54.7	10.7	17.0	87.4	61.0	14.7	19.7
P09	250	12	275	12	66.0	53.5	10.7	17.3	85.6	59.3	14.3	15.0
P13	250	192	275	12	81.4	70.4	10.0	14.7	98.4	76.6	15.7	22.3
P02	175	12	275	96	83.5	75.4	8.7	19.7	102.5	83.4	11.3	20.7
P06	175	192	275	96	83.6	74.2	10.0	19.3	102.4	81.6	14.7	18.3
P10	250	12	275	96	83.2	75.5	9.7	21.3	101.8	82.6	12.7	21.7
P14	250	192	275	96	83.1	75.5	10.0	21.0	102.2	83.4	11.7	18.0
P03	175	12	325	12	79.9	72.9	9.7	23.3	98.9	82.3	14.0	19.0
P07	175	192	325	12	80.0	72.9	10.0	23.3	98.4	81.4	11.3	19.7
P11	250	12	325	12	80.0	73.1	9.0	18.7	98.3	81.4	13.0	19.7
P15	250	192	325	12	80.3	73.3	10.7	24.3	98.1	81.2	12.0	20.0
P04	175	12	325	96	78.6	72.3	10.0	22.7	97.9	82.6	9.0	12.7
P08	175	192	325	96	78.9	72.9	10.3	26.0	99.2	84.3	9.0	12.7
P12	250	12	325	96	78.7	72.6	10.0	25.3	98.3	83.1	10.7	14.3
P16	250	192	325	96	78.2	71.9	10.0	23.0	97.5	82.0	11.7	16.7

DOE Analysis for C458 Plate



- **Tensile and Toughness Primarily Dependent Upon Second Step Aging Practice**
- **Tensile Properties Increase With Increased Second Step Aging Time and to a Lesser Extent Increased Second Step Aging Temperature**
- **Toughness Increases With Decreasing Second Step Aging Time and Temperature**





Aging Treatments resulting Higher Cryogenic Toughness for C458-T8

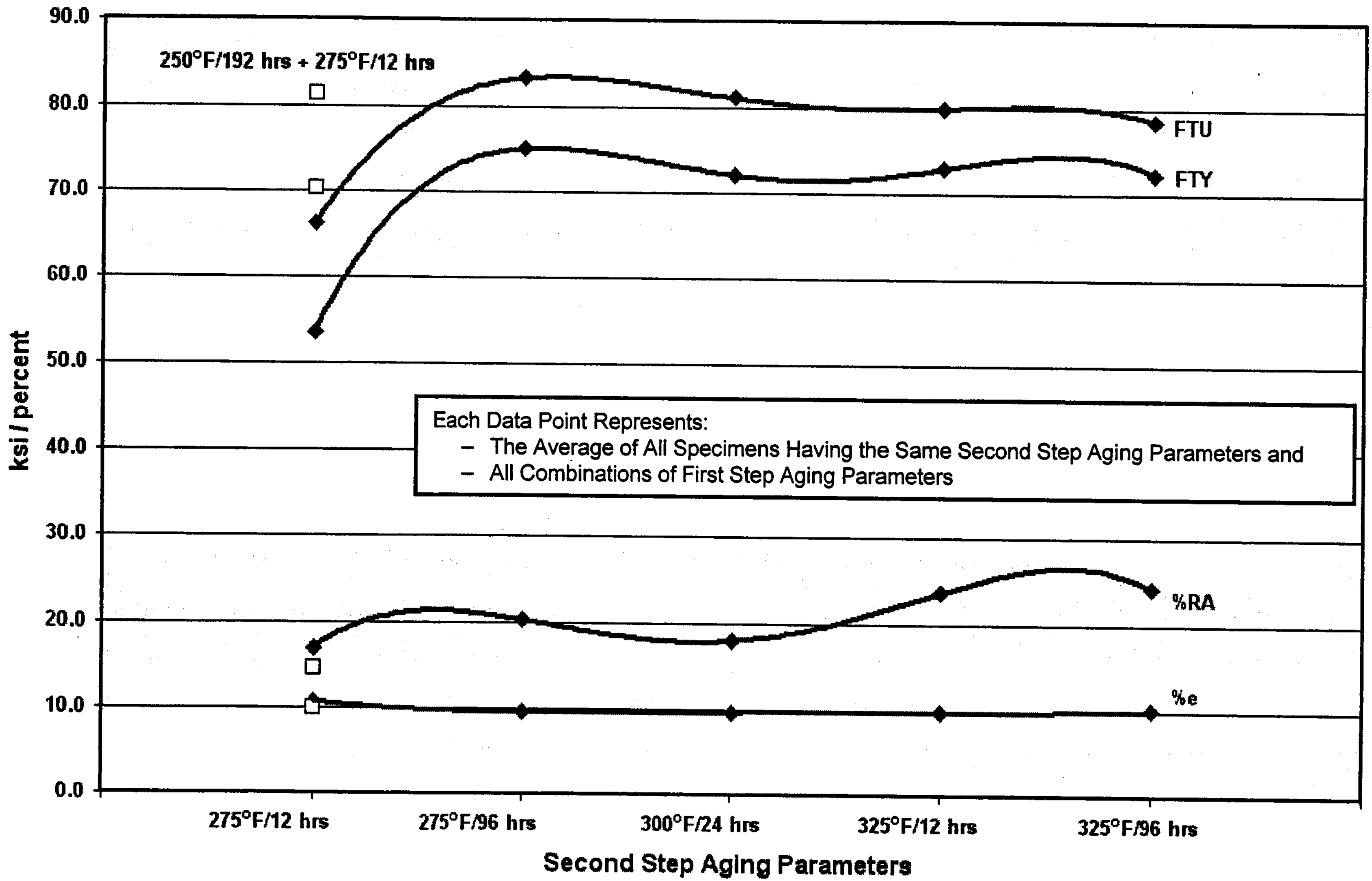
- **Cryogenic Fracture Toughness Is Significantly Improved With Certain Two Step Aging Practices, When Compared to a Single Step Aging Practice (P06/P17 vs. P20)**

- **Compared to the Second Aging Step, the First Step Features:**
  - **Lower Aging Temperature**
  - **Longer Aging Time**

Plate	Temper	Aging Parameters				Tensile Properties (Average of Three Tests)								Toughness (See Note)			
		First Step		Second Step		Room Temperature				-320°F				RT		-320°F	
						Average				Average				Average		Average	
		Temp, °F	Time, hrs	Temp, °F	Time, hrs	FTU	FTY	%e	%RA	FTU	FTY	%e	%RA	K_{Jc}	K_{JQ}	K_{Jc}	K_{JQ}
P06	-T8	175	192	275	96	83.6	74.2	10.0	19.3	102.4	81.6	14.7	18.3			51.9	
P17	-T8	205	48	300	24	81.2	72.2	9.7	18.0	99.7	80.1	13.7	22.3		48.2	54.1	
P20	-T8	300	24	n/a	n/a	81.8	73.3	10.7	20.7	99.2	80.5	13.3	22.0		47.6	41.6	

Note - The toughness values are averages for two tests. If one test met all the validity criteria and the other did not, the values for the two tests are reported separately.

Aging Curves for C458 Plate (RT Properties)



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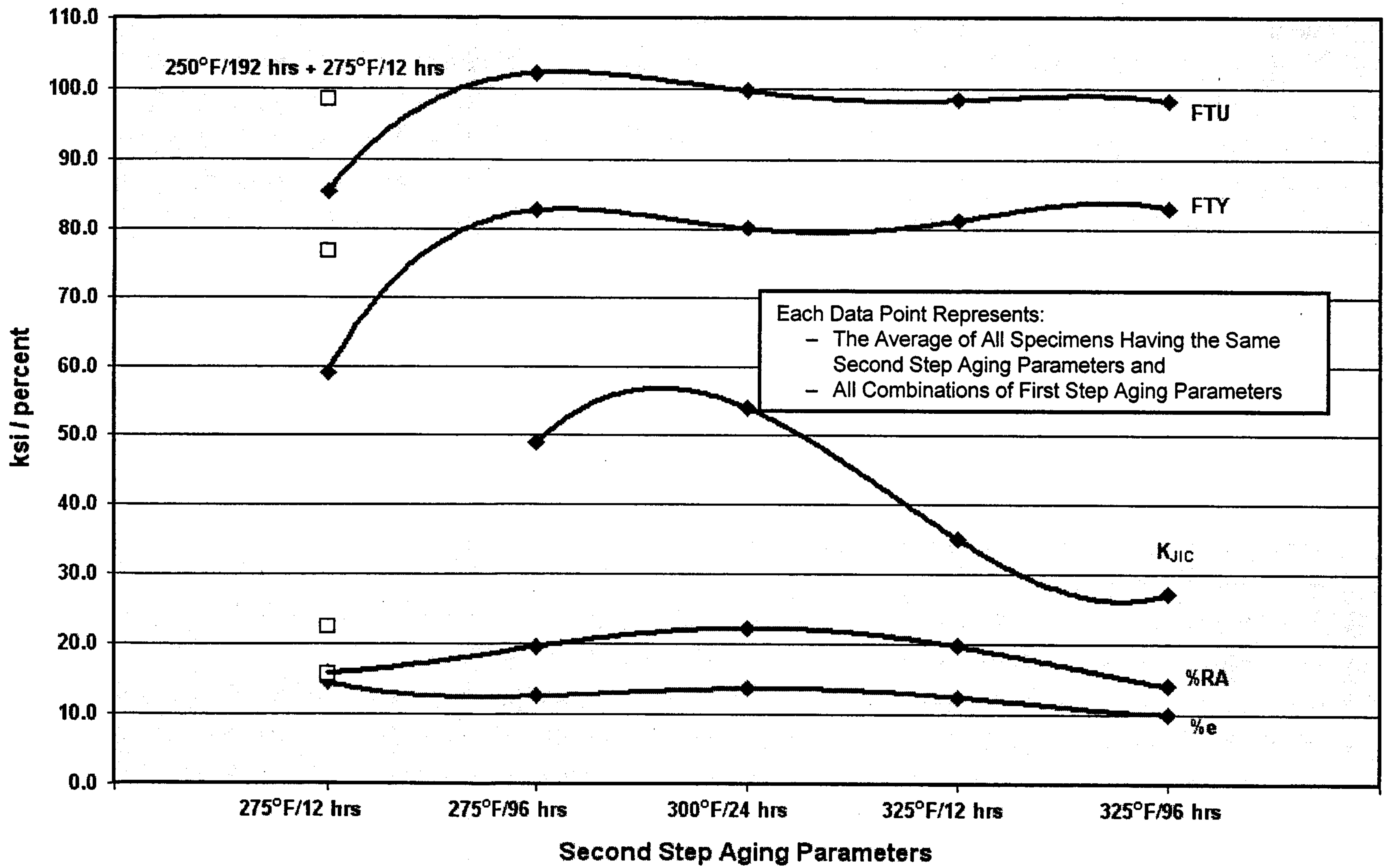
Aging Curves for C458 Plate (-320 F Properties)



Effects of Aging on Properties of C458-T6 Plate

	Plate	Temper	Aging Parameters				Tensile Properties (Average of Three Tests)								Toughness (See Note)			
			First Step		Second Step		Room Temperature				-320°F				RT		-320°F	
							Average				Average				Average		Average	
			Temp, °F	Time, hrs	Temp, °F	Time, hrs	FTU	FTY	%e	%RA	FTU	FTY	%e	%RA	K_{JIC}	K_{JQ}	K_{JIC}	K_{JQ}
Two Step -T6	P30	-T6	175	96	300	24	71.7	51.9	10.7	17.7	89.6	57.8	16.3	15.7	91.4		68.9	68.8
	P31	-T6	250	12	300	24	72.9	53.0	10.7	16.0	91.0	59.6	18.3	16.0				
	P32	-T6	175	96	325	24	77.4	61.0	8.3	12.0	92.3	65.6	14.3	17.3				
	P33	-T6	250	12	325	24	77.4	62.0	7.0	11.3	91.7	65.7	15.0	18.0	45.2	46.9	41.6	35.5

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Recommended Aging Parameters for C458 Plate

Selected C458-T62 Plate Aging Practice

First Step Age:	**250°F/12 Hours**
Second Step Age:	**325°F/24 Hours**

Selected C458-T8 Plate Aging Practice

Option 1 **(Best Combination of Strength and Toughness)**

First Step Age:	**175°F/192 Hours**
Second Step Age:	**275°F/96 Hours**

Option 2 - Selected **(More Practical Aging Times with Approximately 2 ksi Lower Room Temperature Tensile/Yield Strength Than Option 1)**

First Step Age:	**205°F/48 Hours**
Second Step Age:	**300°F/24 Hours**

Summary

- Two Step Aging of C458 Plate Product Resulted in Higher Cryogenic Toughness for
  - T8 and not T6
- The observation can be explained on the basis of
  - The high enough Li content in C458
  - The lack of post-solution heat treat stretch in T6
  - The need for stretch for aging response in the T8
- With the limited number of toughness tests, toughness was generally observed to increase with increasing tensile elongation and reduction of area, suggesting the usefulness of tensile tests for screening heat treatments
- For space vehicle cryotank applications, one could selected an optimized aging cycle for the application rather than the product form.