NUCLEAR DIVISION

Report No. RN-S-0401A

To
AEC-NASA Space Nuclear Propulsion Office

STATISTICAL CORRELATION OF GTR-19 LIQUID HYDROGEN
AND LIQUID NITROGEN IRRADIATION DATA
FOR STRUCTURAL MATERIALS

MASTER

NERVA Program

Contract SNP-1

April 1968

NUCLEAR ROCKET OPERATIONS

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ABSTRACT

This report contains a detailed statistical analysis and correlation of the effects of radiation on the mechanical properties of structural materials irradiated in liquid hydrogen with the radiation effects on identical materials irradiated in liquid nitrogen.

The structural materials irradiated during GTR-19 test 37R007 were aluminum 6061-T6, titanium alloy Ti 5Al 2.5 Sn-ELI, Hastelloy X, Inconel 718, A-286 steel, and AISI-347 stainless steel parent metal and welds. Neutron fluence was approximately 3×10^{17} nvt ($E > 1.0$ Mev).

The results of this statistical analysis and correlation lead to the conclusion that the mechanical properties of certain metals after irradiation at liquid hydrogen temperature can be predicted from properties of the metal measured before and after irradiation at liquid nitrogen temperature.

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CONTENTS

	<u>Page</u>
I. Introduction	1
II. Statistical Analysis	3
A. Derivation of Standard Error	3
B. Data Comparisons	3
III. Correlation of Liquid Hydrogen and Liquid Nitrogen Material Properties Data	5
A. Correlation and Regression Data	5
B. Predictability Analysis	5
IV. Conclusions	10

TABLE LIST

<u>Table</u>	<u>Title</u>	<u>Page</u>
1	LN ₂ /LH ₂ Detail Data	11
2	GTR-19 Averaged Data	15
3	Averaged Ranges, $\bar{R}$	16
4	Sample/Experimental Errors, s'_e	16
5	95% Confidence Bands	17
6	Comparison of Irradiated versus Control Material Properties	17

FIGURE LIST

<u>Figure</u>	<u>Title</u>	
1	Range Control Chart - 95% Confidence Limits	18
2	Irradiated versus Control Comparisons for Al 6061-T6	21
3	Irradiated versus Control Comparisons for Ti 5 Al-2.5 Sn-ELI	22
4	Irradiated versus Control Comparisons for AISI-347 SS	23
5	Irradiated versus Control Comparisons for AISI-347 SS Welds	24
6	Irradiated versus Control Comparisons for Inconel 718	25
7	Irradiated versus Control Comparisons for A-286	26
8	Irradiated versus Control Comparisons for Hastelloy X	27
9	Schematic Diagram Defining Multivariate Statistical Terms	28

I. INTRODUCTION

This document supplements Aerojet-General Report RN-S-0401.* It extends the statistical analysis of the basic report and provides further insight into the dependence of materials properties at liquid hydrogen temperature on corresponding properties at liquid nitrogen temperature and fluence levels. In essence, this document presents only the statistical analysis of tensile test data obtained from cryogenic temperature tests (CTT) of Ground Test Reactor run 19 at the Nuclear Aerospace Research Facility of the General Dynamics Corporation, Fort Worth.

The material of this supplement is presented in two parts. The first part is concerned with the derivation of the standard error from a combined sampling and experimental standard deviation. It also contains a comparison of average irradiated versus control material-property values for the liquid hydrogen and liquid nitrogen tests. The second part presents a detailed correlation between liquid hydrogen and liquid nitrogen materials properties based upon a more extensive statistical analysis. These correlations provide the mathematical basis from which mechanical properties of metals irradiated at liquid hydrogen temperature can be predicted when unirradiated properties at liquid hydrogen temperature and irradiated and unirradiated properties at liquid nitrogen temperature are known.

* Stadig, J. E., Dixon, C. E., GTR-19 Test for Comparison of Property Changes in Alloys After Irradiation in Liquid Nitrogen and Liquid Hydrogen, Aerojet-General Report RN-S-0401, September 1967

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II. STATISTICAL ANALYSIS

A. DERIVATION OF STANDARD ERROR

The standard error was computed first so that proper statistical analyses could be made. This procedure was followed because subsequent data comparisons necessarily must be predicated on the best estimate of the combined sampling and experimental standard deviation. This standard error was obtained from the range of the replicated sample subgroups of four specimens. To develop this, the ranges were analyzed and the best estimates for each metal and each property were obtained by averaging the ranges for the liquid nitrogen, liquid hydrogen, irradiated, and control data groups. A control chart analysis of the ranges shown in Figures 1a through 1c revealed that the ranges were out of statistical control, indicating that a constant-cause system was not in effect. This condition, based on statistical probabilities, suggests that excessive variations occurred during the test. Using a procedure outlined in Appendix A, out-of-control ranges were examined, anomalies (the circled measurements of Table 1) were rejected on the basis of probability, and the average ranges were recalculated. This iterative process was repeated to obtain the best estimate of standard error variance upon which to base the 95% confidence bands. The above is a standard procedure used in process control.

B. DATA COMPARISONS

Once anomalies had been statistically defined and removed, the data were averaged and tabulated as shown in Table 2. These averages then were used as a basis for the comparisons. Table 3 tabulates the average range for each material and property, and Table 4 indicates the combined sampling and experimental error determined from these ranges. The 95% confidence bands for the various metal specimens and properties determined from Students' t-test are summarized in Table 5.

Comparisons between irradiated and control specimens for liquid nitrogen and liquid hydrogen are shown in Figures 2 through 8 for the metals evaluated. The significant differences of each mechanical property for these materials are tabulated in Table 6. Statistically, the mechanical properties are significantly different when the difference between irradiated and control values, as defined by the value of μ on Figures 2 through 8, exceeds the 95% confidence level. Values with differences equal to or exceeding the 95% confidence level have been indicated by asterisks on Table 6.

III. CORRELATION OF LIQUID HYDROGEN AND LIQUID NITROGEN MATERIAL PROPERTIES DATA

A. CORRELATION AND REGRESSION DATA

The second part of this statistical analysis is a correlation of properties data at cryogenic temperatures. This correlation was made to determine the degrees to which material mechanical properties at liquid hydrogen temperature are predictable from the mechanical properties at liquid nitrogen temperatures for both unirradiated specimens and specimens exposed to fast neutron fluences of approximately 3×10^{17} nvt. The predictability of ultimate strength, yield strength, and percent elongation at liquid hydrogen temperature is described in this section.

The correlations are based upon the individual values of Table 1, corrected for anomalies as discussed earlier. Irradiated and unirradiated data at liquid hydrogen temperature for each property of each metal were compared with irradiated and control values at liquid nitrogen temperature.

A multivariate analysis based on standard application of the method of least squares was used in the correlation. It should be remembered that the resultant analysis is subject to interpretation only within the structure of the basic 2×2 test matrix. Thus, no transformations were made; the number of samples, N , is small; and the results are based upon metallurgical interpretation of the variable interactions. The nomenclature of the statistical model used is presented schematically in Figure 9. The regression significance and degree of predictability of the mechanical properties with 95% assurance are summarized in the tabulations given in Part B of this section.

B. PREDICTABILITY ANALYSIS

Once irradiated and unirradiated liquid hydrogen and liquid nitrogen data were correlated, the next step was to determine the predictability of materials properties at liquid hydrogen temperature. Specifically, a

detailed statistical analysis was made to determine if mechanical properties at liquid hydrogen temperature for either irradiated or unirradiated metals could be predicted from known mechanical properties for the same materials before and after irradiation in liquid nitrogen at the same radiation levels.

The comprehensive statistical analysis used in this determination is presented in Appendix B to illustrate how this analytical procedure was applied to Inconel 718 data. The results of the regression analysis for all metals investigated are summarized in the following table. This table provides either a yes or no answer to the ability to predict liquid hydrogen materials properties after irradiation from irradiated and unirradiated properties data at liquid nitrogen temperature with a confidence of 95% or more.

SIGNIFICANT REGRESSION

Material	Mechanical Property		
	Ultimate Strength	Yield Strength	Percent Elongation
Al 6061-T6	Yes	Yes	Yes
Ti 5Al-2.5 Sn-ELI	Yes	Yes	No
Inconel 718	No	Yes	Yes
Hastelloy X	Yes	Yes	No
AISI-347 SS	No	No	No
AISI-347 SS Weld	No	No	No
A-286	No	Yes	No

The table above is a simplified form of the following table which summarizes the results of the F-test of variances. Essentially, this test makes use of Analysis of Variance (ANOVA) which breaks the source of variance into two parts: that part associated with or due to regression, and that part resulting in deviations about the regression. The magnitude of the ratio of these variances establishes the significance of the regressions. The correlations which are significant at the 95% confidence level or greater are marked with asterisks.

REGRESSION

Material	F-Test of Significance		
	Mechanical Property		
	Ultimate Strength	Yield Strength	Percent Elongation
Al 6061-T6	4.6*	185.5*	24.48*
Ti 5 Al-2.5 Sn-ELI	17.4*	5.9*	1.8
Inconel 718	4.2	16.4*	7.8*
Hastelloy X	8.4*	28.2*	1.7
AISI-347 SS	4.3	2.6	1.7
AISI-347 SS Weld	1.0	2.7	0.7
A-286	0.4	12.8*	3.0

The amount of variance of the dependent variable (the material property at liquid hydrogen temperature), which is accounted for by a multivariate regression equation, is expressed by the coefficient of determination, R^2 . The following table lists the percent variance ($100R^2$) explained by the regression. This table is related to the previous table; however, it expresses only the results of the correlation.

% COEFFICIENT OF DETERMINATION, $100 R^2$

Material	Mechanical Property		
	Ultimate Strength	Yield Strength	Percent Elongation
Al 6061-T6	65	99	99
Ti 5Al-2.5 Sn-ELI	90	75	64
Inconel 718	74	92	92
Hastelloy X	81	93	63
AISI-347 SS	63	51	57
AISI-347 SS Weld	33	58	40
A-286	17	87	75

Statistically, no interpretation of the interrelationships of the variables was made although properties such as yield strength and percent elongation appear to be related statistically. Also, within the framework of the 2 x 2 test matrix, the reported regressions are the result of a logical assembly of variables. The limited data of the 2 x 2 matrix used for this experiment preclude assessment of any threshold at which nuclear-induced changes develop.

It should be remembered that this type of regression analyses is valid only over the fluence levels for which correlatable data are available. Uncertainty values increase rapidly as fluence levels are extrapolated upward; however, as fluence levels are interpolated downward, the uncertainty values either remain constant or decrease slightly.

IV. CONCLUSIONS

From the results of this statistical analysis, it can be concluded that the mechanical properties of certain metals after irradiation at liquid hydrogen temperature can be determined from properties of the metal both before and after irradiation at liquid nitrogen temperature.

The analysis revealed that the aluminum, titanium, and nickel alloys collectively responded much better to the liquid hydrogen correlation than did the family of steels. However, for the seven metals and three mechanical properties analyzed (21 cases) in this report, ten, or 47.6% were correlatable at the 95% level of significance.

Finally, the present matrix needs to be extended or internally expanded through additional data. Such an expansion would allow any thresholds of radiation-induced damage at liquid nitrogen or hydrogen temperatures to be determined.

TABLE 1.a

GTR-19

LN₂/LH₂ (CTT) Detail Data

Metal	Specm	- ksi -		- Percent -		nvt x 10 ¹⁷ -		Cryogen	GD/FW Code
		Ult	0.2 Yld	Elong	R Area	Fast	Ther		
Al 6061-T6 Plate	520517	61.8	57.5	16.6	36.2	2.5	.04	LN ₂	F
	05	61.0	57.9	16.3	31.9	2.5	.04		
	19	62.3	58.0	17.5	36.2	3.4	.12		
	17	61.1	57.5	15.6	34.0	3.4	.12		
	520513	74.2	70.0	19.8	29.8	2.6	8.7	LH ₂	C
	01	75.2	70.0	18.9	36.2	2.6	8.7		
	15	78.0	74.3	17.0	31.9	3.5	11.0		
	04	78.0	74.5	16.8	51.0	3.5	11.0		
	520518	60.7	49.5	21.0	40.4	0	0	LN ₂	E
	06	66.4	55.5	21.2	36.1				
	20	61.0	49.8	19.9	34.0				
	08	56.4	43.5	20.9	34.0				
	520514	70.9	51.2	26.4	35.4			LH ₂	B
	02	74.7	52.5	26.5	36.2				
	20	74.7	54.0	26.1	31.9				
	08	74.4	54.2	26.8	31.9				
Ti 5Al-2.5Sn Plate	560617	204.2	197.0	12.5	28.9	2.5	.04	LN ₂	
	05	205.9	196.0	11.6	34.2	2.5	.04		
	19	193.1	186.0	10.2	31.6	3.4	.12		
	07	198.6	192.0	9.9	27.0	3.4	.12		
	560613	216.2	NA	NA	23.7	2.6	8.7	LH ₂	
	09	245.5	240.0	NA	13.5	2.6	8.7		
	15	242.6	228.0	10.9	23.7	3.5	11.0		
	03	245.0	232.0	9.8	15.8	3.5	11.0		
	560618	201.6	190.0	11.4	24.3	0	0	LN ₂	
	06	203.9	192.0	13.0	28.9				
	20	196.0	186.7	14.0	28.9				
	08	188.2	180.0	11.3	28.9				
	560614	219.4	210.0	4.5	5.3			LH ₂	
	02	232.7	216.0	9.6	13.2				
	16	234.2	222.0	9.2	10.8				
	04	237.8	222.0	9.9	13.5				

TABLE 1.b
GTR-19

Metal	Specm	- ksi -		- Percent -		- nvt x 10 ¹⁷ -		Cryogen
		Ult	0.2 Yld	Elong	R Area	Fast	Therm	
AISI 347-SS Plate	590217	214.0	92.0	31.1	40.5	2.5	.04	LN ₂
	05	209.7	73.0	32.6	42.1	2.5	.04	
	19	205.3	98.0	32.8	40.5	3.4	.12	
	07	213.5	78.0	35.9	47.3	3.4	.12	
	590221	232.5	96.5	23.6	48.6	2.6	8.7	LH ₂
	01	227.9	85.0	27.3	37.8	2.6	8.7	
	15	240.4	84.7	29.0	35.1	3.5	11.0	
	03	212.8	83.0	24.7	32.4	3.5	11.0	
	590212	217.0	78.0	31.5	48.6	0	0	LN ₂
	06	216.4	54.0	32.0	50.0			
	20	204.6	75.5	31.4	44.5			
	08	216.5	54.0	34.6	51.4			
	590214	229.0	80.8	28.0	29.8			LH ₂
	02	230.7	63.0	26.7	21.6			
	16	242.0	70.5	28.6	21.6			
	04	218.3	48.0	25.2	43.3			
AISI 347-SS Plate/Weld	590317	204.0	76.0	28.1	35.1	2.5	.04	LN ₂
	21	209.0	81.5	28.6	36.8	3.4	.12	
	05	201.1	75.4	27.5	29.0	4.4	.41	
	07	123.5	72.2	11.9	18.4	4.4	.41	
	590313	207.8	96.0	17.3	23.7	2.6	8.7	LH ₂
	01	190.0	88.0	15.6	21.0	2.6	8.7	
	15	205.8	88.0	21.4	21.6	3.5	11.0	
	03	229.5	88.0	24.5	26.3	3.5	11.0	
	590318	214.1	46.4	25.8	29.7	0	0	LN ₂
	20	207.3	68.0	26.2	29.7			
	06	207.1	49.3	27.8	31.6			
	11	205.1	55.5	28.7	36.9			
	590314	203.6	86.0	22.0	21.0			LH ₂
	02	198.4	60.0	22.2	23.7			
	16	201.4	50.5	20.8	18.9			
	04	211.6	72.0	22.7	21.0			

TABLE 1.c

GTR-19

Metal	Specm	- ksi -		- Percent -		- nvt x 10 ¹⁷ -		
		Ult	0.2 Yld	Elong	R Area	Fast	Therm	Cryogen
Inconel 718 Forg.	150709	253.8	223.0	18.5	25.8	3.4	.12	LN ₂
	15	264.3	228.0	20.4	38.7	3.5	.18	
	13	264.3	228.0	19.9	42.0	3.5	.18	
	11	249.0	221.0	21.5	38.7	3.5	.18	
	150701	NA	NA	7.9	9.7	3.2	11.0	LH ₂
	03	265.0	235.0	19.6	22.6	3.2	11.0	
	05	271.7	230.0	17.8	22.6	3.2	11.0	
	07	272.5	236.0	17.3	25.8	3.2	11.0	
	150716	269.0	216.0	25.3	35.5	0	0	LN ₂
	14	260.0	222.0	18.6	25.8			
	12	241.0	219.6	4.4	9.8			
	21	262.5	214.0	20.2	25.8			
	150708	NA	218.5	19.6	25.8			LH ₂
	06	265.1	203.0	20.6	35.5			
	04	264.3	218.0	13.9	22.6			
	02	267.4	223.0	19.9	35.5			
A-286 Forg.	110413	200.0	143.0	32.6	29.8	3.5	.18	LN ₂
	11	201.0	145.0	34.8	38.3	3.5	.18	
	09	197.9	132.0	37.7	34.1	3.5	.18	
	110401	213.0	163.0	22.1	22.9	3.2	11.0	LH ₂
	3	196.0	147.0	21.0	25.5	3.2	11.0	
	5	211.2	160.0	25.0	22.9	3.2	11.0	
	7	197.5	156.0	23.6	27.6	3.2	11.0	
	110416	195.3	138.0	33.5	27.6	0	0	LN ₂
	14	194.0	121.0	21.9	21.3			
	12	201.8	132.0	29.1	31.9			
	10	198.0	122.0	32.6	31.9			
	110406	206.0	145.0	24.9	23.4			LH ₂
	08	202.0	145.0	24.9	27.7			
	02	214.4	146.0	27.7	27.7			
	04	211.7	151.0	25.5	32.0			

TABLE 1.d
GTR-19

Metal	Specm	- ksi -		- Percent %		- nvt x 10 ¹⁷ -		
		Ult	0.2 Yld	Elong	R Area	Fast	Therm	Cryogen
Hastelloy X Forg.	130113	143.0	108.0	28.5	21.2	3.5	.18	LN ₂
	11	150.7	102.0	37.5	31.9	3.5	.18	
	09	150.7	108.0	43.5	34.0	3.5	.18	
	130101	165.0	121.0	29.6	29.2	2.6	8.7	LH ₂
	03	163.5	119.0	33.5	31.3	2.6	8.7	
	05	163.0	123.0	31.8	29.2	3.5	11.0	
	17	197.0	124.0	36.2	25.0	3.5	11.0	
	130116	144.2	83.0	45.3	31.9	0	0	LN ₂
	14	144.2	76.0	50.8	37.5			
	20	140.9	82.0	41.7	34.0			
	10	141.5	80.8	43.0	36.2			
	130102	150.3	93.0	29.6	29.2			LH ₂
	08	177.1	123.0	34.8	27.1			
	06	177.3	116.0	36.4	31.2			
	04	159.0	104.0	33.7	25.5			

(xxx) Unexplained anomaly

$\begin{bmatrix} x \\ x \\ x \\ x \end{bmatrix}$ Two level indication

TABLE 2

GTR-19
LN₂/LH₂ CTT DATA

Averaged Data (outliers omitted)

		N ₂				H ₂			
		<u>Ult</u>	<u>0.2% Yld</u>	<u>% E</u>	<u>% RA</u>	<u>Ult</u>	<u>0.2% Yld</u>	<u>% E</u>	<u>% RA</u>
Irradiated	Al 6061-T6	61.6	57.7	16.5	34.6	76.6	72.2	18.2	32.6
	Ti 5Al-2.5Sn-ELI	200.5	192.8	11.0	30.4	244.4	233.3	10.4	19.2
	AISI 347SS	210.6	$\begin{bmatrix} 95.0 \\ 75.5 \end{bmatrix}$	33.1	42.6	228.5	87.3	26.2	38.5
	AISI 347SS/Weld	204.7	76.3	28.1	33.6	201.2	90.0	19.4	23.2
	Inconel 718	257.8	225.0	20.1	36.3	269.7	233.7	15.7	20.2
	A-286	199.6	140.0	35.0	34.1	204.4	159.7	23.0	24.7
	Hastelloy X	148.1	106.0	40.5	29.0	163.8	121.8	32.8	28.7
Control	Al 6061-T6	62.7	51.6	20.8	36.1	73.7	53.0	26.4	33.8
	Ti 5Al-2.5Sn-ELI	197.4	187.2	12.4	27.8	231.0	217.5	8.3	10.7
	AISI 347SS	213.7	$\begin{bmatrix} 54.0 \\ 76.8 \end{bmatrix}$	32.4	48.6	230.0	$\begin{bmatrix} 55.5 \\ 75.7 \end{bmatrix}$	27.1	29.1
	AISI 347SS/Weld	208.4	$\begin{bmatrix} 47.8 \\ 61.2 \end{bmatrix}$	27.1	32.0	203.8	$\begin{bmatrix} 55.2 \\ 78.5 \end{bmatrix}$	21.9	21.2
	Inconel 718	263.7	217.9	21.4	24.2	265.6	219.8	18.5	29.9
	A-286	197.3	128.2	29.5	28.2	208.5	146.8	25.8	27.7
	Hastelloy X	142.7	80.5	45.2	34.9	$\begin{bmatrix} 154.7 \\ 177.2 \end{bmatrix}$	$\begin{bmatrix} 98.5 \\ 119.5 \end{bmatrix}$	33.6	28.2

TABLE 3

Average Ranges (outliers omitted), $\bar{R}$

	<u>Ult</u>	<u>0.2% Yld</u>	<u>% E</u>	<u>% RA</u>	<u>$\bar{R}$ Basis:</u>
Al 6061-T6	3.4	3.5	1.7	5.4	
Ti 5Al-2.5Sn-ELI	12.5	11.8	3.0	7.6	LN ₂
AISI 347SS	18.1	9.2	4.2	12.9	LH ₂
AISI 347SS/Weld	12.0	11.2	2.5	6.3	Irradiation
Inconel 718	8.8	6.5	7.8	17.7	Control
A-286	10.1	13.0	5.9	8.1	
Hastelloy X	5.4	7.2	7.1	7.6	

TABLE 4

Sample/Experimental Errors, s'_e

	<u>Ult</u>	<u>0.2% Yld</u>	<u>% E</u>	<u>% RA</u>
Al 6061-T6	1.61	1.66	0.81	2.56
Ti 5Al-2.5Sn-ELI	5.93	5.60	1.42	3.60
AISI 347SS	8.59	5.60	1.98	6.12
AISI 347SS/Weld	6.22	6.50	1.43	2.99
Inconel 718	5.03	3.37	3.59	8.37
A-286	4.79	6.16	2.79	3.83
Hastelloy X	3.08	4.11	3.37	3.61

$$s'_e = \bar{R}/d_2^* \text{ for } \bar{n}.$$

TABLE 5

GTR-19
LN₂/LH₂ CTT DATA

95% Confidence Bands
 $\pm t_{\alpha} s'_e (1/n_1 + 1/n_2)^{1/2}$
LN₂

	U1t	0.2% Y1d	% E	% RA		LH ₂	U1t	0.2% Y1d	% E	% RA
Al 6061-T6	3.16	3.25	1.41	4.45			2.80	2.88	1.41	5.02
Ti 5Al-2.5Sn-ELI	10.30	9.75	2.47	6.26			11.60	11.00	3.42	6.26
AISI 347SS	14.95	24.10	3.44	10.65			14.95	13.45	3.44	10.65
AISI 347SS/Weld	12.20	15.60	2.81	5.90			12.20	15.60	3.45	5.23
Inconel 718	9.87	5.86	7.05	14.60			11.45	7.65	6.25	14.60
A-286	9.40	12.05	5.48	7.50			8.35	10.70	4.85	6.66
Hastelloy X	6.04	8.05	8.10	7.08			8.90	9.90	5.85	6.30

NOTE: All values are prefixed by $\pm$.

TABLE 6

Comparison of Irradiated Versus Control

$$\mu = (\bar{X}_I - \bar{X}_C)$$

	U1t	0.2% Y1d	% E	% RA		LH ₂	U1t	0.2% Y1d	% E	% RA
Al 6061-T6	-1.1	6.1	-4.3*	-1.5			2.9*	19.2*	-8.2*	-1.2
Ti 5Al-2.5Sn-ELI	3.1	5.6	-1.4	2.6			13.4	15.8*	2.1	8.5*
AISI 347SS	-3.1	Indet.(1)	0.7	-6.0			-1.5	Indet.(1)	-0.9	9.4
AISI 347SS/Weld	-3.7	Indet.(1)	1.0	1.6			-2.6	Indet.(1)	-2.5	2.0
Inconel 718	-5.9	7.1*	-1.3	12.1			4.1	13.9*	-2.8	-9.7
A-286	2.3	11.8	5.5*	5.9			-4.1	12.9*	-2.8	-3.0
Hastelloy X	5.4	25.5*	-4.7	-5.9			Indet.(1)	Indet.(1)	-0.8	0.5

* Significant at 95% confidence level.

(1) Indeterminate. See Figures 4, 5, and 8 showing two levels.

CTR-19
LN₂/LN₂ CTT DATA
RANGE CONTROL CHART (n = 4) - 95% CONFIDENCE LIMITS
Ultimates

Figure 1a

CTR-19
 LN₂/LN₂ CTT DATA
 RANGE CONTROL CHART ($n = 4$) - 95% CONFIDENCE LIMITS
 0.2% Yields

Figure 1b

LN₂/LH₂ GTT DATA

RANGE CONTROL CHART (n = 4) - 95% CONFIDENCE LIMITS

% Elongations

Figure 1c

CTR-19
 LN₂/LN₂ CTT DATA
 IRRADIATED VS CONTROL COMPARISONS
 A1 6061-T6

Figure 2

GTR-19
 LN₂/LN₂ CTT DATA
 IRRADIATED VS CONTROL COMPARISONS

Ti 5Al-2.5Sn BLI

Figure 3

CTR-19
LN₂/LN₂ CTT DATA
IRRADIATED VS CONTROL COMPARISONS
AISI 347 SS

Figure 4

GTR-19
 LN₂/LN₂ CPT DATA
 IRRADIATED VS CONTROL COMPARISONS
 AISI 347 SS/Welded

Figure 5

GTH-19
 LN₂/LN₂ CTT DATA
 IRRADIATED VS CONTROL COMPARISONS
 Inconel 718

Figure 6

CTR-19
LN₂/LN₂ CTF DATA
IRRADIATED VS CONTROL COMPARISONS

A286

Figure 7

CTR-19
 LN₂/LH₂ GTT DATA
 IRRADIATED VS CONTROL COMPARISONS
 Hastelloy X

Figure 8

GTR-19
 LN₂/LN₂ CTT DATA
 REGRESSION AND CORRELATION ANALYSIS
 Schematic Identifying Multivariate
 Statistical Terms

Figure 9

APPENDIX A
CONTROL CHART FOR RANGES

APPENDIX A

CONTROL CHART FOR RANGES

Specific parameters are used in sampling theory to define the range distribution for small sample sizes. Parameters σ_w and d_2^* , discussed by Cowden⁽¹⁾ and Duncan⁽²⁾, relate to any range distribution and are used in this case to determine the 95% probability limits for the range based upon four groups of four samples each. This provides a criteria for judging the statistical control of the testing process.

The upper 2-sigma limit (95%) for the range is given by the relation

$$UCL_R = \frac{\bar{R} (2 \sigma_w + d_2^*)}{d_2^*}.$$

The theory of small samples establishes the numerical values of σ_w and d_2^* for four subgroups of four samples each as:

$$\sigma_w = 0.88$$

$$d_2^* = 2.11$$

Based on the derivation of the range distribution statistics, the average range ($\bar{R}$) from each metal and mechanical property provides a criteria for judging the control of the testing process variability. The best estimate of $\bar{R}$ was obtained by successive iteration and elimination of out-of-control values. These $\bar{R}$ estimates are tabulated in Table 3 and shown on Figure 1 together with the best estimate of the upper $2 \sigma_R$ limits for each metal. The plot of Figure 1 for the original ranges summarizes the results of the iterations. The standard deviation, s'_e , is estimated from the values by the relation,

$$s'_e = \bar{R}/d_2^*.$$

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- (1) Cowden, D. J., Statistical Methods in Quality Control, Prentice-Hall, Inc., 1957
(2) Duncan, A. J., Quality Control and Industrial Statistics, R. D. Irwin, Inc., 1959

APPENDIX B

DETAILED EXAMPLE OF CORRELATION AND RESULTS FOR INCONEL 718 FORGINGS

APPENDIX B

DETAILED EXAMPLE OF CORRELATION AND RESULTS FOR INCONEL 718 FORGINGS

The purpose of this appendix is to describe in detail the steps followed to develop the correlation/regression for the randomly paired mechanical properties data of Inconel 718 forgings.

I. YIELD STRENGTH

The observed 0.2% offset yield strength is tabulated below from the data of Table 1.

	<u>Yield strength at liquid hydrogen temperature, ksi</u>	<u>Yield strength at liquid nitrogen temperature, ksi</u>	<u>Fast neutron fluence, nvt x 10¹⁷</u>
Irradiated	NA	(228.0)	3.3
	235.0	223.0	3.3
	230.0	228.0	3.4
	236.0	221.0	3.4
Control	218.5	216.0	0
	203.0	(214.0)	0
	218.0	222.0	0
	223.0	219.0	0

Note: Values in parentheses were omitted from calculations

A multivariate analysis of this randomly paired data was made, where the yield strength at liquid hydrogen temperature is the dependent variable and the yield strength at liquid nitrogen temperature and the fluences are the independent variables. This resulted in the following least squares equation (refer to the schematic of Figure 9):

Appendix B

$$\text{Yield Strength}_{\text{LH}_2} = 309.7 - 0.411 \text{ Yield Strength}_{\text{LN}_2} + 4.78 (\text{Fluence} \times 10^{17})$$

$$R_{1.23} = 0.957 \text{ (Multiple correlation coefficient)}$$

$$S_{1.23} = 3.04 \text{ (Residual standard error of estimate)}$$

$$N = 6$$

Comparison of the observed values with the values calculated from the above equation is as follows:

YIELD STRENGTH AT LIQUID HYDROGEN TEMPERATURE

<u>Observed</u>	<u>Calculated</u>
NA	232.0
235.0	233.9
230.0	231.9
236.0	235.2
218.5	221.0
203.0	223.0
218.0	218.6
223.0	219.4

The 95% prediction limits of individuals* for the dependent variable (yield strength at liquid hydrogen temperature) as a joint function of the independent variables taken at low, medium, and high levels is (refer to schematic of Figure 9):

* Duncan, A. J., Quality Control and Industrial Statistics, Revised Edition, R. D. Irwin, Inc., 1959

Appendix B

			<u>Liquid Nitrogen Temperature</u>		
			<u>Low</u>	<u>Medium</u>	<u>High</u>
	Individual	Yield -	216	222	228
	Limits	Fluence -	0	1.7	3.5
Yield Strength at liquid hydrogen temperature	Upper		233	237	245
	Expected Value (mean)		221	227	233
	Lower		209	216	220

II. PERCENT ELONGATION

The correlation and regression calculations and tabulations for the percent elongation are identical to those illustrated for yield strength in Section I.

The observed percent elongation data is tabulated from the data of Table 1 as follows:

	<u>Percent elongation at liquid hydrogen temperature</u>	<u>Percent elongation at liquid nitrogen temperature</u>	<u>Fluence, nvt x 10¹⁷</u>
Irradiated	(7.9)	(21.5)	3.3
	18.6	18.5	3.3
	17.8	20.4	3.4
	17.3	19.9	3.4
Control	19.6	25.3	0
	20.6	18.6	0
	(13.9)	(4.4)	0
	19.9	20.2	0

Note: Values in parentheses were omitted from the calculations.

Appendix B

The least squares equation for percent elongation at liquid hydrogen temperature is:

$$\% \text{ Elongation}_{\text{LH}_2} = 19.1 + 0.018 \text{ Yield Strength}_{\text{LN}_2} - 0.144\% \text{ Elongation}_{\text{LN}_2} - 0.745 (\text{Fluence} \times 10^{17})$$

$$R_{1.234} = 0.960 \text{ (multiple correlation coefficient)}$$

$$S_{1.234} = 0.57 \text{ (residual standard error of estimate)}$$

$$N = 6$$

Comparison of observed values with values calculated from the above equation is as follows:

PERCENT ELONGATION AT LIQUID HYDROGEN TEMPERATURE

<u>Observed</u>	<u>Calculated</u>
(7.9)	18.5
18.6	18.1
17.8	17.9
17.3	17.7
19.6	19.4
20.6	20.5
(13.9)	19.9
19.9	20.2

The 95% prediction limits of individuals for the dependent variable as a joint function of independent variables is as follows:

Appendix B

		<u>Liquid Nitrogen Temperature</u>		
		<u>Low</u>	<u>Medium</u>	<u>High</u>
	Yield -	216	222	228
	Elongation -	18.0	20.5	23.0
	Fluence -	0	1.7	3.5
<hr/>		<hr/>		
% Elongation at liquid hydrogen temperature	Individual Limits			
	Upper	24.4	21.6	21.6
	Expected value (mean)	20.5	18.9	17.3
	Lower	16.4	16.3	13.0