TITLE PROJECT

Continued From Page

Westmoreland Mechanical Testing & Research, Inc
Old Route 30, Westmoreland Drive
P.O. Box 388, Youngstown, Pa 15696

Certificate of Calibration

This is to certify that the following described measruring equipment has been calibrated by WMT&R and the range(s) shown below found to be within a maximum tolerance of 0.0001 inch.

Equipment:	Micrometer	Cal Frequency:	1 Month
Location:	TD	WMT&R ID:	9330911
Serial Number:	9330911	Zero Reading:	0.0
Calibration Date:	8/22/07	Due Date:	9/22/2007

Method of verification and below recorded data is in accordance with WMT&R Procedure 16303 and ISO 10012.
The testing device(s)used for this verification have certifications traceable to the National Institute of Standards and Technology.
All verifications are as found.

Reference Settings and Equipment Readings are in inches.

REFERENCE SETTING	EQUIPMENT READING	EQUIPMENT ERROR	%	G.B. NO.
.100	0.1	0.00000	0.00	1
.150	0.15005	-0.00005	-0.03	1
.200	0.2	0.00000	0.00	1
.300	.30000	0.00000	0.00	1
.500	.50005	-0.00005	-0.01	1
1.000	1.00000	0.00000	0.00	1

CALIBRATION APPARATUS:

The Gage Blocks used in the above verification, identified as G.B. No.1, MTI 35 pc, Serial Number 00942.
For additional information see associated Certification.

Calibrated by: Date:

MW 8/22/07

Approved by: Date:

[signature] 8-22-07

KNOWINGLY OR WILLFULLY FALSIFYING OR CONCEALING A MATERIAL FACT ON THIS FORM, OR MAKING FALSE, FICTITIOUS OR FRAUDULENT STATEMENTS OR REPRESENTATIONS HERIN COULD CONSTITUTE A FELONY PUNISHABLE UNDER FEDERAL STATUTES.

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 4/8/10

TITLE PROJECT

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INSTRUMENT CALIBRATION REPORT

C & M COLLINS CALIBRATION SERVICE, INC.

This instrument was calibrated to ASTM E83-06. Calibration procedures and practices adhere to ISO/IEC 17025, ISO 10012, ANSI/NCSL Z540-1 & C&M Collins Calibration Service, Inc. procedure number 10.6.

Cert. No. 1825.01

Instrument: MTS **Type:** Extensometer **Model:** 632.53E-14 **Serial No.** 1470163

Location: Westmoreland Mechanical Testing & Research, Inc. Youngstown, PA 15696 **Cert. No.** 0704211470163e

Calibration Date: 04/21/07 **Instrument Readings As Found:** [X] **Readings After Adjustment:** [ ]

Gage Length Of Instrument: 0.500" **Measured Error Reading One:** 0.20% **Measured Error Reading Two:** 0.20%

Method Of Measurement: Indirect **Temperature Of Instrument:** 23 C **Test Type:** Bidirectional

Instrument Travel: 0.0010 to 0.1000 In Tension / -0.0010 to -0.0500 Comp. **Indicator Resolution:** 0.0010 - 0.000001 0.010 - 0.00001 / 0.100 - 0.001 **Uncertainty:** 0.00003 @ 0.001" 0.000031 @ 0.01" / .000065 @ 0.1"

Calibration Factor: Unity **Maximum Errors: (in inches strain)** -0.00020 0.00019 **Class Of Instrument:** B-1

Instrument Position During Verification: Attached To Spindles With Vertical Axis. **Spindle Description:** 0.250" round

Method Of Attachment To Comparator: As Per Manufacturer's Instructions For Service Use.

Calibration Standard Used: C&M Collins Calibration Service, Inc. Instrument Comparator Serial No. C & M 725

Verification Of Calibration Apparatus: Brown & Sharpe Micrometer Head To ASTM E83-06. NIST No. 821/271641-05
See Associated Reports Citing Micrometer Head Errors And NIST Traceability.

Remarks: Bidirectional extensometer calibrated in tension & compression.

Comparator Reading In Inches	Instrument Reading In Strain	Instrument Reading Run One	Instrument Error Run One	Relative Error Run One	Instrument Reading Run Two	Instrument Error Run Two	Relative Error Run Two	Repeatability Error In Percent
0.00000	0.0000000	0.0000001	-0.0000001	N/A	0.0000002	-0.0000002	N/A	N/A
0.00100	0.001000	0.000977	0.000023	2.35	0.000972	0.000028	2.88	-0.53
0.00200	0.00200	0.00197	0.00003	1.52	0.00195	0.00005	2.56	-1.04
0.00400	0.00400	0.00396	0.00004	1.01	0.00396	0.00004	1.01	0.00
0.00700	0.00700	0.00697	0.00003	0.43	0.00696	0.00004	0.57	-0.14
0.01000	0.01000	0.00998	0.00002	0.20	0.00999	0.00001	0.10	0.10
0.02000	0.02000	0.02001	-0.00001	-0.05	0.02002	-0.00002	-0.10	0.05
0.04000	0.04000	0.04005	-0.00005	-0.12	0.04004	-0.00004	-0.10	-0.02
0.07000	0.07000	0.07011	-0.00011	-0.16	0.07014	-0.00014	-0.20	0.04
0.10000	0.10000	0.10010	-0.00010	-0.10	0.10020	-0.00020	-0.20	0.10
0.00000	0.000000	0.0000004	-0.0000004	N/A	0.0000005	-0.0000005	N/A	N/A
-0.00100	-0.001000	-0.001024	0.000024	-2.34	-0.001029	0.000029	-2.82	0.47
-0.00200	-0.00200	-0.00202	0.00002	-0.99	-0.00202	0.00002	-0.99	0.00
-0.00400	-0.00400	-0.00405	0.00005	-1.23	-0.00404	0.00004	-0.99	-0.24
-0.00700	-0.00700	-0.00705	0.00005	-0.71	-0.00704	0.00004	-0.57	-0.14
-0.01000	-0.01000	-0.01007	0.00007	-0.70	-0.01006	0.00006	-0.60	-0.10
-0.02000	-0.02000	-0.02008	0.00008	-0.40	-0.02009	0.00009	-0.45	0.05
-0.03000	-0.03000	-0.03010	0.00010	-0.33	-0.03011	0.00011	-0.37	0.03
-0.04000	-0.04000	-0.04014	0.00014	-0.35	-0.04016	0.00016	-0.40	0.05
-0.05000	-0.05000	-0.05018	0.00018	-0.36	-0.05019	0.00019	-0.38	0.02

The reported uncertainty is based on a standard uncertainty multiplied by a coverage factor K=2, providing a level of confidence of approximately 95%. Uncertainty is done upon request by customer.

Service Technician: [signature]
Witnessed By: [signature] 4-21-07

C & M Collins Calibration Service, Inc
P.O. Box 487, Evans City, PA 16033
(724) 538-1084 Fax: (724) 538-1081

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TITLE **PROJECT**

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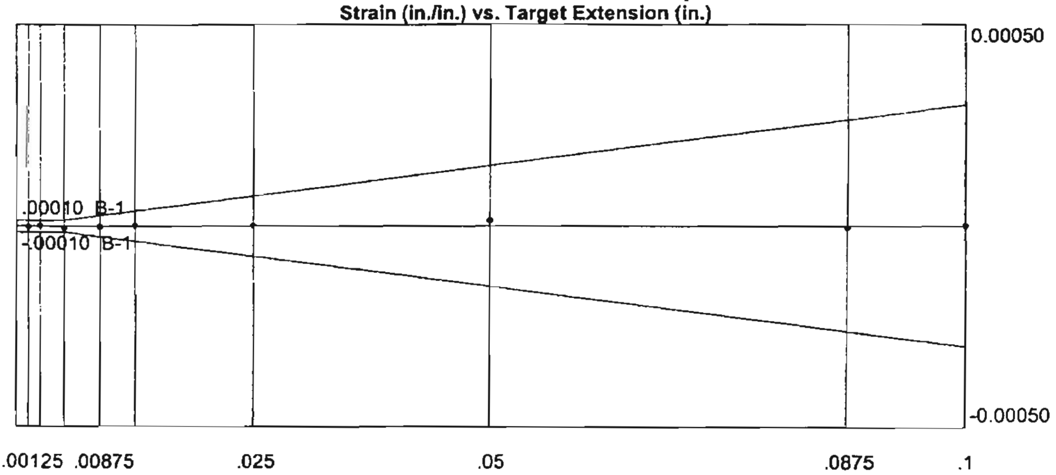
Westmoreland Mechanical Testing & Research, Inc.
Extensometer Verification Report

Date: 8/15/07
Department: TENSILE
Technician: CURT LANTZY
Machine No.: M-9
Extensometer WMT&R No.: 00996

Strain Channel: 1
Cal. Head: 01563
Extensometer Serial No.: 1132
Extensometer Gage Length (Inches): .25
Extensometer Full Scale (Inches): .1
Extensometer Cal. Point (Inches): .1

	Indicated Extension	Target Extension	Error of Extension	Error of Strain
1:	0.00125	0.00125	0.00000	-0.00001
2:	0.00250	0.00250	0.00000	0.00001
3:	0.00499	0.00500	-0.00001	-0.00003
4:	0.00875	0.00875	0.00000	-0.00001
5:	0.01250	0.01250	0.00000	0.00001
6:	0.02500	0.02500	0.00000	0.00001
7:	0.05002	0.05000	0.00002	0.00010
8:	0.08749	0.08750	-0.00001	-0.00002
	0.10000	0.10000	0.00000	0.00001

Extensometer Verification Graph
Strain (in./in.) vs. Target Extension (in.)



Target Extension (Inches)

Classification: B-1

Comments: N/A

Date Printed: 08-15-2007 **Certified By:** [signature]

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WMT&R Procedure No.: WMT&R-6780 Program No.: WMTR-QA-011 Version 1.06

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TITLE **PROJECT**

Continued From Page

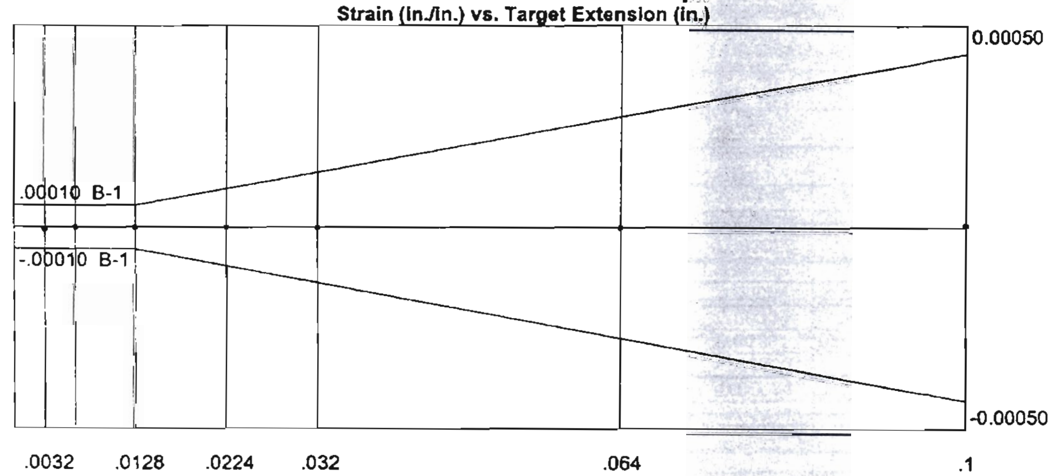
Westmoreland Mechanical Testing & Research, Inc.
Extensometer Verification Report

Date: 8/15/07
Department: TENSILE
Technician: CURT LANTZY
Machine No.: M-9
Extensometer WMT&R No.: 01884

Strain Channel: 2
Cal. Head: 01563
Extensometer Serial No.: 1470163
Extensometer Gage Length (Inches): .64
Extensometer Full Scale (Inches): .1
Extensometer Cal. Point (Inches): .1

	Indicated Extension	Target Extension	Error of Extension	Error of Strain
1:	0.00319	0.00320	-0.00001	-0.00001
2:	0.00640	0.00640	0.00000	0.00000
3:	0.01280	0.01280	0.00000	0.00000
4:	0.02240	0.02240	0.00000	0.00000
5:	0.03200	0.03200	0.00000	0.00000
6:	0.06400	0.06400	0.00000	0.00000
7:	0.10001	0.10000	0.00001	0.00001

Extensometer Verification Graph
Strain (in./in.) vs. Target Extension (in.)



Target Extension (Inches)

Classification: B-1

Comments: N/A

Date Printed: 08-15-2007 **Certified By:** [signature]

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WMT&R Procedure No.: WMT&R-6780 Program No.: WMTR-QA-011 Version 1.06

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TITLE

PROJECT

Continued From Page

WESTMORELAND MECHANICAL TESTING & RESEARCH, Inc.

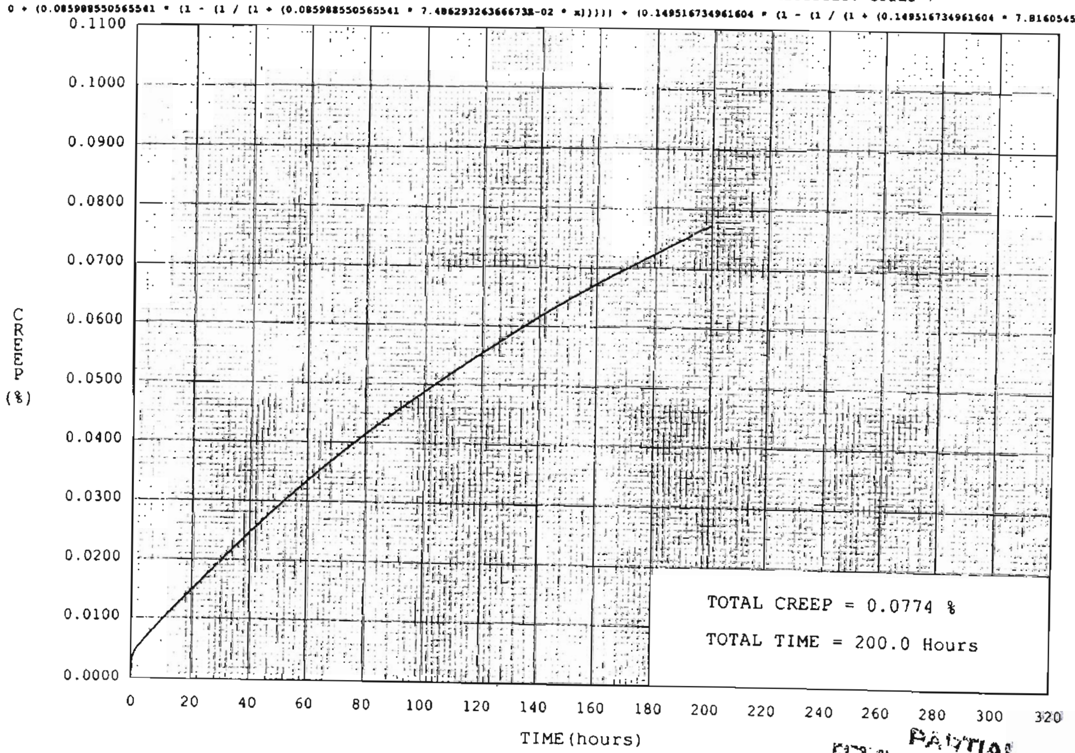
TIME vs CREEP PLOT

Phone 724-537-3131

Customer: Southwest Research
WMT&R Report: 7-37523
Test Log No.: G00558
Machine No.: 55 A

Sample No: ETC-G7-7
Temperature: 302
KSI: 17.490
Material: Grade 7

0 + (0.085988550565541 * (1 - (1 / (1 + (0.085988550565541 * 7.486293263666738E-02 * x))))) + (0.149516734961604 * (1 - (1 / (1 + (0.149516734961604 * 7.816054554630388E-03 * x)))



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TITLE

PROJECT

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WESTMORELAND MECHANICAL TESTING & RESEARCH, Inc.

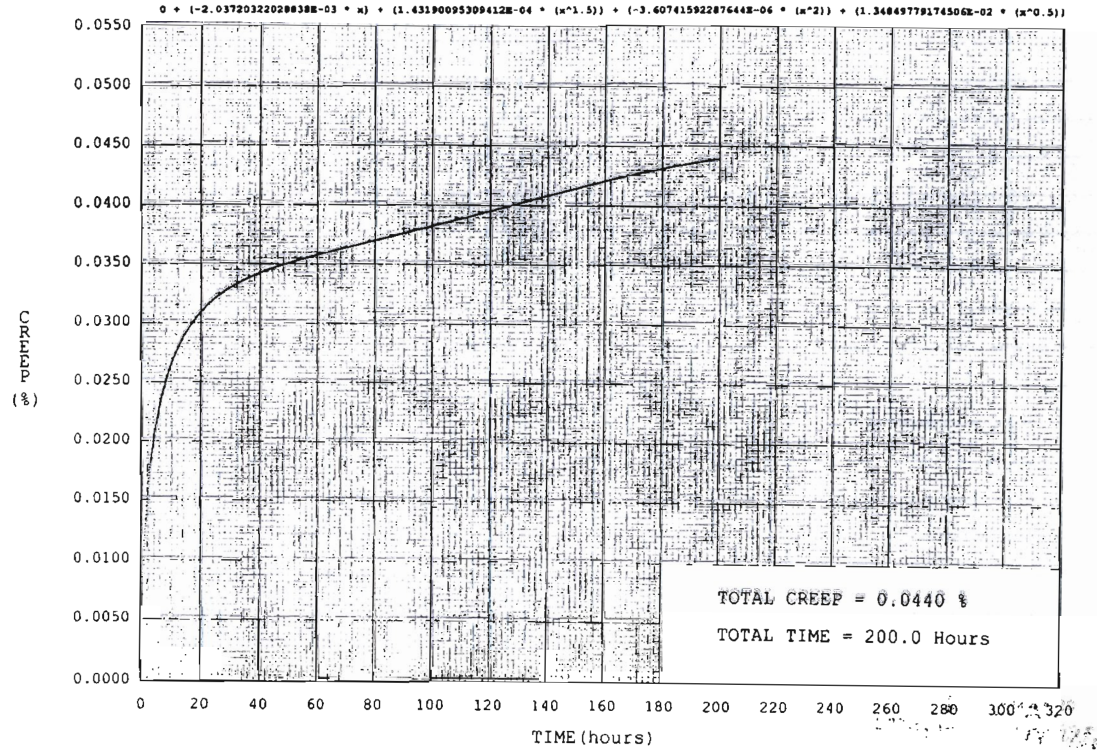
TIME vs CREEP PLOT

Phone 724-537-3131

Customer: Southwest Research
WMT&R Report: 7-37523
Test Log No.: G00559
Machine No.: 107 A

Sample No: ETC-G7-8
Temperature: 302
KSI: 12.720
Material: Grade 7

0 + (-2.037203220208388E-03 * x) + (1.431900953094128E-04 * (x^1.5)) + (-3.607415922876448E-06 * (x^2)) + (1.348497791745062E-02 * (x^0.5))



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Date

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TITLE **PROJECT**

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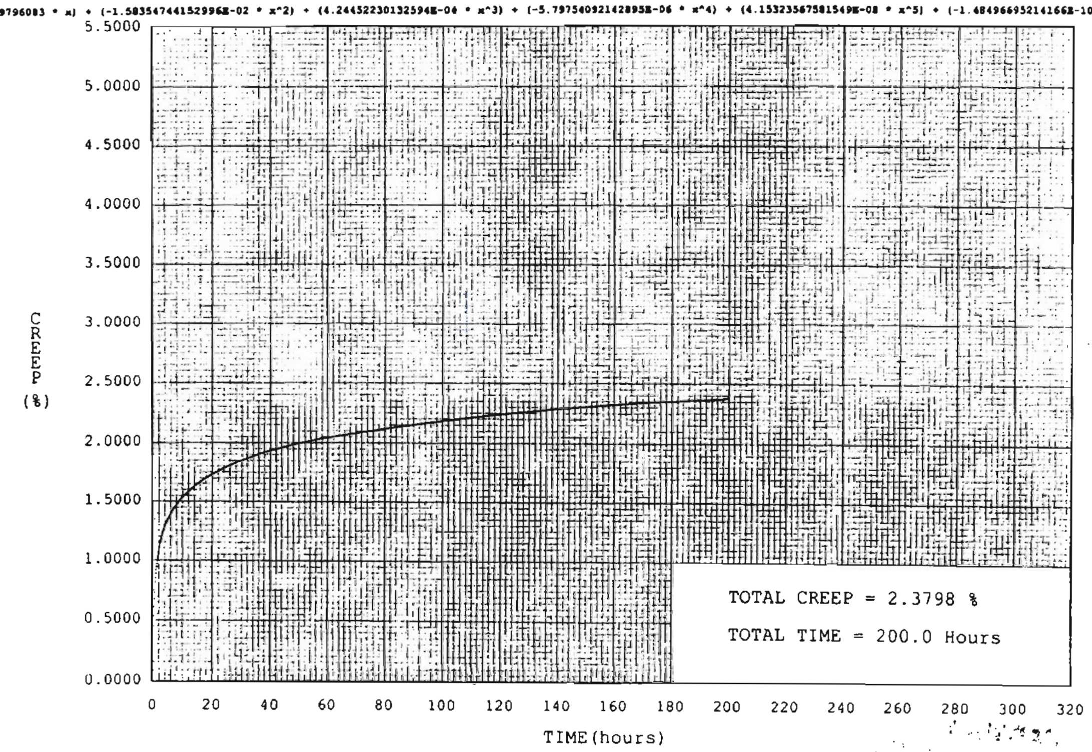
WESTMORELAND MECHANICAL TESTING & RESEARCH, Inc.

TIME vs CREEP PLOT Phone 724-537-3131

Customer: Southwest Research
WMT&R Report: 7-37523
Test Log No.: G00556
Machine No.: 50 A

Sample No: ETC-G7-5
Temperature: 302
KSI: 27.030
Material: Grade 7

89796083 * x) + (-1.583547441529962-02 * x^2) + (4.24452230132594E-04 * x^3) + (-5.79754092142895E-06 * x^4) + (4.15323567581549E-08 * x^5) + (-1.48496695214166E-10 * x^6) + (2.0888



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TITLE **PROJECT**

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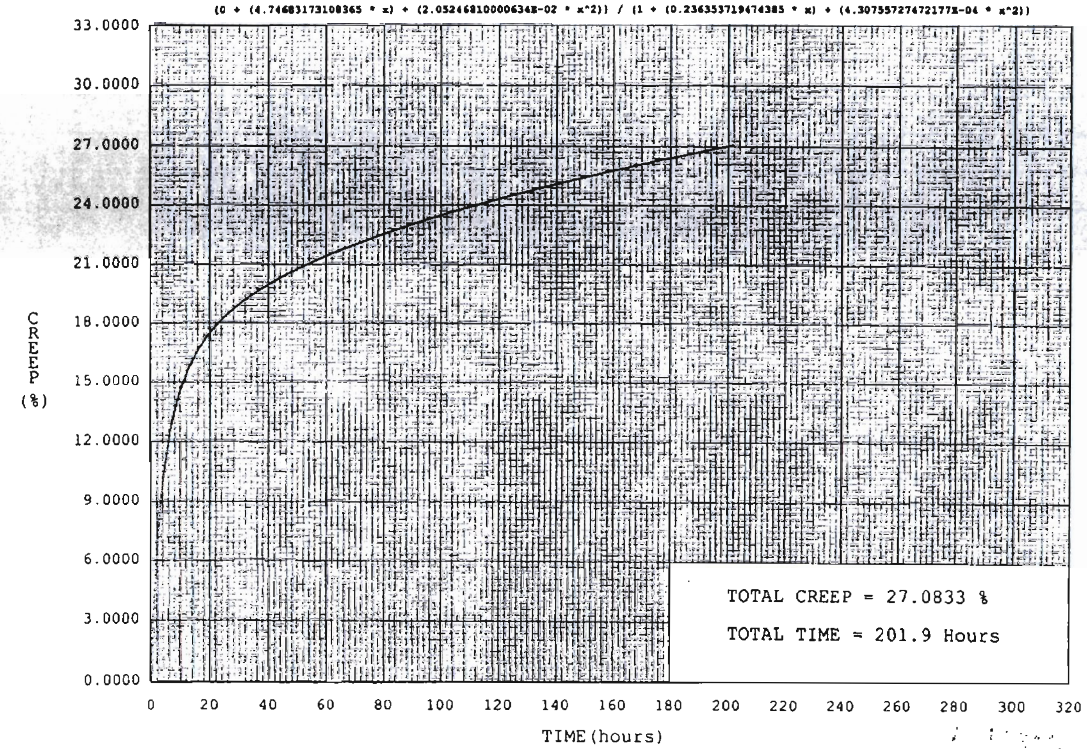
WESTMORELAND MECHANICAL TESTING & RESEARCH, Inc.

TIME vs CREEP PLOT Phone 724-537-3131

Customer: Southwest Research
WMT&R Report: 7-37523
Test Log No.: G00554
Machine No.: 51 A

Sample No: ETC-G7-3
Temperature: 302
KSI: 33.390
Material: Grade 7

(0 + (4.74683173108365 * x) + (2.05246810000634E-02 * x^2)) / (1 + (0.236353719474385 * x) + (4.30755727472177E-04 * x^2))



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TITLE **PROJECT**

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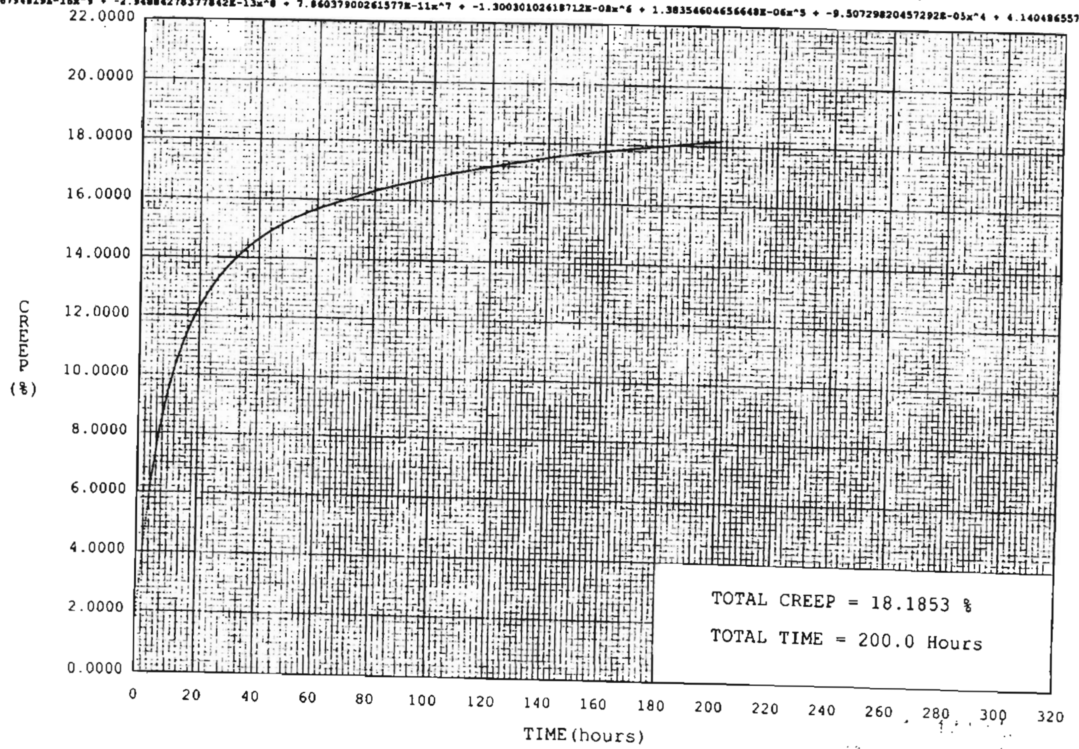
WESTMORELAND MECHANICAL TESTING & RESEARCH, Inc.

TIME vs CREEP PLOT Phone 724-537-3131

Customer: Southwest Research
WMT&R Report: 7-37523
Test Log No.: G00555
Machine No.: 49 A

Sample No: ETC-G7-4
Temperature: 302
KSI: 31.800
Material: Grade 7

.2167948192E-16x^9 + -2.948842783778422E-13x^8 + 7.86037900261577E-11x^7 + -1.30030102618712E-08x^6 + 1.38354604656648E-06x^5 + -9.50729820457292E-05x^4 + 4.14048655712403E-03x^3 + -0.



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TITLE **PROJECT**

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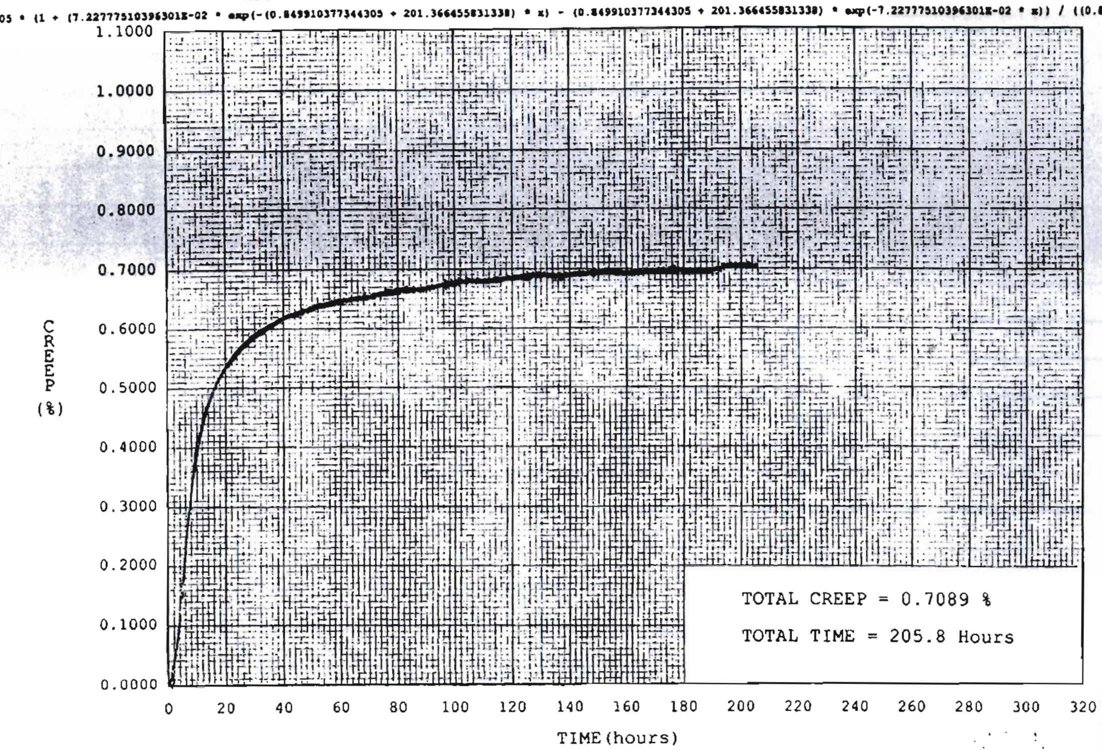
WESTMORELAND MECHANICAL TESTING & RESEARCH, Inc.

TIME vs CREEP PLOT Phone 724-537-3131

Customer: Southwest Research
WMT&R Report: 7-37523
Test Log No.: G00557
Machine No.: 48 A

Sample No:
Temperature: 302
KSI:
Material: Grade 7

05 * (1 + (7.22777510396301E-02 * exp(-(0.849910377344305 + 201.366455831338) * x) - (0.849910377344305 + 201.366455831338) * exp(-7.22777510396301E-02 * x)) / ((0.849910377344305 +



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TITLE

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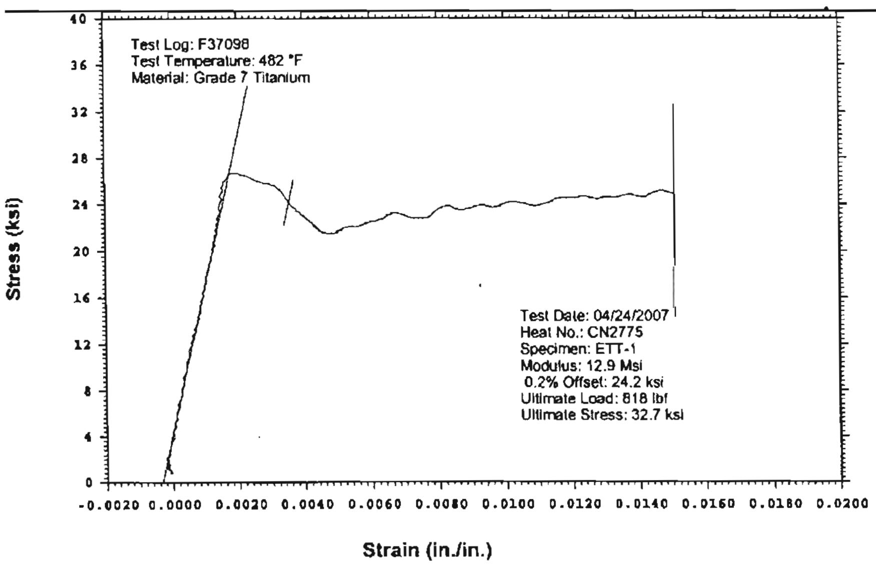
WESTMORELAND MECHANICAL TESTING & RESEARCH, Inc

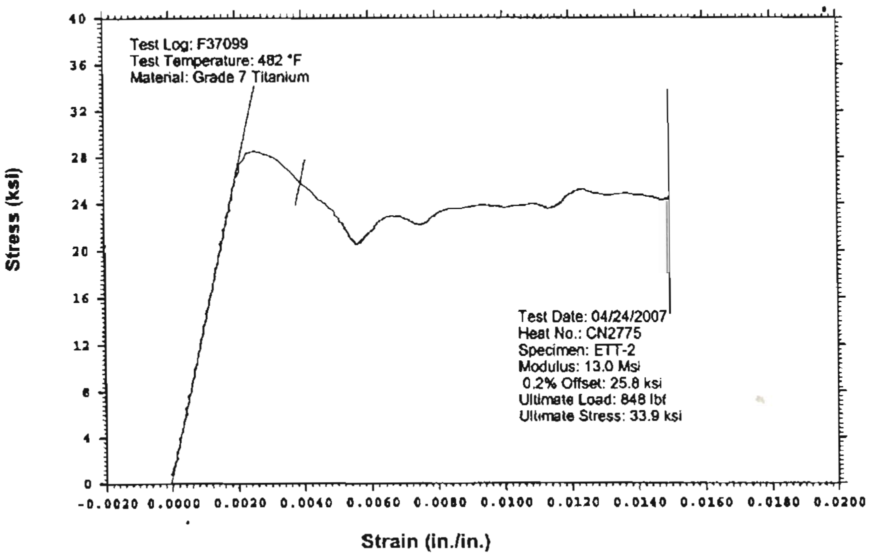
Stress vs. Strain

Phone: (724)537-3131

Customer: Southwest Research
WMT&R Report: 7-28471

P.O. No.: 757847D
WMT&R Quote No.: QN262145 Rev.1
Shipping Ticket No.: 446266
Acct or Project No.: 06002.01.342
SWRI Req. No.: 07010181





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TITLE

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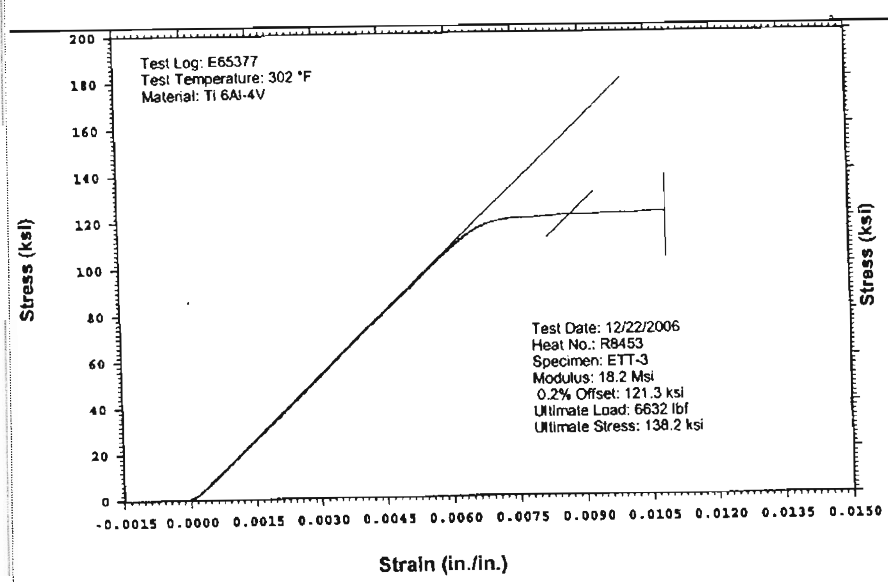
WESTMORELAND MECHANICAL TESTING & RESEARCH, Inc

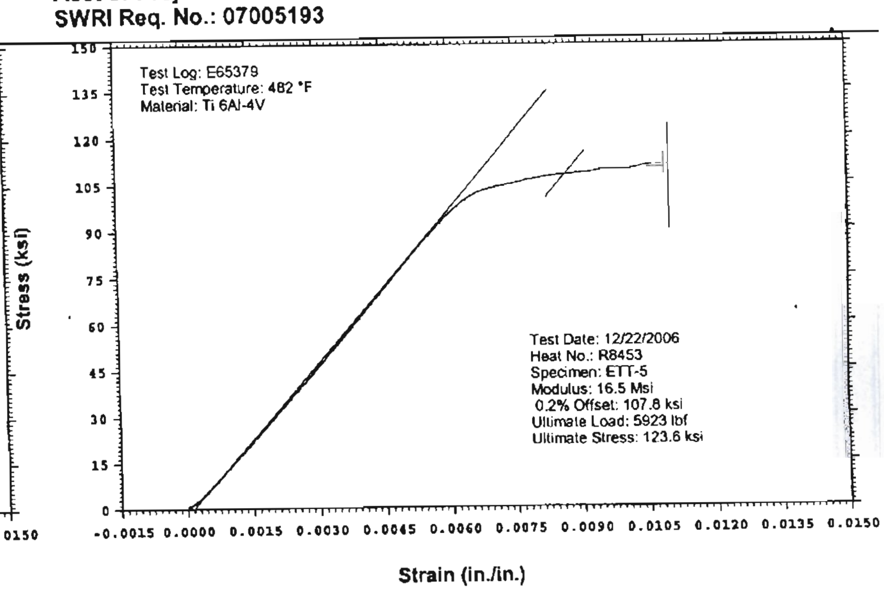
Stress vs. Strain

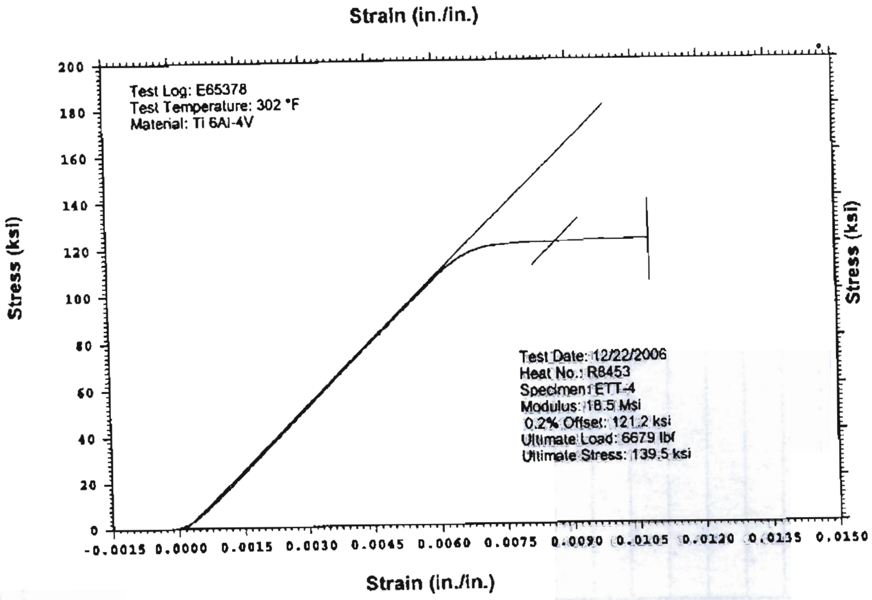
Phone: (724)537-3131

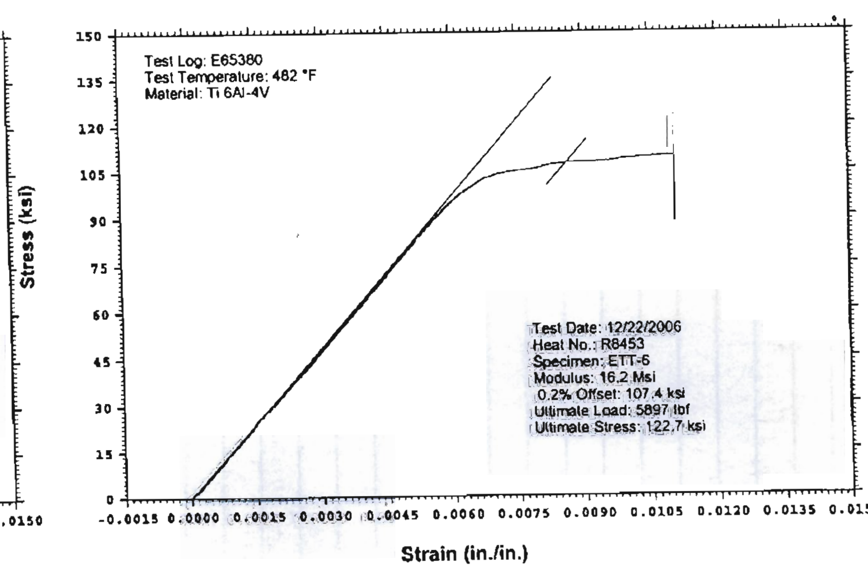
Customer: Southwest Research
WMT&R Report: 6-45031

P.O. No.: 787112J
WMT&R Quote No.: QN262147
Shipping Ticket No.: 446260
Acct or Project No.: 20.06002.01.342
SWRI Req. No.: 07005193









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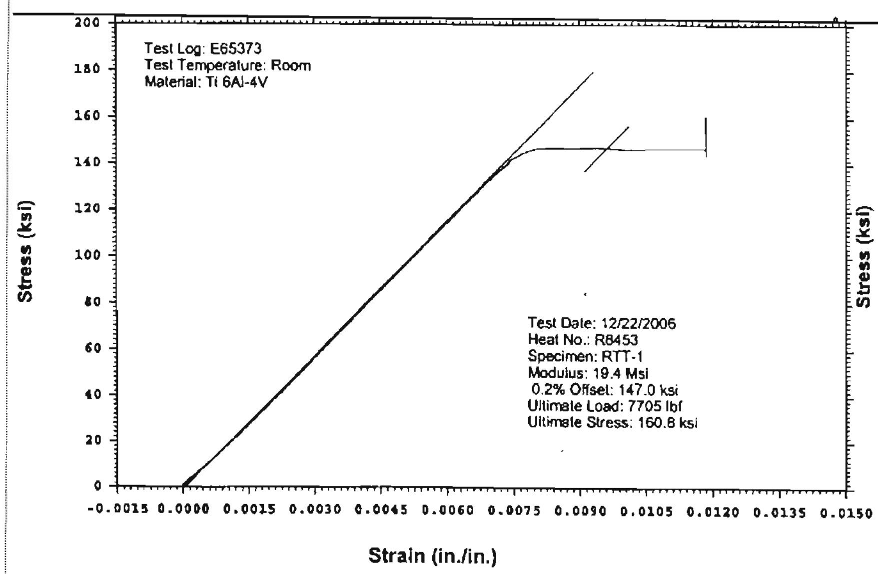
WESTMORELAND MECHANICAL TESTING & RESEARCH, Inc

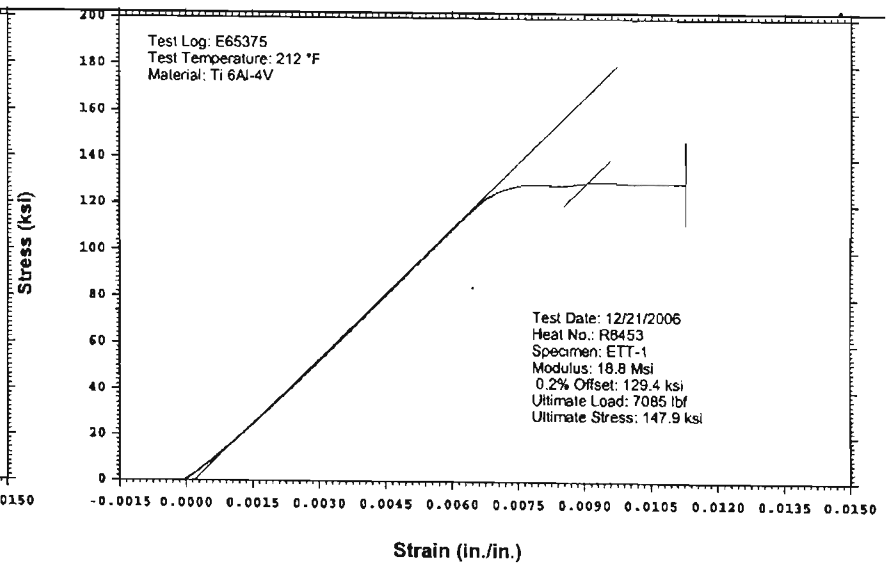
Stress vs. Strain

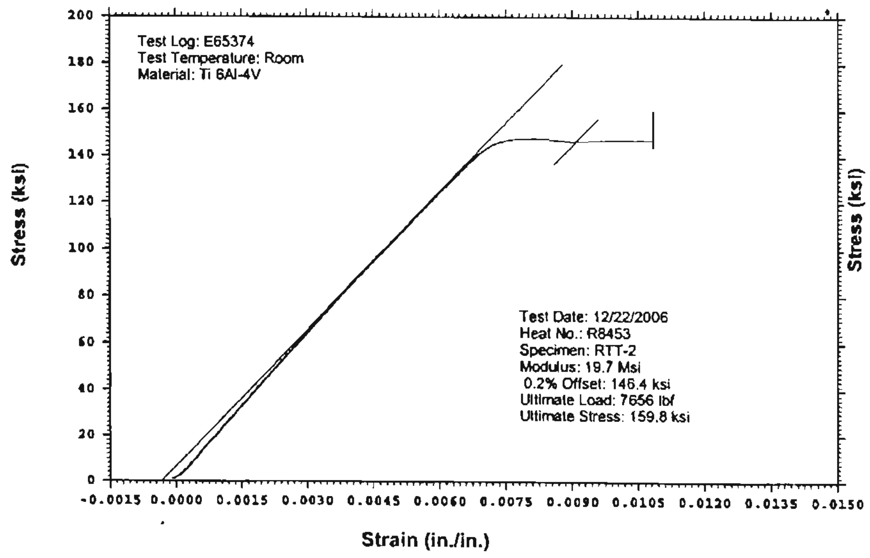
Phone: (724)537-3131

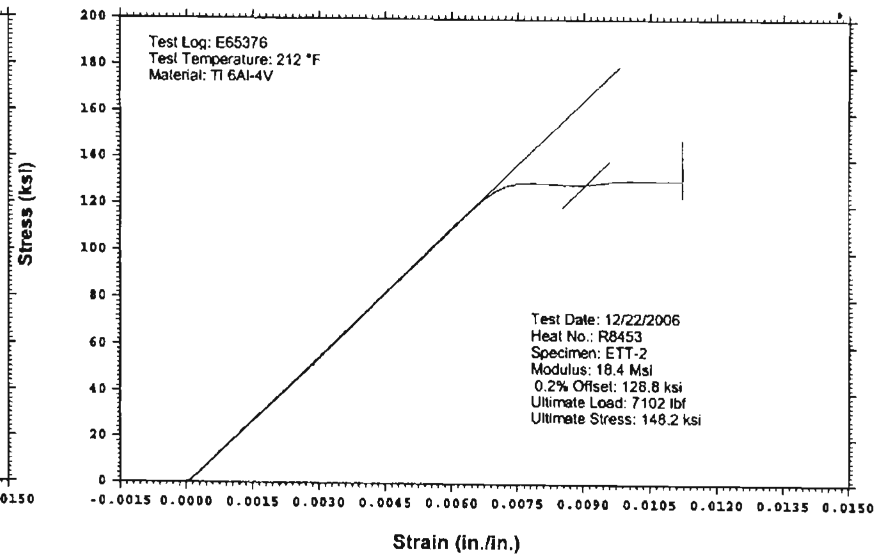
Customer: Southwest Research
WMT&R Report: 6-45031

P.O. No.: 787112J
WMT&R Quote No.: QN262147
Shipping Ticket No.: 446260
Acct or Project No.: 20.06002.01.342
SWRI Req. No.: 07005193









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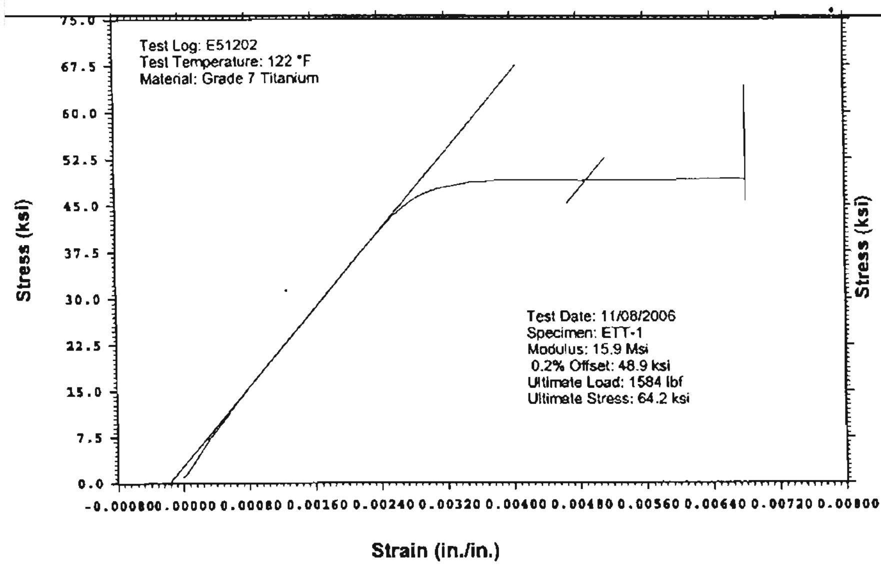
WESTMORELAND MECHANICAL TESTING & RESEARCH, Inc

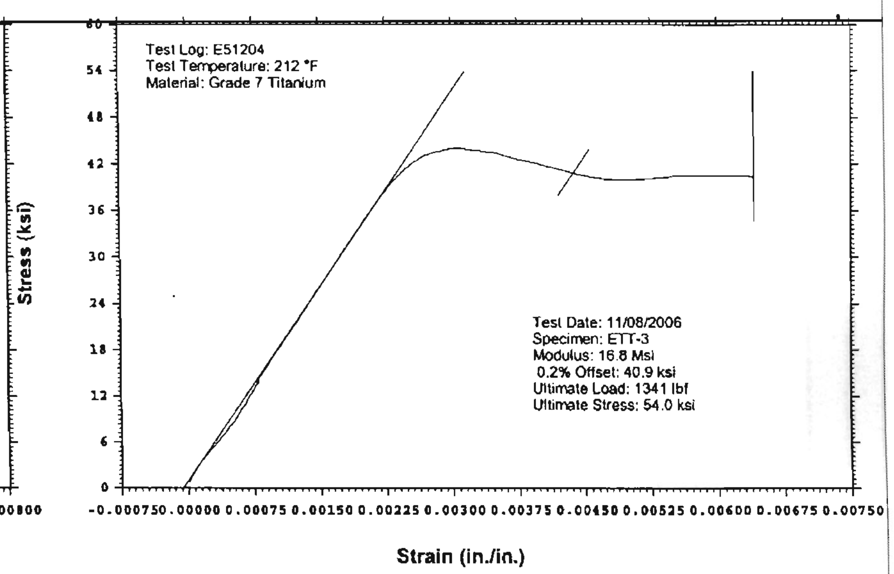
Stress vs. Strain

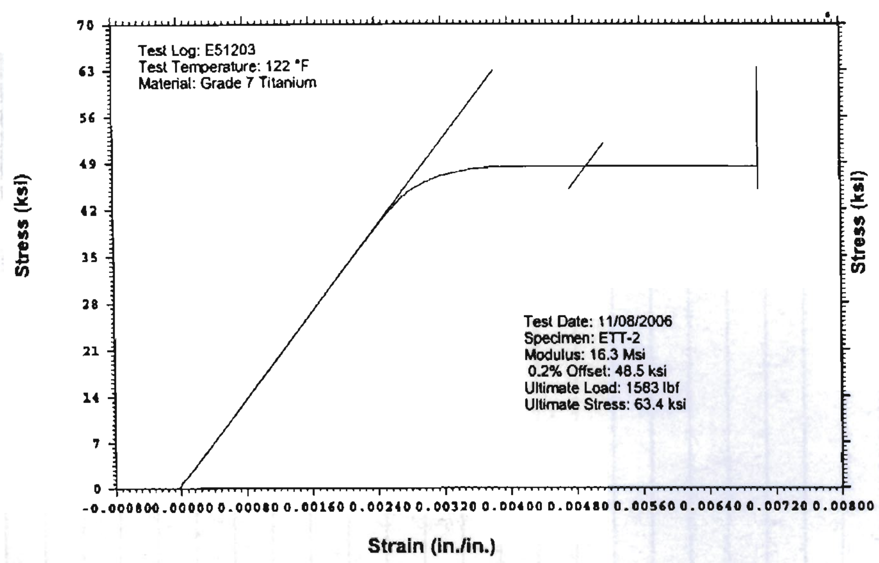
Phone: (724)537-3131

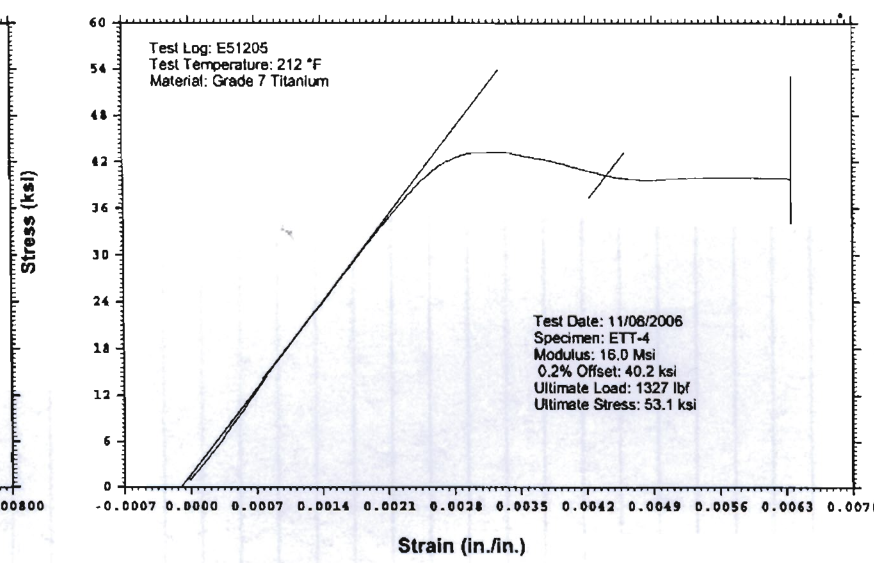
Customer: Southwest Research
WMT&R Report: 6-42990

P.O. No.: 682290E
WMT&R Quote No.: QN262021
Shipping Ticket No.: 446259
Acct or Project No.: 06002.01.342









PROJECT

SIGNATURE K. T. Chiang DATE

DISCLOSED TO AND UNDERSTOOD BY DATE 4/29/08

Continued To Page

~~PROPRIETARY INFORMATION~~ 4/8/10

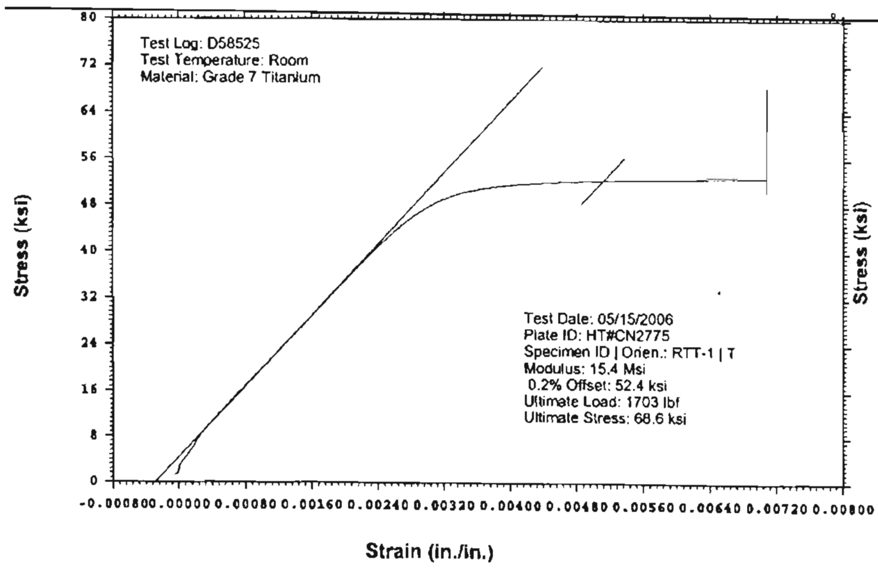
BOOK 770 - 83 PAGE

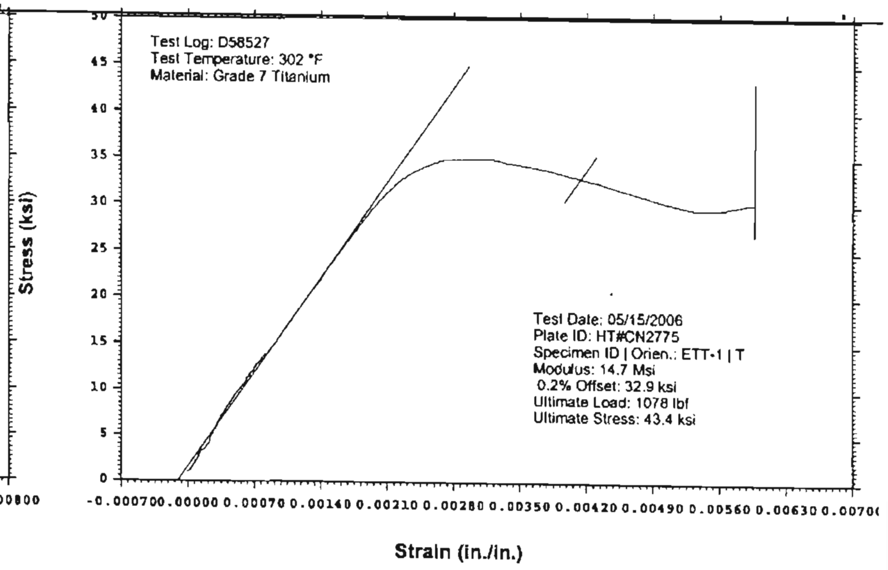
WESTMORELAND MECHANICAL TESTING & RESEARCH, Inc

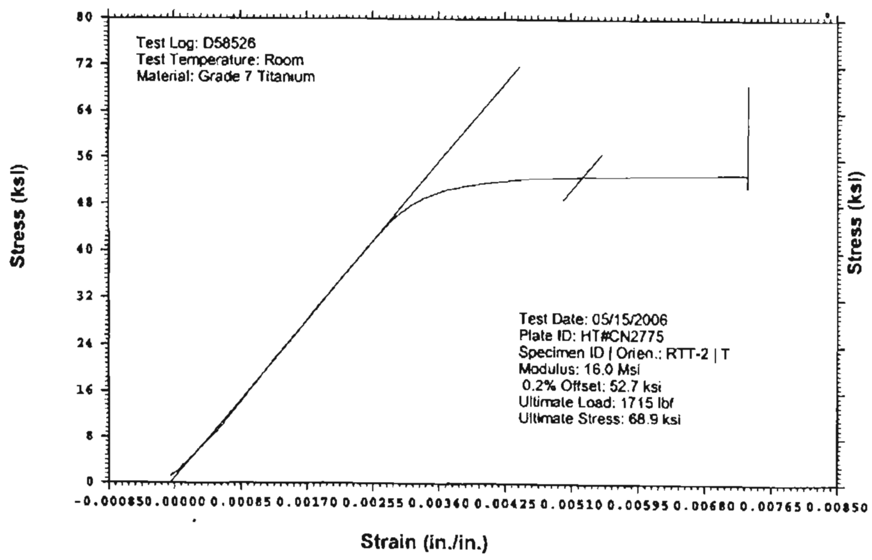
Stress vs. Strain
Phone: (724)537-3131

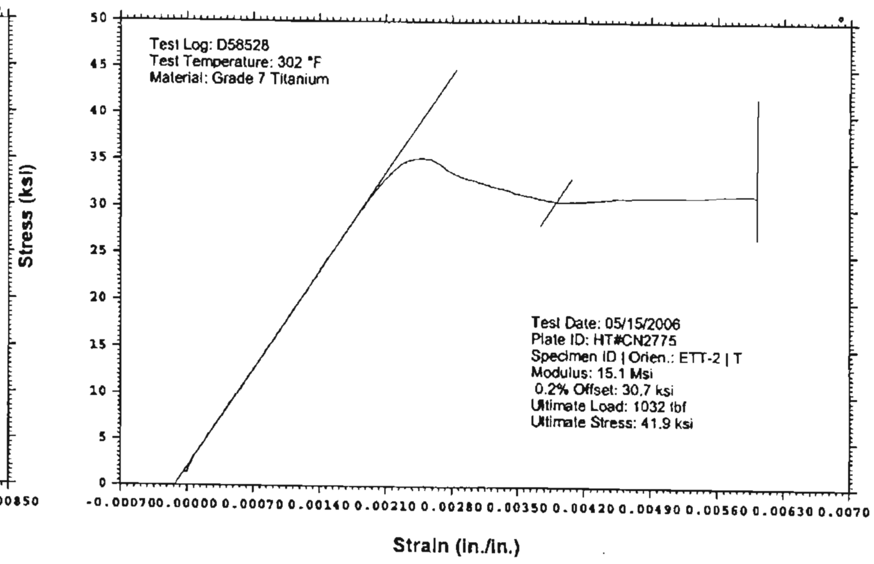
Customer: Southwest Research
WMT&R Report: 6-29304

P.O. No.: 682290E
WMT&R Quote No.: QN260654
Shipping Ticket No.: 428997
Acct or Project No.: 20.06002.01.342
SWRI Req. No.: 06020028









PROJECT

SIGNATURE K. T. Chiang DATE 4/29/08
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~~PROPRIETARY INFORMATION~~ 4/8/10

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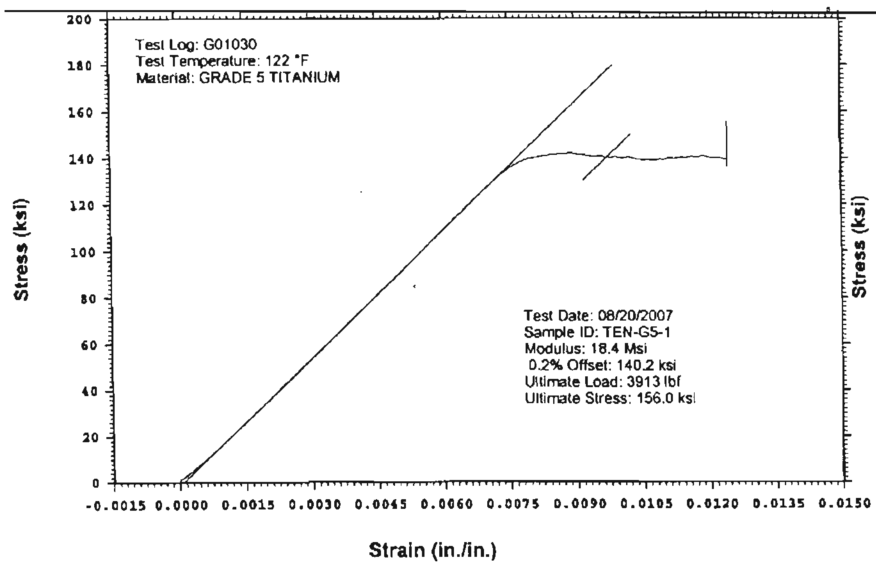
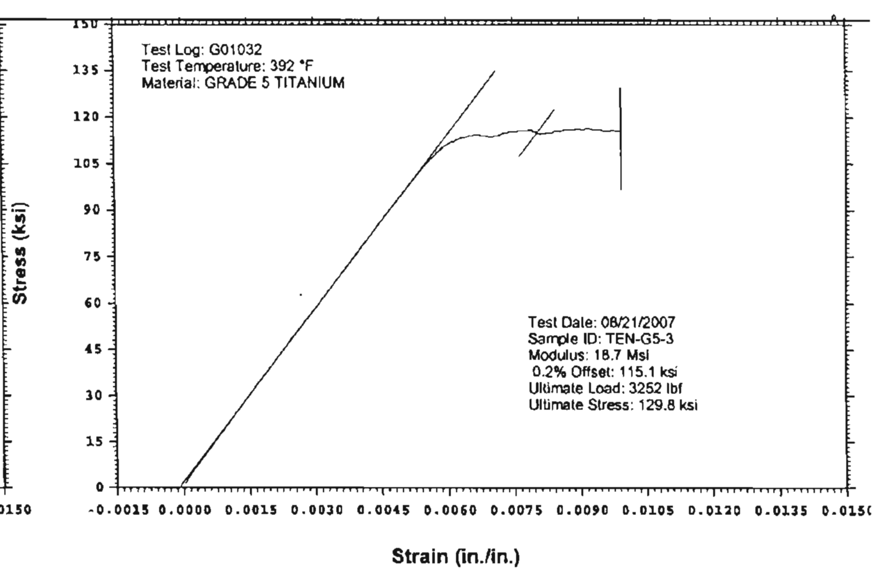
WESTMORELAND MECHANICAL TESTING & RESEARCH, Inc

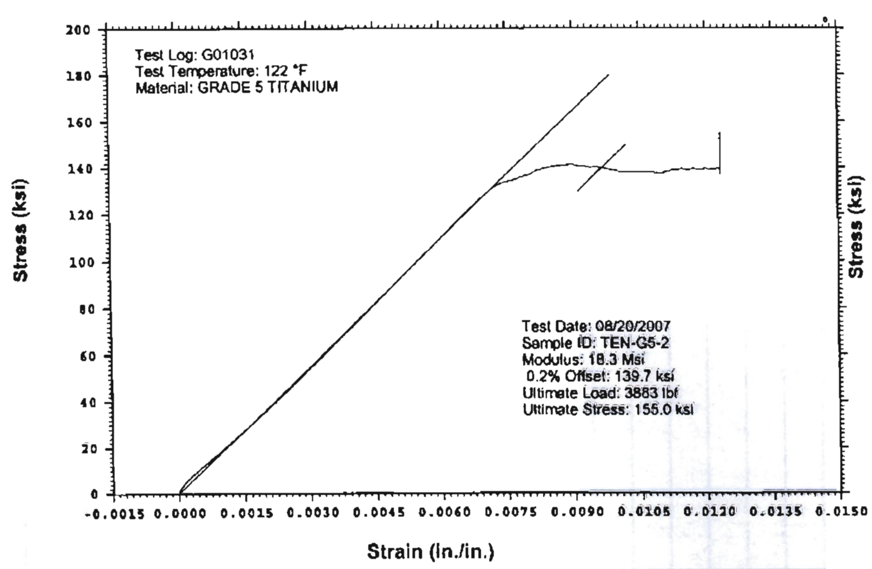
Stress vs. Strain
Phone: (724)537-3131

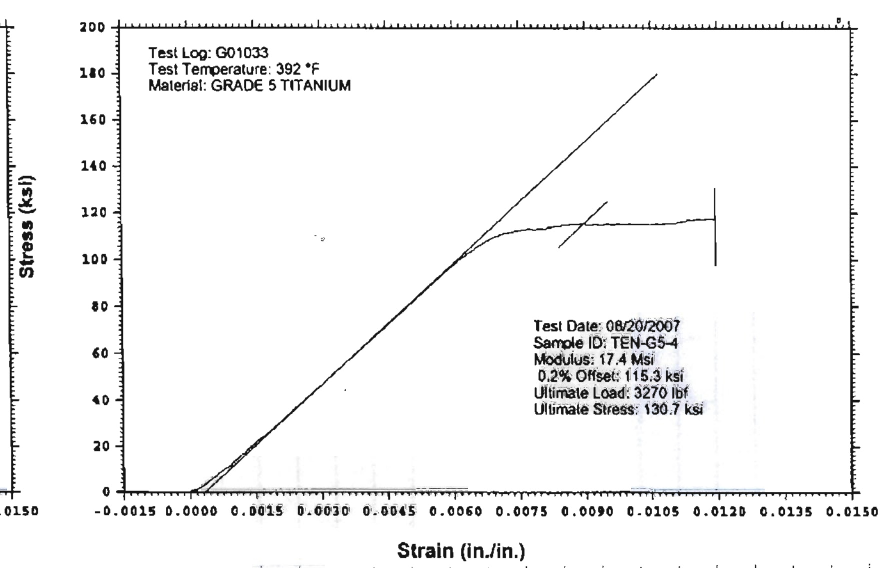
Customer: Southwest Research
WMT&R Report: 7-37523

P.O. No.: 782852E
WMT&R Quote No.: QN270982 Rev. 2









PROJECT

SIGNATURE K. T. Chiang DATE 4/29/08
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~~PROPRIETARY INFORMATION~~ 4/8/10

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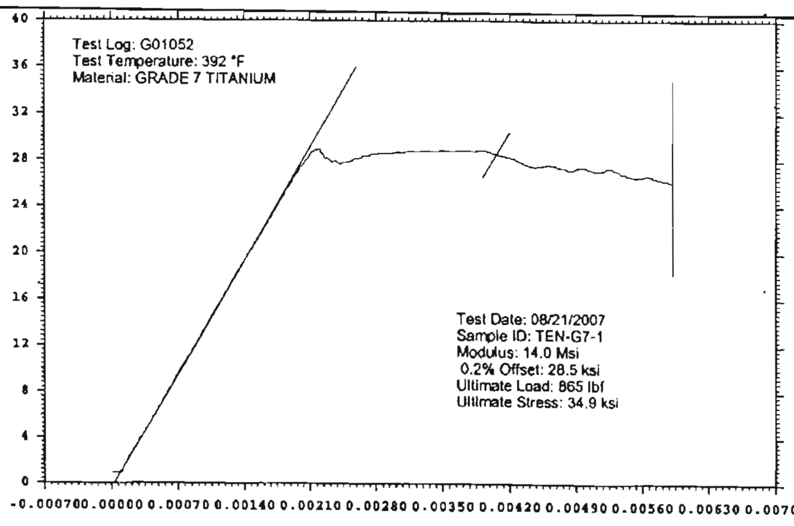
WESTMORELAND MECHANICAL TESTING & RESEARCH, Inc

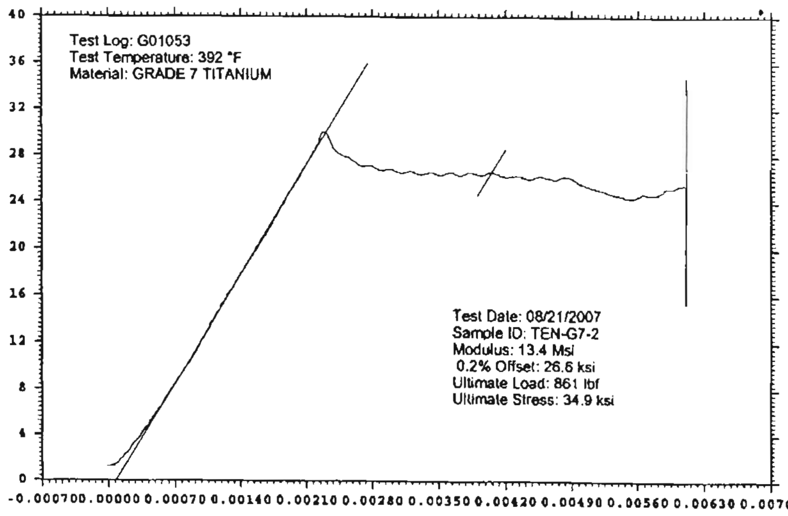
Stress vs. Strain

Phone: (724)537-3131

Customer: Southwest Research
WMT&R Report: 7-37523

P.O. No.: 782852E
WMT&R Quote No.: QN270982 Rev. 2





PROJECT

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SIGNATURE: K. J. Chiang
DATE: 4/29/08
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DATE

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Continued From Page

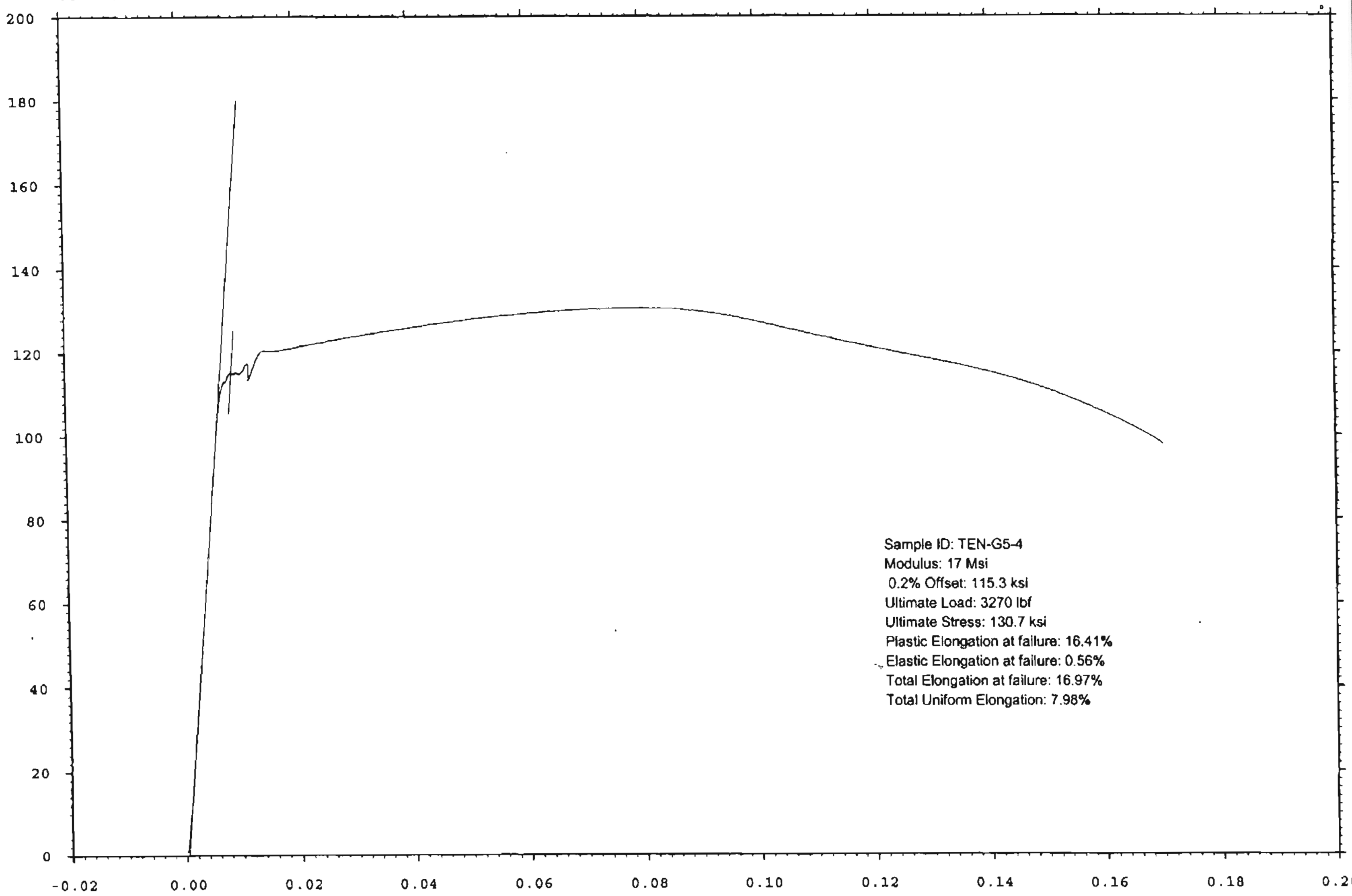
WESTMORELAND MECHANICAL TESTING & RESEARCH, Inc

Stress vs. Strain

Phone: (724)537-3131

Customer: Southwest Research
WMT&R Report: 7-37523
Test Temperature: 392 °F
Material: GRADE 5 TITANIUM
Test Date: 08/20/2007

P.O. No.: 782852E
WMT&R Quote No.: QN270982 Rev. 2



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SIGNATURE: K. J. Chiang
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TITLE

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PROJECT

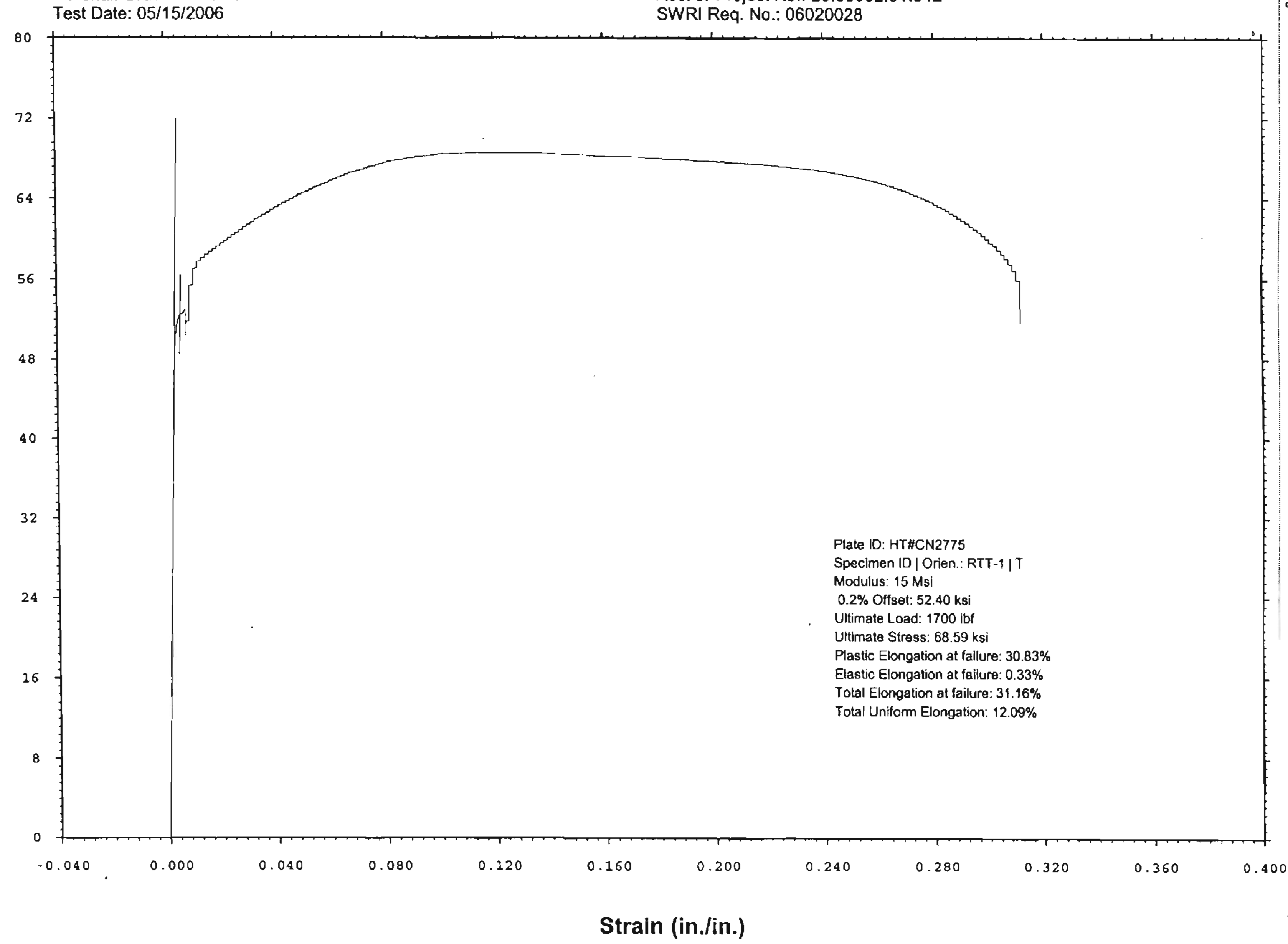
WESTMORELAND MECHANICAL TESTING & RESEARCH, Inc

Stress vs. Strain

Phone: (724)537-3131

Customer: Southwest Research
WMT&R Report: 6-29304
Test Temperature: Room
Material: Grade 7 Titanium
Test Date: 05/15/2006

P.O. No.: 682290E
WMT&R Quote No.: QN260654
Shipping Ticket No.: 428997
Acct or Project No.: 20.06002.01.342
SWRI Req. No.: 06020028



SIGNATURE K. T. Chiang

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PROPRIETARY INFORMATION

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TITLE

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WESTMORELAND MECHANICAL TESTING & RESEARCH, Inc

Stress vs. Strain

Phone: (724)537-3131

Customer: Southwest Research
WMT&R Report: 6-29304
Test Temperature: Room
Material: Grade 7 Titanium
Test Date: 05/15/2006

P.O. No.: 682290E
WMT&R Quote No.: QN260654
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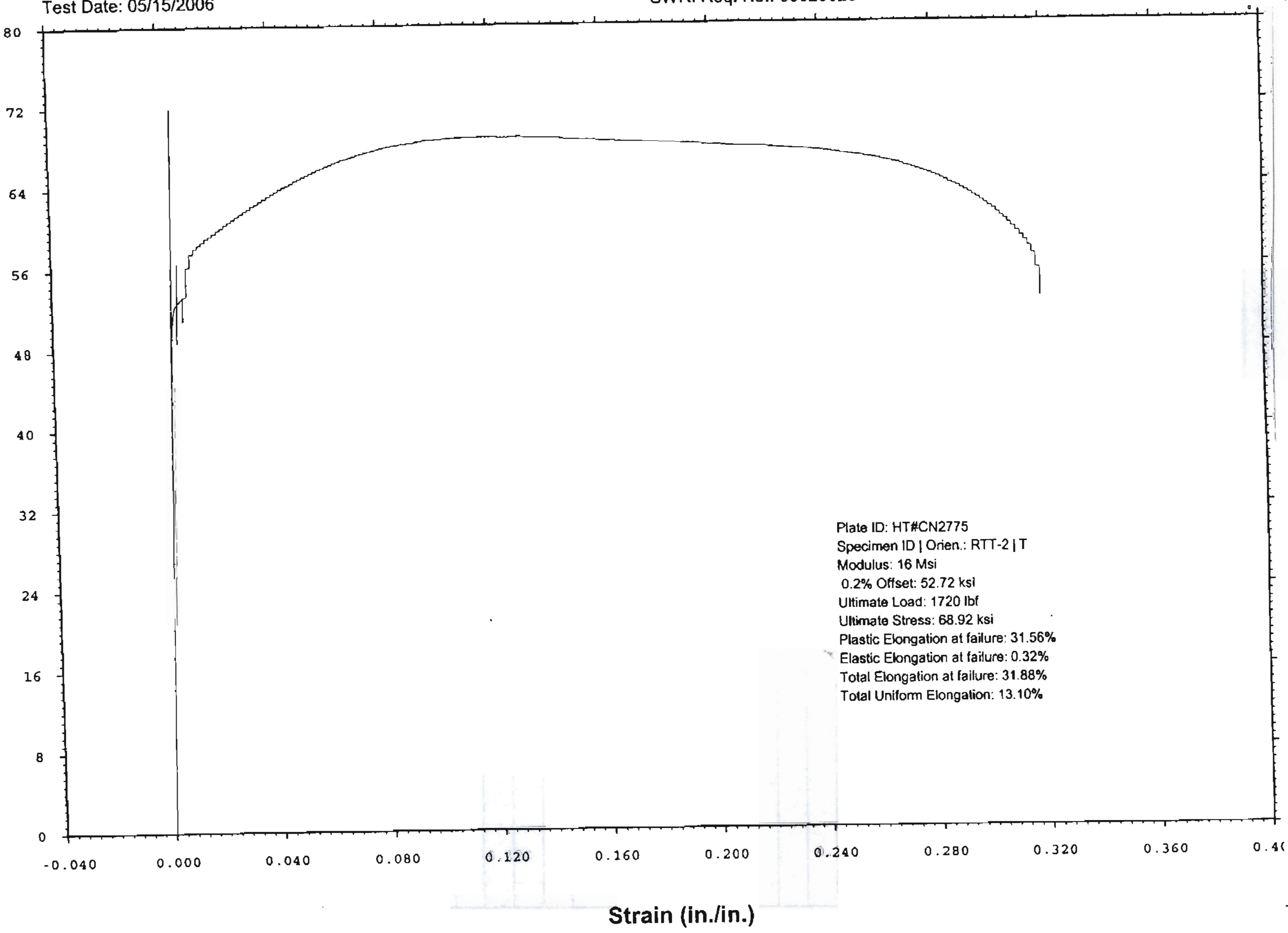

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PROPRIETARY INFORMATION

4/8/10

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TITLE

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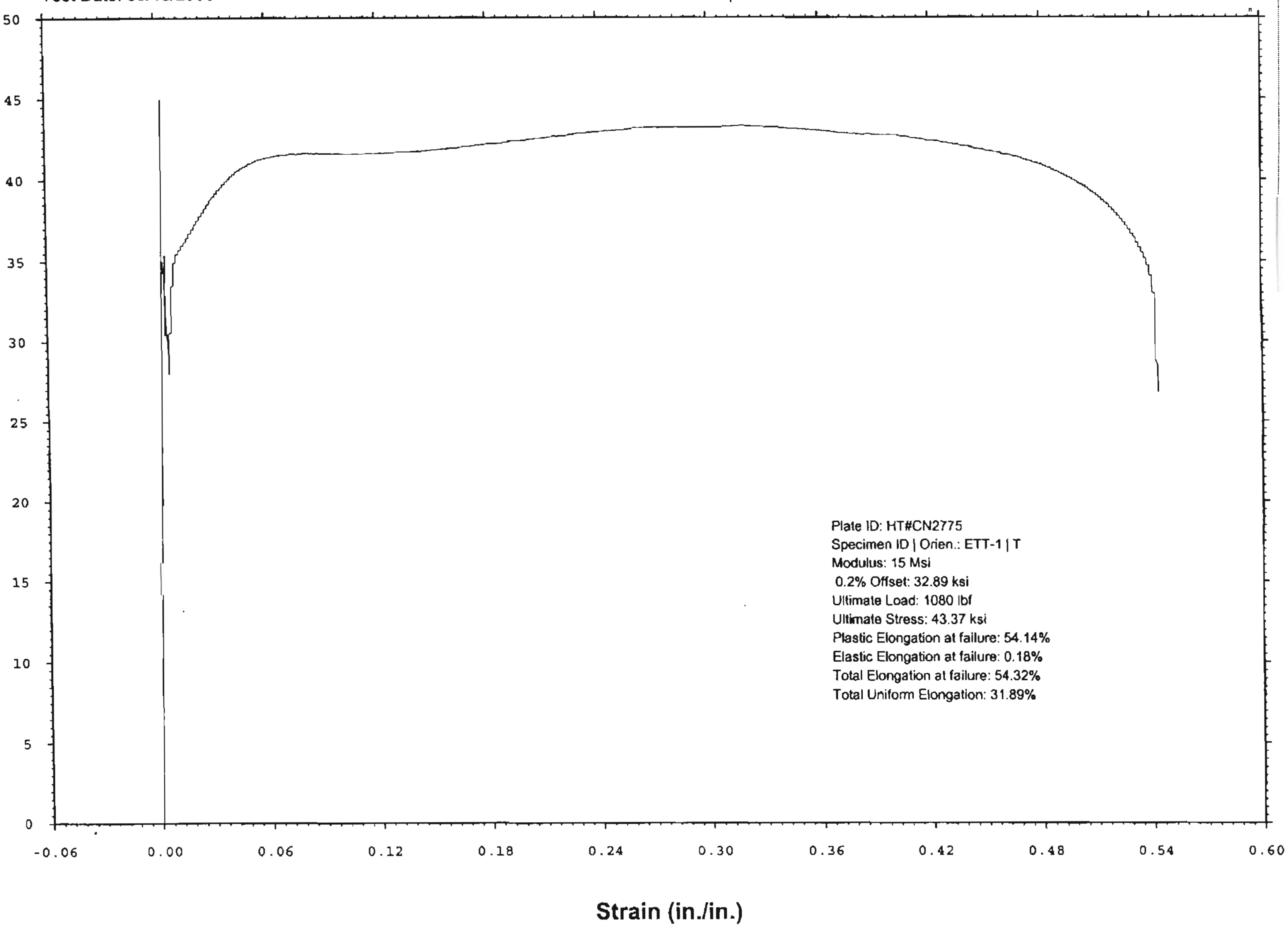
PROJECT

WESTMORELAND MECHANICAL TESTING & RESEARCH, Inc

Stress vs. Strain — Phone: (724)537-3131

Customer: Southwest Research
WMT&R Report: 6-29304
Test Temperature: 302 °F
Material: Grade 7 Titanium
Test Date: 05/15/2006

P.O. No.: 682290E
WMT&R Quote No.: QN260654
Shipping Ticket No.: 428997
Acct or Project No.: 20.06002.01.342
SWRI Req. No.: 06020028



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PROPRIETARY INFORMATION

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TITLE

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PROJECT

WESTMORELAND MECHANICAL TESTING & RESEARCH, Inc

Stress vs. Strain — Phone: (724)537-3131

Customer: Southwest Research
WMT&R Report: 6-29304
Test Temperature: 302 °F
Material: Grade 7 Titanium
Test Date: 05/15/2006

P.O. No.: 682290E
WMT&R Quote No.: QN260654
Shipping Ticket No.: 428997
Acct or Project No.: 20.06002.01.342
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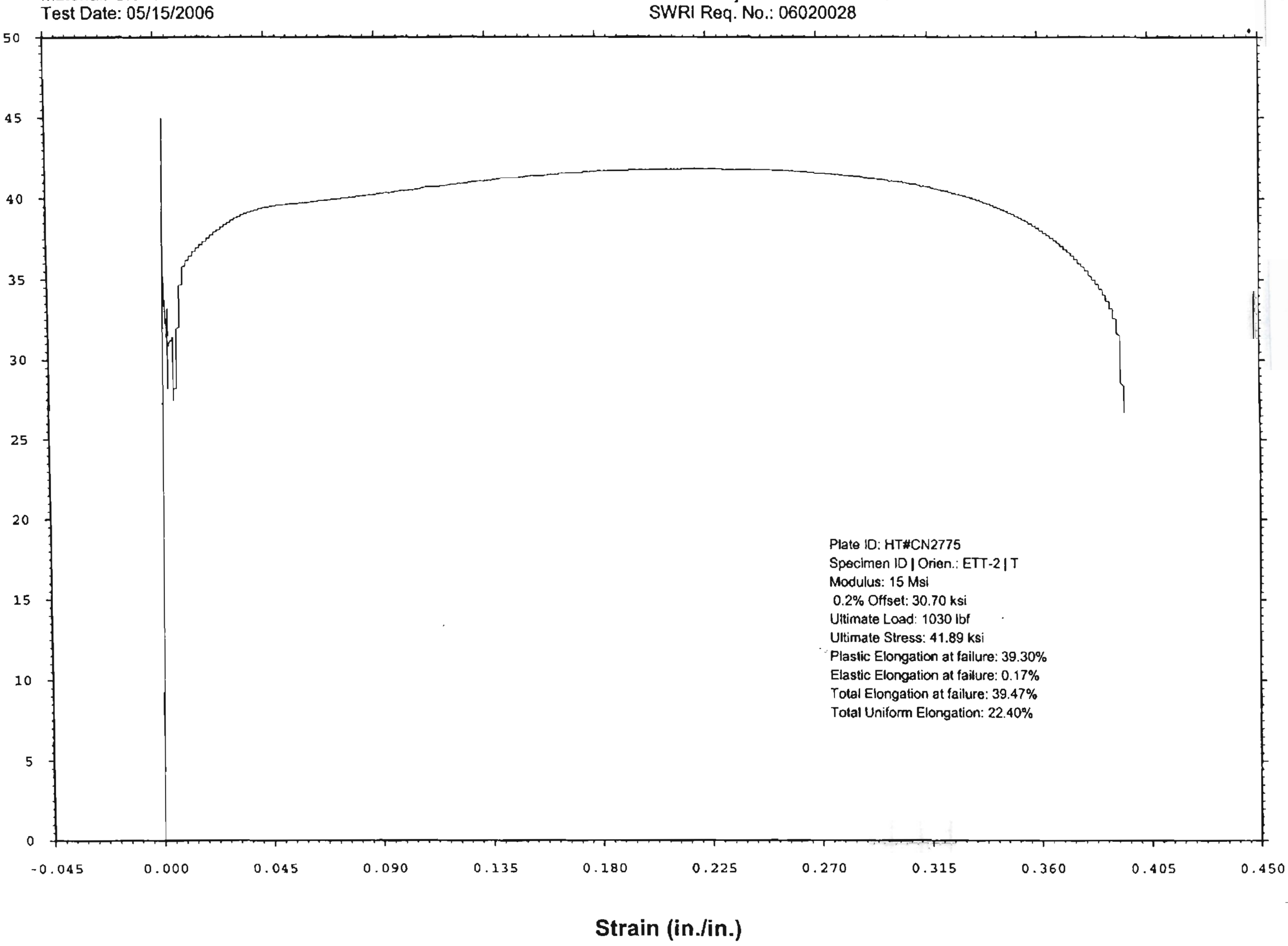

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PROPRIETARY INFORMATION

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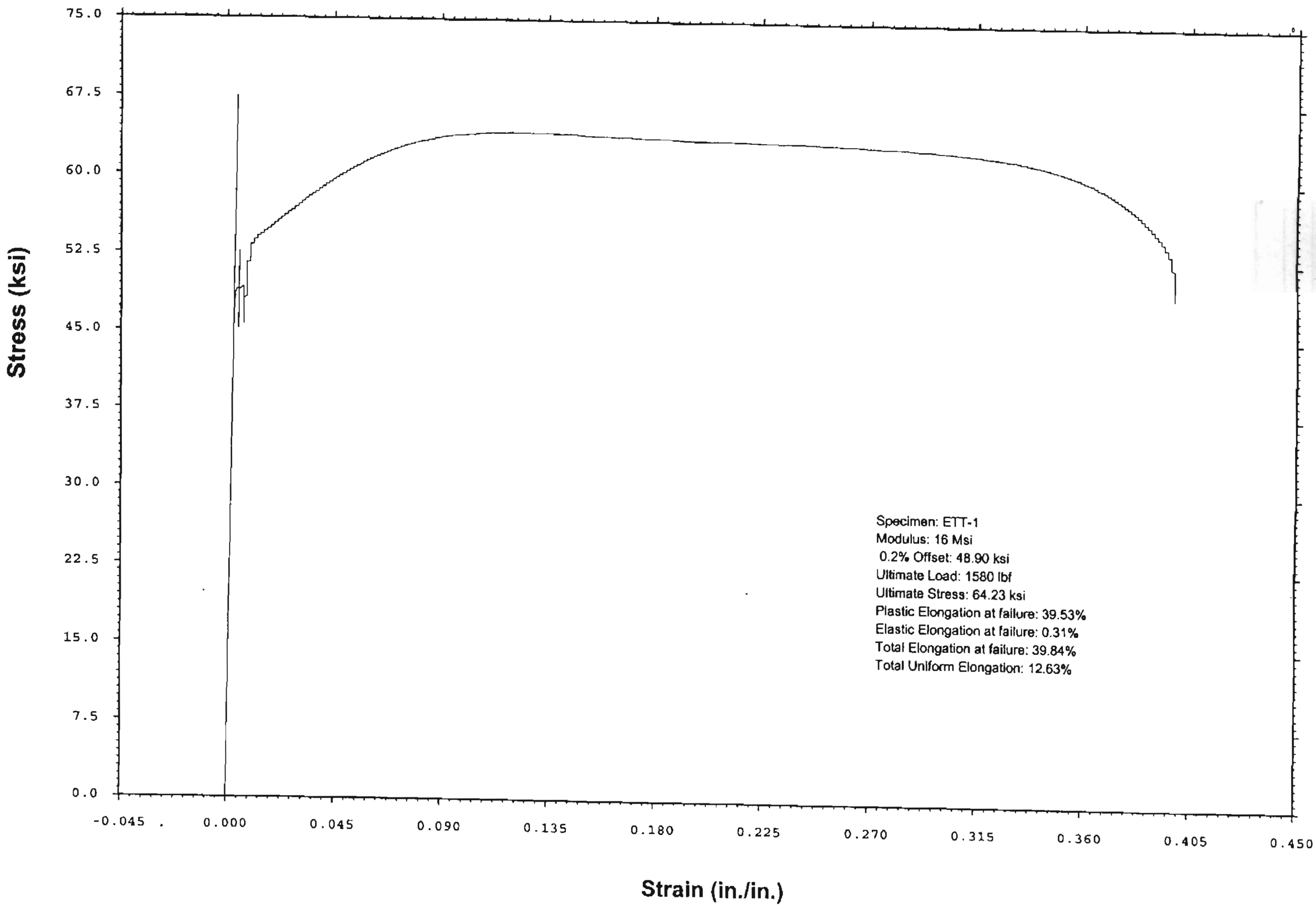
WESTMORELAND MECHANICAL TESTING & RESEARCH, Inc

Stress vs. Strain

Phone: (724)537-3131

Customer: Southwest Research
WMT&R Report: 6-42990
Test Temperature: 122 °F
Material: Grade 7 Titanium
Test Date: 11/08/2006

P.O. No.: 682290E
WMT&R Quote No.: QN262021
Shipping Ticket No.: 446259
Acct or Project No.: 06002.01.342



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TITLE

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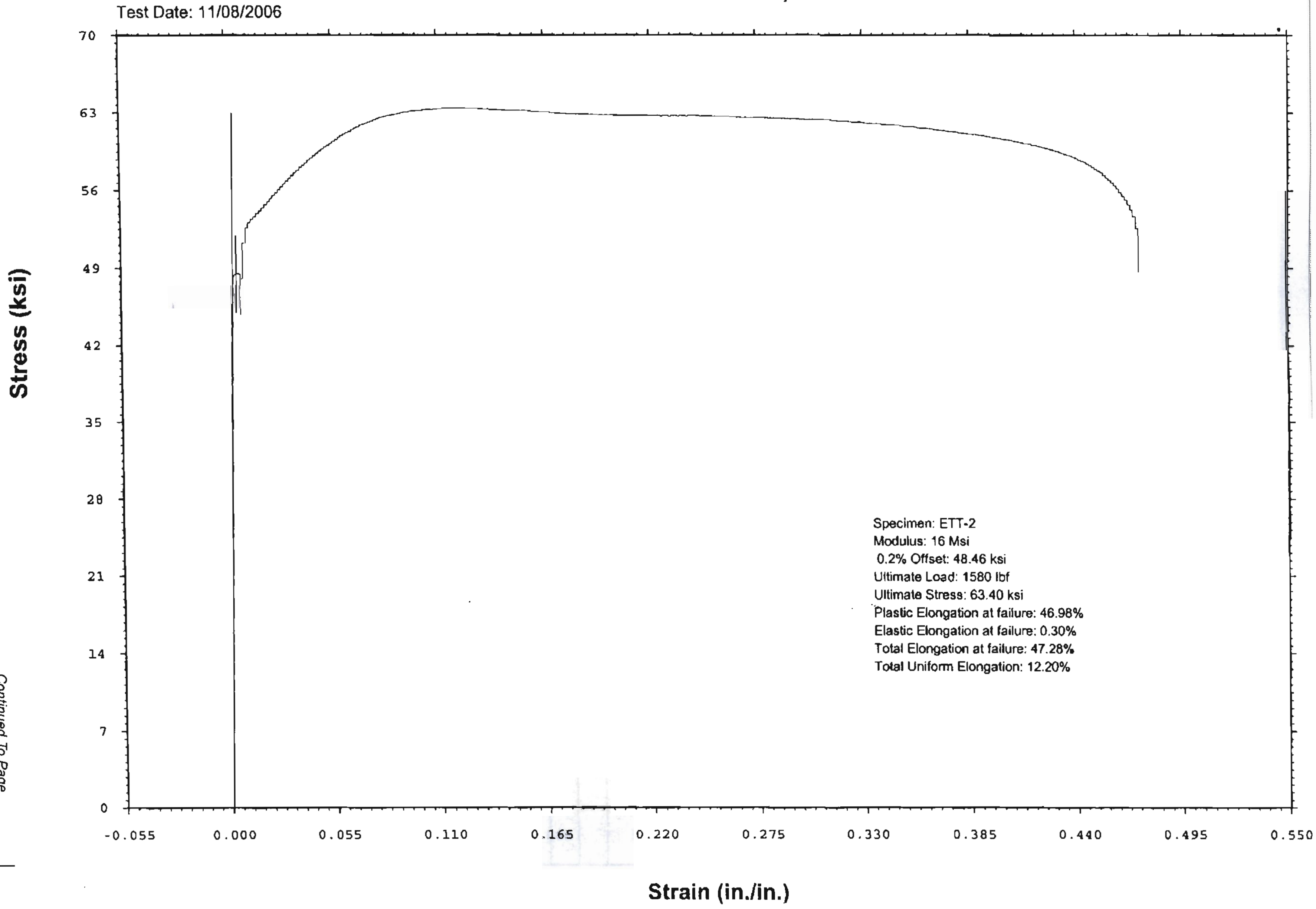
WESTMORELAND MECHANICAL TESTING & RESEARCH, Inc

Stress vs. Strain

Phone: (724)537-3131

Customer: Southwest Research
WMT&R Report: 6-42990
Test Temperature: 122 °F
Material: Grade 7 Titanium
Test Date: 11/08/2006

P.O. No.: 682290E
WMT&R Quote No.: QN262021
Shipping Ticket No.: 446259
Acct or Project No.: 06002.01.342



PROJECT

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DATE

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BOOK PAGE

TITLE

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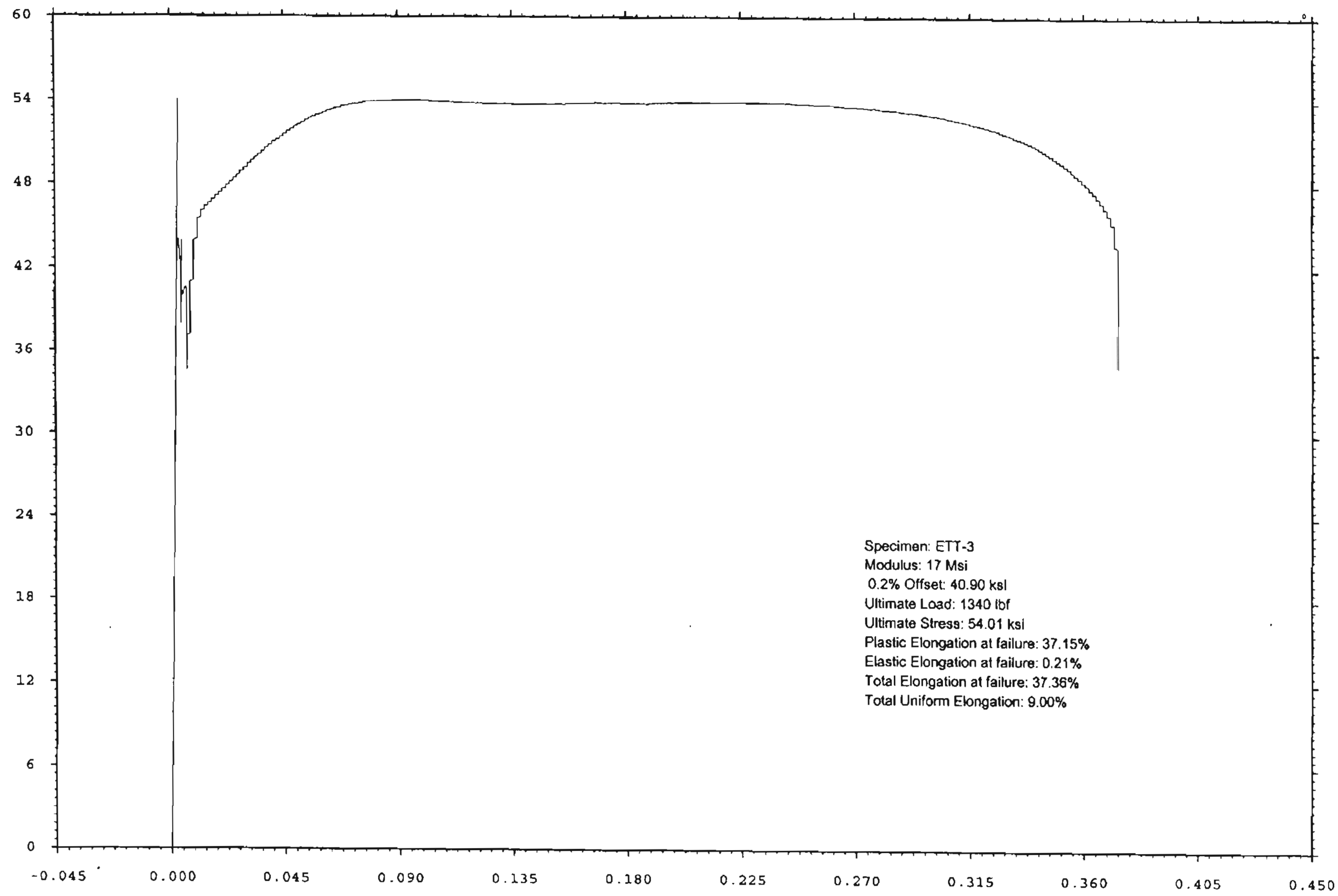
WESTMORELAND MECHANICAL TESTING & RESEARCH, Inc

Stress vs. Strain — Phone: (724)537-3131

Customer: Southwest Research
WMT&R Report: 6-42990
Test Temperature: 212 °F
Material: Grade 7 Titanium
Test Date: 11/08/2006

P.O. No.: 682290E
WMT&R Quote No.: QN262021
Shipping Ticket No.: 446259
Acct or Project No.: 06002.01.342



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~~PROPRIETARY INFORMATION~~ 4/8/10

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TITLE

PROJECT

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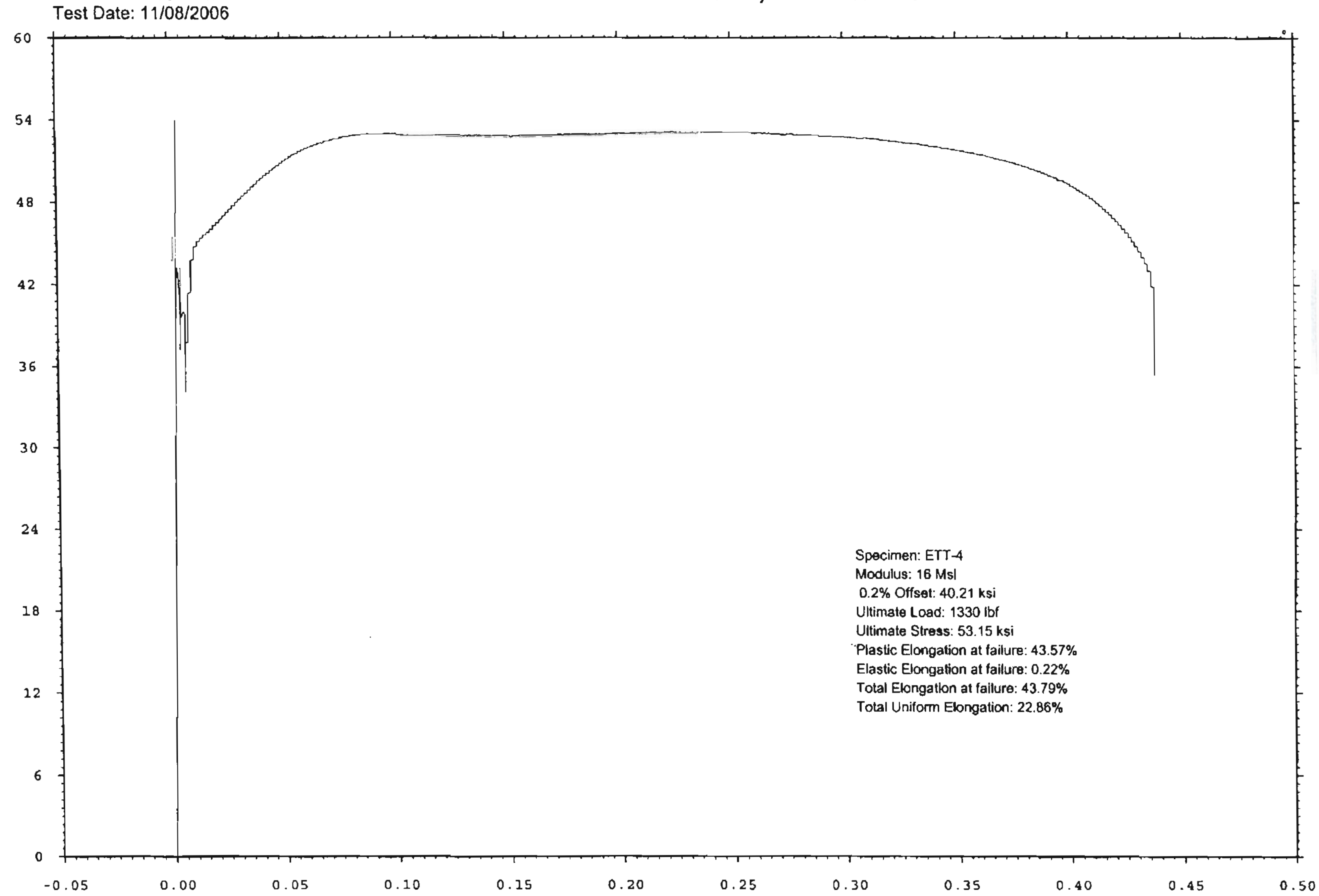
WESTMORELAND MECHANICAL TESTING & RESEARCH, Inc

Stress vs. Strain — Phone: (724)537-3131

Customer: Southwest Research
WMT&R Report: 6-42990
Test Temperature: 212 °F
Material: Grade 7 Titanium
Test Date: 11/08/2006

P.O. No.: 682290E
WMT&R Quote No.: QN262021
Shipping Ticket No.: 446259
Acct or Project No.: 06002.01.342



SIGNATURE: K. T. Chiang — DATE: 5/10/08

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~~PROPRIETARY INFORMATION~~ 4/8/10

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BOOK PAGE

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PROJECT

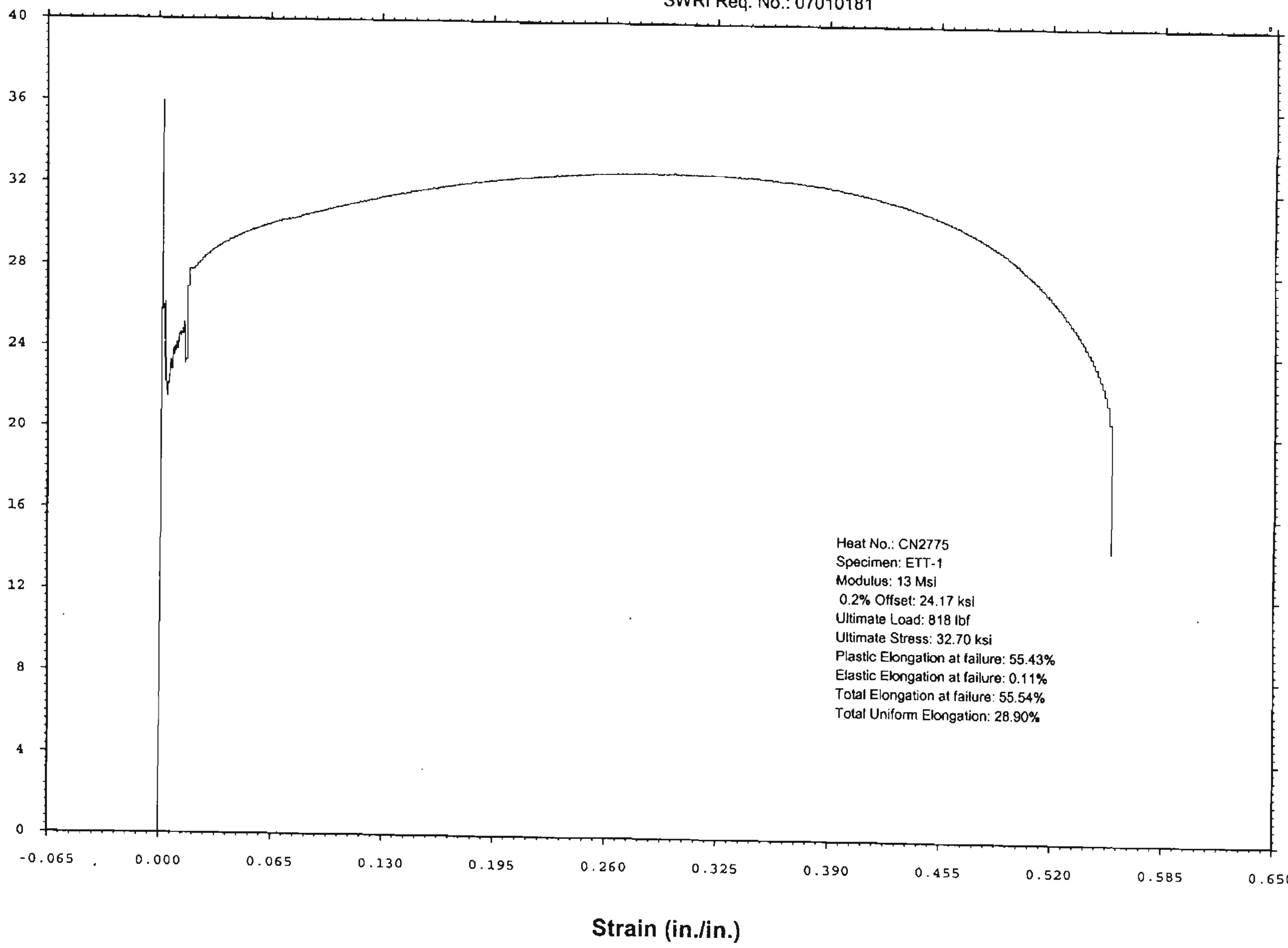
WESTMORELAND MECHANICAL TESTING & RESEARCH, Inc

Stress vs. Strain

Phone: (724)537-3131

Customer: Southwest Research
WMT&R Report: 7-28471
Test Temperature: 482 °F
Material: Grade 7 Titanium
Test Date: 04/24/2007

P.O. No.: 757847D
WMT&R Quote No.: QN262145 Rev.1
Shipping Ticket No.: 446266
Acct or Project No.: 06002.01.342
SWRI Req. No.: 07010181



SIGNATURE K. T. Chi[illegible] DATE 5/10/08

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~~PROPRIETARY INFORMATION~~ 4/8/10

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TITLE

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PROJECT

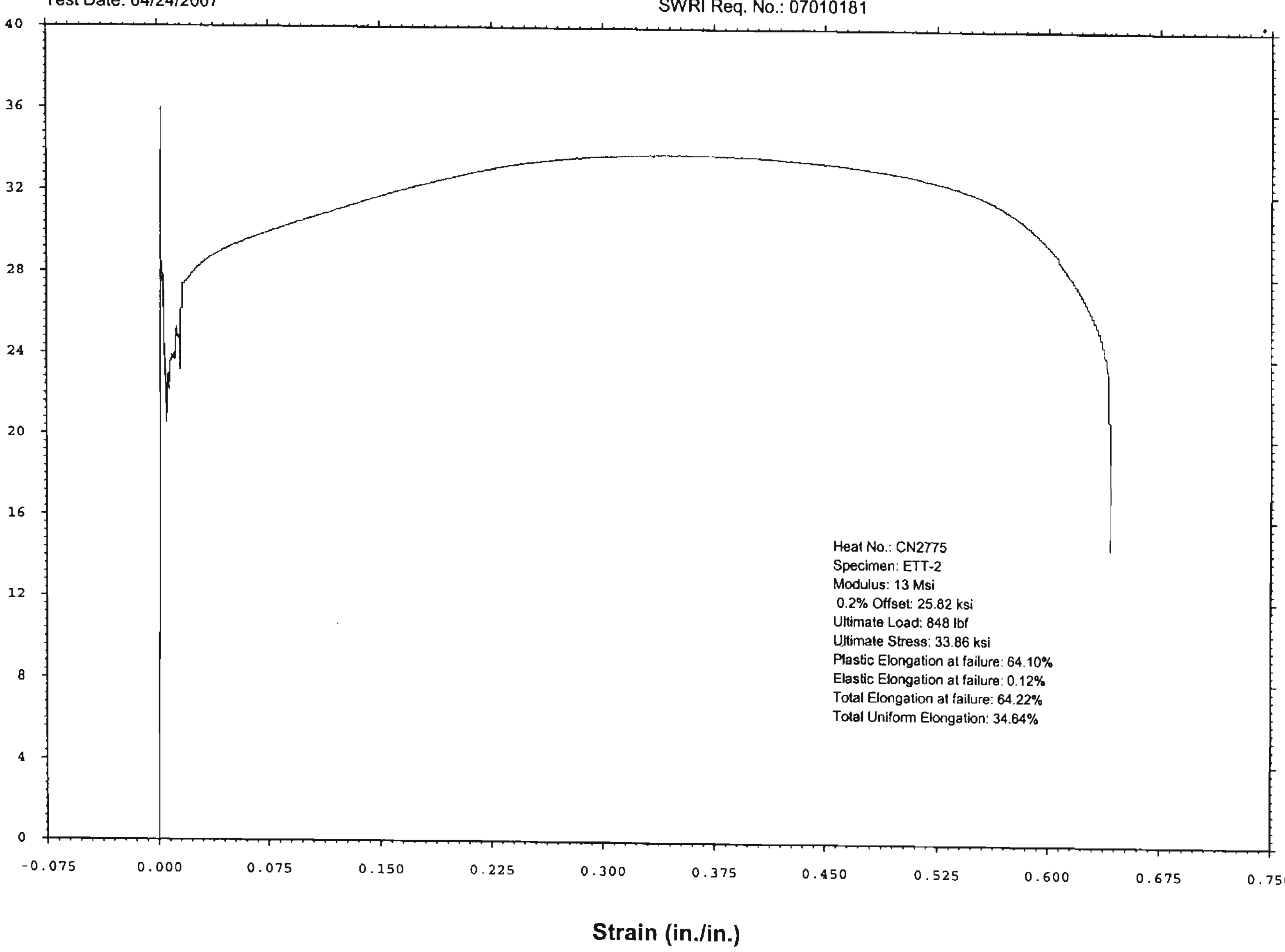
WESTMORELAND MECHANICAL TESTING & RESEARCH, Inc

Stress vs. Strain

Phone: (724)537-3131

Customer: Southwest Research
WMT&R Report: 7-28471
Test Temperature: 482 °F
Material: Grade 7 Titanium
Test Date: 04/24/2007

P.O. No.: 757847D
WMT&R Quote No.: QN262145 Rev.1
Shipping Ticket No.: 446266
Acct or Project No.: 06002.01.342
SWRI Req. No.: 07010181



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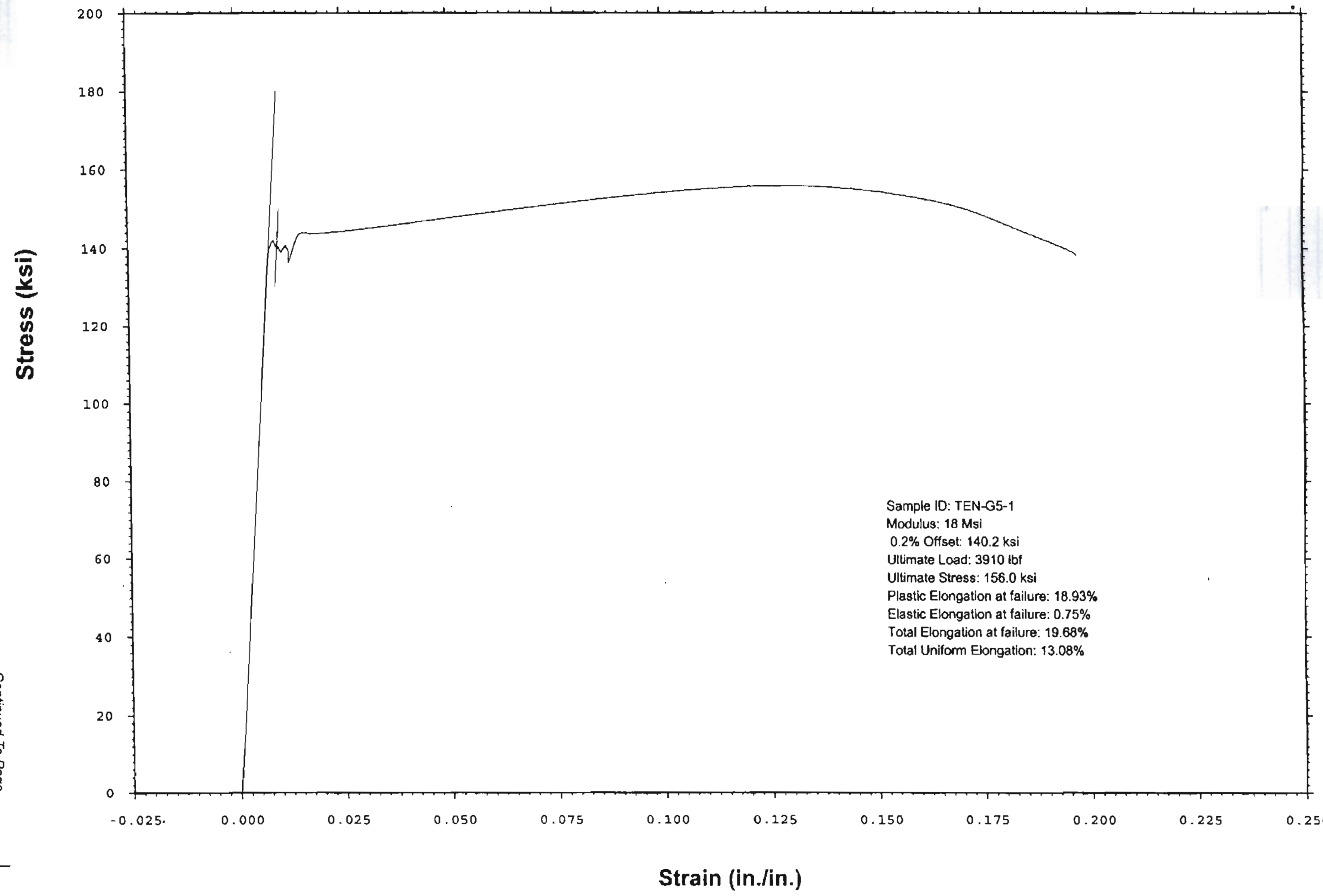
WESTMORELAND MECHANICAL TESTING & RESEARCH, Inc

Stress vs. Strain

Phone: (724)537-3131

Customer: Southwest Research
WMT&R Report: 7-37523
Test Temperature: 122 °F
Material: GRADE 5 TITANIUM
Test Date: 08/20/2007

P.O. No.: 782852E
WMT&R Quote No.: QN270982 Rev. 2



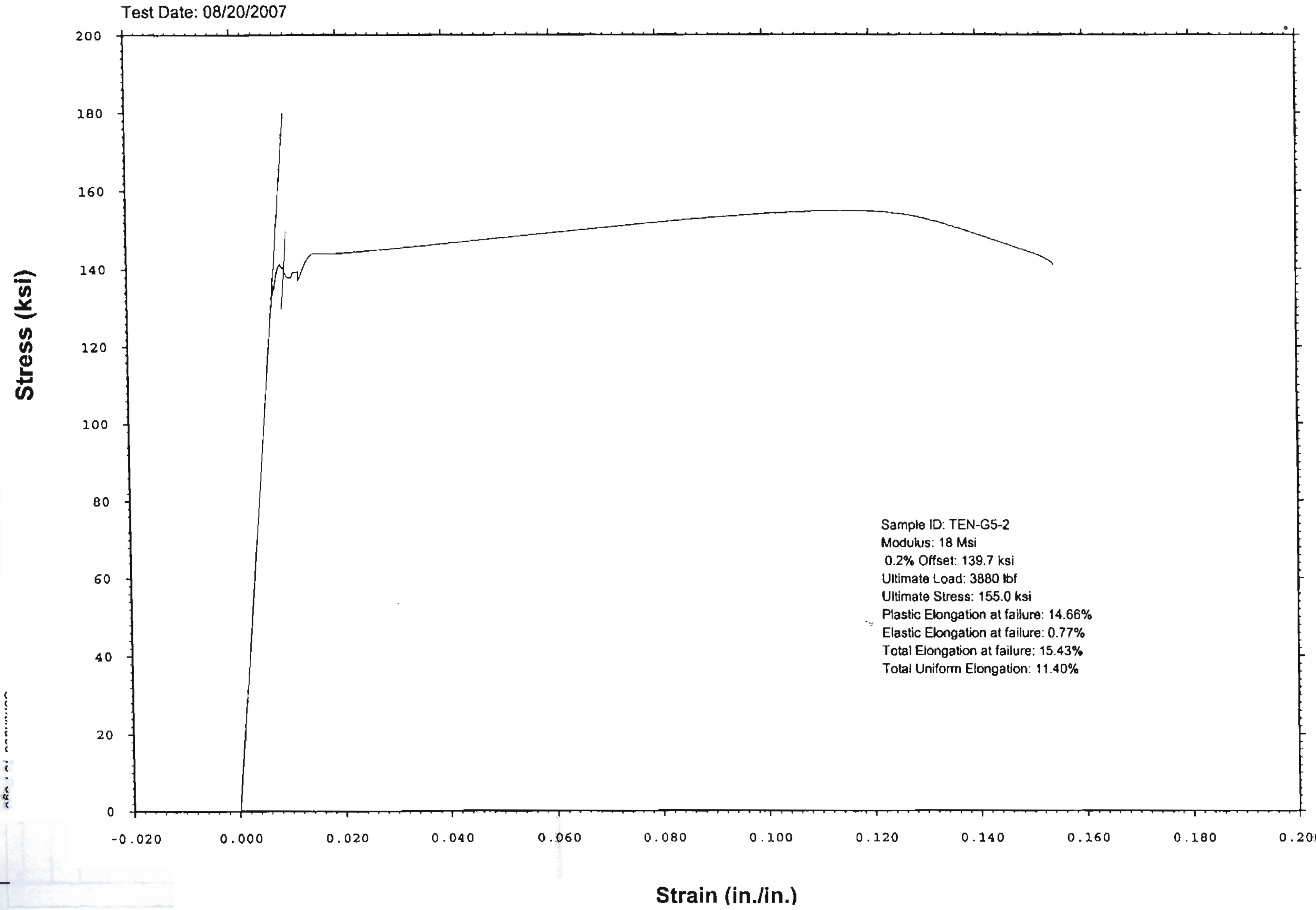
WESTMORELAND MECHANICAL TESTING & RESEARCH, Inc

Stress vs. Strain

Phone: (724)537-3131

Customer: Southwest Research
WMT&R Report: 7-37523
Test Temperature: 122 °F
Material: GRADE 5 TITANIUM
Test Date: 08/20/2007

P.O. No.: 782852E
WMT&R Quote No.: QN270982 Rev. 2



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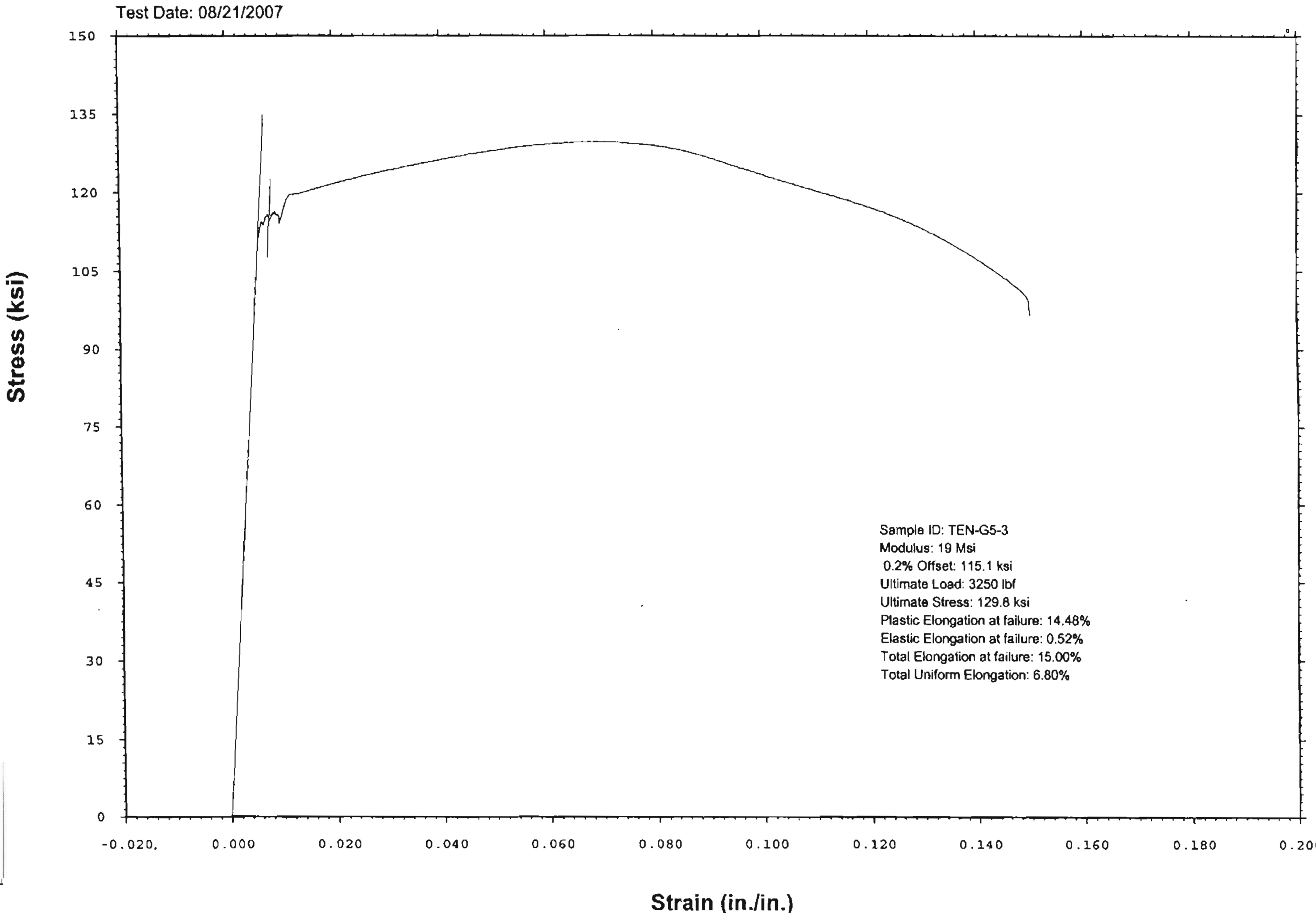
WESTMORELAND MECHANICAL TESTING & RESEARCH, Inc

Stress vs. Strain — Phone: (724)537-3131

Customer: Southwest Research
WMT&R Report: 7-37523
Test Temperature: 392 °F
Material: GRADE 5 TITANIUM
Test Date: 08/21/2007

P.O. No.: 782852E
WMT&R Quote No.: QN270982 Rev. 2



SIGNATURE K. J. Chiang DATE 5/10/08
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PROPRIETARY INFORMATION 4/8/10

Continued To Page

Westmoreland Mechanical Testing & Research, Inc.
P.O. Box 388
Westmoreland Drive
Youngstown, Pa. 15696-0388 U.S.A.
Telephone: 724-537-3131 *Fax: 724-537-3151*
Website: www.wmtr.com
WMT&R is a technical leader in the material testing industry.

ACCREDITED
TESTING CERT 621-01 & 621-02

Accredited Nadcap
Materials Testing Laboratory

July 15, 2008

CERTIFICATION

Section 1 of 2

WMT&R Report No. 8-25518
P.O. No. 884417D
WMT&R Quote No. QN280073
Shipping Ticket No. 446282

Southwest Research
6220 Culebra Road
P.O. Drawer 28510
San Antonio, TX 78238

Attention: Ken Chiang

Subject: All processes, performed upon the material as received, were conducted at WMT&R, Inc. in accordance with the WMT&R Quality Assurance Manual, Rev. 9, dated 4/1/2000.
The following tests were performed on this order: MACHINE ONLY and STRESS

CREEP RESULTS: ASTM E139-06
SOAK TIME: 60 Min
MATERIAL: TITANIUM
DISPOSITION: Report

REFERENCE	TestLog Number	Temp °F	Rupture Time Hrs	Total Creep %	Pan Ld LBS	Stress KSI	Orig Dia (in)	Eff GL (in)	Orig GL (in)	Machine Number	A/U/R
GR5-6	H21496	392	607.0**	.3268	252.6	80640	0.2526	1.3370	1.00	23	R
GR5-7	H21497	392	605.0**	.2365	253.0	80640	0.2528	1.3461	1.00	49	R
GR7-7	H21505	392	606.0**	.1064	59.5	19285	0.2508	1.3467	1.00	5	R
GR7-8	H21506	392	606.0**	.5132	60.0	19285	0.2518	1.3491	1.00	38	R

A\U\R: A=ACCEPTABLE, U=UNACCEPTABLE, R=REPORT

CREEP RESULTS: ASTM E139-06
REQUIREMENTS: 200.0 Hours
SOAK TIME: 60 Min
MATERIAL: TITANIUM
DISPOSITION: Report

REFERENCE	TestLog Number	Temp °F	Rupture Time Hrs	Elong %	RA %	Total Creep %	Pan Ld LBS	Stress KSI	Orig Dia (in)	Final Dia (in)	Eff GL (in)	Orig GL (in)	Final GL (In)	Machine Number	A/U/R
GR5-1	H21491	302	200.0**			3.8122	317.8	103105	0.2506		1.3518	1.00		94	R
GR5-2	H21492	302	34.0	17.0	36.4	9.9216	320.9	103105	0.2518	.2008	1.3435	1.00	1.17	56	R
GR5-3	H21493	302	0.1*	16.0	48.2		321.7	103105	0.2521	.1814	1.3461	1.00	1.16	200	R
GR5-4	H21494	302	200.0**			4.5821	323.2	103105	0.2527		1.3336	1.00		56	R

A\U\R: A=ACCEPTABLE, U=UNACCEPTABLE, R=REPORT

Michael L. Thien
Stress/Creep Foreperson

July 15, 2008

DISCLOSED TO AND UNDERSTOOD BY K. J. Chiang DATE 7/16/08
PROPRIETARY INFORMATION 4/8/10

Westmoreland Mechanical Testing & Research, Inc.
P.O. Box 388
Westmoreland Drive
Youngstown, Pa. 15696-0388 U.S.A.
Telephone: 724-537-3131 *Fax: 724-537-3151*
Website: www.wmtr.com
WMT&R is a technical leader in the material testing industry.

Accredited Nadcap Materials Testing Laboratory

A2LA ACCREDITED TESTING CERT 621-01 & 621-02

July 15, 2008

CERTIFICATION

Section 2 of 2

Southwest Research

WMT&R Report No. 8-25518
P.O. No. 884417D

DISPOSITION: Report

REFERENCE	TestLog Number	Temp °F	Rupture Time Hrs	Elong %	RA %	Total Creep %	Pan Ld LBS	Stress KSI	Orig Dia (in)	Final Dia (in)	Eff GL (in)	Orig GL (in)	Final GL (in)	Machine Number	A/U/R
GR5-5	H21495	302	0.1*	15.0	42.3		321.4	103105	0.2520	.1914	1.3579	1.00	1.15	200	R
GR5-8	H21498	302	200.0**			3.9255	320.9	103105	0.2518		1.3367	1.00		32	R
GR7-1	H21499	302	200.0**			2.4673	83.7	27030	0.2512		1.3409	1.00		34	R
GR7-2	H21500	302	200.0**			2.9041	84.8	27030	0.2528		1.3467	1.00		5	R
GR7-3	H21501	302	200.0**			2.7950	84.7	27030	0.2527		1.3333	1.00		94	R
GR7-4	H21502	302	200.0**			1.9729	84.5	27030	0.2524		1.3737	1.00		145	R
GR7-5	H21503	302	200.0**			.1512	84.1	27030	0.2517		1.3622	1.00		138	R
GR7-6	H21504	302	200.0**			2.1350	83.8	27030	0.2513		1.3445	1.00		34	R
GR7-9	H21507	302	200.0**			1.7562	84.1	27030	0.2518		1.4389	1.00		32	R
GR7-10	H21508	302	200.0**			2.5999	84.6	27030	0.2525		1.3360	1.00		39	R

A\U\R: A=ACCEPTABLE, U=UNACCEPTABLE, R=REPORT

Requirements suplied by Southwest Research Institute
* SAMPLE BROKE WHILE LOAD BEING APPLIED
**Discontinued

Michael L. Thien 7-15-08
Stress/Creep Foreperson
July 15, 2008

DISCLOSED TO AND UNDERSTOOD BY K. J. Chiang
DATE 7/16/08

PROPRIETARY INFORMATION 4/8/10

PROJECT

TITLE

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P.O. Box 388
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Youngstown, Pa. 15696-0388 U.S.A.
Telephone: 724-537-3131 *Fax: 724-537-3151*
Website: www.wmtr.com
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Accredited Nadcap Materials Testing Laboratory

A2LA ACCREDITED TESTING CERT 621-01 & 621-02

July 15, 2008

CERTIFICATION

Section 1 of 2

WMT&R Report No. 8-25518
P.O. No. 884417D
WMT&R Quote No. QN280073
Shipping Ticket No. 446282

Southwest Research
6220 Culebra Road
P.O. Drawer 28510
San Antonio, TX 78238

Corrected Date
September 26, 2008

Attention: Ken Chiang

Subject: All processes, performed upon the material as received, were conducted at WMT&R, Inc. in accordance with the WMT&R Quality Assurance Manual, Rev. 9, dated 4/1/2000. The following tests were performed on this order: MACHINE ONLY and STRESS

CREEP RESULTS: ASTM E139-06
SOAK TIME: 60 Min
MATERIAL: TITANIUM

DISPOSITION: Report

REFERENCE	TestLog Number	Temp °F	Rupture Time Hrs	Elong %	RA %	Total Creep %	Pan Ld LBS	Stress KSI	Orig Dia (in)	Final Dia (in)	Eff GL (in)	Orig GL (in)	Final GL (in)	Machine Number	A/U/R
GR5-1	H21491	302	200.0**			3.8122	317.8	103.105	0.2506		1.3518	1.00		94	R
GR5-2	H21492	302	34.0	17.0	36.4	9.9216	320.9	103.105	0.2518	0.2008	1.3435	1.00	1.17	56	R
GR5-3	H21493	302	0.1*	16.0	48.2		321.7	103.105	0.2521	0.1814	1.3461	1.00	1.16	200	R
GR5-4	H21494	302	200.0**			4.5821	323.2	103.105	0.2527		1.3336	1.00		56	R
GR5-5	H21495	302	0.1*	15.0	42.3		321.4	103.105	0.2520	0.1914	1.3579	1.00	1.15	200	R
GR5-6	H21496	392	607.0**			.3268	252.6	80.640	0.2526		1.3370	1.00		23	R
GR5-7	H21497	392	605.0**			.2365	253.0	80.640	0.2528		1.3461	1.00		49	R

A\U\R: A=ACCEPTABLE, U=UNACCEPTABLE, R=REPORT

Michael L. Thien
Stress/Creep Foreperson
September 26, 2008

SIGNATURE
DISCLOSED TO AND UNDERSTOOD BY K. J. Chiang
DATE 10/3/2008

PROPRIETARY INFORMATION 4/8/10

PROJECT

TITLE PROJECT

Accredited Nadcap Materials Testing Laboratory

ACCREDITED TESTING CERT 821-01 & 821-02

Westmoreland Mechanical Testing & Research, Inc.
P.O. Box 388
Westmoreland Drive
Youngstown, Pa. 15696-0388 U.S.A.
Telephone: 724-537-3131 Fax: 724-537-3151
Website: www.wmtr.com
WMT&R is a technical leader in the material testing industry.

July 15, 2008

Southwest Research

CERTIFICATION

Section 2 of 2
WMT&R Report No. 8-25518
P.O. No. 884417D

Corrected Date
September 26, 2008

DISPOSITION: Report

REFERENCE	TestLog Number	Temp °F	Rupture Time Hrs	Elong %	RA %	Total Creep %	Pan Ld LBS	Stress KSI	Orig Dia (in)	Final Dia (in)	Eff GL (in)	Orig GL (in)	Final GL (in)	Machine Number	A/U/R
GR5-8	H21498	302	200.0**			3.9255	320.9	103.105	0.2518		1.3367	1.00		32	R
GR7-1	H21499	302	200.0**			2.4673	83.7	27.030	0.2512		1.3409	1.00		34	R
GR7-2	H21500	302	200.0**			2.9041	84.8	27.030	0.2528		1.3467	1.00		5	R
GR7-3	H21501	302	200.0**			2.7950	84.7	27.030	0.2527		1.3333	1.00		94	R
GR7-4	H21502	302	200.0**			1.9729	84.5	27.030	0.2524		1.3737	1.00		145	R
GR7-6	H21504	302	200.0**			2.1350	83.8	27.030	0.2513		1.3445	1.00		34	R
GR7-7	H21505	392	606.0**			.1064	59.5	19.285	0.2508		1.3467	1.00		5	R
GR7-8	H21506	392	606.0**			.5132	60.0	19.285	0.2518		1.3491	1.00		38	R
GR7-9	H21507	302	200.0**			1.7562	84.1	27.030	0.2518		1.4389	1.00		32	R
GR7-10	H21508	302	200.0**			2.5999	84.6	27.030	0.2525		1.3360	1.00		39	R

A\U\R: A=ACCEPTABLE, U=UNACCEPTABLE, R=REPORT

Requirements supllied by Southwest Research Institute
* SAMPLE BROKE WHILE LOAD BEING APPLIED
**Discontinued

Michael L. Thien
Stress/Creep Foreperson

5-26-08
September 26, 2008

SIGNATURE K. J. Chiang
DATE 10/3/2008
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DATE
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TITLE PROJECT

Continued From Page

CNWRA *A center of excellence in earth sciences and engineering™*

Geosciences and Engineering Division
6220 Culebra Road • San Antonio, Texas, U.S.A. 78238-5166
(210) 522-5160 • Fax (210) 522-5155

July 18, 2007
Contract No. NRC–02–02–012
Account No. 20.06002.01.342
WM–00011

U.S. Nuclear Regulatory Commission
ATTN: Mrs. Deborah A. DeMarco
Two White Flint North
11545 Rockville Pike
Mailstop T8 A23
Washington, DC 20555

Subject: Transmittal of Revised Abstract Low-Temperature Tensile and Creep Deformation Behavior of Ti-6Al-4V (AI No. 20.06002.01.342.709)

Dear Mrs. DeMarco:

The purpose of this letter is to transmit the revised abstract Low-Temperature Tensile and Creep Deformation Behavior of Ti-6Al-4V. The original abstract was transmitted on June 22, 2007 as AI No. 06002.01.342.709. The abstract was revised to address U.S. Nuclear Regulatory Commission comments. All changes from the original abstract are editorial and programmatic in nature; no substantive technical revisions have been made.

If you have any questions regarding this revised abstract, please contact me at (210) 522-5185 or Ken Chiang at (210) 522-2308. Your cooperation in this matter is appreciated.

Sincerely,

Sitakanta Mohanty

Sitakanta Mohanty, Assistant Director
Engineering and Systems Assessment

SM/rm

Washington Office • Twinbrook Metro Plaza #500
12300 Twinbrook Parkway • Rockville, Maryland 20852-1652

SIGNATURE K. J. Chiang
DATE 2/26/10
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TITLE PROJECT

Continued From Page

Mrs. Deborah A. DeMarco
July 18, 2007
Page 2

cc:

S. Kim
V. Whipple

Letter Only
L. Kokajko
J. Davis
A. Mohseni
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K. Stablein
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The Minerals, Metals and Materials Society (TMS) Annual Meeting, Symposium on Mechanical Behavior, Microstructure, and Modeling of Titanium and Its Alloys, March 9 – 13, 2008, New Orleans, Louisiana

Low-Temperature Tensile and Creep Deformation Behavior of Ti-6Al-4V

P.G. Oberson[1]
U.S. Nuclear Regulatory Commission
Washington, DC 20555, USA
[1]Research performed while employed by
Ankem Technologies Inc.

S. Ankem
Ankem Technologies Inc.
14616 Orangewood St.
Silver Spring, MD 20105, USA

K.T. Chiang[3] and L. Ibarra[2]
[2]Center for Nuclear Waste Regulatory Analyses
[3]Southwest Research Institute®
6220 Culebra Road
San Antonio, TX 78238, USA

ABSTRACT

The drip shield design considered by the U.S. Department of Energy includes Ti-6Al-4V alloy components. The tensile and creep behavior of Ti-6Al-4V alloy was independently investigated by the Center for Nuclear Waste Regulatory Analyses (CNWRA) at low temperatures (25 to 250 °C [77 to 482 °F]). The tensile behavior exhibited work hardening at 250 °C [482 °F] and no work hardening at lower temperatures. This hardening was attributed to a convergence of the critical stress for slip on various slip systems. In regard to creep deformation, at a constant stress level of 85% yield stress, the amount of creep strain increased with an increase in temperature from room temperature to 150 °C [302 °F] and then decreased at 250 °C [482 °F]. This behavior was attributed to a change in the deformation mechanisms from coarse planar slip at lower temperatures to random slip at higher temperatures.

Disclaimer: This abstract is an independent product of the CNWRA and does not necessarily reflect the view or regulatory position of the NRC. The NRC staff views expressed herein are preliminary and do not constitute a final judgment or determination of the matters addressed or of the acceptability of a license application for a geologic repository at Yucca Mountain.

Continued To Page

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(210) 522-5160 • Fax (210) 522-5155

July 18, 2007
Contract No. NRC–02–02–012
Account No. 20.06002.01.342
WM–00011

U.S. Nuclear Regulatory Commission
ATTN: Mrs. Deborah A. DeMarco
Two White Flint North
11545 Rockville Pike
Mailstop T8 A23
Washington, DC 20555

Subject: Transmittal of Revised Abstract Low-Temperature Tensile and Creep Deformation Behavior of Grade 7 Commercially Pure Titanium Alloy (AI No. 06002.01.342.710)

Dear Mrs. DeMarco:

The purpose of this letter is to transmit the revised abstract Low-Temperature Tensile and Creep Deformation Behavior of Grade 7 Commercially Pure Titanium Alloy. The original abstract was transmitted on June 22, 2007 as AI No. 06002.01.342.710. The abstract was revised to address U.S. Nuclear Regulatory Commission comments. All changes from the original abstract are editorial and programmatic in nature; no substantive technical revisions have been made.

If you have any questions regarding this revised abstract, please contact me at (210) 522-5185 or Ken Chiang at (210) 522-2308. Your cooperation in this matter is appreciated.

Sincerely,

Sitakanta Mohanty

Sitakanta Mohanty, Assistant Director
Engineering and Systems Assessment

SM/rm

Washington Office • Twinbrook Metro Plaza #500
12300 Twinbrook Parkway • Rockville, Maryland 20852-1652

SIGNATURE K. T. Chiang DATE 2/26/10

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TITLE PROJECT

Continued From Page

Mrs. Deborah A. DeMarco
July 18, 2007
Page 2

cc:

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S. Kim	L. Kokajko	W. Patrick	GED Directors
V. Whipple	J. Davis	B. Sagar	GED Asst. Directors
	A. Mohseni	K. Chiang	GED Managers
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TITLE PROJECT

Continued From Page

The Minerals, Metals, and Materials Society (TMS) Annual Meeting, Symposium on Mechanical Behavior, Microstructure, and Modeling of Titanium and Its Alloys, March 9 – 13, 2008, New Orleans, Louisiana

Low-Temperature Tensile and Creep Deformation Behavior of Grade 7 Commercially Pure Titanium Alloy

P.G. Oberson[1]
U.S. Nuclear Regulatory Commission
Washington, DC 20555, USA
[1]Research performed while employed by
Ankem Technologies Inc.

S. Ankem
Ankem Technologies Inc.
14616 Orangewood St.
Silver Spring, MD 20105, USA

K.T. Chiang[3] and L. Ibarra[2]
[2]Center for Nuclear Waste Regulatory Analyses
[3]Southwest Research Institute®
6220 Culebra Road
San Antonio, TX 78238, USA

ABSTRACT

The drip shield design considered by the U.S. Department of Energy includes Titanium Grade 7 (Ti-0.2wt%Pd-0.13wt%O) components. The tensile and creep behavior of Grade 7 Titanium alloy was independently investigated by the Center for Nuclear Waste Regulatory Analyses (CNWRA) at low temperatures (25 to 250 °C [77 to 482 °F]). The tensile behavior exhibited flow stress drops that increased with an increase in temperature. This behavior was attributed to a rise in the mobile dislocation density. In regard to creep deformation, there was no change in the amount of creep strain with an increase in temperature at 85% of the respective yield stress. This behavior was attributed to a change in the deformation mechanisms from slip and twinning at low temperatures (25 to 50 °C [77 to 122 °F]) to solely slip at higher temperatures.

Disclaimer: This abstract is an independent product of the CNWRA and does not necessarily reflect the view or regulatory position of the NRC. The NRC staff views expressed herein are preliminary and do not constitute a final judgment or determination of the matters addressed or of the acceptability of a license application for a geologic repository at Yucca Mountain.

Continued To Page

SIGNATURE K. T. Chiang DATE 2/26/10

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TITLE PROJECT

Continued From Page

Maria J. Padilla

From: Kuang-Tsan Ken Chiang [kchiang@swri.edu]
Sent: Wednesday, September 12, 2007 2:53 PM
To: 'Maria J Padilla'
Subject: FW: Center Tickets

For your record.

-----Original Message-----
From: Sitakanta Mohanty [mailto:smohanty@cnwra.swri.edu]
Sent: Wednesday, September 12, 2007 2:30 PM
To: Asadul Chowdhury; Ken Chiang
Cc: Gary Walter; 'Luis Ibarra'; 'Keith Compton'
Subject: FW: Center Tickets

Asad,

Ken Chiang co-authored these abstracts with an NRC staff. Please forward this e-mail to appropriate staff for record keeping.

-Sitakanta

-----Original Message-----
From: Mysore Nataraja [mailto:MSN1@nrc.gov]
Sent: Wednesday, September 12, 2007 1:57 PM
To: Sunny Kim
Cc: Sitakanta Mohanty; Sheena Whaley; Tanya Parwani-Jaimes; Tae Ahn
Subject: Center Tickets

The following Ceneter Tickets may now be closed as the required reviews are completed and the necessary paper work has been completed.

CNWRA 2007 0140 Programmatic Review of Abstract (AI No. 20.06002.01.342.709: Low Temperature Tensile and Creep Deformation Behavior of Ti-6A-4V)

CNWRA 2007 0141 Programmatic Review of Abstract (AI No. 06002.01.342.710: Low Temperature Tensile and Creep Deformation Behavior of Grade 7 Commercially pure Titanium Alloy).

Raj

Continued To Page

SIGNATURE K. T. Chiang DATE 2/26/10

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TITLE PROJECT

Continued From Page

Westmoreland Mechanical Testing & Research, Inc.
P.O. Box 388
Westmoreland Drive
Youngstown, Pa. 15696-0388 U.S.A.
Telephone: 724-537-3131 Fax: 724-537-3151
Website: www.wmtr.com
WMT&R is a technical leader in the material testing industry.

5 July 2007

Southwest Research Institute
6220 Culebra Road
P.O. Box 28510
San Antonio, TX 78238

WMT&R Report No. 7-28471
WMT&R Quote No. QN262145, Rev.1
P.O. No.757847D
Heat No. CN2775

Attention: Mr. Ken Chiang

Subject: Machine and Test Tensiles and Elevated Creep

Introduction:

One (1) plate of Grade 7 Titanium, identified as Heat No. CN2775, was received for sectioning and testing. Two (2) standard 0.178" diameter tensile specimens were excised, machined, and tested at 482°F. Thirty-nine (39) creep specimens were sectioned and machined in accordance with ASTM E139-00, a standard 0.178" diameter specimen was machined. Fifteen (15) specimens were machined, but not tested. These specimens are being kept at WMT&R for additional testing per the customer. Eight (8) creep specimens were tested at room temperature at stress levels as defined by the workscope. The remaining sixteen (16) creep specimens were tested as follows, eight at 212°F and eight at 482°F, all at stress levels as defined by the customer and the workscope. No data was available for ET-Creep-13 due to a machine malfunction during testing. One (1) specimen was tested at 302°F (moved from the original WMT&R Report No. 6-29304). Enclosed please find tabular data for all testing, the tensile and creep charts and the tested specimens, along with a CD containing the digital creep curves. Note: also enclosed please find one (1) untested Grade 7 titanium specimen and one (1) untested Grade 5 creep specimen. Testing of these specimens was cancelled per the customer request.

If you have any questions concerning this report, please feel free to contact me. If I am unavailable, you may also speak with Mr. Roy Starr, Technical Services Manager.

At your service,

Mark A. Phillippi
Technical Service Engineer

kr

K:\markp\Southwest Research\7-28471\7-28471.doc

Continued To Page

SIGNATURE K. T. Chiang DATE 3/2/10

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TITLE PROJECT

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TESTING CERT 621-01 & 621-02

Accredited Nadcap Materials Testing Laboratory

July 5, 2007

CERTIFICATION

Section 1 of 2
WMT&R Report No. 7-28471
P.O. No. 757847D
WMT&R Quote No. QN262145 Rev.1
Shipping Ticket No. 446266
Acct or Project No. 06002.01.342
SWRI Req. No. 07010181

Southwest Research
6220 Culebra Road
P.O. Drawer 28510
San Antonio, TX 78238

Attention: Mr. Ken Chiang

Subject: All processes, performed upon the material as received, were conducted at WMT&R, Inc. in accordance with the WMT&R Quality Assurance Manual, Rev. 9, dated 4/1/2000. The following tests were performed on this order: MACHINE ONLY, STRESS and TENSILE

TENSILE RESULTS: ASTM E21-05
SOAK TIME: 30 Minutes
SPEED OF TESTING: 0.005 in./in./min., 0.05 in./min./in.
MATERIAL: Grade 7 Titanium

DISPOSITION: Report

Heat No.	Specimen	TestLog Number	Temp. °F	UTS ksi	0.2% YS ksi	Elong %	RA %	Modulus Msi	Ult. Load lbf	0.2% YLD. lbf	Orig. Dia. (in.)	Final Dia. (in.)	4D Orig GL (in.)	4D Final GL (in.)	Orig. Area (sq. in.)	Machine Number	A\U\R
CN2775	ETT-1	F37098	482	32.7	24.2	50.0	74.5	12.9	818	605	0.1785	0.0900	0.70	1.05	0.02502455	M14	R
CN2775	ETT-2	F37099	482	33.9	25.8	55.5	68.5	13.0	848	647	0.1786	0.1004	0.70	1.09	0.02505260	M14	R

A\U\R: A=ACCEPTABLE, U=UNACCEPTABLE, R=REPORT

CREEP RESULTS: ASTM E139-00
SOAK TIME: 60 Min
MATERIAL: Grade 7 Titanium

DISPOSITION: Report

HEAT NO.	SPECIMEN	TestLog Number	Temp °F	Rupture Time Hrs	Elong %	RA %	Total Creep %	Pan Ld LBS	Stress KSI	Orig Dia (in)	Final Dia (in)	Eff GL (in)	Orig GL (in)	Final GL (in)	Machine Number	A/U/R
CN2775	RT-Creep-1	F37100	Room	8.7	42.9	48.9	28.1924	94.0	60.433	0.1780	.1272	1.0036	.70	1.00	118	R
CN2775	RT-Creep-2	F37101	Room	60.0	40.0	56.2	12.9429	89.9	57.805	0.1780	.1178	1.0046	.70	.98	68	R
CN2775	RT-Creep-3	F37102	Room	200.0**	---	---	17.4777	85.5	55.0178	0.1777	---	0.9950	.70	---	73	R
CN2775	RT-Creep-4	F37103	Room	200.0**	---	---	5.8585	80.3	52.550	0.1764	---	0.9631	.70	---	70	R
CN2775	RT-Creep-5	F37104	Room	200.0**	---	---	2.1661	67.9	44.668	0.1760	---	0.9732	.70	---	101	R
CN2775	RT-Creep-6	F37105	Room	200.0**	---	---	.4252	57.3	36.785	0.1782	---	1.0042	.70	---	119	R

A\U\R: A=ACCEPTABLE, U=UNACCEPTABLE, R=REPORT

Roy E. Starr\Matt Wojton
____ Technical Services Manager____ Tensile Supervisor July 5, 2007

SIGNATURE K. T. Chiang DATE 3/2/10

DISCLOSED TO AND UNDERSTOOD BY DATE

PROPRIETARY INFORMATION 4/8/10

TITLE PROJECT

Westmoreland Mechanical Testing & Research, Inc.
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Youngstown, Pa. 15696-0388 U.S.A.
Telephone: 724-537-3131 Fax: 724-537-3151
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WMT&R is a technical leader in the material testing industry.

ACCREDITED
TESTING CERT 621-01 & 621-02

Nadcap Materials Testing Lab

July 5, 2007

Southwest Research

CERTIFICATION

Section 2 of 2
WMT&R Report No. 7-28471
P.O. No. 757847D

DISPOSITION: Report

HEAT NO.	SPECIMEN	TestLog Number	Temp °F	Rupture Time Hrs	Elong %	RA %	Total Creep %	Pan Ld LBS	Stress KSI	Orig Dia (in)	Final Dia (in)	Eff GL (in)	Orig GL (in)	Final GL (in)	Machine Number	A/U/R
CN2775	RT-Creep-7	F37106	Room	200.0**	---	---	.0832	44.2	28.903	0.1765	---	0.9983	.70	---	100	R
CN2775	RT-Creep-8	F37107	Room	200.0**	---	---	.0163	32.7	21.020	0.1780	---	0.9600	.70	---	118	R
CN2775	ET-Creep-1	F37108	212	3.3	45.7	57.6	32.8954	72.0	46.633	0.1773	.1154	0.9796	.70	1.02	54	R
CN2775	ET-Creep-2	F37109	212	16.7	54.3	59.0	42.1628	69.1	44.605	0.1776	.1137	1.0042	.70	1.08	50	R
CN2775	ET-Creep-3	F37110	212	62.0	60.0	59.0	41.8227	66.2	42.578	0.1780	.1140	0.9538	.70	1.12	109	R
CN2775	ET-Creep-4	F37111	212	83.8	47.1	53.6	35.3417	62.7	40.550	0.1775	.1209	0.9987	.70	1.03	48	R
CN2775	ET-Creep-5	F37112	212	200.0**	---	---	4.2944	53.7	34.468	0.1781	---	0.9606	.70	---	108	R
CN2775	ET-Creep-6	F37113	212	200.0**	---	---	1.2912	43.9	28.385	0.1776	---	1.0030	.70	---	72	R
CN2775	ET-Creep-7	F37114	212	200.0**	---	---	.2598	34.5	22.303	0.1775	---	0.9964	.70	---	52	R
CN2775	ET-Creep-8	F37115	212	200.0**	---	---	.1134	25.1	16.220	0.1774	---	0.9696	.70	---	121	R
CN2775	ET-Creep-9	F37116	482	200.0**	---	---	3.7763	44.7	28.750	0.1779	---	1.0037	.70	---	106	R
CN2775	ET-Creep-10	F37117	482	200.0**	---	---	.7814	42.5	27.500	0.1774	---	1.0040	.70	---	54	R
CN2775	ET-Creep-11	F37118	482	0.4	52.9	66.5	.2491	51.7	26.250	0.1766	.1022	0.9964	.70	1.07	51	R
CN2775	ET-Creep-12	F37119	482	200.0**	---	---	4.7993	38.4	25.000	0.1769	---	0.9826	.70	---	56	R
CN2775	ET-Creep-13	F37120	482	0.0*	---	---	---	33.1	21.250	0.1780	---	0.9791	.70	---	40	R
CN2775	ET-Creep-14	F37121	482	200.0**	---	---	.4450	27.1	17.500	0.1777	---	0.9948	.70	---	37	R
CN2775	ET-Creep-15	F37122	482	200.0**	---	---	.1705	21.3	13.750	0.1776	---	0.9607	.70	---	19	R
CN2775	ET-Creep-16	F37123	482	200.0**	---	---	.0287	15.4	10.000	0.1774	---	1.0025	.70	---	41	R
CN2775	ETC-2	F37125	302	3200.0**	---	---	14.0736	49.7	31.800	0.1785	---	0.9954	.70	---	109	R

A\U\R: A=ACCEPTABLE, U=UNACCEPTABLE, R=REPORT

** DISCONTINUED

* TL#F37120/ET-CREEP-13 graph unavailable machine malfunction.

Roy E. Starr, Technical Services Manager — Matt Wolton, Tensile Supervisor — 7-5-07 — July 5, 2007

Continued To Page

SIGNATURE K. J. Chiang DATE 3/2/10

DISCLOSED TO AND UNDERSTOOD BY DATE

TITLE PROJECT

Continued From Page

Westmoreland Mechanical Testing & Research, Inc.
P.O. Box 388
221 Westmoreland Drive
Youngstown, Pa. 15696-0388 U.S.A.
Telephone: 724-537-3131 Fax: 724-537-3151
Website: www.wmtr.com
WMT&R is a technical leader in the material testing industry.

31 October 2007

Southwest Research Institute
6220 Culebra Road
P.O. Box 28510
San Antonio, TX 78238

WMT&R Report No. 7-37523
WMT&R Quote No. QN270982 Rev.2
P.O. No.782852E

Attention: Mr. Ken Chiang

Subject: Machine and Test Tensiles and Elevated Creep

Introduction:

Fifteen (15) already machined Grade 7 Titanium and fifteen (15) already machined Grade 5 Titanium creep specimens were received for testing. The creep specimens were tested in accordance ASTM E139-00 and with the customer workscope at their designated stress level and temperatures. Six (6) tensile specimens were received already machined and tested in accordance with ASTM E21-05 to provide yield strength values for subsequent creep testing. Enclosed please find tabular data for all testing, the tensile and creep charts and the tensile tested specimens, along with a CD containing the digital creep curves that include the heat up and loading curves as requested. All creep specimens have been previously returned to the customer.

If you have any questions concerning this report, please feel free to contact me. If I am unavailable, you may also speak with Mr. Roy Starr, Technical Services Manager.

At your service,

Mark A. Phillippi
Technical Service Engineer

kr

K:\markp\Southwest Research\PO 782852E 7-37523\7-37523.doc

Continued To Page

SIGNATURE K. J. Chiang DATE 3/5/10

DISCLOSED TO AND UNDERSTOOD BY DATE

SIGNATURE K. T. Chiang
DISCLOSED TO AND UNDERSTOOD BY
DATE
DATE 3/5/10
~~PROPRIETARY INFORMATION~~ 4/8/10

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TESTING CERT 621-01 & 621-02
Accredited Nadcap Materials Testing Laboratory

October 31, 2007

CERTIFICATION

Section 1 of 4
WMT&R Report No. 7-37523
P.O. No. 782852E
WMT&R Quote No. QN270982 Rev. 2

Southwest Research
6220 Culebra Road
P.O. Drawer 28510
San Antonio, TX 78238

Attention: Ken Chiang

Subject: All processes, performed upon the material as received, were conducted at WMT&R, Inc. in accordance with the WMT&R Quality Assurance Manual, Rev. 9, dated 4/1/2000. The following tests were performed on this order: STRESS and TENSILE

TENSILE RESULTS: ASTM E21-05
SOAK TIME: 30 Minutes
SPEED OF TESTING: 0.005 in./in./min., 0.05 in./min./in.
MATERIAL: GRADE 5 TITANIUM

DISPOSITION: Report

Sample ID	TestLog Number	Temp. °F	UTS ksi	0.2% YS ksi	Elong %	RA %	Modulus Msi	Ult. Load lbf	0.2% YLD. lbf	Orig. Dia. (in.)	Final Dia. (in.)	4D Orig GL (in.)	4D Final GL (in.)	Orig. Area (sq. in.)	Machine Number	A\U\R
TEN-G5-1	G01030	122	156.0	140.2	18.5	31.0	18.4	3913	3516	0.1787	0.1482	0.70	0.83	0.02508066	M9	R
TEN-G5-2	G01031	122	155.0	139.7	13.0	39.5	18.3	3883	3501	0.1786	0.1388	0.70	0.79	0.02505260	M9	R

A\U\R: A=ACCEPTABLE, U=UNACCEPTABLE, R=REPORT

TENSILE RESULTS: ASTM E21-05
SOAK TIME: 30 Minutes
SPEED OF TESTING: 0.005 in./in./min., 0.05 in./min./in.
MATERIAL: GRADE 5 TITANIUM

DISPOSITION: Report

Sample ID	TestLog Number	Temp. °F	UTS ksi	0.2% YS ksi	Elong %	RA %	Modulus Msi	Codes	Ult. Load lbf	0.2% YLD. lbf	Orig. Dia. (in.)	Final Dia. (in.)	4D Orig GL (in.)	4D Final GL (in.)	Orig. Area (sq. in.)	Machine Number	A\U\R
TEN-G5-3	G01032	392	129.8	115.1	15.5	49.0	18.7	D	3252	2884	0.1786	0.1278	0.70	0.81	0.02505260	M9	R
TEN-G5-4	G01033	392	130.7	115.3	15.5	50.5	17.4	---	3270	2886	0.1785	0.1259	0.70	0.81	0.02502455	M9	R

A\U\R: A=ACCEPTABLE, U=UNACCEPTABLE, R=REPORT

Roy E. Starr\Matt Wojton
____ Technical Services Manager____ Tensile Supervisor October 31, 2007

SIGNATURE K. T. Chiang
DISCLOSED TO AND UNDERSTOOD BY
DATE
DATE 3/5/10
~~PROPRIETARY INFORMATION~~ 4/8/10

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ACCREDITED
TESTING CERT 621-01 & 621-02
Accredited Nadcap Materials Testing Laboratory

October 31, 2007

CERTIFICATION

Section 2 of 4
WMT&R Report No. 7-37523
P.O. No. 782852E

Southwest Research

TENSILE RESULTS: ASTM E21-05
SOAK TIME: 30 Minutes
SPEED OF TESTING: 0.005 in./in./min., 0.05 in./min./in.
MATERIAL: GRADE 7 TITANIUM

DISPOSITION: Report

Sample ID	TestLog Number	Temp. °F	UTS ksi	0.2% YS ksi	Elong %	RA %	Modulus Msi	Codes	Ult. Load lbf	0.2% YLD. lbf	Orig. Dia. (in.)	Final Dia. (in.)	4D Orig GL (in.)	4D Final GL (in.)	Orig. Area (sq. in.)	Machine Number	A\U\R
TEN-G7-1	G01052	392	34.9	28.5	37.0	66.5	14.0	D	865	707	0.1776	0.1030	0.70	0.96	0.02477284	M9	R
TEN-G7-2	G01053	392	34.9	26.6	15.5	67.5	13.4	H	861	657	0.1774	0.1009	0.70	0.81	0.02471708	M9	R

A\U\R: A=ACCEPTABLE, U=UNACCEPTABLE, R=REPORT

Roy E. Starr\Matt Wojton
____ Technical Services Manager____ Tensile Supervisor October 31, 2007

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October 31, 2007

CERTIFICATION

Section 3 of 4
WMT&R Report No. 7-37523
P.O. No. 782852E

Southwest Research

CREEP RESULTS: ASTM E139-06
SOAK TIME: 60 Min
MATERIAL: GRADE 5 TITANIUM

DISPOSITION: Report

SAMPLE ID	TestLog Number	Temp °F	Rupture Time Hrs	Elong %	RA %	Total Creep %	Pan Ld LBS	Stress KSI	Orig Dia (in)	Final Dia (in)	Eff GL (in)	Orig GL (in)	Final GL (in)	Machine Number	A/U/R
ETC-G5-1	G00564	302	0.1***	15.7	38.7	---	174.5	139.495	0.1785	.1398	0.9456	.70	.81	S35	R
ETC-G5-2	G00565	302	0.6	12.9	37.5	2.7092	167.7	133.43	0.1789	.1414	0.9703	.70	.79	S29	R
ETC-G5-3	G00566	302	200.0**	---	---	1.8431	159.9	127.365	0.1788	---	0.9473	.70	---	S43	R
ETC-G5-4	G00567	302	200.0**	---	---	1.1466	151.4	121.3	0.1783	---	0.9376	.70	---	S47	R
ETC-G5-5	G00568	302	200.0**	---	---	.0547	129.2	103.105	0.1786	---	0.9907	.70	---	S30	R
ETC-G5-6	G00569	302	200.0**	---	---	.0469	106.5	84.91	0.1787	---	0.9543	.70	---	S29	R
ETC-G5-7	G00570	302	200.0**	---	---	.0339	83.2	66.715	0.1782	---	0.9418	.70	---	S20	R
ETC-G5-8	G00571	302	200.0**	---	---	.0289	60.6	48.52	0.1783	---	0.9722	.70	---	S35	R
ETC-G5-9	G00572	ROOM	200.0**	---	---	.0590	156.5	124.695	0.1788	---	0.9612	.70	---	S27	R
ETC-G5-10	G00573	122	200.0**	---	---	.0495	148.2	118.958	0.1781	---	0.9508	.70	---	S31	R
ETC-G5-11	G00574	212	200.0**	---	---	.0851	171.2	109.735	0.1783	---	0.9607	.70	---	56	R
ETC-G5-12	G00575	482	200.0**	---	---	.0804	141.4	91.46	0.1775	---	0.9830	.70	---	74	R
ETC-G5-13	G01027	122	200.0**	---	---	.0571	149.0	118.958	0.1786	---	0.9531	.70	---	S47	R
ETC-G5-14	G01028	392	200.0**	---	---	.0776	153.7	97.92	0.1788	---	0.9799	.70	---	62	R
ETC-G5-15	G01029	392	200.0**	---	---	.0509	153.7	97.92	0.1788	---	0.9646	.70	---	118	R

A\U\R: A=ACCEPTABLE, U=UNACCEPTABLE, R=REPORT

Roy E. Starr\Matt Wojton
____ Technical Services Manager____ Tensile Supervisor October 31, 2007

SIGNATURE K. T. Chiang
DATE 3/5/10
DISCLOSED TO AND UNDERSTOOD BY
DATE 4/8/10

~~PROPRIETARY INFORMATION~~

PROJECT

TITLE

Westmoreland Mechanical Testing & Research, Inc.
P.O. Box 388
Westmoreland Drive
Youngstown, Pa. 15696-0388 U.S.A.
Telephone: 724-537-3131 *Fax: 724-537-3151*
Website: www.wmtr.com
WMT&R is a technical leader in the material testing industry.

ACCREDITED
TESTING CERT 621-01 & 621-02
Accredited Nadcap Materials Testing Laboratory

October 31, 2007

CERTIFICATION

Section 4 of 4
WMT&R Report No. 7-37523
P.O. No. 782852E

Southwest Research

CREEP RESULTS: ASTM E139-06
SOAK TIME: 60 Min
MATERIAL: GRADE 7 TITANIUM

DISPOSITION: Report

SAMPLE ID	TestLog Number	Temp °F	Rupture Time Hrs	Elong %	RA %	Total Creep %	Pan Ld LBS	Stress KSI	Orig Dia (in)	Final Dia (in)	Eff GL (in)	Orig GL (in)	Final GL (in)	Machine Number	A/U/R
ETC-G7-1	G00552	302	0.0*	55.7	61.7	---	45.5	36.57	0.1779	.1101	0.9878	.70	1.09	S43	R
ETC-G7-2	G00553	302	118.6	55.7	62.1	41.6022	54.6	34.98	0.1784	.1099	1.0050	.70	1.09	47	R
ETC-G7-3	G00554	302	201.9**	---	---	27.0833	52.3	33.39	0.1787	---	0.9960	.70	---	51	R
ETC-G7-4	G00555	302	200.0**	---	---	18.1853	49.8	31.8	0.1786	---	0.9988	.70	---	49	R
ETC-G7-5	G00556	302	200.0**	---	---	2.3798	42.3	27.03	0.1786	---	1.0006	.70	---	50	R
ETC-G7-6	G00557	302	200.0**	---	---	.7049	35.0	22.26	0.1791	---	1.0035	.70	---	48	R
ETC-G7-7	G00558	302	200.0**	---	---	.0774	27.5	17.49	0.1789	---	1.0015	.70	---	55	R
ETC-G7-8	G00559	302	200.0**	---	---	.0440	20.0	12.72	0.1790	---	0.9966	.70	---	107	R
ETC-G7-9	G00560	ROOM	200.0**	---	---	2.2921	55.7	44.668	0.1782	---	0.9978	.70	---	S26	R
ETC-G7-10	G00561	122	200.0**	---	---	3.3756	51.7	41.395	0.1784	---	0.9963	.70	---	S43	R
ETC-G7-11	G00562	212	200.0**	---	---	8.8736	54.3	34.425	0.1793	---	0.9985	.70	---	34	R
ETC-G7-12	G00563	482	200.0**	---	---	.1230	33.2	21.25	0.1784	---	1.0021	.70	---	123	R
ETC-G7-13	G01024	482	200.0**	---	---	.1600	33.5	21.25	0.1792	---	0.9975	.70	---	53	R
ETC-G7-14	G01025	392	200.0**	---	---	1.4280	36.4	23.418	0.1780	---	1.0004	.70	---	47	R
ETC-G7-15	G01026	392	200.0**	---	---	.9677	36.7	23.418	0.1787	---	0.9946	.70	---	25	R

A\U\R: A=ACCEPTABLE, U=UNACCEPTABLE, R=REPORT

*Sample had too many restarts
**Discontinued
***Sample broke after load applied
D - Ruptured outside middle half of gage length.
H - Ruptured outside gage length.

Matthew Wojton 10-31-07
Roy E. Starr\Matt Wojton
____ Technical Services Manager____ Tensile Supervisor October 31, 2007

SIGNATURE K. T. Chiang
DATE 3/5/10
DISCLOSED TO AND UNDERSTOOD BY
DATE 4/8/10

~~PROPRIETARY INFORMATION~~

PROJECT

PROJECT

Westmoreland Mechanical Testing & Research, Inc.
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TESTING CERT 621-01 & 621-02

Accredited Nadcap Materials Testing Laboratory

July 15, 2008

CERTIFICATION

Section 1 of 2

WMT&R Report No. 8-25518
P.O. No. 884417D
WMT&R Quote No. QN280073
Shipping Ticket No. 446282

Southwest Research
6220 Culebra Road
P.O Drawer 28510
San Antonio, TX 78238

Attention: Ken Chiang

Subject: All processes, performed upon the material as received, were conducted at WMT&R, Inc. in accordance with the WMT&R Quality Assurance Manual, Rev. 9, dated 4/1/2000.
The following tests were performed on this order: MACHINE ONLY and STRESS

CREEP RESULTS: ASTM E139-06
SOAK TIME: 60 Min
MATERIAL: TITANIUM

DISPOSITION: Report

REFERENCE	TestLog Number	Temp °F	Rupture Time Hrs	Total Creep %	Pan Ld LBS	Stress KSI	Orig Dia (in)	Eff GL (in)	Orig GL (in)	Machine Number	A/U/R
GR5-6	H21496	392	607.0**	.3268	252.6	80640	0.2526	1.3370	1.00	23	R
GR5-7	H21497	392	605.0**	.2365	253.0	80640	0.2528	1.3461	1.00	49	R
GR7-7	H21505	392	606.0**	.1064	59.5	19285	0.2508	1.3467	1.00	5	R
GR7-8	H21506	392	606.0**	.5132	60.0	19285	0.2518	1.3491	1.00	38	R

A\U\R: A=ACCEPTABLE, U=UNACCEPTABLE, R=REPORT

CREEP RESULTS: ASTM E139-06
REQUIREMENTS: 200.0 Hours
SOAK TIME: 60 Min
MATERIAL: TITANIUM

DISPOSITION: Report

REFERENCE	TestLog Number	Temp °F	Rupture Time Hrs	Elong %	RA %	Total Creep %	Pan Ld LBS	Stress KSI	Orig Dia (in)	Final Dia (in)	Eff GL (in)	Orig GL (in)	Final GL (in)	Machine Number	A/U/R
GR5-1	H21491	302	200.0**			3.8122	317.8	103105	0.2506		1.3518	1.00		94	R
GR5-2	H21492	302	34.0	17.0	36.4	9.9216	320.9	103105	0.2518	.2008	1.3435	1.00	1.17	56	R
GR5-3	H21493	302	0.1*	16.0	48.2		321.7	103105	0.2521	.1814	1.3461	1.00	1.16	200	R
GR5-4	H21494	302	200.0**			4.5821	323.2	103105	0.2527		1.3336	1.00		56	R

A\U\R: A=ACCEPTABLE, U=UNACCEPTABLE, R=REPORT

Michael L. Thien
Stress/Creep Foreperson

July 15, 2008

Testing Specialists for Aerospace, Automotive, and Material Testing Fields
Locations in Youngstown, PA U.S.A. ~ Tel. (724) 537-3131 and
Banbury U.K. ~ Tel. +44 (0) 1295 261211

SIGNATURE K. T. Chiang DATE 3/5/10

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July 15, 2008

CERTIFICATION

Section 2 of 2

WMT&R Report No. 8-25518
P.O. No. 884417D

Southwest Research

DISPOSITION: Report

REFERENCE	TestLog Number	Temp °F	Rupture Time Hrs	Elong %	RA %	Total Creep %	Pan Ld LBS	Stress KSI	Orig Dia (in)	Final Dia (in)	Eff GL (in)	Orig GL (in)	Final GL (in)	Machine Number	A/U/R
GR5-5	H21495	302	0.1*	15.0	42.3		321.4	103105	0.2520	.1914	1.3579	1.00	1.15	200	R
GR5-8	H21498	302	200.0**			3.9255	320.9	103105	0.2518		1.3367	1.00		32	R
GR7-1	H21499	302	200.0**			2.4673	83.7	27030	0.2512		1.3409	1.00		34	R
GR7-2	H21500	302	200.0**			2.9041	84.8	27030	0.2528		1.3467	1.00		5	R
GR7-3	H21501	302	200.0**			2.7950	84.7	27030	0.2527		1.3333	1.00		94	R
GR7-4	H21502	302	200.0**			1.9729	84.5	27030	0.2524		1.3737	1.00		145	R
GR7-5	H21503	302	200.0**			.1512	84.1	27030	0.2517		1.3622	1.00		138	R
GR7-6	H21504	302	200.0**			2.1350	83.8	27030	0.2513		1.3445	1.00		34	R
GR7-9	H21507	302	200.0**			1.7562	84.1	27030	0.2518		1.4389	1.00		32	R
GR7-10	H21508	302	200.0**			2.5999	84.6	27030	0.2525		1.3360	1.00		39	R

A\U\R: A=ACCEPTABLE, U=UNACCEPTABLE, R=REPORT

Requirements suplied by Southwest Research Institute
* SAMPLE BROKE WHILE LOAD BEING APPLIED
**Discontinued

KNOWINGLY OR WILLFULLY FALSIFYING OR CONCEALING A MATERIAL FACT ON THIS FORM OR MAKING FALSE, FICTITIOUS OR FRAUDULENT STATEMENTS OR REPRESENTATIONS HEREIN COULD CONSTITUTE A FELONY PUNISHABLE UNDER FEDERAL STATUTES. THIS CERTIFICATE OR REPORT SHALL NOT BE REPRODUCED EXCEPT IN FULL WITHOUT THE WRITTEN APPROVAL OF WMTR, INC

Michael L. Thien
Stress/Creep Foreperson 7-15-08

July 15, 2008

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SIGNATURE K. T. Chiang DATE 3/5/10

DISCLOSED TO AND UNDERSTOOD BY DATE

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July 15, 2008

CERTIFICATION

Section 1 of 2
WMT&R Report No. 8-25518
P.O. No. 884417D
WMT&R Quote No. QN280073
Shipping Ticket No. 446282

Southwest Research
6220 Culebra Road
P.O. Drawer 28510
San Antonio, TX 78238

Attention: Ken Chiang

Subject: All processes, performed upon the material as received, were conducted at WMT&R, Inc. in accordance with the WMT&R Quality Assurance Manual, Rev. 9, dated 4/1/2000. The following tests were performed on this order: MACHINE ONLY and STRESS

CREEP RESULTS: ASTM E139-06
SOAK TIME: 60 Min
MATERIAL: TITANIUM
DISPOSITION: Report

REFERENCE	TestLog Number	Temp °F	Rupture Time Hrs	Total Creep %	Pan Ld LBS	Stress KSI	Orig Dia (in)	Eff GL (in)	Orig GL (in)	Machine Number	A/U/R
GR5-6	H21496	392	607.0**	.3268	252.6	80640	0.2526	1.3370	1.00	23	R
GR5-7	H21497	392	605.0**	.2365	253.0	80640	0.2528	1.3461	1.00	49	R
GR7-7	H21505	392	606.0**	.1064	59.5	19285	0.2508	1.3467	1.00	5	R
GR7-8	H21506	392	606.0**	.5132	60.0	19285	0.2518	1.3491	1.00	38	R

A\U\R: A=ACCEPTABLE, U=UNACCEPTABLE, R=REPORT

CREEP RESULTS: ASTM E139-06
REQUIREMENTS: 200.0 Hours
SOAK TIME: 60 Min
MATERIAL: TITANIUM
DISPOSITION: Report

REFERENCE	TestLog Number	Temp °F	Rupture Time Hrs	Elong %	RA %	Total Creep %	Pan Ld LBS	Stress KSI	Orig Dia (in)	Final Dia (in)	Eff GL (in)	Orig GL (in)	Final GL (in)	Machine Number	A/U/R
GR5-1	H21491	302	200.0**			3.8122	317.8	103105	0.2506		1.3518	1.00		94	R
GR5-2	H21492	302	34.0	17.0	36.4	9.9216	320.9	103105	0.2518	.2008	1.3435	1.00	1.17	56	R
GR5-3	H21493	302	0.1*	16.0	48.2		321.7	103105	0.2521	.1814	1.3461	1.00	1.16	200	R
GR5-4	H21494	302	200.0**			4.5821	323.2	103105	0.2527		1.3336	1.00		56	R

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Michael L. Thien
Stress/Creep Foreperson
July 15, 2008

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Section 2 of 2
WMT&R Report No. 8-25518
P.O. No. 884417D

Southwest Research

DISPOSITION: Report

REFERENCE	TestLog Number	Temp °F	Rupture Time Hrs	Elong %	RA %	Total Creep %	Pan Ld LBS	Stress KSI	Orig Dia (in)	Final Dia (in)	Eff GL (in)	Orig GL (in)	Final GL (in)	Machine Number	A/U/R
GR5-5	H21495	302	0.1*	15.0	42.3		321.4	103105	0.2520	.1914	1.3579	1.00	1.15	200	R
GR5-8	H21498	302	200.0**			3.9255	320.9	103105	0.2518		1.3367	1.00		32	R
GR7-1	H21499	302	200.0**			2.4673	83.7	27030	0.2512		1.3409	1.00		34	R
GR7-2	H21500	302	200.0**			2.9041	84.8	27030	0.2528		1.3467	1.00		5	R
GR7-3	H21501	302	200.0**			2.7950	84.7	27030	0.2527		1.3333	1.00		94	R
GR7-4	H21502	302	200.0**			1.9729	84.5	27030	0.2524		1.3737	1.00		145	R
GR7-5	H21503	302	200.0**			.1512	84.1	27030	0.2517		1.3622	1.00		138	R
GR7-6	H21504	302	200.0**			2.1350	83.8	27030	0.2513		1.3445	1.00		34	R
GR7-9	H21507	302	200.0**			1.7562	84.1	27030	0.2518		1.4389	1.00		32	R
GR7-10	H21508	302	200.0**			2.5999	84.6	27030	0.2525		1.3360	1.00		39	R

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Section 1 of 2

Southwest Research
6220 Culebra Road
P.O. Drawer 28510
San Antonio, TX 78238

Corrected Date
September 26, 2008

WMT&R Report No. 8-25518
P.O. No. 884417D
WMT&R Quote No. QN280073
Shipping Ticket No. 446282

Attention: Ken Chiang

Subject: All processes, performed upon the material as received, were conducted at WMT&R, Inc. in accordance with the WMT&R Quality Assurance Manual, Rev. 9, dated 4/1/2000.
The following tests were performed on this order: MACHINE ONLY and STRESS

CREEP RESULTS: ASTM E139-06
SOAK TIME: 60 Min
MATERIAL: TITANIUM

DISPOSITION: Report

REFERENCE	TestLog Number	Temp °F	Rupture Time Hrs	Elong %	RA %	Total Creep %	Pan Ld LBS	Stress KSI	Orig Dia (in)	Final Dia (in)	Eff GL (in)	Orig GL (in)	Final GL (in)	Machine Number	A/U/R
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GR5-3	H21493	302	0.1*	16.0	48.2		321.7	103.105	0.2521	0.1814	1.3461	1.00	1.16	200	R
GR5-4	H21494	302	200.0**			4.5821	323.2	103.105	0.2527		1.3336	1.00		56	R
GR5-5	H21495	302	0.1*	15.0	42.3		321.4	103.105	0.2520	0.1914	1.3579	1.00	1.15	200	R
GR5-6	H21496	392	607.0**			.3268	252.6	80.640	0.2526		1.3370	1.00		23	R
GR5-7	H21497	392	605.0**			.2365	253.0	80.640	0.2528		1.3461	1.00		49	R

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Michael L. Thien
Stress/Creep Foreperson

September 26, 2008

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Southwest Research

WMT&R Report No. 8-25518
P.O. No. 884417D

Corrected Date
September 26, 2008

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REFERENCE	TestLog Number	Temp °F	Rupture Time Hrs	Elong %	RA %	Total Creep %	Pan Ld LBS	Stress KSI	Orig Dia (in)	Final Dia (in)	Eff GL (in)	Orig GL (in)	Final GL (in)	Machine Number	A/U/R
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GR7-6	H21504	302	200.0**			2.1350	83.8	27.030	0.2513		1.3445	1.00		34	R
GR7-7	H21505	392	606.0**			.1064	59.5	19.285	0.2508		1.3467	1.00		5	R
GR7-8	H21506	392	606.0**			.5132	60.0	19.285	0.2518		1.3491	1.00		38	R
GR7-9	H21507	302	200.0**			1.7562	84.1	27.030	0.2518		1.4389	1.00		32	R
GR7-10	H21508	302	200.0**			2.5999	84.6	27.030	0.2525		1.3360	1.00		39	R

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Michael L. Thien
Stress/Creep Foreperson

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Draft paper derived from ENG2 work (Not reviewed) The paper may be submitted to Materials Sci & Eng Journal

The Effect of Temperature and Stress Level on the Low Temperature Creep Behavior of Grade 7 Titanium Alloy

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KTC 3/5/10

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Abstract

The low temperature (less than one-fourth of the melting temperature) creep behavior of Grade 7 Titanium (Ti-0.2wt.%Pd-0.13wt.%O) was studied at various stress levels (40 to 100% yield stress) at the temperature of 150°C and at various temperatures (room temperature to 150°C) at 85% of the respective yield stress at these temperatures. At 150°C, creep strain increases with increasing stress level and the threshold stress for onset of creep was calculated to be approximately 32% of the yield stress. At 85% of the respective yield stress, the creep strain did not necessarily increase with temperature. The creep strain increases from room temperature to 50°C, then decreases at 100°C and decreases further at 150°C. This behavior is attributed to two factors, the first being that the creep deformation mechanism changes from slip and twinning at room temperature and 50°C to primarily slip at 100° and 150°C. The second reason is related to a flow stress drop after yielding, which is significant at 100° and 150°C. Due to this flow stress drop at 100° and 150°C, the 85% yield stress in relation to the peak stress is much lower than at room temperature and 50°C, where there is no flow stress drop.

1. Introduction

For over twenty years, the United States Department of Energy has studied Yucca Mountain in Nevada as the potential site for a high-level radioactive waste geologic repository. It is proposed that the radioactive waste will be encapsulated in waste packages and placed in tunnels (drifts) below ground. Drip shields will be placed over the waste packages for the purposes of diverting water and preventing damage to the waste packages from rockfall and drift degradation. As currently designed, the drip shield will be made of titanium alloys due to their high strength and corrosion resistance (DOE, 2002). The shell of the drip shield will be made of Grade 7 Titanium (commercially pure with 0.15 to 0.25 wt.% Pd) plates with Grade 24 Titanium (Ti-6 wt.% Al-4 wt.% V-0.04 to 0.08 wt.% Pd) support beams and bulkheads. Sustained static loading of the drip shield may occur as a result of accumulated rockfall or drift collapse and such loads may cause residual stresses that approach the yield stresses of the titanium alloys (Neuberger et al., 2002). Titanium alloys are know to deform over time, or creep, at low temperatures (less than one-fourth of the melting temperature of the material), at stresses less than the yield stress (YS) (Adenstedt, 1949; Rieman, 1971; Zeyfang et al., 1971; Thompson and Odegard, 1973; Odegard and Thompson, 1973; Imam and Gilmore, 1979; Ankem et al., 1994; Hultgren et al., 1999; Neeraj et al., 2000; Hasija et al., 2003; Ramesh and Ankem, 2003; Aiyangar et al., 2005), which could compromise the structural integrity of the drip shield. Thus, it is critical to understand the creep behavior of the drip shield materials.

Prior to this investigation, there has been no systematic study of the creep behavior of Grade 7 Titanium in the range of temperatures (room temperature to 150°C) and stress levels (40 to 100 % YS) to which the drip shield could be subjected. In particular, it is known that such factors as temperature, stress level, microstructure, and texture can have a significant effect on the deformation mechanisms, and hence creep behavior of titanium alloys. In this regard, the aim of the present investigation is to study the creep behavior of Grade 7 Titanium at the range of temperatures from room temperature to 150°C and stress levels from 40 to 100 % YS to better understand the role of microstructure, texture, and deformation mechanisms on the creep response of the alloy.

2. Materials and Methods

2.1. Alloy Composition

The material used in this investigation is Grade 7 Titanium, obtained from Tricor Industrial, Inc. This is a commercially pure, Hexagonally Close-Packed (HCP) α-Ti alloy, with the addition of a small amount of palladium for enhanced corrosion resistance. The chemical composition of the alloy used in this investigation is given in Table 1. The specimen was rolled and mill annealed at 843°C for 24 minutes then air cooled. Tensile and creep specimens were cut such that the loading axis is transverse to the rolling direction.

Table 1: Chemical Composition of Grade 7 Titanium Alloy Used in this Investigation

C	Fe	H	N	O	Pd	Ti
0.01 wt.%	0.08 wt.%	10 wppm	0.01 wt.%	0.13 wt.%	0.16 wt.%	Balance

2.2. Alloy Texture

Pole figures were generated by Lambda Technologies Inc. to characterize the texture of the material before testing. Pole figures were obtained using Cu K_α radiation and a Schulz back-reflection pole figure device mounted on an automated Bragg-Brentano focusing geometry horizontal x-ray diffractometer. WIMV analysis was used to calculate the inverse pole figures for the sample coordinate axes directions. The inverse pole figures for the material used in this investigation are shown in Figure 1.

2.3. Alloy Microstructure

The microstructure of the as-received Grade 7 Titanium was revealed by polishing and etching the material surface. Specimens were first polished using silica paper followed by a colloidal silica suspension on a polishing cloth to produce a smooth, mirror finish. Grain boundaries were revealed by a two-step etching process. The first etchant is known as Kroll's reagent (88 mL, 10 mL nitric acid, 2 mL hydrofluoric acid). This is a low-contrast etchant so the specimen is rinsed with water and etched with R-etch (40 mL glycerine, 35 mL ethanol, 25 mL

hydrofluoric acid, 18.5 g benzalkonium chloride). Optical micrographs of the surface were taken with a Zeiss 405 inverted light microscope. The specimen has an average grain size of approximately 55 μm and the grains are mostly equiaxed. Typical microstructure is shown in Figure 2.

2.4. Mechanical Testing

2.4.1. Tensile Testing

Prior to creep testing, tensile tests were performed at room temperature, 50°C, 100°C, and 150°C to determine the 0.2% YS so that creep tests could be performed at a known percentage of the YS. The tests were performed in air on an Instron 4208 universal testing machine equipped with a split furnace with an accuracy of ±0.8°C. Strain was measured with an MTS 632.53 Extensometer with an accuracy of ±0.02%. The strain rate was 0.005/minute up to 0.4% strain, then 0.05/minute beyond 0.4% strain.

2.4.2. Creep Testing

To determine the relationship between stress level and creep strain, tests were performed at various stress levels at a constant temperature. At the temperature of 150°C, specimens were creep tested at 40%, 55%, 70%, 85%, and 100% YS. Further, to determine the relation between temperature and creep strain, tests were performed at various temperatures at a constant relative stress level. At the stress level of 85% of the respective yield stress at that temperature, specimens were creep tested at room temperature, 50°C, 100°C, and 150°C. Specimens were tested in air on an Instron Model M3 machine equipped with a split furnace with an accuracy of ±0.8°C. Strain was measured with an MTS 632.53 Extensometer with an accuracy of ±0.02%.

2.5. Transmission Electron Microscopy

Creep deformed Grade 7 Titanium was investigated by Transmission Electron Microscopy (TEM) to identify and characterize the deformation mechanisms. TEM specimens were sectioned from the creep specimen with a Buehler Isomet Low Speed Saw with a diamond wafering blade. The disks were then thinned with a Southbay Technologies Model 515 dimpling instrument. Final thinning was performed by jet polishing in a Fischione 120 twin jet polishing unit. The polishing solution used was 94 % methanol, 3% sulfuric acid, and 3% hydrochloric

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acid. The specimens were polished in the range of -60 to -70°C. The TEM investigation was performed using a JEOL 2100 LaB_6 microscope.

3. Results and Discussion

3.1. Tensile Testing

The true stress-strain curves for the Grade 7 Ti specimens tested at room temperature, 50°C, 100°C, and 150°C are shown in Figure 3. The notable feature of the stress-strain curves is the decrease in stress, or load drop, after yielding at 100°C and 150°C. These specimens were not examined by optical or TEM microscopy, but the load drop phenomenon after yielding has been previously observed for α-Ti alloys. Orava et al. (1966) have recorded such a load drop in A-70 Ti (commercially pure Ti with 0.27 wt.%O) wire, with the greatest load drop between 77°C and 177°C. This temperature rage is consistent with the temperatures where the load drop is recorded in the present study for Grade 7 Ti.

Jones and Conrad (1969) performed measurements of the dislocation density in A-70 Ti before testing at the initial peak point of the stress-strain curve (the maximum point before the load drop), during the load drop (halfway between the maximum and the minimum), and at the minimum point of the stress-strain curve (after the load drop and before any re-hardening). Before testing they found relatively few, randomly distributed dislocations. At the initial peak point there were discrete narrow bands of dislocations in about half of the grains. During the load drop, the dislocation density increased significantly, mainly by the number of slip bands in some of the grains. Finally, at the minimum point, the dislocation density had increased further and almost all the grains contained dislocations. Straining beyond this point required additional stress, indicative of conventional strain hardening. Thus, the load drop could be attributed to an increase in the density of mobile dislocations before dislocation tangling. Also, this type of behavior has been observed by Vijayshankar and Ankem (1990) for β-Ti alloys at high temperature.

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3.2. Creep Testing

3.2.1. Specimens Tested at 150°C at Various Stress Levels

The 200 hour creep curves for Grade 7 Ti tested at the temperature of 150°C at various stress levels are shown in Figure 4.

3.2.1.1 Equation to Describe Creep Data

Generally, transient creep of metallic materials can be described by one of two empirical equations (Aiyangar et al., 2005). The first is a power-law equation where creep strain, ε, is related to the time of testing, t, by an equation of the type:

$$\varepsilon = At^n \quad (3.1)$$

where A is the creep constant of proportionality, and n is the creep exponent. Alternatively, a creep curve may follow a logarithmic equation of the type:

$$\varepsilon = A' + B\ln(t) \quad (3.2)$$

where A' and B are constants.

To determine which equation best describes the creep data for Grade 7 Ti in this investigation, the experimental data shown in Figure 4 was fit using both Equations (3.1) and (3.2). The accuracy with which the fitting equation describes the creep data is measured by the R^2 value (where R is the Pearson product moment correlation coefficient through the data points). An R^2 value of 1 indicates that the fitting equation perfectly describes the data, while an R^2 value of significantly less than 1 indicates that the fitting equation poorly describes the data. It was found, particularly at higher stress levels (70% to 100%YS), that the logarithmic equation best describes the creep data, and the values of A' and B taken from the fitting equation at the various stress levels are shown in Table 2, as is the R^2 value for the logarithmic fit.

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Table 2: Creep Strain, Creep Constants, and R^2 Value at Various Stress Levels for Grade 7 Ti at 150°C

Stress Level (%YS)	*Creep Strain after 200 Hours (%)*	*A′*	*B*	*R^2*
40	0.05	0.0360	0.0028	0.9972
55	0.17	0.0111	0.0291	0.9532
70	0.39	0.1783	0.0419	0.8854
85	2.09	0.8786	0.2322	0.9960
100	13.71	1.3203	2.4284	0.9742

The constants A' and B increase with increasing stress and can be expressed in terms of the applied stress, σ, where σ is expressed in terms of %YS (i.e. σ = 85 when the applied stress is 85%YS):

$$A' = 6.90x10^{-4}\exp(0.0771\sigma) \qquad (3.3)$$

$$B = 4.94x10^{-5}\exp(0.1041\sigma) \qquad (3.4)$$

Substituting Equations (3.3) and (3.4) into Equation (3.2) gives the general equation for creep of Grade 7 Ti at 150°C at any time, t (in hours):

$$\varepsilon(\%) = 6.90x10^{-4}\exp(0.0771\sigma) + 4.94x10^{-5}\exp(0.1041\sigma) * \ln t \qquad (3.5)$$

3.2.1.2 Threshold Stress for Onset of Creep at 150°C

For commercially pure titanium, Adenstedt (1949) reported creep at a stress level of 60%YS. However, no definitive threshold stress for the onset of creep has been reported for Grade 7 Ti. The experimental data from the creep tests can be used to derive a minimum threshold below which creep deformation is negligible for Grade 7 Ti. At the lowest stress level

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at which testing was performed (40%YS), Grade 7 Ti crept. Therefore, the data must be extrapolated to determine the minimum stress level at which creep would occur. As seen in Figure 5, creep strain after 200 hours, ε, increases exponentially with stress level, σ, where σ is expressed in terms of %YS. The equation that best describes this relationship is given as:

$$\varepsilon(\%) = 1.05x10^{-3}\exp(0.0913\sigma) \qquad (3.6)$$

However, this type of an exponential equation will never go to zero even at $\sigma = 0$. Therefore, the stress threshold will be defined as the stress level below which creep strain is considered to be undetectable given the accuracy instruments. Based on the extensometer used for the creep test, the accuracy is ±0.02%. As such, the stress level that corresponds to 0.02 percent strain will be assumed as the stress threshold for creep deformation. Solving Equation (3.6) for ε = 0.02%, gives a value for the stress threshold as approximately 32.3 percent yield stress.

3.2.2. Specimens Tested at 85% of the Respective Yield Stress at Various Temperatures

In this investigation, Grade 7 Ti specimens were creep tested at various temperatures: room temperature, 50°C, 100°C, and 150°C, at 85% of the respective yield stress at these temperatures. The creep curves for these specimens are shown in Figure 6. The unexpected result from this investigation is that at the same relative stress level, creep strain does not necessarily increase with increasing temperature. There is less strain at 100°C than at 50°C, and still less at 150°C. Such behavior is unusual for metallic materials where creep strain typically increases with temperature (Dieter, 1986). This is because the creep deformation mechanism is usually thermally activated, as is the case for slip or diffusion.

The activation energy for creep deformation of a material helps to determine the rate-controlling creep deformation mechanism, which is very useful for understanding creep behavior. Miller et al. (1987), have shown that for Ti alloys, the activation energy may change if the deformation mechanism responsible for creep changes. For instance, the creep mechanism may change from slip at low temperature to self-diffusion at high temperatures, which is reflected in a change in activation energy.

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The activation energy, Q, for non-steady state creep at a constant stress for Ti alloys was first determined by Thompson and Odegard (1973) using Equation (3.7):

$$Q = -R\left[\frac{\Delta \ln \dot{\varepsilon}(\varepsilon)}{\Delta(1/T)}\right] \qquad (3.7)$$

where R is the universal gas constant, T is the temperature, and $\dot{\varepsilon}$ is the instantaneous creep strain rate at the strain level, ε, at which the activation energy is calculated.

To help identify the active creep deformation mechanism, the activation energy for creep was calculated at various strain levels. This process involves measuring the instantaneous creep strain rate, $\dot{\varepsilon}$, at various strain levels for each temperature. When natural logarithm of instantaneous creep strain rate at the particular strain level is plotted against the reciprocal of the temperature, a line is obtained with a slope proportional (by a factor of $-R$) to the activation energy for creep at that strain level.

Consider first the earliest stages of creep where, as can be seen in Figure 6, the creep strain rate does increase with temperature. At three different strain levels, 0.1%, 0.2%, and 0.4%, the instantaneous creep strain rate was measured at the various temperatures. For these strain levels, the natural logarithm of the instantaneous creep strain rate was plotted against reciprocal temperature, and a best fit line relating these variables was drawn. To determine the activation energy for creep at these strain levels, the slope of the best fit line was multiplied by $-R$ (−8.31 J/K*mol). The calculated activation energy values are shown in Table 3. The measured activation energy of ~30 kJ/mol is consistent with previously measured values for the activation energy for creep of α-Ti when slip is the predominant creep deformation mechanism (Zeyfang et al., 1971; Tung and Sommer, 1970). Slip is a thermally activated process, which explains the increase in creep strain rate as temperature increases during the earliest stages of creep.

The fact that the creep strain rate of the specimens tested 100°C and 150°C begins to decrease compared to those of the specimens tested at room temperature and 50°C suggests that after the earliest stages of creep, an athermal creep deformation mechanism is operative. One such deformation mechanism is twinning, which is a common deformation mechanism in Ti alloys (Ankem et al., 1994; Aiyangar et al., 2005; Partridge, 1968; Akhtar, 1975; Christian and Mahajan, 1995; Song and Gray, 1995a,b). The critical stress for twinning shows little

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temperature dependence and twinning becomes more common as temperature decreases (Song and Gray, 1995c). This is because at high temperatures, the critical stress for slip is less than the critical stress for twinning. Thus, slip is the predominant deformation mechanism. As temperature decreases, the critical stress for slip increases while the critical stress for twinning remains nearly constant. When the critical stress for slip becomes higher than the critical stress for twinning, twinning will become a predominant deformation mechanism. Twinning activity at lower temperatures could explain the continued creep at these temperatures, whereas at higher temperatures, creep is limited because twinning is not active.

While twin initiation may be an athermal process, twins must grow for creep strain to proceed and twin growth is a thermally activated process. It has been shown (Oberson and Ankem, 2005) that twin growth is rate-limited by the diffusion of oxygen due to the non-conservation of octahedral interstitial lattice where oxygen atoms can reside. Thus, for the temperature range where twinning is an active deformation mechanism, the twin growth rate will increase with increasing temperature, and the activation energy for creep should correspond to the activation energy for the diffusion of oxygen in titanium. Therefore, Equation 3.7 can be used to calculate the activation energy for creep beyond the initial stage only at room temperature and 50°C, where the creep strain rate increases with temperature.

For the specimens tested at room temperature and 50°C, the instantaneous creep strain rate was measured at the stress levels of 1.0%, 1.5%, 2.0%, and 2.5%, and the natural logarithm of the instantaneous strain rate was plotted against reciprocal temperature. The slope of the best-fit line connecting the data points was multiplied by $-R$ to calculate the activation energy for creep at the various strain levels. These values are shown in Table 3. The value of the activation energy for creep measured at the higher strain level is slightly above that measured for low strain, suggesting that there could be a change in deformation mechanism from solely slip at low strain to a mixed mode of slip and twinning at higher strain. The activation energy for the diffusion of oxygen in α-Ti is in the range of 65 to 200 kJ/mol (Liu and Welsch, 1998), which is somewhat higher than the measured activation energy for creep in this investigation. That is because at the strain levels from 1.0 to 2.5 percent slip and twinning are simultaneous deformation mechanisms for Grade 7 Ti with slip likely more active. Thus, the overall activation energy for creep will be closer to that of slip than twinning. If creep strain were to proceed further, twinning would become relatively more common compared to slip and the activation

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energy for creep would increase to higher values approaching that of the activation energy for the diffusion of oxygen α-Ti.

Table 3: Activation Energy, *Q*, for Creep of Grade 7 Ti at Various Strain Levels

Strain (%)	Activation Energy (kJ/mol)
0.1	29.9
0.2	27.5
0.4	25.6
1.0	29.0
1.5	35.2
2.0	30.0
2.5	30.0

The other factor that must be considered for the decrease in creep strain with increasing temperature is the way the applied stress level was determined. The applied stress level was based on the 0.2%YS at the various temperatures. Due to the lack of a clear transition from linear elastic to plastic strain, the yield stress can be defined as the stress at some arbitrary plastic strain (typically 0.2%). In most cases, the stress flattens off after yielding or increases due to strain hardening. Thus, the 0.2%YS will usually be the same, or slightly higher, than the actual stress at which instantaneous plastic deformation begins. This is the case for Grade 7 Ti tested at room temperature and 50°C. However, for Grade 7 Ti tested at 100°C and 150°C, there is a significant decrease in stress after a peak stress is reached at the end of the linear elastic portion of the stress-strain curve. When the 0.2%YS is determined at 100°C and 150°C, it is somewhat smaller than the peak stress at which instantaneous plastic deformation will begin. Thus, when the applied stress level is 85% of the 0.2%YS at 100°C and 150°C, it is in fact a smaller percentage of the actual stress level at which instantaneous plastic deformation begins. This

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could contribute to decreased creep strain at the elevated temperatures compared to the lower temperatures.

3.3. TEM Investigation

In this investigation, Grade 7 Ti specimens were examined by TEM to identify and characterize the creep deformation mechanisms. As described earlier, based on the calculated activation energy, there is evidence that slip and twinning are operative mechanisms, but TEM is necessary to confirm this suggestion and to more fully understand the creep deformation behavior at various temperatures and stress levels.

3.3.1. Specimens Tested at Various Stress Levels at 150°C

For the specimens tested at 150°C, *a*-type prism slip was identified as an operative deformation mechanism at all stress levels. *a*-type dislocations are those with Burgers vector of the type: $\bar{b} = \frac{1}{3}\langle 11\bar{2}0\rangle$ and they are commonly found in α-Ti alloys (Zeyfang et al., 1971; Neeraj et al., 2000; Partridge, 1968; Song and Gray, 1995a; Conrad et al., 1973; Paton et al., 1973). Prism slip refers to glide on $\{1\bar{1}00\}$ type planes. These dislocations are typically found in orderly arrays, as seen in Figure 7.

For the specimens tested at stress levels of less than 100%YS, slip was the only observed deformation mechanism. However, for the specimen tested at 100%YS, deformation twins were observed by TEM, as seen in Figure 8. Based on the Selected Area Diffraction Patterns (SADPs), the twins were identified as $\{1\bar{1}02\}$ type twins, which are commonly found in α-Ti alloys (Song and Gray, 1995a).

The fact that slip is the only observed deformation mechanism in Grade 7 Ti tested at 150°C at stress levels less than 100%YS suggests that, at 150°C, the critical stress for the onset of slip is less than that for twin nucleation. Therefore, the first result of the applied stress will be to initiate slip in favorably oriented grains, namely, those in which the basal plane of the HCP unit cell is parallel to the loading axis. When dislocations encounter a grain boundary with a non-favorably oriented grain, energy is required for the dislocations to overcome such a barrier. If thermal energy is not sufficient for the dislocations to cross the grain boundary, they will

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instead pile up there, limiting the amount of plastic strain that is possible due solely to slip (Song and Gray, 1995c). For the stresses less than 100%YS in this investigation, this is likely the situation that will lead to creep exhaustion.

For the specimen tested at 100%YS, however, there will be more dislocation activity and the dislocation pileups will become longer, increasing the stress concentration at the grain boundary ahead of the pileup (Meyers et al., 2001). If the energy for twin nucleation is less than that required for dislocations to overcome the grain boundary, this dislocation pileup will provide the energy necessary for twin nucleation in the adjacent grain. Thus, twinning can become the predominant deformation mechanism even though the critical stress for slip is less than that for twinning. This is likely the case for Grade 7 Ti tested at 100%YS, where both slip and twinning are active deformation mechanisms. Indeed, a critical strain for the onset of twinning has been observed during tensile and fatigue testing of α-Ti (Salem et al., 2003) and HCP Zr (Song and Gray, 1995c), and this critical strain decreases with decreasing temperature.

3.3.2. Specimens Tested at 85% of the Respective Yield Stress at Various Temperatures

For the Grade 7 Ti specimens tested at 85% of the respective yield stress, the activation energy for creep, as calculated earlier, suggests that the specimens tested at room temperature and 50°C deform by slip and twinning, whereas those tested at 100°C and 150°C deform solely by slip. This suggestion is verified by the TEM investigation, where slip is observed at all temperatures, but twinning is only observed for the lower temperature specimens.

In regard to the higher temperature specimens, the predominant deformation mechanism is *a*-type slip (see Figure 7). For the lower temperature specimens, while slip is an active deformation mechanism, $\{1\bar{1}02\}$ type twinning was also observed for the specimens tested at room temperature and 50°C, as seen in Figure 9. This suggests that at these temperatures, the critical stress, and hence strain, for the onset of twinning has been reached, whereas is has not for the elevated temperature specimens.

4. Conclusions

1. During constant strain-rate tensile testing, Grade 7 Ti shows a load drop after yielding at 100°C and 150°C, whereas no load drop is observed at room temperature and 50°C. The load drop may be attributed to an increased density of mobile dislocations.

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2. At the temperature of 150°C, for Grade 7 Ti specimens tested at various stress levels, the creep strain, ε, is best related to time of testing, t, by an equation of the type: $\varepsilon = A' + B\ln t$, where A' and B are constants that increase with an increase in stress level.

3. At the temperature of 150°C, for Grade 7 Ti specimens tested at various stress levels, the creep strain after 200 hours increases exponentially with increasing stress level. The threshold stress for the onset of measurable creep is calculated to be approximately 32%YS.

4. At the stress level of 85% of the respective yield stress the extent of creep strain does not necessarily increase with increasing temperature. The creep strain rate increases with increasing temperature up to approximately 1% strain, then decreases for the specimens tested at 100°C and 150°C compared to the specimens tested at room temperature and 50°C. The calculated activation energy for creep suggests that slip is the predominant deformation mechanism at low strains at all temperatures. At higher strains, the specimens tested at room temperature and 50°C can deform by twinning whereas the specimens tested at 100°C and 150°C do not.

5. Transmission Electron Microscopy (TEM) investigation of the creep deformed Grade 7 Ti specimens reveals that *a*-type slip is an active deformation mechanism at all temperatures and stress levels for this investigation. For the specimens tested at 150°C, deformation twinning was only observed in the specimen tested at the stress level of 100%YS. For the specimens tested at 85% of the respective yield stress at various temperatures, twinning was observed in the specimens tested at room temperature and 50°C.

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Figures

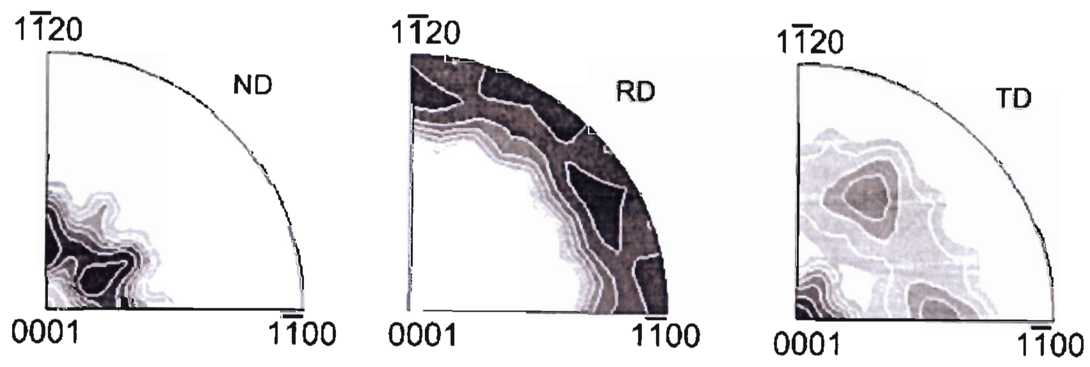

Figure 1: Inverse pole figures for as-received Titanium Grade 7 for the normal direction (ND), rolling direction (RD), and transverse direction (TD). Darker areas indicate areas of higher pole density.

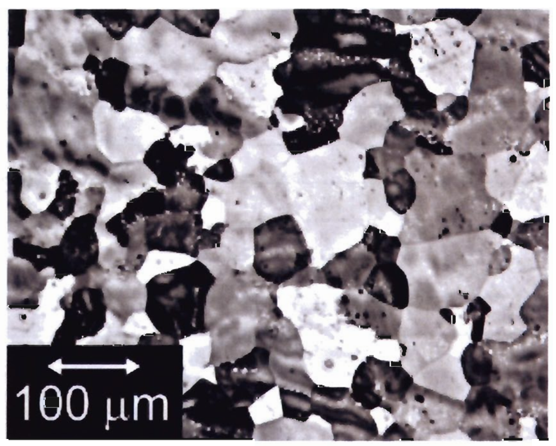

Figure 2: Optical micrograph of the microstructure of the as-received Grade 7 Ti alloy used in this investigation.

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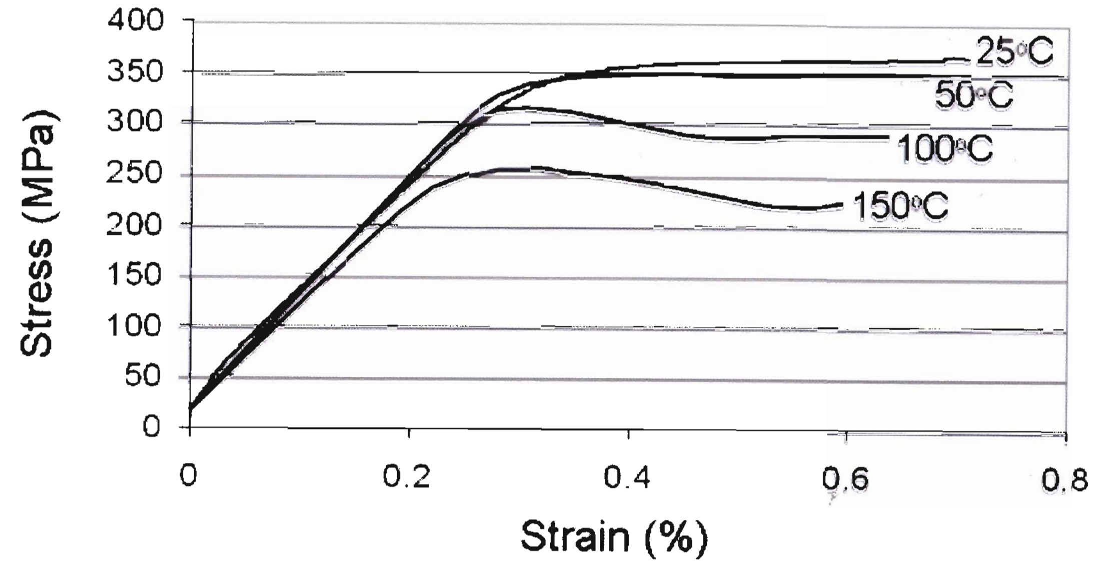

Figure 3: True stress-true strain curves for Grade 7 Ti at various temperatures.

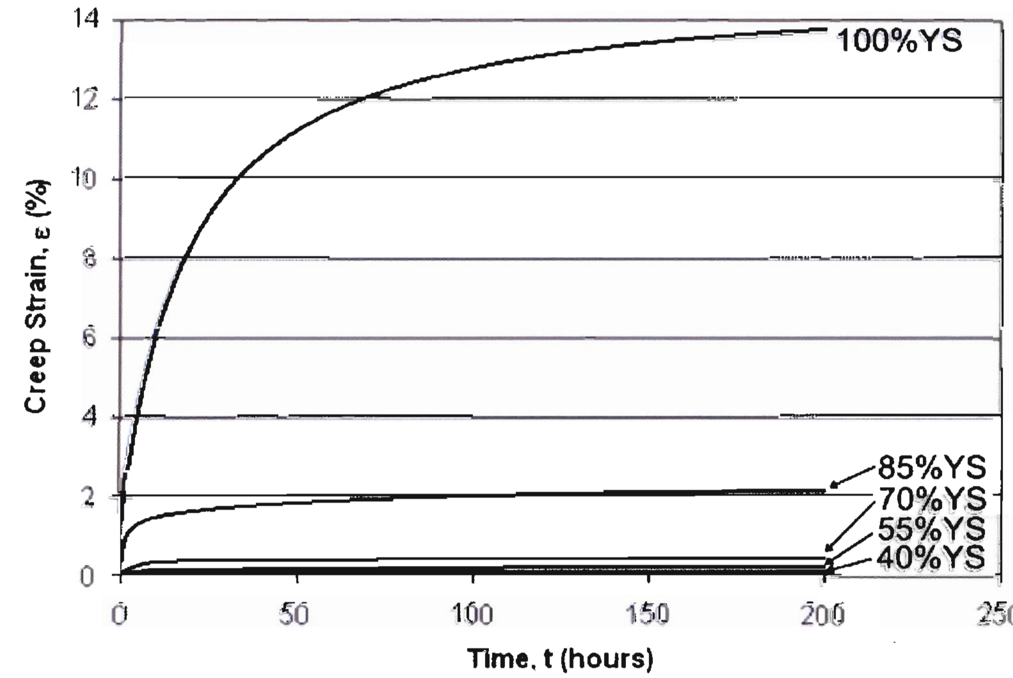

Figure 4: Creep curves for Grade 7 Ti tested at 150°C at various stress levels from 40% yield stress (YS) to 100%YS.

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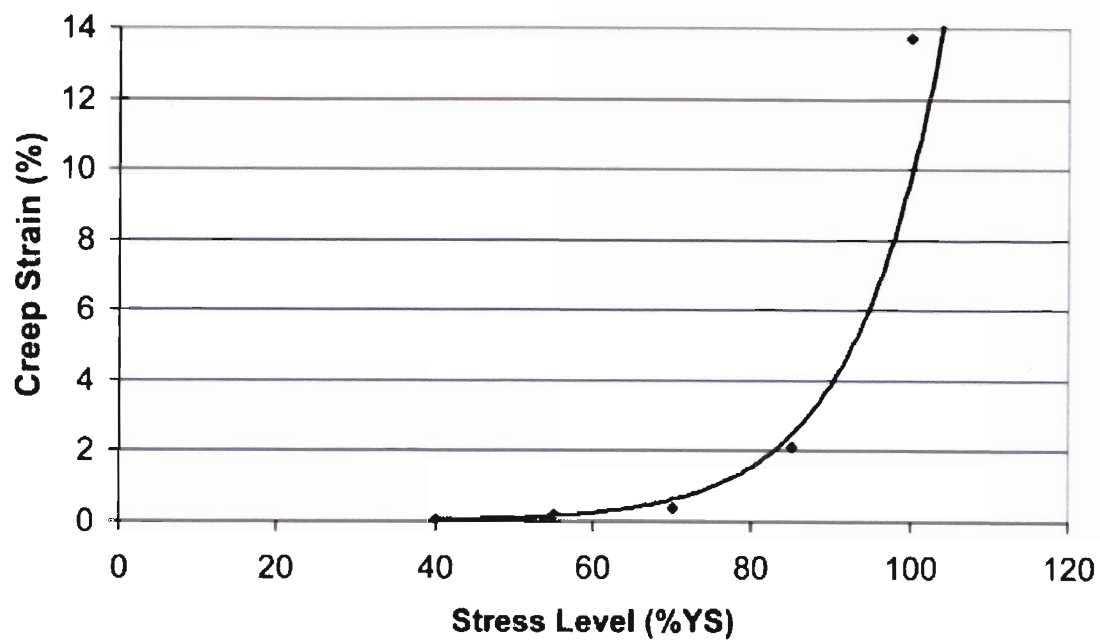

Figure 5: Plot of the creep strain after 200 hours for Grade 7 Ti tested at 150°C at various stress levels. The line indicates the best fit exponential equation to describe the data.

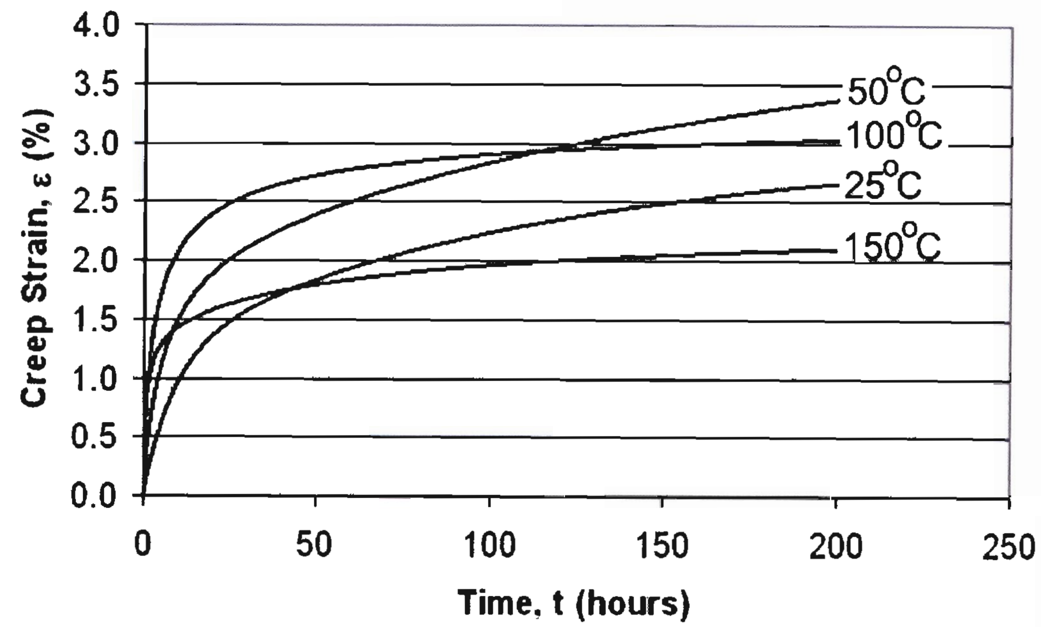

Figure 6: Creep curves for Grade 7 Ti tested at 85% of the respective yield stress at various temperatures from room temperature to 150°C.

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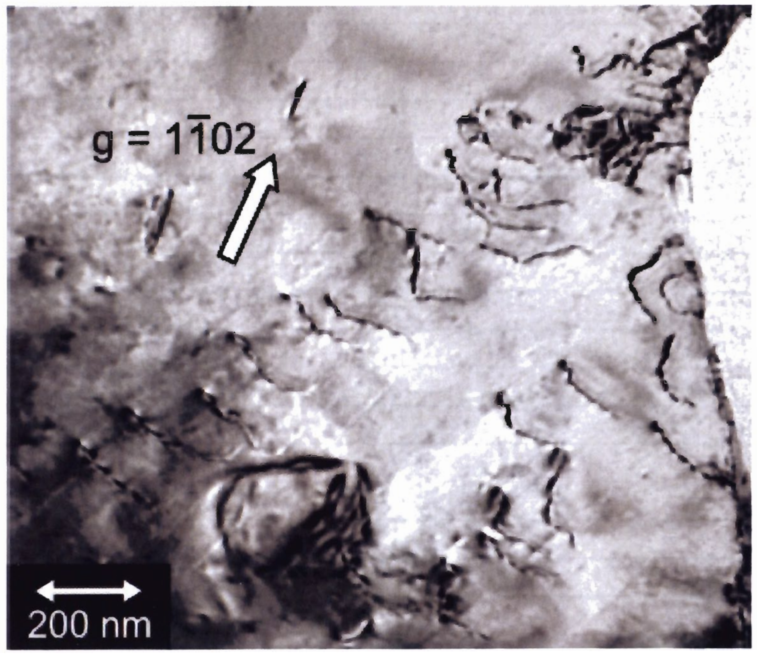

Figure 7: Bright-field TEM micrograph of *a*-type screw dislocations in Grade 7 Ti creep tested at 85%YS at 150°C.

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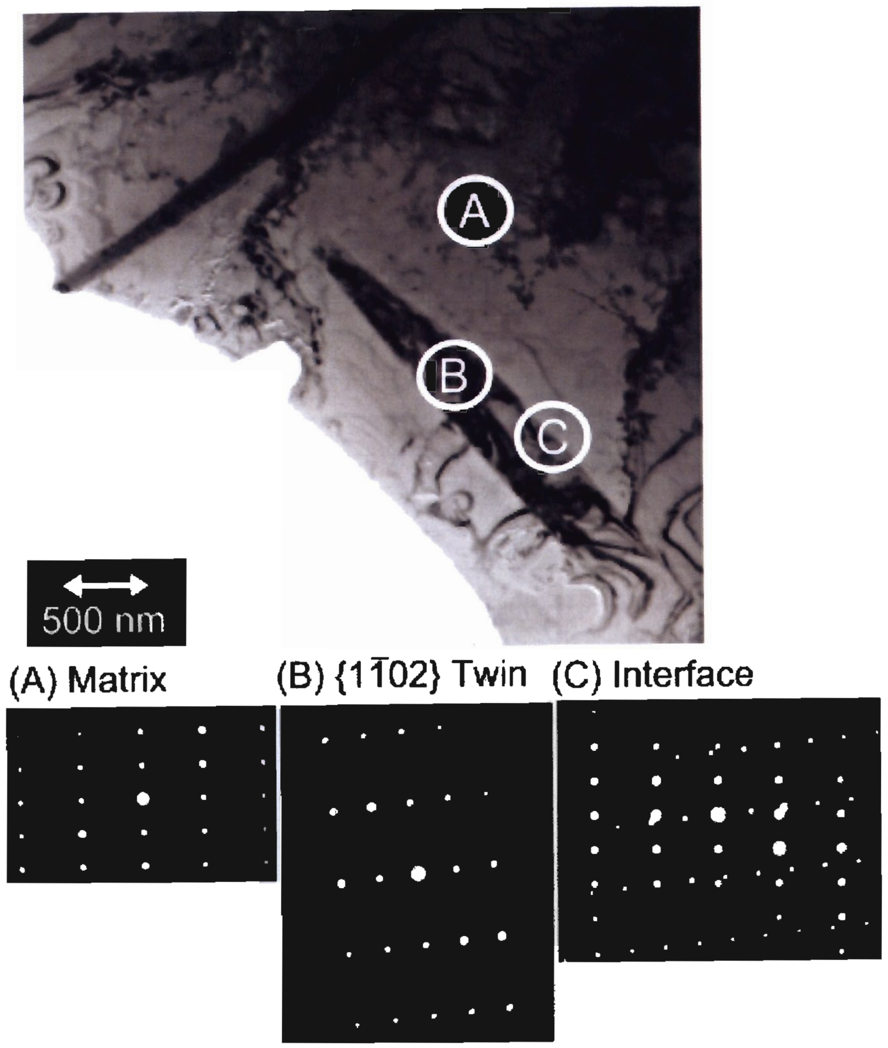

Figure 8: Bright-field TEM micrograph of $\{1\bar{1}02\}$ twins in Grade 7 Ti creep tested at 100%YS at 150°C. Circles indicate the areas from which the Selected Area Diffraction Patterns (SADPs) were taken. The zone axis of the SADPs is $\langle 11\bar{2}0\rangle$. (A) SADP of untwinned matrix. (B) SADP from inside $\{1\bar{1}02\}$ twin. (C) SADP across the twin-matrix interface.

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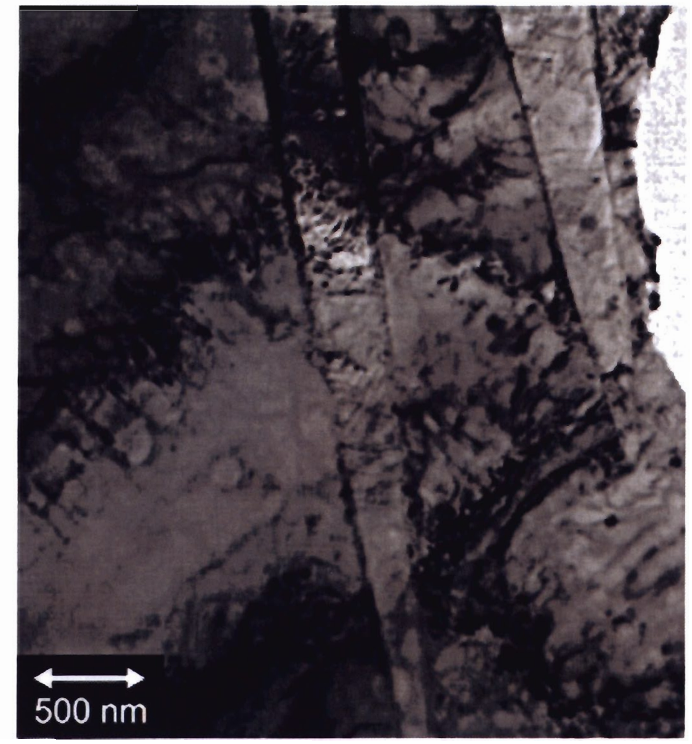

Figure 9: Two parallel $\{1\bar{1}02\}$ twins in Grade 7 Ti creep tested at 85%YS at room temperature.

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Continued From Page A summary of All Tensile and Creep tests in ENG-2 project

LOW TEMPERATURE TENSILE AND CREEP TESTS OF TITANIUM GRADE 7 AND GRADE 5

Tensile Test Results

Westmoreland Mechanical Testing and Research, Inc. conducted tensile tests of both Titanium Grade 7 and Grade 5 at four temperatures—25, 100, 150, and 250 °C [77, 212, 302, and 72 °F]. Moreover, an additional tensile test for Titanium Grade 7 was performed at 50 °C [122 °F]. The room temperature {25 °C [77 °F]} test was conducted in accordance with ASTM E-8 specification (ASTM International, 2007a). Elevated temperature tensile tests were performed in accordance with ASTM E-21 specification (ASTM International, 2007b). For each temperature, two specimens were tested. The tensile test results, including ultimate tensile strength, 0.2 percent yield stress, percentage elongation, percentage reduction in area, and modulus of elasticity for Titanium Grade 7 and Grade 5 are reported in Tables 1, and 2, respectively.

Creep Test Results

Creep deformation tests were conducted for several different scenarios based on previous studies, such as the investigation of fundamental mechanical properties of Alloy 22 Dunn, et al. (2005) performed. The general factors that affect creep deformation are the stress levels, temperature, loading time, and microstructure of the material. Therefore, a matrix of loading conditions covering the parameter combinations at the emplacement level was generated. The parameter ranges considered in the tests for samples of Titanium Grade 7 and Grade 5 are as follows:

- Creep tests were conducted at the stress levels of 115, 110, 105, 100, 85, 70, 55, and 40 percent of the material yield stress. Three stress levels higher than the material yield stress were included to detect potential fracture mechanisms due to creep deformation. The five stress levels lower than or equal to the material yield stress provided information about the stress threshold level for creep initiation, as well as data required to estimate long-term creep behavior.

- For the experimental tests, the temperature value of 150 °C [302 °F] was selected because, according to U.S. Department of Energy, this is the base drip shield temperature and is not expected to be exceeded during 98.5 percent of the first 10,000 years (Bechtel SAIC Company, LLC, 2004, Section 5.5). The temperature value of 250 °C [482 °F] was selected as an upper boundary for the experimental tests because the results derived by Manepally, et al. (2004) indicate that this temperature may be reached in the drip shield components if the drift collapses within several hundreds of years after the permanent closure. Moreover, creep tests were performed at room temperature—the commonly used value for this type of test—and at 100 °C [212 °F]—the temperature at which water undergoes a phase transition. Finally, a single test was conducted at 50 °C [108 °F] for 85 percent of the material yield strength for the Titanium Grade 7 as an intermediate value.

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Table 1. Tensile Properties of Titanium Grade 7

Material	Temperature	Tensile Strength MPa [ksi]	Yield Strength MPa [ksi]	Elongation Percent	Reduction in Area, Percent	Modulus, MPa [ksi]
HT# CN2775	25 °C [77 °F]	472.9 [68.6]	361.3 [52.4]	29	52	1.06×10^5 [1.54×10^4]
HT# CN2775	25 °C [77 °F]	475.0 [68.9]	363.4 [52.7]	29.0	47.0	1.10×10^5 [1.60×10^4]
HT# CN2775	50 °C [122 °F]	442.6 [64.2]	337.2 [48.9]	35.5	48.0	1.10×10^5 [1.59×10^4]
HT# CN2775	50 °C [122 °F]	437.1 [63.4]	334.4 [48.5]	41.5	49.5	1.12×10^5 [1.63×10^4]
HT# CN2775	100 °C [212 °F]	372.3 [54.0]	281.9 [40.9]	34.5	52.5	1.16×10^5 [1.68×10^4]
HT# CN2775	100 °C [212 °F]	366.1 [53.1]	277.2 [40.2]	37.0	54.5	1.10×10^5 [1.60×10^4]
HT# CN2775	150 °C [302 °F]	299.2 [43.4]	226.8 [32.9]	47	61	1.01×10^5 [1.47×10^4]
HT# CN2775	150 °C [302 °F]	288.9 [41.9]	211.7 [30.7]	35.5	58.5	1.04×10^5 [1.51×10^4]
HT# CN2775	200 °C [392 °F]	240.6 [34.9]	196.5 [28.5]	37.0	66.5	0.96×10^5 [1.4×10^4]
HT# CN2775	200 °C [392 °F]	240.6 [34.9]	183.4 [26.6]	15.5	67.5	0.92×10^5 [1.34×10^4]
HT# CN2775	250 °C [482 °F]	225.5 [32.7]	166.9 [24.2]	50.0	74.5	8.89×10^4 [1.29×10^4]
HT# CN2775	250 °C [482 °F]	233.7 [33.9]	177.9 [25.8]	55.5	68.5	8.96×10^4 [1.30×10^4]

- Most of the samples were subjected to short-term creep tests of 200 hours. Some of the samples with stress levels higher than 100 percent yield stress (i.e., 115, 110, and 105 percent yield stress), however, had a short creep life or broke when the load was applied.

The creep tests were performed in accordance with ASTM E–139–00 (ASTM International, 2007c).

The average yield stress of two test specimens conducted in the tensile tests was used as the 100 percent yield stress for the creep tests at a specific temperature. The creep test results at different temperatures, including stress levels, failure time, and total creep strain at the end of the tests, are summarized in Tables 3 and 4 for Titanium Grade 7 and Grade 5 alloys.

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Table 2. Tensile Properties of Titanium Grade 5

Material	Temperature °C [°F]	Tensile Strength MPa [ksi]	Yield Strength MPa [ksi]	Elongation Percent	Reduction in Area Percent	Modulus, MPa [ksi]
HT# R8453	25 °C [77 °F]	1108.7 [160.8]	1013.5 [147.0]	15.0	27.0	1.34×10^5 [1.94×10^4]
HT# R8453	25 °C [77 °F]	1101.8 [159.8]	1009.4 [146.4]	13.0	27.0	1.36×10^5 [1.97×10^4]
HT# R8453	50 °C [122 °F]	1075.6 [156.0]	966.6 [140.2]	18.5	31.0	1.27×10^5 [1.84×10^4]
HT# R8453	50 °C [122 °F]	1068.7 [155.0]	963.2 [139.7]	13.0	39.5	1.26×10^5 [1.83×10^4]
HT# R8453	100 °C [212 °F]	1019.7 [147.9]	892.2 [129.4]	13.0	31.0	1.30×10^5 [1.88×10^4]
HT# R8453	100 °C [212 °F]	1021.8 [148.2]	888.0 [128.8]	14.0	37.0	1.27×10^5 [1.84×10^4]
HT# R8453	150 °C [302 °F]	952.9 [138.2]	836.3 [121.3]	13.0	42.0	1.25×10^5 [1.82×10^4]
HT# R8453	150 °C [302 °F]	961.8 [139.5]	835.6 [121.2]	15.0	45.5	1.28×10^5 [1.85×10^4]
HT# R8453	200 °C [392 °F]	894.9 [129.8]	793.6 [115.1]	15.5	49.0	1.29×10^5 [1.87×10^4]
HT# R8453	200 °C [392 °F]	901.1 [130.7]	795.0 [115.3]	15.5	50.5	1.20×10^5 [1.74×10^4]
HT# R8453	250 °C [482 °F]	852.2 [123.6]	743.3 [107.8]	16.0	51.5	1.14×10^5 [1.65×10^4]
HT# R8453	250 °C [482 °F]	845.9 [122.7]	740.5 [107.4]	13.0	56.0	1.11×10^5 [1.62×10^4]

Table 3. Creep Properties of Titanium Grade 7 Alloy

Material	Temperature	Yield Strength, MPa [ksi]	Percent of Yield Strength	Stress Level, MPa [ksi]	Time Hours	Total Creep Percent
HT#CN2775	25 °C [77 °F]	362.3 [52.6]	115	417 [60.4]	8.7	28.2
HT#CN2775	25 °C [77 °F]	326.3 [52.6]	110	399 [57.8]	60.0	12.9
HT#CN2775	25 °C [77 °F]	362.3 [52.6]	105	380 [55.0]	200*	17.5
HT# CN2775	25 °C [77 °F]	362.3 [52.6]	100	362 [52.6]	200*	5.86
HT#CN2775	25 °C [77 °F]	362.3 [52.6]	85	308 [44.7]	200*	2.17
HT#CN2775	25 °C [77 °F]	362.3 [52.6]	70	254 [36.8]	200*	0.43
HT#CN2775	25 °C [77 °F]	362.3 [52.6]	55	199 [28.9]	200*	0.18
HT#CN2775	25 °C [77 °F]	362.3 [52.6]	40	145 [21.0]	200*	0.18

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Table 3. Creep Properties of Titanium Grade 7 Alloy (continued)

Material	Temperature	Yield Strength, MPa [ksi]	Percent of Yield Strength	Stress Level, MPa [ksi]	Time Hours	Total Creep Percent
HT#CN2775	50 °C [122 °F]	335.8 [48.7]	85	285 [41.4]	200*	3.36
HT#CN2775	100 °C [212 °F]	279.6 [40.6]	115	322 [46.6]	3.3	32.9
HT#CN2775	100 °C [212 °F]	279.6 [40.6]	110	308 [44.6]	16.7	42.2
HT#CN2775	100 °C [212 °F]	279.6 [40.6]	105	294 [42.6]	62.0	41.8
HT#CN2775	100 °C [212 °F]	279.6 [40.6]	100	280 [40.6]	83.8	35.3
HT#CN2775	100 °C [212 °F]	279.6 [40.6]	85	238 [34.5]	200*	3.02
HT#CN2775	100 °C [212 °F]	279.6 [40.6]	70	196 [28.4]	200*	1.29
HT#CN2775	100 °C [212 °F]	279.6 [40.6]	55	154 [22.3]	200*	0.26
HT#CN2775	100 °C [212 °F]	279.6 [40.6]	40	112 [16.2]	200*	0.11
HT#CN2775	150 °C [302 °F]	219.3 [31.8]	115	252 [36.6]	1.8	16.5
HT#CN2775	150 °C [302 °F]	219.3 [31.8]	110	241 [35.0]	200*	1
HT#CN2775	150 °C [302 °F]	219.3 [31.8]	105	230 [33.4]	10.0	14
HT#CN2775	150 °C [302 °F]	219.3 [31.8]	100	219 [31.8]	200*	13.7
HT#CN2775	150 °C [302 °F]	219.3 [31.8]	85	186 [27.0]	200*	2.1
HT#CN2775	150 °C [302 °F]	219.3 [31.8]	70	154 [22.3]	200*	0.39
HT#CN2775	150 °C [302 °F]	219.3 [31.8]	55	121 [17.5]	200*	0.17
HT#CN2775	150 °C [302 °F]	219.3 [31.8]	40	88 [12.8]	200*	0.05
HT#R8453	250 °C [482 °F]	172.4 [25.0]	115	198 [28.8]	200*	3.78
HT#R8453	250 °C [482 °F]	172.4 [25.0]	110	190 [27.5]	200*	0.78
HT#R8453	250 °C [482 °F]	172.4 [25.0]	105	181 [26.3]	0.4	0.25
HT#R8453	250 °C [482 °F]	172.4 [25.0]	100	172 [25.0]	200*	4.8
HT#R8453	250 °C [482 °F]	172.4 [25.0]	85	147 [21.3]	0†	—
HT#R8453	250 °C [482 °F]	172.4 [25.0]	70	121 [17.5]	200*	0.45

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Table 3. Creep Properties of Titanium Grade 7 Alloy (continued)

Material	Temperature	Yield Strength, MPa [ksi]	Percent of Yield Strength	Stress Level, MPa [ksi]	Time Hours	Total Creep Percent
HT#R8453	250 °C [482 °F]	172.4 [25.0]	55	94.8 [13.8]	200*	0.17
HT#R8453	250 °C [482 °F]	172.4 [25.0]	40	68.9 [10.0]	200*	0.03

*Discontinued
†Machine malfunction

Table 4. Creep Properties of Titanium Grade 5 Alloy

Material	Temperature	Yield Strength, MPa [ksi]	Percent of Yield Strength	Stress Level, MPa [ksi]	Time Hours	Total Creep Percent
HT#R8453	25 °C [77 °F]	1011.5 [146.7]	115	1163 [168.7]	0.1*	—
HT# R8453	25 °C [77 °F]	1011.5 [146.7]	110	1113 [161.4]	0.1*	—
HT# R8453	25 °C [77 °F]	1011.5 [146.7]	105	1062 [154.0]	4.4	2.31
HT# R8453	25 °C [77 °F]	1011.5 [146.7]	100	1012 [146.7]	200†	5.36
HT# R8453	25 °C [77 °F]	1011.5 [146.7]	85	860 [124.7]	200†	0.04
HT# R8453	25 °C [77 °F]	1011.5 [146.7]	70	708 [102.7]	200†	0.03
HT# R8453	25 °C [77 °F]	1011.5 [146.7]	55	556 [80.7]	200†	0.05
HT# R8453	25 °C [77 °F]	1011.5 [146.7]	40	405 [58.7]	200†	0.23
HT# R8453	100 °C [212 °F]	890.1 [129.1]	115	1024 [148.5]	0.1*	—
HT# R8453	100 °C [212 °F]	890.1 [129.1]	110	979 [142.0]	0.5	1.75
HT# R8453	100 °C [212 °F]	890.1 [129.1]	105	935 [135.6]	200†	2.2
HT# R8453	100 °C [212 °F]	890.1 [129.1]	100	890 [129.1]	200†	0.55
HT# R8453	100 °C [212 °F]	890.1 [129.1]	85	757 [109.7]	200†	0.06
HT# R8453	100 °C [212 °F]	890.1 [129.1]	70	623 [90.4]	200†	0.03
HT# R8453	100 °C [212 °F]	890.1 [129.1]	55	490 [71.0]	200†	0.04
HT# R8453	100 °C [212 °F]	890.1 [129.1]	40	356 [51.6]	200†	0.02
HT# R8453	150 °C [302 °F]	836.3 [121.3]	115	962 [139.5]	0.1*	—

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Table 4. Creep Properties of Titanium Grade 5 Alloy (continued)

Material	Temperature	Yield Strength, MPa [ksi]	Percent of Yield Strength	Stress Level, MPa [ksi]	Time Hours	Total Creep Percent
HT# R8453	150 °C [302 °F]	836.3 [121.3]	110	920 [133.4]	0.2	1.34
HT# R8453	150 °C [302 °F]	836.3 [121.3]	105	878 [127.4]	0.1	—
HT# R8453	150 °C [302 °F]	836.3 [121.3]	100	836 [121.3]	200†	1.38
HT# R8453	150 °C [302 °F]	836.3 [121.3]	85	711 [103.1]	200†	0.08
HT# R8453	150 °C [302 °F]	836.3 [121.3]	70	585 [84.9]	200†	0.02
HT# R8453	150 °C [302 °F]	836.3 [121.3]	55	460 [66.7]	200†	0.04
HT# R8453	150 °C [302 °F]	836.3 [121.3]	40	335 [48.5]	200†	0.03
HT# R8453	250 °C [482 °F]	741.9 [107.6]	115	853 [123.7]	0.1*	—
HT# R8453	250 °C [482 °F]	741.9 [107.6]	110	816 [118.4]	200†	0.18
HT# R8453	250 °C [482 °F]	741.9 [107.6]	105	779 [113.0]	200†	0.26
HT# R8453	250 °C [482 °F]	741.9 [107.6]	100	742 [107.6]	200†	0.14
HT# R8453	250 °C [482 °F]	741.9 [107.6]	85	631 [91.5]	200†	0.05
HT# R8453	250 °C [482 °F]	741.9 [107.6]	70	519 [75.3]	200†	0.05
HT# R8453	250 °C [482 °F]	741.9 [107.6]	55	408 [59.2]	200†	0.4
HT# R8453	250 °C [482 °F]	741.9 [107.6]	40	297 [43.0]	200†	0.26

*Sample broke when load was applied
†Discontinued

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June 30, 2008
Contract No. NRC–02–07–006
Account No. 20.14002.01.191
WM–00011

ATTN: Document Control Desk
U.S. Nuclear Regulatory Commission
Mrs. Sheena Whaley
Division of High-Level Waste Repository Safety
11555 Rockville Pike
Washington, DC 20852

Subject: Transmittal of Intermediate Milestone 20.14002.01.191.830, Low Temperature Creep of Titanium Alloys—Letter Report

Dear Mrs. Whaley:

This letter transmits the intermediate milestone An Investigation of the Low Temperature Creep Deformation Behavior of Titanium Grade 7 and Grade 5 Alloys—Progress Report authored by A. Bhattacharyya, S. Ankem, P.G. Oberson, R.V. Kazban, K.T. Chiang, L.F. Ibarra, and A.H. Chowdhury.

This study focuses on the creep deformation behavior of Titanium Grade 7 and Grade 5 at temperatures ranging from 25 to 250 °C [77 to 482 °F] and at stress levels ranging from 40 to 100 percent yield stress. In particular, the creep behavior of both titanium alloys is evaluated for a range of stress levels at the constant temperature of 150 °C [302 °F], and for a range of temperatures at the constant stress level of 85 percent yield stress of the corresponding material. This investigation includes: (i) analysis of the creep response, including determination of the activation energy for creep deformation, (ii) characterization of the as-received plate microstructures using optical and scanning electron microscopy, and (iii) transmission electron microscopy of the creep specimens.

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Mrs. Sheena Whaley
June 30, 2008
Page 2

If you have any questions regarding this milestone, please contact R.V. Kazban at (210) 522-6651 or me at (210) 522-5151.

Sincerely yours,

Asadul H. Chowdhury, Manager
Mining, Geotechnical, and Facility Engineering

AHC:ar

cc:

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Maria

From: Asadul Chowdhury [achowdhury@cnwra.swri.edu]
Sent: Wednesday, August 06, 2008 11:42 AM
To: Lucy Gutierrez; Maria Padilla
Cc: Asadul Chowdhury; Budhi Sagar; Luis Ibarra; Roman Kazban; Sitakanta Mohanty; Wesley Patrick
Subject: FW: CNWRA 2008 0085: Transmittal of Intermediate Milestone 20.14002.01.191.830, Low Temperature Creep of Titanium Alloys

Lucy:

NRC has accepted the subject deliverable without any comments.

Please revise the CCL accordingly.

Asad

-----Original Message-----
From: Mysore Nataraja [mailto:Mysore.Nataraja@nrc.gov]
Sent: Wednesday, August 06, 2008 10:04 AM
To: RidsNmssLASKim Resource
Cc: Sheena Whaley; Tae Ahn; Greg Oberson; Asadul Chowdhury; Rolonda Jackson
Subject: RE: CNWRA 2008 0085: Transmittal of Intermediate Milestone 20.14002.01.191.830, Low Temperature Creep of Titanium Alloys

We have reviewed the Subject Report: CNWRA 2008 0085: Transmittal of Intermediate Milestone 20.14002.01.191.830, Low Temperature Creep of Titanium Alloys(revised by the Center in response to staff comments). We find it acceptable. The subject ticket may be closed. If you have any questions, please call me.

Raj

-----Original Message-----
From: RidsNmssLASKim Resource
Sent: Friday, August 01, 2008 5:35 PM
To: Mysore Nataraja
Subject: FW: CNWRA 2008 0085: Transmittal of Intermediate Milestone 20.14002.01.191.830, Low Temperature Creep of Titanium Alloys

Raj,

I moved its due date to August 8. Please let me know if you have any questions.
Sunny

-----Original Message-----
From: RidsNmssLASKim Resource
Sent: Monday, July 07, 2008 12:53 PM
To: King Stablein; James Rubenstone; Jack Guttmann; Sheena Whaley; Eugene Peters; Mysore Nataraja; Tae Ahn; Hipolito Gonzalez; Greg Oberson; Deborah DeMarco; David Dancer
Subject: CNWRA 2008 0085: Transmittal of Intermediate Milestone 20.14002.01.191.830, Low Temperature Creep of Titanium Alloys

The subject document can be found in ADAMS by searching Accession Number ML081830101.

Document ticketed to M. Nataraja - CNWRA 2008 0085

Title: Transmittal of Intermediate Milestone 20.14002.01.191.830, Low Temperature Creep of Titanium Alloys - Letter Report.

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