

Gas Turbine Blade Superalloy Material Property Handbook



WARNING:
Please read the License Agreement
on the back cover before removing
the Wrapping Material.

Effective December 6, 2006, this report has been made publicly available in accordance with Section 734.3(b)(3) and published in accordance with Section 734.7 of the U.S. Export Administration Regulations. As a result of this publication, this report is subject to only copyright protection and does not require any license agreement from EPRI. This notice supersedes the export control restrictions and any proprietary licensed material notices embedded in the document prior to publication.

Technical Report

Gas Turbine Blade Superalloy Material Property Handbook

1004652

Topical Report, July 2001

EPRI Project Manager
R. Viswanathan

DISCLAIMER OF WARRANTIES AND LIMITATION OF LIABILITIES

THIS DOCUMENT WAS PREPARED BY THE ORGANIZATION(S) NAMED BELOW AS AN ACCOUNT OF WORK SPONSORED OR COSPONSORED BY THE ELECTRIC POWER RESEARCH INSTITUTE, INC. (EPRI). NEITHER EPRI, ANY MEMBER OF EPRI, ANY COSPONSOR, THE ORGANIZATION(S) BELOW, NOR ANY PERSON ACTING ON BEHALF OF ANY OF THEM:

(A) MAKES ANY WARRANTY OR REPRESENTATION WHATSOEVER, EXPRESS OR IMPLIED, (I) WITH RESPECT TO THE USE OF ANY INFORMATION, APPARATUS, METHOD, PROCESS, OR SIMILAR ITEM DISCLOSED IN THIS DOCUMENT, INCLUDING MERCHANTABILITY AND FITNESS FOR A PARTICULAR PURPOSE, OR (II) THAT SUCH USE DOES NOT INFRINGE ON OR INTERFERE WITH PRIVATELY OWNED RIGHTS, INCLUDING ANY PARTY'S INTELLECTUAL PROPERTY, OR (III) THAT THIS DOCUMENT IS SUITABLE TO ANY PARTICULAR USER'S CIRCUMSTANCE; OR

(B) ASSUMES RESPONSIBILITY FOR ANY DAMAGES OR OTHER LIABILITY WHATSOEVER (INCLUDING ANY CONSEQUENTIAL DAMAGES, EVEN IF EPRI OR ANY EPRI REPRESENTATIVE HAS BEEN ADVISED OF THE POSSIBILITY OF SUCH DAMAGES) RESULTING FROM YOUR SELECTION OR USE OF THIS DOCUMENT OR ANY INFORMATION, APPARATUS, METHOD, PROCESS, OR SIMILAR ITEM DISCLOSED IN THIS DOCUMENT.

ORGANIZATION(S) THAT PREPARED THIS DOCUMENT

Southwest Research Institute

ORDERING INFORMATION

Requests for copies of this report should be directed to EPRI Customer Fulfillment, 1355 Willow Way, Suite 278, Concord, CA 94520, (800) 313-3774, press 2.

Electric Power Research Institute and EPRI are registered service marks of the Electric Power Research Institute, Inc. EPRI. ELECTRIFY THE WORLD is a service mark of the Electric Power Research Institute, Inc.

Copyright © 2001 Electric Power Research Institute, Inc. All rights reserved.

CITATIONS

This report was prepared by

Southwest Research Institute
6220 Culebra Road
San Antonio, Texas 78238

Principal Investigators
J. H. Feiger
V. P. Swaminathan

This report describes research sponsored by EPRI.

The report is a corporate document that should be cited in the literature in the following manner:

Gas Turbine Blade Superalloy Material Property Handbook, EPRI, Palo Alto, CA: 2001.
1004652.

REPORT SUMMARY

Published material property data on superalloy bucket (blade) materials used in land-based combustion turbines is meager and widely scattered in literature. This handbook provides a comprehensive resource of all available material property data for superalloys used in combustion turbine buckets. Such data are critical for use in remaining life assessment calculations, failure analysis, comparison of various alloys, and alloy selection. The material data presented in this handbook were developed from experimental alloys and actual turbine components.

Background

Under EPRI direction, Southwest Research Institute (SwRI™) created a material property database for superalloys used in rotating blades of industrial gas turbines. SwRI consolidated the material property data from many sources in a computerized relational database. In the early 1990s, dBase IV software was widely used for this purpose, and the subject database was developed using this software. However, due to rapid changes in software architecture and variability in computer operating systems, users found it difficult to take full advantage of the database. EPRI initiated this project to compile and update in a single handbook all available data for the nickel-base superalloys used in hot section blade applications in land-based gas turbines.

Objective

To provide combustion turbine (CT) owners with a ready reference handbook of material property data on superalloy bucket materials.

Approach

Included in the handbook are tables of raw data as well as several plots and tables from the original database references. Users may scan plots using a digitizer for further processing and comparative plotting. For each subject alloy, the handbook describes the alloy property represented, and where available, lists codes for heat treatment, chemical composition, refurbishment identification, and coating identification. The handbook provides separate tabs for original database references, chemical composition, and heat treatment details. Rather than relying on a computerized database, EPRI decided to present all available data in a loose-leaf notebook format for ease of access, use, and update as new data becomes available.

Results

The superalloy material property handbook provides data for the following alloys—Inconel 700, Inconel 939, Inconel X-750, Inconel 738, Inconel 738 LC, Inconel 792, MAR-M002, MAR-

M200, MAR-M247, Nimonic 115, Rene 80, Udimet 500, Udimet 520, Udimet 700, Udimet 710, Udimet 720, GTD 111 DS, and GTD 111 EA. The handbook cites physical properties such as density, dynamic and static moduli of elasticity, and coefficient of thermal expansion for each alloy. It also presents mechanical properties—including tensile, stress rupture, creep, and thermal-mechanical fatigue properties—as well as high-cycle fatigue, low-cycle fatigue, and impact strength in graphical and tabular format. Limited data that became available following in-service degradation of some of the base alloys are included in the handbook. Finally, where possible, the handbook lists property variation as a function of temperature.

EPRI Perspective

CT owners must make informed decisions about reuse, repair, or replacement of hot section components. Most often, original equipment manufacturer recommendations are conservative, allowing valuable, unused remaining life of the components to go untapped due to premature replacement. CT operators who wish to make remaining life assessments require material property data. This handbook serves as a one-step ready reference for CT bucket material properties and is expected to prove valuable in remaining life assessment calculations, alloy comparisons, and materials selection. The ring binder format permits easy addition of new data, as they become available. EPRI hopes that in future years, the handbook will be expanded to include nozzle, combustor, transition piece, and other hot section components.

Keywords

Combustion turbines

Blades

Alloys

Material properties

DISCUSSION OF HANDBOOK CONTENTS

In the current competitive and deregulated environment, turbine users are forced to explore ways of reducing the cost of maintenance and operation of their engines. They need to make informed decisions about reuse, repair, or replacement of the hot section components. Most often, the recommendations of the original equipment manufacturers are conservative. Very valuable and unused remaining life of the components may go untapped when the components are prematurely replaced. The gas turbine operators with these alloy buckets have a need for the material data to conduct condition and remaining life assessment of their buckets and to make independent decisions about their gas turbine components.

Southwest Research Institute (SwRI™) created a material property database for EPRI under project RP2775-6 for superalloys used in rotating blades of industrial gas turbines. Various material properties were gathered from many sources and consolidated in a computerized relational database. In the early 1990's dBase IV software was widely used for this purpose and the subject database was created using this software. However, due to rapid changes in the software architecture and variability in the computer operating systems, users found it difficult to take full advantage of this database. Thus, EPRI initiated this project to compile and update all the available data for the nickel base superalloys used in hot section blading application in land-based gas turbines. Instead of computer software, it was decided to present all of the available data in a format similar to that used in the Aerospace Structural Metals Handbook for ease of access and use. Updating of this manual with additional data will be more practical as new data becomes available.

The database includes physical properties such as density, dynamic and static moduli of elasticity, and coefficient of thermal expansion. Mechanical properties such as tensile properties, stress rupture properties, creep properties, impact strength, high-cycle fatigue, low-cycle fatigue and thermal mechanical fatigue properties are also presented in graphical and tabular format. Limited data was also available after in-service degradation of some of the base alloys. Property variation as a function of temperature is presented when available. This database was intended to provide a good source of data that can be used in remaining life assessment calculations, comparison of various alloys, and material selection. The material data presented in this handbook were developed both from experimental alloys and actual turbine components.

The following alloys are included in this handbook:

Inconel 700, Inconel 939, Inconel X750, Inconel 738, Inconel 738 LC, Inconel 792, MAR-M002, MAR-M200, MAR-M247, Nimonic 115, Rene 80, Udimet 500, Udimet 520, Udimet 700, Udimet 710, Udimet 720, GTD 111 DS, and GTD 111 EA.

The data for this handbook was collected, collated and plotted to generate hard copy plots similar to those published in the Aerospace Structural Metals Handbook. Tables of raw data gathered whenever available are also printed and included in the manual. Several plots and tables were directly scanned in from the original references and a new page was created to fit the format of this handbook. If the user wishes, the plots can be scanned using a digitizer for further processing and comparative plotting. Each page includes alloy identification, the property represented, and whenever available, codes for heat treatment, chemical composition, refurbishment identification, and coating identification. The units on the axes are shown in both the English and SI units wherever possible. If the plots are directly scanned in from the source, the units are the same as in the references since no further modifications were made to these plots. At the end of the handbook, separate tabs are provided for original references, chemical composition, and heat treatment details.

CONTENTS

1 INCONEL 700.....	1-1
2 INCONEL 939.....	2-1
3 INCONEL X750	3-1
4 INCONEL 738.....	4-1
5 INCONEL 738 LC	5-1
6 INCONEL 792.....	6-1
7 MAR-M002.....	7-1
8 MAR-M200.....	8-1
9 MAR-M247.....	9-1
10 NIMONIC 115	10-1
11 RENE 80	11-1
12 UDIMET 500	12-1
13 UDIMET 520	13-1
14 UDIMET 700	14-1
15 UDIMET 710	15-1
16 UDIMET 720	16-1
17 GTD 111 DS	17-1

18 GTD 111 EA	18-1
19 SOURCE REFERENCES	19-1
20 CHEMICAL COMPOSITION.....	20-1
Chemical Composition IDs	20-3
21 HEAT TREATMENT	21-1
Heat Treatment IDs	21-1

LIST OF FIGURES

Figure 1-1 Tensile Strength as a Function of Temperature for Inconel 700.	1-3
Figure 1-2 Tensile Elongation as a Function of Temperature for Inconel 700.	1-4
Figure 1-3 Larson-Miller Plot for Inconel 700.	1-5
Figure 2-1 Tensile Strengths for Inconel 939 at Room Temperature.	2-3
Figure 2-2 Tensile Elongation at Room Temperature for Inconel 939.	2-4
Figure 2-3 Reduction in Area (Tensile) at Room Temperature for Inconel 939.	2-5
Figure 2-4 Tensile Properties of the Alloy as a Function of Temperature.	2-6
Figure 2-5 Room Temperature Impact Properties After Soaking at Elevated Temperatures.	2-7
Figure 2-6 Fatigue Crack Growth at $R = 0.1$ and 0.9 (Room Temperature).	2-8
Figure 2-7 Elevated Temperature Fatigue Crack Growth at $R = 0.3$	2-9
Figure 2-8 Elevated Temperature Fatigue Crack Growth at $R = 0.1$ and 0.3 (Vacuum).	2-10
Figure 2-9 The Stress Rupture Properties at 850°C ; Standard Heat Treatment.	2-11
Figure 2-10 The Stress Rupture Properties with Two-Stage Heat Treatment.	2-12
Figure 2-11 Larson-Miller Plot for Inconel 939.	2-13
Figure 2-12 Stress to Rupture vs. Time at Elevated Temperatures.	2-14
Figure 2-13 Strain to 1% Creep as a Function of Stress.	2-15
Figure 2-14 High Cycle Fatigue Properties at 750°C and 850°C	2-16
Figure 2-15 High Cycle Fatigue Properties at 600°C . Results from INCO Europe.	2-17
Figure 2-16 Low Cycle Fatigue Properties of IN939 with Results for IN738LC for Comparison.	2-18
Figure 3-1 Specific Heat as a Function of Temperature for Inconel X750.	3-3
Figure 3-2 Thermal Conductivity as a Function of Temperature for Inconel X750.	3-4
Figure 3-3 Thermal Expansion as a Function of Temperature.	3-5
Figure 3-4 Yield and Tensile Strengths vs. Temperature for Inconel X750.	3-6
Figure 3-5 Tensile Elongation vs. Temperature.	3-7
Figure 3-6 Dynamic Modulus as a Function of Temperature.	3-8
Figure 3-7 100 hr Rupture Strength as a Function of Temperature.	3-9
Figure 3-8 Fatigue Crack Growth Behavior at 650°C and 540°C Under Air and Vacuum Conditions.	3-10
Figure 4-1 Specific Heat as a Function of Temperature.	4-3
Figure 4-2 Thermal Conductivity as a Function of Temperature.	4-4

Figure 4-3 Coefficient of Thermal Expansion as a Function of End Temperature.	4-5
Figure 4-4 Yield and Tensile Strengths as a Function of Temperature.	4-6
Figure 4-5 Tensile Elongation as a Function of Temperature.	4-7
Figure 4-6 Yield and Tensile Strengths as a Function of Temperature.	4-8
Figure 4-7 Dynamic Modulus as a Function of Temperature.	4-9
Figure 4-8 Charpy Impact Energy as a Function of Aging Time.....	4-10
Figure 4-9 Charpy Impact Energy as a Function of Aging Temperature.	4-11
Figure 4-10 Fatigue Crack Growth Behavior at Room Temperature Under Vacuum Conditions. (Low R).	4-12
Figure 4-11 Fatigue Crack Growth Behavior at R = 0.1 and 0.85 (Room Temperature, Air).	4-13
Figure 4-12 Fatigue Crack Growth Behavior at 1562°F.	4-14
Figure 4-13 Fatigue Crack Growth Rate as a Function of ΔK in IN-738 at 927°C in Air and in Vacuum.	4-15
Figure 4-14 Comparison of Fatigue Crack Growth Rate for Three Alloys.	4-16
Figure 4-15 Fatigue Crack Growth Rate in Superalloys at 927°C in Vacuum.	4-17
Figure 4-16 100 hr Rupture Strength as a Function of Temperature.	4-18
Figure 4-17 1000 hr Rupture Strength as a Function of Temperature.....	4-19
Figure 4-18 Larson-Miller Plot for Inconel 738.....	4-20
Figure 4-19 Stress vs. Rupture Time at Three Elevated Temperatures.	4-21
Figure 4-20 Stress vs. Strain-Rate at Three Temperatures Including Repeat Runs.....	4-22
Figure 4-21 Multiple Relaxation Runs at 850°C Showing Transient Effects for Low Stresses.	4-23
Figure 4-22 Creep Data at 850°C for Various Initial Thermal Treatments.....	4-24
Figure 4-23 IN-738 VPS Coated Creep Test Results at 900°C/124 MPa.....	4-25
Figure 4-24 IN-738 VPS Coated Creep Test Results at 982°C/69 MPa.....	4-26
Figure 4-25 Strain Rate vs. Stress for IN738LC at 850°C in Tests Containing (i) pp and pc and (ii) pp and cp.	4-27
Figure 4-26 Influence of Environment on Creep Crack Growth Rate in IN-738 at 927°C and Comparison with Fatigue Crack Growth Rate Converted to Time Domain.	4-28
Figure 4-27 Total Strain Range vs. Life to Failure.	4-29
Figure 4-28 Total Strain Range vs. Life to Crack Initiation.....	4-30
Figure 4-29 Elastic Strain Range vs. Life to Failure.....	4-31
Figure 4-30 Elastic Strain Range vs. Life to Crack Initiation.	4-32
Figure 4-31 Inelastic Strain Range vs. Life to Failure.	4-33
Figure 4-32 Inelastic Strain Range vs. Life to Crack Initiation.....	4-34
Figure 4-33 Typical Test Results and Partitioned Strain Ranges.....	4-35
Figure 4-34 (HTLCF) Results of IN 738 in the Standard and the Exposed Conditions, Inelastic Strain Range ($\Delta\epsilon$ in %) vs. Number of Cycles to Failure (N_f).....	4-36

Figure 4-35 (HTLCF) Results of IN 738 at 1123 K, for the Two Types of Specimens Tested Under Continuous Strain Cycling and Cycling with Tensile Hold Times, Inelastic Strain range ($\Delta\epsilon$ in %) vs. Number of Cycles to Failure (N_f).	4-37
Figure 4-36 Inelastic Strain Range vs. Cycles to Failure for Cast IN 738 LC (a) pp components only; 750°C and 850°C, (b) pp and pc components 850°C (c) pp and cp components; 850°C.	4-38
Figure 4-37 Inelastic Strain Range vs. Cycles to Failure for Cast IN 738 at 870°C.	4-39
Figure 4-38 Inelastic Strain Range vs. Cycles to Failure for Cast IN 738 at 870°C, pp and cp components.	4-40
Figure 4-39 Inelastic Strain Range vs. Cycles to Failure for Cast IN 738 at 870°C, pp and pc components.	4-41
Figure 4-40 Low Cycle Fatigue at 1600°F with Three Hold Times Investigated (Total Strain Range).	4-42
Figure 5-1 Tensile Strengths as a Function of Temperature.	5-3
Figure 5-2 Tensile Elongation as a Function of Temperature.	5-4
Figure 5-3 Reduction in Area (Tensile) as a Function of Temperature.	5-5
Figure 5-4 Impact Resistance of IN-738 at Room Temperature and 900°C as a Function of Aging Time at 950°C.	5-6
Figure 5-5 Loss of High Temperature Impact Resistance Correlation in Terms of a Time-Temperature Parameter Analogous to that of Larson-Miller.	5-7
Figure 5-6 Fatigue Crack Growth Behavior at $R = 0$ (Room Temperature, Lab Air Conditions).	5-8
Figure 5-7 Fatigue Crack Growth Behavior at 1382°F at $R = 0.1$ (Lab Air).	5-9
Figure 5-8 Fatigue Crack Growth Behavior at 1562°F for $R = 0.25$ and 0.3 (Lab Air).	5-10
Figure 5-9 Crack Growth for Nimocast 738 LC and 739 at Cyclic Frequencies Between 60 and 100 Hz and $R = 0.1$; δ is Crack Tip Opening Displacement.	5-11
Figure 5-10 Influence of Environment on Fatigue Crack Growth of Nimocast 738 LC and 739 at 850°C and Cyclic Frequencies Between 10 and 100 Hz and $R = 0.1$	5-12
Figure 5-11 Larson-Miller Plot for Inconel 738 LC.	5-13
Figure 5-12 Larson-Miller Plot at Two Test Temperatures (Light Oil Conditions).	5-14
Figure 5-13 Stress vs. Rupture Time at Two Elevated Temperatures (Light Oil Conditions).	5-15
Figure 5-14 Larson-Miller Plot ($P = T (20 + \log t_r) \times 10^{-3}$, where T is in K and t_r in hr) of Cast and Hipped IN-738LC Turbine Blades Showing Unexposed and Service Exposed Creep-Rupture Properties.	5-16
Figure 5-15 Dependence of the Time to Rupture on the Minimum Creep Rate, for IN-738LC (Monkman-Grant Relationship).	5-17
Figure 5-16 Dependence of Primary Plus Secondary, Creep Life on the Minimum Creep Rate for Cast IN-738LC.	5-18
Figure 5-17 Time to Rupture Dependence on the Tertiary Life for Cast IN-738LC.	5-19
Figure 5-18 Low Cycle Fatigue at 1699°F (Total Strain Range).	5-20
Figure 5-19 Low Cycle Fatigue Behavior at Two Elevated Temperatures (Total Strain Range).	5-21

Figure 5-20 Low Cycle Initiation and Failure at Four Elevated Temperatures.....	5-22
Figure 5-21 Strain-Amplitude-Life Relations for IN738LC at 650°C as an Effect of Casting Process.	5-23
Figure 5-22 Strain-Amplitude-Life Relations for IN738LC at 650°C as an Effect of Casting Process.	5-24
Figure 5-23 Stress vs. Reversals of IN738LC at 650°C (1202°F) as an Effect of Casting Process.	5-25
Figure 5-24 Strain-Amplitude-Life Relations for IN738LC at 850°C as an Effect of Casting Process.	5-26
Figure 5-25 Stress vs. Reversals of IN738LC at 850°C (1532°F) as an Effect of Casting Process.	5-27
Figure 5-26 Strain-Amplitude-Life Relations for IN738LC at 850°C as an Effect of Casting Process.	5-28
Figure 5-27 Low Cycle Fatigue Behavior for Inconel 738 LC.....	5-29
Figure 5-28 Thermal-Mechanical Fatigue Behavior of Inconel 738 LC.	5-30
Figure 6-1 Tensile Strengths as a Function of Temperature.....	6-3
Figure 6-2 Tensile Elongation as a Function of Temperature.	6-4
Figure 6-3 Fatigue Crack Growth Rate as a Function of ΔK in IN-792 at 927°C in Air and in Vacuum.	6-5
Figure 6-4 Comparison of Fatigue Crack Growth Rate in Terms for Three Alloys.....	6-6
Figure 6-5 Fatigue Crack Growth Rate in Superalloys at 927°C in Vacuum.	6-7
Figure 6-6 100 hr Rupture Strength as a Function of Temperature.	6-8
Figure 6-7 1000 hr Rupture Strength as a Function of Temperature.	6-9
Figure 6-8 Larson-Miller Plot for Inconel 792.....	6-10
Figure 6-9 Influence of Environment on Creep Crack Growth Rate in IN-792 at 927°C and Comparison with Fatigue Crack Growth Rate (Fatigue Crack Growth Rate Given on a Time Basis).	6-11
Figure 7-1 Influence of R on Crack Growth in Directionally Solidified and Single Crystal Materials at 950°C and a Frequency of 0.1 Hz.	7-3
Figure 7-2 Influence of Grain Structure and R on Crack Growth at 950°C and a Frequency of 20 Hz.	7-4
Figure 7-3 Effect of Frequency on Crack Growth in Directionally Solidified Alloy at 950°C and R = 0.1.....	7-5
Figure 7-4 Effect of Temperature on Crack Growth/Cycle in Directionally Solidified and Single Crystal Materials at a Frequency of 0.1 Hz and R = 0.1.	7-6
Figure 7-5 Effect of Prior Creep Damage on Crack Growth in Directionally Solidified and Single Crystal Material at 950°C at a Frequency of 20 Hz and R = 0.7.	7-7
Figure 7-6 Effect of R on Crack Growth Per Cycle in the Threshold Region at 950°C.	7-8
Figure 7-7 Effect of Prior Creep Damage on Crack Growth Per Cycle at 950°C for R = 0.9.	7-9
Figure 7-8 Crack Growth for MAR-M002 at Cyclic Frequency of 0.25 Hz and R = 0.1.....	7-10

Figure 7-9 Influence of R on Crack Growth Rate for MAR-M002 at 950°C and 20 Hz, da/dN versus ΔK	7-11
Figure 7-10 Influence of R on Crack Growth Rate for MAR-M002 at 950°C and 20 Hz, da/dt versus K_{max}	7-12
Figure 7-11 Influence of Grain Structure and Temperature on Creep Crack Growth Rate.....	7-13
Figure 7-12 Effect of Prior Creep Damage on Creep Crack Growth Rate at 950°C in Directionally Solidified Material.....	7-14
Figure 7-13 Accumulation of Creep Strain at 950°C and a Stress of 256 MPa in Directionally Solidified and Single Crystal Material.	7-15
Figure 8-1 Comparison of Crack Growth Rates of MAR-M200 Single Crystals at 25 and 982°C. (ΔK_{eff} is a Function of Three Nodes of Cracking.)	8-3
Figure 8-2 Fatigue Crack Growth Rate Results of MAR-M200 Single Crystals Under Uniaxially Applied Cyclic Loading at 982°C. (ΔK_{eff} is a Function of Three Nodes of Cracking.).....	8-4
Figure 8-3 Comparison of Theoretical and Experimental Thermal Fatigue Lives of MAR M200 and MAR M200DS Double Wedges (0.6 and 1.0 mm Radius Edge, Heating and Cooling in Fluidized Beds at 320 and 1090°C).....	8-5
Figure 9-1 Prediction of Isothermal Fatigue Data at 500°C.....	9-3
Figure 9-2 Prediction of 871°C Isothermal Fatigue Test Results.	9-4
Figure 9-3 Prediction of Out-of-Phase TMF (500°C–871°C) Test Results.	9-5
Figure 9-4 Prediction of In-Phase TMF (500°C–871°C) Test Results.	9-6
Figure 9-5 Prediction of Diamond Shape (Nonproportional) Strain-Temperature History.....	9-7
Figure 9-6 Mechanical Strain Range Versus Life for Out-of-Phase and In-Phase TMF Experiments, $\dot{\epsilon} = 5 \times 10^{-5} \text{ s}^{-1}$	9-8
Figure 10-1 Thermal Conductivity as a Function of Temperature.	10-3
Figure 10-2 Coefficient of Thermal Expansion as a Function of Temperature.	10-4
Figure 10-3 Tensile Strengths as a Function of Temperature.....	10-5
Figure 10-4 Tensile Elongation as a Function of Temperature.	10-6
Figure 10-5 Dynamic Modulus as a Function of Temperature.	10-7
Figure 10-6 100 hr Rupture Strength as a Function of Temperature.	10-8
Figure 10-7 1000 hr Rupture Strength as a Function of Temperature.....	10-9
Figure 10-8 Partial Larson-Miller Plot for Nimonic 115.	10-10
Figure 11-1 Temperature Dependence of Yield Strength (σ_y) of Unused and Used Coatings and Substrates in Comparison with Tensile Test Data of Unused Substrate.....	11-3
Figure 11-2 Temperature Dependence of Ductility (ϵ_f) Obtained from SP Tests on Unused and Used Coatings and Substrates, Compared with Tensile Test Data of Unused Substrate.....	11-4
Figure 11-3 Temperature Dependence of Strength and Ductility of the Rene 80 Alloy Specimens.	11-5
Figure 11-4 Fatigue Crack Growth Rate as a Function of ΔK in Rene 80 at 927°C in Air and in Vacuum.	11-6

Figure 11-5 Comparison of Fatigue Crack Growth Rate for Three Alloys.	11-7
Figure 11-6 Fatigue Crack Growth Rate in Superalloys at 927°C in Vacuum.	11-8
Figure 11-7 Influence of Environment on Creep Crack Growth Rate in Rene 80 at 927°C and Comparison with Fatigue Crack Growth Rate. (Fatigue Crack Growth Rate Give on a Time Basis.)	11-9
Figure 11-8 A Larson Miller Plot Comparing the GTD111 Alloy Test Points with Rene 80 Data from the Literature and the GTD111 Larson Miller Curve Published by General Electric.	11-10
Figure 12-1 Thermal Conductivity as a Function of Temperature.	12-3
Figure 12-2 Coefficient of Thermal Expansion as a Function of Final Temperature.....	12-4
Figure 12-3 Tensile Strengths as a Function of Temperature.....	12-5
Figure 12-4 Tensile Elongation as a Function of Temperature.	12-6
Figure 12-5 Dynamic Modulus as a Function of Temperature.	12-7
Figure 12-6 100 hr Rupture Strength as a Function of Temperature.	12-8
Figure 12-7 1000 hr Rupture Strength as a Function of Temperature.....	12-9
Figure 12-8 Larson-Miller Plot for Udimet 500.	12-10
Figure 13-1 Tensile Strengths as a Function of Temperature.....	13-3
Figure 13-2 Tensile Elongation as a Function of Temperature.	13-4
Figure 13-3 100 hr Rupture Strength as a Function of Temperature.	13-5
Figure 13-4 1000 hr Rupture Strength as a Function of Temperature.....	13-6
Figure 13-5 Larson-Miller Plot for Udimet 520.	13-7
Figure 14-1 Specific Heat as a Function of Temperature.....	14-3
Figure 14-2 Thermal Conductivity as a Function of Temperature.	14-4
Figure 14-3 Coefficient of Thermal Expansion as a Function of Temperature.	14-5
Figure 14-4 Tensile Strengths as a Function of Temperature.....	14-6
Figure 14-5 Tensile Elongation as a Function of Temperature.	14-7
Figure 14-6 Dynamic Modulus as a Function of Temperature.	14-8
Figure 14-7 Fatigue Crack Growth Behavior at R = 0, 0.05, 0.24, and 0.53 (Lab Air, Room Temperature).	14-9
Figure 14-8 Fatigue Crack Growth Behavior Under Vacuum Conditions (Room Temperature).....	14-10
Figure 14-9 Elevated Temperature Fatigue Crack Growth Behavior at R = 0.	14-11
Figure 14-10 Elevated Fatigue Crack Growth Behavior Under Vacuum Conditions.....	14-12
Figure 14-11 Crack Growth for Udimet 700 at 850°C, R = 0.05, and Cyclic Frequency of 0.17 Hz.....	14-13
Figure 14-12 The Effect of the Environment on the Creep Crack Growth in Udimet 700 at 850°C: o , 14.2 kN, vacuum, batch 2; △ , 16.0 kN, vacuum, batch 2; — air, batch 1; —, air, batch 2.	14-14
Figure 14-13 100 hr Rupture Strength as a Function of Temperature.....	14-15
Figure 14-14 1000 hr Rupture Strength as a Function of Temperature.....	14-16

Figure 14-15 Larson-Miller Plot for Udimet 700.	14-17
Figure 14-16 Low-Cycle Fatigue at 1400°F (Total Strain Range).	14-18
Figure 14-17 High-Cycle Fatigue Behavior at 1500°F (Fully Reversed Loading).	14-19
Figure 15-1 Thermal Conductivity as a Function of Temperature.	15-3
Figure 15-2 Coefficient of Thermal Expansion as a Function of Temperature.	15-4
Figure 15-3 Tensile Strengths as a Function of Temperature.	15-5
Figure 15-4 Tensile Elongation as a Function of Temperature.	15-6
Figure 15-5 Dynamic Modulus as a Function of Temperature.	15-7
Figure 15-6 Charpy Impact Energy as a Function of Aging Time.	15-8
Figure 15-7 Charpy Impact Energy as a Function of Aging Temperature.	15-9
Figure 15-8 100 hr Rupture Strength as a Function of Temperature.	15-10
Figure 15-9 1000 hr Rupture Strength as a Function of Temperature.	15-11
Figure 15-10 Larson-Miller Plot for Udimet 710.	15-12
Figure 15-11 Effect of Mean Stress on the Fatigue Strength of Udimet 710. ($A = \frac{\sigma_{\text{ALTERNATING}}}{\sigma_{\text{MEAN}}}$).	15-13
Figure 16-1 Coefficient of Thermal Expansion as a Function of Temperature.	16-3
Figure 16-2 Tensile Strengths as a Function of Temperature.	16-4
Figure 16-3 Tensile Elongation as a Function of Temperature.	16-5
Figure 16-4 Crack Growth Rates in Air and in Vacuum for Single Crystal U720.	16-6
Figure 16-5 Crack Growth Rates in Air and in Vacuum for Polycrystalline U720.	16-7
Figure 16-6 Graph of da/dN Data for SENB Specimens in Vacuum at 20, 300 and 600°C.	16-8
Figure 16-7 Showing da/dN Data at R = 0.5 in Air and Vacuum.	16-9
Figure 16-8 100 hr Rupture Strength as a Function of Temperature.	16-10
Figure 16-9 100 hr Rupture Strength as a Function of Temperature.	16-11
Figure 16-10 1000 hr Rupture Strength as a Function of Temperature.	16-12
Figure 16-11 Larson-Miller Plot for Udimet 720.	16-13
Figure 16-12 High Cycle Fatigue Behavior at 1600°F in Saline and Air Environments.	16-14
Figure 16-13 Effects of Environment and Frequency of Cycling on HCF Strength of Udimet 720 at 1300°F (704°C) and R = 0.2 to 0.3.	16-15
Figure 16-14 HCF Strength of Udimet 720 in Salt Environment at 1300°F (704°C) for R = -1.0 and 0.6.	16-16
Figure 16-15 Effect of Salt Environment and Low Alternating Stress on Stress Rupture of Udimet 710 and 720 Alloys at 1300°F (704°C).	16-17
Figure 16-16 Effect of Environment on Creep/Fatigue Strength of Udimet 720 at 1300°F (704°C) and Constant Maximum Stress.	16-18
Figure 16-17 Creep/Fatigue Strength of Udimet 720 in Air and Salt Under Constant Mean Stress at 1300°F (704°C).	16-19

Figure 16-18 Relationship Between Strain Range and Number of Cycles to Failure Obtained During the Low Cycle Fatigue Testing of Udimet 710 and Coated and Uncoated Udimet 720 at 1350°F (732°C) at 1 cpm.....	16-20
Figure 16-19 Relationship Between the Strain Range Components and Number of Cycles to Failure Obtained During the Low Cycle Fatigue Testing of Udimet 720 at 1350°F (732°C) as a Function of Hold Time and Test Environment.....	16-21
Figure 16-20 Relationship Between the Strain Range Components and Number of Cycles to Failure Obtained During the Low Cycle Fatigue Testing of RT-22 Coated Udimet 720 at 1350°F (732°C) at 1 cpm as a Function of Hold Time and Test Environment.	16-22
Figure 16-21 Low-Cycle Fatigue Results for Udimet 720 at 1350°F (732°C) and 1 cpm.....	16-23
Figure 16-22 Low-Cycle Fatigue Results for RT-22 Coated Udimet 720 Tested at 1350°F (732°C) and 1 cpm.	16-24
Figure 17-1 Tensile Properties and Hardness in the Service Aged Condition.....	17-3
Figure 17-2 Tensile and Hardness Properties after Refurbishment.	17-4
Figure 17-3 Bucket to Bucket Variation of Yield and Tensile Strengths of GTD-111 DS (Undegraded).	17-5
Figure 17-4 Bucket to Bucket Variation of Percent Elongation and Reduction of Area (Undegraded).	17-6
Figure 17-5 Variation of Yield Strength of the Longitudinal and Transverse Specimens.....	17-7
Figure 17-6 Variation of Tensile Strength for the Longitudinal and Transverse Specimens.	17-8
Figure 17-7 Variation of Tensile Ductility of Longitudinal and Transverse Specimens as a Function of Temperature.	17-9
Figure 17-8 Airfoil Stress Rupture Data for IN-738, GTD-111EA and GTD-111DS Alloys Before and After Rejuvenation.....	17-10
Figure 17-9 Iso-Stress Creep Rupture Data of Longitudinal Specimens Machined from the Shank Section (Unaged).....	17-11
Figure 17-10 Iso-Stress Creep Rupture Data of Transverse Specimens Machined from the Shank Section.	17-12
Figure 17-11 LMP Plot of GTD-111 DS and IN-738 LC Creep Data.	17-13
Figure 17-12 Larson-Miller Plot of Longitudinal Shank (Undegraded) Creep Data.....	17-14
Figure 17-13 LMP Plot of Transverse Specimen Data from Undegraded Shank Location...	17-15
Figure 17-14 Influence of Specimen Orientation on Creep Rupture Strength of Unaged (Shank) Material.	17-16
Figure 18-1 Tensile Properties and Hardness in the Service Aged Condition.....	18-3
Figure 18-2 Tensile and Hardness Properties after Refurbishment.	18-4
Figure 18-3 Tensile Strengths as a Function of Temperature.....	18-5
Figure 18-4 Tensile Strengths as a Function of Temperature.....	18-6
Figure 18-5 Tensile Properties for Root and Airfoil Material at 70°F and 1600°F.....	18-7
Figure 18-6 Tensile Properties for Root and Airfoil Material at 70°F and 1600°F.....	18-8
Figure 18-7 Tensile Elongation as a Function of Temperature.	18-9

Figure 18-8 Tensile Elongation and Reduction in Area as a Function of Temperature.	18-10
Figure 18-9 Stress vs. Rupture Time for Two Material Conditions.	18-11
Figure 18-10 Stress-Rupture Results for Root and Airfoil Material.	18-12
Figure 18-11 Stress-Rupture Data for GTD-111 EA and DS Compared to IN-738.....	18-13
Figure 18-12 Stress-Rupture Results for Root and Airfoil Material.	18-14
Figure 18-13 Larson-Miller Plot of GTD-111 EA (Standard Heat Treat and Thermally Exposed).	18-15
Figure 18-14 Larson-Miller Plot for GTD-111 EA.....	18-16
Figure 18-15 Larson-Miller Plot for GTD-111 for Different Exposure Conditions.....	18-17
Figure 18-16 Larson-Miller Plot for GTD-111 EA.....	18-18
Figure 18-17 A Larson Miller Plot Comparing the GTD111 Alloy Test Points with Rene 80 Data from the Literature and the GTD111 Larson Miller Curve Published by General Electric.....	18-19
Figure 18-18 A Least Squares Regression Model ($Y = \beta_0 + \beta_1 X + e$) Fitted to the GTD111 Creep Rupture Data Illustrating the Fit. The 95% Confidence Intervals About the Mean and the 95% Prediction Interval for an Individual Observation. Test Data from the Thermally Exposed GTD111 Material and Select Service Exposed GTD111 Data Points are Plotted.	18-20
Figure 18-19 A Plot of Percent Creep Deformation (Strain) Versus Time for the Creep Rupture Samples in the Standard Heat Treated Condition and After Thermal Exposures at 816°C and 899°C.....	18-21
Figure 18-20 A Plot of Percent Creep Deformation (Strain) Versus Time for the Creep Rupture Samples in the Standard Heat Treated Condition and After Thermal Exposures at 816°C and 899°C.....	18-22
Figure 18-21 A Plot of Percent Creep Deformation (Strain) Versus Time for the Creep Rupture Samples in the Standard Heat Treated Condition and After Thermal Exposures at 816°C and 899°C.....	18-23
Figure 18-22 A Plot of Percent Creep Deformation (Strain) Versus Time for the Creep Rupture Samples in the Standard Heat Treated Condition and After Thermal Exposures at 816°C and 899°C.....	18-24
Figure 18-23 A Plot of Percent Creep Deformation (Strain) Versus Time for the Creep Rupture Samples in the Standard Heat Treated Condition and After Thermal Exposures at 816°C and 899°C.....	18-25

1

INCONEL 700

Inconel 700

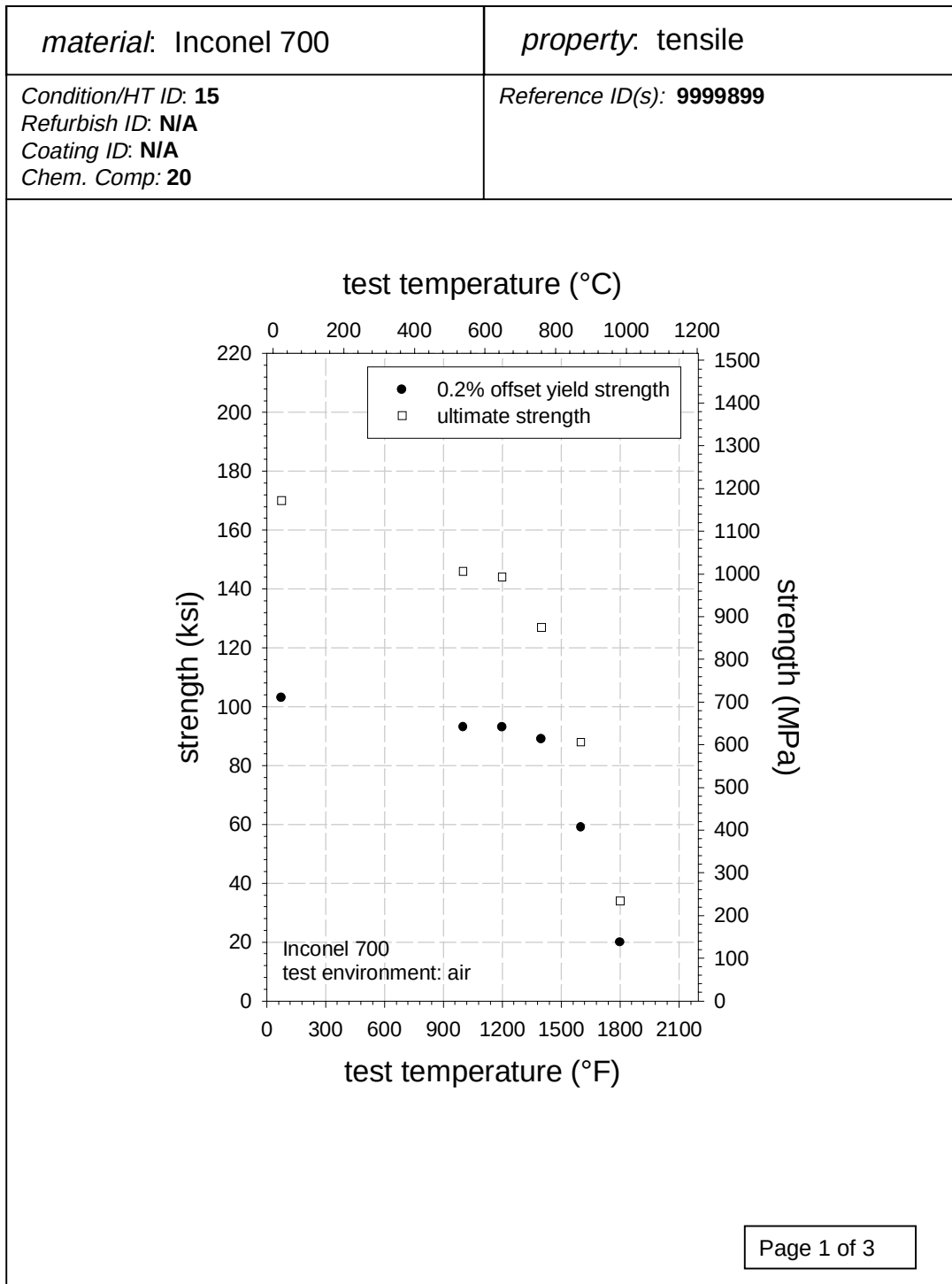


Figure 1-1
Tensile Strength as a Function of Temperature for Inconel 700.

Inconel 700

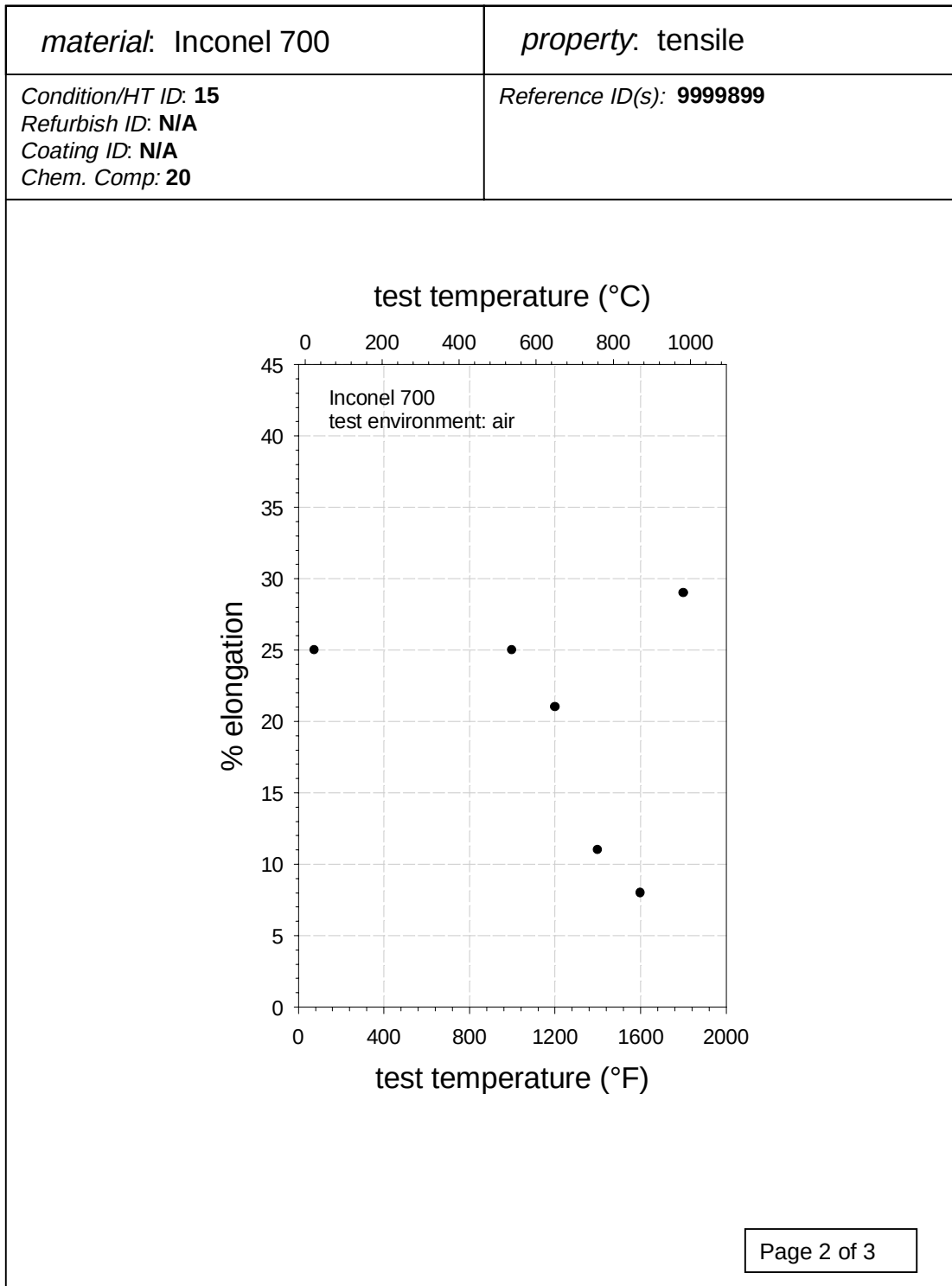


Figure 1-2
Tensile Elongation as a Function of Temperature for Inconel 700.

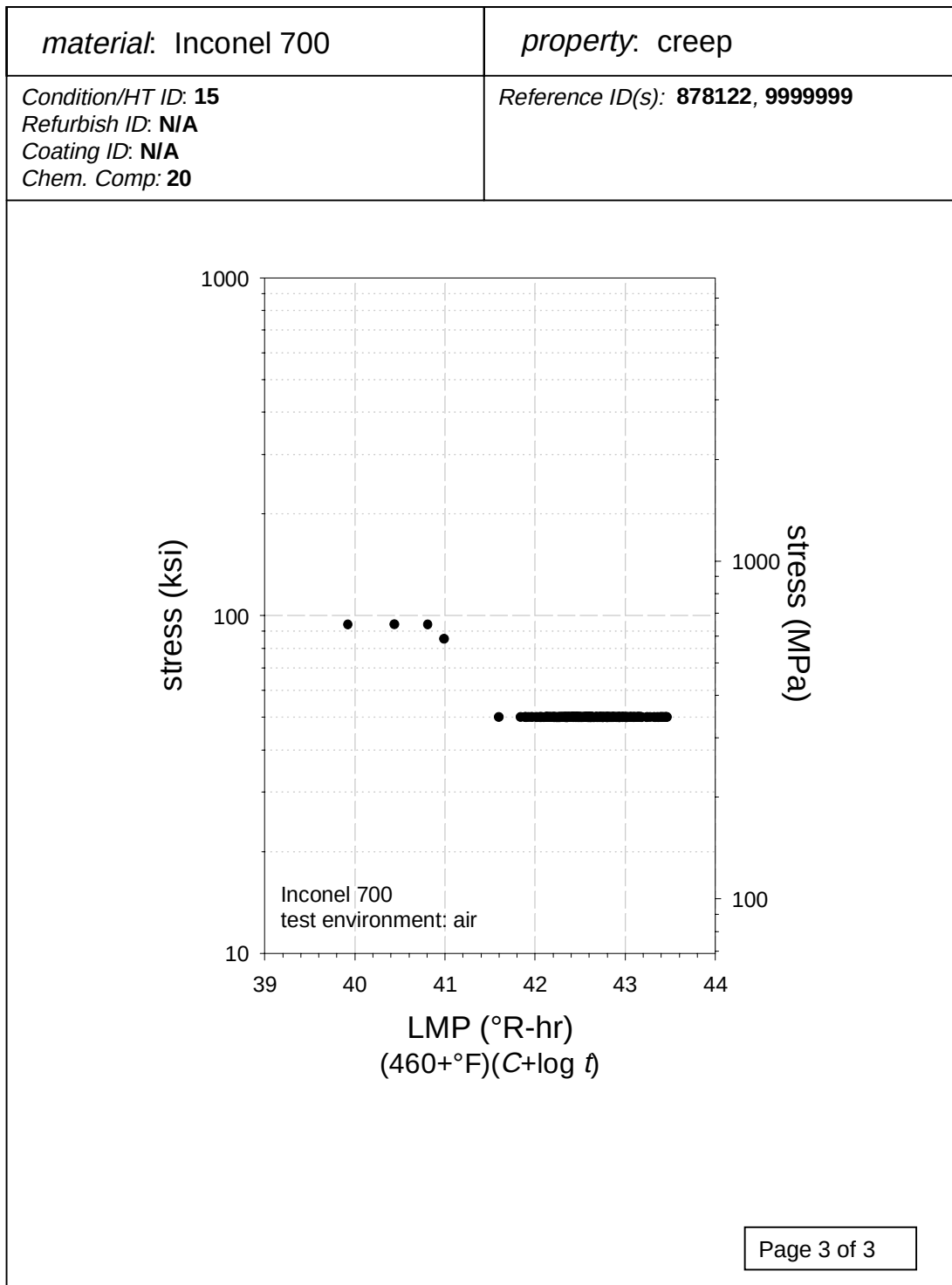


Figure 1-3
Larson-Miller Plot for Inconel 700.

2

INCONEL 939

Inconel 939

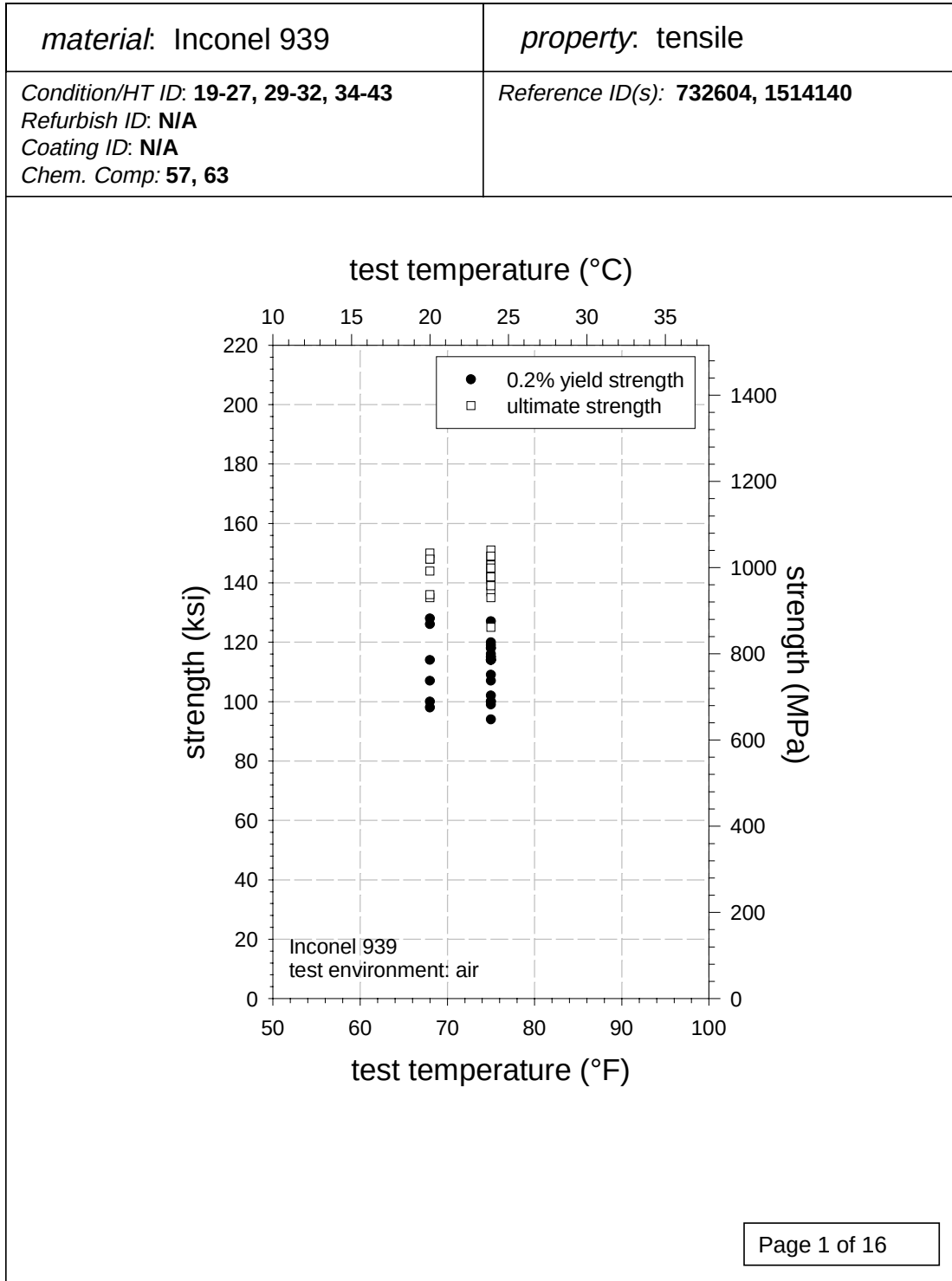


Figure 2-1
Tensile Strengths for Inconel 939 at Room Temperature.

Inconel 939

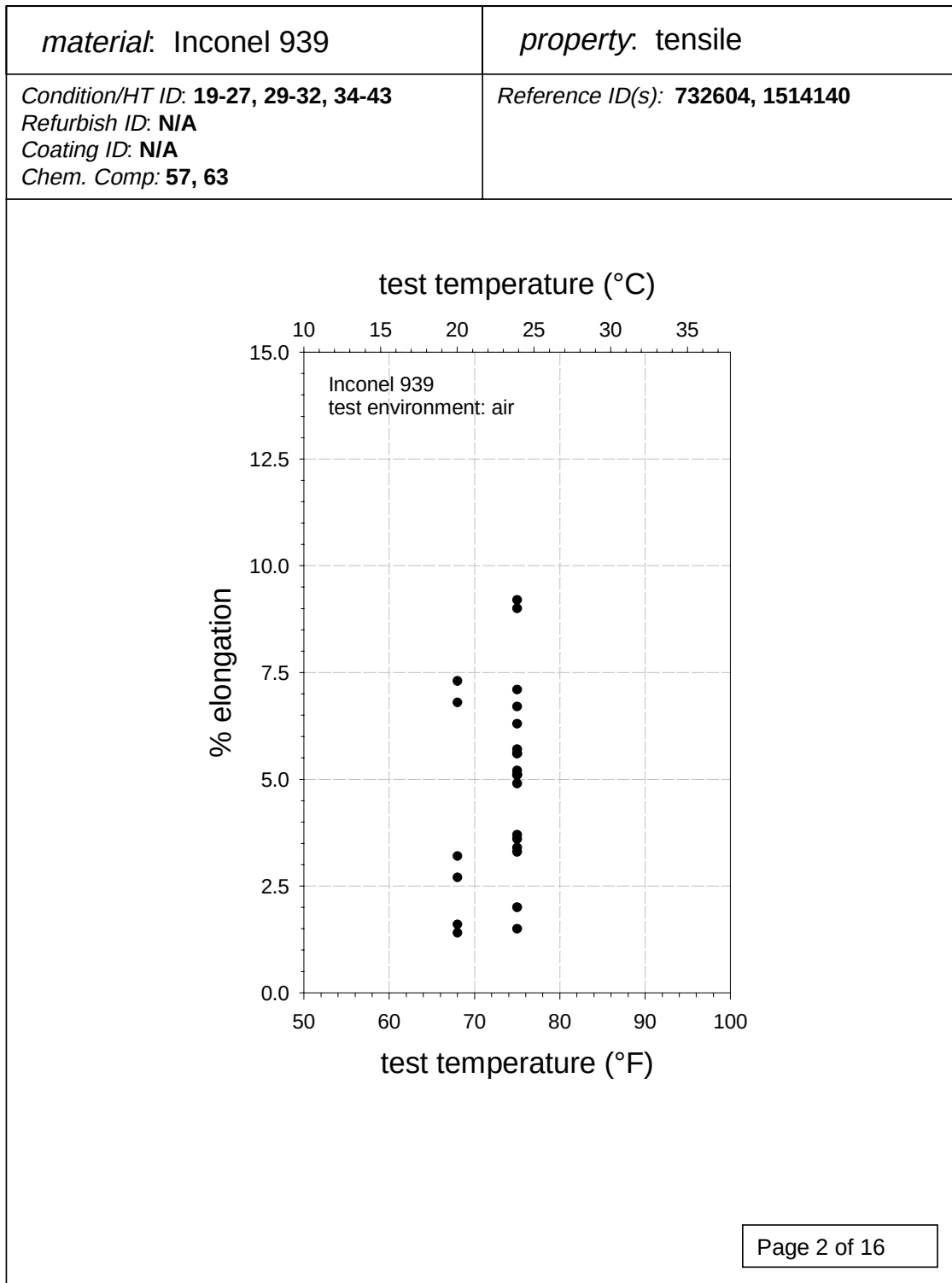


Figure 2-2
Tensile Elongation at Room Temperature for Inconel 939.

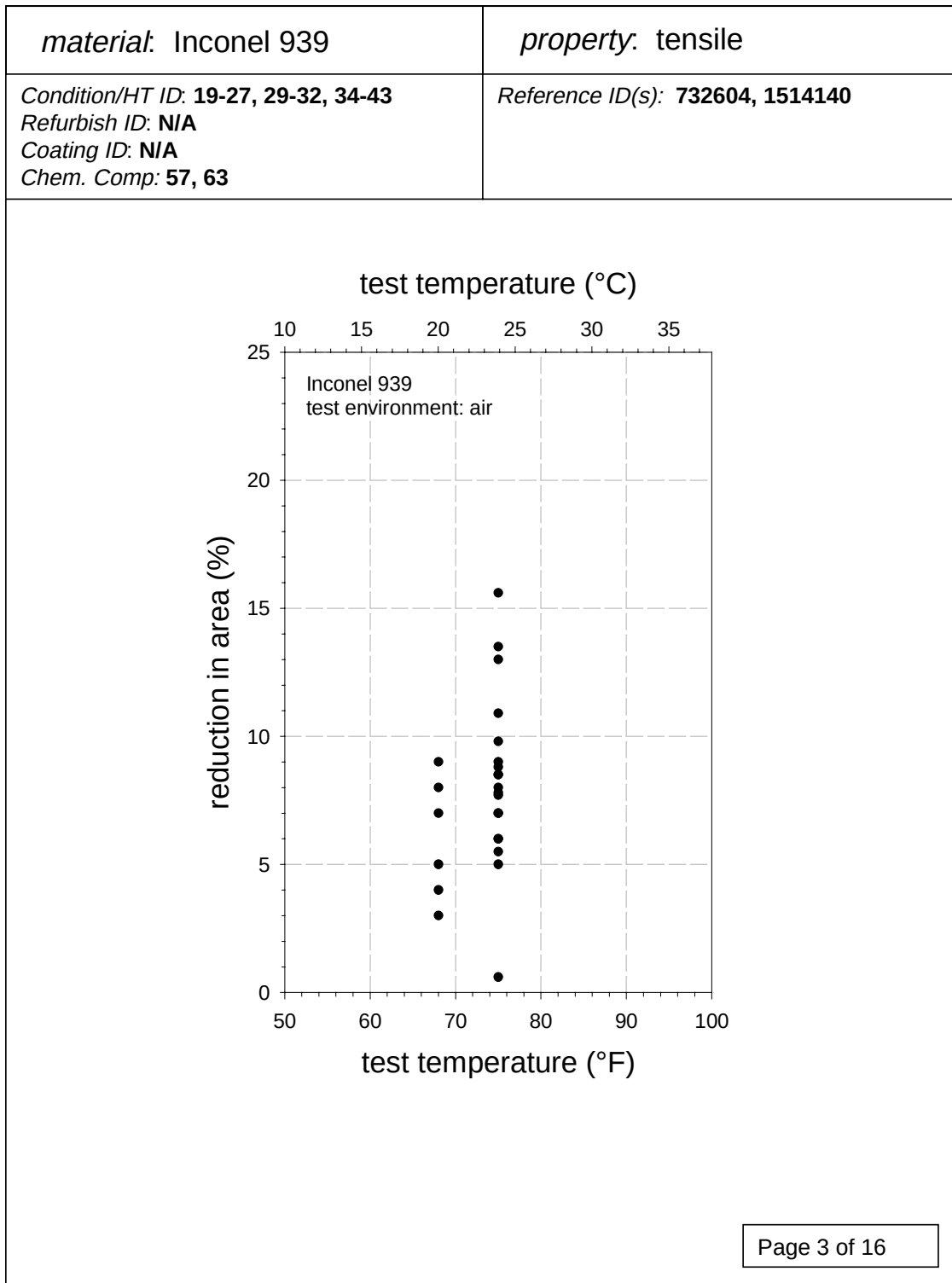


Figure 2-3
Reduction in Area (Tensile) at Room Temperature for Inconel 939.

Inconel 939

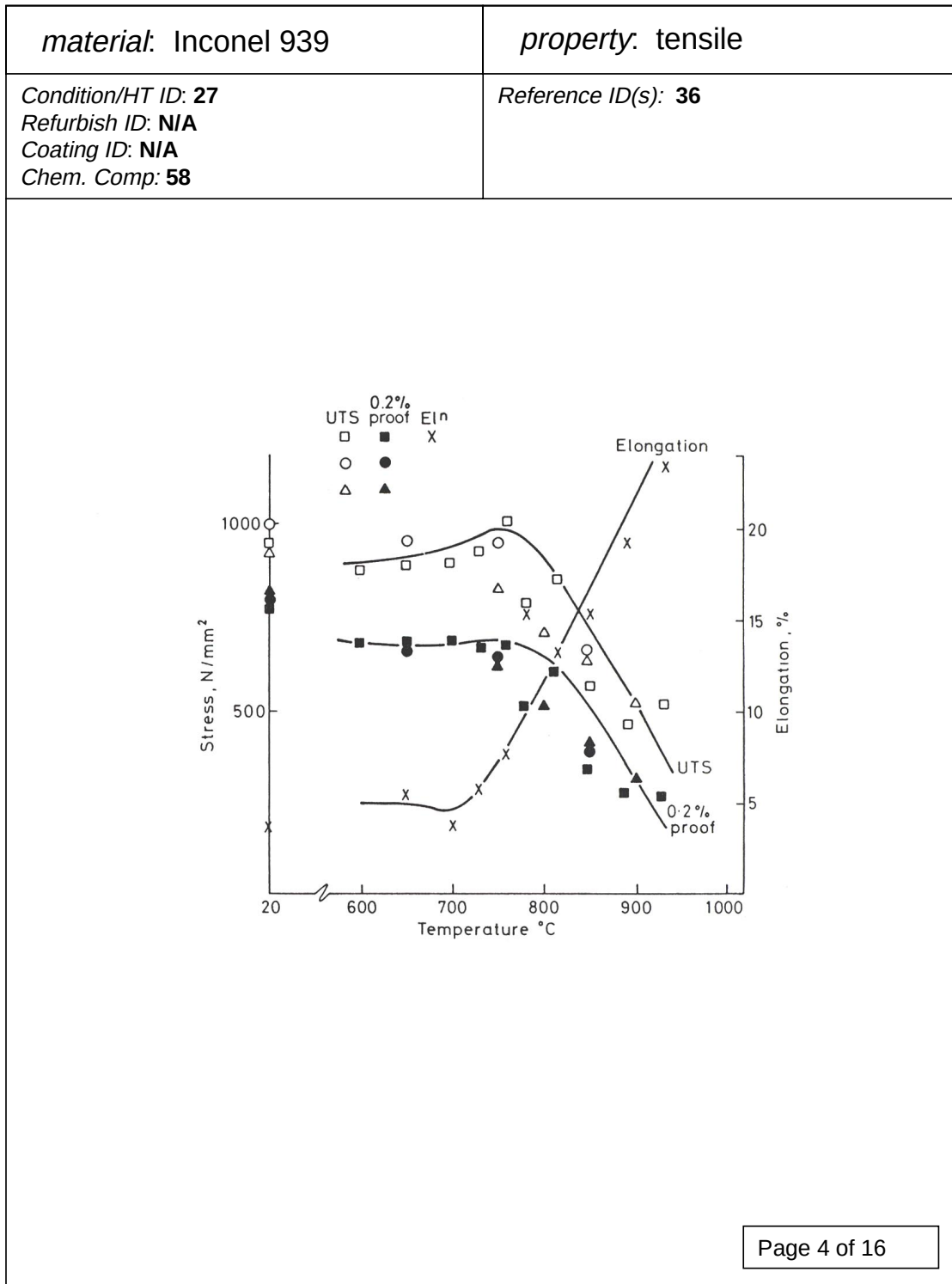


Figure 2-4
Tensile Properties of the Alloy as a Function of Temperature.

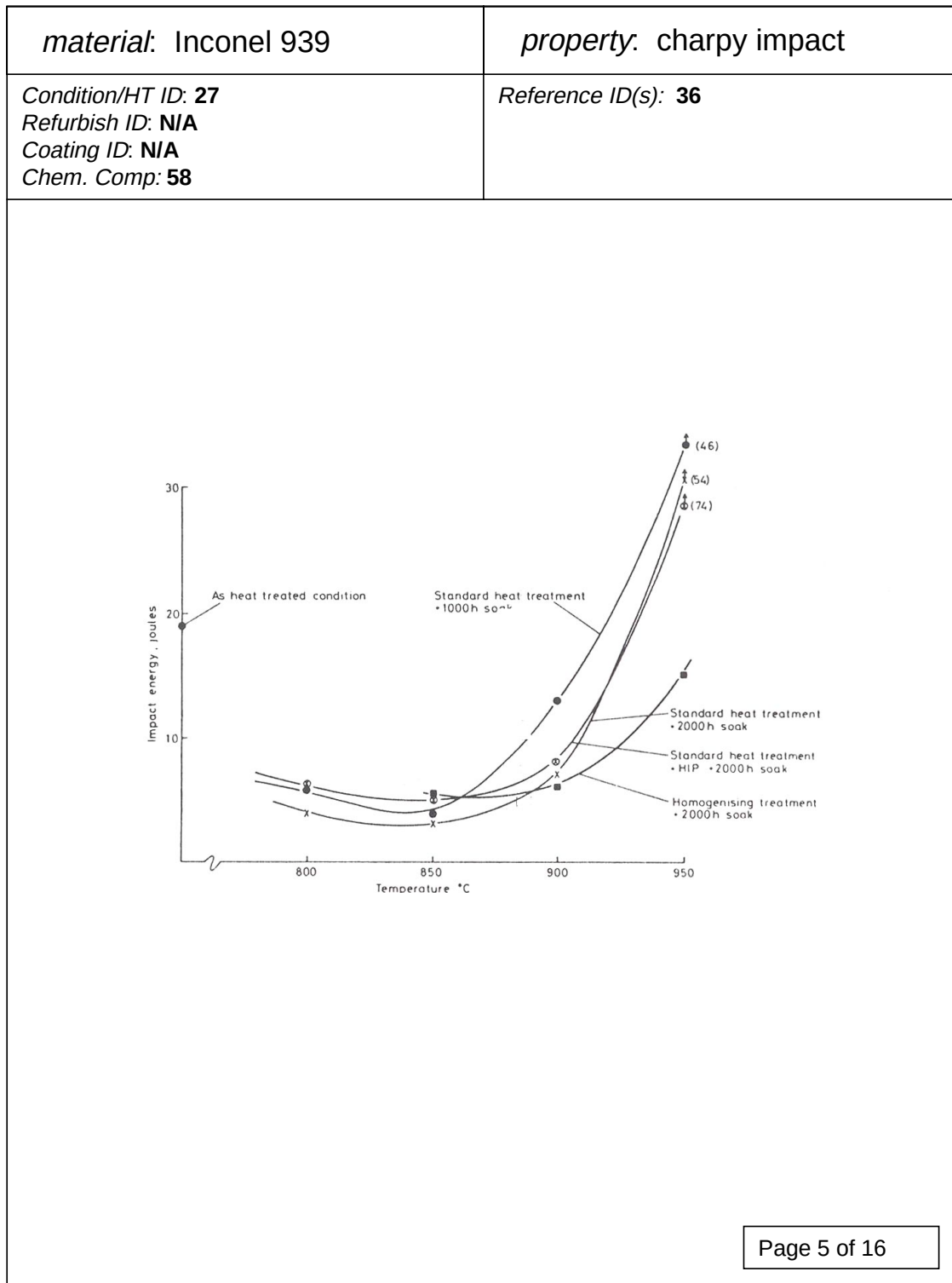


Figure 2-5
Room Temperature Impact Properties After Soaking at Elevated Temperatures.

Inconel 939

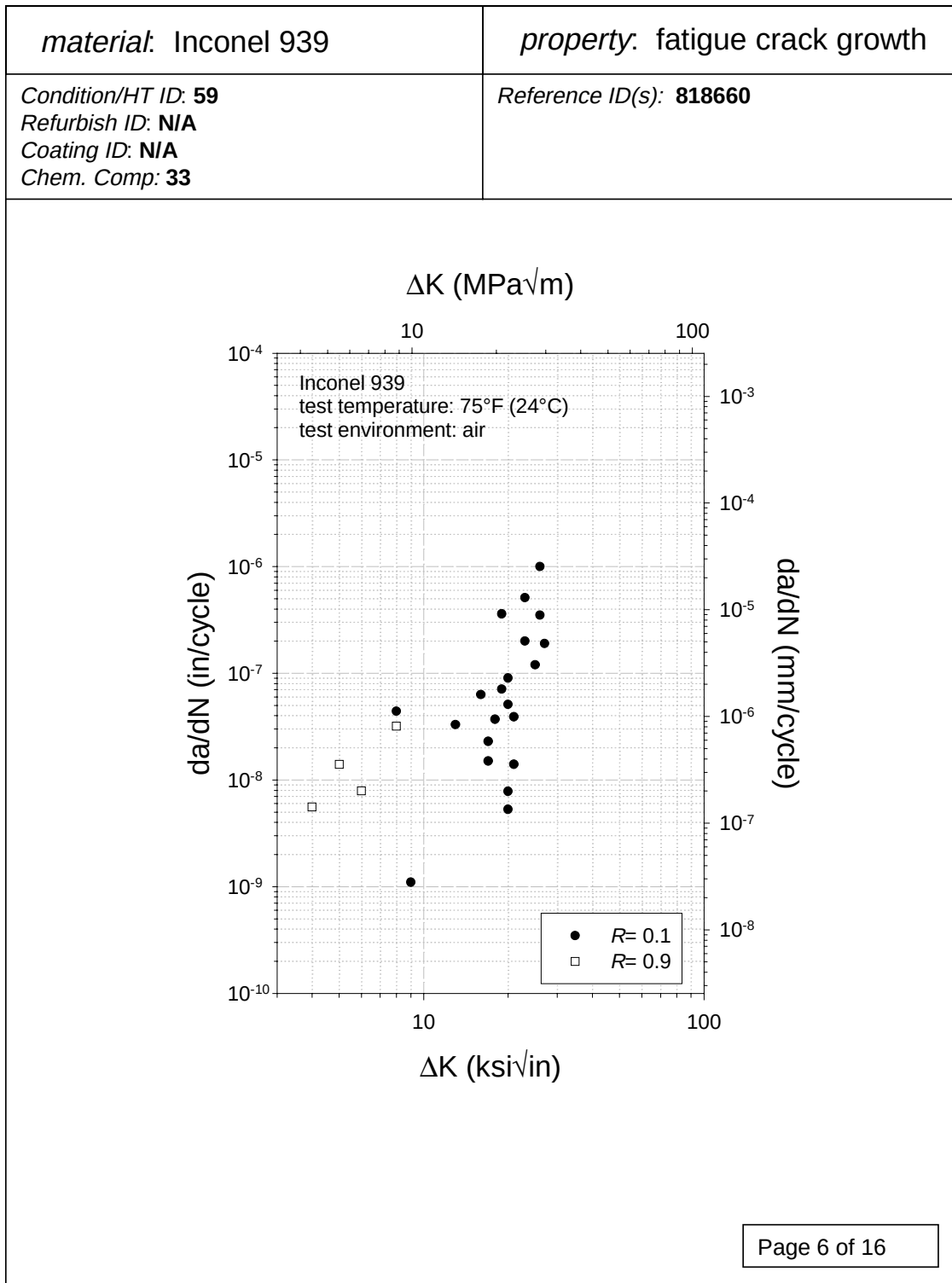


Figure 2-6
Fatigue Crack Growth at R = 0.1 and 0.9 (Room Temperature).

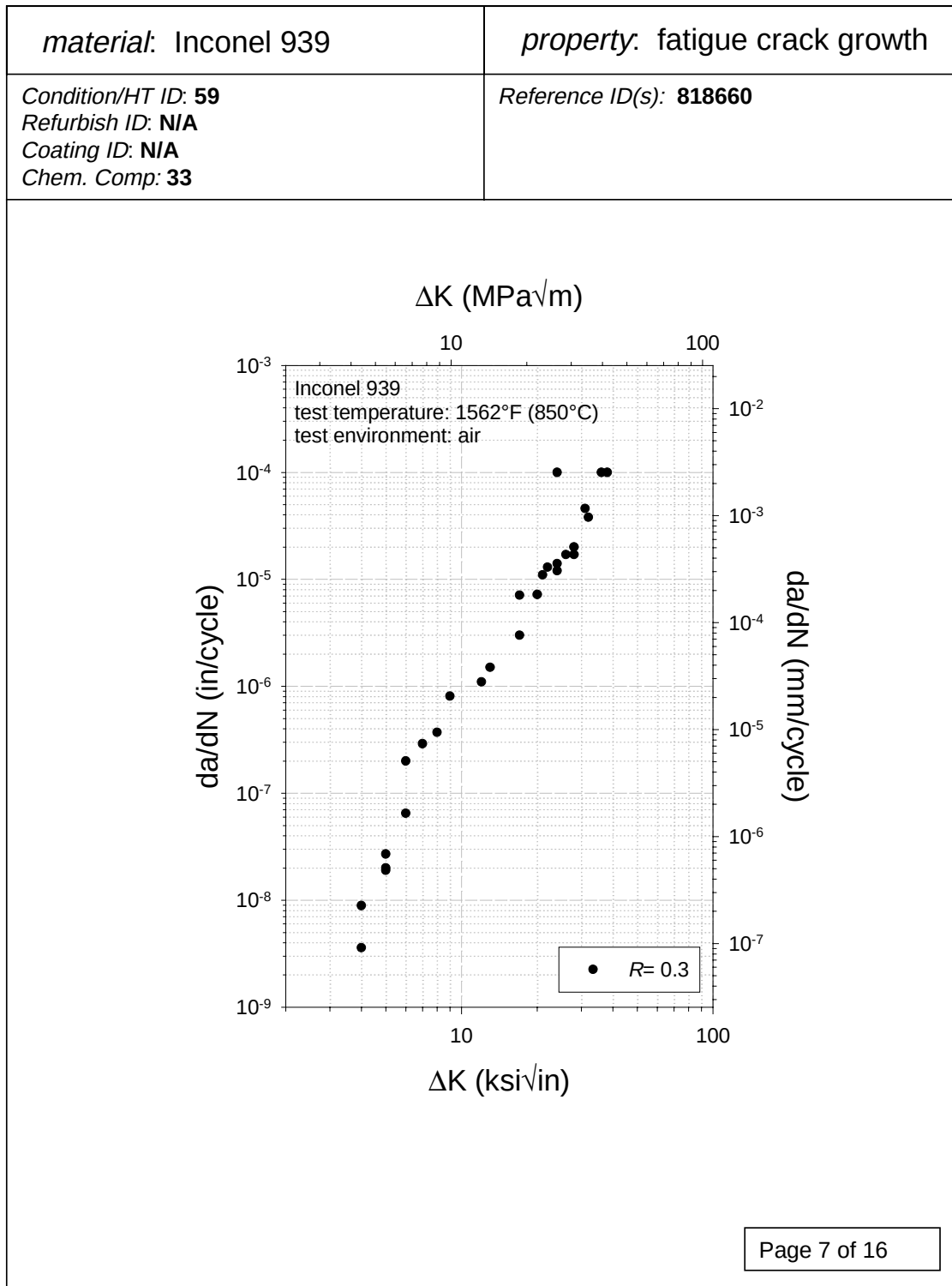


Figure 2-7
Elevated Temperature Fatigue Crack Growth at R = 0.3.

Inconel 939

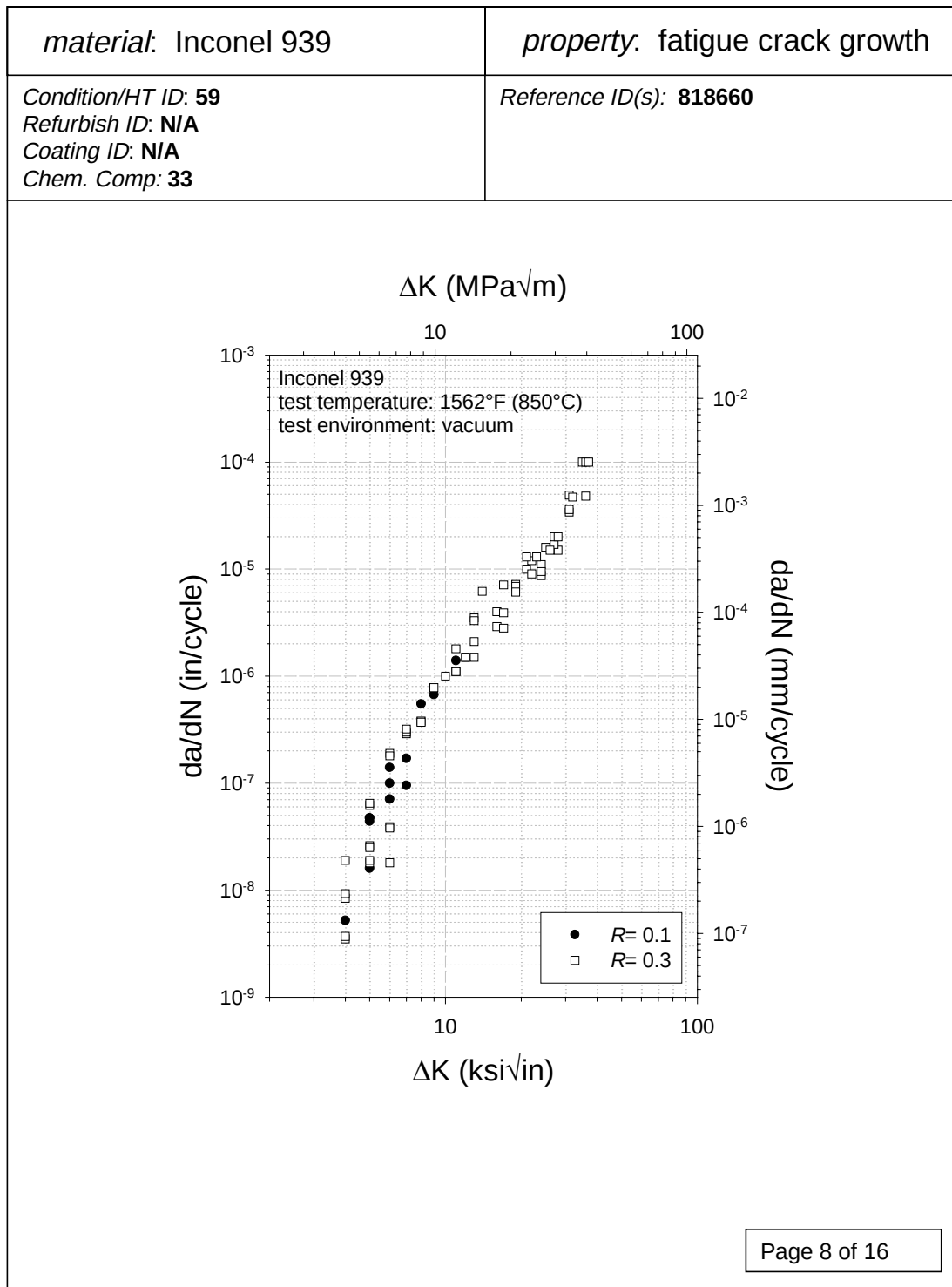


Figure 2-8
Elevated Temperature Fatigue Crack Growth at R = 0.1 and 0.3 (Vacuum).

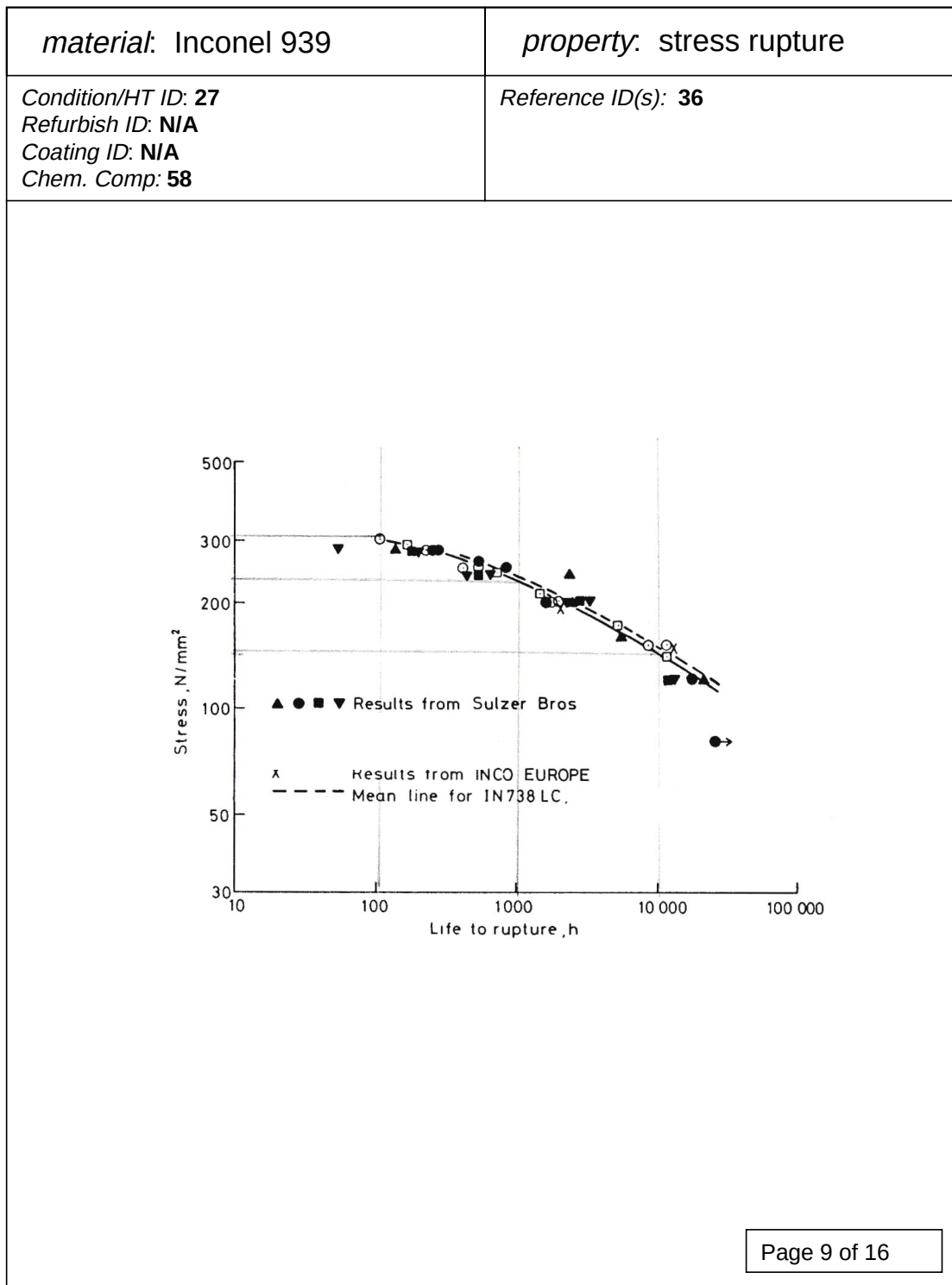


Figure 2-9
The Stress Rupture Properties at 850°C; Standard Heat Treatment.

Inconel 939

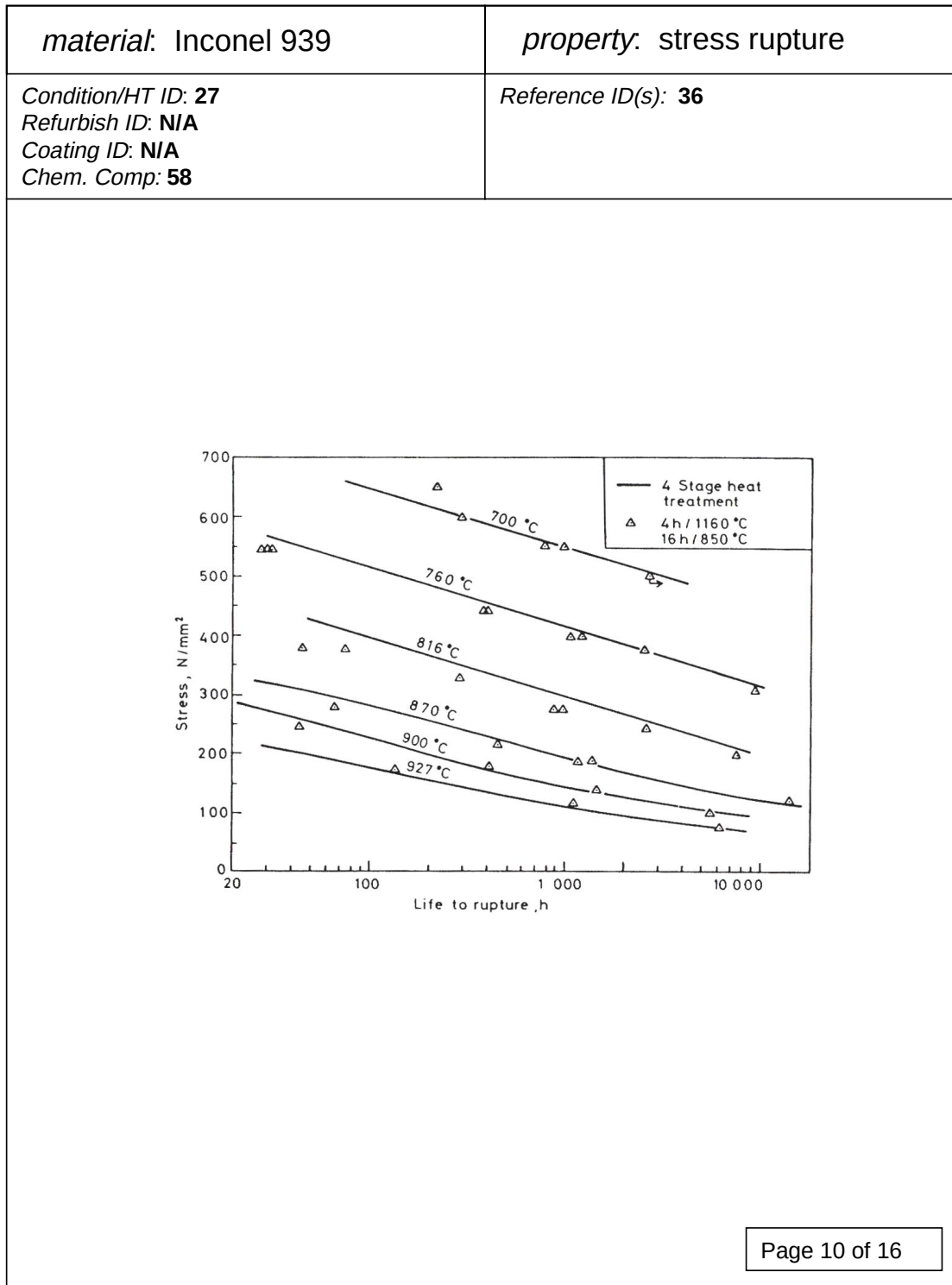


Figure 2-10
The Stress Rupture Properties with Two-Stage Heat Treatment.

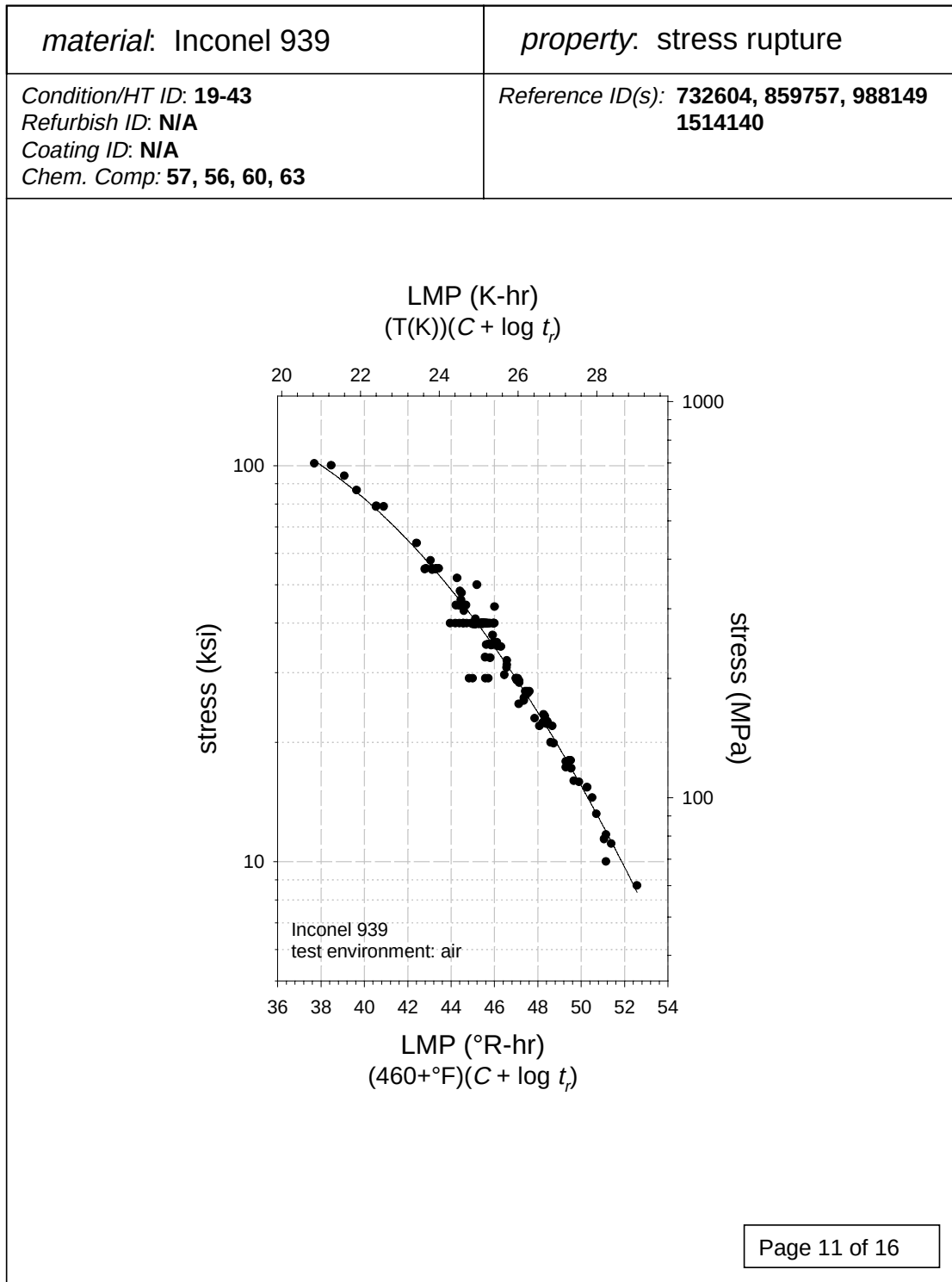


Figure 2-11
Larson-Miller Plot for Inconel 939.

Inconel 939

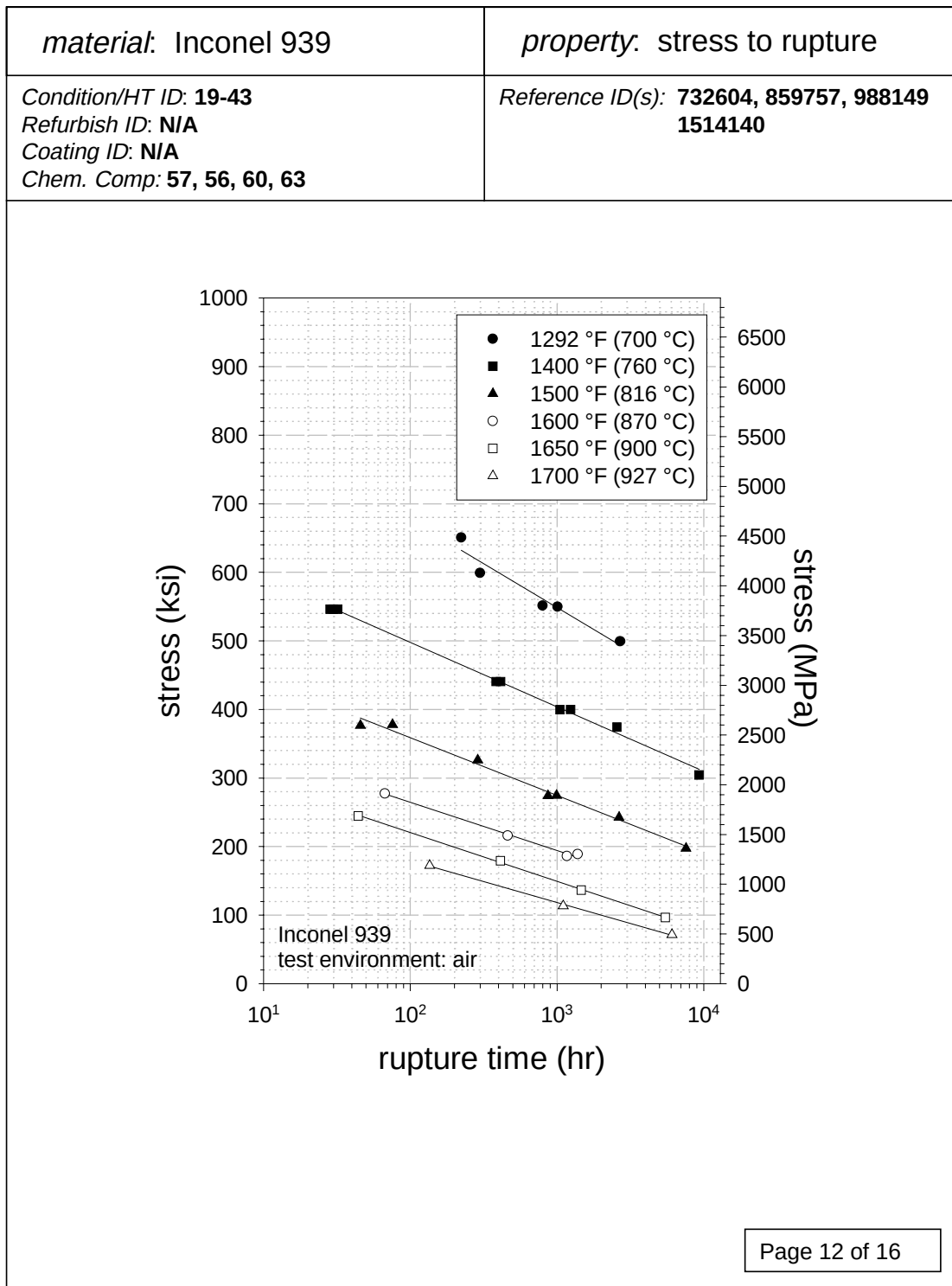


Figure 2-12
Stress to Rupture vs. Time at Elevated Temperatures.

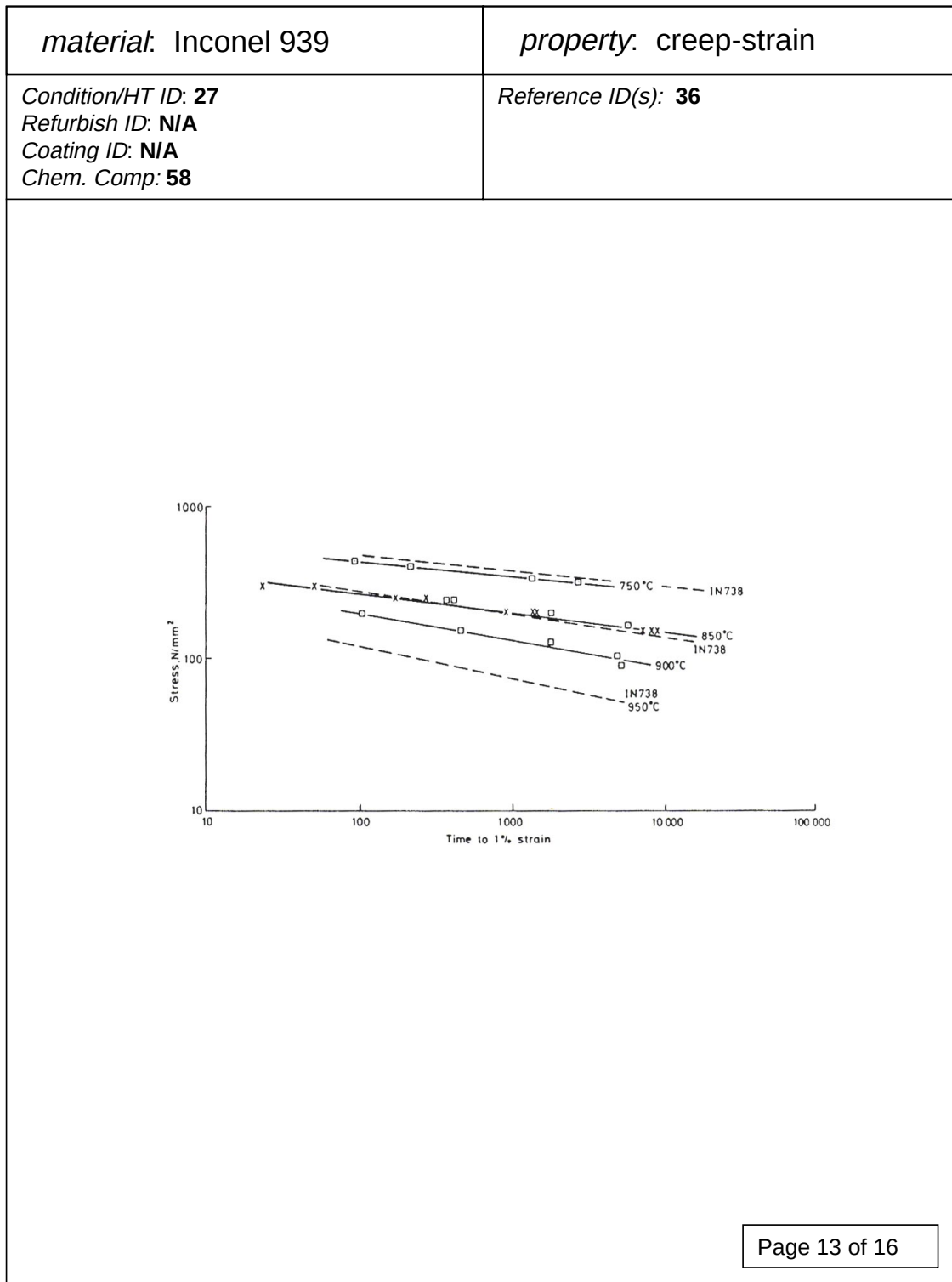


Figure 2-13
Strain to 1% Creep as a Function of Stress.

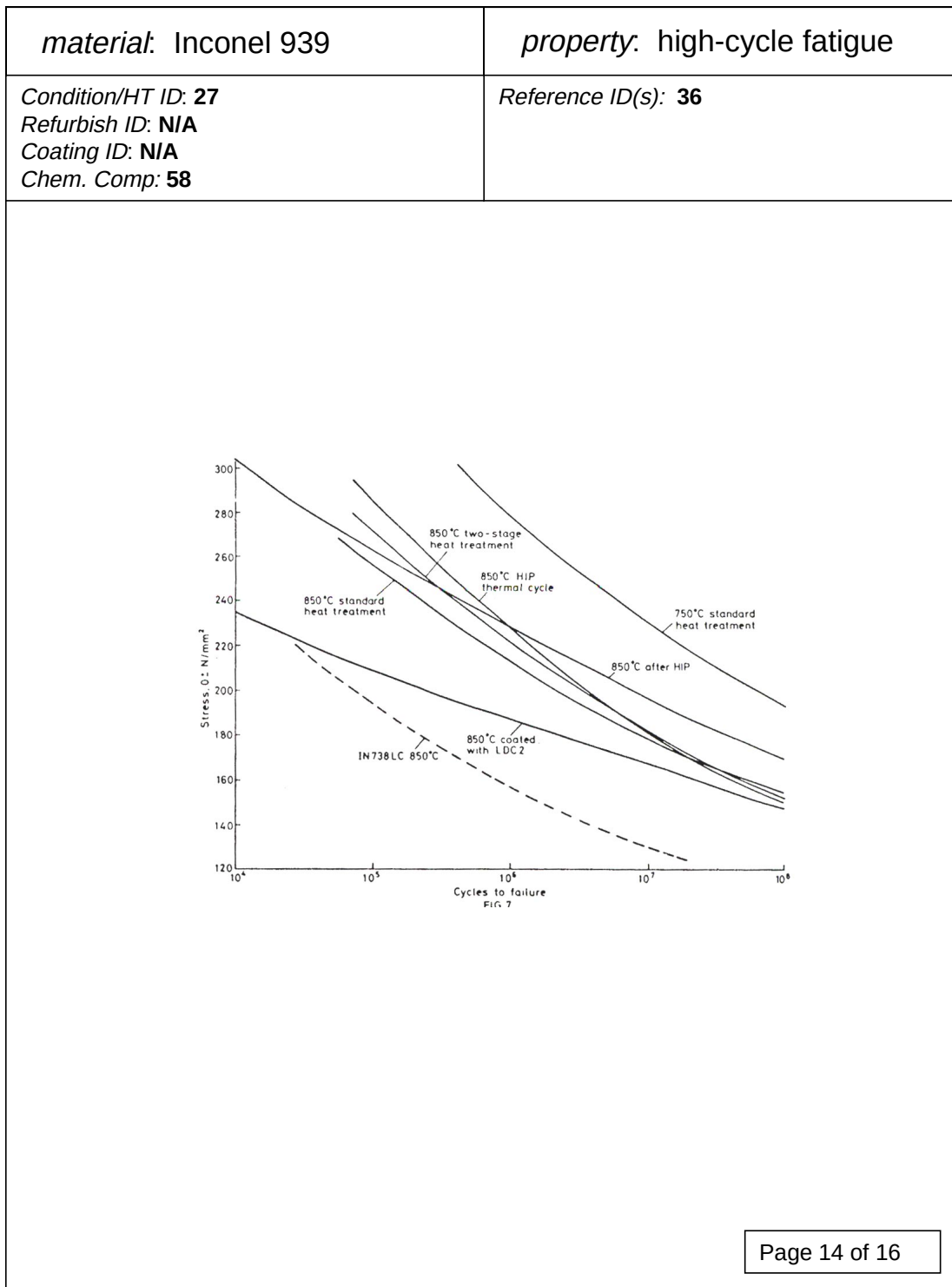


Figure 2-14
High Cycle Fatigue Properties at 750°C and 850°C.

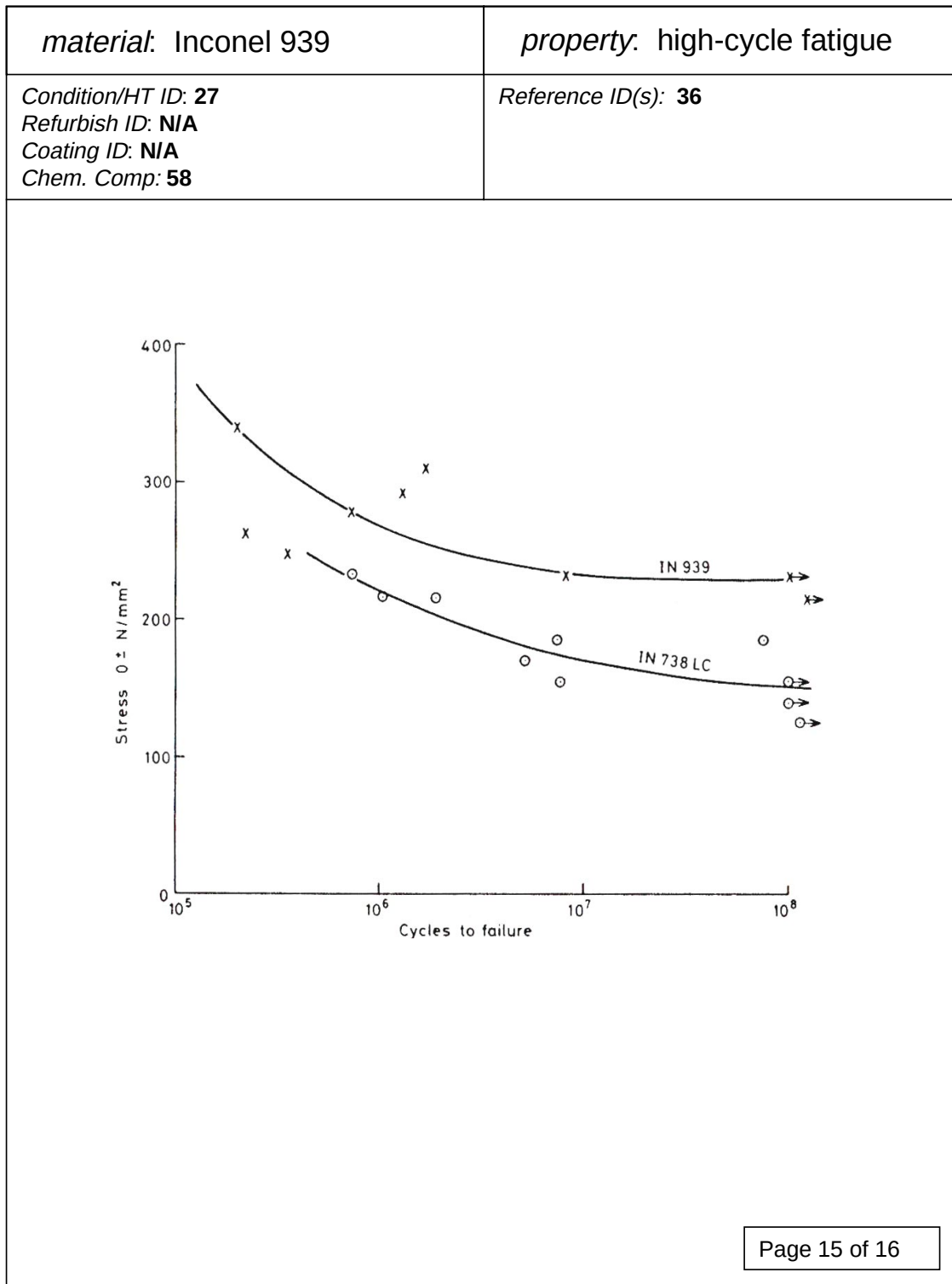


Figure 2-15
High Cycle Fatigue Properties at 600°C. Results from INCO Europe.

Inconel 939

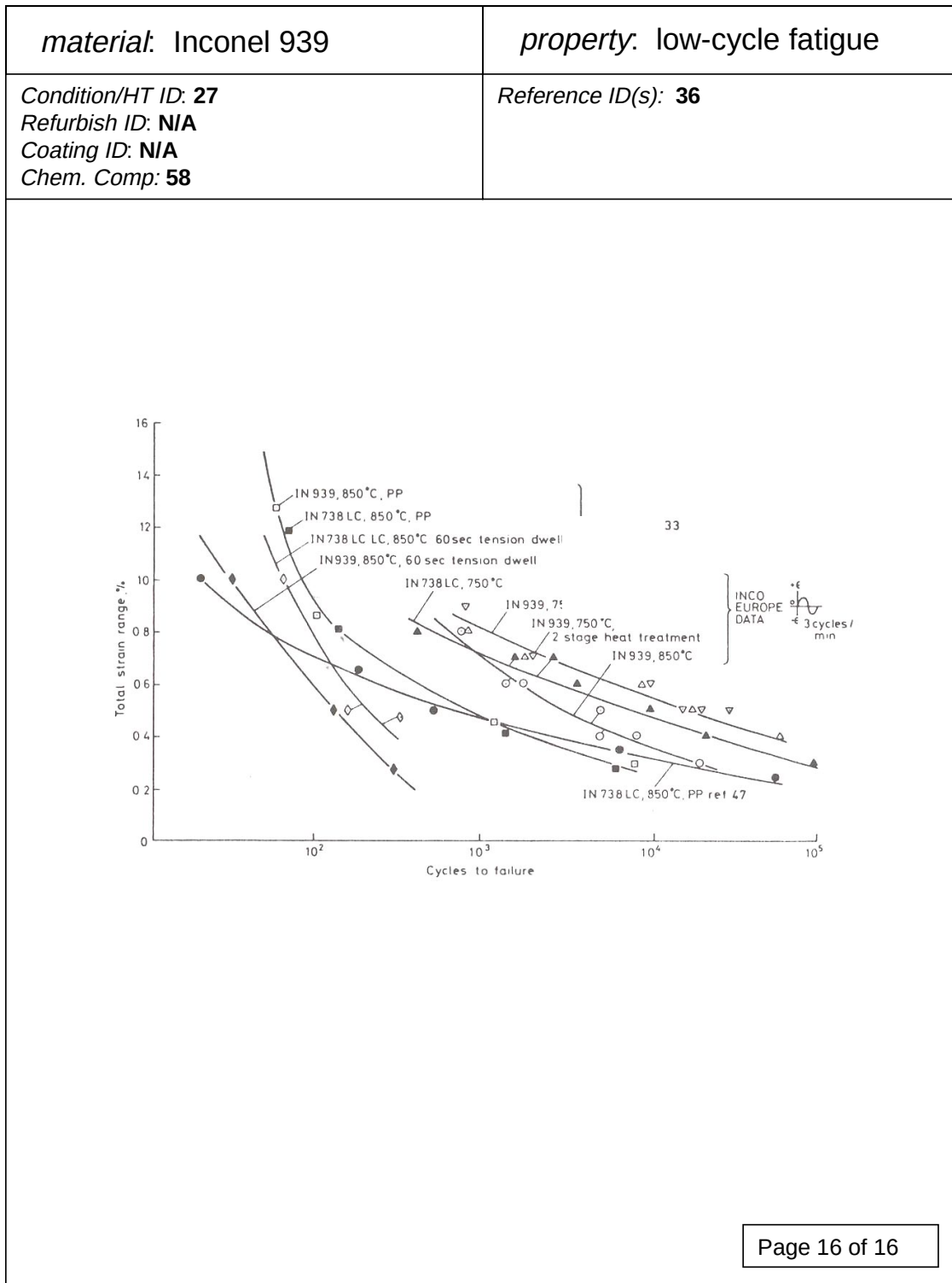


Figure 2-16
Low Cycle Fatigue Properties of IN939 with Results for IN738LC for Comparison.

3

INCONEL X750

Inconel X750

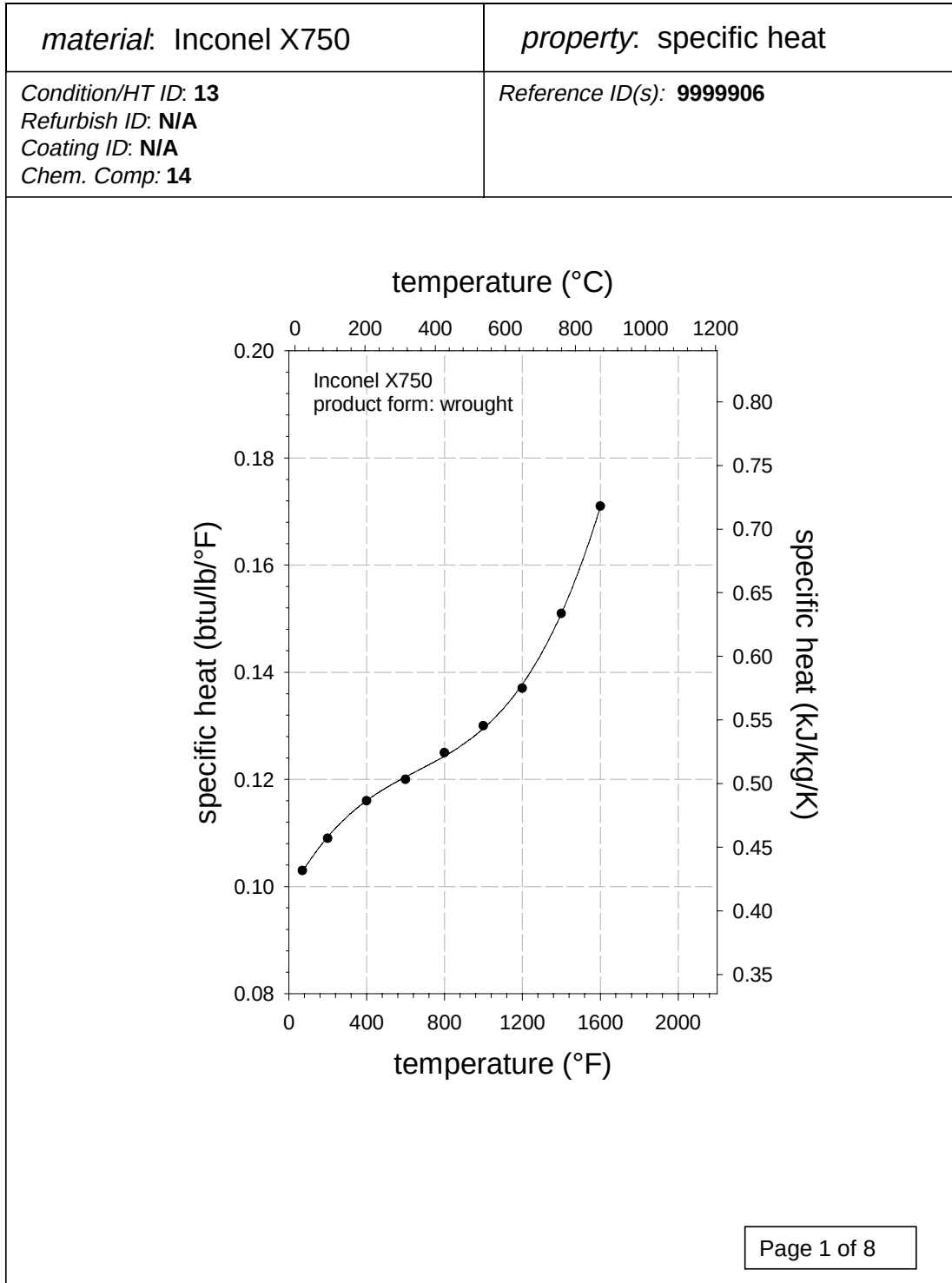


Figure 3-1
Specific Heat as a Function of Temperature for Inconel X750.

Inconel X750

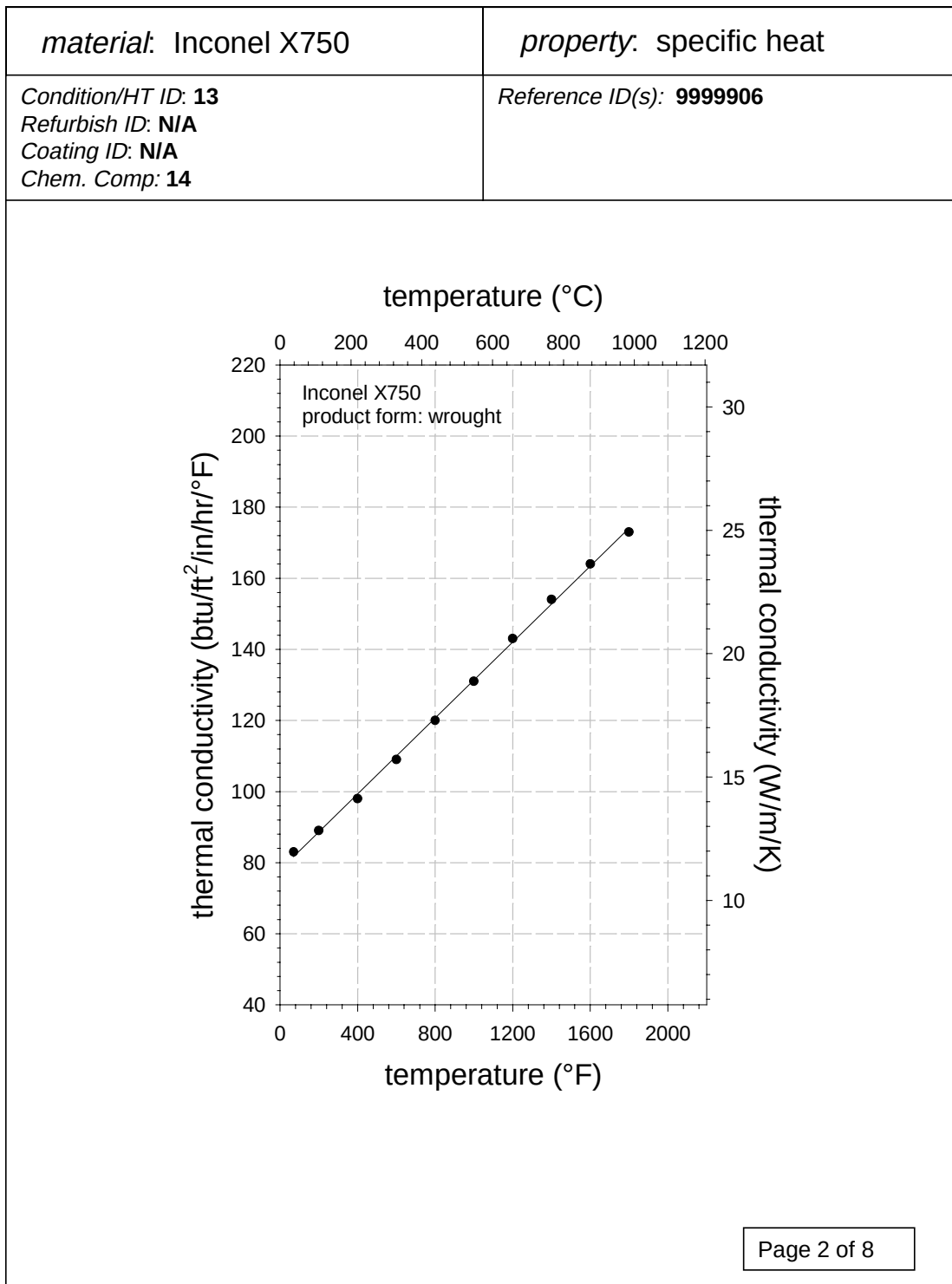


Figure 3-2
Thermal Conductivity as a Function of Temperature for Inconel X750.

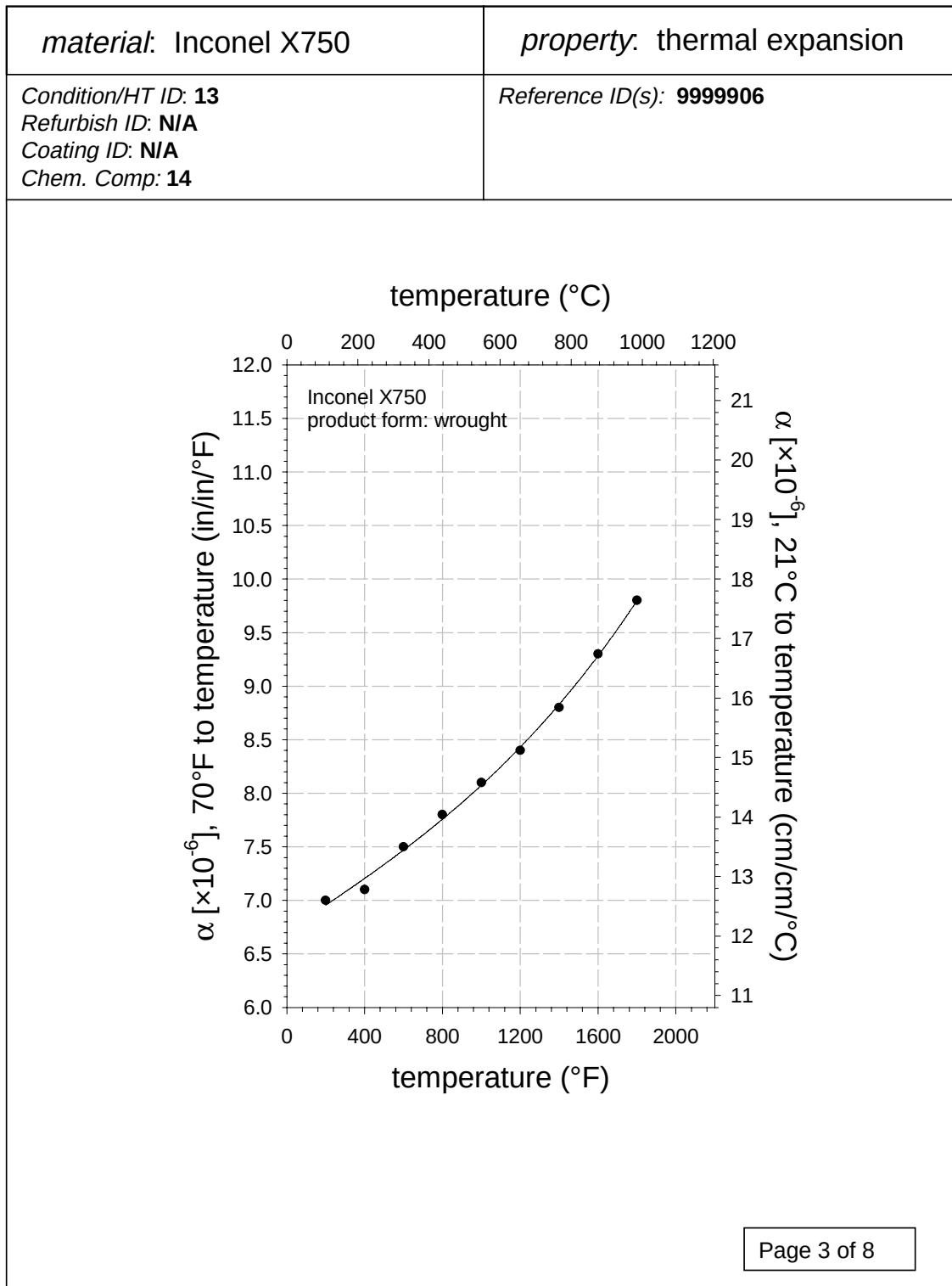


Figure 3-3
Thermal Expansion as a Function of Temperature.

Inconel X750

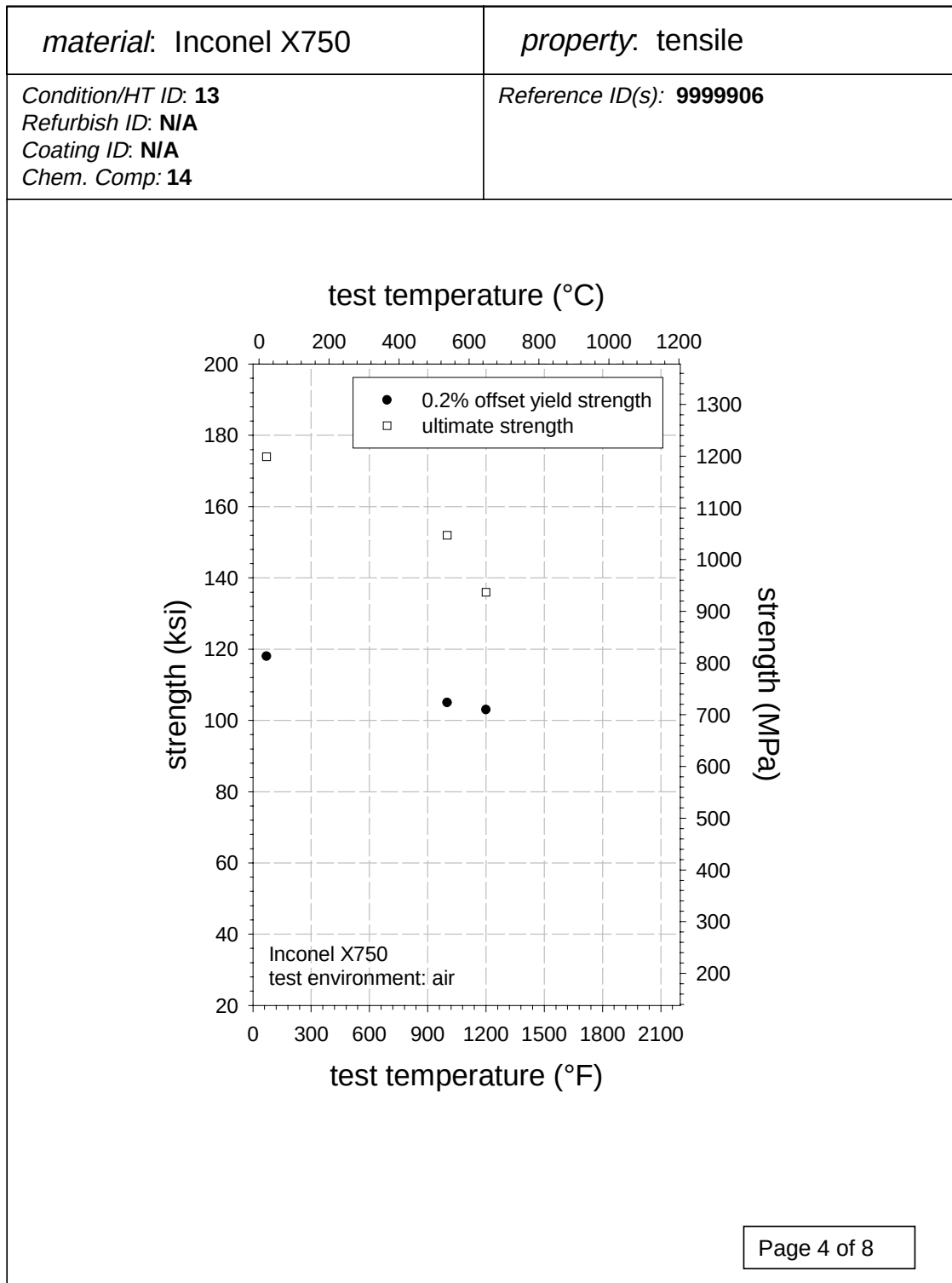


Figure 3-4
Yield and Tensile Strengths vs. Temperature for Inconel X750.

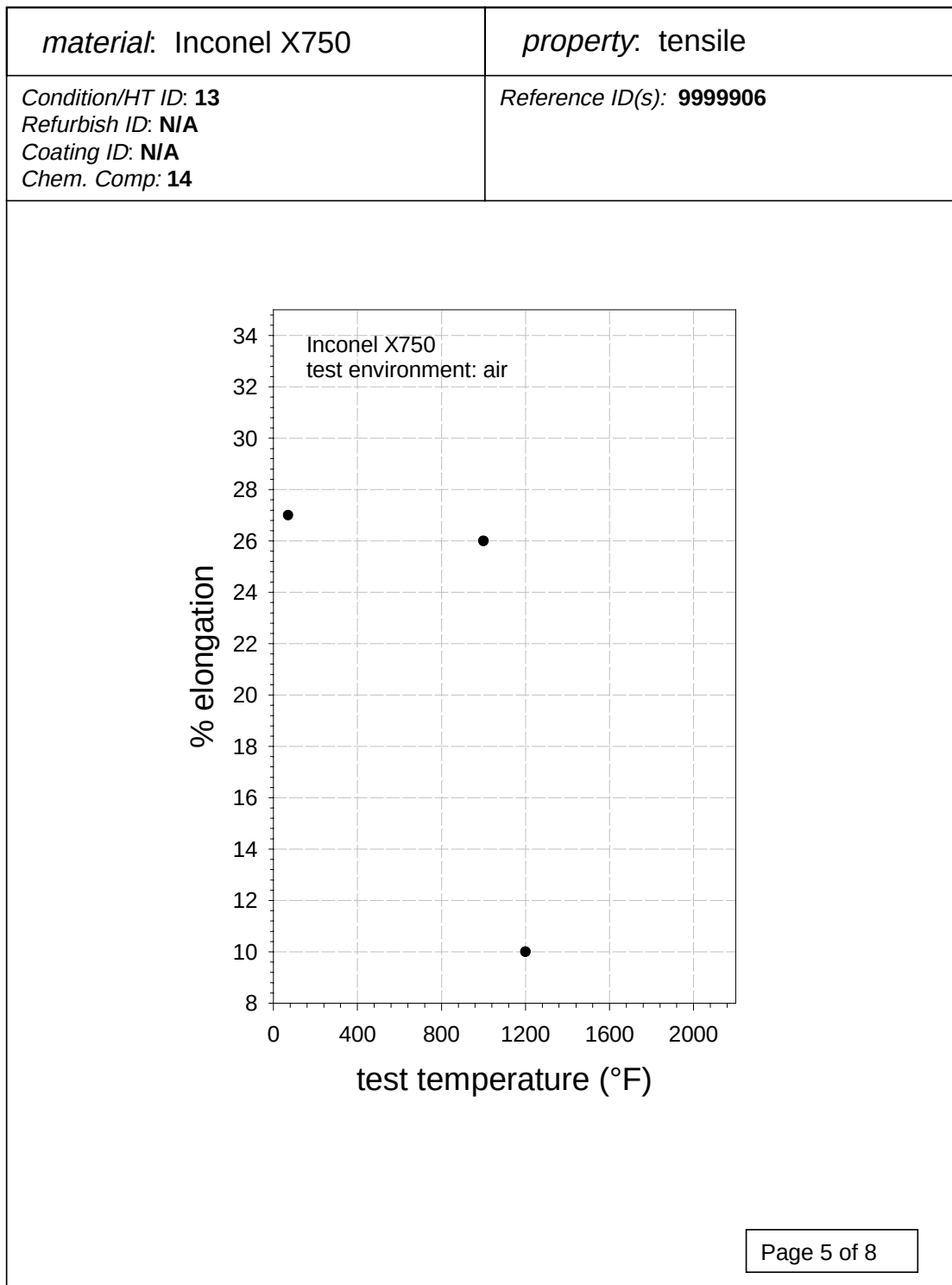


Figure 3-5
Tensile Elongation vs. Temperature.

Inconel X750

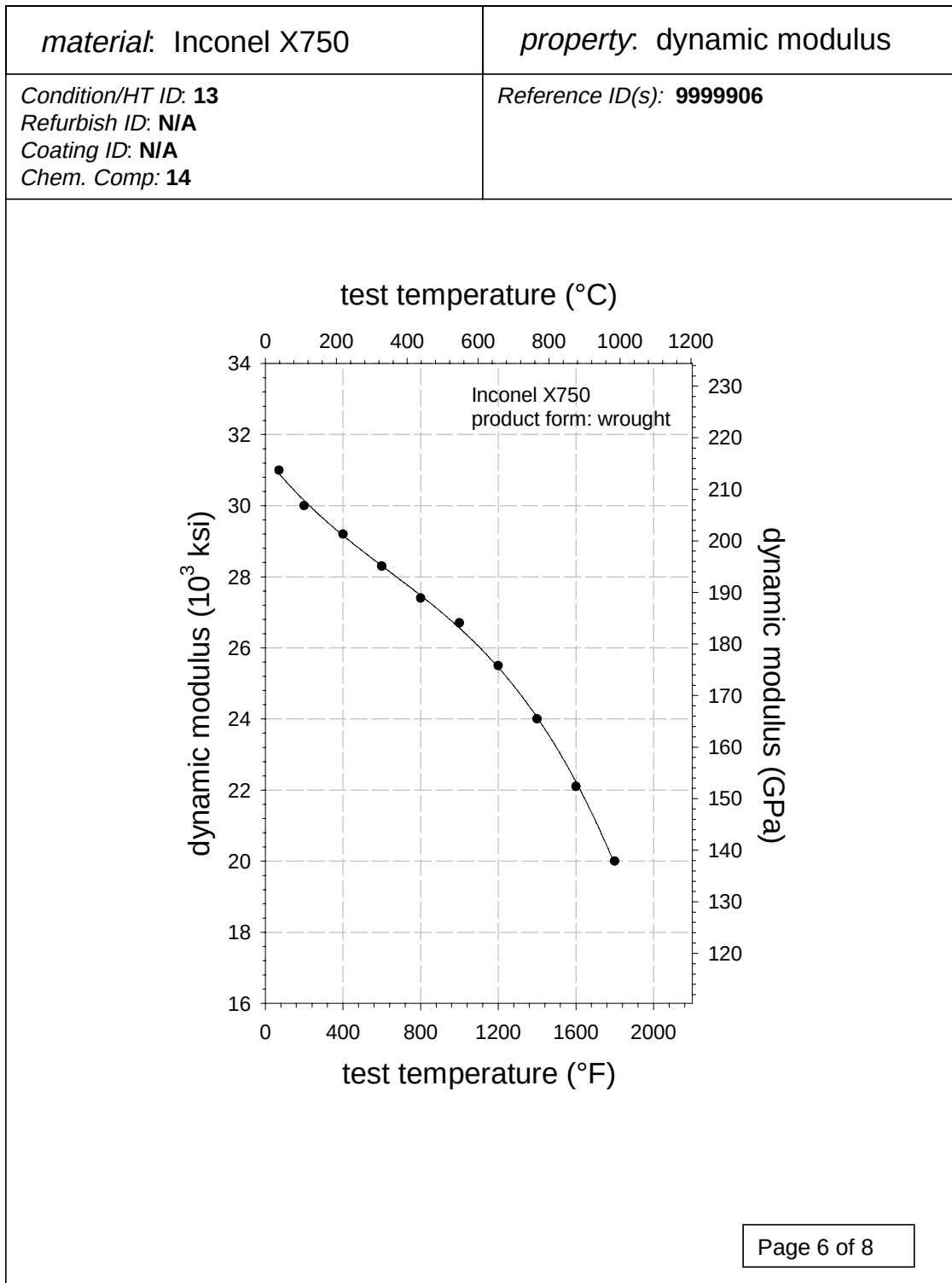


Figure 3-6
Dynamic Modulus as a Function of Temperature.

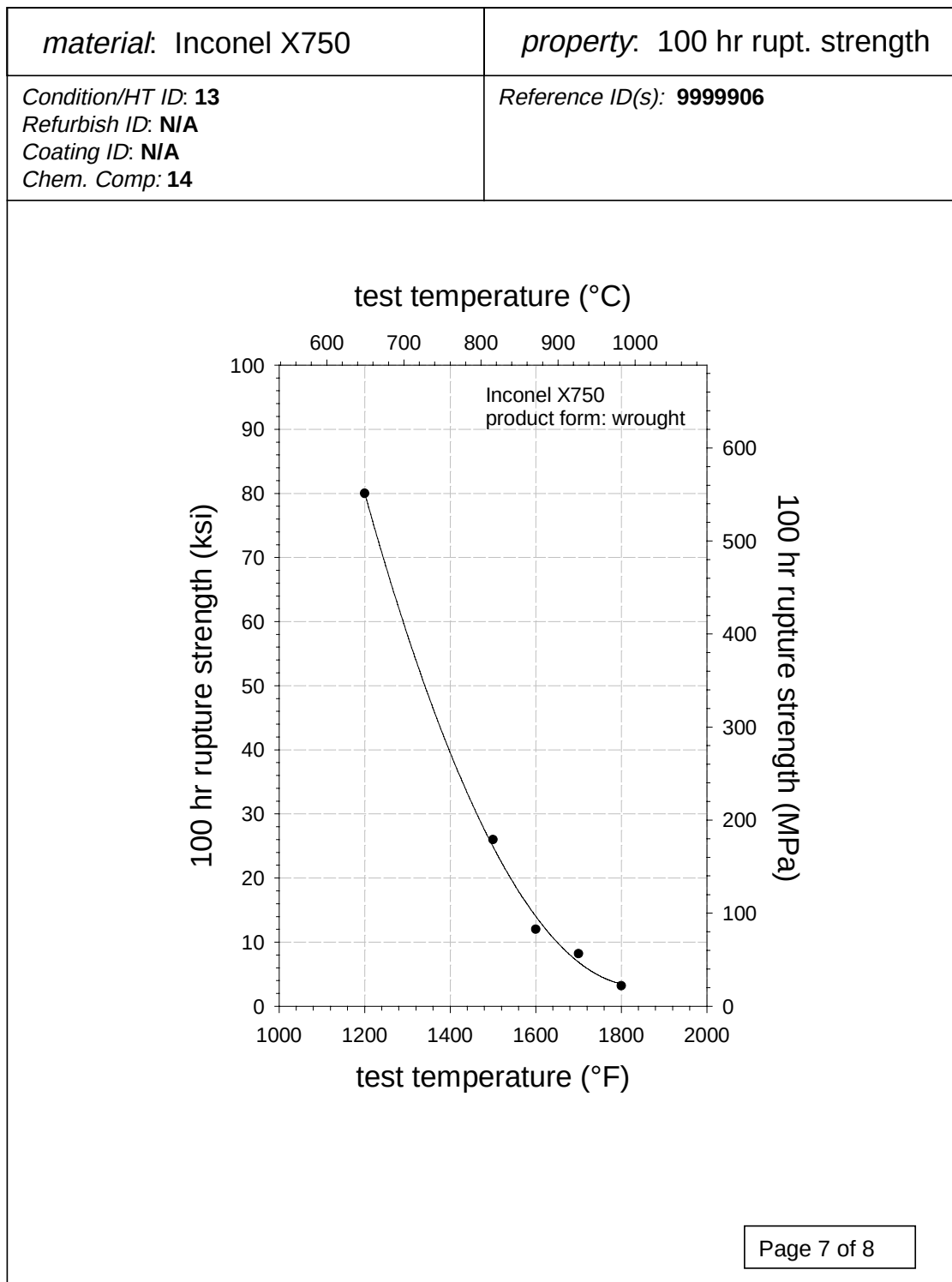


Figure 3-7
100 hr Rupture Strength as a Function of Temperature.

Inconel X750

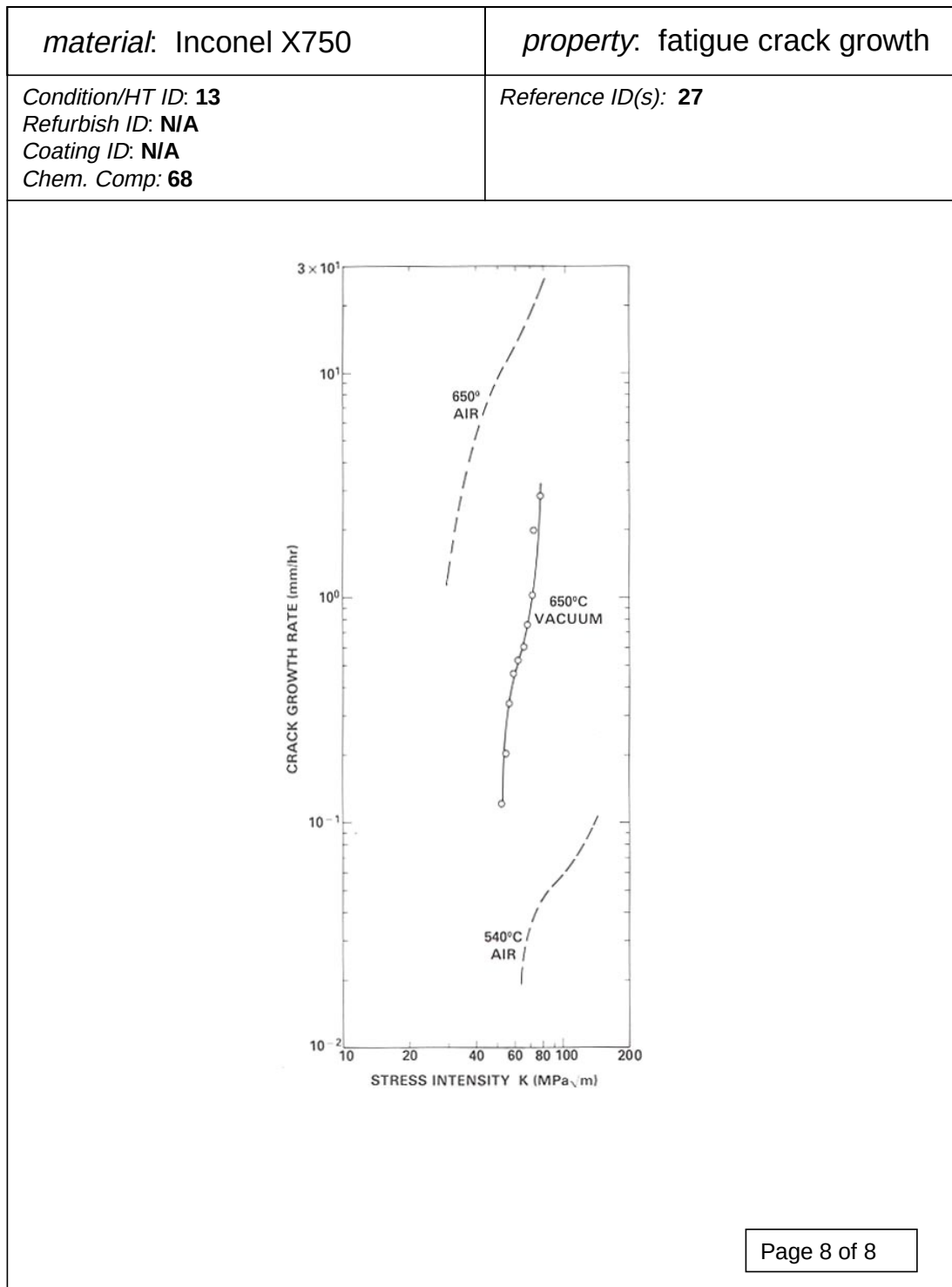


Figure 3-8
Fatigue Crack Growth Behavior at 650°C and 540°C Under Air and Vacuum Conditions.

4

INCONEL 738

Inconel 738

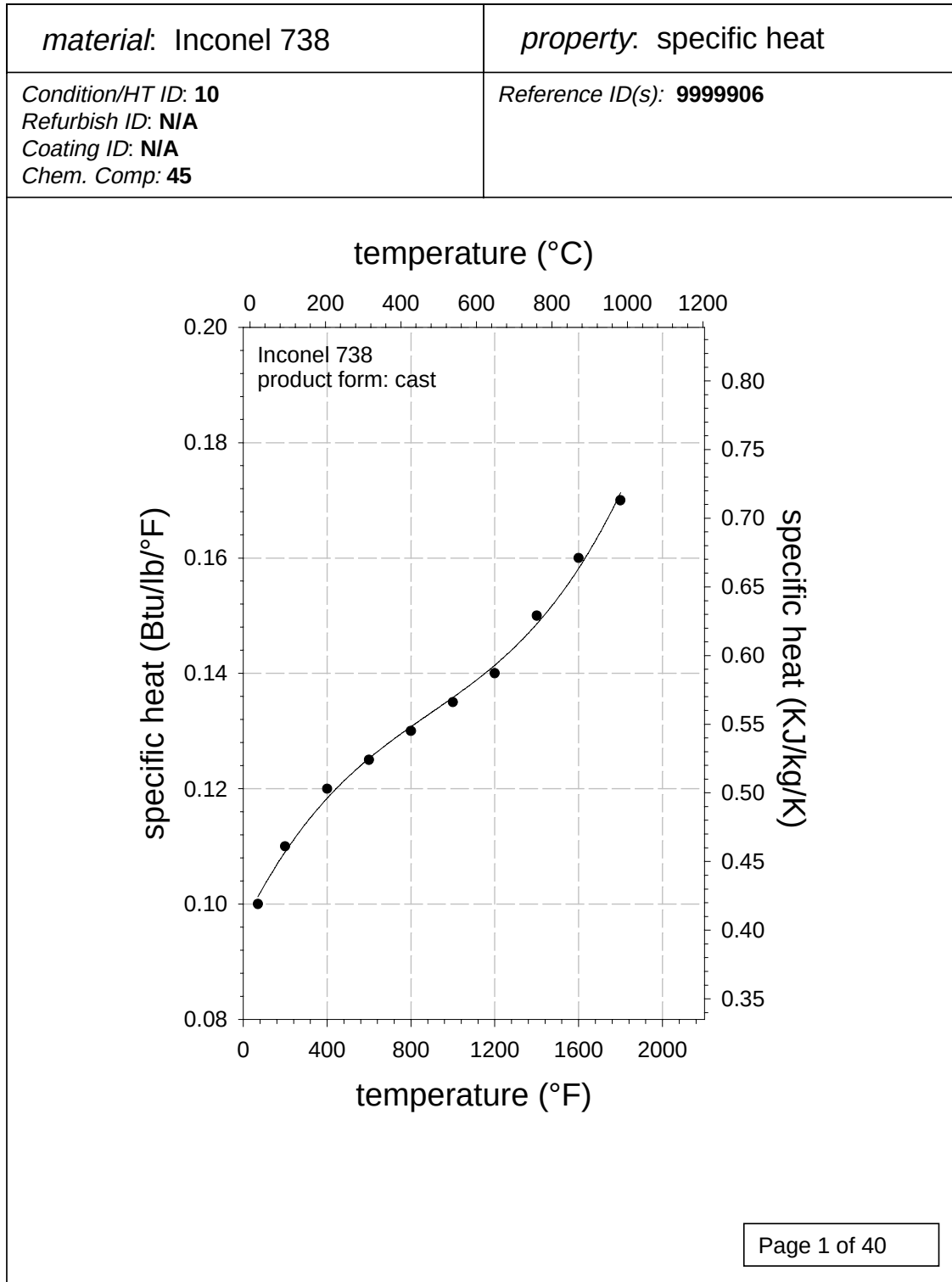


Figure 4-1
Specific Heat as a Function of Temperature.

Inconel 738

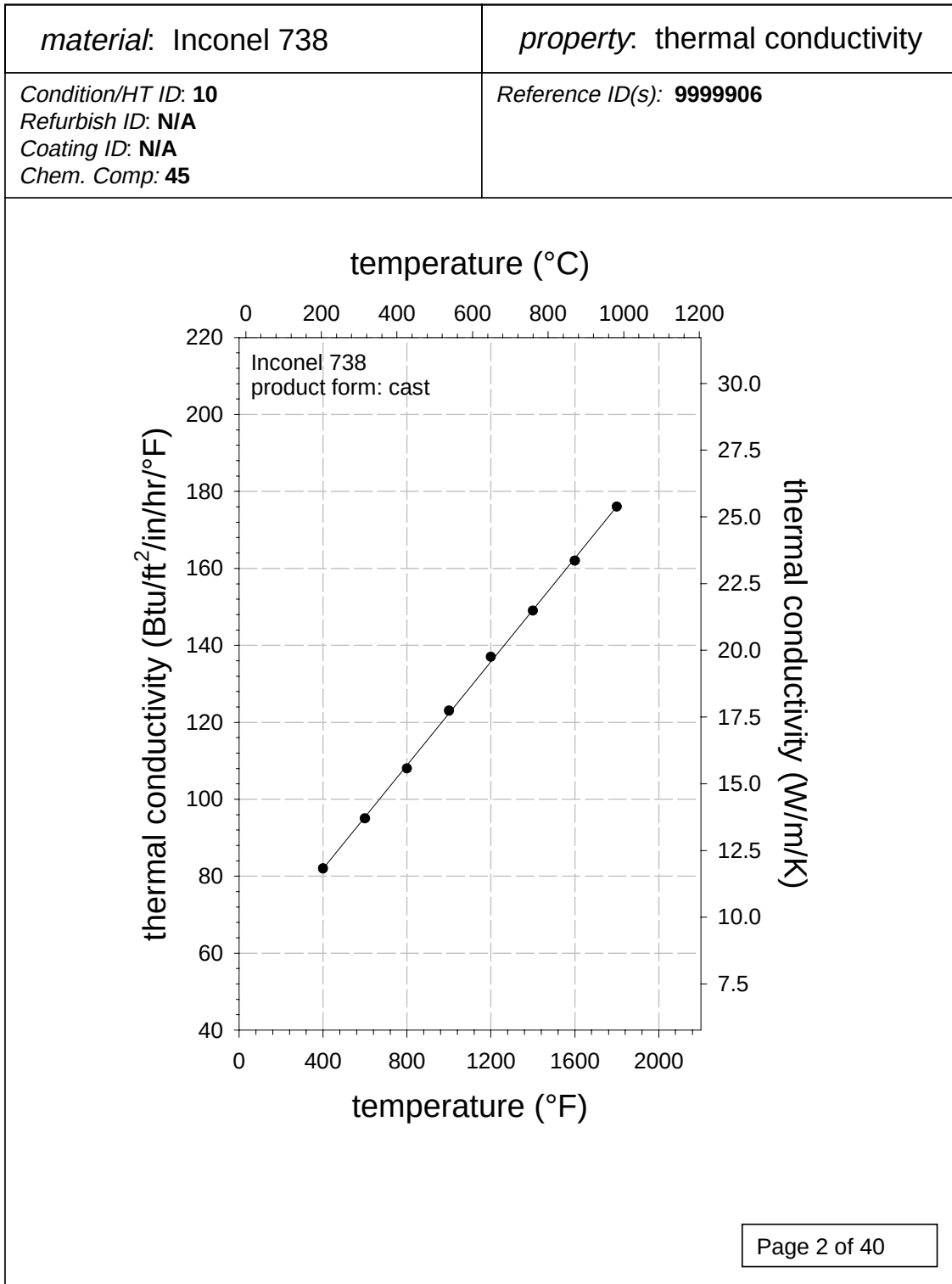


Figure 4-2
Thermal Conductivity as a Function of Temperature.

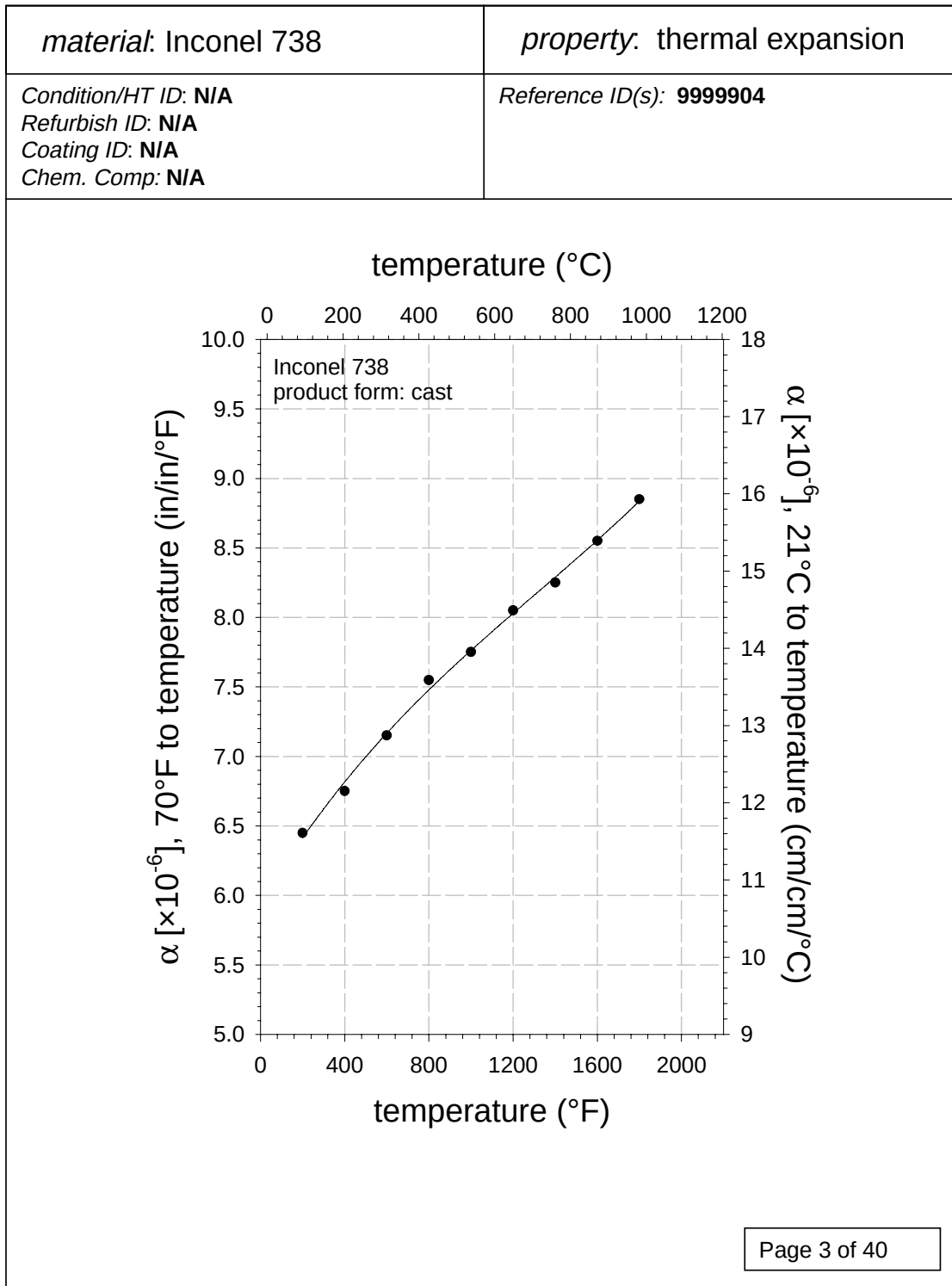


Figure 4-3
Coefficient of Thermal Expansion as a Function of End Temperature.

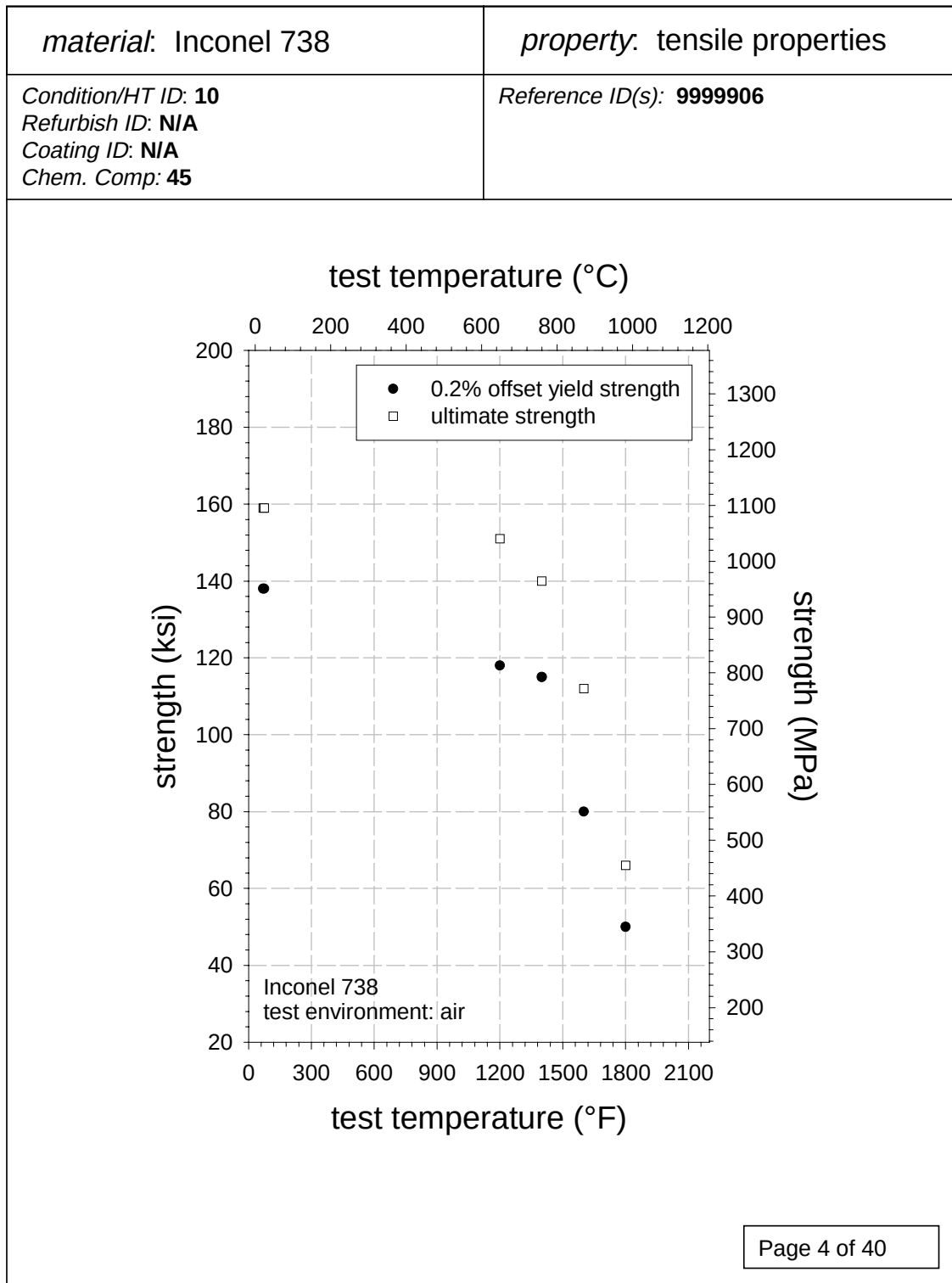


Figure 4-4
Yield and Tensile Strengths as a Function of Temperature.

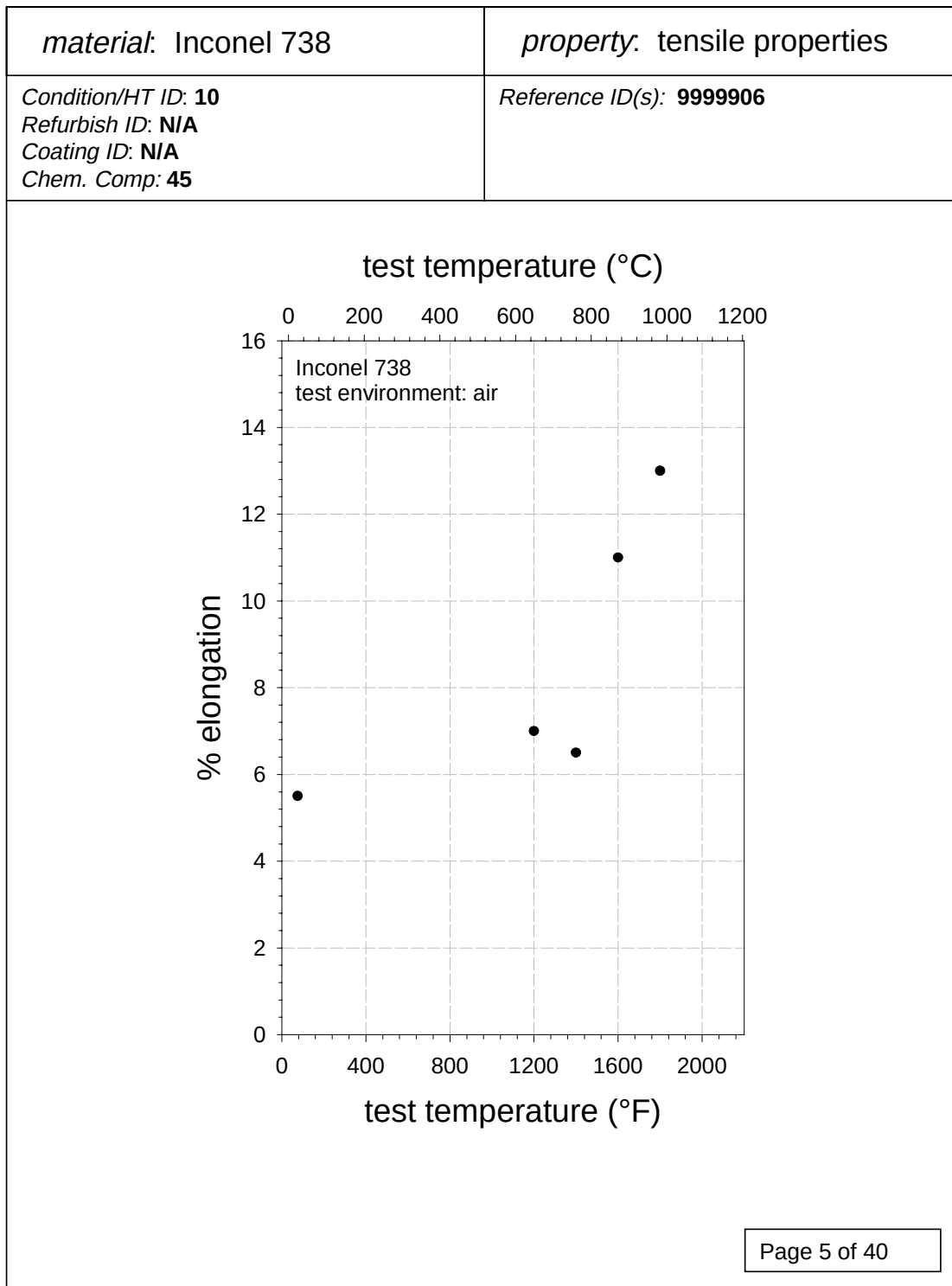


Figure 4-5
Tensile Elongation as a Function of Temperature.

Inconel 738

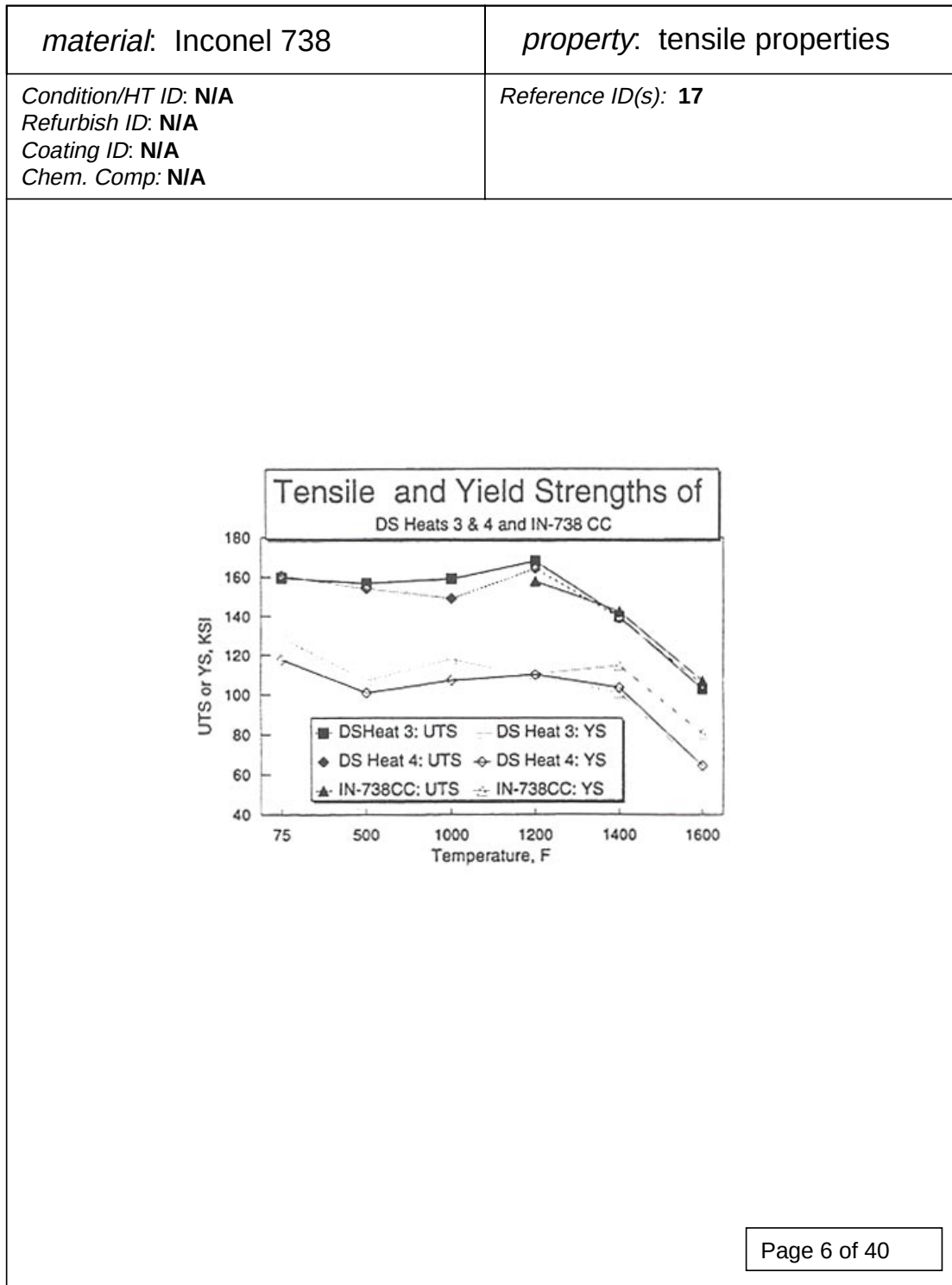


Figure 4-6
Yield and Tensile Strengths as a Function of Temperature.

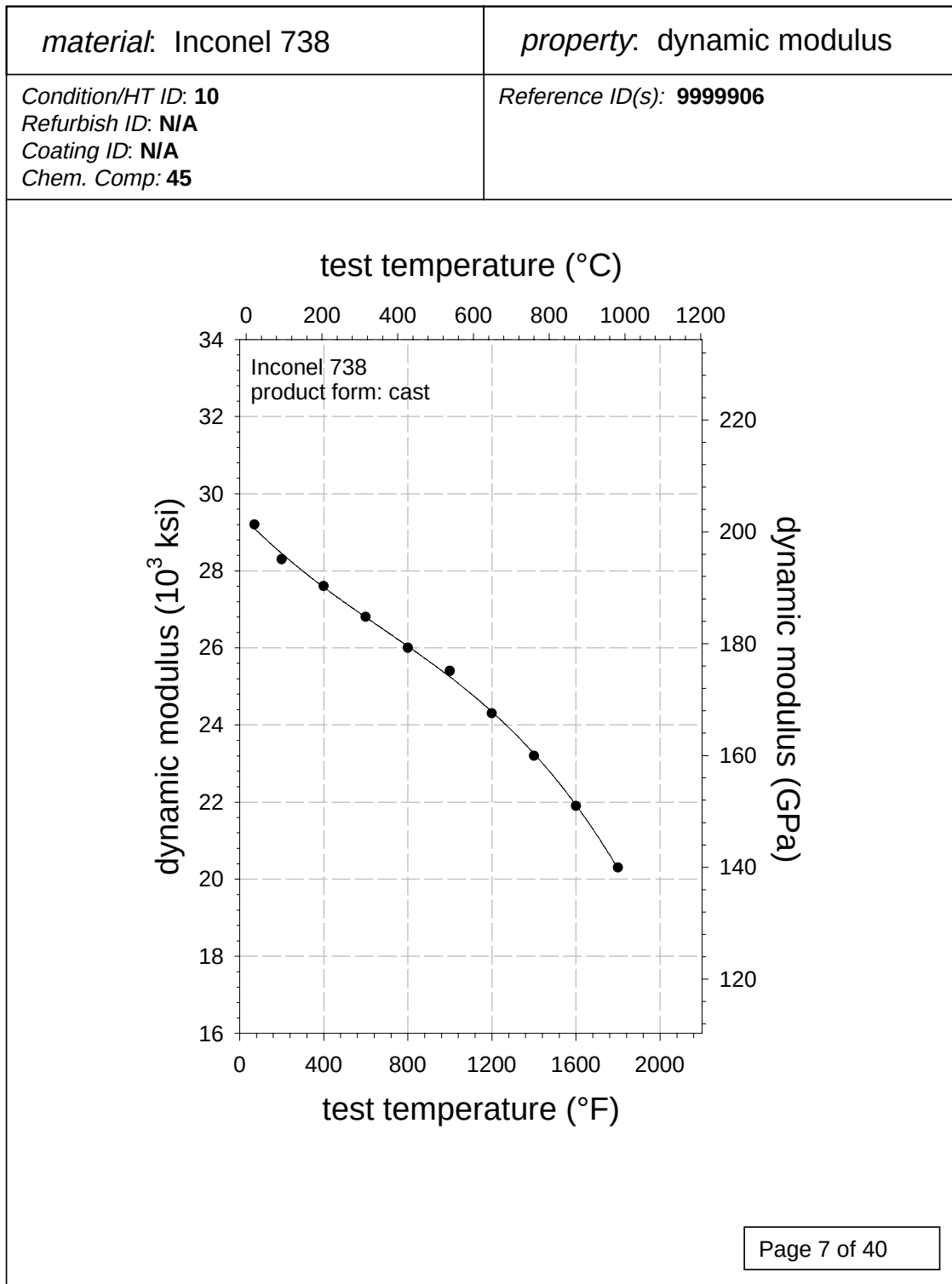


Figure 4-7
Dynamic Modulus as a Function of Temperature.

Inconel 738

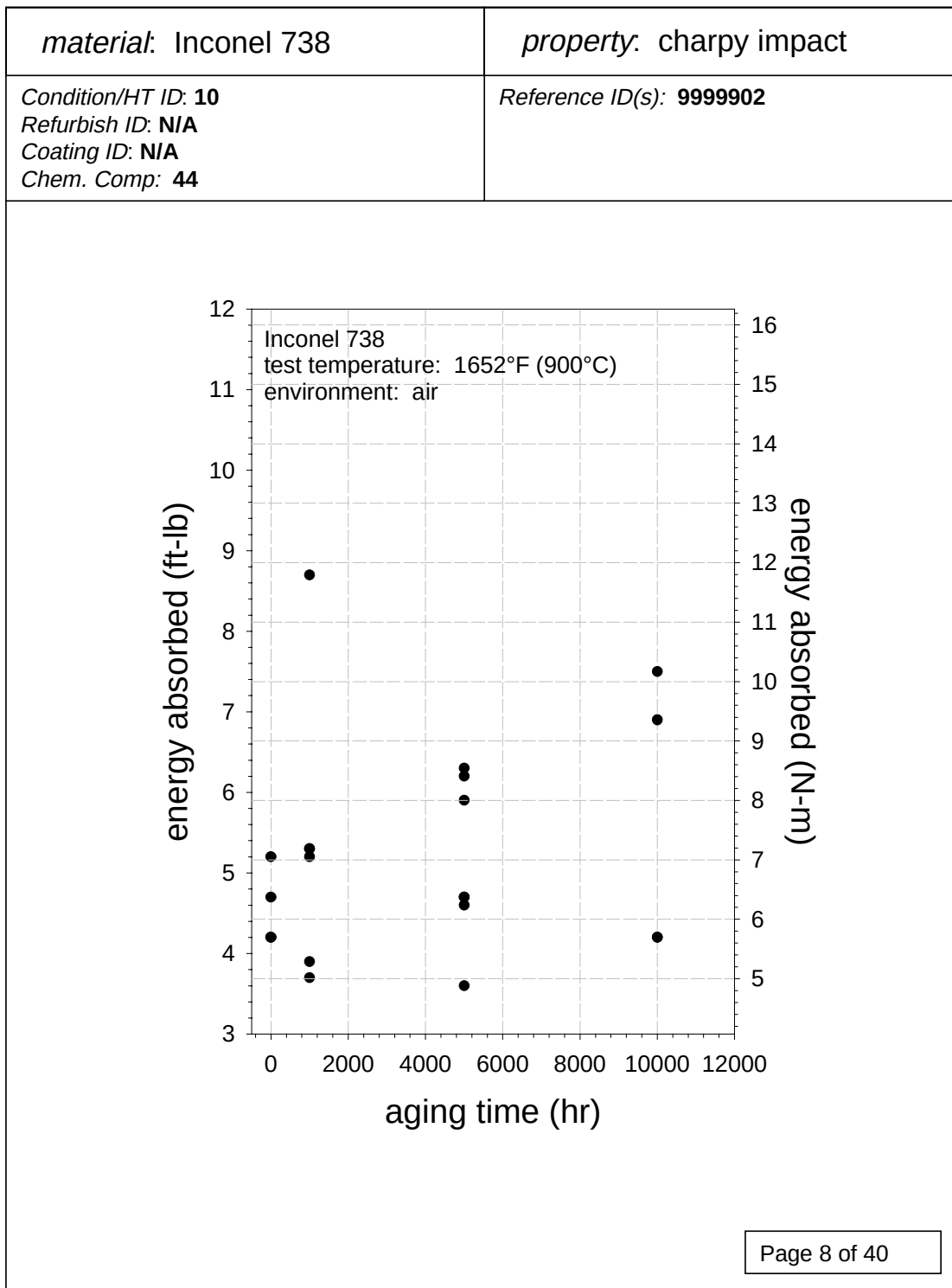


Figure 4-8
Charpy Impact Energy as a Function of Aging Time.

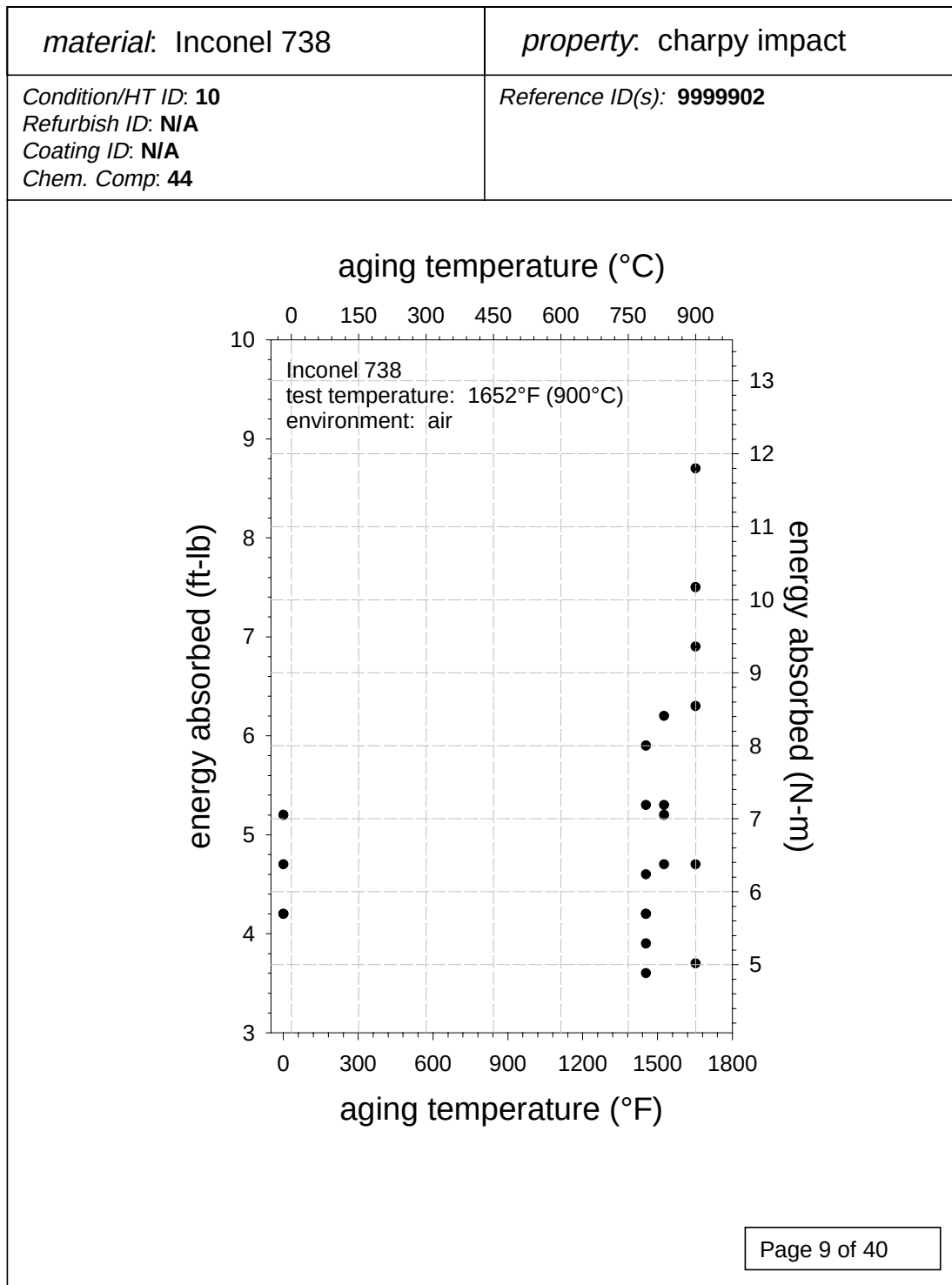


Figure 4-9
Charpy Impact Energy as a Function of Aging Temperature.

Inconel 738

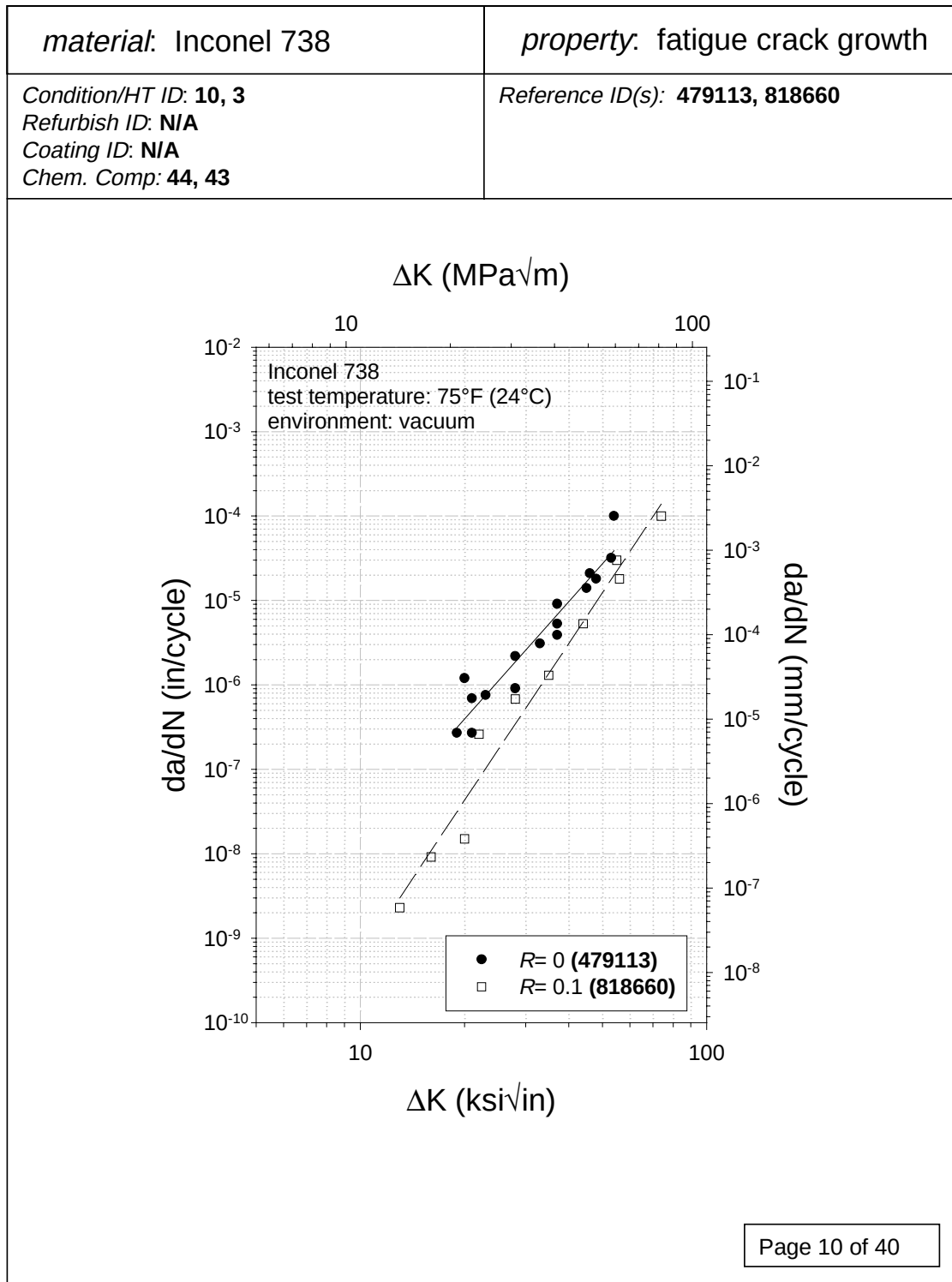


Figure 4-10
Fatigue Crack Growth Behavior at Room Temperature Under Vacuum Conditions. (Low R).

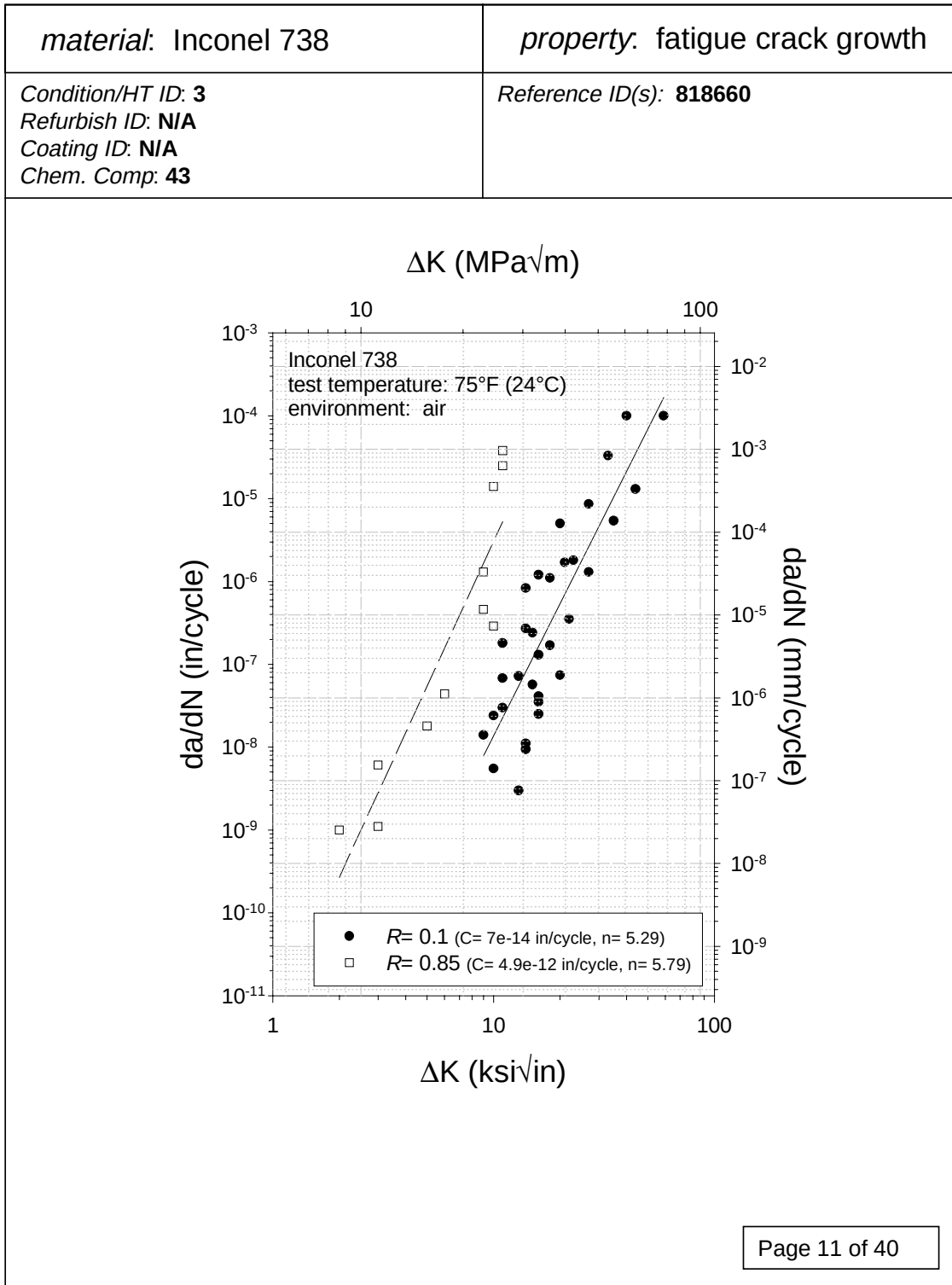


Figure 4-11
Fatigue Crack Growth Behavior at R = 0.1 and 0.85 (Room Temperature, Air).

Inconel 738

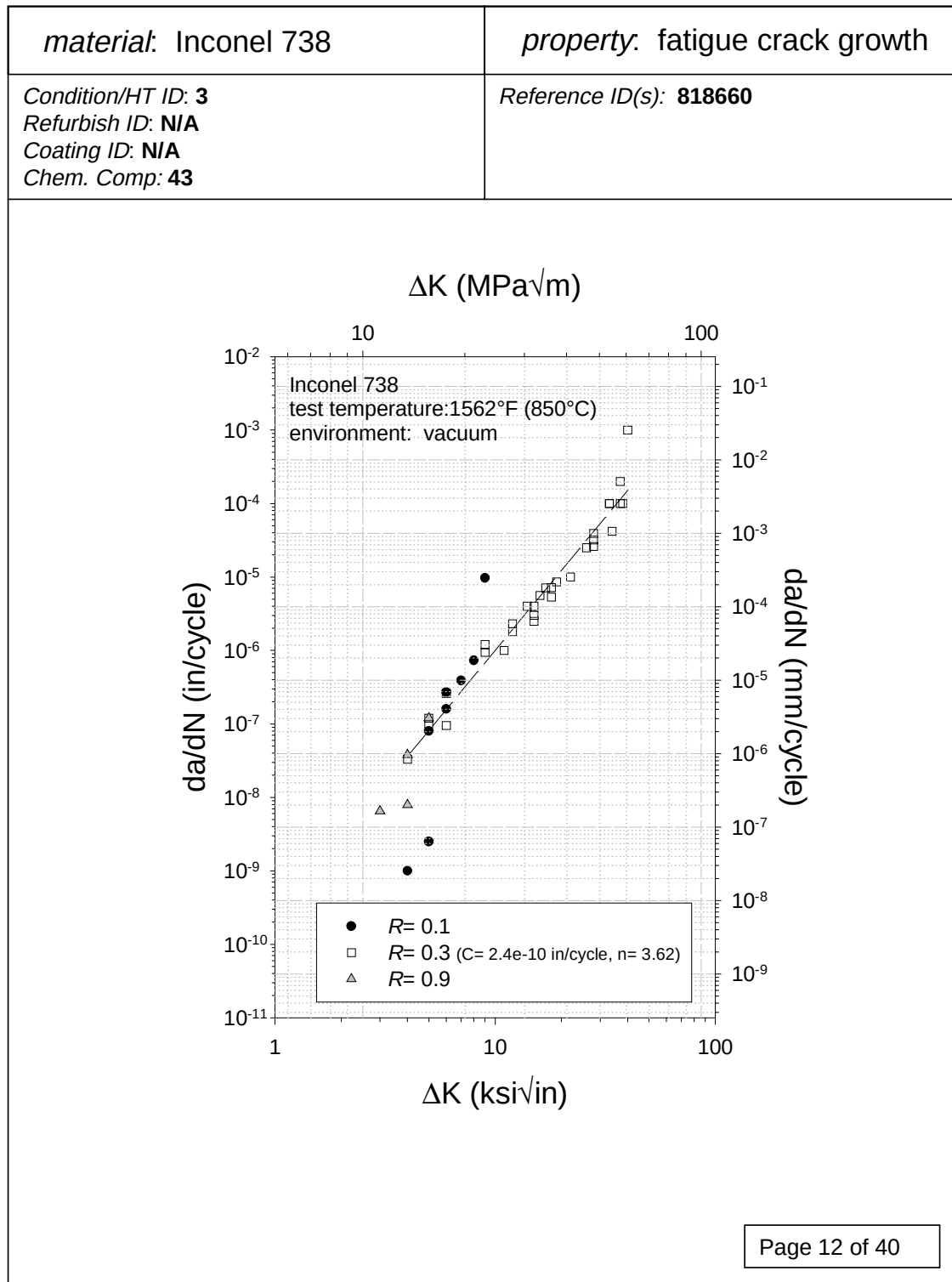


Figure 4-12
Fatigue Crack Growth Behavior at 1562°F.

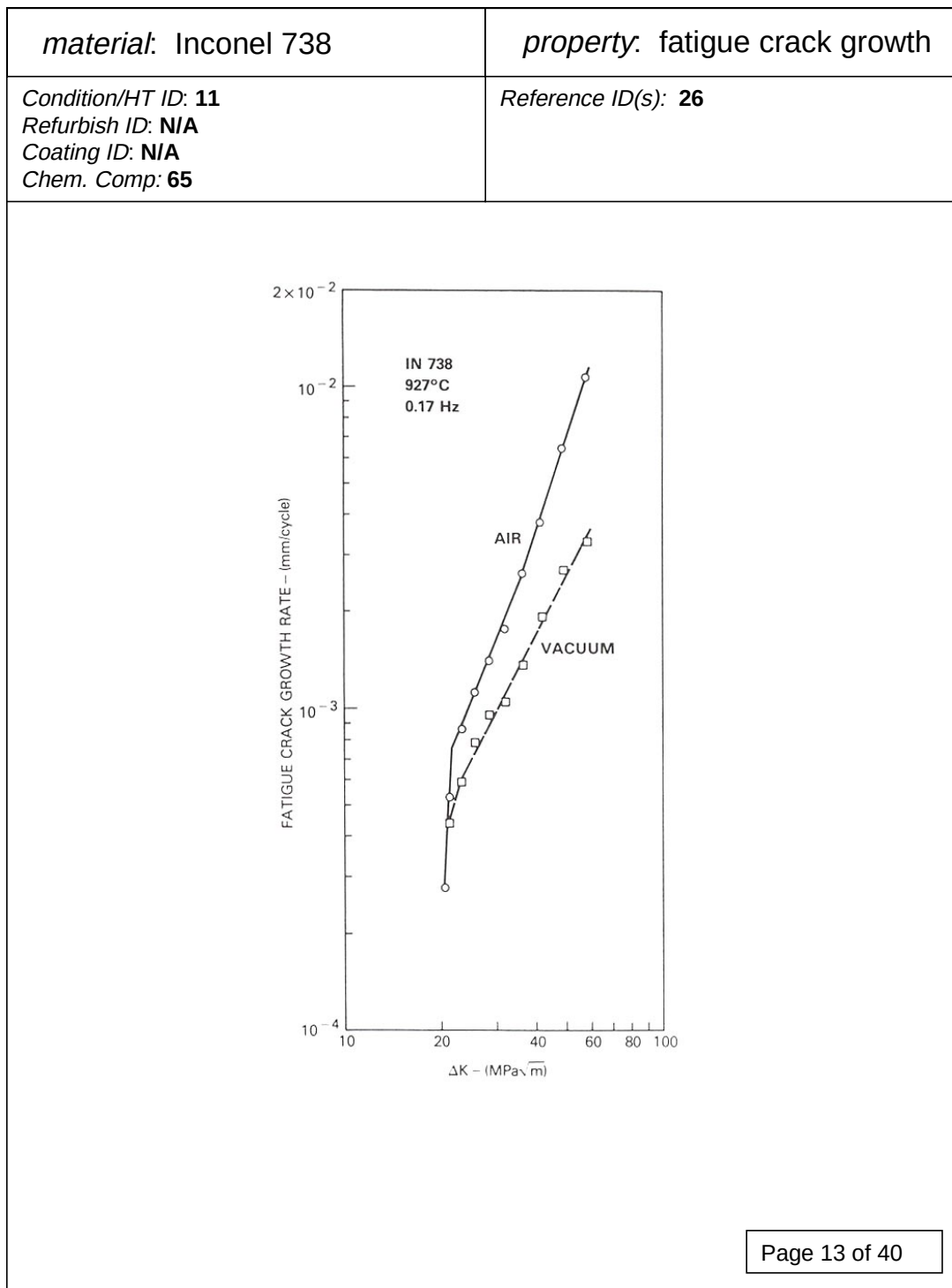


Figure 4-13
Fatigue Crack Growth Rate as a Function of ΔK in IN-738 at 927°C in Air and in Vacuum.

Inconel 738

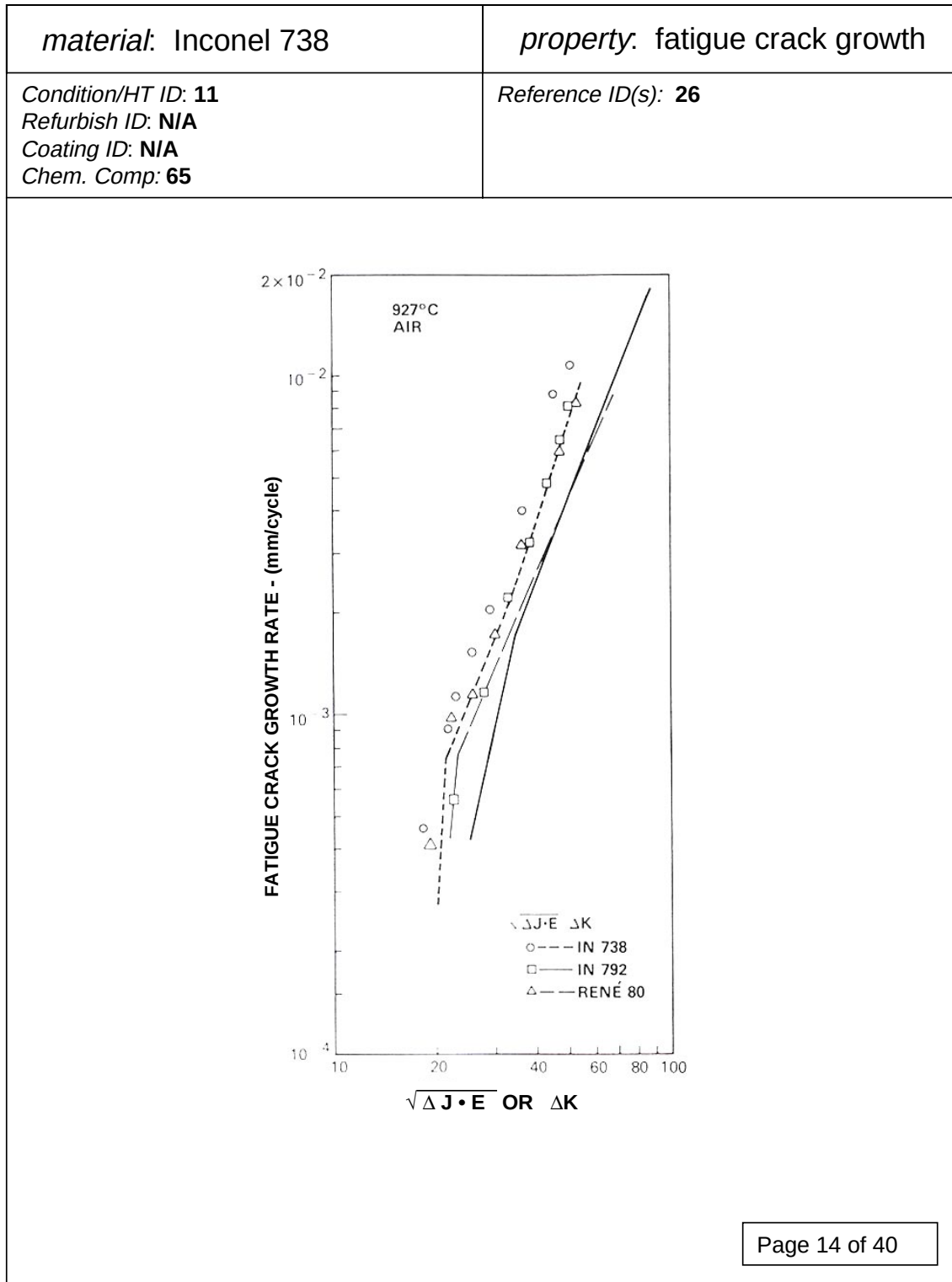


Figure 4-14
Comparison of Fatigue Crack Growth Rate for Three Alloys.

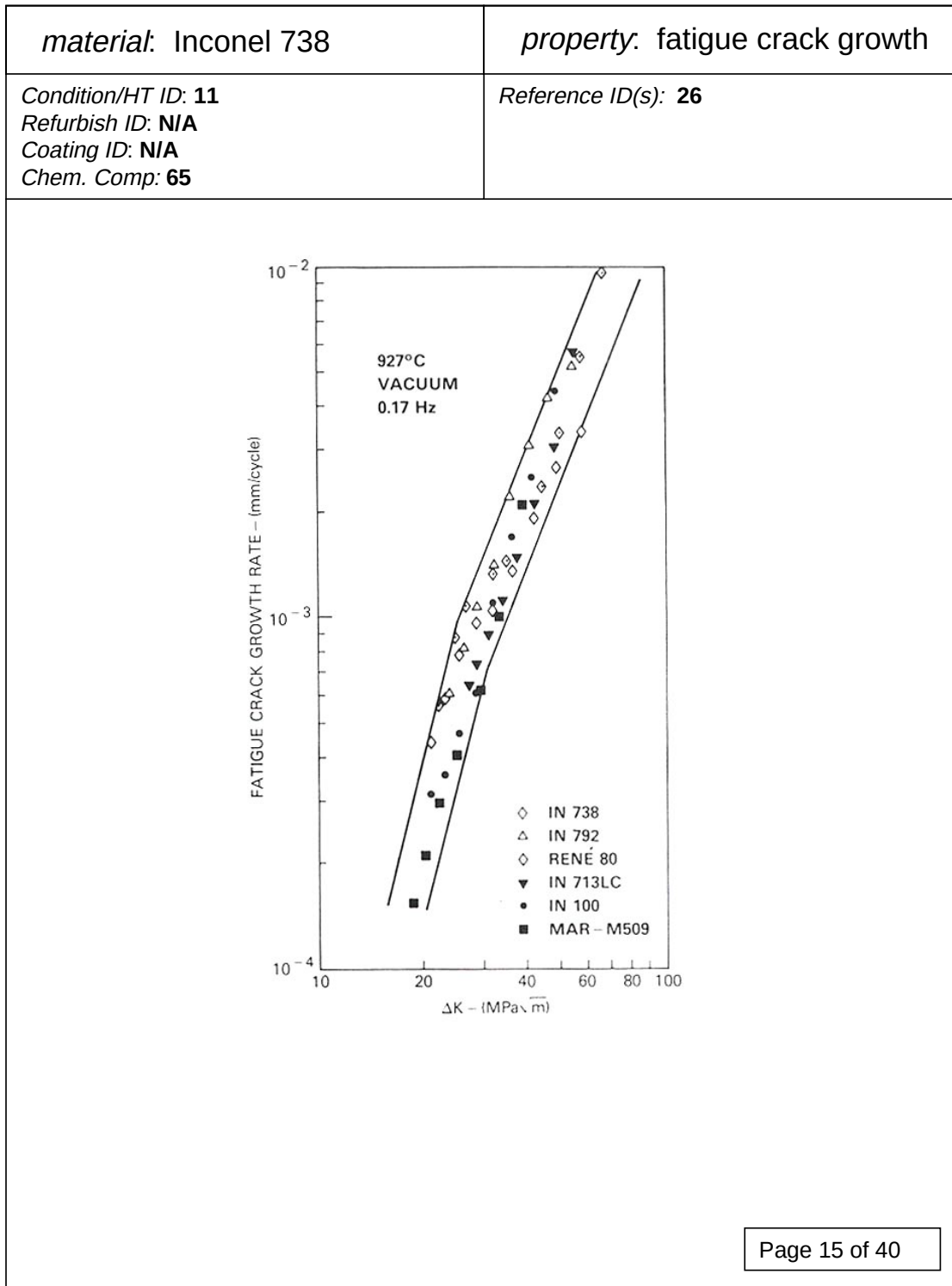


Figure 4-15
Fatigue Crack Growth Rate in Superalloys at 927°C in Vacuum.

Inconel 738

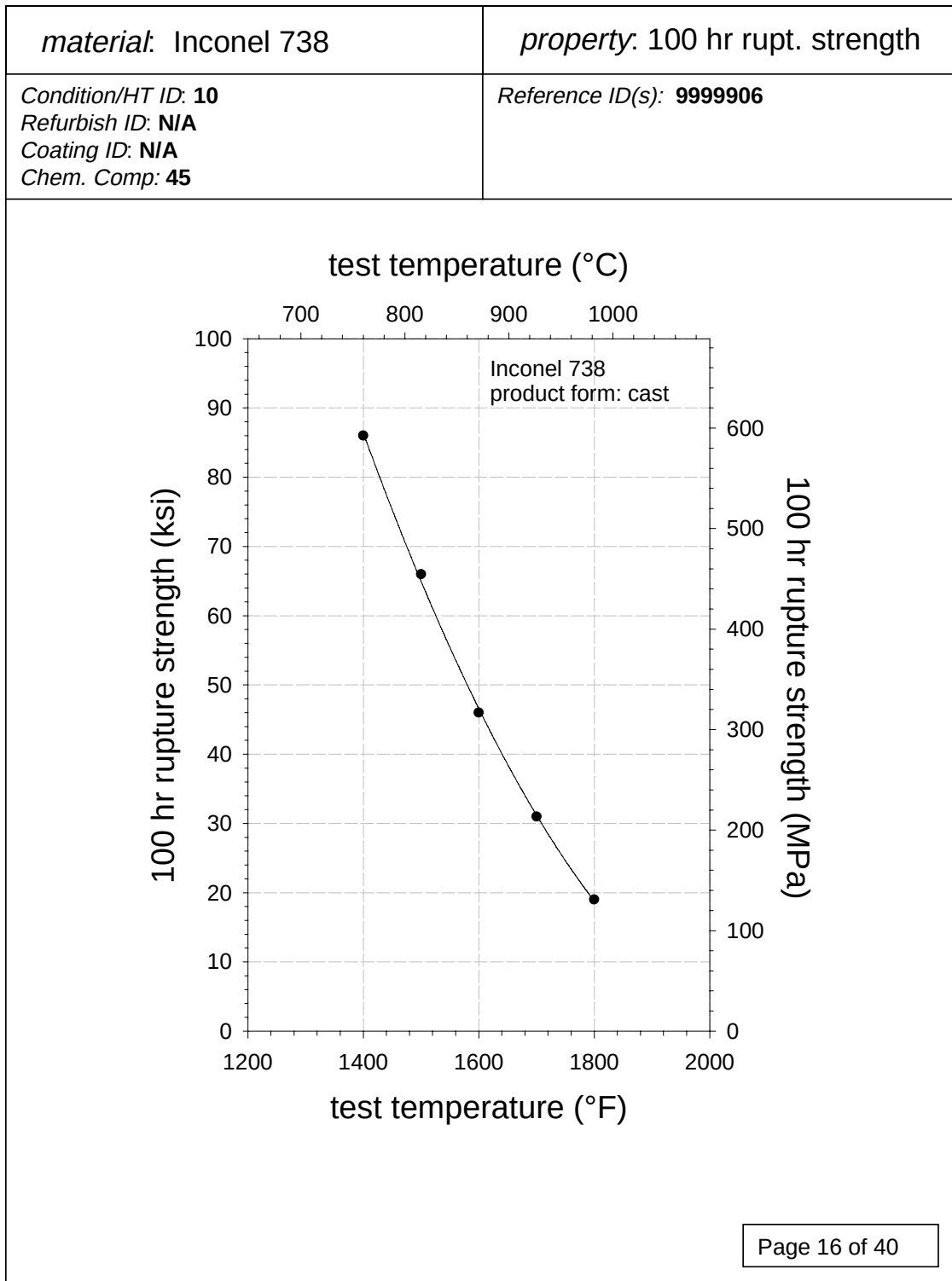


Figure 4-16
100 hr Rupture Strength as a Function of Temperature.

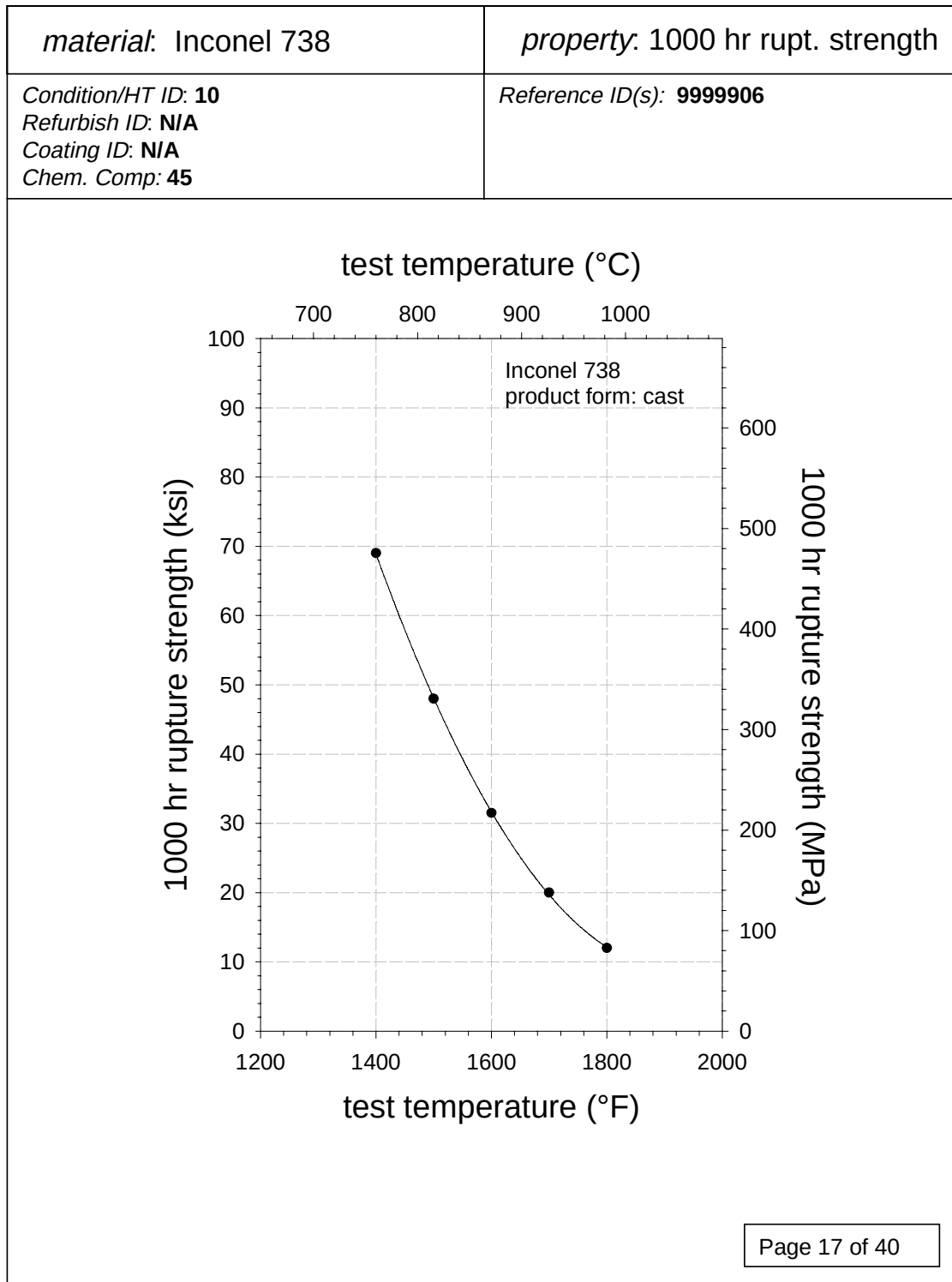


Figure 4-17
1000 hr Rupture Strength as a Function of Temperature.

Inconel 738

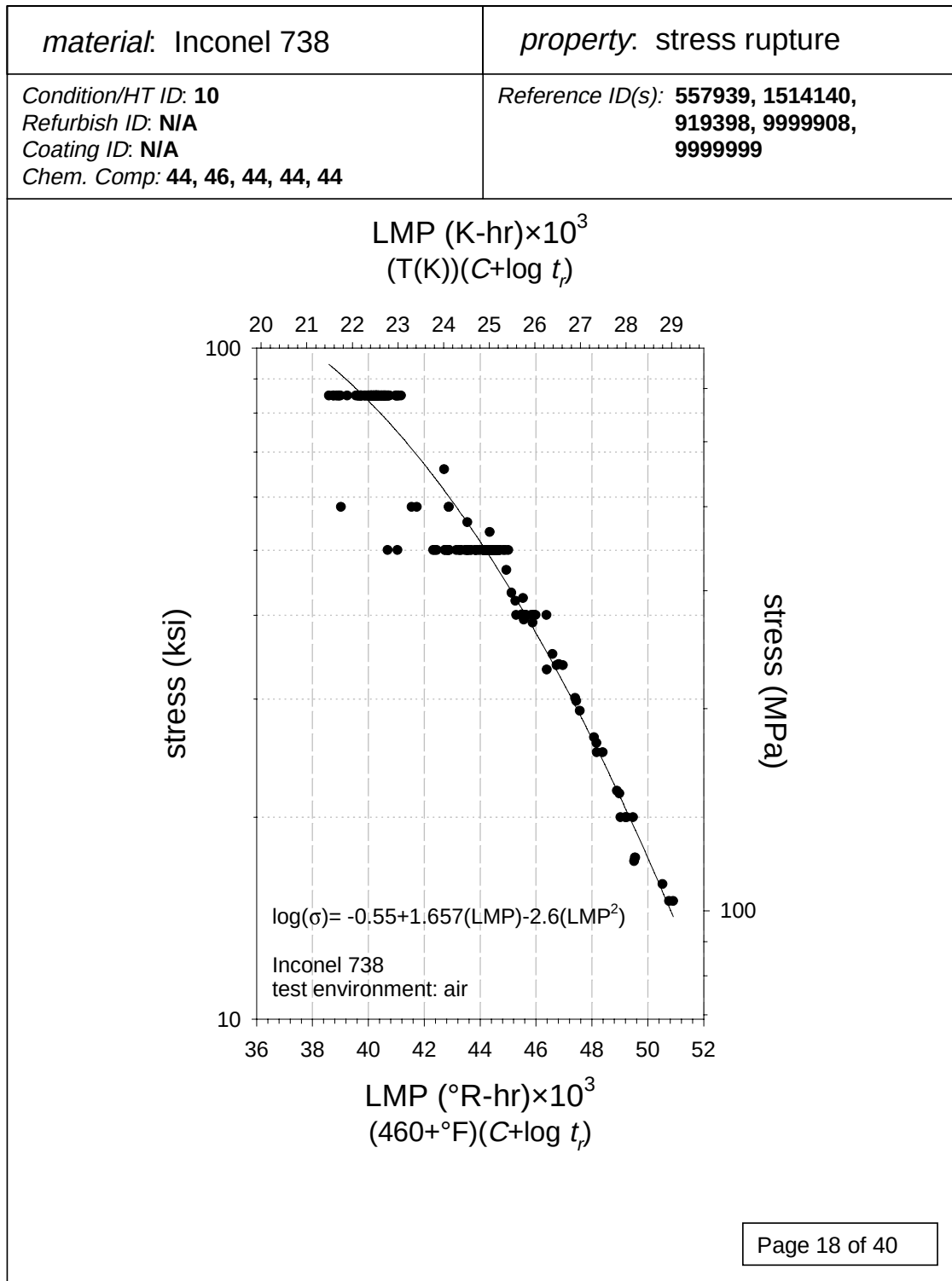


Figure 4-18
Larson-Miller Plot for Inconel 738.

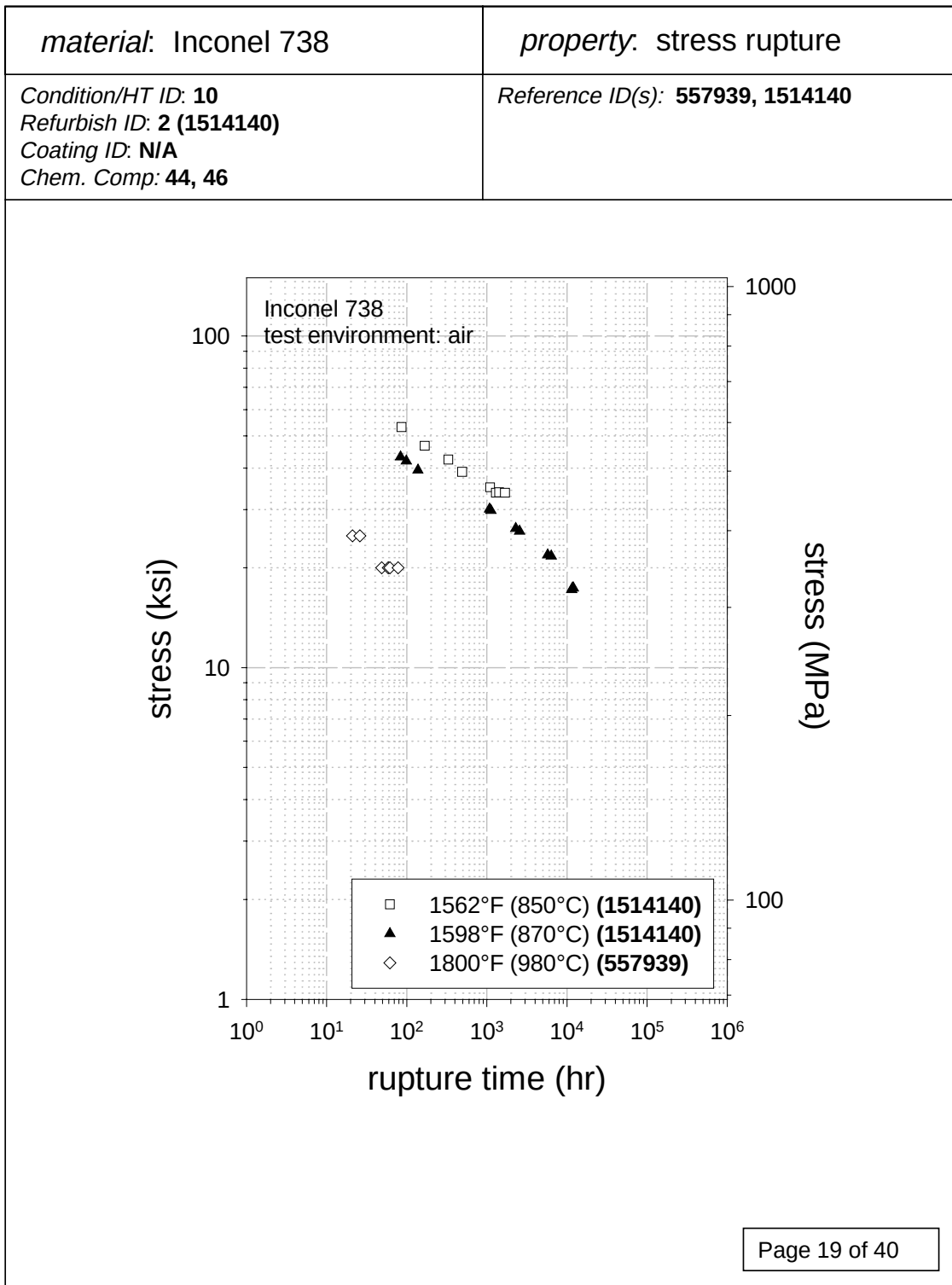


Figure 4-19
Stress vs. Rupture Time at Three Elevated Temperatures.

Inconel 738

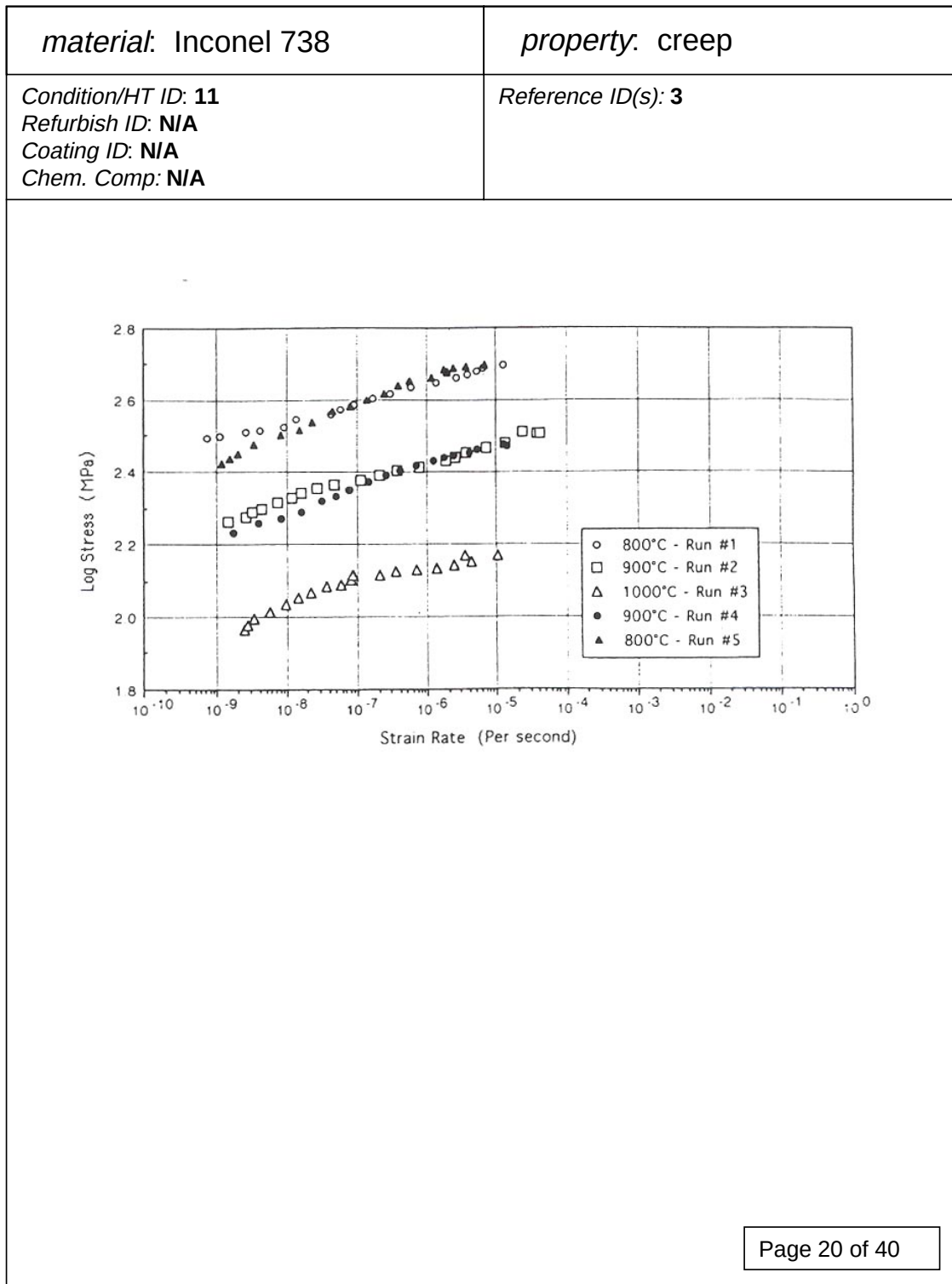


Figure 4-20
Stress vs. Strain-Rate at Three Temperatures Including Repeat Runs.

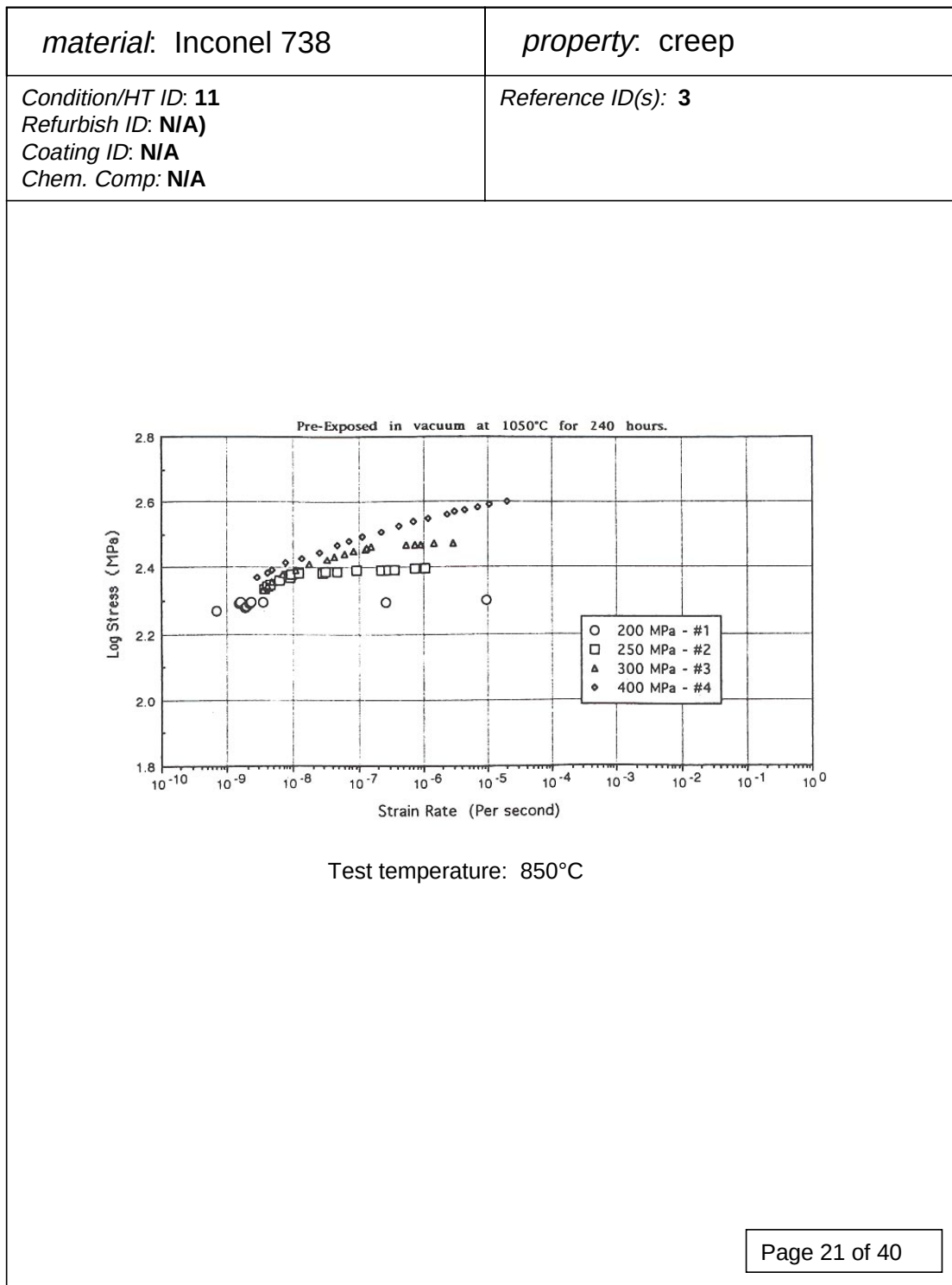


Figure 4-21
Multiple Relaxation Runs at 850°C Showing Transient Effects for Low Stresses.

Inconel 738

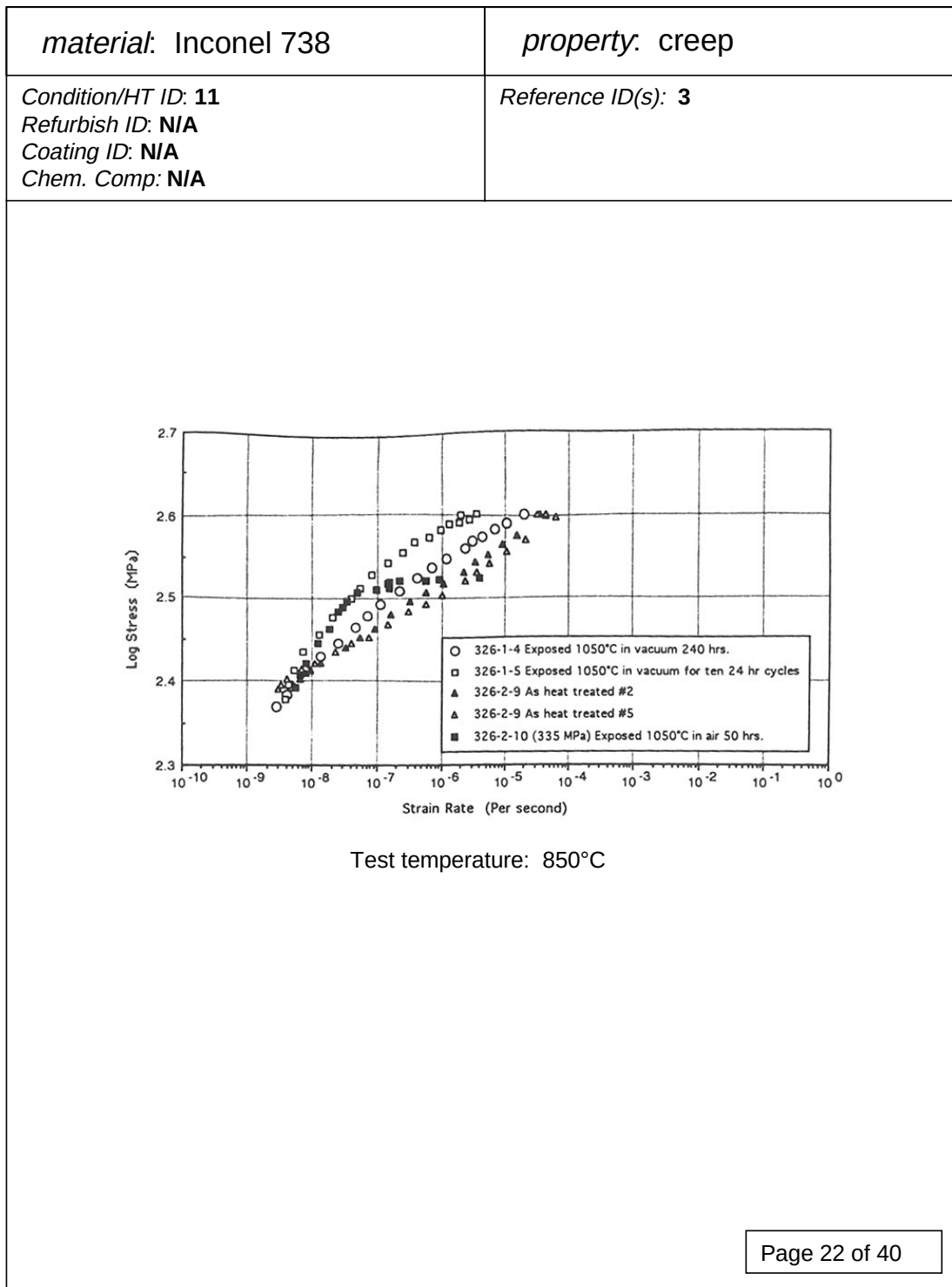


Figure 4-22
Creep Data at 850°C for Various Initial Thermal Treatments.

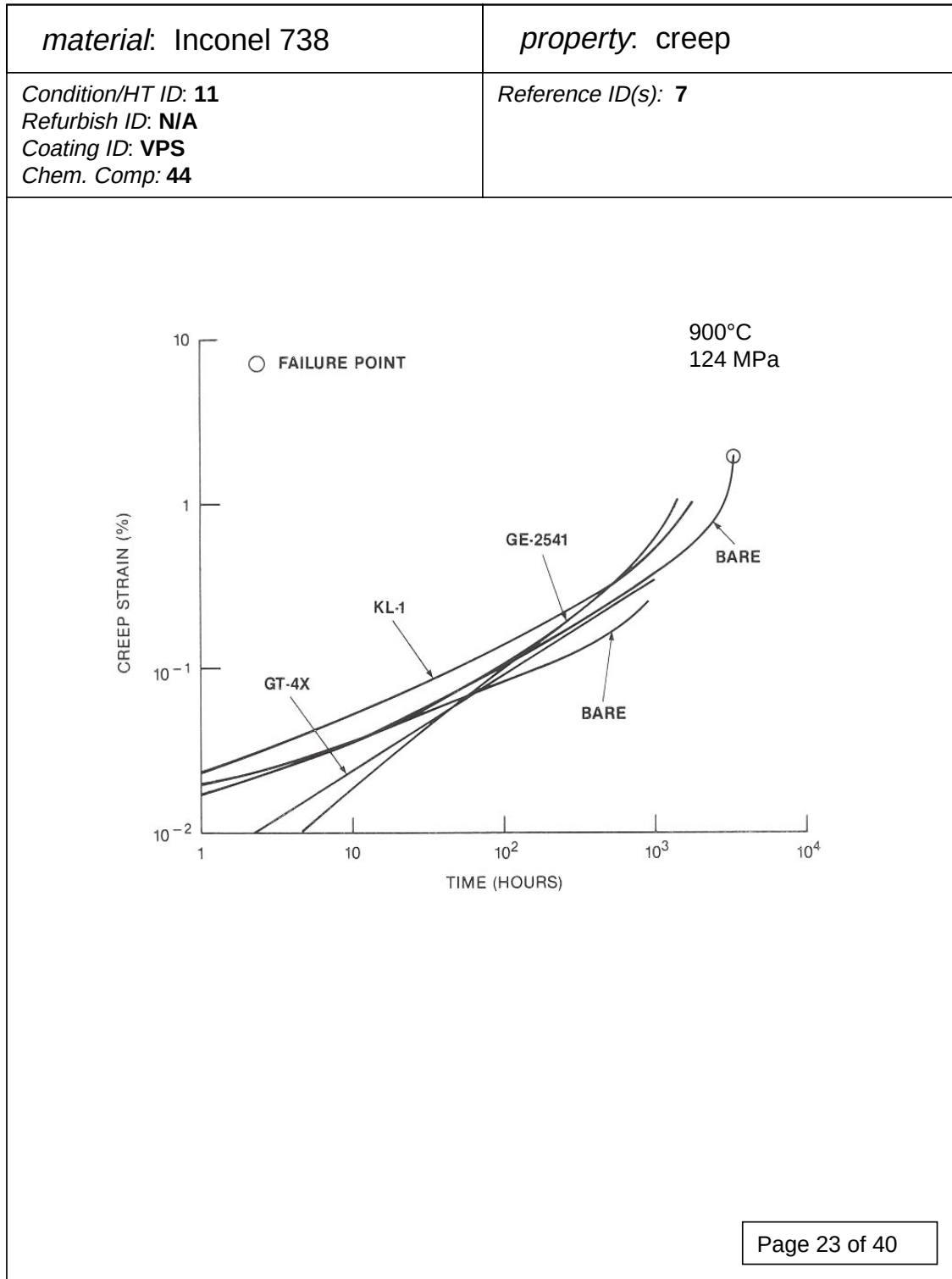


Figure 4-23
IN-738 VPS Coated Creep Test Results at 900°C/124 MPa.

Inconel 738

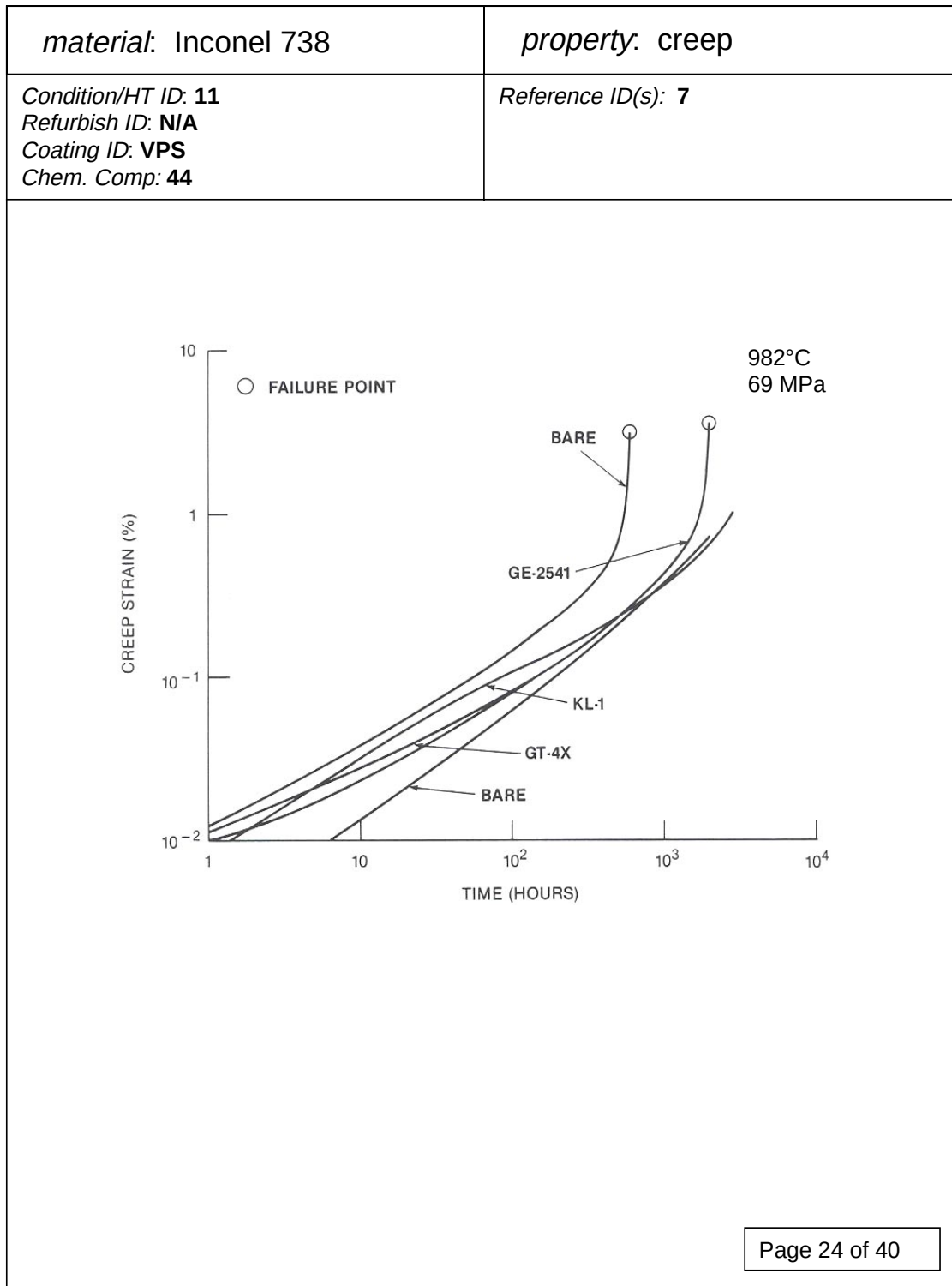


Figure 4-24
IN-738 VPS Coated Creep Test Results at 982°C/69 MPa.

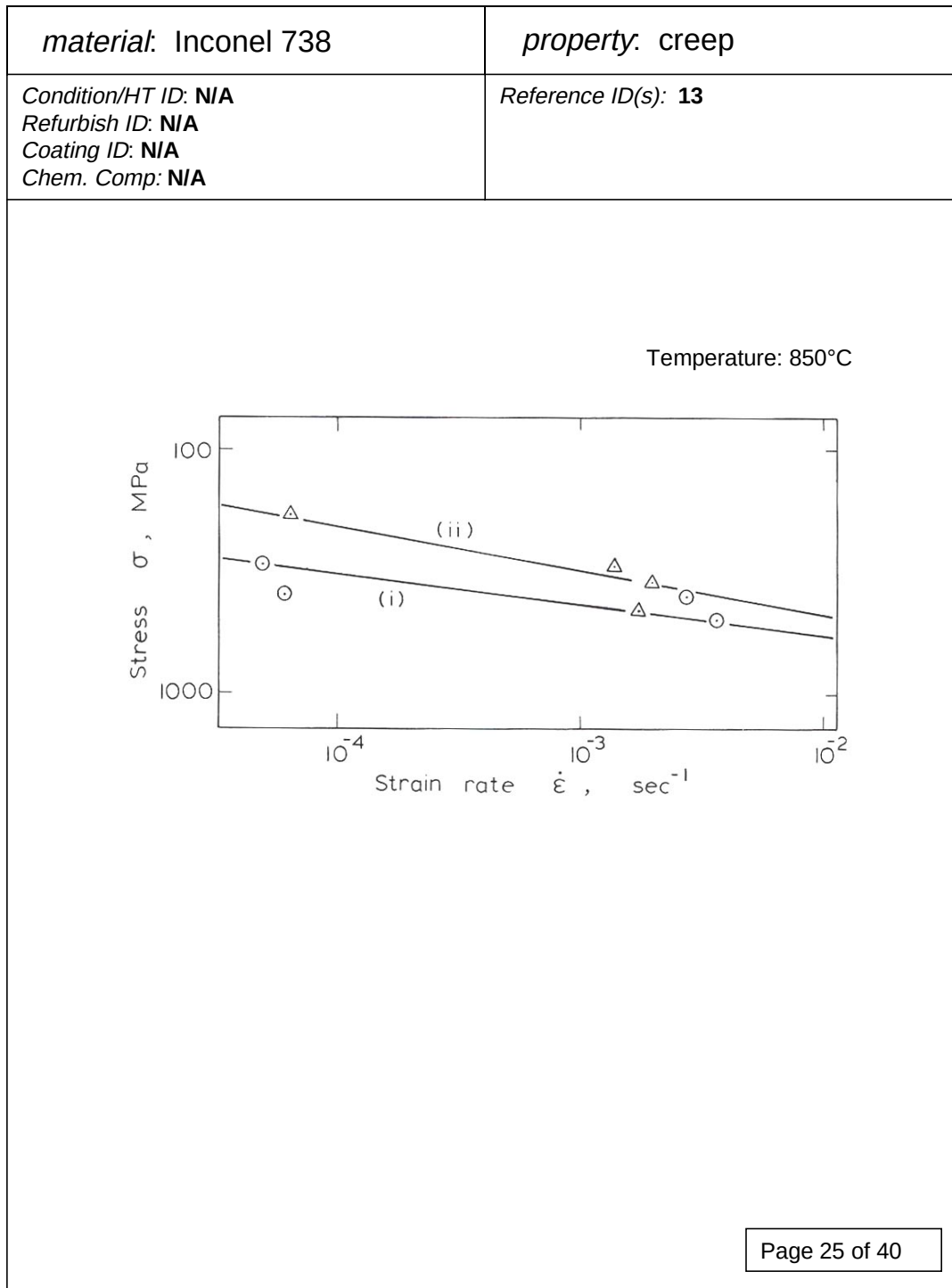


Figure 4-25
Strain Rate vs. Stress for IN738LC at 850°C in Tests Containing (i) pp and pc and (ii) pp and cp.

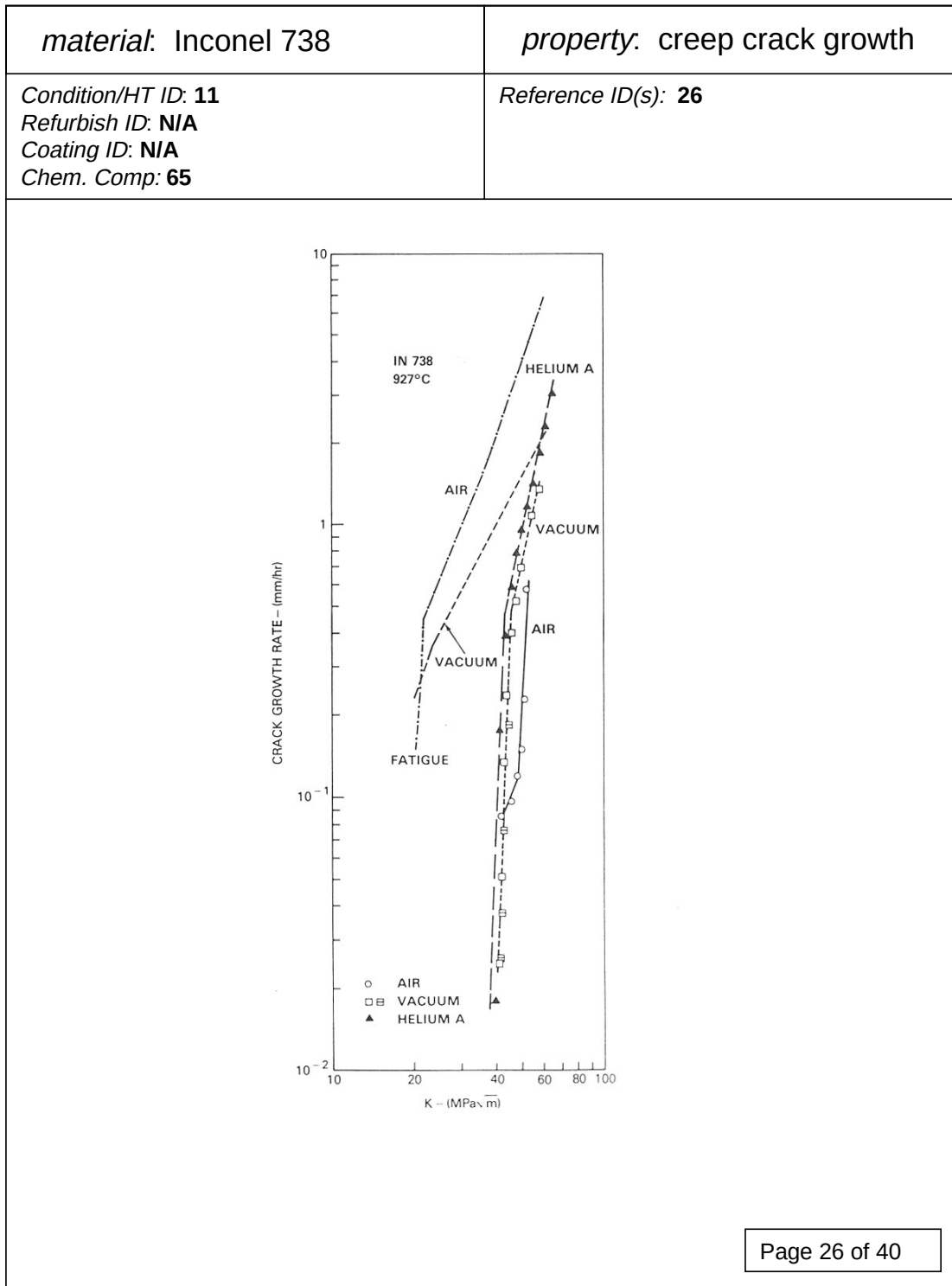


Figure 4-26
Influence of Environment on Creep Crack Growth Rate in IN-738 at 927°C and Comparison with Fatigue Crack Growth Rate Converted to Time Domain.

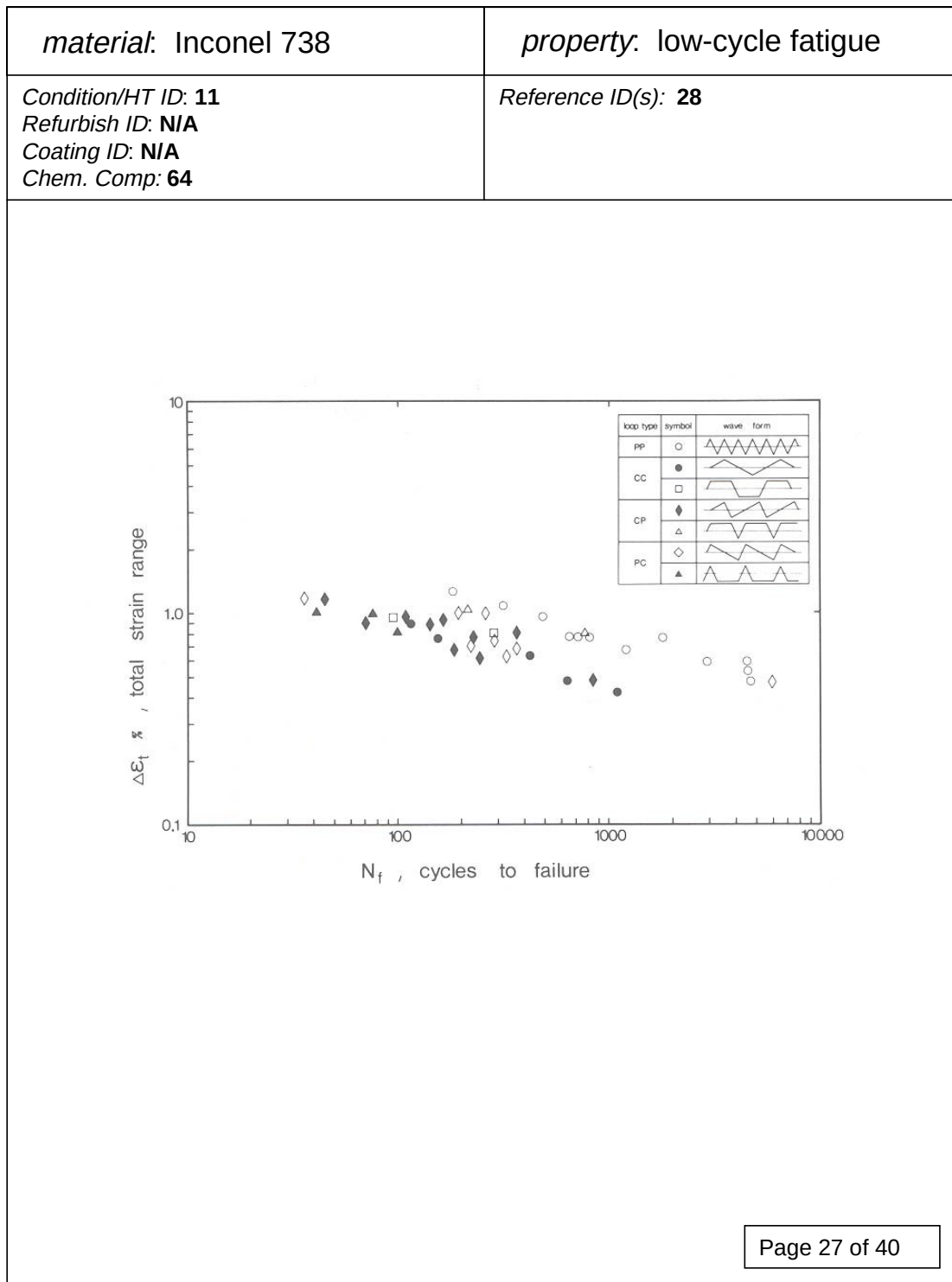


Figure 4-27
Total Strain Range vs. Life to Failure.

Inconel 738

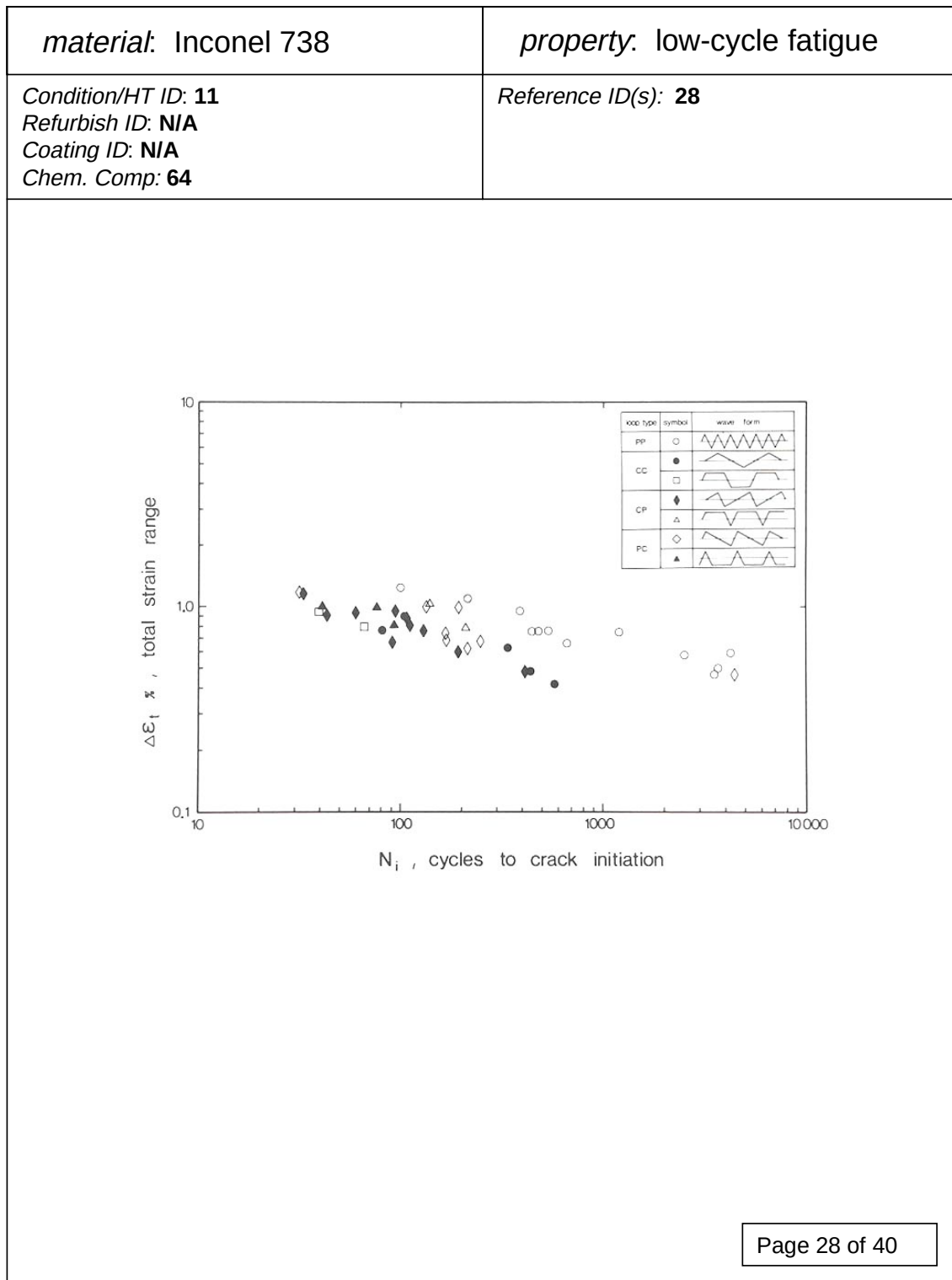


Figure 4-28
Total Strain Range vs. Life to Crack Initiation.

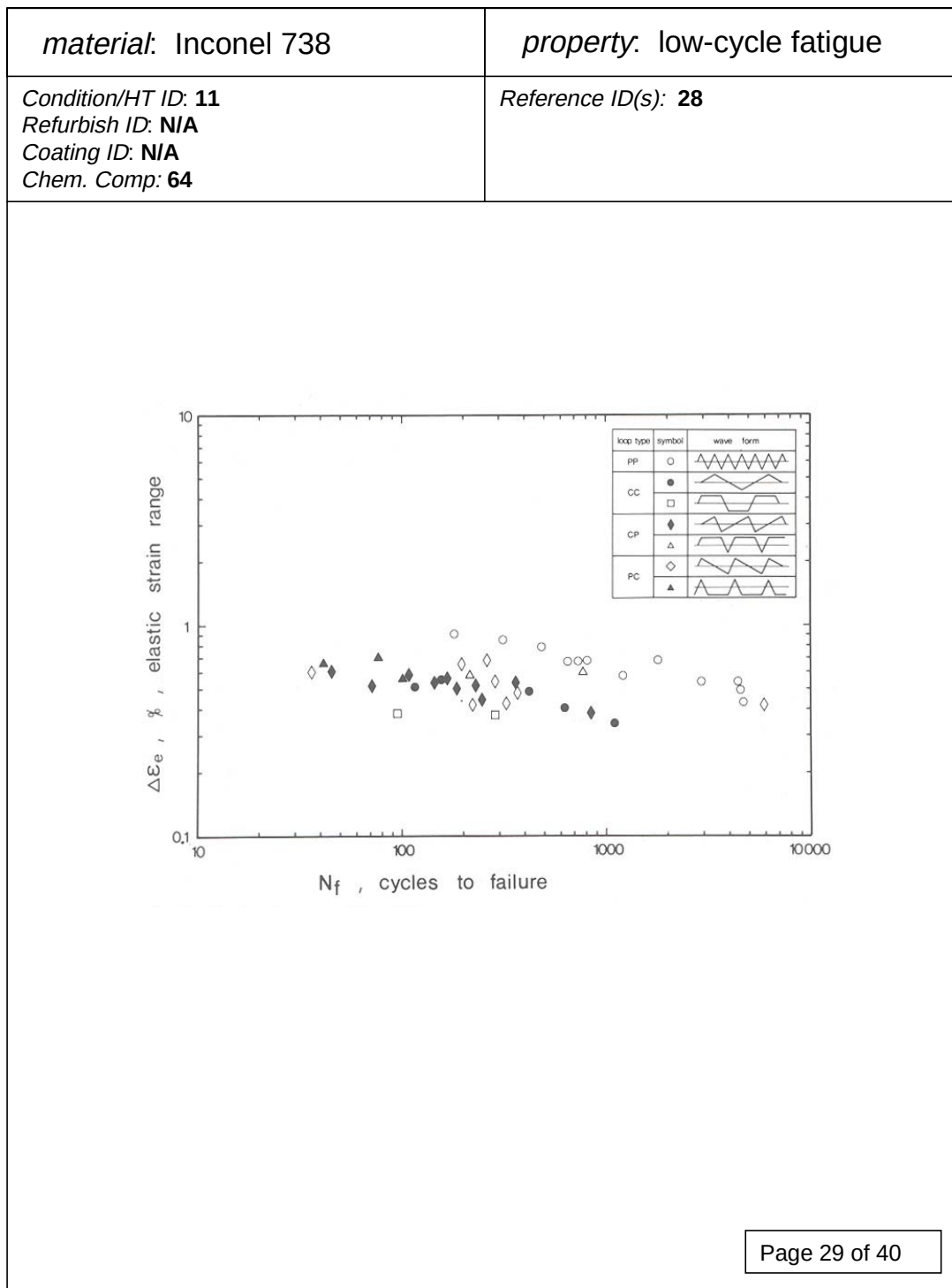


Figure 4-29
Elastic Strain Range vs. Life to Failure.

Inconel 738

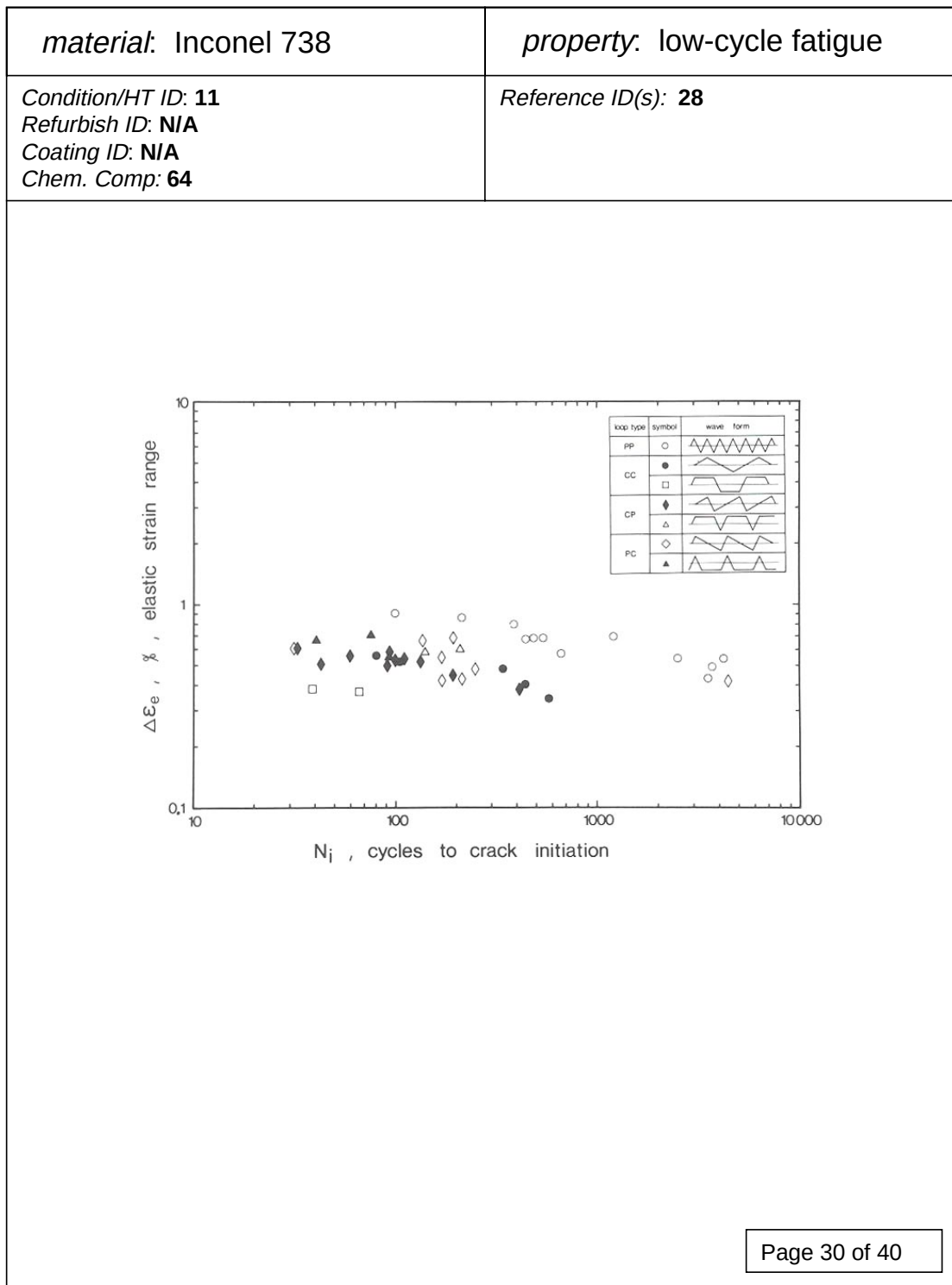


Figure 4-30
Elastic Strain Range vs. Life to Crack Initiation.

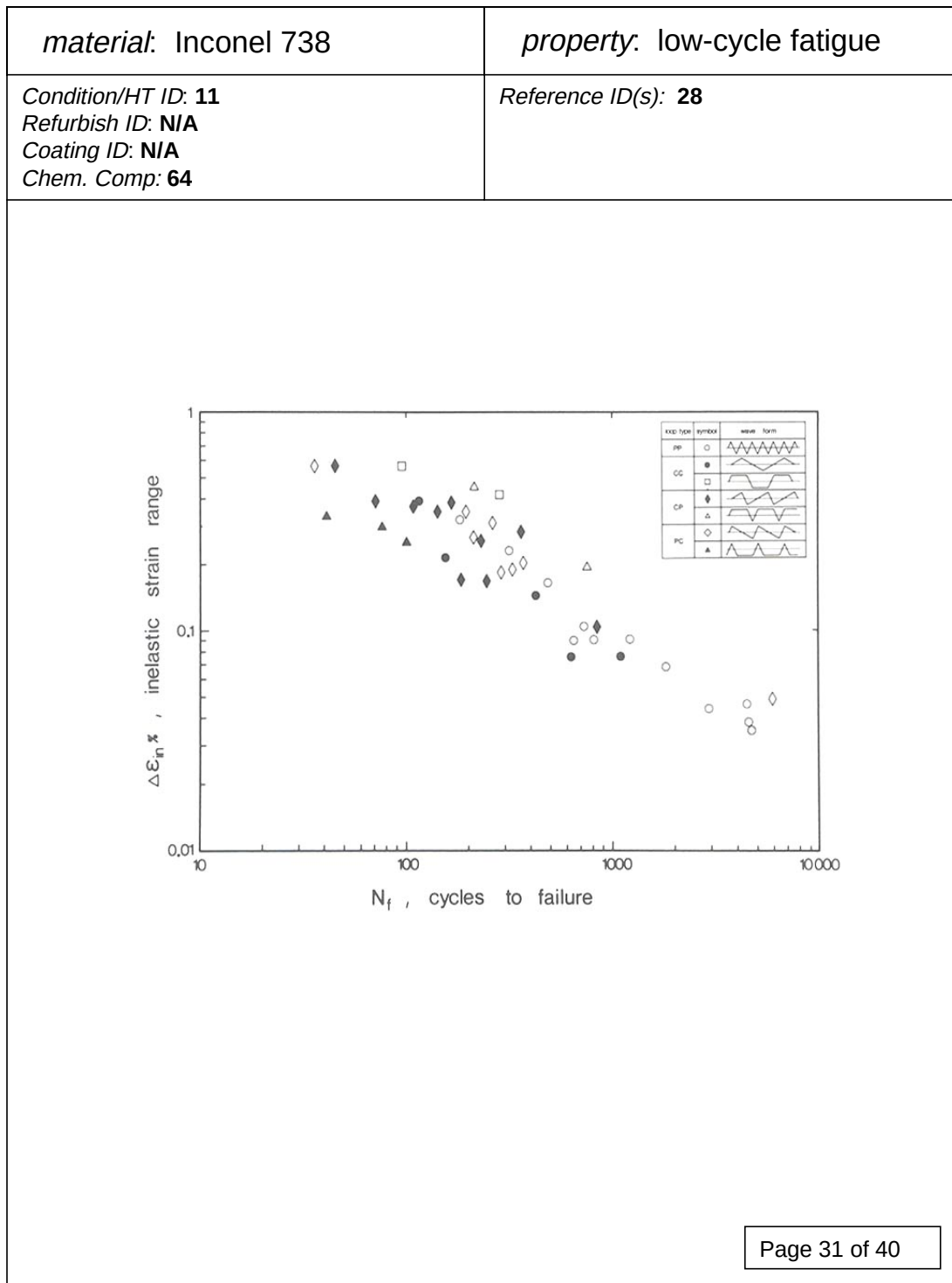


Figure 4-31
Inelastic Strain Range vs. Life to Failure.

Inconel 738

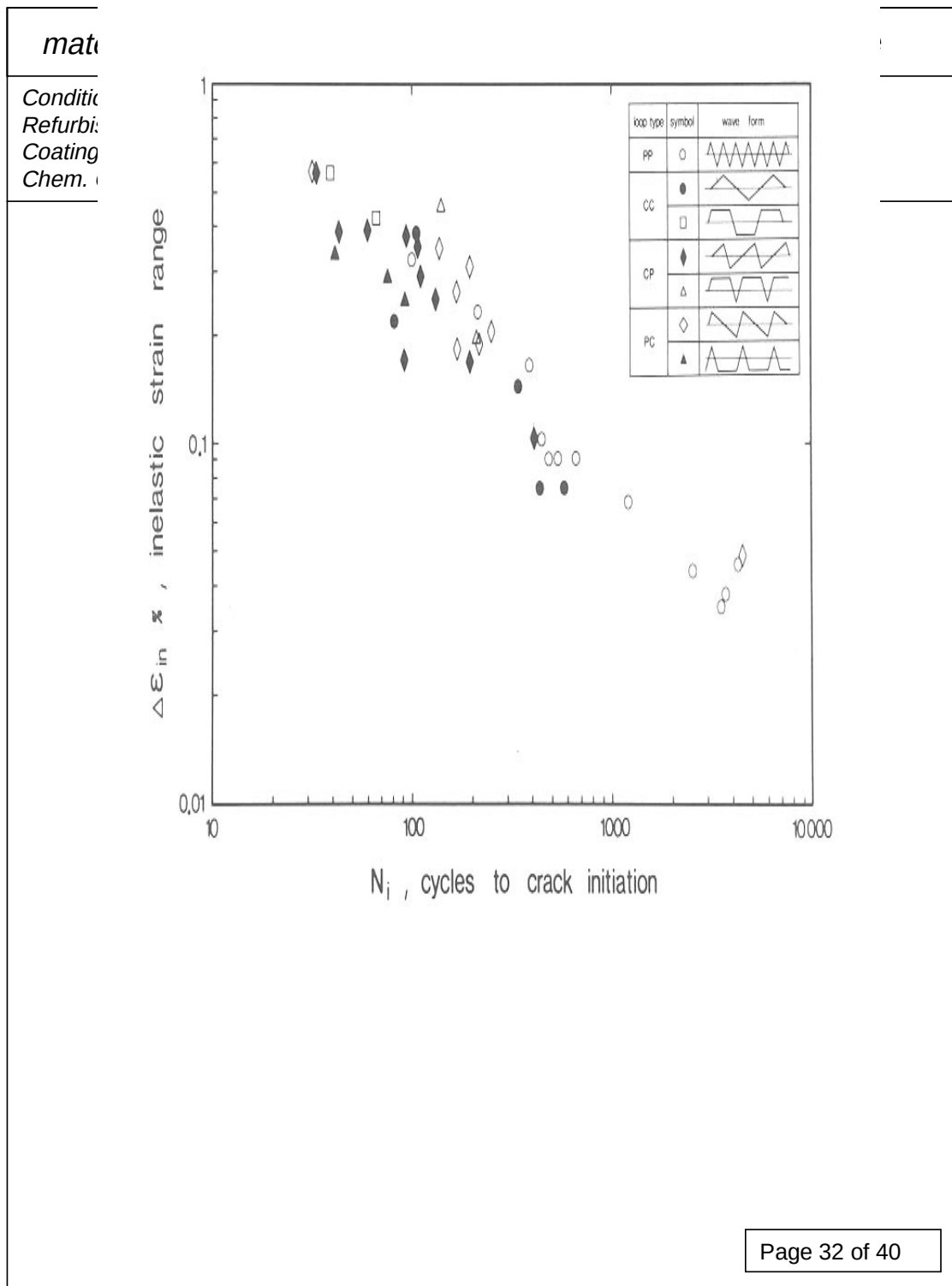


Figure 4-32
Inelastic Strain Range vs. Life to Crack Initiation.

material: Inconel 738							property: low-cycle fatigue						
Condition/HT ID: 11 Refurbish ID: N/A Coating ID: N/A Chem. Comp: 64							Reference ID(s): 28						

Figure 4-33
Typical Test Results and Partitioned Strain Ranges.

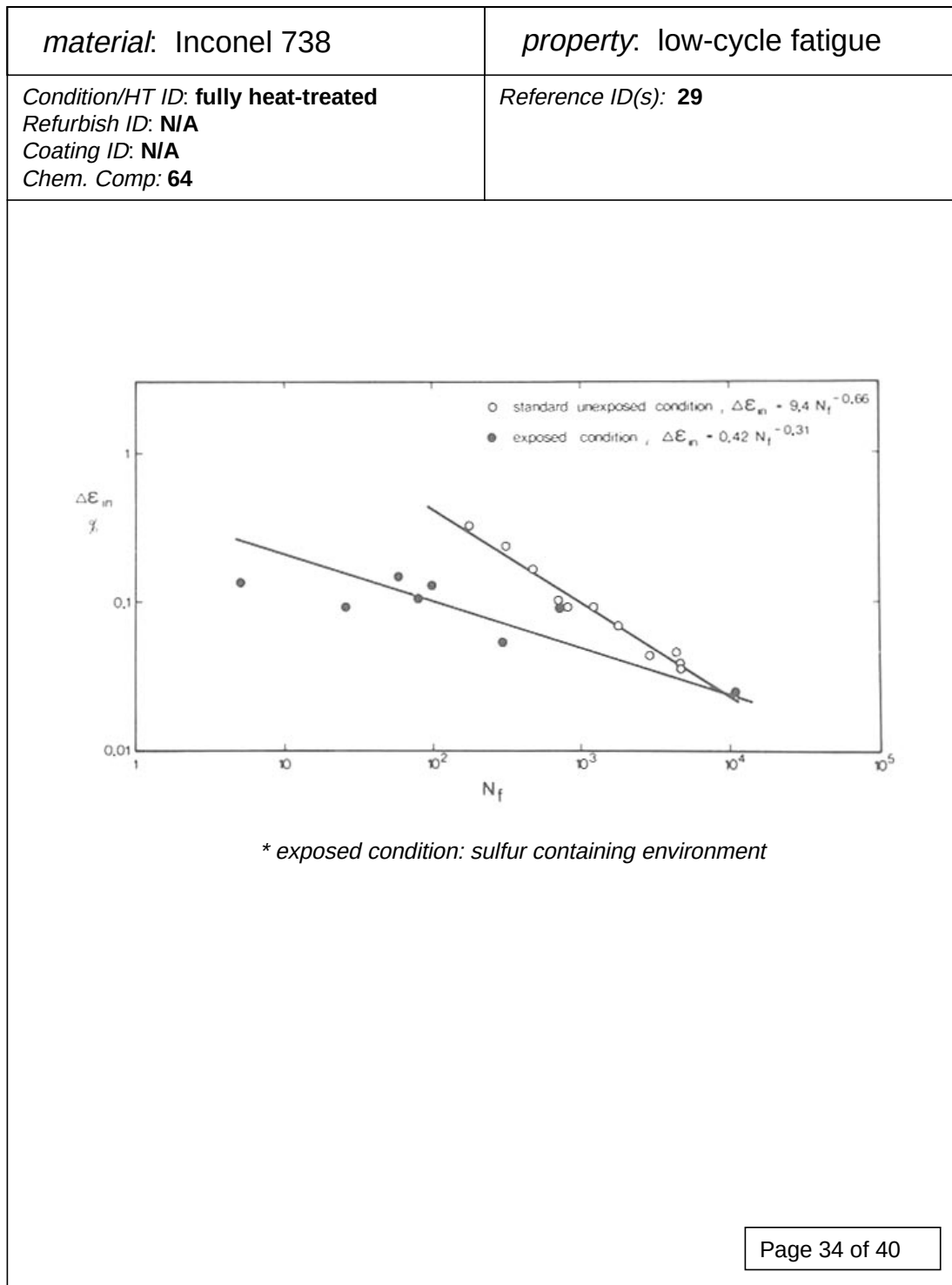


Figure 4-34
(HTLCF) Results of IN 738 in the Standard and the Exposed Conditions, Inelastic Strain Range ($\Delta\epsilon$ in %) vs. Number of Cycles to Failure (N_f).

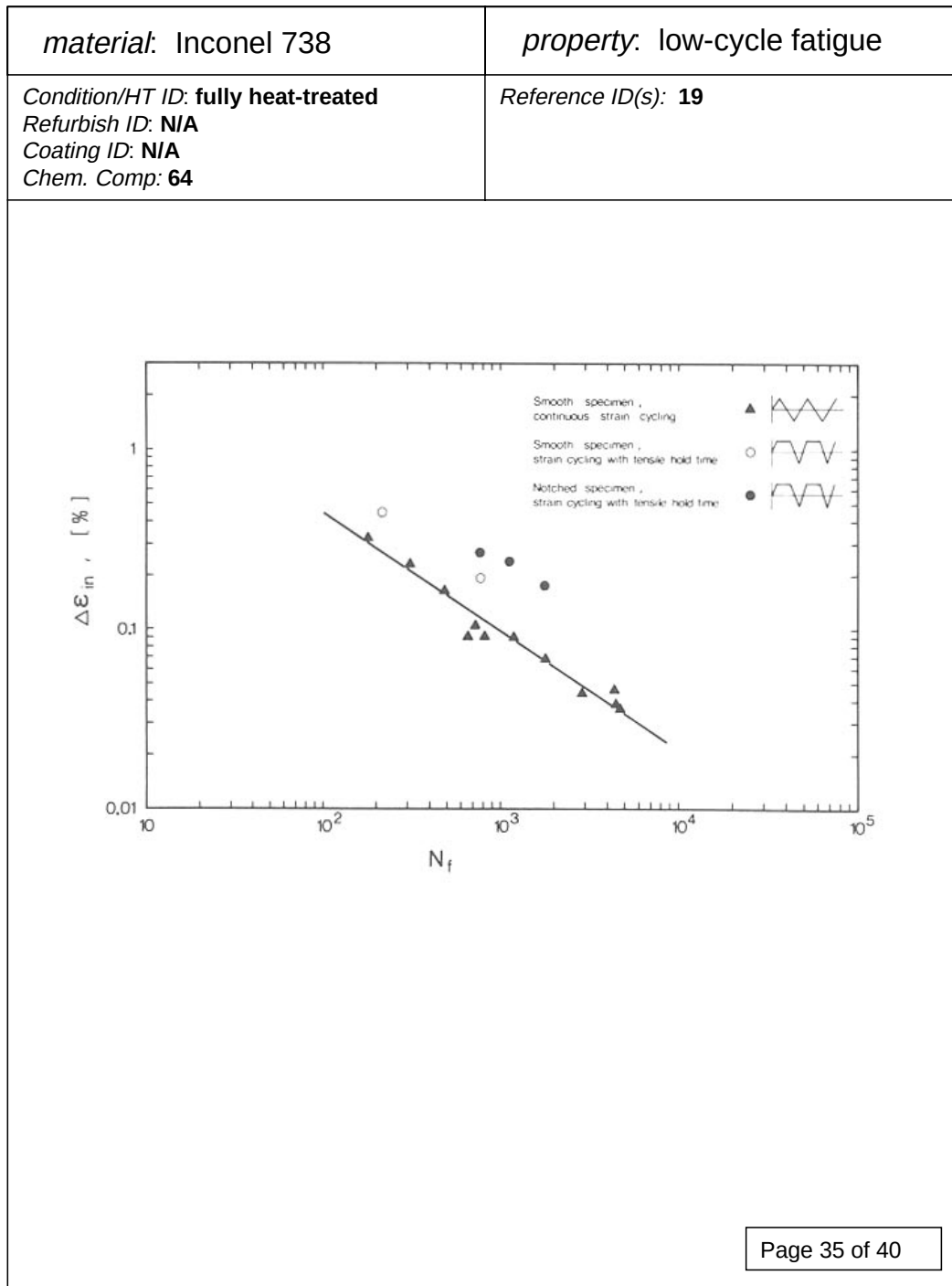


Figure 4-35
 (HTLCF) Results of IN 738 at 1123 K, for the Two Types of Specimens Tested Under Continuous Strain Cycling and Cycling with Tensile Hold Times, Inelastic Strain range ($\Delta \epsilon$ in %) vs. Number of Cycles to Failure (N_f).

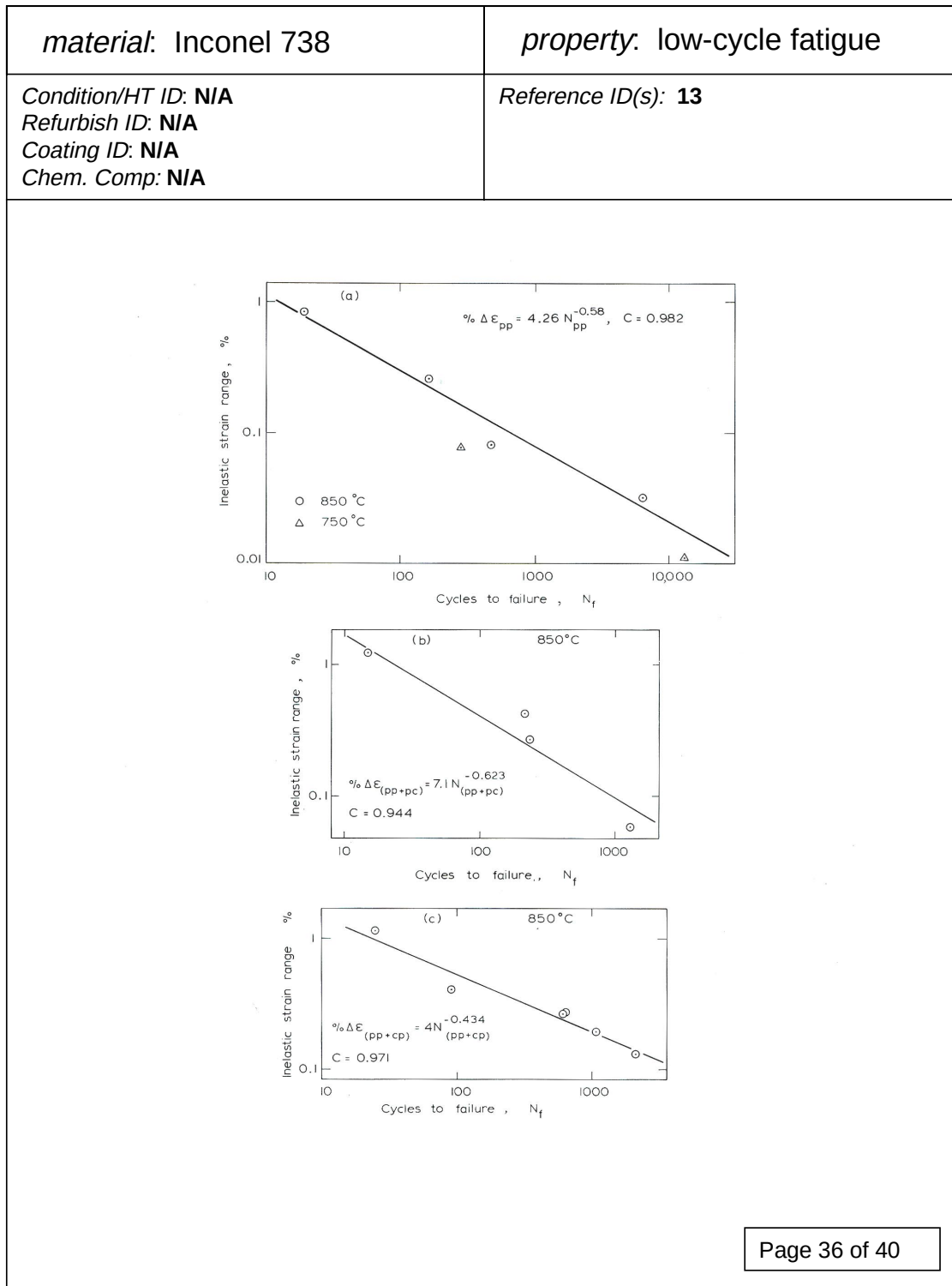


Figure 4-36
Inelastic Strain Range vs. Cycles to Failure for Cast IN 738 LC (a) pp components only; 750°C and 850°C, (b) pp and pc components 850°C (c) pp and cp components; 850°C.

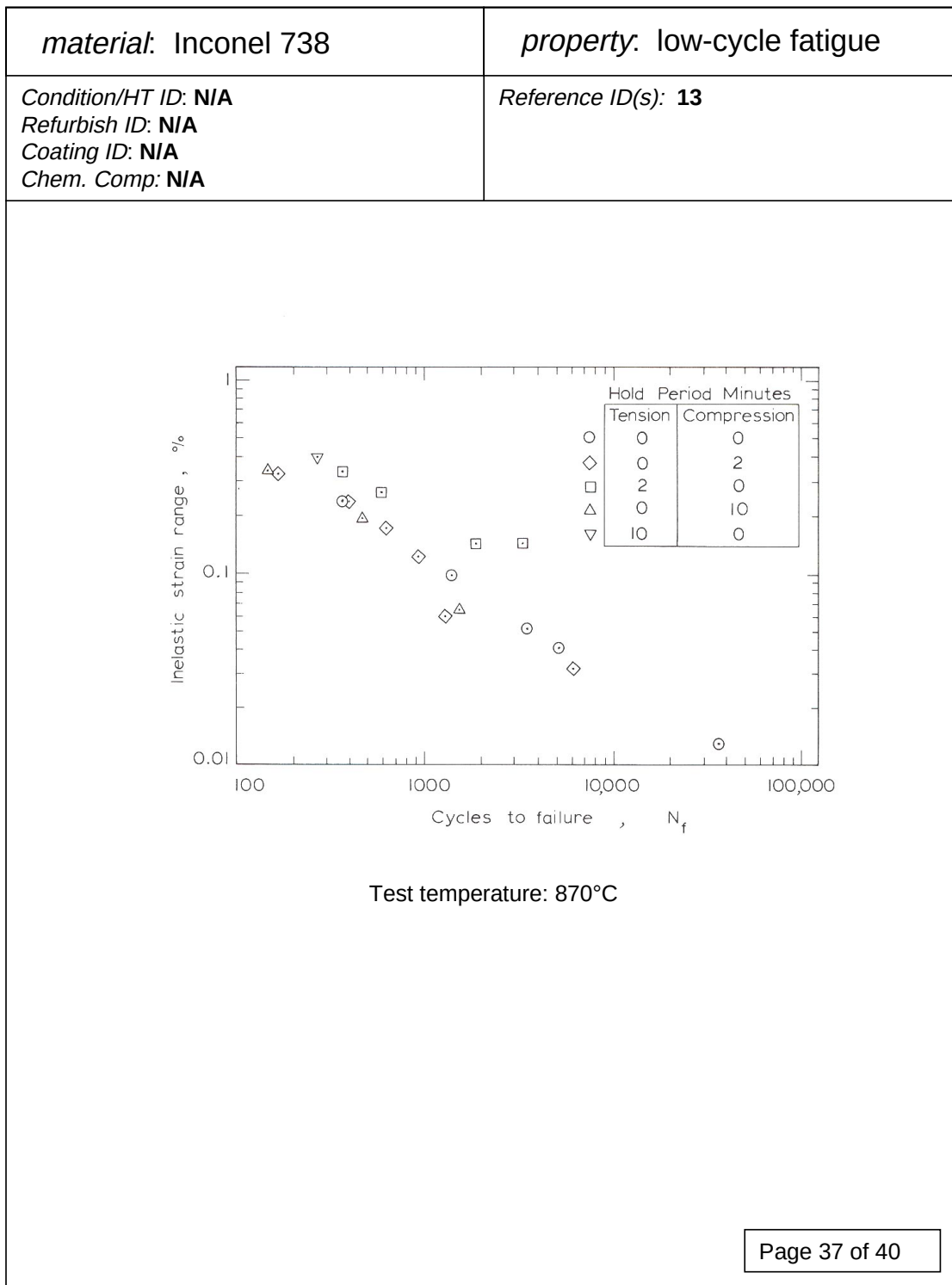


Figure 4-37
Inelastic Strain Range vs. Cycles to Failure for Cast IN 738 at 870°C.

Inconel 738

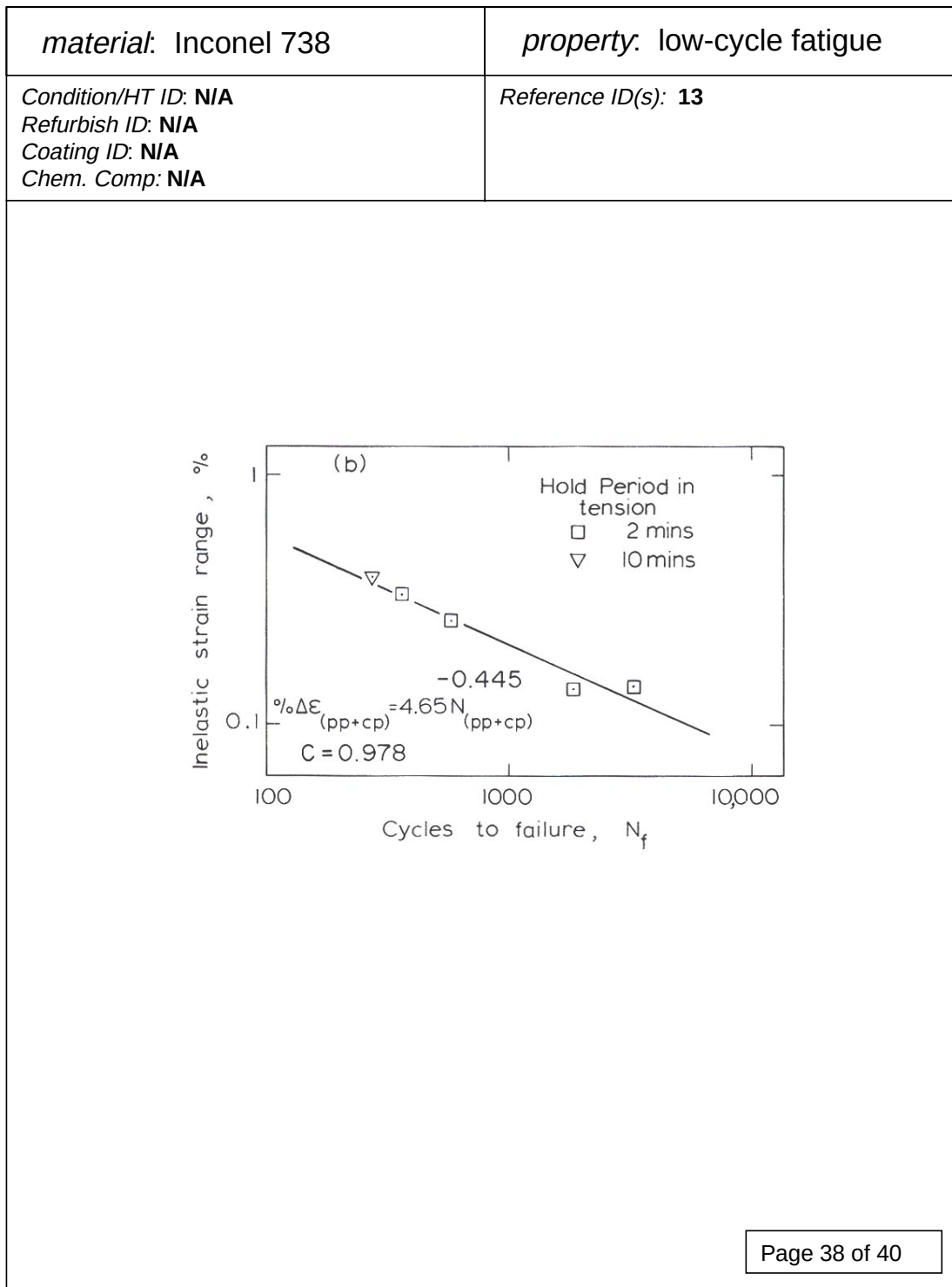


Figure 4-38
Inelastic Strain Range vs. Cycles to Failure for Cast IN 738 at 870°C, pp and cp components.

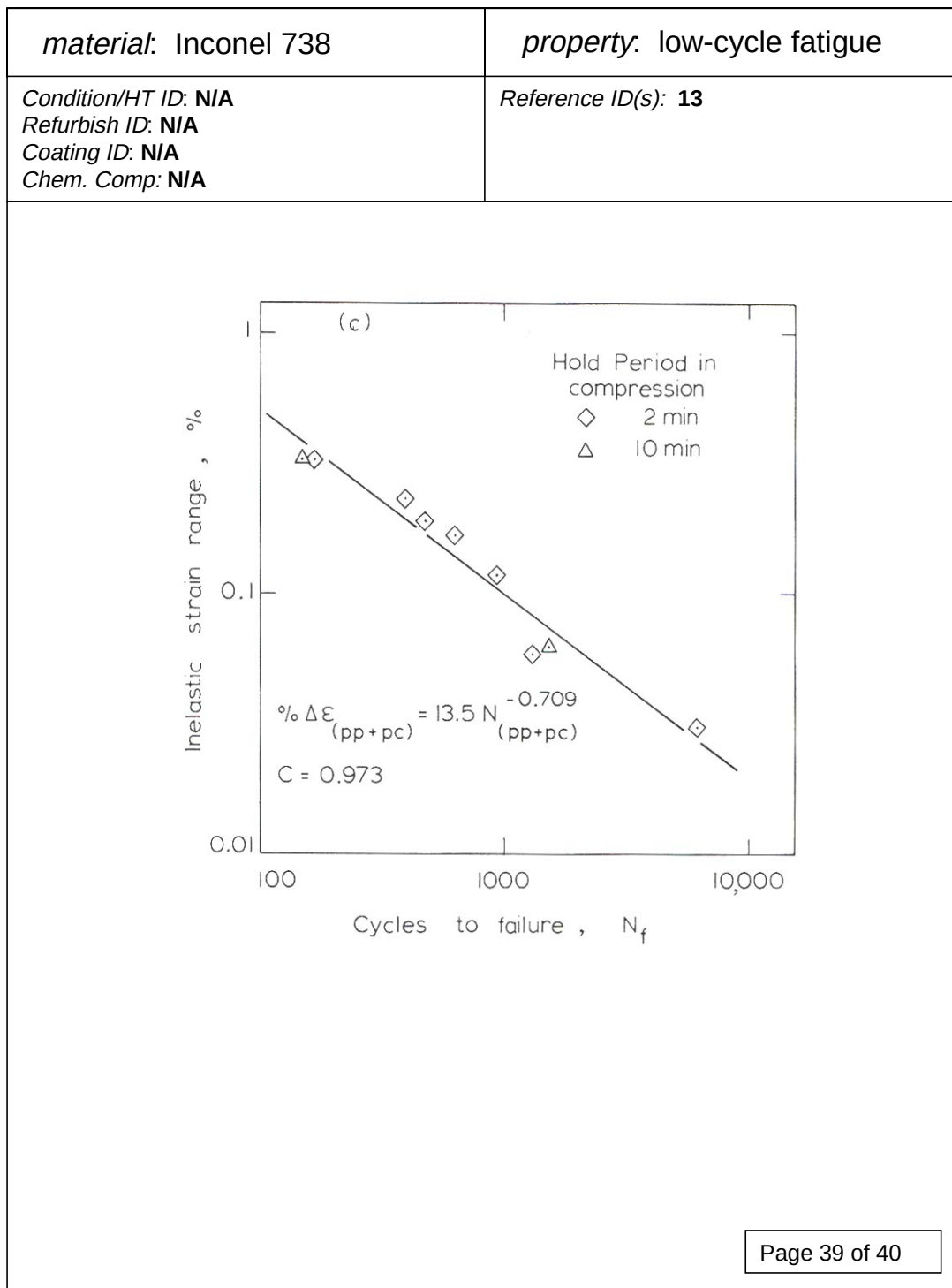


Figure 4-39
Inelastic Strain Range vs. Cycles to Failure for Cast IN 738 at 870°C, pp and pc components.

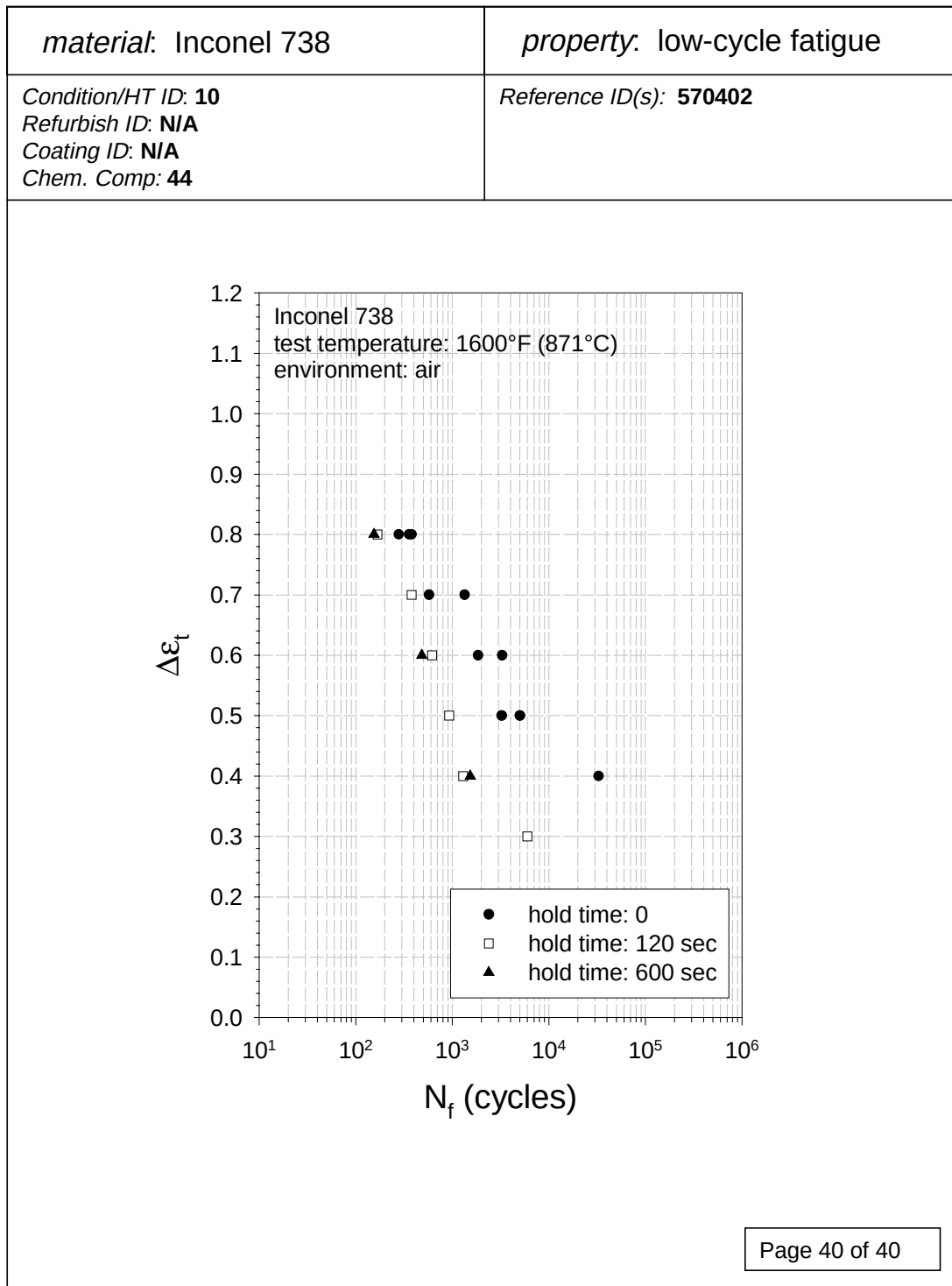


Figure 4-40
Low Cycle Fatigue at 1600°F with Three Hold Times Investigated (Total Strain Range).

5

INCONEL 738 LC

Inconel 738 LC

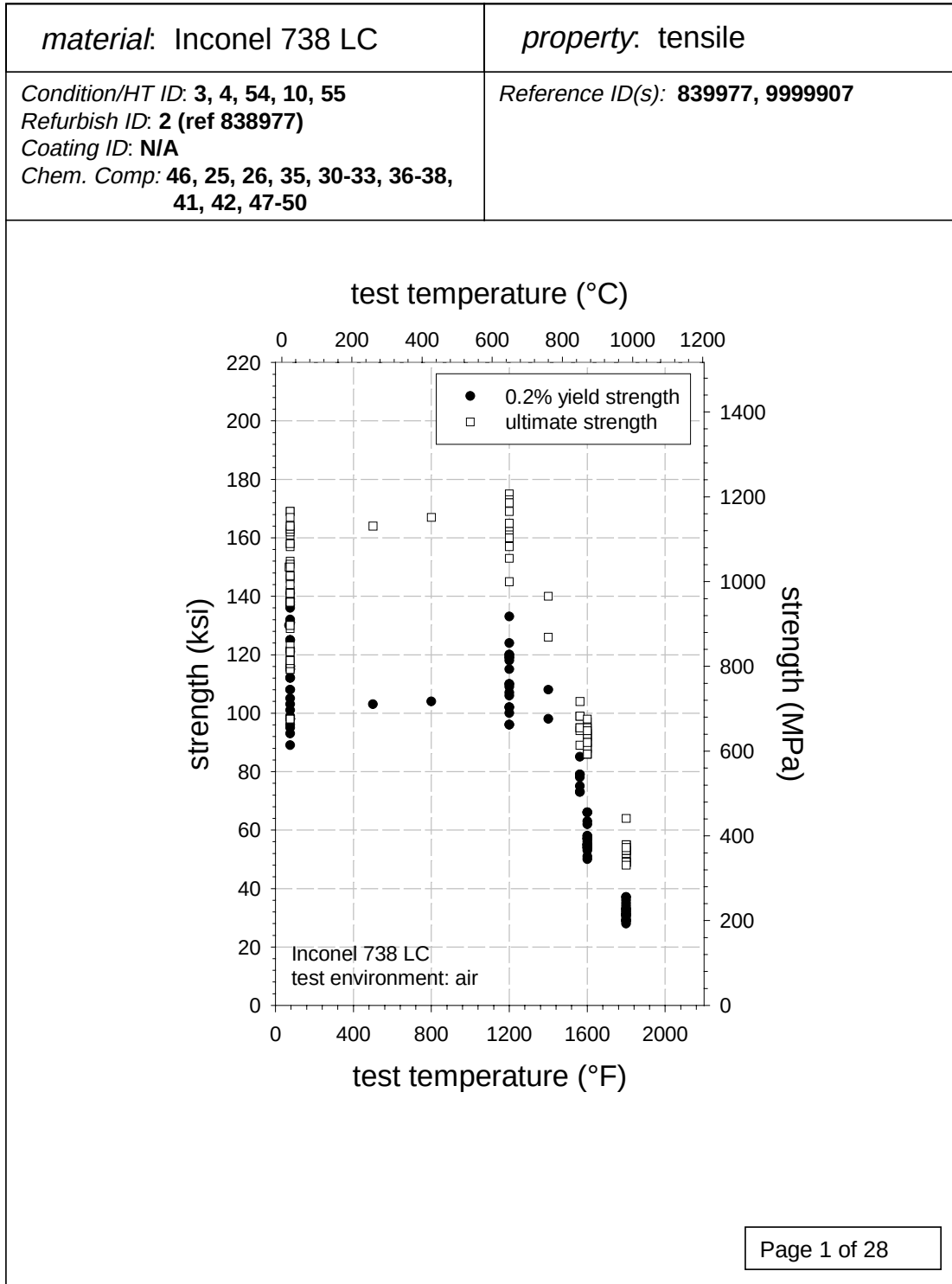


Figure 5-1
Tensile Strengths as a Function of Temperature.

Inconel 738 LC

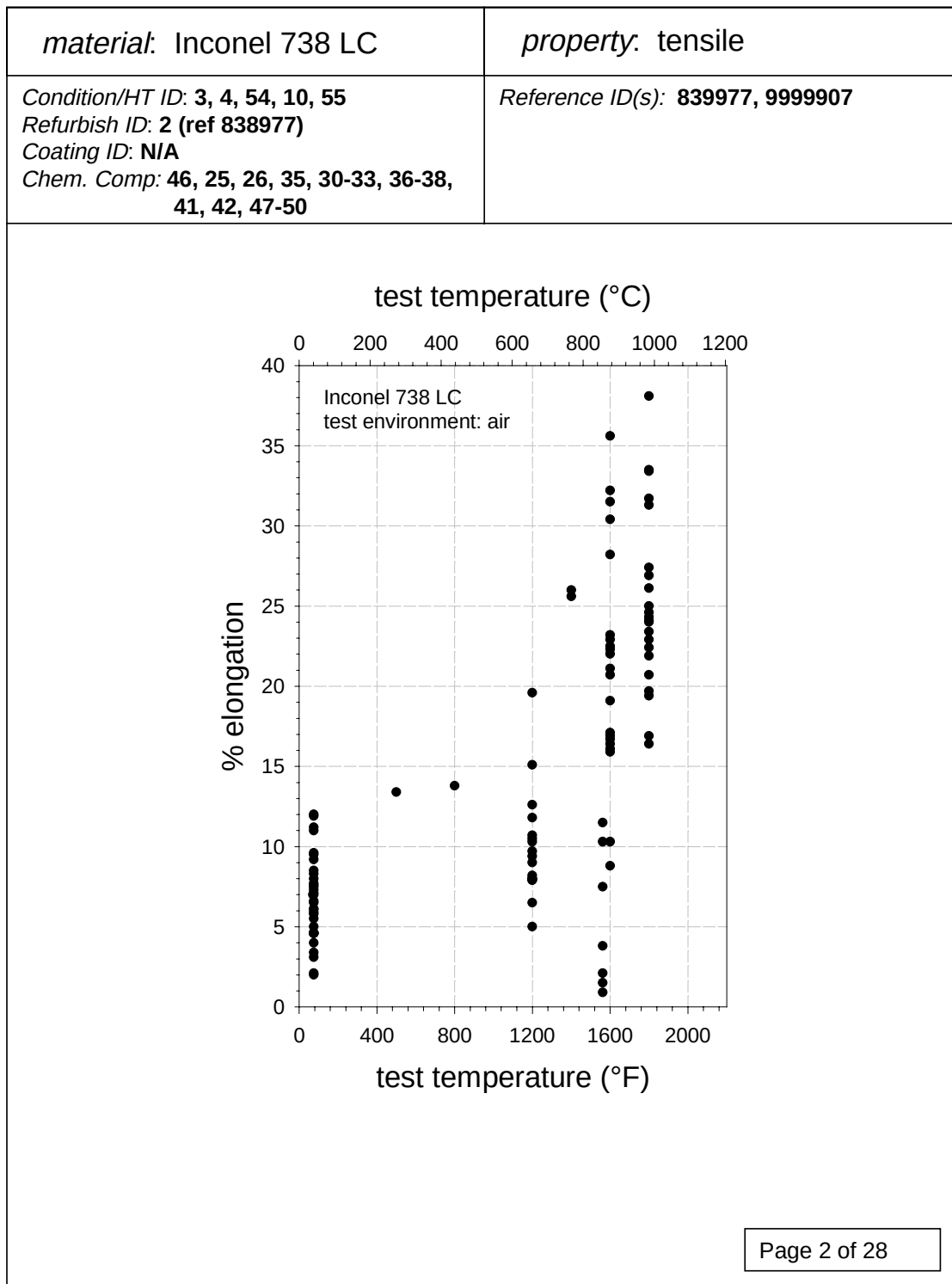


Figure 5-2
Tensile Elongation as a Function of Temperature.

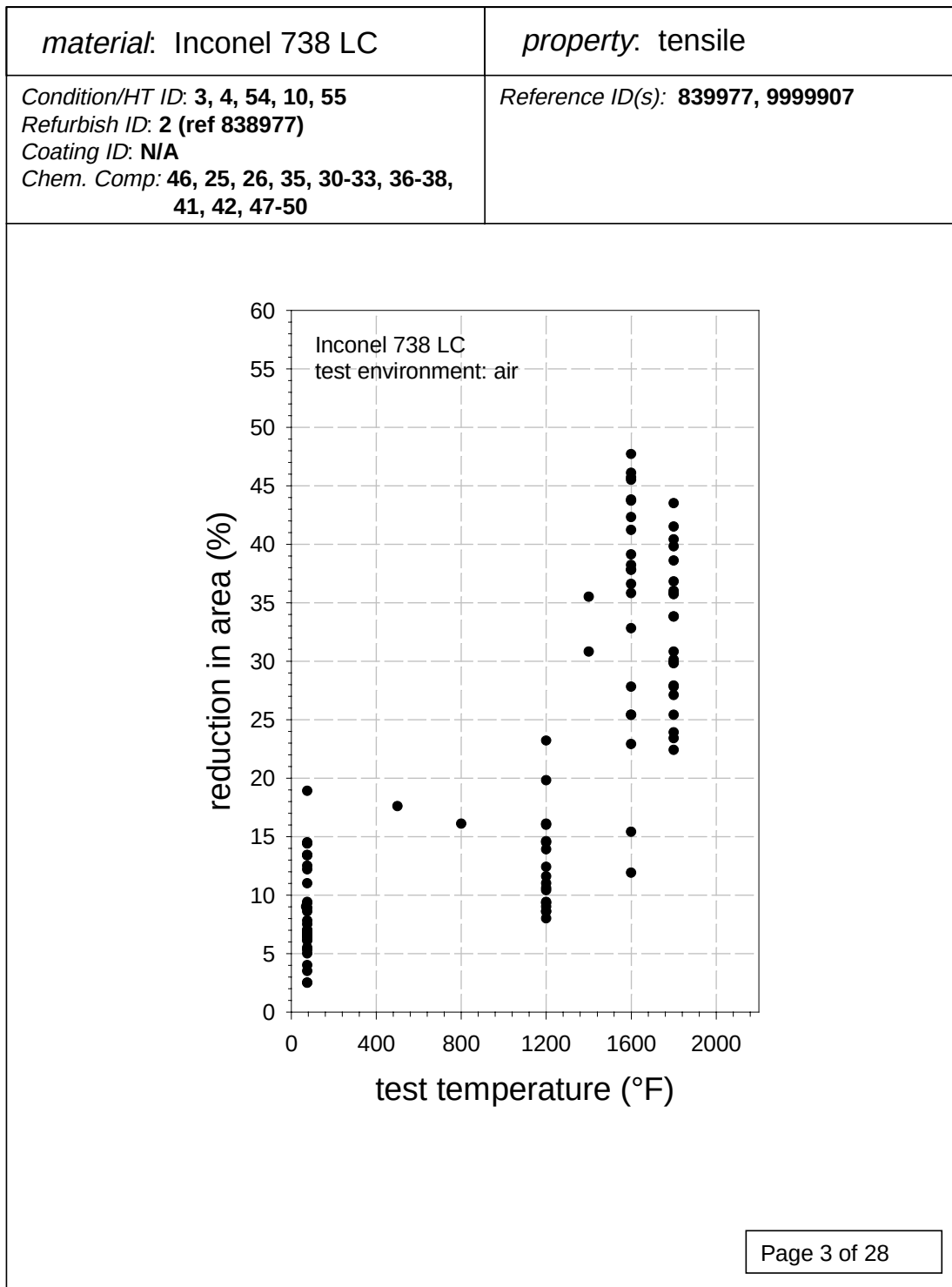


Figure 5-3
Reduction in Area (Tensile) as a Function of Temperature.

Inconel 738 LC

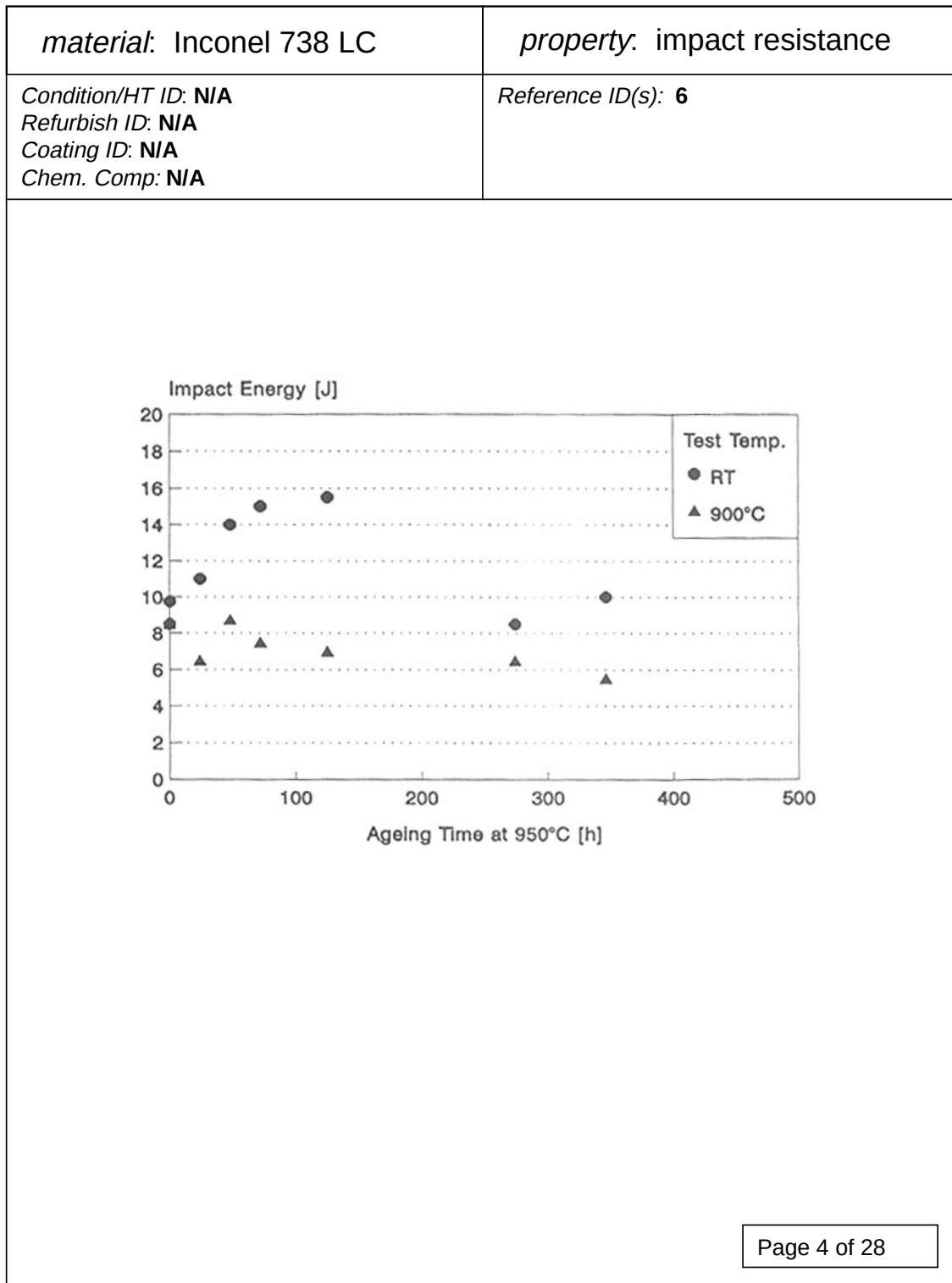


Figure 5-4
Impact Resistance of IN-738 at Room Temperature and 900°C as a Function of Aging Time at 950°C.

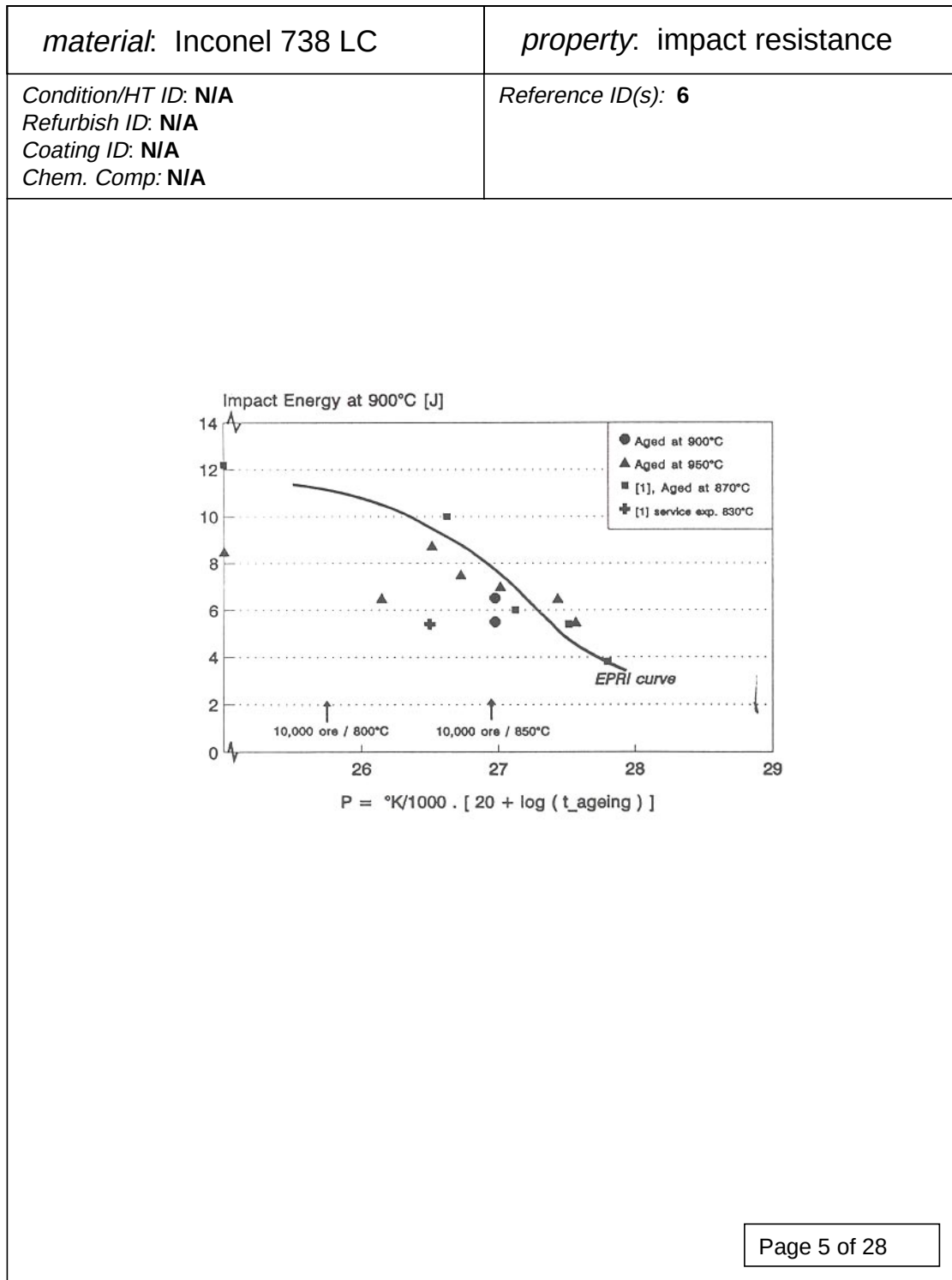


Figure 5-5
Loss of High Temperature Impact Resistance Correlation in Terms of a Time-Temperature Parameter Analogous to that of Larson-Miller.

Inconel 738 LC

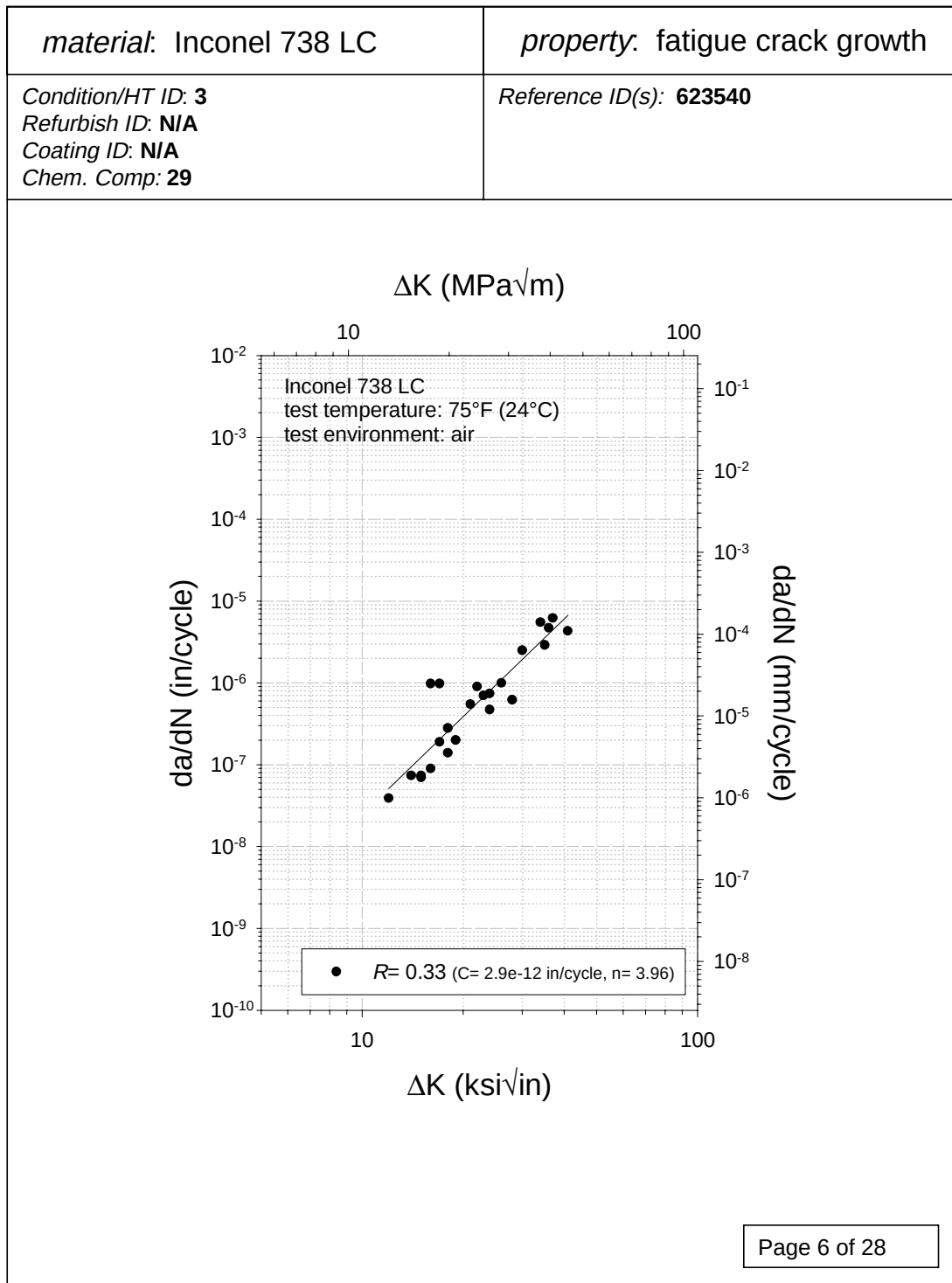


Figure 5-6
Fatigue Crack Growth Behavior at R = 0 (Room Temperature, Lab Air Conditions).

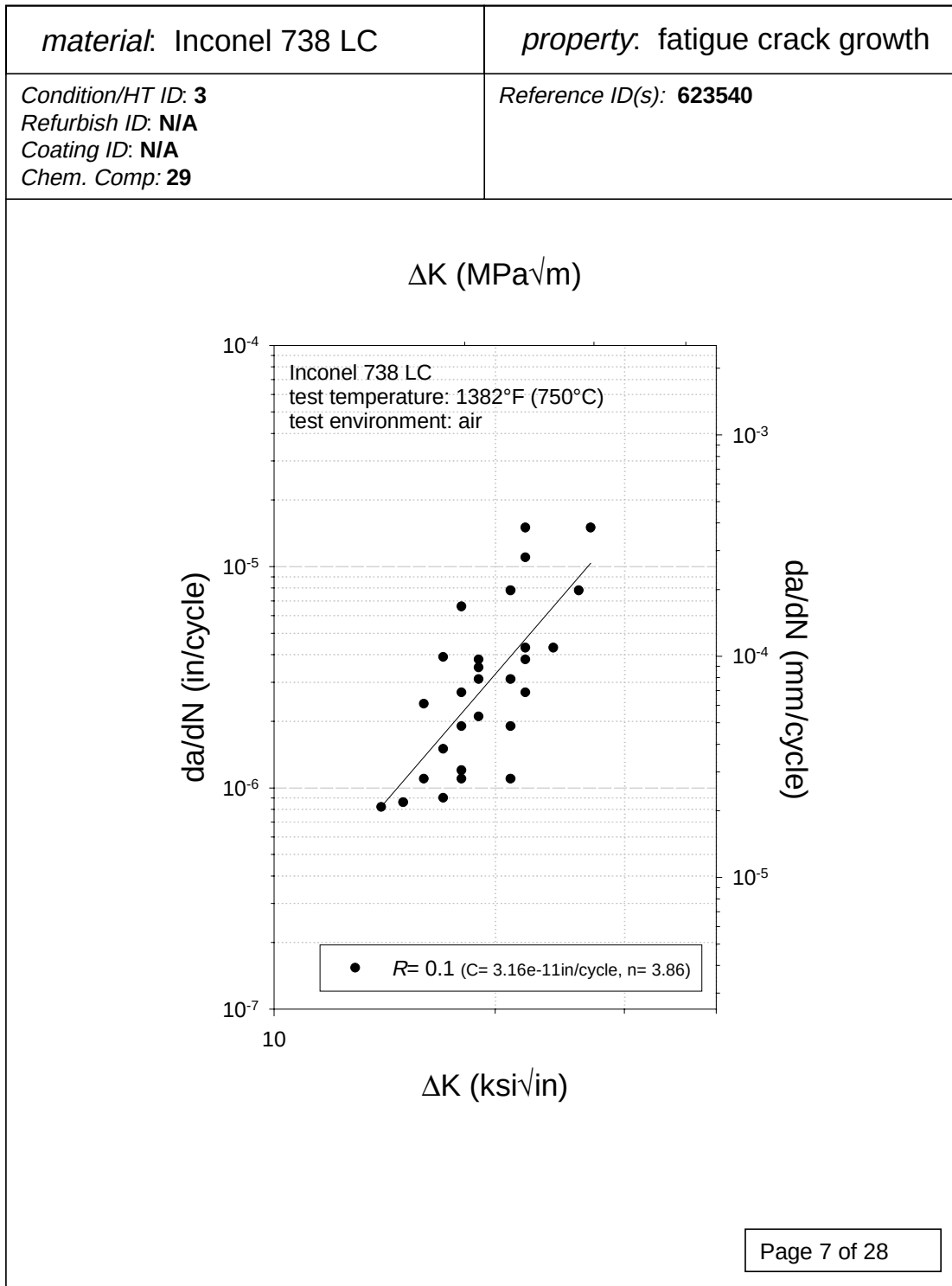


Figure 5-7
Fatigue Crack Growth Behavior at 1382°F at R = 0.1 (Lab Air).

Inconel 738 LC

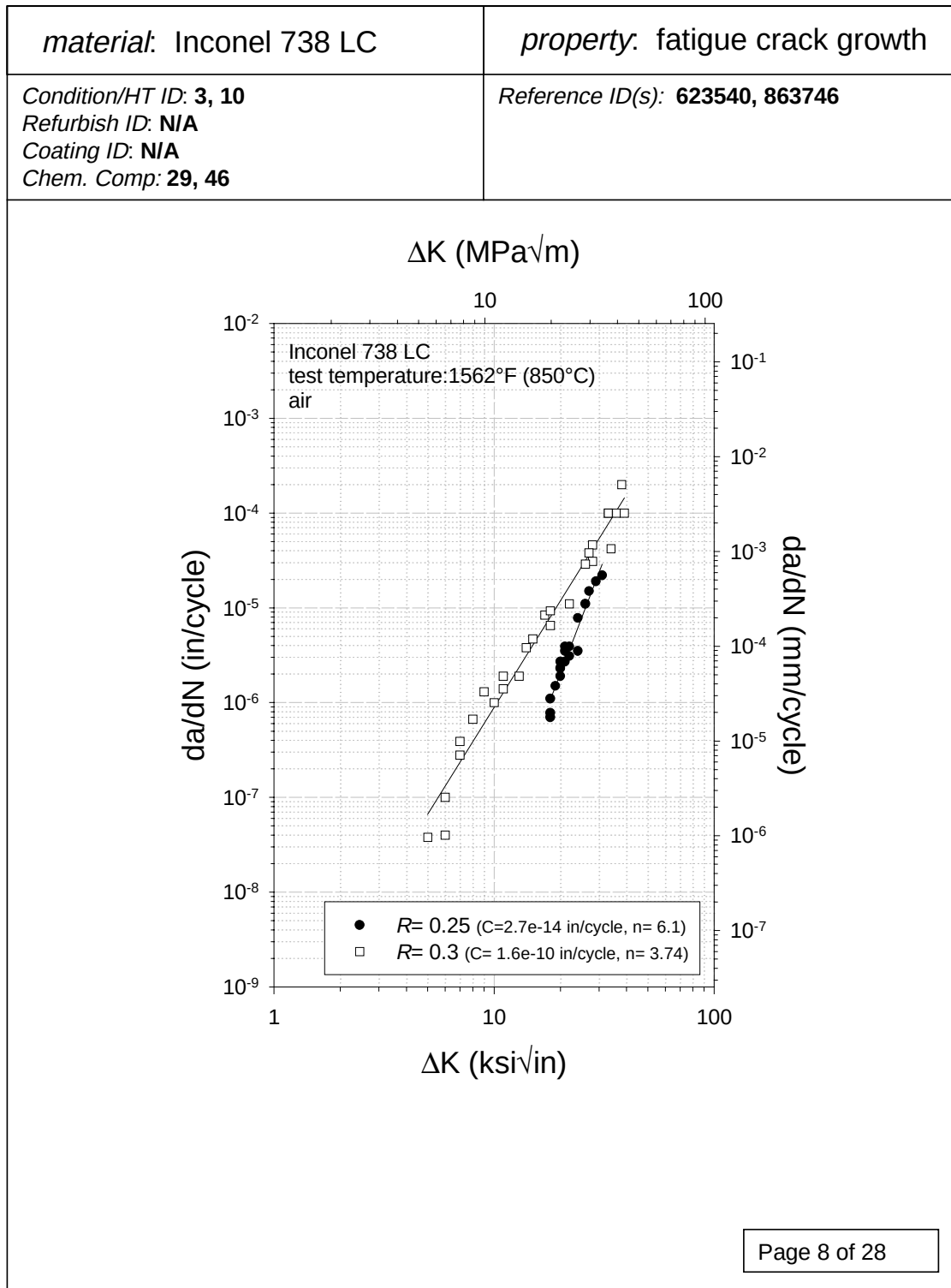


Figure 5-8
Fatigue Crack Growth Behavior at 1562°F for R = 0.25 and 0.3 (Lab Air).

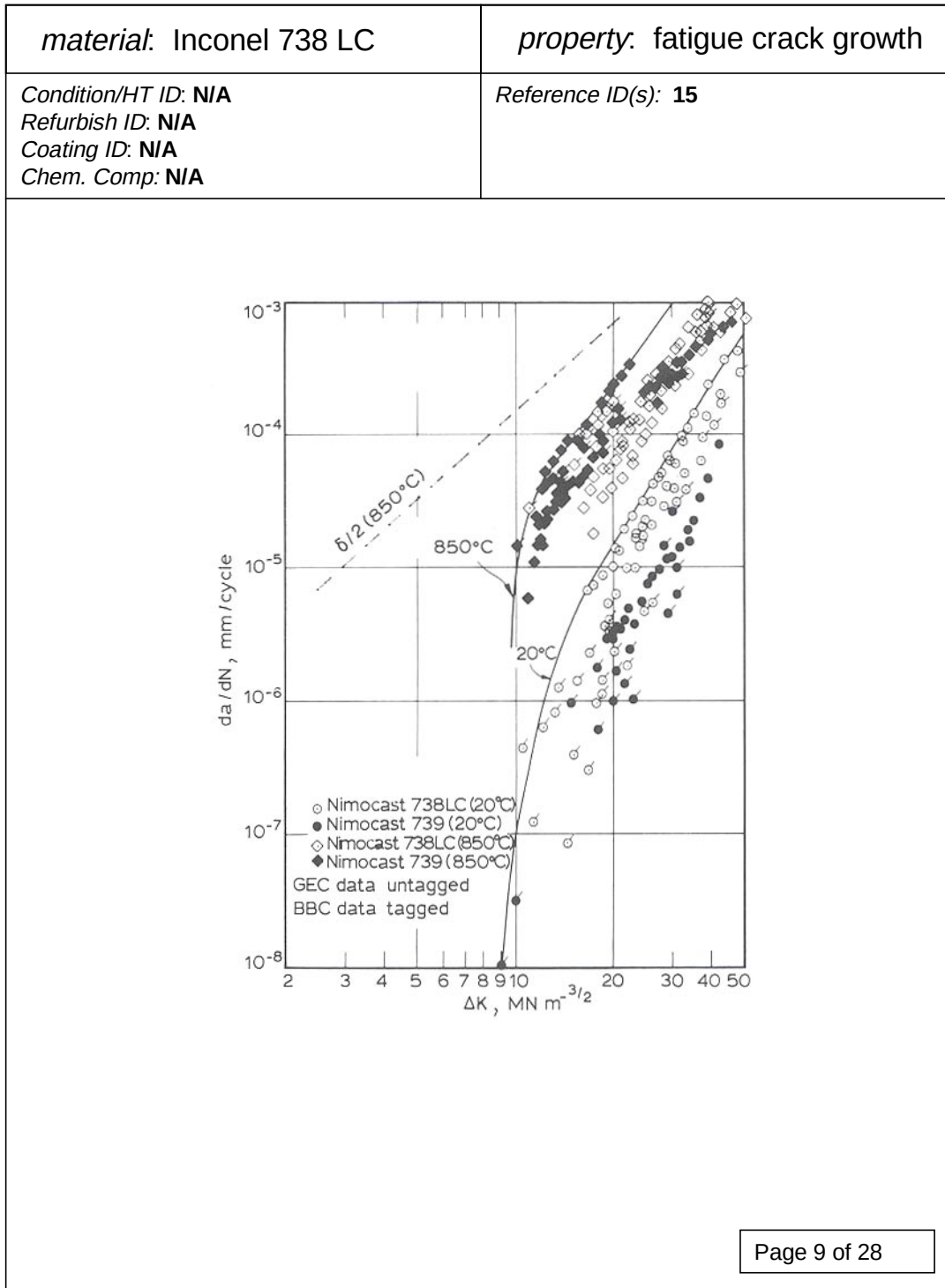


Figure 5-9
Crack Growth for Nimocast 738 LC and 739 at Cyclic Frequencies Between 60 and 100 Hz and $R = 0.1$; δ is Crack Tip Opening Displacement.

Inconel 738 LC

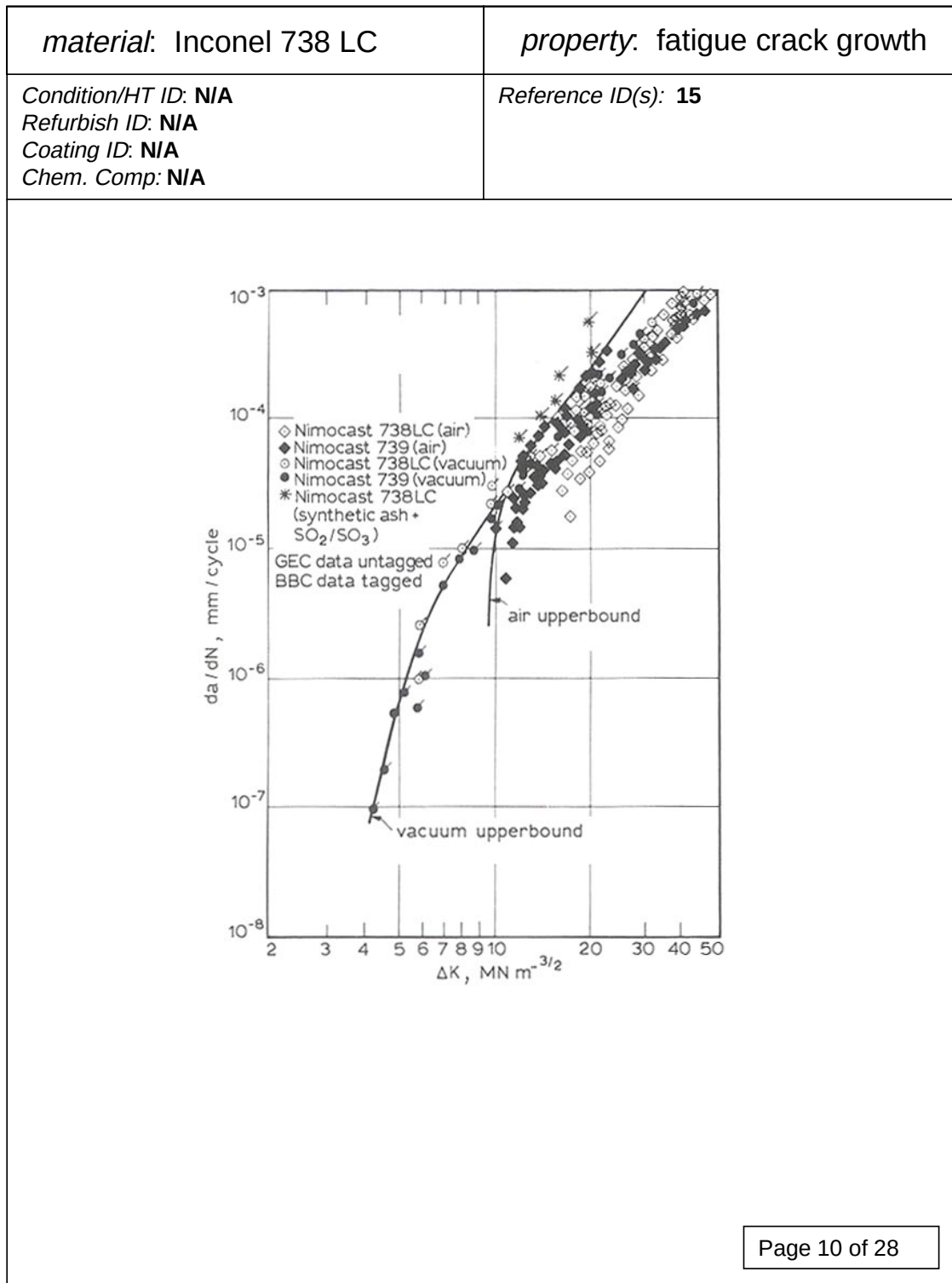


Figure 5-10
Influence of Environment on Fatigue Crack Growth of Nimocast 738 LC and 739 at 850°C
and Cyclic Frequencies Between 10 and 100 Hz and R = 0.1.

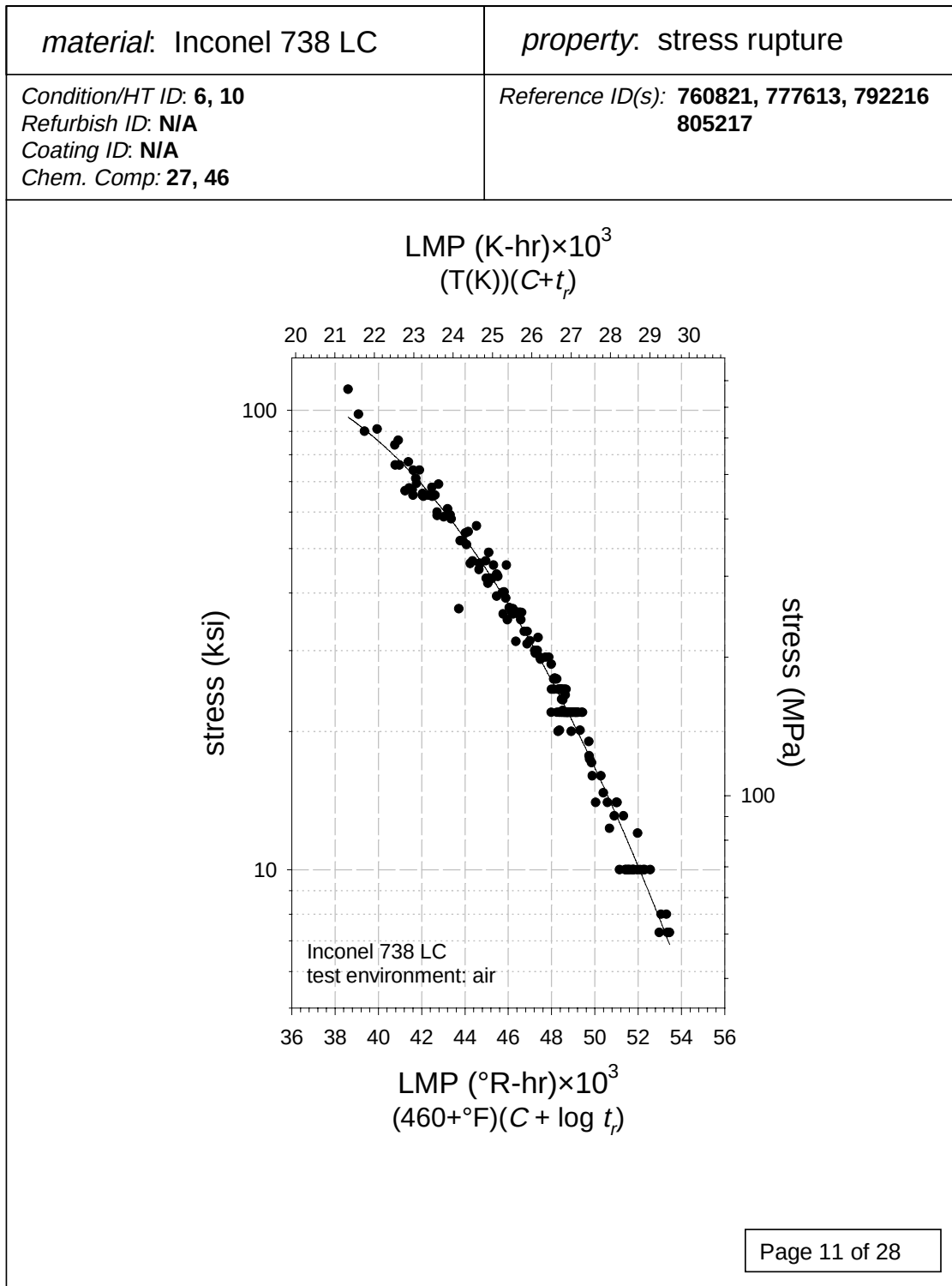


Figure 5-11
Larson-Miller Plot for Inconel 738 LC.

Inconel 738 LC

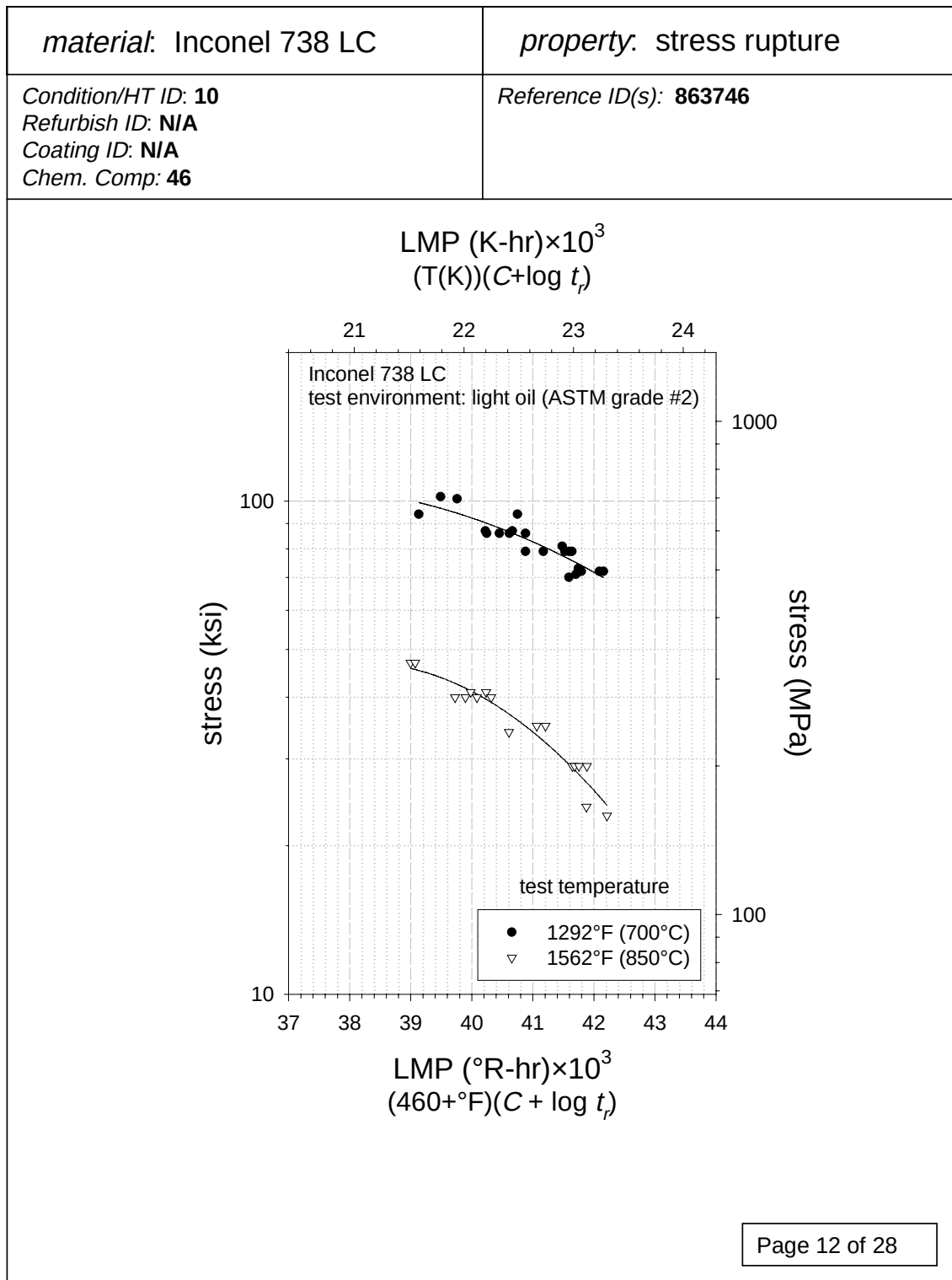


Figure 5-12
Larson-Miller Plot at Two Test Temperatures (Light Oil Conditions).

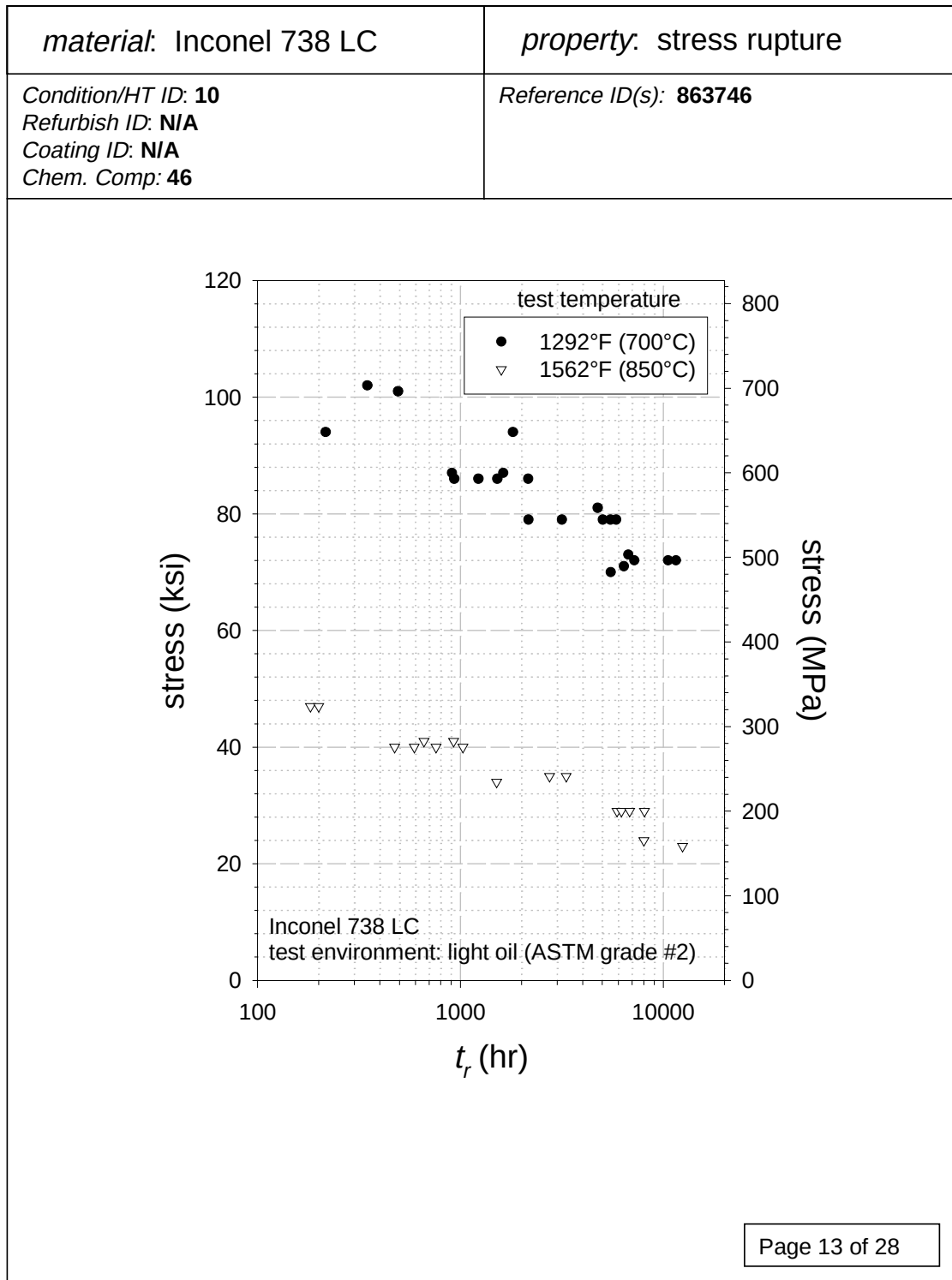
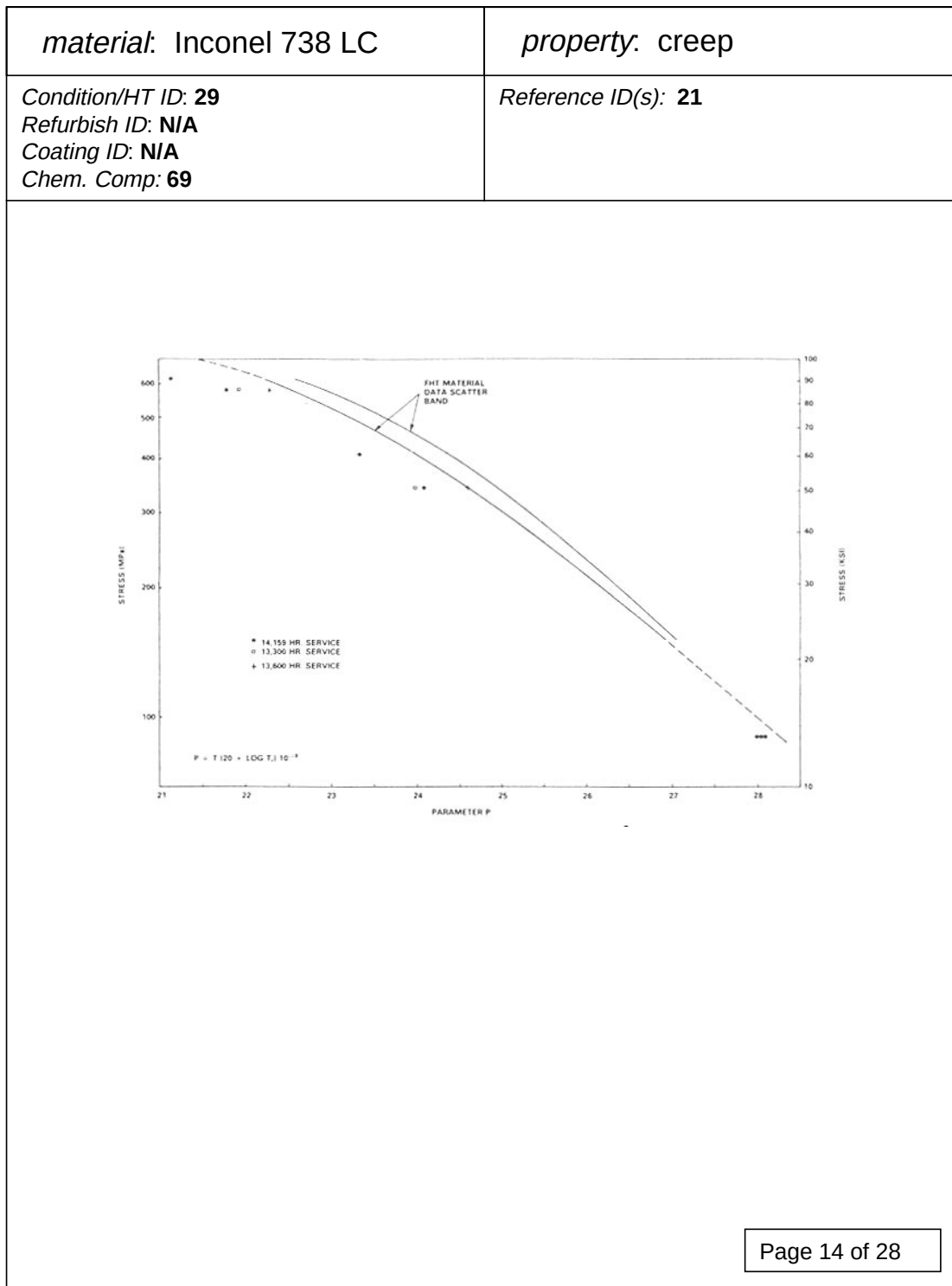


Figure 5-13
Stress vs. Rupture Time at Two Elevated Temperatures (Light Oil Conditions).

Inconel 738 LC



Page 14 of 28

Figure 5-14
Larson-Miller Plot ($P = T(20 + \log t_r) \times 10^{-3}$, where T is in K and t_r in hr) of Cast and Hipped IN-738LC Turbine Blades Showing Unexposed and Service Exposed Creep-Rupture Properties.

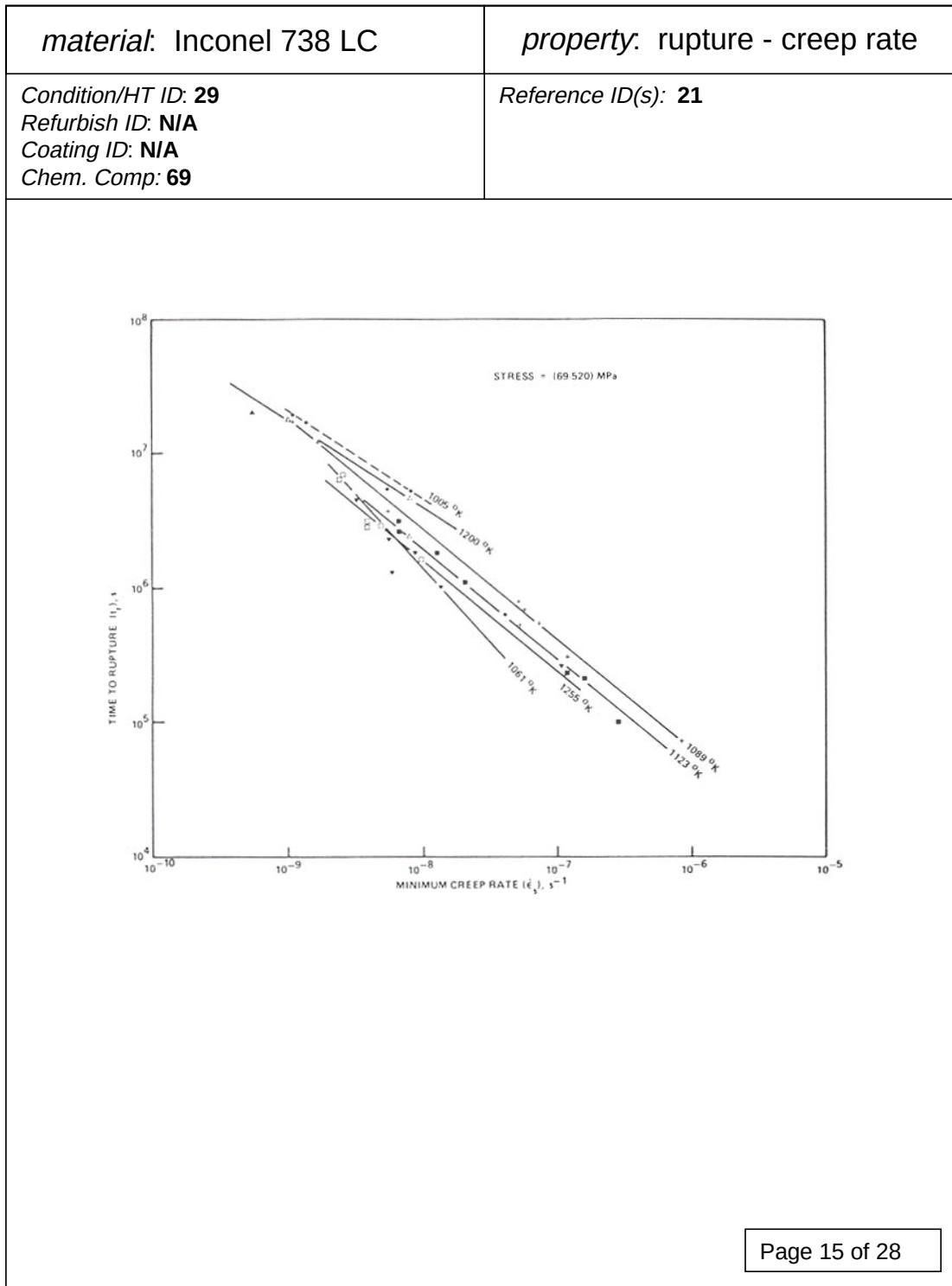


Figure 5-15
 Dependence of the Time to Rupture on the Minimum Creep Rate, for IN-738LC (Monkman-Grant Relationship).

Inconel 738 LC

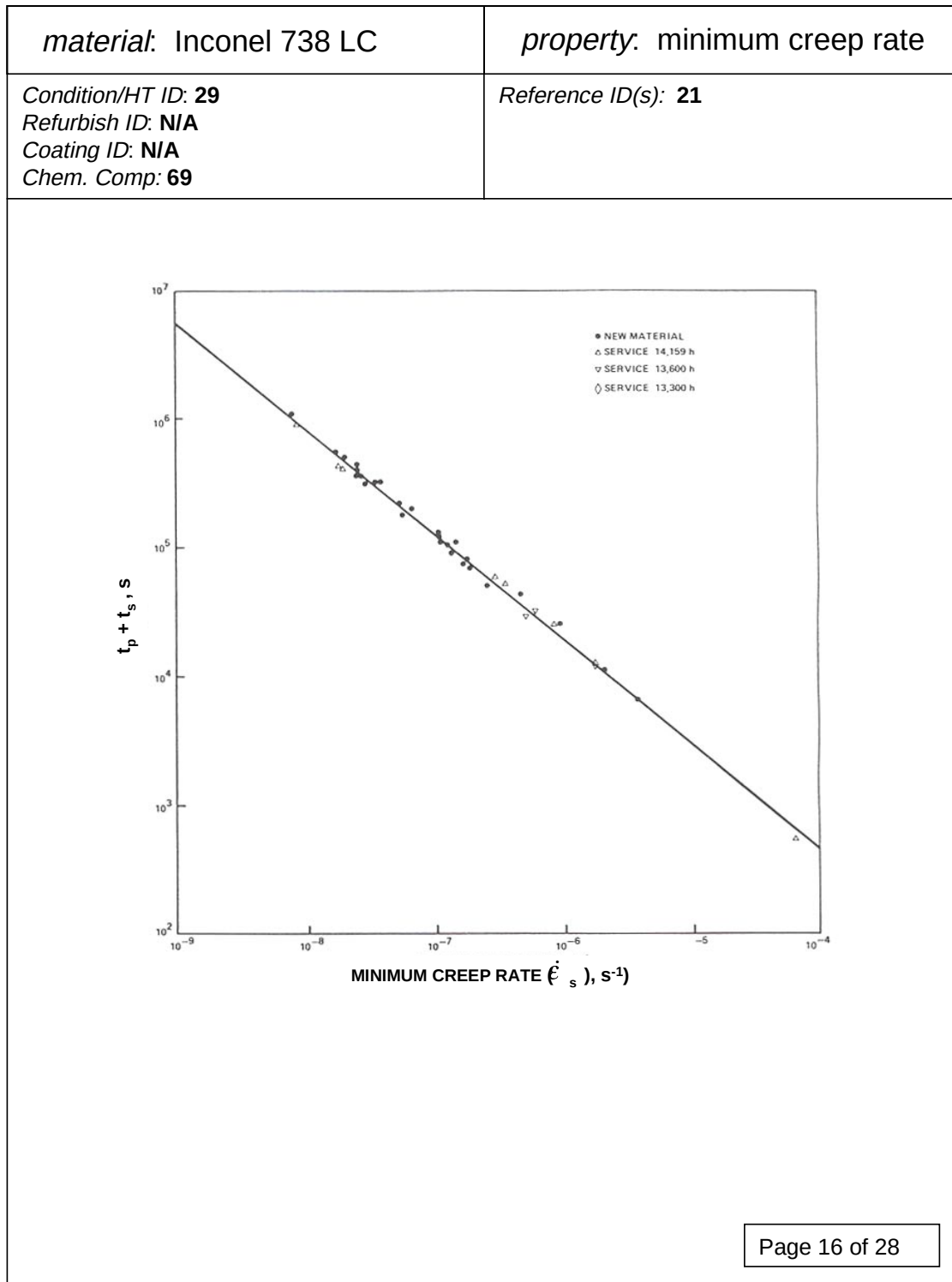


Figure 5-16
Dependence of Primary Plus Secondary, Creep Life on the Minimum Creep Rate for Cast IN-738LC.

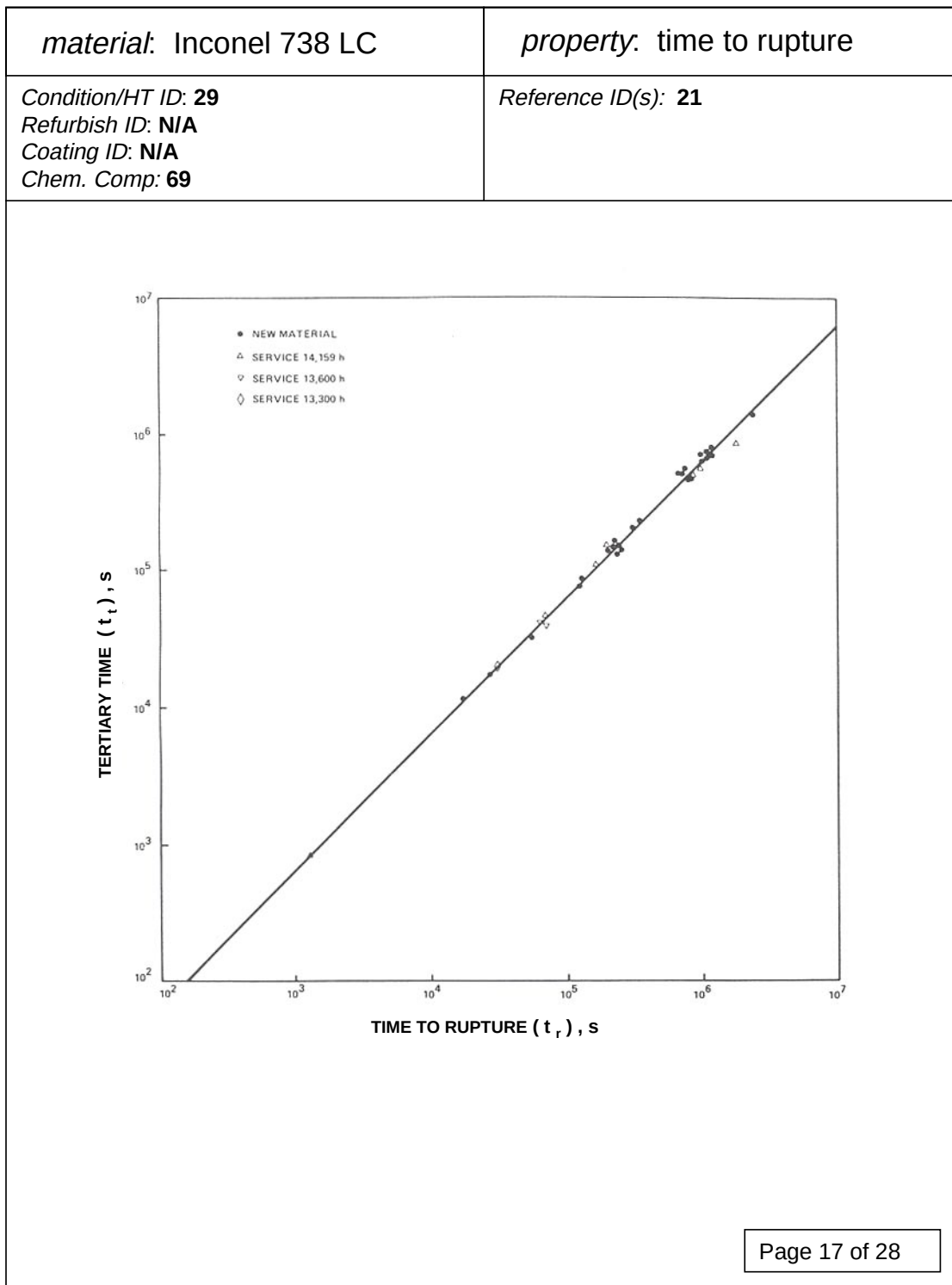


Figure 5-17
Time to Rupture Dependence on the Tertiary Life for Cast IN-738LC.

Inconel 738 LC

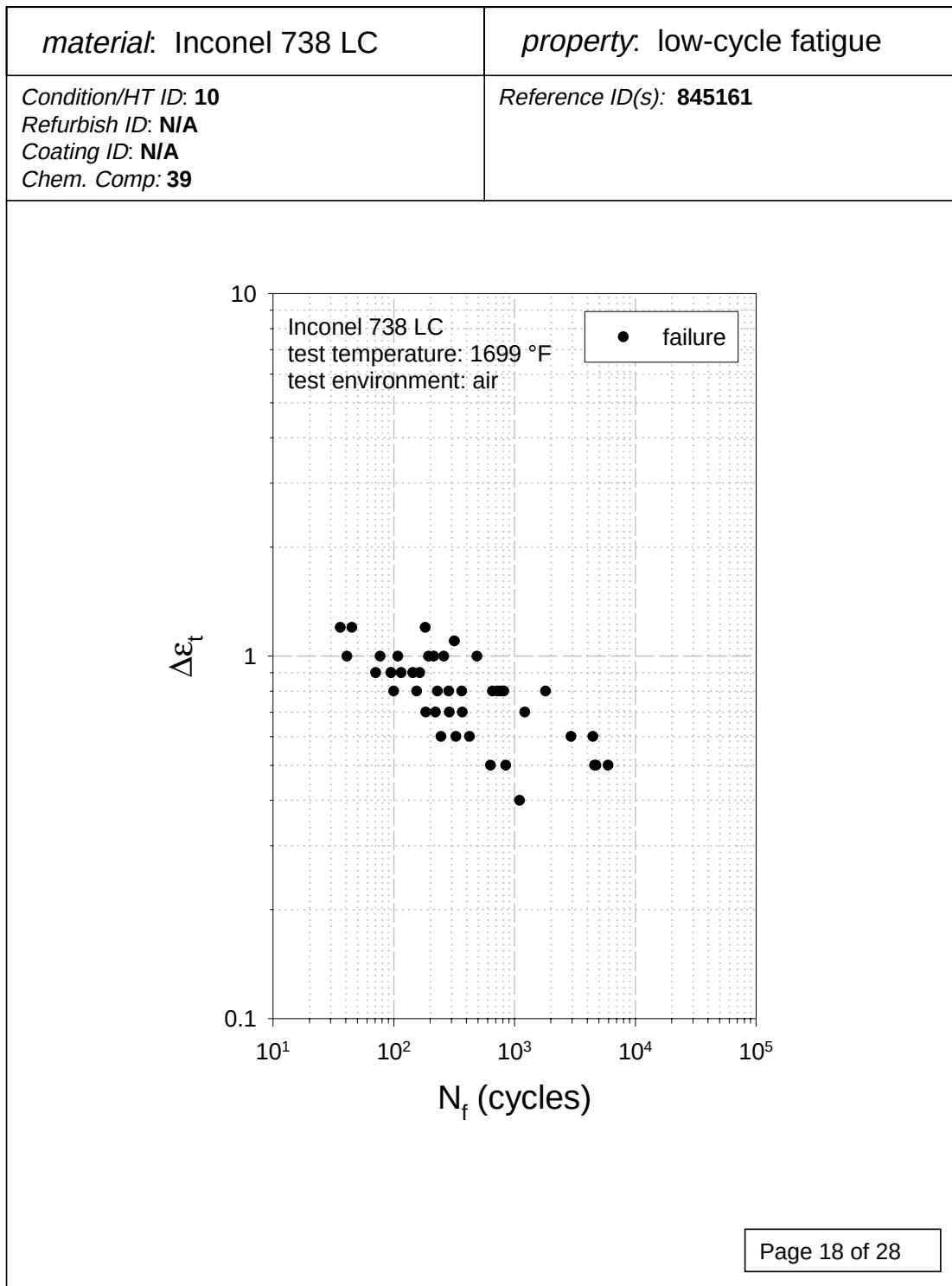


Figure 5-18
Low Cycle Fatigue at 1699°F (Total Strain Range).

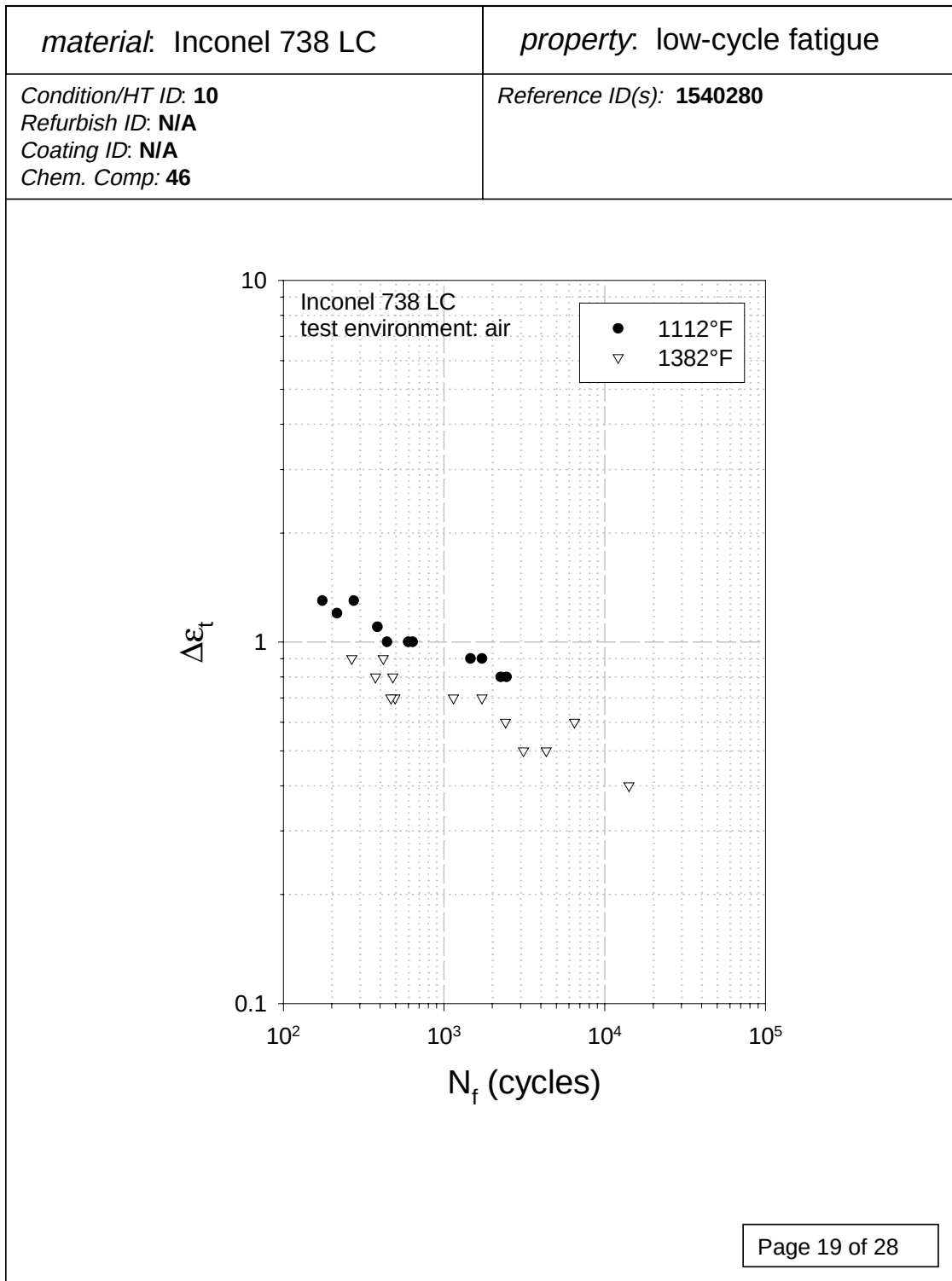


Figure 5-19
Low Cycle Fatigue Behavior at Two Elevated Temperatures (Total Strain Range).

Inconel 738 LC

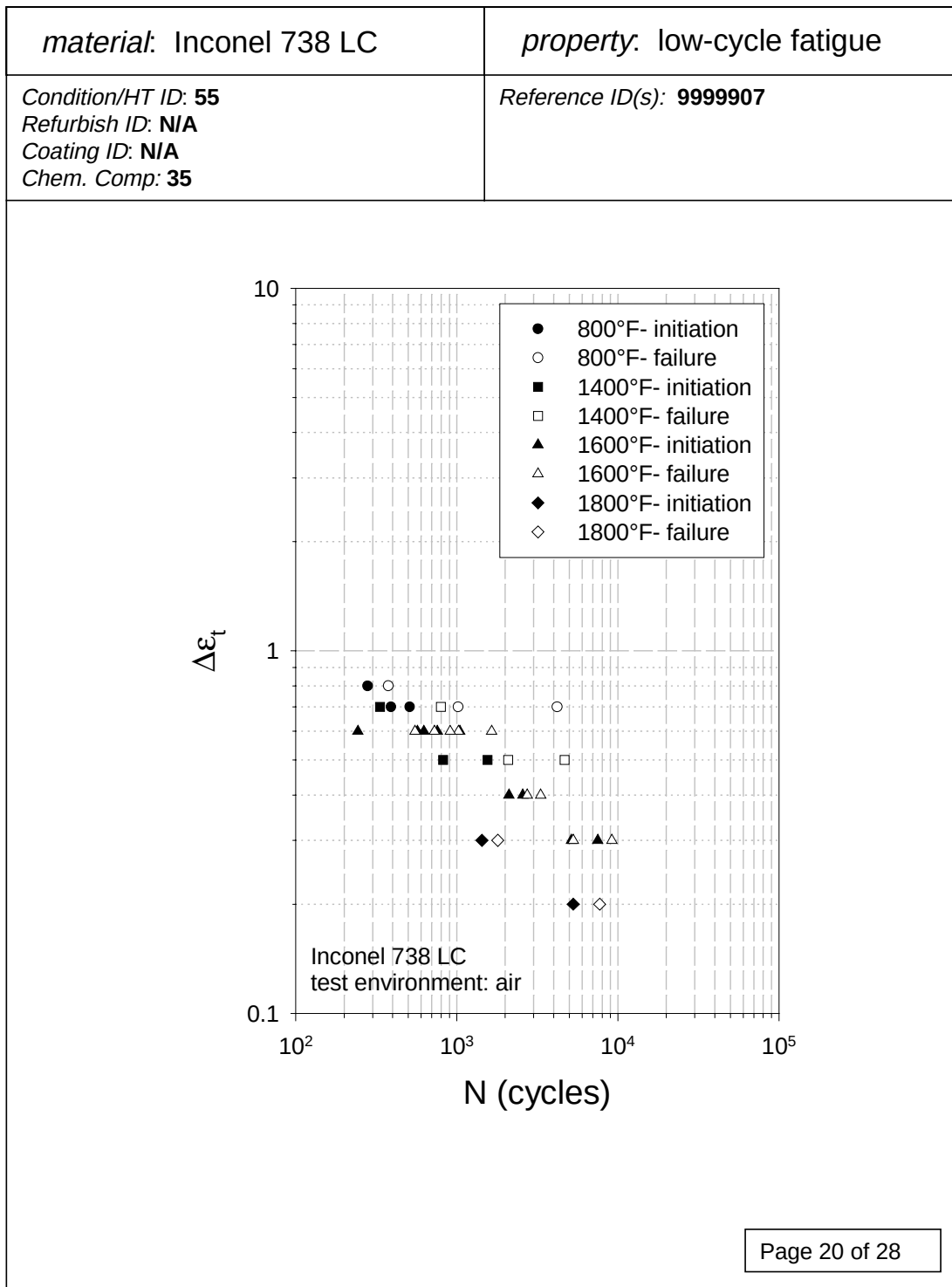


Figure 5-20
Low Cycle Initiation and Failure at Four Elevated Temperatures.

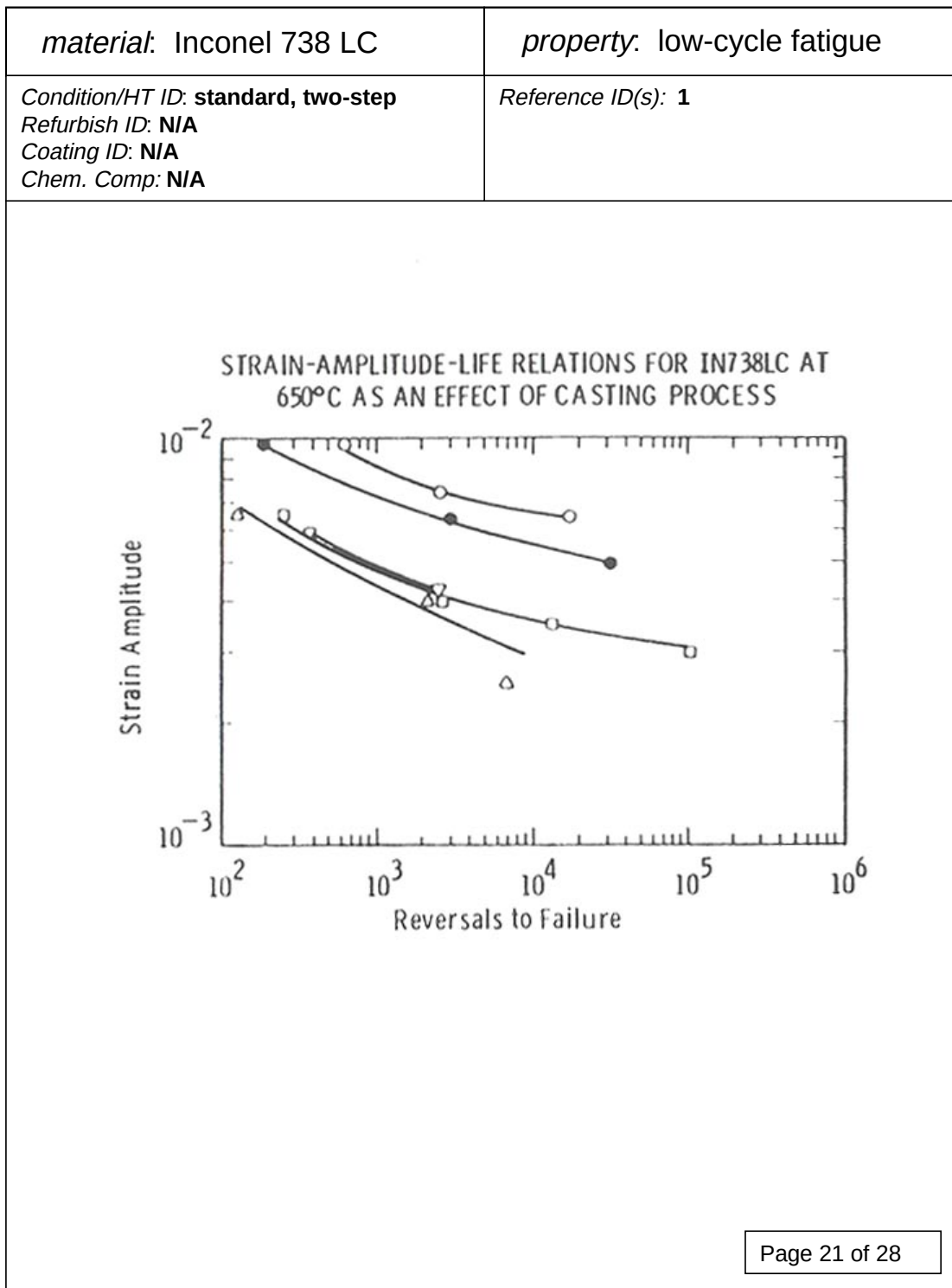


Figure 5-21
Strain-Amplitude-Life Relations for IN738LC at 650°C as an Effect of Casting Process.

Inconel 738 LC

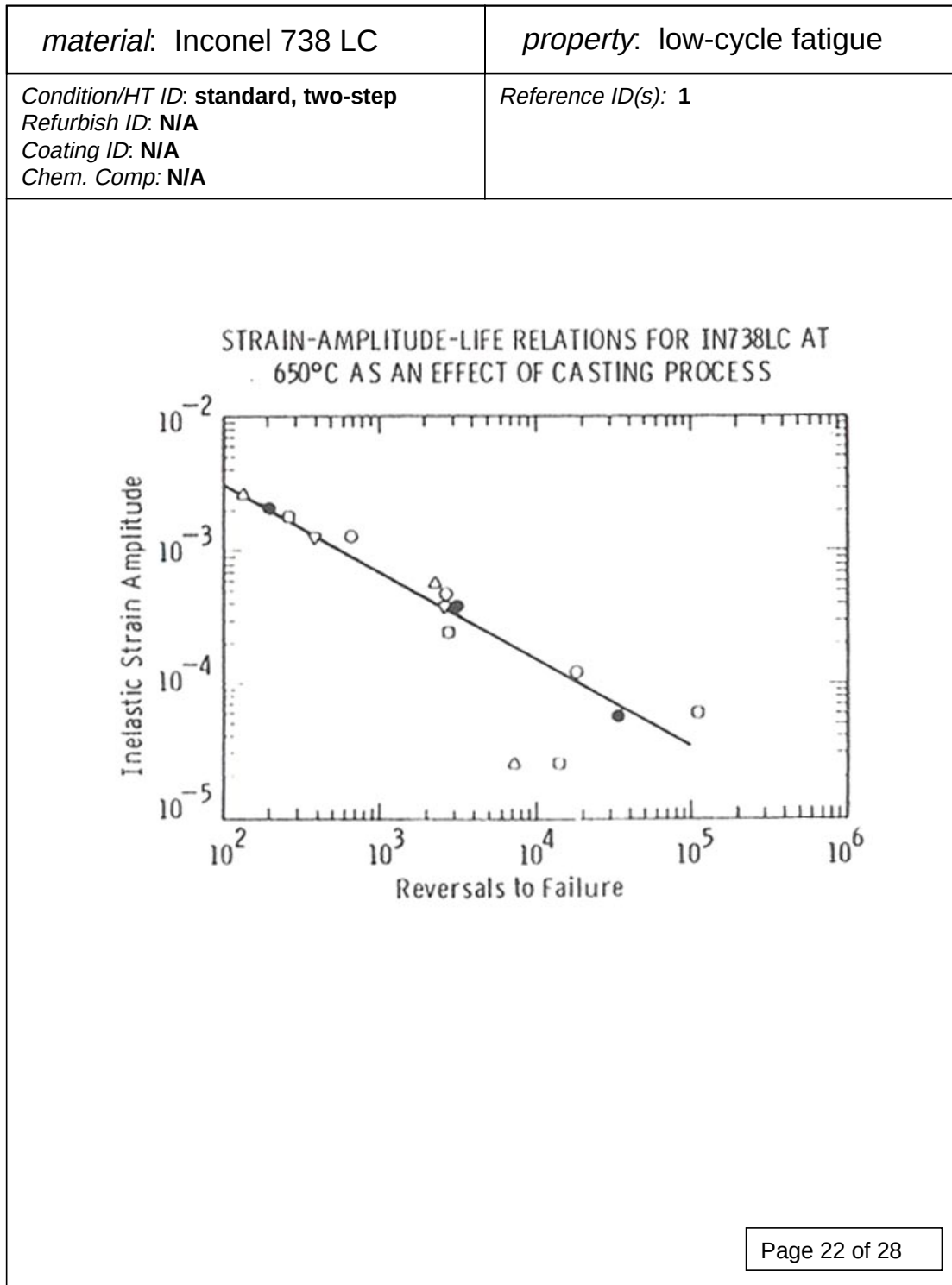


Figure 5-22
Strain-Amplitude-Life Relations for IN738LC at 650°C as an Effect of Casting Process.

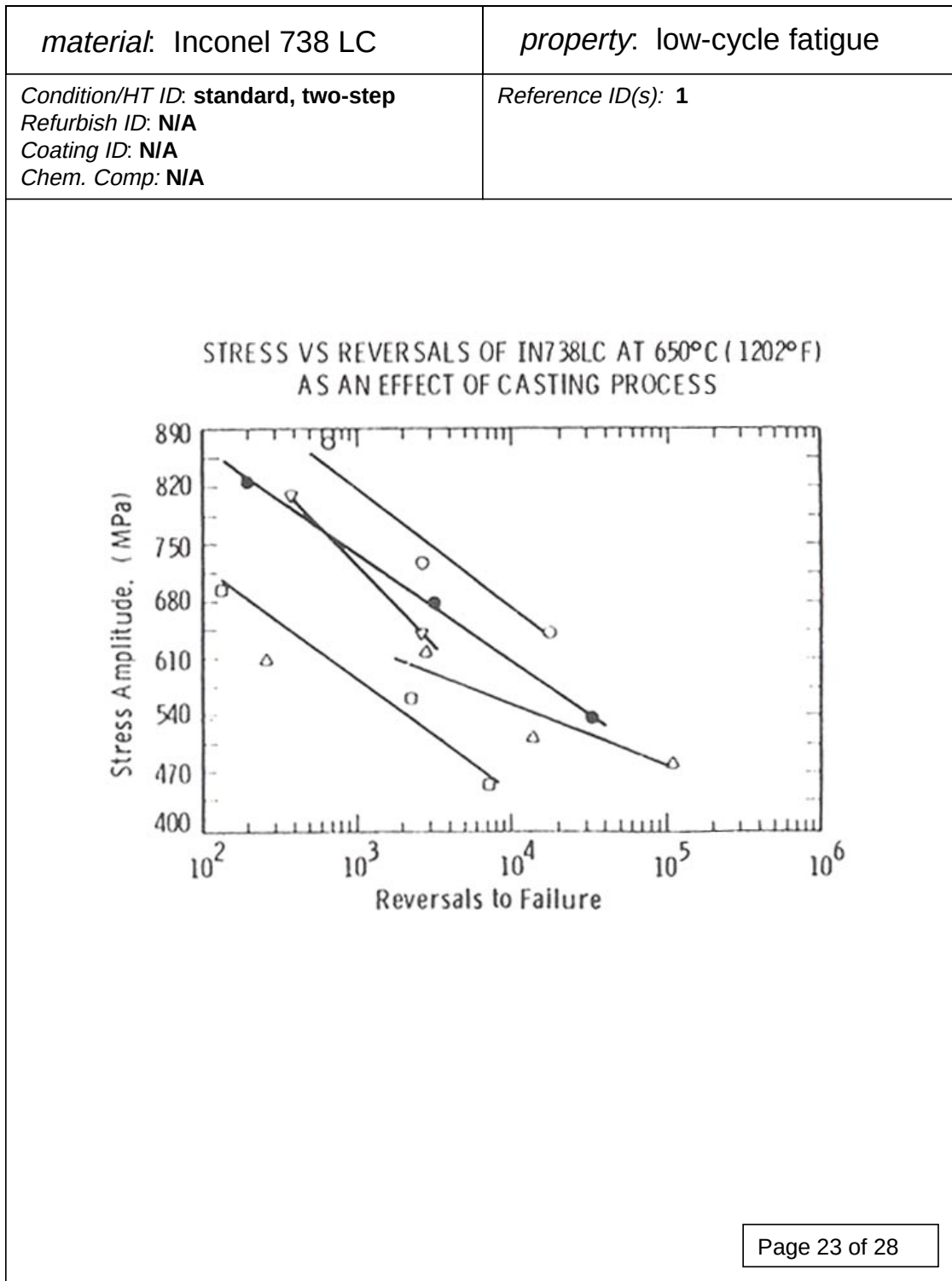


Figure 5-23
Stress vs. Reversals of IN738LC at 650°C (1202°F) as an Effect of Casting Process.

Inconel 738 LC

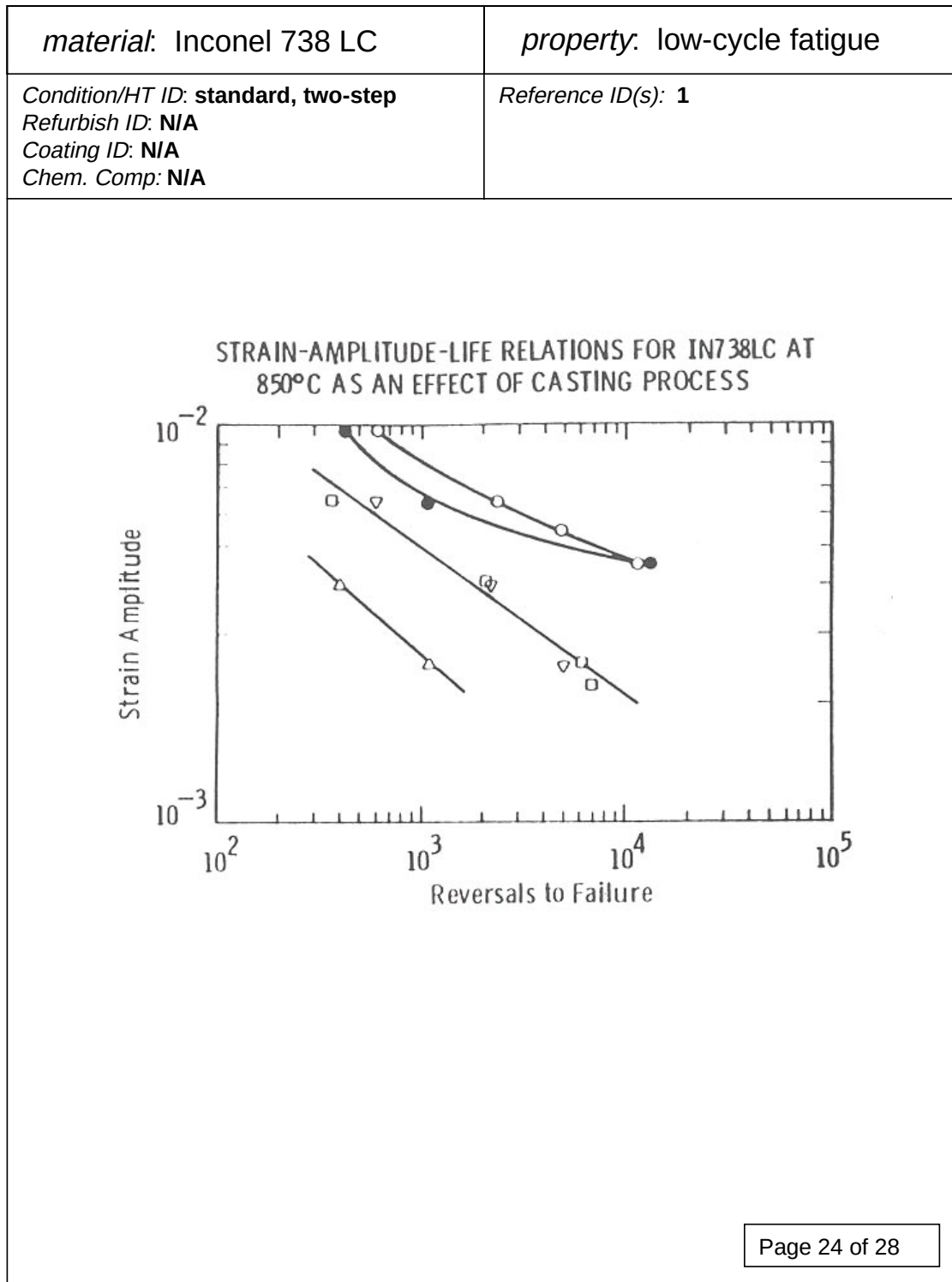


Figure 5-24
Strain-Amplitude-Life Relations for IN738LC at 850°C as an Effect of Casting Process.

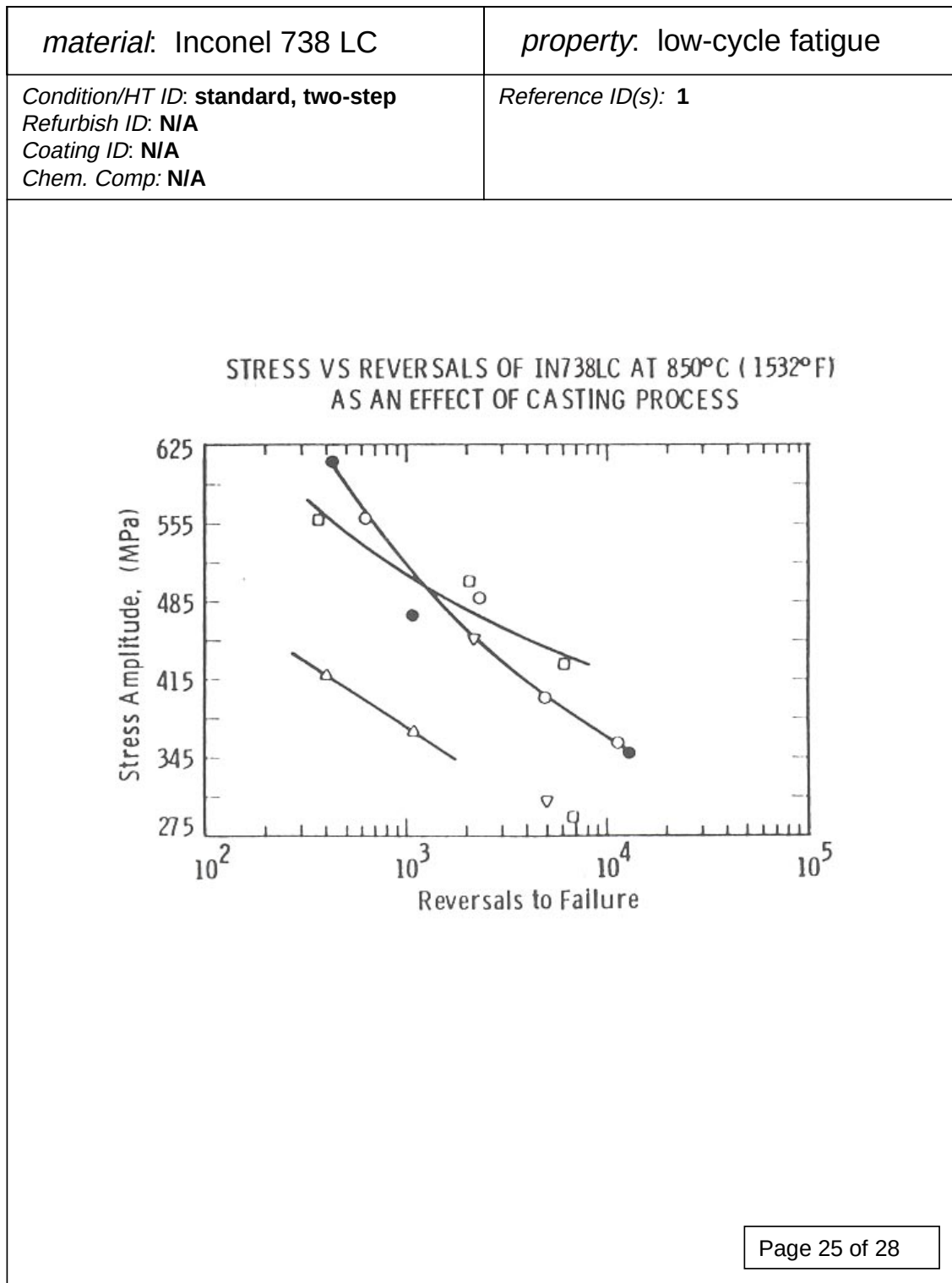


Figure 5-25
Stress vs. Reversals of IN738LC at 850°C (1532°F) as an Effect of Casting Process.

Inconel 738 LC

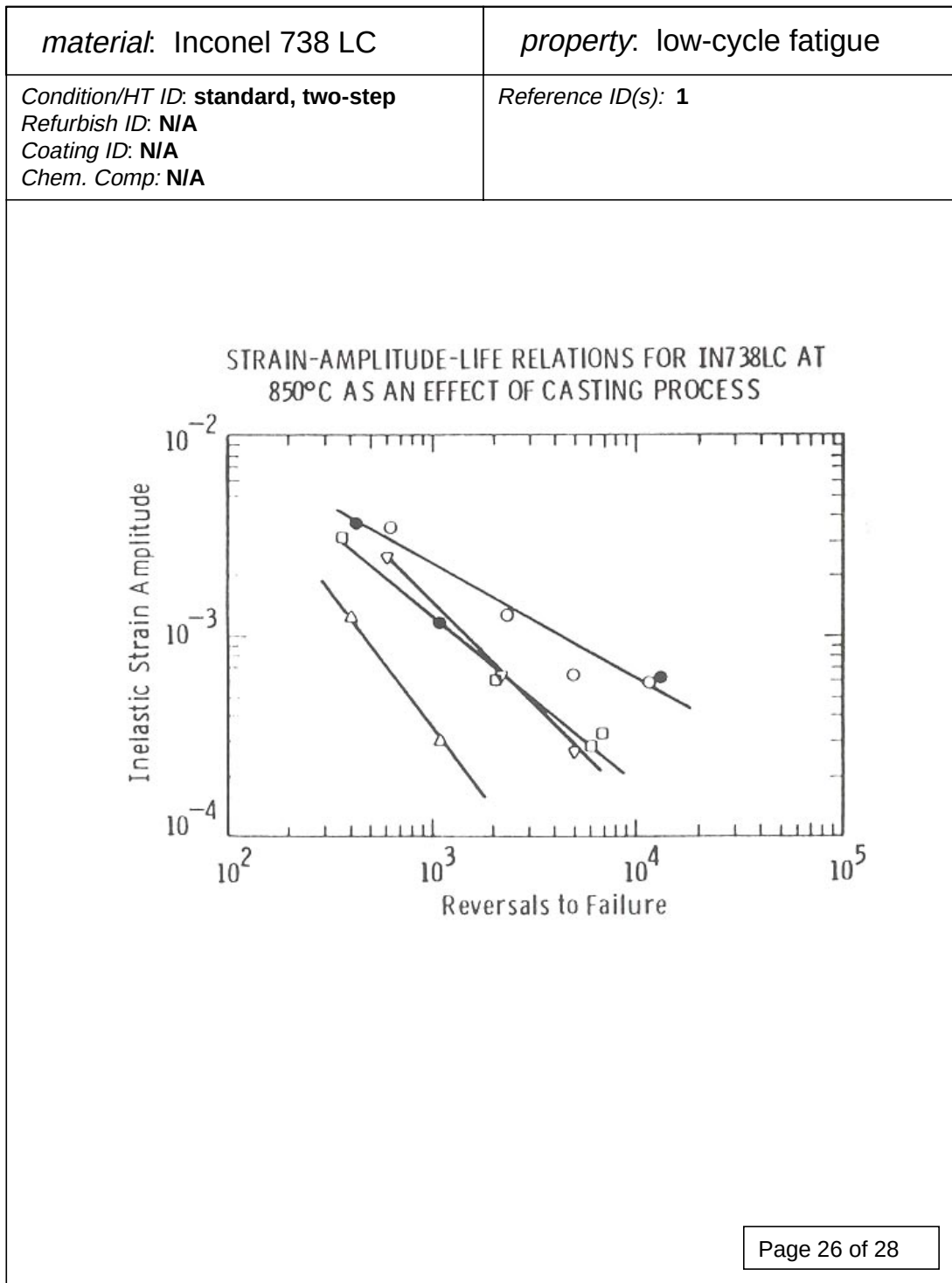


Figure 5-26
Strain-Amplitude-Life Relations for IN738LC at 850°C as an Effect of Casting Process.

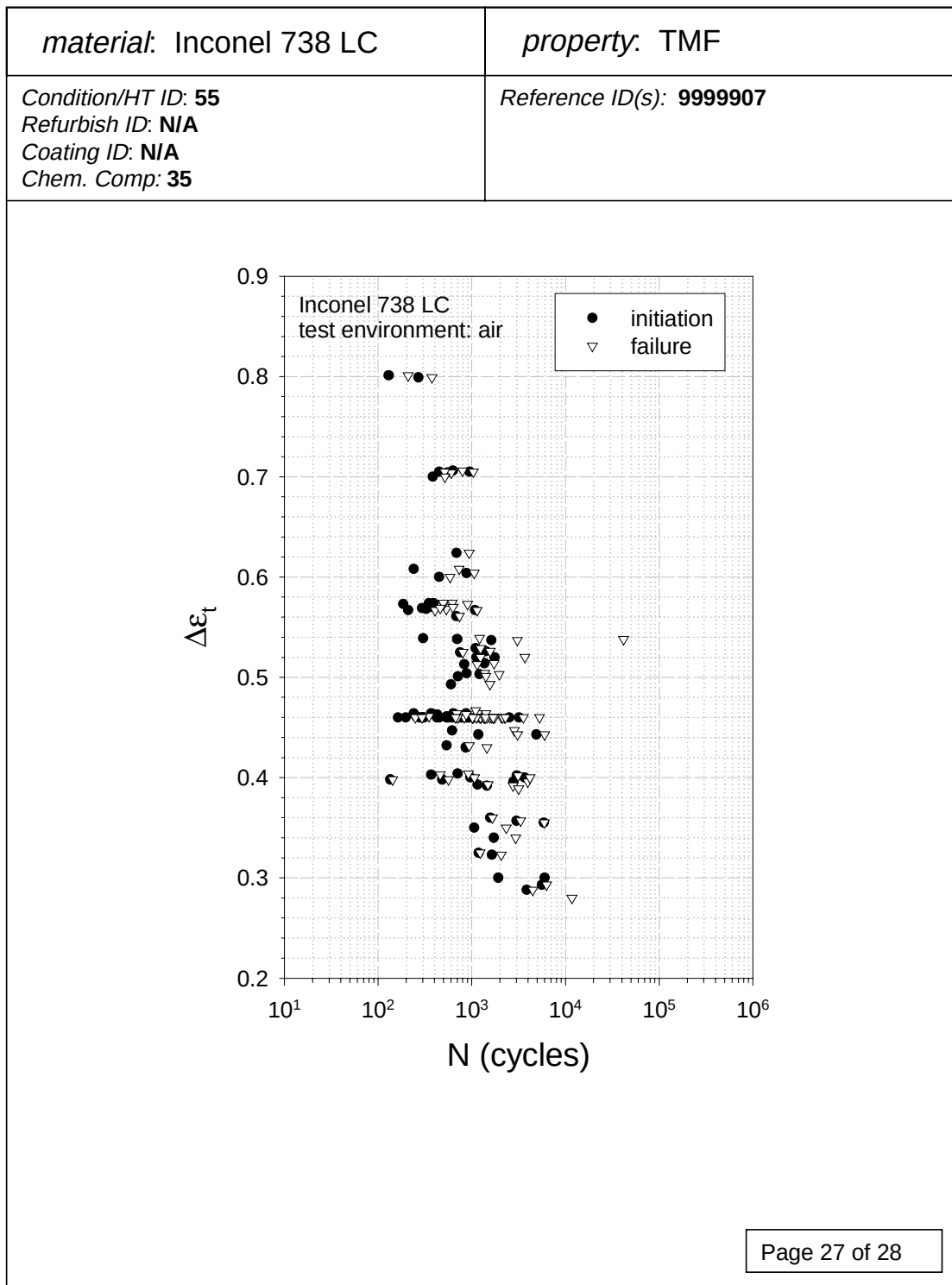


Figure 5-27
Low Cycle Fatigue Behavior for Inconel 738 LC.

Inconel 738 LC

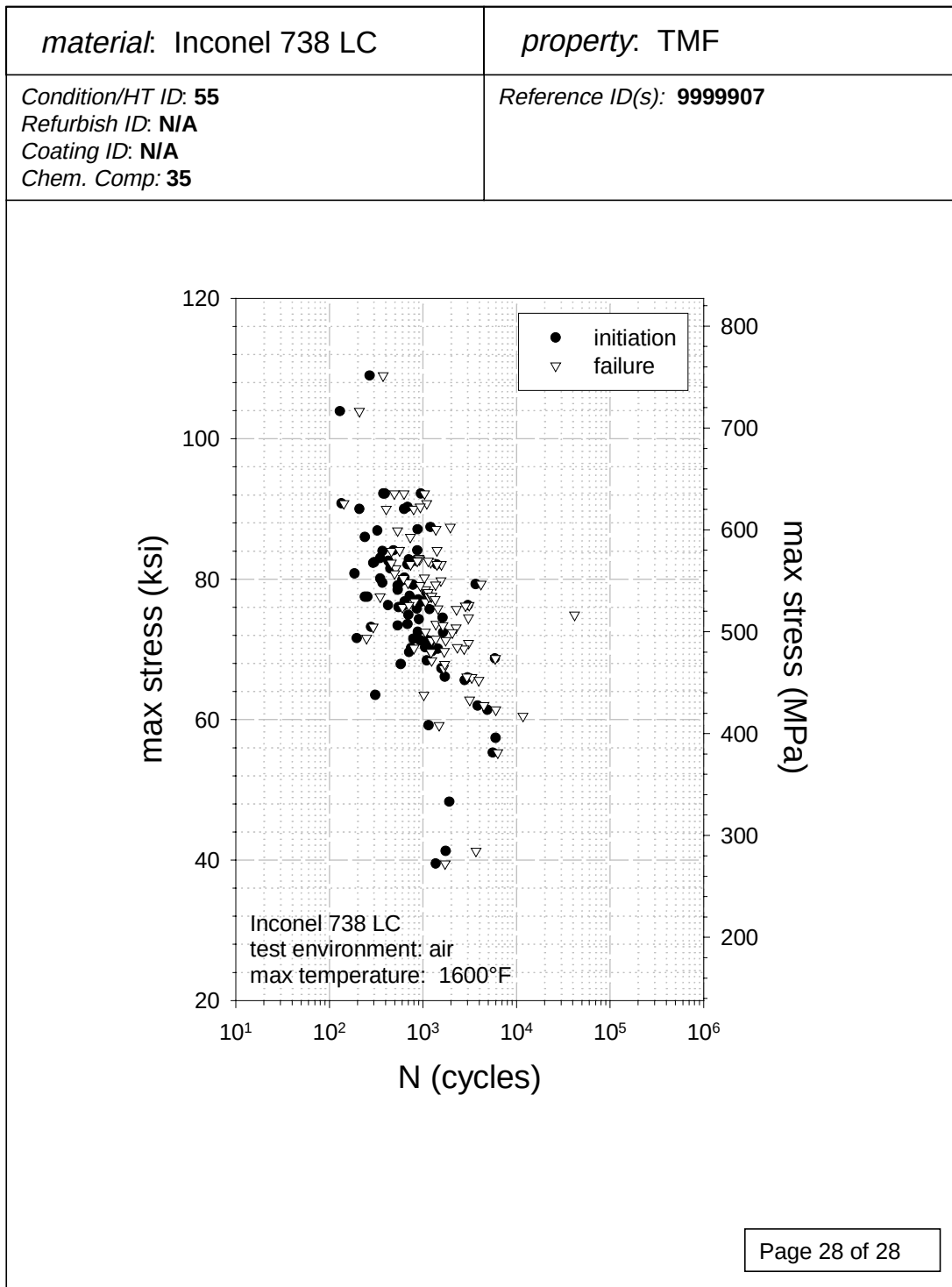


Figure 5-28
Thermal-Mechanical Fatigue Behavior of Inconel 738 LC.

6

INCONEL 792

Inconel 792

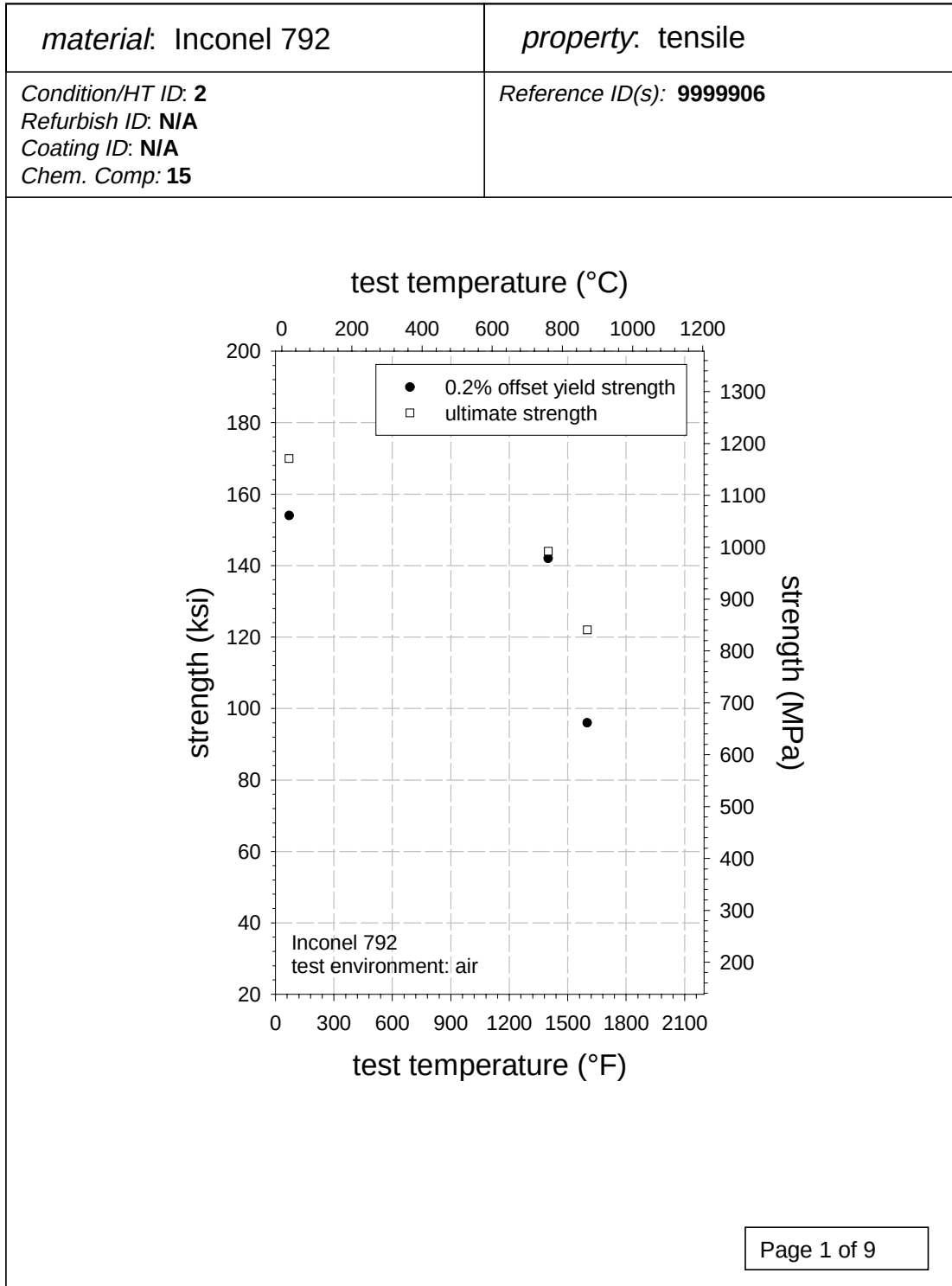


Figure 6-1
Tensile Strengths as a Function of Temperature.

Inconel 792

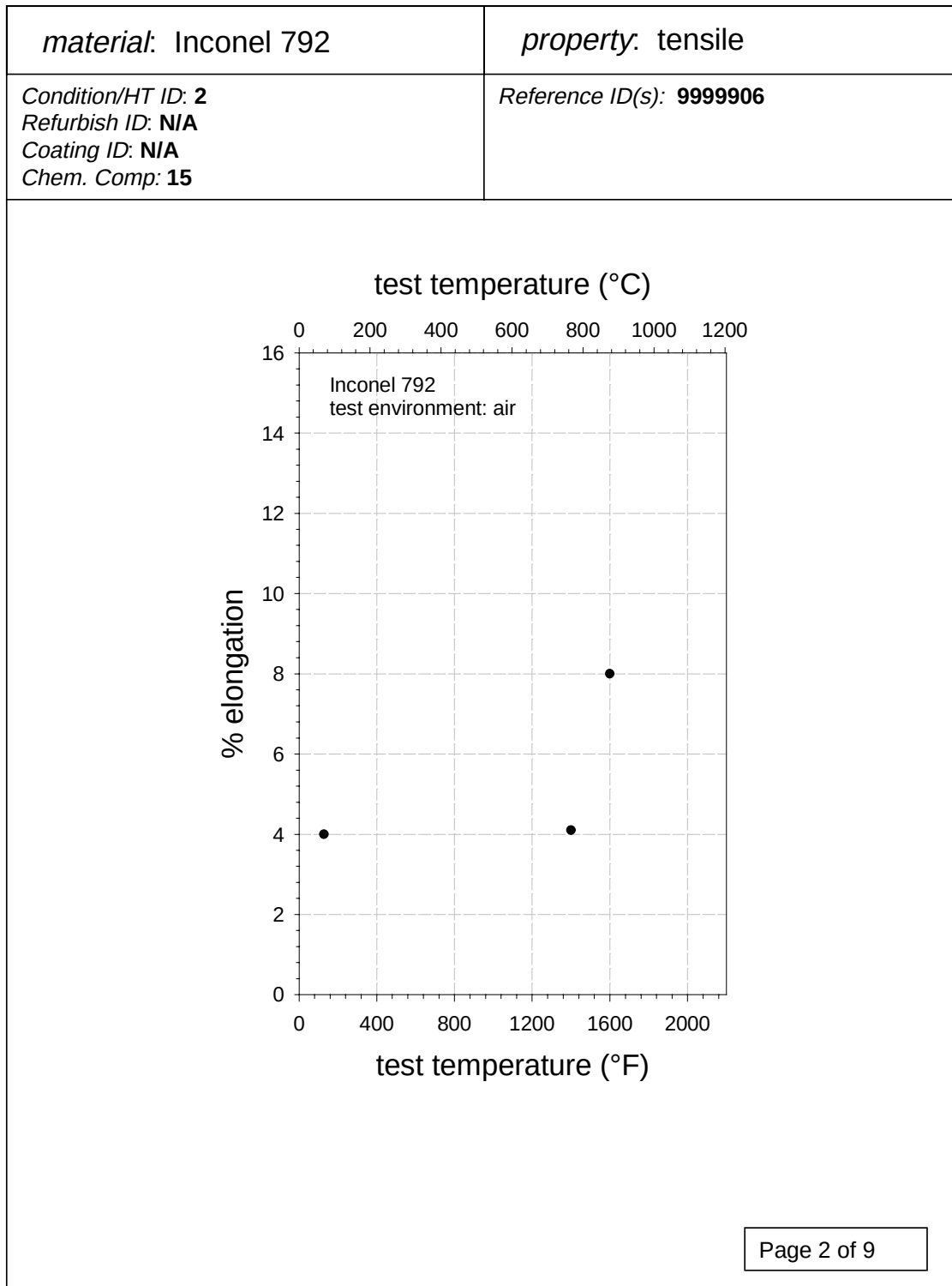


Figure 6-2
Tensile Elongation as a Function of Temperature.

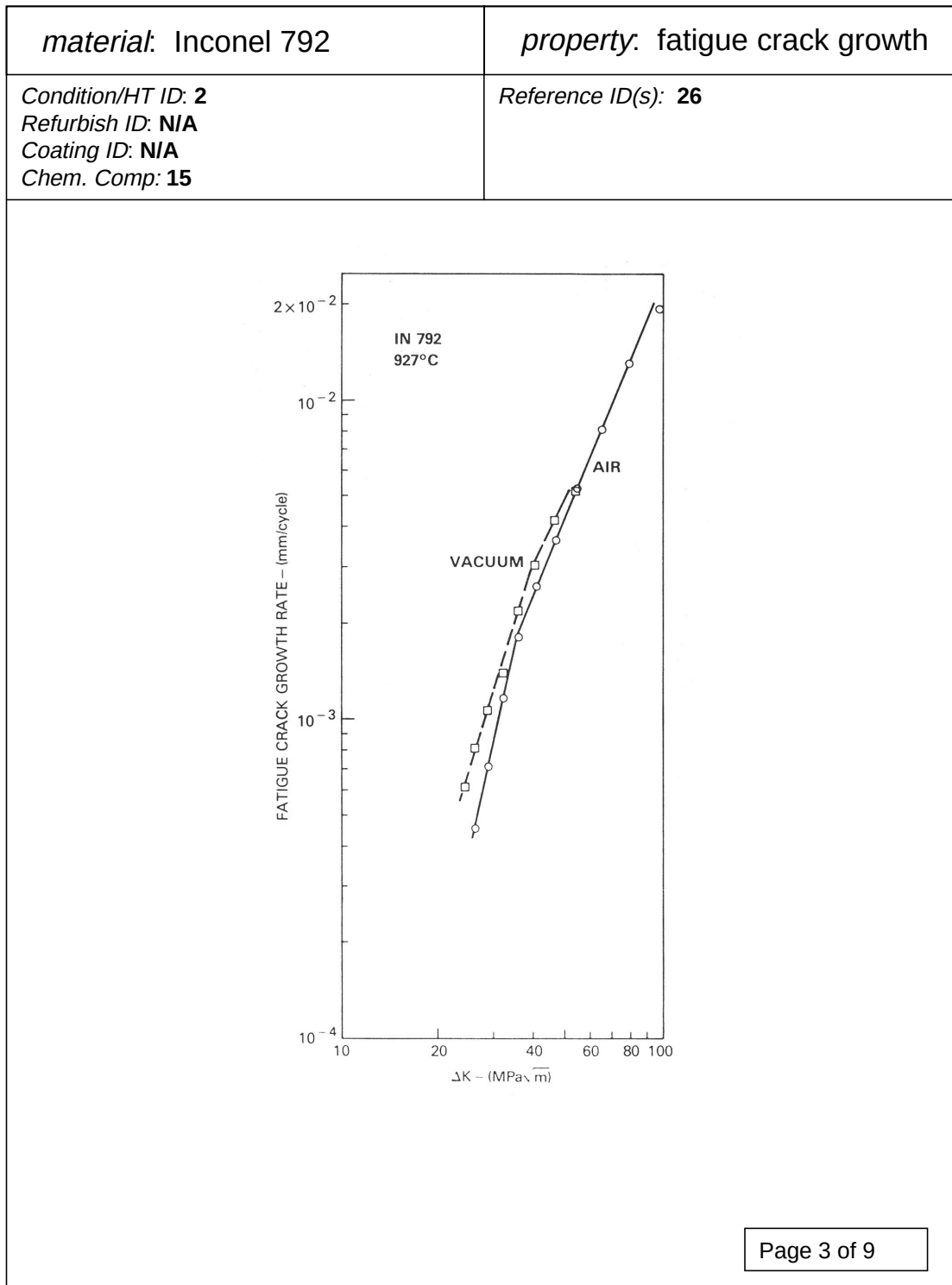


Figure 6-3
Fatigue Crack Growth Rate as a Function of ΔK in IN-792 at 927°C in Air and in Vacuum.

Inconel 792

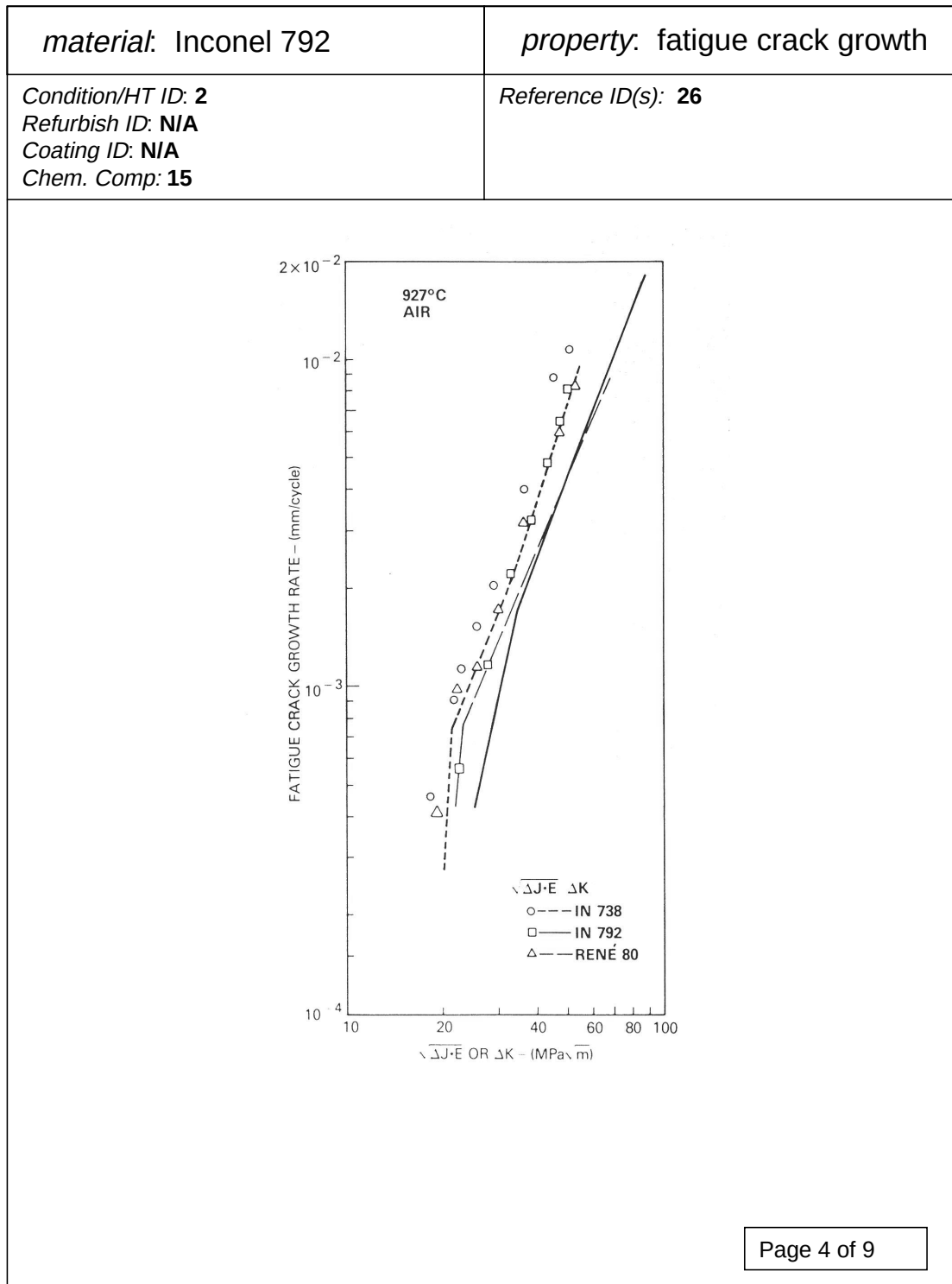


Figure 6-4
Comparison of Fatigue Crack Growth Rate in Terms for Three Alloys.

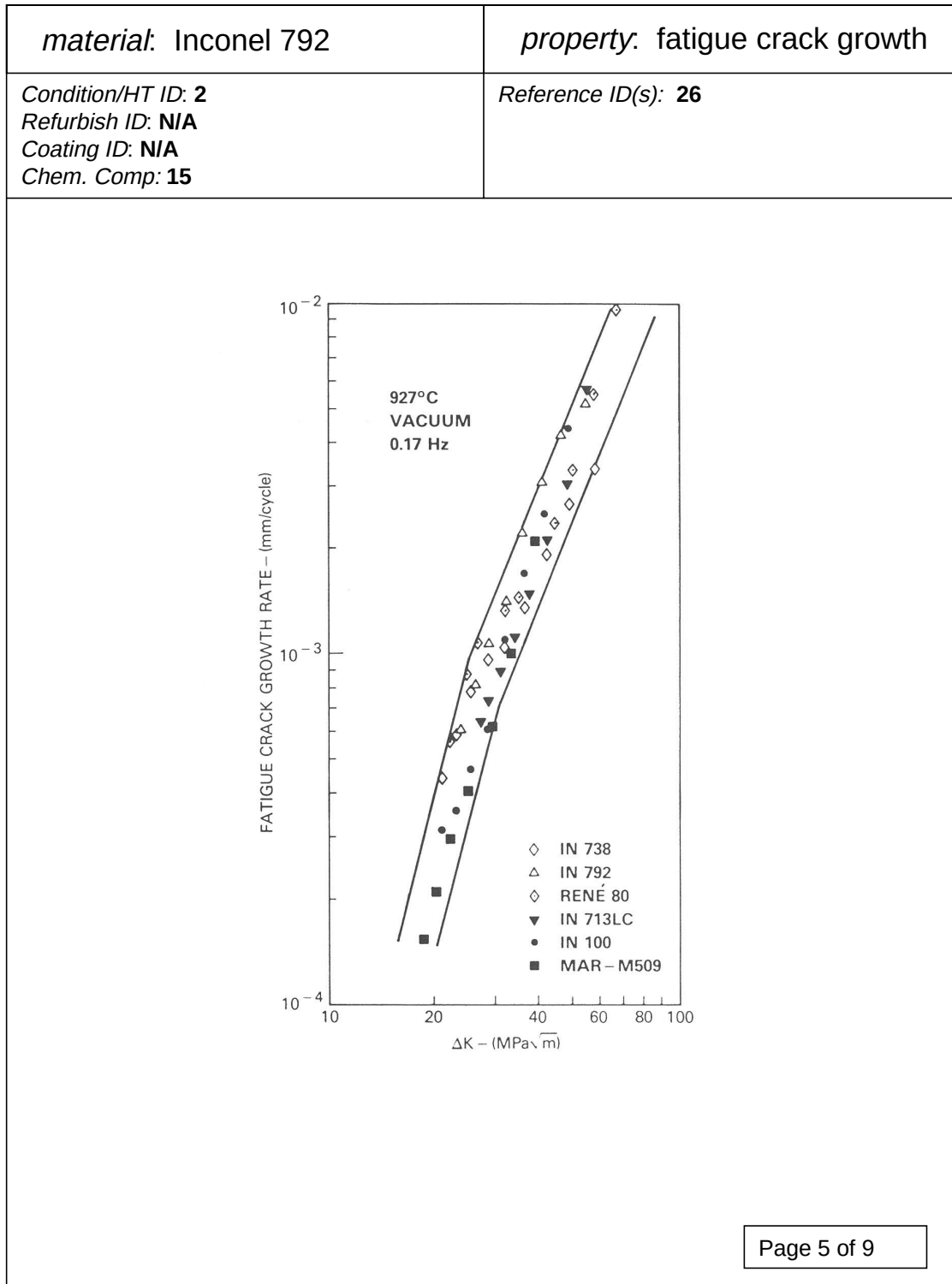


Figure 6-5
Fatigue Crack Growth Rate in Superalloys at 927°C in Vacuum.

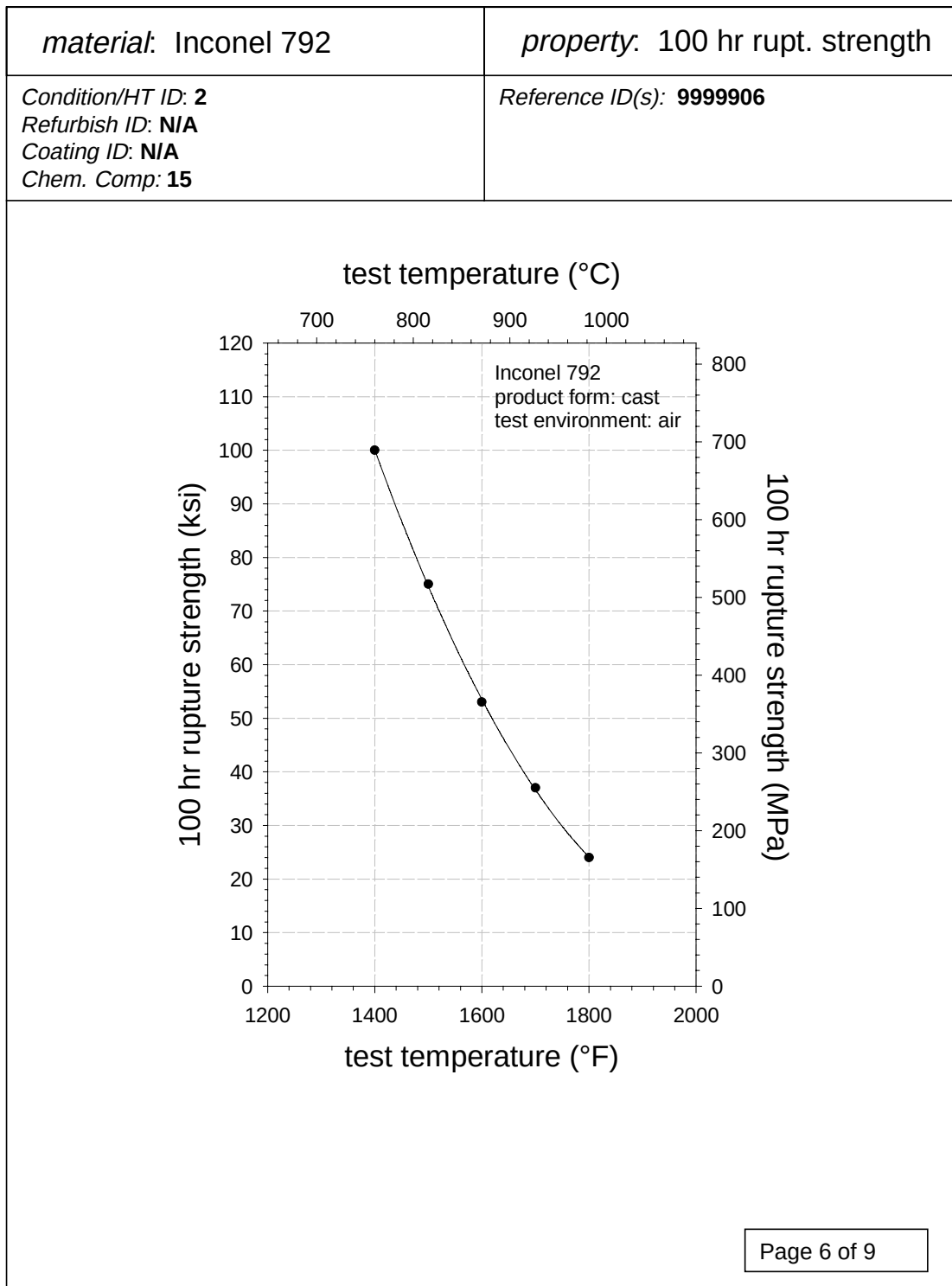


Figure 6-6
100 hr Rupture Strength as a Function of Temperature.

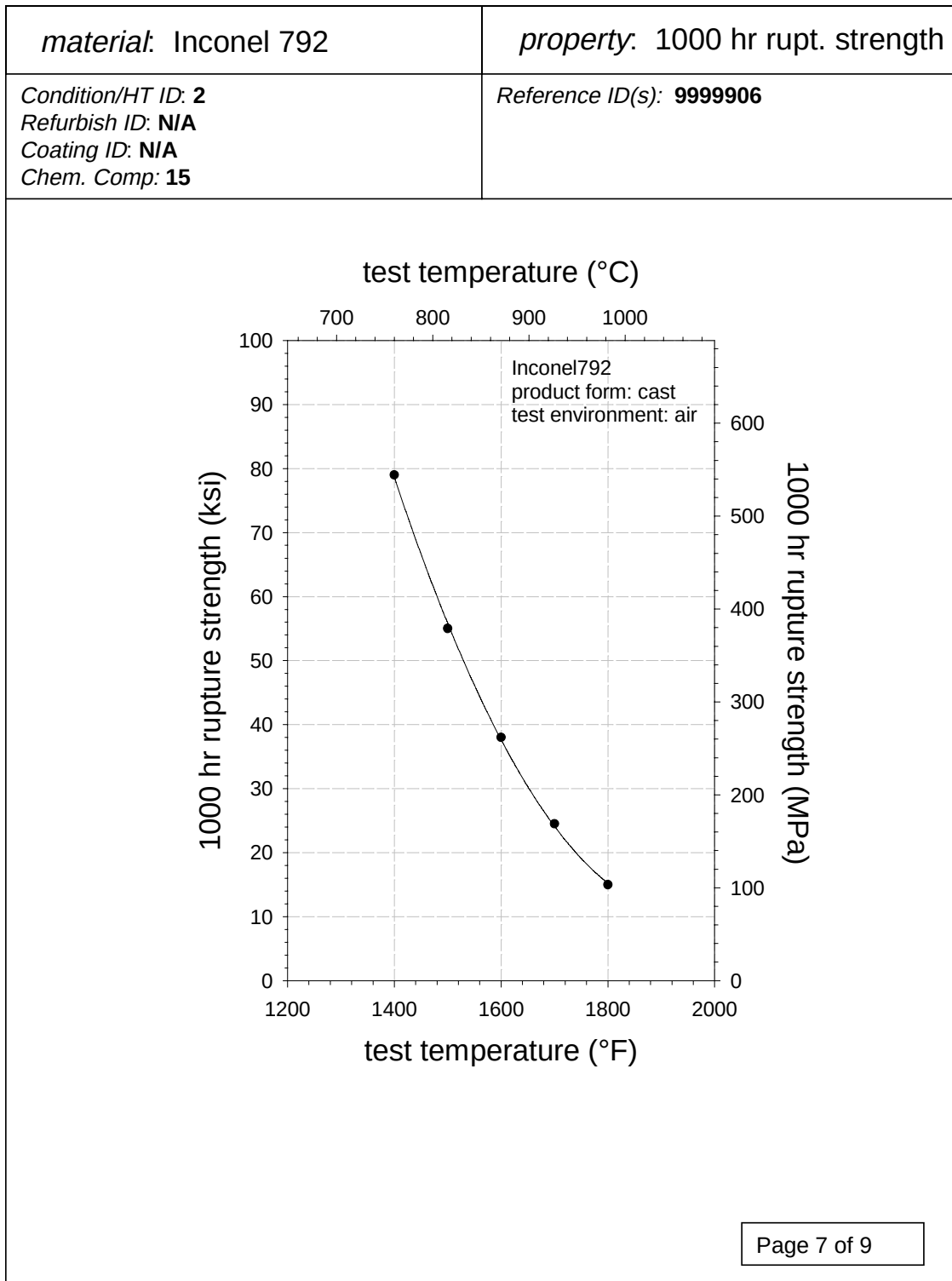


Figure 6-7
1000 hr Rupture Strength as a Function of Temperature.

Inconel 792

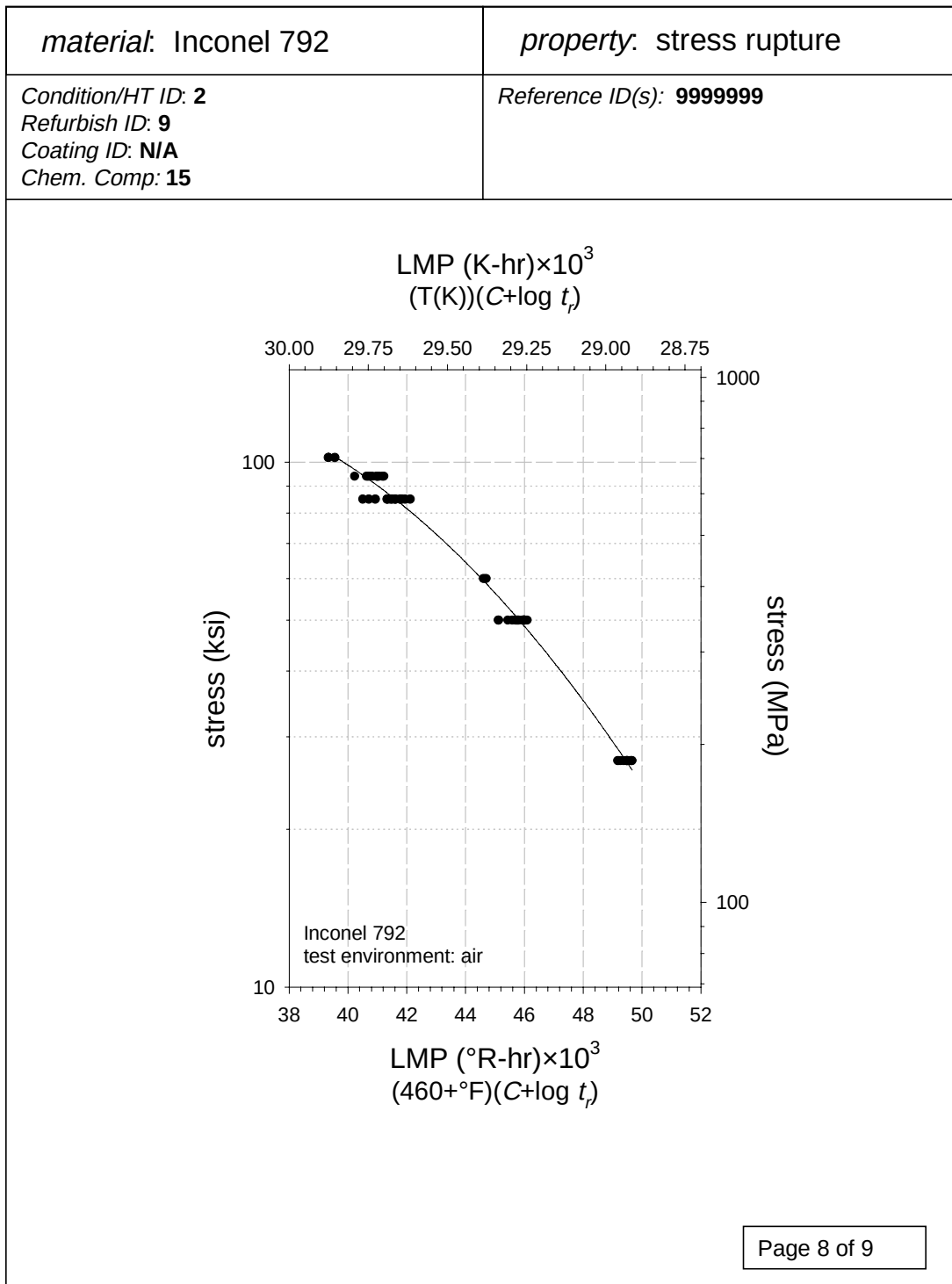


Figure 6-8
Larson-Miller Plot for Inconel 792.

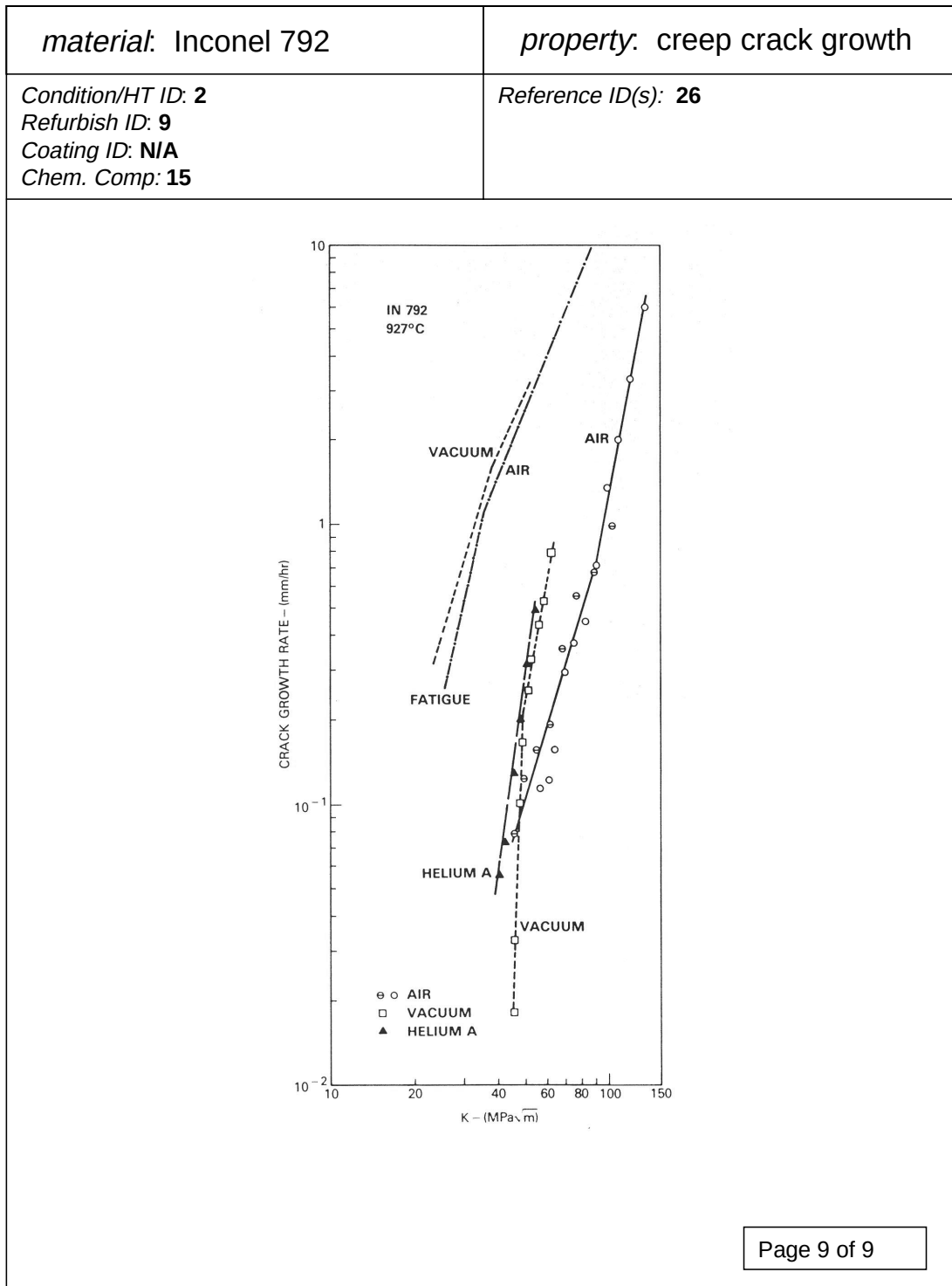


Figure 6-9
Influence of Environment on Creep Crack Growth Rate in IN-792 at 927°C and Comparison with Fatigue Crack Growth Rate (Fatigue Crack Growth Rate Given on a Time Basis).

7

MAR-M002

MAR-M002

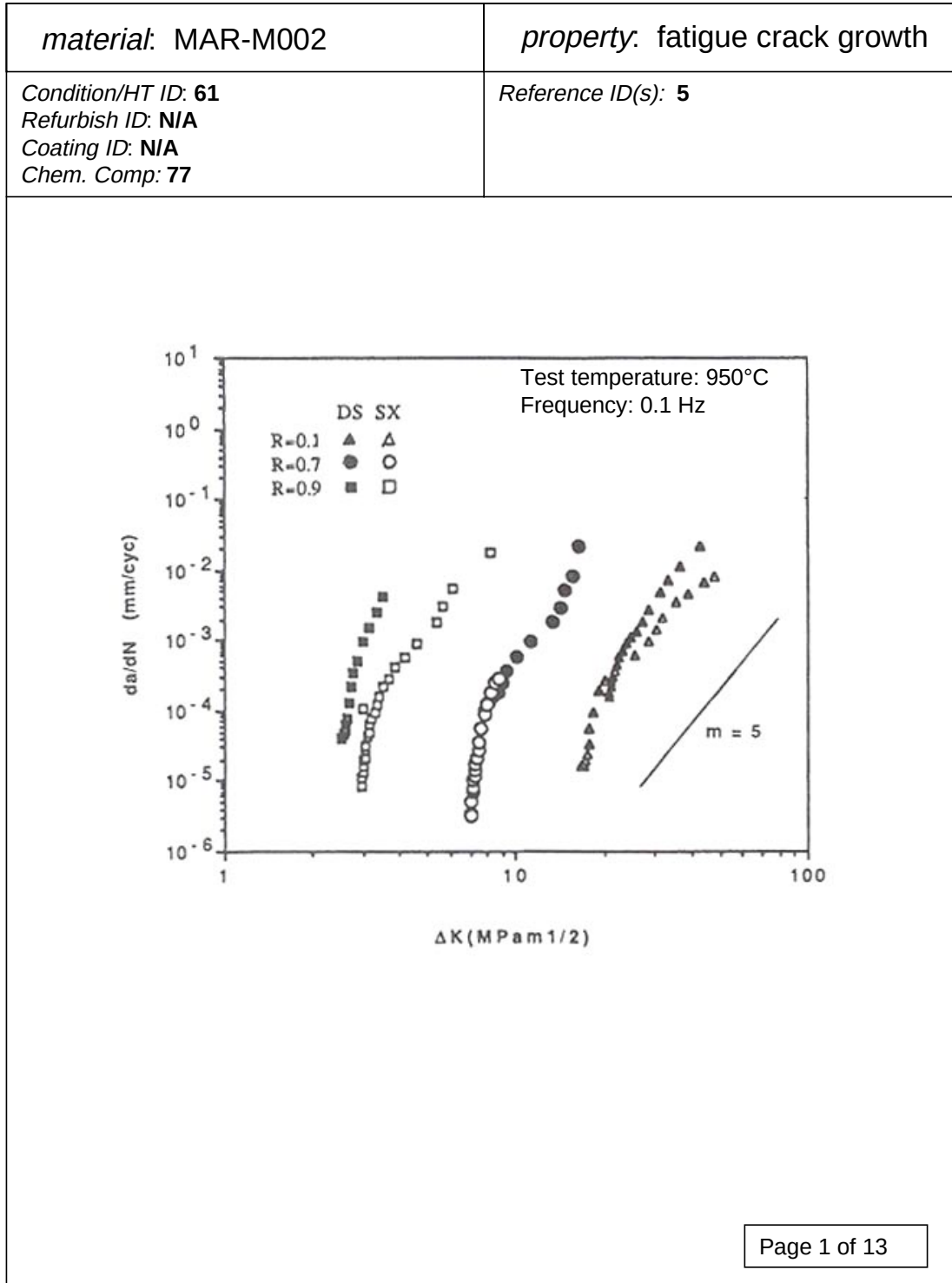


Figure 7-1
Influence of R on Crack Growth in Directionally Solidified and Single Crystal Materials at 950°C and a Frequency of 0.1 Hz.

MAR-M002

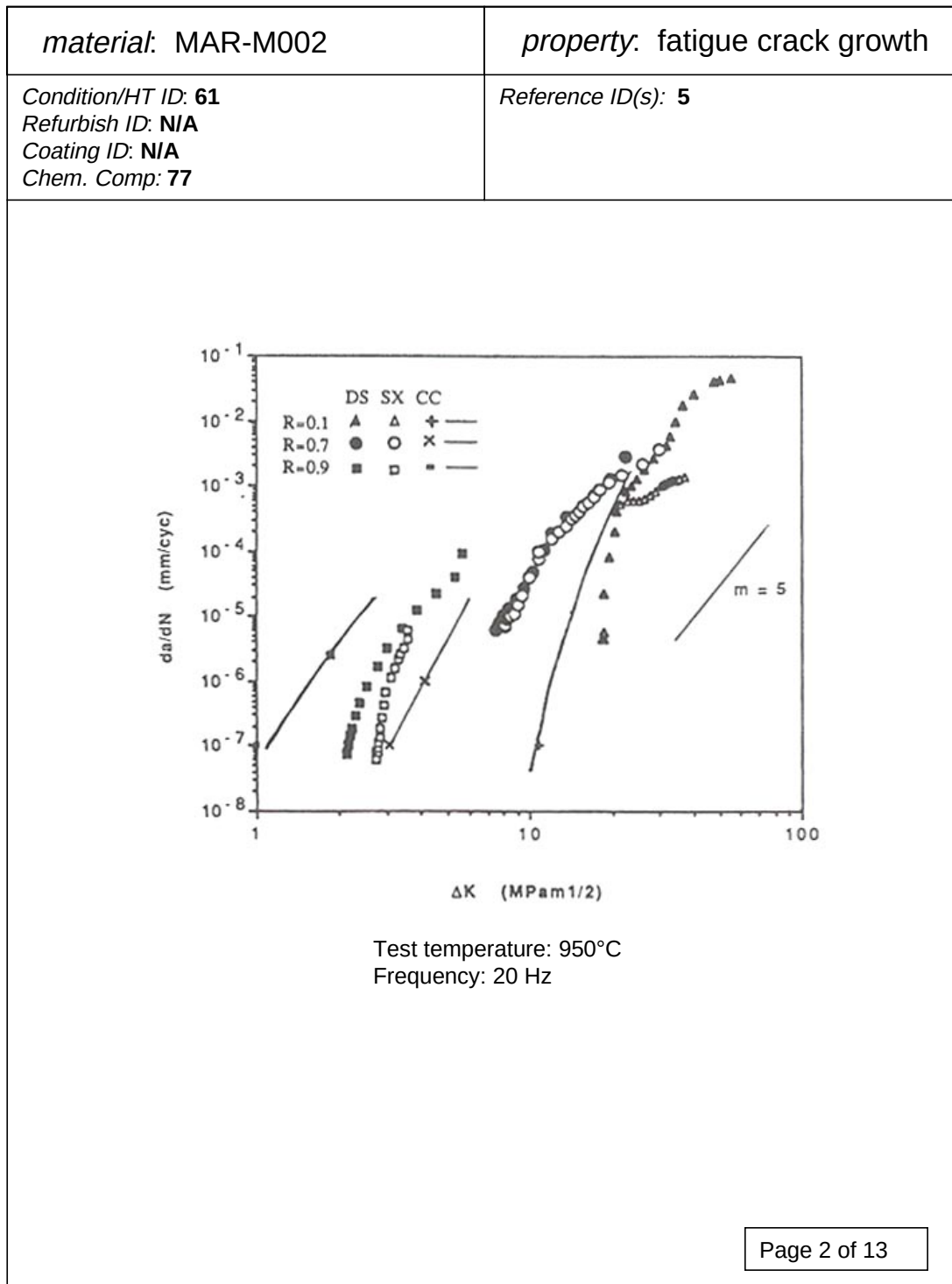


Figure 7-2
Influence of Grain Structure and R on Crack Growth at 950°C and a Frequency of 20 Hz.

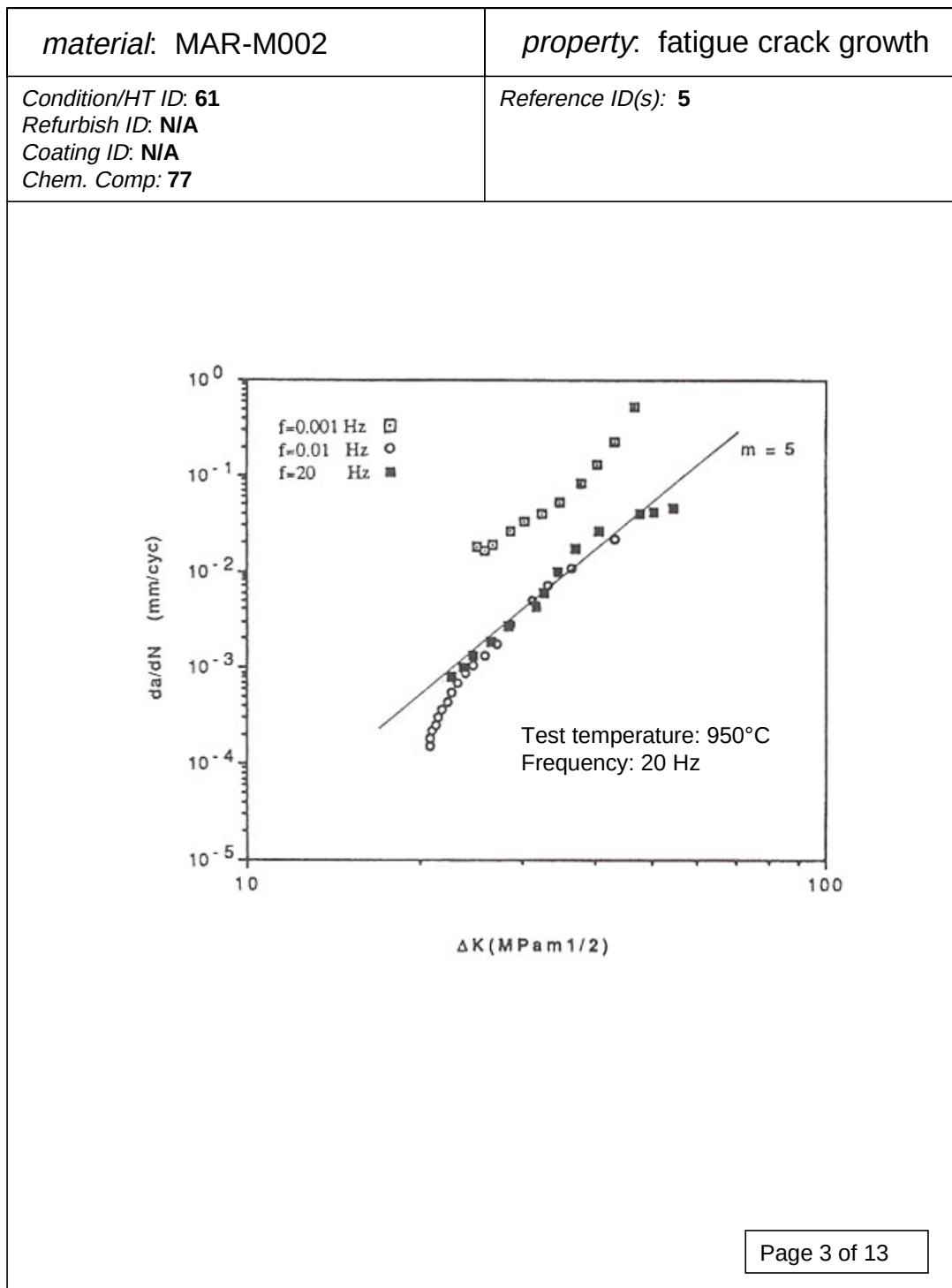


Figure 7-3
Effect of Frequency on Crack Growth in Directionally Solidified Alloy at 950°C and R = 0.1.

MAR-M002

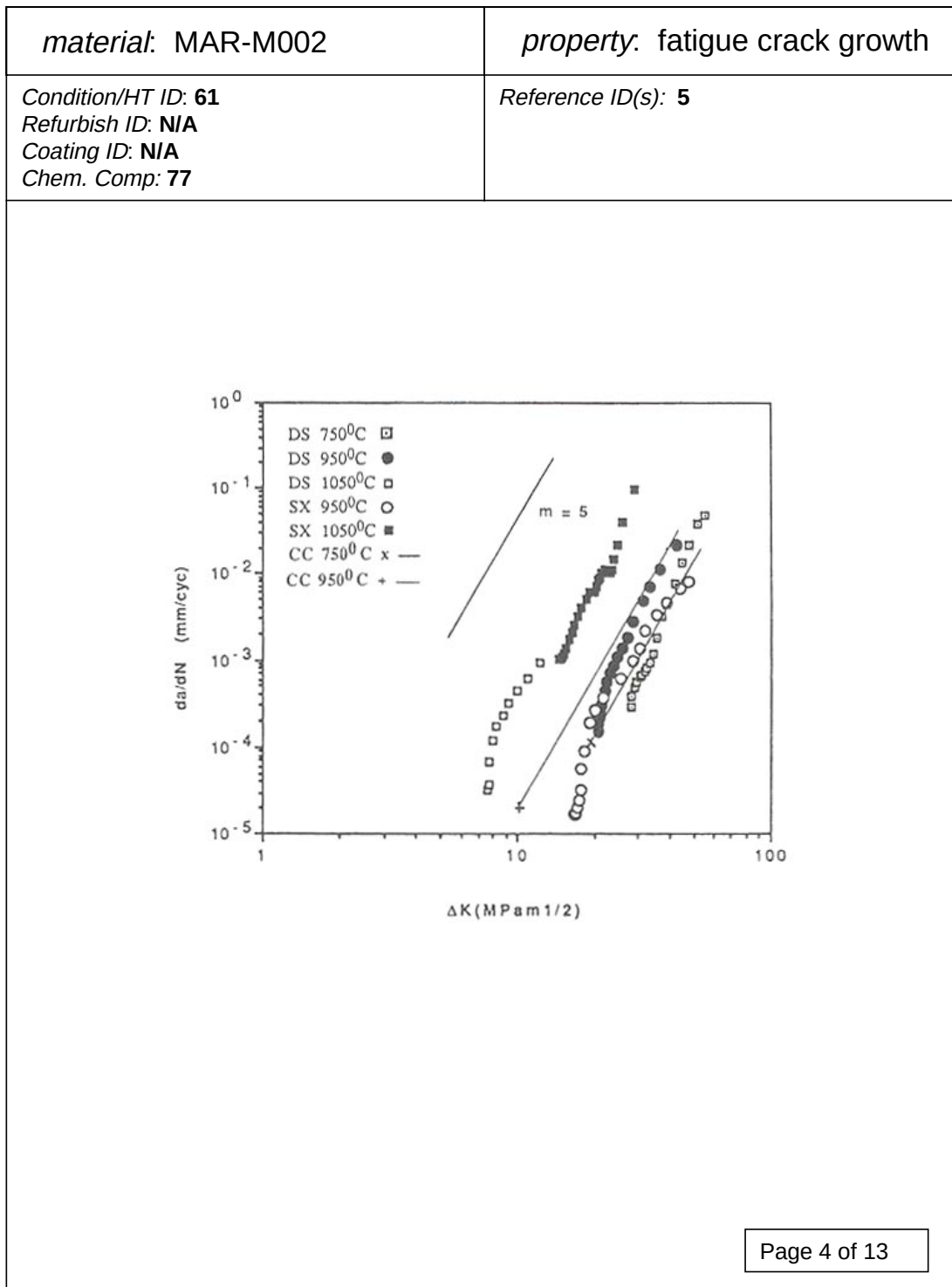


Figure 7-4
Effect of Temperature on Crack Growth/Cycle in Directionally Solidified and Single Crystal Materials at a Frequency of 0.1 Hz and R = 0.1.

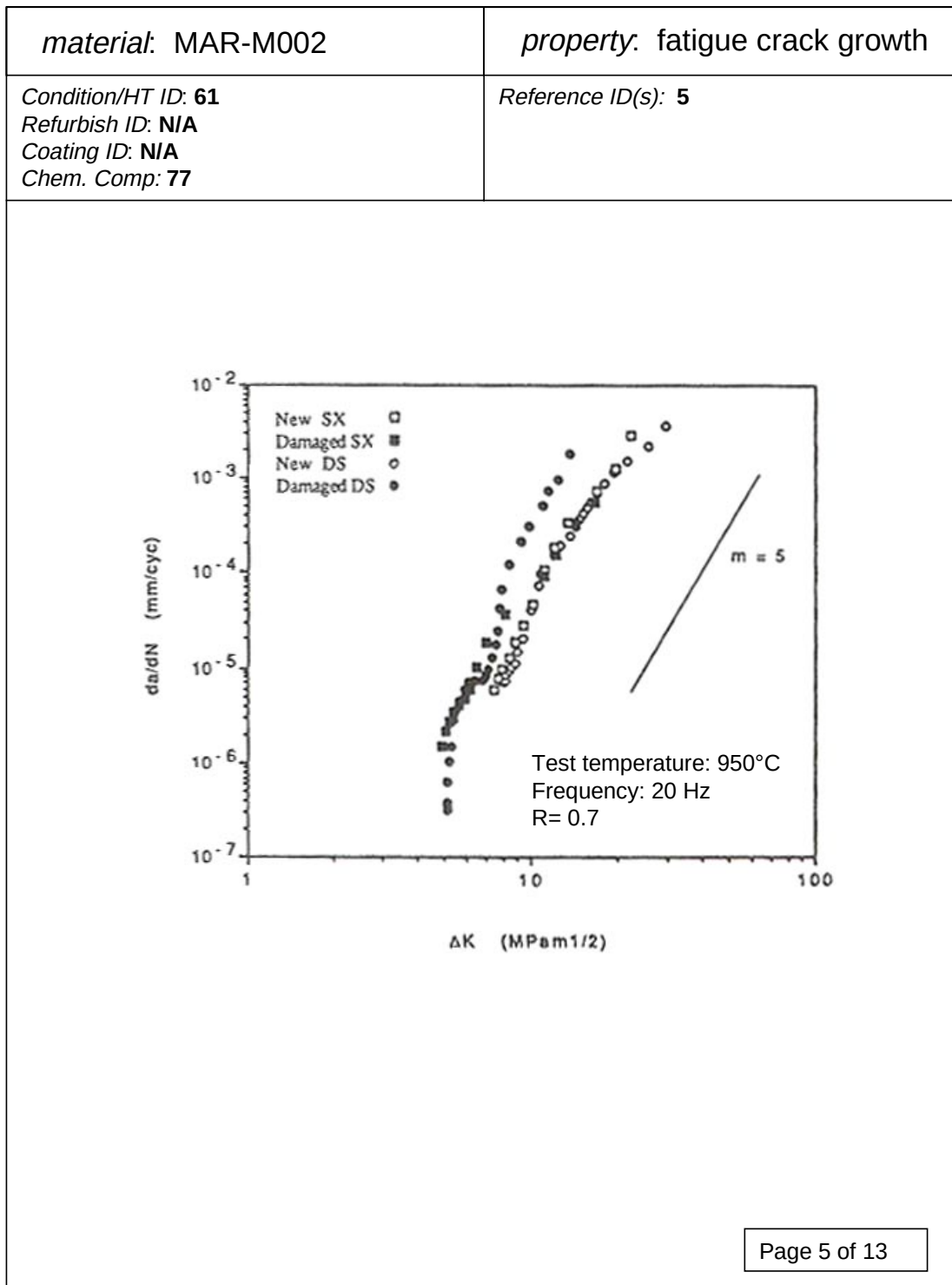


Figure 7-5
Effect of Prior Creep Damage on Crack Growth in Directionally Solidified and Single Crystal Material at 950°C at a Frequency of 20 Hz and R = 0.7.

MAR-M002

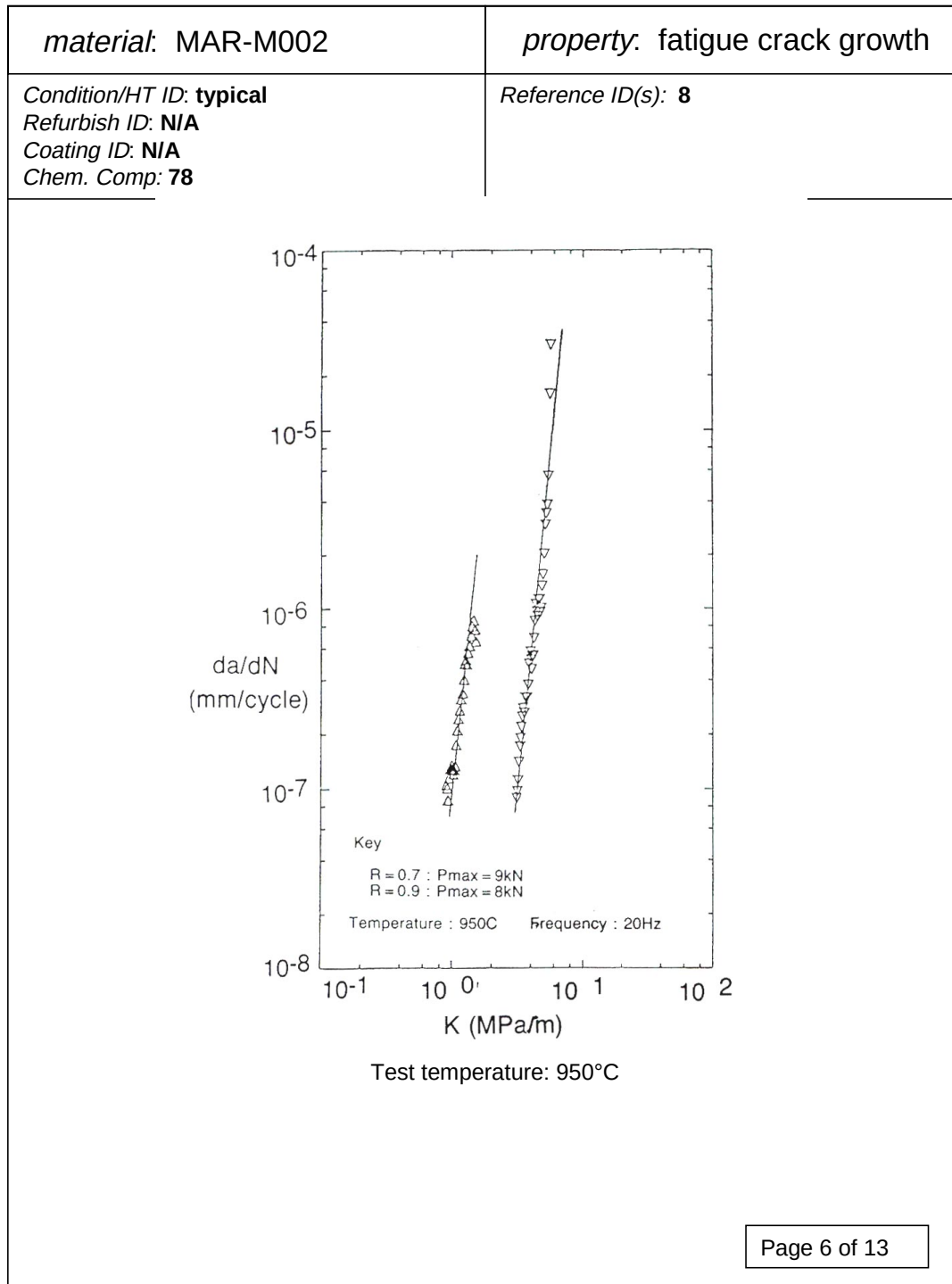


Figure 7-6
Effect of R on Crack Growth Per Cycle in the Threshold Region at 950°C.

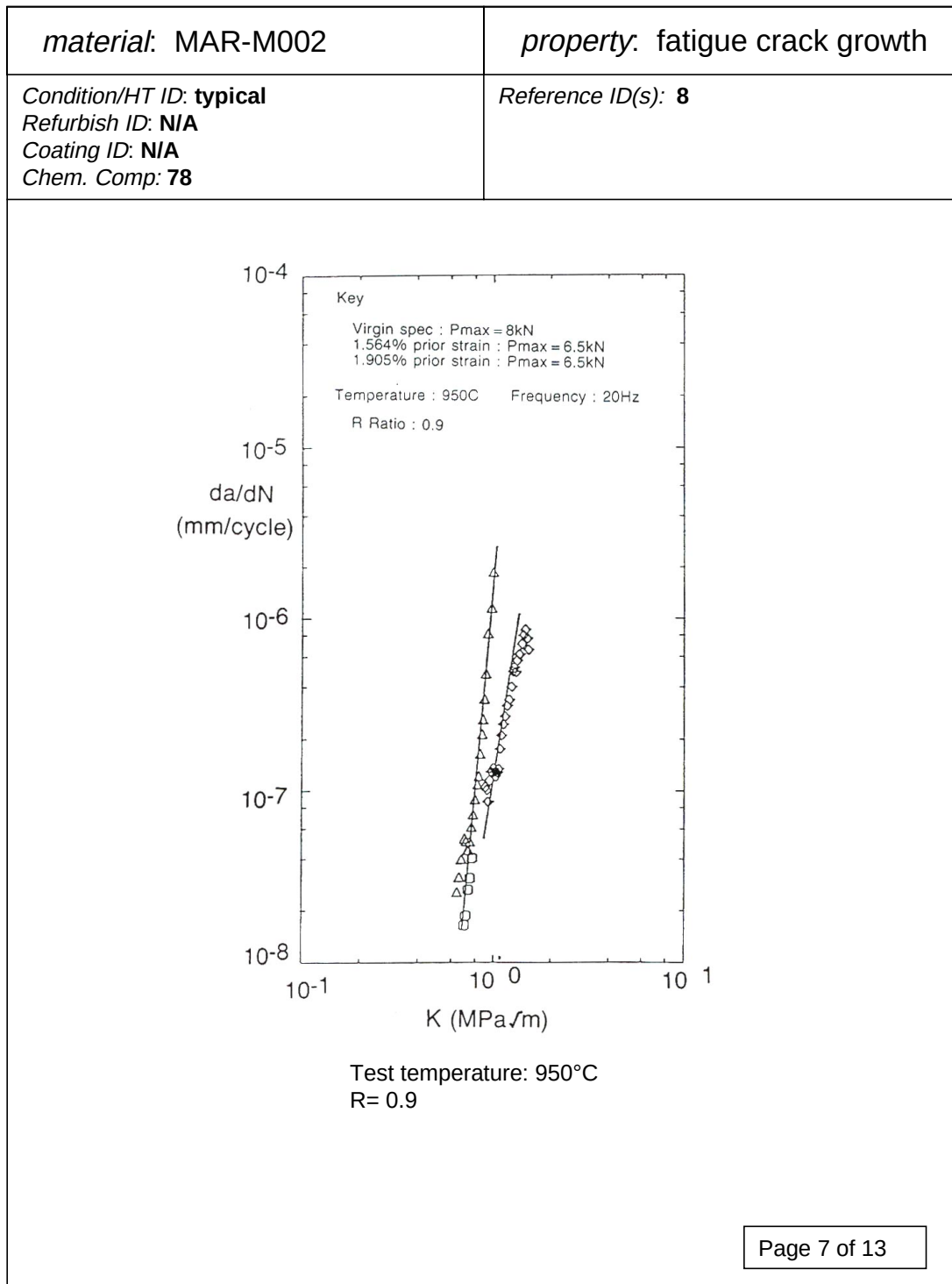


Figure 7-7
Effect of Prior Creep Damage on Crack Growth Per Cycle at 950°C for R = 0.9.

MAR-M002

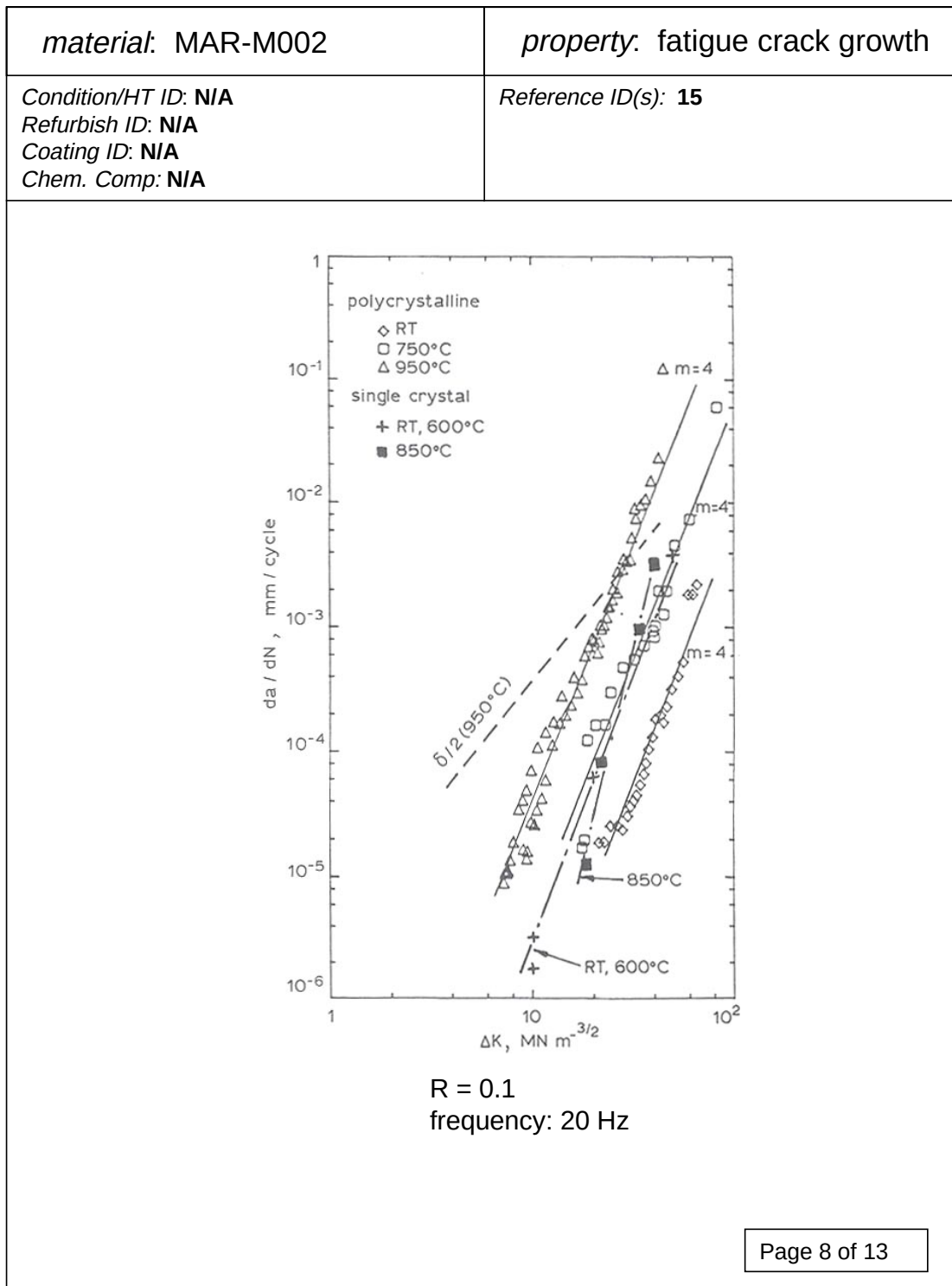


Figure 7-8
Crack Growth for MAR-M002 at Cyclic Frequency of 0.25 Hz and R = 0.1.

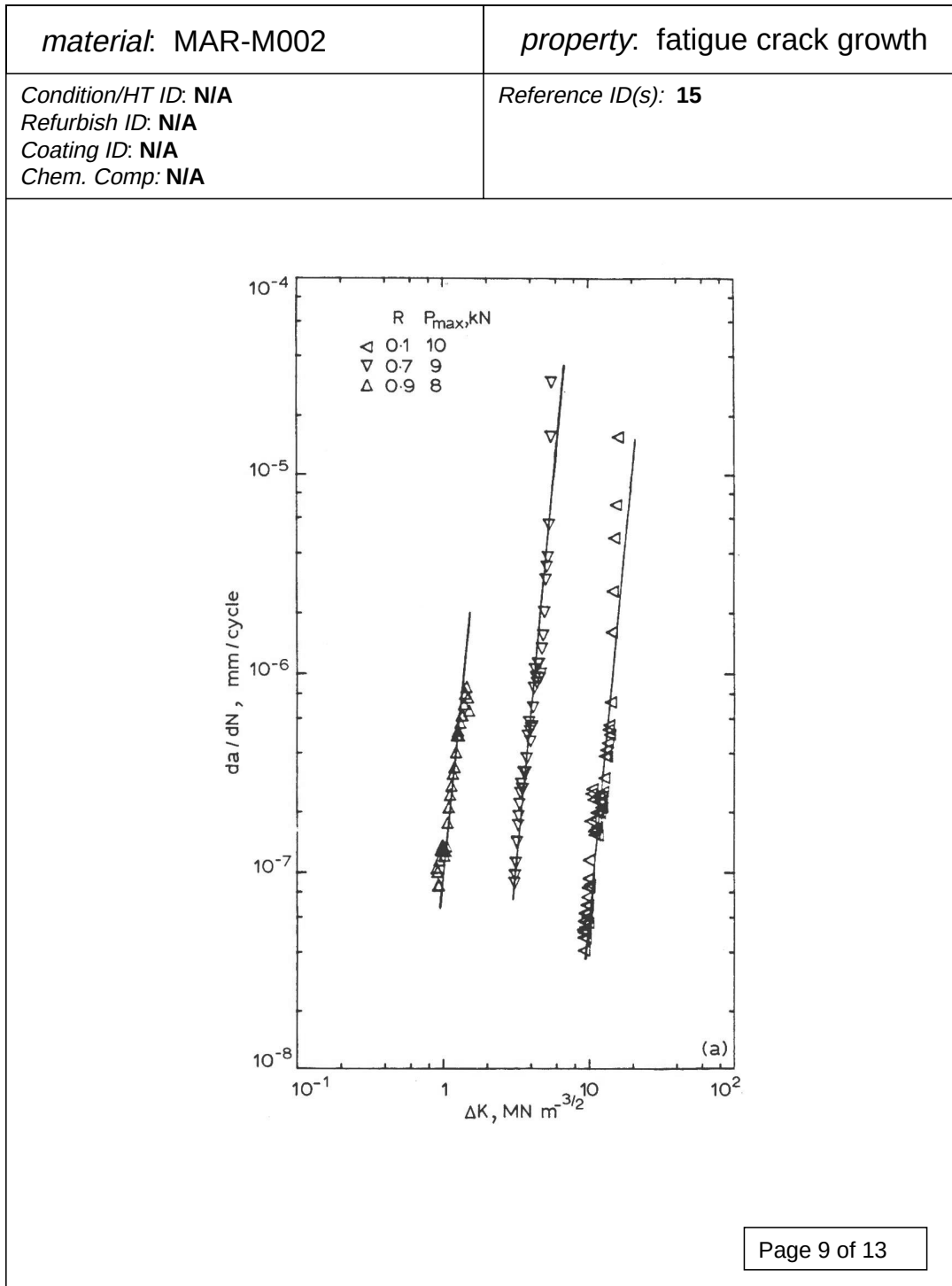


Figure 7-9
Influence of R on Crack Growth Rate for MAR-M002 at 950°C and 20 Hz, da/dN versus ΔK .

MAR-M002

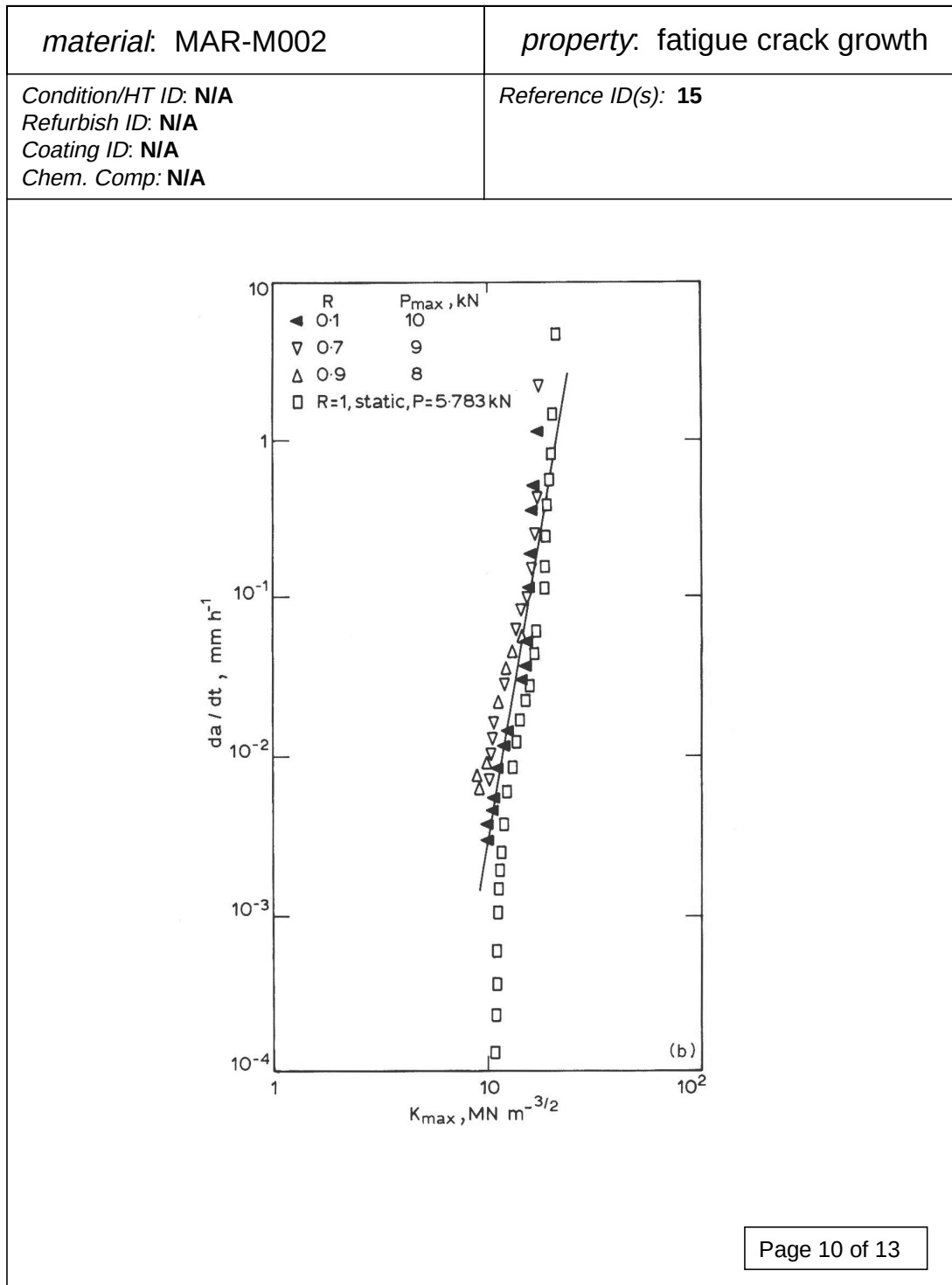


Figure 7-10
Influence of R on Crack Growth Rate for MAR-M002 at 950°C and 20 Hz, da/dt versus K_{max} .

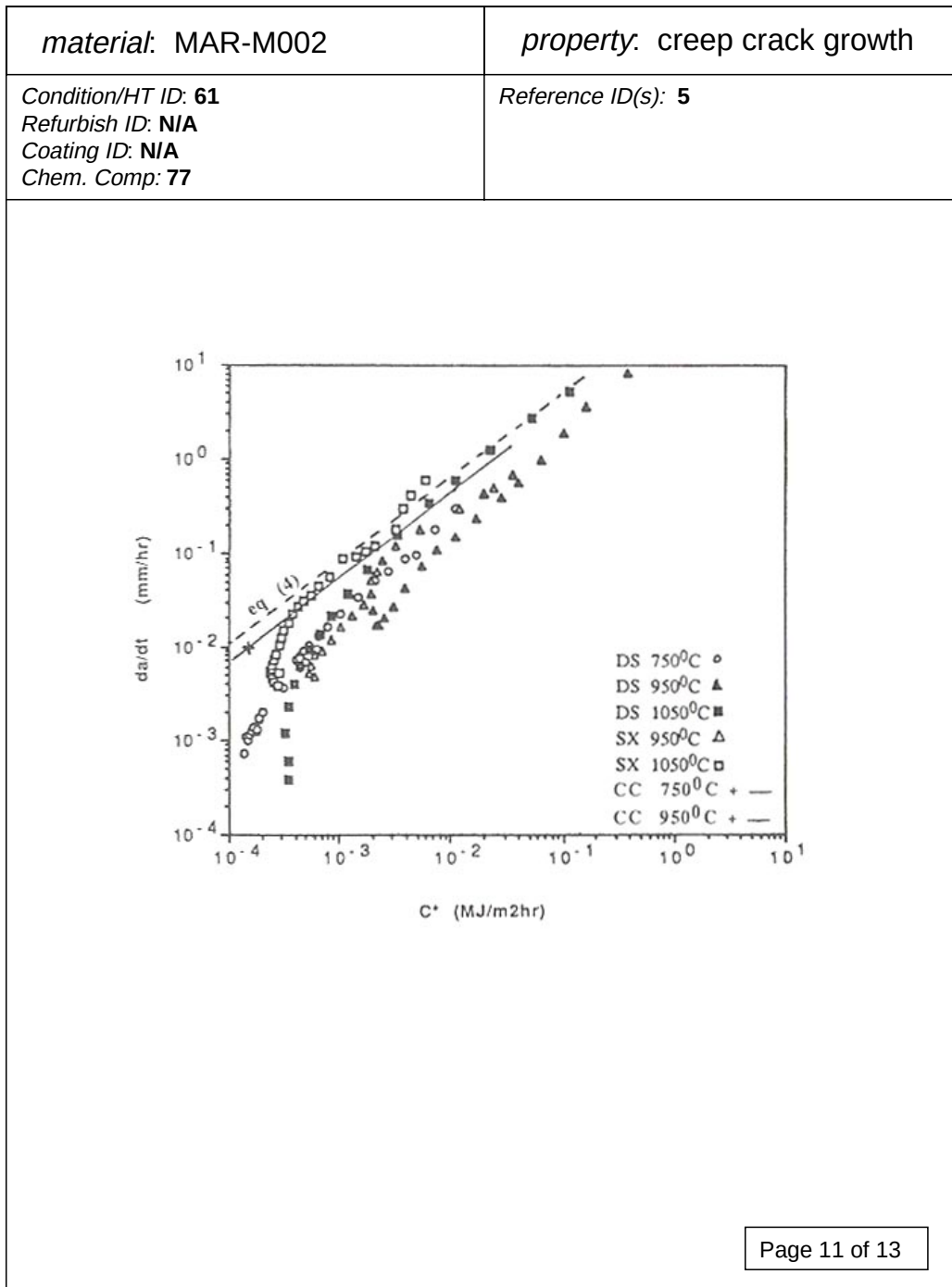


Figure 7-11
Influence of Grain Structure and Temperature on Creep Crack Growth Rate.

MAR-M002

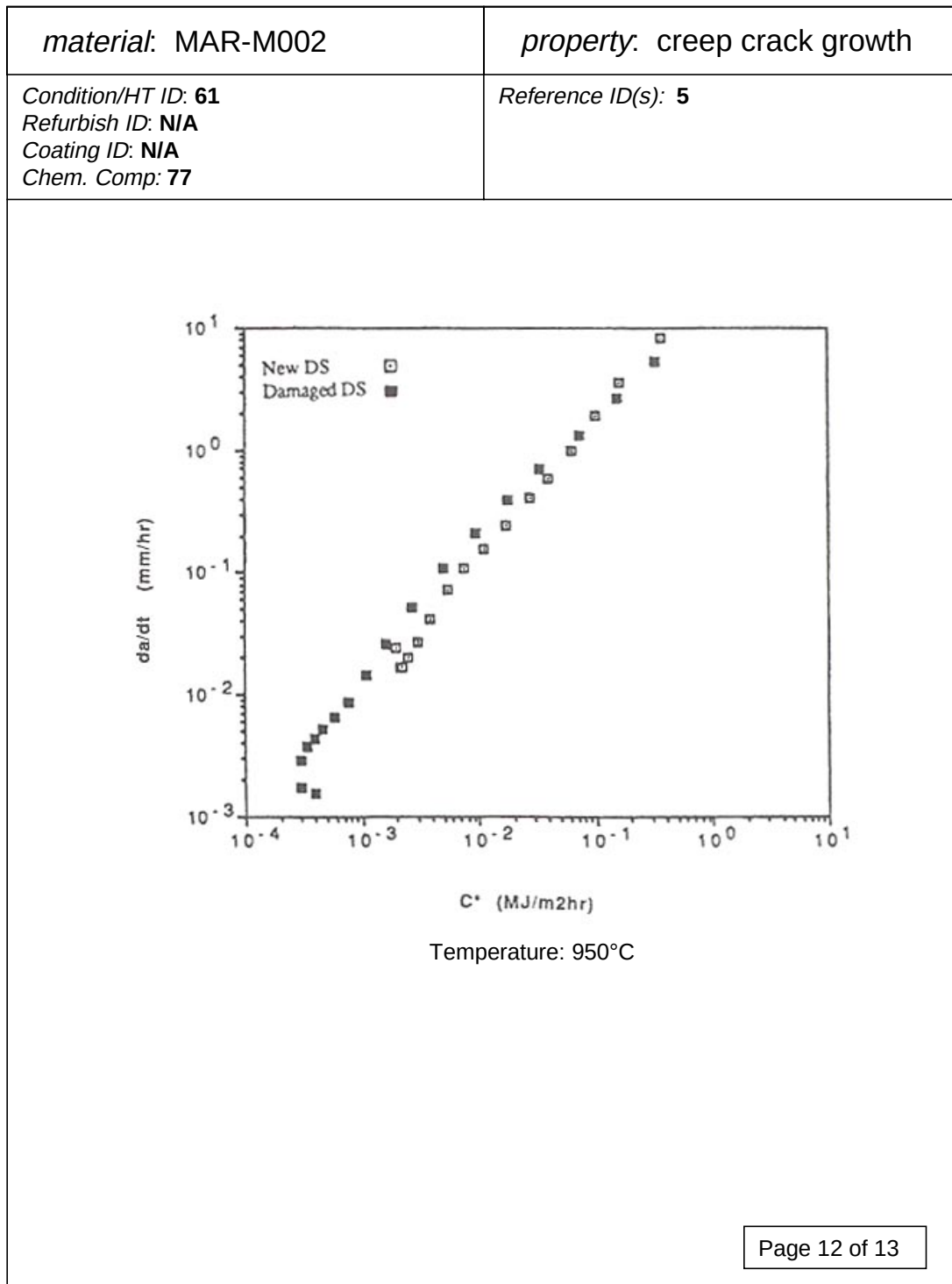


Figure 7-12
Effect of Prior Creep Damage on Creep Crack Growth Rate at 950°C in Directionally Solidified Material.

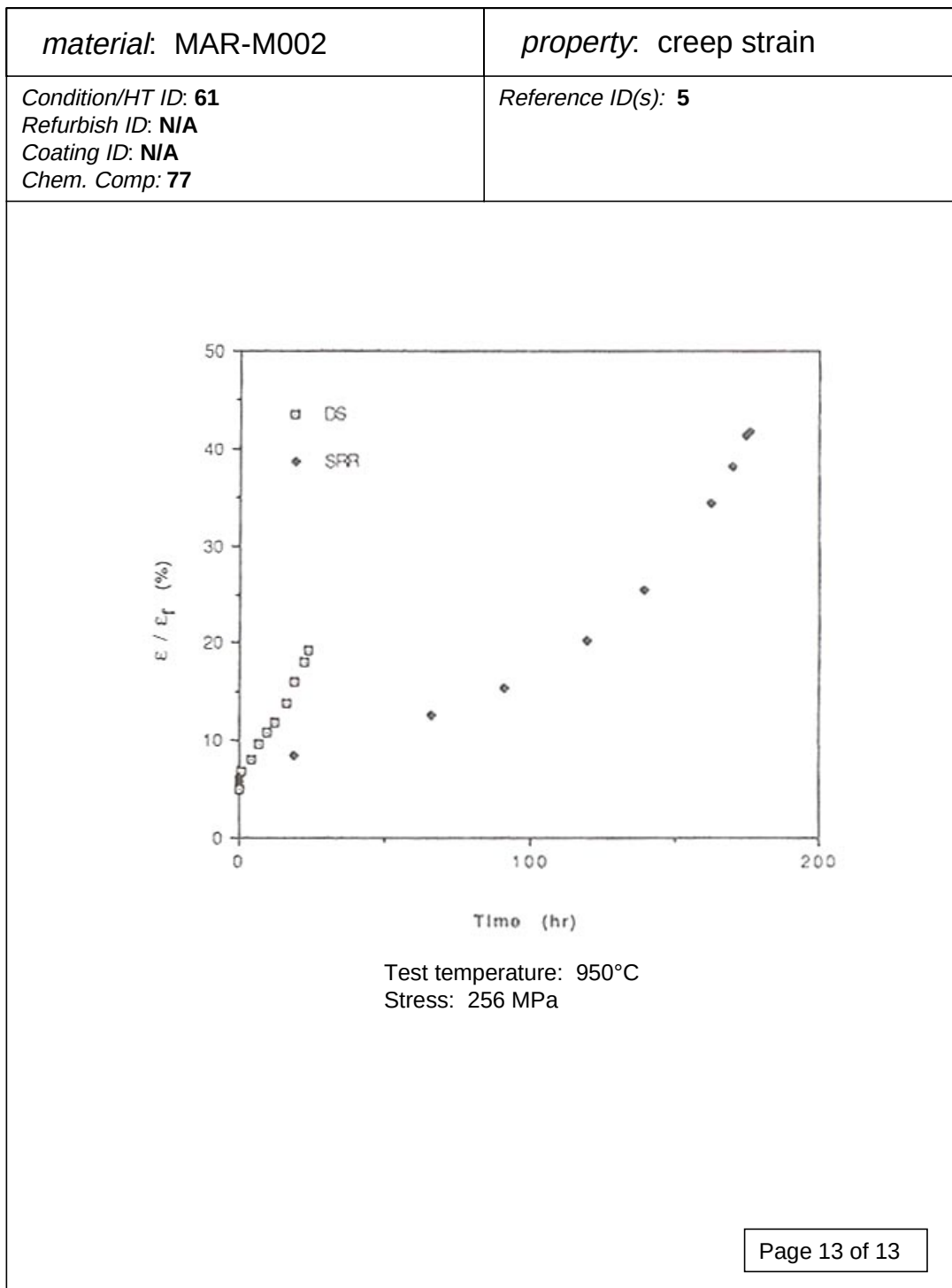
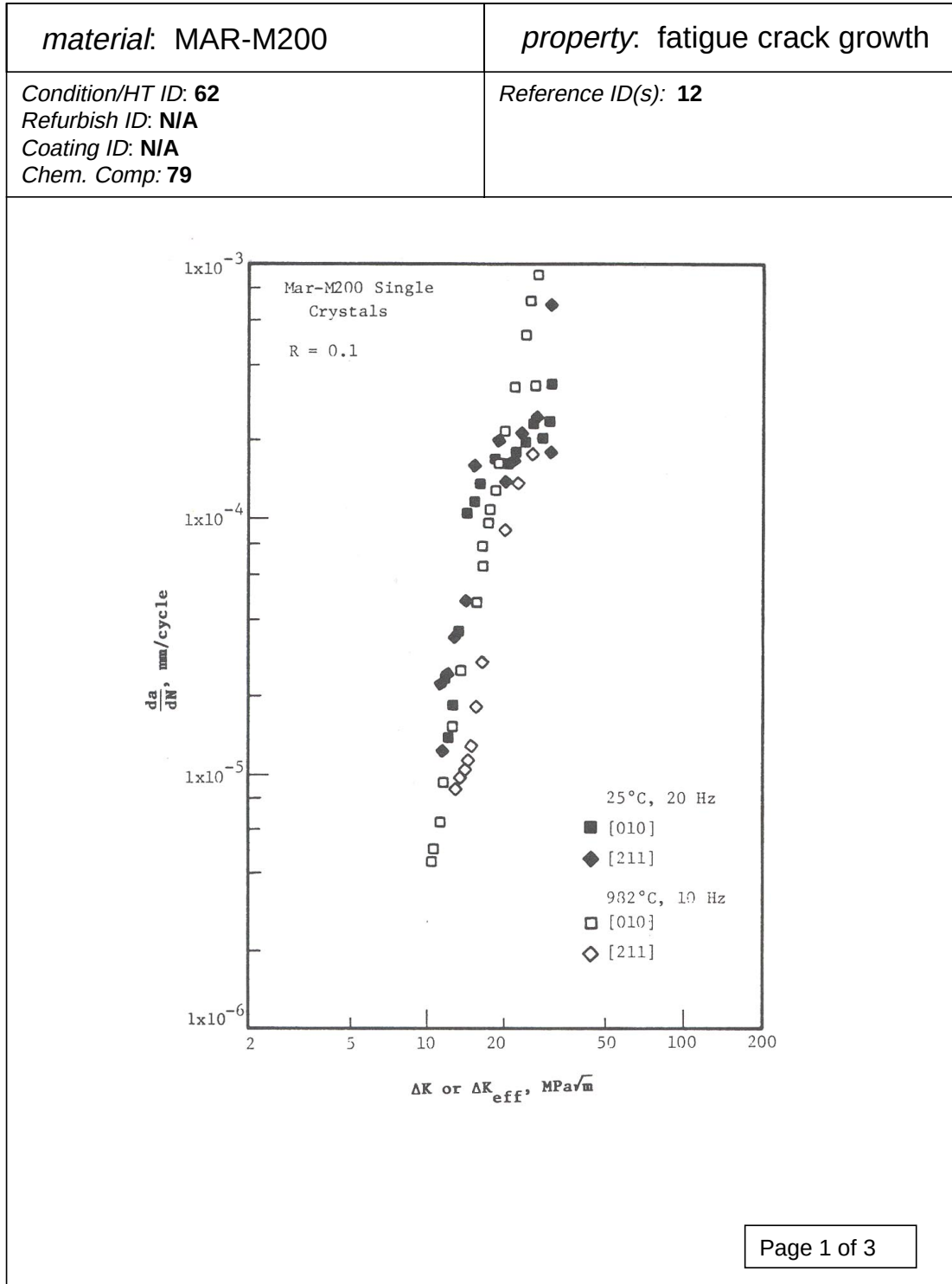


Figure 7-13
Accumulation of Creep Strain at 950°C and a Stress of 256 MPa in Directionally Solidified and Single Crystal Material.

8

MAR-M200

MAR-M200

**Figure 8-1**

Comparison of Crack Growth Rates of MAR-M200 Single Crystals at 25 and 982°C. (ΔK_{eff} is a Function of Three Nodes of Cracking.)

MAR-M200

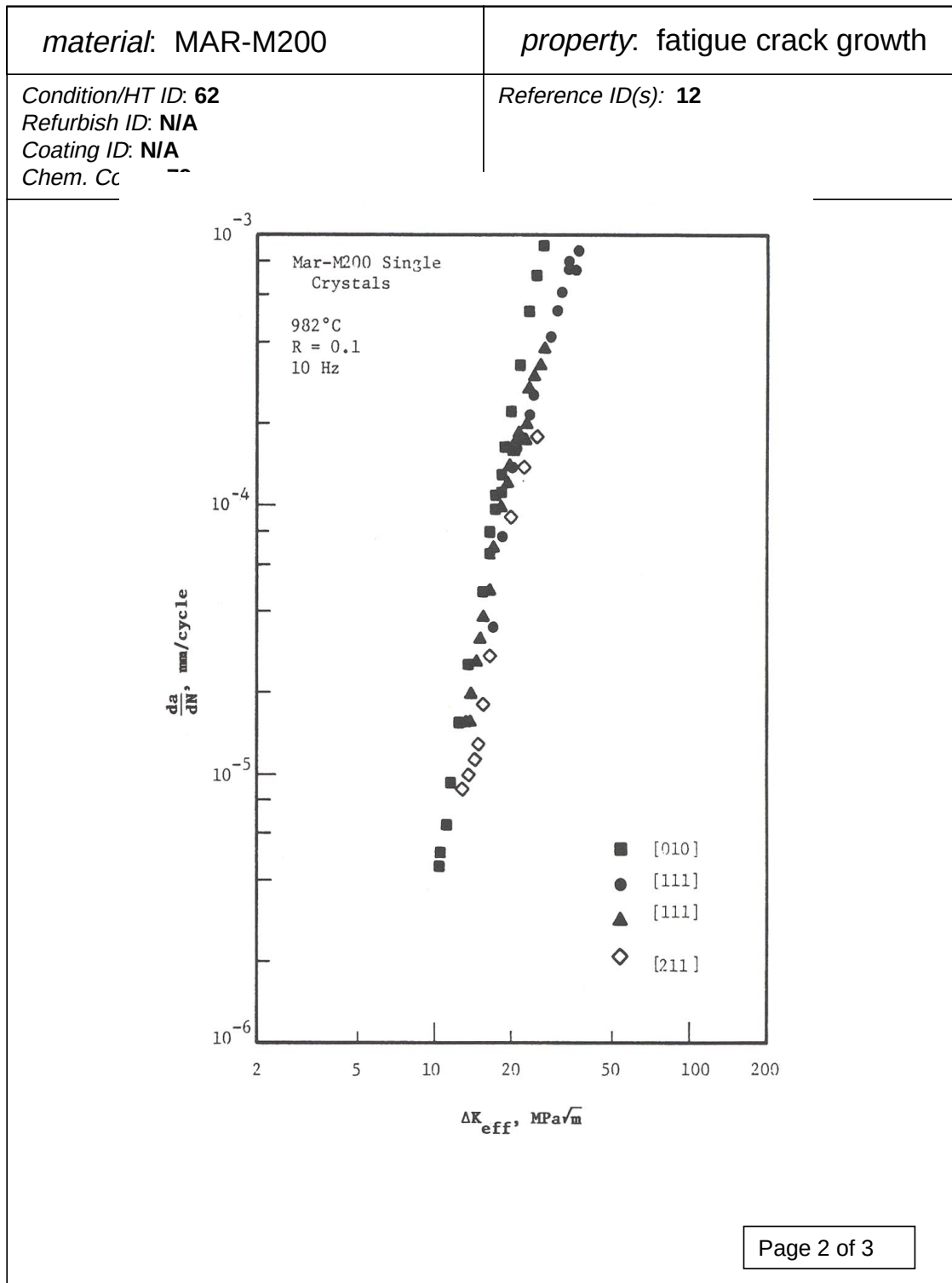


Figure 8-2
Fatigue Crack Growth Rate Results of MAR-M200 Single Crystals Under Uniaxially Applied Cyclic Loading at 982°C. (ΔK_{eff} is a Function of Three Nodes of Cracking.)

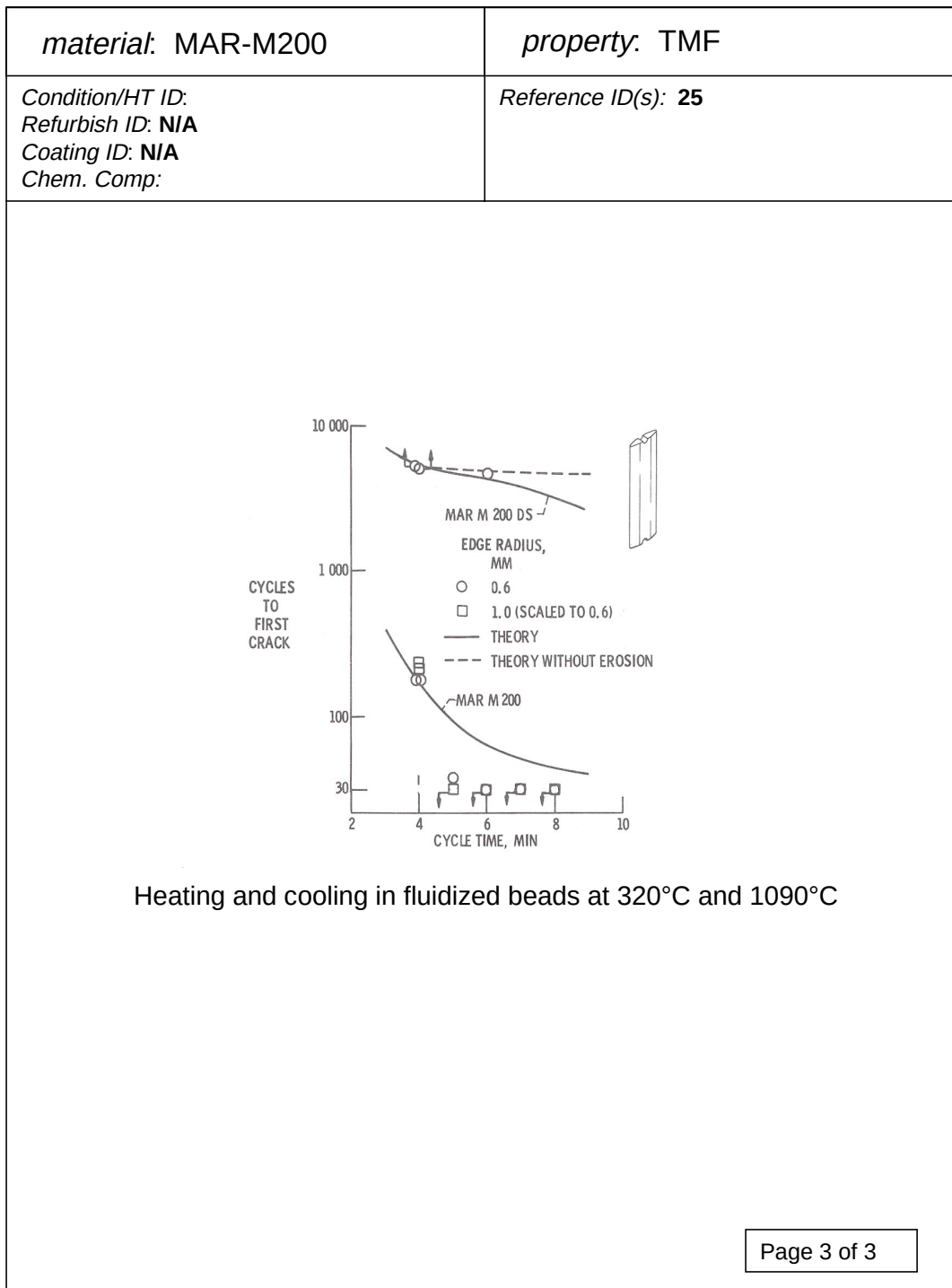


Figure 8-3
Comparison of Theoretical and Experimental Thermal Fatigue Lives of MAR M200 and MAR M200DS Double Wedges (0.6 and 1.0 mm Radius Edge, Heating and Cooling in Fluidized Beds at 320 and 1090°C).

9

MAR-M247

MAR-M247

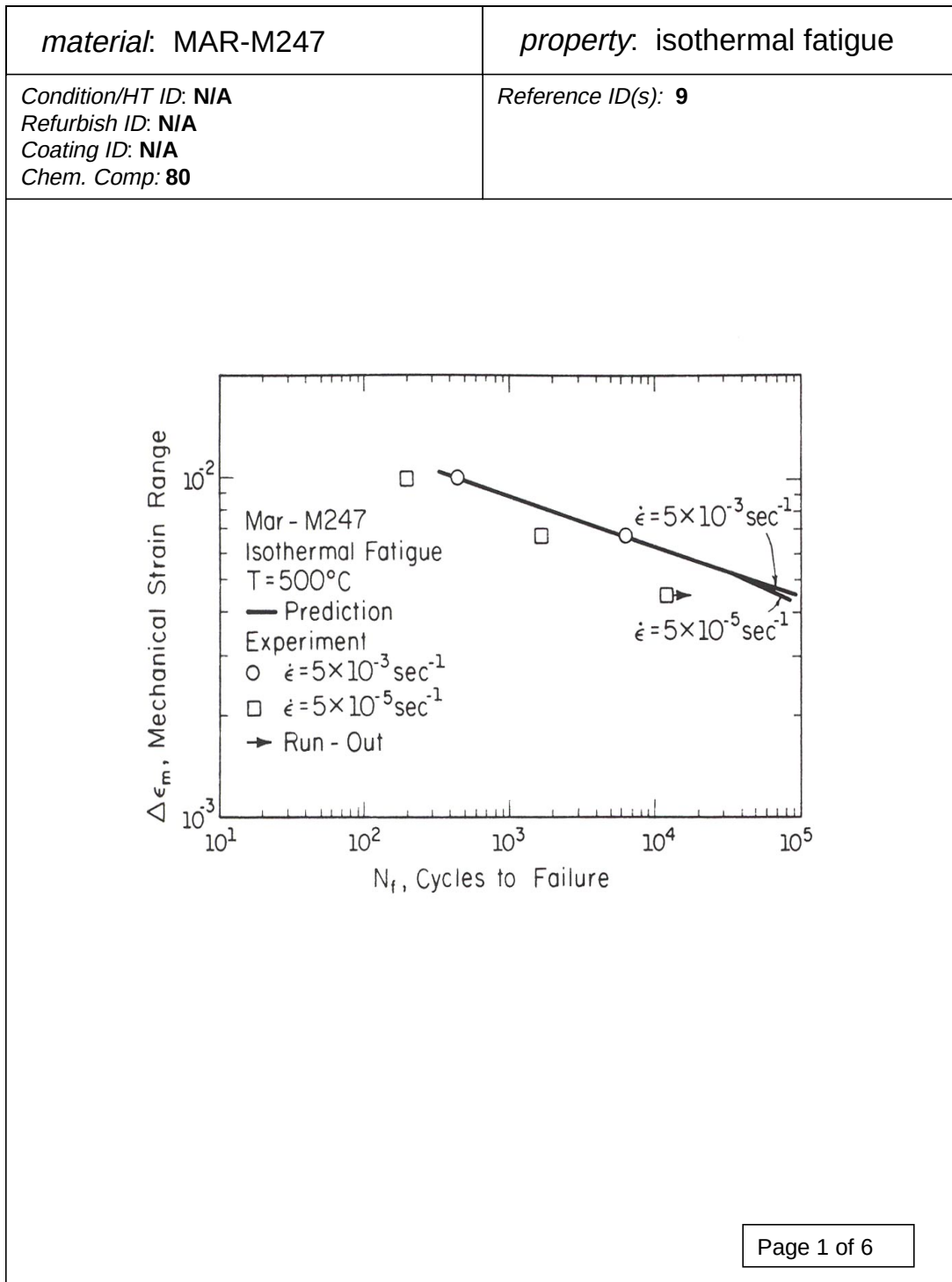


Figure 9-1
Prediction of Isothermal Fatigue Data at 500°C.

MAR-M247

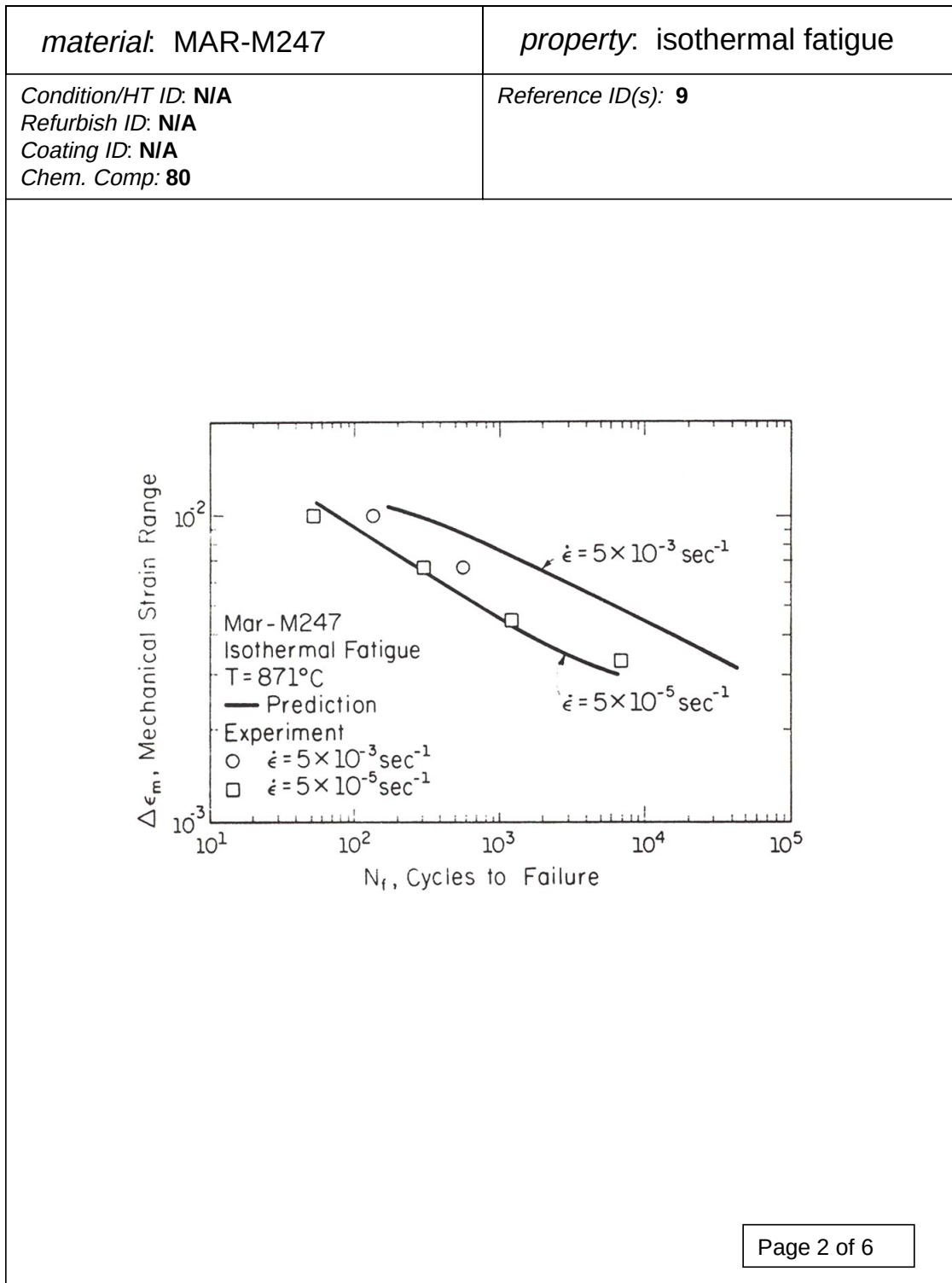


Figure 9-2
Prediction of 871°C Isothermal Fatigue Test Results.

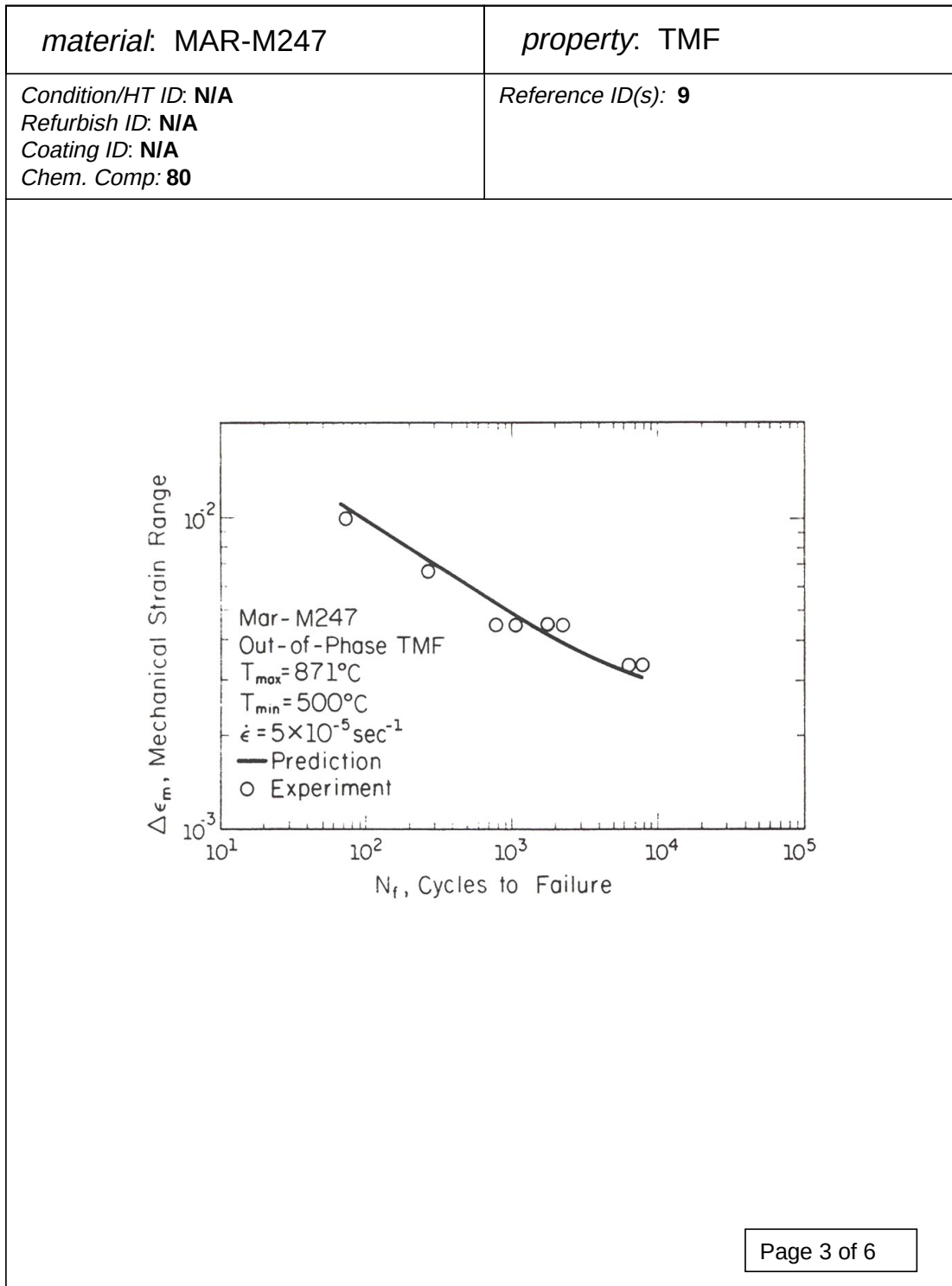


Figure 9-3
Prediction of Out-of-Phase TMF (500°C–871°C) Test Results.

MAR-M247

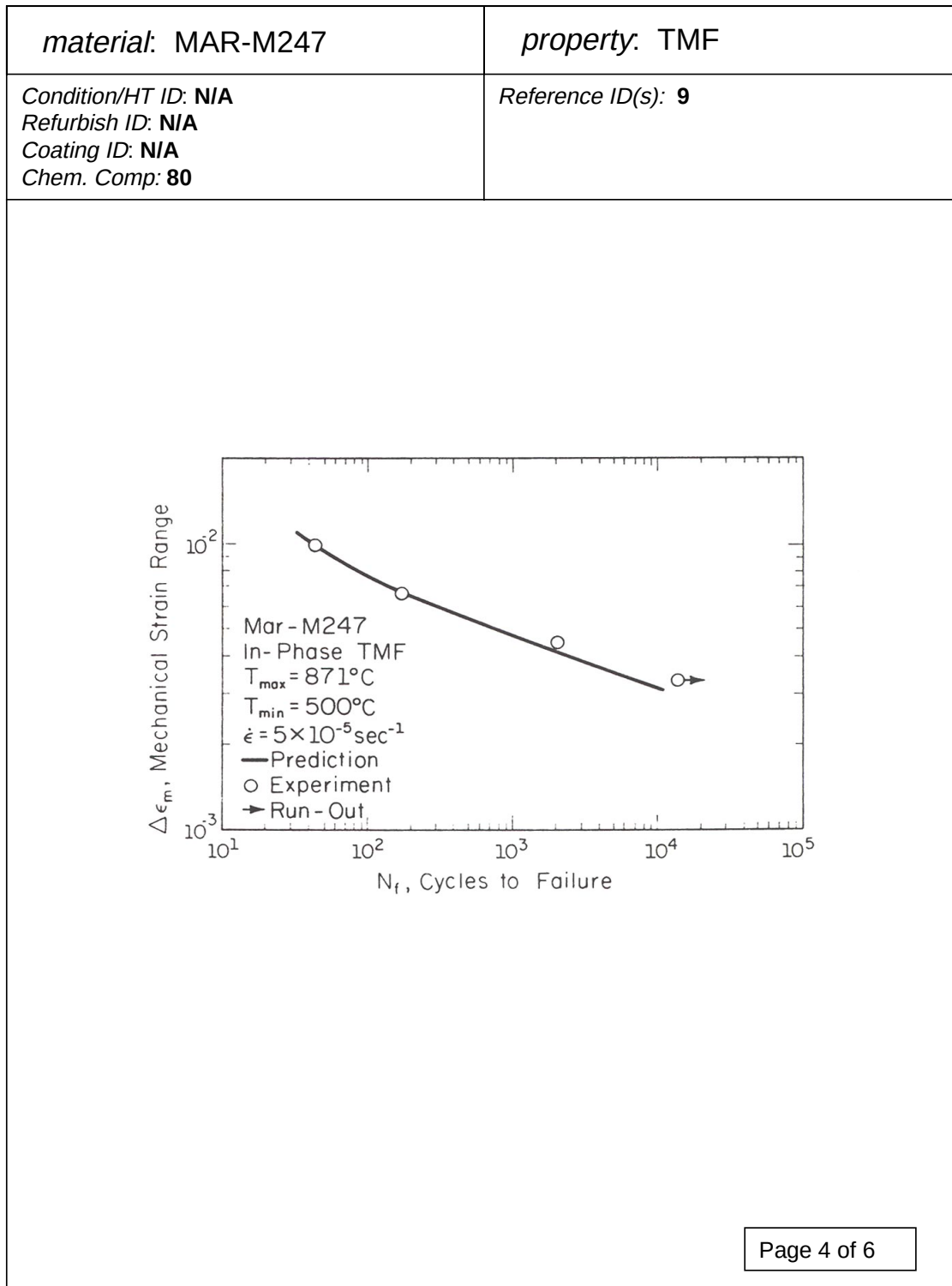


Figure 9-4
Prediction of In-Phase TMF (500°C–871°C) Test Results.

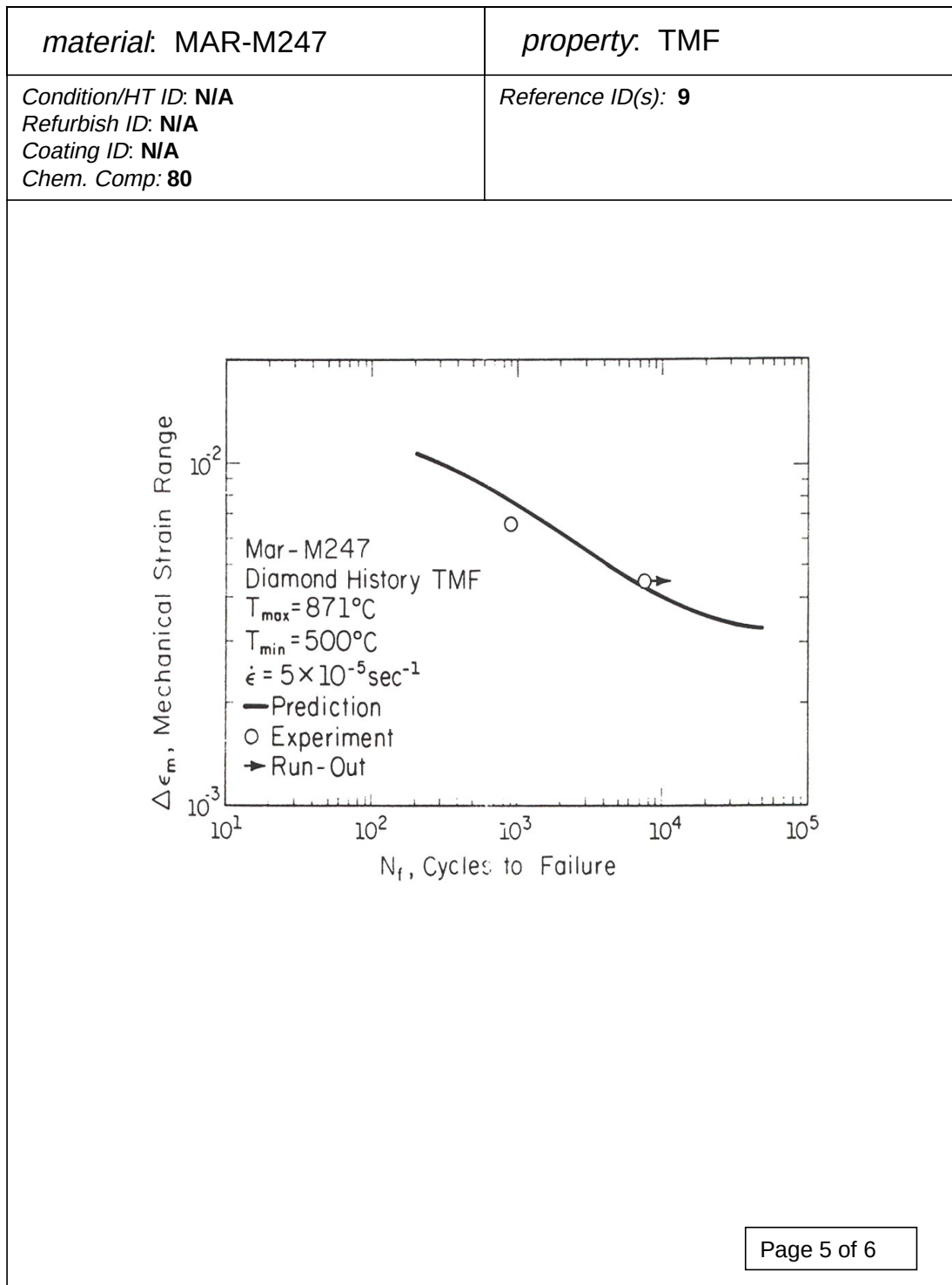


Figure 9-5
Prediction of Diamond Shape (Nonproportional) Strain-Temperature History.

MAR-M247

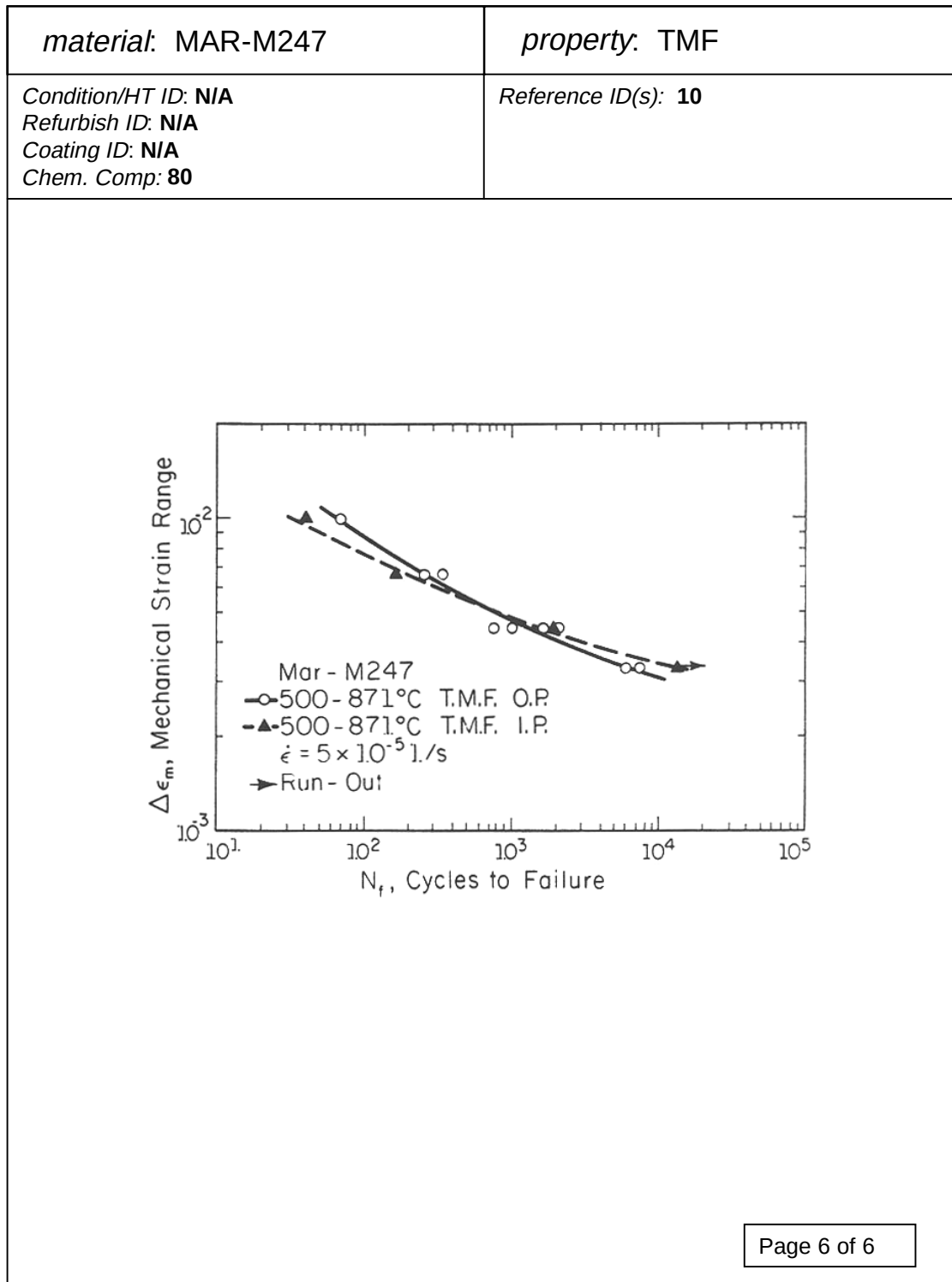


Figure 9-6
Mechanical Strain Range Versus Life for Out-of-Phase and In-Phase TMF Experiments,
 $\dot{\epsilon} = 5 \times 10^{-5} \text{ s}^{-1}$

10

NIMONIC 115

Nimonic 115

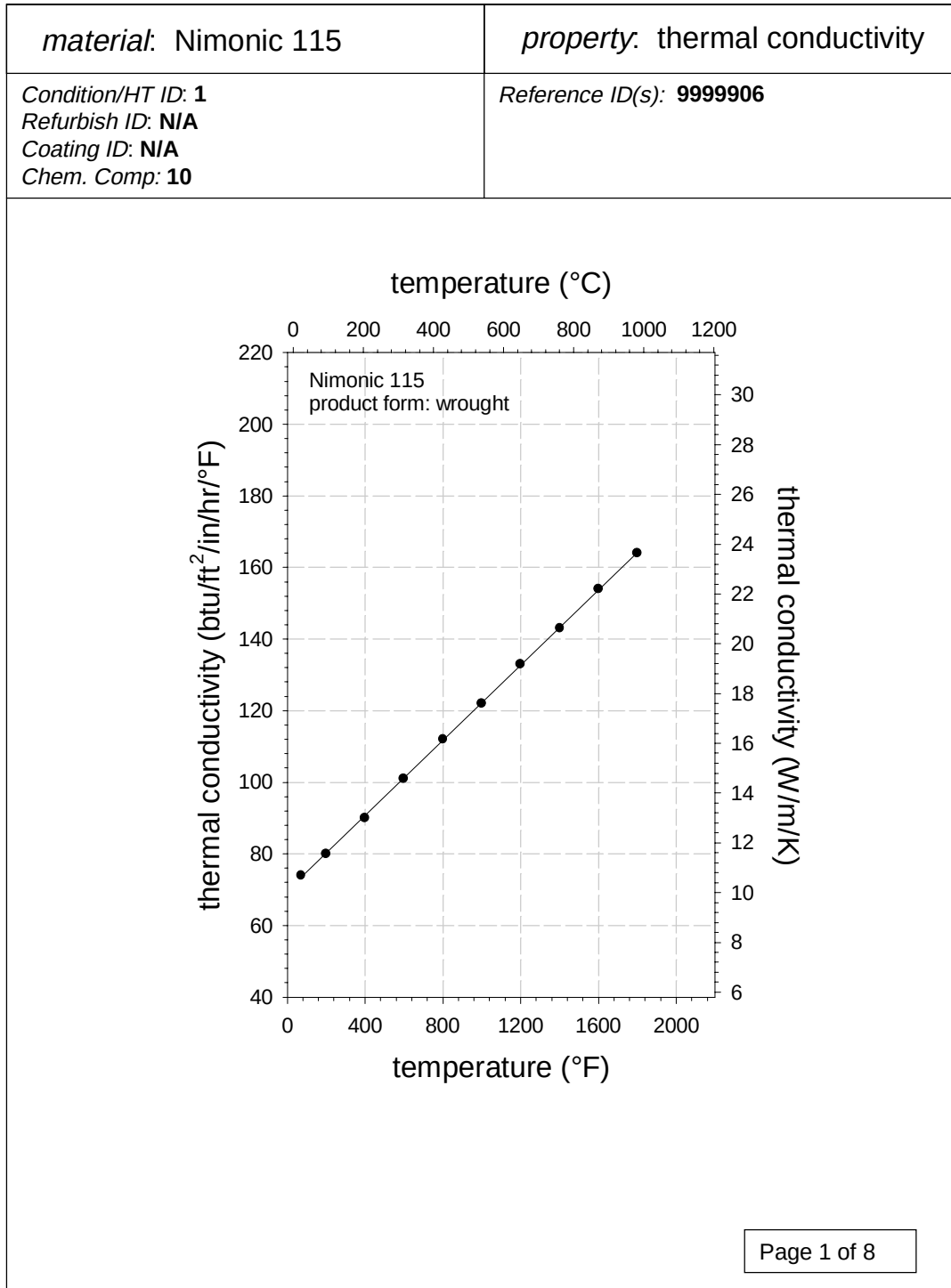


Figure 10-1
Thermal Conductivity as a Function of Temperature.

Nimonic 115

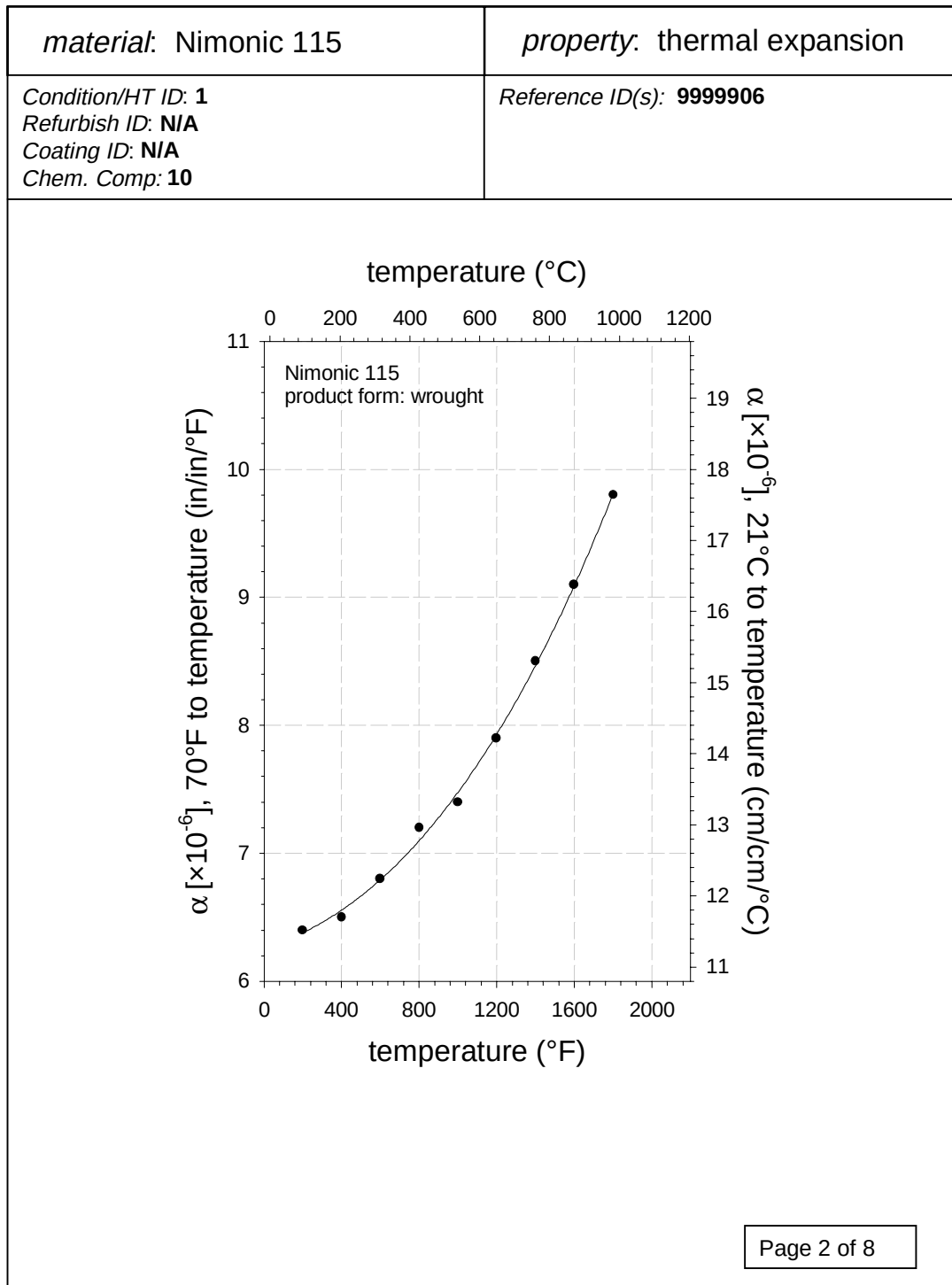


Figure 10-2
Coefficient of Thermal Expansion as a Function of Temperature.

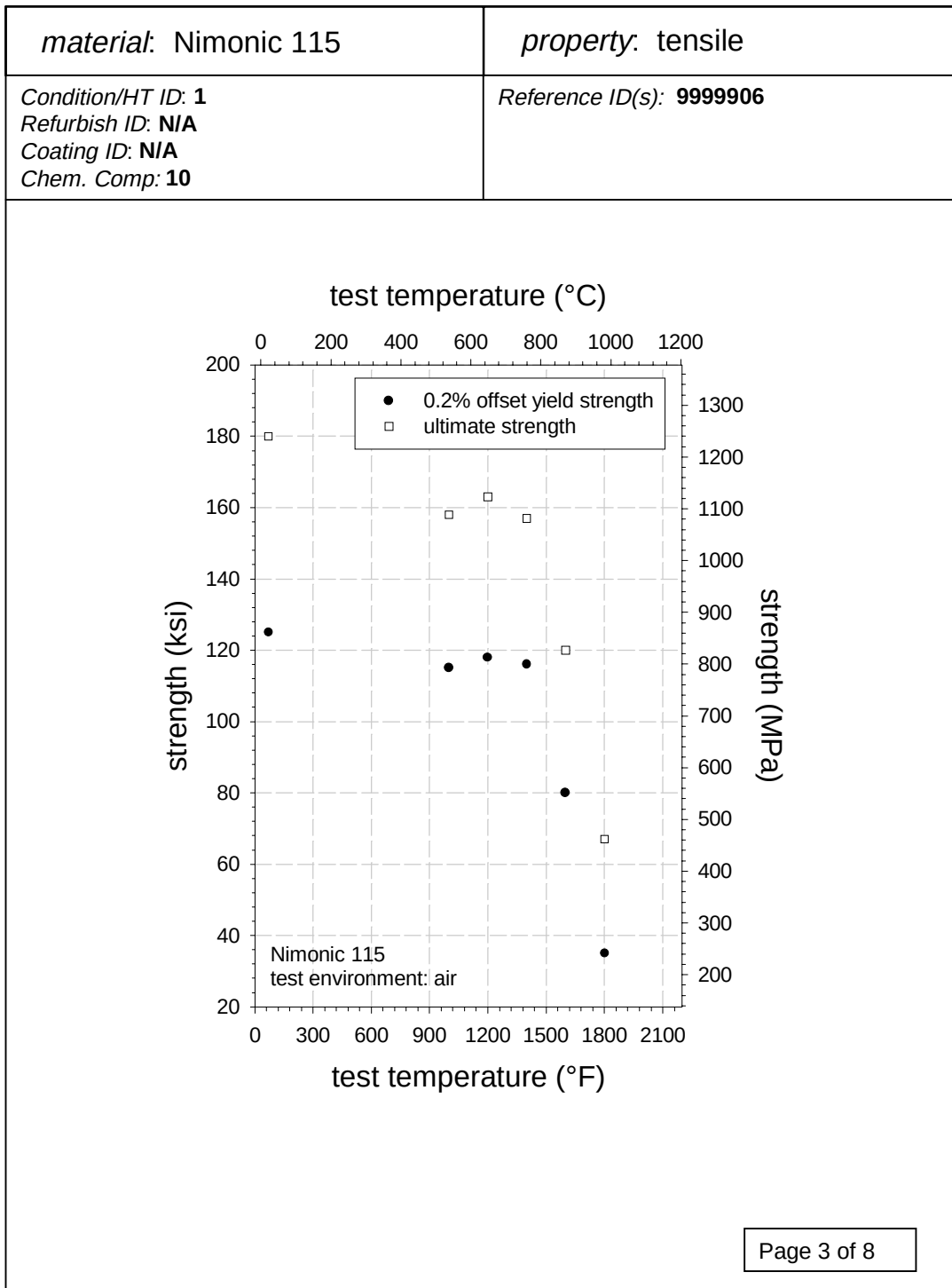


Figure 10-3
Tensile Strengths as a Function of Temperature.

Nimonic 115

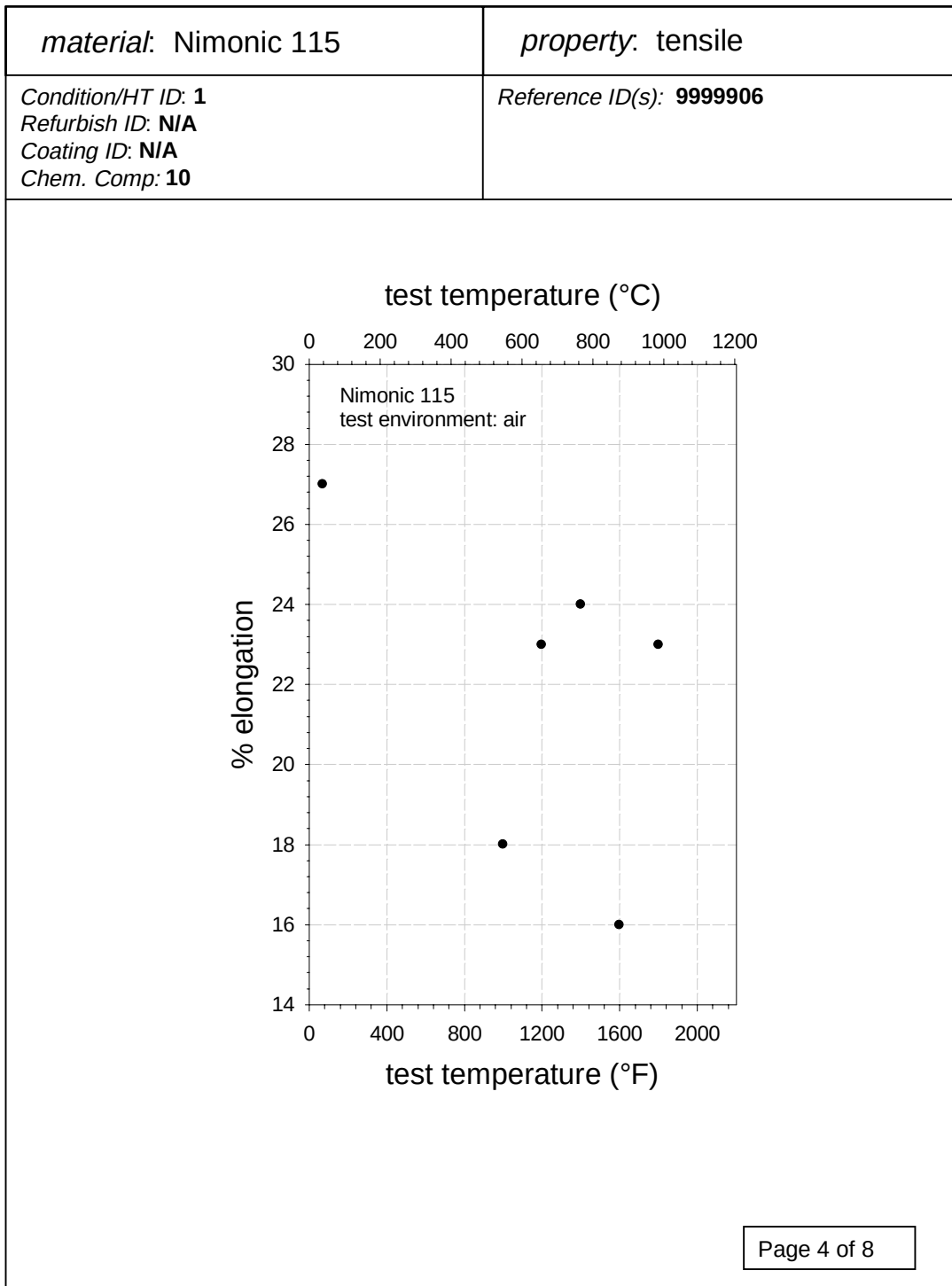


Figure 10-4
Tensile Elongation as a Function of Temperature.

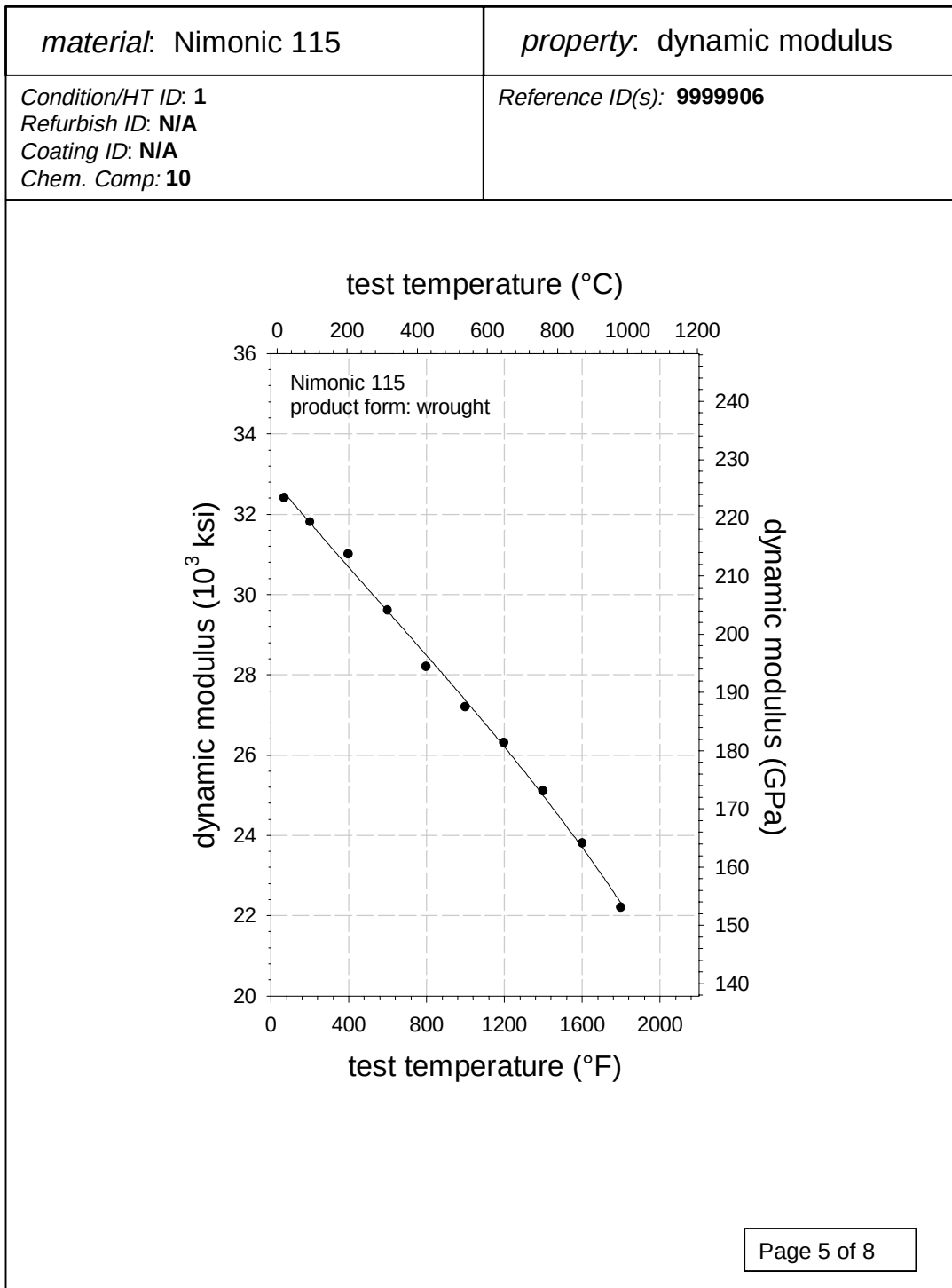


Figure 10-5
Dynamic Modulus as a Function of Temperature.

Nimonic 115

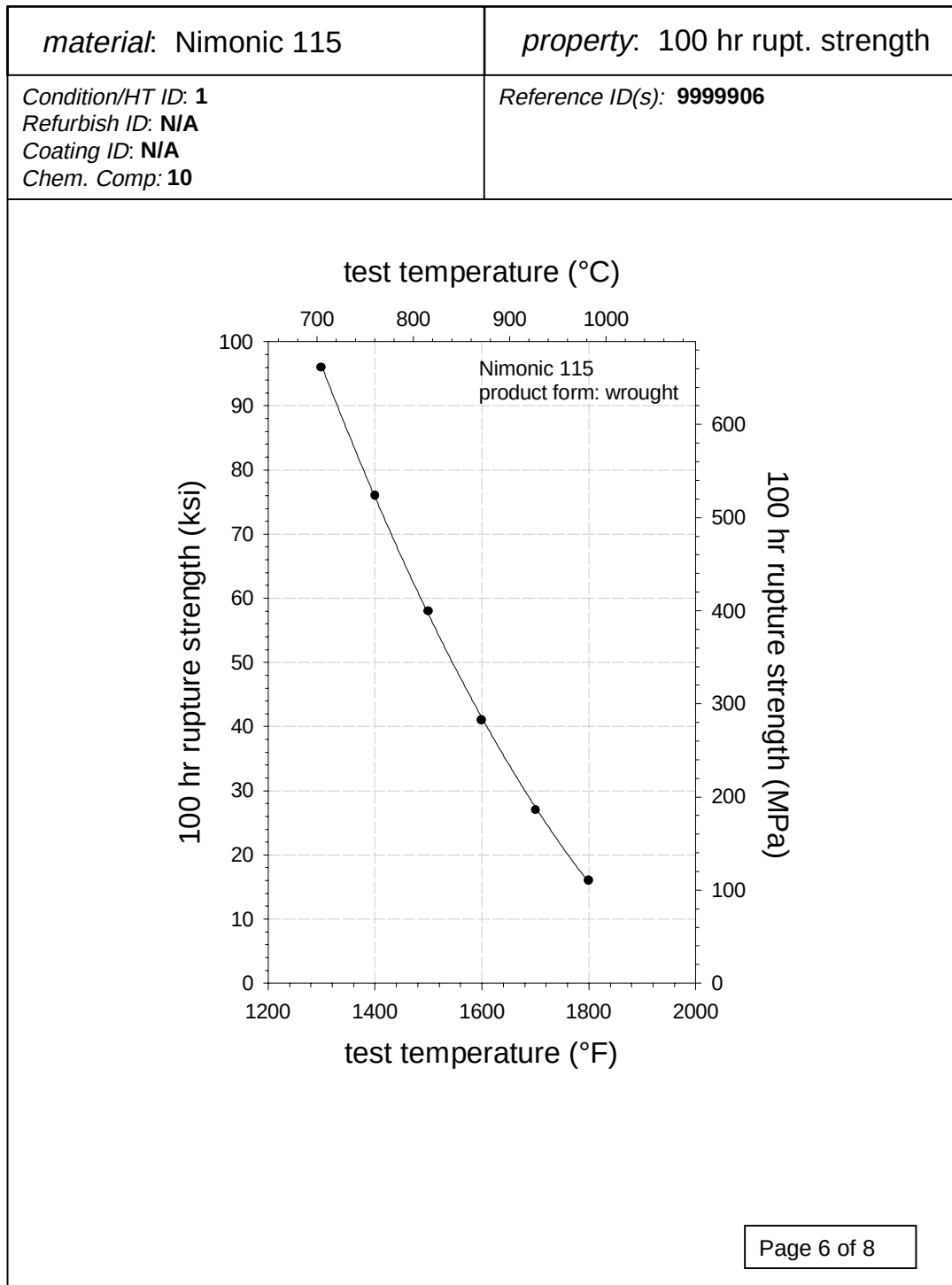


Figure 10-6
100 hr Rupture Strength as a Function of Temperature.

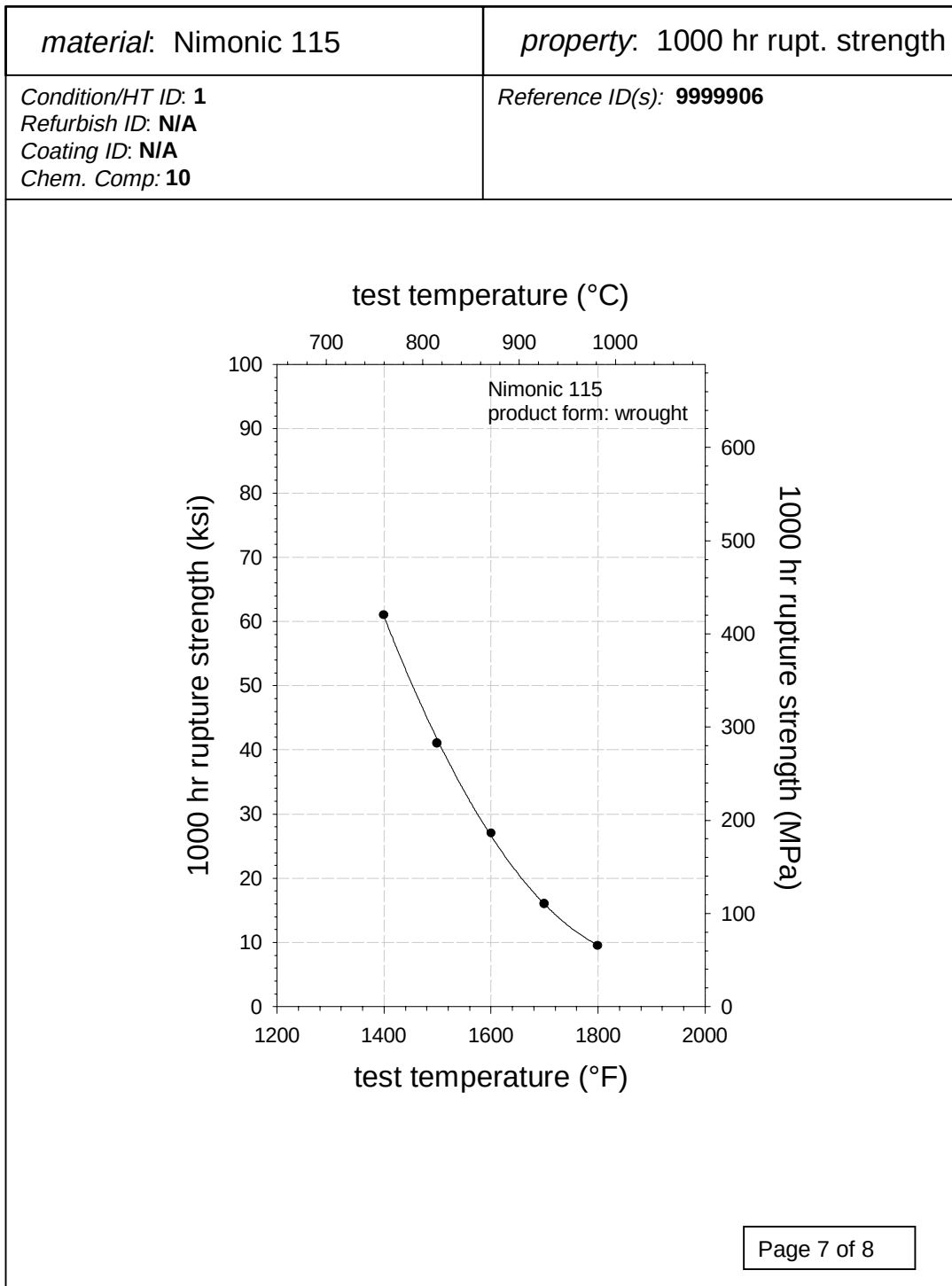


Figure 10-7
1000 hr Rupture Strength as a Function of Temperature.

Nimonic 115

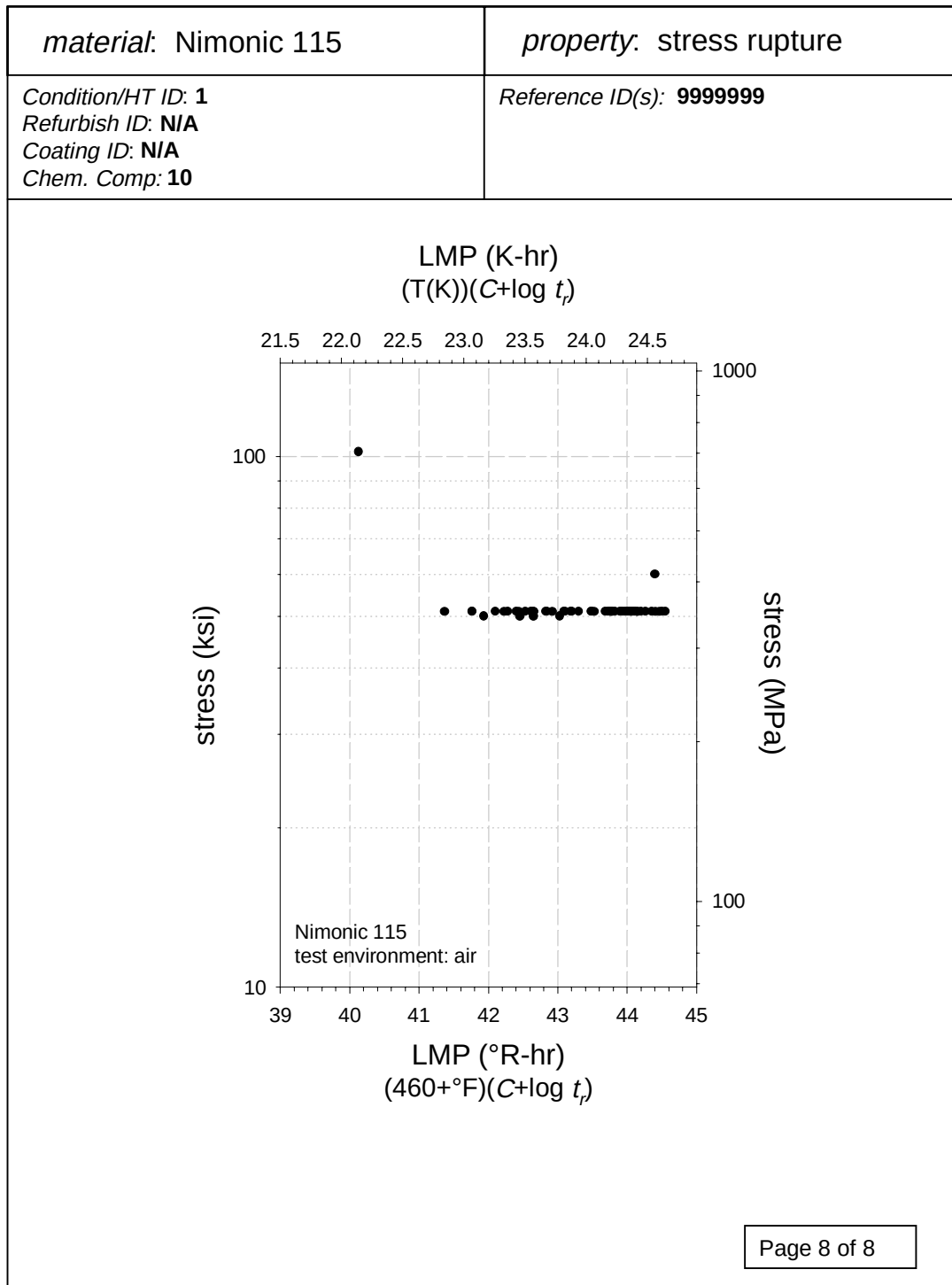


Figure 10-8
Partial Larson-Miller Plot for Nimonic 115.

11

RENE 80

Rene 80

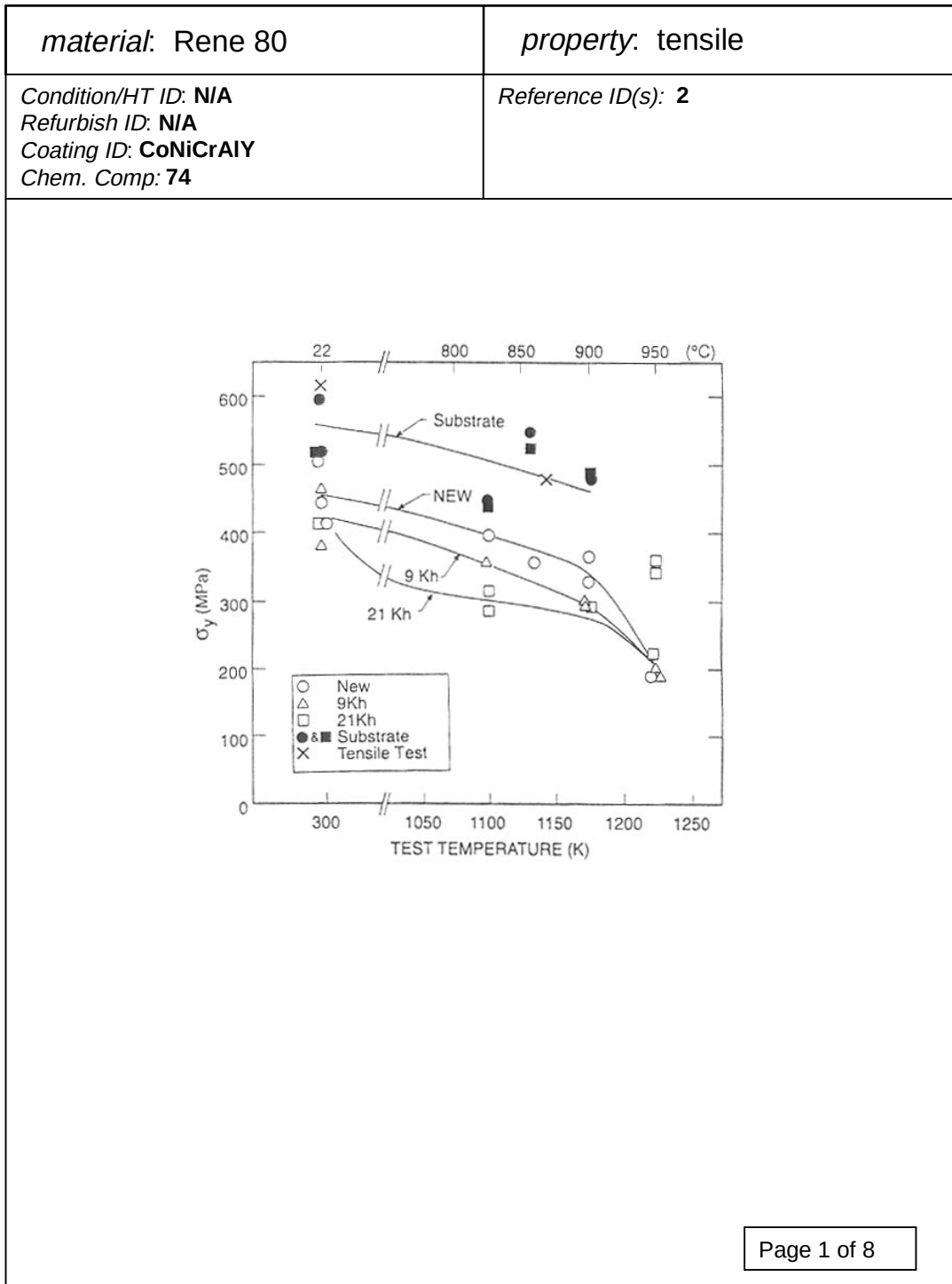
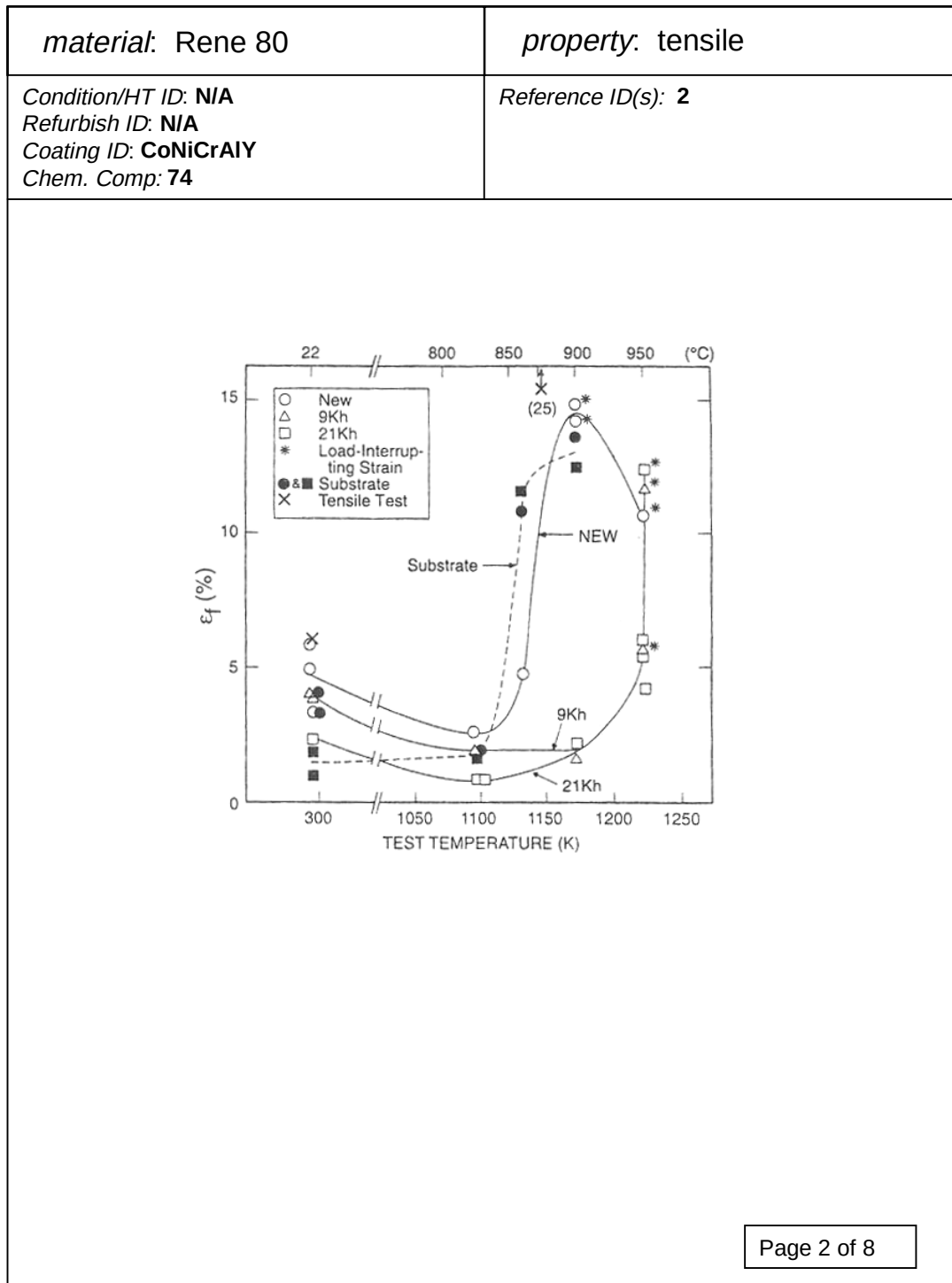


Figure 11-1
Temperature Dependence of Yield Strength (σ_y) of Unused and Used Coatings and Substrates in Comparison with Tensile Test Data of Unused Substrate.

Rene 80

**Figure 11-2**

Temperature Dependence of Ductility (ϵ_f) Obtained from SP Tests on Unused and Used Coatings and Substrates, Compared with Tensile Test Data of Unused Substrate.

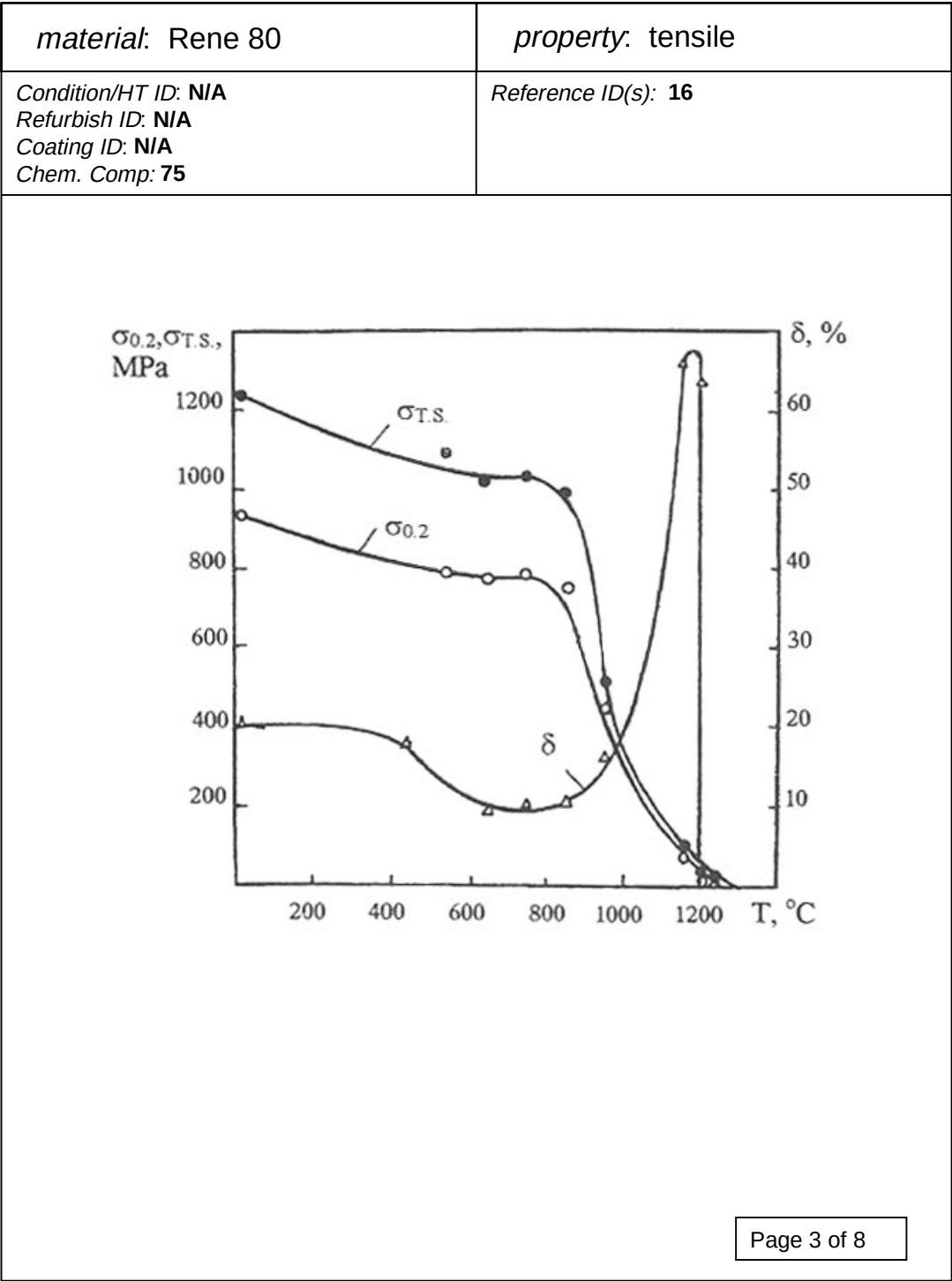
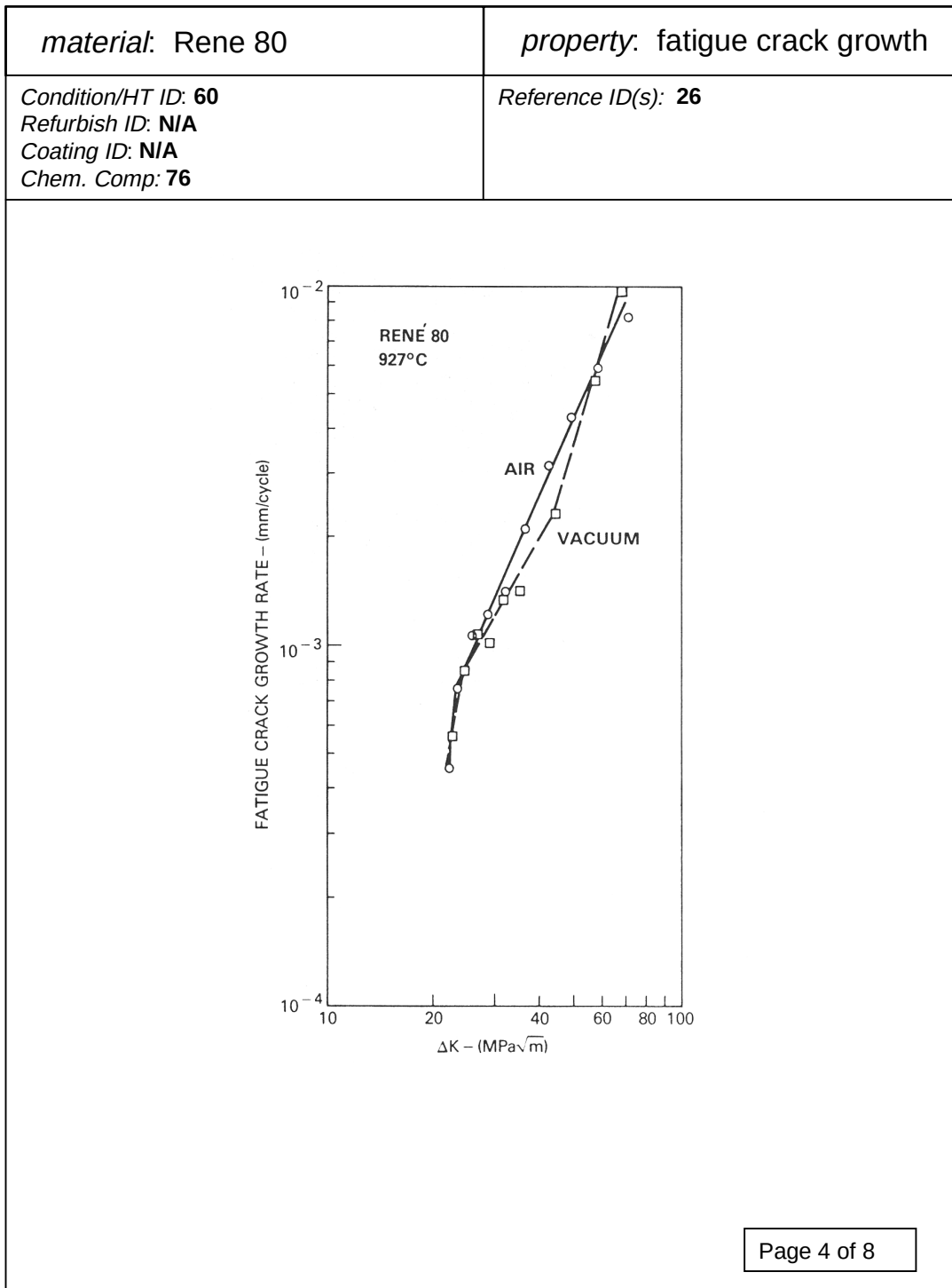


Figure 11-3
Temperature Dependence of Strength and Ductility of the Rene 80 Alloy Specimens.

Rene 80

**Figure 11-4****Fatigue Crack Growth Rate as a Function of ΔK in Rene 80 at 927°C in Air and in Vacuum.**

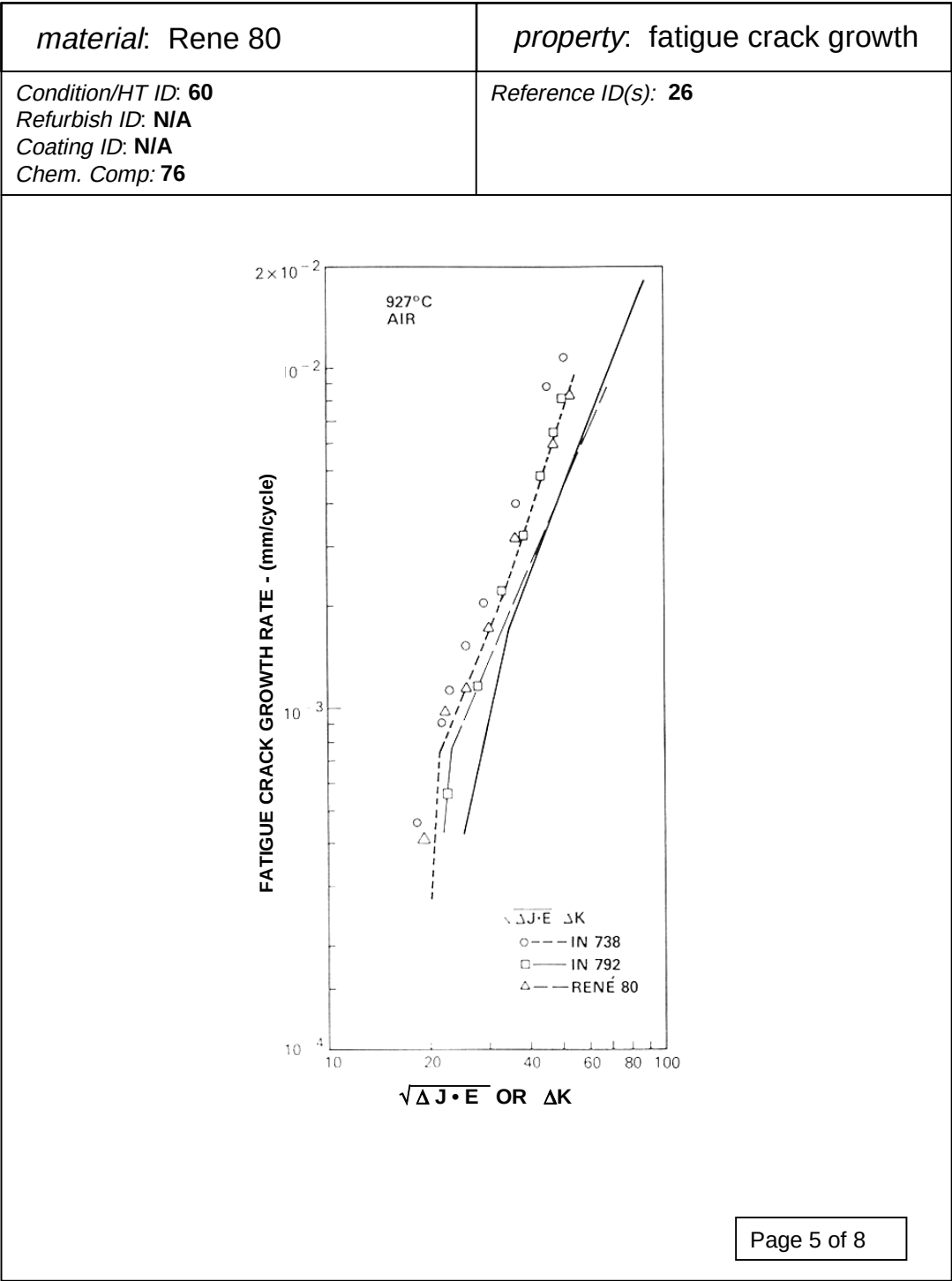


Figure 11-5
Comparison of Fatigue Crack Growth Rate for Three Alloys.

Rene 80

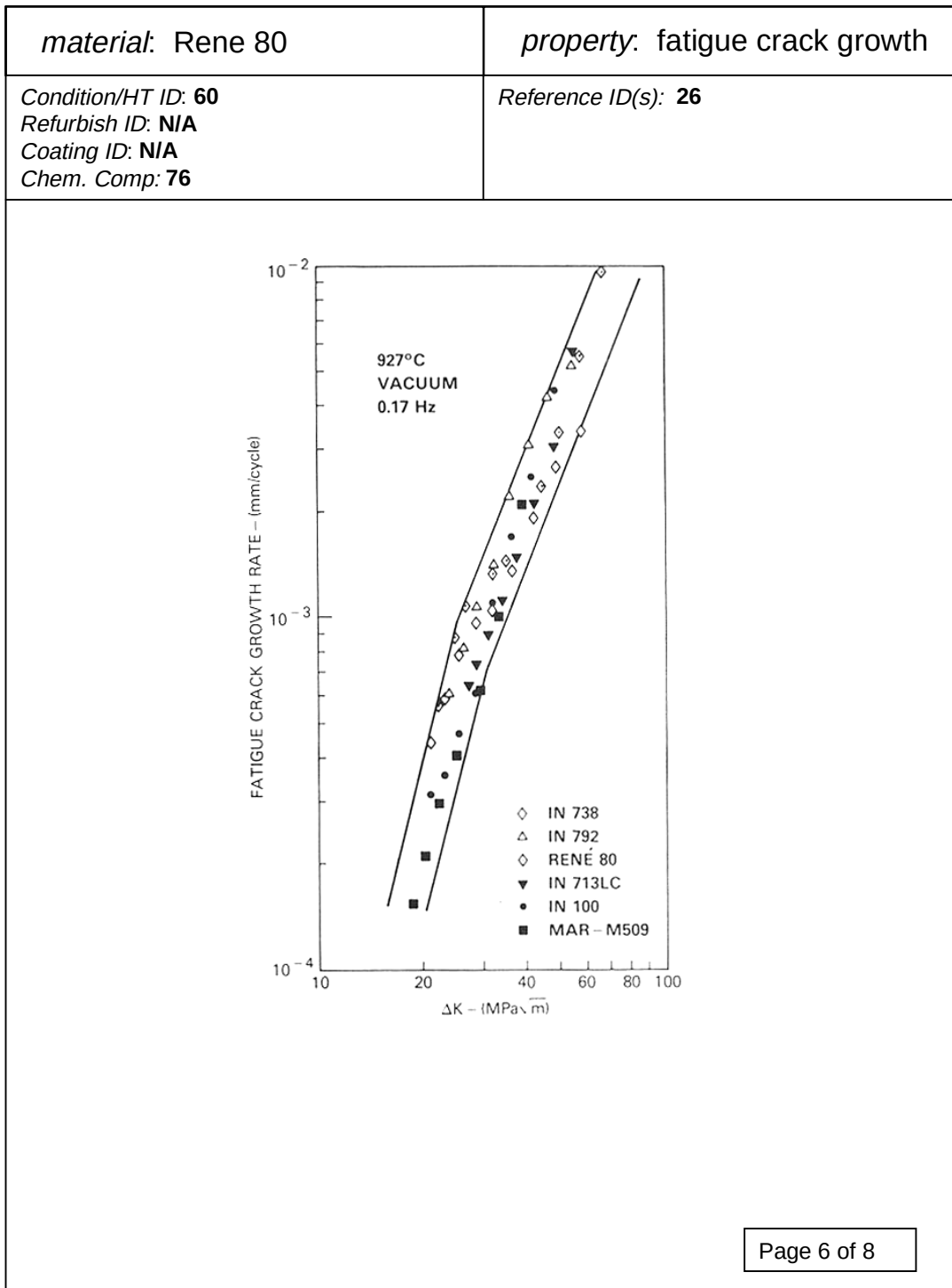


Figure 11-6
Fatigue Crack Growth Rate in Superalloys at 927°C in Vacuum.

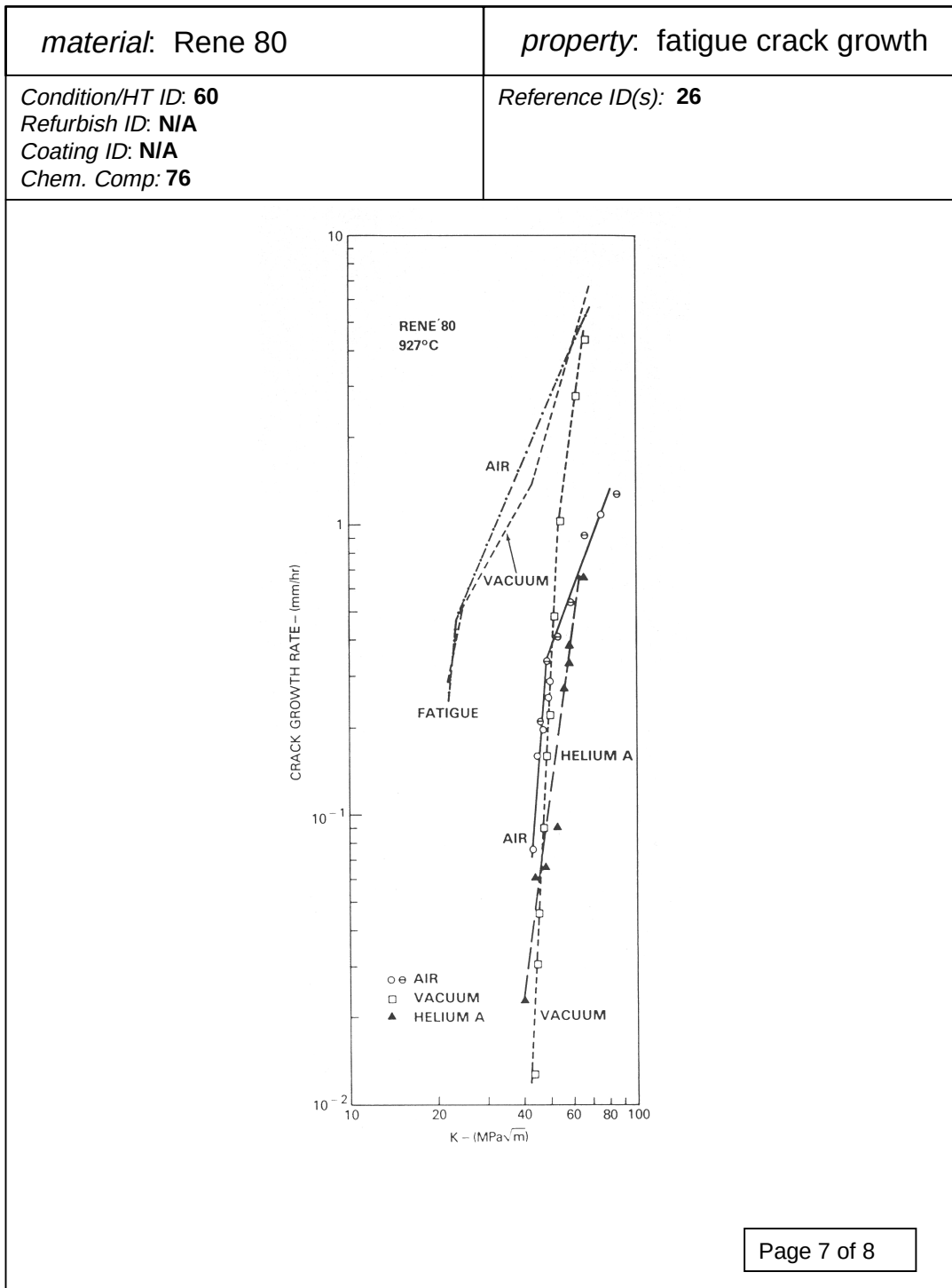
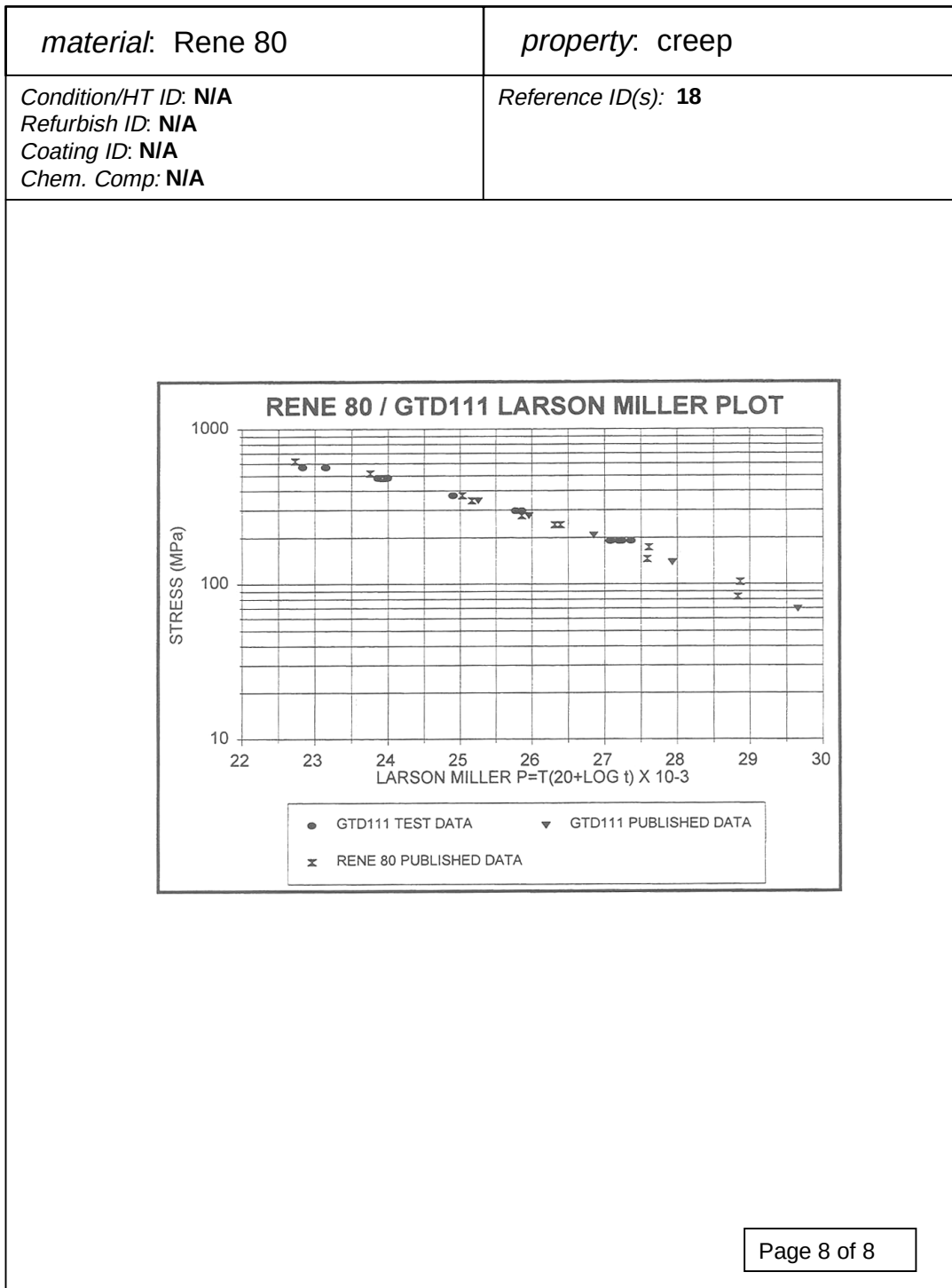


Figure 11-7
Influence of Environment on Creep Crack Growth Rate in Rene 80 at 927°C and Comparison with Fatigue Crack Growth Rate. (Fatigue Crack Growth Rate Give on a Time Basis.)

Rene 80

**Figure 11-8**

A Larson Miller Plot Comparing the GTD111 Alloy Test Points with Rene 80 Data from the Literature and the GTD111 Larson Miller Curve Published by General Electric.

12

UDIMET 500

Udimet 500

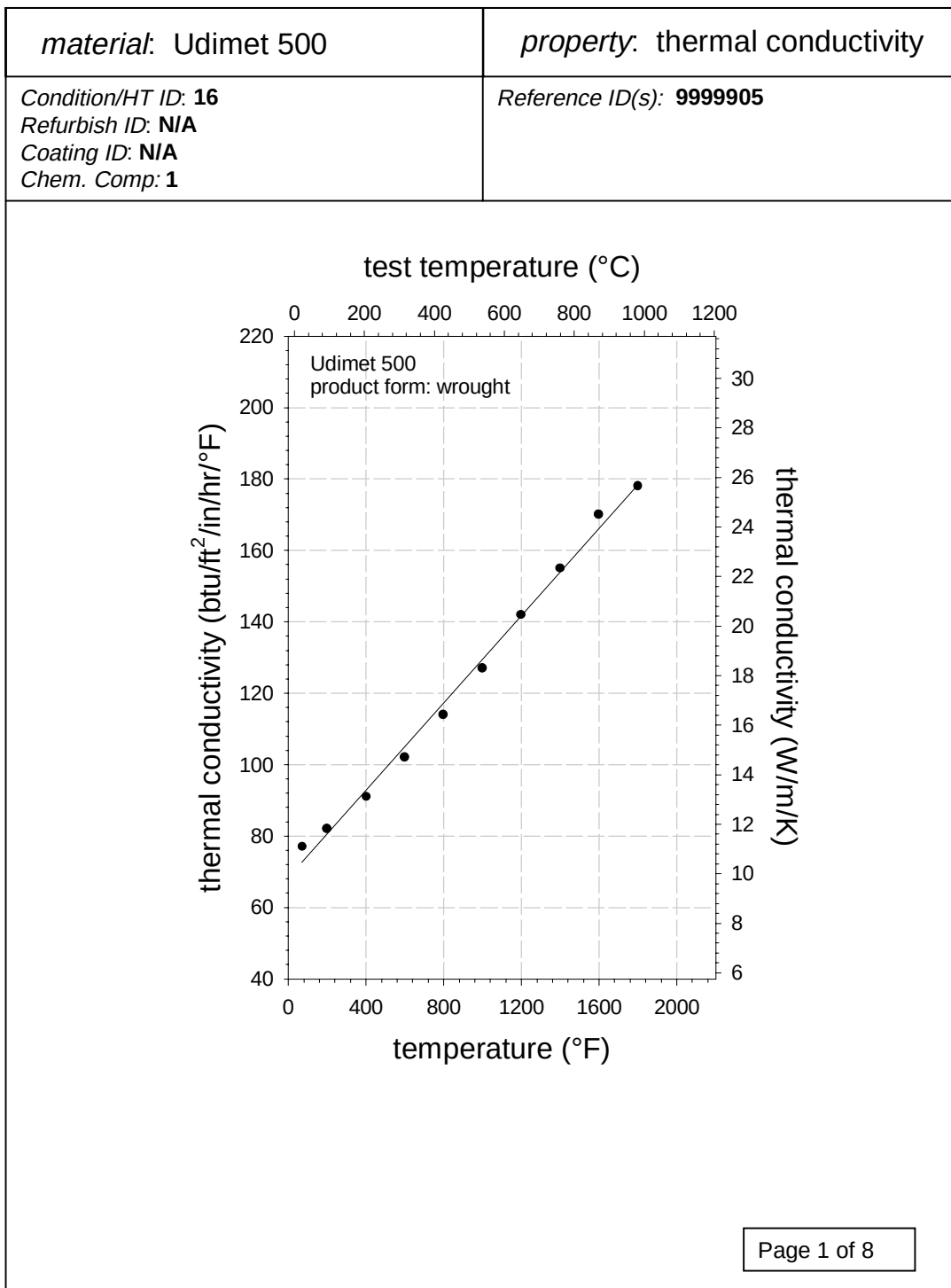


Figure 12-1
Thermal Conductivity as a Function of Temperature.

Udimet 500

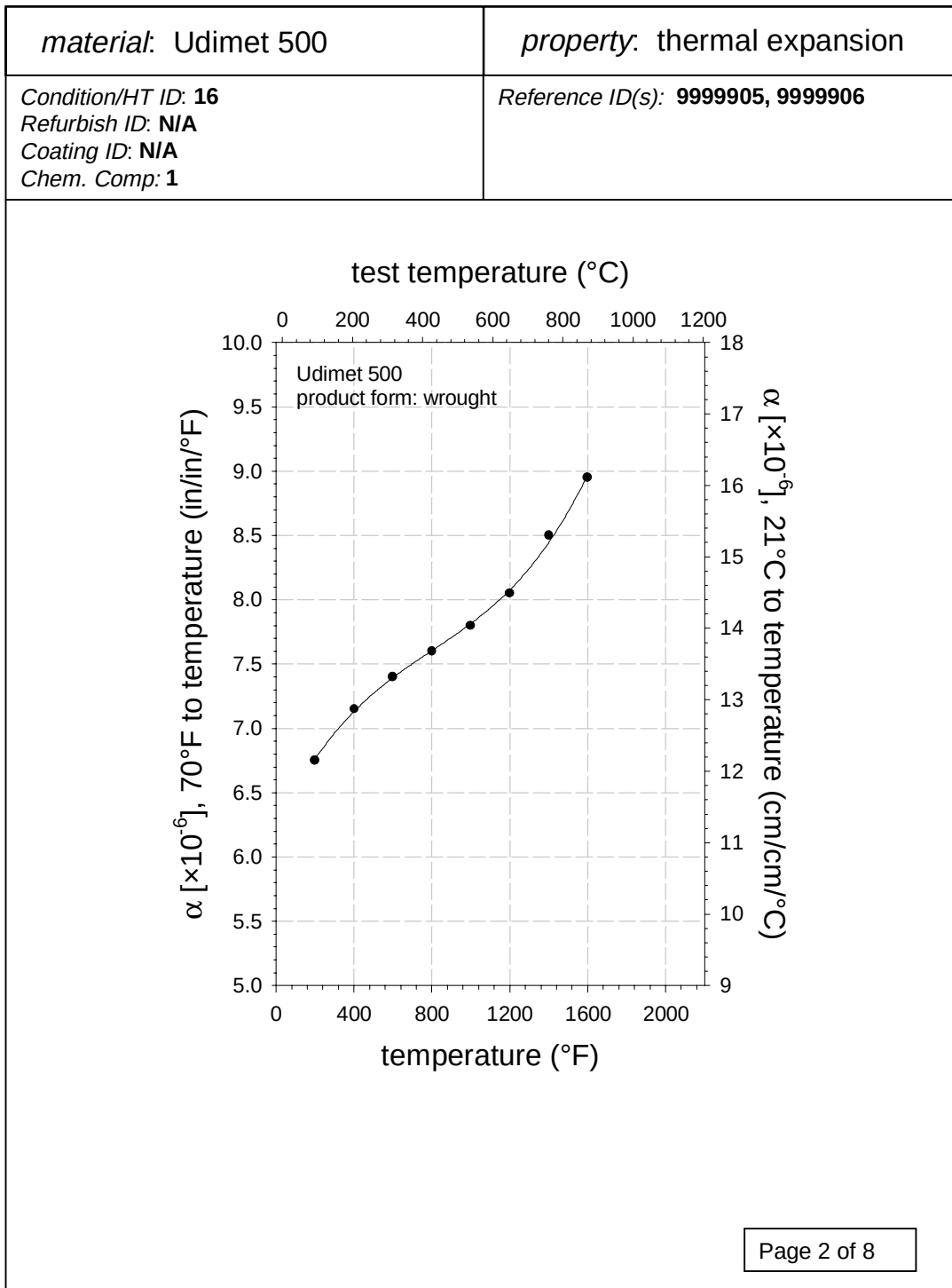


Figure 12-2
Coefficient of Thermal Expansion as a Function of Final Temperature.

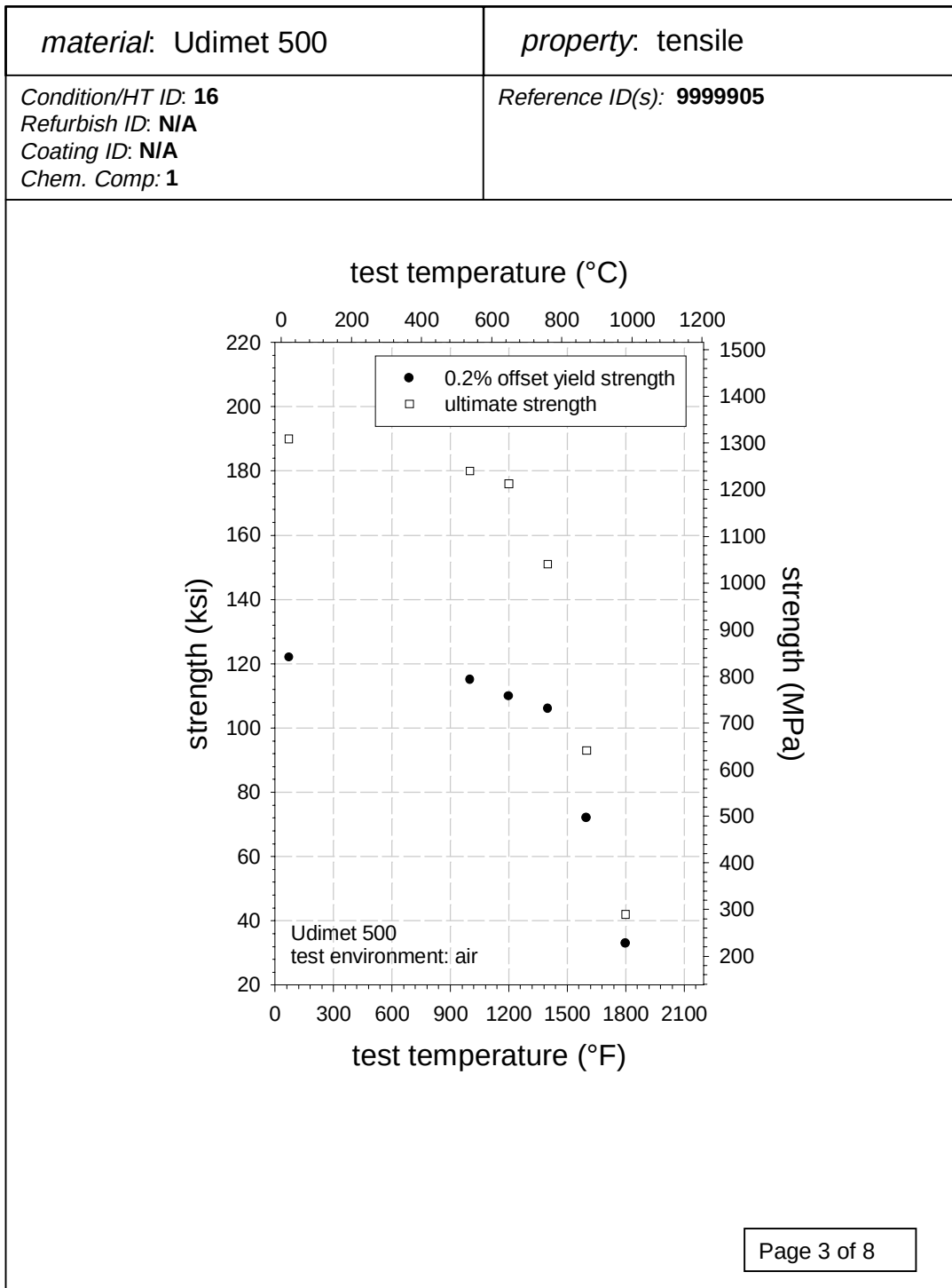


Figure 12-3
Tensile Strengths as a Function of Temperature.

Udimet 500

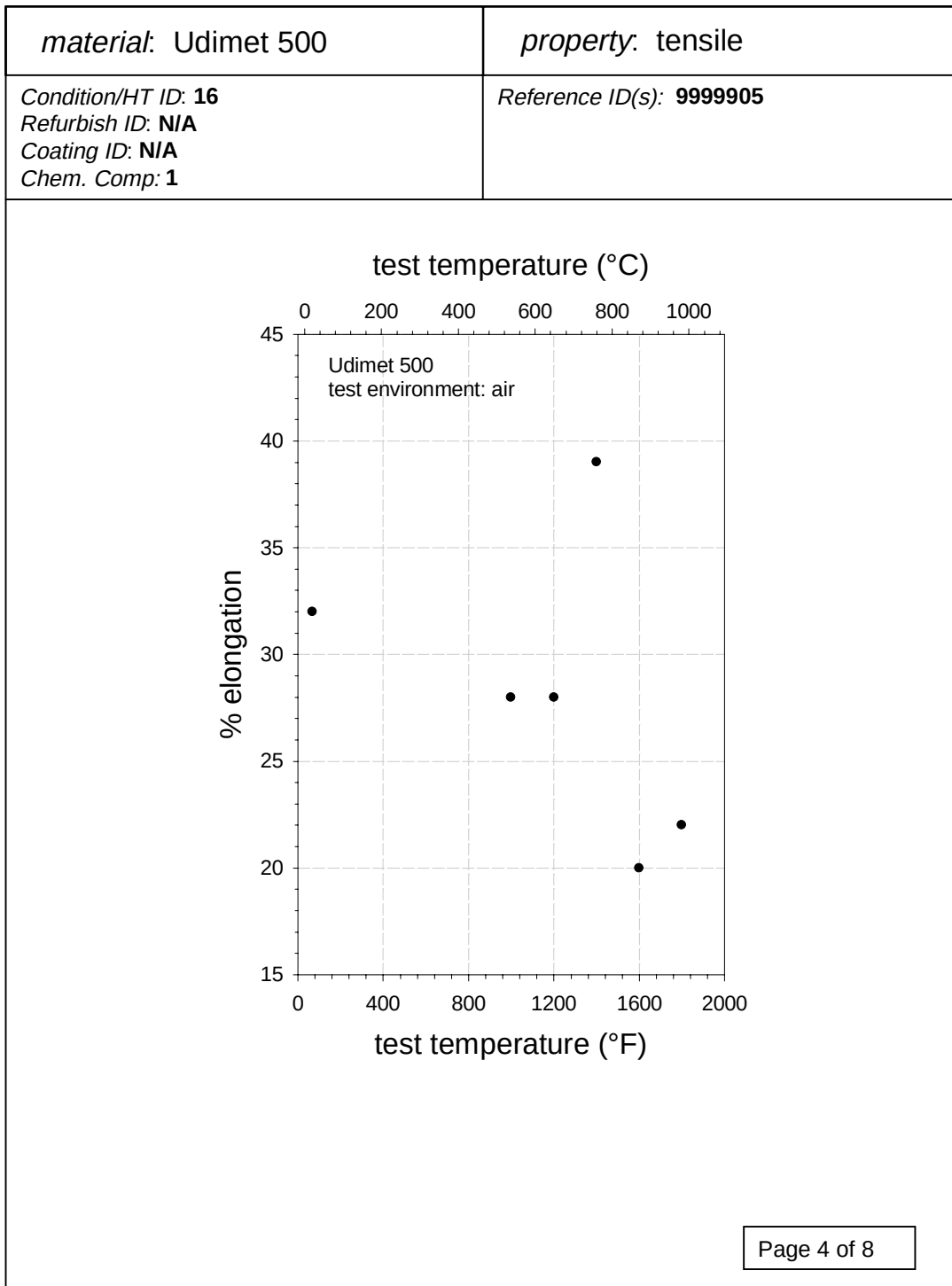


Figure 12-4
Tensile Elongation as a Function of Temperature.

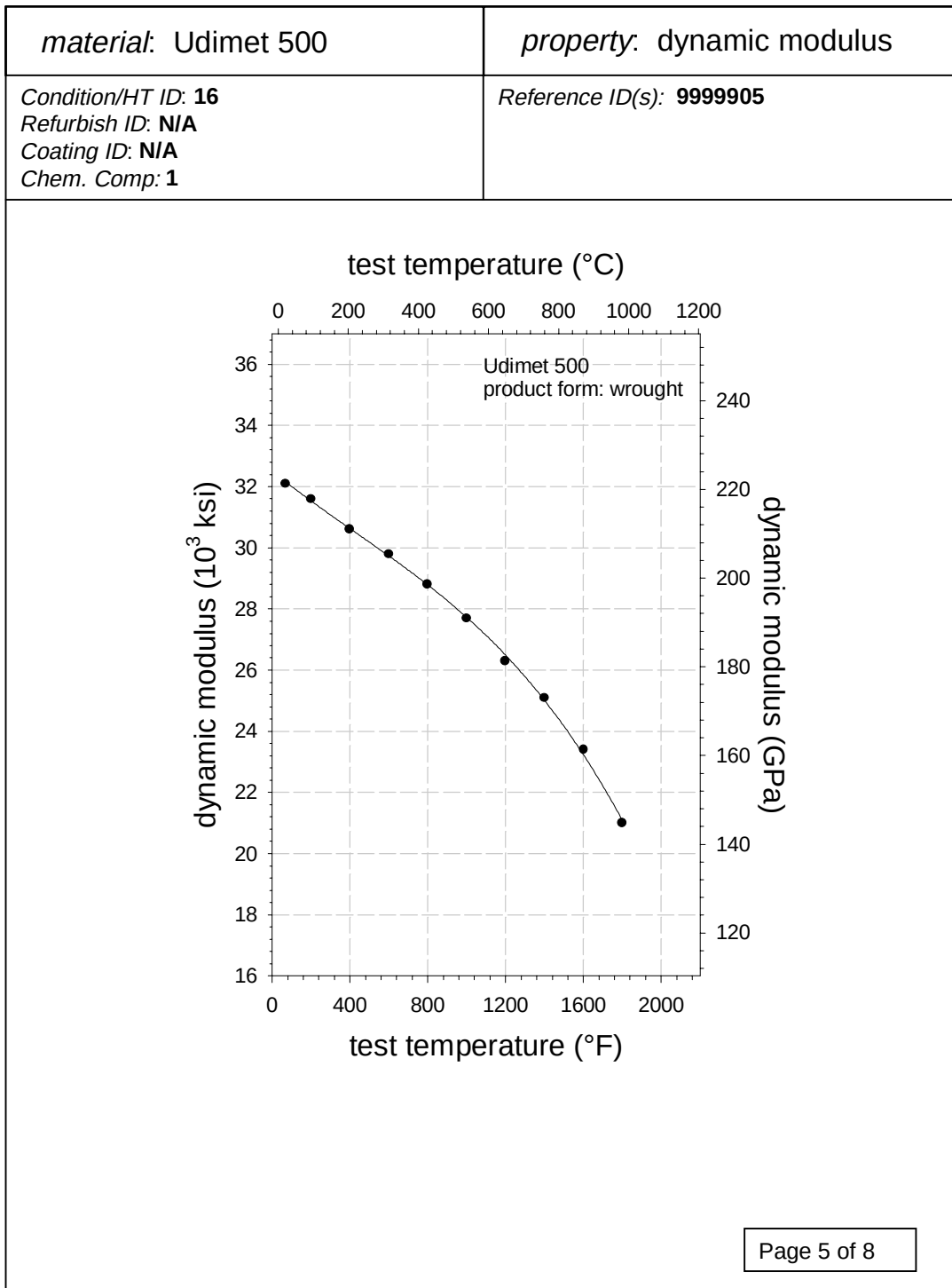


Figure 12-5
Dynamic Modulus as a Function of Temperature.

Udimet 500

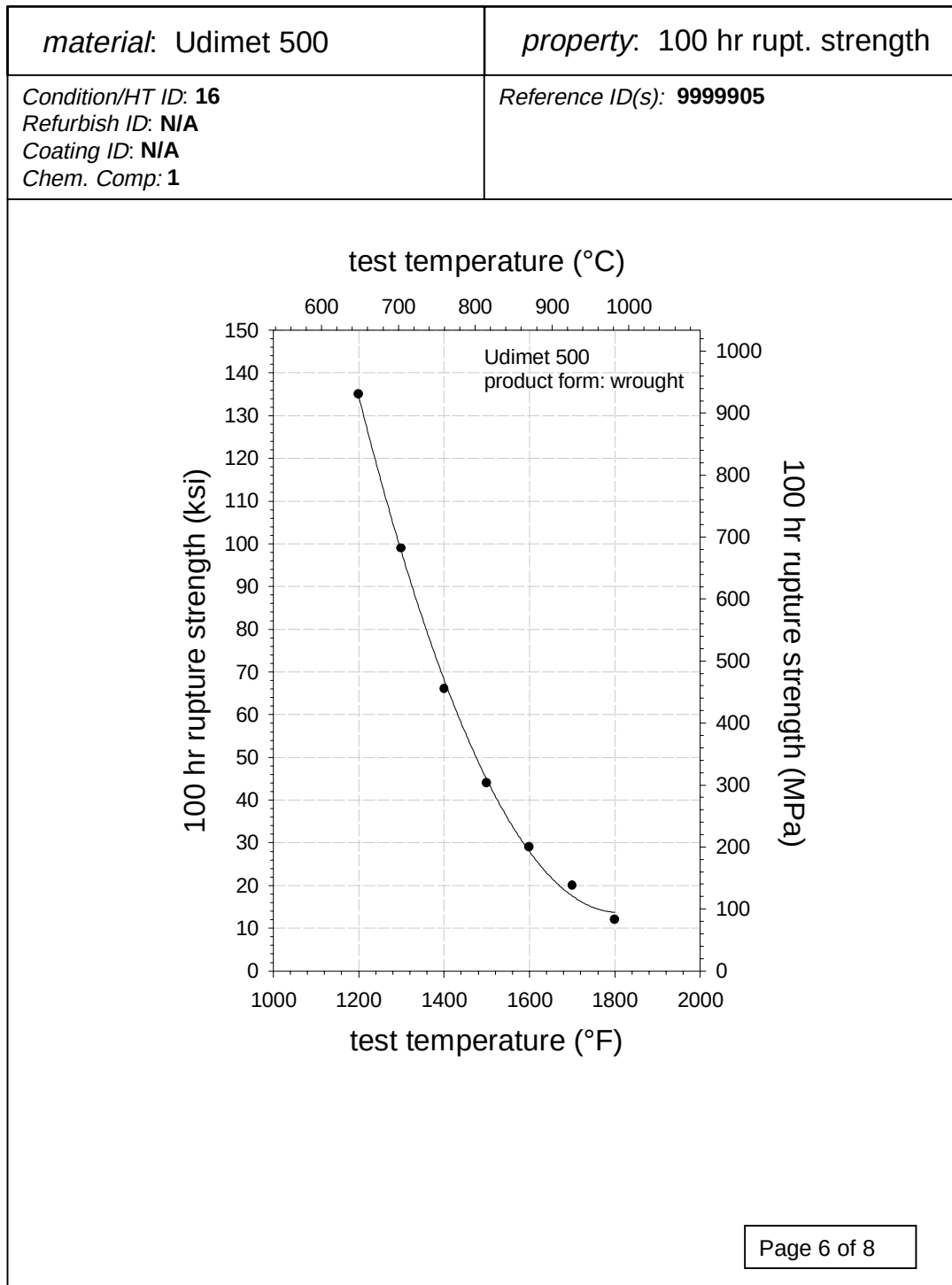


Figure 12-6
100 hr Rupture Strength as a Function of Temperature.

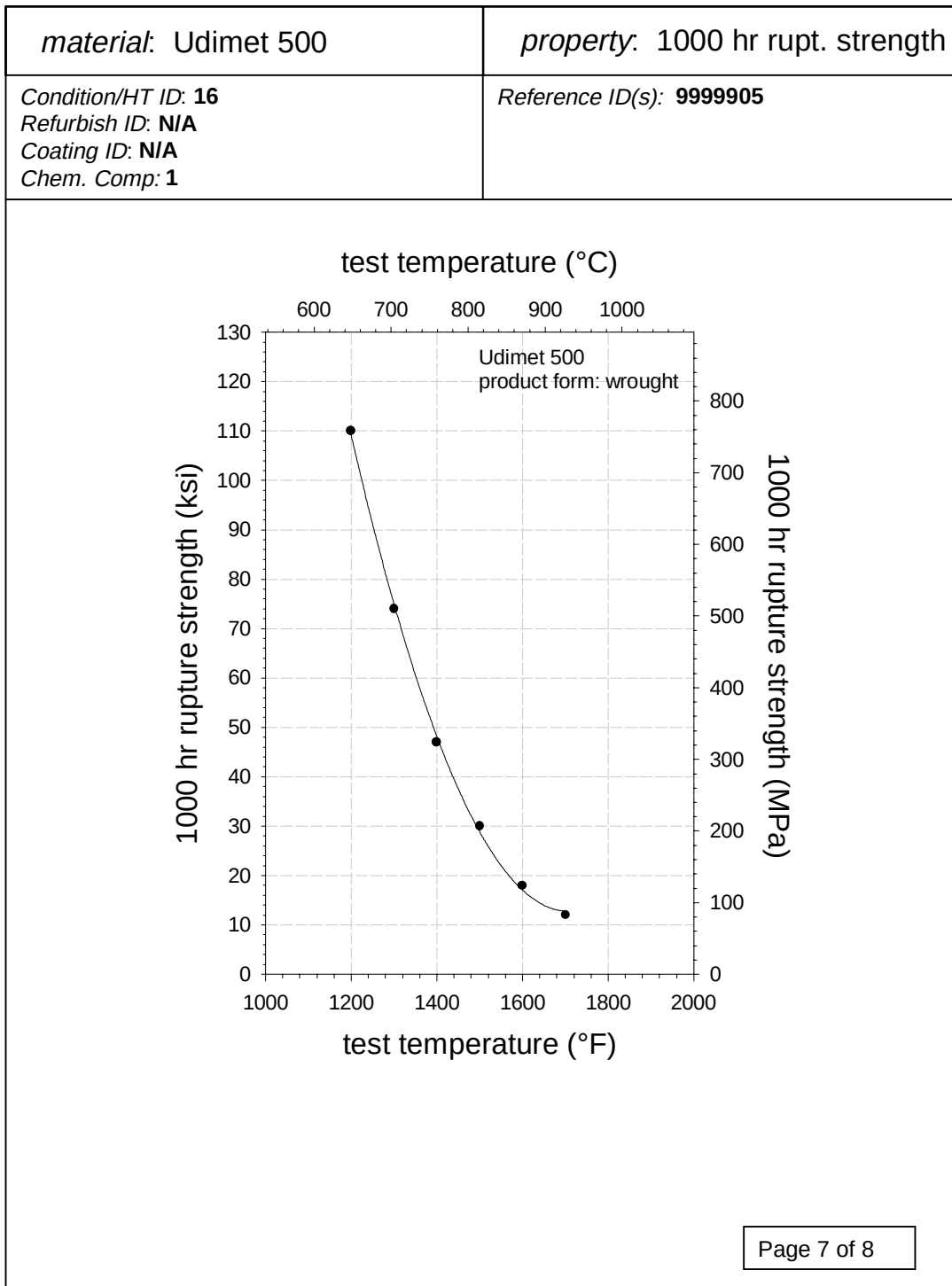


Figure 12-7
1000 hr Rupture Strength as a Function of Temperature.

Udimet 500

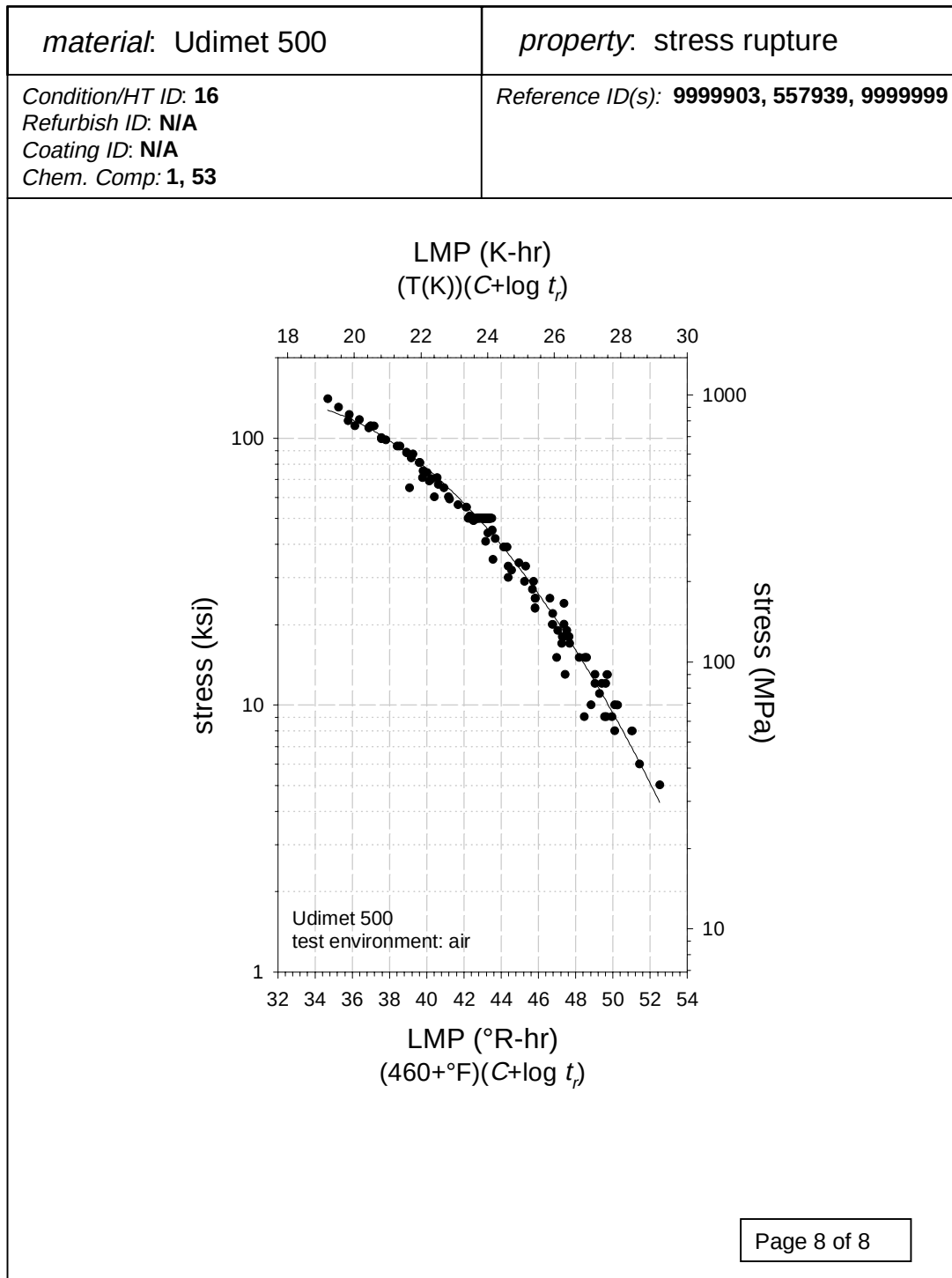


Figure 12-8
Larson-Miller Plot for Udimet 500.

13

UDIMET 520

Udimet 520

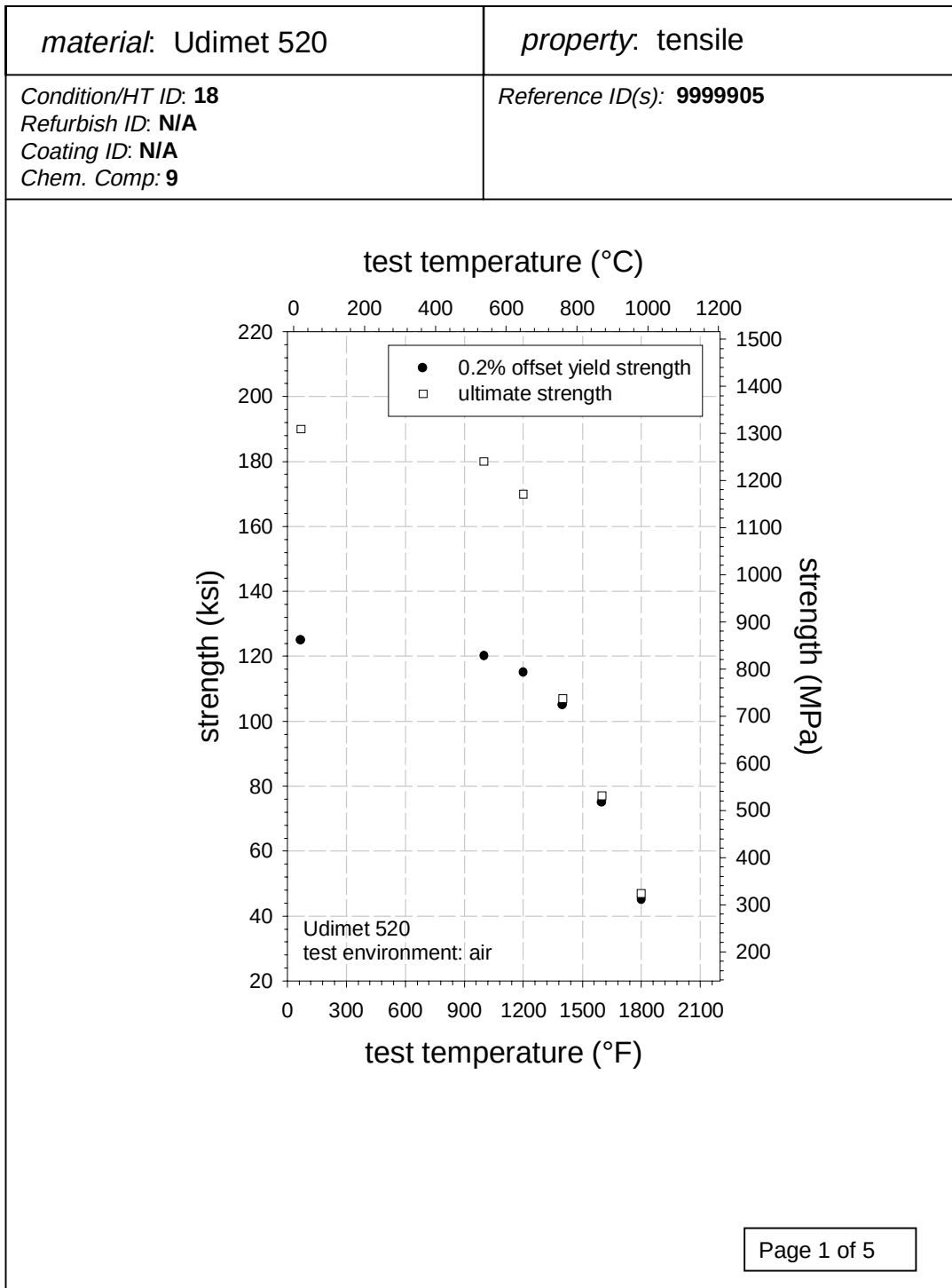


Figure 13-1
Tensile Strengths as a Function of Temperature.

Udimet 520

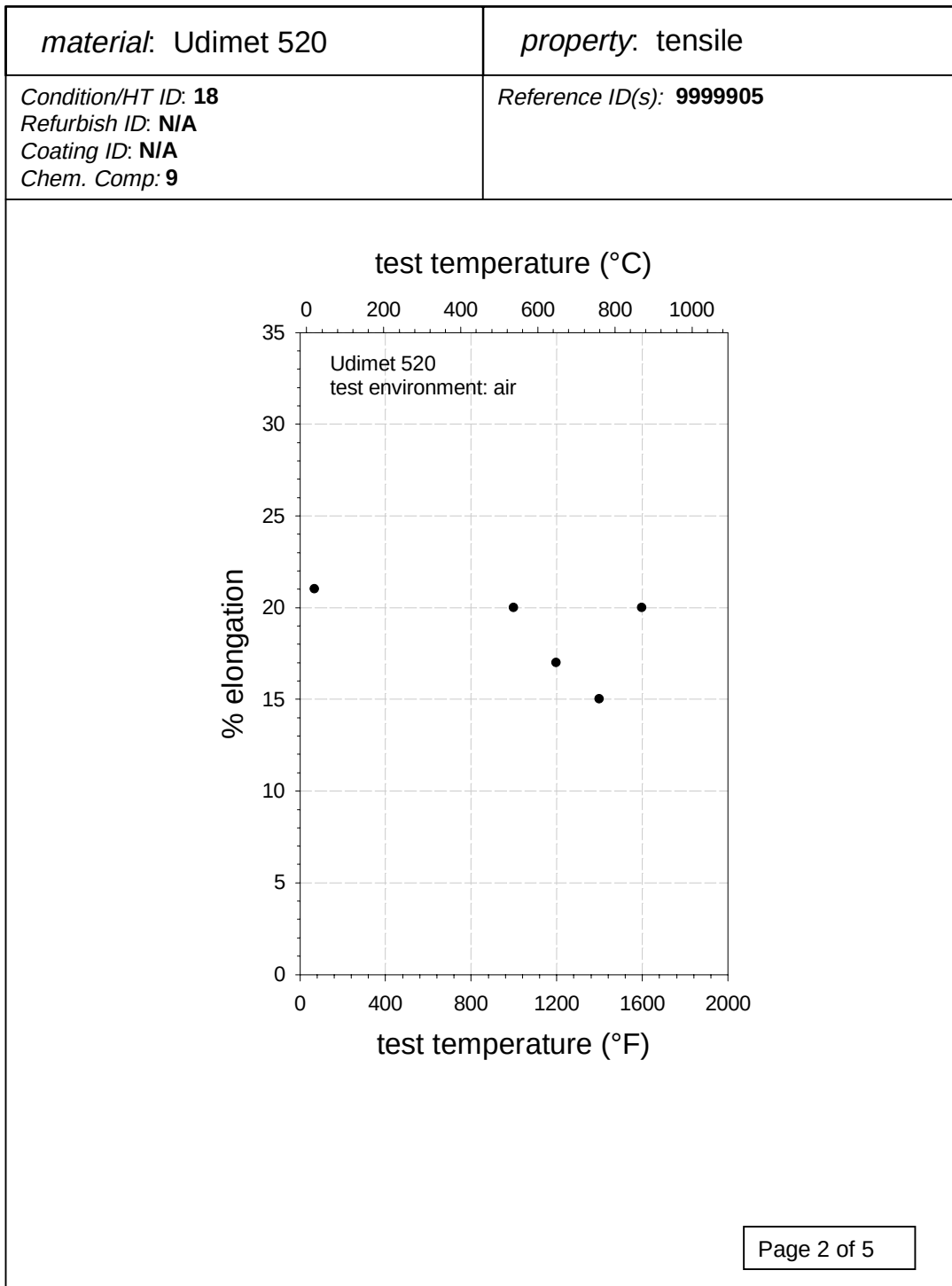


Figure 13-2
Tensile Elongation as a Function of Temperature.

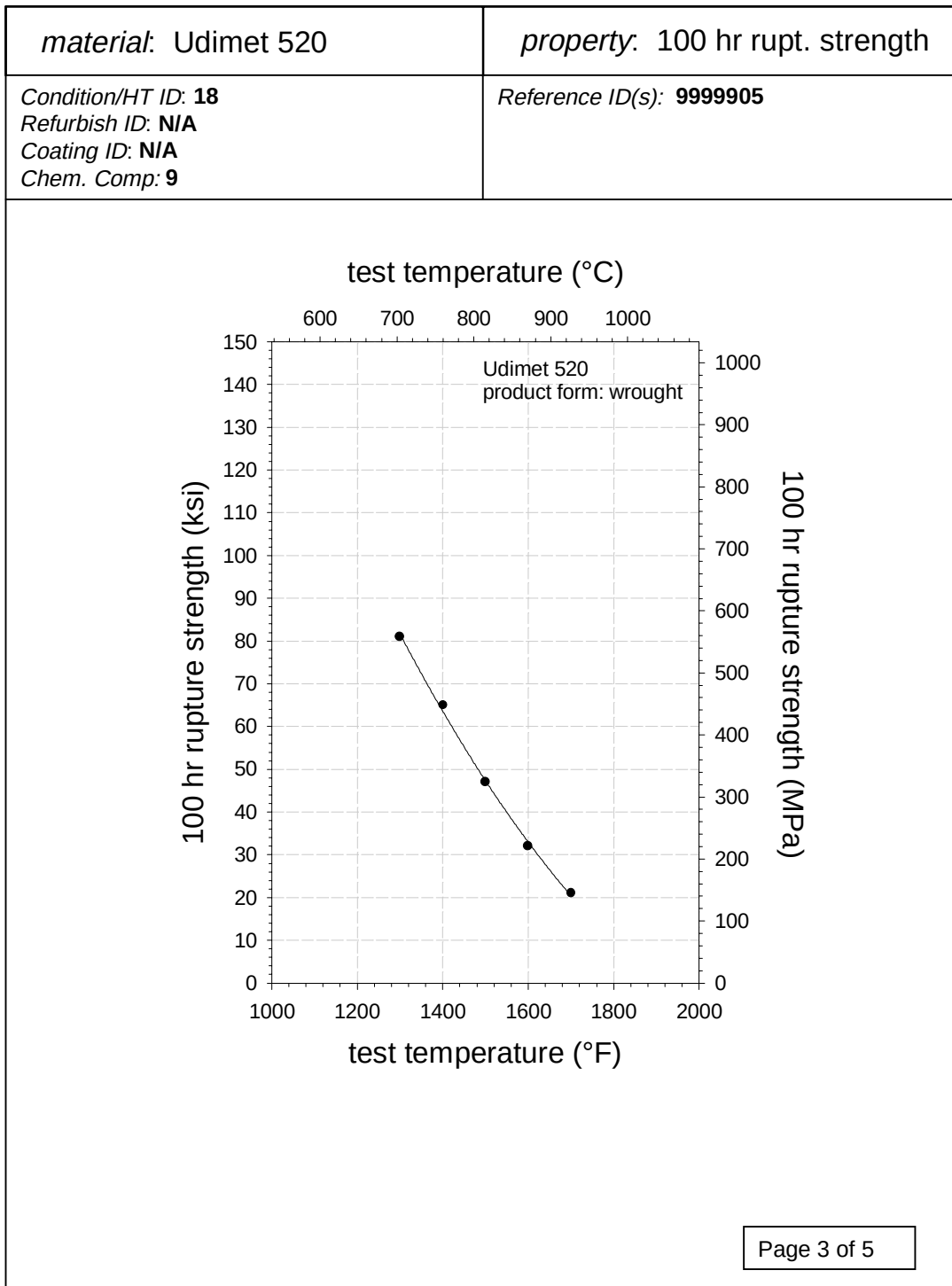


Figure 13-3
100 hr Rupture Strength as a Function of Temperature.

Udimet 520

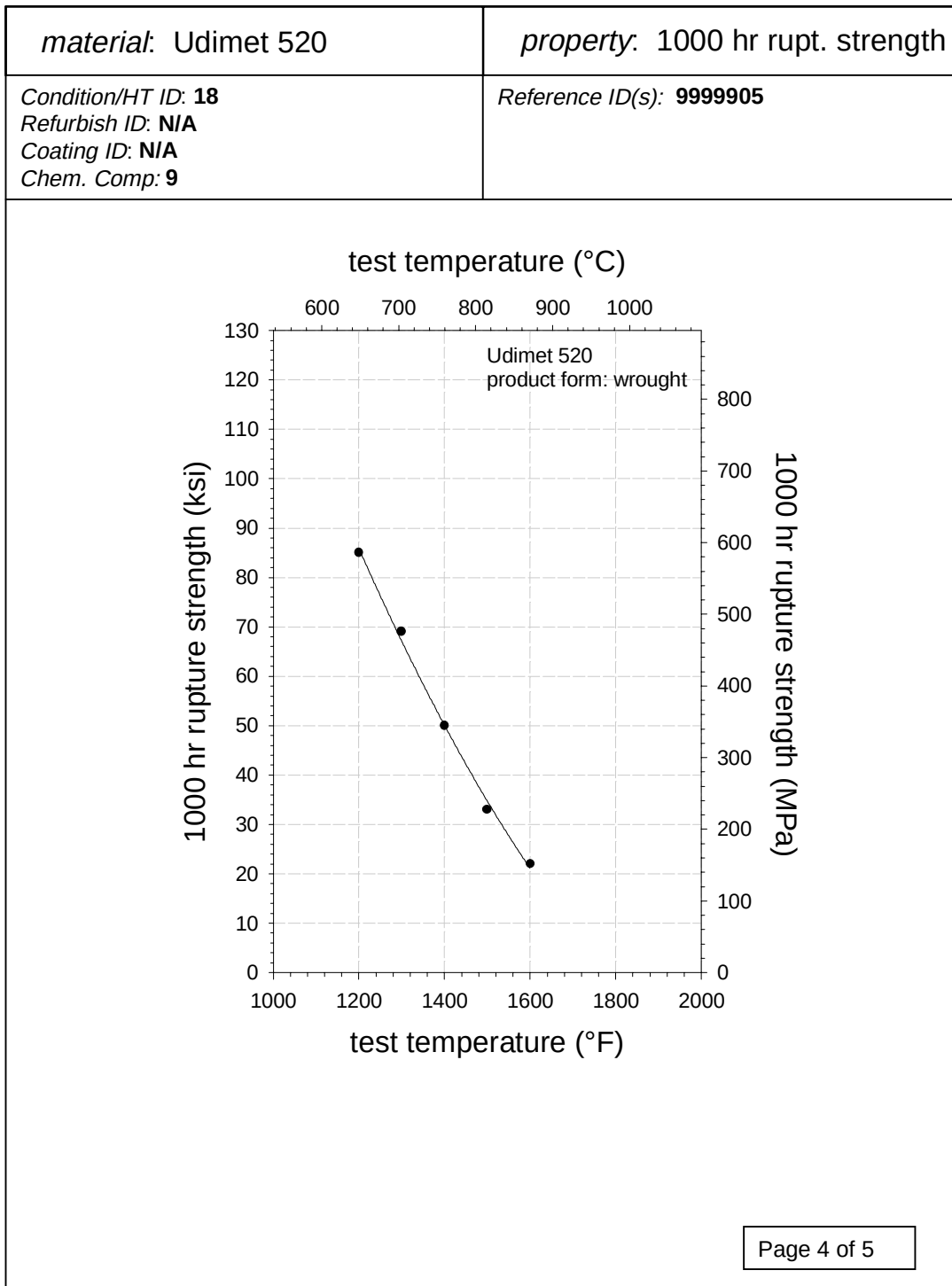


Figure 13-4
1000 hr Rupture Strength as a Function of Temperature.

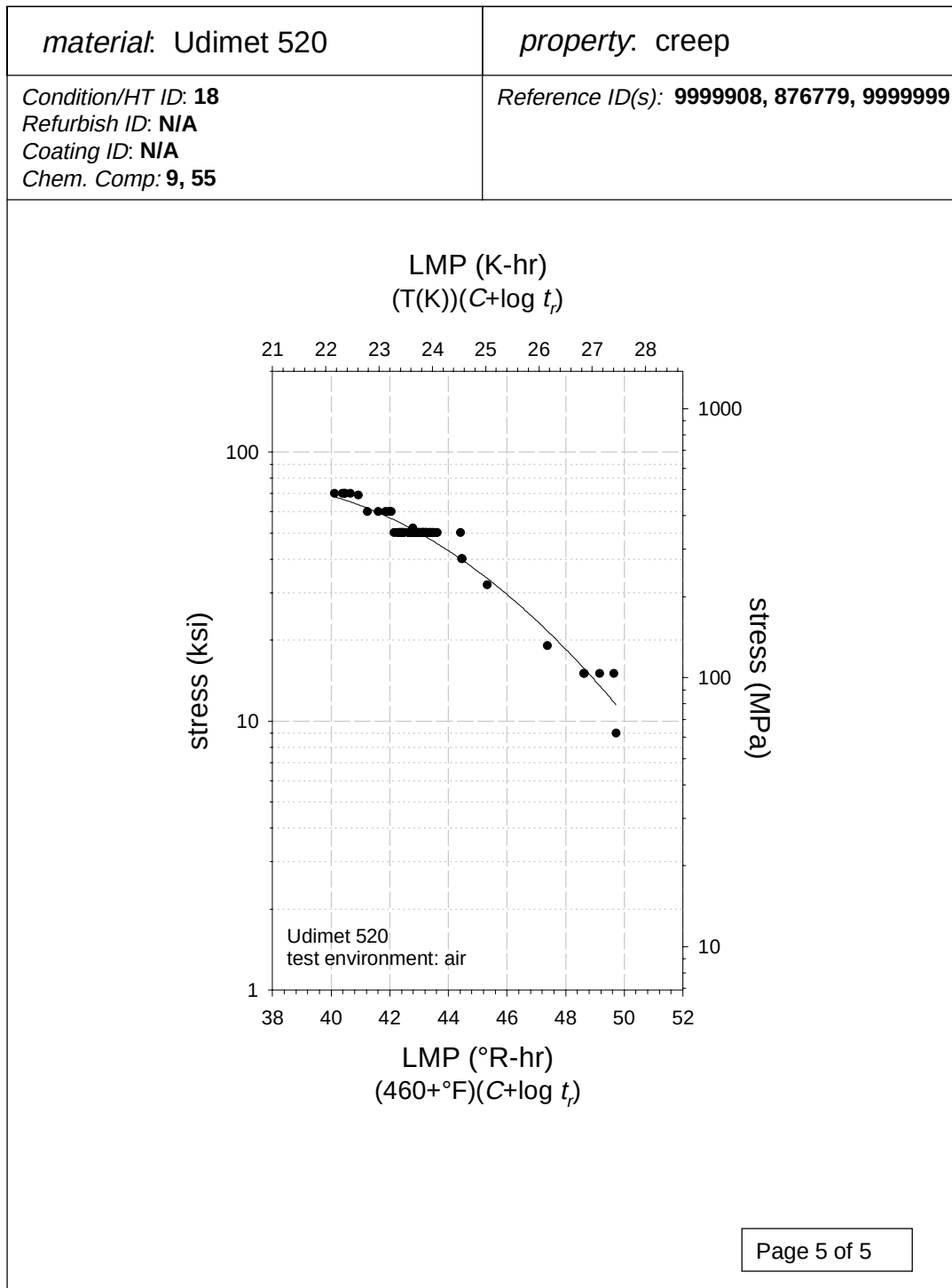


Figure 13-5
Larson-Miller Plot for Udimet 520.

14

UDIMET 700

Udimet 700

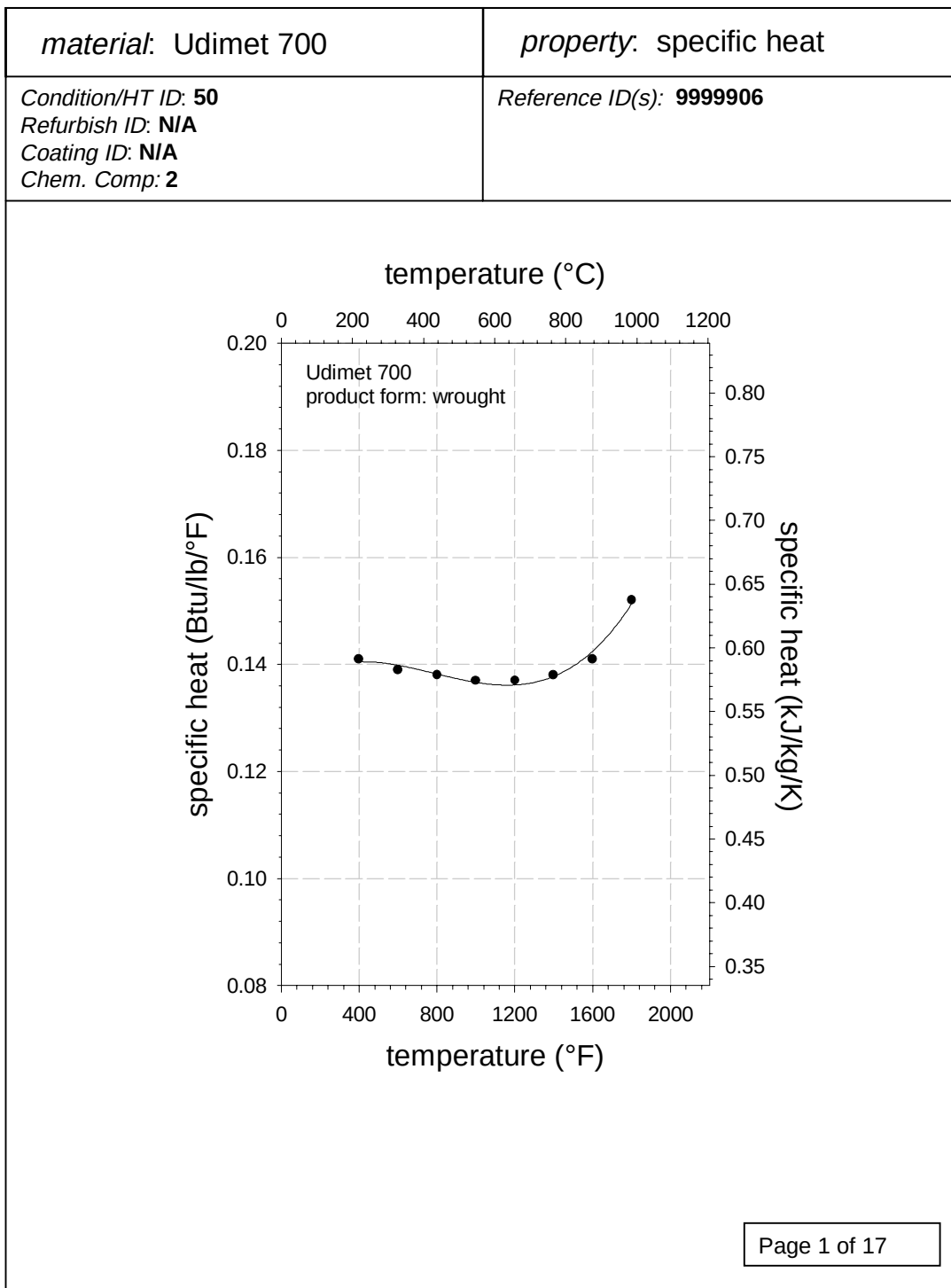


Figure 14-1
Specific Heat as a Function of Temperature.

Udimet 700

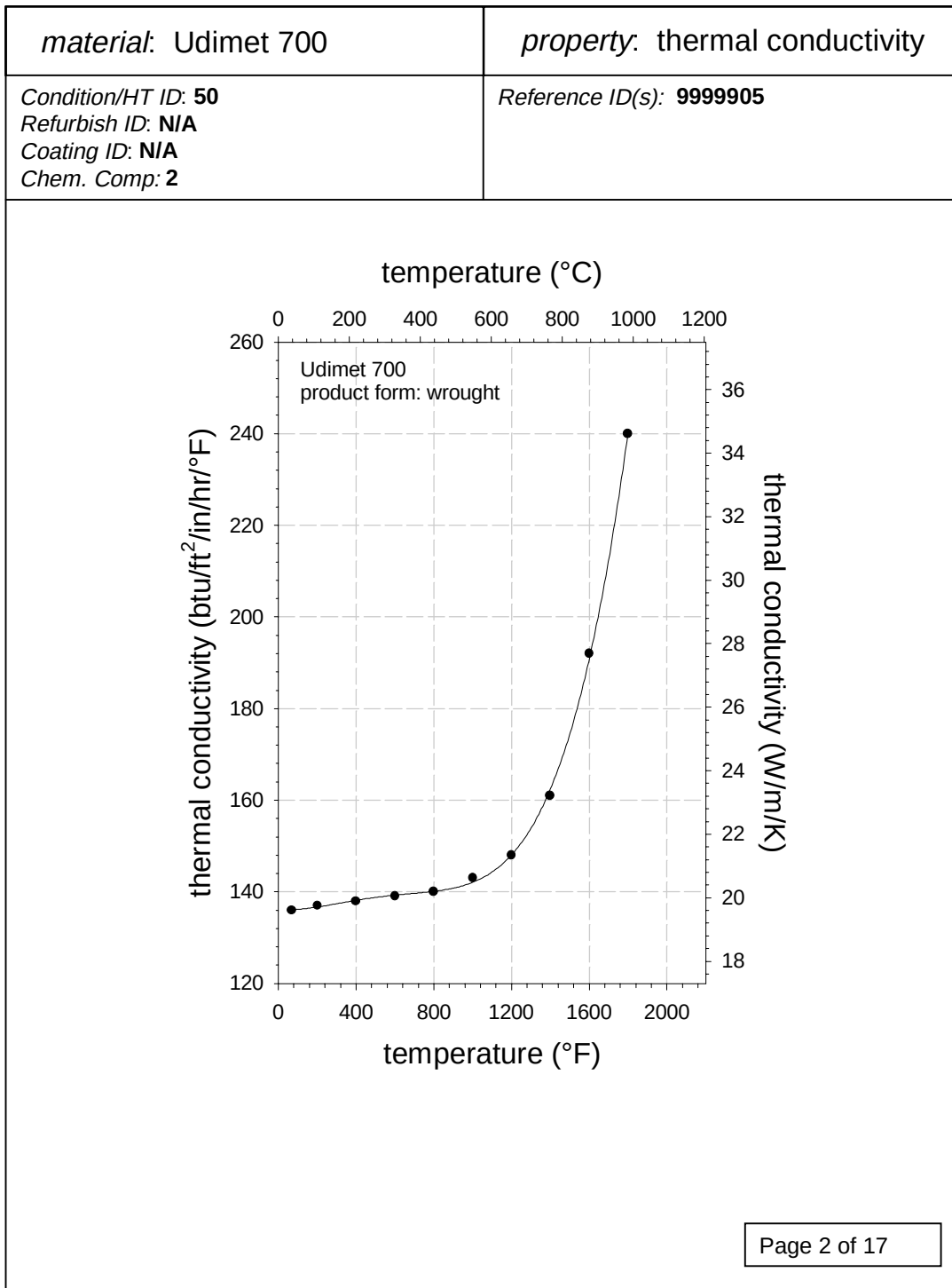


Figure 14-2
Thermal Conductivity as a Function of Temperature.

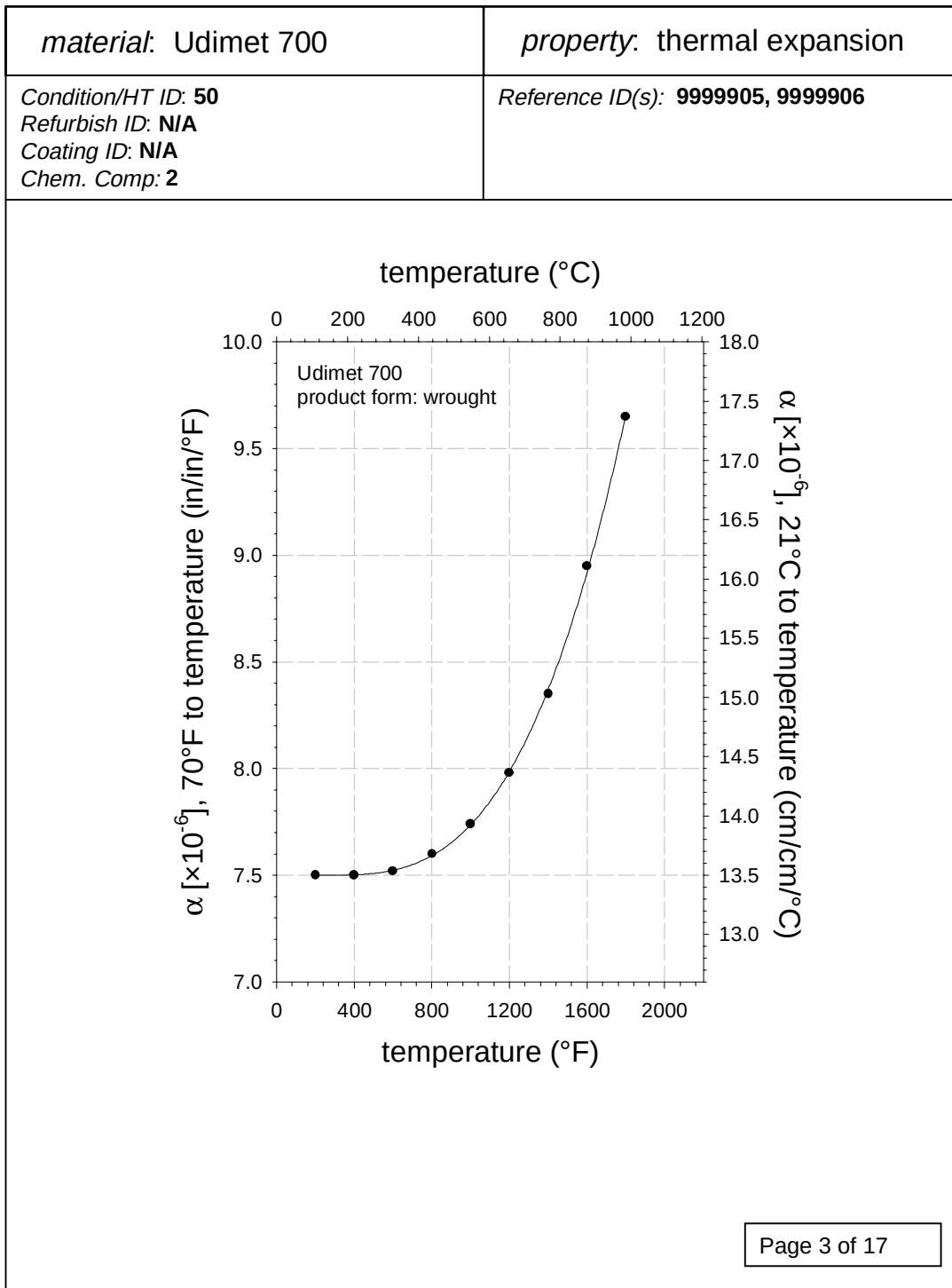


Figure 14-3
Coefficient of Thermal Expansion as a Function of Temperature.

Udimet 700

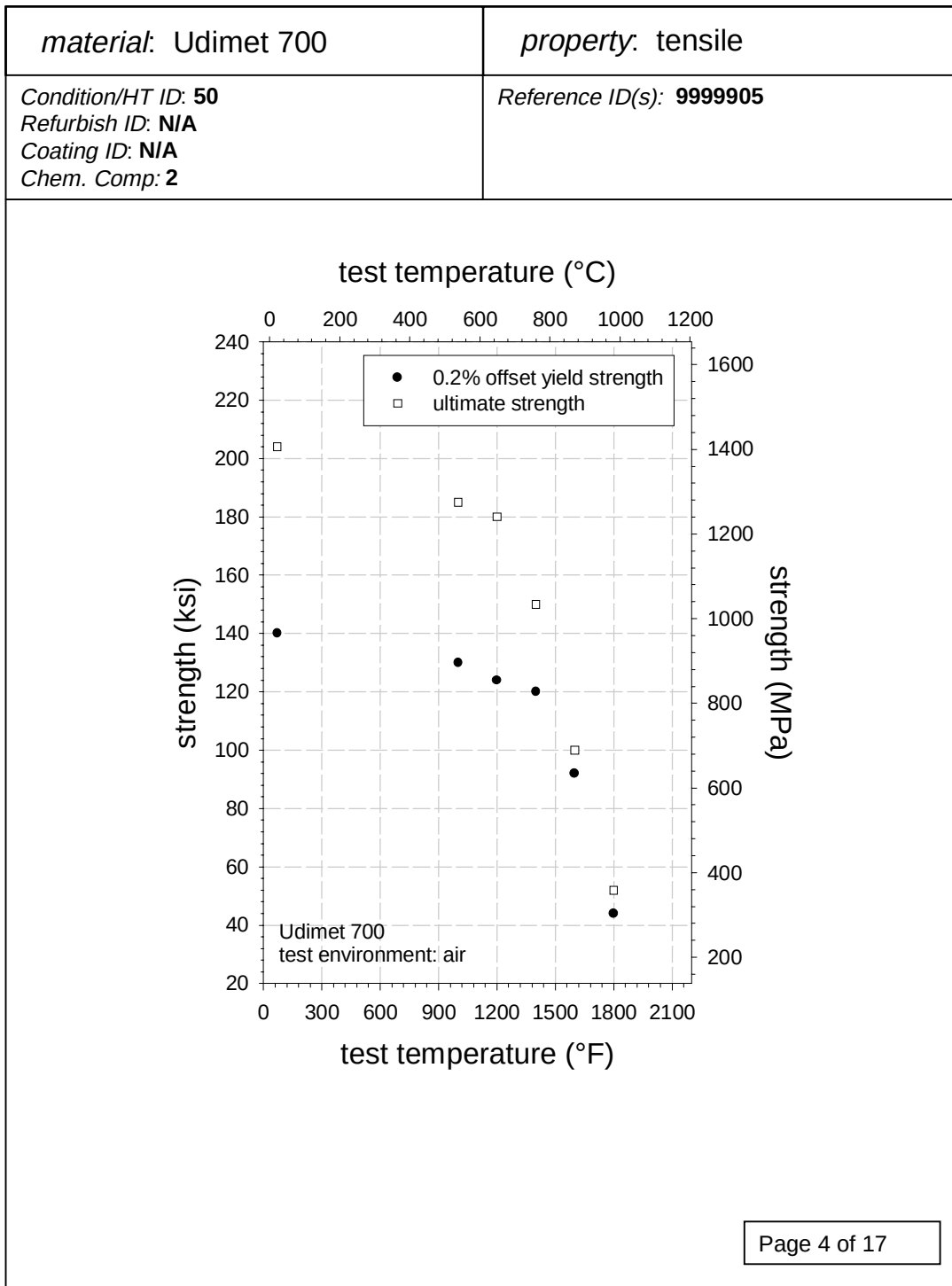


Figure 14-4
Tensile Strengths as a Function of Temperature.

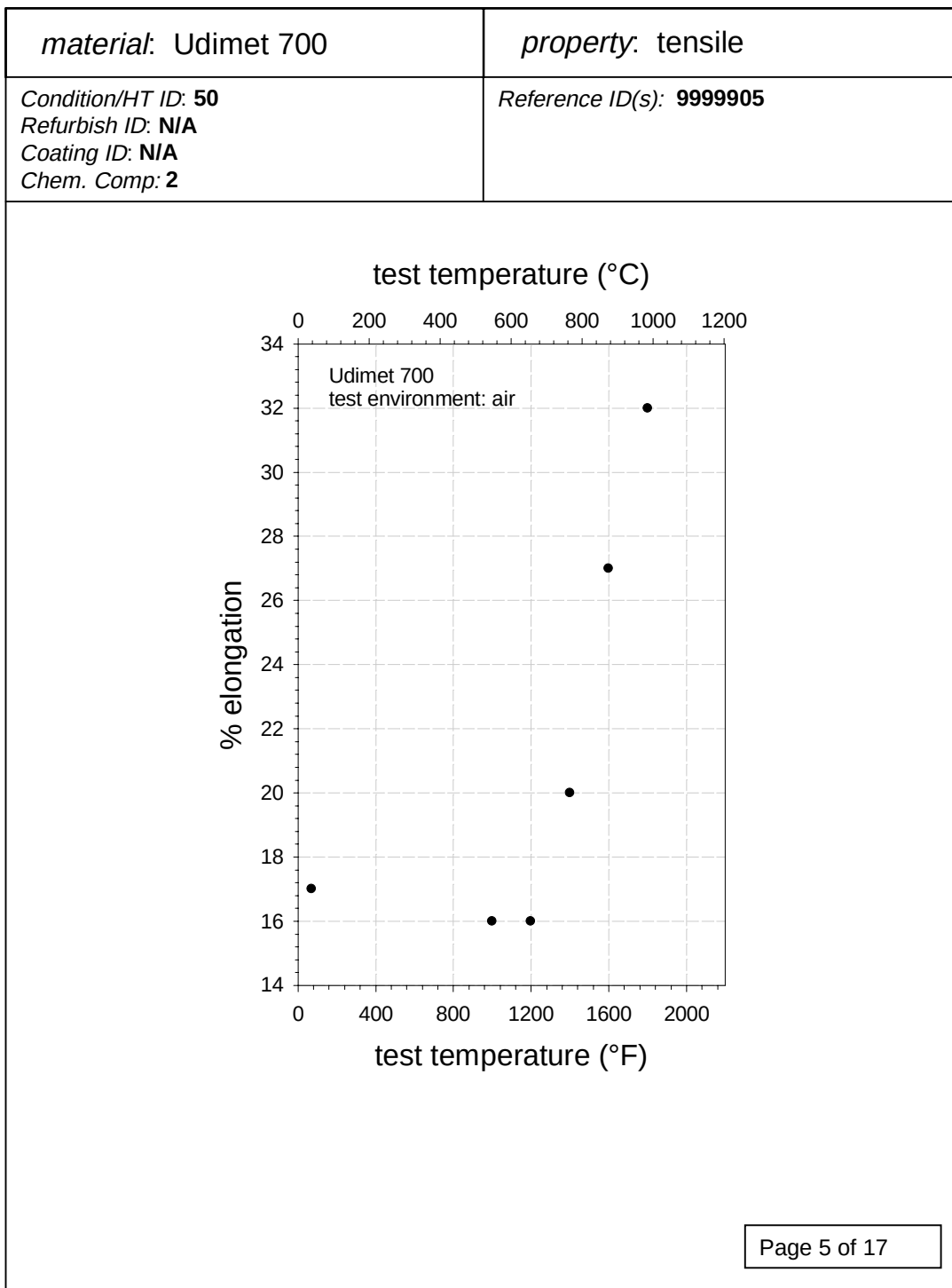


Figure 14-5
Tensile Elongation as a Function of Temperature.

Udimet 700

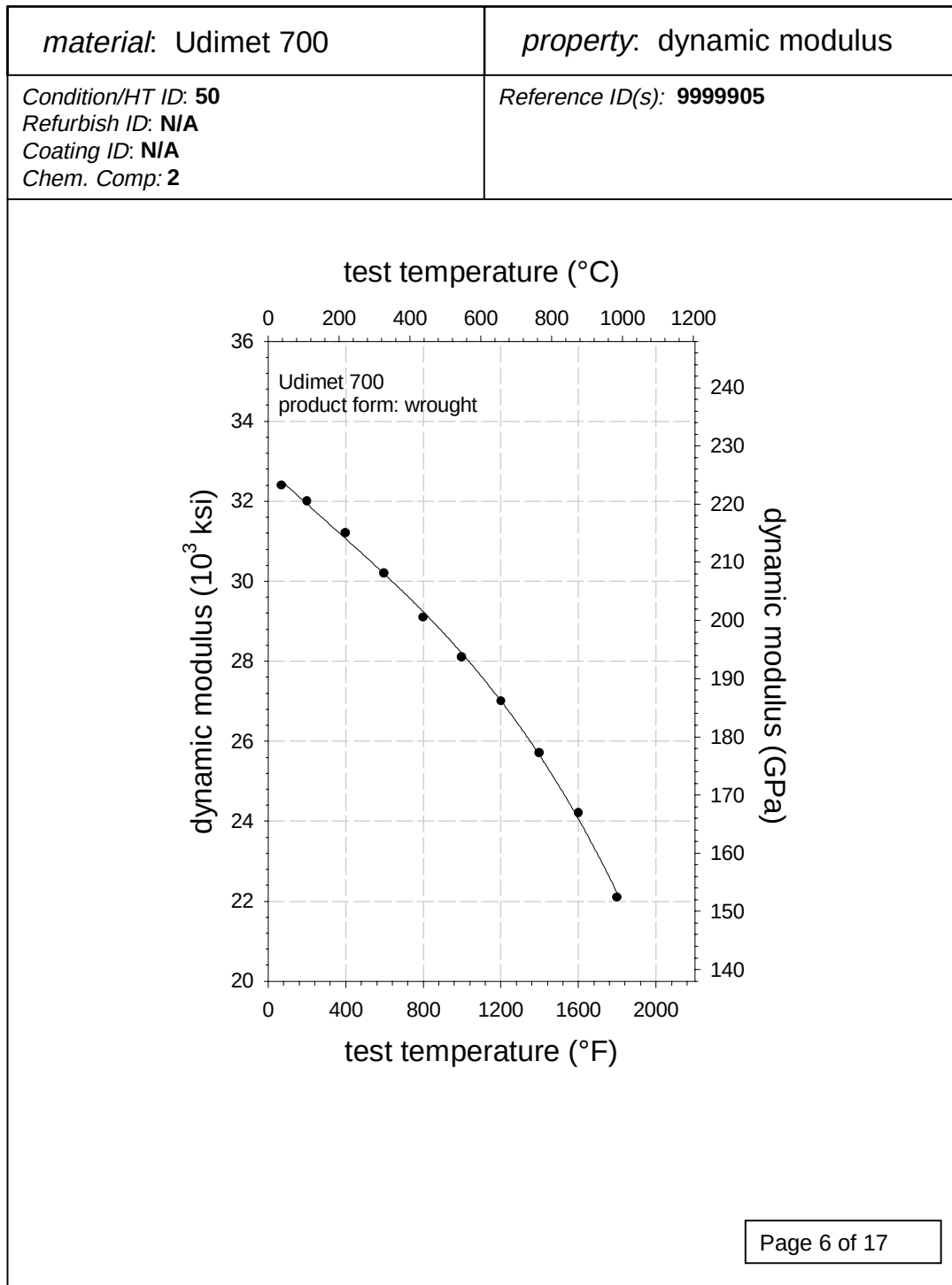


Figure 14-6
Dynamic Modulus as a Function of Temperature.

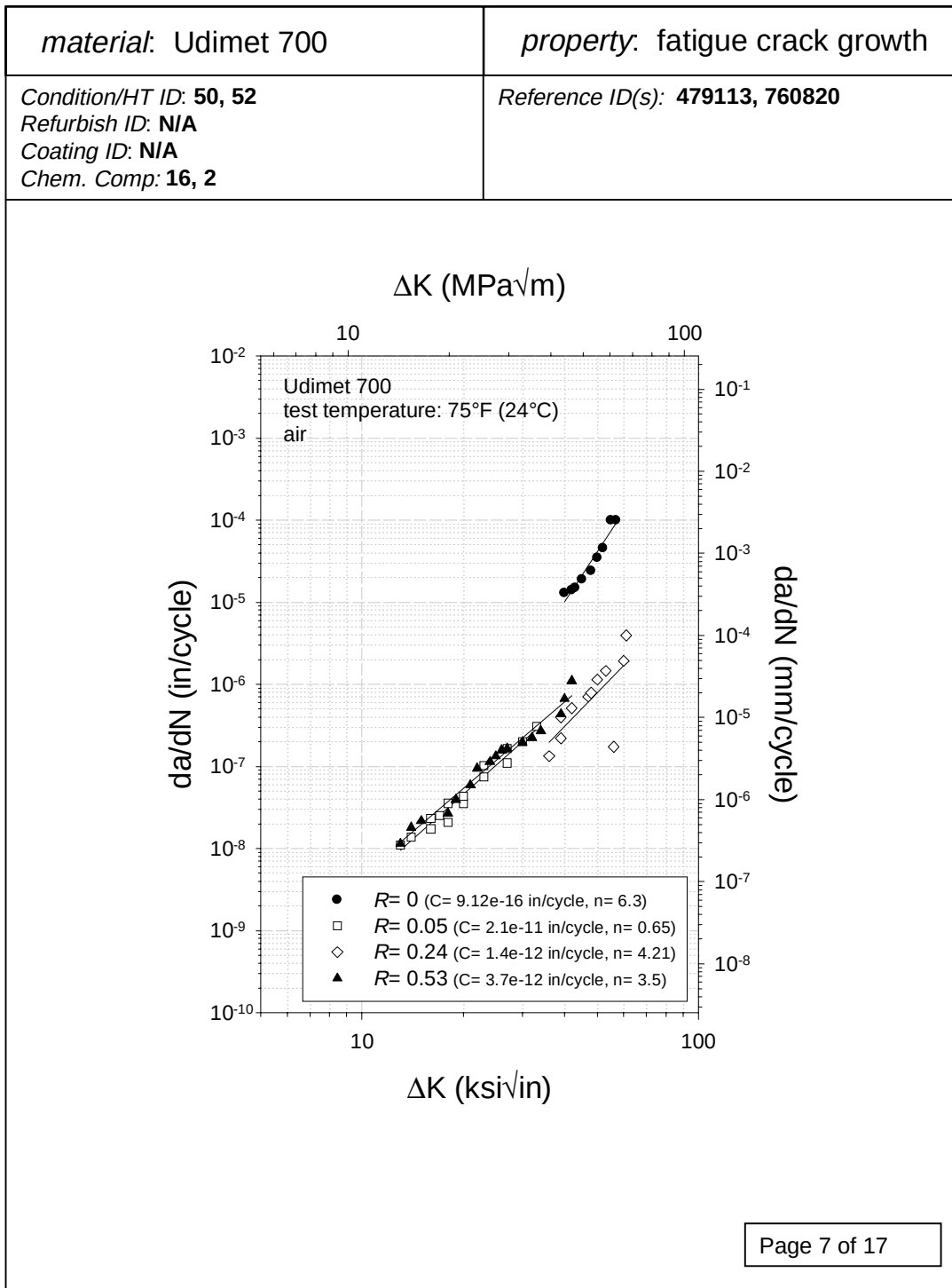


Figure 14-7
Fatigue Crack Growth Behavior at $R = 0, 0.05, 0.24$, and 0.53 (Lab Air, Room Temperature).

Udimet 700

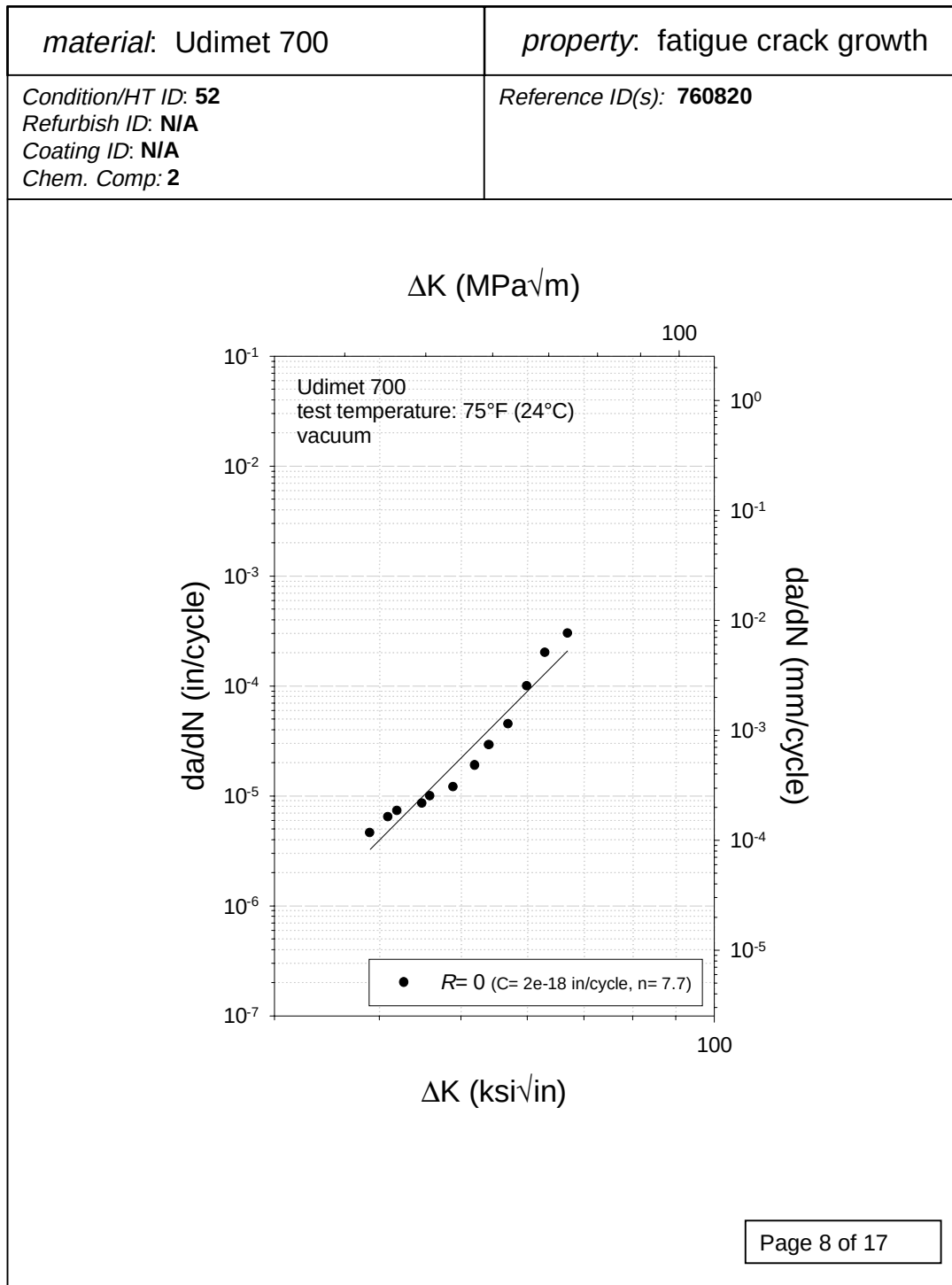


Figure 14-8
Fatigue Crack Growth Behavior Under Vacuum Conditions (Room Temperature).

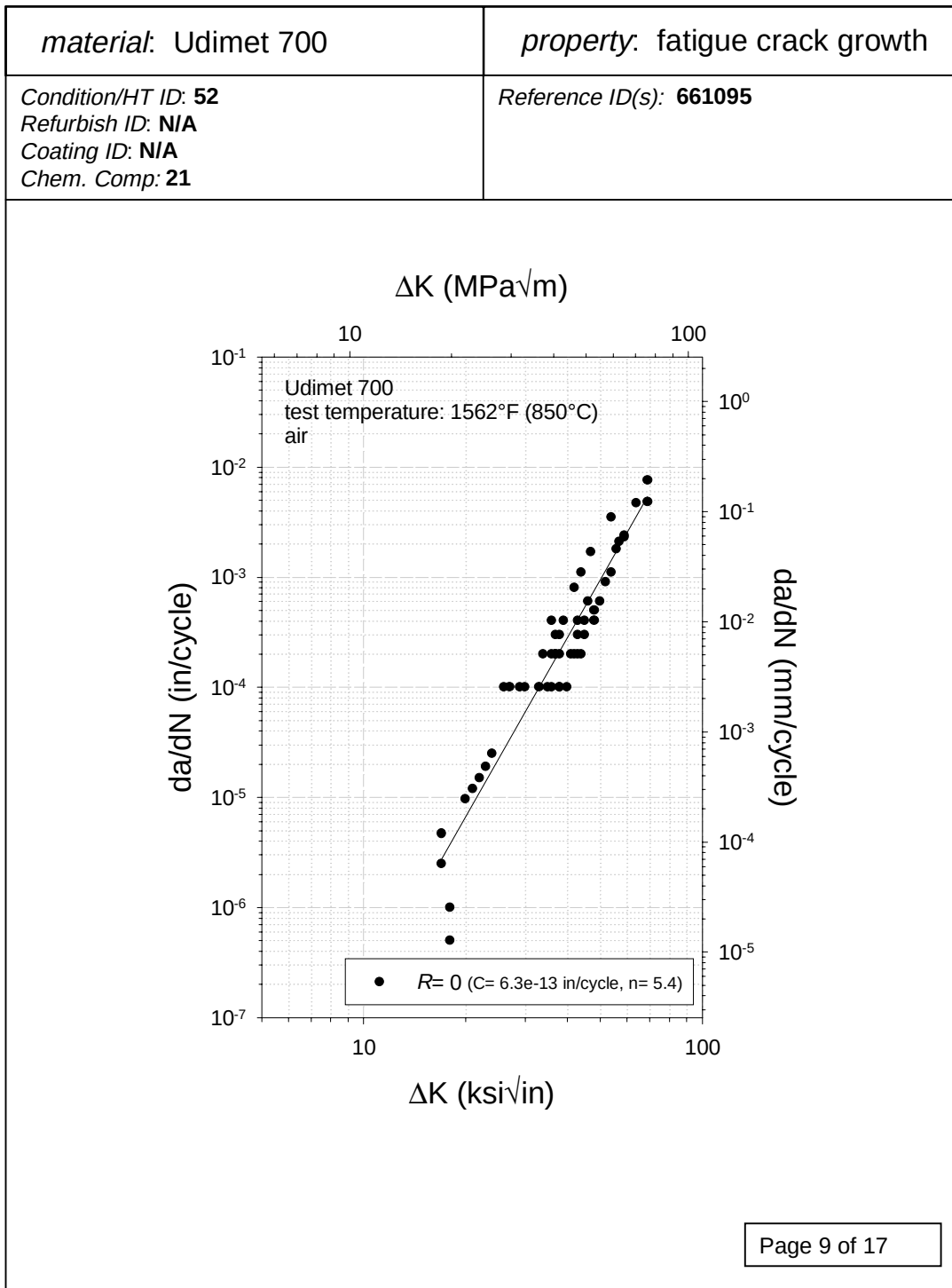


Figure 14-9
Elevated Temperature Fatigue Crack Growth Behavior at R = 0.

Udimet 700

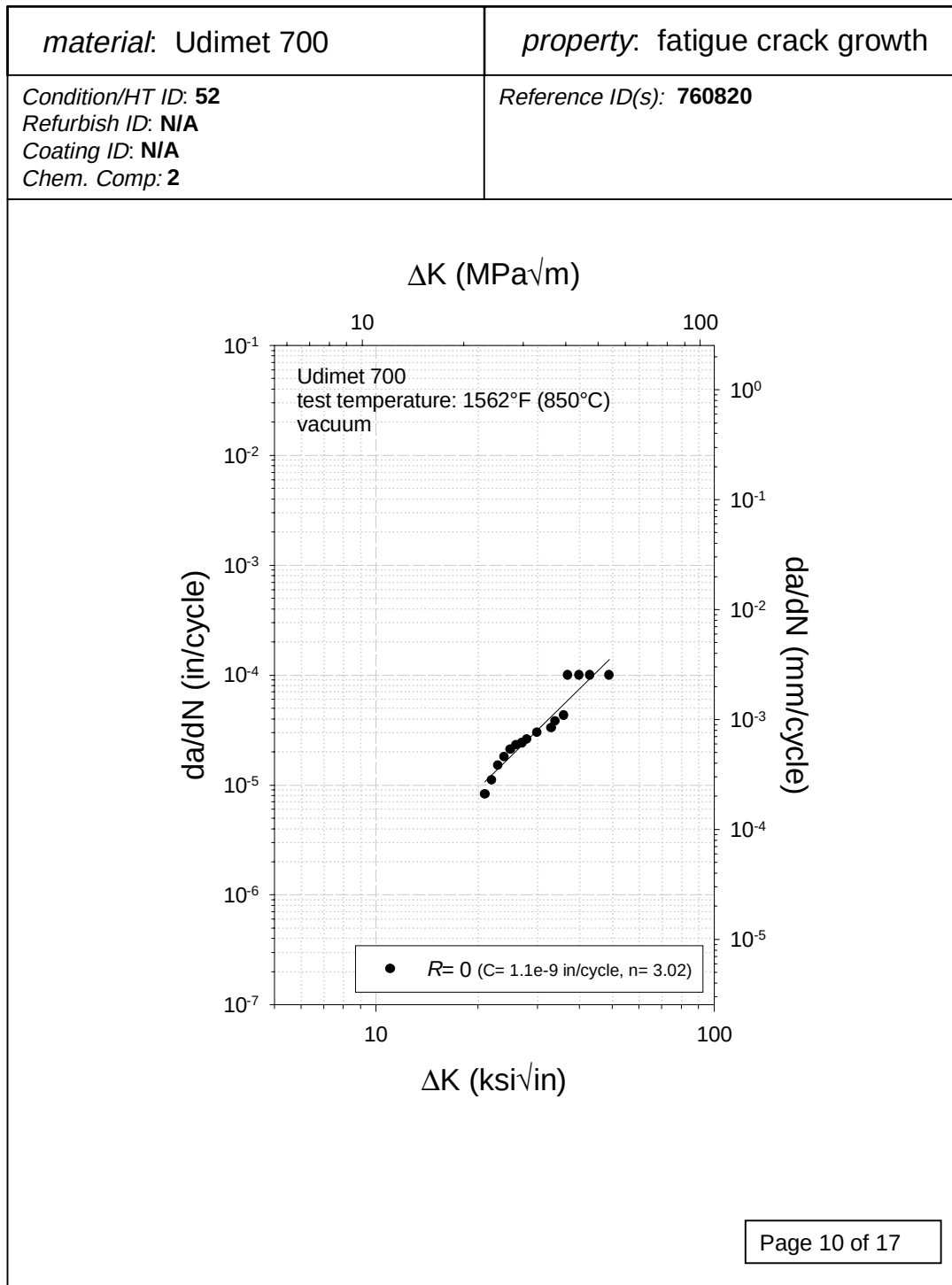


Figure 14-10
Elevated Fatigue Crack Growth Behavior Under Vacuum Conditions.

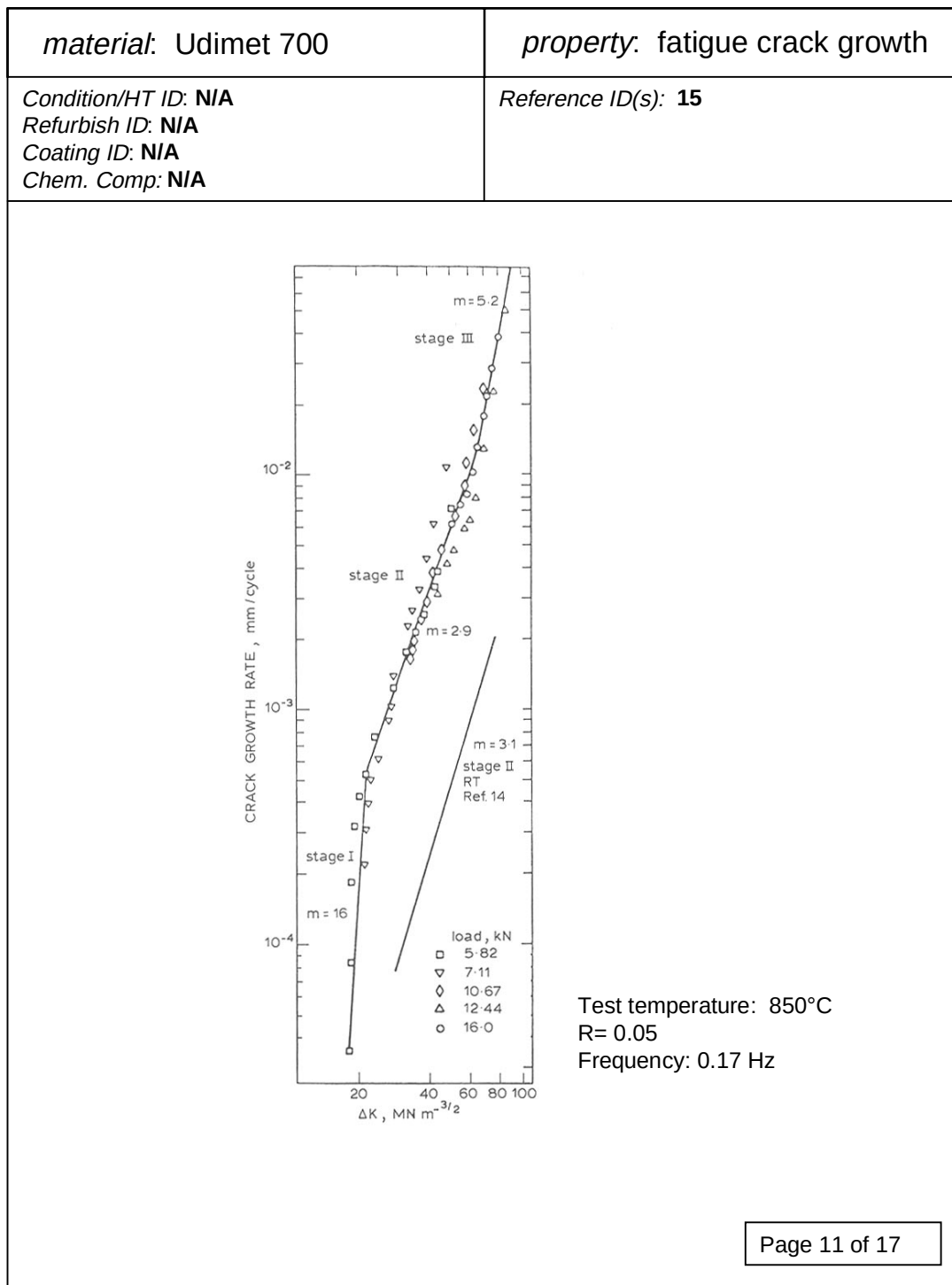
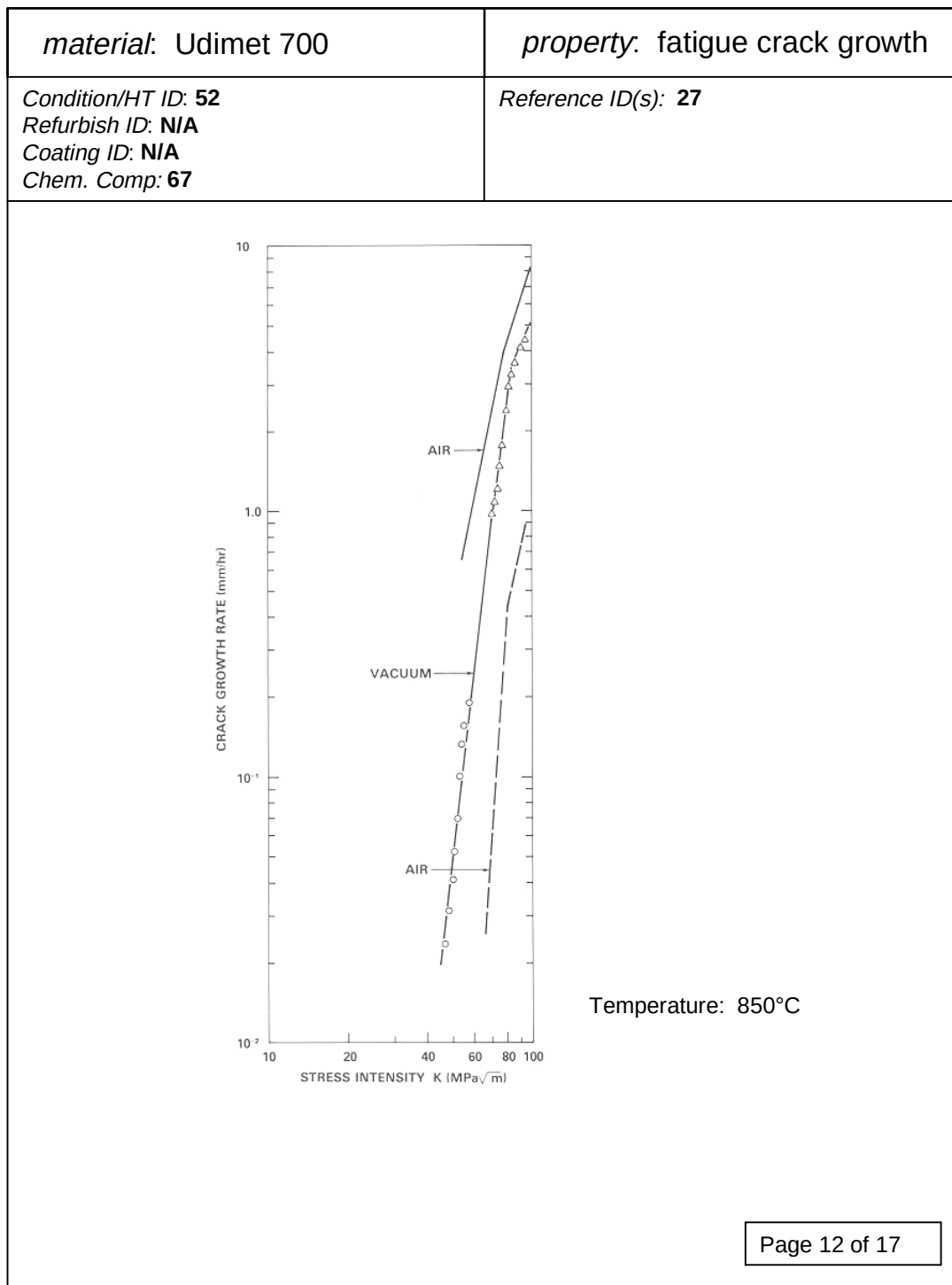


Figure 14-11

Crack Growth for Udimet 700 at 850°C, R = 0.05, and Cyclic Frequency of 0.17 Hz.

Udimet 700

**Figure 14-12**

The Effect of the Environment on the Creep Crack Growth in Udimet 700 at 850°C: o , 14.2 kN, vacuum, batch 2; △ , 16.0 kN, vacuum, batch 2; — air, batch 1; —, air, batch 2.

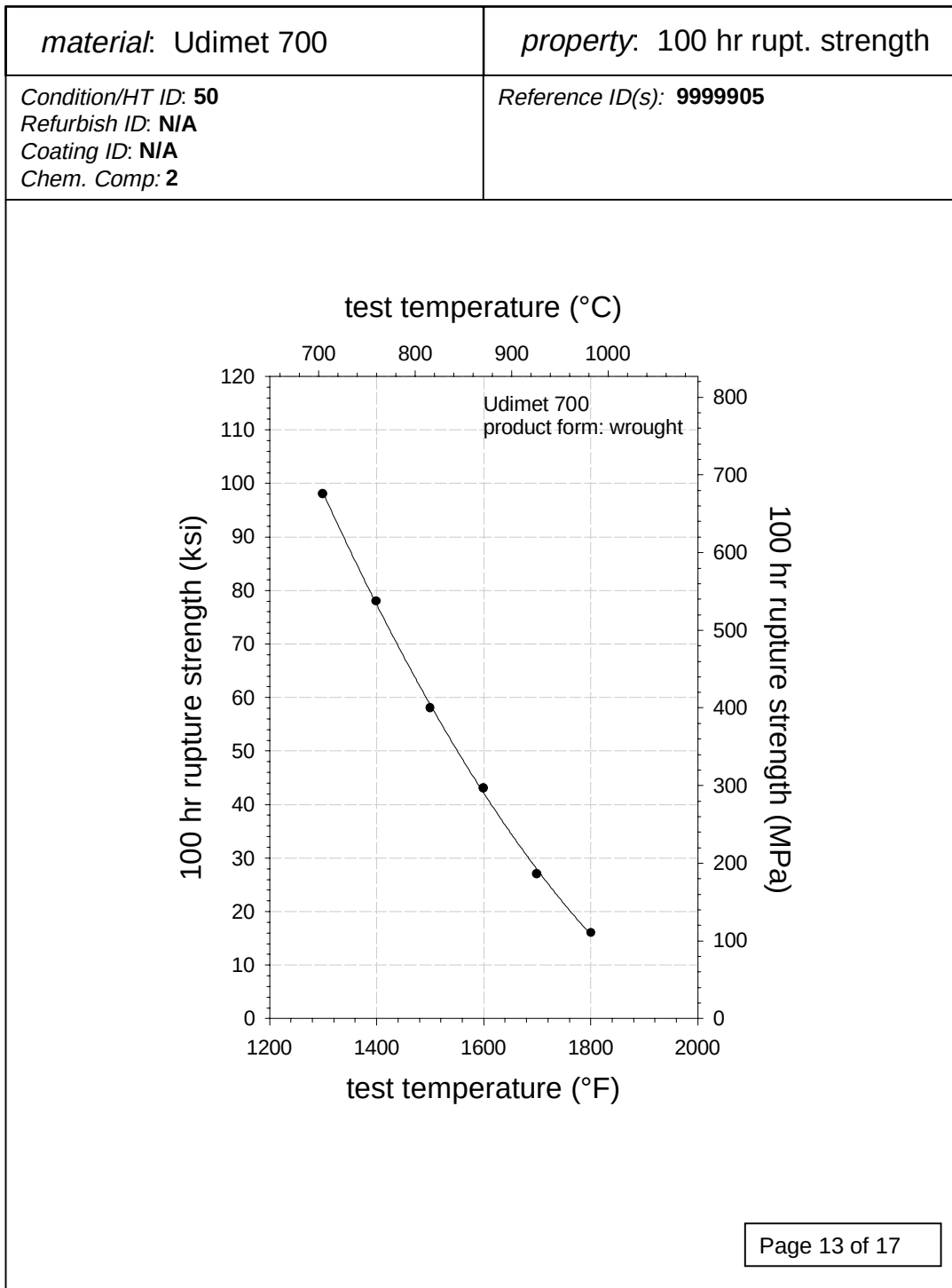


Figure 14-13
100 hr Rupture Strength as a Function of Temperature.

Udimet 700

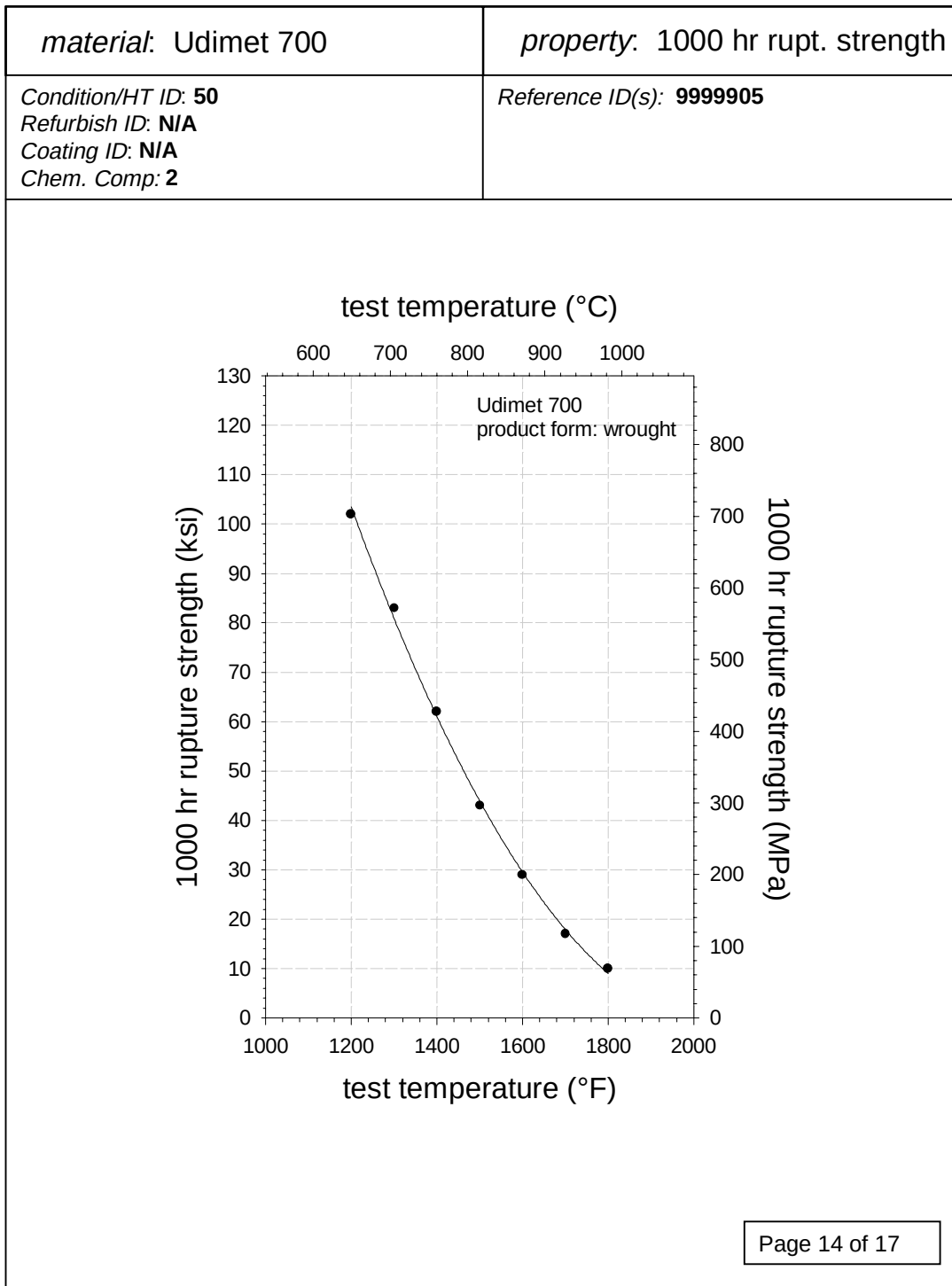


Figure 14-14
1000 hr Rupture Strength as a Function of Temperature.

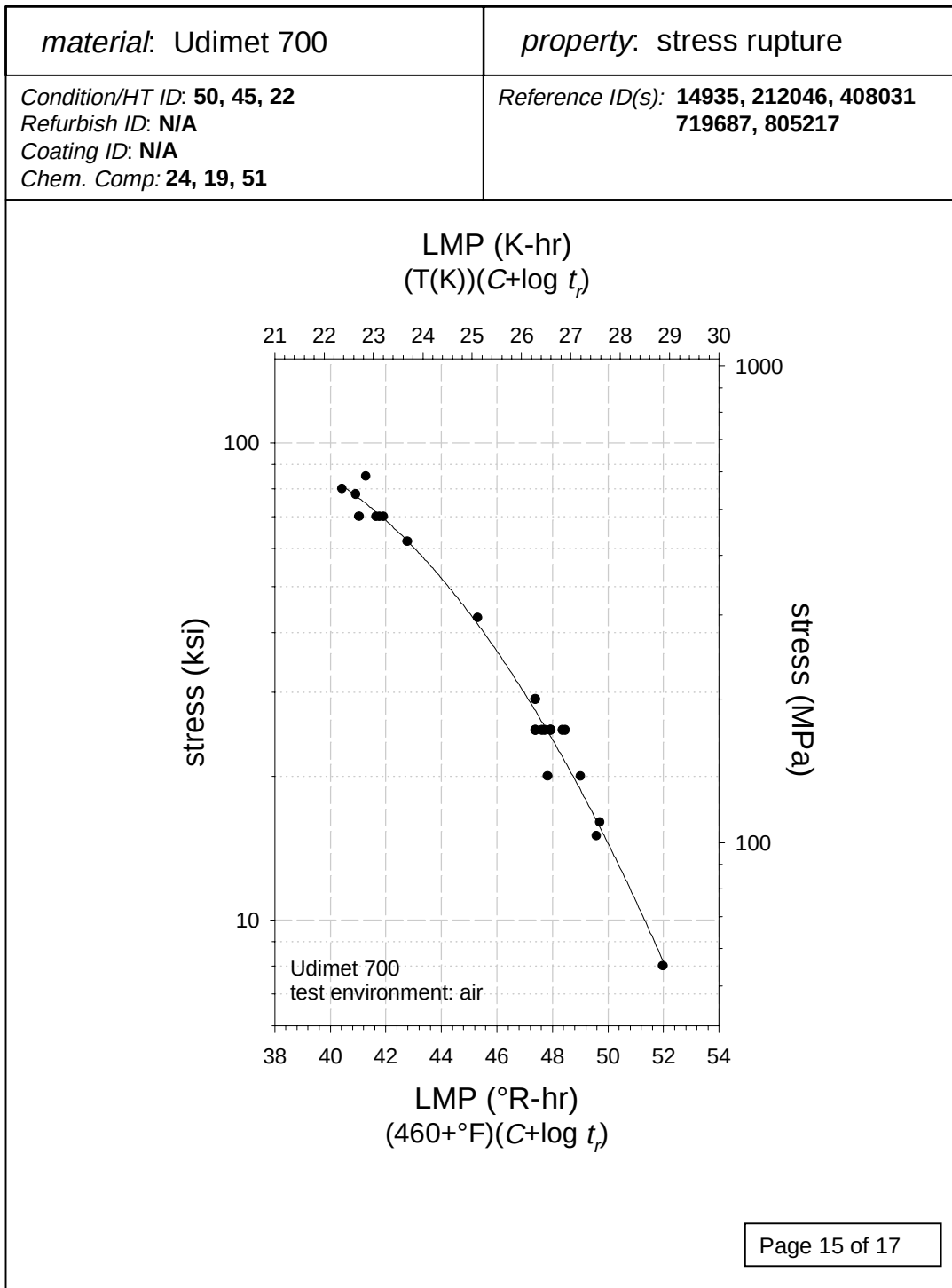


Figure 14-15
Larson-Miller Plot for Udimet 700.

Udimet 700

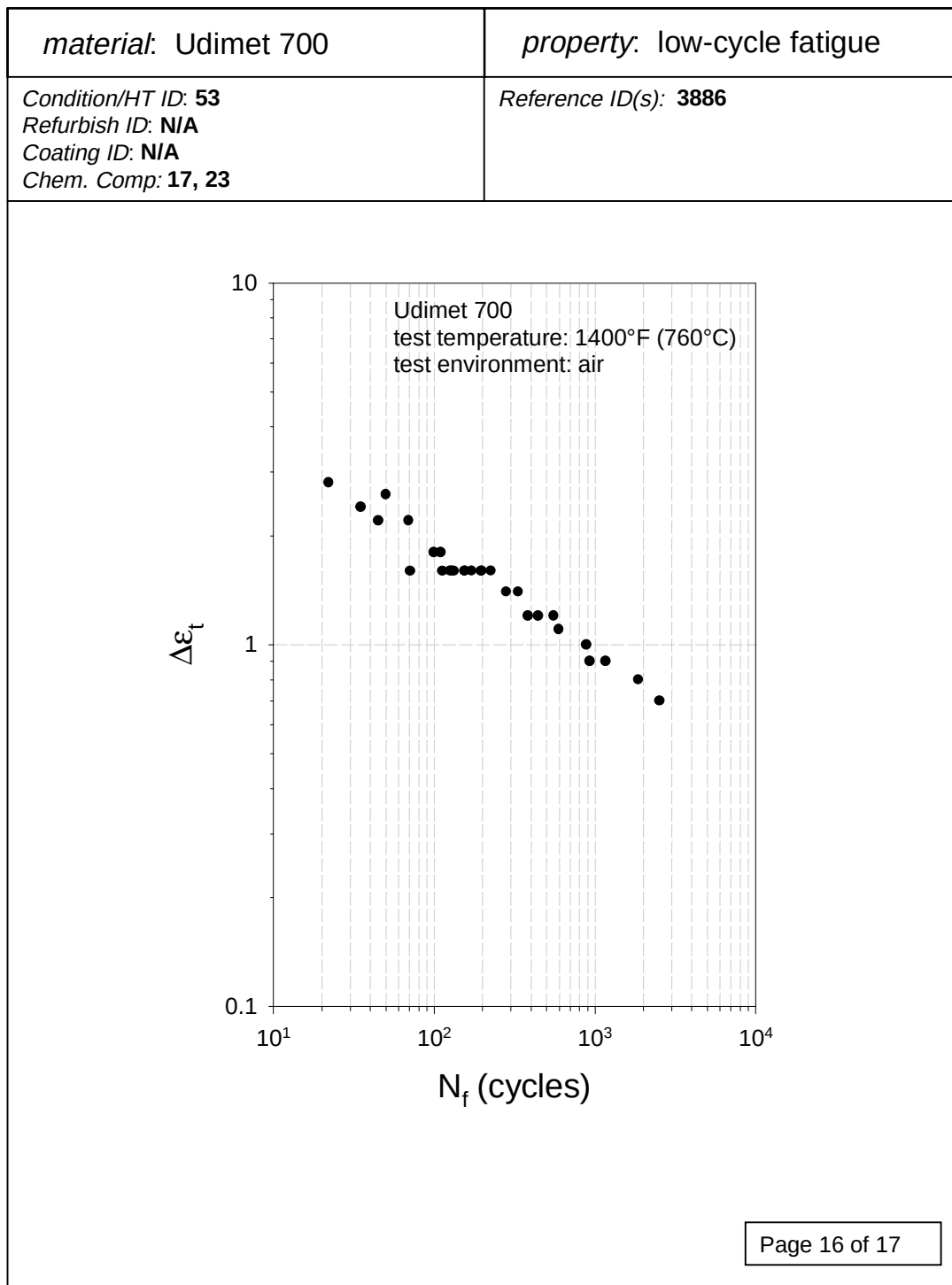


Figure 14-16
Low-Cycle Fatigue at 1400°F (Total Strain Range).

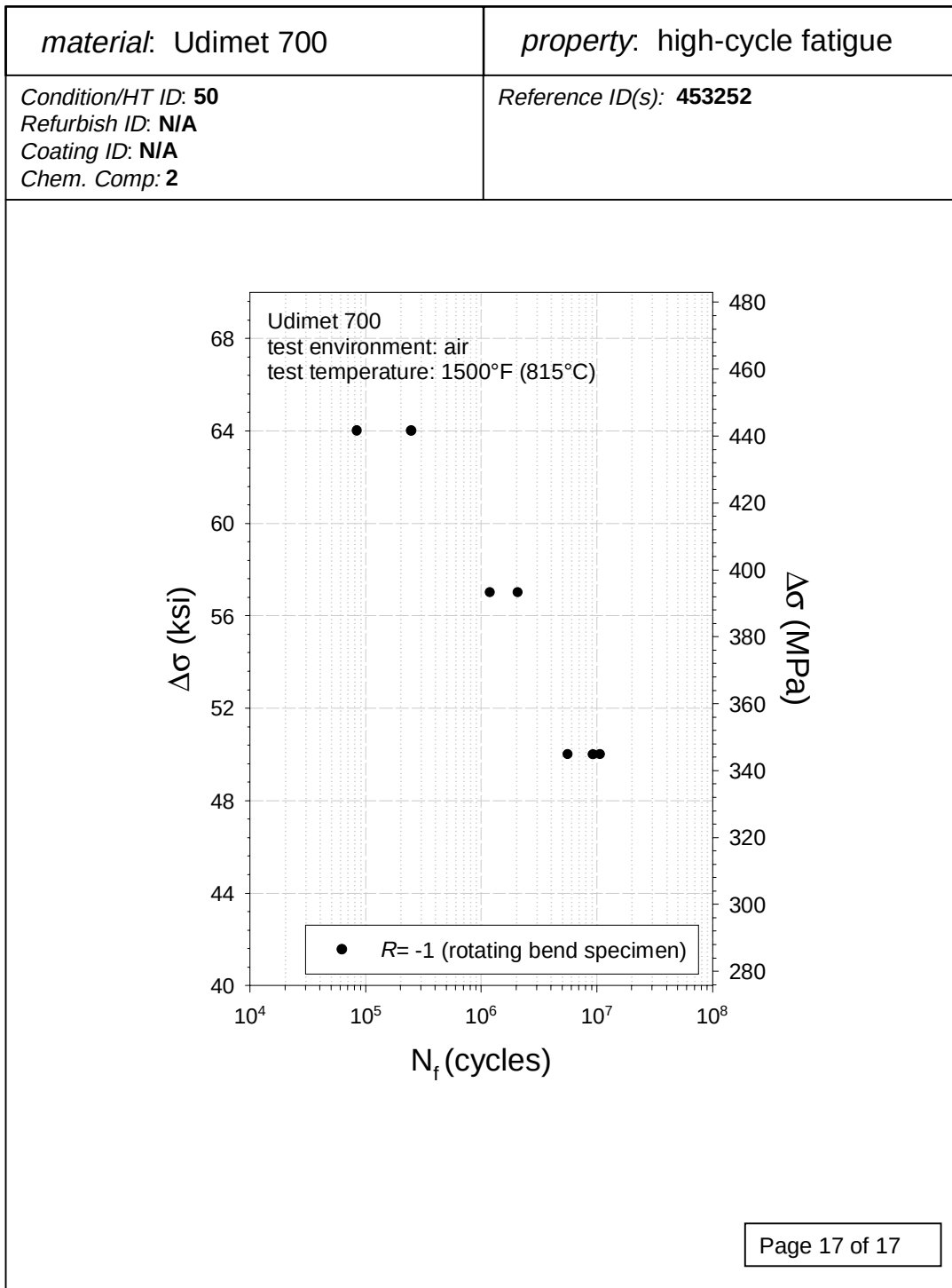


Figure 14-17
High-Cycle Fatigue Behavior at 1500°F (Fully Reversed Loading).

15

UDIMET 710

Udimet 710

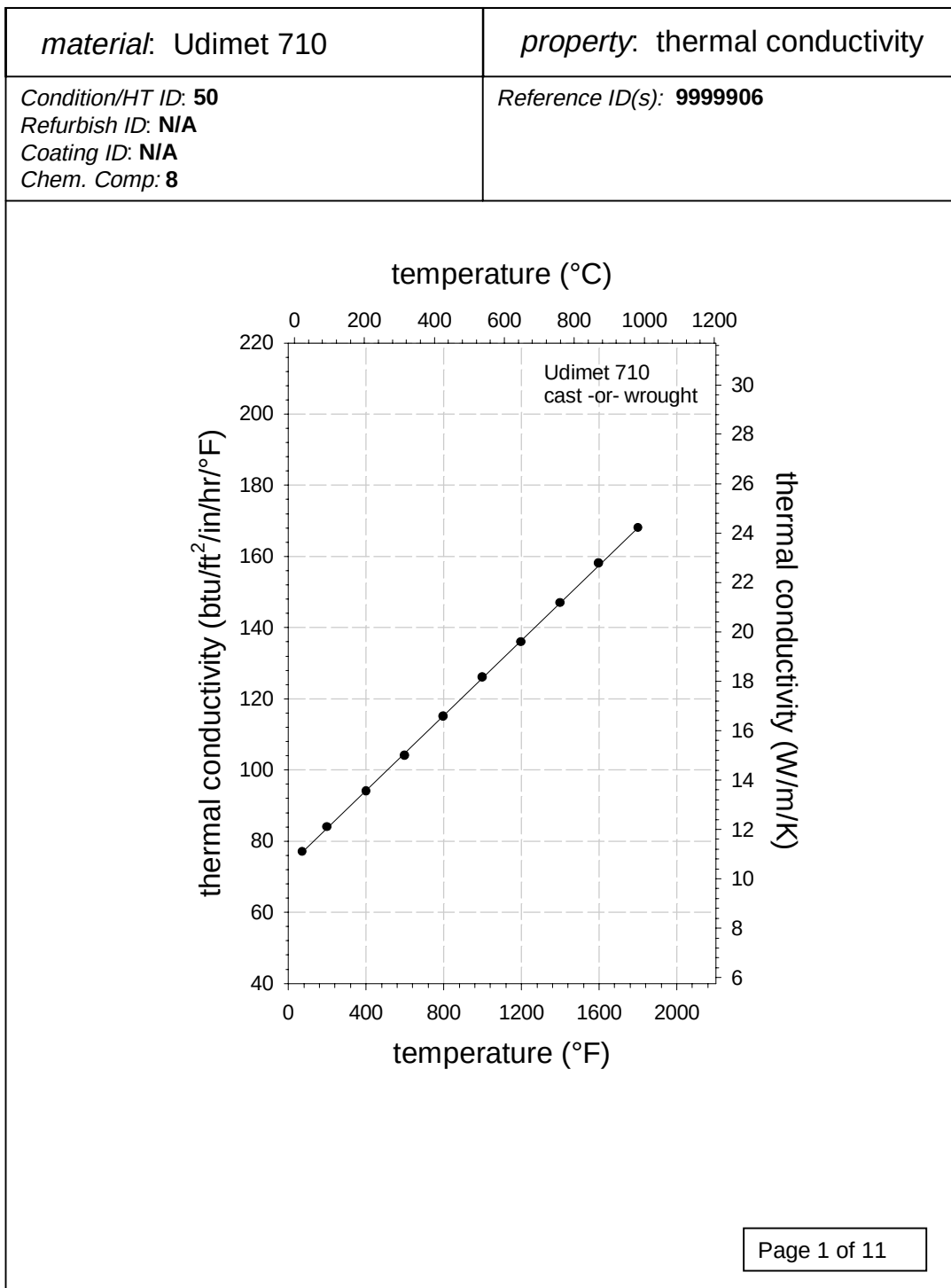


Figure 15-1
Thermal Conductivity as a Function of Temperature.

Udimet 710

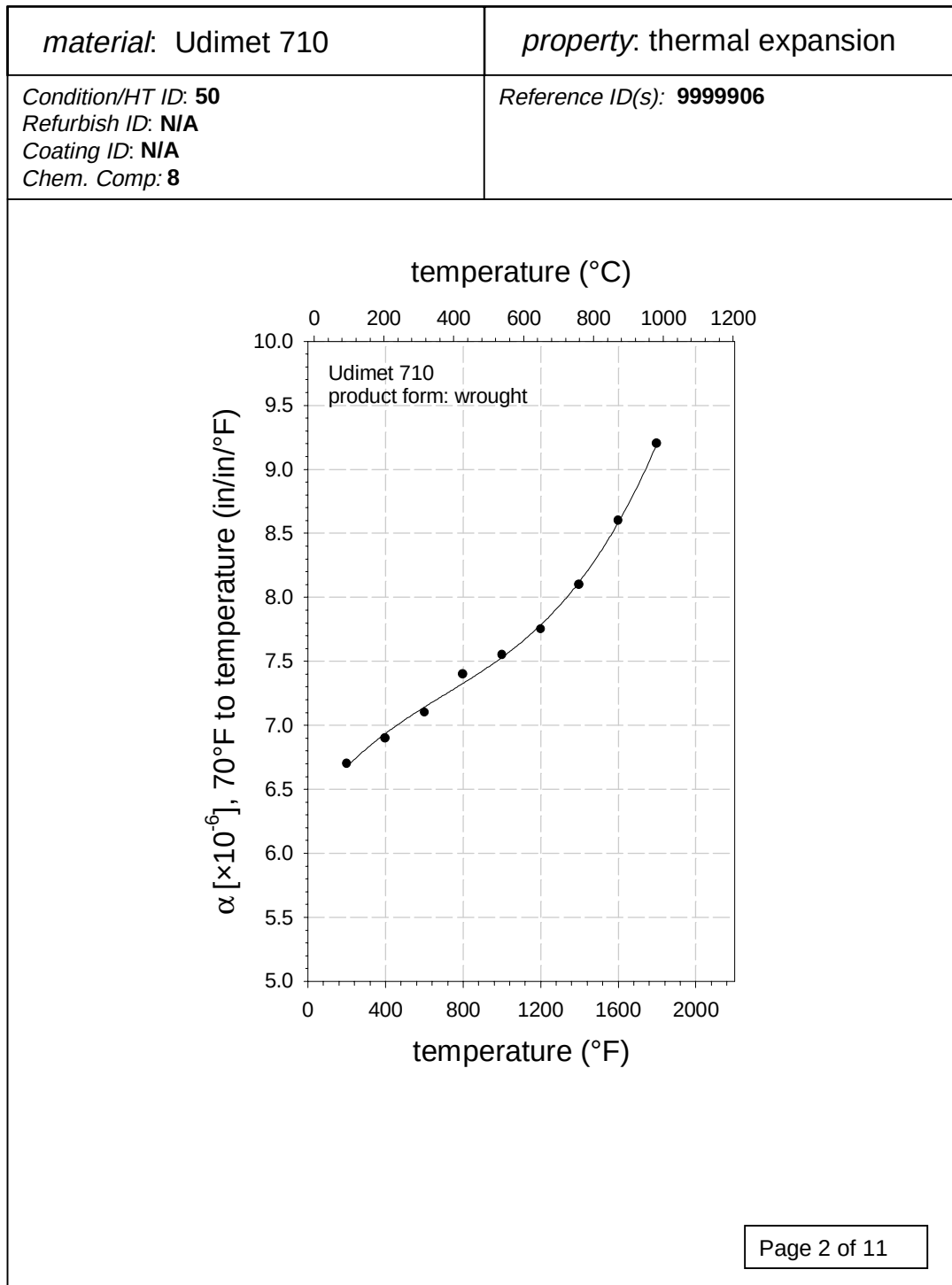


Figure 15-2
Coefficient of Thermal Expansion as a Function of Temperature.

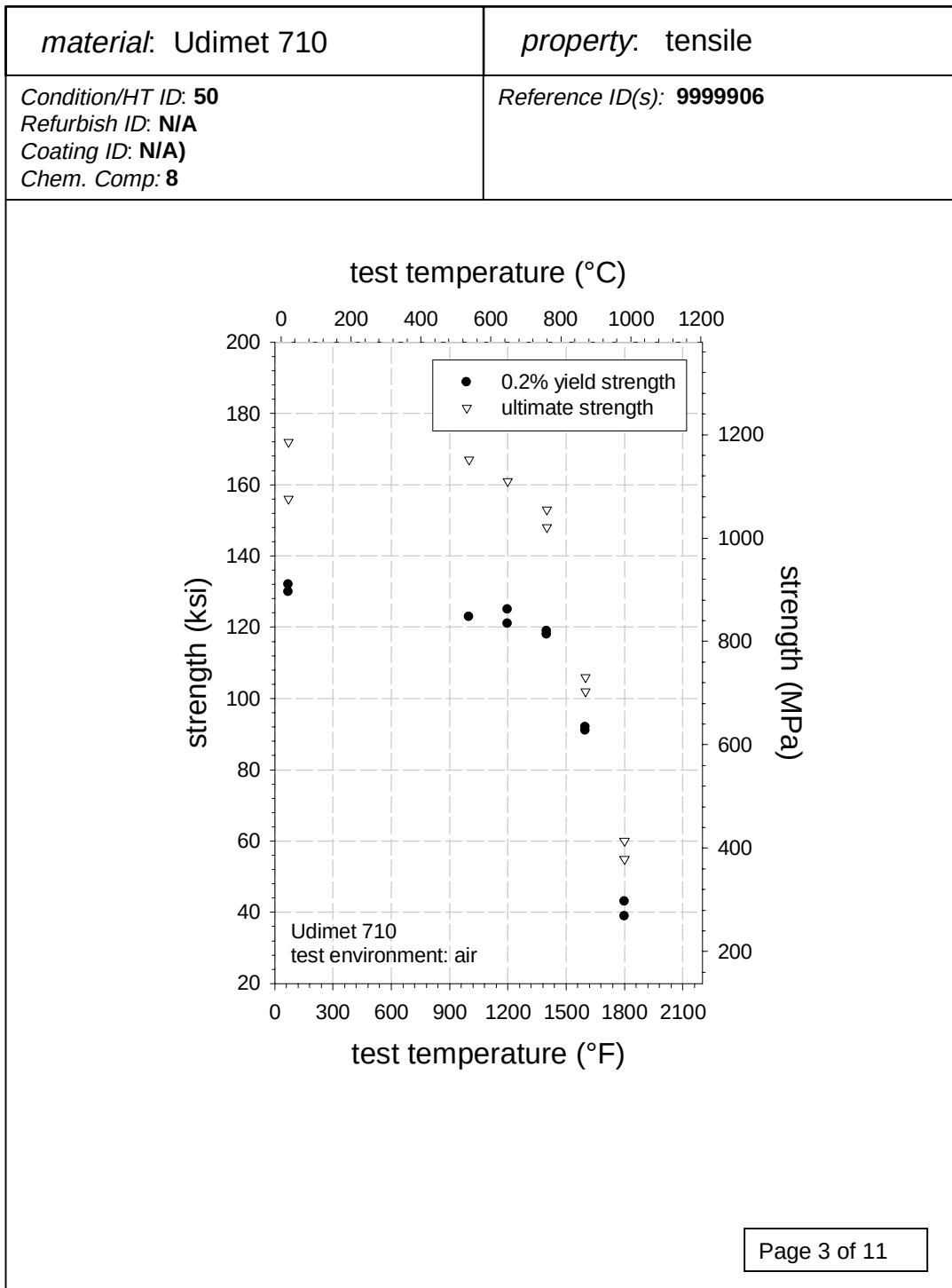


Figure 15-3
Tensile Strengths as a Function of Temperature.

Udimet 710

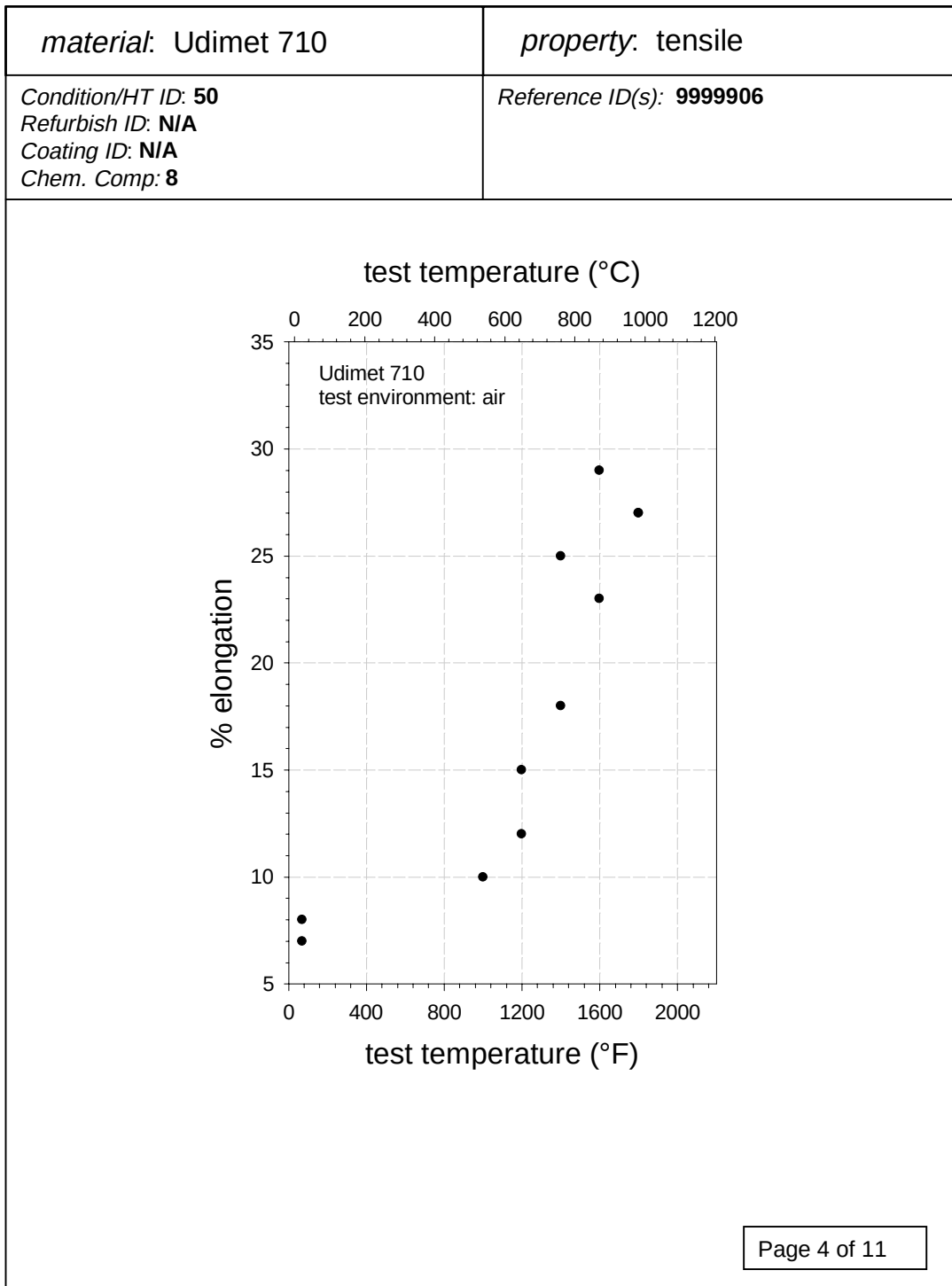


Figure 15-4
Tensile Elongation as a Function of Temperature.

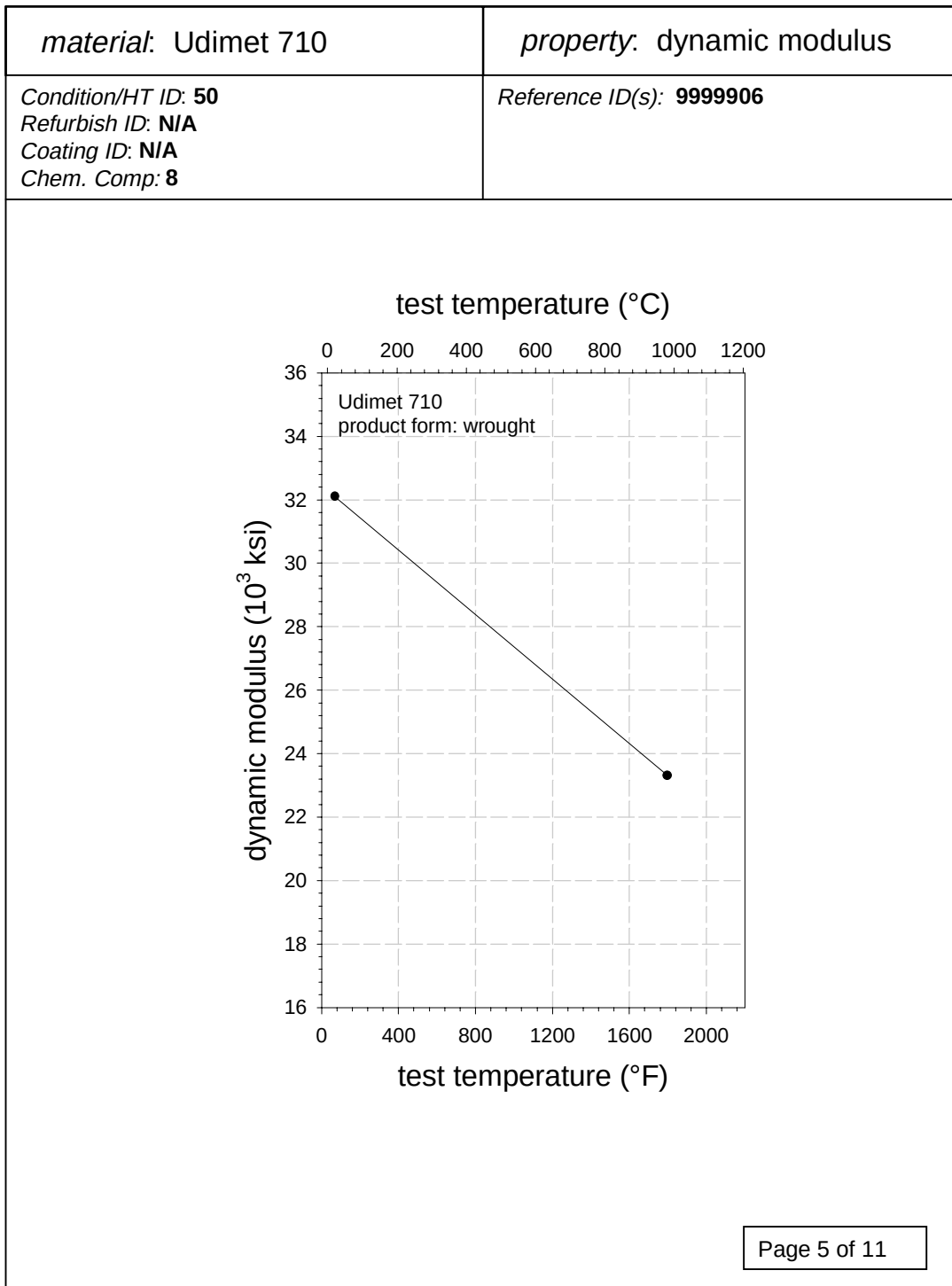


Figure 15-5
Dynamic Modulus as a Function of Temperature.

Udimet 710

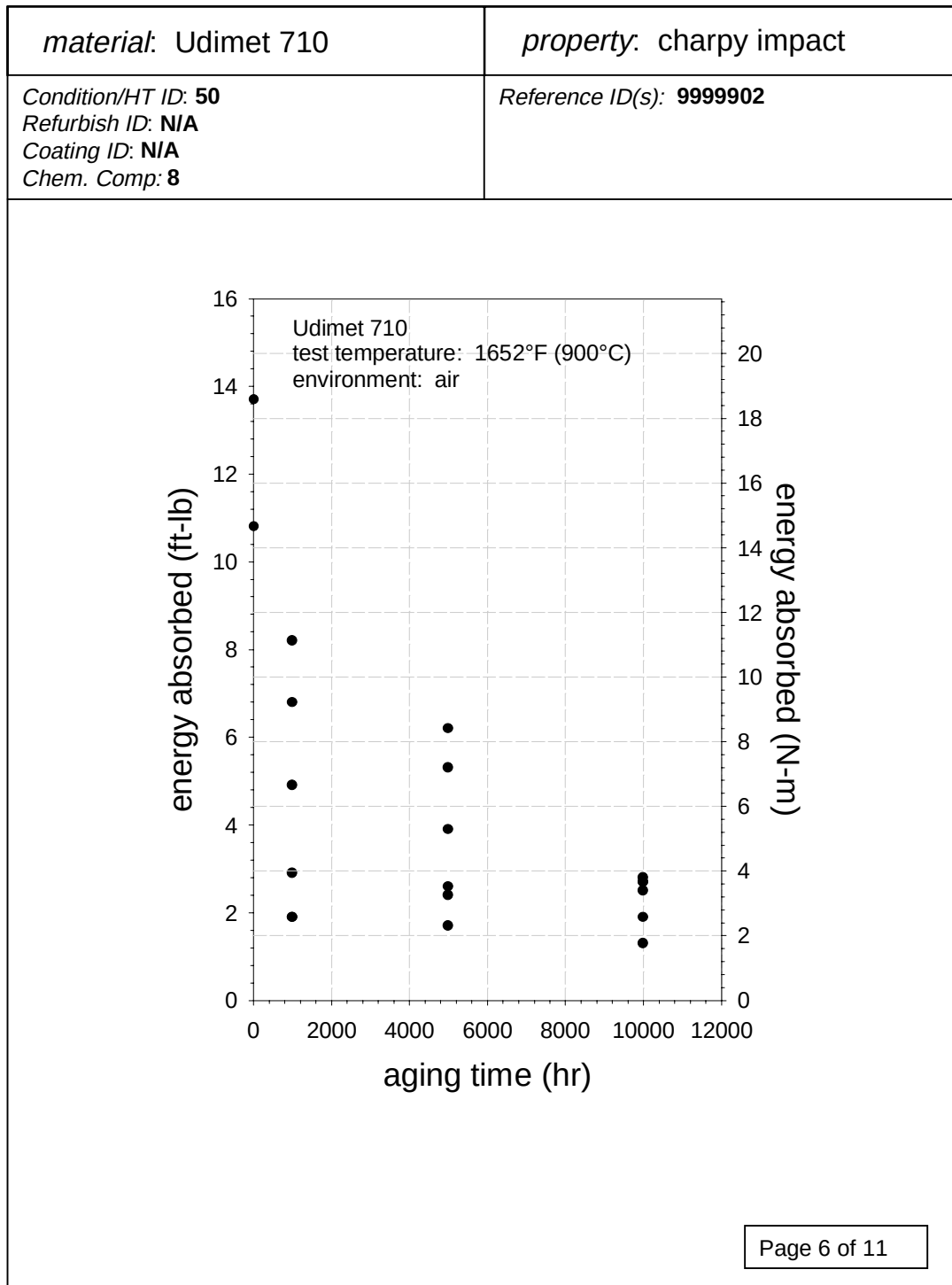


Figure 15-6
Charpy Impact Energy as a Function of Aging Time.

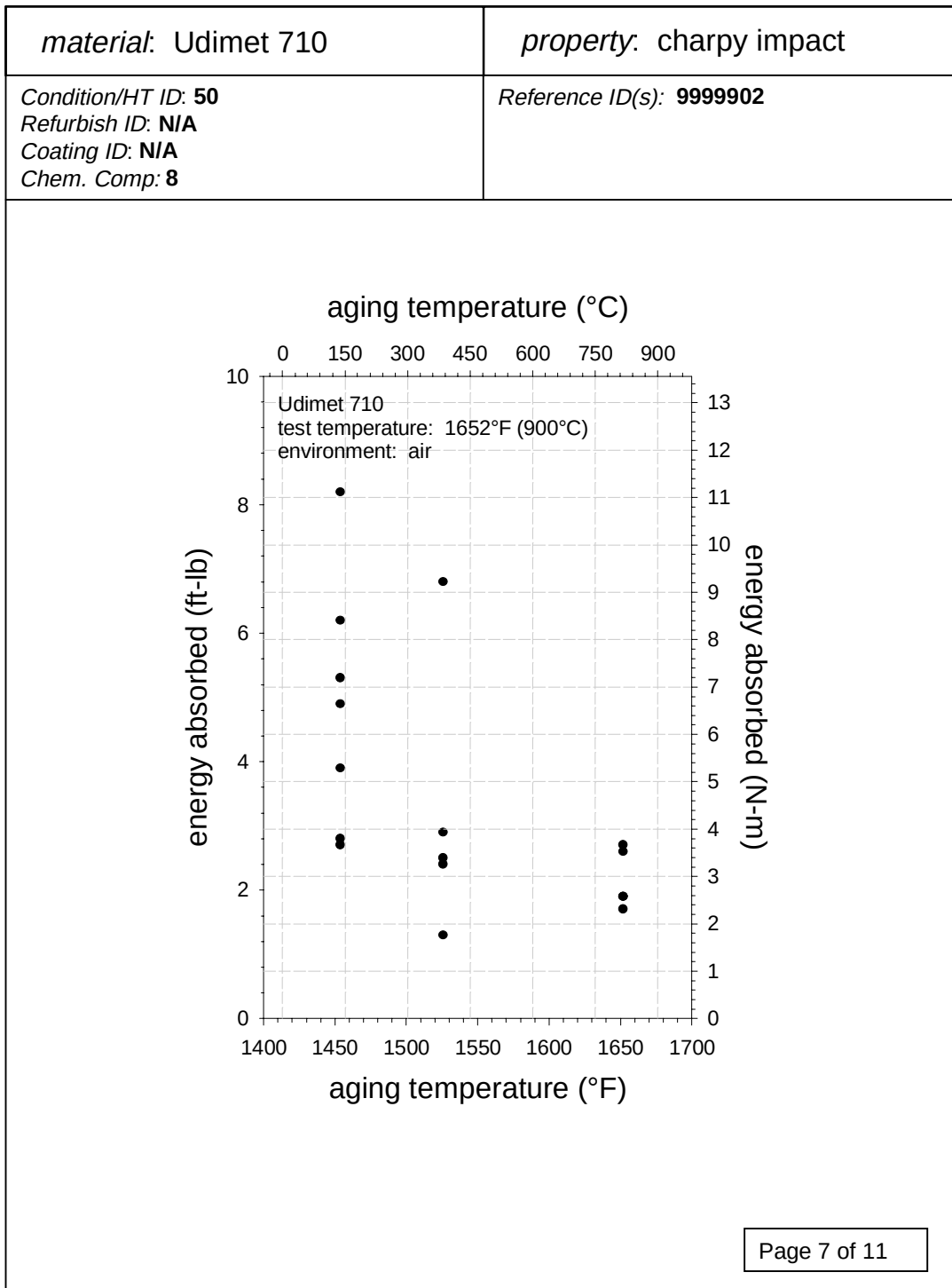


Figure 15-7
Charpy Impact Energy as a Function of Aging Temperature.

Udimet 710

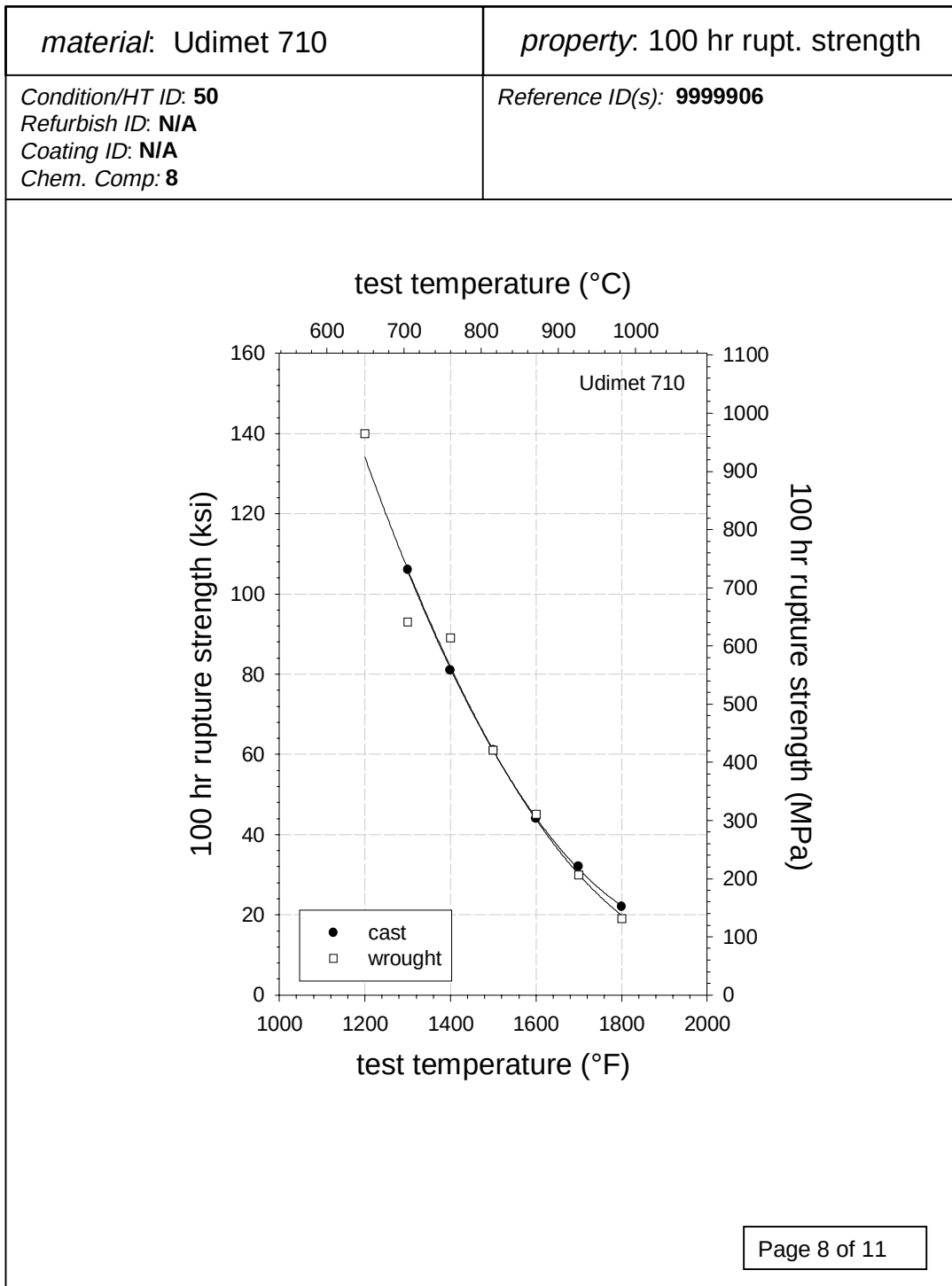


Figure 15-8
100 hr Rupture Strength as a Function of Temperature.

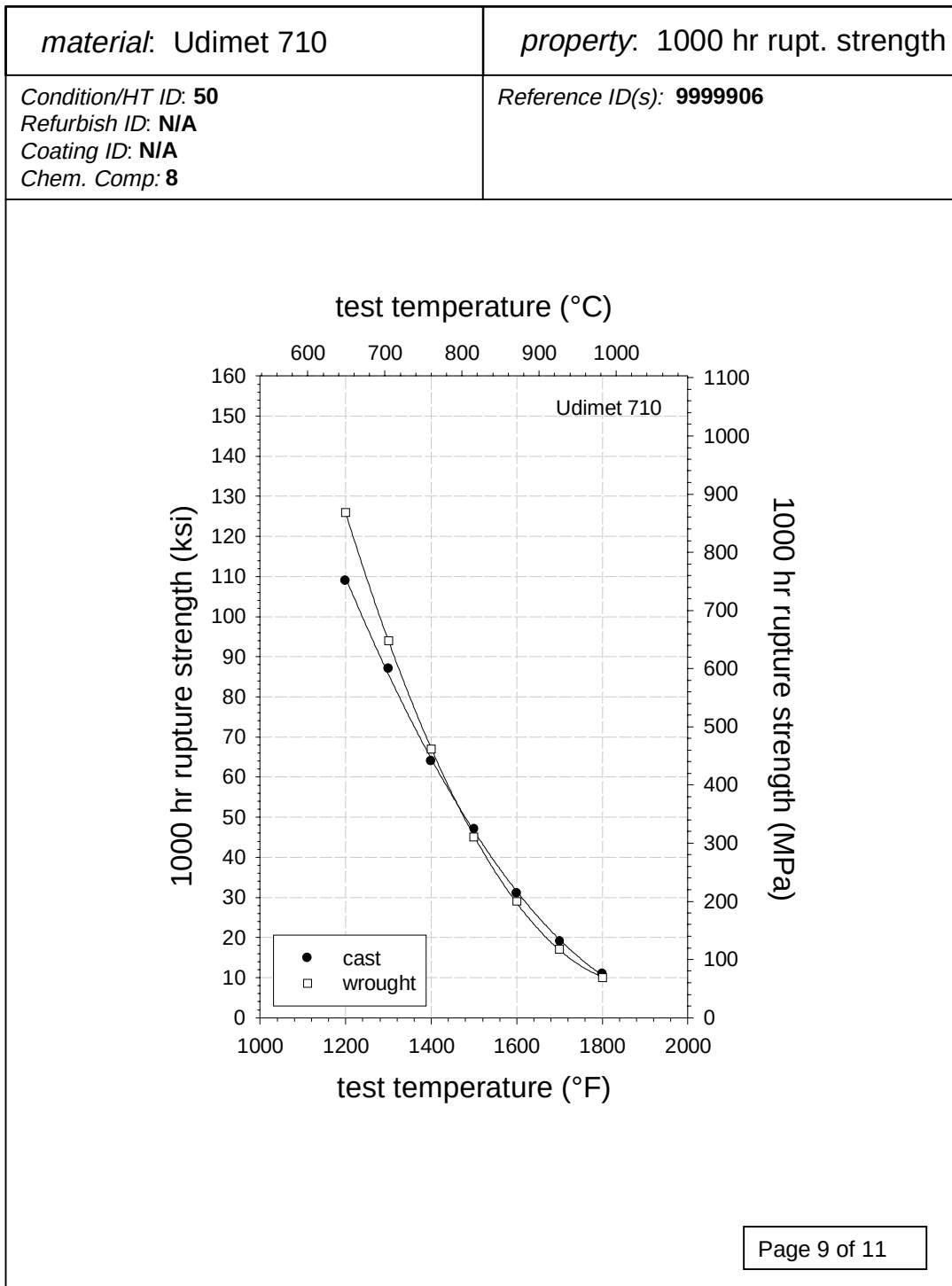


Figure 15-9
1000 hr Rupture Strength as a Function of Temperature.

Udimet 710

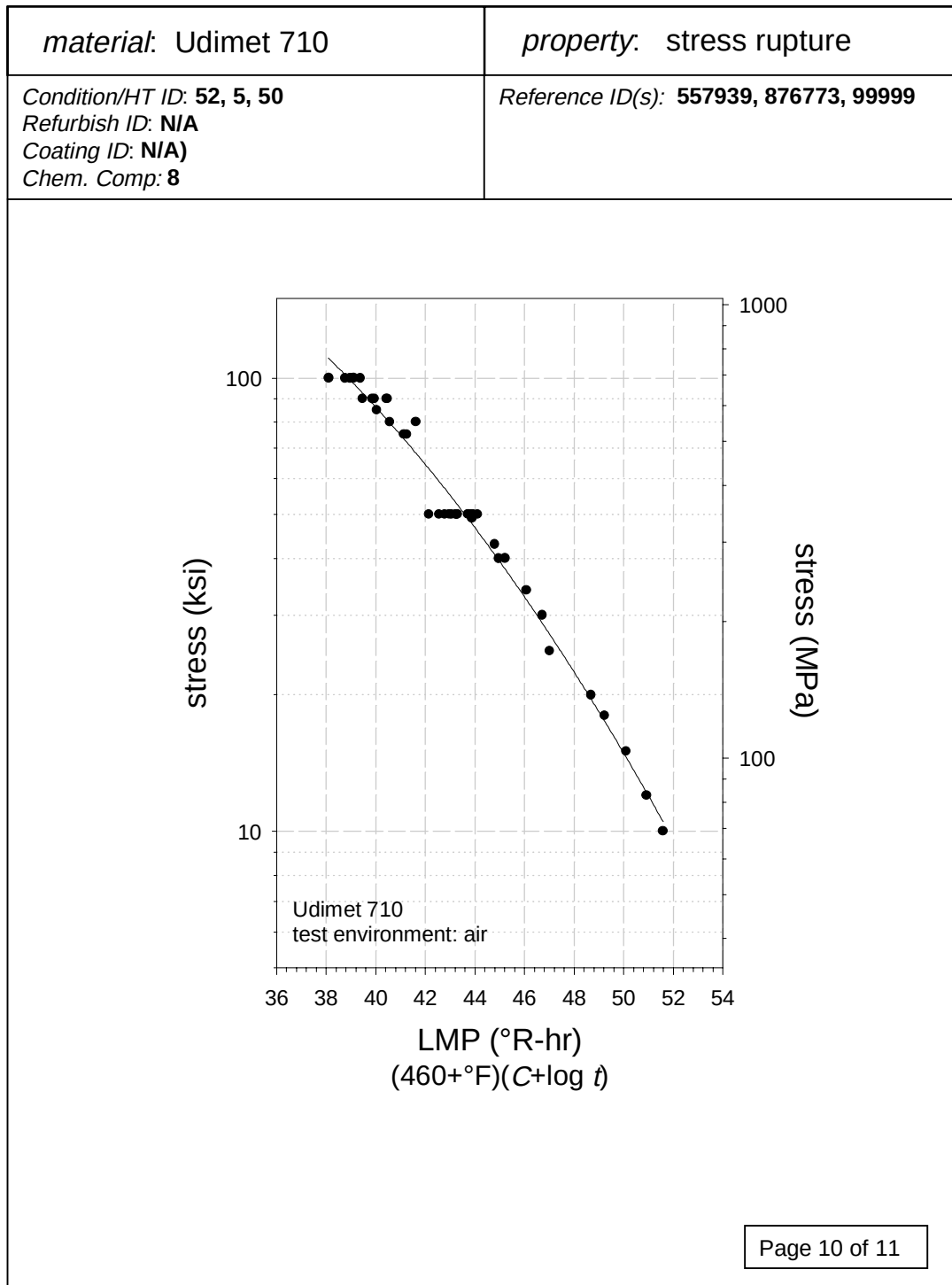
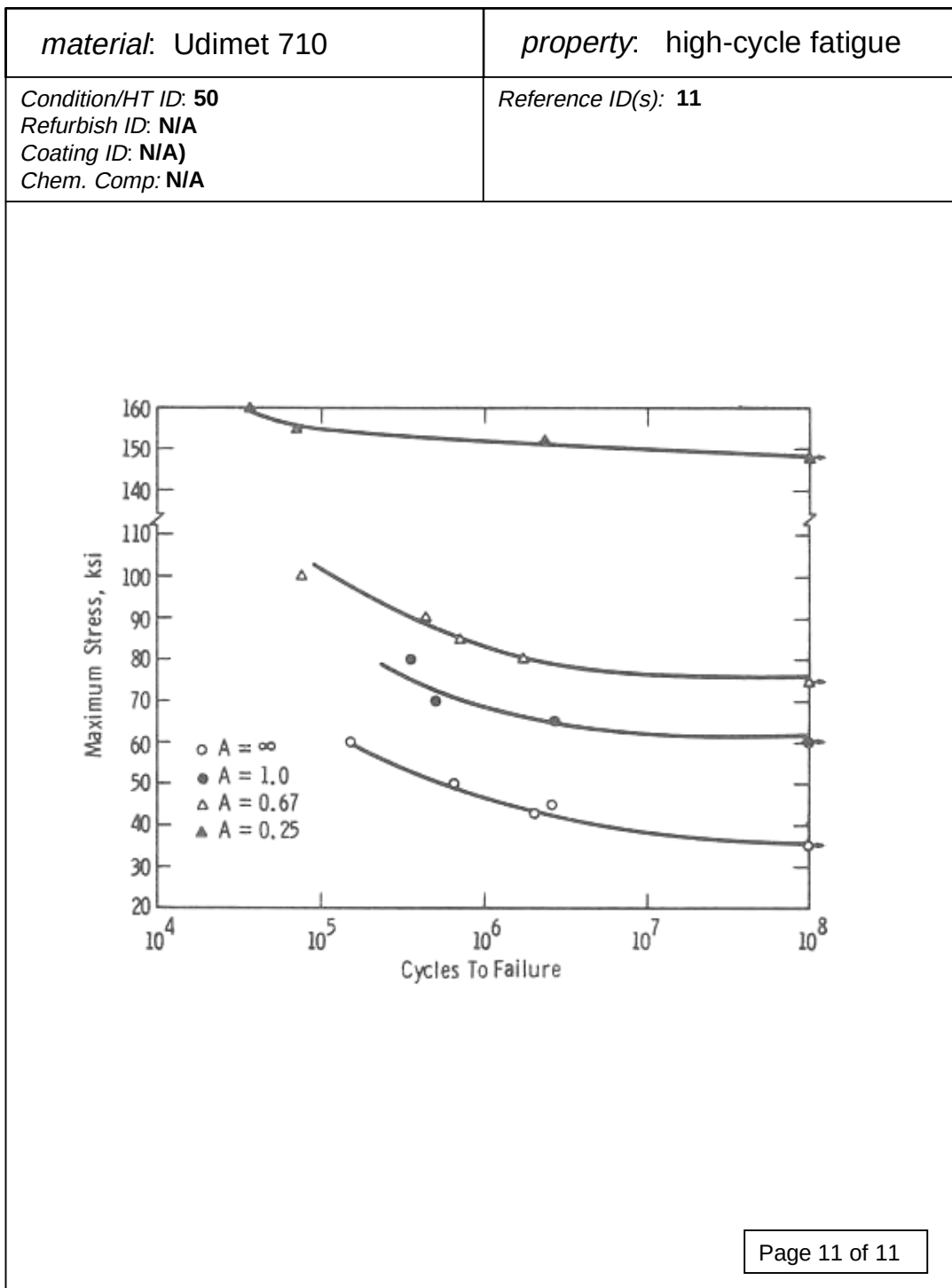


Figure 15-10
Larson-Miller Plot for Udimet 710.

**Figure 15-11****Effect of Mean Stress on the Fatigue Strength of Udimet 710. ($A = \sigma_{\text{ALTERNATING}} / \sigma_{\text{MEAN}}$).**

16

UDIMET 720

Udimet 720

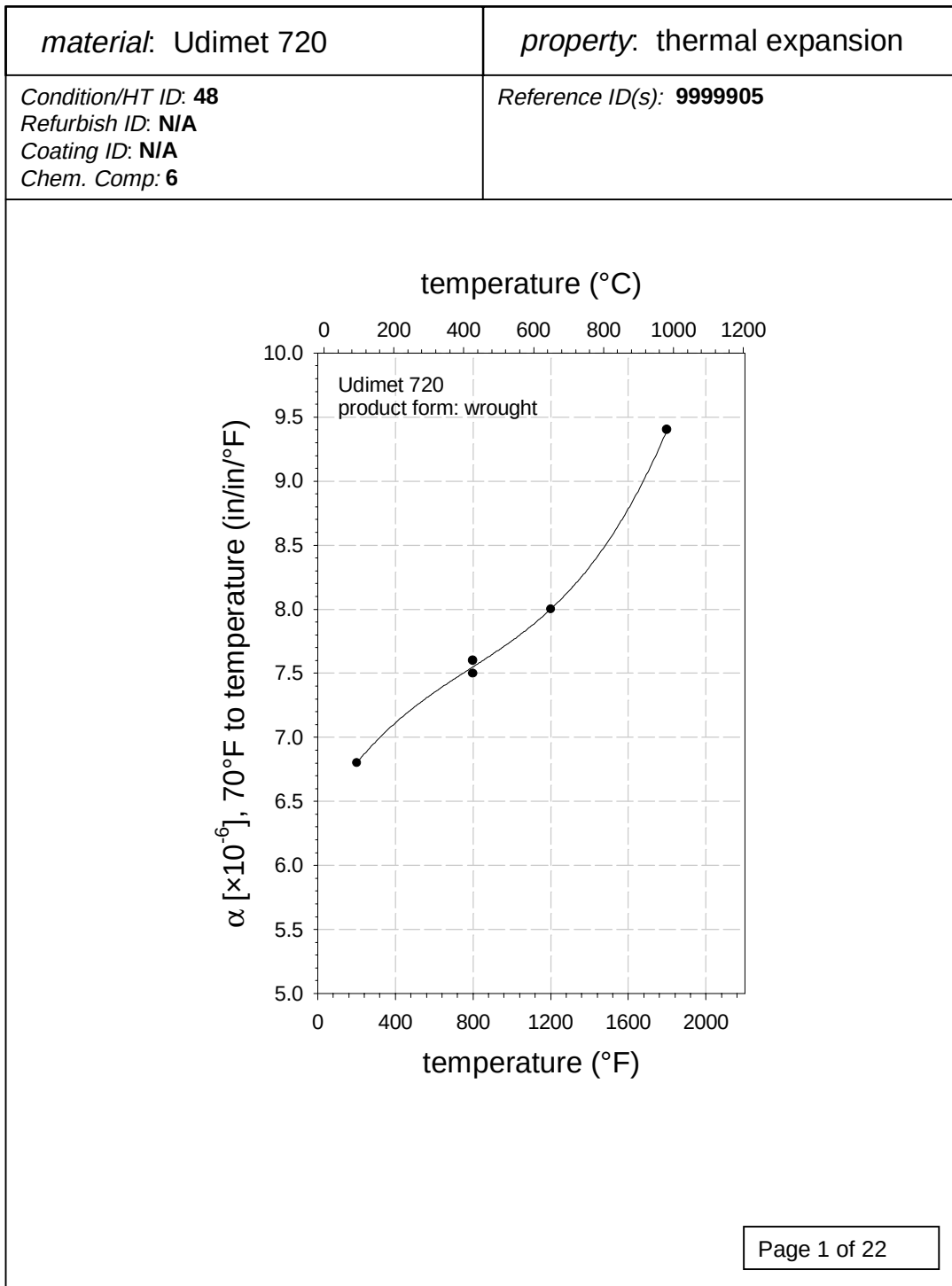


Figure 16-1
Coefficient of Thermal Expansion as a Function of Temperature.

Udimet 720

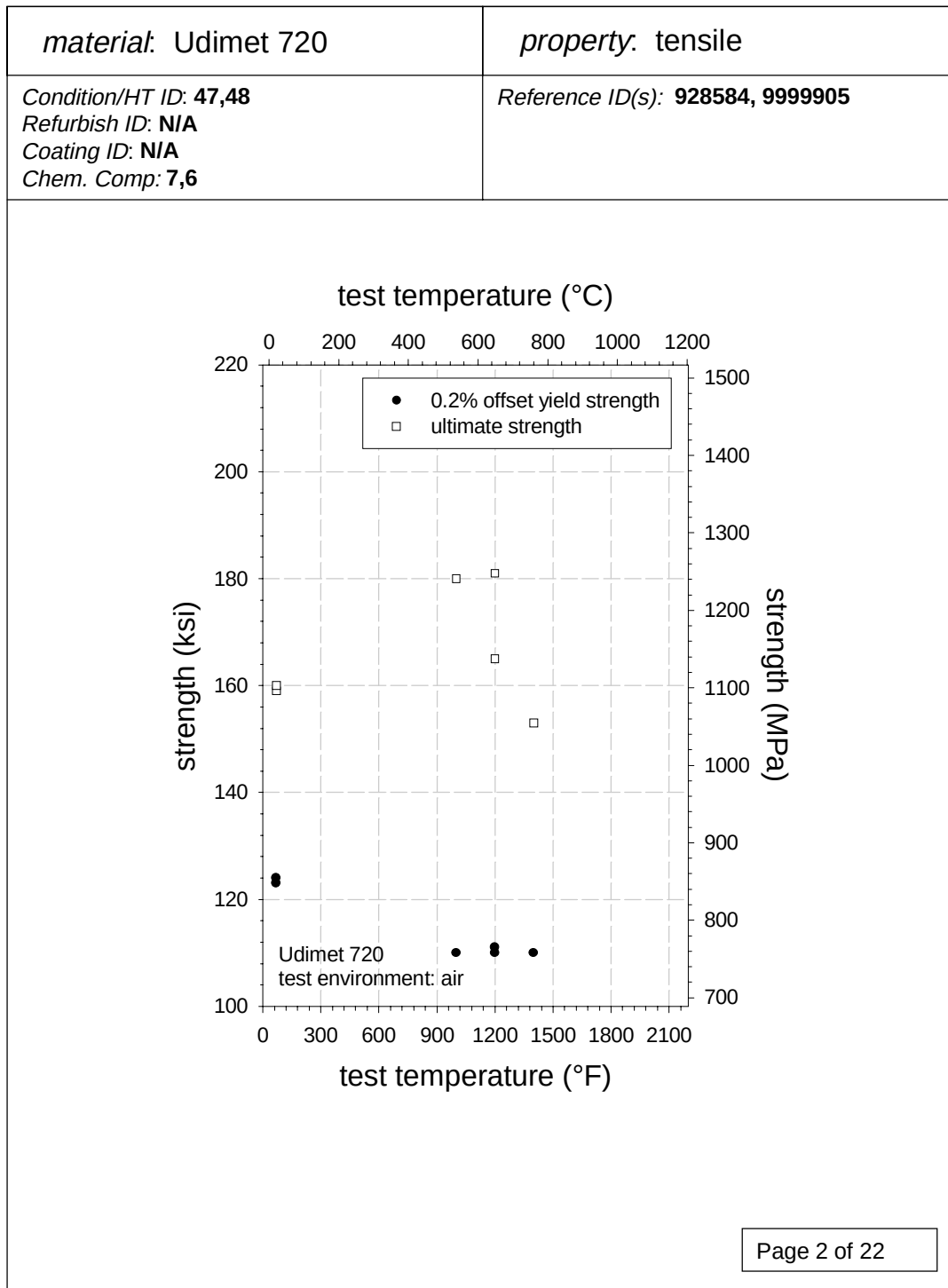


Figure 16-2
Tensile Strengths as a Function of Temperature.

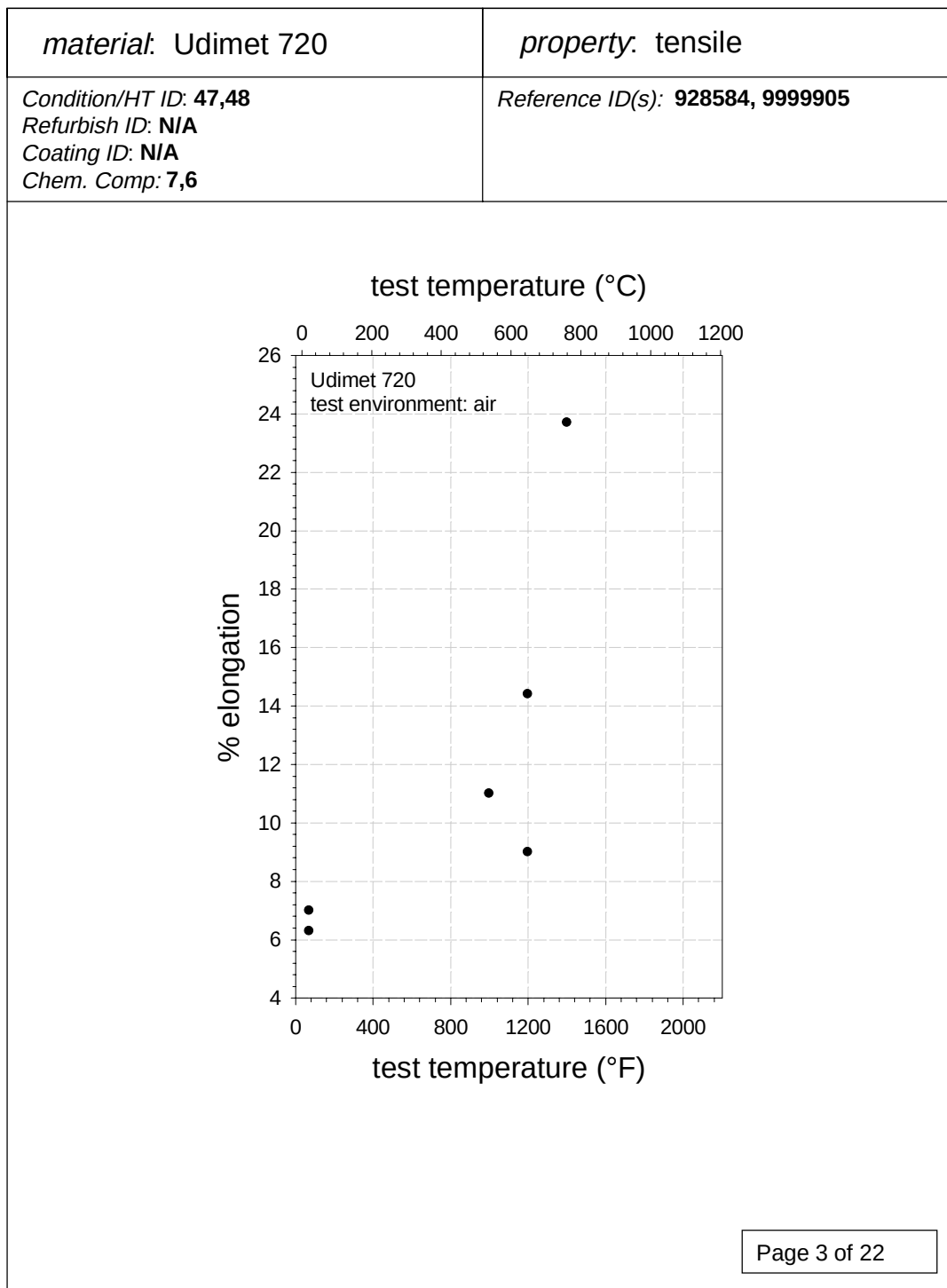


Figure 16-3
Tensile Elongation as a Function of Temperature.

Udimet 720

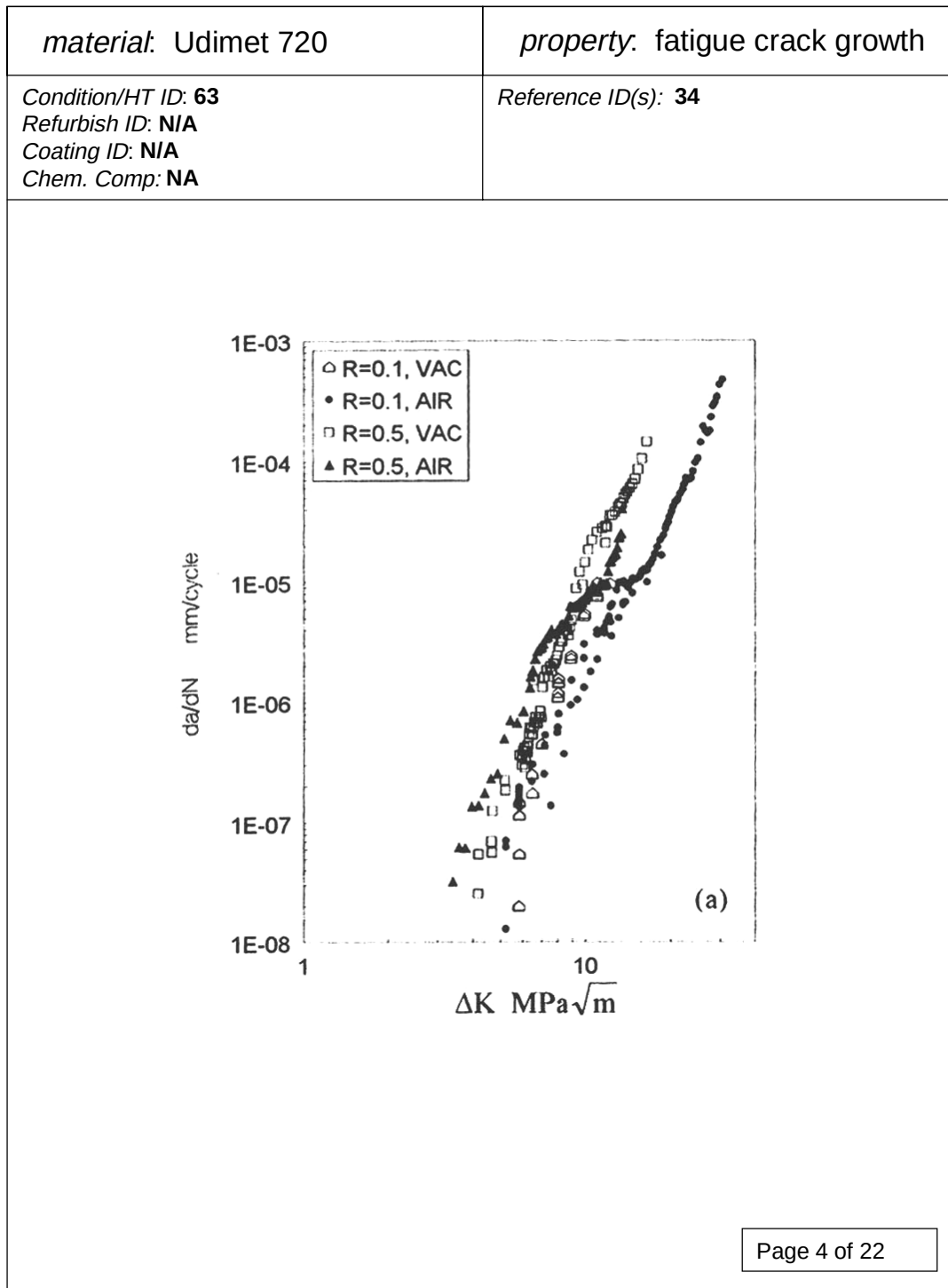


Figure 16-4
Crack Growth Rates in Air and in Vacuum for Single Crystal U720.

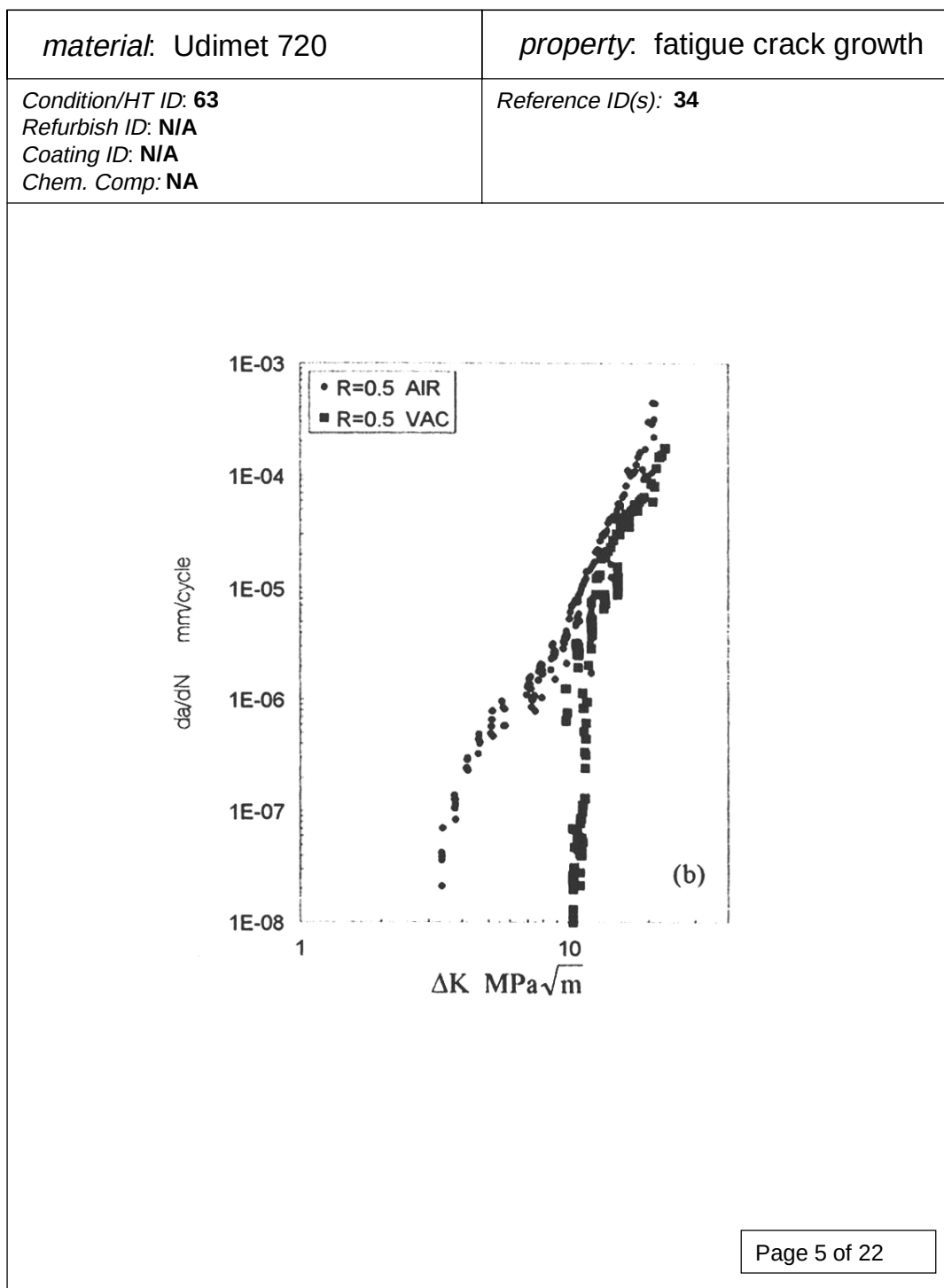


Figure 16-5
Crack Growth Rates in Air and in Vacuum for Polycrystalline U720.

Udimet 720

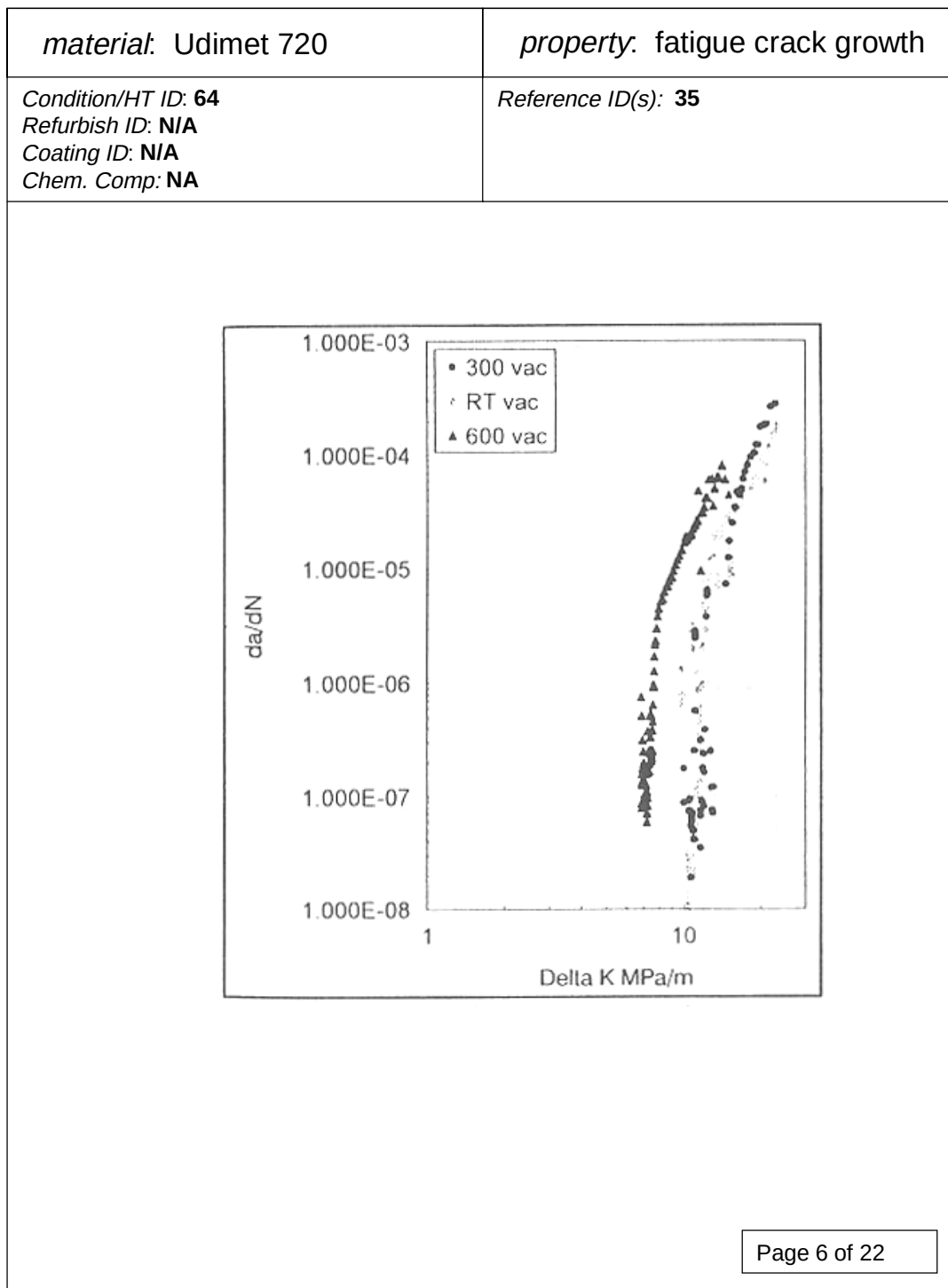


Figure 16-6
Graph of da/dN Data for SENB Specimens in Vacuum at 20, 300 and 600°C.

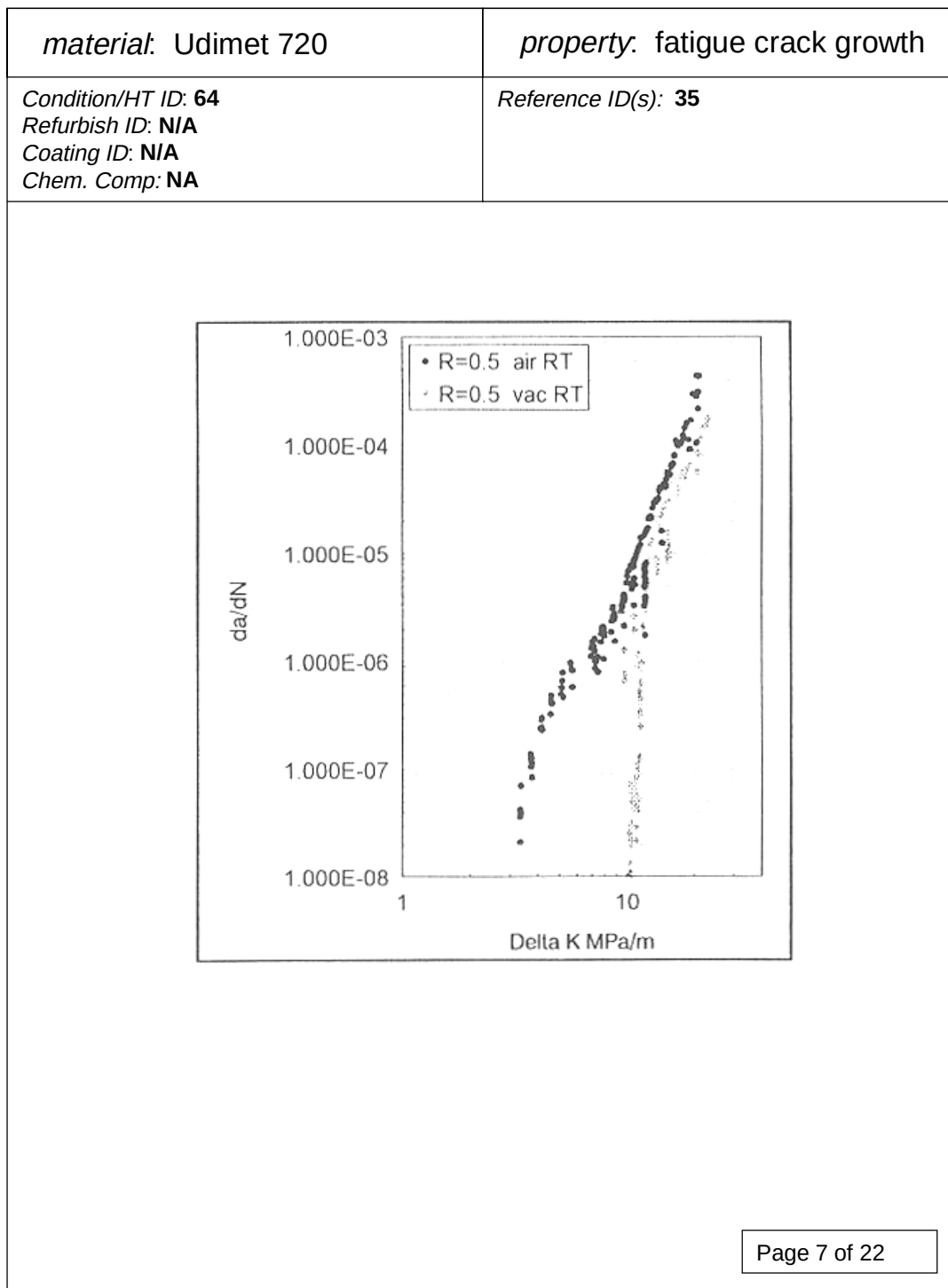


Figure 16-7
Showing da/dN Data at $R = 0.5$ in Air and Vacuum.

Udimet 720

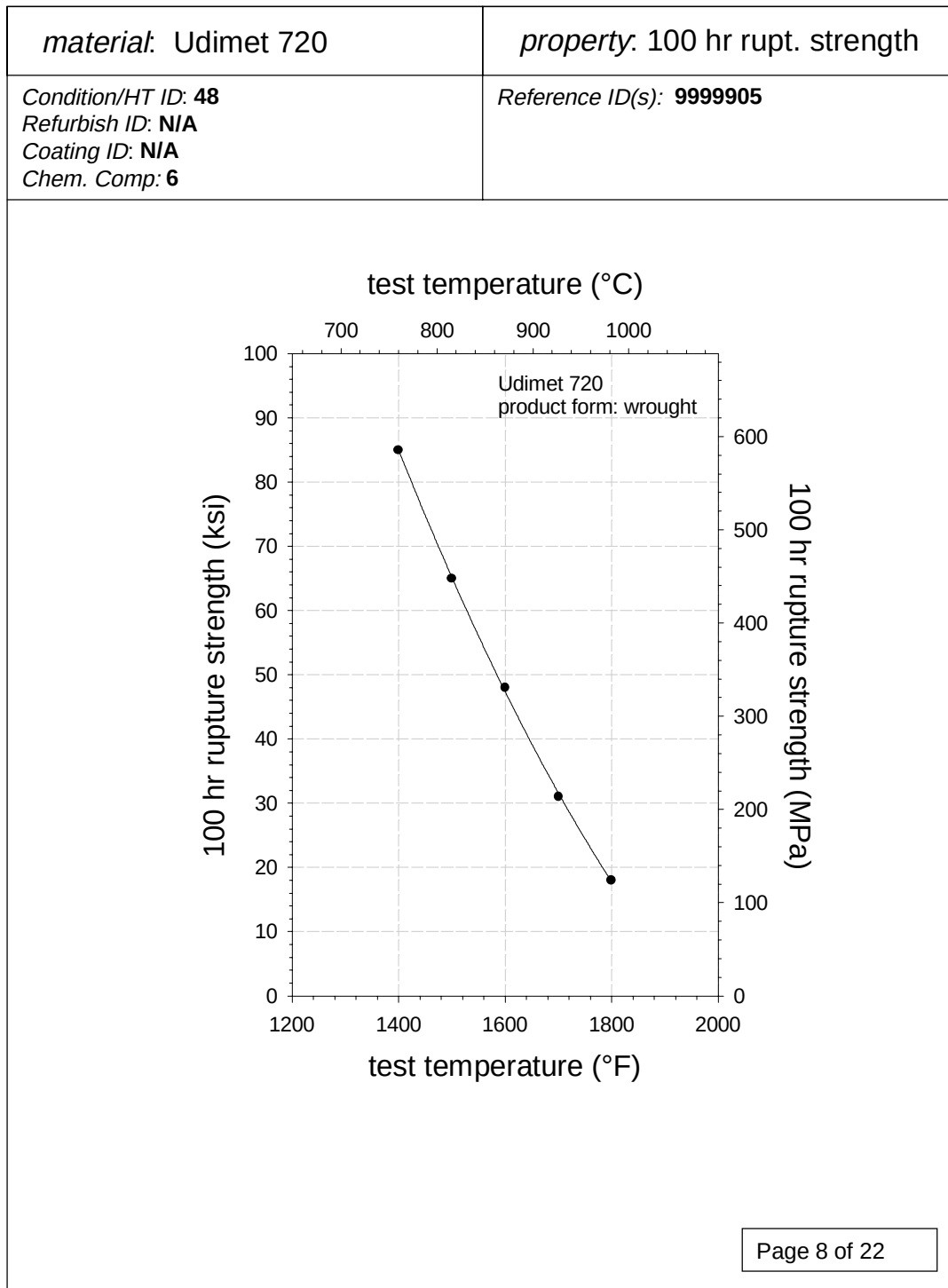


Figure 16-8
100 hr Rupture Strength as a Function of Temperature.

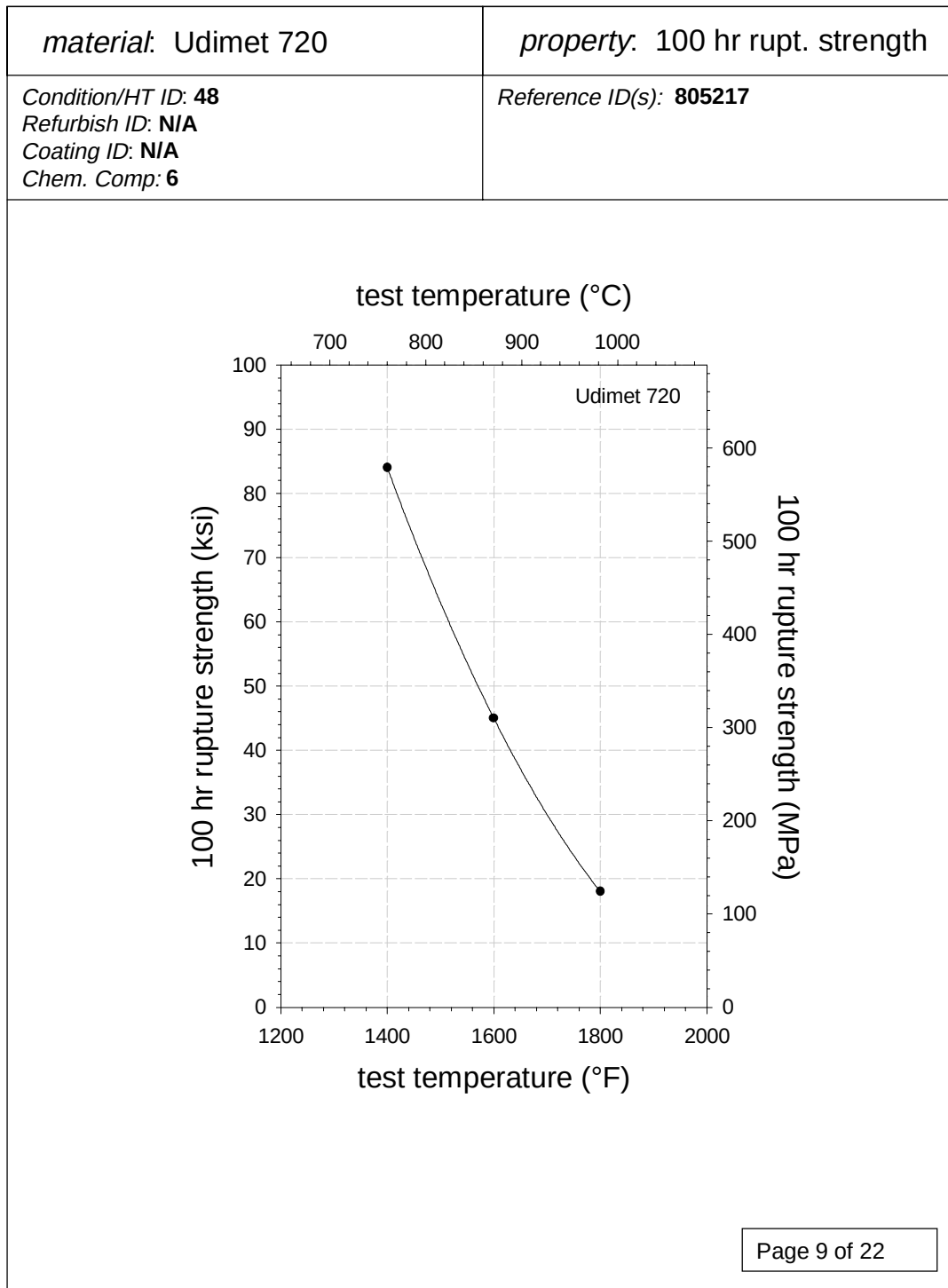


Figure 16-9
100 hr Rupture Strength as a Function of Temperature.

Udimet 720

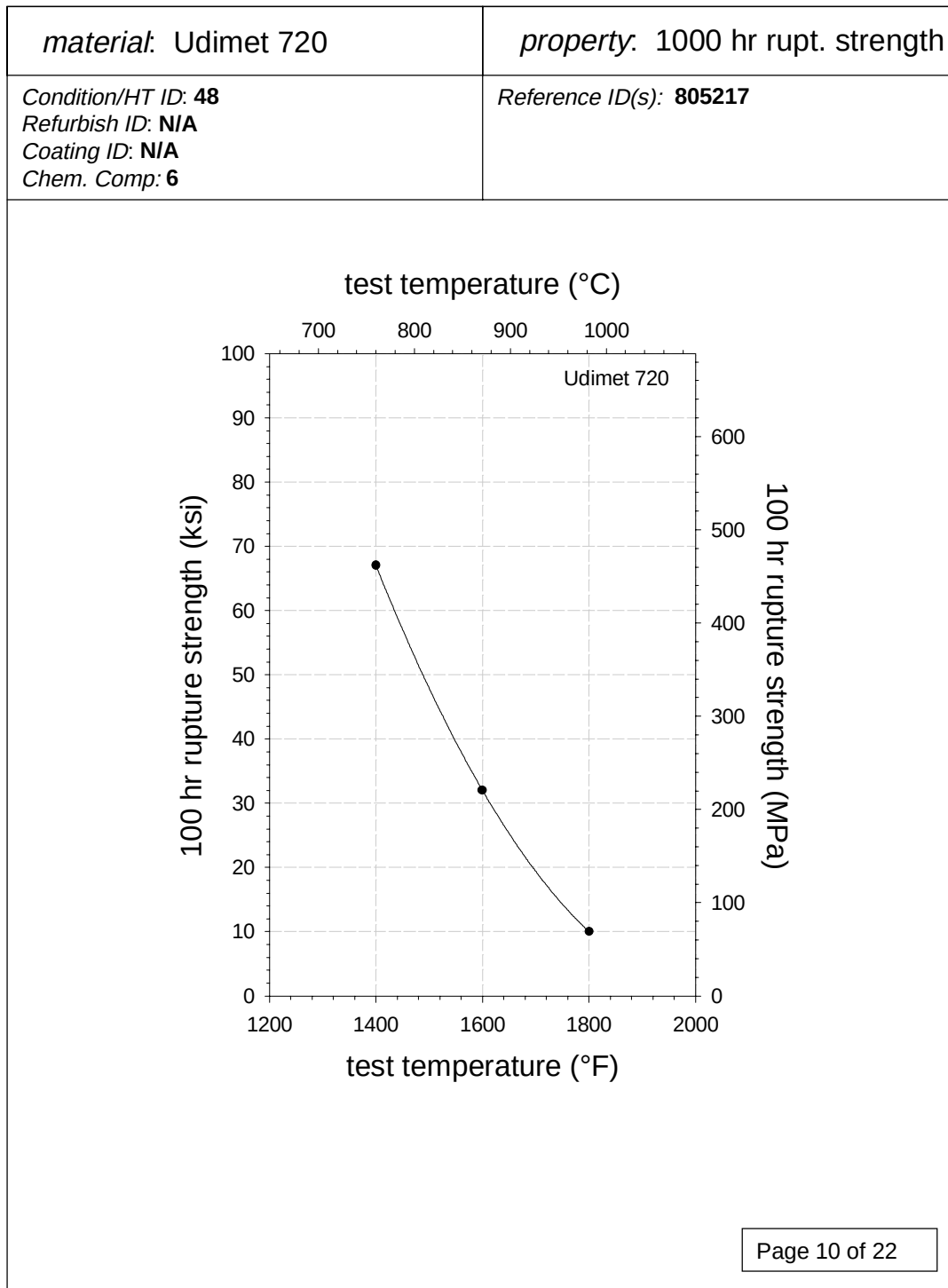


Figure 16-10
1000 hr Rupture Strength as a Function of Temperature.

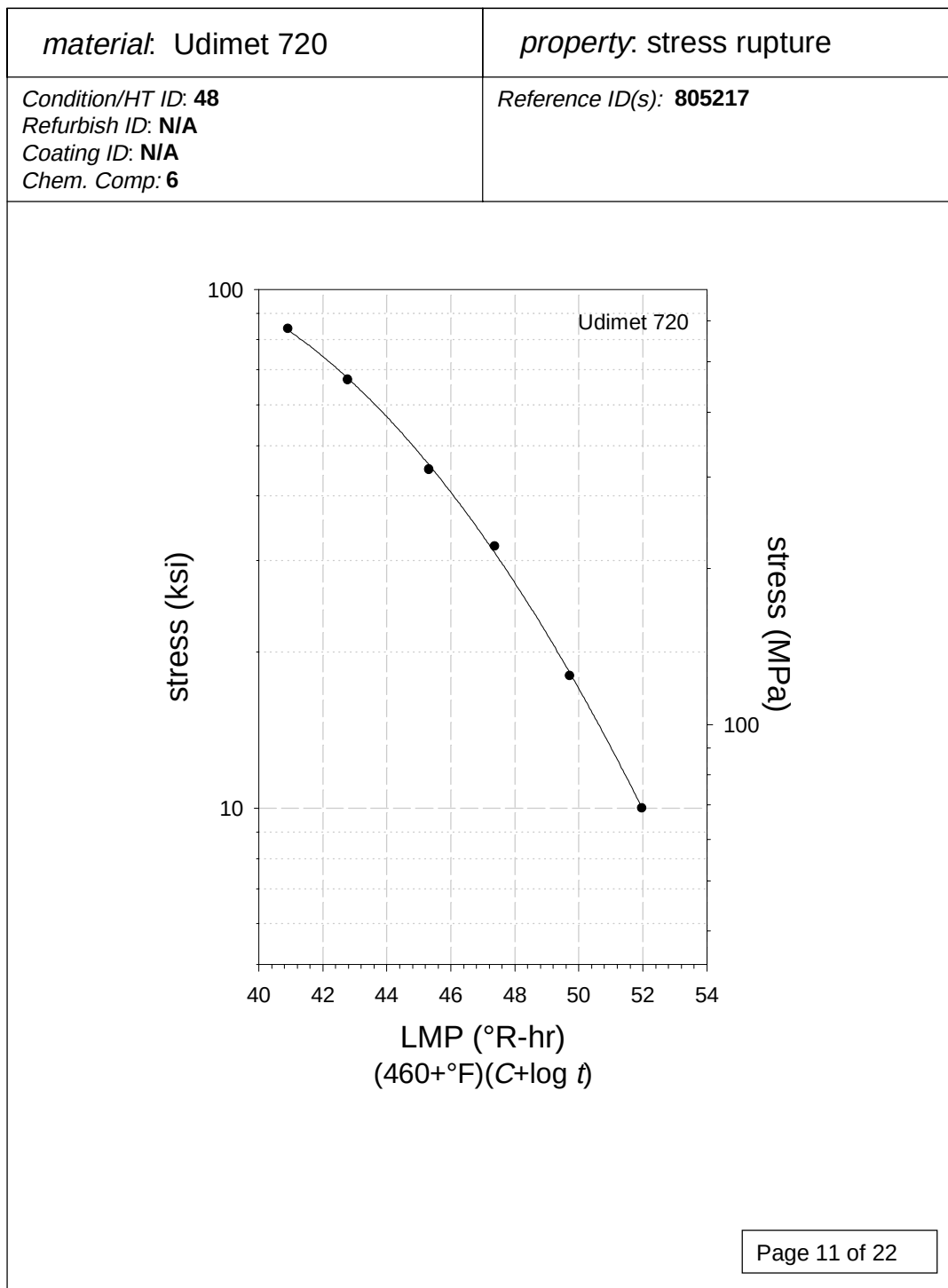


Figure 16-11
Larson-Miller Plot for Udimet 720.

Udimet 720

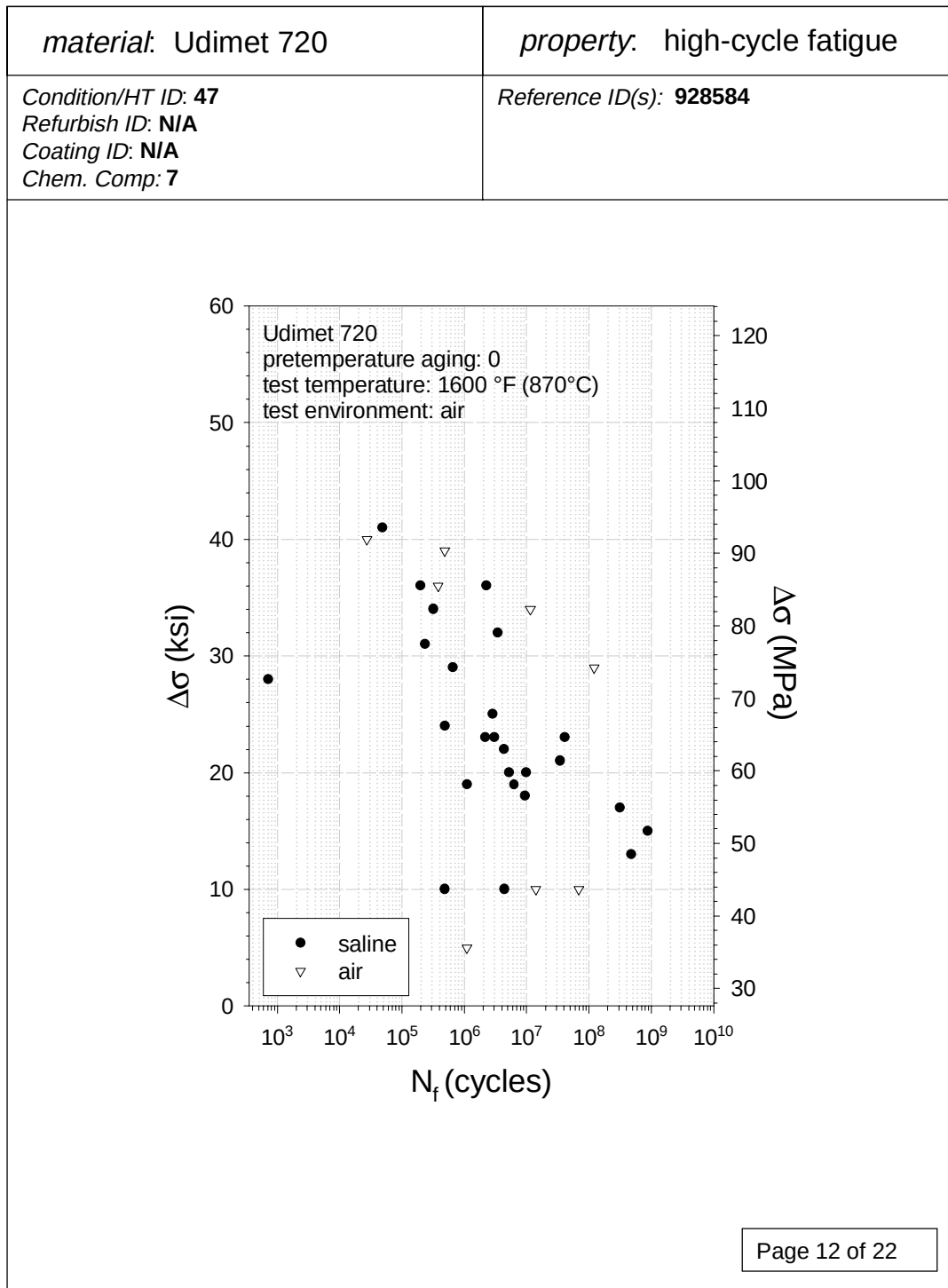
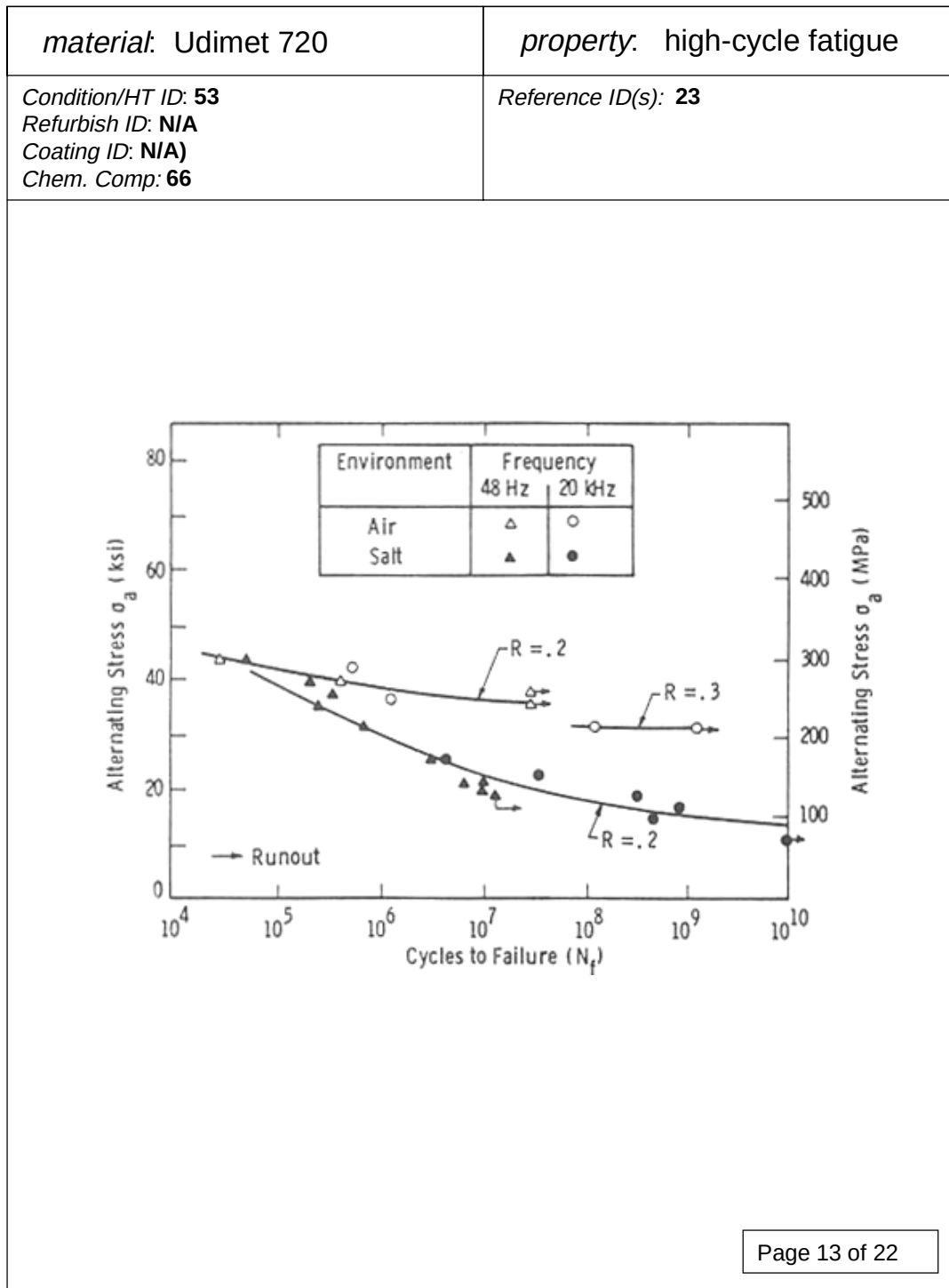


Figure 16-12
High Cycle Fatigue Behavior at 1600°F in Saline and Air Environments.

**Figure 16-13**

Effects of Environment and Frequency of Cycling on HCF Strength of Udimet 720 at 1300°F (704°C) and R = 0.2 to 0.3.

Udimet 720

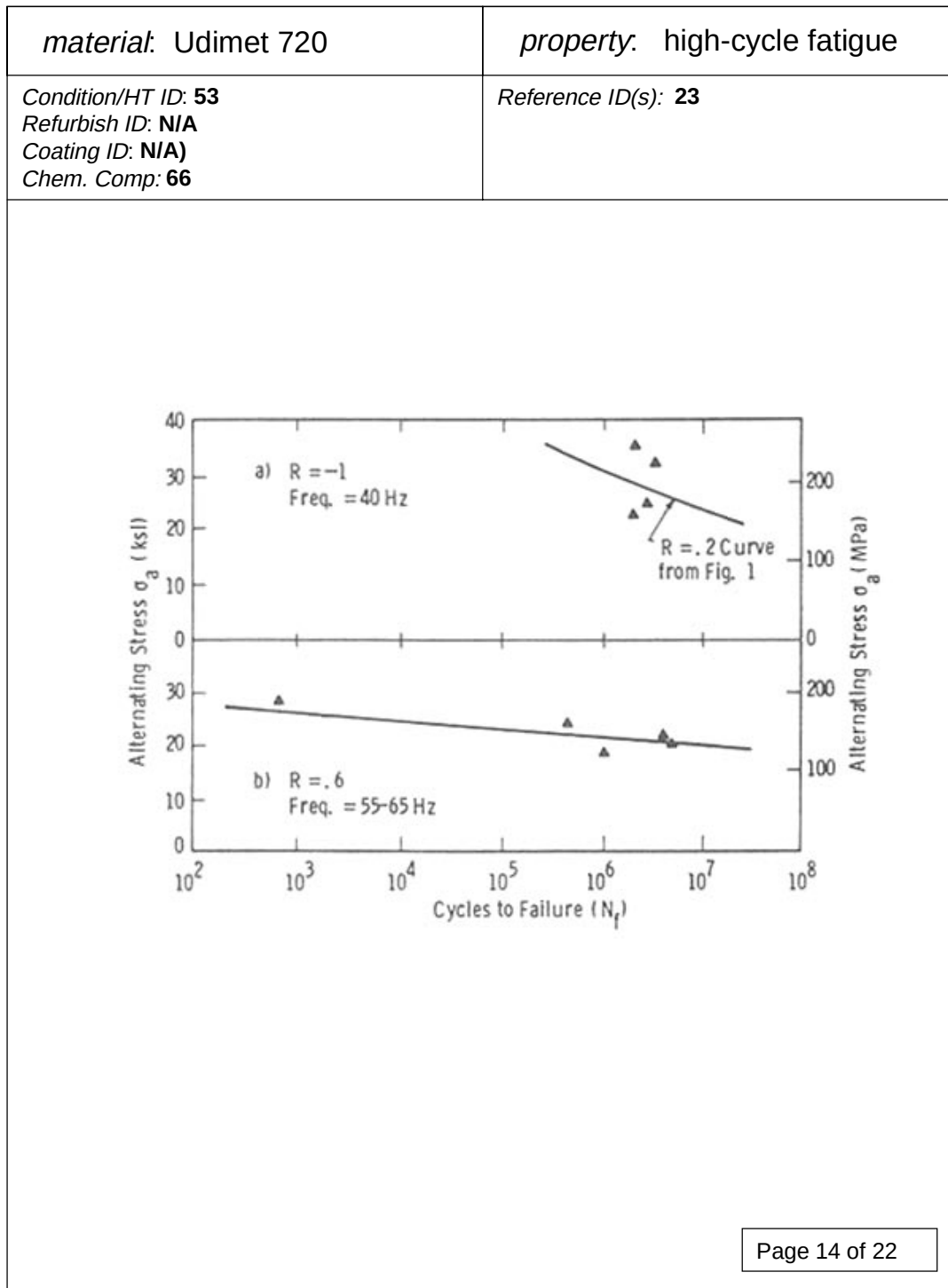


Figure 16-14
HCF Strength of Udimet 720 in Salt Environment at 1300°F (704°C) for $R = -1.0$ and 0.6 .

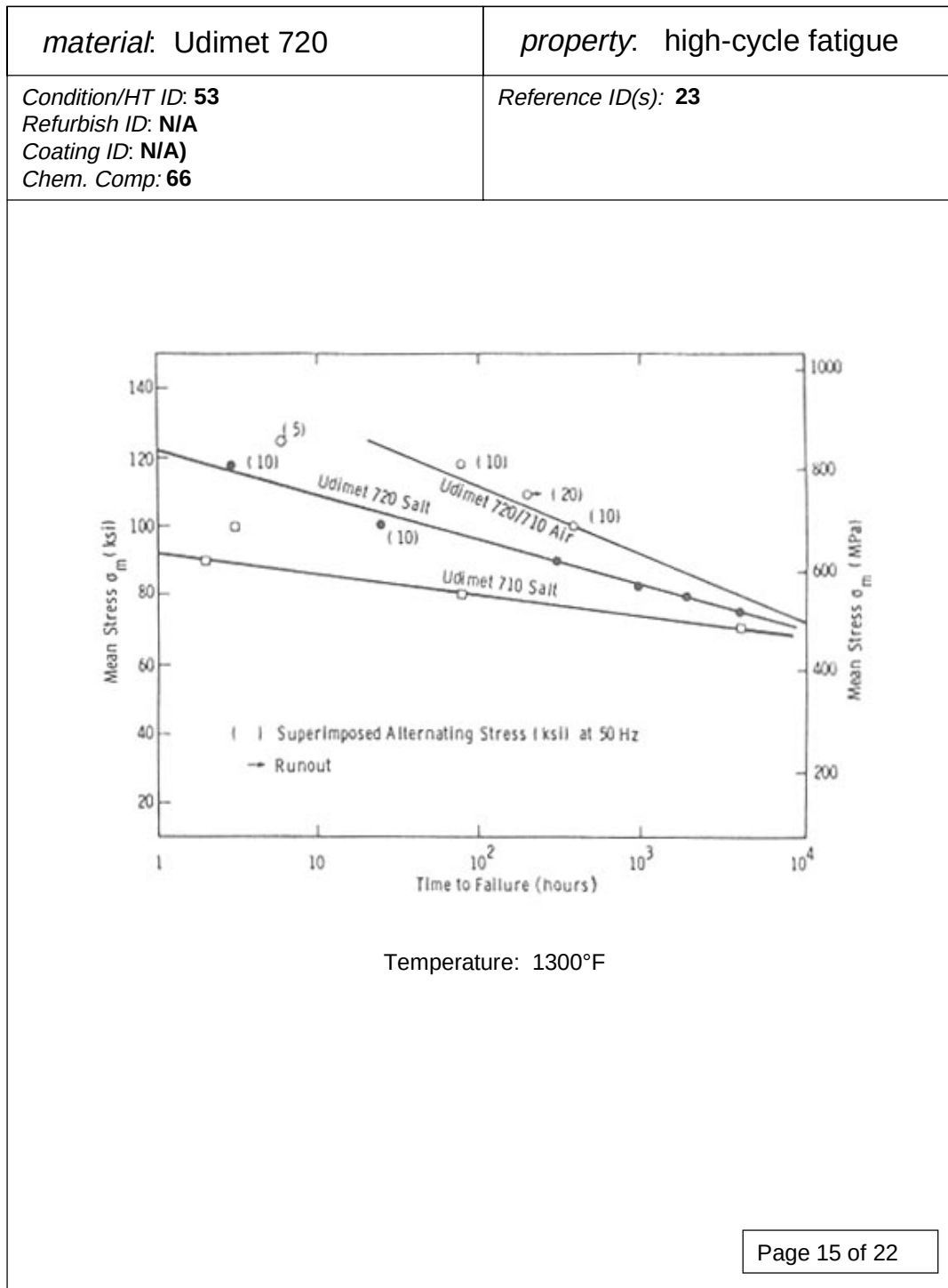


Figure 16-15
Effect of Salt Environment and Low Alternating Stress on Stress Rupture of Udimet 710 and 720 Alloys at 1300°F (704°C).

Udimet 720

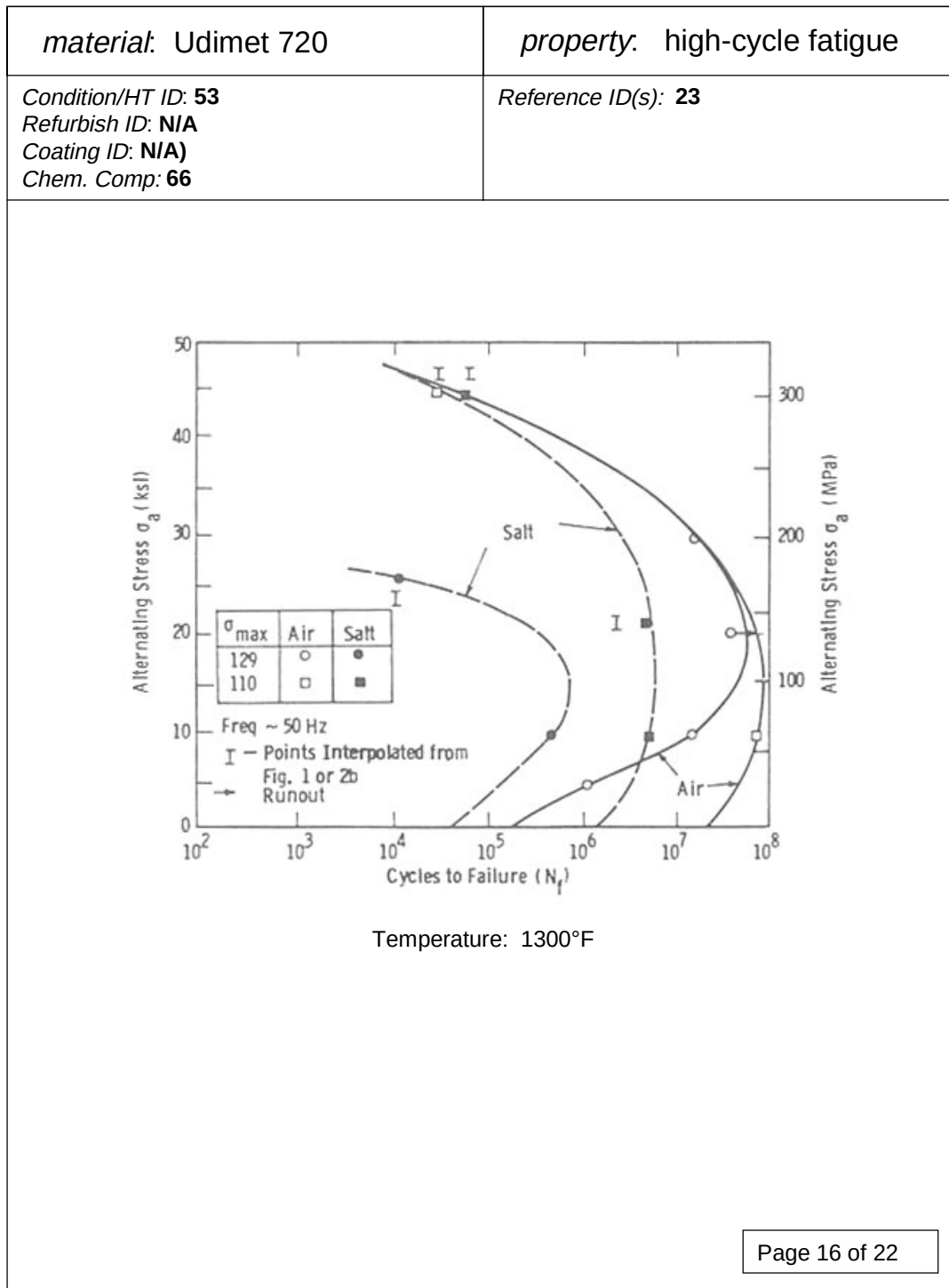


Figure 16-16
Effect of Environment on Creep/Fatigue Strength of Udimet 720 at 1300°F (704°C) and Constant Maximum Stress.

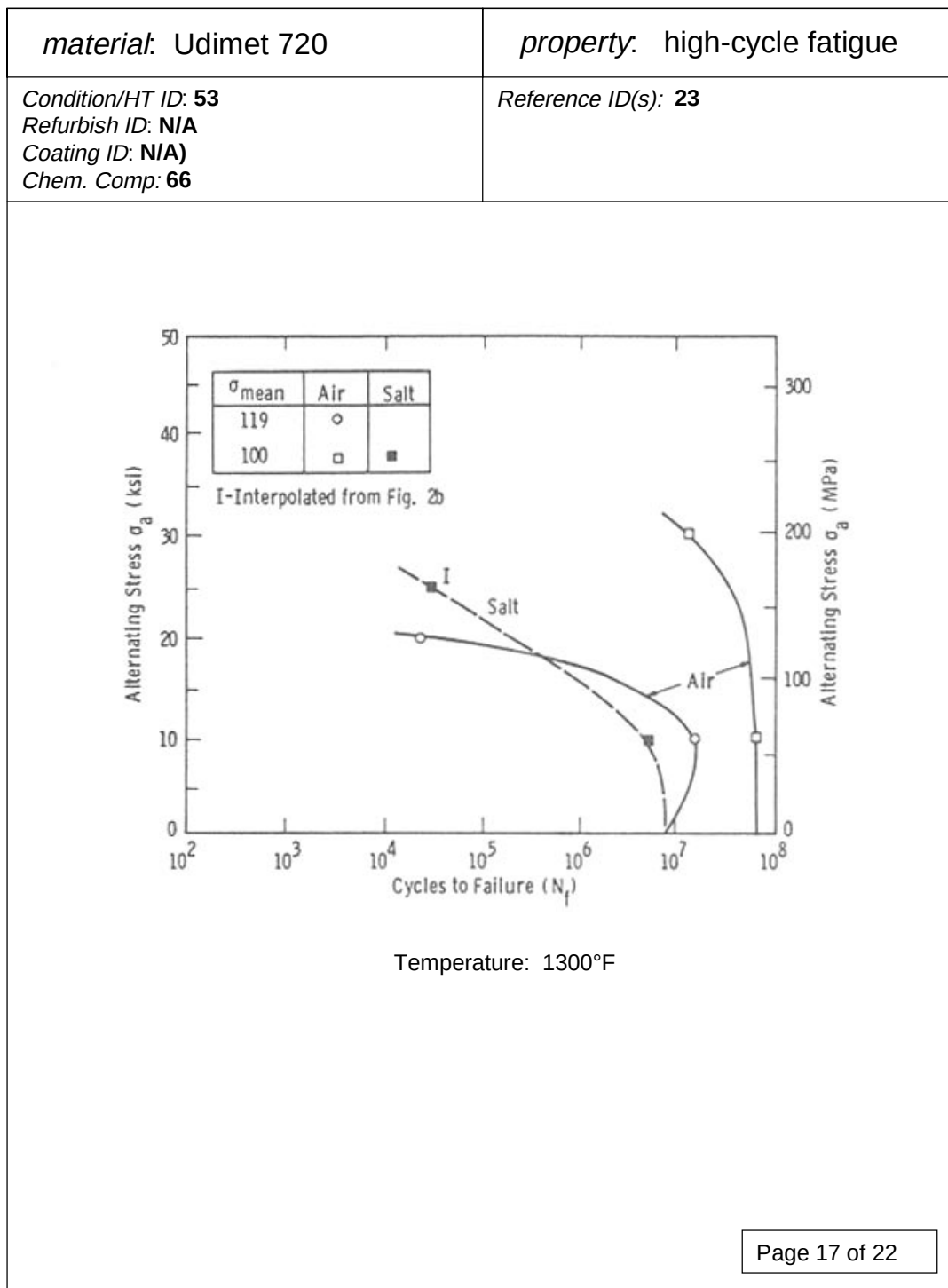


Figure 16-17
Creep/Fatigue Strength of Udimet 720 in Air and Salt Under Constant Mean Stress at 1300°F (704°C).

Udimet 720

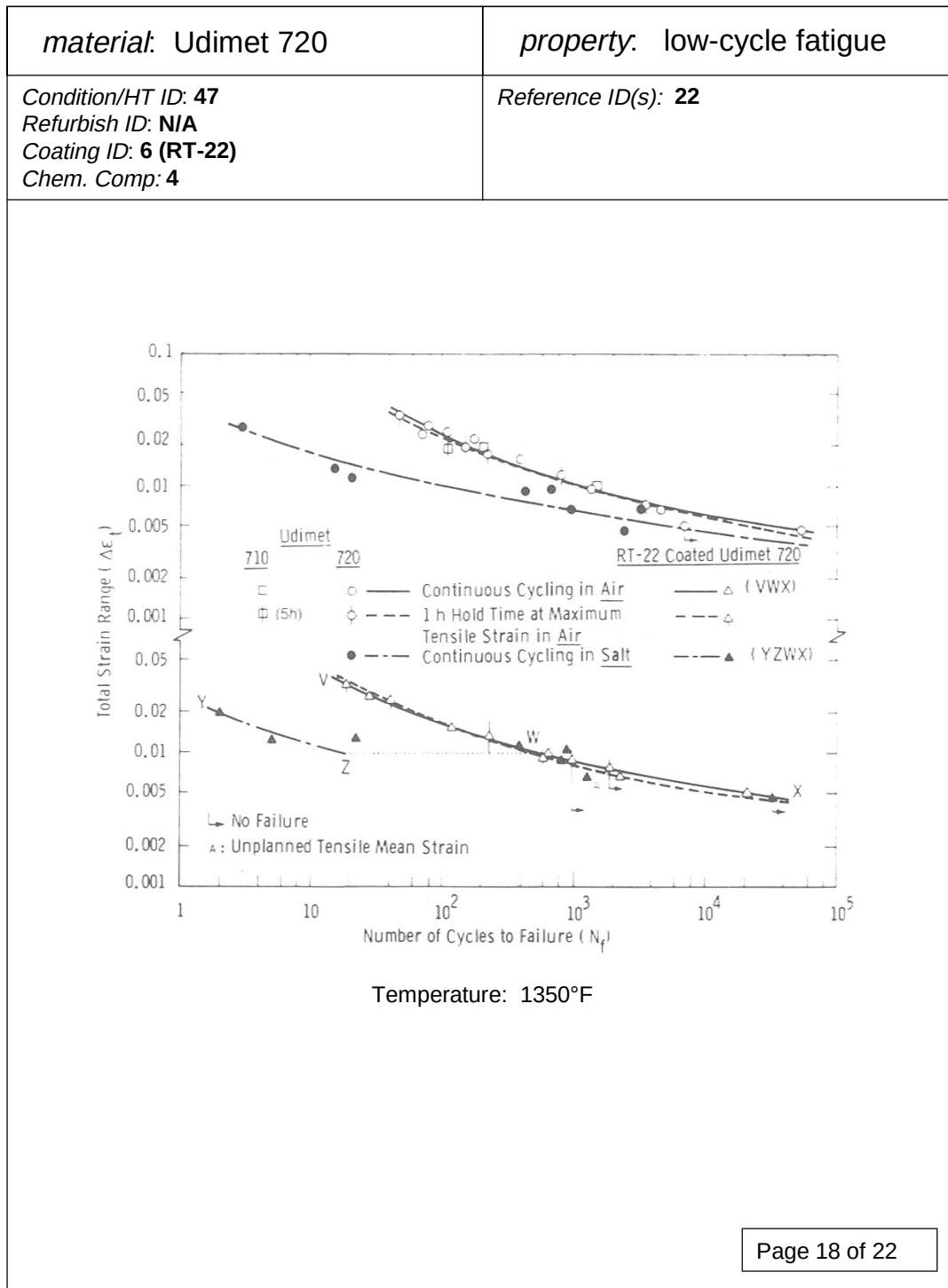


Figure 16-18
Relationship Between Strain Range and Number of Cycles to Failure Obtained During the Low Cycle Fatigue Testing of Udimet 710 and Coated and Uncoated Udimet 720 at 1350°F (732°C) at 1 cpm.

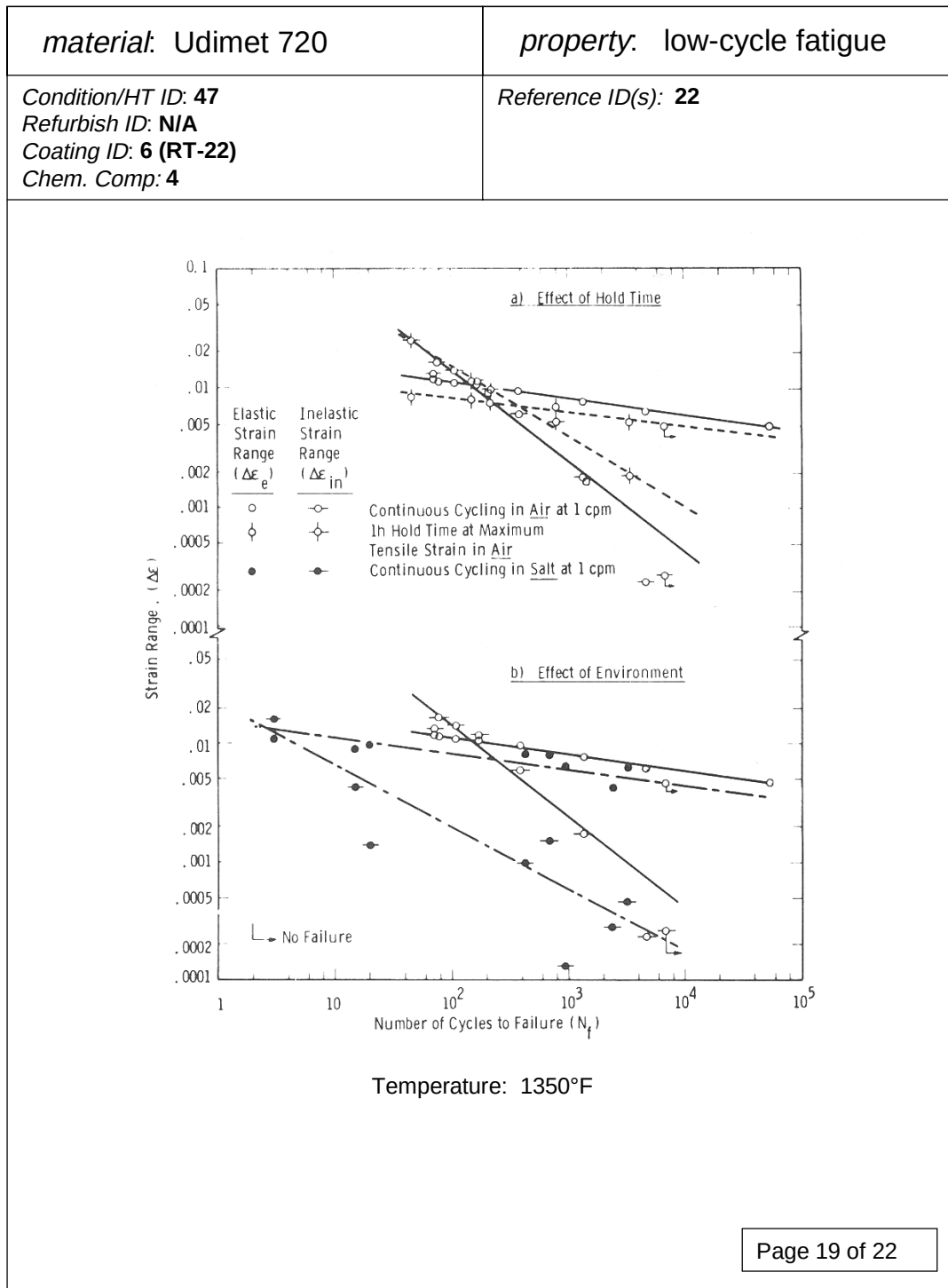


Figure 16-19
Relationship Between the Strain Range Components and Number of Cycles to Failure
Obtained During the Low Cycle Fatigue Testing of Udimet 720 at 1350°F (732°C) as a
Function of Hold Time and Test Environment.

Udimet 720

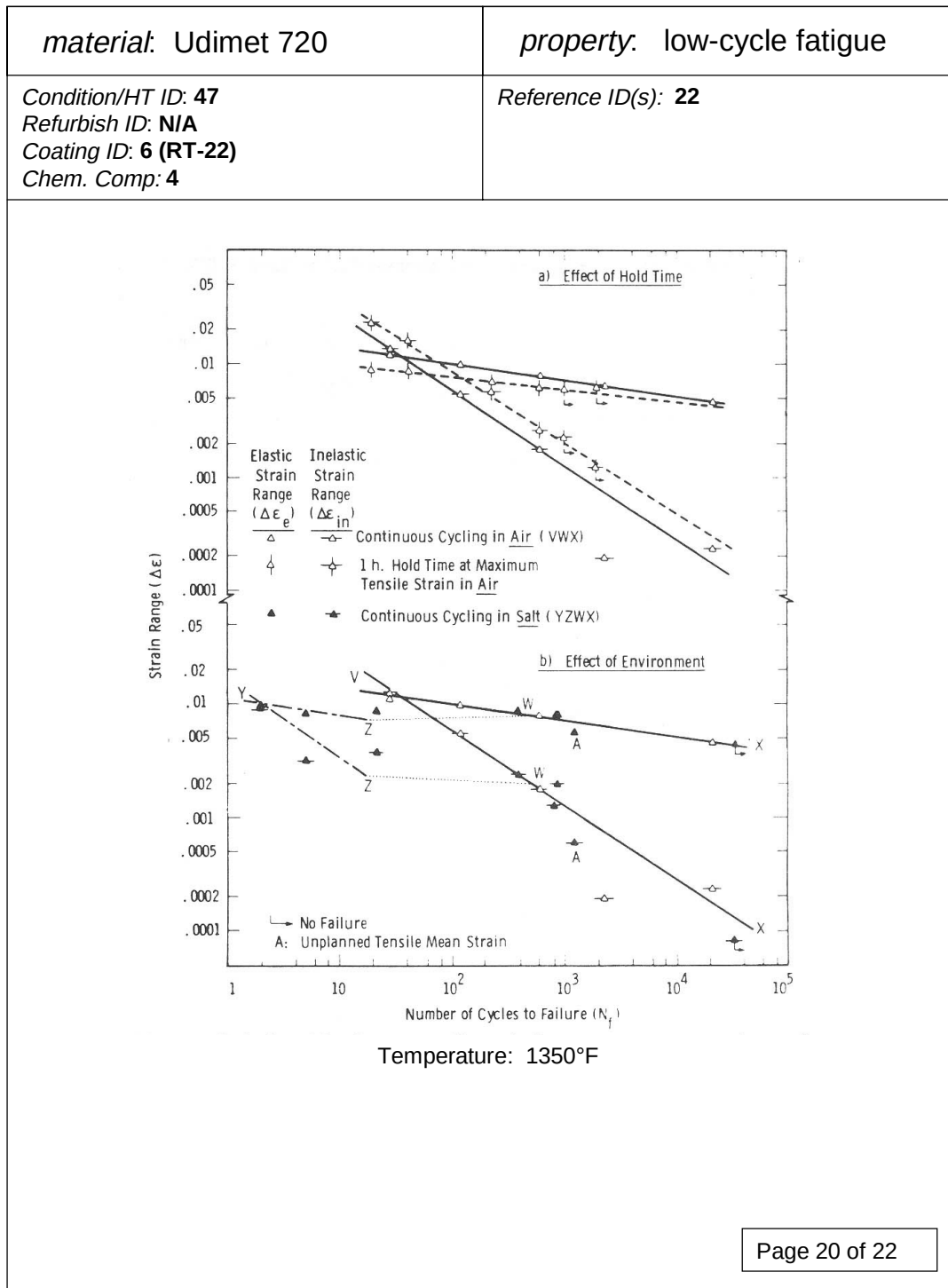


Figure 16-20
Relationship Between the Strain Range Components and Number of Cycles to Failure
Obtained During the Low Cycle Fatigue Testing of RT-22 Coated Udimet 720 at 1350°F
(732°C) at 1 cpm as a Function of Hold Time and Test Environment.

material: Udimet 720					property: low-cycle fatigue				
Condition/HT ID: 47 Refurbish ID: N/A Coating ID: 6 (RT-22) Chem. Comp: 4					Reference ID(s): 22				

Temperature: 1350°F

Test No.	$\Delta\epsilon_t$	$\Delta\epsilon_e$	$\Delta\epsilon_{in}$	N_f	σ_T (ksi)	σ_C (ksi)	$\Delta\sigma$ (ksi)	σ_R (ksi)	$\Delta\sigma_R$ (ksi)
Continuous Cycling Tests in Air									
2	0.0275	0.0112	0.0163	77	142	-159	301	-	-
4	0.0248	0.0108	0.0140	108	136	-152	288	-	-
1	0.0245	0.0117	0.0128	71	149	-165	314	-	-
5	0.0220	0.0106	0.0114	171	130	-146	276	-	-
10	0.0153	0.0094	0.0059	386	124	-129	253	-	-
6	0.0093	0.0076	0.0017	1354	95	-107	202	-	-
8	0.0065	0.0063	0.0002	4772	88	-83	171	-	-
7	0.0050	0.0047	0.0003	~6897*	67	-60	127	-	-
9	0.0047	0.0047	0.0000	53837	64	-59	123	-	-
Tests With One Hour Hold Time at Maximum Tensile Strain in Air									
3	0.0333	0.0083	0.0250	46	129	-161	290	70	231
13	0.0192	0.0080	0.0112	151	105	-148	253	65	213
12	0.0169	0.0074	0.0095	222	91	-139	230	58	197
11	0.0120	0.0068	0.0052	798	64	-136	200	48	184
14	0.0070	0.0052	0.0018	3456	42	-100	142	36	136
Continuous Cycling Tests in Salt									
S-1	0.0268	0.0109	0.0159	3	141	-147	288	-	-
S-6	0.0132	0.0089	0.0043	15	110	-120	230	-	-
S-7	0.0110	0.0096	0.0014	20	124	-136	260	-	-
S-2	0.0094	0.0079	0.0015	686	100	-112	212	-	-
S-9	0.0089	0.0079	0.0010	430	97	-94	191	-	-
S-8	0.0067	0.0063	0.0004	3247	79	-90	169	-	-
S-3	0.0064	0.0063	0.0001	943	79	-86	165	-	-
S-4	0.0045	0.0042	0.0003	2415	52	-59	111	-	-

* Test No. 7 Terminated Because of Equipment Malfunction. Values Are Shown for Cycle No. 6833
1 ksi = 6.89 MPa

Page 21 of 22

Figure 16-21
Low-Cycle Fatigue Results for Udimet 720 at 1350°F (732°C) and 1 cpm.

Udimet 720

material: Udimet 720	property: low-cycle fatigue
Condition/HT ID: 47 Refurbish ID: N/A Coating ID: 6 (RT-22) Chem. Comp: 4	Reference ID(s): 22

Temperature: 1350°F

Test No.	$\Delta\epsilon_t$	$\Delta\epsilon_e$	$\Delta\epsilon_{in}$	N_f	σ_T (ksi)	σ_C (ksi)	$\Delta\sigma$ (ksi)	σ_R (ksi)	$\Delta\sigma_R$ (ksi)
Continuous Cycling Tests in Air									
1-1	0.0253	0.0120	0.0133	28	139	-157	296	—	—
1-7	0.0152	0.0097	0.0055	120	119	-133	252	—	—
1-4	0.0096	0.0078	0.0018	618	89	-117	206	—	—
1-3	0.0066	0.0064	0.0002	2300*	81	-85	166	—	—
1-6	0.0049	0.0047	0.0002	21687	63	-57	120	—	—
Tests With One Hour Hold Time at Maximum Tensile Strain in Air									
1-2	0.0314	0.0088	0.0226	19	125	-166	291	68	234
1-8	0.0246	0.0087	0.0159	41	115	-158	273	69	227
1-9	0.0126	0.0069	0.0057	230	71	-129	200	50	179
1-10	0.0089	0.0063	0.0026	606	60	-115	175	47	162
1-11	0.0082	0.0060	0.0022	>1006**	45	-114	159	37	151
1-12	0.0072	0.0060	0.0012	>1938***	46	-112	158	40	152
Continuous Cycling Tests in Salt									
S1-1	0.0191	0.0098	0.0093	2	112	-131	243	—	—
S1-5	0.0123	0.0086	0.0037	22	102	-111	213	—	—
S1-7	0.0113	0.0081	0.0032	5	101	-109	210	—	—
S1-8	0.0109	0.0086	0.0023	393	105	-115	220	—	—
S1-6	0.0098	0.0079	0.0019	879	93	-103	196	—	—
S1-3	0.0091	0.0078	0.0013	842	98	-109	207	—	—
S1-2	0.0063	0.0057	0.0006	1267	119††	-32††	151	—	—
S1-4	0.0045	0.0044	0.0001	>34,000†	51	-58	109	—	—

* Approximate Value Due to Recorder Failure ($2058 \leq N_f \leq 2524$). Note: 1 ksi = 6.89 MPa

** Test No. 1-11 Terminated Because of Equipment Malfunction. Values are Shown for Cycle No. 1006

*** Test No. 1-12 Terminated Because of Equipment Malfunction. Value of $\Delta\epsilon_t$ Derived from Calibration Curve.

† Run Out †† Equipment Malfunction Caused a Tensile Mean Strain

Page 22 of 22

Page 22 of 22

Figure 16-22
Low-Cycle Fatigue Results for RT-22 Coated Udimet 720 Tested at 1350°F (732°C) and 1 cpm.

17

GTD 111 DS

GTD 111 DS

<i>material:</i> GTD 111 EA and DS		<i>property:</i> tensile	
Condition/HT ID: 59 Refurbish ID: N/A Coating ID: N/A Chem. Comp: 71, 72		Reference ID(s): 31	

Property	IN-738		GTD-111EA		GTD-111DS	
	75°F	1600°F	75°F	1600°F	75°F	1600°F
Yield Strength, ksi (0.2%)	109	67	101.5	63.2	96.9	74.4
Tensile Strength, ksi	122.7	95.4	126.1	91.9	141.9	93.6
% Elongation	4.1	21.5	1.8	6.6	5.7	24.4
% Reduction of Area	5.0	32.6	3.5	8.1	6.4	38.8
Hardness* (R _c)	40.1 (R)	--	40.4 (R)	--	--	40.5 (R)
	37.6 (A)		35.8 (A)			36.0 (A)

* R=Root; A=Airfoil

Page 1 of 14

Figure 17-1
Tensile Properties and Hardness in the Service Aged Condition.

GTD 111 DS

material: GTD 111 EA and DS		property: tensile	
Condition/HT ID: 59 Refurbish ID: HIPPED, coated, re-heattreat Coating ID: N/A Chem. Comp: 71, 72		Reference ID(s): 31	

Property	IN-738		GTD-111EA		GTD-111DS	
	75°F	1600°F	75°F	1600°F	75°F	1600°F
Yield Strength, ksi (0.2%)	109.8	95.3	117.6	79.7	124.5	75.6
Tensile Strength, ksi	119.2	65.8	164.0	103.4	145.2	105.8
% Elongation	9.0	20.1	14.3	22.0	9.0	26.1
% Reduction of Area	15.5	27.4	15.2	33.8	15.5	30.6
Hardness, (R _c)	36.8	--	41.4	--	37.8	--

Page 2 of 14

Figure 17-2
Tensile and Hardness Properties after Refurbishment.

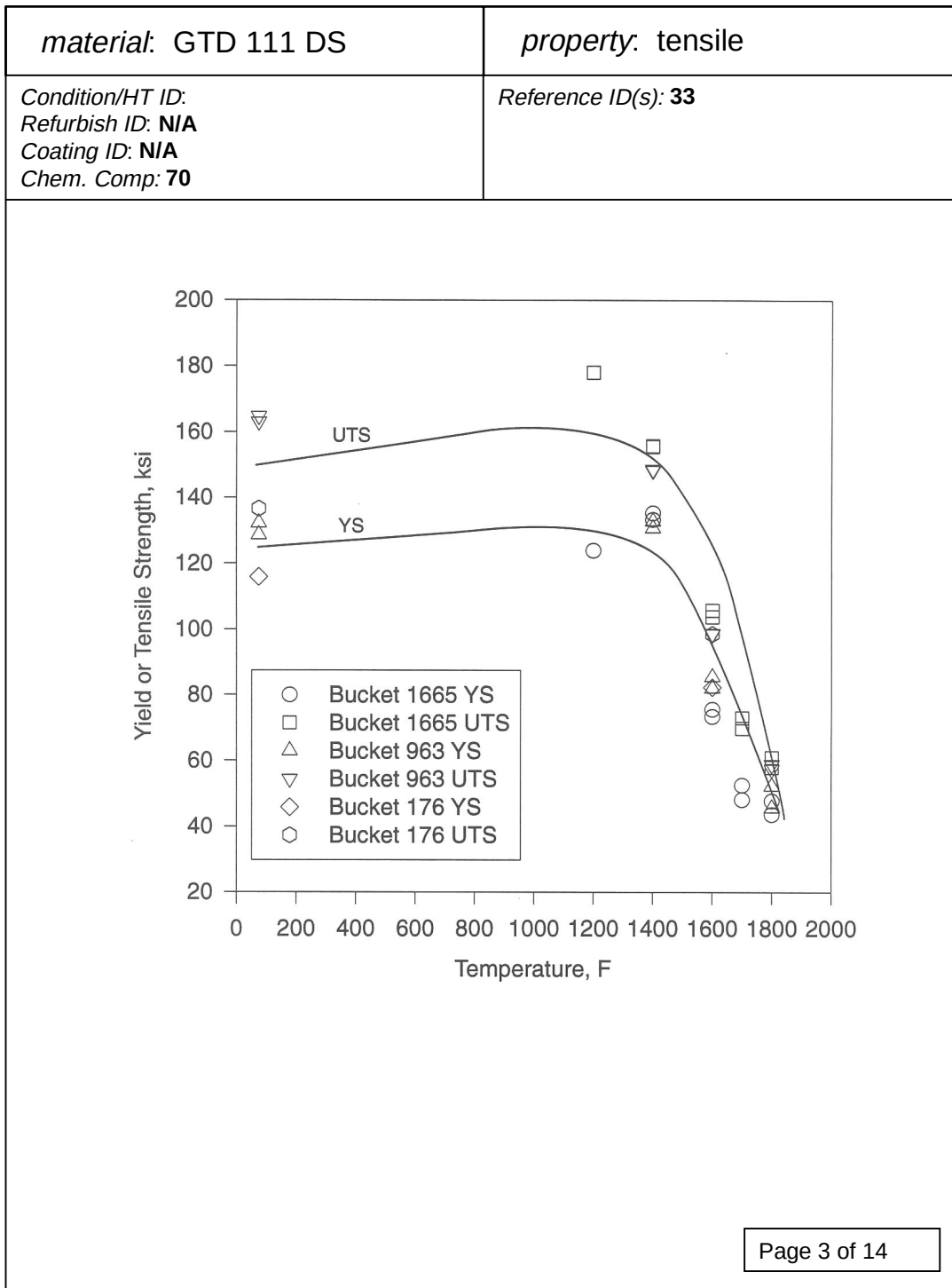


Figure 17-3
Bucket to Bucket Variation of Yield and Tensile Strengths of GTD-111 DS (Undegraded).

GTD 111 DS

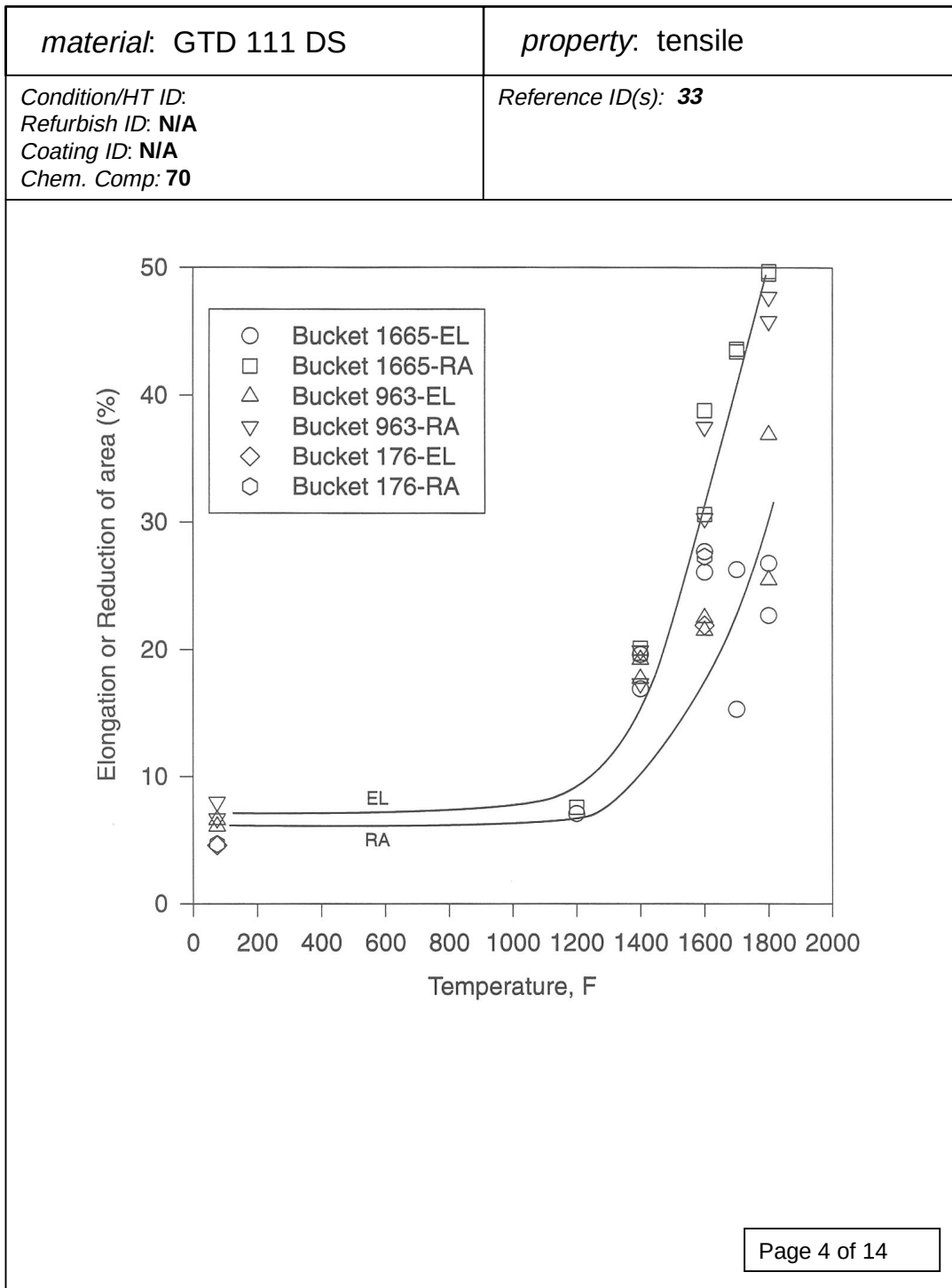


Figure 17-4
Bucket to Bucket Variation of Percent Elongation and Reduction of Area (Undegraded).

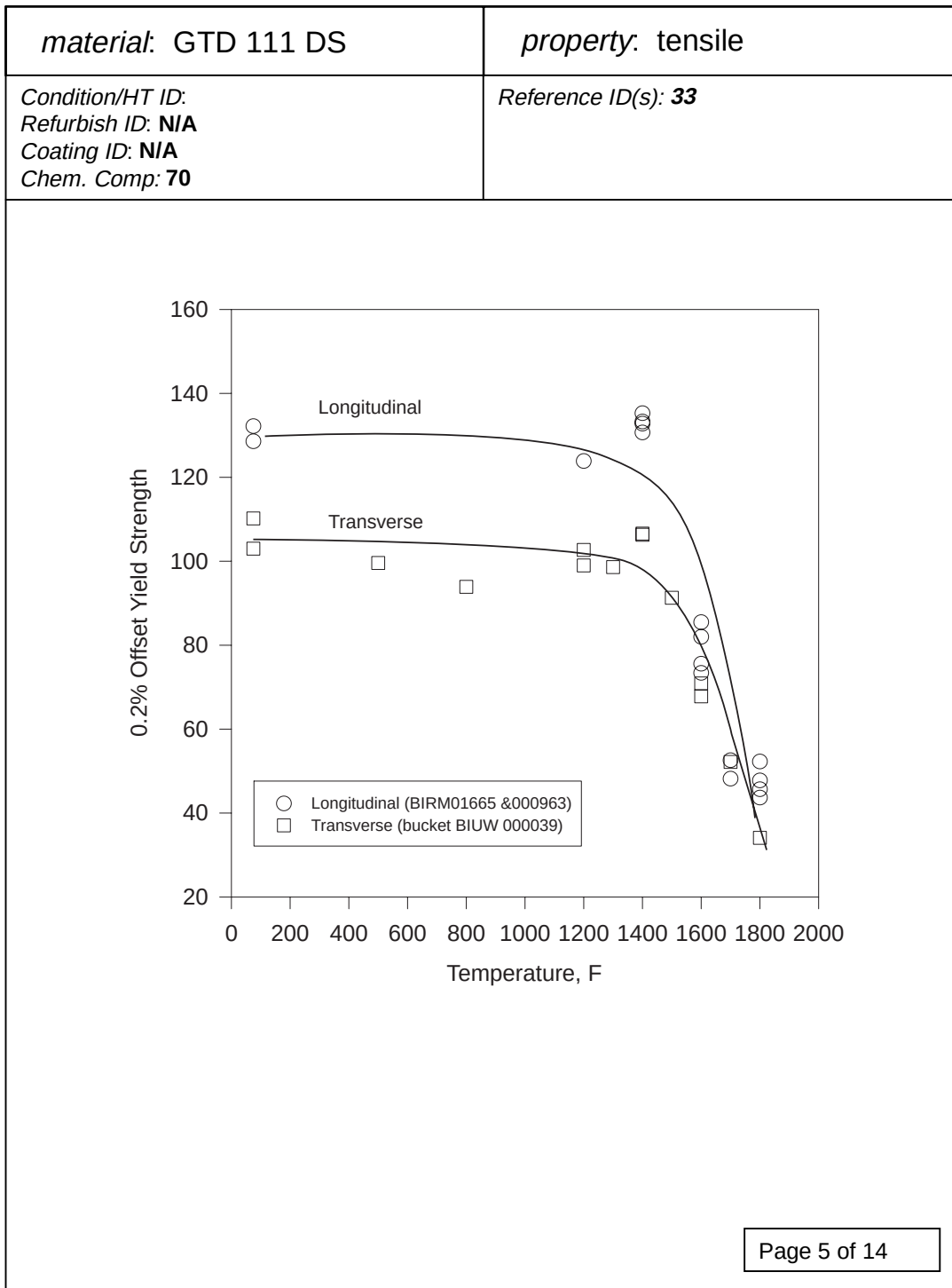


Figure 17-5
Variation of Yield Strength of the Longitudinal and Transverse Specimens.

GTD 111 DS

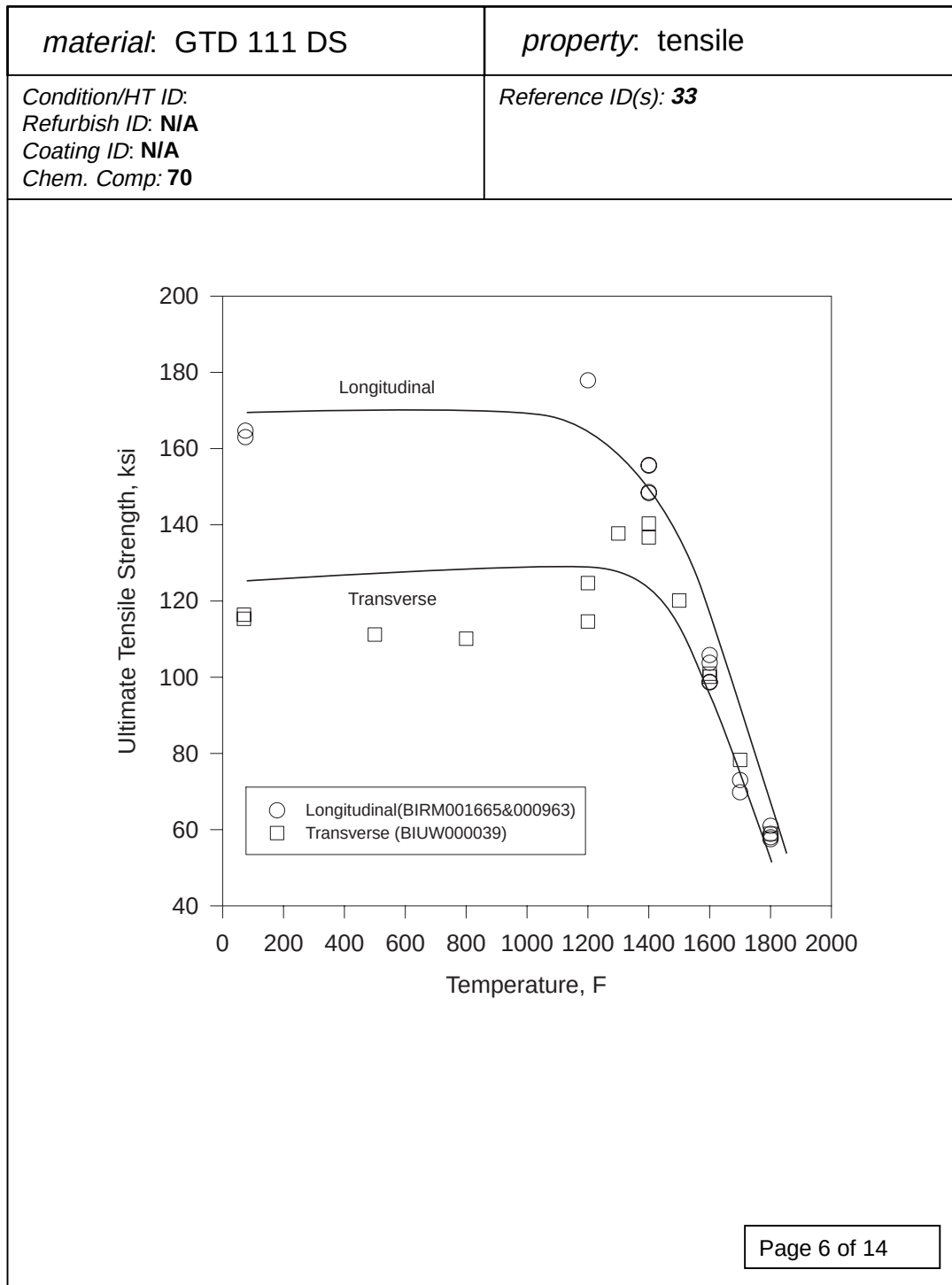


Figure 17-6
Variation of Tensile Strength for the Longitudinal and Transverse Specimens.

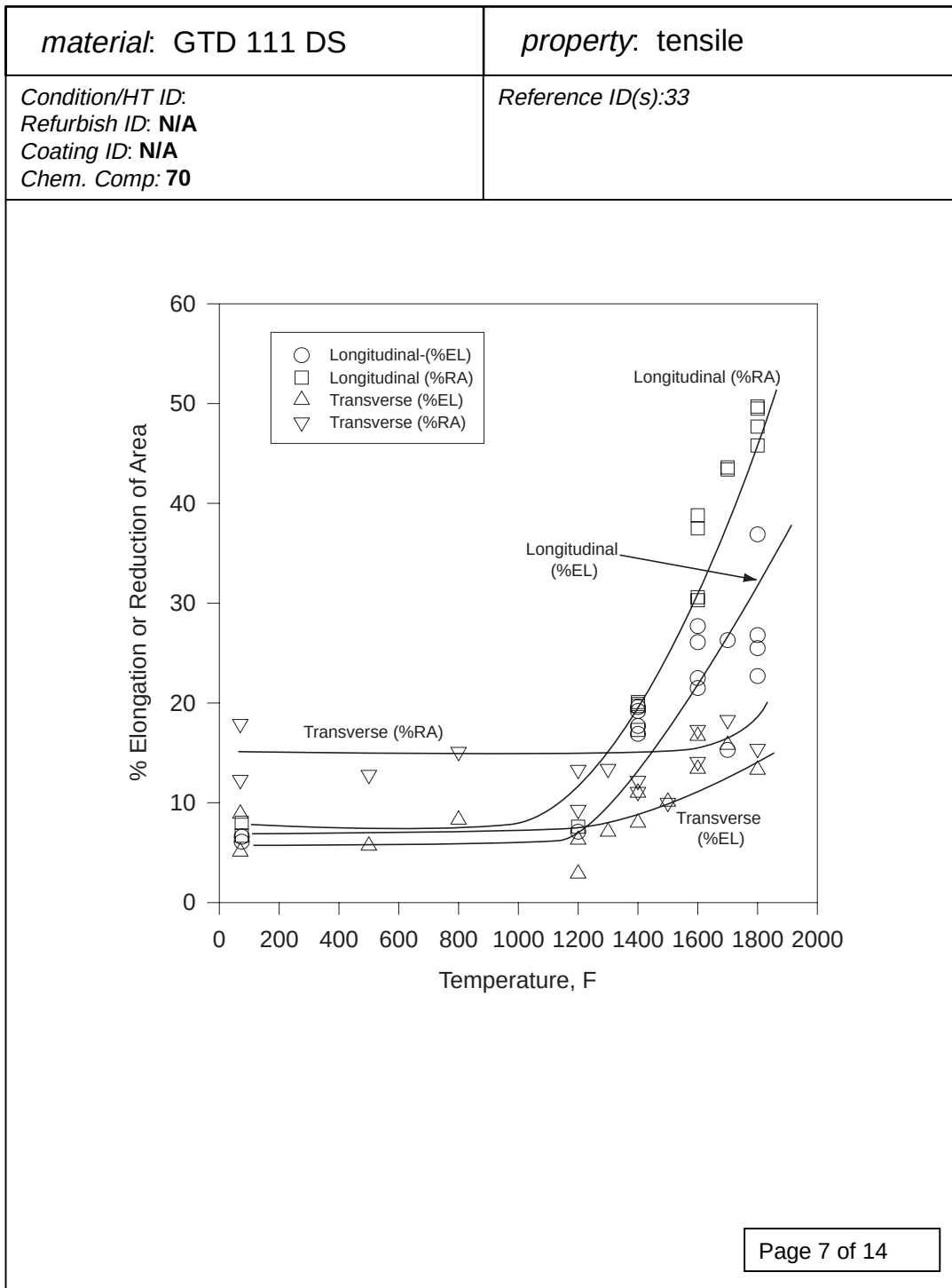


Figure 17-7
Variation of Tensile Ductility of Longitudinal and Transverse Specimens as a Function of Temperature.

GTD 111 DS

<i>material:</i> GTD 111 EA and DS				<i>property:</i> stress rupture																																																																																	
Condition/HT ID: 59 Refurbish ID: NIA Coating ID: NIA Chem. Comp: 71, 72				Reference ID(s): 31																																																																																	
<table><tr><th>Material</th><th>Condition</th><th>Test Temp. (°F)</th><th>Stress (ksi)</th><th>Rupture Hours</th><th>% Elongation</th><th>% Reduction of Area</th></tr><tr><td rowspan="2">IN-738</td><td>Service Aged</td><td>1600</td><td>45</td><td>40.4</td><td>9.0</td><td>12.2</td></tr><tr><td>Service Aged</td><td>1600</td><td>40</td><td>126.1</td><td>7.3</td><td>7.5</td></tr><tr><td rowspan="2">IN-738</td><td>Rejuvenated</td><td>1600</td><td>45</td><td>49.7</td><td>10.6</td><td>11.5</td></tr><tr><td>Rejuvenated</td><td>1600</td><td>40</td><td>142.4</td><td>10.8</td><td>16.3</td></tr><tr><td rowspan="2">GTD-111EA</td><td>Service Aged</td><td>1600</td><td>45</td><td>44.0</td><td>10.2</td><td>18.4</td></tr><tr><td>Rejuvenated</td><td>1600</td><td>45</td><td>141.1</td><td>17.4</td><td>19.8</td></tr><tr><td rowspan="4">GTD-111DS</td><td>Rejuvenated</td><td>1600</td><td>40</td><td>315.7</td><td>12.7</td><td>17.5</td></tr><tr><td>Service Aged</td><td>1600</td><td>45</td><td>71.2</td><td>21</td><td>33.2</td></tr><tr><td>Service Aged</td><td>1600</td><td>40</td><td>197.7</td><td>17.6</td><td>21.0</td></tr><tr><td>Rejuvenated</td><td>1600</td><td>45</td><td>232.2</td><td>36.6</td><td>59.6</td></tr><tr><td></td><td>Rejuvenated</td><td>1600</td><td>40</td><td>606.6</td><td>22.5</td><td>36</td></tr></table>								Material	Condition	Test Temp. (°F)	Stress (ksi)	Rupture Hours	% Elongation	% Reduction of Area	IN-738	Service Aged	1600	45	40.4	9.0	12.2	Service Aged	1600	40	126.1	7.3	7.5	IN-738	Rejuvenated	1600	45	49.7	10.6	11.5	Rejuvenated	1600	40	142.4	10.8	16.3	GTD-111EA	Service Aged	1600	45	44.0	10.2	18.4	Rejuvenated	1600	45	141.1	17.4	19.8	GTD-111DS	Rejuvenated	1600	40	315.7	12.7	17.5	Service Aged	1600	45	71.2	21	33.2	Service Aged	1600	40	197.7	17.6	21.0	Rejuvenated	1600	45	232.2	36.6	59.6		Rejuvenated	1600	40	606.6	22.5	36
Material	Condition	Test Temp. (°F)	Stress (ksi)	Rupture Hours	% Elongation	% Reduction of Area																																																																															
IN-738	Service Aged	1600	45	40.4	9.0	12.2																																																																															
	Service Aged	1600	40	126.1	7.3	7.5																																																																															
IN-738	Rejuvenated	1600	45	49.7	10.6	11.5																																																																															
	Rejuvenated	1600	40	142.4	10.8	16.3																																																																															
GTD-111EA	Service Aged	1600	45	44.0	10.2	18.4																																																																															
	Rejuvenated	1600	45	141.1	17.4	19.8																																																																															
GTD-111DS	Rejuvenated	1600	40	315.7	12.7	17.5																																																																															
	Service Aged	1600	45	71.2	21	33.2																																																																															
	Service Aged	1600	40	197.7	17.6	21.0																																																																															
	Rejuvenated	1600	45	232.2	36.6	59.6																																																																															
	Rejuvenated	1600	40	606.6	22.5	36																																																																															

Page 8 of 14

Figure 17-8
Airfoil Stress Rupture Data for IN-738, GTD-111EA and GTD-111DS Alloys Before and After Rejuvenation.

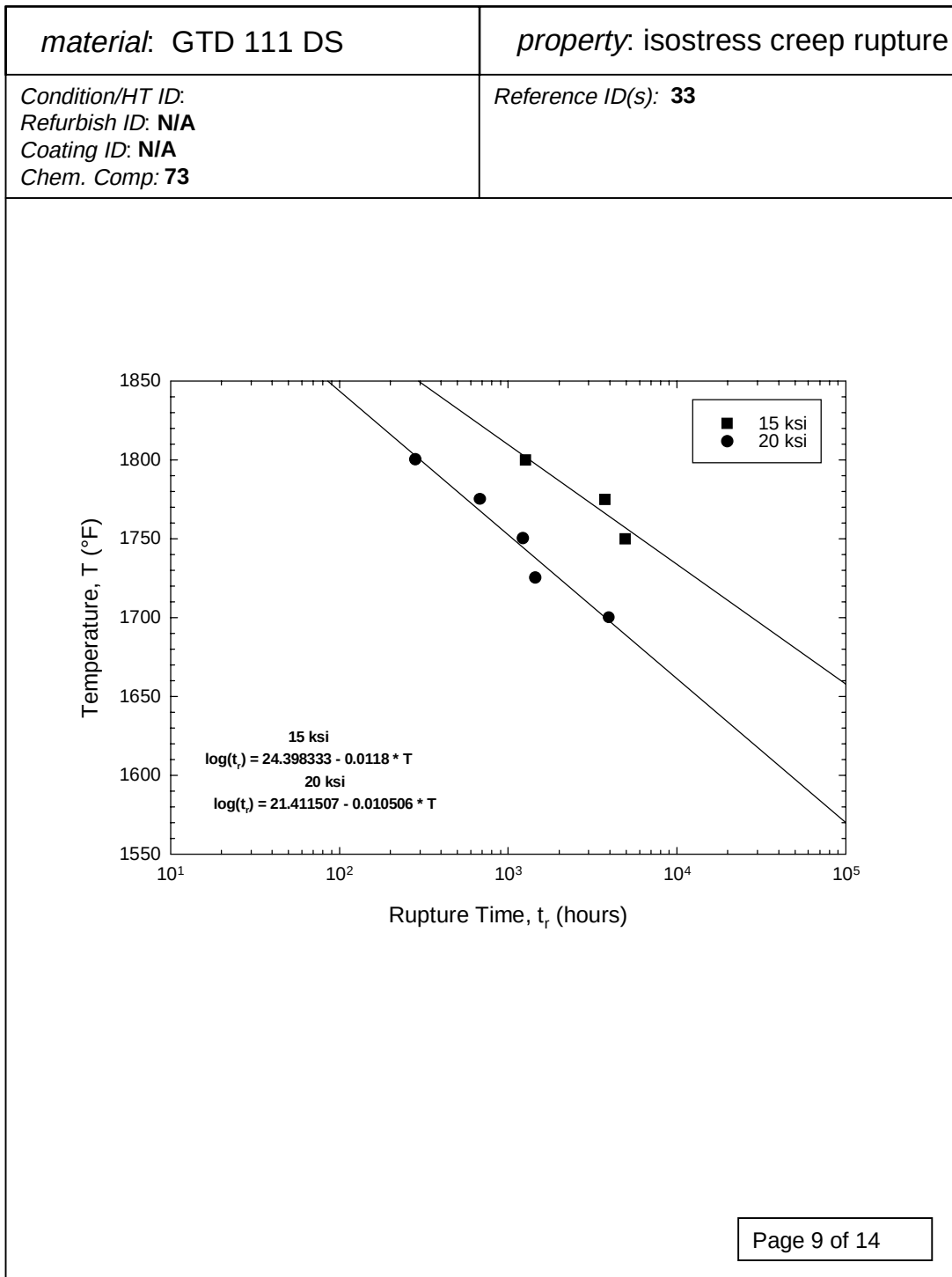


Figure 17-9
Iso-Stress Creep Rupture Data of Longitudinal Specimens Machined from the Shank Section (Unaged).

GTD 111 DS

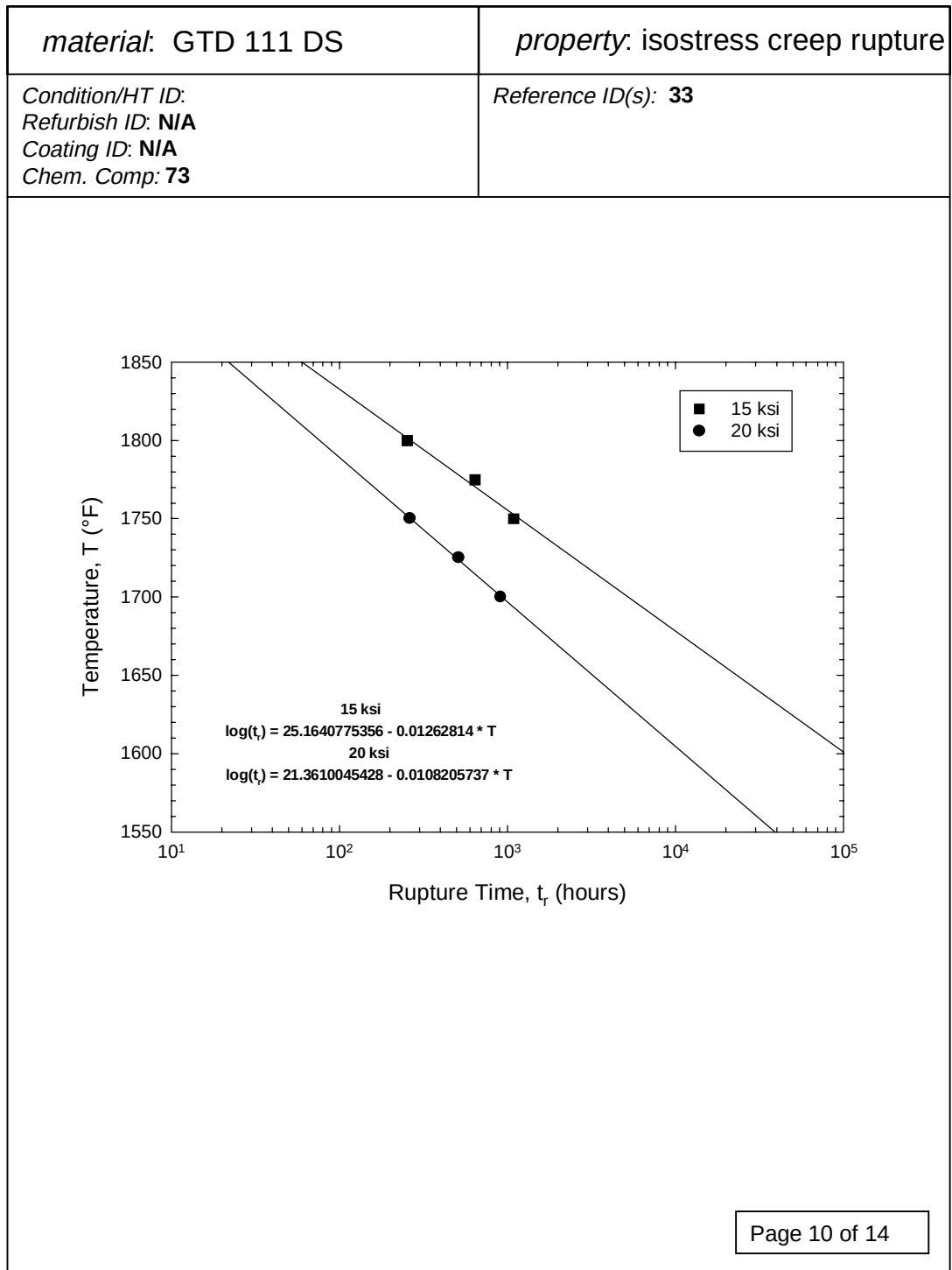


Figure 17-10
Iso-Stress Creep Rupture Data of Transverse Specimens Machined from the Shank Section.

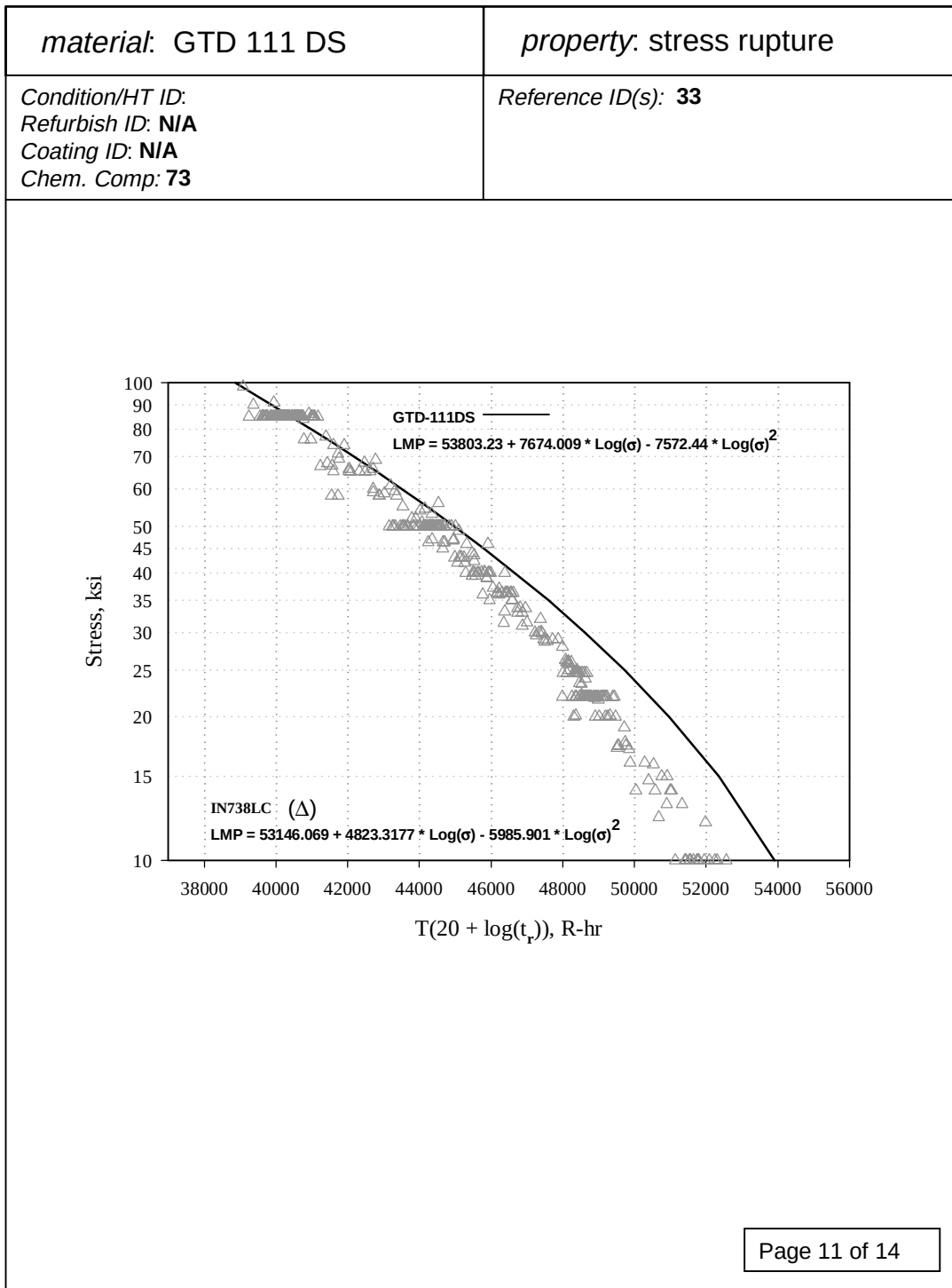


Figure 17-11
LMP Plot of GTD-111 DS and IN-738 LC Creep Data.

GTD 111 DS

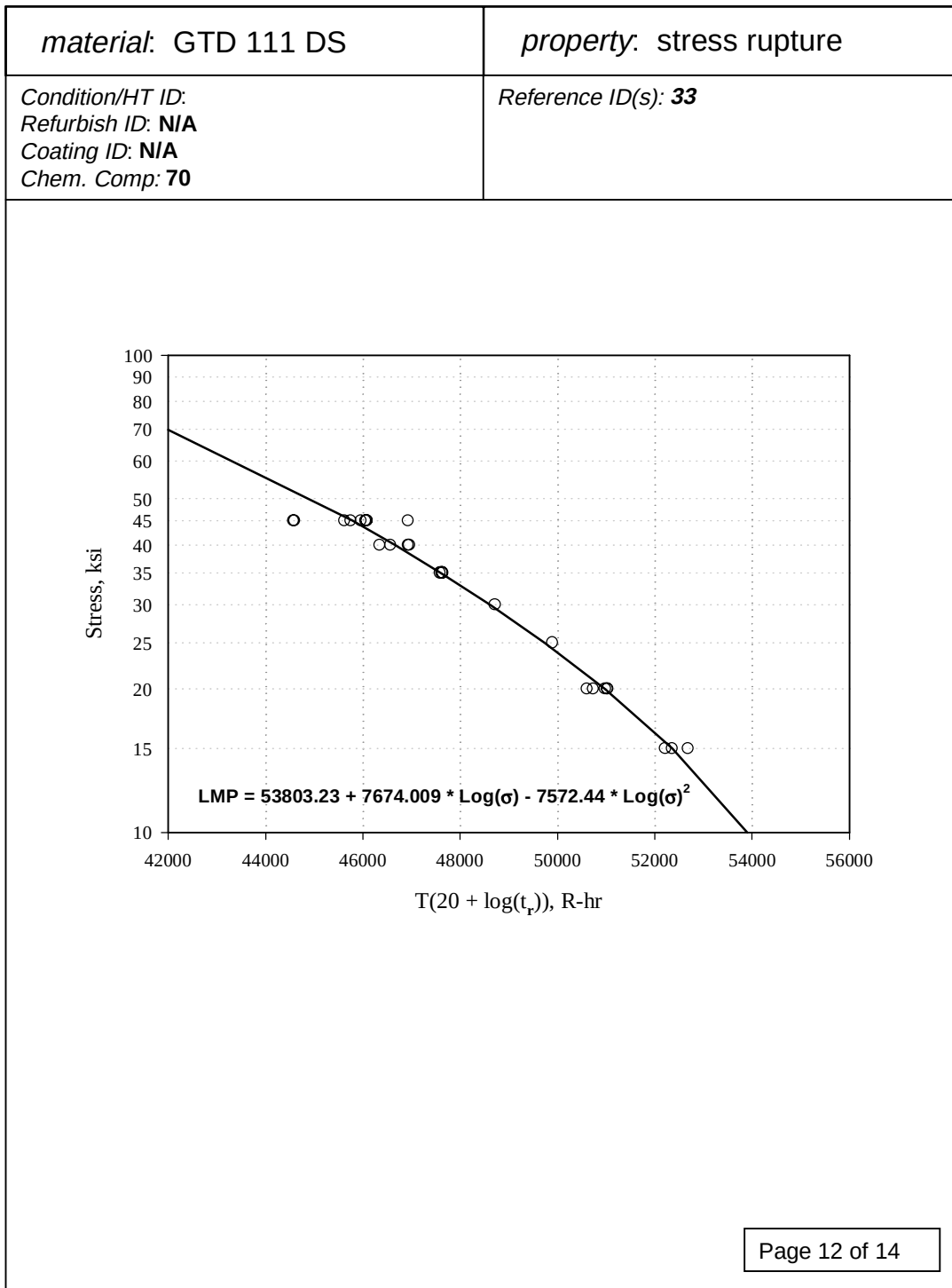


Figure 17-12
Larson-Miller Plot of Longitudinal Shank (Undegraded) Creep Data.

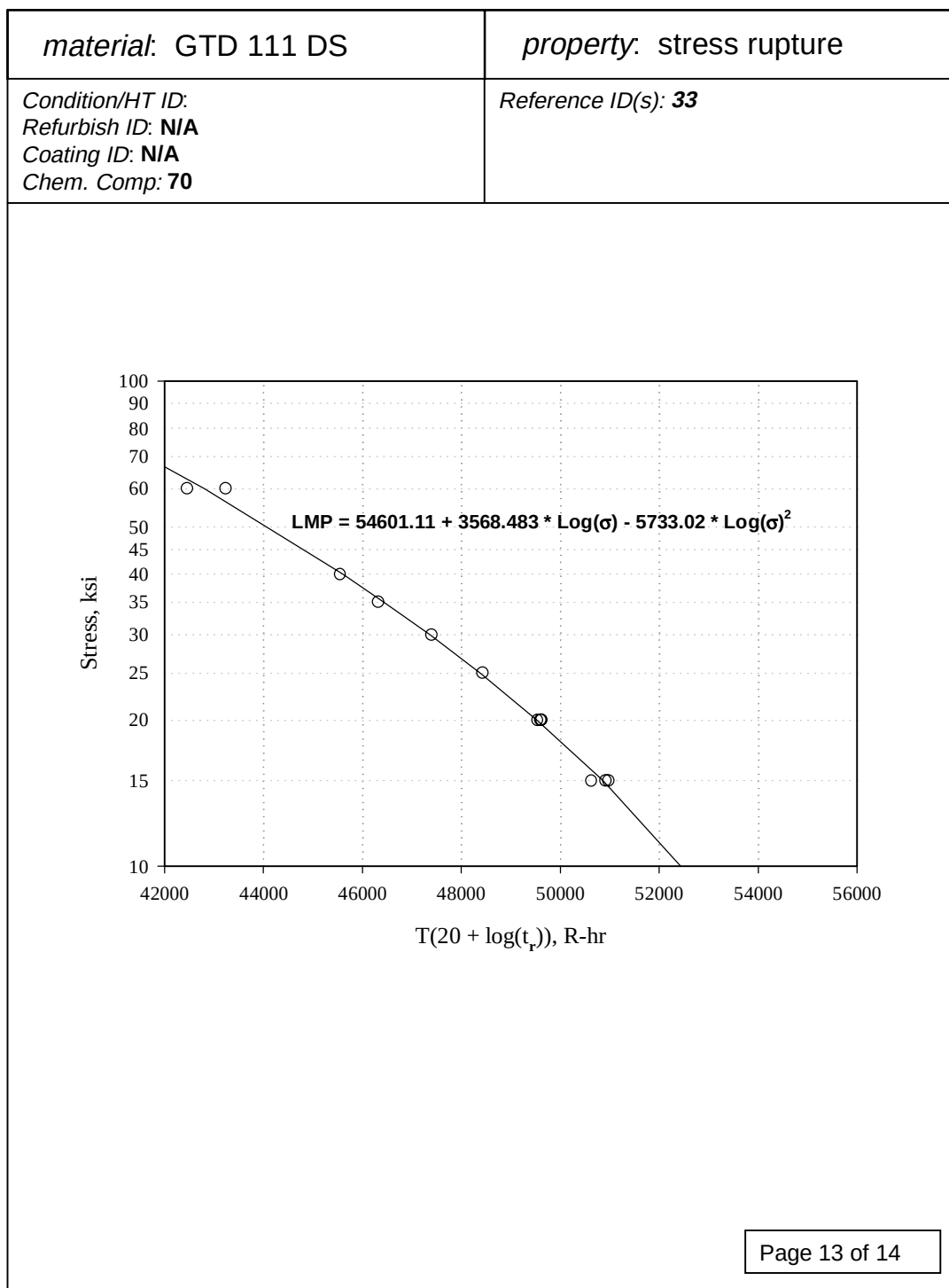


Figure 17-13
LMP Plot of Transverse Specimen Data from Undegraded Shank Location.

GTD 111 DS

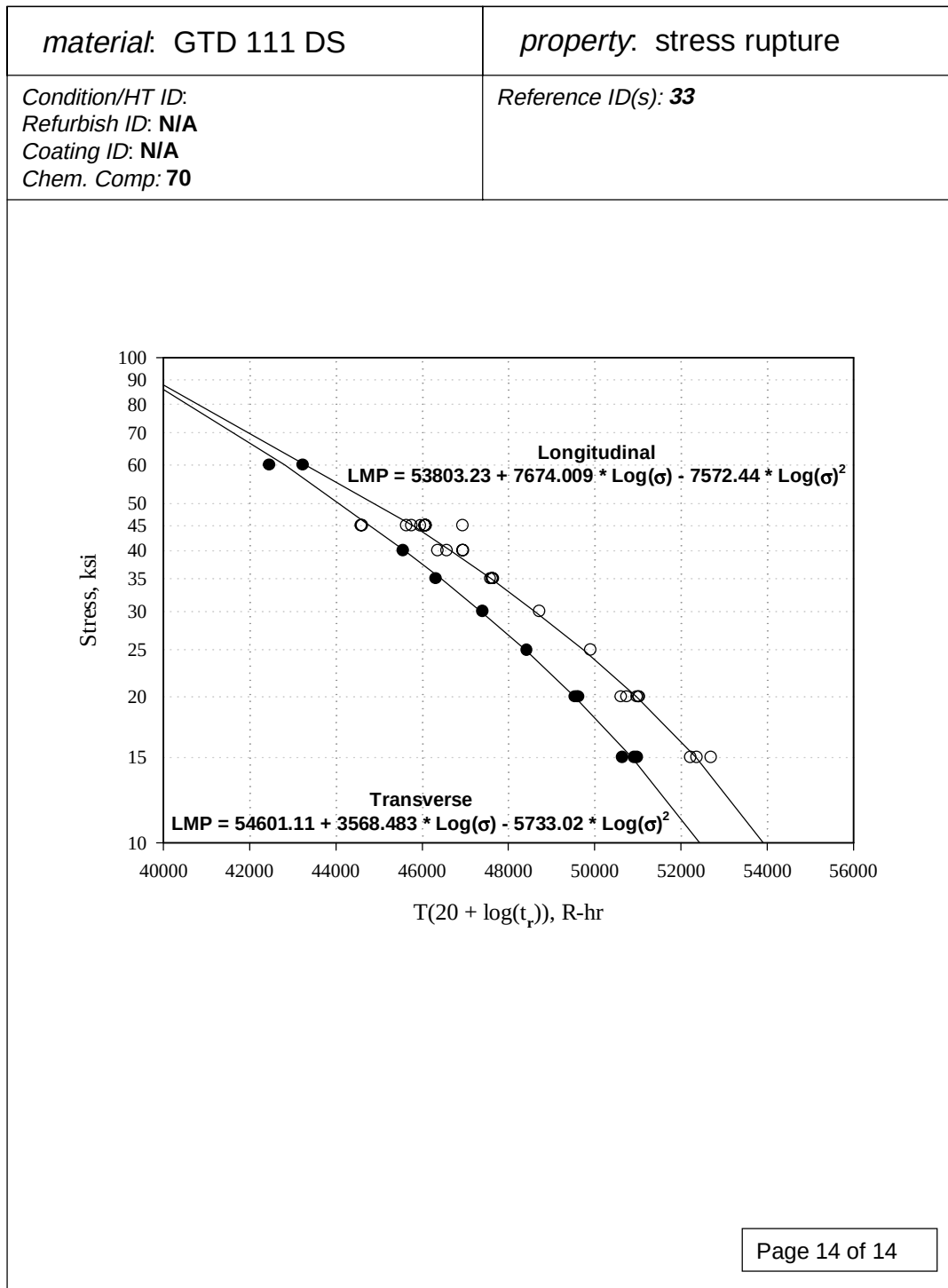


Figure 17-14
Influence of Specimen Orientation on Creep Rupture Strength of Unaged (Shank) Material.

18

GTD 111 EA

GTD 111 EA

<i>material:</i> GTD 111 EA and DS		<i>property:</i> tensile	
Condition/HT ID: 59 Refurbish ID: N/A Coating ID: N/A Chem. Comp: 71, 72		Reference ID(s): 31	

Property	IN-738		GTD-111EA		GTD-111DS	
	75°F	1600°F	75°F	1600°F	75°F	1600°F
Yield Strength, ksi (0.2%)	109	67	101.5	63.2	96.9	74.4
Tensile Strength, ksi	122.7	95.4	126.1	91.9	141.9	93.6
% Elongation	4.1	21.5	1.8	6.6	5.7	24.4
% Reduction of Area	5.0	32.6	3.5	8.1	6.4	38.8
Hardness* (R _c)	40.1 (R)	--	40.4 (R)	--	--	40.5 (R)
	37.6 (A)		35.8 (A)			36.0 (A)

* R=Root; A=Airfoil

Page 1 of 23

Figure 18-1
Tensile Properties and Hardness in the Service Aged Condition.

GTD 111 EA

material: GTD 111 EA and DS		property: tensile	
Condition/HT ID: 59 Refurbish ID: HIPPED, coated, re-heat Coating ID: NIA Chem. Comp: 71, 72		Reference ID(s): 31	

Property	IN-738		GTD-111EA		GTD-111DS	
	75°F	1600°F	75°F	1600°F	75°F	1600°F
Yield Strength, ksi (0.2%)	109.8	95.3	117.6	79.7	124.5	75.6
Tensile Strength, ksi	119.2	65.8	164.0	103.4	145.2	105.8
% Elongation	9.0	20.1	14.3	22.0	9.0	26.1
% Reduction of Area	15.5	27.4	15.2	33.8	15.5	30.6
Hardness, (R _c)	36.8	--	41.4	--	37.8	--

Page 2 of 23

Figure 18-2
Tensile and Hardness Properties after Refurbishment.

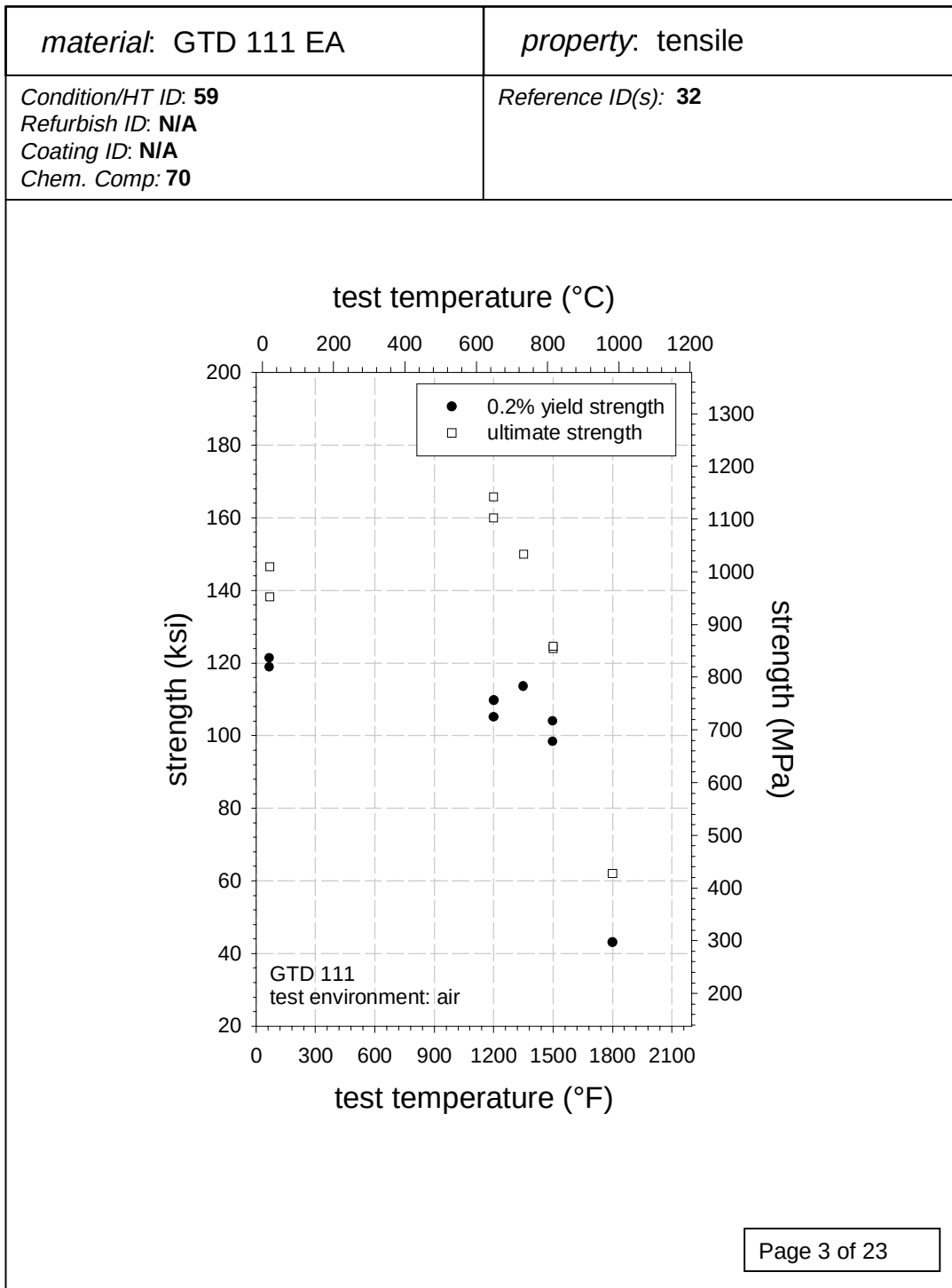


Figure 18-3
Tensile Strengths as a Function of Temperature.

GTD 111 EA

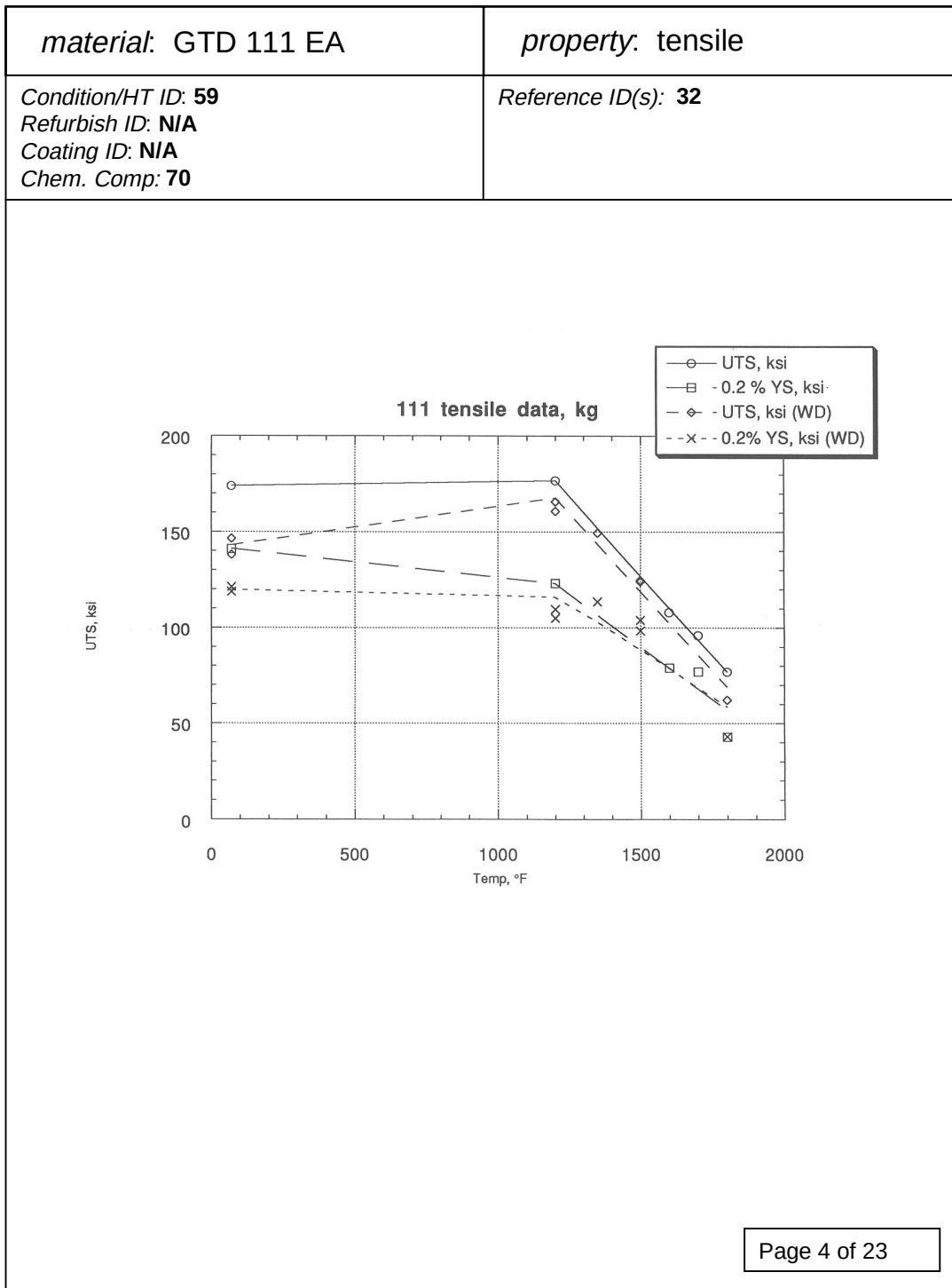


Figure 18-4
Tensile Strengths as a Function of Temperature.

material: GTD 111 EA		property: tensile																																				
Condition/HT ID: 59 Refurbish ID: N/A Coating ID: N/A Chem. Comp: 70		Reference ID(s): 32																																				
No. of Hours = 3.612 ROOM TEMPERATURE AND 1600°F TENSILE DATA MS5001 BUCKET, GTD111EA <table><thead><tr><th>ID</th><th>Test Temp., F</th><th>0.02% Offset Yield Strength Psi</th><th>0.2% Offset Yield Strength Psi</th><th>Ultimate Tensile Strength, Psi</th><th>% Elongation</th><th>% RA</th></tr></thead><tbody><tr><td>Root</td><td>70</td><td>96,500</td><td>116,700</td><td>143,600</td><td>7.9</td><td>10.6</td></tr><tr><td>Airfoil</td><td>70</td><td>87,700</td><td>100,300</td><td>128,500</td><td>6.9</td><td>9.1</td></tr><tr><td>Root</td><td>1600</td><td>63,200</td><td>77,400</td><td>105,200</td><td>21.5</td><td>42.0</td></tr><tr><td>Airfoil</td><td>1600</td><td>62,900</td><td>75,400</td><td>97,400</td><td>27.4</td><td>36.6</td></tr></tbody></table>				ID	Test Temp., F	0.02% Offset Yield Strength Psi	0.2% Offset Yield Strength Psi	Ultimate Tensile Strength, Psi	% Elongation	% RA	Root	70	96,500	116,700	143,600	7.9	10.6	Airfoil	70	87,700	100,300	128,500	6.9	9.1	Root	1600	63,200	77,400	105,200	21.5	42.0	Airfoil	1600	62,900	75,400	97,400	27.4	36.6
ID	Test Temp., F	0.02% Offset Yield Strength Psi	0.2% Offset Yield Strength Psi	Ultimate Tensile Strength, Psi	% Elongation	% RA																																
Root	70	96,500	116,700	143,600	7.9	10.6																																
Airfoil	70	87,700	100,300	128,500	6.9	9.1																																
Root	1600	63,200	77,400	105,200	21.5	42.0																																
Airfoil	1600	62,900	75,400	97,400	27.4	36.6																																
Page 5 of 23																																						

Figure 18-5
Tensile Properties for Root and Airfoil Material at 70°F and 1600°F.

GTD 111 EA

material: GTD 111 EA				property: tensile																																						
Condition/HT ID: 59 Refurbish ID: NIA Coating ID: NIA Chem. Comp: 70				Reference ID(s): 32																																						
No. of Hours = 10.311 ROOM TEMPERATURE AND 1600°F TENSILE DATA MS5001 BUCKET, GTD111EA <table><thead><tr><th>ID</th><th>Test Temp., F</th><th>0.02% Offset Yield Strength Psi</th><th>0.2% Offset Yield Strength Psi</th><th>Ultimate Tensile Strength Psi</th><th>% Elongation</th><th>% RA</th></tr></thead><tbody><tr><td>Root</td><td>70</td><td>90,900</td><td>115,700</td><td>137,300</td><td>7.9</td><td>10.9</td></tr><tr><td>Airfoil</td><td>70</td><td>92,200</td><td>108,000</td><td>135,800</td><td>4.4</td><td>4.7</td></tr><tr><td>Root</td><td>1600</td><td>68,300</td><td>81,300</td><td>103,200</td><td>24.3</td><td>39.7</td></tr><tr><td>Airfoil</td><td>1600</td><td>60,600</td><td>72,300</td><td>100,500</td><td>22.6</td><td>29.2</td></tr></tbody></table>								ID	Test Temp., F	0.02% Offset Yield Strength Psi	0.2% Offset Yield Strength Psi	Ultimate Tensile Strength Psi	% Elongation	% RA	Root	70	90,900	115,700	137,300	7.9	10.9	Airfoil	70	92,200	108,000	135,800	4.4	4.7	Root	1600	68,300	81,300	103,200	24.3	39.7	Airfoil	1600	60,600	72,300	100,500	22.6	29.2
ID	Test Temp., F	0.02% Offset Yield Strength Psi	0.2% Offset Yield Strength Psi	Ultimate Tensile Strength Psi	% Elongation	% RA																																				
Root	70	90,900	115,700	137,300	7.9	10.9																																				
Airfoil	70	92,200	108,000	135,800	4.4	4.7																																				
Root	1600	68,300	81,300	103,200	24.3	39.7																																				
Airfoil	1600	60,600	72,300	100,500	22.6	29.2																																				
Page 6 of 23																																										

Figure 18-6
Tensile Properties for Root and Airfoil Material at 70°F and 1600°F.

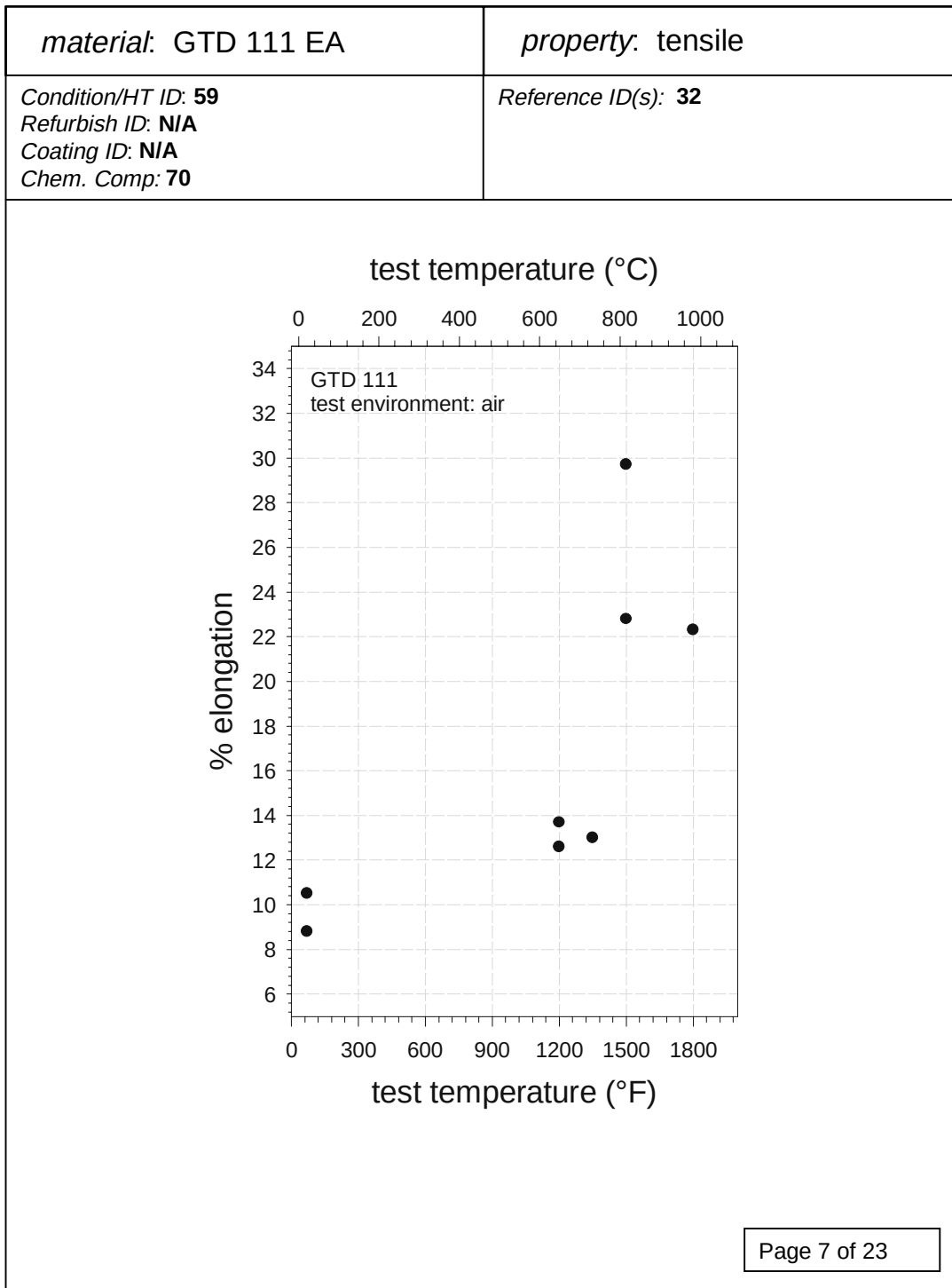


Figure 18-7
Tensile Elongation as a Function of Temperature.

GTD 111 EA

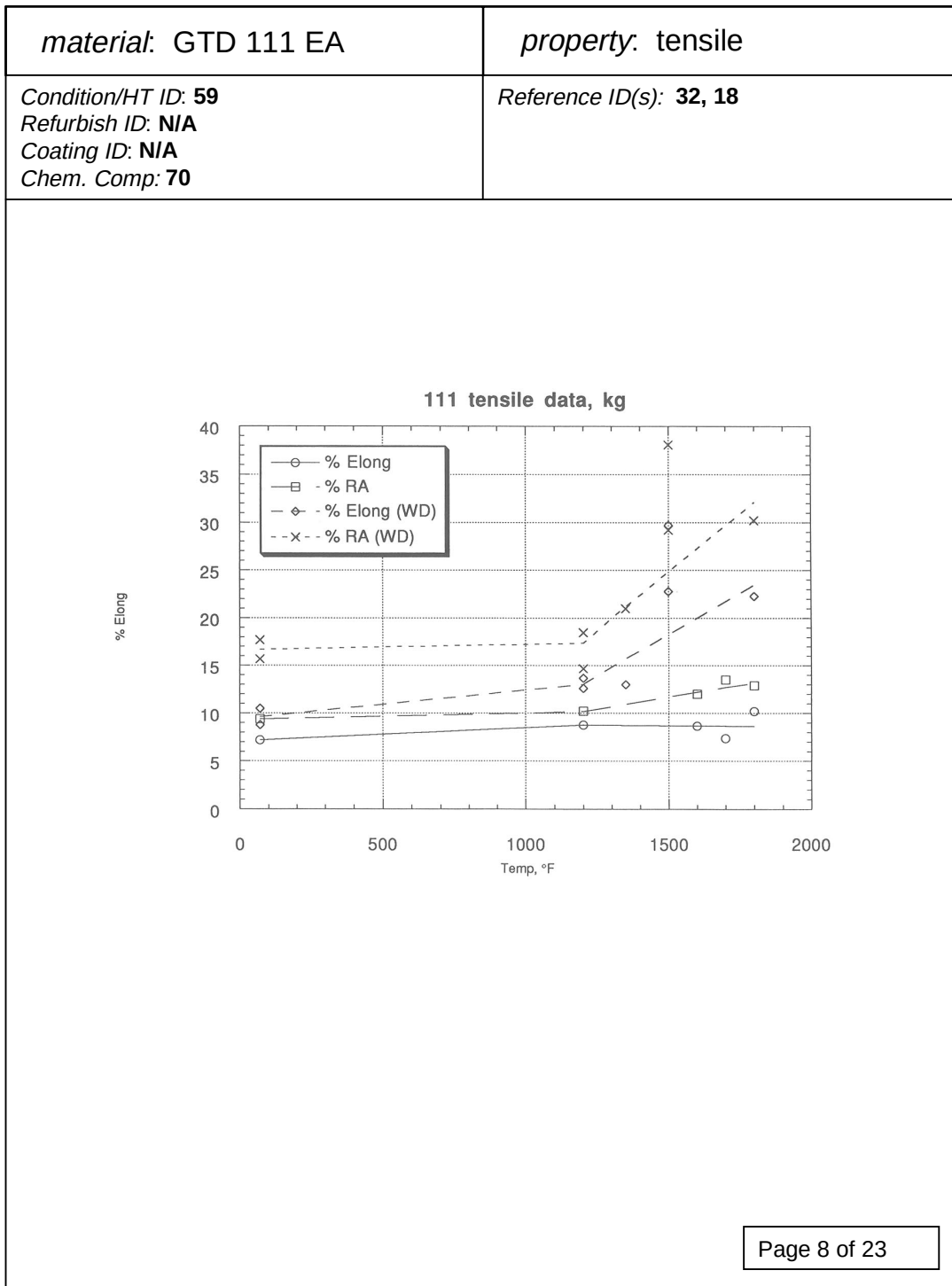


Figure 18-8
Tensile Elongation and Reduction in Area as a Function of Temperature.

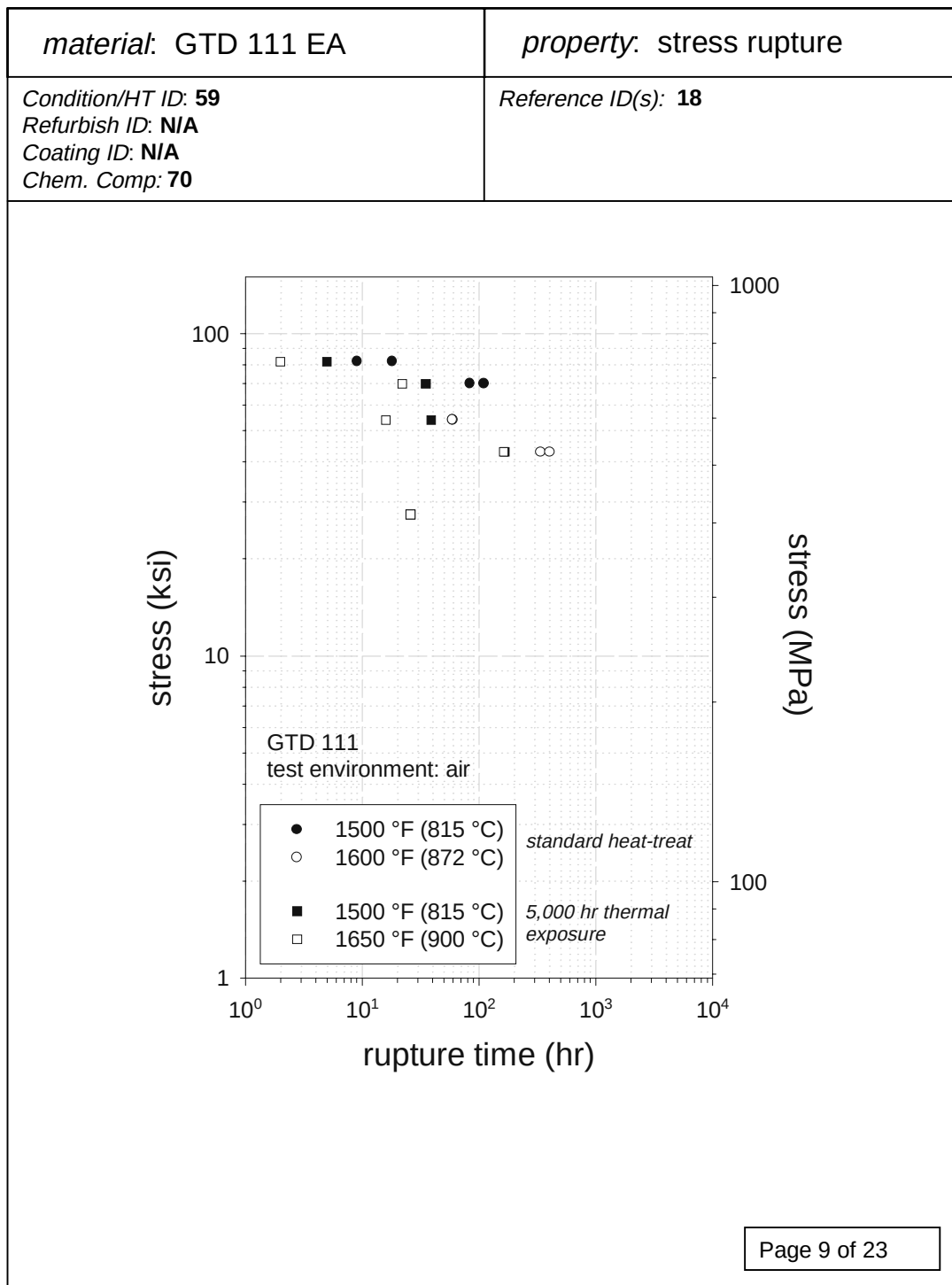


Figure 18-9
Stress vs. Rupture Time for Two Material Conditions.

GTD 111 EA

<i>material:</i> GTD 111 EA		<i>property:</i> stress rupture																					
Condition/HT ID: 59 Refurbish ID: N/A Coating ID: N/A Chem. Comp: 70		Reference ID(s): 32																					
No. of Hours = 3.612 STRESS-RUPTURE TESTS MS5001 BUCKET, GTD111EA (1800°F — 27.5 ksi with 0.160 Inch Diameter Bar Specimens) <table><tr><th>ID</th><th>RUPTURE TIME, HOURS</th><th>% ELONGATION</th><th>% RA</th></tr><tr><td>Root</td><td>30.1</td><td>11.4</td><td>11.6</td></tr><tr><td>Root</td><td>34.2</td><td>9.5</td><td>7.2</td></tr><tr><td>Airfoil</td><td>19.3</td><td>11.8</td><td>12.3</td></tr><tr><td>Airfoil</td><td>20.7</td><td>10.0</td><td>10.1</td></tr></table>				ID	RUPTURE TIME, HOURS	% ELONGATION	% RA	Root	30.1	11.4	11.6	Root	34.2	9.5	7.2	Airfoil	19.3	11.8	12.3	Airfoil	20.7	10.0	10.1
ID	RUPTURE TIME, HOURS	% ELONGATION	% RA																				
Root	30.1	11.4	11.6																				
Root	34.2	9.5	7.2																				
Airfoil	19.3	11.8	12.3																				
Airfoil	20.7	10.0	10.1																				

Page 10 of 23

Figure 18-10
Stress-Rupture Results for Root and Airfoil Material.

<i>material:</i> GTD 111 EA and DS				<i>property:</i> stress rupture																																																																																	
Condition/HT ID: 59 Refurbish ID: NIA Coating ID: NIA Chem. Comp: 71, 72				Reference ID(s): 31																																																																																	
<table><tr><th>Material</th><th>Condition</th><th>Test Temp. (°F)</th><th>Stress (ksi)</th><th>Rupture Hours</th><th>% Elongation</th><th>% Reduction of Area</th></tr><tr><td rowspan="2">IN-738</td><td>Service Aged</td><td>1600</td><td>45</td><td>40.4</td><td>9.0</td><td>12.2</td></tr><tr><td>Service Aged</td><td>1600</td><td>40</td><td>126.1</td><td>7.3</td><td>7.5</td></tr><tr><td rowspan="2">IN-738</td><td>Rejuvenated</td><td>1600</td><td>45</td><td>49.7</td><td>10.6</td><td>11.5</td></tr><tr><td>Rejuvenated</td><td>1600</td><td>40</td><td>142.4</td><td>10.8</td><td>16.3</td></tr><tr><td rowspan="2">GTD-111EA</td><td>Service Aged</td><td>1600</td><td>45</td><td>44.0</td><td>10.2</td><td>18.4</td></tr><tr><td>Rejuvenated</td><td>1600</td><td>45</td><td>141.1</td><td>17.4</td><td>19.8</td></tr><tr><td rowspan="4">GTD-111DS</td><td>Rejuvenated</td><td>1600</td><td>40</td><td>315.7</td><td>12.7</td><td>17.5</td></tr><tr><td>Service Aged</td><td>1600</td><td>45</td><td>71.2</td><td>21</td><td>33.2</td></tr><tr><td>Service Aged</td><td>1600</td><td>40</td><td>197.7</td><td>17.6</td><td>21.0</td></tr><tr><td>Rejuvenated</td><td>1600</td><td>45</td><td>232.2</td><td>36.6</td><td>59.6</td></tr><tr><td></td><td>Rejuvenated</td><td>1600</td><td>40</td><td>606.6</td><td>22.5</td><td>36</td></tr></table>								Material	Condition	Test Temp. (°F)	Stress (ksi)	Rupture Hours	% Elongation	% Reduction of Area	IN-738	Service Aged	1600	45	40.4	9.0	12.2	Service Aged	1600	40	126.1	7.3	7.5	IN-738	Rejuvenated	1600	45	49.7	10.6	11.5	Rejuvenated	1600	40	142.4	10.8	16.3	GTD-111EA	Service Aged	1600	45	44.0	10.2	18.4	Rejuvenated	1600	45	141.1	17.4	19.8	GTD-111DS	Rejuvenated	1600	40	315.7	12.7	17.5	Service Aged	1600	45	71.2	21	33.2	Service Aged	1600	40	197.7	17.6	21.0	Rejuvenated	1600	45	232.2	36.6	59.6		Rejuvenated	1600	40	606.6	22.5	36
Material	Condition	Test Temp. (°F)	Stress (ksi)	Rupture Hours	% Elongation	% Reduction of Area																																																																															
IN-738	Service Aged	1600	45	40.4	9.0	12.2																																																																															
	Service Aged	1600	40	126.1	7.3	7.5																																																																															
IN-738	Rejuvenated	1600	45	49.7	10.6	11.5																																																																															
	Rejuvenated	1600	40	142.4	10.8	16.3																																																																															
GTD-111EA	Service Aged	1600	45	44.0	10.2	18.4																																																																															
	Rejuvenated	1600	45	141.1	17.4	19.8																																																																															
GTD-111DS	Rejuvenated	1600	40	315.7	12.7	17.5																																																																															
	Service Aged	1600	45	71.2	21	33.2																																																																															
	Service Aged	1600	40	197.7	17.6	21.0																																																																															
	Rejuvenated	1600	45	232.2	36.6	59.6																																																																															
	Rejuvenated	1600	40	606.6	22.5	36																																																																															

Page 11 of 23

Figure 18-11
Stress-Rupture Data for GTD-111 EA and DS Compared to IN-738.

GTD 111 EA

<i>material:</i> GTD 111 EA		<i>property:</i> stress rupture																					
Condition/HT ID: 59 Refurbish ID: N/A Coating ID: N/A Chem. Comp: 70		Reference ID(s): 32																					
No. of Hours = 10.311 STRESS-RUPTURE TESTS MS5001 BUCKET, GTD111EA (1800°F —27.5 ksi with 0.160 Inch Diameter Bar Specimens) <table><tr><th>ID</th><th>RUPTURE TIME, HOURS</th><th>% ELONGATION</th><th>% RA</th></tr><tr><td>Root</td><td>28.2</td><td>10.0</td><td>9.1</td></tr><tr><td>Root</td><td>30.3</td><td>14.6</td><td>13.7</td></tr><tr><td>Airfoil</td><td>22.0</td><td>10.1</td><td>11.2</td></tr><tr><td>Airfoil</td><td>22.5</td><td>11.0</td><td>7.6</td></tr></table>				ID	RUPTURE TIME, HOURS	% ELONGATION	% RA	Root	28.2	10.0	9.1	Root	30.3	14.6	13.7	Airfoil	22.0	10.1	11.2	Airfoil	22.5	11.0	7.6
ID	RUPTURE TIME, HOURS	% ELONGATION	% RA																				
Root	28.2	10.0	9.1																				
Root	30.3	14.6	13.7																				
Airfoil	22.0	10.1	11.2																				
Airfoil	22.5	11.0	7.6																				

Page 12 of 23

Figure 18-12
Stress-Rupture Results for Root and Airfoil Material.

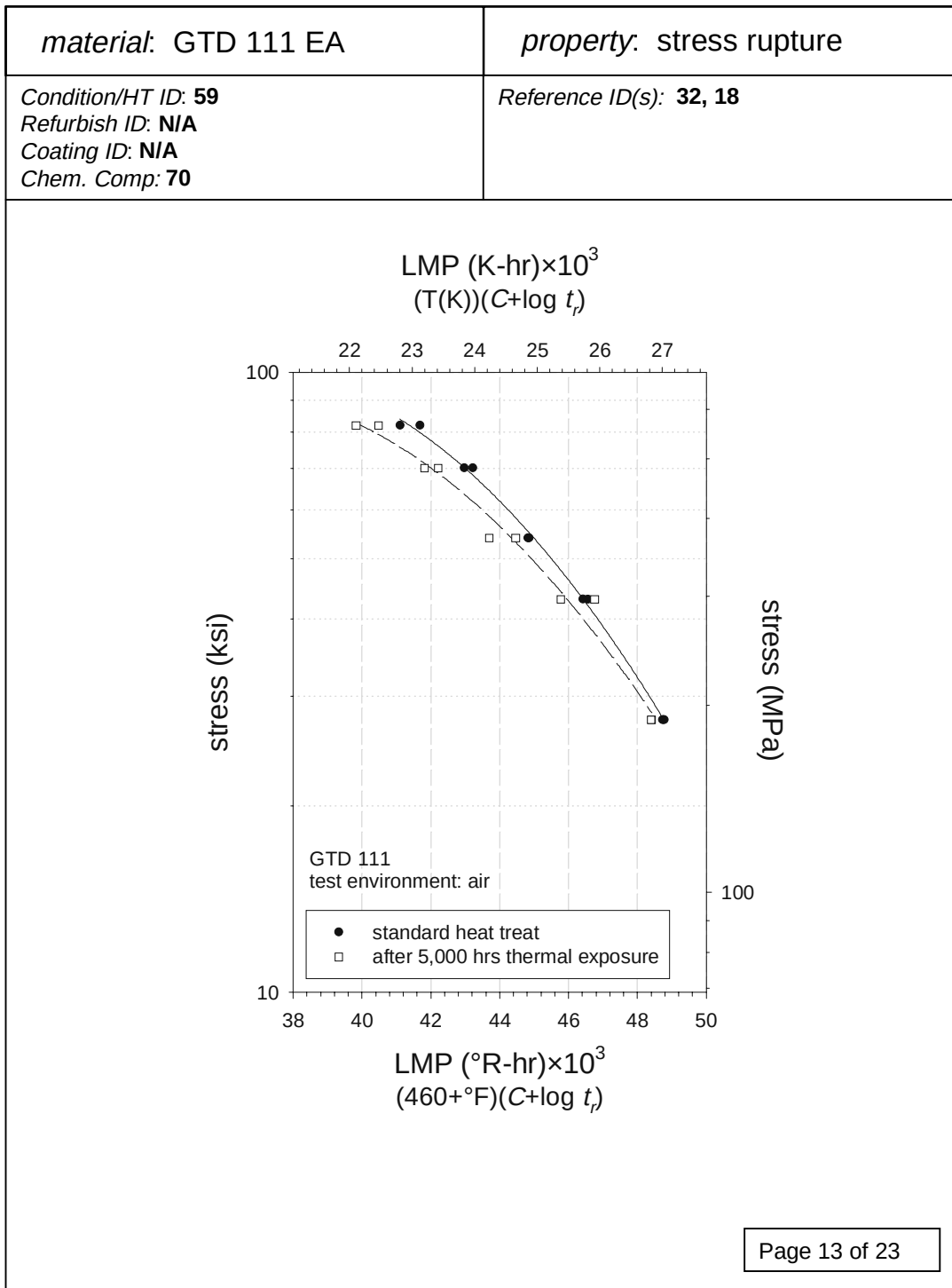


Figure 18-13
Larson-Miller Plot of GTD-111 EA (Standard Heat Treat and Thermally Exposed).

GTD 111 EA

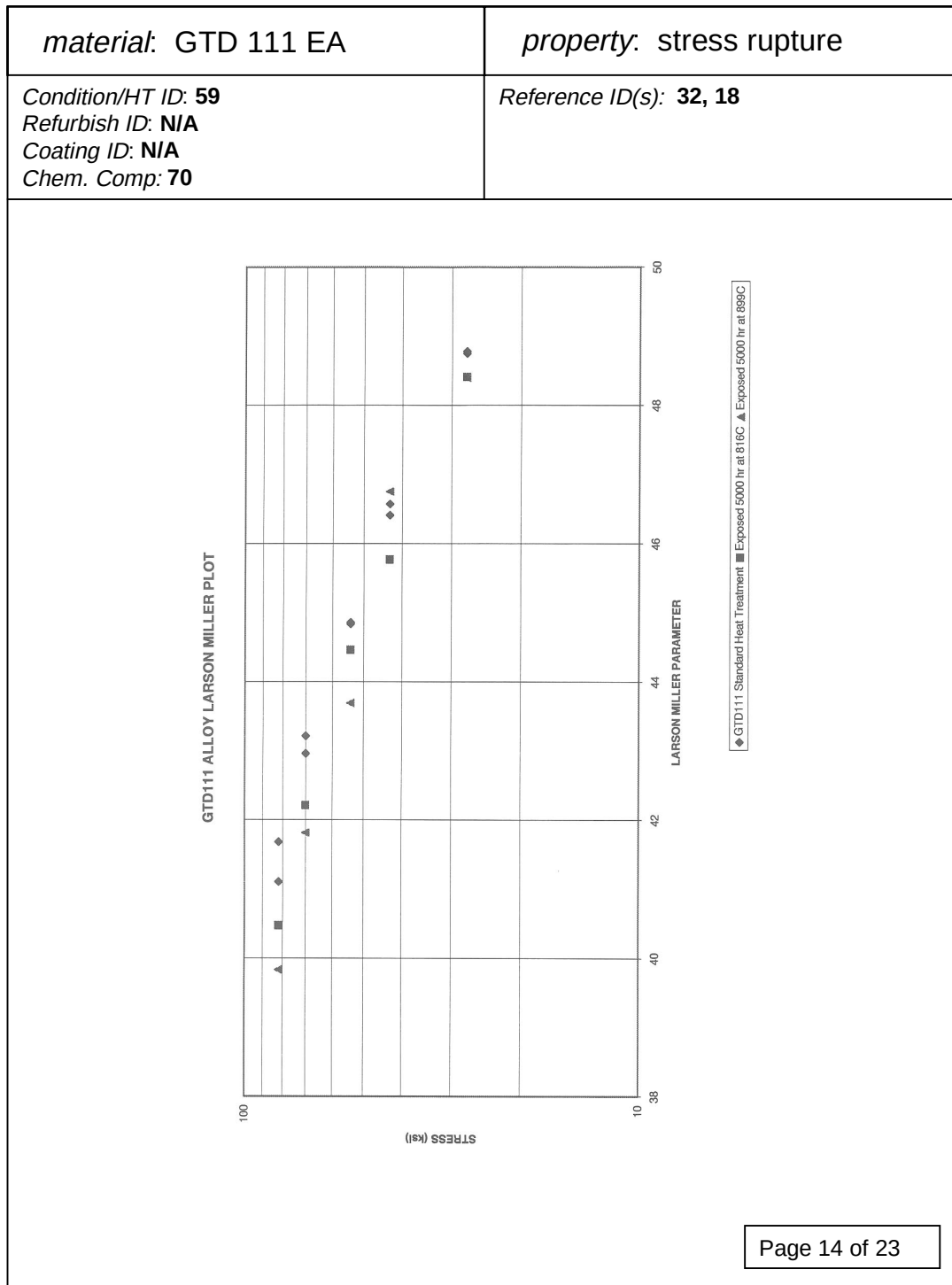


Figure 18-14
Larson-Miller Plot for GTD-111 EA.

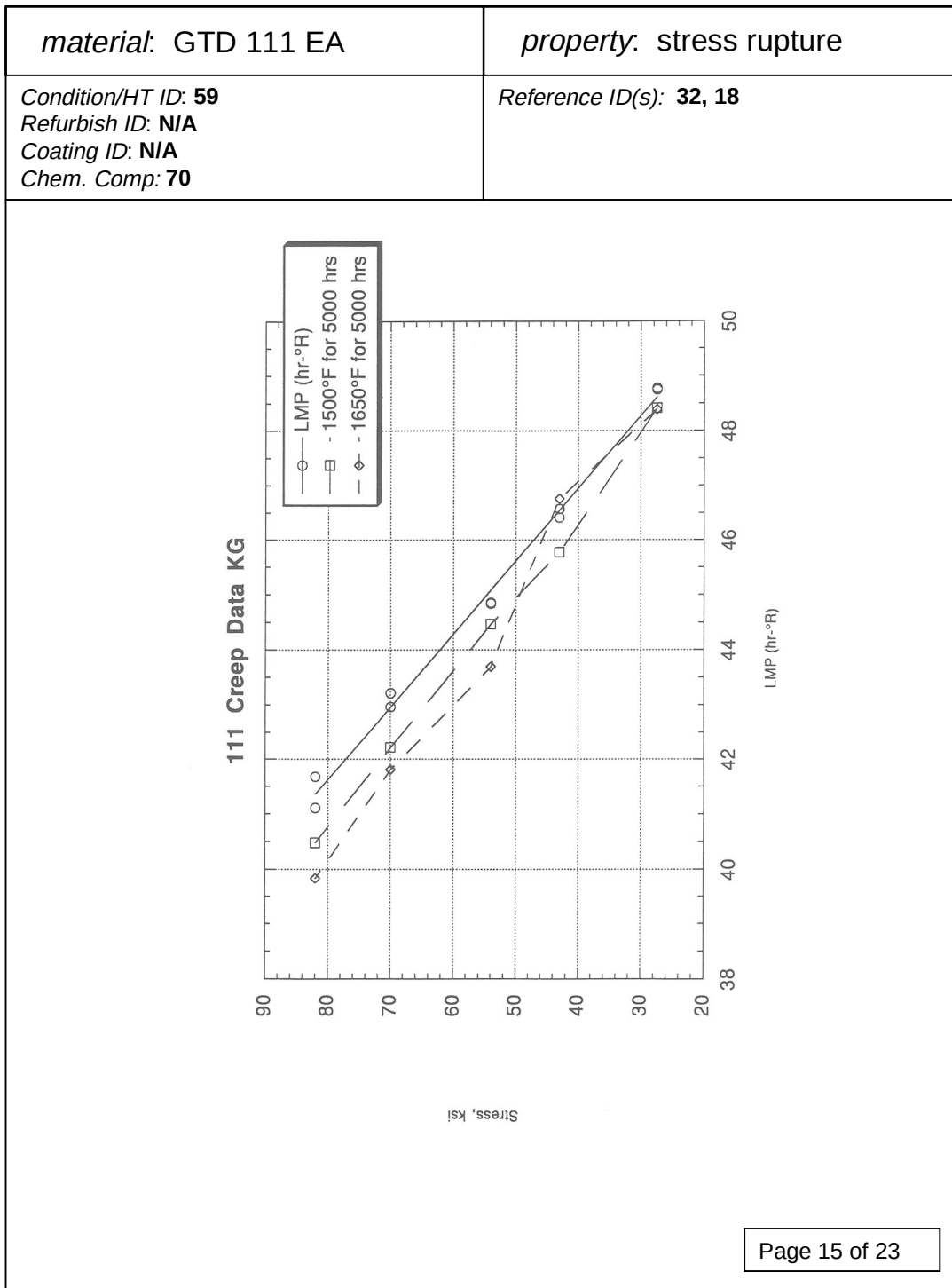


Figure 18-15
Larson-Miller Plot for GTD-111 for Different Exposure Conditions.

GTD 111 EA

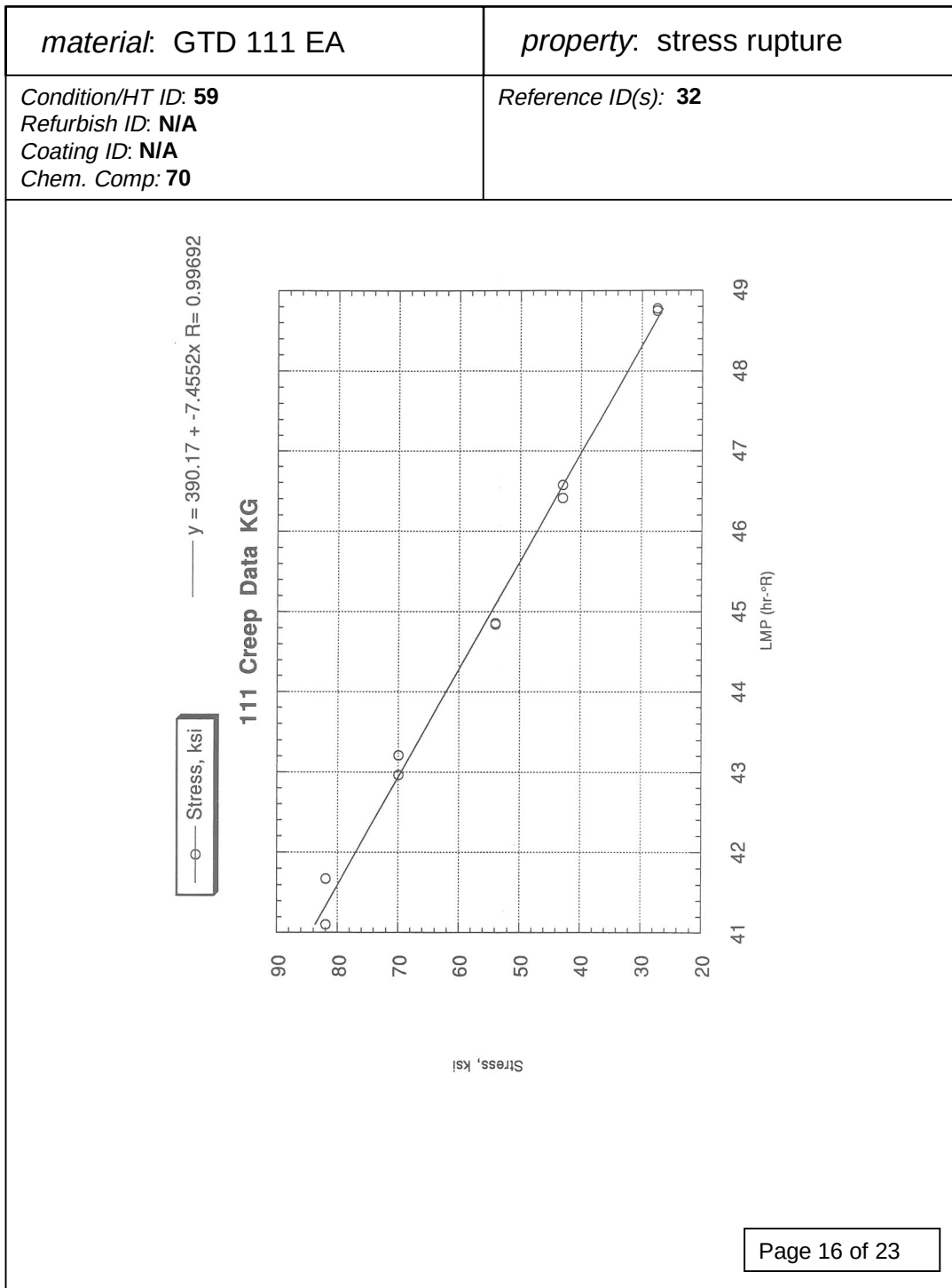


Figure 18-16
Larson-Miller Plot for GTD-111 EA.

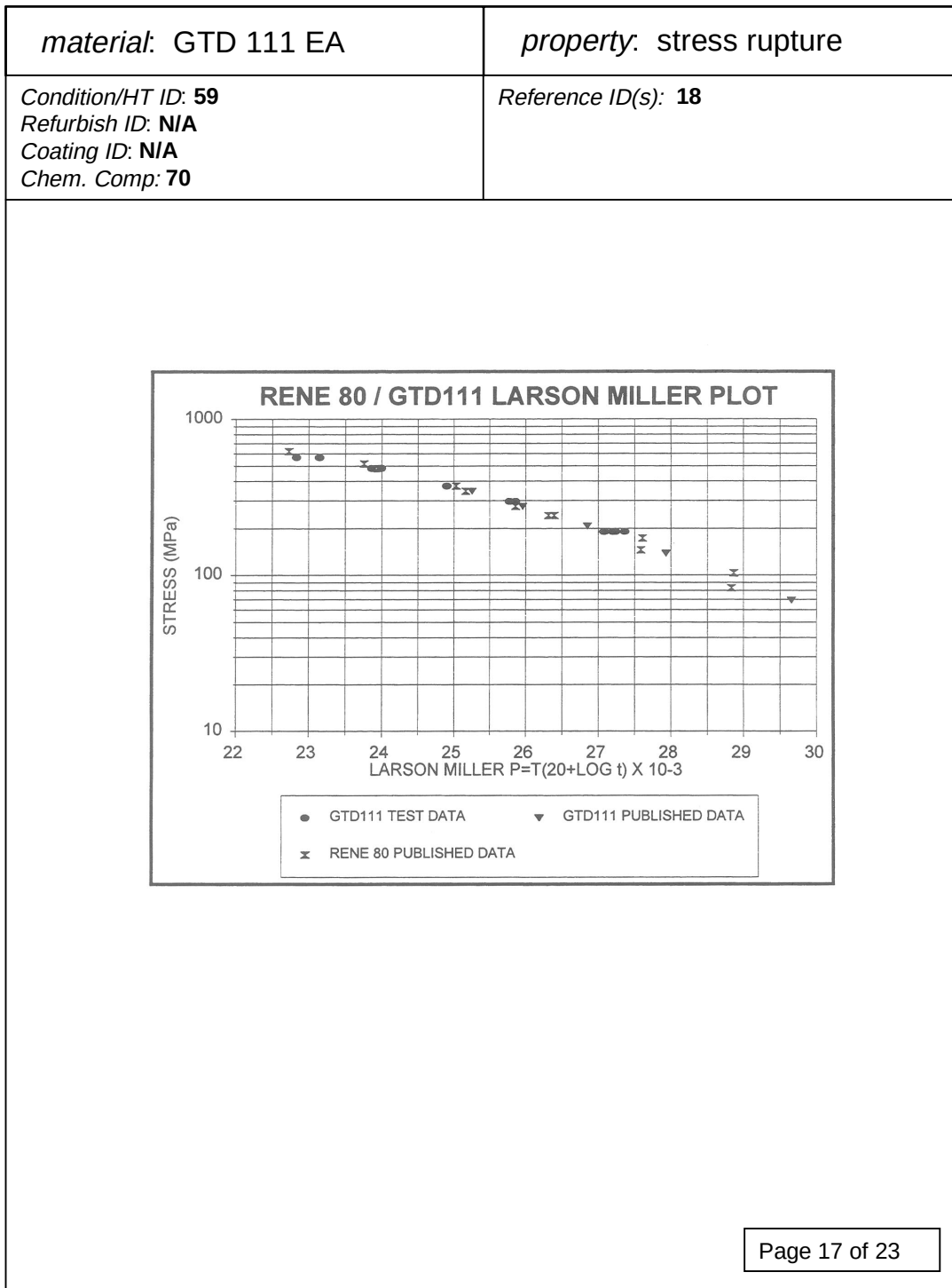
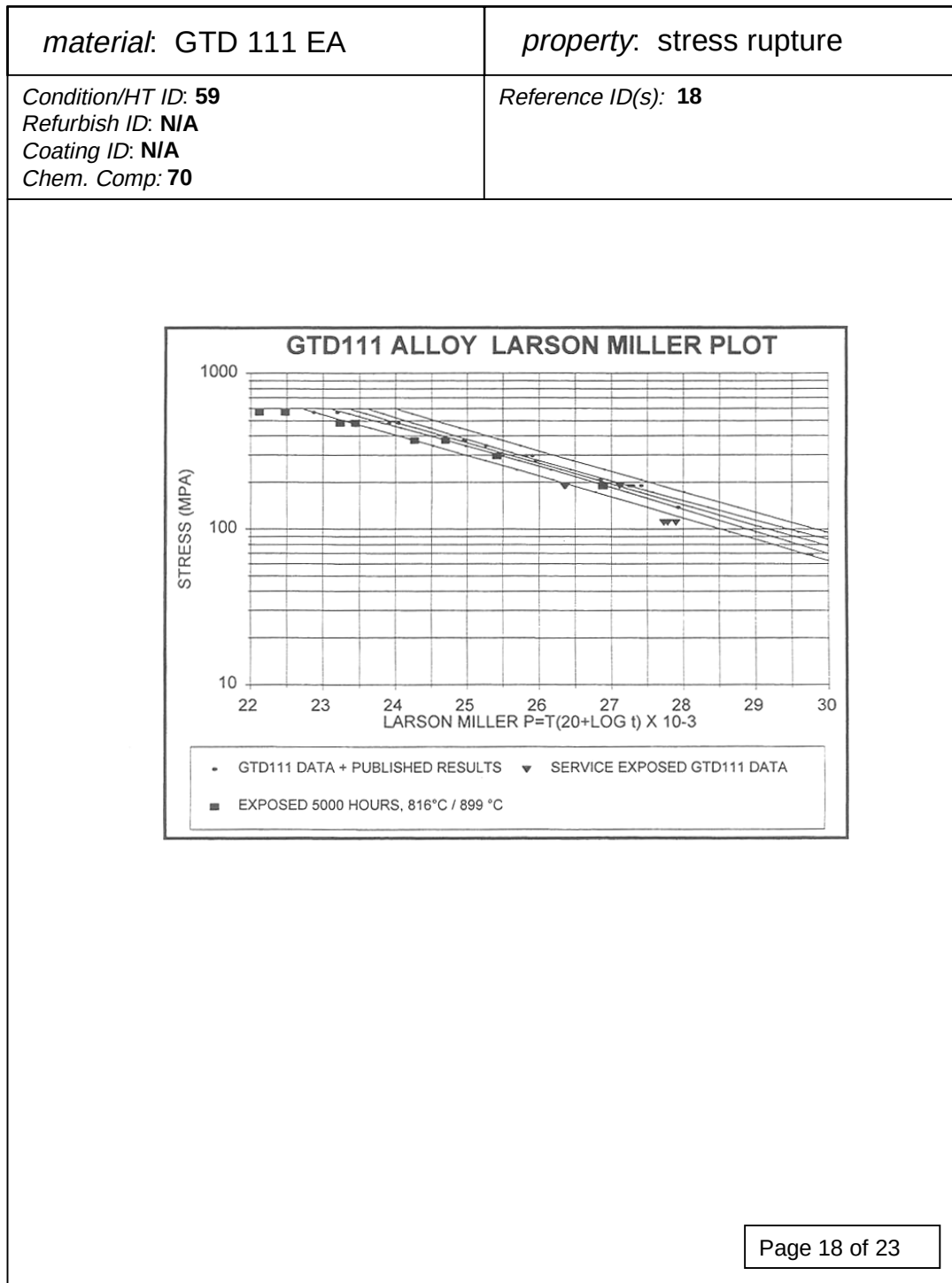


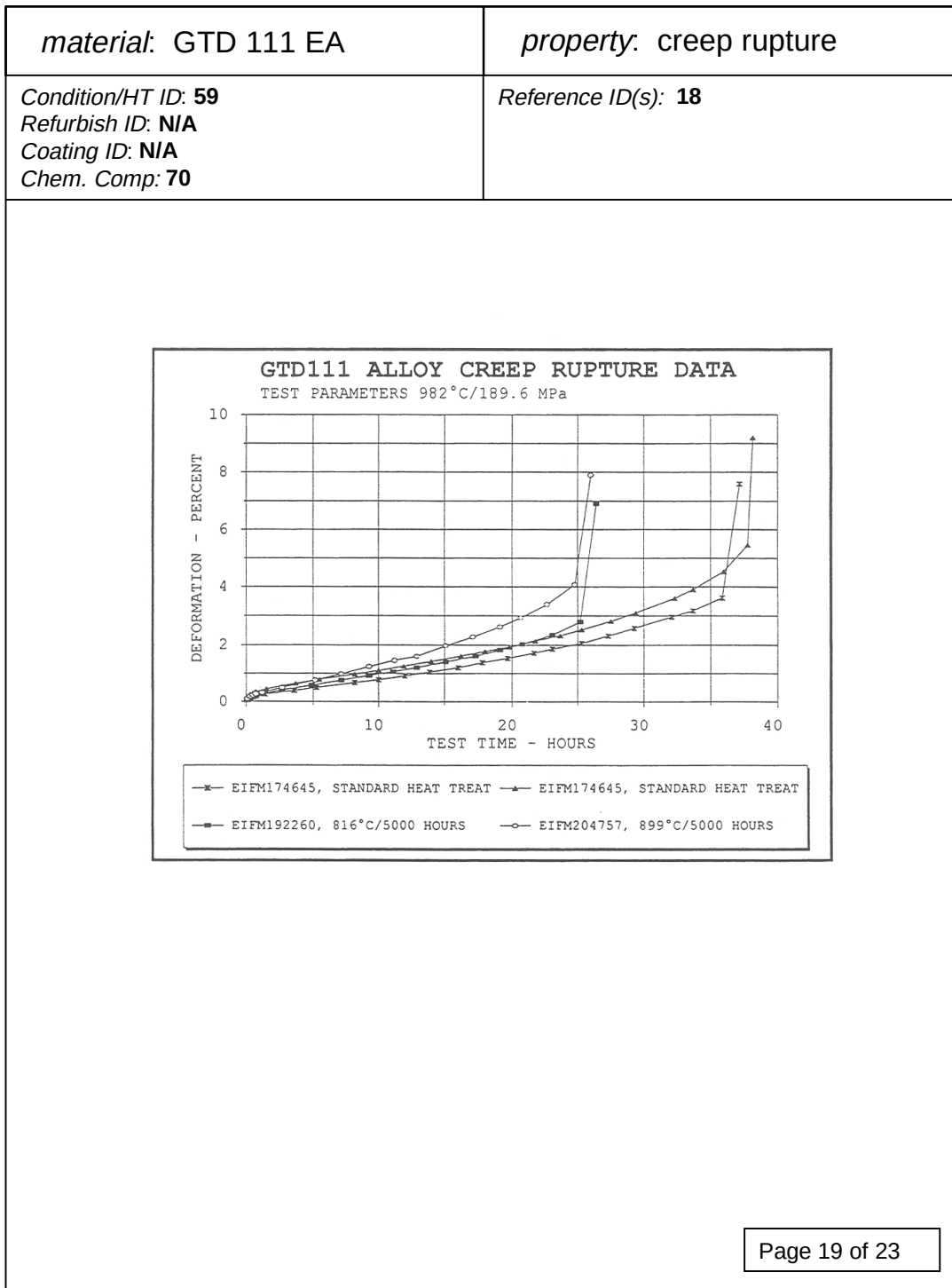
Figure 18-17

A Larson Miller Plot Comparing the GTD111 Alloy Test Points with Rene 80 Data from the Literature and the GTD111 Larson Miller Curve Published by General Electric.

GTD 111 EA

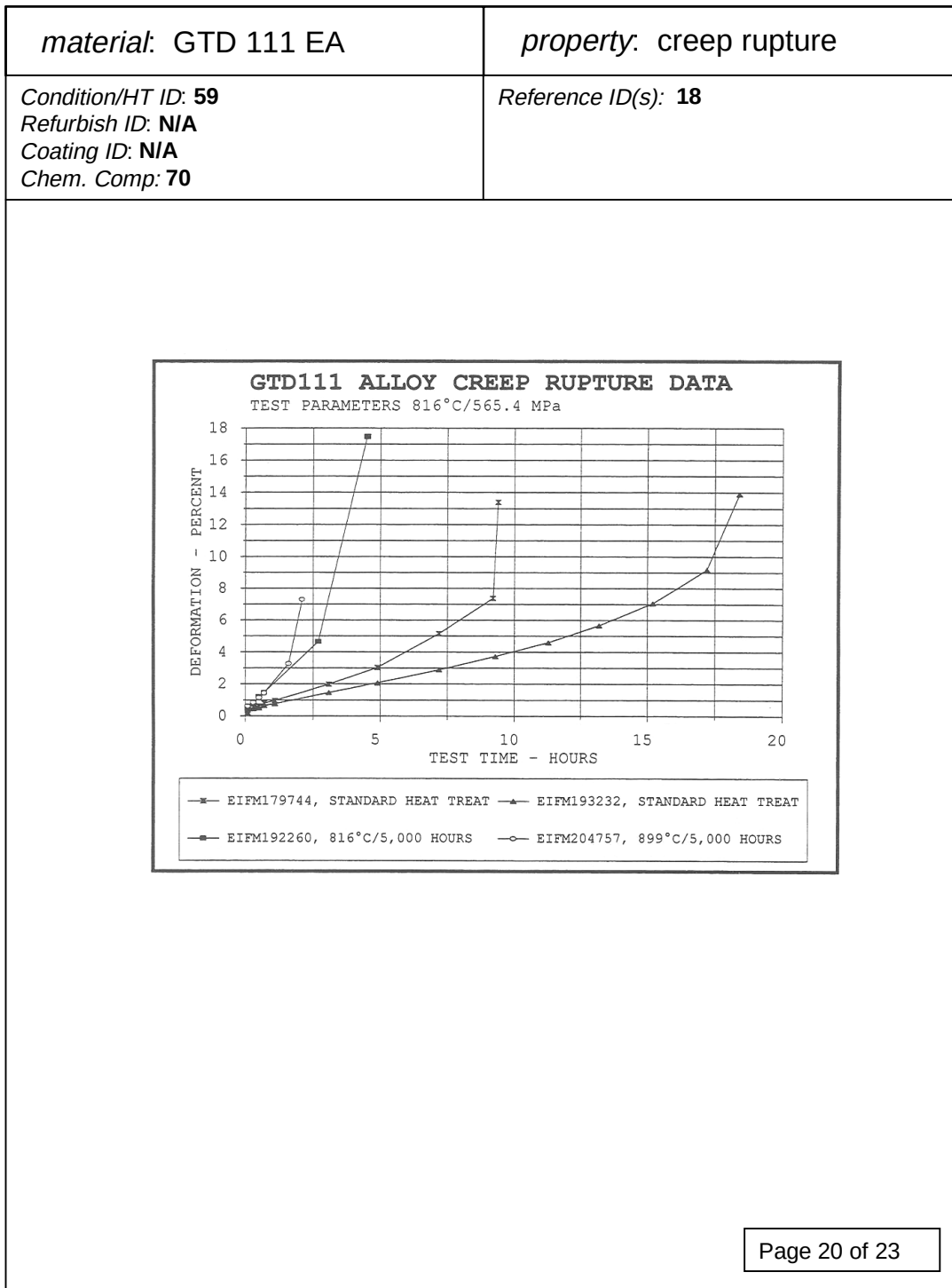
**Figure 18-18**

A Least Squares Regression Model ($Y = \beta_0 + \beta_1 X + e$) Fitted to the GTD111 Creep Rupture Data Illustrating the Fit. The 95% Confidence Intervals About the Mean and the 95% Prediction Interval for an Individual Observation. Test Data from the Thermally Exposed GTD111 Material and Select Service Exposed GTD111 Data Points are Plotted.

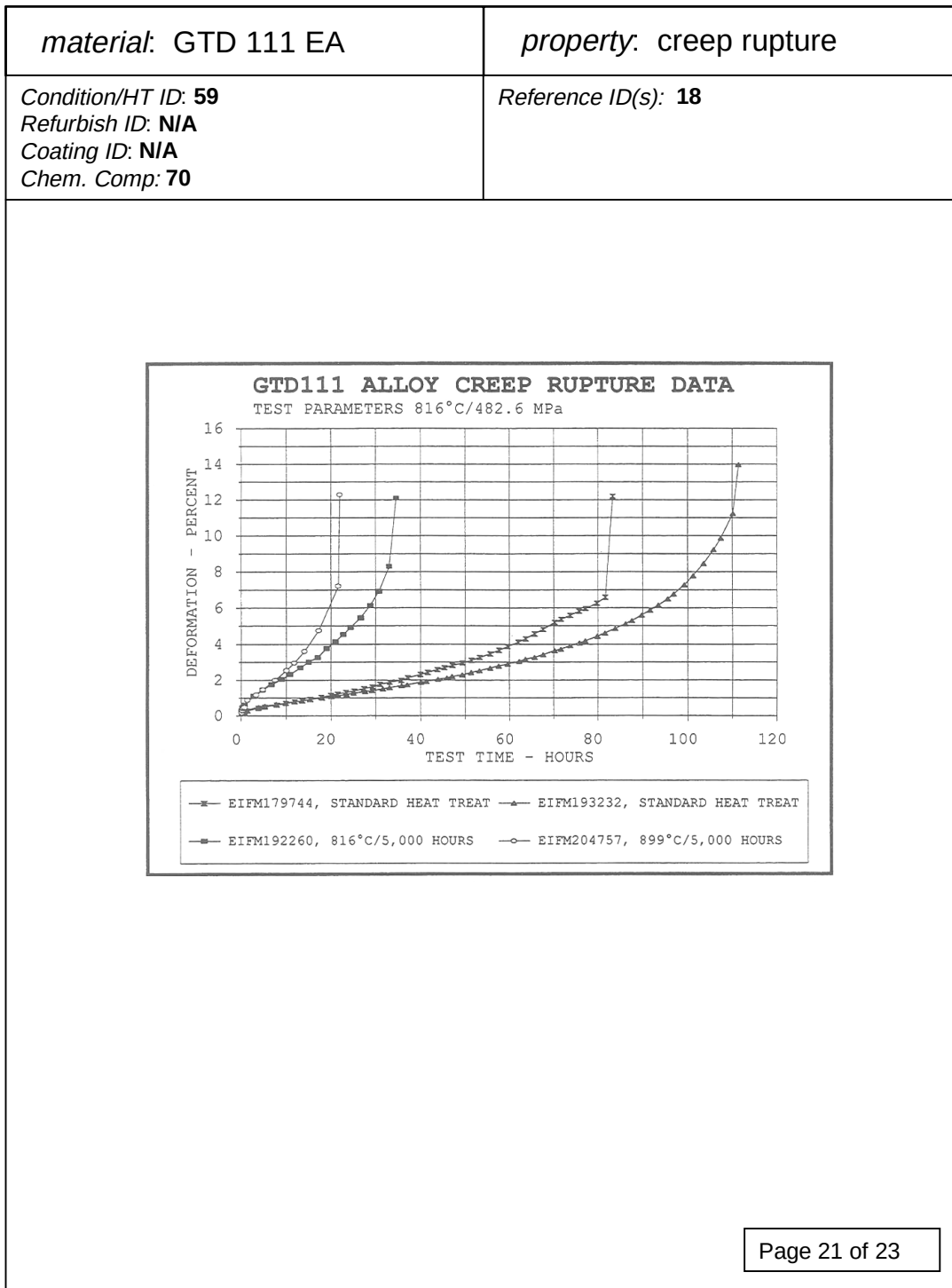
**Figure 18-19**

A Plot of Percent Creep Deformation (Strain) Versus Time for the Creep Rupture Samples in the Standard Heat Treated Condition and After Thermal Exposures at 816°C and 899°C.

GTD 111 EA

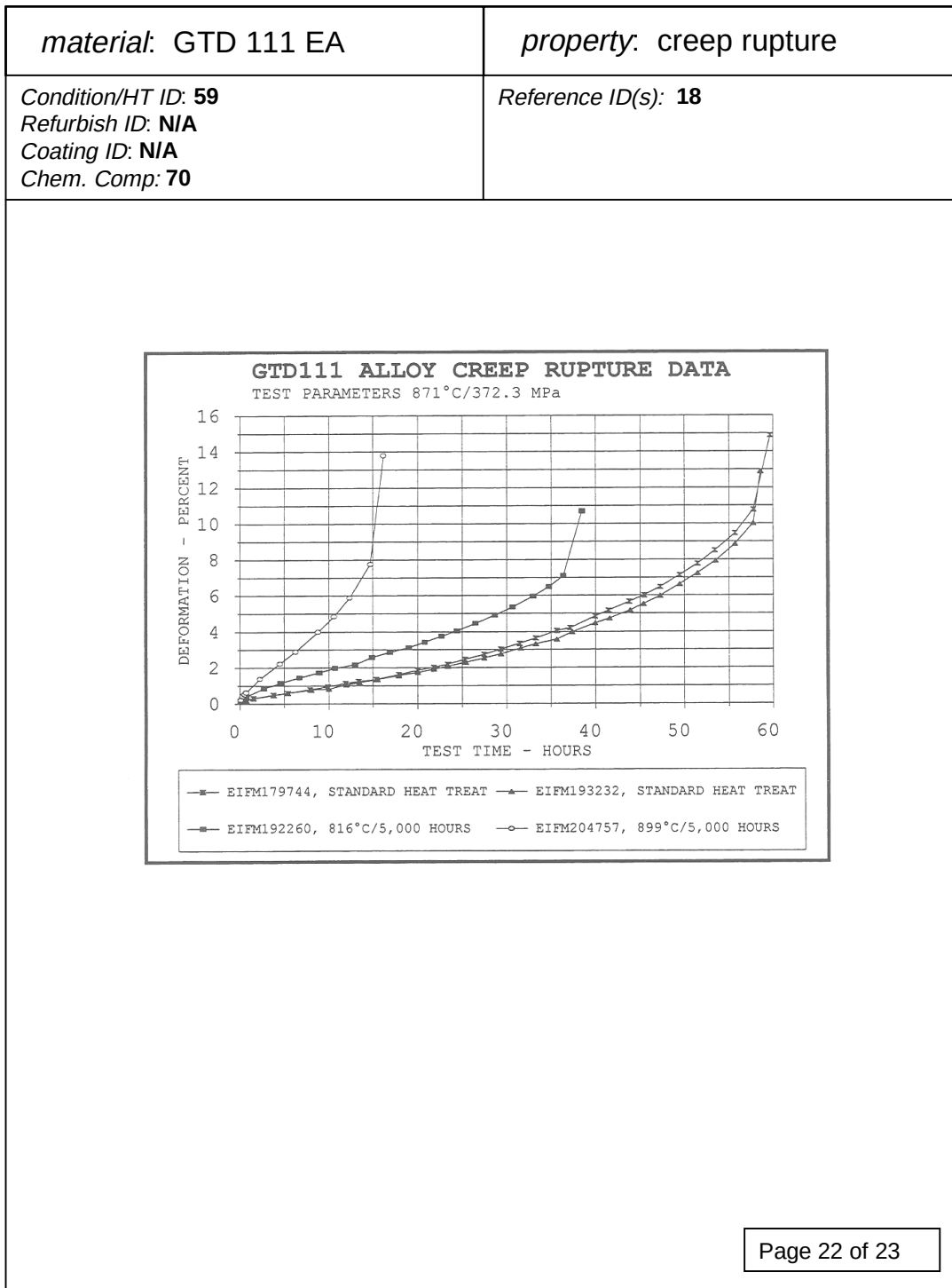
**Figure 18-20**

A Plot of Percent Creep Deformation (Strain) Versus Time for the Creep Rupture Samples in the Standard Heat Treated Condition and After Thermal Exposures at 816°C and 899°C.

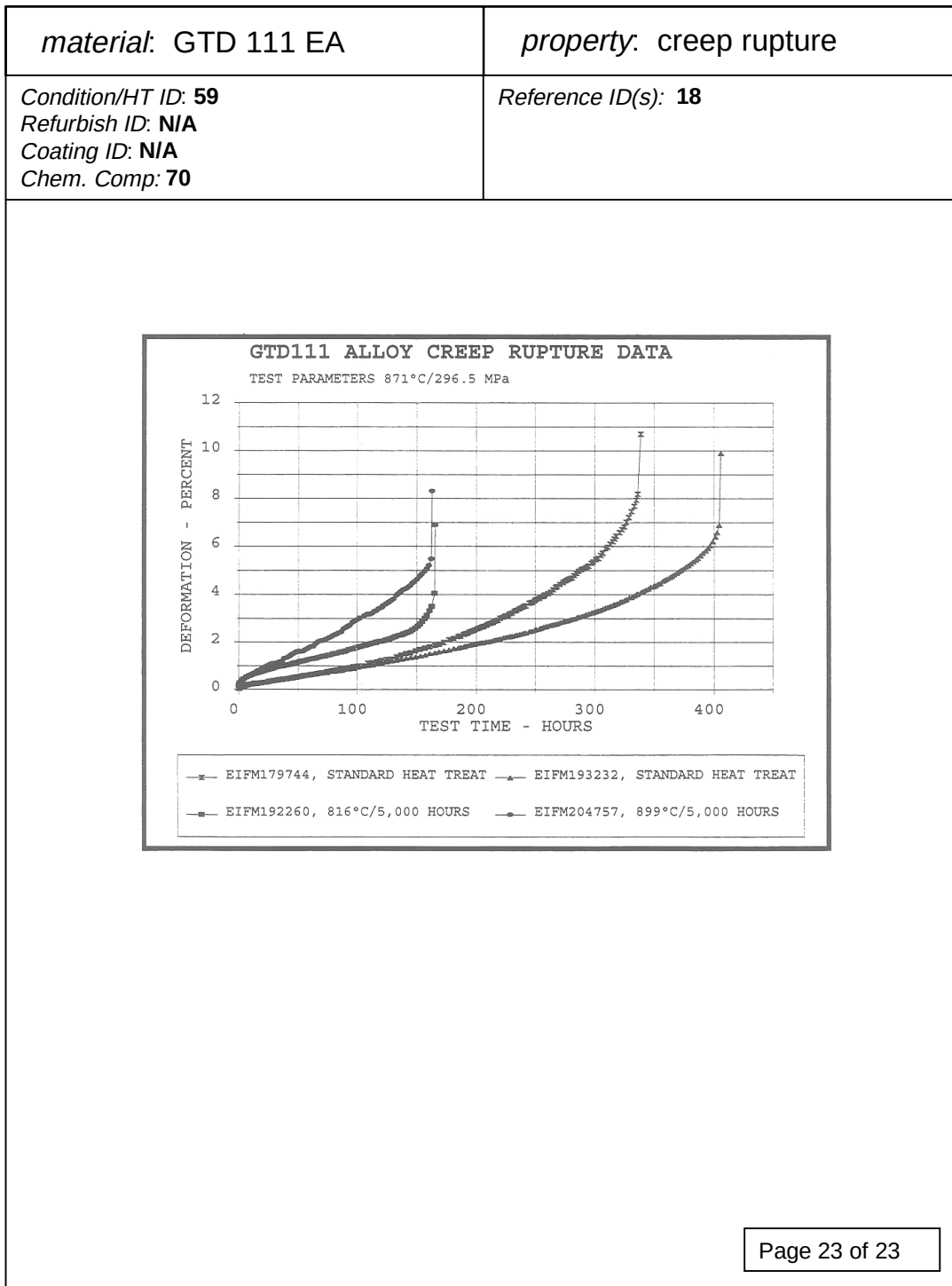
**Figure 18-21**

A Plot of Percent Creep Deformation (Strain) Versus Time for the Creep Rupture Samples in the Standard Heat Treated Condition and After Thermal Exposures at 816°C and 899°C.

GTD 111 EA

**Figure 18-22**

A Plot of Percent Creep Deformation (Strain) Versus Time for the Creep Rupture Samples in the Standard Heat Treated Condition and After Thermal Exposures at 816°C and 899°C.

**Figure 18-23**

A Plot of Percent Creep Deformation (Strain) Versus Time for the Creep Rupture Samples in the Standard Heat Treated Condition and After Thermal Exposures at 816°C and 899°C.

19

SOURCE REFERENCES

1. M. A. Burke, C. G. Beck, and E. A. Crombie, "The Influence of Materials Processing on the High Temperature Low Cycle Fatigue Properties of the Cast Alloy IN-738LC," Scientific Paper 84-1D7-MATCO-P1, Westinghouse R&D Center, Pittsburgh, PA 15235, Presented at 4th International Conference on Superalloys, Seven Springs, PA, 1984.
2. Y. Sugita, M. Ito, N. Isobe, S. Sakurai, C. R. Gold, T. E. Bloomer, and J. Kameda, "Degradation Characteristics of Intermetallic Coating on Nickel Base Superalloy Substrate in Gas Turbine Blade," *Materials and Manufacturing Processes*, Vol. 10, No. 5, 1995, pp. 987-1005.
3. D. A. Woodford, D. R. Van Steele, K. Amberge, and D. Stiles, "Creep Strength Evaluation for IN 738 Based on Stress Relaxation," *Superalloys 1992*, edited by S. D. Antolovich, R. W. Stusrud, R. A. MacKay, D. L. Anton, T. Khan, R. D. Kissinger, D. L. Klarstrom, The Minerals, Metals & Materials Society, 1992, pp. 657-664.
4. Fax communication from Jim Allen, Consulting Engineer-Gas Turbines, to Vis Viswanathan, EPRI, Subject IN-792 DS and EA LCF Curves, June 30, 2000.
5. R. Yang and G. A. Webster, "Creep/Fatigue Crack Growth in a Gas Turbine Blade Nickel Base Superalloy," presented at the Winter Annual Meeting of the American Society of Mechanical Engineers, Dallas, TX, November 25-30, 1990, pp. 31-36.
6. N. Taylor and P. Bontempi, "Impact Resistance of Superalloys at Gas Turbine Operating Temperatures," *Structural Integrity: Experiments, Models and Applications: Proceedings of the 10th Biennial European Conference on Fracture – ECF 10*, Berlin, Federal Republic of Germany, September 20-23, 1994, pp. 315-320.
7. G. T. Embley and V. V. Kallianpur, "Long-Term Creep Response of Gas Turbine Bucket Alloys," presented at Minnowbrook Conference on Life Prediction for High-Temperature Gas Turbine Materials, Blue Mountain Lake, NY, August 27-30, 1985.
8. D. W. Dean, M. C. Woodhall, A. C. Pickard, and G. A. Webster, "Interaction of Creep and Fatigue Damage in Gas Turbine Blade Material," *Mechanical Engineering Publications*, Suffolk, UK, 1987, pp. 25-36.
9. H. Sehitoglu and D. A. Boismier, "Thermo-Mechanical Fatigue of Mar-M247: Part 2 – Life Prediction," *Journal of Engineering Materials and Technology*, Transactions of the ASME, Vol. 112, January 1990, pp. 80-89.

Source References

10. D. A. Boismier and H. Sehitoglu, "Thermo-Mechanical Fatigue of Mar-M247: Part 1 – Experiments," *Journal of Engineering Materials and Technology*, Transactions of the ASME, Vol. 112, January 1990, pp. 68-79.
11. D. M. Moon and G. P. Sabol, "Effect of Mean Stress on the High-Cycle Fatigue Behavior of Udimet 710 at 1000 F," STP 520, American Society for Testing and Materials, Philadelphia, PA, 1973, pp. 438-450.
12. K. S. Chan and G. R. Leverant, "Elevated-Temperature Fatigue Crack Growth Behavior of MAR-M200 Single Crystals," *Metallurgical Transactions A*, Vol. 18A, April 1987, pp. 593-602.
13. M. Y. Nazmy, "The Applicability of Strain-Range Partitioning to High Temperature Low Cycle Fatigue Life Prediction of 'IN 738' Alloy," *Fatigue of Engineering Materials and Structures*, Vol. 4, No. 3, 1981, pp. 253-261.
14. D. A. Woodford, "Creep Design Analysis for Superalloys Based on Stress Relaxation Testing," Sixth International Conference on Creep and Fatigue: Design and Life Assessment at High Temperature, April 15-17, 1996, C494/090/96, ImechE Conference Transactions, 1996, pp. 61-69.
15. G. A. Webster, "High Temperature Fatigue Crack Growth in Superalloy Blade Materials," *Materials Science and Technology*, Vol. 3, September 1987, pp. 716-725.
16. N. Czech, F. Staif, V. S. Savchenko, and K. A. Yushchenko, "Evaluation of the Weldability of the Gas Turbine Blade Materials In738LC and Rene 80," Proceedings from Materials Solutions '97 on Joining and Repair of Gas Turbine Components, Indianapolis, IN, September 15-18, 1997, pp. 7-10.
17. N. S. Cheruvu, "Development of a Corrosion Resistant Directionally Solidified Material for Land Based Turbine Blades," *Journal of Engineering for Gas Turbines and Power*, Transactions of the ASME, Vol. 120, October 1998, pp. 744-750.
18. J. A. Daleo and J. R. Wilson, "GTD111 Alloy Material Study," 96-GT-520, The American Society of Mechanical Engineers, 1996, presented at the International Gas Turbine and Aeroengine Congress & Exhibition, Birmingham, UK, June 10-13, 1996.
19. M. Y. Nazmy, "Effect of Multiple Crack Propagation on the High Temperature Low Cycle Fatigue of a Cast Nickel-Base Alloy," *Scripta METALLURGICA*, Vol. 17, 1983, pp. 491-494.
20. A. K. Koul, R. Castillo, and K. Willett, "Creep Life Predictions in Nickel-Based Superalloys," *Materials Science and Engineering*, Vol. 66, 1984, pp. 213-226.
21. R. Castillo, A. K. Koul, and E. H. Toscano, "Lifetime Prediction Under Constant Load Creep Conditions for a Cast Ni-Base Superalloy," *Journal of Engineering for Gas Turbines and Power*, Transactions of the ASME, Vol. 109, January 1987, pp. 99-106.

22. G. A. Whitlow, R. L. Johnson, W. H. Pridemore, and J. M. Allen, "Intermediate Temperature, Low-Cycle Fatigue Behavior of Coated and Uncoated Nickel Base Superalloys in Air and Corrosive Sulfate Environments," *Journal of Engineering Materials and Technology*, Transactions of the ASME, Vol. 106, January 1984, pp. 43-49.
23. J. M. Allen and G. A. Whitlow, "Observations on the Interaction of High Mean Stress and Type II Hot Corrosion on the Fatigue Behavior of a Nickel Base Superalloy," *Journal of Engineering for Gas Turbines and Power*, Transactions of the ASME, Vol. 107, January 1985, pp. 220-224.
24. M. A. Burke, C. G. Beck, Jr., and E. A. Crombie, "The Influence of Materials Processing on the High Temperature Low Cycle Fatigue Properties of the Cast Alloy IN-738LC," *Superalloys 1984*, edited by M. Gell, C. S. Kortovich, R. H. Bricknell, W. B. Kent, and J. F. Radavich, 1984, pp. 63-71.
25. D. A. Spera, "Comparison of Experimental and Theoretical Thermal Fatigue Lives for Five Nickel-Base Alloys," STP 520, American Society for Testing and Materials, Philadelphia, PA, 1973, pp. 648-656.
26. P. Shahinian and K. Sadananda, "Creep and Fatigue Crack Growth Behavior of Some Cast Nickel-base Alloys," *Materials Science and Engineering*, Vol. A108, 1989, pp. 131-140.
27. K. Sadananda and P. Shahinian, "The Effect of Environment on the Creep Crack Growth Behavior of Several Structural Alloys," *Materials Science and Engineering*, Vol. 43, 1980, pp. 159-168.
28. M. Y. Nazmy, "High Temperature Low Cycle Fatigue of IN 738 and Application of Strain Range Partitioning," *Metallurgical Transactions A*, Volume 14A, March 1983, pp. 449-461.
29. M. Y. Nazmy, "The Effect of Sulfur Containing Environment on the High Temperature Low Cycle Fatigue of a Cast Ni-Base Alloy," *Scripta METALLURGICA*, Vol. 16, 1982, pp. 1329-1332.
30. N. S. Cheruvu, "Development of a Corrosion Resistant Directionally Solidified Material for Land Based Turbine Blades," 97-GT-425, The American Society of Mechanical Engineers, 1997, presented at the International Gas Turbine and Aeroengine Congress & Exhibition, Orlando, FL, June 2-5, 1997.
31. V. P. Swaminathan, N. S. Cheruvu, J. M. Klein, and W. M. Robinson, "Microstructure and Property Assessment of Conventionally Cast and Directionally Solidified Buckets Refurbished After Long-Term Service," 98-GT-510, The American Society of Mechanical Engineers, 1998, presented at the International Gas Turbine and Aeroengine Congress & Exhibition, Stockholm, Sweden, June 2-5, 1998.
32. V. P. Swaminathan and N. Sastry Cheruvu, "Bucket Alloy Definition and Experience," Southwest Research Institute Final Task Report, "Durability and Life Assessment of GTD-111 Buckets," August 1997.

Source References

33. N. S. Cheruvu and V. P. Swaminathan, "Physical and Mechanical Properties of GTD-111 DS Bucket Material," Southwest Research Institute Draft Final Task Report, SwRI Project 18-7297, April 1999.
34. X. D. Wu and P. A. S. Reed, "Mode I and Mixed Mode I/II Fatigue of Ni-Base Single Crystal Udimet 720 in Air and in Vacuum," *Fatigue '96*, Vol. II, pp. 855-860.
35. M. Loo Morrey and P. A. S. Reed, "Elevated Temperature Behaviour of Udimet 720 – A Study of Tear Drop Cracking," *Fatigue 96*, Vol. II, pp. 867-872.
36. T. B. Gibbons and R. Stickler, "IN939: Metallurgy, Properties and Performance," COST 50 Report, 1982, pp. 369-393.

9999999. Internal data, Liburdi Engineering Ltd.
9999908. Material Property-Microstructural Correlations, taken from EPRI Report RP2775-2 (IITRI).
9999907. Cincotta, G, Final Report from General Electric Co. to EPRI on Contract RP 2421-2, Feb. 1988.
9999906. High Temperature, High Strength Nickel Base Alloys, The International Nickel Co. Inc. July 1977.
9999905. Data booklet, Special Metals Corp. 1988.
9999903. u500.
9999902. Kellogg, L, Monthly Report from Rockwell International to EPRI on Contract RP2775-1, dated 14 Oct. 1987.
9999899. High Temperature, High Strength Nickel Base Alloys, The International Nickel Co. Inc. July 1964.
1541028. Pieraggi, B, Effect of Creep or Low Cycle Fatigue on the Oxidation or Hot Corrosion Behaviour of Nickel-Base Superalloys, First International Symposium on High Temperature Corrosion of Materials and Coatings for Energy Systems and Turboengines. II, Marseille, France, 7-11 July 1986, Mater. Sci. Eng. 88, (1-2), 199-204, Apr. 1987.
1540280. Grunling, W H; Schneider, K; Singheiser, L, Mechanical Properties of Coated Specimens, First International Symposium on High Temperature Corrosion of Materials and Coatings for Energy Systems and Turboengines. II, Marseille, France, 7-11 July 1986 Mater. Sci. Eng. 88, (1-2), 177-189, Apr., 1987.
1514140. Delargy, K M; Shaw, S W K; Smith, G D W, Effects of Heat Treatment on Mechanical Properties of High-Chromium Nickel-Base Superalloy IN 939, Mater. Sci. Technol. 2, (10), 1031-1037, Oct. 1986.
988149. Basso, S; Lupinc, V, Particle Coarsening and Long Duration Tertiary Creep Nickel-Base Superalloy IN-939, Strength of Metals and Alloys, vol. 1, Montreal, Canada 12-16 Aug. 1985 Publ: Pergamon Press Ltd., Headington Hill Hall, Oxford OX3 OBW, UK, 1985 719-724.
950683. McLean, M; Peck, M S, Comparison of Property Regeneration Techniques and Life Prediction Procedures Applied to Laboratory Tested and Service Exposed Ni--Cr Alloys, National Physical Laboratory Pp 54, 1984, Report No.: PB85-164804/wms.
936020. Day, M F; Thomas, G B, Analysis of the Low-Cycle Fatigue Behaviour of Two Ni--Cr-Base Alloys, Fatigue Fract. Eng. Mater. Struct. 8, (1), 33-48, 1985.

Source References

928584. Allen, J M; Whitlow, G A, Observations on the Interaction of High Mean Stress and Type II Hot Corrosion on the Fatigue Behavior of a Nickel Base Superalloy, J. Eng. Gas Turbines Power (Trans. ASME) 107, (1), 220-224, Jan. 1985.
919398. Hancock, P; Nicholls, J R, The Industrial Challenge to High-Temperature Alloys, Physical Chemistry of the Solid State: Applications to Metals and Their Compounds, Paris, France, 19-23 Sept. 1983 Publ: Elsevier Science Publishers BV, 1 Molenwerf, P.O. Box 211, 1000 AE Amsterdam, The Netherlands, 1984 581-598.
878122. Floyd, P H; Wallace, W; Immarigeon, J -P A, Rejuvenation of Properties in Turbine Engine Hot Section Components by Hot Isostatic Pressing, Heat Treatment '81, Birmingham, England, 15-16 Sept, 1981 Publ: The Metals Society, 1 Carlton House Terrace, London SW1Y 5DB, England, 1983 97-102.
876779. Castillo, R; Willettt, K, The Effect of Protective Coatings on the High-Temperature Properties of a Gamma Prime-Strengthened Nickel-Base Superalloy, Metall. Trans. A 15A, (1), 229-236, Jan. 1984.
876773. Whitlow, G A; Beck, C G; Viswanathan, R; Crombie, E A, The Effects of a Liquid Sulfate/Chloride Environment on Superalloy Stress Rupture Properties at 704 deg C, Metall. Trans. A 15A, (1), 23-28 Jan. 1984.
876647. Nazmy, M Y; Wuthrich, C, Creep Crack Growth in IN 738 and IN 939 Nickel-Base Superalloys, Mater. Sci. Eng. 61, (2), 119-125, Nov. 1983.
863746. Grunling, H W; Keienburg, K H; Schweitzer, K K, The Interaction of High Temperature Corrosion and Mechanical Properties of Alloys, High Temperature Alloys for Gas Turbines 1982, Liege, Belgium, 4-6 Oct. 1982 Publ: D. Reidel Publishing Co., P.O. Box 17, 3300 AA Dordrecht, The Netherlands, 1982, 507-543.
863150. Schneider, K; Gnirss, G, High Cycle Fatigue Properties of Cast Nickel Base Superalloys IN 738 LC and IN 939, High Temperature Alloys for Gas Turbines 1982, Liege, Belgium, 4-6 Oct. 1982 Publ: D. Reidel Publishing Co., P.O. Box 17, 3300 AA Dordrecht, The Netherlands, 1982, 319-344.
859757. Osgerby, S; Gibbons, T B, Creep Cavitation in a Cast Ni--Cr Base Alloy, Mater. Sci. Eng., 59, (2), L11-L14, June 1983.
845161. Nazmy, M Y, High-Temperature Low-Cycle Fatigue of IN 738 and Application of Strain Range Partitioning, Metall. Trans A 14A, (3), 449-461, Mar. 1983.
839977. Jahnke, B, High-Temperature Electron Beam Welding of the Nickel-Base Superalloy IN-738 LC, Weld. J. 61, (11), 343s-347s, Nov. 1982.
838332. Nazmy, M Y, The Effect of Sulfur-Containing Environment on the High-Temperature Low-Cycle Fatigue of a Cast Nickel-Base Alloy, Scr. Metall. 16, (12), 1329-1332, Dec. 1982.

835155. Schmidt, H; Hoffelner, W, High-Cycle Fatigue and Creep of the Cast Nickel-Base Superalloy IN738LC at 850 deg C, Fracture and the Role of Microstructure, Vol. 2. Fatigue, Leoben, Austria, 22-24 Sept. 1982 Publ: Engineering Materials Advisory Services Ltd., 339, Halesowen Rd., Cradley Heath, Warley, West Midlands B64 6PH, U.K., 1982 701-708.
831755. Nazmy, M Y, The Effect of Environment on the High-Temperature Low-Cycle Fatigue Behavior of Cast Nickel-Base IN-738 Alloy, Mater. Sci. Eng. 55, (2), 231-237, Sept. 1982.
828491. Schneider, K; vonArnim, H; Grunling, H W, Influence of Coatings and Hot Corrosion on the Fatigue Behaviour of Nickel-Based Superalloys, Thin Solid Films 84, (1), 29-36, 2 Oct. 1981.
818660. Hoffelner, W, High-Cycle Fatigue Life of the Cast Nickel-Base-Superalloys IN 738 LC and IN 939, Metall. Trans A 13A, (7), 1245-1255, July 1982.
805217. An Alloy for Stationary Gas Turbines, Diesel Gas Turb. Worldwide 14, (1), 42, Jan.-Feb. 1982.
797981. Stevens, R A; Flewitt, P E J, Intermediate Regenerative Heat Treatments for Extending the Creep Life of the Superalloy IN-738, Mater. Sci. Eng. 50, (2), 271-284, Oct. 1981.
792216. Hartnagel, W; Bauer, R; Grunling, H W, Constant Strain Rate Creep Tests With Gas Turbine Blade Materials Under Hot Corrosion Environmental Conditions, Corrosion and Mechanical Stress at High Temperatures, Petten, The Netherlands, May 1980, Publ: Applied Science Publishers, Ltd., Ripple Rd., Barking, Essex, England, 1981, 257-273.
792212. Galsworthy, J C, The Effects of Seasalt on the High-Temperature Creep Properties of a Nickel-Base Gas Turbine Blade Alloy, Corrosion and Mechanical Stress at High Temperatures, Petten, The Netherlands, May 1980, Publ: Applied Science Publishers, Ltd., Ripple Rd., Barking, Essex, England, 1981, 197-206.
777613. Stevens, R A; Flewitt, P E J, The Dependence of Creep Rate on Microstructure in a Gamma Prime Strengthened Superalloy, Acta Metall. 29, (5), 867-882, May 1981.
760821. Woodford, D A, Environmental Damage of a Cast Nickel-Base Superalloy, Metall. Trans. A 12A, (2), 299-308, Feb. 1981.
760820. Sadananda, K; Shahinian, P, Analysis of Crystallographic High-Temperature Fatigue Crack Growth in a Nickel-Base Alloy, Metall. Trans. A 12A, (2), 343-351, Feb. 1981.
732604. Cutler, C P; Shaw, S W K, The Interrelationship of Gamma Prime Size, Grain Size and Mechanical Properties in IN-939, a Cast Nickel-Base Superalloy, Strength of Metals and Alloys, Vol. 2. Fifth International Conference, Aachen, W. Germany, 27-

Source References

- 31 Aug. 1979 Publ: Pergamon Press Ltd., Headington Hill Hall, Oxford OX3 OBW, England, 1980 1357-1362.
719687. Aning, K; Tien, J K, Creep and Stress Rupture Behavior of a Wrought Nickel-Base Superalloy in Air and Vacuum, Mater. Sci. Eng. 43, (1), 23-33, Mar. 1980.
710478. Chambers, W L; Ostergren, W J; Wood, J H, Creep Failure Criteria for High-Temperature Alloys, J. Eng. Mater. Technol. (Trans. ASME) 101, (4), 374-379, Oct. 1979.
667215. Shaw, S W K, Datasheet: Properties and Characteristics of IN 939, Met. Prog. 115, (3), 66-67, Mar. 1979.
661095. Sadananda, K; Shahinian, P, Hold-Time Effects on High Temperature Fatigue Crack Growth in Udimet 700, J. Mater. Sci. 13, (11), 2347-2357, Nov. 1978.
623540. Bacon, M C; Smart, R F, Dynamic Fracture Toughness of IN 738, Metallurgia Feb. 1978, 45, (2), 68-72.
608459. Woodford, D A, Effect of Prior Temperature Cycling on Rupture Life of Superalloys, Proc Conf on Fracture 1977, 2, 803-812.
570402. Ostergren, W J, Correlation of Hold Time Effects in Elevated Temperature Low Cycle Fatigue Using a Frequency Modified Damage Function, Creep-Fatigue Interaction ASME, New York, 1976, 179-202.
557939. Watanabe, Rikizo; Kuno, Tsuneo, Alloy Design of Ni-Base Precipitation-Hardened Superalloys, Trans Iron Steel Inst Jpn 1976, 16, (8), 437-446.
479113. Speidel, Markus O, Fatigue-Crack Growth at High Temperatures, Symposium on High-Temperature Materials in Gas Turbines Elsevier Scientific Publishing Co., London, New York and Amsterdam. 1974, 207-255.
465312. Weiss, I; Rosen, A; Brandon, D G, Creep of Udimet 500 During Thermal Cycling. Pt. 2. Time to Failure, Metall Trans A Apr. 1975, 6A, (4), 767-772.
453252. Nakamura, Yoshikazu, Some Metallographic Observations on the 1500 F (815 C) Fatigue Fracture Surface of Wrought Udimet 700, Metall Trans, Dec. 1974, 5, (12), 2605-2607.
408031. Chaku, P N; McMahon Jr, C J, Effect of an Air Environment on the Creep and Rupture Behavior of a Ni-Base High-Temperature Alloy, Metall Trans, Feb. 1974, 5, (2), 441-450.
304709. Coffin Jr, L F, Effect of Frequency on the Cyclic Strain and Low Cycle Fatigue Behavior of Cast Udimet 500 at Elevated Temperature, Metall Trans, Nov. 1971, 2, 3105-3113.

- 212046. Wells, C H; Sullivan, C P, Interactions Between Creep and Low-Cycle Fatigue in Udimet 700 at 1400 f, Paper From Fatigue at High Temperature ASTM, Philadelphia, Pa. 1969, 59-74.
- 109860. Wells, C H; Sullivan, C P, Low-Cycle Fatigue of Udimet 700 at 1700 f, ASM Trans Quart mar. 1968, 61, 149-155.
- 14935. Smith, W E; Donachie Jr, M J; Johnson, J L, Relationship of Prior Creep Exposure to Strength of Wrought Udimet 700 Nickel-Base Alloy, J Basic Eng V 88, No 1, Mar. 1966, p 4-6.
- 3886. Wells, C H; Sullivan, C P, Low-Cycle Fatigue Damage of Udimet 700 at 1400 f, ASM Trans V 58, No 3, 1965, p 391-402.
- 9999904. Properties of Superalloys, American Society for Metals, ASM Metals Handbook Ninth Edition, p 242-268.

20

CHEMICAL COMPOSITION

Chemical Composition

Chemical Composition IDs

		ELEMENT (% by weight)													
ID	MATERIAL	NI	CR	CO	MO	TI	AL	C	W	TA	CB	ZR	B	HF	V
1	Udimet 500	52.3	18.560	18.480	3.940	3.210	3.110	0.100	0.000	0.000	0.000	0.000	0.000	0.000	0.000
2	Udimet 700	53.0	15.000	18.500	5.200	3.500	4.300	0.080	0.000	0.000	0.000	0.000	0.030	0.000	0.000
3	Udimet 500	53.6	18.000	18.500	4.000	2.900	2.900	0.080	0.000	0.000	0.000	0.050	0.006	0.000	0.000
4	Udimet 720	54.9	18.000	15.000	3.000	5.000	2.500	0.030	1.500	0.000	0.000	0.050	0.035	0.000	0.000
5	Udimet 710	54.9	18.000	15.000	3.000	5.000	2.500	0.070	1.500	0.000	0.000	0.050	0.020	0.000	0.000
6	Udimet 720	55.0	18.000	15.000	3.000	5.000	2.500	0.035	1.250	0.000	0.000	0.035	0.035	0.000	0.000
7	Udimet 720	55.0	18.000	15.000	3.000	5.000	2.500	0.035	1.400	0.000	0.000	0.035	0.035	0.000	0.000
8	Udimet 710	55.0	18.000	15.000	3.000	5.000	2.500	0.070	1.500	0.000	0.000	0.050	0.020	0.000	0.000
9	Udimet 520	57.0	19.000	12.000	6.000	3.000	2.000	0.050	1.000	0.000	0.000	0.000	0.005	0.000	0.000
10	Nimonic115	60.0	14.300	13.200	3.300	3.700	4.900	0.150	0.000	0.000	0.000	0.040	0.160	0.000	0.000
12	IN 738 LC	61.6	15.760	8.350	1.840	3.460	3.400	0.120	2.600	1.550	0.940	0.053	0.010	0.160	0.050
13	IN 738 LC	61.8	15.900	8.300	1.600	3.300	3.400	0.120	2.500	1.720	0.960	0.070	0.009	0.160	0.000
14	IN X750	73.0	15.500	0.000	0.000	2.500	0.700	0.040	0.000	0.000	1.000	0.000	0.000	0.000	0.000
15	IN 792	bal	12.400	9.000	1.900	4.500	3.100	0.120	3.800	3.900	0.000	0.100	0.020	0.000	0.000
16	Udimet 700	bal	15.000	19.000	5.000	3.000	4.000	0.150	0.000	0.000	0.000	0.000	0.000	0.000	0.000
17	Udimet 700	bal	15.000	19.500	5.050	3.450	4.420	0.060	0.000	0.000	0.000	0.000	0.031	0.000	0.000
18	Udimet 700	bal	15.000	19.500	5.050	3.450	4.420	0.060	0.000	0.000	0.000	0.050	0.031	0.000	0.000
19	Udimet 700	bal	15.000	19.500	5.100	3.500	4.400	0.060	0.000	0.000	0.000	0.050	0.030	0.000	0.000
20	IN 700	bal	15.000	28.500	3.700	2.200	3.000	0.120	0.000	0.000	0.000	0.000	0.000	0.000	0.000
21	Udimet 700	bal	15.100	16.600	4.950	3.480	4.150	0.060	0.000	0.000	0.000	0.040	0.025	0.000	0.000
22	Udimet 700	bal	15.100	17.500	4.900	3.250	4.150	0.080	0.000	0.000	0.000	0.000	0.029	0.000	0.000
23	Udimet 700	bal	15.200	18.400	4.950	3.430	4.420	0.060	0.000	0.000	0.000	0.000	0.031	0.000	0.000
24	Udimet 700	bal	15.000	18.500	4.820	3.330	4.320	0.060	0.000	0.000	0.000	0.050	0.030	0.000	0.000
25	IN 738 LC	bal	15.720	8.290	1.710	3.340	3.470	0.090	2.620	1.580	0.760	0.030	0.010	0.000	0.000
26	IN 738 LC	bal	15.760	8.240	1.570	3.340	3.550	0.100	2.510	1.800	0.860	0.030	0.008	0.000	0.000
27	IN 738 LC	bal	15.780	8.300	1.740	3.490	3.430	0.100	2.600	1.690	0.810	0.060	0.011	0.000	0.000
28	IN 738 LC	bal	15.800	8.200	1.700	3.400	3.430	0.115	2.460	1.640	0.860	0.045	0.010	0.000	0.000
29	IN 738 LC	bal	15.800	8.200	1.700	3.470	3.400	0.114	2.500	1.910	0.860	0.050	0.010	0.000	0.000
30	IN 738 LC	bal	15.800	8.230	1.610	3.340	3.490	0.100	2.520	1.780	0.910	0.045	0.011	0.000	0.000
31	IN 738 LC	bal	15.800	8.390	1.660	3.350	3.450	0.110	2.430	1.580	0.770	0.030	0.011	0.000	0.000
32	IN 738 LC	bal	15.810	8.570	1.720	3.340	3.560	0.110	2.640	1.610	0.750	0.030	0.011	0.000	0.000
33	IN 738 LC	bal	15.820	8.150	1.620	3.290	3.440	0.110	2.470	1.790	0.860	0.040	0.010	0.000	0.000
34	IN 738 LC	bal	15.840	8.420	1.820	3.540	3.380	0.100	2.600	1.780	0.860	0.050	0.011	0.000	0.000
35	IN 738 LC	bal	15.890	8.340	1.680	3.300	3.460	0.090	2.640	1.570	0.730	0.030	0.010	0.000	0.000
36	IN 738 LC	bal	15.900	8.360	1.660	3.450	3.490	0.100	2.620	1.740	0.740	0.030	0.011	0.000	0.000
37	IN 738 LC	bal	15.920	8.310	1.540	3.300	3.500	0.100	2.500	1.810	0.830	0.030	0.010	0.000	0.000
38	IN 738 LC	bal	15.940	8.420	1.700	3.340	3.500	0.090	2.610	1.540	0.730	0.030	0.010	0.000	0.000
39	IN 738 LC	bal	15.950	8.250	1.620	3.450	3.500	0.090	2.480	1.600	0.700	0.500	0.011	0.000	0.000
40	IN 738 LC	bal	15.950	8.250	1.620	3.450	3.500	0.090	2.480	1.600	0.700	0.050	0.011	0.000	0.000
41	IN 738 LC	bal	15.970	8.410	1.660	3.340	3.320	0.100	2.580	1.540	0.730	0.030	0.010	0.000	0.000
42	IN 738 LC	bal	16.000	8.200	1.900	3.400	3.440	0.090	2.600	1.600	0.700	0.030	0.009	0.000	0.000
43	IN 738	bal	16.000	8.500	1.700	3.400	3.400	0.170	2.600	1.700	0.900	0.100	0.000	0.000	0.000
44	IN 738	bal	16.000	8.500	1.700	3.400	3.400	0.170	2.600	1.700	0.900	0.100	0.010	0.000	0.000
45	IN 738	bal	16.000	8.500	1.700	3.400	3.400	0.170	2.600	1.700	0.900	0.100	0.100	0.000	0.000
46	IN 738 LC	bal	16.000	8.500	1.750	3.400	3.400	0.110	2.600	1.750	0.900	0.050	0.010	0.000	0.000
47	IN 738 LC	bal	16.000	8.640	1.710	3.450	3.570	0.090	2.670	1.660	0.700	0.030	0.011	0.000	0.000
48	IN 738 LC	bal	16.020	8.320	1.720	3.250	3.420	0.090	2.640	1.630	0.760	0.030	0.011	0.000	0.000
49	IN 738 LC	bal	16.150	8.200	1.600	3.300	3.450	0.110	2.580	1.670	0.700	0.030	0.011	0.000	0.000
50	IN 738 LC	bal	16.200	8.690	1.630	3.380	3.570	0.090	2.540	1.500	0.690	0.030	0.010	0.000	0.000
51	IN 738	bal	16.300	8.350	1.760	3.380	3.340	0.170	2.620	1.780	0.870	0.000	0.000	0.000	0.000
52	Udimet 710	bal	18.000	15.000	3.000	5.000	2.500	0.070	1.500	0.000	0.000	0.000	0.020	0.000	0.000
53	Udimet 500	bal	18.000	18.500	4.000	2.900	2.900	0.080	0.000	0.000	0.000	0.010	0.006	0.000	0.000
54	Udimet 500	bal	18.560	18.710	4.530	3.010	3.040	0.080	0.000	0.000	0.000	0.013	0.000	0.000	0.000
55	Udimet 520	bal	19.010	12.440	6.320	3.070	1.960	0.047	1.060	0.000	0.000	0.000	0.006	0.000	0.000
56	IN 939	bal	22.400	19.000	0.000	3.700	1.900	0.150	2.000	1.400	1.000	0.100	0.009	0.000	0.000
57	IN 939	bal	22.500	19.000	0.000	3.700	1.900	0.150	2.000	1.400	1.000	0.100	0.009	0.000	0.000
58	IN 939	bal	22.500	19.000	0.000	3.700	1.900	0.150	2.000	1.400	1.000	0.100	0.010	0.000	0.000
59	IN 939	bal	22.600	19.100	0.000	3.700	1.900	0.150	2.000	1.000	1.000	0.100	0.000	0.000	0.000
60	IN 939	bal	22.600	19.500	0.050	3.580	1.940	0.140	2.080	1.370	0.950	0.095	0.000	0.000	2.000
62	IN 738 LC	bal	15.800	8.300	1.720	3.440	3.460	0.120	2.580	1.770	0.830	0.055	0.010	0.000	0.000
63	IN 939	bal	22.530	19.100	0.000	3.720	1.930	0.155	2.140	1.400	1.000	0.108	0.009	0.000	0.000
64	IN 738	bal	15.800	8.300	1.800	3.600	3.540	0.130	2.650	2.300		0.090	0.007	0.000	0.000
65	IN 738	bal	15.950	8.250	1.620	3.450	3.500	0.090	2.480	1.600	0.700	0.500	0.011	0.000	0.000
66	Udimet 720	bal	18.000	15.000	3.000	5.000	2.500	0.035	1.400	0.000	0.000	0.040	0.035	0.000	0.000
67	Udimet 700	bal	15.100	16.600	4.950	3.480	4.150	0.060	0.000	0.000	0.000	0.000	0.000	0.000	0.000
68	IN X750	73.0	15.500	0.000	0.000	2.500	0.900	0.040	0.000	0.000	1.000	0.000	0.000	0.000	0.000
69	IN 738 LC	bal	16.000	8.300	1.700	3.390	3.400	0.090	2.500	1.700	0.700	0.030	0.010	0.000	0.000
70	GTD 111	bal	14.000	9.500	1.500	4.900	3.000	0.100	3.800	2.800	0.000	0.010	0.010	0.000	0.000
71	GTD 111EA	bal	14.000	8.900	1.720	4.900	3.040	0.090	3.740	2.860	<0.01	0.000	0.010	0.000	0.000
72	GTD 111DS	bal	13.600	9.140	1.600	4.900	2.970	0.090	3.440	2.870	<0.01	0.000	0.010	0	

Chemical Composition

ID	MATERIAL	ELEMENT (% by weight)													
		NI	CR	CO	MO	TI	AL	C	W	TA	CB	ZR	B	HF	V
75	Rene 80	bal	13.800	9.300	3.900	5.000	3.000	0.160	4.000	0.000	0.000	0.000	0.000	0.000	0.000
76	Rene 80	bal	13.800	9.400	3.900	5.000	3.150	0.160	3.800	0.000	0.000	0.040	0.017	0.000	0.000
77	MAR-M002	bal	9.000	10.000	0.250	1.500	5.500	0.150	10.000	2.500	0.000	0.055	0.015	1.250	0.050
78	MAR-M002	bal	9.000	10.000	0.250	1.500	5.500	0.150	10.000	2.500	0.000	0.055	0.015	1.500	0.050
79	MAR-M200	bal	9.000	10.000	0.000	1.700	4.700	<50 ppm	12.500	0.000	1.000	0.000	0.000	0.000	0.000
80	MAR-M247	bal	8.400	10.000	0.650	1.050	5.500	0.130	10.000	3.050	0.000	0.055	0.015	1.400	0.000

21

HEAT TREATMENT

Heat Treatment IDs

ID	HEAT TREAT SCHEDULE
1	1.5h,1190c ac+6h,1100c ac
2	2H,1120c ac+24h,840c ac
3	2h,1120c ac+24h,845c ac
4	2h,1120c ac+24h,845c ac+2h,1120c ac
5	2h,1120c ac+24h,850c ac
6	2h,1120c vac+24h,840c vac
7	2h,1120c vacuum ac+10000h,850c ac
8	2h,1120c vacuum ac+15000h,850c ac
9	2h,1120c vacuum ac+24h,845c ac
9	2h,1120c vacuum ac+24h,845c ac
10	2h,1120c+16h,843c
11	2h,1120c ac+24h,845c ac
12	2h,1130c in hydrogen, cooled to RT, 24h,840c in argon
13	2h,1150c ac+24h,840c ac+20h,705c ac
14	2h,1175c+4H,1075 ac+24h,840c+16h,755c ac in vacuum
15	2h,2160f ac+4h,1600f ac
16	4h,1080c ac+24h,843c ac+16h,760c ac
17	4h,1105c ac+24h,840c ac+16h,760c ac
18	4h,1121c ac+24h,843c ac+16h,760c ac
19	4h,1150c+24h,900c+16h,700c
20	4h,1150c+6h,1000c+16h,700c
21	4h,1150c+6h,1000c+24h,900c
22	4h,1150c+6h,1000c+24h,900c+16h,700c
23	4h,1150c+6h,850c
24	4h,1150c+6h,1000c
25	4h,1160c ac+24h,900c ac+16h,700c ac
26	4h,1160c ac+6h,1000c ac+24h,900c ac
27	4h,1160c ac+6h,1000c ac+24h,900c ac+16h,700c ac
28	4h,1160c ac+6h,1000c ac+24h,900c ac+16h,700c ac+10000h,850c
29	4h,1160c ac+6h,1010c ac+24h,900c ac+16h,700c ac
30	4h,1160c ac+6h,1020c ac+24h,900c ac+16h,700c ac
31	4h,1160c ac+6h,1030c ac+24h,900c ac+16h,700c ac
32	4h,1160c ac+6h,980c ac+24h,900c ac+16h,700c ac
33	4h,1160c fac+6h,1000c fac+24h,900c ac+16h,700c ac
34	4h,1160c sc+6h,1000c sc+24h,900c sc+16h,700c sc
35	4h,1160c+6h,1000c+.5h,800c
36	4h,1160c+6h,1000c+16h,700c
37	4h,1160c+6h,1000c+16h,800c
38	4h,1160c+6h,1000c+16h,845c
39	4h,1160c+6h,1000c+16h,850c
40	4h,1160c+6h,1000c+1h,800c
41	4h,1160c+6h,1000c+2h,800c
42	4h,1160c+6h,1000c+4h,800c
43	4h,1160c+6h,1000c+8h,800c
44	4h,1160c+6h,1000c
45	4h,1163c ac+4h,1079c ac+4h,843c ac+16h,760c ac
46	4h,1163c+4h,1080c+16h,760c vacuum heat gas quench

Heat Treatment

47	4h,1168c ac+4h,1079c ac+24h,843c ac+16h,760c ac
48	4h,1170c ac+4h,1080c ac+24h,843c ac+16h,760c ac
49	4h,1171c ac+4h,1079c ac+4h,843c ac+16h,760c ac
50	4h,1175c ac+4h,1080c ac+24h,840c ac+16h,760c ac
51	4h,1177c ac+4h,1080c ac+24h,843c ac+16h,760c ac
52	4h,1180c ac+4h,1080c ac+24h,845c furc+16h,760c furc
53	4h,2125f fac+4h,1975f fac+4h,1550f fac+16h,1400f fac
54	as cast
55	HIP 2h,2050f cool to 1000f @>=75f/min+heat up 24h,1550f vacuum or argon gas cool
56	4h,1170c ac+4h,1080c ac+24h,843c ac+16h,760c ac
57	4h,1171c ac+4h,1079c ac+24h,843c ac+16h,760c ac
58	2h,1120c vac+24h,850c vac
59	2h, 2050f + 24h, 1550f
60	2h, 1204c + Ar cool; 4h, 1903c + Ar cool; 4h, 1052c + control cool; 16h, 843c + Ar cool
61	1h, 1190c + inert gas cool; 1hr, 1100h + furnace cool; 16h, 870c + air cool
62	4h, 1232c; 32h, 871c
63	4h, 1220c; 4h, 1100c; 24h, 650c; 16h, 760c
64	4h, 1080c; 24h, 650c; 16h, 760c

About EPRI

EPRI creates science and technology solutions for the global energy and energy services industry. U.S. electric utilities established the Electric Power Research Institute in 1973 as a nonprofit research consortium for the benefit of utility members, their customers, and society. Now known simply as EPRI, the company provides a wide range of innovative products and services to more than 1000 energy-related organizations in 40 countries. EPRI's multidisciplinary team of scientists and engineers draws on a worldwide network of technical and business expertise to help solve today's toughest energy and environmental problems.

EPRI. Electrify the World

SINGLE USER LICENSE AGREEMENT

THIS IS A LEGALLY BINDING AGREEMENT BETWEEN YOU AND THE ELECTRIC POWER RESEARCH INSTITUTE, INC. (EPRI). PLEASE READ IT CAREFULLY BEFORE REMOVING THE WRAPPING MATERIAL.

BY OPENING THIS SEALED PACKAGE YOU ARE AGREEING TO THE TERMS OF THIS AGREEMENT. IF YOU DO NOT AGREE TO THE TERMS OF THIS AGREEMENT, PROMPTLY RETURN THE UNOPENED PACKAGE TO EPRI AND THE PURCHASE PRICE WILL BE REFUNDED.

1. GRANT OF LICENSE

EPRI grants you the nonexclusive and nontransferable right during the term of this agreement to use this package only for your own benefit and the benefit of your organization. This means that the following may use this package: (I) your company (at any site owned or operated by your company); (II) its subsidiaries or other related entities; and (III) a consultant to your company or related entities, if the consultant has entered into a contract agreeing not to disclose the package outside of its organization or to use the package for its own benefit or the benefit of any party other than your company.

This shrink-wrap license agreement is subordinate to the terms of the Master Utility License Agreement between most U.S. EPRI member utilities and EPRI. Any EPRI member utility that does not have a Master Utility License Agreement may get one on request.

2. COPYRIGHT

This package, including the information contained in it, is either licensed to EPRI or owned by EPRI and is protected by United States and international copyright laws. You may not, without the prior written permission of EPRI, reproduce, translate or modify this package, in any form, in whole or in part, or prepare any derivative work based on this package.

3. RESTRICTIONS

You may not rent, lease, license, disclose or give this package to any person or organization, or use the information contained in this package, for the benefit of any third party or for any purpose other than as specified above unless such use is with the prior written permission of EPRI. You agree to take all reasonable steps to prevent unauthorized disclosure or use of this package. Except as specified above, this agreement does not grant you any right to patents, copyrights, trade secrets, trade names, trademarks or any other intellectual property, rights or licenses in respect of this package.

4. TERM AND TERMINATION

This license and this agreement are effective until terminated. You may terminate them at any time by destroying this package. EPRI has the right to terminate the license and this agreement immediately if you fail to comply with any term or condition of this agreement. Upon any termination you may destroy this package, but all obligations of nondisclosure will remain in effect.

5. DISCLAIMER OF WARRANTIES AND LIMITATION OF LIABILITIES

NEITHER EPRI, ANY MEMBER OF EPRI, ANY COSPONSOR, NOR ANY PERSON OR ORGANIZATION ACTING ON BEHALF OF ANY OF THEM:

(A) MAKES ANY WARRANTY OR REPRESENTATION WHATSOEVER, EXPRESS OR IMPLIED, (I) WITH RESPECT TO THE USE OF ANY INFORMATION, APPARATUS, METHOD, PROCESS OR SIMILAR ITEM DISCLOSED IN THIS PACKAGE, INCLUDING MERCHANTABILITY AND FITNESS FOR A PARTICULAR PURPOSE, OR (II) THAT SUCH USE DOES NOT INFRINGE ON OR INTERFERE WITH PRIVATELY OWNED RIGHTS, INCLUDING ANY PARTY'S INTELLECTUAL PROPERTY, OR (III) THAT THIS PACKAGE IS SUITABLE TO ANY PARTICULAR USER'S CIRCUMSTANCE; OR

(B) ASSUMES RESPONSIBILITY FOR ANY DAMAGES OR OTHER LIABILITY WHATSOEVER (INCLUDING ANY CONSEQUENTIAL DAMAGES, EVEN IF EPRI OR ANY EPRI REPRESENTATIVE HAS BEEN ADVISED OF THE POSSIBILITY OF SUCH DAMAGES) RESULTING FROM YOUR SELECTION OR USE OF THIS PACKAGE OR ANY INFORMATION, APPARATUS, METHOD, PROCESS OR SIMILAR ITEM DISCLOSED IN THIS PACKAGE.

6. EXPORT

The laws and regulations of the United States restrict the export and re-export of any portion of this package, and you agree not to export or re-export this package or any related technical data in any form without the appropriate United States and foreign government approvals.

7. CHOICE OF LAW

This agreement will be governed by the laws of the State of California as applied to transactions taking place entirely in California between California residents.

8. INTEGRATION

You have read and understand this agreement, and acknowledge that it is the final, complete and exclusive agreement between you and EPRI concerning its subject matter, superseding any prior related understanding or agreement. No waiver, variation or different terms of this agreement will be enforceable against EPRI unless EPRI gives its prior written consent, signed by an officer of EPRI.

