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by F. T. Inouye

Prepared by
AEROJET-GENERAL CORPORATION
Sacramento, Calif.
for Lewis Research Center

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FOREWORD

The research described herein, which was conducted by Aerojet-General Corporation, Liquid Rocket Operations, was performed under NASA Contract NAS 3-2555 with Mr. J. M. Kazaroff, Chemical Rocket Division, NASA Lewis Research Center, as Technical Manager. The report was originally issued as Aerojet-General Report No. 8800-20, November 1965.

ABSTRACT

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Large 7079-T652 hand forgings were evaluated for pump impeller and inducer applications in liquid oxygen/liquid hydrogen rocket engines.

The results of mechanical property tests, reheat-treatment experiments, and microstructural studies are presented. The application of 7079 alloy in a cryogenic environment is discussed based upon the test results, and recommendations are made for metallurgical analysis of the more promising alloys.

TABLE OF CONTENTS

I. SUMMARY

Several large 7079-T652 aluminum alloy forgings, which were candidate materials for use as pump impellers and inducers in liquid oxygen-liquid hydrogen rocket engines, were evaluated.

A number of factors were determined, including the influence of cryogenic temperatures upon smooth- and notched-bar tensile properties, the effect of -T6 temper reheat treatment (after rough machining) upon tensile properties, mechanical fatigue strengths under completely reversed bending and tension/compression axial stressing, and microstructure.

The 7079 forgings were characterized by good notch toughness at ambient temperature. These forgings were slightly notch sensitive at -320°F and extremely notch sensitive at -423°F. Notch sensitivity varied with specimen orientation as well as material strength and ductility. The poor notch toughness of 7079 forgings also appears to be influenced by impurities (inclusions), a cored microstructure, and high alloy content. The -T6 reheat treatment significantly increased tensile strength but decreased smooth-bar ductility as well as notch toughness. In reversed bending, fatigue strengths closely approximated those for commercial-size products and were higher than the fatigue strengths obtained in tension/compression stressing.

These studies show that the 7079-T652 forgings appear to have satisfactory properties for impeller service in liquid engines at temperatures down to -320°F; however, application in inducers at -423°F is not recommended for the sizes being considered because of poor notch toughness and low fatigue strength. Nickel-base alloys, alpha A-110-AT-ELI titanium alloy, and aluminum alloys developed specifically for cryogenic service are considered more promising for inducer service. However, the nickel and titanium alloys are only applicable if their higher densities can be tolerated. All of these alloys must be metallurgically analyzed to determine their suitability for large -423°F inducers.

II. INTRODUCTION

Aluminum alloys offer unique advantages as a material of a construction because of their low density, good strength, and ductility. They also have excellent corrosion resistance. Certain aluminum alloys possess good toughness and they are used in liquid rocket engine hardware as well as ground equipment exposed to liquid oxygen (-297°F) and liquid hydrogen (-423°F). Several of the typical grades commonly used are 2014 (Thor and Titan structural tankage), 5456 (first-stage Saturn C-1 kerosene and liquid oxygen tanks), 2219 (Saturn S-1C launch vehicle), 5083 (liquid hydrogen storage tanks), and 6061 (used extensively in systems and controls hardware, such as valve bodies, seals, and conduits, at temperatures down to -423°F).

The 7000-series alloys are the highest strength aluminum alloys. These alloys have been used at temperatures as low as -320°F, but not generally below that point because of their relatively poorer toughness. Grade 7075 is used in Titan I pump impellers, which operate in kerosene and liquid oxygen (-297°F). The major factors for selecting Grade 7075 over other alloys and steels were material availability, its high strength-to-density ratio, its propellant compatibility, and its excellent machinability. Because of earlier successful experience with 7075 in Titan I, 7075 was again used in Titan II pump impellers which operate in noncryogenic propellant combinations of AeroZINE 50(1) and nitrogen tetroxide.

A major problem in large 7075 impeller forgings is the low strength found near the center. This is caused partly by the low depth-of-hardening at the reduced cooling rates that result from the hot water quench (see Table 1). Low center properties have limited design allowables.

In 1957, a study(2) was made to determine the minimum properties obtainable in a "special product" forging (13-in. diameter x 9-in.) of 7079 aluminum alloy. The 7079 aluminum has higher magnesium and lower zinc, chromium, and copper contents than 7075, which results in greater depth of hardening. The 7079 properties presented in Table 2 and Figures 1 through 8 show conclusively that the 7079 depth of hardening is superior to that of 7075. The trend of decreasing properties with forging size and the superiority of 7079 over 7075 is further shown in Tables 3 and 4, which are the results from recent George C. Marshall Space Center tests.(3)

Experience has demonstrated that 7079 aluminum alloy has the highest mechanical properties of the 7000 series alloys. When a strength-to-density basis is considered, the 7079 alloy appeared promising for pump impellers and inducers of the newer liquid oxygen-liquid hydrogen engines because the lower strength 7079 alloy operated successfully in liquid rocket engines at temperatures down to -320°F. However, impeller and inducer sizes have increased, and mechanical properties of large 7079 forgings were nonexistent for design analysis.

An investigation was undertaken to obtain design mechanical property data for five large 7079-T652 forgings of interest for pump applications in a liquid rocket engine operating in liquid oxygen and liquid hydrogen environments. It is this data that is delineated in this report. Conclusions and recommendations regarding the usage of 7079-T652 forgings exposed to a cryogenic environment are also included.

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(1) AeroZINE 50 is a 50/50 fuel blend of unsymmetrical dimethyl hydrazine (UDMH) and hydrazine (N_2H_4).

(2) Mechanical Properties of 7075-T6 and 7079-T6 Aluminum Alloy Forgings, Report MM-58, Aerojet-General Corp., 1957.

(3) Aluminum Alloy Forgings, 7075-T652 and 7079-T652, Summary Report R-RE-MMP, George C. Marshall Space Center, 1964.

TABLE 1

MINIMUM TENSILE PROPERTIES OF 7075 ALUMINUM ALLOY IMPELLER FORGINGS

Condition	Size (in.)	Orientation*	Temperature (^oF)	Ultimate Strength (ksi)	0.2% Offset Yield Strength (ksi)	Elongation (%)
T6	13 D x 9	A	RT	62	42	8
T652	--	A	RT	66	55	4
		45° to axis		65	52	4
T652		A	RT	68	62	4
T652	8 D x 4	A	RT	67	49	11.5
T652	11.3 D x 8.5	A	RT	67	50	12
T6	12 D x 6.7	A	RT	57	50	2.5
		A	-320	66	56	2.0
		R	RT	67	57	5.5
		R	-320	66	57	2.5
T652	11.3 D x 8.5	A	RT	68	55	10.5
		T	RT	80	67	7.8
		A	RT	71	58	14.0
		T	RT	75	66	10.9
T65	5 D x 4	A	RT	68	56	9.5
		R	RT	68	58	9.0
		T	RT	73	64	7.5
T6	5-1/4 D x 4-1/2	A	RT	62	45	5.5
		A	RT	65	53	2.5
		R	RT	71	58	7.5
		R	RT	75	61	7.5
		T	RT	65	51	7.0
		T	RT	74	62	5.0

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*A = axial, R = radial, T = tangential

TABLE 2

MECHANICAL PROPERTIES OF STANDARD 7075-T6 AND SPECIAL PRODUCT 7079-T6 ALUMINUM ALLOY FORGINGS*

A. Room Temperature

Specimens	Tensile Strength ksi		Yield Strength 0.2% Offset, ksi		Elongation In 1 inch (4D) %		Hardness, BHN	
	7075-T6	7079-T6	7075-T6	7079-T6	7075-T6	7079-T6	7075-T6	7079-T6
1-A	53.2	69.3	42.6	59.0	2.5	6.0	122	143
B	57.5	62.6	43.6	53.5	**	2.5	113	137
C	51.0	70.5	41.5	59.6	3.0	6.5	113	140
2-A	54.8	69.6	42.8	59.5	3.5	6.5	115	140
B	57.8	67.8	44.2	53.6	5.5	7.0	115	140
C	52.8	69.5	41.3	59.7	3.5	6.0	113	143
4-A	59.5	69.4	46.7	58.7	4.0	5.5	113	148
B	57.8	68.7	43.2	55.6	5.5	6.5	104	138
C	57.3	69.1	42.7	58.8	4.5	5.0	104	146
6-A	61.9	70.0	51.6	57.7	3.5	5.0	140	145
B	58.1	70.0	42.5	57.2	5.5	7.0	118	137
C	58.8	69.9	43.8	57.1	**	6.5	111	145
8-A	62.5	71.9	53.2	60.6	2.5	4.5	137	143
B	59.2	70.0	45.4	58.1	5.0	6.5	124	140
C	58.5	71.4	47.1	60.3	3.5	4.5	127	146
10-A	58.5	71.3	44.5	60.3	4.0	11.0	115	142
B	64.5	71.7	54.6	57.4	3.5	9.5	129	140
C	65.1	72.7	57.4	58.2	2.5	7.0	140	140
11-A	--	73.4	--	60.2	-	8.5	-	143
B	--	73.9	--	60.9	-	8.5	-	145
12-A	59.2	74.4	43.2	65.8	5.0	7.0	118	145
B	58.5	72.9	40.9	64.2	5.0	7.0	115	140
C	58.7	68.9	41.8	57.9	5.0	8.0	109	140
D	58.8	70.6	42.5	58.4	4.5	8.0	111	137

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*Dimensions of 13-in. diameter by 9-in.

TABLE 2 (cont.)

Specimens	Tensile Strength ksi		Yield Strength 0.2% Offset, ksi		Elongation In 1 inch (4D) %		Hardness, BHN	
	7075-T6	7079-T6	7075-T6	7079-T6	7075-T6	7079-T6	7075-T6	7079-T6
12-E	59.5	70.8	42.6	57.2	5.0	9.0	112	137
F	60.1	69.1	43.0	55.6	7.5	10.5	115	136
G	60.1	68.5	43.4	55.1	7.5	12.5	115	130
H	60.5	69.1	43.6	55.7	7.0	12.0	111	130
I	60.1	70.5	43.8	56.5	6.5	12.0	115	130
J	59.3	73.0	43.5	57.5	5.0	11.0	118	130
K	58.6	71.5	43.6	57.5	5.0	10.0	118	136
L	59.0	66.5	44.3	58.0	**	**	118	137
M	61.4	72.5	48.1	62.5	5.0	6.5	124	140
N	60.5	73.0	44.2	64.0	5.5	6.5	118	140
13-A	59.5	76.0	43.9	66.8	4.0	7.0	118	142
B	59.7	73.0	42.2	62.5	6.0	7.5	113	137
C	59.1	70.0	42.5	57.5	5.0	8.0	113	136
D	60.7	72.0	43.8	59.0	7.5	7.5	116	136
E	59.7	70.0	48.8	56.0	5.5	11.0	113	136
F	60.5	70.0	43.8	56.5	7.0	12.5	107	135
G	60.1	69.0	43.6	56.0	7.0	11.5	113	134
H	59.6	69.5	42.7	57.0	7.0	12.5	113	134
I	61.5	70.5	44.5	57.1	7.5	13.0	112	136
J	59.9	71.6	44.0	57.3	7.0	13.0	115	135
K	59.4	71.2	44.0	59.2	5.0	7.0	118	134
L	60.1	71.2	45.0	60.5	5.0	6.0	120	136
M	62.8	72.1	48.3	61.5	6.5	6.0	122	138
N	60.1	74.8	41.5	65.4	8.5	6.5	113	140
15-A	63.2	75.1	47.5	65.3	7.5	7.5	122	143
B	62.2	71.3	46.1	58.8	7.0	10.0	120	138
C	60.8	72.0	44.5	59.5	6.5	9.0	120	137
D	60.0	71.7	43.5	59.4	7.0	8.5	118	137
E	60.4	71.2	43.5	58.0	7.5	10.0	115	134
F	60.4	71.0	43.0	57.9	7.5	12.5	118	135

TABLE 2 (cont.)

Specimens	Tensile Strength ksi		Yield Strength 0.2% Offset, ksi		Elongation In 1 inch (4D) %		Hardness, BHN	
	7075-T6	7079-T6	7075-T6	7079-T6	7075-T6	7079-T6	7075-T6	7079-T6
15-G	60.8	70.2	43.3	57.7	7.5	12.5	118	135
H	61.2	70.5	44.1	58.1	7.0	12.5	118	136
I	60.7	70.0	44.5	58.0	6.5	11.0	111	134
J	61.2	71.5	46.0	57.5	5.0	12.5	115	136
K	62.0	71.5	47.3	58.0	5.0	10.5	122	135
L	62.2	73.0	49.0	60.0	5.0	8.0	115	138
M	65.7	71.5	53.2	60.5	5.0	7.0	118	138
N	68.4	74.5	54.5	65.5	7.0	7.0	120	138
17-A	65.6	76.0	50.1	66.5	7.5	8.5	104	140
B	63.6	73.0	48.4	62.0	6.5	8.5	115	138
C	63.2	73.0	46.5	60.5	8.0	8.5	104	138
D	62.3	72.0	45.2	57.5	8.0	12.5	109	136
E	62.0	71.5	44.5	57.0	7.0	13.0	100	138
F	61.7	71.5	44.5	58.5	8.0	10.5	107	136
G	61.2	72.0	43.7	59.5	7.5	10.5	101	138
H	62.1	72.0	44.9	60.0	7.5	10.5	107	138
I	62.9	71.8	46.5	59.4	7.5	11.5	115	140
J	64.1	72.5	48.5	59.3	7.5	12.5	109	136
K	65.5	71.6	51.0	58.1	7.0	14.0	104	137
L	67.2	72.8	53.4	60.1	7.5	12.0	120	136
M	69.0	70.0	56.1	57.0	7.0	11.0	113	137
N	69.0	75.0	57.5	65.4	6.5	7.5	120	140
19-A	65.9	74.2	53.5	65.2	**	7.5	122	143
B	66.5	74.5	52.8	62.1	5.0	11.0	122	140
C	65.8	73.8	52.8	62.1	4.5	12.0	124	138
D	65.9	74.8	53.1	63.0	4.5	10.5	122	140
E	64.5	73.8	52.1	62.0	4.5	11.5	129	138
F	62.6	74.2	52.0	62.1	4.5	10.0	120	140
G	64.7	72.2	52.1	62.1	**	10.0	120	138
H	63.3	73.8	51.7	62.4	4.5	10.5	124	137

TABLE 2 (cont.)

Specimens	Tensile Strength ksi		Yield Strength 0.2% Offset, ksi		Elongation In 1 inch (4D) %		Hardness, BHN	
	7075-T6	7079-T6	7075-T6	7079-T6	7075-T6	7079-T6	7075-T6	7079-T6
19-I	66.3	72.5	53.1	61.2	4.5	10.5	129	138
J	66.4	72.7	54.6	60.0	**	11.0	129	138
K	67.7	72.5	56.4	59.5	**	11.0	124	138
L	67.6	73.0	57.0	61.8	**	10.0	129	140
M	68.5	73.0	57.7	61.0	**	11.0	127	142
N	70.8	74.5	59.2	63.0	5.5	11.5	129	138
21-A	63.4	76.0	55.5	65.3	2.5	12.0	129	143
B	67.5	75.5	55.6	65.0	3.5	12.5	144	148
C	66.5	78.5	56.9	66.5	**	11.0	140	143
D	64.6	79.0	55.2	70.0	3.5	7.5	120	140
E	64.6	79.0	56.0	69.6	3.5	**	111	143
F	65.4	79.0	56.5	69.3	3.5	6.0	127	143
G	64.7	76.2	56.2	66.2	3.5	6.0	127	143
H	65.9	78.0	55.3	67.0	3.5	6.5	133	142
I	68.1	78.1	57.8	67.4	4.5	7.0	124	137
J	64.1	78.0	54.6	67.8	4.5	7.5	124	142
K	66.8	77.0	57.0	65.6	4.5	9.0	113	143
L	65.9	76.4	56.9	65.0	4.5	11.0	133	142
M	62.8	73.2	54.5	61.9	2.5	13.0	118	137
N	63.4	72.3	54.2	61.0	2.5	11.0	118	143

**No value obtained - specimen failed outside the gage mark.

TABLE 2 (cont.)

B. Minus 320°F

Specimens	Tensile Strength ksi		Yield Strength 0.2% Offset, ksi		Elongation In 1 inch (4D) %	
	7075-T6	7079-T6	7075-T6	7079-T6	7075-T6	7079-T6
3-A	63.9	75.6	54.4	70.6	3.0	2.0
B	63.9	77.4	52.5	63.1	2.0	2.8
C	61.6	78.4	51.5	69.2	2.5	**
5-A	66.4	78.2	58.5	70.4	**	1.8
B	61.8	78.2	52.0	65.1	2.0	2.5
C	65.0	77.6	53.4	*	2.5	2.0
7-A	68.8	78.8	62.2	62.4	1.0	2.0
B	64.1	79.8	52.0	54.3	2.5	2.5
C	65.0	77.4	53.7	64.1	2.5	2.0
9-A	65.5	81.0	63.4	69.7	1.0	**
B	67.4	77.0	63.8	67.0	1.5	**
C	67.9	81.0	61.2	70.6	2.0	2.0
14-A	67.4	82.0	55.1	72.6	3.5	1.0
B	68.4	80.5	53.6	73.4	4.5	**
C	67.2	79.5	53.5	61.9	3.5	**
D	68.0	81.2	53.3	59.6	4.0	2.5
E	68.8	82.2	53.4	*	4.0	5.0
F	69.2	81.7	53.4	66.1	5.0	6.0
G	68.2	80.5	53.2	65.2	5.0	5.3
H	69.0	81.7	54.0	68.0	4.0	5.0
I	69.3	81.2	54.2	66.4	4.0	4.0
J	67.2	83.1	54.5	68.9	3.5	5.0
K	66.9	81.1	56.4	67.4	2.5	**
L	66.8	80.2	57.7	71.1	2.5	**
M	71.4	80.0	61.4	73.1	**	1.2
N	70.0	81.5	58.3	75.4	3.5	1.0
16-A	71.1	82.6	58.9	68.1	3.5	**
B	70.5	79.7	56.8	68.4	**	2.5
C	70.5	82.5	55.9	70.0	**	3.0
D	68.1	83.0	53.5	70.5	3.5	3.5

TABLE 2 (cont.)

Specimens	Tensile Strength ksi		Yield Strength 0.2% Offset, ksi		Elongation In 1 inch (4D) %	
	7075-T6	7079-T6	7075-T6	7079-T6	7075-T6	7079-T6
16-E	69.0	82.5	53.4	68.5	3.5	4.9
F	69.7	82.5	52.8	69.5	4.5	4.6
G	68.6	82.0	53.0	66.0	4.5	3.5
H	68.9	81.5	52.5	69.5	4.5	**
I	70.7	81.5	55.0	69.5	5.0	4.0
J	69.5	82.0	56.0	66.1	2.5	5.0
K	71.5	82.5	59.4	67.5	**	5.5
L	74.0	82.2	64.0	*	**	**
M	76.0	79.8	68.1	70.7	**	2.5
N	76.5	81.5	69.2	75.4	2.5	2.0
18-A	71.0	83.7	60.8	77.0	2.5	2.0
B	72.9	69.5	62.1	70.5	2.5	**
C	72.4	85.7	62.6	72.8	4.0	4.5
D	70.0	85.7	61.1	73.1	2.5	3.6
E	70.5	84.4	62.0	71.1	3.0	4.5
F	70.5	85.0	62.5	73.0	3.5	4.0
G	70.4	83.8	61.5	72.4	3.5	3.0
H	68.5	83.3	55.6	72.2	2.5	3.0
I	70.5	82.6	58.1	71.8	2.5	3.0
J	72.5	85.1	61.6	71.2	2.0	4.0
K	73.8	85.6	61.5	72.6	2.0	4.0
L	75.1	86.4	62.1	72.2	2.0	5.0
M	75.6	82.0	63.2	68.6	**	5.5
N	77.5	81.7	67.7	*	2.0	1.0
20-A	--	84.1	--	71.9	-	5.0
B	80.6	86.4	74.5	74.2	2.0	**
C	77.0	83.9	70.2	74.7	2.0	2.5
D	73.5	86.4	66.9	71.9	2.5	5.8
E	72.8	88.0	65.4	75.9	2.0	4.0
F	70.5	86.1	63.9	73.0	2.0	5.0

TABLE 2 (cont.)

Specimens	Tensile Strength ksi		Yield Strength 0.2% Offset, ksi		Elongation In 1 inch (4D) %	
	7075-T6	7079-T6	7075-T6	7079-T6	7075-T6	7079-T6
20-G	71.4	86.5	63.9	75.2	**	4.0
H	71.5	86.2	62.7	74.8	2.0	3.0
I	72.2	86.6	63.8	74.3	2.0	3.5
J	72.5	86.9	67.2	74.6	1.5	4.0
K	73.5	87.0	65.2	74.4	2.0	3.5
L	74.8	88.0	68.0	75.0	2.0	5.0
M	76.5	87.6	70.0	74.2	**	5.0
N	81.0	87.0	74.5	75.5	2.0	4.5

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*No value obtained - extensometer slipped.

**No value obtained - specimen failed outside the gage mark.

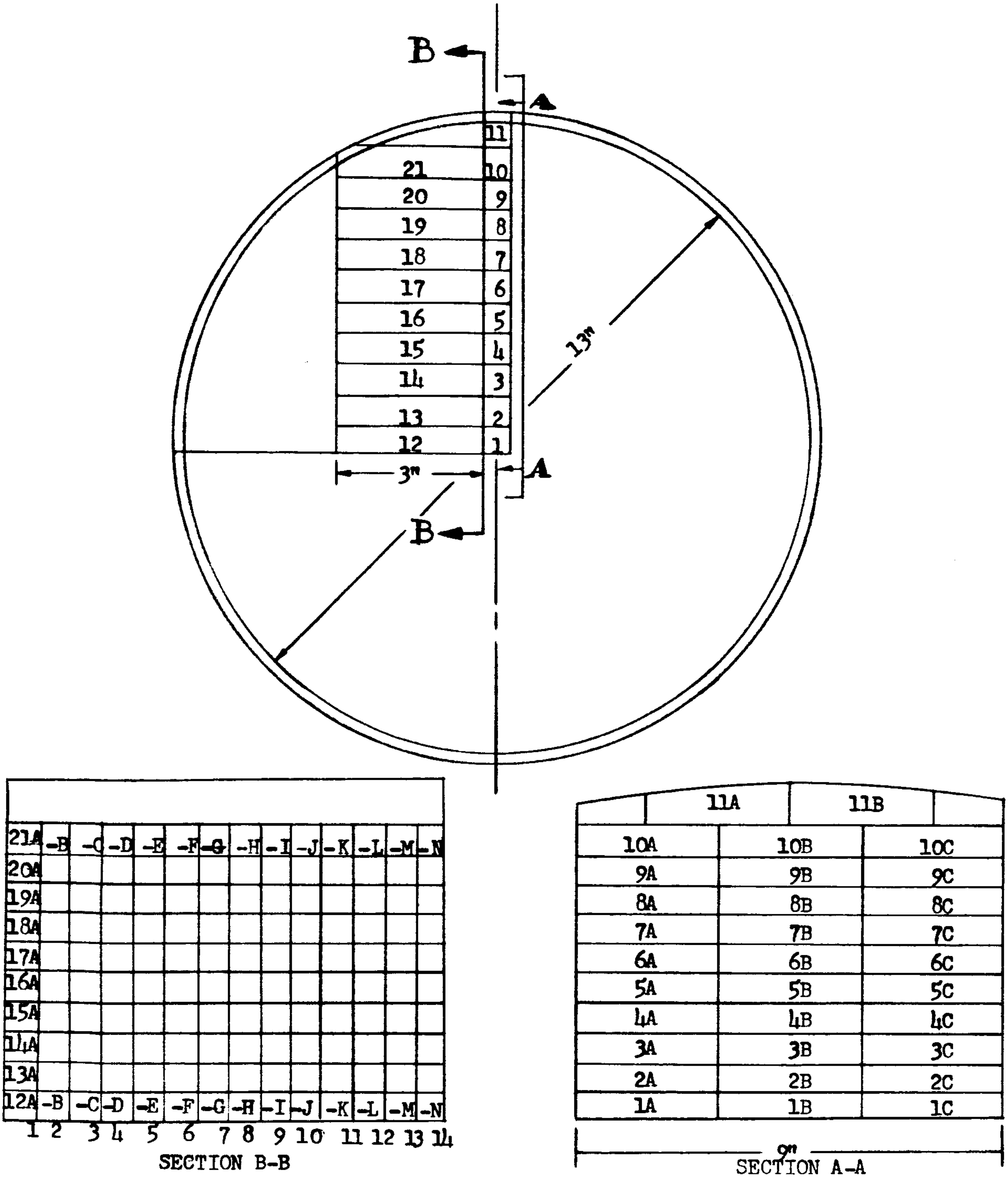

Figure 1
Specimen Locations of Standard 7075-T6 and Special
Product 7079-T6 Hand Forgings

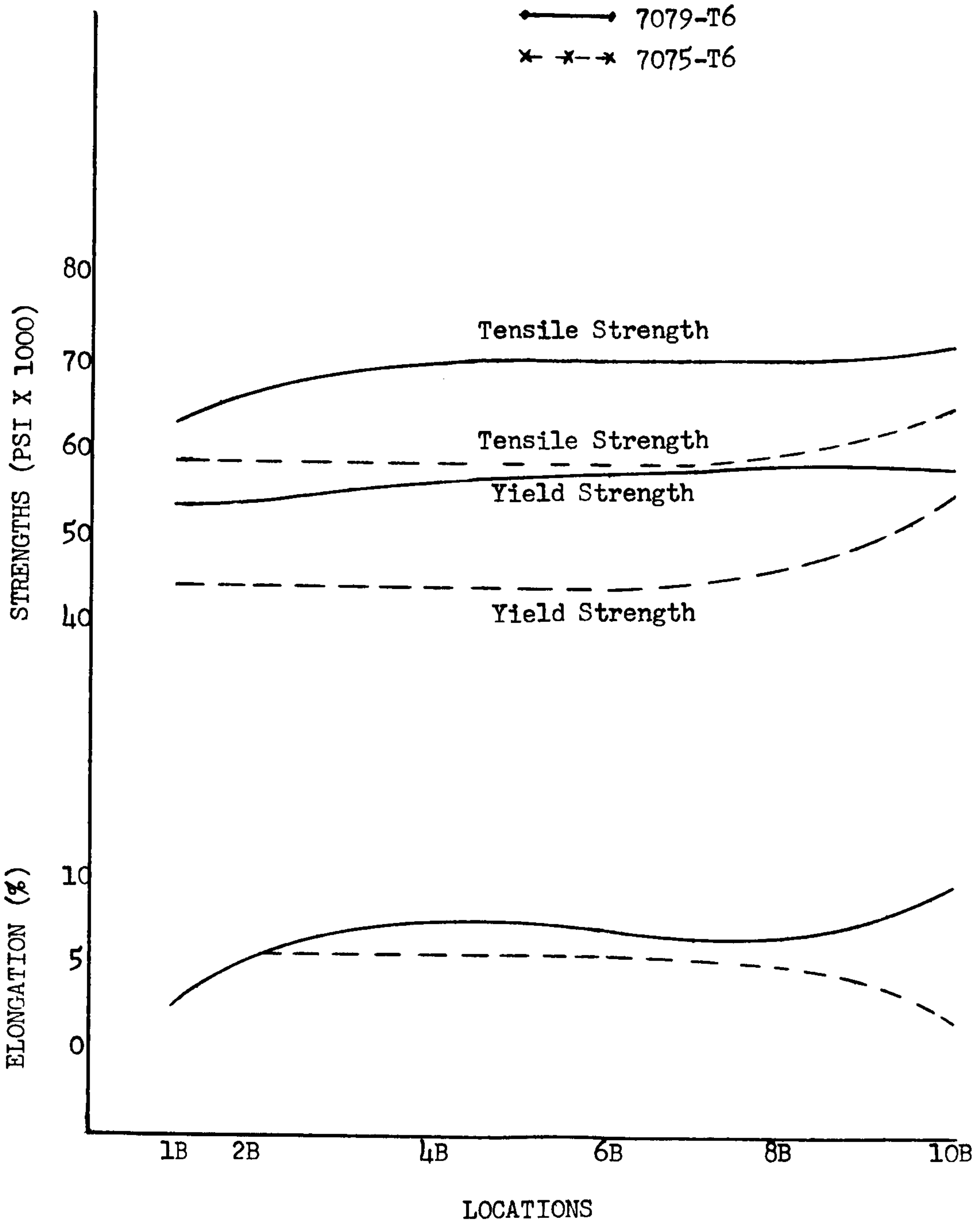

Figure 2
Mechanical Properties vs Specimen Locations of Standard 7075-T6 and Special Product 7079-T6 Hand Forgings

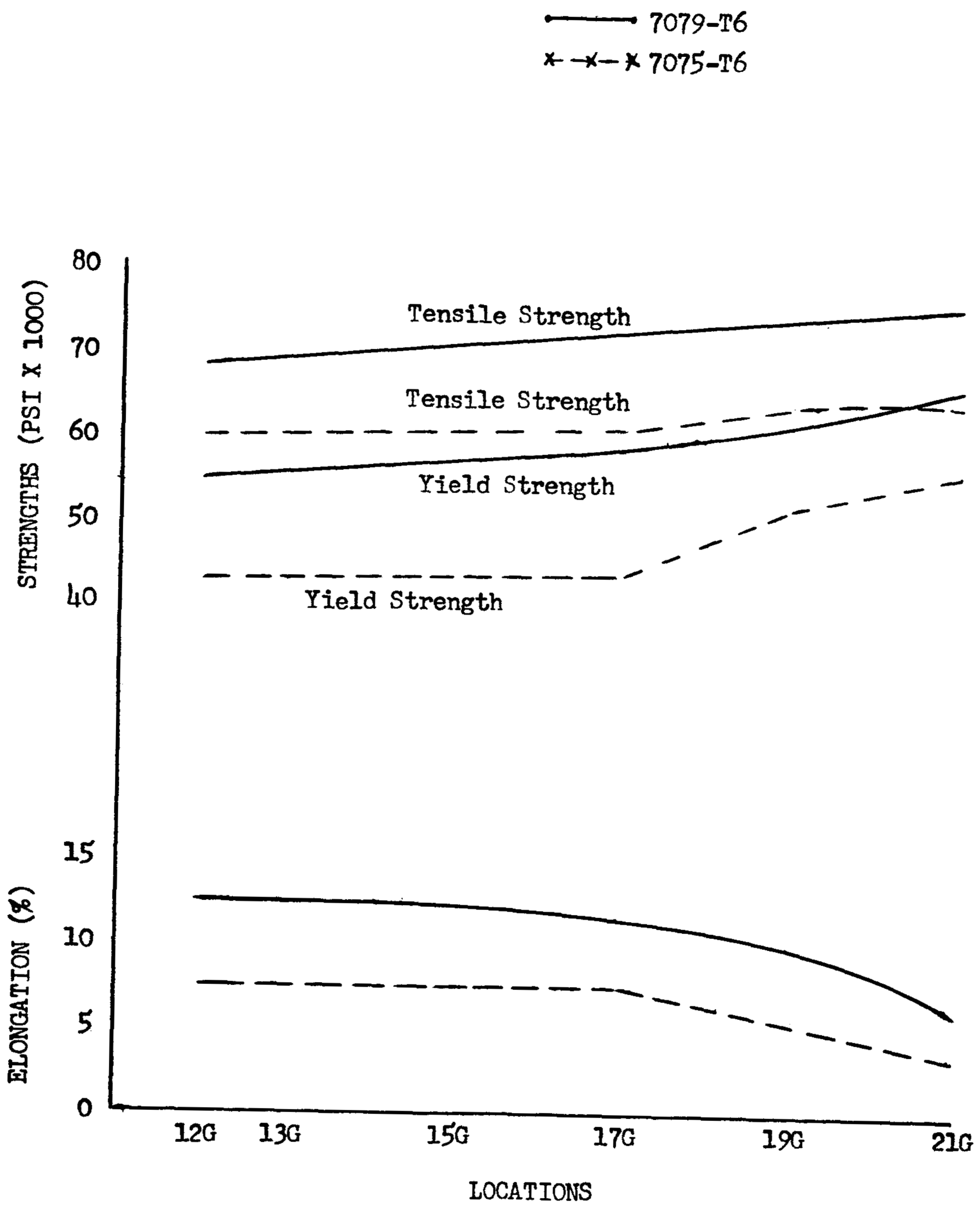

Figure 3
Mechanical Properties vs Specimen Locations of Standard
7075-T6 and Special Product 7079-T6 Hand Forgings

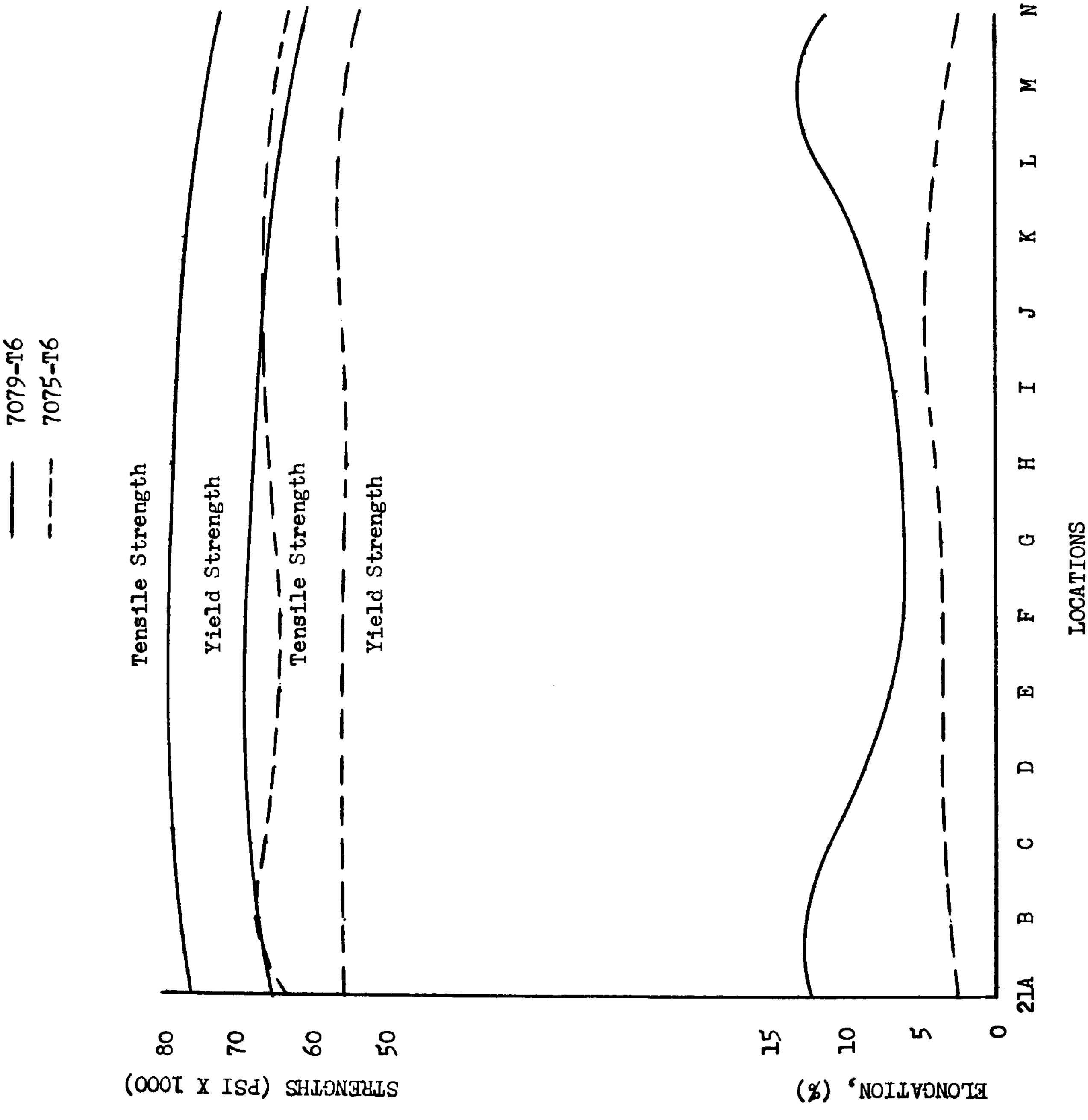

Figure 4
Mechanical Properties vs Specimen Locations of Standard
7075-T6 and Special Product 7079-T6 Hand Forgings

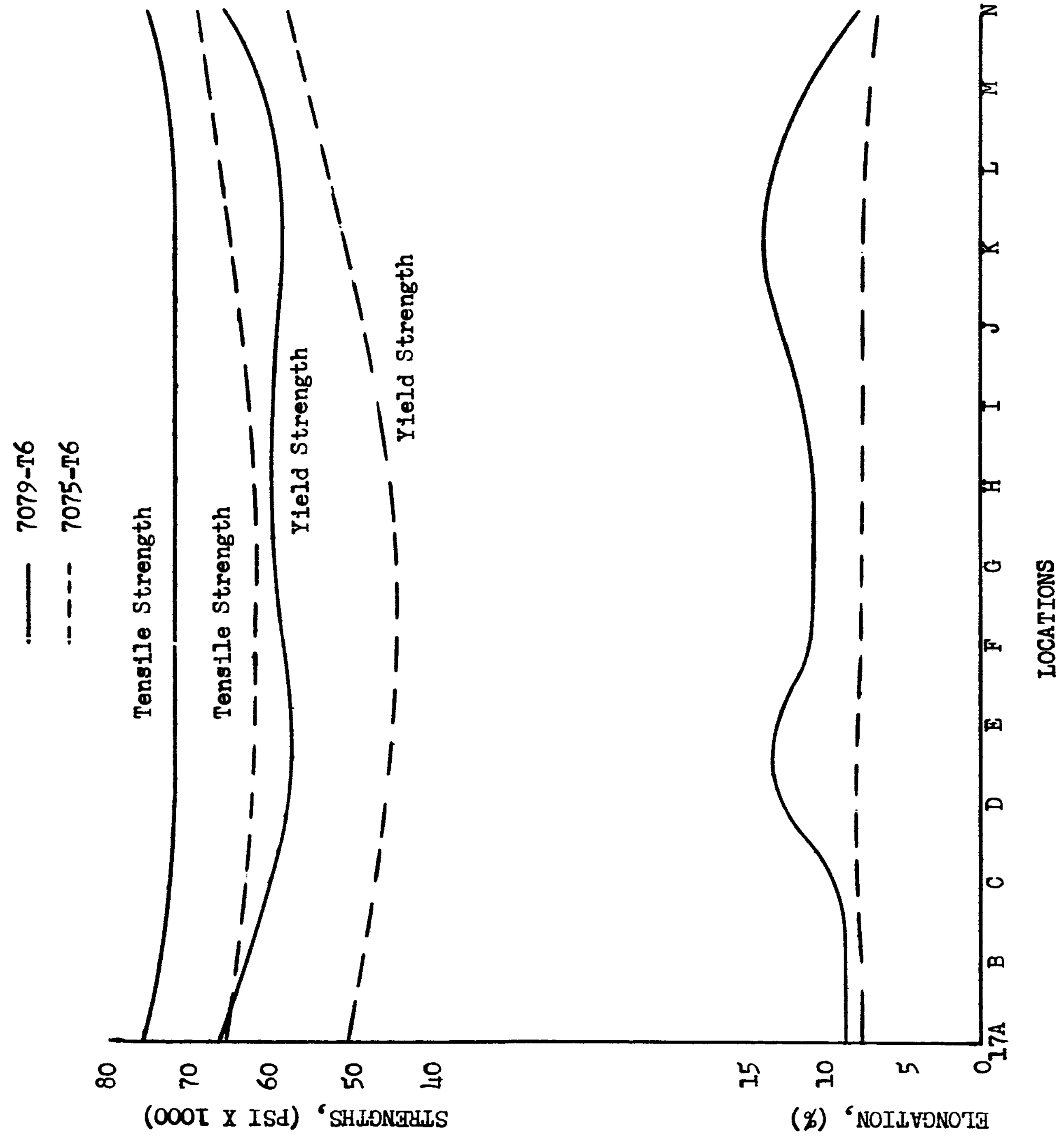

Figure 5
Mechanical Properties vs Specimen Locations of Standard
7075-T6 and Special Product 7079-T6 Hand Forgings

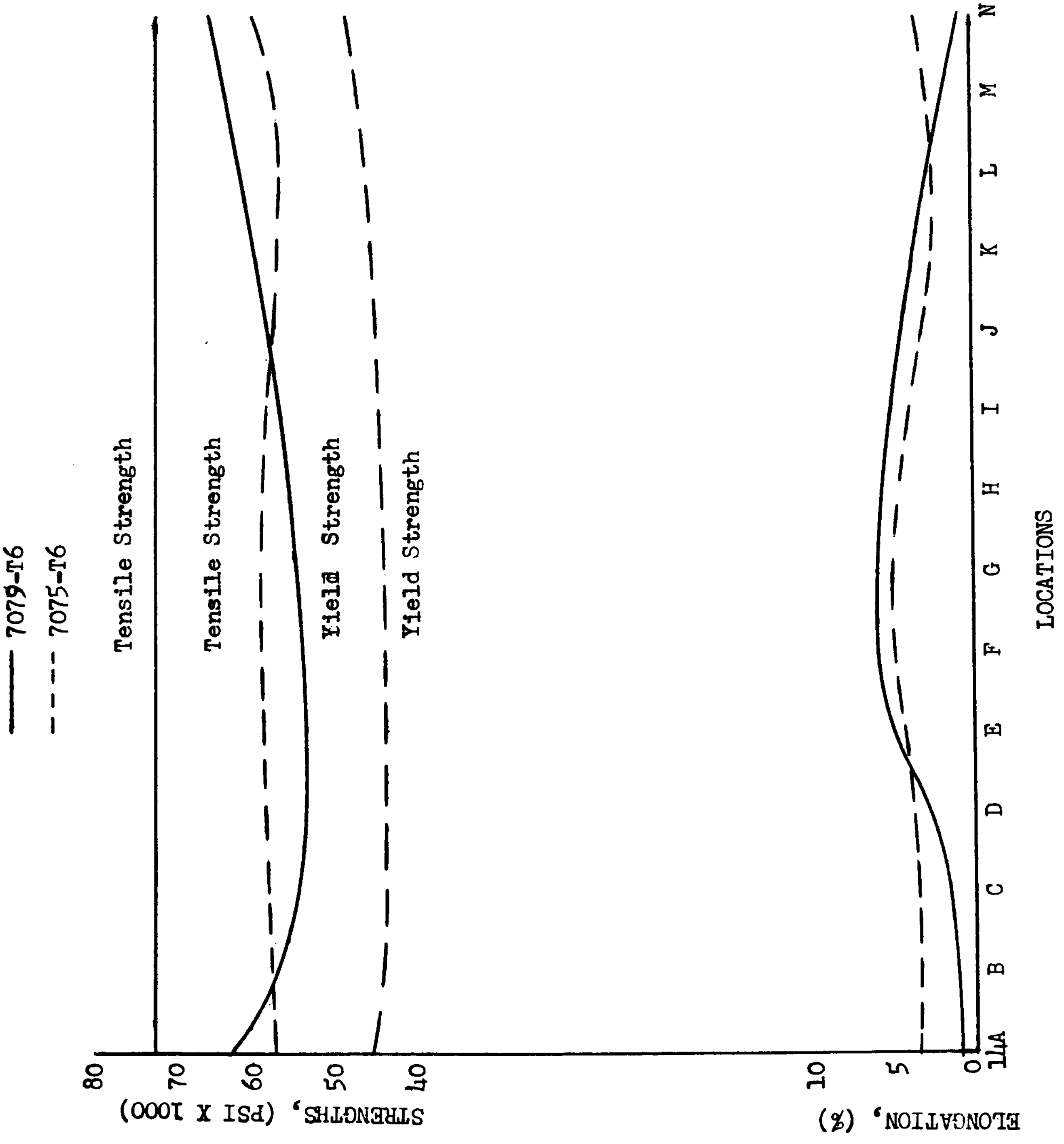

Figure 6
Mechanical Properties vs Specimen Locations of Standard
7075-T6 and Special Product 7079-T6 Hand Forgings

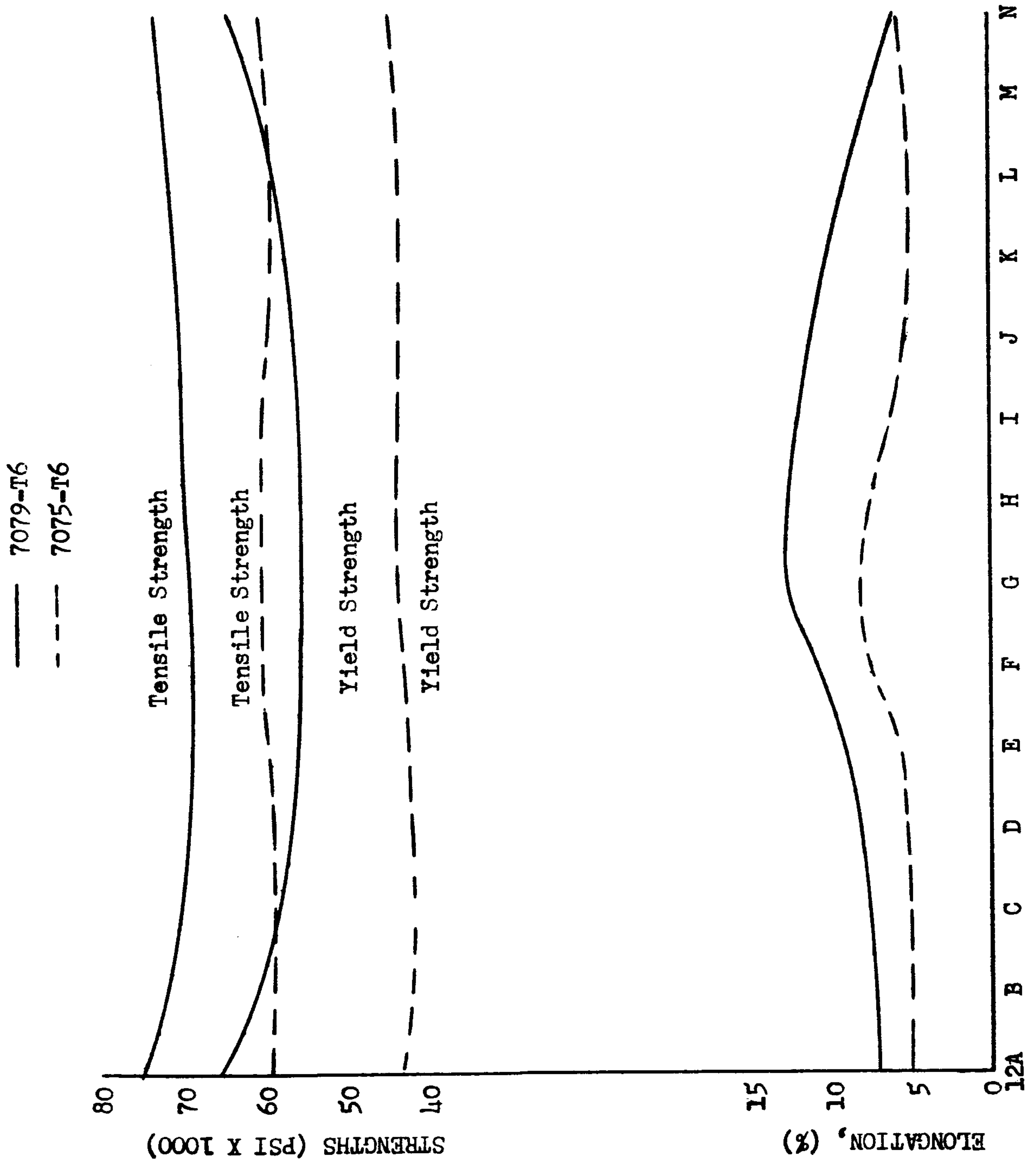

Figure 7
Mechanical Properties vs Specimen Locations of Standard 7075-T6 and Special Product 7079-T6 Hand Forgings

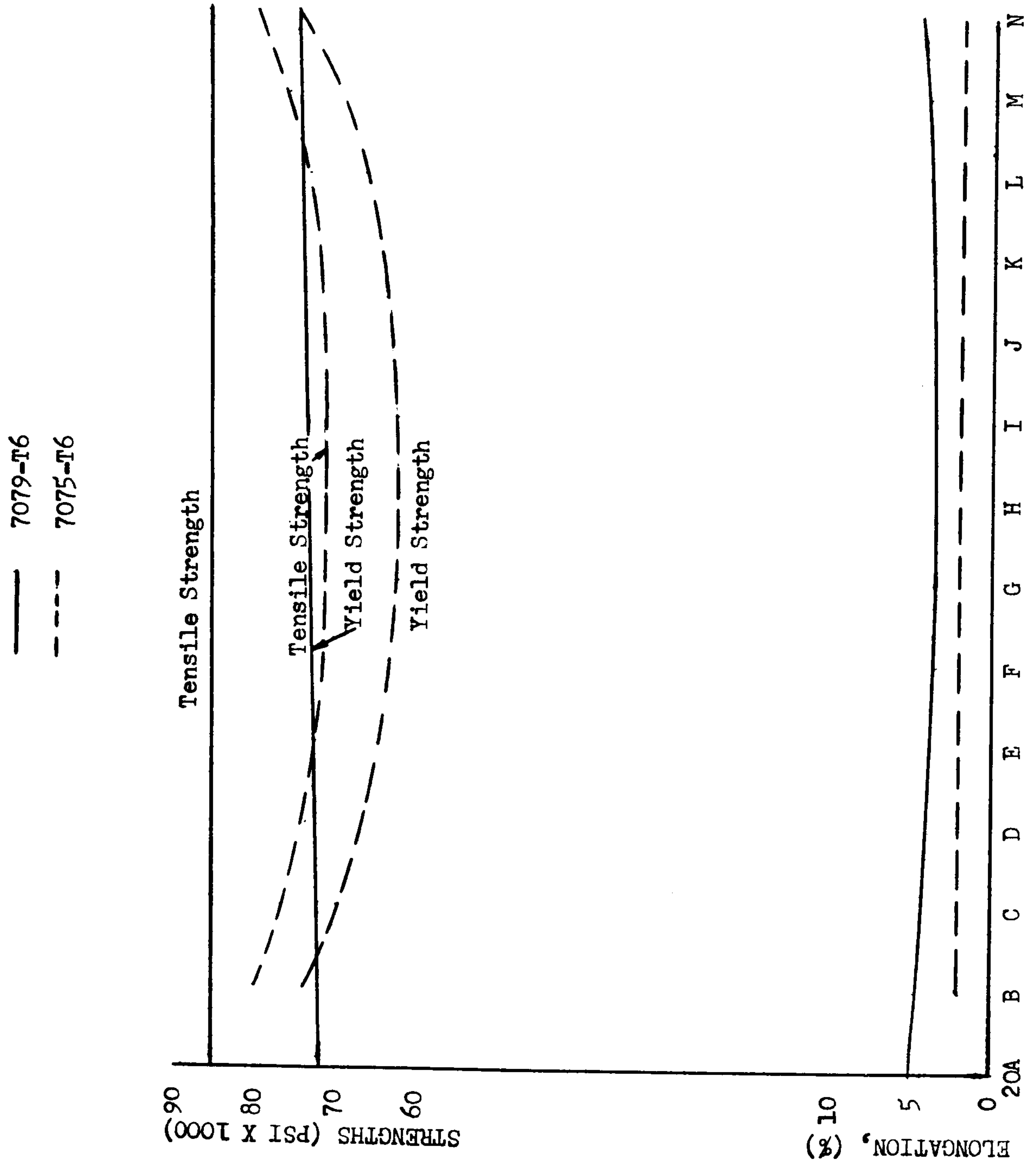

Figure 8
Mechanical Properties vs Specimen Locations of Standard 7075-T6 and Special Product 7079-T6 Hand Forgings

TABLE 3

EFFECT OF FORGING THICKNESS ON THE ROOM TEMPERATURE MECHANICAL PROPERTIES OF 7075-T652 HAND FORGINGS(1)

Size (in.)	Direction	F_{tu} (ksi)	F_{ty} (ksi)	Elongation (% in 4D)
2 x 32 x 12	Longitudinal	78 - 88	65 - 77	10 - 12
	Long Trans.	74 - 80	63 - 68	6 - 10
	Short Trans.	68 - 81	55 - 63	3 - 6
4 x 32 x 12	Longitudinal	74 - 83	60 - 73	6 - 13
	Long Trans.	69 - 81	59 - 70	5 - 10
	Short Trans.	65 - 77	52 - 63	4 - 6
6 x 32 x 12	Longitudinal	63 - 83	48 - 73	8 - 15
	Long Trans.	60 - 81	46 - 70	2 - 10
	Short Trans.	57 - 76	43 - 60	3 - 8
8 x 32 x 12	Longitudinal	61 - 87	46 - 73	8 - 14
	Long Trans.	57 - 79	45 - 71	3 - 8
	Short Trans.	53 - 76	43 - 64	3 - 7
10 x 32 x 12	Longitudinal	57 - 81	43 - 68	7 - 14
	Long Trans.	55 - 77	43 - 69	2 - 7
	Short Trans.	56 - 73	39 - 63	3 - 8
12 x 32 x 12	Longitudinal	53 - 81	36 - 71	6 - 15
	Long Trans.	53 - 76	37 - 68	4 - 8
	Short Trans.	52 - 77	33 - 66	5 - 8
18 x 32 x 18	Longitudinal	55 - 82	36 - 73	4 - 15
	Long Trans.	52 - 82	34 - 66	5 - 12
	Short Trans.	52 - 82	35 - 71	5 - 12

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(1) Aluminum Alloy Forgings, 7075-T652 and 7079-T652, Summary Report R-RE-MMP, George C. Marshall Space Center, 1964.

TABLE 4

EFFECT OF FORGING THICKNESS ON THE ROOM TEMPERATURE MECHANICAL PROPERTIES OF 7079-T652 HAND FORGINGS(1)

Size (in.)	Direction	F_{tu} (ksi)	F_{ty} (ksi)	Elongation (% in 4D)
2 x 32 x 12	Longitudinal	80 - 83	71 - 74	10 - 12
	Long Trans.	81.5 - 84	71 - 75	8 - 13
	Short Trans.	80 - 82	66 - 68	6 - 10
4 x 32 x 12	Longitudinal	77 - 84	67 - 76	7 - 11
	Long Trans.	77 - 80	65.5 - 70	8 - 11
	Short Trans.	72 - 78	60 - 65	6 - 9
6 x 32 x 12	Longitudinal	74 - 84	64 - 75	9 - 13
	Long Trans.	73 - 78	61 - 70	7 - 11
	Short Trans.	70 - 77	57 - 63	6 - 10
8 x 32 x 12	Longitudinal	73 - 81	61 - 73	9 - 14
	Long Trans.	70 - 79	60 - 71	6 - 10
	Short Trans.	70 - 77	57 - 65	5 - 11
10 x 32 x 12	Longitudinal	69 - 78	56.5 - 70	10 - 14
	Long Trans.	69 - 79	57 - 70	5 - 11
	Short Trans.	68 - 79	54.5 - 68	5 - 11
12 x 32 x 12	Longitudinal	69 - 80	57 - 72	9 - 12
	Long Trans.	67 - 79	55 - 69	4 - 12
	Short Trans.	66.5 - 78	52 - 67	5 - 12
18 x 32 x 18	Longitudinal	59 - 78	44 - 70	7 - 14
	Long Trans.	55 - 75	41 - 65	4 - 11
	Short Trans.	57 - 77	44 - 70	4 - 10

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(1) Aluminum Alloy Forgings, 7075-T652 and 7079-T652, Summary Report R-RE-MMP, George C. Marshall Space Center, 1964.

III. TECHNICAL DISCUSSION

A. MATERIAL

The forging material condition and chemistry are listed in Table 5 along with the forgings dimensions and test section dimensions. The test sections are shown in Figures 9 through 11.

B. TESTING PROCEDURE

The general test procedure consists of cutting test rings from the peripheral area of the forgings, as shown in Figures 9 and 10. These test rings were machined into tensile specimens which were subsequently tested; the test results were then compared with those of like tensile specimens, which had been taken from the interior areas of the sectioned forging.

Control specimens in the -T652 temper were tested for base-line properties; the test results were compared with those of specimens that were taken from test rings parted from the forging and given the -T6 heat-treatment (per MIL-H-6088) after rough machining. The samples used in the reheat-treatment studies were taken from the areas shown in Figure 11.

The configuration and dimensions of tensile specimens are shown in Figure 12. They are standard designs and the stress concentration of the notched specimen is approximately 6.3. Specimen orientations were axial, radial, and tangential.

Tension tests were conducted using standard test equipment at 0.005 in./in./min strain rate at ambient temperature, at -320°F by immersion in liquid nitrogen, and at -423°F by immersion in liquid hydrogen.

Fatigue tests were conducted under tension/compression and bending stress at ambient temperature using standard test equipment. The fatigue specimens were taken from the interior areas of the sectioned forging; their configuration and dimensions are shown in Figures 13 and 14.

C. TEST RESULTS

1. Mechanical Properties of Hand Forging "A"

The tension data for the test ring and center section are listed in Tables 6 and 7 and shown graphically in Figures 15 through 20. The relative location of these sections is seen in Figure 9.

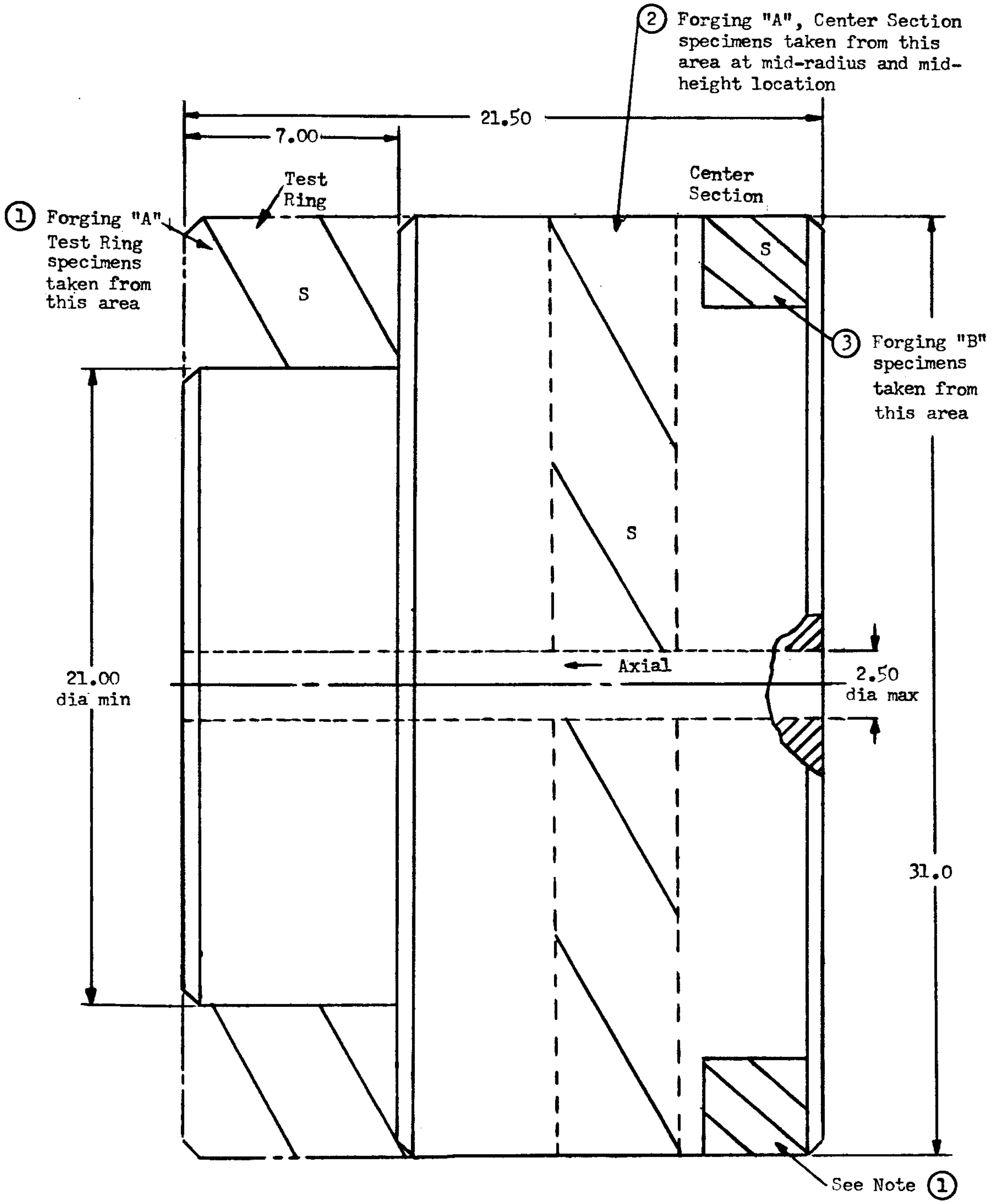
The test results substantiated the following conclusions regarding the large 7079-T652 impeller forging.

a. The increase of the 0.2% offset yield strength with decreasing temperature was gradual over the entire temperature range from ambient to -423°F.

TABLE 5

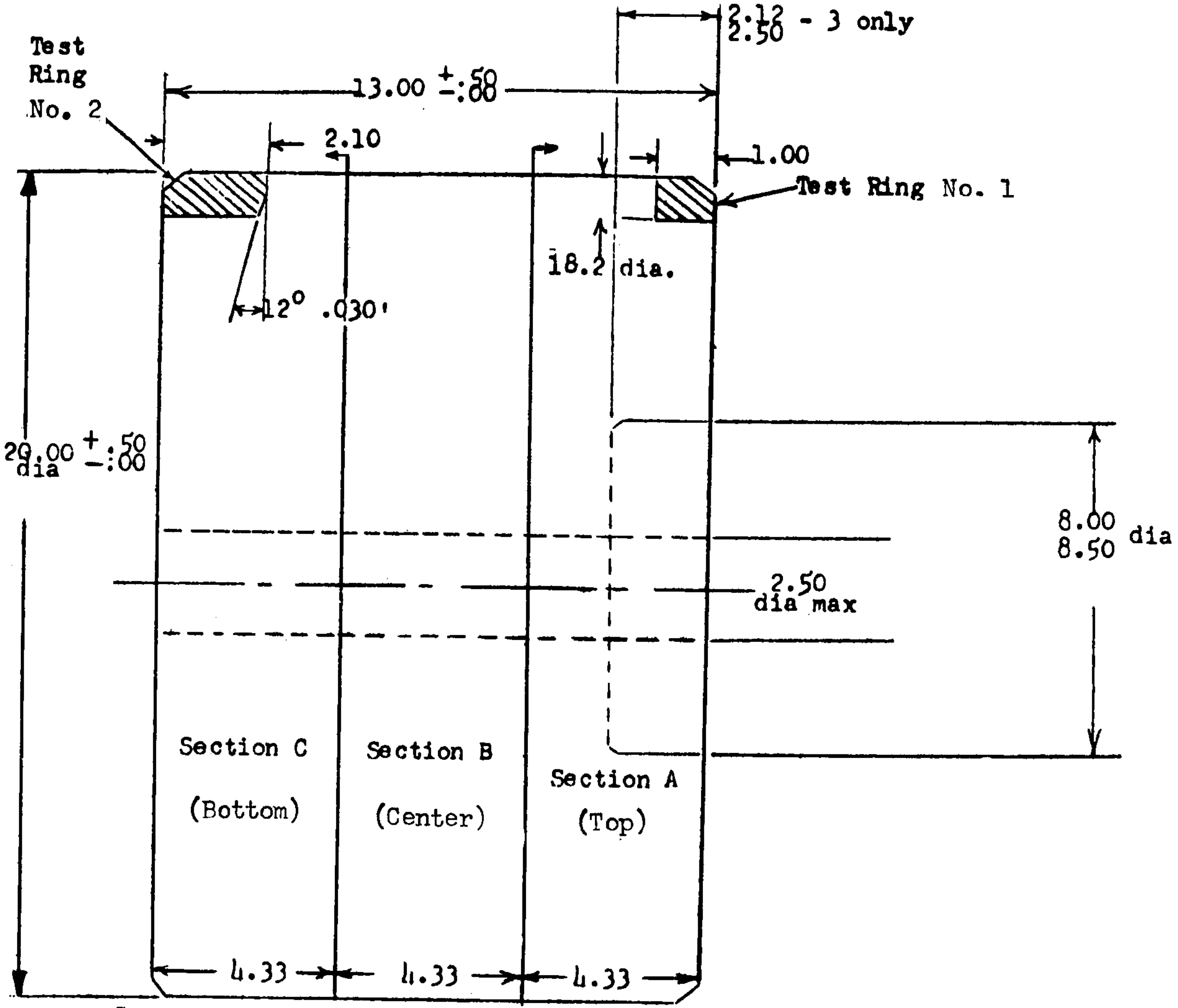
FORGING SIZE, CONDITION, TEST SECTION DIMENSIONS, AND MATERIAL CHEMISTRY OF 7079 HAND FORGINGS

					Material Chemistry								
Part	Hand Forging	Size in inches Dia x Length	Condition	Test Section Dimensions in inches	Cu	Si	Fe	Mn	Mg	Zn	Cr	Ti	Ni
A	Oxidizer Impeller	31 x 21.5	-T652	Test Ring 31D x 21ID x 7L	0.65	0.07	0.11	0.21	3.05	4.8	.14	.03	0.03
				Center 31D x 4.8L									
B	Oxidizer Impeller	31 x 21.5	-T652	Test Ring 31D x 25ID x 4L	0.54	0.10	0.11	0.195	3.51	4.45	0.15	0.07	0.05
C	Fuel Inducer	20 x 13	-T652	Test Ring 20D x 18ID x 1.5L	0.73	0.09	0.18	0.21	2.85	4.8	0.17	0.056	0.05
				Top Section A 20D x 4.3L									
				Center Section B 20D x 4.3L									
				Bottom Section C 20D x 4.3L									
D	Fuel Inducer	20 x 13	-T652	Test Ring 20D x 18ID x 1.5L	0.80	0.08	0.18	0.20	3.25	4.6	0.18	0.046	0.05
E	Fuel Inducer	20 x 13	-T652, then rough machined and reheat-treated to -T6 per MIL-H-6088	Center and Periphery	0.68	0.09	0.21	0.23	3.4	4.8	0.16	0.05	0.02



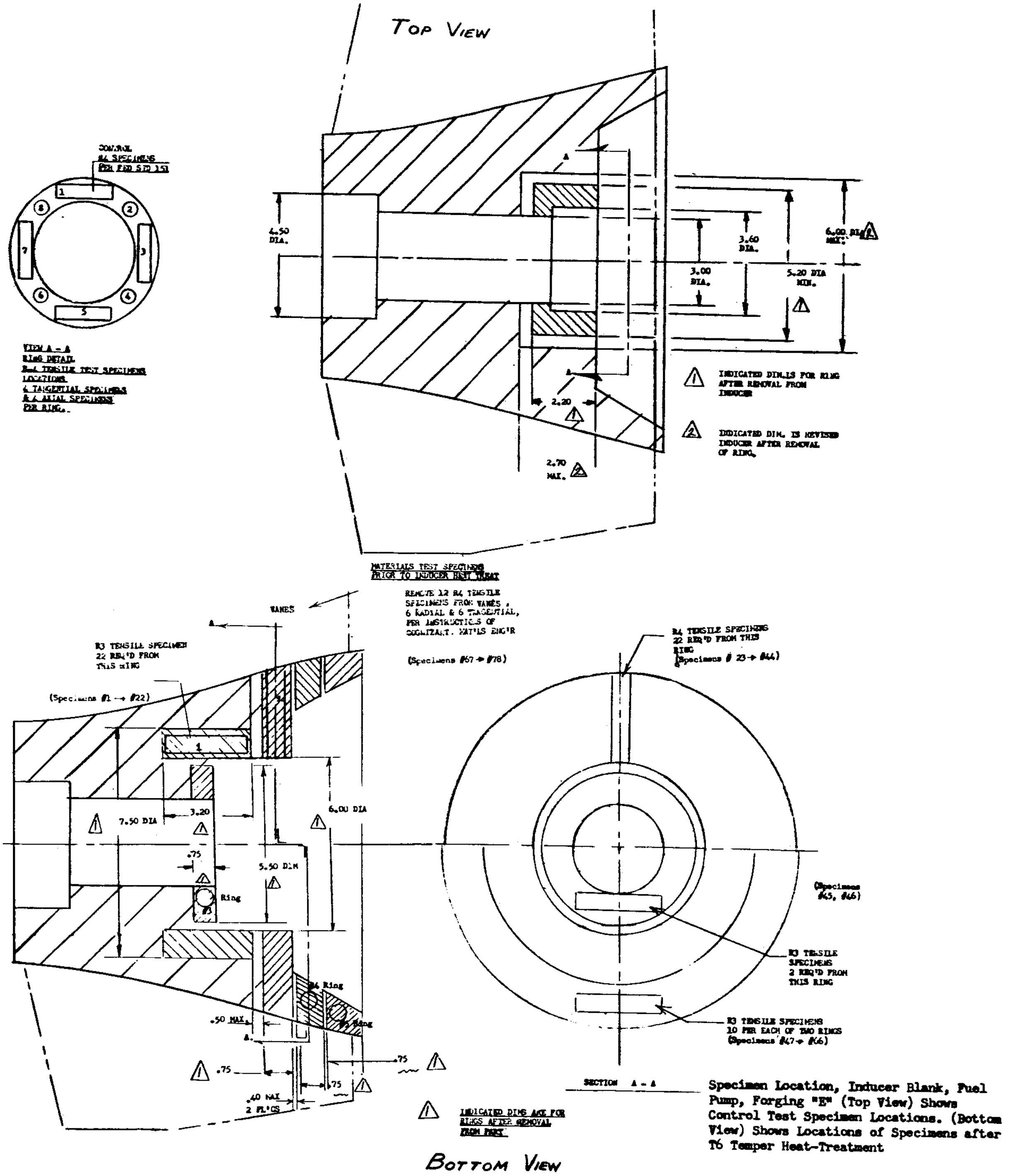
Specimen location, Impeller Blank, Oxidizer Pump, Forgings "A" and "B" specimens from Test Ring and Center Section were of axial, radial, and tangential orientations. Specimens were smooth and notched types per Figure 12.

Figure 9
Specimen Location, Impeller Blank, Oxidizer Pump, Forgings "A" and "B"



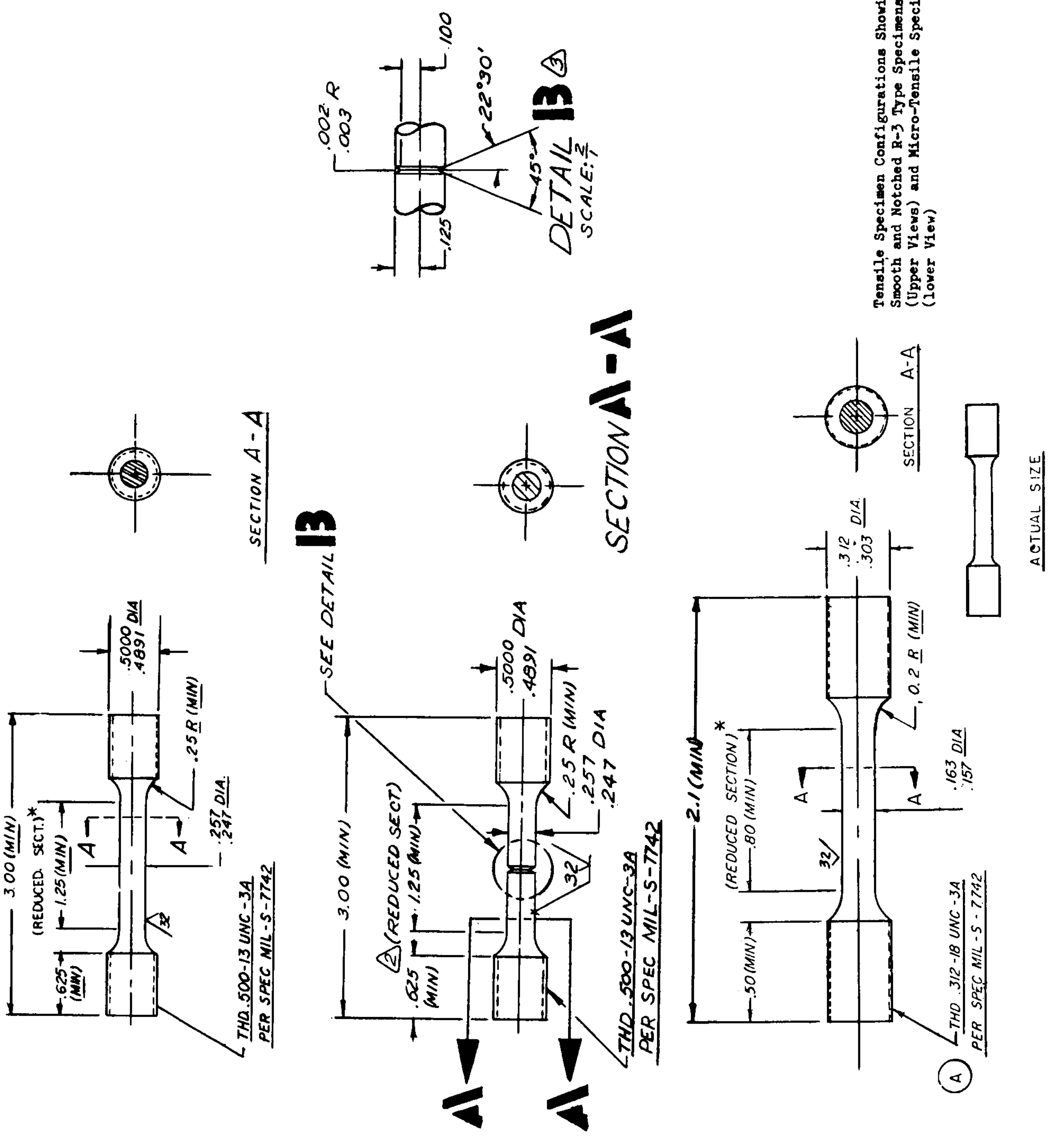
Specimen location, Inducer Blank, Fuel Pump, Forgings "C" and "D" specimens from Test Rings were of tangential orientation. Those from test sections were of axial, radial, and tangential orientations. Specimens were smooth and notched types per Figure 12. Specimens from Inducer, Fuel Pump, Forging "D" were of like tangential orientation as Test Ring specimens and were taken from similar locations.

Figure 10
Specimen Location, Inducer Blank, Fuel Pump, Forgings "C" and "D"



Specimen Location, Inducer Blank, Fuel Pump, Forging "E" (Top View) Shows Control Test Specimen Locations. (Bottom View) Shows Locations of Specimens after T6 Temper Heat-Treatment

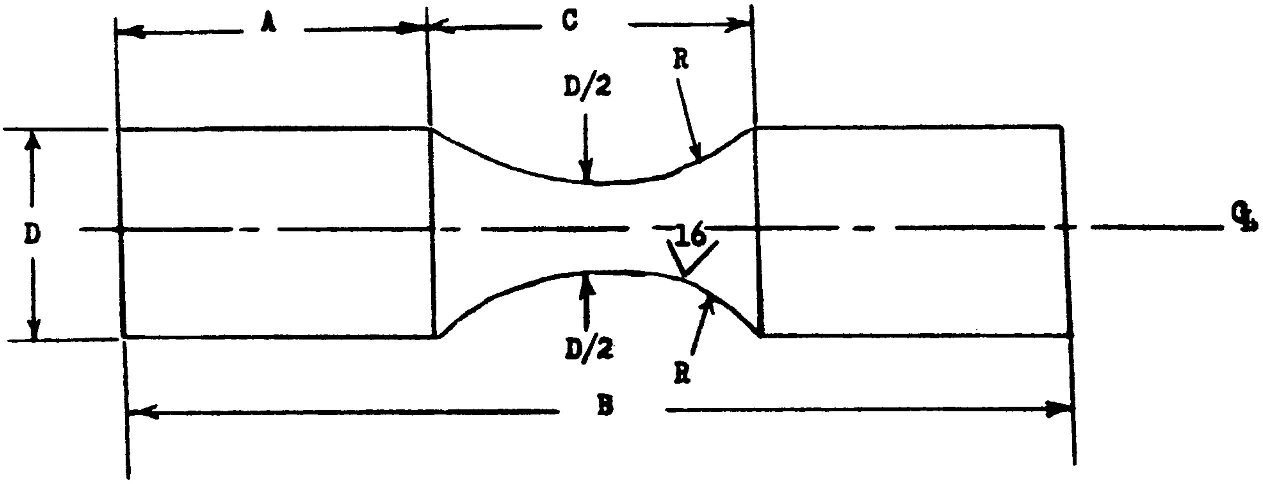
Figure 11
Specimen Location, Inducer Blank, Fuel Pump, Forging "E"



Tensile Specimen Configurations Showing Smooth and Notched R-3 Type Specimens (Upper Views) and Micro-Tensile Specimen (lower View)

Figure 12

Tensile Specimen Configurations



NOT TO SCALE

Dimensions: D = 0.5000 ± 0.0005 in.

A = 1.25 ± 0.125

B = 4.00 ± 0.125

C = 1.50 ± 0.005

R = 2.3125 ± 0.002

Notes: Diameter "D" and "D/2" shall be concentric within 0.001 in.

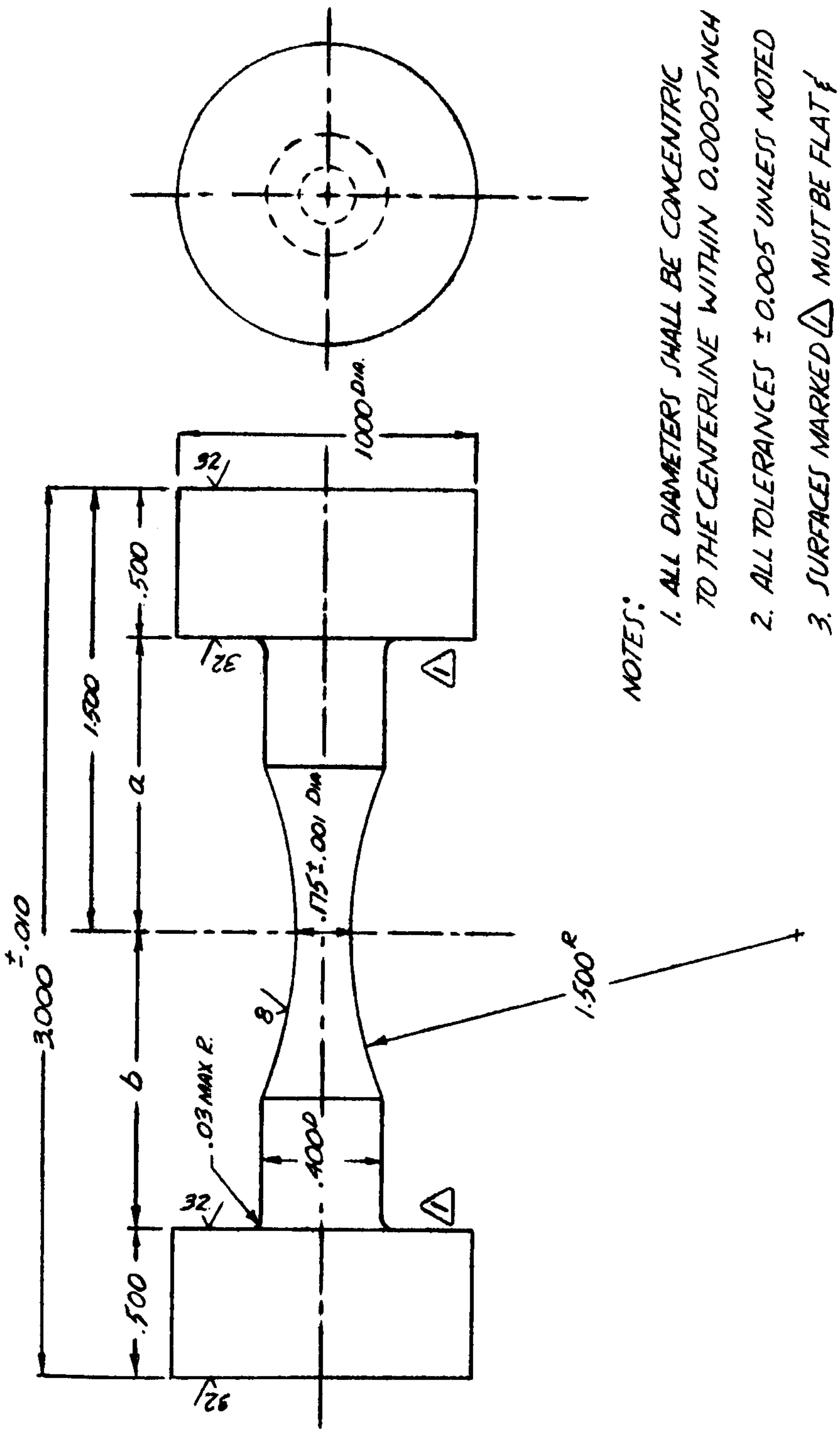
Adjust dimension "D/2" to identify through all specimens ± 0.0002 in.

Specimen not to scale

"C" section shall have √16 max. finish. All other surfaces √32

Figure 13

Rotating Beam Fatigue Specimens



NOTES:

1. ALL DIAMETERS SHALL BE CONCENTRIC TO THE CENTERLINE WITHIN 0.0005 INCH
2. ALL TOLERANCES ± 0.005 UNLESS NOTED
3. SURFACES MARKED △ MUST BE FLAT & PARALLEL WITHIN .0005 AND PERPENDICULAR TO THE CENTER LINE WITHIN .0005.
4. a = b

Figure 14

Tension/Compression Fatigue Specimen

TABLE 6

MECHANICAL PROPERTIES OF 7079-T652 FORGING "A" TEST RING

Specimen	Orientation	Test Temp (°F)	Ultimate Strength (ksi)	0.2% Yield Strength (ksi)	Elongation (% in 4D)	Reduction of Area (%)	Notch Tensile Ratio	Notch Yield Ratio
1	Axial	RT	67.3	49.7	13.5	25.8		
2	Axial	RT	70.5	53.7	14.0	26.4		
3	Axial	RT	75.4	60.1	14.0	19.6		
		Avg.	71.1	54.5	13.8	23.9		
10	Axial	RT	78.4	Notched tensile specimen				
11	Axial	RT	78.9	Notched tensile specimen			(K_t = 6.3)	
12	Axial	RT	84.4	Notched tensile specimen				
		Avg.	80.2	--	--	--	1.13	1.47
19	Radial	RT	63.8	48.4	10.0	11.5		
20	Radial	RT	67.5	51.9	10.0	10.8		
21	Radial	RT	68.6	54.8	9.5	9.9		
		Avg.	66.7	51.7	9.8	10.7		
28	Radial	RT	72.3	Notched tensile specimen				
29	Radial	RT	74.5	Notched tensile specimen			(K_t = 6.3)	
30	Radial	RT	80.4	Notched tensile specimen				
		Avg.	75.7	--	--	--	1.13	1.46
37	Tangential	RT	71.9	59.9	9.5	13.7		
38	Tangential	RT	68.9	56.6	9.5	13.0		
39	Tangential	RT	68.8	57.0	7.5	13.0		
		Avg.	69.9	57.8	8.8	13.2		
46	Tangential	RT	73.9	Notched tensile specimen				
47	Tangential	RT	78.7	Notched tensile specimen			(K_t = 6.3)	
48	Tangential	RT	73.2	Notched tensile specimen				
		Avg.	75.3	--	--	--	1.08	1.30

TABLE 6 (cont.)

Specimen	Orientation	Test Temp (°F)	Ultimate Strength (ksi)	0.2% Yield Strength (ksi)	Elongation (% in 4D)	Reduction of Area (%)	Notch Tensile Ratio	Notch Yield Ratio
4	Axial	-320	77.8	50.1	8.0	15.2		
5	Axial	-320	82.6	63.8	7.0	9.3		
6	Axial	-320	85.6	69.6	4.0	5.5		
		Avg.	82.0	61.2	6.3	10.0		
13	Axial	-320	83.0	Notched tensile specimen				
14	Axial	-320	88.6	Notched tensile specimen			(K_t = 6.3)	
15	Axial	-320	87.9	Notched tensile specimen				
		Avg.	86.5	--	--	--	1.05	1.41
22	Radial	-320	73.5	57.6	5.5	3.15		
23	Radial	-320	76.8	65.0	3.0	3.9		
24	Radial	-320	75.7	68.1	2.0	2.3		
		Avg.	75.3	63.6	3.5	3.1		
31	Radial	-320	75.7	Notched tensile specimen				
32	Radial	-320	67.4	Notched tensile specimen			K_t = 6.3	
33	Radial	-320	62.0	Notched tensile specimen				
		Avg.	68.4	--	--	--	0.91	1.08
40	Tangential	-320	77.7	70.1	2.5	2.3		
41	Tangential	-320	73.7	61.2	4.0	3.9		
42	Tangential	-320	72.0	58.7	3.0	4.7		
		Avg.	74.5	63.3	3.2	3.6		
49	Tangential	-320	74.6	Notched tensile specimen				
50	Tangential	-320	70.7	Notched tensile specimen			K_t = 6.3	
51	Tangential	-320	71.7	Notched tensile specimen				
		Avg.	72.3	--	--	--	0.97	1.14

TABLE 6 (cont.)

Specimen	Orientation	Test Temp (°F)	Ultimate Strength (ksi)	0.2% Yield Strength (ksi)	Elongation (% in 4D)	Reduction of Area (%)	Notch Tensile Ratio	Notch Yield Ratio
7	Axial	-423	82.4	63.7	4.0	6.2		
8	Axial	-423	82.7	63.1	5.0	9.1		
9	Axial	-423	84.0	68.0	4.5	7.0		
		Avg.	83.0	64.9	4.5	7.4		
16	Axial	-423	73.5	Notched tensile specimen				
17	Axial	-423	88.9	Notched tensile specimen			$K_t = 6.3$	
18	Axial	-423	84.3	Notched tensile specimen				
		Avg.	82.2	--	--	--	0.98	1.27
25	Radial	-423	75.2	63.1	3.5	5.4		
26	Radial	-423	76.4	65.6	3.5	4.7		
27	Radial	-423	71.6	--	--	2.3		
		Avg.	74.4	64.4	3.5	4.1		
34	Radial	-423	73.9	Notched tensile specimen				
35	Radial	-423	69.7	Notched tensile specimen			$K_t = 6.3$	
36	Radial	-423	54.5	Notched tensile specimen				
		Avg.	66.0	--	--	--	0.89	1.02
43	Tangential	-423	73.3	--	2.0	3.2		
44	Tangential	-423	69.8	56.8	2.5	4.0		
45	Tangential	-423	66.5	57.3	2.5	4.0		
		Avg.	69.9	57.1	2.3	3.7		
52	Tangential	-423	39.2	Notched tensile specimen				
53	Tangential	-423	69.7	Notched tensile specimen			$K_t = 6.3$	
54	Tangential	-423	54.7	Notched tensile specimen				
		Avg.	54.5	--	--	--	0.78	0.95

TABLE 7

MECHANICAL PROPERTIES OF 7079-T652 FORGING "A" CENTER-SECTION

Specimen	Orientation	Test Temp (°F)	Ultimate Strength (ksi)	0.2% Yield Strength (ksi)	Elongation (% in 4D)	Reduction of Area (%)	Notch Tensile Ratio	Notch Yield Ratio
1	Axial	RT	58.1	--	19.0	32.9		
2	Axial	RT	57.8	--	18.0	29.8		
3	Axial	RT	57.2	36.8	18.0	34.1		
4	Axial	RT	57.9	37.5	19.0	36.1		
		Avg.	57.8	37.2	18.5	33.2		
37	Axial	RT	80.5	Notched tensile specimen				
38	Axial	RT	72.3	Notched tensile specimen			$K_t = 6.3$	
39	Axial	RT	69.8	Notched tensile specimen				
40	Axial	RT	70.8	Notched tensile specimen				
		Avg.	73.4	--	--	--	1.27	1.97
13	Radial	RT	59.2	39.0	15.5	18.9		
14	Radial	RT	58.4	39.2	13.0	20.1		
15	Radial	RT	58.7	39.7	12.0	17.5		
16	Radial	RT	58.3	40.2	13.0	19.5		
		Avg.	58.7	39.5	13.4	19.0		
49	Radial	RT	63.5	Notched tensile specimen				
50	Radial	RT	63.6	Notched tensile specimen				
51	Radial	RT	61.3	Notched tensile specimen			$K_t = 6.3$	
52	Radial	RT	62.5	Notched tensile specimen				
		Avg.	62.7	--	--	--	1.07	1.59
25	Tangential	RT	60.1	41.2	11.5	13.8		
26	Tangential	RT	60.3	41.4	11.5	18.1		
27	Tangential	RT	60.9	42.2	11.5	15.1		
28	Tangential	RT	61.8	43.8	10.5	18.1		
		Avg.	60.8	42.2	11.3	16.3		

TABLE 7 (cont.)

Specimen	Orientation	Test Temp (°F)	Ultimate Strength (ksi)	0.2% Yield Strength (ksi)	Elongation (% in 4D)	Reduction of Area (%)	Notch Tensile Ratio	Notch Yield Ratio
61	Tangential	RT	60.7	Notched tensile specimen				
62	Tangential	RT	60.3	Notched tensile specimen				
63	Tangential	RT	61.0	Notched tensile specimen			$K_t = 6.3$	
64	Tangential	RT	63.0	Notched tensile specimen				
		Avg.	61.3	--	--	--	1.01	1.45
5	Axial	-320	73.3	45.2	19.0	24.3		
6	Axial	-320	73.8	44.9	21.0	24.3		
7	Axial	-320	74.6	46.6	16.0	18.9		
8	Axial	-320	74.0	45.3	17.0	16.7		
		Avg.	73.9	45.5	18.3	21.1		
41	Axial	-320	81.0	Notched tensile specimen				
42	Axial	-320	80.6	Notched tensile specimen				
43	Axial	-320	79.7	Notched tensile specimen			$K_t = 6.3$	
44	Axial	-320	82.3	Notched tensile specimen				
		Avg.	80.9	--	--	--	1.09	1.78
17	Radial	-320	70.2	48.3	6.5	8.5		
18	Radial	-320	72.6	50.1	8.0	10.1		
19	Radial	-320	73.0	50.3	7.5	9.3		
20	Radial	-320	72.2	50.7	6.5	8.5		
		Avg.	72.0	49,9	7.1	9.1		
53	Radial	-320	64.0	Notched tensile specimen				
54	Radial	-320	66.2	Notched tensile specimen				
55	Radial	-320	60.5	Notched tensile specimen			$K_t = 6.3$	
56	Radial	-320	73.5	Notched tensile specimen				
		Avg.	66.1	--	--	--	0.92	1.32

TABLE 7 (cont.)

Specimen	Orientation	Test Temp (°F)	Ultimate Strength (ksi)	0.2% Yield Strength (ksi)	Elongation (% in 4D)	Reduction of Area (%)	Notch Tensile Ratio	Notch Yield Ratio
29	Tangential	-320	72.1	51.9	5.0	4.8		
30	Tangential	-320	73.0	52.7	4.5	7.0		
31	Tangential	-320	74.4	54.8	5.0	7.0		
32	Tangential	-320	75.1	56.7	5.0	6.3		
		Avg.	73.7	54.0	4.9	6.3		
65	Tangential	-320	66.3	Notched tensile specimen				
66	Tangential	-320	69.0	Notched tensile specimen				
67	Tangential	-320	66.7	Notched tensile specimen			K_t = 6.3	
68	Tangential	-320	68.8	Notched tensile specimen				
		Avg.	67.7	--	--	--	0.92	1.26
9	Axial	-423	80.3	49.7	10.0	10.8		
10	Axial	-423	82.1	50.7	10.0	13.7		
11	Axial	-423	80.5	50.6	10.0	14.4		
12	Axial	-423	81.3	0.3	10.0	13.8		
		Avg.	81.1	50.3	10.0	13.2		
45	Axial	-423	71.1	Notched tensile specimen				
46	Axial	-423	76.8	Notched tensile specimen				
47	Axial	-423	78.0	Notched tensile specimen			K_t = 6.3	
48	Axial	-423	71.0	Notched tensile specimen				
		Avg.	74.2	--	--	--	0.915	1.48

TABLE 7 (cont.)

Specimen	Orientation	Test Temp (°F)	Ultimate Strength (ksi)	0.2% Yield Strength (ksi)	Elongation (% in 4D)	Reduction of Area (%)	Notch Tensile Ratio	Notch Yield Ratio
21	Radial	-423	75.5	57.1	4.0	5.8		
22	Radial	-423	77.1	62.2	4.0	6.3		
23	Radial	-423	76.0	55.0	5.0	7.3		
24	Radial	-423	79.2	58.2	5.0	6.3		
		Avg.	76.95	58.1	4.5	6.4		
58	Radial	-423	63.0	Notched tensile specimen				
59	Radial	-423	46.4	Notched tensile specimen			$K_t = 6.3$	
60	Radial	-423	54.9	Notched tensile specimen				
		Avg.	54.8	--	--	--	0.71	0.94
33	Tangential	-423	70.2	59.6	3.5	4.8		
34	Tangential	-423	73.4		3.0	4.8		
35	Tangential	-423	71.8	55.2	3.5	4.8		
36	Tangential	-423	74.5		3.5	4.8		
		Avg.	72.5	57.4	3.4	4.8		
69	Tangential	-423	59.1	Notched tensile specimen				
70	Tangential	-423	70.0	Notched tensile specimen			$K_t = 6.3$	
71	Tangential	-423	53.2	Notched tensile specimen				
		Avg.	60.8	--	--	--	0.84	1.06

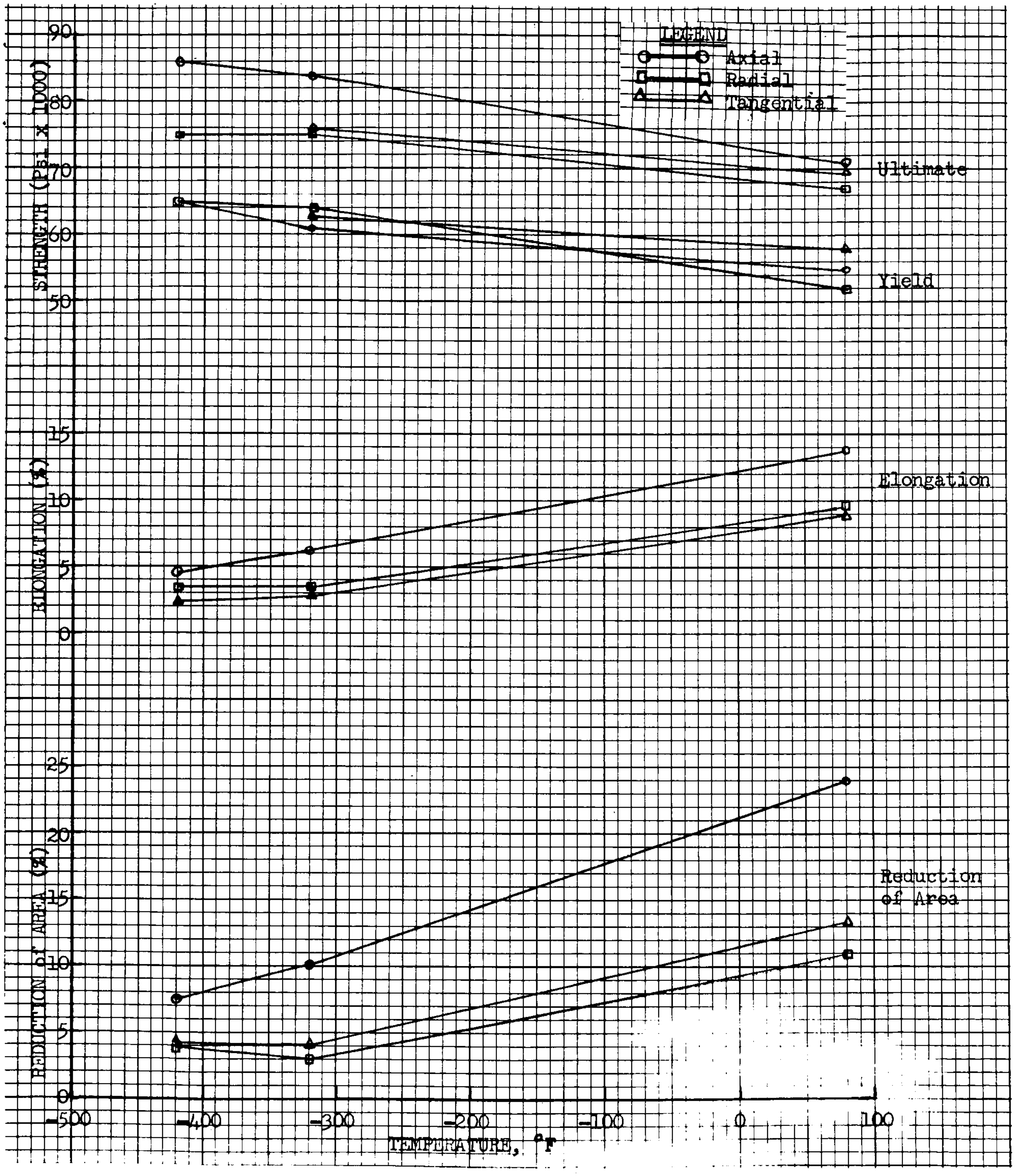


Figure 15
The Effect of Temperature on the Smooth-Bar
Mechanical Properties of Forging "A" Test Ring

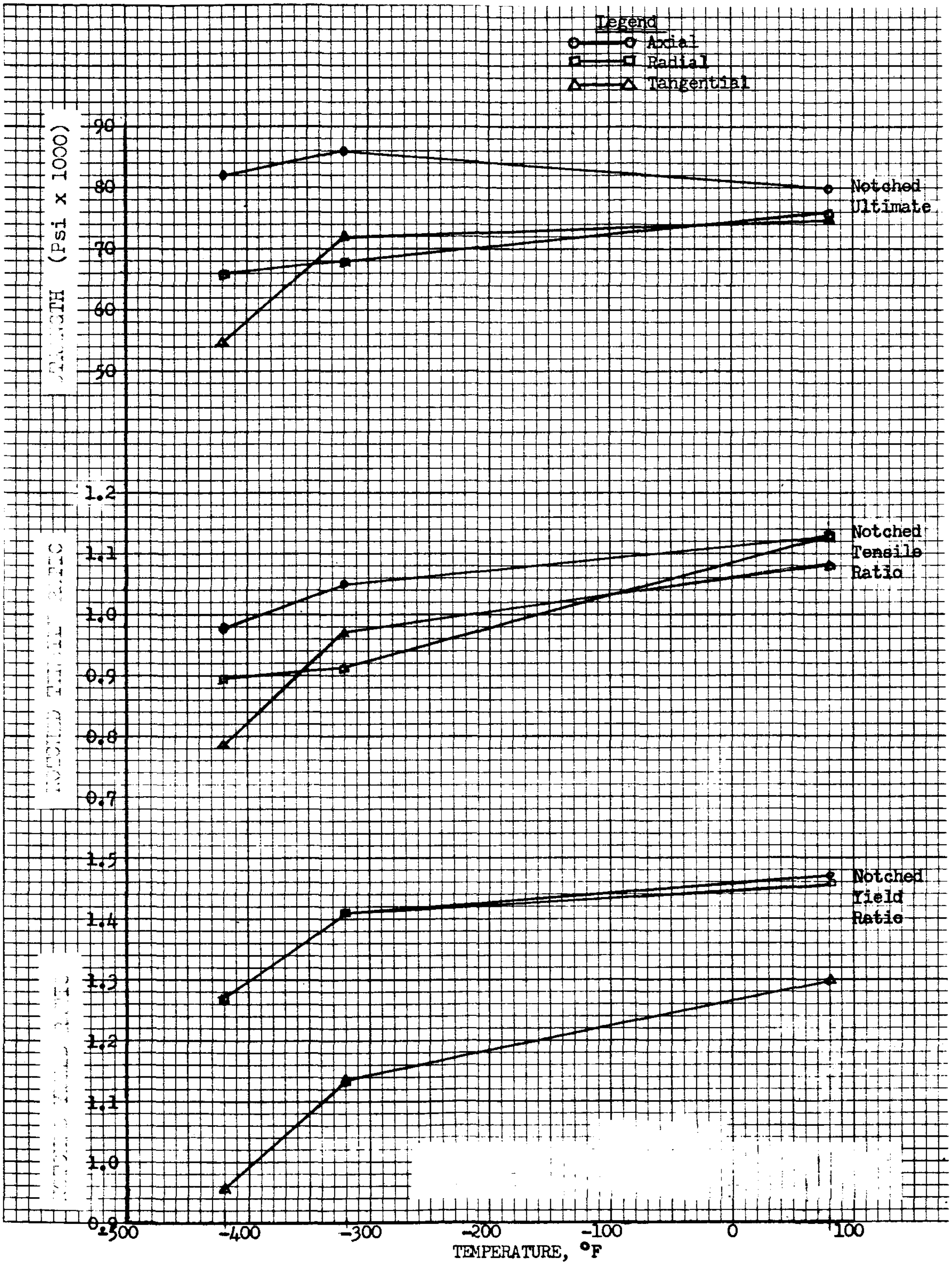


Figure 16
The Effect of Temperature on the Notched-Bar Mechanical Properties of Forging "A" Test Ring

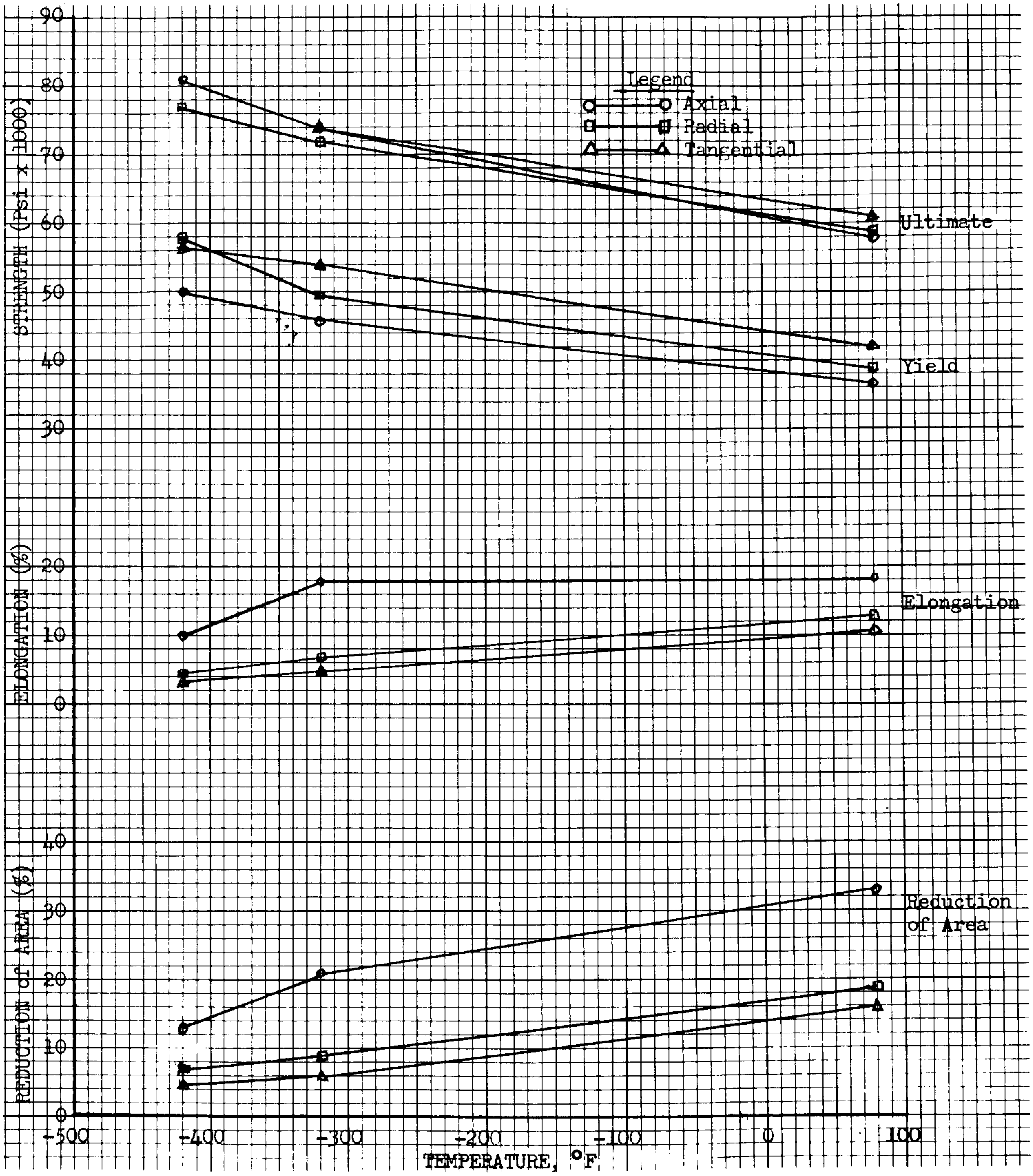


Figure 17
The Effect of Temperature on the Smooth-Bar
Mechanical Properties of Forging "A" Center Section

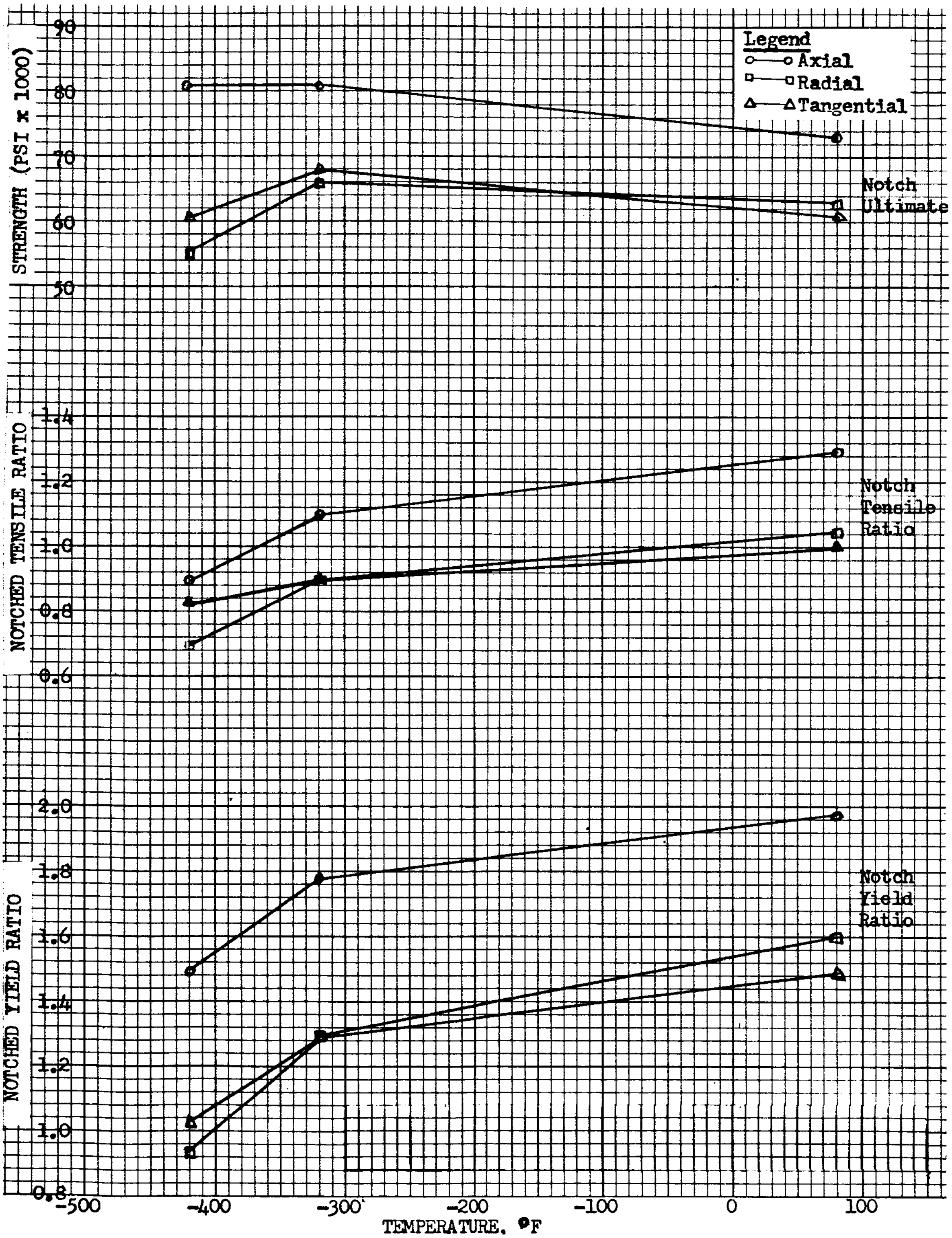


Figure 18
The Effect of Temperature on the Notched-Bar
Mechanical Properties of Forging "A" Center Section

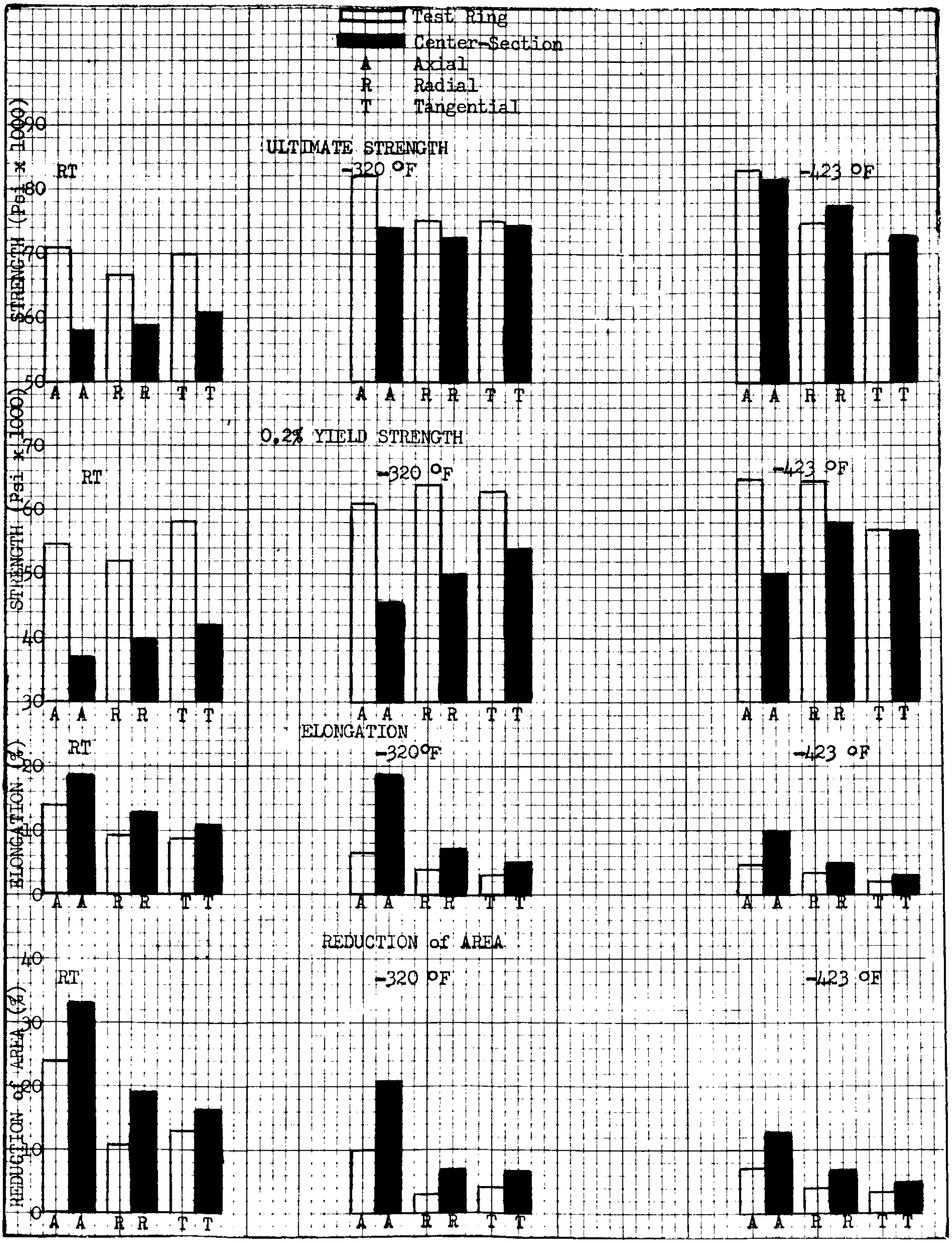


Figure 19
Comparison of Forging "A" Test Ring and Center Section Mechanical Properties

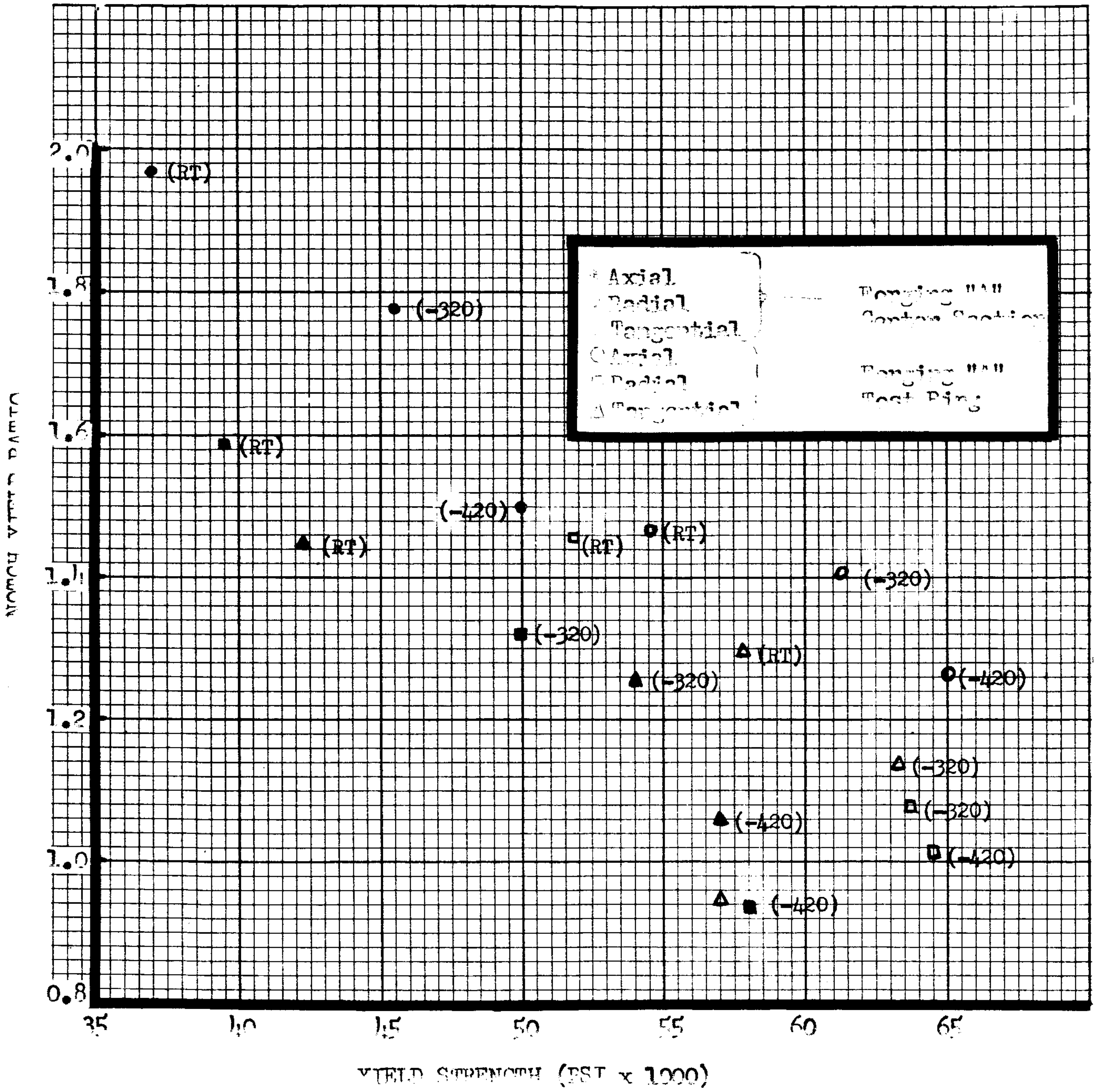


Figure 20
Forging "A" Notch-Yield Ratio vs Yield Strength

b. The ultimate strength increased as the testing temperature was decreased and at approximately the same gradual rate as the yield strength. The 7079 alloy experienced a low work hardening rate, as indicated by the gradual increase with a lowering of temperature.

c. Ductility, as measured by elongation and area reduction, exhibited a reverse trend -- a decrease with lowering of temperature. This is uncommon for a wrought, face-centered-cubic alloy where ductility does not change appreciably with a temperature decrease.

d. The notch-tensile strength and the notch-tensile (notched tensile strength/smooth bar tensile strength) and notch-yield (notched tensile strength/smooth bar yield strength) ratios decreased as the testing temperature was decreased. This is an indication of reduced toughness. The toughness, as measured by notch-yield ratio, is quite good at ambient temperature, is marginal at -320°F, and is poor at -423°F. There was considerable scatter of notch-tensile data at very low temperature, partly because of the relatively poor toughness of Grade 7079.

e. The forging exhibited an anisotropic condition, which is illustrated by the variance of the smooth-bar properties of specimens in the axial, radial, and tangential orientations. The properties were generally highest in the grain flow (axial) direction as is common in other alloys.

f. The mechanical properties were strongly influenced by the mass-quench effect. This is illustrated by the significant variation of the center-section and test ring properties at the corresponding testing temperatures, as shown in Figure 19. The test ring generally had higher strength and lower ductility than the center section. The variation was consistent in the axial, radial and tangential specimen orientations. In a subsequent section of this report it will be shown that the properties are influenced by grain size, which is controlled by hot-working.

g. The notch-yield ratio is an inverse function of yield strength, as shown in Figure 20. Yield strength and ductility are also inversely related. For cryogenic service, a material with a high notch-yield ratio (greater than unity) as well as high yield strength is desired. This condition is not satisfied with Grade 7079 in forgings of the size under consideration.

Recent data (4) related the notch-yield ratio and yield strength for 6061, 5456, 2014, 2019, 7039, and X7106 in a similar notch-yield ratio versus yield-strength plot. Highest notch-yield ratios were obtained with the lowest yield strengths in these aluminum alloys. Adequate combination of high notch-yield ratios and high yield strengths are not observed in these commercial aluminum alloys at very low temperatures.

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(4) Campbell, J.E., Properties and Applications of Aluminum Alloys at Low Temperatures, Battelle Memorial Institute, 1964.

2. Mechanical Properties of Hand Forging "B"

Tensile data for the test ring are listed in Table 8 and shown graphically in Figure 21.

The strengths are slightly higher and the ductilities are lower than those of the Hand Forging "A" test ring. The relative position of the test rings with respect to the periphery of the forging is shown in Figure 9. Specimens of Hand Forging "B" were taken closer to the surface where greater hardening response and mechanical working resulted in higher strength.

In agreement with previous data, strength and ductility are influenced in a manner similar to that described previously upon exposure to low temperatures. At low temperatures, the YS/UTS ratios (yield strength to ultimate strength in a smooth-bar test specimen) were notably high, which is undesirable in a cryogenic alloy.

Based upon notch-yield criteria, the test ring is relatively notch tough at ambient temperature and when axially oriented at -320°F. Notch-sensitivity is apparent in the radial and tangential orientations at -320°F, and in all orientations at -423°F.

3. Mechanical Properties of Hand Forging "C"

The low temperature tests described earlier were performed using a slightly smaller forging (see Figure 10). Properties at the test ring, top, center, and bottom locations were studied. These data are listed in Tables 9 and 10 and illustrated graphically in Figures 22 through 24.

The test results indicate the following significant features:

a. The data are in agreement with previous findings regarding the effect of temperature upon mechanical properties. It confirmed that when the temperature is lowered, strengths and notch sensitivity are increased while ductility is decreased.

b. Highest strengths were obtained in the test ring. Lowest strength, superior toughness, and highest ductilities were obtained at the center section. The top and bottom section properties were essentially equivalent.

Generally, when comparing the center-section properties of the impeller and inducer forgings (viz., Forgings "A" and "C", respectively), Forging "A" has inferior strength but superior ductility (see Figures 25 and 26). Highest strengths are obtained near the quenched surface while ductility variations are smaller (see Figure 27).

All of the above observations are based upon experimental results and allow the following general conclusions to be drawn. The 7079-T652 forgings have relatively poor toughness at a temperature of -423°F. Also,

TABLE 8

MECHANICAL PROPERTIES OF 7079-T652 FORGING "B" TEST RING

Specimen	Orientation	Test Temp (°F)	Ultimate Strength (ksi)	0.2% Yield Strength (ksi)	Elongation (% in 4D)	Reduction of Area (%)	Notch Tensile Ratio	Notch Yield Ratio
1	Axial	RT	75.5	62.5	10.5	22.4		
2	Axial	RT	76.3	62.4	10.0	19.8		
3	Axial	RT	75.4	62.2	12.0	16.1		
4	Axial	RT	73.1	61.0	9.0	17.4		
		Avg.	75.1	62.0	10.4	18.9		
37	Axial	RT	93.5	Notched tensile specimen			$K_t = 6.3$	
38	Axial	RT	93.9	Notched tensile specimen				
39	Axial	RT	95.1	Notched tensile specimen				
40	Axial	RT	94.1	Notched tensile specimen				
		Avg.	94.2				1.25	1.52
13	Radial	RT	71.1	63.4	5.0	9.1		
14	Radial	RT	72.0	63.6	5.0	7.0		
15	Radial	RT	72.1	63.5	5.5	7.7		
16	Radial	RT	79.6	62.2	4.0	4.7		
		Avg.	71.2	63.2	4.9	7.1		
49	Radial	RT	83.4	Notched tensile specimen				
50	Radial	RT	79.2	Notched tensile specimen			$K_t = 6.3$	
51	Radial	RT	85.8	Notched tensile specimen				
52	Radial	RT	87.3	Notched tensile specimen				
		Avg.	88.9				1.25	1.41
25	Tangential	RT	74.4	64.4	6.0	9.2		
26	Tangential	RT	71.2	61.1	6.0	7.8		
27	Tangential	RT	71.3	60.9	6.0	6.3		
28	Tangential	RT	70.9	61.4	5.0	7.0		
		Avg.	72.0	62.0	5.8	7.6		

TABLE 8 (cont.)

Specimen	Orientation	Test Temp (°F)	Ultimate Strength (ksi)	0.2% Yield Strength (ksi)	Elongation (% in 4D)	Reduction of Area (%)	Notch Tensile Ratio	Notch Yield Ratio
61	Tangential	RT	77.8	Notched tensile specimen				
62	Tangential	RT	76.9	Notched tensile specimen			$K_t = 6.3$	
63	Tangential	RT	74.4	Notched tensile specimen				
		Avg.	76.4			1.10		1.23
5	Axial	-320	83.3	72.5	3.5	3.9		
6	Axial	-320	80.9	71.1	3.5	5.5		
7	Axial	-320	87.4	--	3.5	5.6		
8	Axial	-320	86.7	75.2	3.5	4.0		
		Avg.	84.6	72.9	3.5	4.8		
41	Axial	-320	88.5	Notched tensile specimen				
42	Axial	-320	88.4	Notched tensile specimen			$K_t = 6.3$	
43	Axial	-320	--					
44	Axial	-320	83.4	Notched tensile specimen				
		Avg.	86.8				1.03	1.19
17	Radial	-320	74.7	--	2.0	1.6		
18	Radial	-320	78.1	78.1	2.0	4.7		
19	Radial	-320	75.4	71.8	2.0	3.1		
20	Radial	-320	73.5	71.3	2.0	5.4		
		Avg.	75.4	73.7	2.0	3.7		
53	Radial	-320	64.1	Notched tensile specimen				
54	Radial	-320	67.9	Notched tensile specimen			$K_t = 6.3$	
55	Radial	-320	--					
56	Radial	-320	61.6	Notched tensile specimen				
		Avg.	64.5				0.86	0.87

TABLE 8 (cont.)

Specimen	Orientation	Test Temp (°F)	Ultimate Strength (ksi)	0.2% Yield Strength (ksi)	Elongation (% in 4D)	Reduction of Area (%)	Notch Tensile Ratio	Notch Yield Ratio
29	Tangential	-320	75.8	73.2	3.0	3.1		
30	Tangential	-320	77.1	73.4	2.5	2.3		
31	Tangential	-320	78.4	78.1	2.0	2.3		
32	Tangential	-320	75.8	--	2.5	2.3		
		Avg.	76.8	74.9	2.0	2.5		
65	Tangential	-320	50.2	Notched tensile specimen				
66	Tangential	-320	62.1	Notched tensile specimen				
67	Tangential	-320	44.8	Notched tensile specimen			$K_t = 6.3$	
68	Tangential	-320	43.7	Notched tensile specimen				
		Avg.	50.2				0.65	0.67
9	Axial	-423	86.6	77.0	(1)	2.4		
10	Axial	-423	90.9	84.3	3.0	0.8		
11	Axial	-423	89.5	83.6	3.0	0.8		
12	Axial	-423	86.1	82.8	(1)	0.8		
		Avg.	88.0	81.9	3.0	1.2		
45	Axial	-423	49.2	Notched tensile specimen				
46	Axial	-423	68.5	Notched tensile specimen				
47	Axial	-423	75.2	Notched tensile specimen			$K_t = 6.3$	
48	Axial	-423	87.1	Notched tensile specimen				
		Avg.	70.0				0.80	0.86
21	Radial	-423	78.1	77.8	1.0	0.0		
22	Radial	-423	73.2(3)	(2)	1.0	0.0		
23	Radial	-423	76.4(3)	(2)	0.0	0.0		
24	Radial	-423	78.7(3)	(2)	0.0	0.0		
		Avg.	78.1	77.8	0.5	0.0		

TABLE 8 (cont.)

Specimen	Orientation	Test Temp (°F)	Ultimate Strength (ksi)	0.2% Yield Strength (ksi)	Elongation (% in 4D)	Reduction of Area (%)	Notch Tensile Ratio	Notch Yield Ratio
57	Radial	-423	55.9	Notched tensile specimen				
58	Radial	-423	55.9	Notched tensile specimen				
59	Radial	-423	45.8	Notched tensile specimen			$K_t = 6.3$	
60	Radial	-423	58.8	Notched tensile specimen				
		Avg.	54.1				0.69	0.695
34	Tangential	-423	75.8(3)	(2)	0.0	0.0		
34	Tangential	-423	60.6(3)	(2)	0.0	0.0		
35	Tangential	-423	78.1(3)	(2)	1.0	0.0		
36	Tangential	-423	82.3	81.7	1.0	0.8		
		Avg.	82.3	81.7	0.5	0.8		
69	Tangential	-423	27.6	Notched tensile specimen				
70	Tangential	-423	16.1	Notched tensile specimen				
71	Tangential	-423	46.9	Notched tensile specimen			$K_t = 6.3$	
72	Tangential	-423	49.5	Notched tensile specimen				
		Avg.	35.0				0.426	0.428

NOTES:

1. Specimen fractured outside of the gage mark.
2. No yield obtained in specimen during stressing.
3. Not included in average of results.

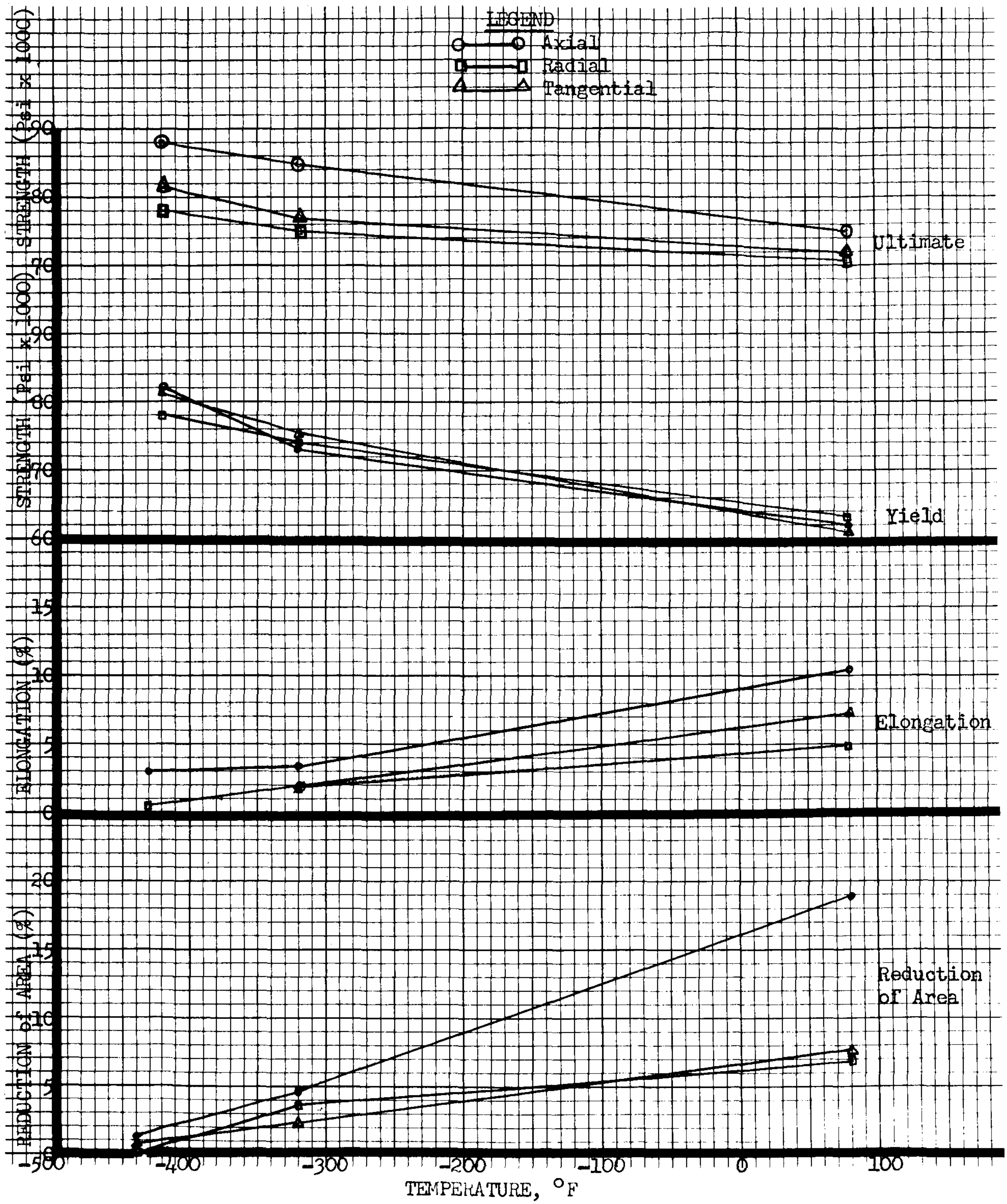

Figure 21
The Effect of Temperature on Test Ring Smooth-Bar Mechanical Properties of Forging "B" Test Ring

TABLE 9

MECHANICAL PROPERTIES OF 7079-T652 FORGING "C" TEST RING

Specimen	Orientation	Area	Test Temp ($^{\circ}F$)	Ultimate Strength (KSI)	0.2% Yield Strength (KSI)	Elongation (% in 4D)	Reduction of Area (%)	Stress Concentr. (K_T)	Notch Tensile Ratio	Notch Yield Ratio
A. Test Ring No. 1										
24-C	Tangential	Periphery	RT	76.4	66.6	9.0	15.5			
26-C	Tangential	Periphery	RT	74.5	63.9	7.0	15.5			
28-C	Tangential	Periphery	RT	76.4	67.9	7.0	9.4			
			Avg.	75.8	66.1	7.7	13.5			
23-C	Tangential	Periphery	RT	84.6	Notched tensile specimen			5.2		
25-C	Tangential	Periphery	RT	83.4	Notched tensile specimen			5.4		
27-C	Tangential	Periphery	RT	87.1	Notched tensile specimen			6.2		
			Avg.	85.0					1.12	1.29
B. Test Ring No. 2										
10-A	Tangential	Periphery	-423	93.4	87.9	2.0	2.5			
12-A	Tangential	Periphery	-423	91.7	82.5	1.5	0.8			
14-A	Tangential	Periphery	-423	94.8	83.2	2.0	1.6			
16-A	Tangential	Periphery	-423	97.5	89.3	1.0	0.8			
			Avg.	94.4	87.7	1.6	1.4			
9-A	Tangential	Periphery	-423	61.8	Notched tensile specimen			7.3		
11-A	Tangential	Periphery	-423	62.7	Notched tensile specimen			6.9		
13-A	Tangential	Periphery	-423	77.9	Notched tensile specimen			6.6		
15-A	Tangential	Periphery	-423	79.0	Notched tensile specimen			6.2		
			Avg.	70.6					0.75	0.805

TABLE 10

MECHANICAL PROPERTIES OF 7079-T652 FORGING "C"
TOP, CENTER, AND BOTTOM SECTIONS

A. TOP SECTION

SPECIMEN	ORIENTATION	AREA	TEST TEMP (°F)	ULTIMATE STRENGTH (KSI)	0.2% YIELD STRENGTH (KSI)	ELONGATION (% IN 4D)	REDUCTION OF AREA (%)	STRESS CONCENTR. (K_T)	NOTCH TENSILE RATIO	NOTCH YIELD RATIO
1	TANGENTIAL	1/2 RADIUS	RT	68.4	54.6	9.0	13.0			
4	TANGENTIAL	1/2 RADIUS	RT	66.9	NOTCHED TENSILE SPECIMEN			4.4	0.98	1.22
2	AXIAL	1/2 RADIUS	RT	65.4	51.1	6.5	13.1			
5	AXIAL	1/2 RADIUS	RT	64.6	NOTCHED TENSILE SPECIMEN				0.99	1.26
16	AXIAL	3/4 RADIUS	RT	64.1	49.1	11.0	14.6			
3	RADIAL	1/2 RADIUS	RT	67.3	53.1	11.5	15.9			
6	RADIAL	1/2 RADIUS	RT	78.7	NOTCHED TENSILE SPECIMEN			5.2	1.17	1.48
18	RADIAL	3/4 RADIUS	RT	60.2	NOTCHED TENSILE SPECIMEN			4.2		
1A	TANGENTIAL	1/2 RADIUS	-320	78.4	--	3.0	3.3			
2A	TANGENTIAL	1/4 RADIUS	-320	75.6	66.4	3.0	4.0			
			AVG.	77.0	66.4	3.0	3.7			
7A	TANGENTIAL	1/4 RADIUS	-320	78.3	NOTCHED TENSILE SPECIMEN			6.3		
8A	TANGENTIAL	1/4 RADIUS	-320	80.1	NOTCHED TENSILE SPECIMEN			6.3		
			AVG.	79.2					1.03	1.19
3A	AXIAL	1/4 RADIUS	-320	78.3	68.3	2.0	3.2			
4A	AXIAL	1/4 RADIUS	-320	79.9	60.2	2.5	3.2			
			AVG.	75.8	64.3	2.25	3.2			

TABLE 10 (CONT.)

Specimen	Orientation	Area	Test Temp (°F)	Ultimate Strength (ksi)	0.2% Yield Strength (ksi)	Elongation (% in 4D)	Reduction of Area (%)	Stress Concentr. (K_T)	Notch Tensile Ratio	Notch Yield Ratio
5A	Axial	1/4 Radius	-320	72.7	Notched tensile specimen			6.3		
6A	Axial	1/4 Radius	-320	65.0	Notched tensile specimen			6.3		
			Avg.	68.9					0.91	1.07
9A	Radial	1/4 Radius	-320	78.7	68.5	3.0	4.7			
10A	Radial	1/4 Radius	-320	78.5	66.7	4.0	4.8			
			Avg.	78.6	67.6	3.5	4.75			
11A	Radial	1/4 Radius	-320	87.6	Notched tensile specimen			6.3		
12A	Radial	1/4 Radius	-320	84.7	Notched tensile specimen			6.3		
			Avg.	86.2					1.10	1.27
7	Tangential	1/2 Radius	-423	83.9	72.0	3.0	2.4			
13	Tangential	1/2 Radius	-423	80.3	71.0	2.0	2.4			
			Avg.	82.1	71.5	2.5	2.4			
10	Tangential	1/2 Radius	-423	56.6	Notched tensile specimen			4.8	0.69	0.791
17	Tangential	3/4 Radius	-423	80.7	64.4	3.0	2.4			
8	Axial	1/2 Radius	-423	79.4	65.2	2.0	2.4			
14(1)	Axial	1/2 Radius	-423	78.6	--	3.0	0.8			
			Avg.	79.0	65.2	2.5	1.6			
11	Axial	1/2 Radius	-423	58.0	Notched tensile specimen			4.6	0.734	0.89
19	Axial	3/4 Radius	-423	74.1	Notched tensile specimen					
12	Radial	1/2 Radius	-423	70.9	Notched tensile specimen			4.7	0.86	1.01

TABLE 10 (CONT.)

SPECIMEN	ORIENTATION	AREA	TEST TEMP (°F)	ULTIMATE STRENGTH (KSI)	0.2% YIELD STRENGTH (KSI)	ELONGATION (% IN 4D)	REDUCTION OF AREA (%)	STRESS CONCENTR. (K_T)	NOTCH TENSILE RATIO	NOTCH YIELD RATIO
9	RADIAL	1/2 RADIUS	-423	83.0	72.2	2.0	3.1			
15	RADIAL	1/2 RADIUS	-423	82.6	68.4	3.0	3.2			
			AVG.	82.8	70.3	2.5	3.15			
B. CENTER SECTION										
26	TANGENTIAL	1/4 RADIUS	RT	64.6	48.7	8.5	13.8			
28	TANGENTIAL	1/2 RADIUS	RT	66.6	50.9	12.0	16.7			
31	TANGENTIAL	1/2 RADIUS	RT	76.7	NOTCHED TENSILE SPECIMEN			6.1	1.15	1.5
27	AXIAL	1/4 RADIUS	RT	64.0	48.5	10.0	11.5			
29	AXIAL	1/2 RADIUS	RT	62.0	44.7	9.0	13.1			
32	AXIAL	1/2 RADIUS	RT	62.1	NOTCHED TENSILE SPECIMEN			4.5	1.0	1.39
43	AXIAL	3/4 RADIUS	RT	62.3	45.9	8.5	14.5			
30	RADIAL	1/2 RADIUS	RT	64.8	48.7	12.0	16.7			
33	RADIAL	1/2 RADIUS	RT	67.9	NOTCHED TENSILE SPECIMEN			4.95	1.15	1.39
45	RADIAL	3/4 RADIUS	RT	62.2	46.7	7.0	13.7			
17B	TANGENTIAL	1/4 RADIUS	-320	79.0	66.1	3.0	5.5			
18B	TANGENTIAL	1/4 RADIUS	-320	79.1	66.0	3.0	4.8			
			AVG.	79.05	66.05	3.0	5.2			

TABLE 10 (CONT.)

Specimen	Orientation	Area	Test Temp (°F)	Ultimate Strength (ksi)	0.2% Yield Strength (ksi)	Elongation (% in 4D)	Reduction of Area (%)	Stress Concentr. (K_T)	Notch Tensile Ratio	Notch Yield Ratio
19B	Tangential	1/4 Radius	-320	82.0	Notched tensile specimen			6.3		
20B	Tangential	1/4 Radius	-320	77.7	Notched tensile specimen			6.3		
			Avg.	79.9					1.01	1.21
13B	Axial	1/4 Radius	-320	71.2	56.0	2.5	4.0			
14B	Axial	1/4 Radius	-320	71.4	57.4	2.5	4.8			
			Avg.	71.3	56.7	2.5	4.4			
15B	Axial	1/4 Radius	-320	69.4	Notched tensile specimen			6.3		
16B	Axial	1/4 Radius	-320	75.6	Notched tensile specimen			6.3		
			Avg.						1.02	1.28
21B	Radial	1/4 Radius	-320	77.3	63.6	4.0	4.0			
22B	Radial	1/4 Radius	-320	77.2	64.2	3.5	4.7			
			Avg.	77.25	63.9	3.75	4.35			
23B	Radial	1/4 Radius	-320	79.4	Notched tensile specimen			6.3		
24B	Radial	1/4 Radius	-320	80.4	Notched tensile specimen			6.3		
			Avg.	79.9					1.03	1.25
20	Tangential	1/4 Radius	-423	84.9	69.0	2.0	4.0			
23	Tangential	1/4 Radius	-423	63.0	Notched tensile specimen			4.6	0.74	0.914
34	Tangential	1/2 Radius	-423	84.7	65.8	2.0	3.2			
40	Tangential	1/2 Radius	-423	84.1	65.2	2.0	3.2			
			Avg.	84.4	65.5	2.0	3.2			
37	Tangential	1/2 Radius	-423	66.4	Notched tensile specimen			4.9	0.786	1.01

TABLE 10 (CONT.)

Specimen	Orientation	Area	Test Temp (^{o}F)	Ultimate Strength (ksi)	0.2% Yield Strength (ksi)	Elongation (% in 4D)	Reduction of Area (%)	Stress Concentr. (K_T)	Notch Tensile Ratio	Notch Yield Ratio
44	Tangential	3/4 Radius	-423	88.6	67.5	3.0	5.0			
22(2)	Axial	1/4 Radius	-423	74.0	59.4	2.0	2.4			
25	Axial	1/4 Radius	-423	54.1	Notched tensile specimen			4.5	0.73	0.91
35(2)	Axial	1/2 Radius	-423	74.0	59.0	3.0	2.4			
41(3)	Axial	1/2 Radius	-423	73.2	60.7	2.0	2.4			
			Avg.	73.6	59.9	2.5	2.4			
38	Axial	1/2 Radius	-423	60.6	Notched tensile specimen			5.8	0.823	1.01
46	Axial	3/4 Radius	-423	87.2	66.3	3.0	3.2			
21	Radial	1/4 Radius	-423	82.1	71.3	2.0	2.4			
24	Radial	1/4 Radius	-423	65.6	Notched tensile specimen			4.8	0.80	0.92
36	Radial	1/2 Radius	-423	80.9	64.4	3.0	4.0			
42	Radial	1/2 Radius	-423	81.7	65.0	2.0	3.2			
			Avg.	81.3	64.7	2.5	3.6			
39	Radial	1/2 Radius	-423	60.4	Notched tensile specimen			5.1	0.744	0.934
C. Bottom Section										
47	Tangential	1/2 Radius	RT	67.5	56.7	8.5	11.5			
50	Tangential	1/2 Radius	RT	71.1	Notched tensile specimen			4.4	1.05	1.25

TABLE 10 (CONT.)

SPECIMEN	ORIENTATION	AREA	TEST TEMP (°F)	ULTIMATE STRENGTH (KSI)	0.2% YIELD STRENGTH (KSI)	ELONGATION (% IN 4D)	REDUCTION OF AREA (%)	STRESS CONCENTR. (K_T)	NOTCH TENSILE RATIO	NOTCH YIELD RATIO
48	AXIAL	1/2 RADIUS	RT	64.4	49.9	7.5	13.7			
51	AXIAL	1/2 RADIUS	RT	66.0	NOTCHED TENSILE SPECIMEN			4.7	1.03	1.32
62	AXIAL	3/4 RADIUS	RT	64.2	50.1	8.5	13.7			
49	RADIAL	1/2 RADIUS	RT	68.4	57.2	8.0	10.8			
52	RADIAL	1/2 RADIUS	RT	70.2	NOTCHED TENSILE SPECIMEN			4.2	1.03	1.23
64	RADIAL	3/4 RADIUS	RT	65.1	51.3	10.0	15.3			
33	TANGENTIAL	1/4 RADIUS	-320	77.3	63.6	4.0	6.3			
34	TANGENTIAL	1/4 RADIUS	-320	78.4	63.1	5.0	5.5			
			AVG.	77.9	63.4	4.5	5.9			
35	TANGENTIAL	1/4 RADIUS	-320	80.7	NOTCHED TENSILE SPECIMEN			6.3		
36	TANGENTIAL	1/4 RADIUS	-320	83.8	NOTCHED TENSILE SPECIMEN			6.3		
			AVG.	82.3					1.06	1.30
29	AXIAL	1/4 RADIUS	-320	75.1	65.6	3.0	4.0			
30	AXIAL	1/4 RADIUS	-320	76.3	62.9	4.0	5.6			
			AVG.	75.7	64.3	3.5	4.8			
31	AXIAL	1/4 RADIUS	-320	84.7	NOTCHED TENSILE SPECIMEN			6.3		
32	AXIAL	1/4 RADIUS	-320	83.0	NOTCHED TENSILE SPECIMEN			6.3		
			AVG.	83.9					1.11	1.31
25CX	RADIAL	1/4 RADIUS	-320	73.7	61.6	3.0	5.4			
26CX	RADIAL	1/4 RADIUS	-320	71.8	59.1	3.0	4.8			
			AVG.	72.8	60.4	3.0	5.1			

TABLE 10 (CONT.)

Specimen	Orientation	Area	Test Temp (°F)	Ultimate Strength (ksi)	0.2% Yield Strength (ksi)	Elongation (% in 4D)	Reduction of Area (%)	Stress Concentr. (K_T)	Notch Tensile Ratio	Notch Yield Ratio
27CX	Radial	1/4 Radius	-320	72.5	Notched tensile specimen			6.3		
28CX	Radial	1/4 Radius	-320	72.7	Notched tensile specimen			6.3		
			Avg.	72.6					0.99	1.20
53	Tangential	1/2 Radius	-423	79.1	68.2	3.0	2.4			
59(5)	Tangential	1/2 Radius	-423	77.3		1.0	2.4			
			Avg.	78.2	68.2	2.0	2.4			
56	Tangential	1/2 Radius	-423	57.2	Notched tensile specimen			3.1	0.73	0.84
63	Tangential	3/4 Radius	-423	81.7	77.5	1.0	1.6			
54(4)	Axial	1/2 Radius	-423	75.7	64.2	1.0	2.4			
60	Axial	1/2 Radius	-423	76.0	60.7	3.0	2.4			
			Avg.	75.9	62.5	2.0	2.4			
57	Axial	1/2 Radius	-423	54.2	Notched tensile specimen			3.5	0.715	0.87
65	Axial	3/4 Radius	-423	77.5	68.4	1.0	1.6			
55	Radial	1/2 Radius	-423	85.7	77.9	2.0	1.6			
58	Radial	1/2 Radius	-423	58.0	Notched tensile specimen			3.2	0.676	0.745
61(6)	Radial	1/2 Radius	-423	78.7	71.2	--	0.8			

NOTES:

1. Extensometer froze
2. Specimen may not have been completely covered with LH_2 due to a short in the liquid sensor
3. Specimen was undercut in the radius
4. Specimen failed at point of extensometer attachment
5. Extensometer slipped
6. Specimen failed at gage marks

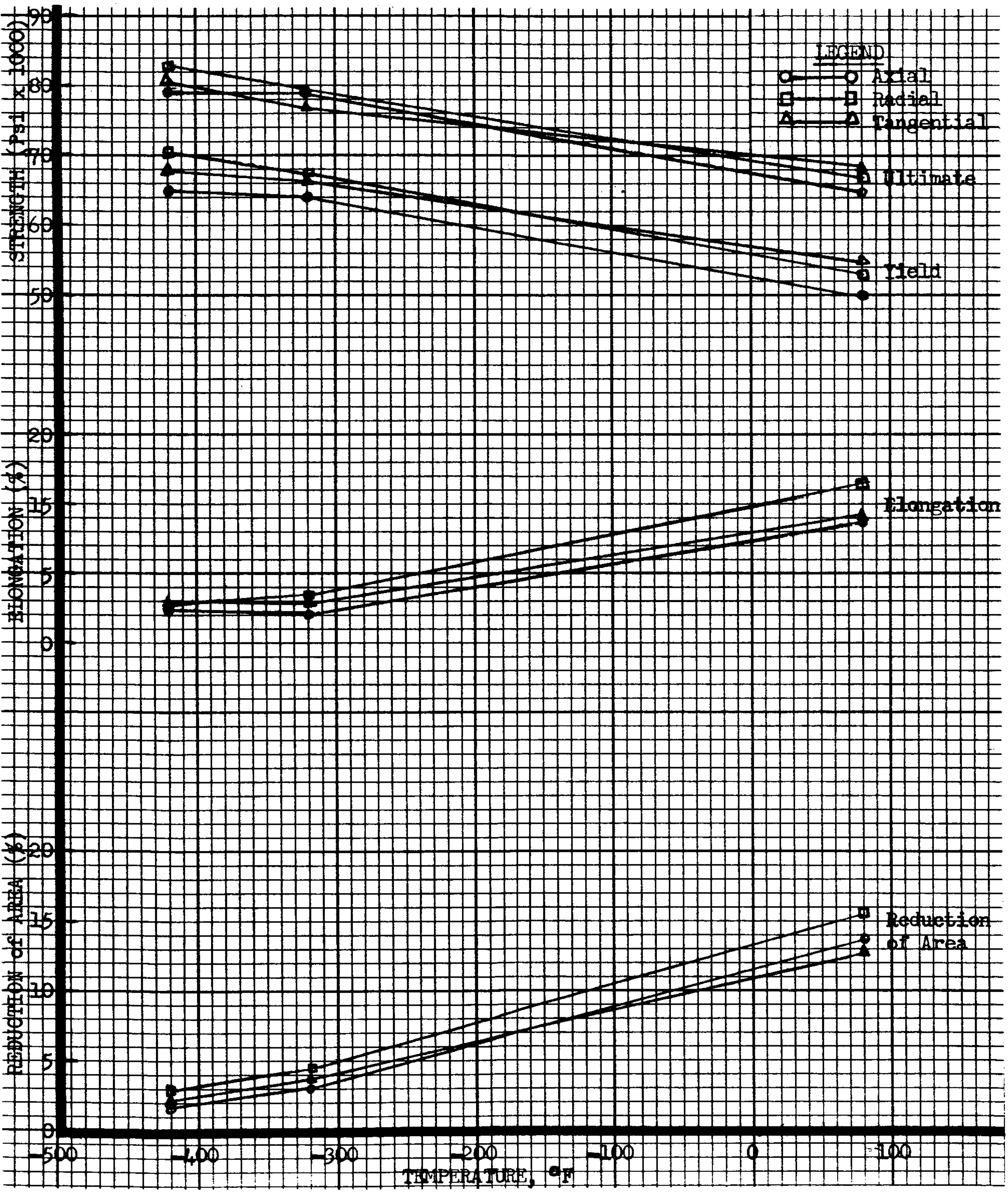

Figure 22
The Effect of Temperature on the Smooth Bar Mechanical Properties of Forging "C" at the Top Section Area

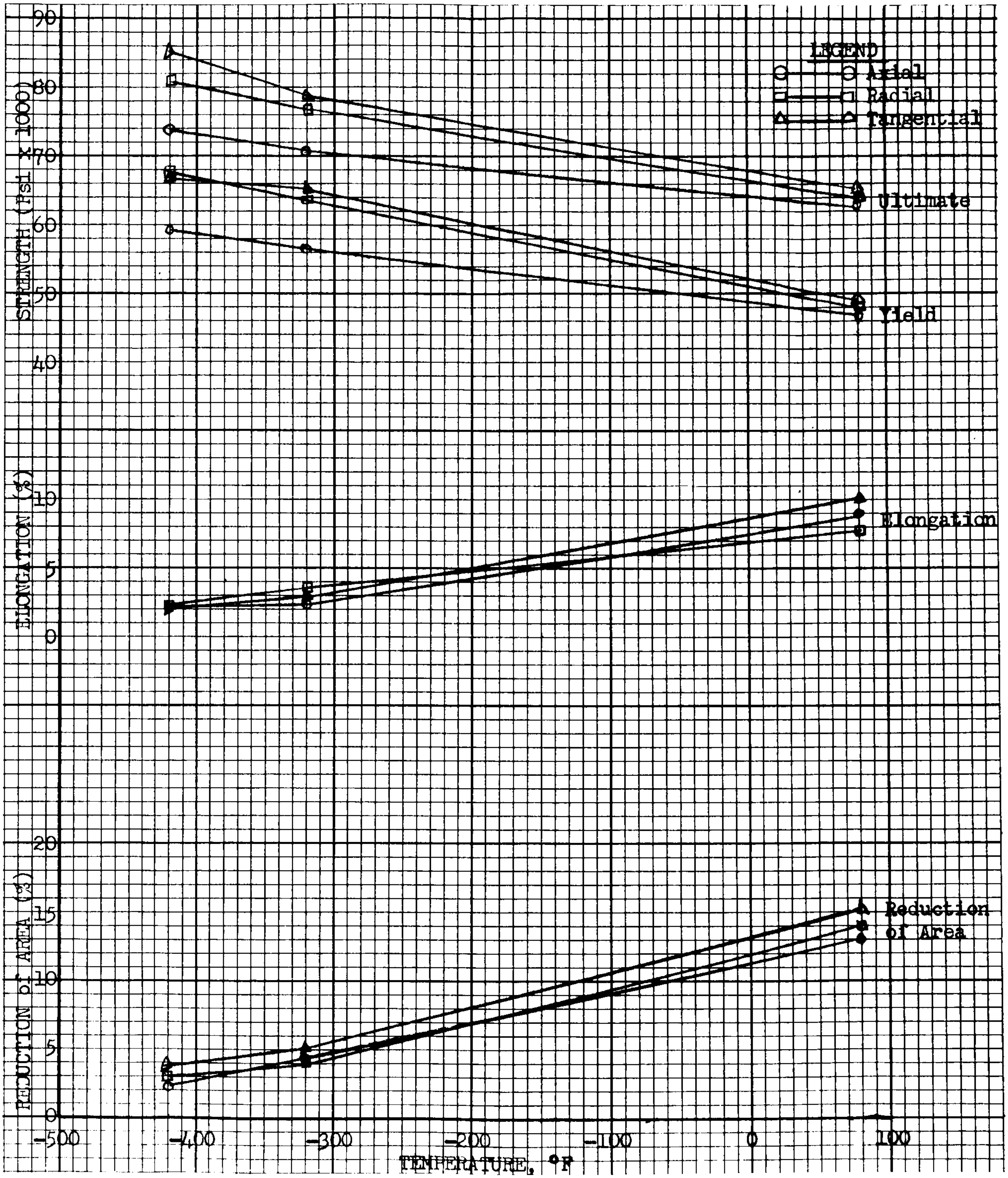

Figure 23
The Effect of Temperature on the Smooth Bar Mechanical Properties of Forging "C" at the Center Section Area

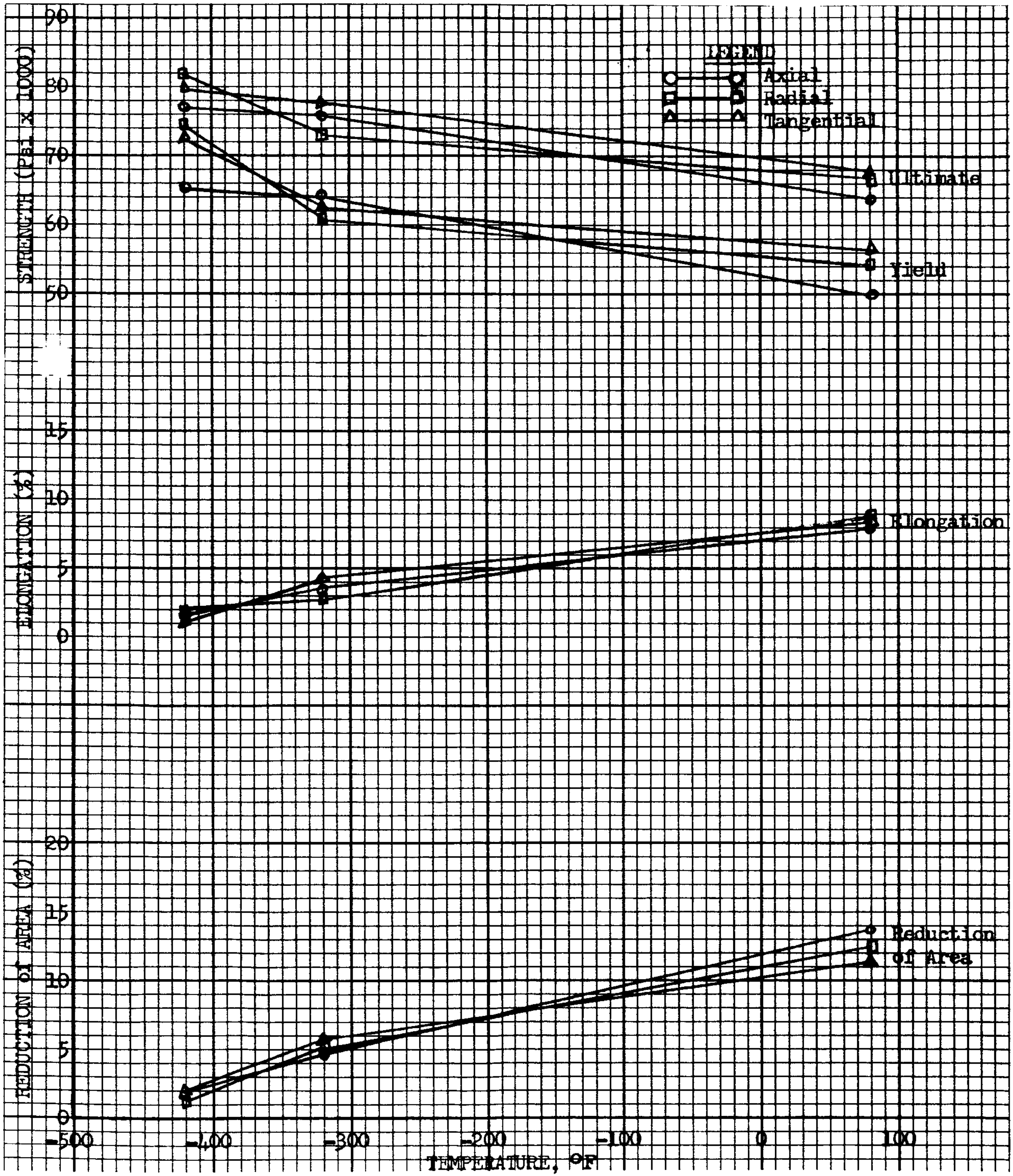

Figure 24
The Effect of Temperature on the Smooth Bar Mechanical Properties of Forging "C" at the Bottom Section Area

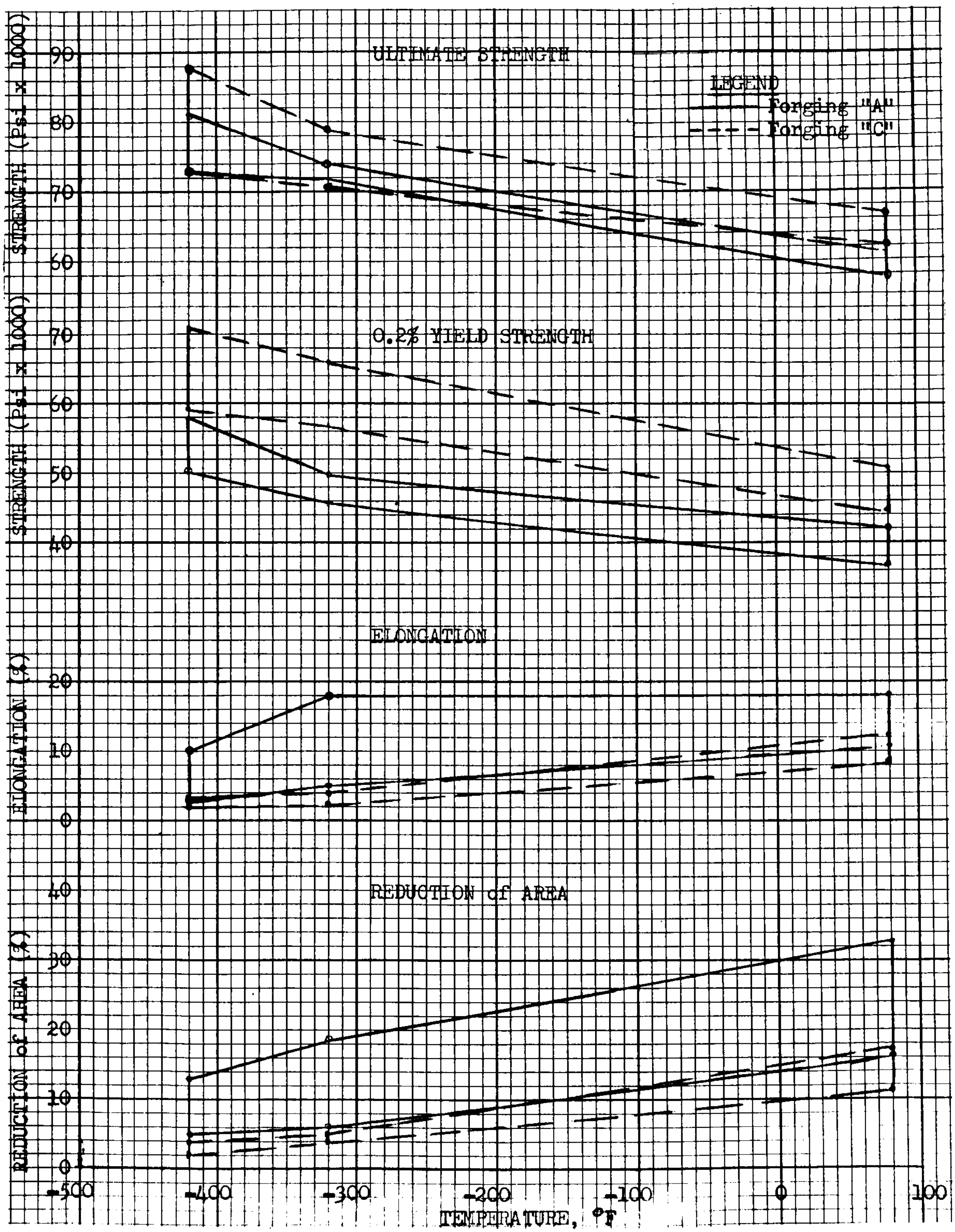

Figure 25
Comparative Forging "C" Center Section
Mechanical Property Range

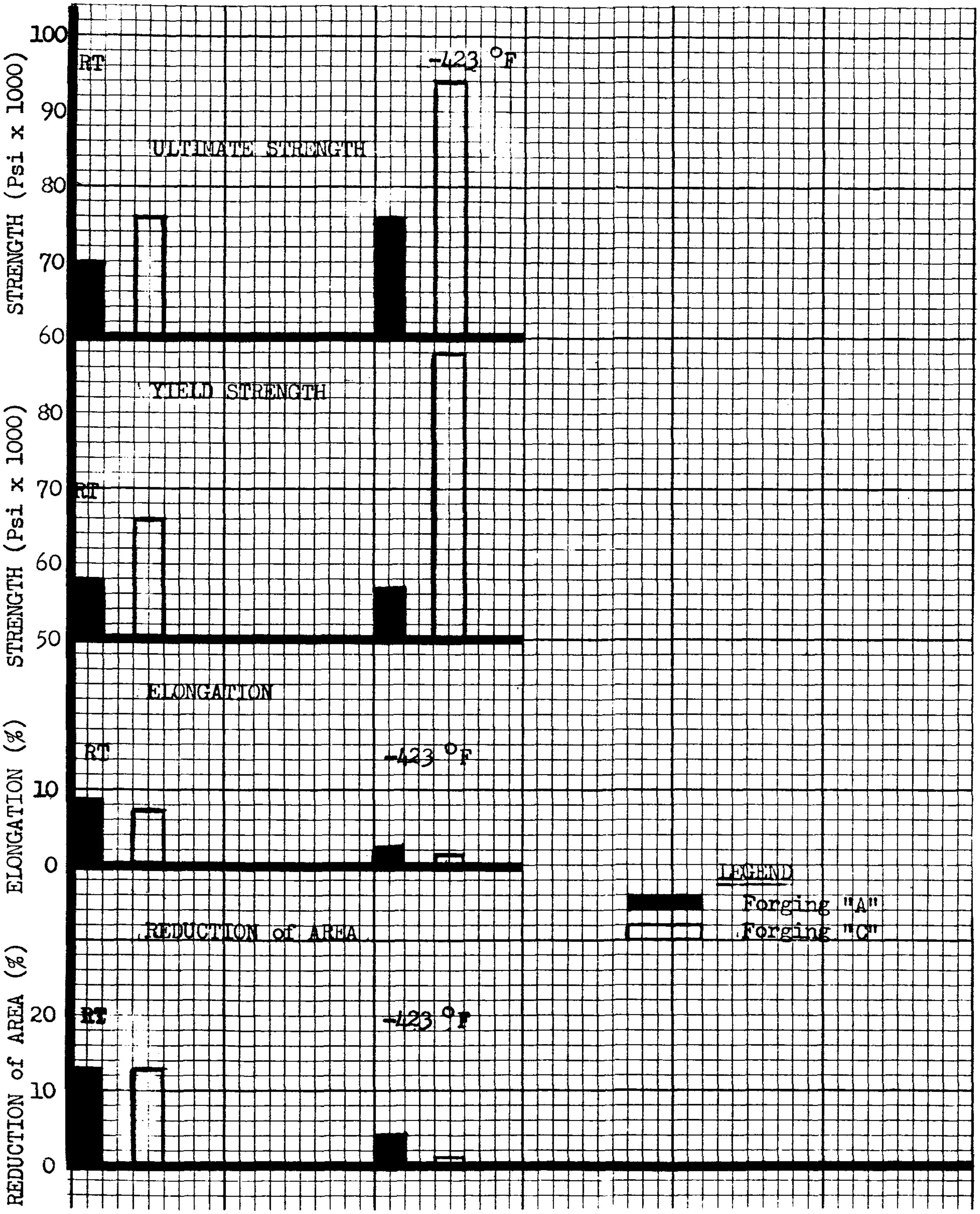

Figure 26

Comparative Forging "C" Test Ring Mechanical Properties

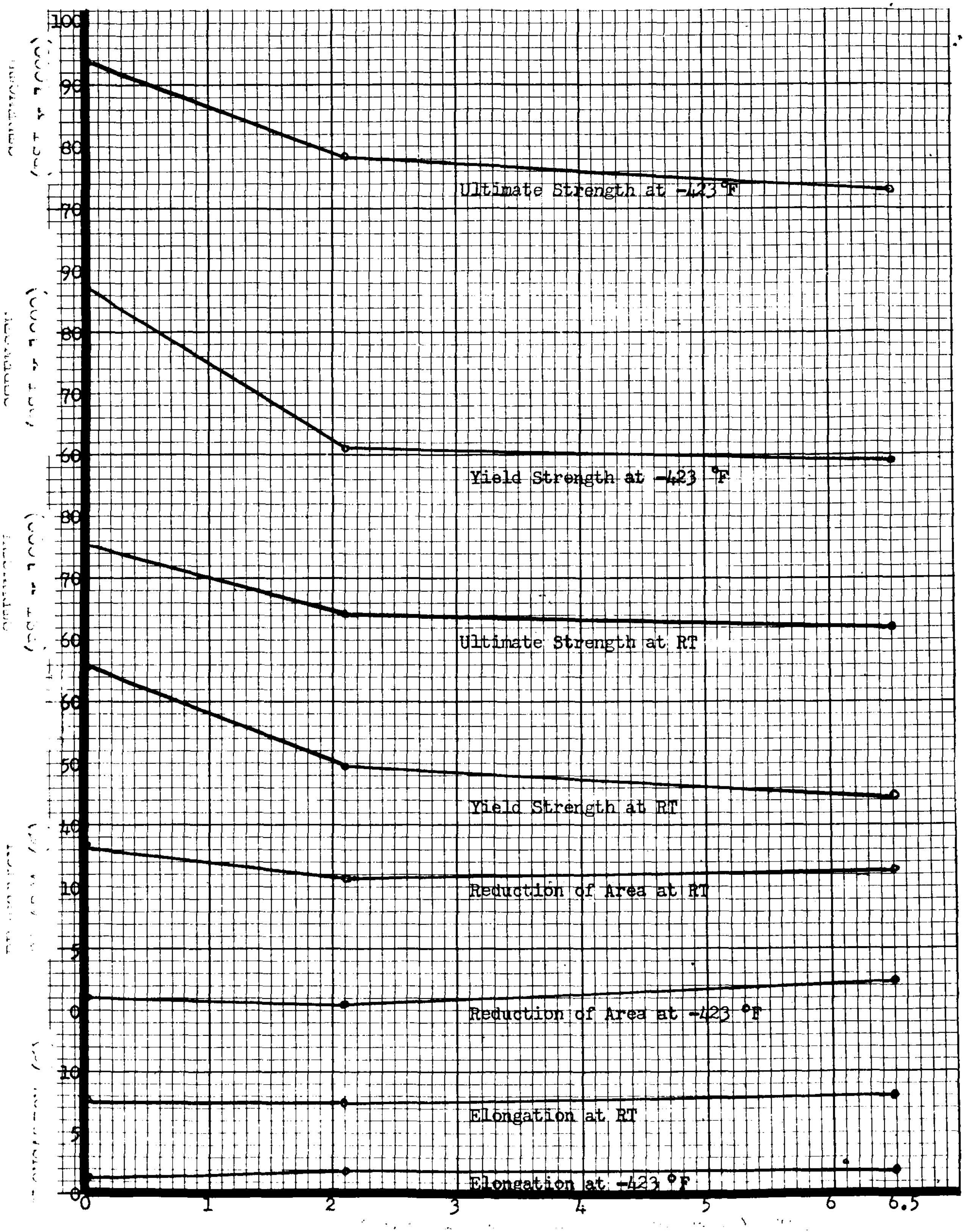

Figure 27
Effect of Forging Thickness on the Room- and Low-Temperature Mechanical Properties of Forging "C"

the toughness does not vary greatly in forgings of the two different sizes; the impeller (30-in. diameter) and the inducer (20-in. diameter). Properties of extremely large 7079 forgings are influenced in part by orientation, specimen location, and mass-quench effect.

4. Mechanical Properties of Hand Forging "D"

The tensile data for Hand Forging "D" (Figure 10) are listed in Table 11. Pronounced variations in strength and ductility at ambient temperature and -423°F are evident. The effect of cryogenic temperatures upon the test ring mechanical properties is in agreement with previous results.

Although the 7079 test ring was notch tough (based on notch-yield ratio) at ambient temperature, it was notch sensitive at -423°F.

5. Effects of -T6 Temper Reheat-Treatment (After Rough Machining) on Properties of Hand Forging "E"

As previously stated, the tensile strength of the center sections was considerably lower than the tensile strength of the peripheral test rings. Therefore, tests were performed to determine whether improvements in strength and ductility would result when the -T6 temper reheat treatment was used after rough machining to remove extraneous material.

The properties of the control specimens and the -T6 reheat-treatment specimens are listed in Table 12. The control specimen test results compared favorably with those of the Forging "C" center section, which is of equivalent "as forged" dimensions. Both strength and ductility are good.

As shown in Figure 28, reheat treatment produced the following effects upon axial properties:

a. At ambient temperature, ultimate and 0.2% offset yield strengths were increased approximately 12% and 28%, respectively.

b. A similar percentage increase in strength was noted at cryogenic temperatures.

c. Ductilities were lowered. Ambient temperature elongation and reduction of area were lowered approximately 33% and 20%, respectively. Axial reduction of area was lowered approximately 42% at -320°F.

d. Notch-yield ratio was lowered from approximately 1.28 to 0.87 at 320°F.

The increase of strength is ascribed to the mass-quench effect. The -T6 treatment of a smaller rough machined section resulted in faster cooling from solution treatment; therefore, higher properties were obtained after aging.

TABLE 11

MECHANICAL PROPERTIES OF 7079-T652 FORGING "D" TEST RING

Tangential Specimens	Test Temp (^{o}F)	Ultimate Strength (ksi)	0.2% Offset Yield Strength (ksi)	Elongation (% in 4D)	Reduction of Area (%)	Hardness @ RT (R-B)	Stress Conc. (K_T)	Notch Tensile Ratio	Notch Yield Ratio
18	RT	77.0	--	7.0	14.5	88			
20	RT	74.4	64.1	7.5	16.2	88			
22	RT	75.6	67.8	7.0	15.5				
	Avg.	75.7	65.95	7.2	15.4	88.3			
17	RT	90.3	Notched tensile specimen			88	7.2		
19	RT	92.7	Notched tensile specimen			87	6.9		
21	RT	84.4	Notched tensile specimen			85	4.9		
	Avg.	89.1				86.7		1.18	1.35
2	-423	91.1	86.5	1.5	0.8				
4	-423	89.3	87.4	1.5	0.8				
6	-423	88.5	86.4	1.0	1.6				
8	-423	90.7	87.6	1.0	2.5				
	Avg.	89.9	87.1	1.25	1.43				
1	-423	79.3	Notched tensile specimen				6.8		
3	-423	69.8	Notched tensile specimen				7.1		
5	-423	70.1	Notched tensile specimen				7.7		
7	-423	85.1	Notched tensile specimen				6.9		
	Avg.	76.1						0.85	0.874

TABLE 12

MECHANICAL PROPERTIES OF 7079-T652 FORGING "E" HEAT-TREATED TO THE -T6 TEMPER CONDITION AFTER ROUGH MACHINING

A. Control Specimens (-T652 Temper Condition)

Specimen	Orientation	Test Temp (^{o}F)	Ultimate Strength (ksi)	0.2% Offset Yield Strength (ksi)	Elongation (% in 4D)	Reduction of Area (%)
1	Tangential	RT	64.7	50.7	7.0	19.9
5	Tangential	RT	67.4	51.0	7.8	13.4
		Avg.	66.1	50.9	7.4	16.7
3	Tangential	-320	76.6	63.4	2.3	7.5
7	Tangential	-320	76.9	63.4	2.5	7.5
		Avg.	76.8	63.4	2.4	7.5
2	Axial	RT	63.5	45.6	6.3	7.4
6	Axial	RT	62.4	46.0	7.0	11.9
		Avg.	62.9	45.8	6.7	9.7
4	Axial	-320	65.4	56.0	1.6	3.5
8	Axial	-320	67.7	52.7	3.1	6.0
		Avg.	66.6	54.4	2.4	4.8

TABLE 12 (CONT.)

B. HEAT TREATED SPECIMENS FROM TEST RINGS (-T6 TEMPER CONDITION) (HEAT TREATED AFTER ROUGH MACHINING)

SPECIMEN NUMBER	TEST RING NUMBER	SPECIMEN ORIENTATION	TEST TEMP (^{o}F)	ULTIMATE STRENGTH (KSI)	0.2% OFFSET YIELD STRENGTH (KSI)	ELONGATION (% IN 4D)	REDUCTION OF AREA (%)	STRESS CONC. (K_T)	NOTCH TENSILE RATIO	NOTCH YIELD RATIO
1	1	AXIAL	RT	71.1	63.6	4.5	9.3			
2	1	AXIAL	RT	71.8	63.8	4.5	6.4			
3	1	AXIAL	RT	71.3	63.7	4.5	7.8			
			AVG.	71.4	63.7	4.5	7.8			
12	1	AXIAL	RT	81.5	NOTCHED TENSILE SPECIMEN			6.3		
13	1	AXIAL	RT	78.4	NOTCHED TENSILE SPECIMEN			6.3		
14	1	AXIAL	RT	84.7	NOTCHED TENSILE SPECIMEN			6.3		
			AVG.	81.5					1.14	1.28
4	1	AXIAL	-320	79.2	74.6	3.0	2.3			
5	1	AXIAL	-320	78.8	74.4	2.5	3.2			
6	1	AXIAL	-320	79.9	74.8	2.5	2.3			
7	1	AXIAL	-320	79.1	74.5	2.0	3.2			
			AVG.	79.3	74.6	2.5	2.8			
15	1	AXIAL	-320	61.8	NOTCHED TENSILE SPECIMEN			6.3		
16	1	AXIAL	-320	64.0	NOTCHED TENSILE SPECIMEN			6.3		
17	1	AXIAL	-320	63.3	NOTCHED TENSILE SPECIMEN			6.3		
18	1	AXIAL	-320	69.4	NOTCHED TENSILE SPECIMEN			6.3		
			AVG.	64.6					0.81	0.866

TABLE 12 (CONT.)

Specimen Number	Test Ring Number	Specimen Orientation	Test Temp (°F)	Ultimate Strength (ksi)	0.2% Offset Yield Strength (ksi)	Elongation (% in 4D)	Reduction of Area (%)	Stress Conc. (K_T)	Notch Tensile Ratio	Notch Yield Ratio
8	1	Axial	-423	83.5	80.1	1.0	0.8			
9	1	Axial	-423	82.9	82.5	1.0	1.6			
10	1	Axial	-423	83.7	80.1	1.0	1.6			
11	1	Axial	-423	83.5	80.9	1.0	1.6			
			Avg.	83.4	80.9	1.0	1.4			
19	1	Axial	-423	55.2	Notched tensile specimen			6.3		
20	1	Axial	-423	53.2	Notched tensile specimen			6.3		
21	1	Axial	-423	63.4	Notched tensile specimen			6.3		
22	1	Axial	-423	56.6	Notched tensile specimen			6.3		
			Avg.	57.1					0.684	0.706
23	2	Radial	RT	72.8	70.4	6.3	13.1			
24	2	Radial	RT	72.8	67.2	7.0	13.2			
25	2	Radial	RT	73.1	68.4	6.3	14.4			
26	2	Radial	RT	72.1	66.2	6.3	13.4			
27	2	Radial	RT	73.9	67.4	5.5	13.4			
28	2	Radial	RT	72.3	68.1	5.5	12.3			
			Avg.	72.8	67.9	6.2	13.3			
29	2	Radial	-320	82.7	76.4	1.6	2.5			
30	2	Radial	-320	80.3	73.9	1.6	5.0			
31	2	Radial	-320	81.3	73.6	1.6	6.0			
32	2	Radial	-320	79.6	74.9	1.6	5.0			
33	2	Radial	-320	78.1	74.6	1.6	5.0			
34	2	Radial	-320	81.1	76.1	1.6	6.0			
			Avg.	80.5	74.9	1.6	4.9			

TABLE 12 (CONT.)

SPECIMEN NUMBER	TEST RING NUMBER	SPECIMEN ORIENTATION	TEST TEMP (°F)	ULTIMATE STRENGTH (KSI)	0.2% OFFSET YIELD STRENGTH (KSI)	ELONGATION (% IN 4D)	REDUCTION OF AREA (%)	STRESS CONC. (K_T)	NOTCH TENSILE RATIO	NOTCH YIELD RATIO
45	3	TANGENTIAL	-423	89.9	82.1	2.0	2.3			
46	3	TANGENTIAL	-423	89.5	79.7	1.0	2.4			
			AVG.	89.7	80.9	1.5	2.35			
47	4	TANGENTIAL	RT	75.6	66.6	7.0	12.3			
52	4	TANGENTIAL	RT	91.1	NOTCHED TENSILE SPECIMEN			6.3	1.2	1.37
48	4	TANGENTIAL	-320	86.2	80.2	2.0	2.4			
49	4	TANGENTIAL	-320	83.8	78.2	2.0	3.2			
			AVG.	85.0	79.2	2.0	2.8			
53	4	TANGENTIAL	-320	78.6	NOTCHED TENSILE SPECIMEN			6.3		
54	4	TANGENTIAL	-320	86.9	NOTCHED TENSILE SPECIMEN			6.3		
			AVG.	82.8					0.97	1.05
50	4	TANGENTIAL	-423	92.4	86.1	1.0	0.8			
51	4	TANGENTIAL	-423	88.9	82.8	1.0	1.6			
			AVG.	90.7	84.5	1.0	1.2			
55	4	TANGENTIAL	-423	66.4	NOTCHED TENSILE SPECIMEN			6.3		
56	4	TANGENTIAL	-423	55.5	NOTCHED TENSILE SPECIMEN			6.3		
			AVG.	60.9					0.67	0.72

TABLE 12 (CONT.)

Specimen Number	Test Ring Number	Specimen Orientation	Test Temp (^{o}F)	Ultimate Strength (ksi)	0.2% Offset Yield Strength (ksi)	Elongation (% in 4D)	Reduction of Area (%)	Stress Conc. (K_T)	Notch Tensile Ratio	Notch Yield Ratio
57	5	Tangential	RT	74.0	65.2	7.5	14.6			
62	5	Tangential	RT	89.4	Notched tensile specimen			6.3	1.2	1.37
58	5	Tangential	-320	81.6	75.6	2.0	1.6			
59	5	Tangential	-320	82.1	80.1	2.0	2.3			
			Avg.	81.9	77.9	2.0	1.95			
63	5	Tangential	-320	73.7	Notched tensile specimen			6.3	0.9	0.946
60	5	Tangential	-423	88.1	84.3	1.0	1.6			
61	5	Tangential	-423	88.5	83.8	1.0	1.6			
			Avg.	88.3	84.05	1.0	1.6			
64	5	Tangential	-423	53.8	Notched tensile specimen			6.3		
65	5	Tangential	-423	63.9	Notched tensile specimen			6.3		
			Avg.	58.9					0.67	0.702
66	Vanes	Radial	RT	76.0	69.8	7.0	16.7			
67	Vanes	Radial	RT	76.1	69.7	7.8	13.4			
68	Vanes	Radial	RT	73.8	69.6	7.9	11.3			
			Avg.	75.3	69.7	7.5	13.8			

TABLE 12 (CONT.)

SPECIMEN NUMBER	TEST RING NUMBER	SPECIMEN ORIENTATION	TEST TEMP (^{o}F)	ULTIMATE STRENGTH (KSI)	0.2% OFFSET YIELD STRENGTH (KSI)	ELONGATION (% IN 4D)	REDUCTION OF AREA (%)	STRESS CONC. (K_T)	NOTCH TENSILE RATIO	NOTCH YIELD RATIO
69	VANES	RADIAL	-320	81.4	77.7	1.6	4.9			
70	VANES	RADIAL	-320	81.6	77.7	1.6	4.9			
71	VANES	RADIAL	-320	82.1	79.7	1.6	4.9			
			AVG.	81.7	78.4	1.6	4.9			
75	VANES	TANGENTIAL	RT	75.0	--	7.0	15.7			
76	VANES	TANGENTIAL	RT	73.3	66.4	9.4	19.1			
77	VANES	TANGENTIAL	RT	72.1	68.4	7.8	16.9			
			AVG.	73.5	67.4	8.1	17.2			
78	VANES	TANGENTIAL	-320	81.6	77.9	1.6	4.9			
79	VANES	TANGENTIAL	-320	72.6	--	1.6	3.4			
80	VANES	TANGENTIAL	-320	77.2	76.2	1.6	3.4			
			AVG.	77.1	77.05	1.6	3.9			

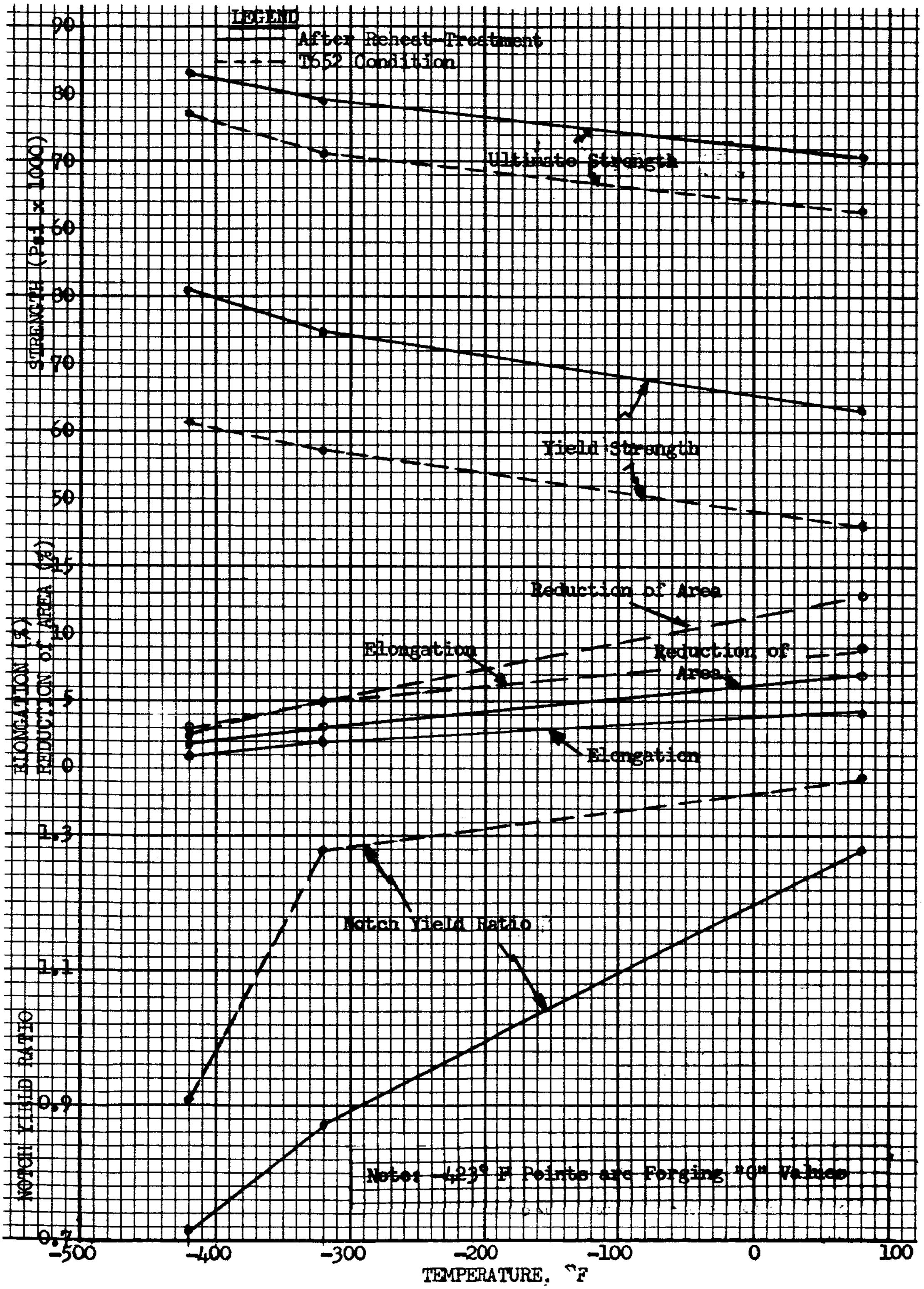

Figure 28
The Effect of -T6 Reheat-Treatment After Rough Machining
on Room- and Low-Temperature Mechanical Properties of Forging "E"

The data shows that toughness was impaired by -T6 reheat-treatment temper. Formerly notch tough at room temperature and -320°F, notch-toughness is apparent only at room temperature in the -T6 reheat-treatment temper. Both conditions display notch sensitivity at -423°F.

In considering the above described influence of -T6 reheat-treatment temper on alloy properties, the 7079 forging, in the section size and physical condition as tested, was superior in toughness when -T652 tempered.

6. Microstructure

The microstructure of Forging "C" at three locations is shown in Figures 29 through 31. The important features illustrated in these micrographs are a finer grain structure at the peripheral area, a slightly cored center section, and inclusions in the matrix.

The coarse, cored-grain structure apparently contributed to the lower strength of the forging center section. Although an investigation was not performed to study the effect of hot working, it appears that -T6 reheat treatment would have been more beneficial if the center-section grain had been refined by hot working prior to the -T6 reheat treatment. This is evident when the test ring properties of Forging "C" are compared with the reheat treated center section properties of Forging "E". The only apparent difference is the grain size because the two sections are at their maximum heat-treatment strength level; however, the test ring had superior properties.

It is concluded that grain size is equally as important as heat-treatment in controlling the properties of large 7079 forgings. Because grain size is primarily controlled by hot working, it is essential that billet stock be grain refined extensively at all areas to obtain a forging with higher properties.

Inclusions were found in the 7079 forgings. The poor toughness of 7079 forgings are ascribed to these inclusions as well as the cored structure and the high alloy content. Work of other investigators(5) with 7000 series aluminum alloys also related the poor toughness of these microstructural conditions. These investigations also observed that 7079-T6 sheet (0.080-in. thick) possessed higher toughness, as measured by notch-tensile ratio, than a 7079-T6 forging (5.0-in. billet). This is probably because of the greater dispersal, orientation, and refinement of inclusions in the sheet (by the rolling operation) which minimized their notch effect in the high-strength matrix. The inclusions in the large 7079 forgings were generally segregated at grain boundaries and they appear to be less effective as stress-risers in a low strength matrix as compared with a high strength matrix. The superior

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(5) Christian, J. L., and Watson, J. F., "Properties of 7000 Series Aluminum Alloys at Cryogenic Temperatures," Advances in Cryogenic Engineering, vol. 6, pp. 604-621, 1960.

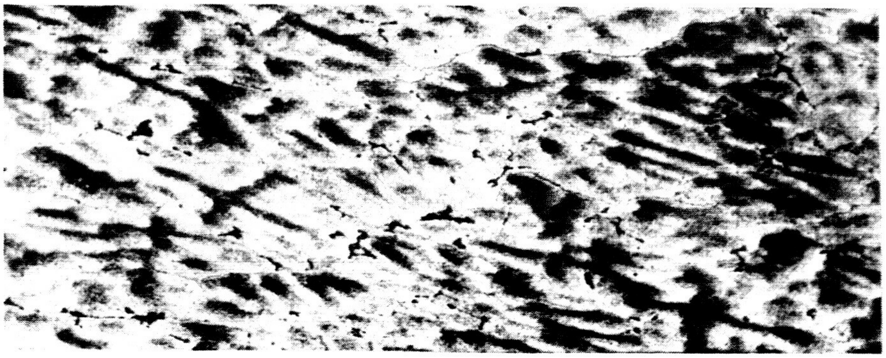

Figure 29
Microstructure of Forging C (Peripheral Location)
Magnification: 100X Etchant: Flick's

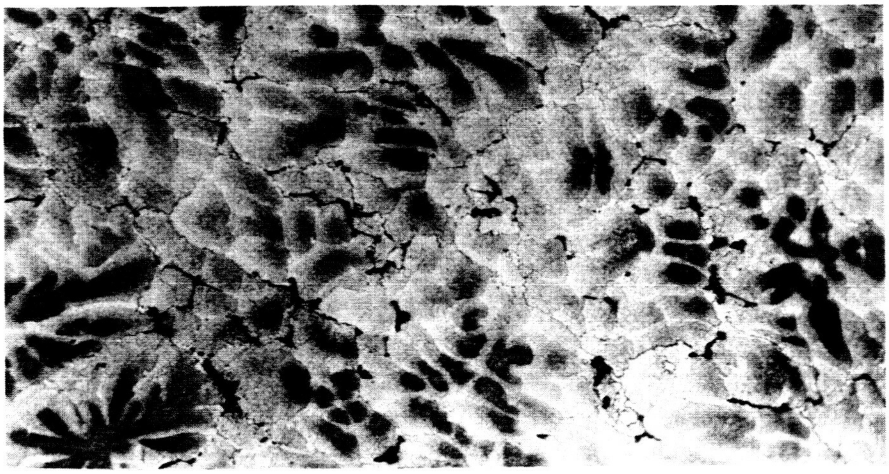

Figure 30
Microstructure of Forging C (One-Half Radius Location)
Magnification: 100S Etchant: Flick's

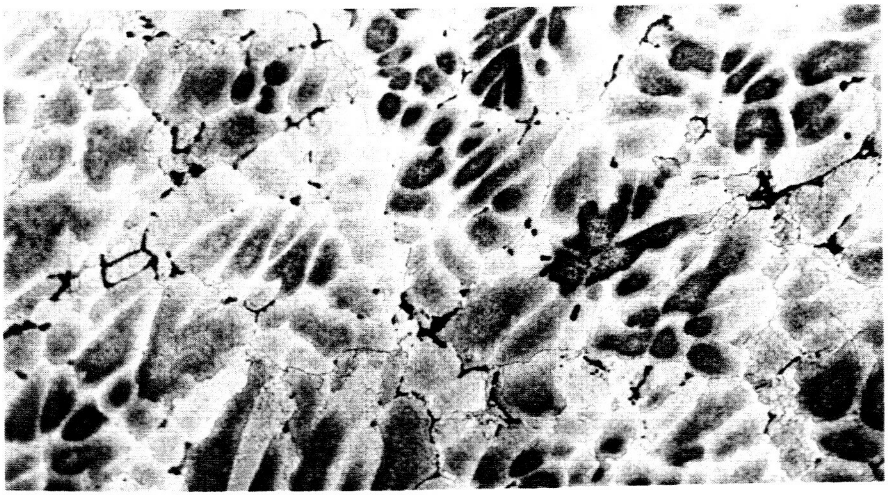

Figure 31
Microstructure of Forging C (Three-Quarter Radius Location)
Magnification: 100X Etchant: Flick's

toughness found at the center section of these large forgings appears to be partly caused by these factors of low matrix strength and inclusion distribution.

7. Fatigue Properties

The results of rotating beam and tension/compression fatigue tests are listed in Tables 13 through 15 and plotted in Figure 32. The S-log N curve for 7079 conventional size wrought product, as reported in the literature(6), is included in Figure 32. Analysis of the data revealed the following:

a. The fatigue strengths in reversed bending closely approximated those reported in the literature(7) for commercial-size wrought products. There was good data agreement in the 10^6 and 10^8 cycle range; the widest disparity occurred at 10^5 cycle.

b. The fatigue strengths in tension/compression were lower than those obtained in reversed bending. For example, at 10^8 cycles, the difference is approximately 40%; this is not unusual. One investigator(8) found that for round specimens of 2014-T4, bending stress gave approximately 41% higher results than axial stress.

c. The agreement of fatigue test data with literature data indicates that although the latter might not be directly applicable to final design of hardware, they serve as good first-approximation design values.

The results of the tension-tension fatigue tests are listed in Table 16. These results permitted construction of the S-Log N curve shown in Figure 33 and the Stress Range Diagram shown in Figure 34. The diagram is based upon the assumption that the ability of a material to withstand combined alternating (F_a) and steady (F_m) stresses can be defined by a straight-line function of the tensile ultimate (F_u) strength and the fatigue (F_e) strength; it is assumed that the following relationship is applicable.

$$F_a = F_e \, (1 - F_m/F_u)$$

The diagram in Figure 34 is for axial tests. The plotted points for 10^6 and 10^7 cycles are well below the Goodman line, while those for the 10^5 cycle are above the Goodman line (see Figure 32).

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(6) Reynolds Aluminum Data Book, p. 37, 1961.

(7) ibid.

(8) Saver, J. A., and Lemon, D. C., "Effect of Steady Stress of Fatigue Behavior of Aluminum," Trans ASM, vol. 42, p. 559, 1950.

TABLE 13

CYCLES TO FAILURE FOR 7079-T652 FORGING "C" AT VARIOUS STRESS LEVELS UNDER CONDITIONS OF COMPLETE BENDING STRESS REVERSAL AT ROOM TEMPERATURE

Stress (ksi)	Cycles to Failure
65	1,300
60	2,450
50	8,900
45	16,300
40	23,900
37.5	49,100
35	46,100
30	314,100
30	484,000
30	1,871,600
30	131,700
27.5	1,129,000
25	5,742,000
22.5	100,000,000

TABLE 14

CYCLES TO FAILURE FOR 7079-T652 FORGING "A" AT VARIOUS STRESS LEVELS UNDER CONDITIONS OF COMPLETE ALTERNATING TENSION/COMPRESSION STRESS REVERSAL AT ROOM TEMPERATURE

Stress (ksi)	Cycles to Failure
55	2,400
45	16,000
38	18,500
35	37,700
30	73,000
30	58,000
25	98,000
25	49,000
20	307,000
20	253,000
15	597,000
15	10,763,000

TABLE 15

GRADE 7079-T652 FATIGUE STRENGTHS AND FATIGUE STRENGTH - ULTIMATE TENSILE AND YIELD STRENGTH RATIOS AT ROOM TEMPERATURE

A. Forging "C" in completely reversed stress

Cycles	Fatigue Strength (ksi)	Fatigue Strength - Ultimate Tensile Strength Ratio	Fatigue Strength 0.2% Offset Yield Strength Ratio
10^4	48	0.726	0.927
10^5	31	0.470	0.600
10^6	28	0.424	0.540
10^7	25	0.379	0.484
10^8	22	0.334	0.425

B. Forging "A" in tension/compression

Cycles	Fatigue Strength (ksi)	Fatigue Strength - Ultimate Tensile Strength Ratio	Fatigue Strength 0.2% Offset Yield Strength Ratio
10^4	38	0.535	0.696
10^5	21	0.296	0.386
10^6	15	0.211	0.275
10^7	15	0.211	0.275

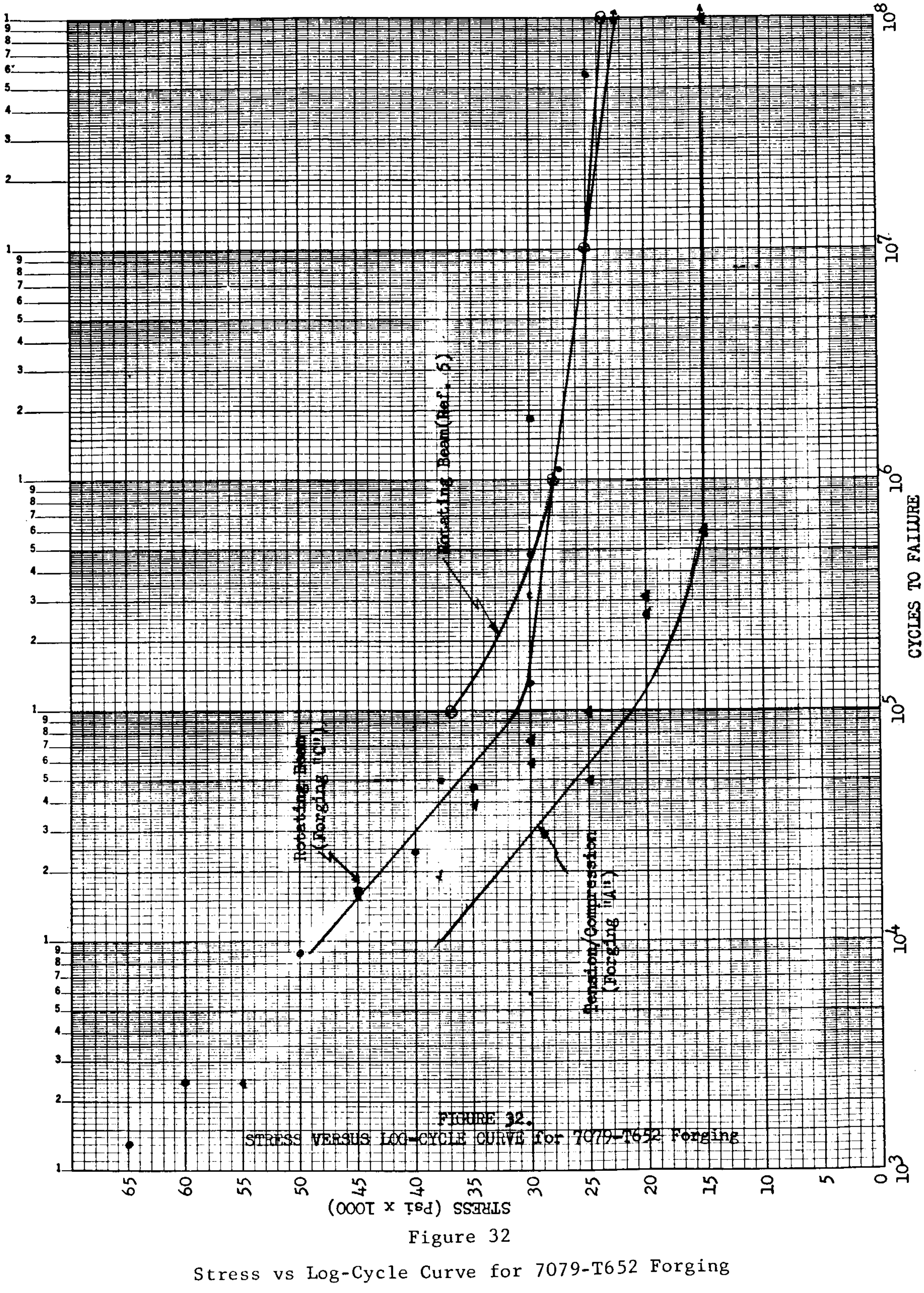

Figure 32

Stress vs Log-Cycle Curve for 7079-T652 Forging

TABLE 16

TENSION-TENSION FATIGUE TEST RESULTS OF GRADE 7079-T652 FORGING AT ROOM TEMPERATURE

Steady Stress (ksi)	Alternating Stress (ksi)	Cycles to Failure
30	15	34,000
30	12.5	67,000
30	10	119,000
30	10	183,000
30	7.5	8,086,000
30	6.25	787,000
30	5	10,725,000
20	15	71,300
20	12.5	95,700
20	10	2,173,000
20	10	256,000
20	7.5	799,000
20	7.5	6,958,000
20	5	15,490,000
10	20	37,000
10	17.5	53,000
10	15	3,224,000
10	12.5	1,140,000
10	12.5	187,000
10	12.5	250,000
10	10	2,893,000

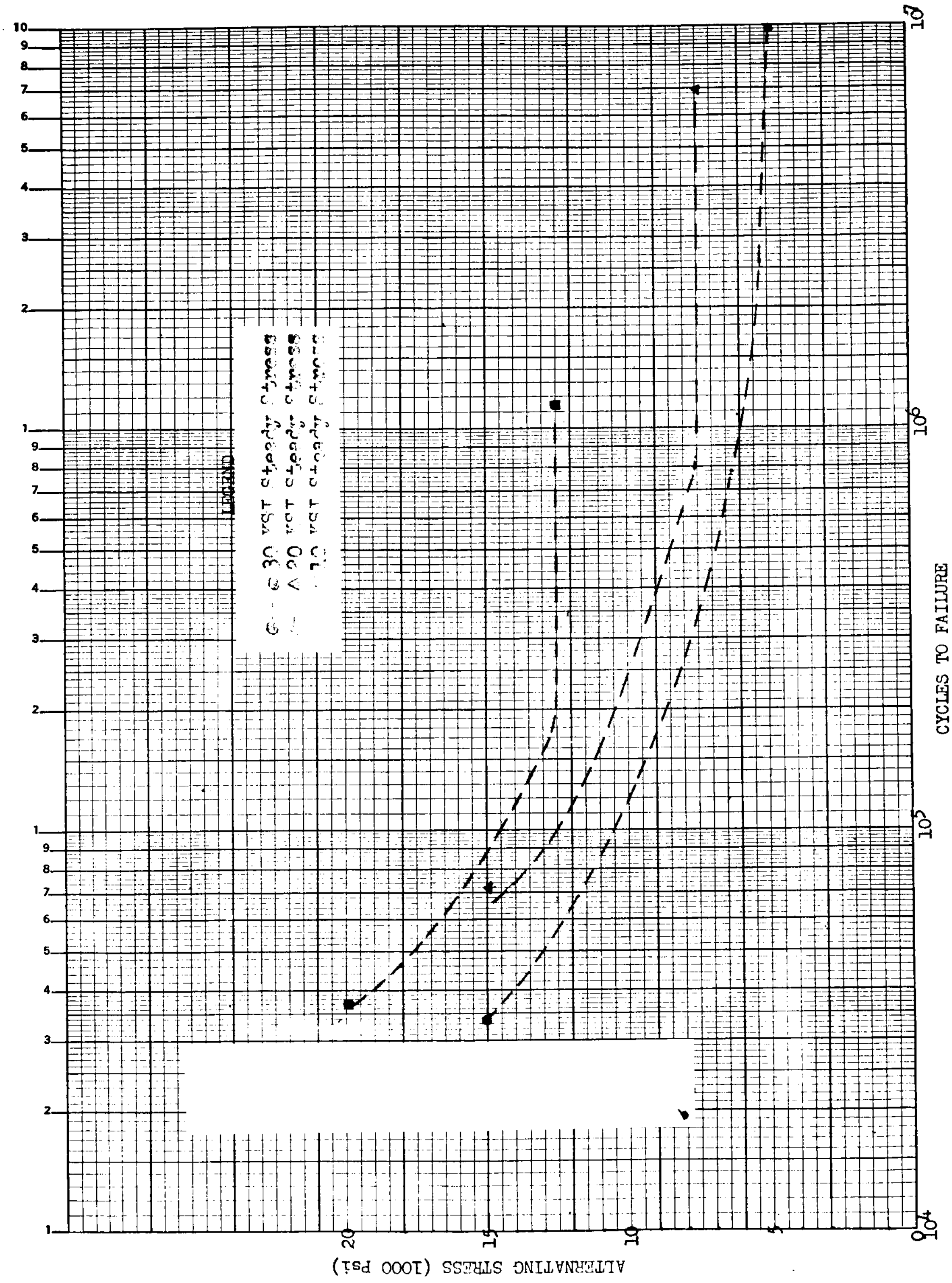

Figure 33
Steady Plus Alternating Stresses vs
Log-Cycle Curves for 7079-T652 Forging

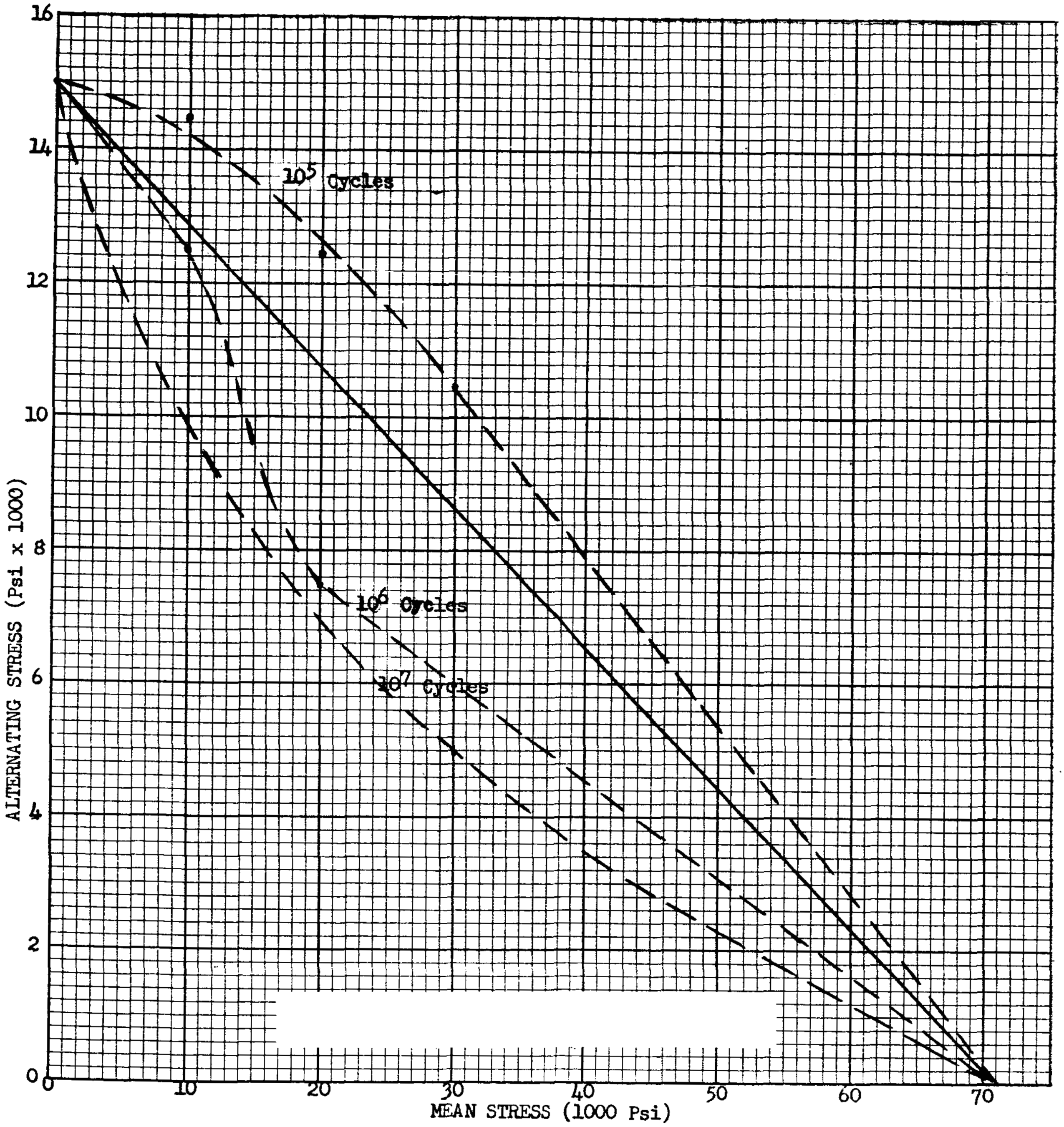

Figure 34

Stress Range Diagram for 7079-T652 Forging

The data points for fatigue properties showed considerable scatter; these properties were apparently influenced by flow lines and grain size. The results of the fatigue tests emphasized the importance of determining individual forging fatigue strength.

These tests serve to demonstrate that large 7079 forgings have low fatigue strength. This property factor, together with its low toughness, make 7079 a poor candidate for inducer application in liquid hydrogen.

8. Inducer and Impeller Blanks and Finish-Machined Parts

The impeller and inducer forging blanks are shown in Figures 35 and 37, respectively. The partially machined impeller and finished machined subscale inducer are shown in Figures 36 and 38. A comparison between the photographs of the forgings and the machined parts indicates the amount of metal removed during machining.

IV. CONCLUSIONS

The results were analyzed and the conclusions as regards the large 7079-T652 hand forgings are as follows:

A. The forgings were notch tough at ambient temperature. They were notch sensitive at -423°F, and slightly notch sensitive at -320°F. The notch sensitivity appeared to be partially dependent upon matrix strength and ductility levels, as well as grain size and orientation.

B. The forgings appeared satisfactory for service at temperatures down to -320°F for the M-1 impellers. However, Grade 7079 is not considered satisfactory for liquid hydrogen (-423°F) service in this size and application because of poor notch toughness; if used, conservative design values must be applied.

C. Ambient temperature fatigue properties closely approximated those of commercial size wrought products, but additional fatigue testing is required to obtain data at liquid hydrogen temperature.

V. RECOMMENDATIONS

The following recommendations are based upon the investigation described herein:

A. Continue evaluation of 7079-T652 to obtain fatigue data to -423°F.

B. Consider higher toughness titanium (Ti-5Al-2.5Sn) and nickel-base (Inconel 718) alloys for impeller service at -423°F. Several of the new aluminum alloys developed specifically for cryogenic service are of interest, including X7106, X7005, and X7039. The mechanical properties of these alloys should be assessed in large forgings.

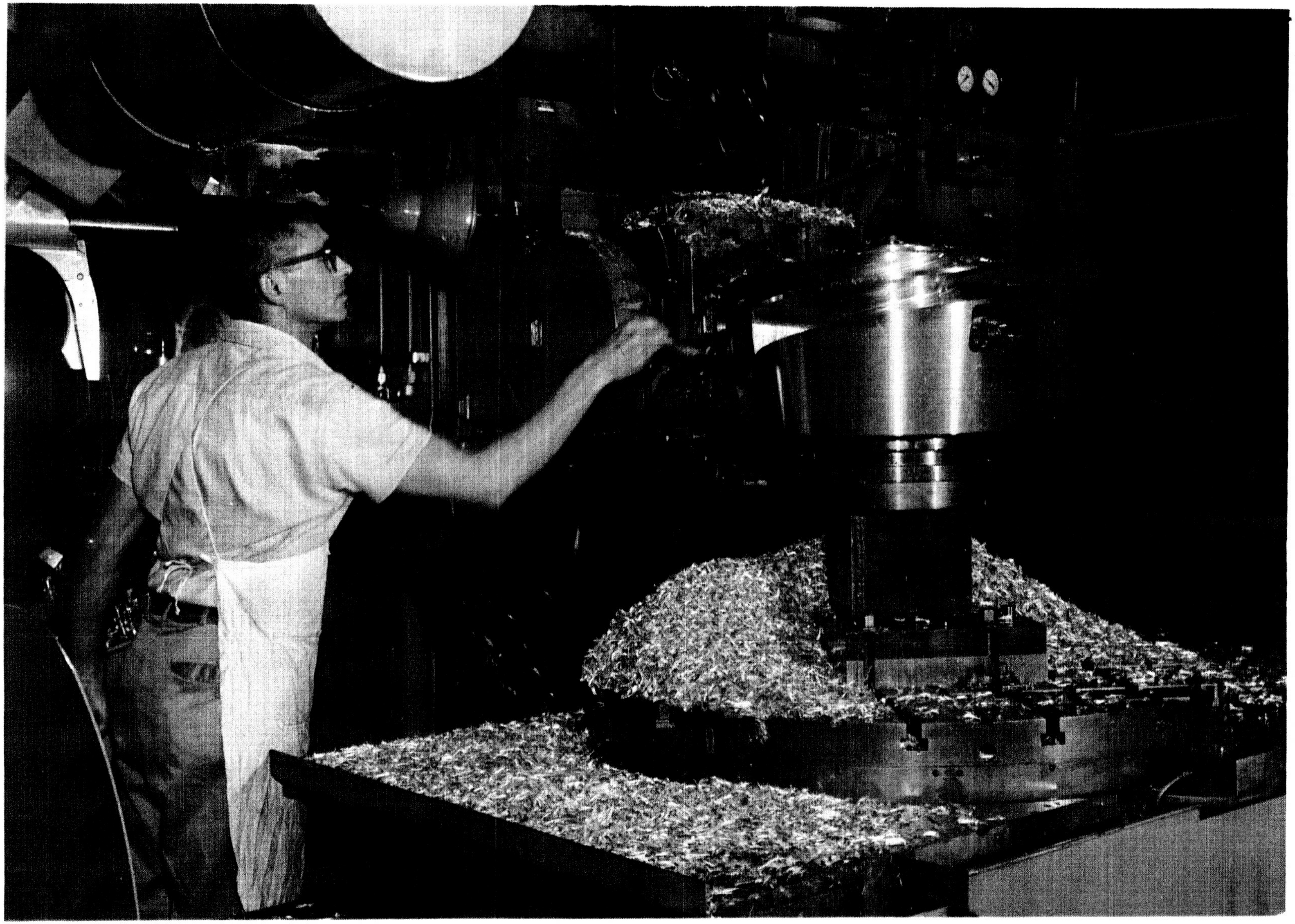

Figure 35

Fuel Pump Inducer Blank

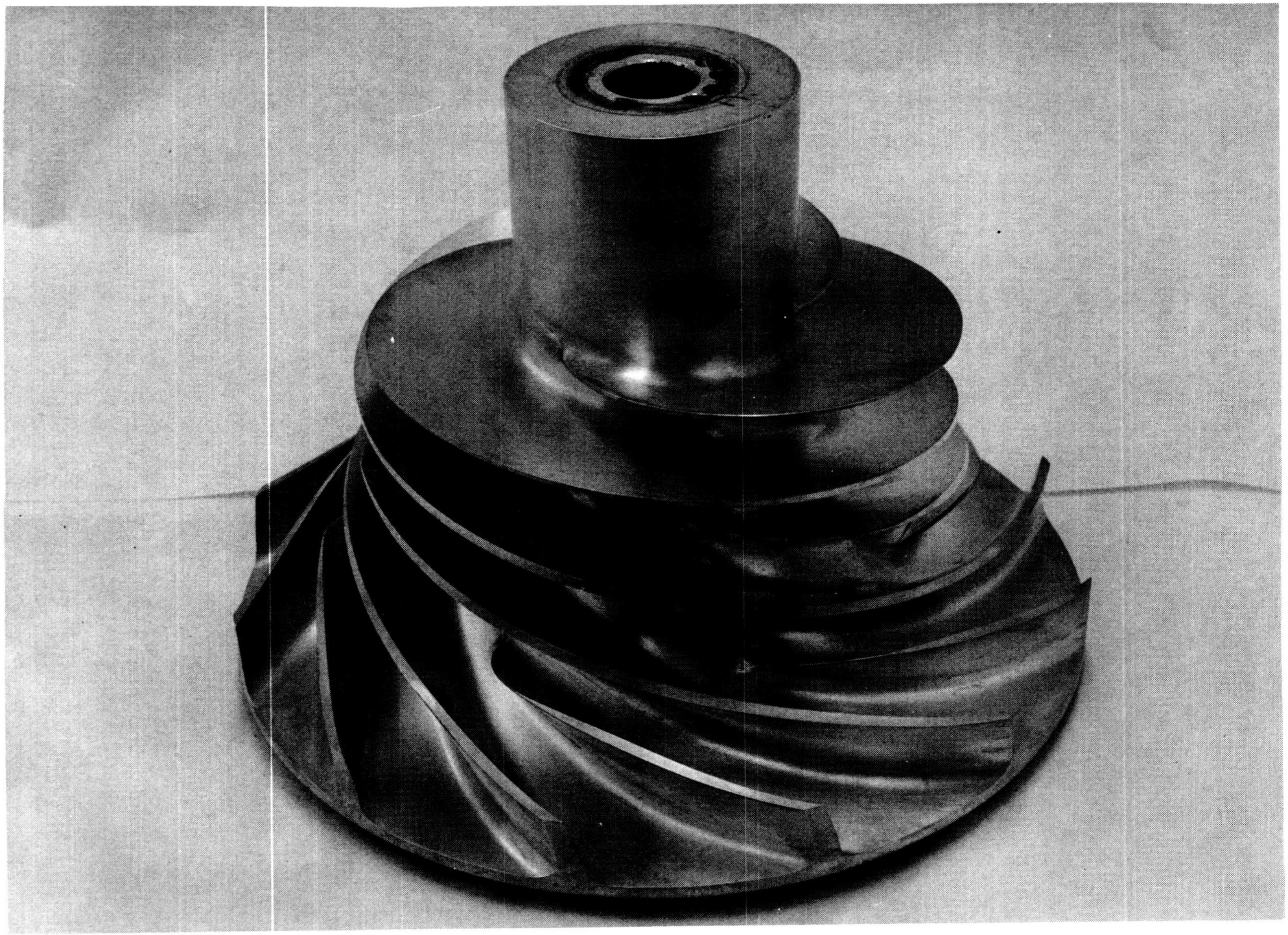

Figure 36

Machined Fuel Pump Inducer Blank

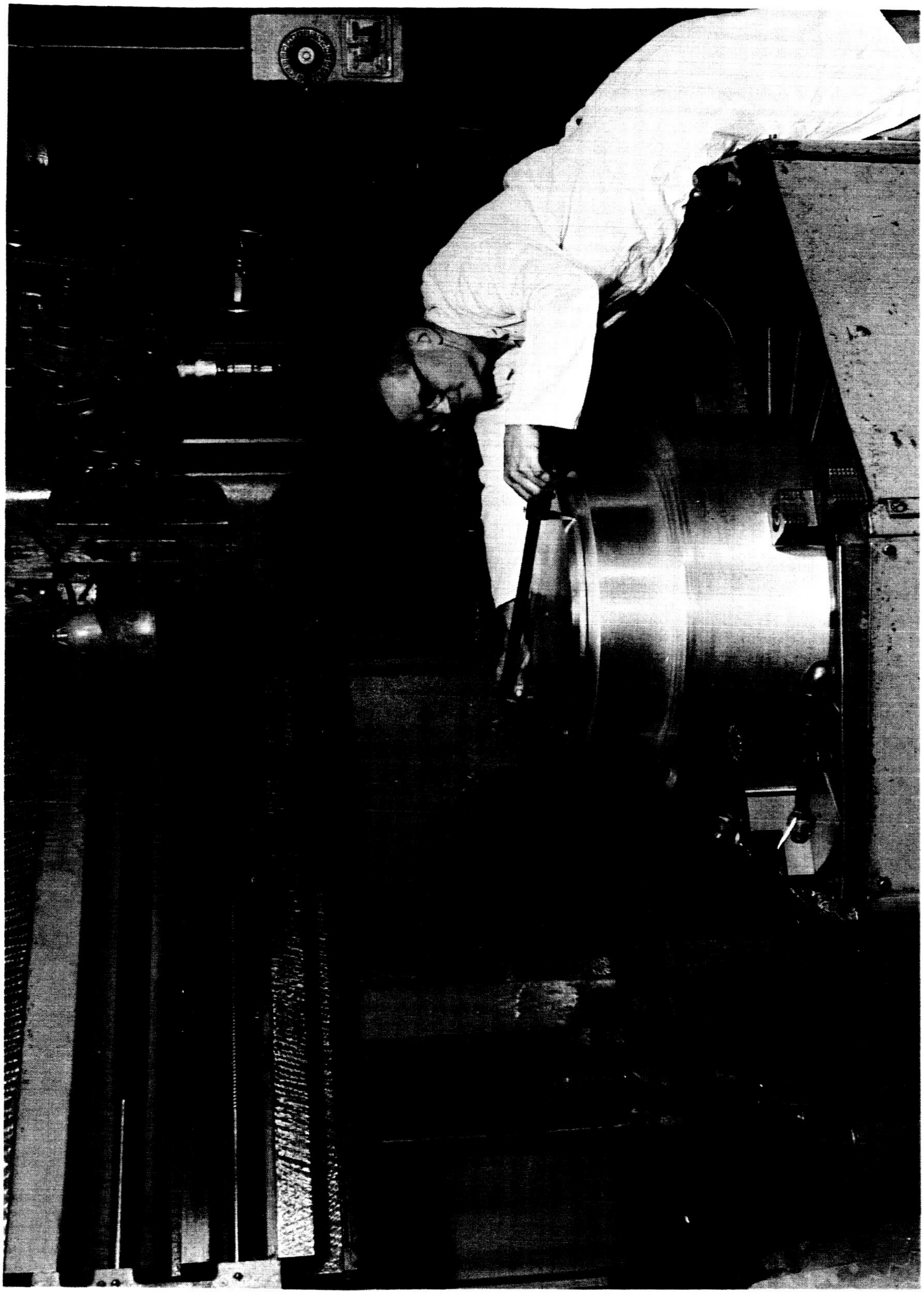

Figure 37

Oxidizer Impeller Blank

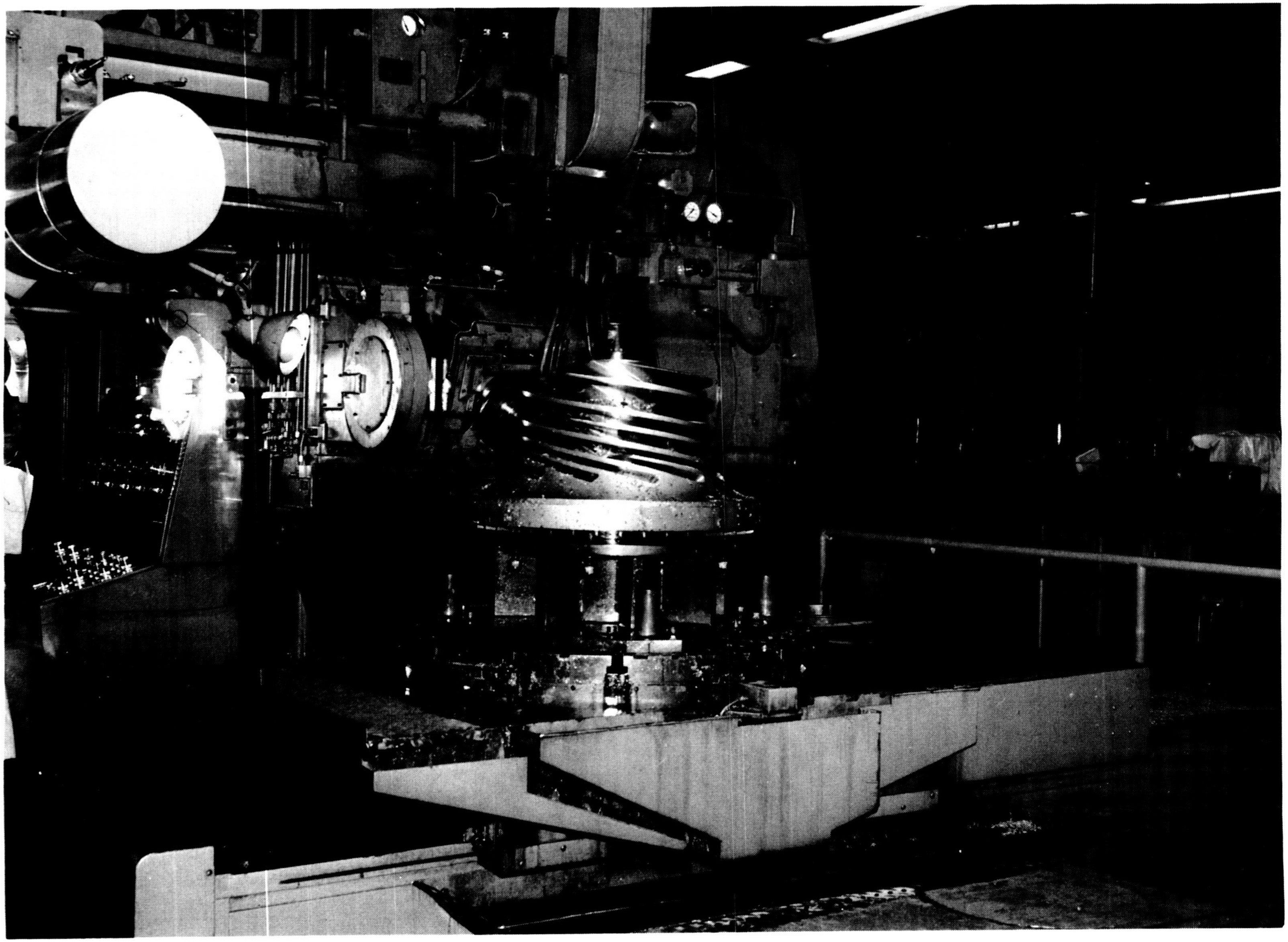

Figure 38

Partially Machined Oxidizer Impeller

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