ASME STANDARDS
TECHNOLOGY, LLC

STP-PT-096-1

ELEVATED TEMPERATURE MATERIAL PROPERTY COMPILATION FOR DESIGN-BY-ANALYSIS

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12	Table 4-2	Equation corrected by errata from $\log(\dot{\varepsilon}_0) = -C_{avg} - \frac{1}{T}\left(a_1 + a_2\log(\sigma) + a_3\log(\sigma)^2 + a_4\log(\sigma)^3\right)$ to $\log(\dot{\varepsilon}_0) = -C_{avg} - \frac{1}{T+460}\left(a_1 + a_2\log(\sigma) + a_3(\log(\sigma))^2 + a_4(\log(\sigma))^3\right)$
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FOREWORD

The goal of this publication is to organize and compile high-temperature material property data for select alloys, to be used in the ASME Boiler and Pressure Vessel Code. The authors acknowledge, with deep appreciation, the activities of ASME staff and volunteers who have provided valuable technical input, advice, and assistance with review of, commenting on, and editing of, this document.

Established in 1880, the ASME is a professional not-for-profit organization with more than 135,000 members and volunteers promoting the art, science and practice of mechanical and multidisciplinary engineering and allied sciences. ASME develops codes and standards that enhance public safety and provides lifelong learning and technical exchange opportunities benefiting the engineering and technology community. Visit https://www.asme.org/ for more information.

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ABBREVIATIONS AND ACRONYMS

API – American Petroleum Institute
ASME – American Society of Mechanical Engineers
ASTM – American Society for Testing and Materials
BPVC – Boiler and Pressure Vessel Code
DBA – Design-By-Analysis
ECCC – European Collaborative Creep Committee
EPRI – Electric Power Research Institute
ISO – International Standards Organization
LM – Larson-Miller
LMP – Larson-Miller Parameter
MPC – Materials Properties Council
NASA – National Aeronautics and Space Administration
NIMS – National Institute of Material Science (Japanese)
NRIM – National Research Institute (Japanese)
NSMH – Nuclear Systems Materials Handbook
N&T – Normalized and Tempered
PRG – Peer Review Group
Q&T – Quenched and Tempered
STP – Standards Technology Publication
WRC – Welding Research Council

1 INTRODUCTION

E^{2}G | The Equity Engineering Group, Inc. was contracted by ASME Standards Technology, LLC (ASME ST-LLC) to compile high-temperature material property data for select alloys, to be used in the ASME Boiler and Pressure Vessel Code (BPVC). It is expected that the properties compiled in this project will be used to support continued and expanded use of elevated temperature design-by-analysis (DBA), to support initiatives such as advanced ultra-supercritical fossil power generation and Gen IV high-temperature nuclear reactor, among other applications. The data collected as part of this project will be utilized in Sections I, III, and VIII of the BPVC. During the course of this project, periodic milestones were shared with ASME for distribution and review by the project's Peer Review Group (PRG).

In 2012, ASME developed a materials properties database in support of the BPVC's development and maintenance. E^{2}G was contracted to update and modify this material property database for various materials. The goal of this project was to collect, interpret, qualify, analyze, and prepare elevated temperature material properties for various materials relevant to the BPVC. This unified effort is intended to ensure a baseline consistency between different parts of the BPVC and to leverage funds and resources to the maximum extent through avoidance of duplicate efforts.

2 EXECUTIVE SUMMARY

This comprehensive report details the methodology and deliverables of this project and includes figures for essential material properties. As a deliverable, the material properties for each material are embedded within this report as Microsoft Excel files. Along with the compilation of the collected data, including digitization where necessary, analysis and fitting of the data was conducted for several material properties. Physical properties collected (i.e., Young's Modulus of elasticity, coefficient of thermal expansion, thermal conductivity, and thermal diffusivity) are presented in tabular and graphical form as a function of temperature. Similarly, yield and tensile strengths are presented as a function of temperature in both tabular and graphical form. Where applicable, yield and tensile strength trend curves are presented in the traditional code fashion as 5^{th}-order polynomials as a function of temperature. Creep strain data compiled includes both traditional creep rupture as well as relaxation testing data and is presented in tabular and graphical form as a function of time. For the creep rupture isothermal figures, a comparison per API Std. 530 is presented for each temperature defined. Elevated temperature cyclic and hold time fatigue S-N curves are presented for varying temperatures and hold times, respectively.

Materials property data was compiled for the following materials:

Phase 1 materials:

- Grade 91
- Inconel 740H
- Type 304H
- Type 347H
- Grade 22
- Grade 92
- Grade 22V
- Grade 9
- Alloy 617
- Carbon Steel (SA-516, SA-299)[1]
- Carbon Steel (SA-508) [2]
- Mn-0.5Mo (SA-533) [3]
- C-1/2Mo
- Type 316H
- 5Cr
- 5Cr-0.5Mo-Si[4]
- Alloy 800H;
- Grade 11

Phase 2 materials:

- A709
- Grade 23
- Type 321H
- 3Cr
- Type 410 and 12Cr[5]
- Grade 12
- B16 bolting
- B7 bolting
- B8 bolting
- Grade 660 (bolting)[6]
- Alloy 601
- Inconel bolting (718)[7]

Additional details regarding the precise nominal compositions of the alloys listed above and listing example specification and grade combinations as well as applicable targeted tensile strength ranges (room temperature) is provided in Table 2.1 below.

Table 2-1: Clarification and Example Specification/Grade Combinations, Strength Ranges, and UNS Numbers Included in Data Collection Efforts

ASME ST LLC NAME	NOMINAL COMPOSITION (BPVC IX FOR MOST)	MOST COMMON APPLICABLE II-A SPECS & GRADES	APPLICABLE UNS NUMBERS	MIN RT TENSILE, OR RT TS RANGE TARGETED, KSI
Grade 91	9Cr-1Mo-V	SA-182 F91, SA-213 T91, SA-234 WP91, SA-335 P91, SA-387 91	K90901, K91560, J84090	85
Inconel 740H	51Ni-24.5Cr-20Co-Al-Ti-V	B983, B1007, & B637 (ASTM) – precipitation hardened cond.	N07740	150
Type 304H	18Cr-8Ni-C>0.04%	SA-182 F304H, SA-213 TP304H, SA-249 TP304H, SA-376 TP304H ...	S30409	75
Type 347H	18Cr-10Ni-Cb-C>0.04%	SA-182 F347H, SA-213 TP347H, SA-240 Type 347H …	S34709	75
Grade 22	2.25Cr–1Mo	SA-182 F22 Cl. 1 & 3, SA-213 T22, A199 T22, etc.	K21590, J21890, J22091, J22090, K21390	60-85
Grade 92	9Cr-2W	SA-182 F92, SA-213 T92, SA-369 FP92, SA-335 P92	K92460	90
Grade 22V	2.25Cr–1Mo–V	SA-182 F22V, SA-336 F22V, SA-541 22V, SA-542 D Cl. 4a, SA-832 22V	K31835	85
Grade 9	9Cr-1Mo	SA-182 F9, A-199 T9, SA-213 T9, SA-234 WP9 Cl. 1 & 3, SA-335 P9 …	K90941, K81590	60-85
Inconel Bolting	52Ni–20Cr–5Cb–3Mo-Al+Ti	SB-637 Grade UNS N07718 (bar)	N07718	185
Alloy 617	52Ni–22Cr–13Co–9Mo	SB-166, SB-167, SB-168, SB-564 N06617	N06617	85
CS(SA-516, SA-299)	C–Mn–Si	SA-516 70, SA-299 Gr. A & B (>0.25 max carbon)	K02700, K02803	70-80
C-1/2Mo	C-0.5Mo	SA-204 Gr. A-C; SA-209 & SA-250 Gr. T1b, T1, T1a; SA–217 WC1; SA-234 WP1; SA-352 CF1; SA-182 & SA-336 F1; A356 Gr. 2	J12523, K11820, K12020, K12320, K11422, K11522, K12023, K12822, J12524, K12821, K12520, J12522	55-75
SA-533/SA-508	C (SA-508)	SA-508 Gr. 1 & 1A	K13502	70
SA-533/SA-508	Mn–0.5Mo (SA-533)	SA-533 Type A, Cl. 1-3	K12521	80-100
Type 316H	18Cr-12Ni-2Mo-C>0.04%	SA-182 F316H, SA-213 TP316H, SA-240 Type 316H, SA-249 TP316H	S31609	70-75
5Cr	5Cr–0.5Mo	SA-182 F5, A199 T5, SA-213 T5, SA-335 P5, SA-336 F5, SA-234 WP5, Cl. 1-3, SA-387 5, Cl. 1 & 2	K41545	60-75

ASME ST LLC NAME	NOMINAL COMPOSITION (BPVC IX FOR MOST)	MOST COMMON APPLICABLE II-A SPECS & GRADES	APPLICABLE UNS NUMBERS	MIN RT TENSILE, OR RT TS RANGE TARGETED, KSI
Alloy 800H	33Ni–42Fe–21Cr	SB-163, SB-407, SB-408, SB-409, SB-514, SB-515, SB-564, N08810	N08810	65
Grade 11	1.25Cr–0.5Mo–Si (& 1.25Cr–0.5Mo)	SA-182 F11, Cl. 1-3, A199 T11, SA-213 T11, SA-234 WP11, Cl. 1 & 3, SA-250 T11, SA-335 P11, SA-336 F11, Cl. 1-3, SA-387 11, Cl. 1 & 2	K11572, K11597, K11789, J12072, J12073, K11797	60-75
A709 (Alloy 709)	22Cr-25Ni-Mn-Mo-V-Nb-C-N	Alloy 709/SA-213 Grade TP310MoCbN (smls tube)	S31025	93
Grade 23	2.25Cr-1.6W	SA-182 F23, SA-213 T23, SA-335 P23, SA-1017 23	K41650 & K40712	74
Type 321H	18Cr-10Ni-Ti-C>0.04%	SA-182 F321H, SA-213 TP321H, SA-240 Type 321H, etc.	S32109	70-75
3Cr	3Cr–1Mo	SA-182 F21, SA-213 T21, A199 T21, SA-335 P21, SA-336 F21, Cl. 1 & 3, SA-387 21, Cl. 1 & 2	K31545 & J31545	60-75
Type 410	13Cr	SA-182 F6a, Cl. 1 & 2, SA-240 Type 410, SA-268 TP410, SA-276 TP410, SA-336 F6, SA-479 410	S41000	60-85
Grade 660	25Ni-15Cr-1Mo-2Ti-Mn-Al-V	SA-453 Grade 660 (bolts), Types A, B, C, D, & SA-638 Grade 660 (bars, forgings), Types 1 & 2	S66286	130
Grade 12	1Cr–0.5Mo	SA-182 F12 Cl. 1 & 2, SA-213 T12, SA-234 WP12, Cl. 1 & 2, SA-335 P12, SA-336 F12, SA-387 12 Cl. 1 & 2	K11562, K11564, K12062, K11757, J11562	55-70
12Cr	12Cr	SA-479 Grade 403 (Bars & shapes)	S40300	70
B16, B7 Bolting	1Cr-0.3Mo	SA-193 Grade B7	G41400	100-125
B16, B7 Bolting	1Cr-0.5Mo-V	SA-193 Grade B16	Unknown	100-125
B8 Bolting	18Cr-8Ni	SA-193 Grade B8/B8A (bolting)	S30400	varies
Alloy 601	60Ni–23Cr–12Fe–Al	SB-166, SB-163, SB-167, SB-168 UNS N06601	N06601	80
5Cr-0.5Mo-Si	5Cr-0.5Mo-Si	SA-213 T5b, SA-335 P5	K11597	60

As part of this project, E^2G personnel participating in the data compilation gained access to the ASME database (XCAMS), hosted by Oak Ridge National Lab. Some data compiled for the project was taken from this database. Currently, login credentials for E^2G personnel are no longer active for the database. E^2G understands that the data compiled through the current project will be uploaded to the XCAMS database after approval and acceptance by the PRG/ASME. E^2G proposes that any uploading of material be performed after the final project report is completed and finished material property spreadsheets have been provided to ASME. Much of the content in the current XCAMS database is in the form of MS Excel spreadsheets. A spreadsheet will be provided for each material in this project which can be uploaded to the XCAMS database.

3 ANALYSIS

3.1 Compilation and Digitization of Material Properties

The lead investigator for this work was David A. Osage, with support from the Materials & Corrosion Team, Mechanical & Structural Team, and the Applied Research & Development Team at E^2G. Data sources used included those mentioned in RFP-17-02, Project Number STEX-0160 Project Title *Elevated Temperature Material Property Compilation for Design-By-Analysis*, such as:

- ASME data packages, as provided;
- ASME ST-LLC reports, as provided;
- API (American Petroleum Institute) data packages;
- Japanese NRIM/NIMS (National Research Institute for Metals/National Institute of Materials Science) Creep and Fatigue Data Sheets;
- U.S. Department of Energy (National Lab) Reports, including Oak Ridge, Argonne, Idaho, etc.
- WRC (Welding Research Council) Bulletins
- MPC (Material Properties Council) Archives, including many historical ASME boiler code record files
- ECCC (European Collaborative Creep Committee) Data Sheets
- Nuclear Systems Materials Handbook
- Aerospace Systems Materials Handbook
- Structural Alloys Handbook
- ISO (International Standards Organization) Publications
- EPRI (Electric Power Research Institute) Publications
- International Codes and Standards

In addition to those listed above, several other sources of data were used, including academic research reports, dissertations and theses, journal articles, conference proceedings, and manufacturer data sheets. Note that some of the sources used for this compilation project may not be as readily accessible as other sources to ASME or others intending to use this data. These data sources have been identified in order to be acquired. Where applicable, several sources of data which were only available in print form (to the best of E^2G's knowledge), were digitized into tabular form for ease of use.

Where available from the original data source, in addition to the material property collected, test conditions/results and material characteristics such as chemical composition, specimen size and product form, and heat treatment were collected. Where necessary, metric data have been converted to the customary unit system.

3.2 Physical Properties

In general, for well-characterized materials that have been utilized for ASME BPVC construction for many years, the physical properties are well established and contained in Section II of the code. In such cases, E^2G compiled these code properties to characterize the physical property trends of the project materials and satisfy the contract task requirements. However, an exhaustive effort to compile physical property data from the literature was not undertaken. For alloys that are included in the project but have not been typically used for code construction and are therefore not included in the Section II tables of physical properties, the sources listed above as well as other sources were utilized for collecting physical property data. In the subsequent sections of this report, where this was performed, results are shown. For materials where code (Section II) properties were utilized, results are included in the embedded material spreadsheets but are not reproduced in the body of this report. Initial feedback from the PRG indicated that this approach was acceptable for Physical Properties.

3.3 Yield and Tensile Strength

Elevated temperature tensile and yield strength curves were obtained from WRC Bulletin 541 and the MPC trend curves, where available. These curves were substituted with data from the sources listed above. Due to the sheer number of data sources present in the published literature that contain elevated temperature yield and tensile test data, it is likely that additional results could be found, if desired, as part of a later project phase. However, in the current work, the volume of data collected and contained in the spreadsheets was deemed to be sufficient for a robust comparison to current code allowable stresses. No lot-centering analysis has yet performed on the yield and tensile strength data.

3.4 Creep Data (Creep Rupture, Minimum Creep Rate, and Ductility)

These data forms were generally found reported together in the same sources. Despite being listed as separate milestones in the project contract, therefore, data were obtained in one effort. Many sources, such as ASTM, NIMS, Supplier data packages from boiler code committee correspondence, etc. contain tables of creep test results, including temperature, stress, heat ID, and rupture time for the specimen, as well as (often) elongation, reduction of area, and minimum creep rate. Some of the shorter-duration tests do not report minimum creep rate as this was not sufficiently measured during the test, especially for older data sources. In many cases, tests at less aggressive conditions were terminated after a few thousand hours, or results were reported on a preliminary basis prior to specimen rupture. In such cases, the minimum creep rate is reported without a corresponding rupture time for the sample.

For both creep and fatigue data (including hold times), ASME requested that, where applicable, the chemistry and material condition (e.g., heat-treatment history, grain size, hardness, strength, etc.) be captured and reported. Data were collected in the attached spreadsheet regardless of whether this additional information was available. Many sources, however, do not report all of this information. Both rupture and strain rate (minimum creep rate, expressed as true strain per hours) were regressed according to a Larson-Miller time-temperature-parameter model, with a 3rd-order polynomial of stress (ksi). All of the tables and property equations presented in this report are for units of °F for temperature, ksi for stress, hours for rupture time, and strain per hour (not % strain per hour) on creep rate.

Many efforts have been made throughout recent decades to compile and cross-reference data from various sources. This has resulted in different publications containing the same non-unique data. E^2G initially collected data for most sources, unless the analysis team determined that the data was duplicate to existing data. In many cases, however, it was not evident that data may be duplicated in the spreadsheets until the collection was complete. To eliminate duplicate data from the final material property tables, the data were filtered and data points with very similar values of stress, rupture time, and temperature were flagged for review. The analysis team determined whether these flagged points were duplicates, and if so, removed whichever data point had less background information (chemistry, heat treatment, etc.).

3.5 Continuous Cycling Fatigue and Hold Time Fatigue Curves

The amount of data available at high temperature for many of the alloys in this project was limited, particularly for high-temperature hold time fatigue curves. Additionally, the hold times reported in the data were relatively short (typically no data in excess of 60 minutes was available). Many of the fatigue plots included only contain data for which total strain range was determined from the original source. Total strain range being the combination of the elastic and inelastic strain ranges, measured in the positive direction (tensile direction). R values associated with individual data points on the plots can be obtained in the material property spreadsheets. E^2G views this area as a potential field for additional research for many of the materials, especially considering the current demands for flexibility of process and power generating equipment, including on-demand availability, peak power-use periods, and higher-efficiency targets.

4 GRADE 91, 9CR-1MO-V

4.1 Physical Properties

Well-established physical properties were referenced from the BPVC Section II for this material. Physical property curves from *WRC Bulletin 503* were plotted for comparison, and data from two literature sources (EPRI Grade 91 Handbook and Vallourec & Mannesmann *The T91/P91 Book*) were obtained. Figure 4-1 shows the trends of Elastic Modulus (E_y), Thermal Conductivity (k), Thermal Diffusivity (TD), and Thermal Expansion (α) with temperature.

4.2 Yield and Tensile Strength

Elevated temperature Yield and Tensile Strength over the range of existing allowable stresses (up to 1200°F) were readily available, including data beyond the current range of allowable stresses, up to approximately 1400°F, as shown in Figures 4-2 and 4-3. The sources for both high-temperature yield and high-temperature tensile strength are provided in the embedded spreadsheet at the end of this section. This spreadsheet also contains ductility data corresponding to the tensile test results presented in this report. Note that ductility (percent elongation and percent reduction in area) was not available for all sources referenced for the Grade 91 material.

To facilitate comparison of the data obtained to existing allowable stresses (Section II-D Table 1A), yield and tensile data were normalized on a heat-by-heat basis to express the ratio of yield or tensile strength at temperature to that measured for the heat at room temperature. In cases where data were not delineated by heats within a given source, or in cases where more than one room-temperature tensile test existed for a given heat of material, ratios are equal to the measured tensile or yield strength at temperature, divided by the average of all of the appropriate room-temperature values for the particular data source or heat of material. As a result of this approach, it is possible to have ratios in excess of 1.0. E^2G understands that this approach is similar to the normalizing procedure performed by ASME in typical analysis of yield and tensile data to obtain Table Y and Table U (Section II-D) trend curves, as well as for the calculation of allowable stresses. Figures 4-4 and 4-5 show the heat-by-heat variation in yield and tensile strength ratios (respectively) as a function of temperature. It should be emphasized that even though the figure legends reference an entire source of data, the ratios, wherever possible, were calculated on a heat-by-heat basis; this is evident in the embedded spreadsheet at the end of this section. Figures 4-6 and 4-7 contain all of the yield and tensile (respectively) ratios plotted together, to facilitate regression of a 5^{th}-order polynomial that is subsequently used for allowable stress comparison.

4.3 Creep Data (Creep Rupture, Minimum Creep Rate, and Ductility)

Creep Rupture data is shown in Figures 4-8 and 4-9, plotted as isotherms. The temperatures have been separated onto separate plots to minimize data overlap, with Figure 4-8 showing those temperatures where most of the data were concentrated, and Figure 4-9 showing those temperatures with significantly less data. It should be emphasized that these plots contain data for all product forms of material classified in the referenced publications as "Grade 91." This certainly includes material meeting the requirements of ASME BPVC Section II-A specifications (e.g., SA-213 T91, SA-182 F91, SA-387 Gr. 91, etc.). However, due to the diversity of data sources utilized for the compilation of the material property tables, it is likely that some of the material shown in Figures 4-8 and 4-9 may not meet existing specifications for this grade of material. Especially for Grade 91, recent publications by ASME, EPRI, ETD, and other entities, have demonstrated the importance of chemistry control for certain elements and certain ratios of elements (e.g., N:Al). Where older publications are referenced, the chemistry (and for that matter, manufacturing, processing, and heat treatment) corresponding to the heat of material in the original data source, may not be consistent with modern specifications. Where possible, E^2G has documented the chemical composition if contained within the original source. In many cases, the project team has also made efforts to trace cross-referenced data back to original test results to determine if the heat treatment, product form, chemistry, etc. details can be obtained. This information is provided with the embedded spreadsheet to facilitate additional analysis on the part of ASME.

Creep Minimum strain rates (%/hour) are shown in Figures 4-10 and 4-11, separated by temperature. As in the case of rupture data, temperatures of minimum creep rates have been separated onto separate plots to minimize data overlap, with Figure 4-10 showing those temperatures where most of the data were concentrated, and Figure 4-11 showing those temperatures with significantly less data. Creep Ductility, as % elongation, is plotted in Figure 4-12. As is typical, the data show significant overlap, and it is difficult to observe clear trends in the data. The data is not intended to be used as plotted but is available in the spreadsheet for additional analysis. Note that much of the data with less than 10% total elongation at failure corresponds to cross-weld specimens contained in the data.

Creep data were analyzed using E^2G's proprietary *Lot-Centered Analysis* web-based software tool, in order to obtain creep properties. This regression is based on a Mandel-Paule algorithm and considers the variation within individual heats of material (for both rupture and strain rate data) as well as the variation between heats. The weight assigned to each datapoint and each heat is scaled based on the relative variation. Both rupture and strain rate (minimum creep rate, expressed as true strain per hours) were regressed according to a Larson-Miller time-temperature-parameter model, with a 3rd-order polynomial of stress. Lot-specific constant behavior was accounted for in this analysis, but the variation of LMP with stress was assumed to be constant (no non-parallel terms were included in the analysis). A 95% predictive limit was utilized to obtain the lower-bound (minimum LM constant for both rupture and strain rate) properties. The results of this analysis are summarized in Table 4-1 for rupture data and Table 4-2 for strain rate data. The *Lot-Centered Analysis* software tool generates property tables in the creep regime using the criteria outlined in Mandatory Appendix 1 of ASME Section II-D; the nomenclature of variables is consistent with II-D Appendix 1. For visualization of the allowable stress trends, Figure 4-13 is provided (for rupture allowable stresses and creep rate allowable stresses). Figure 4-14 shows a comparison of the various allowable stress criteria from Section II-D, Appendix 1, to the existing (2019) Section II-D Table 1A allowable stresses for all product forms of Grade 91 other than forgings (which have a higher tensile strength that was not shown).

Creep Strain vs. time data are shown in Figure 4-15 and 4-16 for short-term data (up to 2,500 hour test durations); Figure 4-17 for 2,500 to 5,000 hour test durations; Figure 4-18 for up to 10,000 hour test durations, and Figure 4-19 for excess of 10,000 hour test durations. Curves are only plotted where more than 10 strain vs. time points are present for the test. Additional curves are available with fewer datapoints (typically obtained from data in the form of time-until-specified-strain, in the embedded spreadsheet. Both creep rate and creep strain vs. time data are provided to satisfy ASME's request for creep strain vs. time curves, and both forms of data are applicable in developing allowable stresses. Although digitalization of creep curve data was not explicitly necessary per the project contract, E^2G did perform digitalization of creep curves where only graphical data was available (as is often the case in the published literature).

4.4 Continuous Cycling Fatigue and Hold Time Fatigue Curves

A portion of the data obtained for continuous cycling fatigue data at elevated temperatures for Grade 91 is shown in Figure 4-20, includes a limited amount of room temperature data contained in sources that also present high-temperature data. Figure 4-20 only contains data for which total strain range was determined from the original source. Additional data points for continuous cycling fatigue data of Grade 91 are presented in the attached spreadsheet; however, due to the complexities of various forms of fatigue data, compatible plots for each type of data expression and failure criteria are not included in this report. Hold time fatigue data at high temperature is shown in Figure 4-21 (932°F, 1000°F, 1076°F, and 1100°F), Figure 4-22 (1022°F), Figure 4-23 (1112°F), and Figure 4-24 (1157°F) with separate plots for temperatures at which at least a moderate collection of data points existed. Additional data is provided in the embedded spreadsheet.

Table 4-1 : Model Parameters, Larson-Miller Property Results, and Allowable Stress (Rupture) Criteria, Grade 91

Equation Format:

$$\log(t_r) = C_{avg} + \frac{1}{T+460}\left(b_1 + b_2\log(\sigma) + b_3(\log(\sigma))^2 + b_4(\log(\sigma))^3\right)$$

C_{avg}	**-30.61**
C_{min}	**-31.03**
b_1	**66827.7**
b_2	**-13274.4**
b_3	**7936.3**
b_4	**-4320.9**

Number Data Points		**2975**
Correlation Coefficient	R^2	0.8822
Average Variance within Heats	V_w	0.06444
Variance between Heats	V_b	0.124
Standard Error of Estimate	SEE	0.2539

Properties provided are for T in °F, stress in ksi, and t_R in hours

Temperature, °F	**S_{avg} (ksi)**	***n***	**F_{avg} (calc)**	**F_{avg} (used)**	**$F_{avg} \times S_{avg}$**	**S_{min} (ksi)**	**80% S_{min}**
850	46.84	17.51	0.8768	0.67	31.39	44.3	35.44
900	38.83	15.28	0.8601	0.67	26.02	36.42	29.13
950	31.53	13.19	0.8398	0.67	21.12	29.26	23.41
1000	24.93	11.23	0.8146	0.67	16.7	22.83	18.27
1050	19.06	9.402	0.7828	0.67	12.77	17.15	13.72
1100	13.94	7.746	0.7428	0.67	9.338	12.26	9.806
1150	9.629	6.337	0.6954	0.67	6.452	8.231	6.585
1200	6.24	5.331	0.6493	0.67	4.181	5.189	4.152
1250	3.861	4.926	0.6266	0.67	2.587	3.179	2.543
1300	2.407	5.174	0.6408	0.67	1.613	2.008	1.606

Table 4-2 : Model Parameters, Larson-Miller Property Results, and Allowable Stress (Strain Rate) Criteria, Grade 91

Equation Format:

$$\log(\dot{\varepsilon}_0) = -C_{avg} - \frac{1}{T+460}\left(a_1 + a_2\log(\sigma) + a_3(\log(\sigma))^2 + a_4(\log(\sigma))^3\right)$$

C_{avg} (A_0)	**-22.36**
C_{min} ($A_0+\Delta_\Omega^{SR,LB}$)	**-23.3**
a_1	**48760.4**
a_2	**-317.1**
a_3	**-652.7**
a_4	**-1897.7**

Number Data Points		**694**
Correlation Coefficient	R^2	0.8003
Average Variance within Heats	V_w	0.3251
Variance between Heats	V_b	0.167
Standard Error of Estimate	SEE	0.5701

Properties provided are for T in °F, stress in ksi, and t_R in hours

Temperature, °F	**$S_{C,avg}$ (ksi)**
850	57.48
900	48.91
950	41.06
1000	33.9
1050	27.4
1100	21.52
1150	16.24
1200	11.52
1250	7.273
1300	3.299

Figure 4-1: Grade 91 Modulus (E_y), Thermal Conductivity (k), Thermal Diffusivity (TD), & Thermal Expansion (α) With Temperature

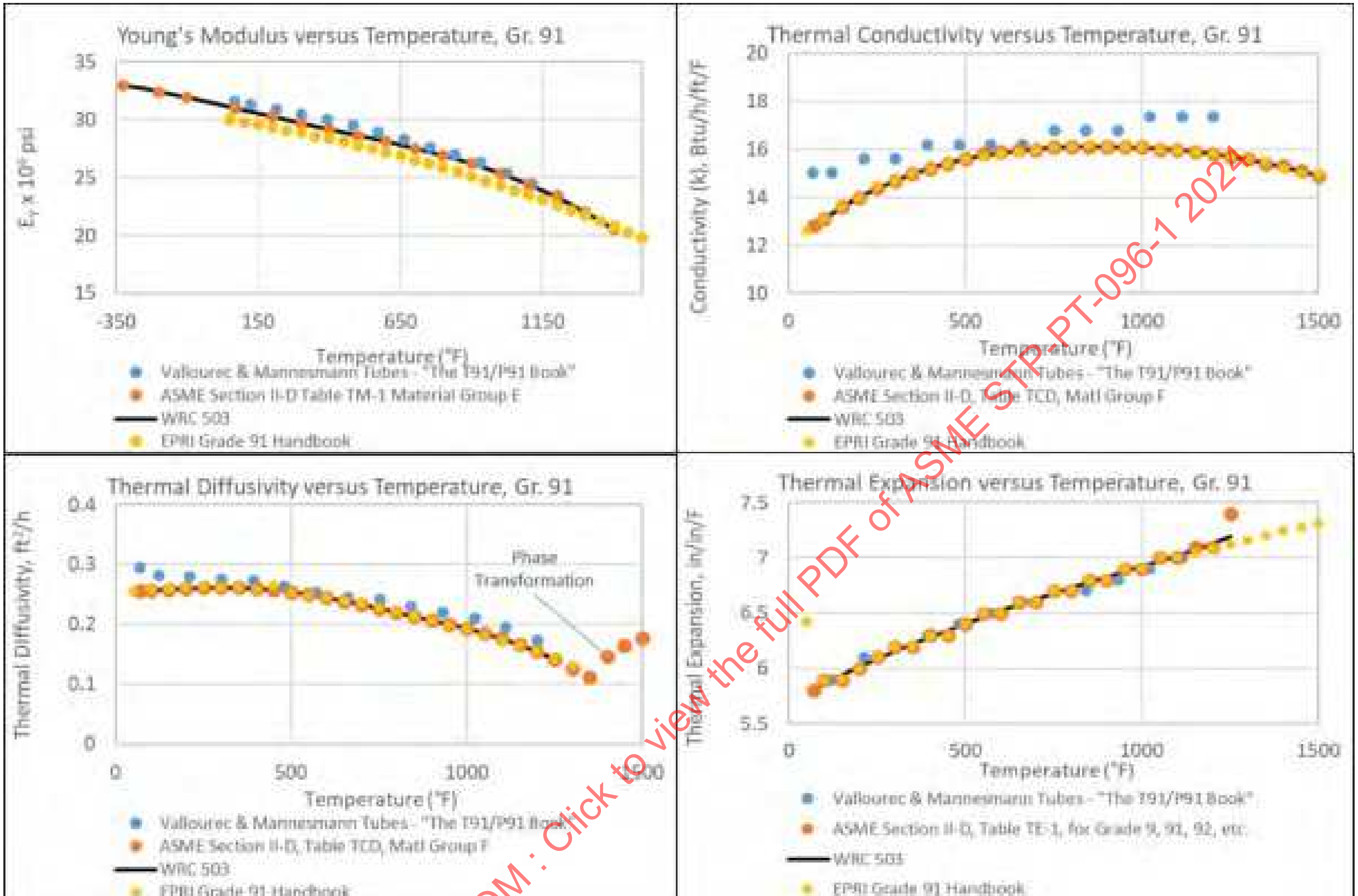


Figure 4-2: Grade 91 Yield Strength Vs. Temperature, By Data Source, Including Trend Curves

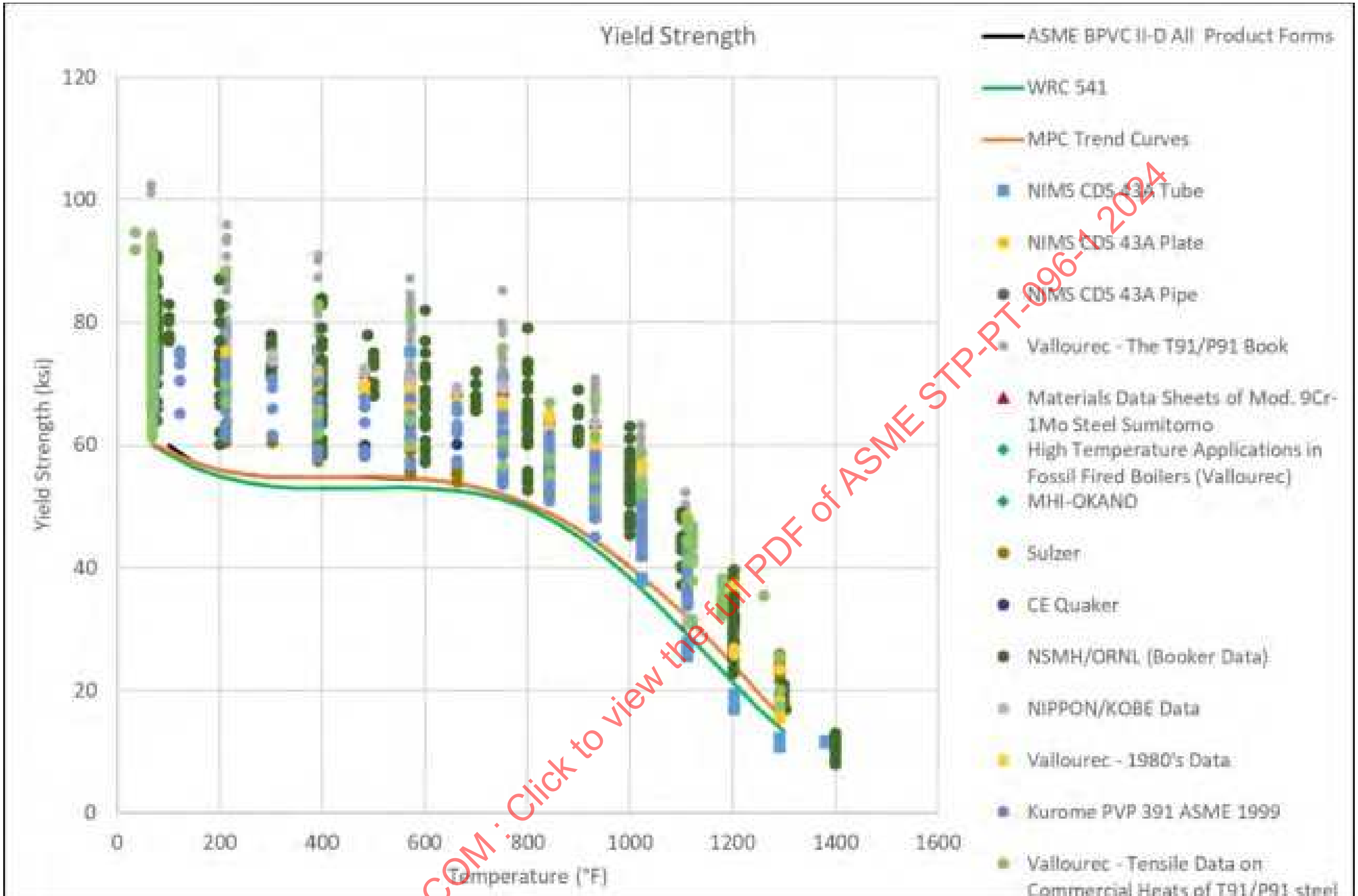


Figure 4-3: Grade 91 Tensile Strength Vs. Temperature, By Data Source, Including Trend Curves

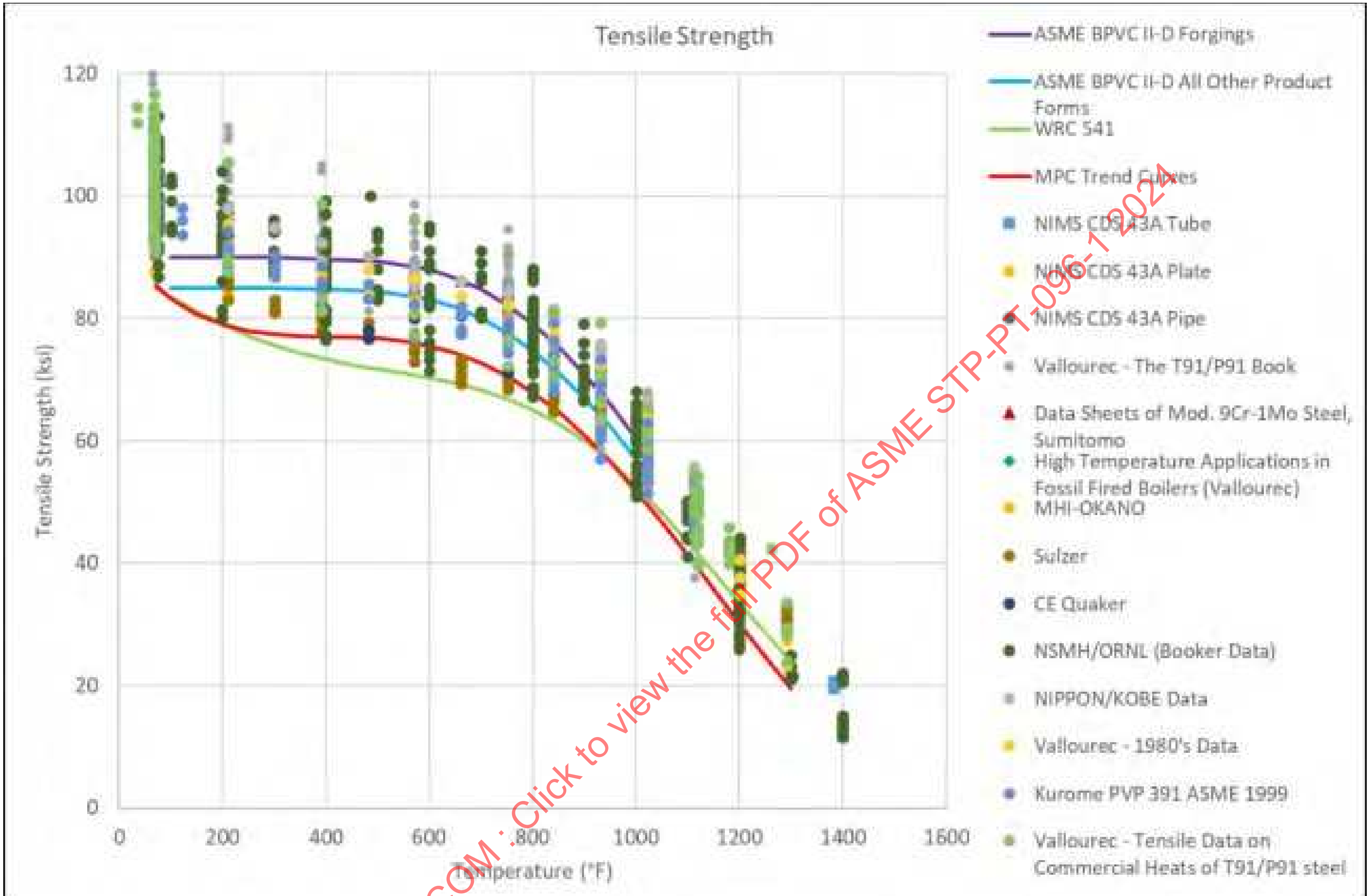


Figure 4-4: Grade 91 Yield Strength Ratios Vs. Temperature (Calculated on a Heat-By-Basis, By Data Source)

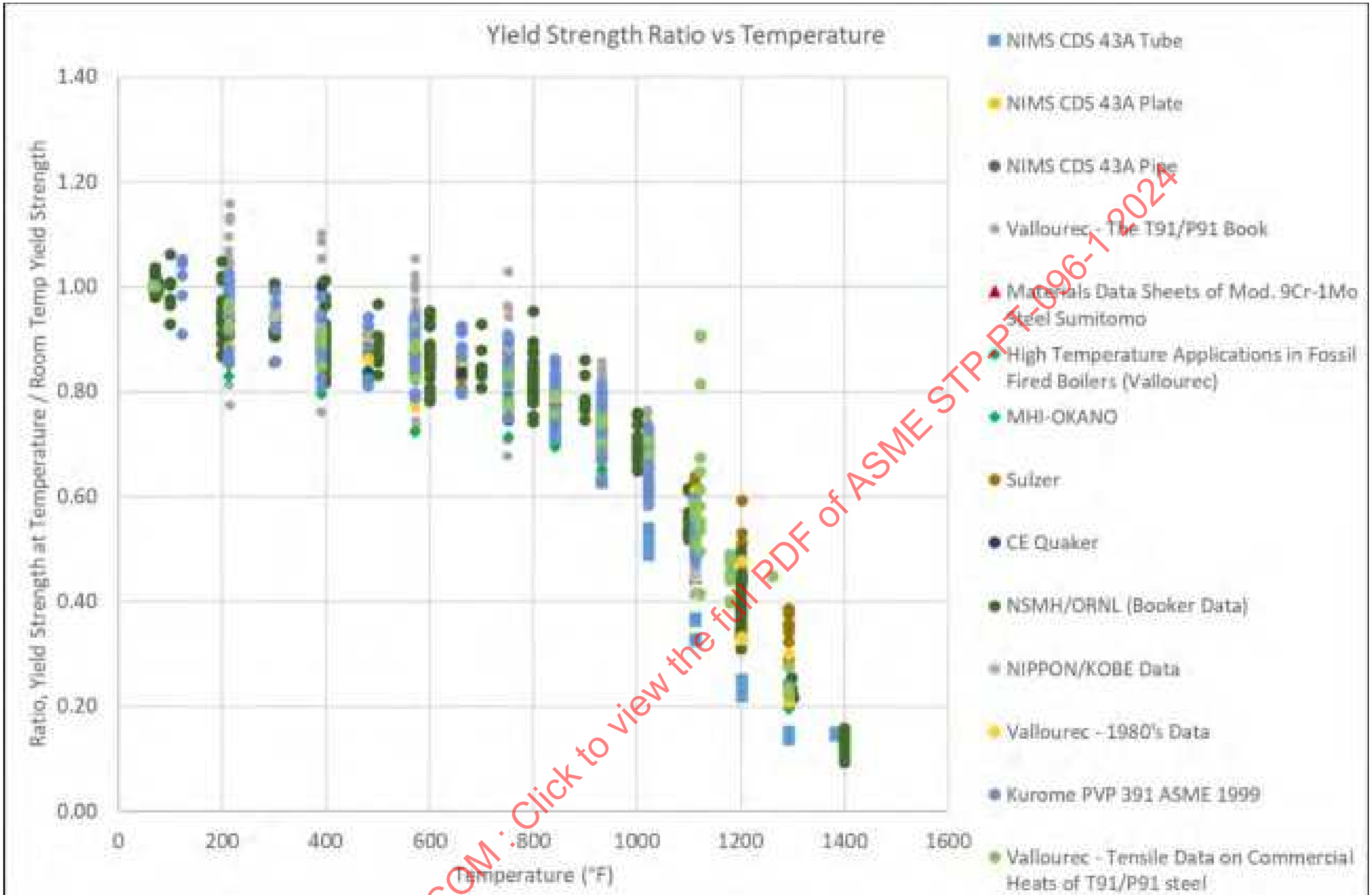


Figure 4-5: Grade 91 Tensile Strength Ratios Vs. Temperature (Calculated on a Heat-By-Basis, By Data Source)

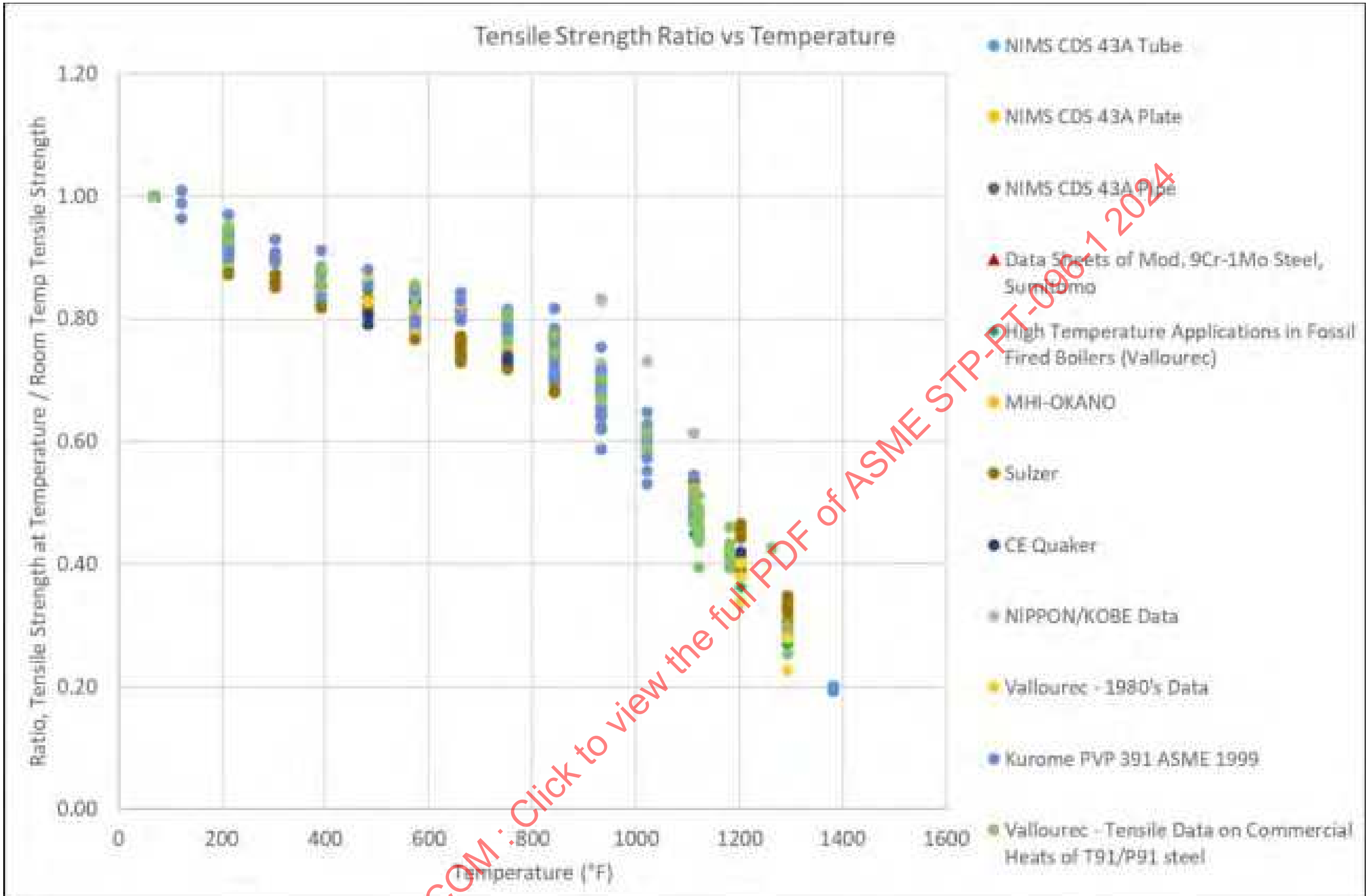


Figure 4-6: Grade 91 Yield Strength Ratios Vs. Temperature, All Combined Data, With Polynomial Regression

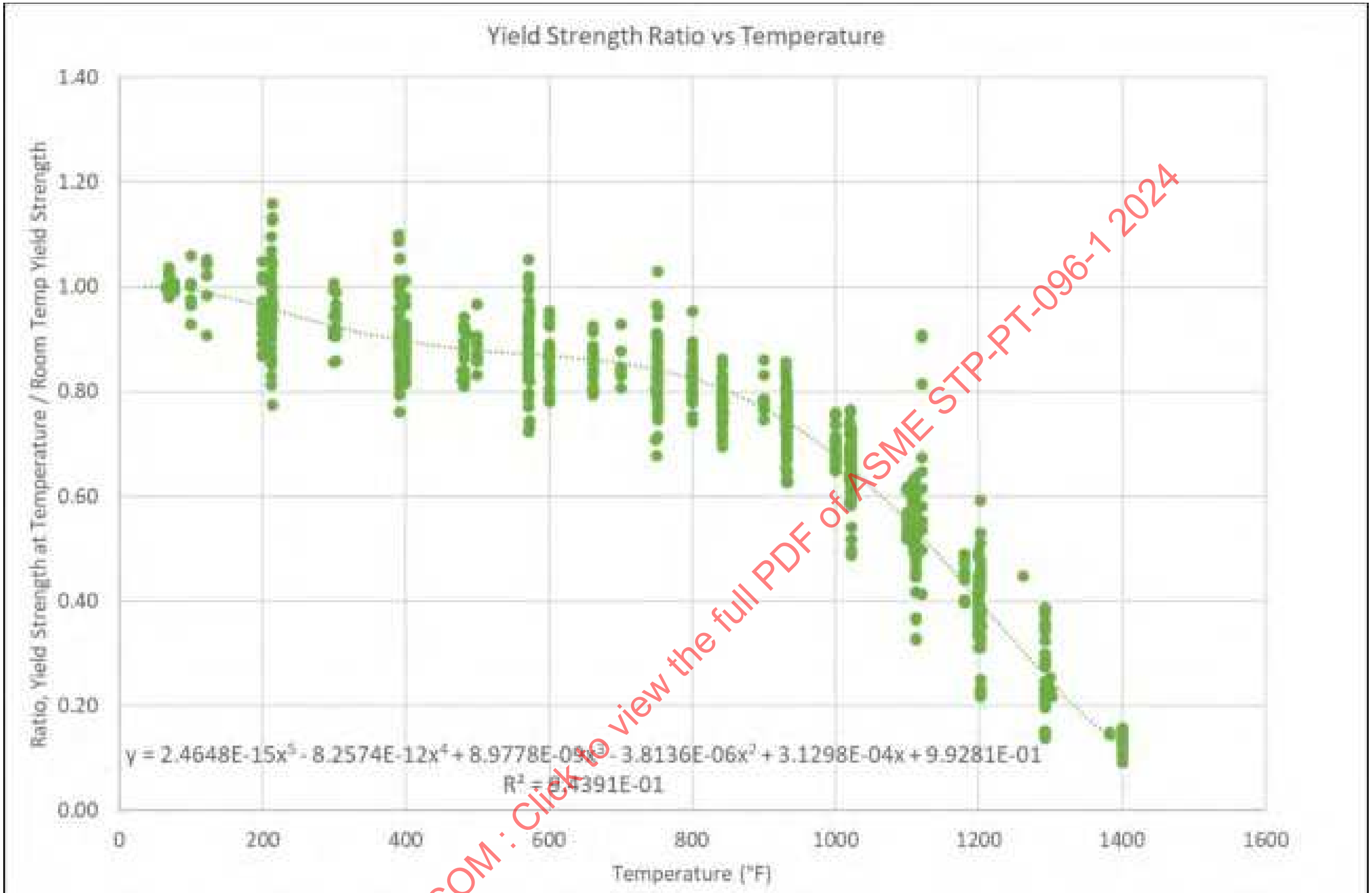


Figure 4-7: Grade 91 Tensile Strength Ratios Vs. Temperature, All Combined Data, With Polynomial Regression

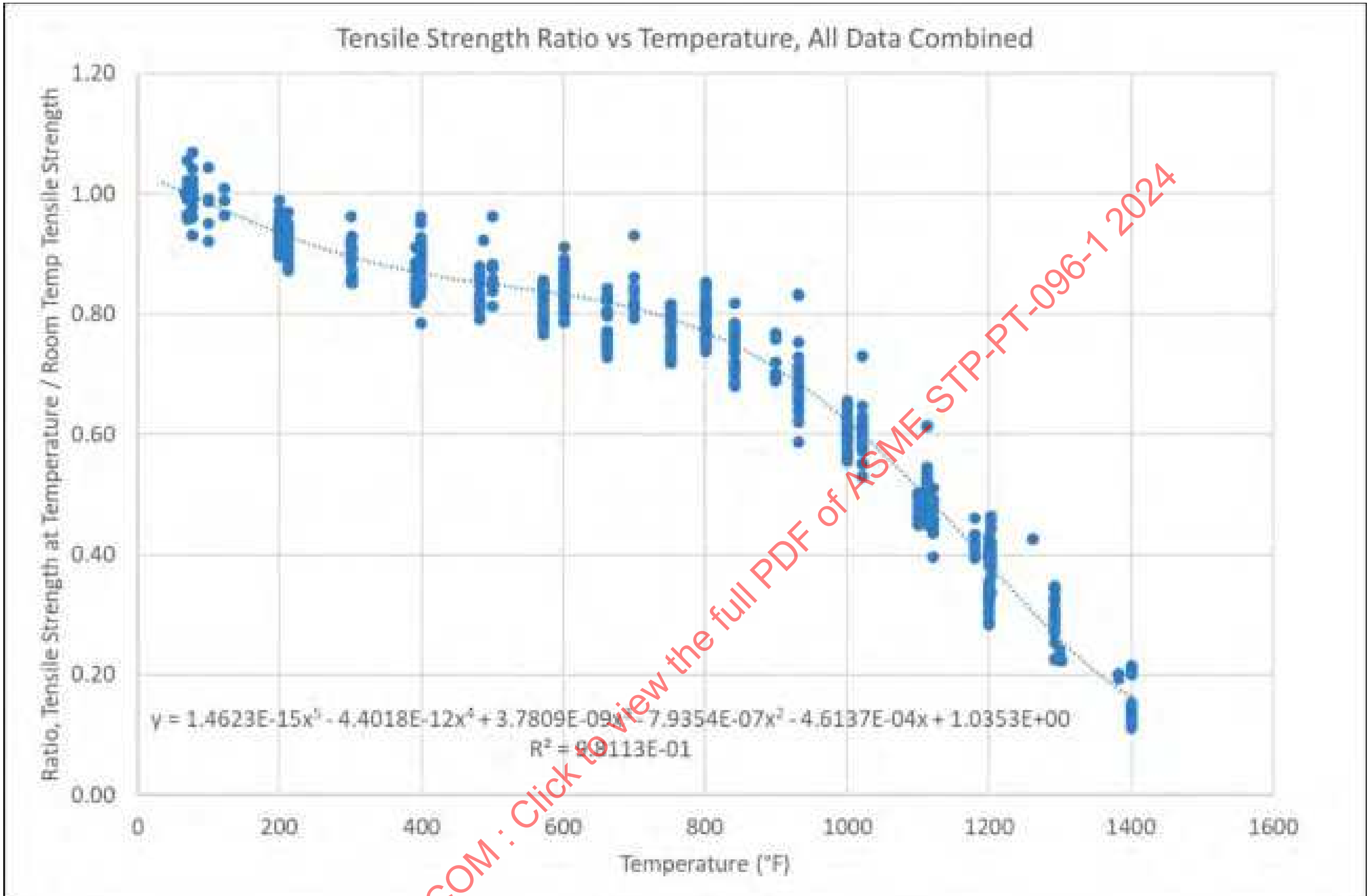


Figure 4-8: Grade 91 Creep Rupture Isotherm Curves, Temperatures With High Concentration of Data Points

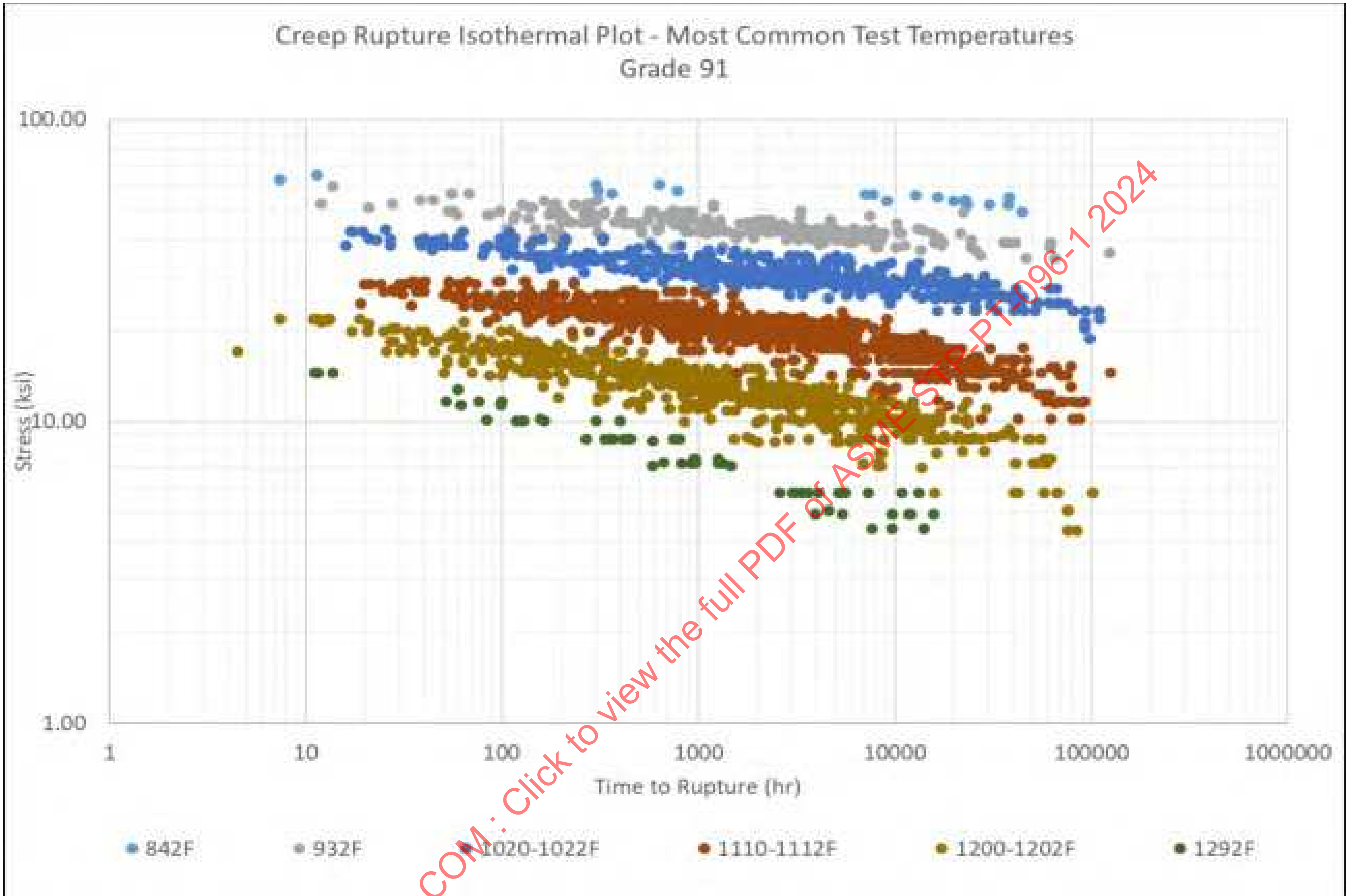


Figure 4-9: Grade 91 Creep Rupture Isotherm Curves for Additional and Intermediate Temperatures

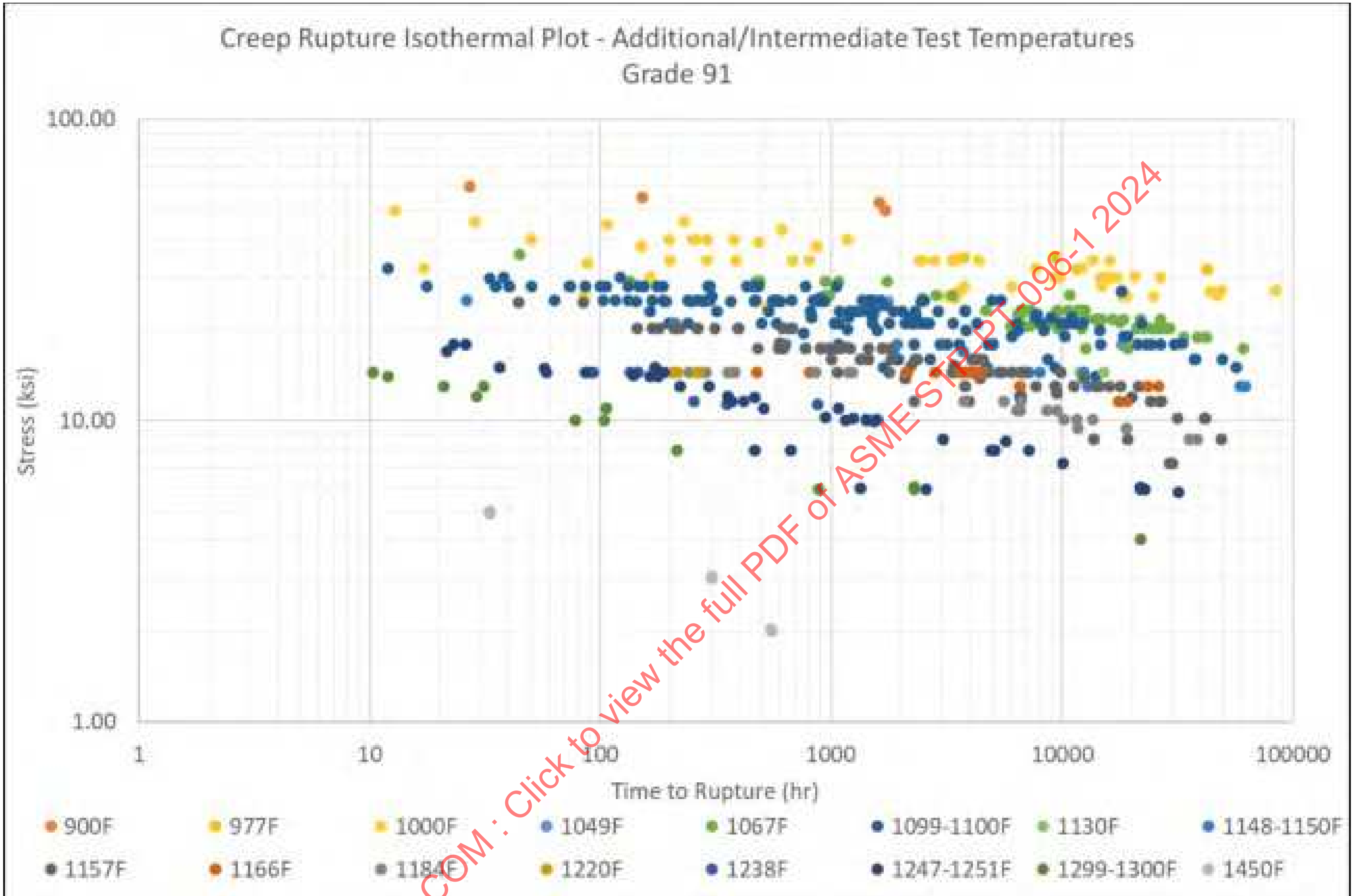


Figure 4-10: Grade 91 Creep Strain Rate (MCR) Isotherm Curves, Temperatures with High Concentration of Data Points

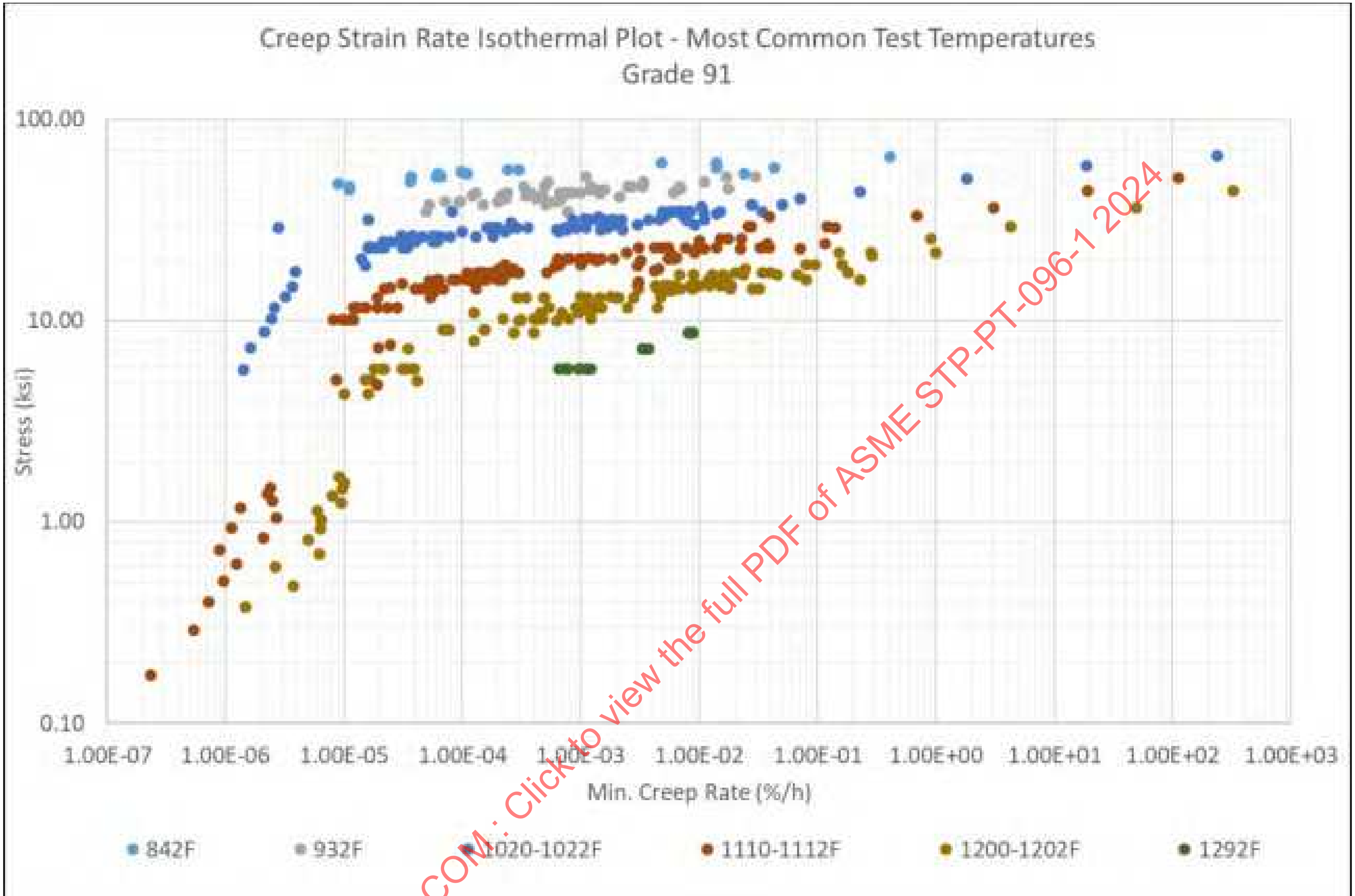


Figure 4-11: Grade 91 Creep Strain Rate (MCR) Isotherm Curves for Additional and Intermediate Temperatures

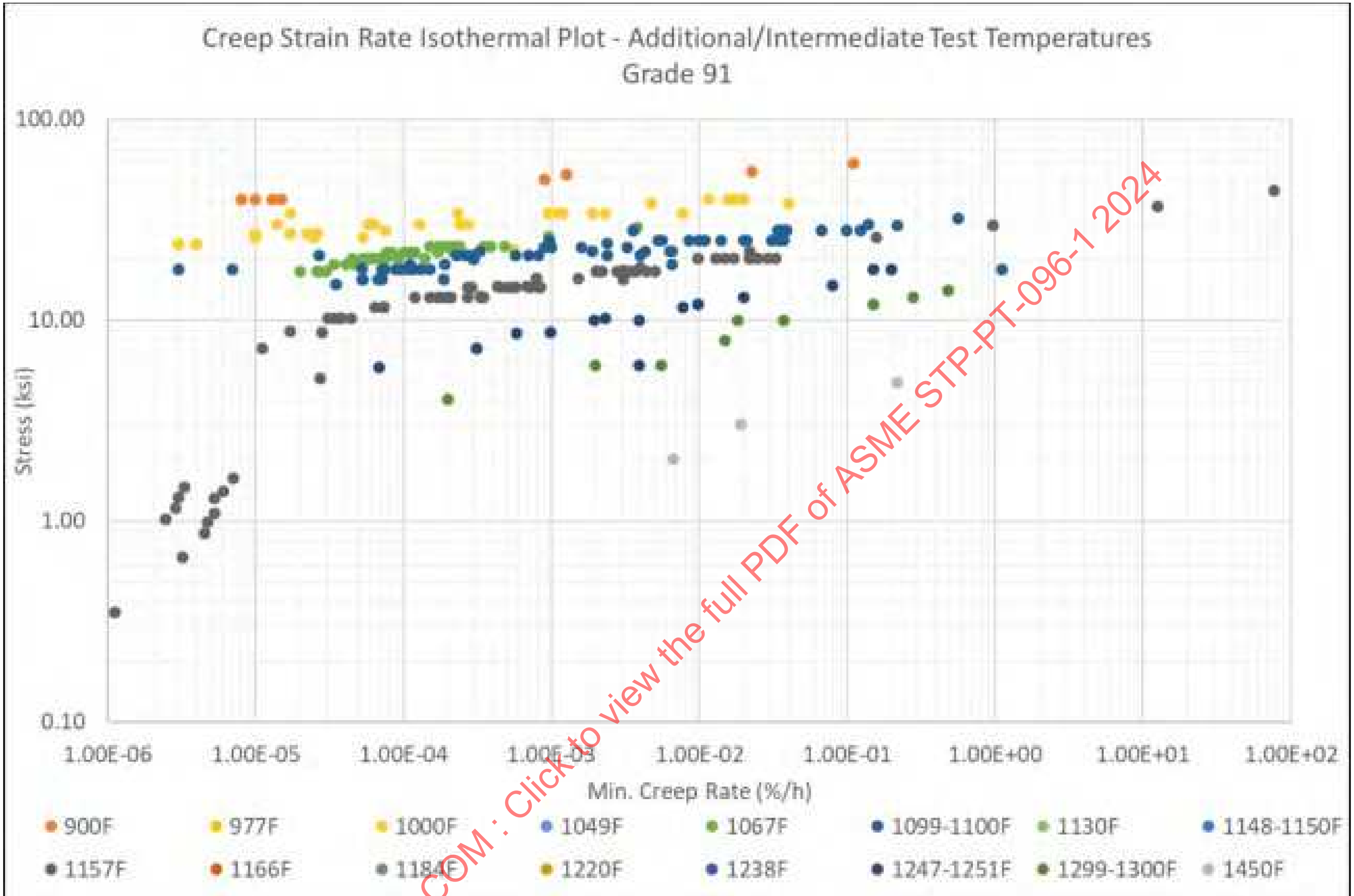


Figure 4-12: Grade 91 Creep Ductility (% Elongation) Vs. Rupture Time Isotherms

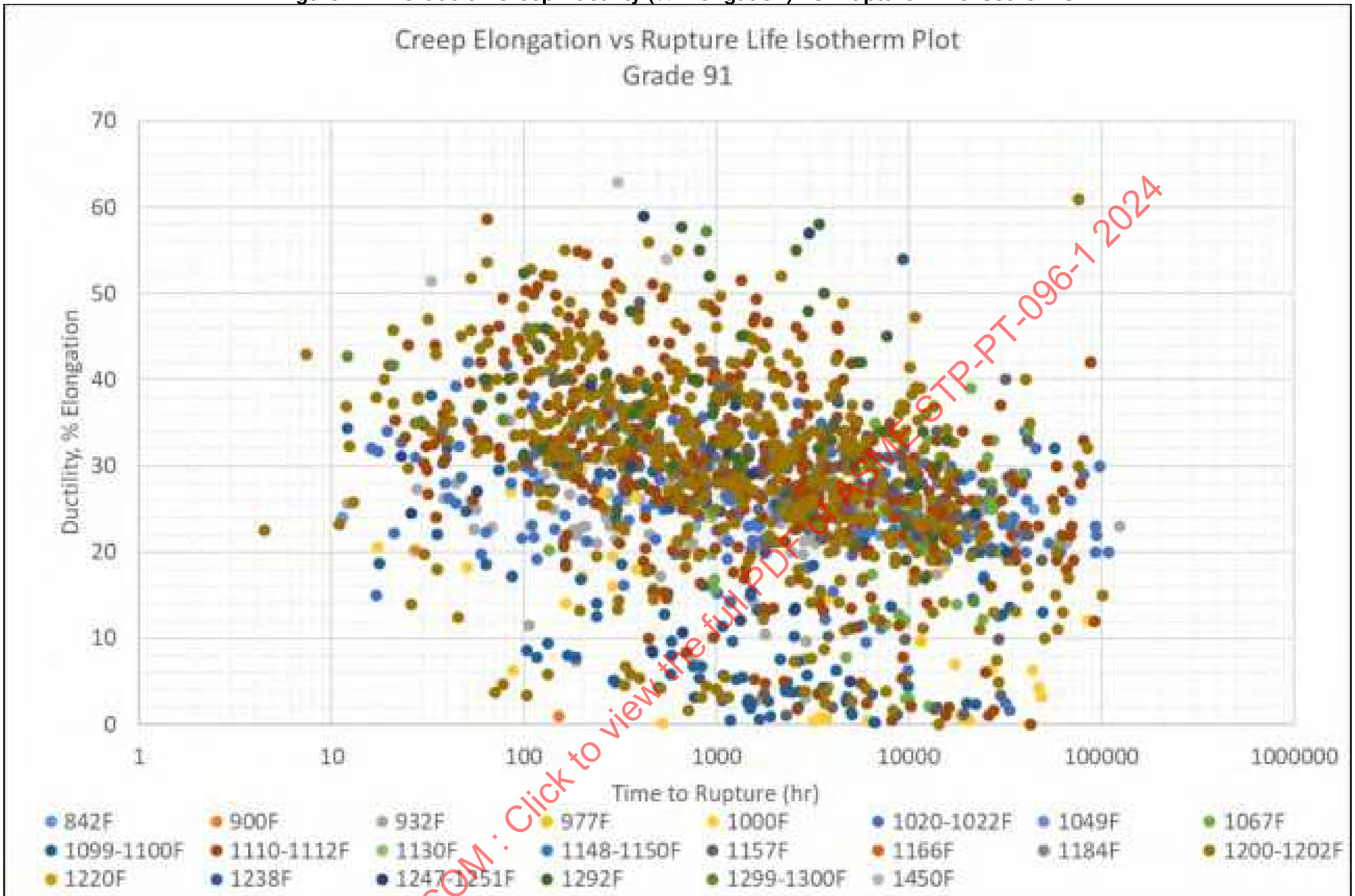
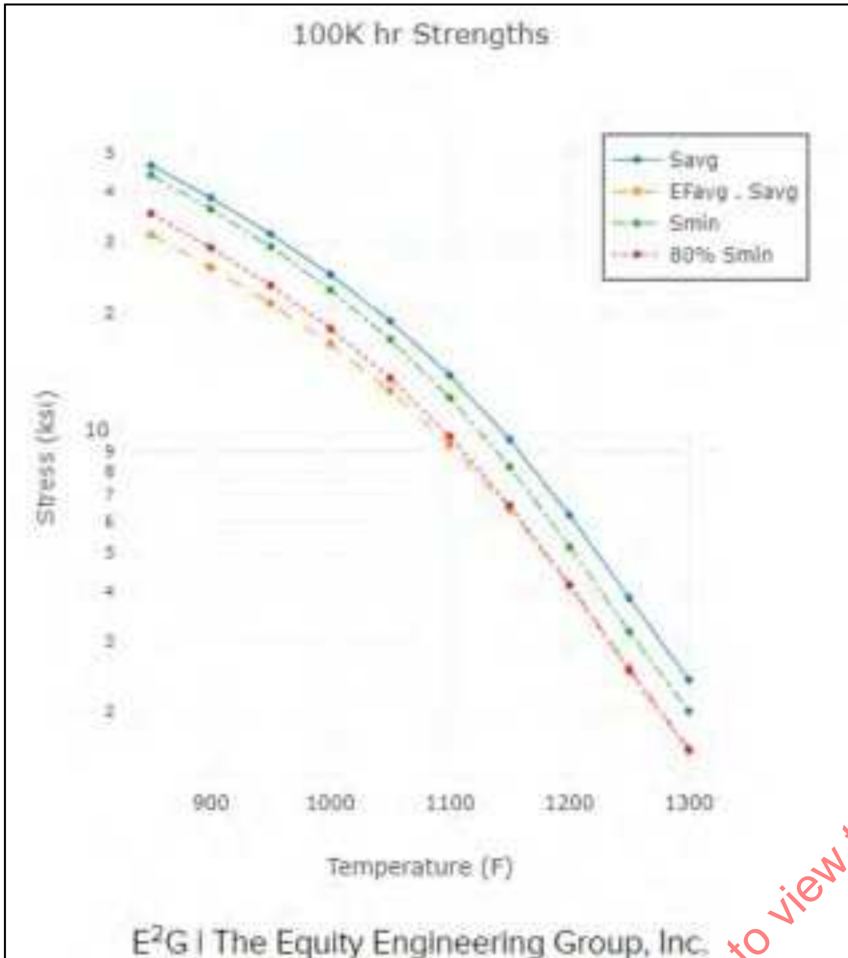


Figure 4-13: Calculated Allowable Stresses Based on Rupture and Creep Strain Rate and ASME II-D Appendix 1 Criteria (Grade 91)



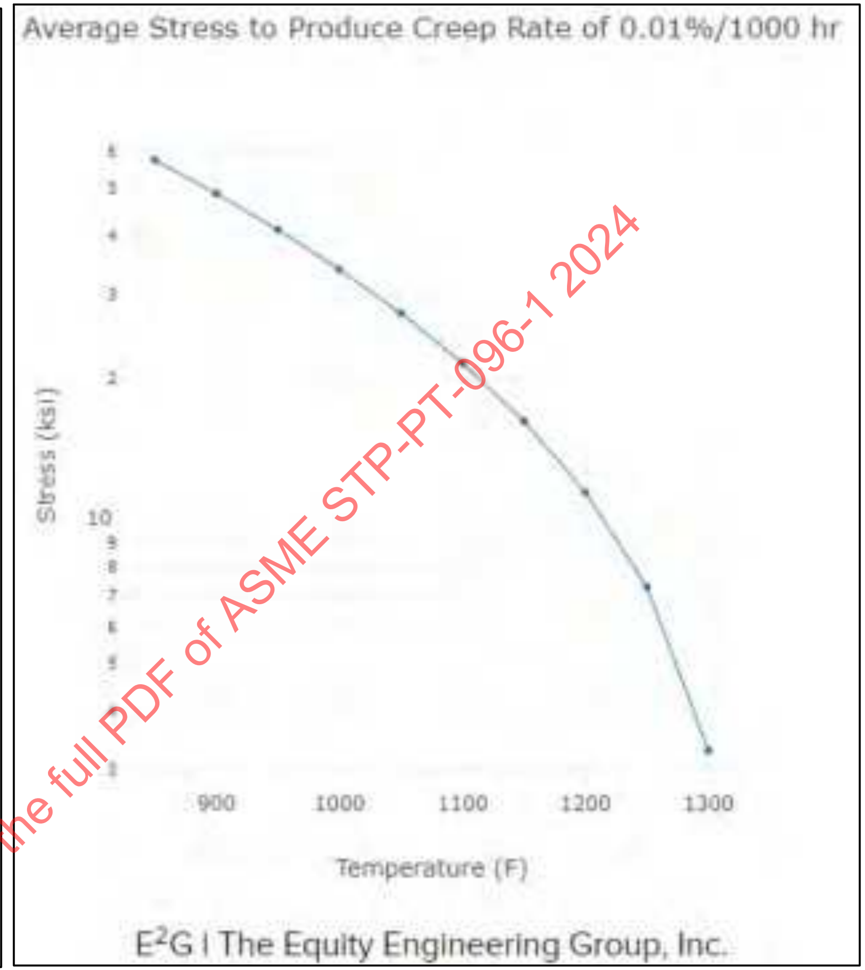


Figure 4-14: Comparison of Current Grade 91 Allowable Stresses (Except Forgings) Vs. ASME II-D Appendix 1 Criteria Applied to Data

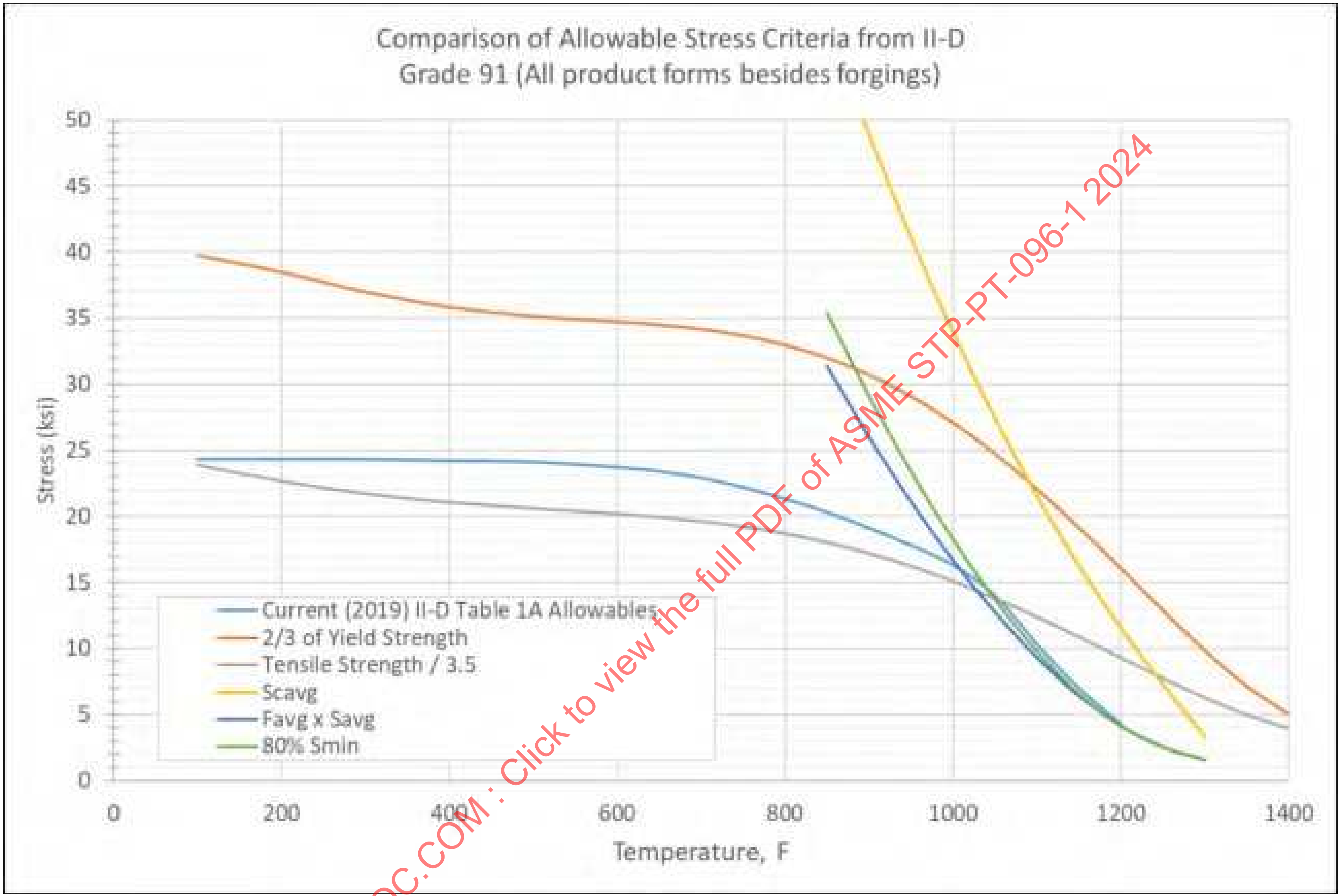


Figure 4-15: Short-Term Strain Vs. Time Data, up to 2,500 Hour Test Durations (Grade 91), 1 of 2

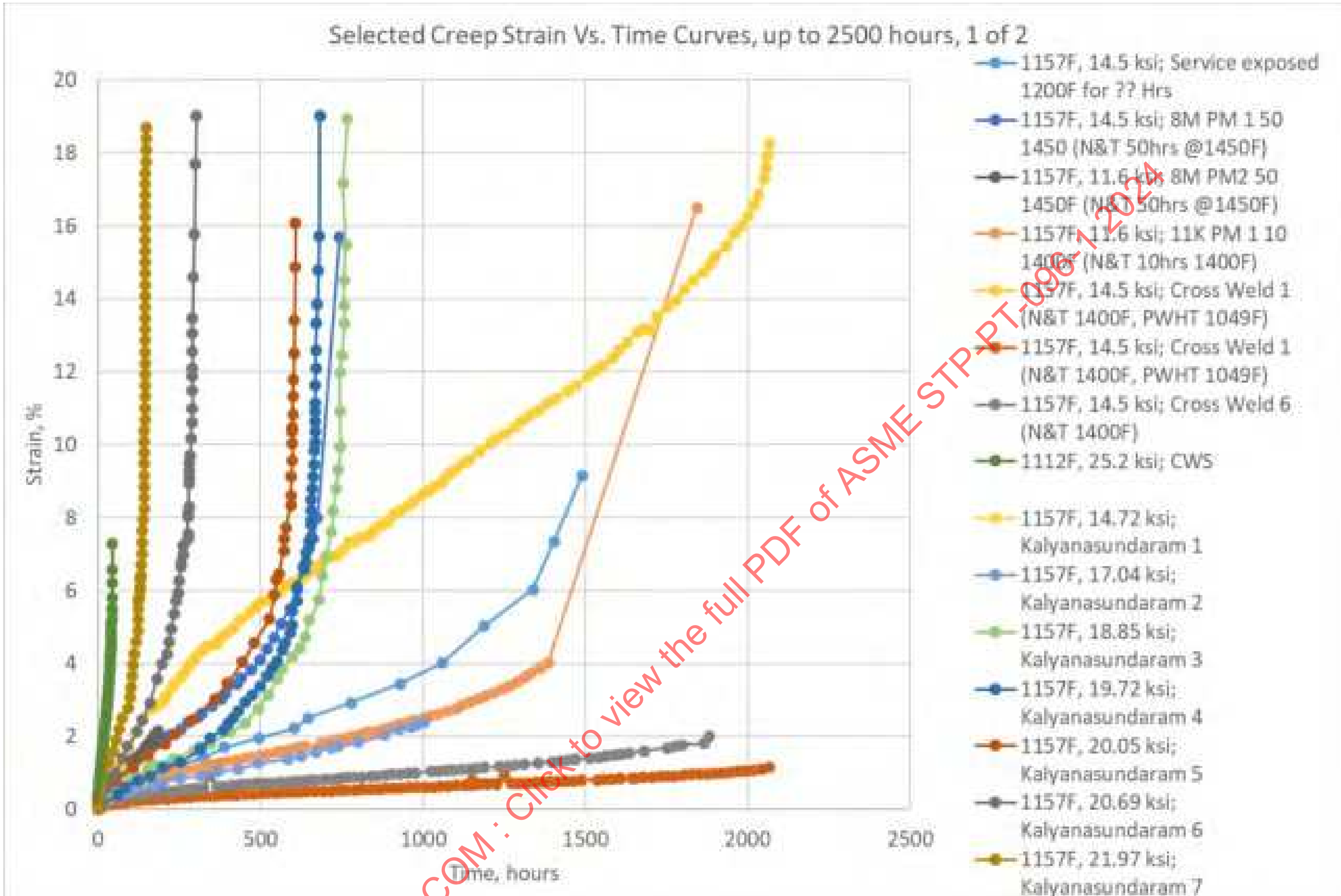


Figure 4-16: Short-Term Strain Vs. Time Data, Up to 2,500 Hour Test Durations (Grade 91), 2 of 2

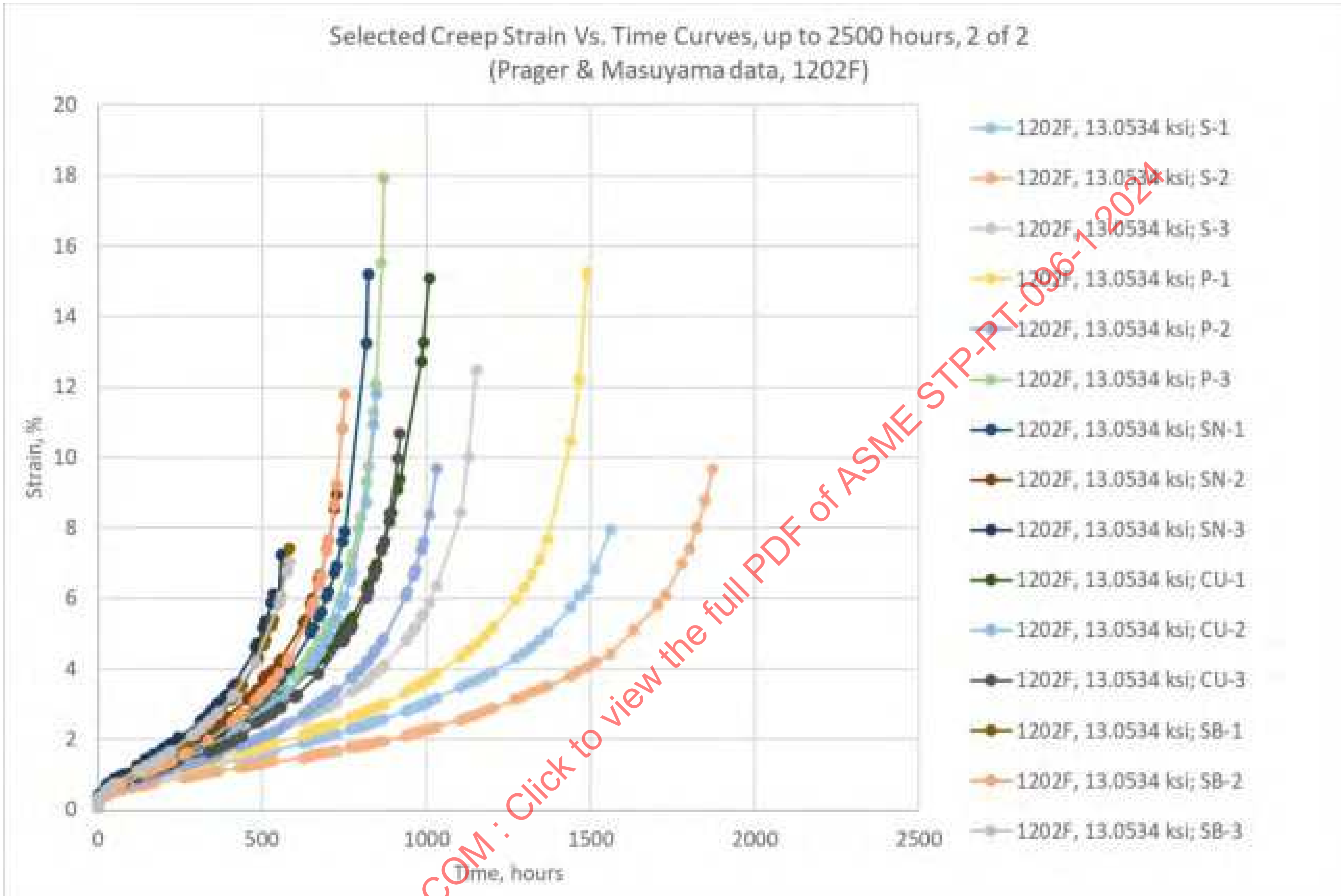


Figure 4-17: Medium-Term Strain Vs. Time Data, 2,500 to 5,000 Hour Test Durations (Grade 91)

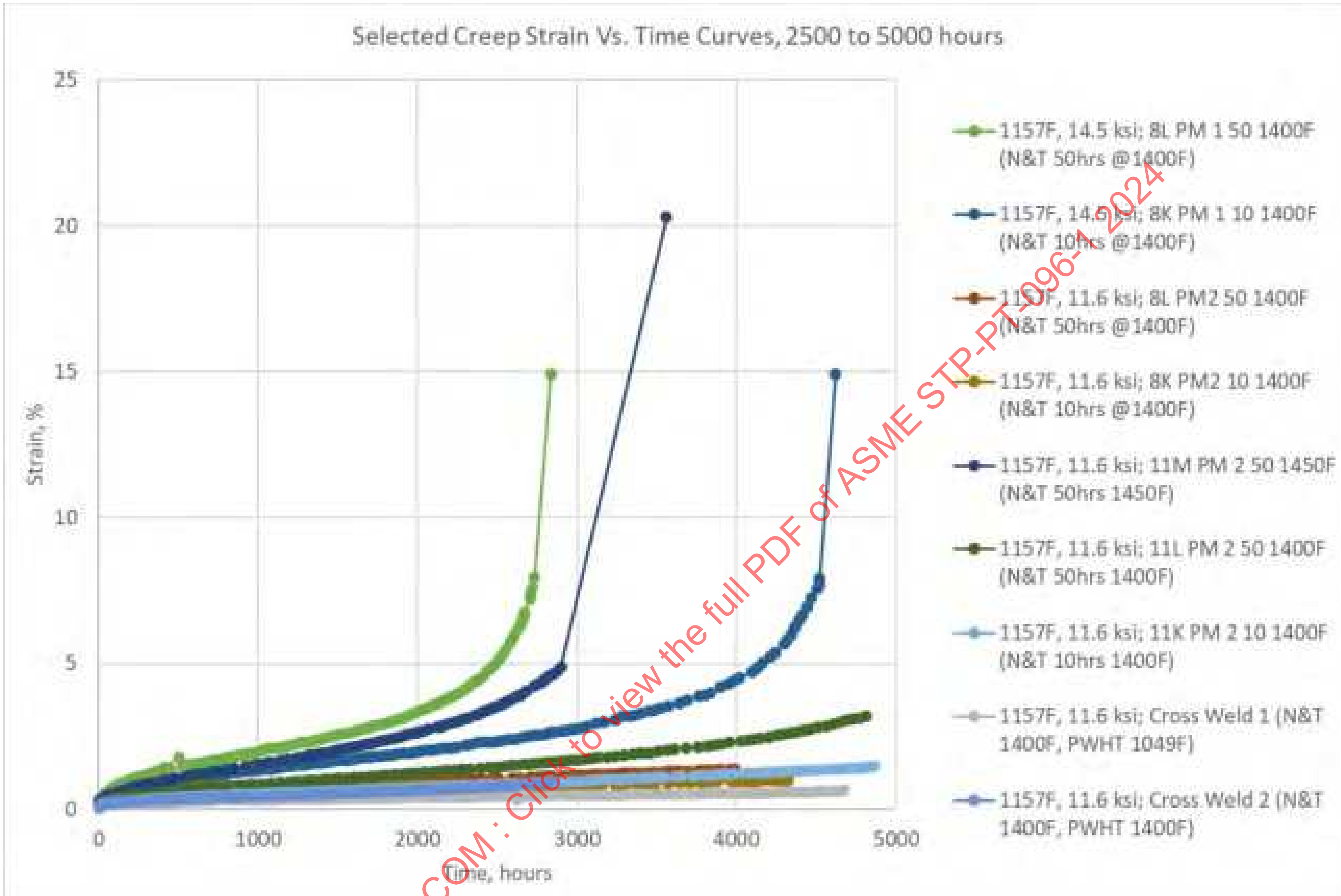


Figure 4-18: Long-Term Strain Vs. Time Data, Up to 10,000 Hour Test Durations (Grade 91)

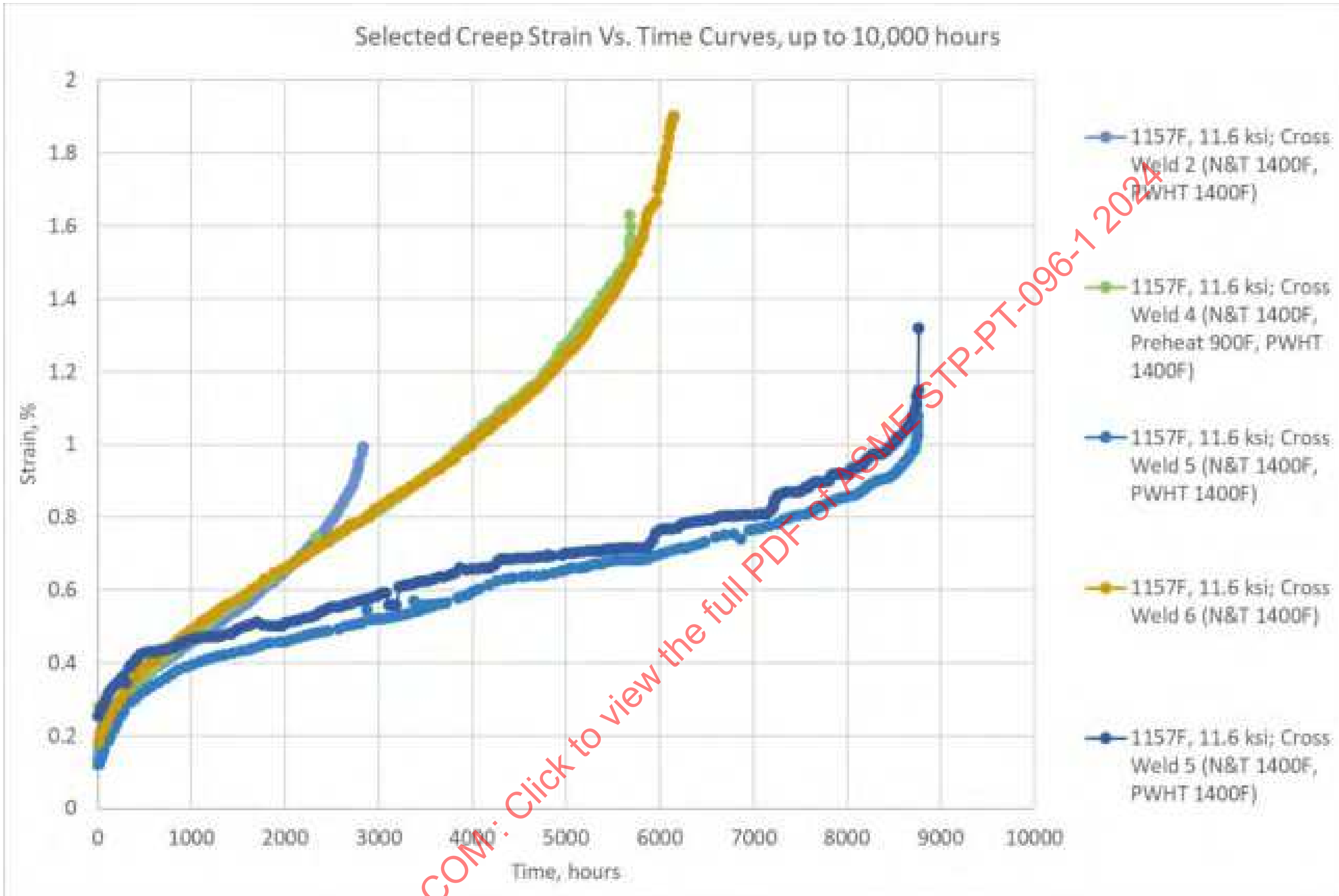


Figure 4-19: Long-Term Strain Vs. Time Data, In Excess of 10,000 Hour Test Durations (Grade 91)

Figure 4-20: Grade 91 Continuous Cycling Fatigue (Grade 91), Including Room Temperature and Elevated Temperature Data

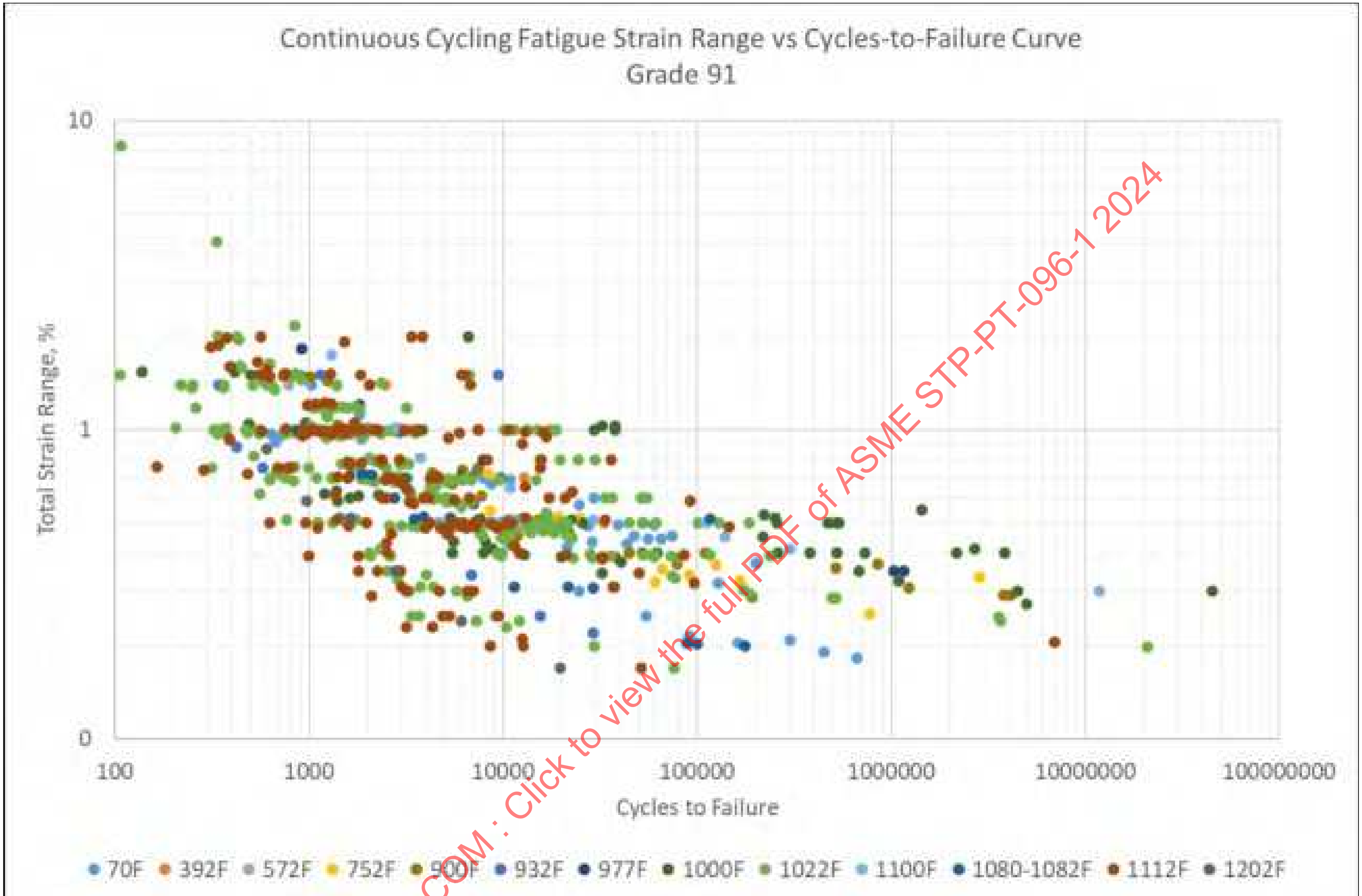


Figure 4-21: Grade 91 Hold Time Data (Creep Fatigue) For Grade 91, Temperatures of 932°F, 1000°F, 1076°F, & 1100°F

Figure 4-22: Grade 91 Hold Time Data (Creep Fatigue) for Grade 91, Temperature of 1022°F

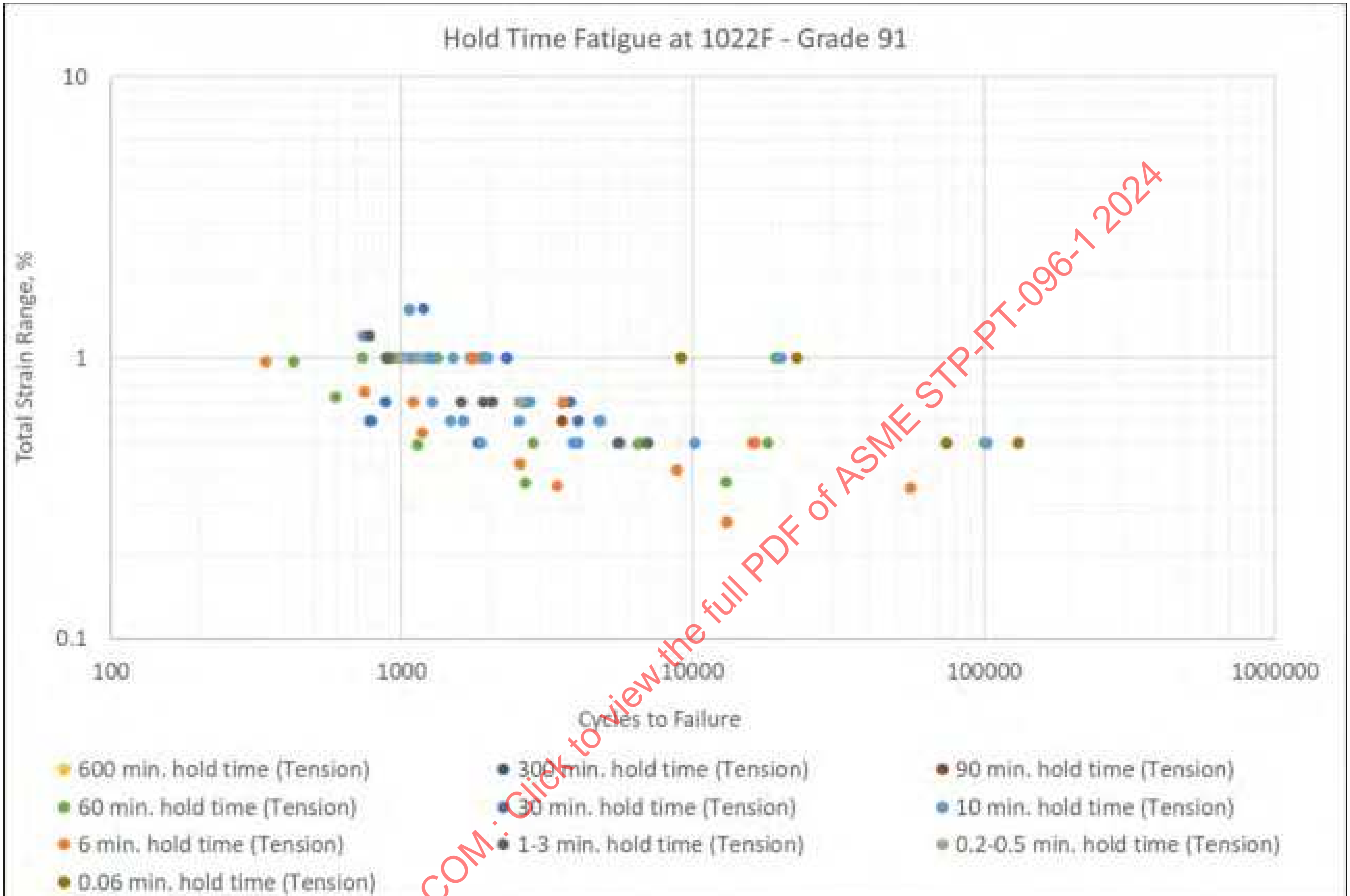


Figure 4-23: Grade 91 Hold Time Data (Creep Fatigue) For Grade 91, Temperature of 1112°F

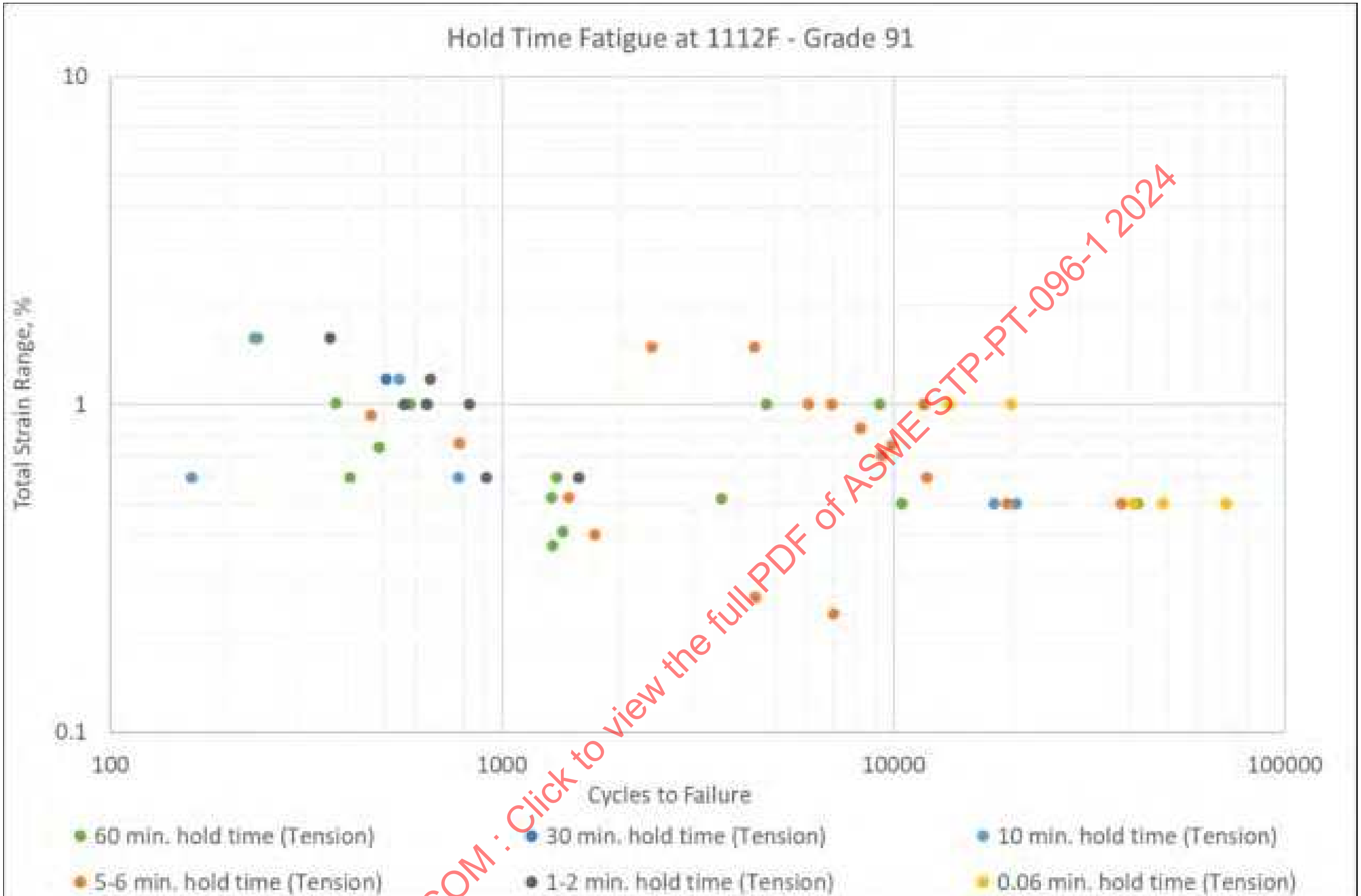
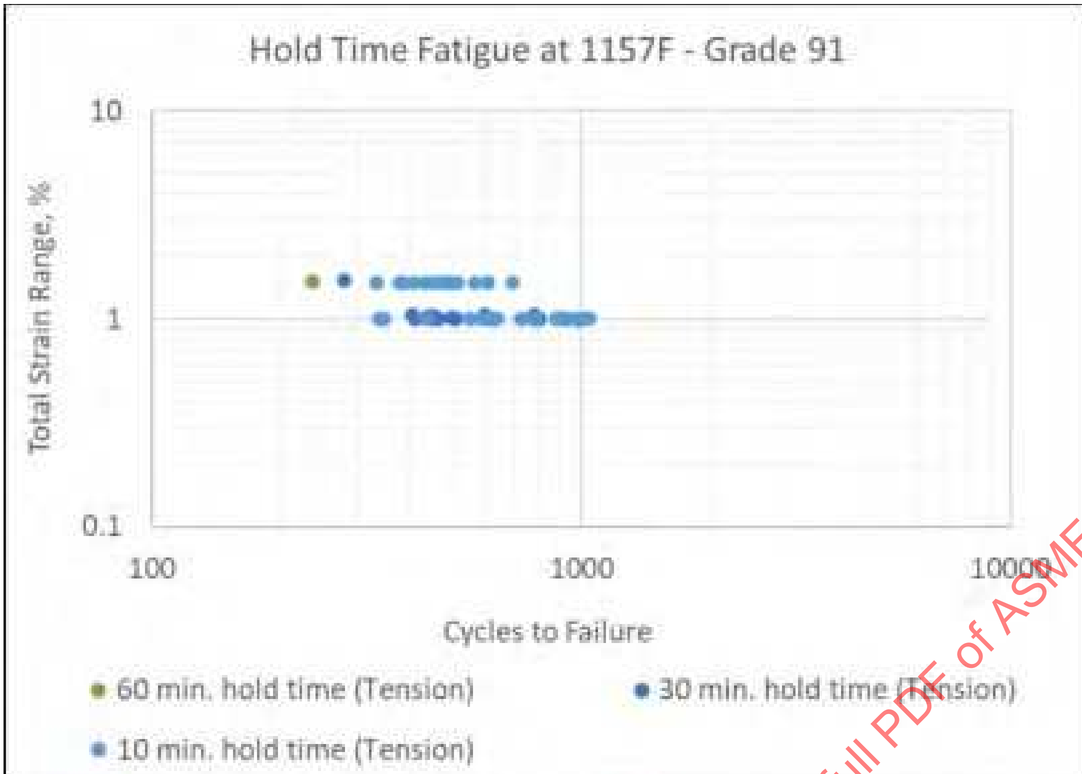


Figure 4-24: Grade 91 Hold Time Data (Creep Fatigue) For Grade 91, Temperature of 1157°F



Attachment 4: Grade 91 Property Data

If you want the referenced embedded spreadsheet with additional data, please email a request to research@asme.org.

5 CARBON STEEL (SA-516/SA-299) AND SIMILAR

Data collected for this material includes multiple specifications beyond just SA-516 and SA-299. In general, these two specifications contain as-rolled, stress-relieved, normalized or normalized and tempered materials; as explained in reference [1], therefore, material test results meeting this heat treatment condition, as well as the nominal chemical composition of SA-516 and SA-299 (various grades) are included in the analysis. The spreadsheet containing data for this material, wherever possible, includes the chemical composition and heat treatment details for the data points listed, which can be used to verify that the material either does or does not meet the specification.

5.1 Physical Properties

Well-established physical properties were referenced from the BPVC Section II for this material. Physical property curves from *WRC Bulletin 503* were plotted for comparison. Figure 5-1 shows the trends of Elastic Modulus (E_y), Thermal Conductivity (k), Thermal Diffusivity (TD), and Thermal Expansion (α) with temperature. For thermal expansion, available data were digitized from figures in the Nuclear Systems Materials Handbook (NSMH) to provide additional data.

5.2 Yield and Tensile Strength

Elevated temperature Yield and Tensile Strength were readily available up to approximately 1000°F, with additional data beyond the current range of allowable stresses, up to approximately 1800°F, as shown in Figures 5-2 and 5-3. The sources for both high-temperature yield and high-temperature tensile strength are provided in the embedded spreadsheet at the end of this section. This spreadsheet also contains ductility data corresponding to the tensile test results presented in this report. Note that ductility (percent elongation and percent reduction in area) was not available for all sources referenced for this material.

To facilitate comparison of the data obtained to existing allowable stresses (Section II-D Table 1A), yield and tensile data were normalized on a heat-by-heat basis to express the ratio of yield or tensile strength at temperature to that measured for the heat at room temperature. For this material, all data from original sources were able to be separated by heat. E^2G understands that this approach is similar to the normalizing procedure performed by ASME in typical analysis of yield and tensile data to obtain Table Y and Table U (Section II-D) trend curves, as well as for the calculation of allowable stresses. Figures 5-4 and 5-5 show the heat-by-heat variation in yield and tensile strength ratios (respectively) as a function of temperature. It should be emphasized that even though the figure legends reference an entire source of data, the ratios were calculated on a heat-by-heat basis; this is evident in the embedded spreadsheet at the end of this section. Figures 5-6 and 5-7 contain all of the yield and tensile (respectively) ratios plotted together, to facilitate regression of a 4^{th}-order (yield) or 6^{th}-order (tensile) polynomial that is subsequently used for allowable stress comparison.

5.3 Creep Data (Creep Rupture, Minimum Creep Rate, and Ductility)

Creep Rupture data is shown in Figure 5-8 and 5-9, plotted as isotherms. The temperatures have been separated onto separate plots to reduce data overlap. These plots contain data for all product forms of material classified in the referenced publications as "carbon steel" and with a heat treatment similar to that noted above for typical SA-516/SA-299. The data tables and these two figures likely includes data that may not meet existing specifications for this grade of material. For carbon steels in general, the available data span nearly a century, with the original ASTM Creep Data book being released in the 1930s; some of these data were included in subsequent ASMT *DS* and *STP* publications into the 1970s and are, in fact, are included in the dataset used to make up allowable stresses in ASME and API codes. Of course, significant improvement in steelmaking practices has occurred over the time period. The background and source information are included in the attached spreadsheet for this material. Some of the modern data classified as carbon steel displays significantly better than expected properties; this is believed to be due to microalloying. In particular, a fraction of the material heats contained in the NIMS Creep data sheets for carbon steel materials contain higher-than-typical (but still within spec) molybdenum content, which imparts significant creep resistance not observed in other materials.

Creep Minimum strain rates (%/hour) are shown in Figure 5-10, 5-11, and 5-12 separated by temperature. As in the case of rupture data, temperatures of minimum creep rates have been separated onto separate plots to minimize data overlap, with Figure 5-10 and 5-11 showing those temperatures where most of the data were concentrated, and Figure 5-12 showing those temperatures with significantly less data. Creep Ductility, as % elongation, is plotted in Figure 5-13. As is typical, the data show significant overlap, and it is difficult to observe clear trends in the ductility data. The data is not intended to be used as plotted but is available in the spreadsheet for additional analysis.

Creep data were analyzed using E^2G's proprietary *Lot-Centered Analysis* web-based software tool (Mandel-Paule algorithm), according to a Larson-Miller 3rd-order polynomial of stress, assuming parallel behavior and a 95% predictive limit. This procedure was utilized to obtain the lower-bound (minimum LM constant for both rupture and strain rate) properties. The results of this analysis are summarized in Table 5-1 for rupture data and Table 5-2 for strain rate data. The *Lot-Centered Analysis* software tool generates property tables in the creep regime using the criteria outlined in Mandatory Appendix 1 of ASME Section II-D; the nomenclature of variables is consistent with II-D Appendix 1. For visualization of the allowable stress trends, Figure 5-14 is provided (for rupture allowable stresses and creep rate allowable stresses). Figure 5-15 shows a comparison of the various allowable stress criteria from Section II-D, Appendix 1, to the existing (2019) Section II-D Table 1A allowable stresses for a common carbon steel as-rolled/normalized plate material (SA-516-70).

Creep Strain vs. time data are shown in Figure 5-16 through 5-22. Additional creep strain vs. time data are located in the embedded spreadsheet. Both creep rate and creep strain vs. time data are provided to satisfy ASME's request for creep strain vs. time curves, and both forms of data are applicable in developing allowable stresses. Although digitalization of creep curve data was not explicitly necessary per the project contract, E^2G did perform digitalization of creep curves where only graphical data was available (as is often the case in the published literature).

5.4 Continuous Cycling Fatigue and Hold Time Fatigue Curves

Due to the amount of readily accessible room temperature fatigue data available for general carbon steels, E^2G has included approx. 500 data points at ambient temperature in the attached spreadsheet (not reproduced in the figures). The remainder of the data, at elevated temperatures, are shown in Figure 5-23 for continuous cycling fatigue. A very limited amount of hold time fatigue data was located in E^2G's review; this data is plotted in Figure 5-24. Additional stress-controlled fatigue data are shown in Figure 5-25; results indicating that the test was terminated after 10^8 cycles are omitted from the figure.

Table 5-1: Model Parameters, Larson-Miller Property Results, and Allowable Stress (Rupture) Criteria, CS (516/299)

Equation Format:

$$\log(t_r) = C_{avg} + \frac{1}{T+460}\left(b_1 + b_2\log(\sigma) + b_3(\log(\sigma))^2 + b_4(\log(\sigma))^3\right)$$

C_{avg}	**-19.35**
C_{min}	**-19.95**
b_1	**39310.5**
b_2	**-7068.2**
b_3	**1554.3**
b_4	**-1233.8**

Number Data Points		**1416**
Correlation Coefficient	R^2	0.8483
Average Variance within Heats	V_w	0.1305
Variance between Heats	V_b	0.5666
Standard Error of Estimate	SEE	0.3612

Properties provided are for T in °F, stress in ksi, and t_R in hours

Temperature, °F	**S_{avg} (ksi)**	***n***	**F_{avg} (calc)**	**F_{avg} (used)**	**$F_{avg} \times S_{avg}$**	**S_{min} (ksi)**	**80% S_{min}**
850	12.13	6.143	0.6874	0.67	8.129	9.64	7.712
900	8.426	5.413	0.6535	0.67	5.646	6.494	5.195
950	5.67	4.842	0.6216	0.67	3.799	4.246	3.397
1000	3.717	4.451	0.5962	0.67	2.491	2.724	2.179
1050	2.405	4.252	0.5819	0.67	1.611	1.745	1.396
1100	1.561	4.234	0.5805	0.67	1.046	1.137	0.9094
1150	1.034	4.363	0.5899	0.67	0.6924	0.7618	0.6095
1200	0.7042	4.595	0.6058	0.67	0.4718	0.528	0.4224
1250	0.4956	4.889	0.6244	0.67	0.332	0.3783	0.3026
1300	0.3598	5.215	0.643	0.67	0.2411	0.2793	0.2235

Table 5-2: Model Parameters, Larson-Miller Property Results, and Allowable Stress (Strain Rate) Criteria, CS (516/299)

Equation Format:

$$\log(\dot{\varepsilon}_0) = -C_{avg} - \frac{1}{T+460}\left(a_1 + a_2\log(\sigma) + a_3(\log(\sigma))^2 + a_4(\log(\sigma))^3\right)$$

C_{avg} (A_0)	**-18.17**
C_{min} ($A_0+\Delta_\Omega^{SR,LB}$)	**-18.95**
a_1	**38558.3**
a_2	**-5289**
a_3	**670.6**
a_4	**-1136.8**

Number Data Points		**702**
Correlation Coefficient	R^2	0.7898
Average Variance within Heats	V_w	0.225
Variance between Heats	V_b	1.361
Standard Error of Estimate	SEE	0.4743

Properties provided are for T in °F, stress in ksi, and t_R in hours

Temperature, °F	**S_{CAVG}**
850	19.78
900	14.61
950	10.42
1000	7.129
1050	4.653
1100	2.897
1150	1.744
1200	1.042
1250	0.6388
1300	0.4089

Figure 5-1: CS (516/299) Modulus (E_y), Thermal Conductivity (k), Thermal Diffusivity (TD), & Thermal Expansion (α) With Temperature

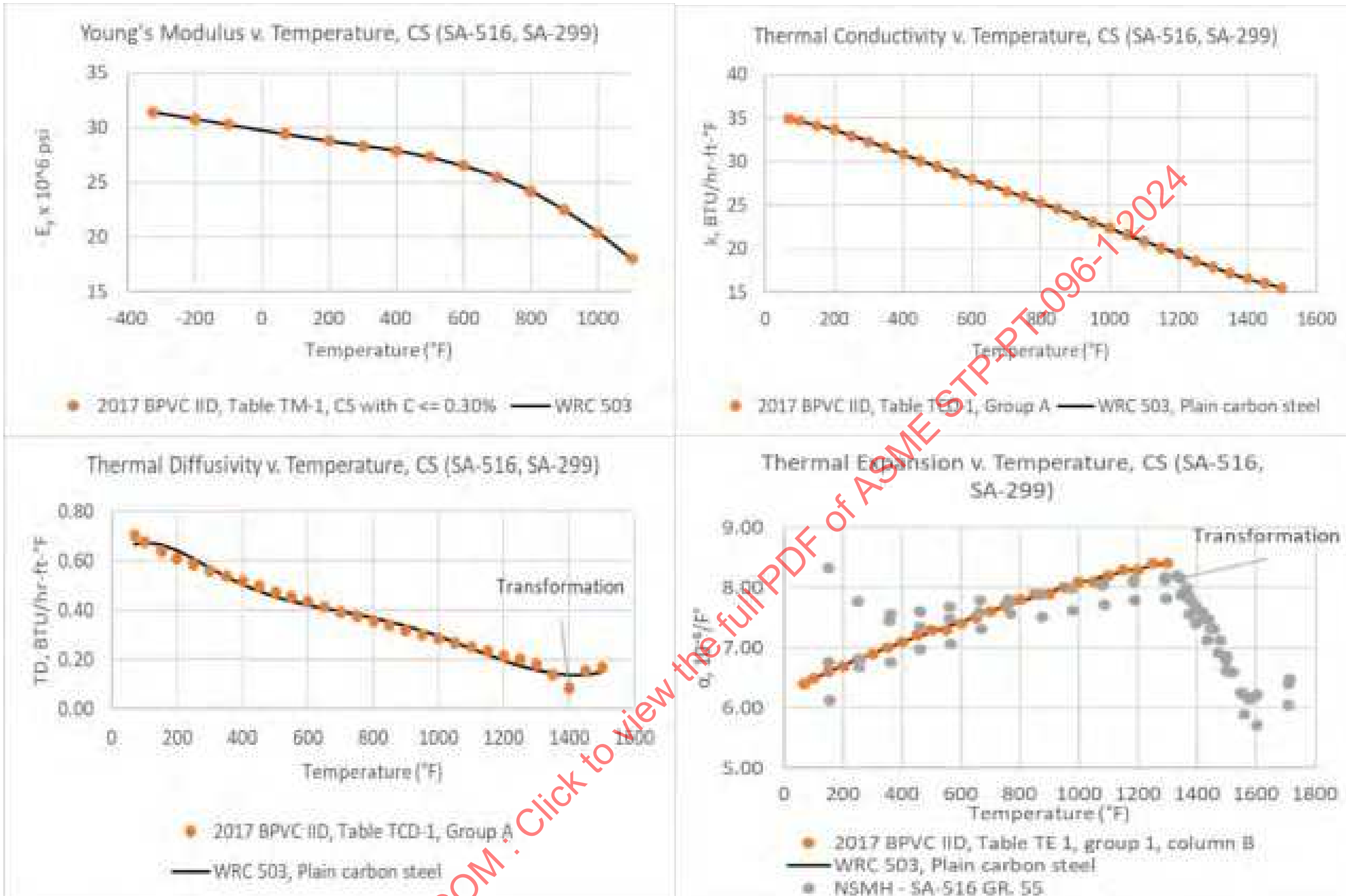


Figure 5-2: CS (516/299) Yield Strength Vs. Temperature, By Data Source, Including Trend Curves

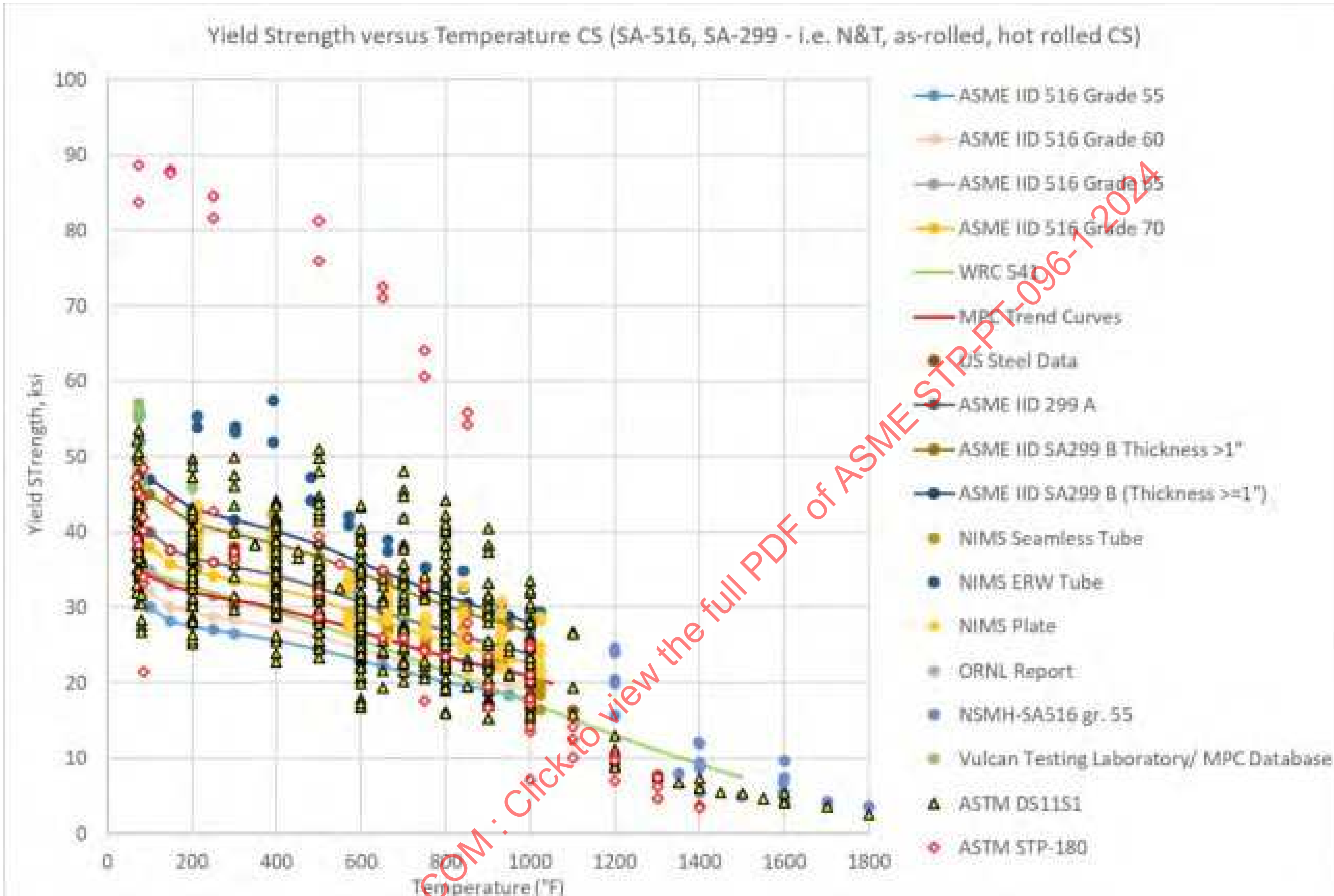


Figure 5-3: CS (516/299) Tensile Strength Vs. Temperature, By Data Source, Including Trend Curves

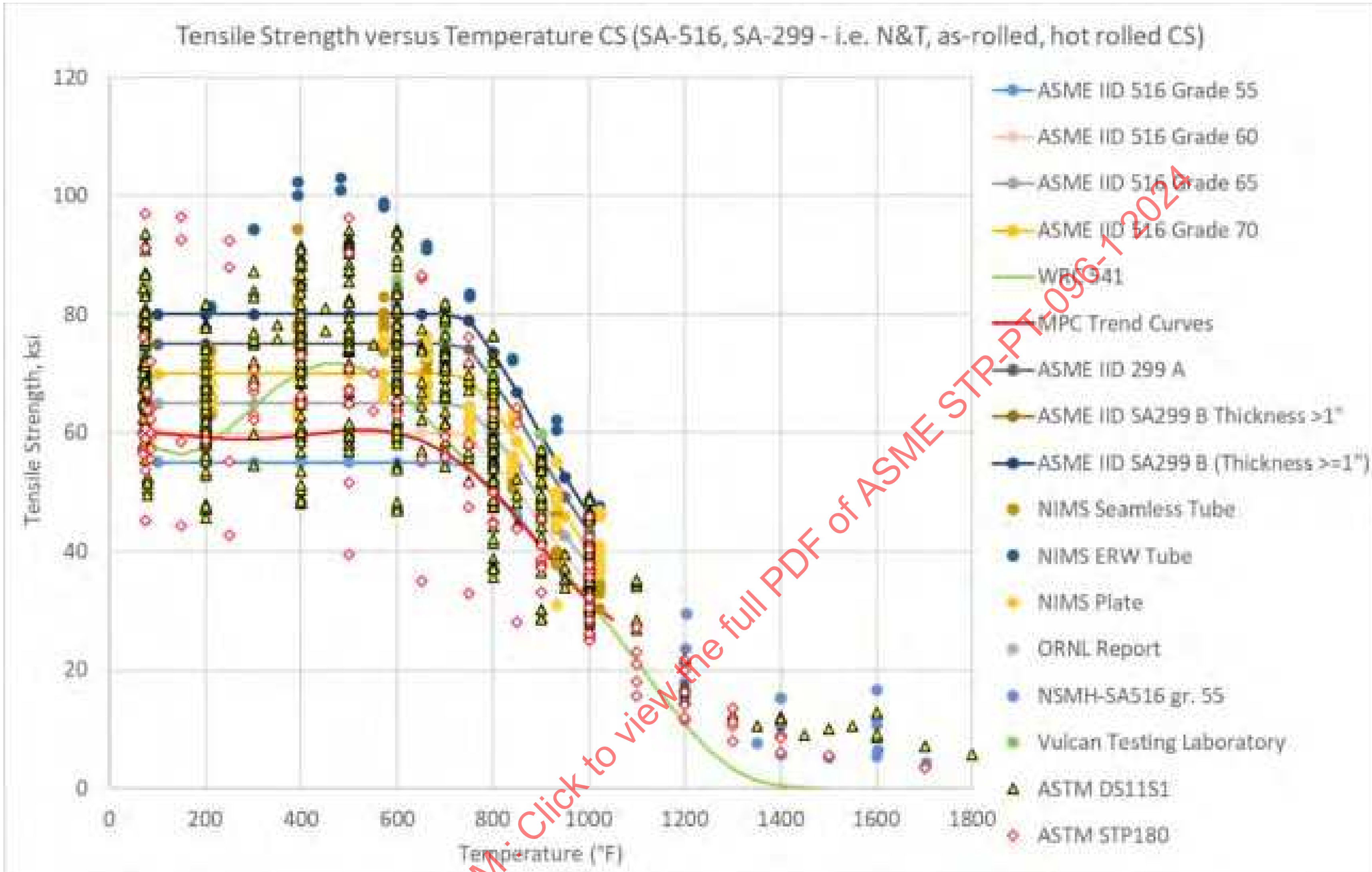


Figure 5-4: CS (516/299) Yield Strength Ratios Vs. Temperature (Calculated on a Heat-By-Heat Basis, By Data Source)

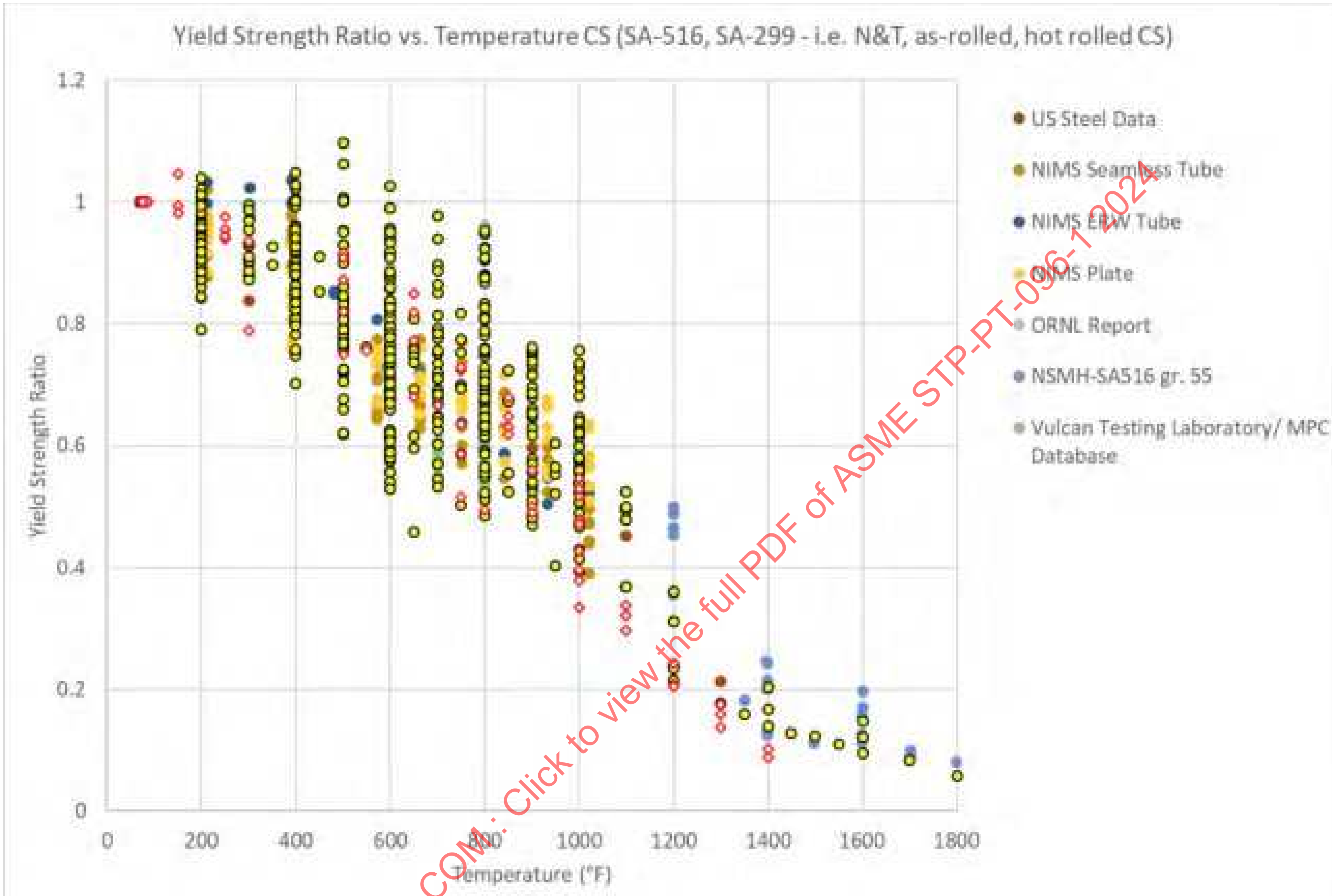


Figure 5-5: CS (516/299) Tensile Strength Ratios Vs. Temperature (Calculated on a Heat-By-Heat Basis, By Data Source)

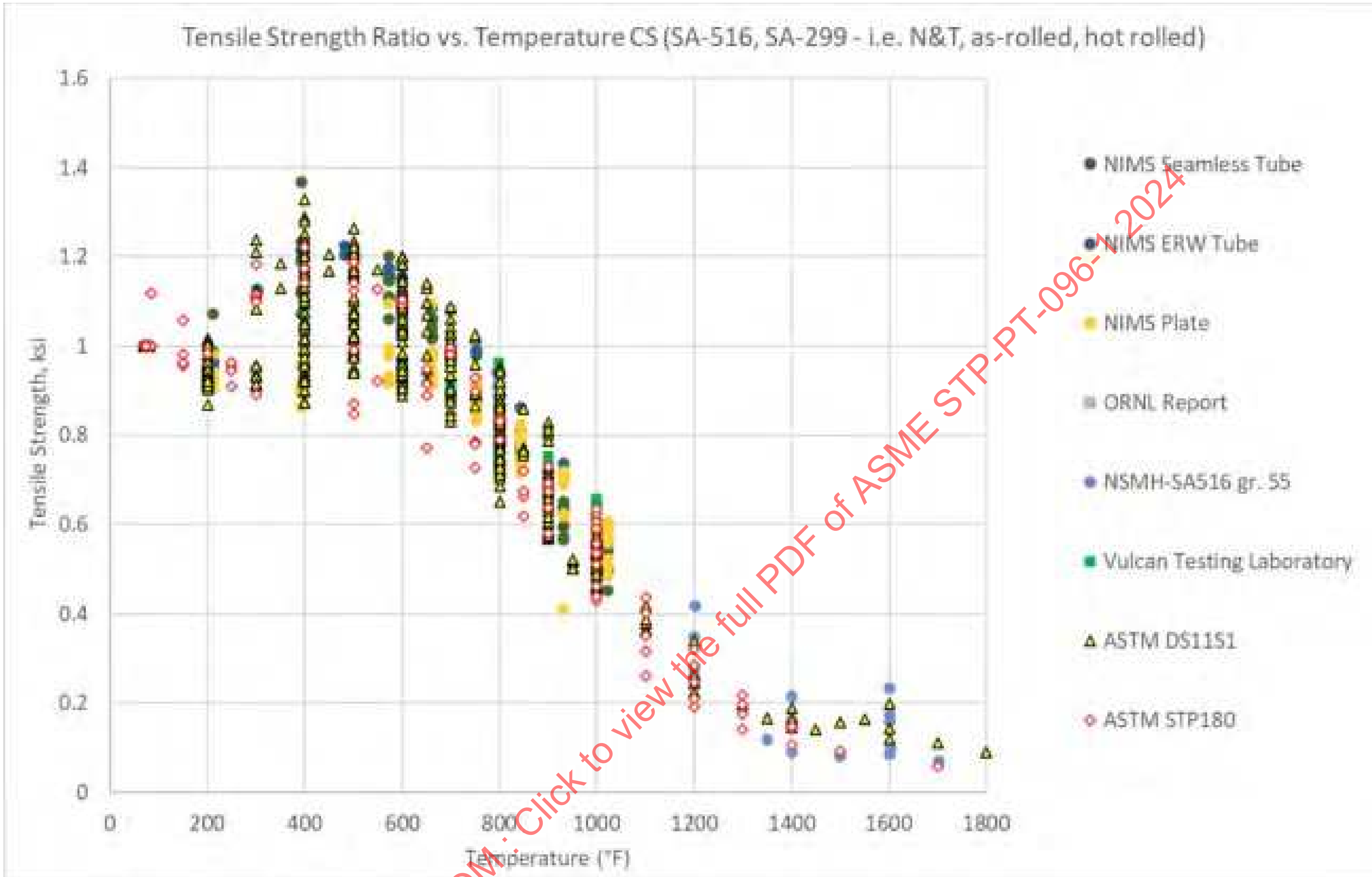


Figure 5-6: CS (516/299) Yield Strength Ratios Vs. Temperature, All Combined Data, With Polynomial Regression

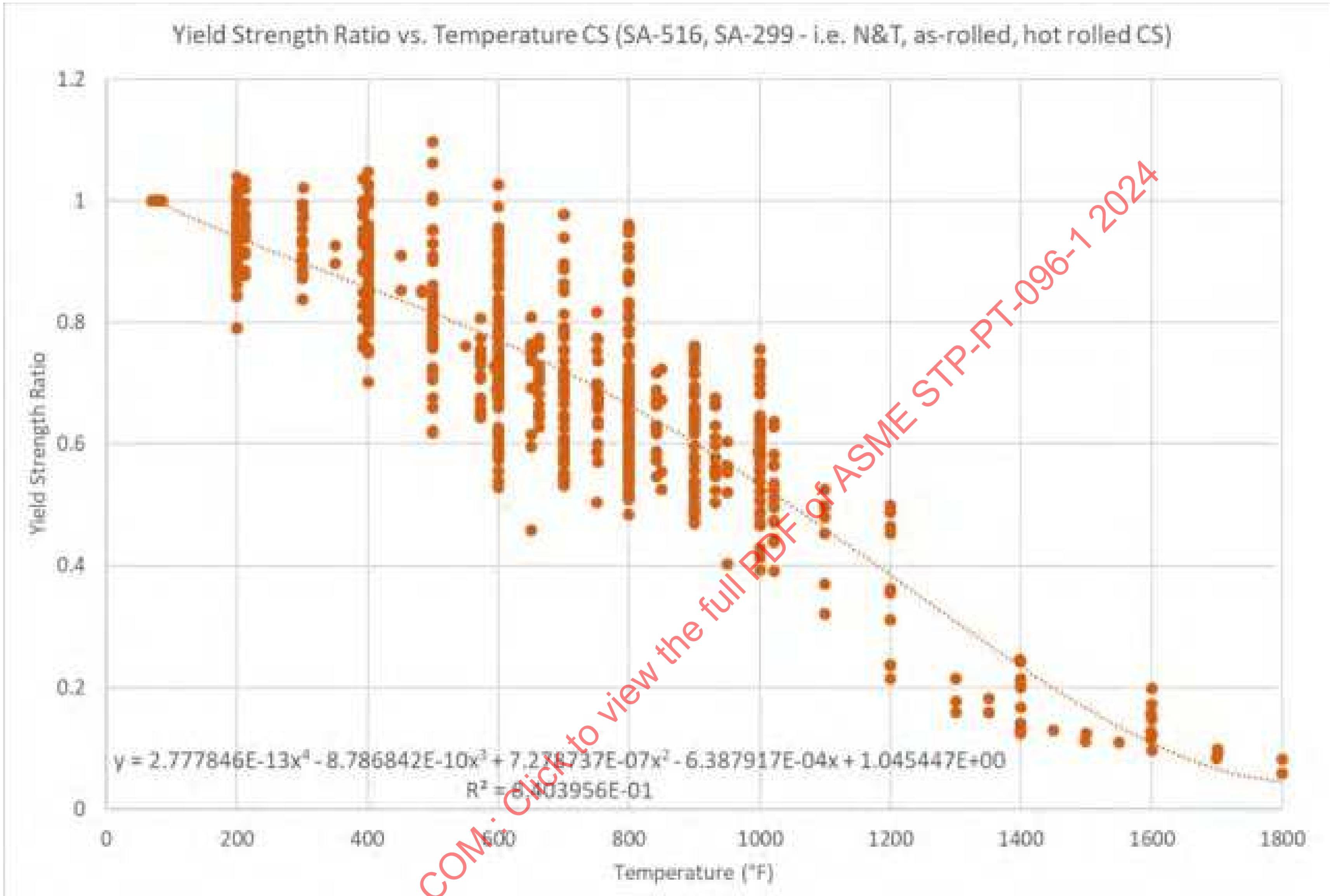


Figure 5-7: CS (516/299) Tensile Strength Ratios Vs. Temperature, All Combined Data, With Polynomial Regression

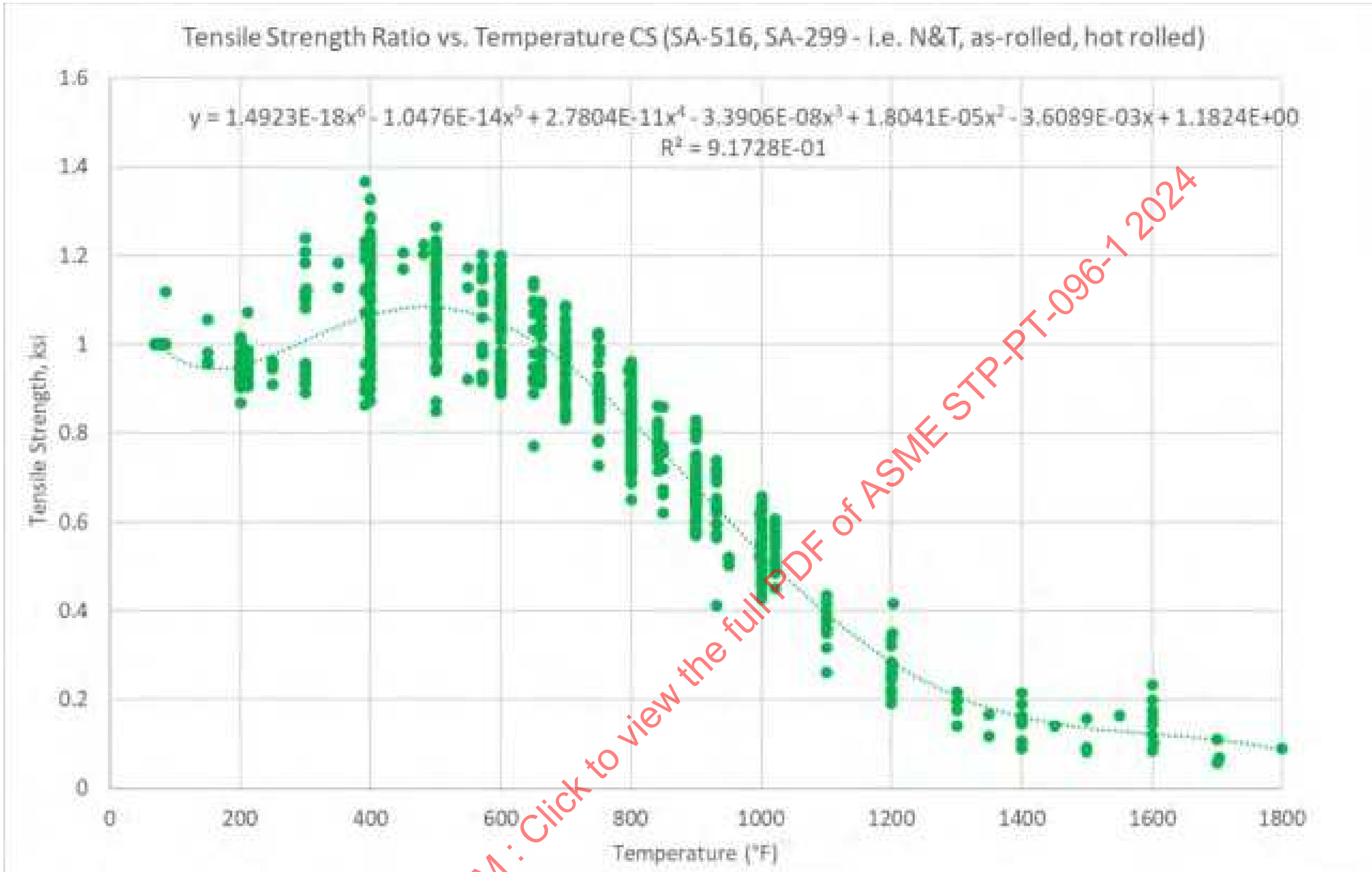


Figure 5-8: CS (516/299) Creep Rupture Isotherm Curves, Temperatures with High Concentration of Data Points

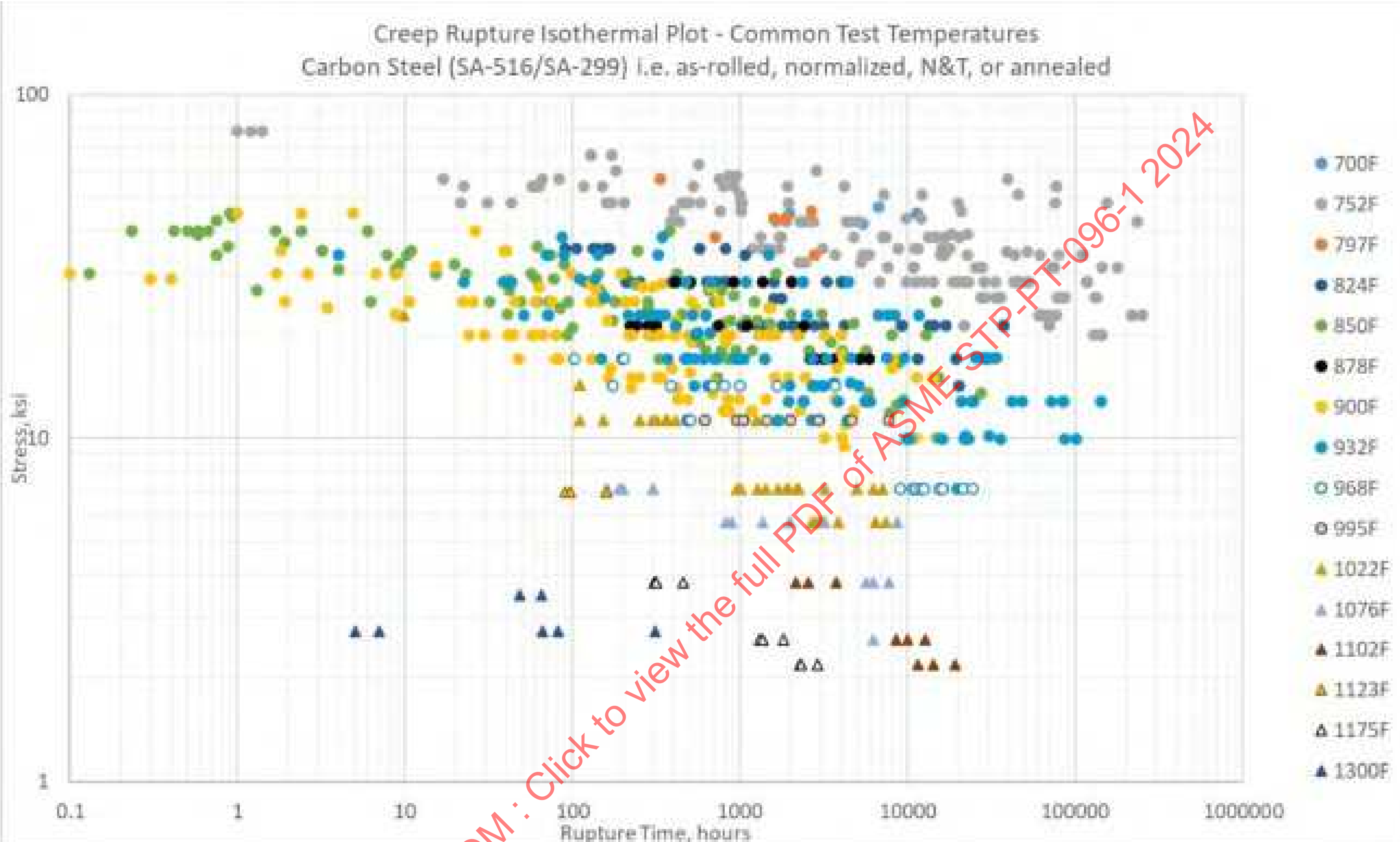


Figure 5-9: CS (516/299) Creep Rupture Isotherm Curves for Additional and Intermediate Temperatures

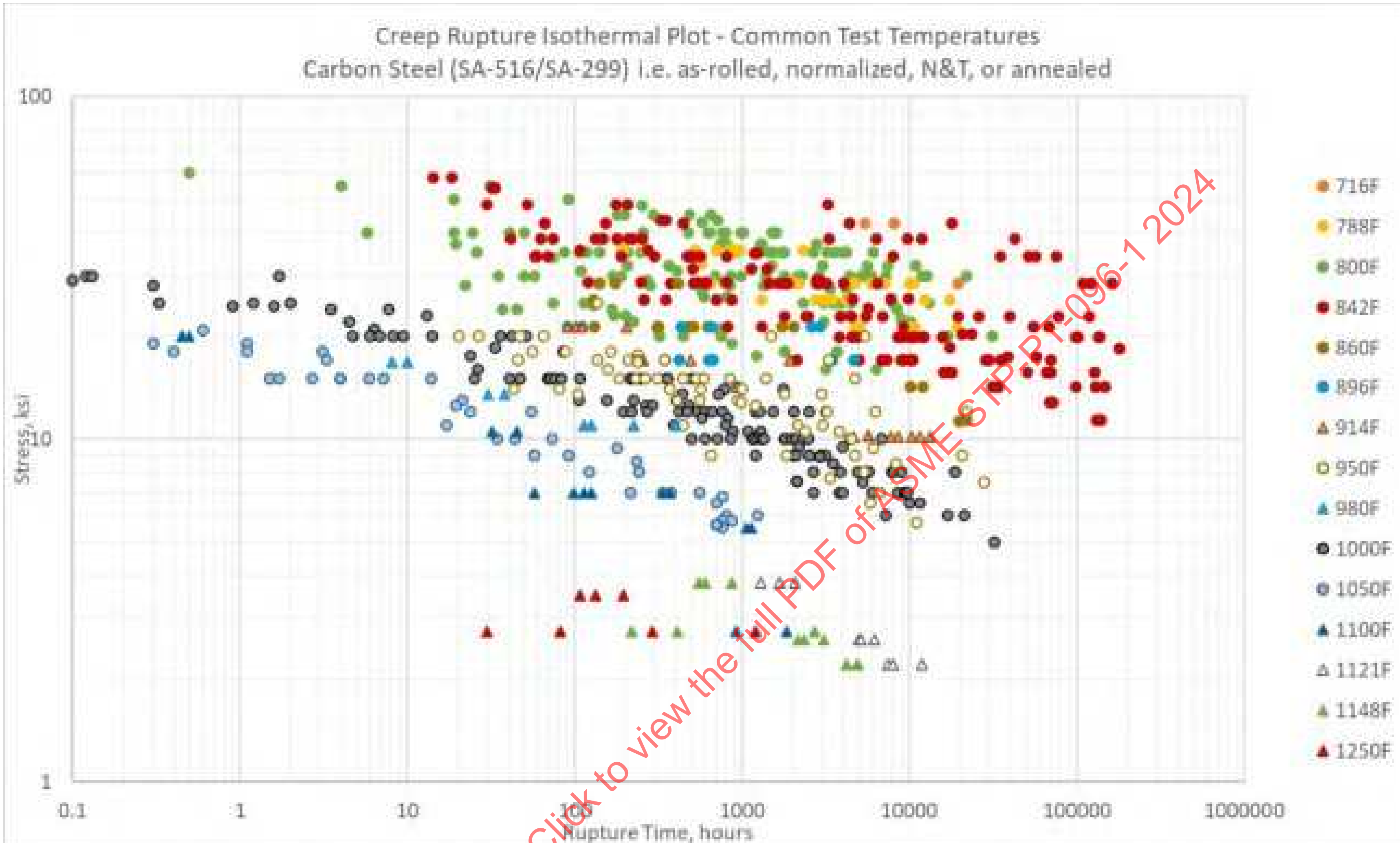


Figure 5-10: CS (516/299) Creep Strain Rate (MCR) Isotherm Curves, 1 of 3

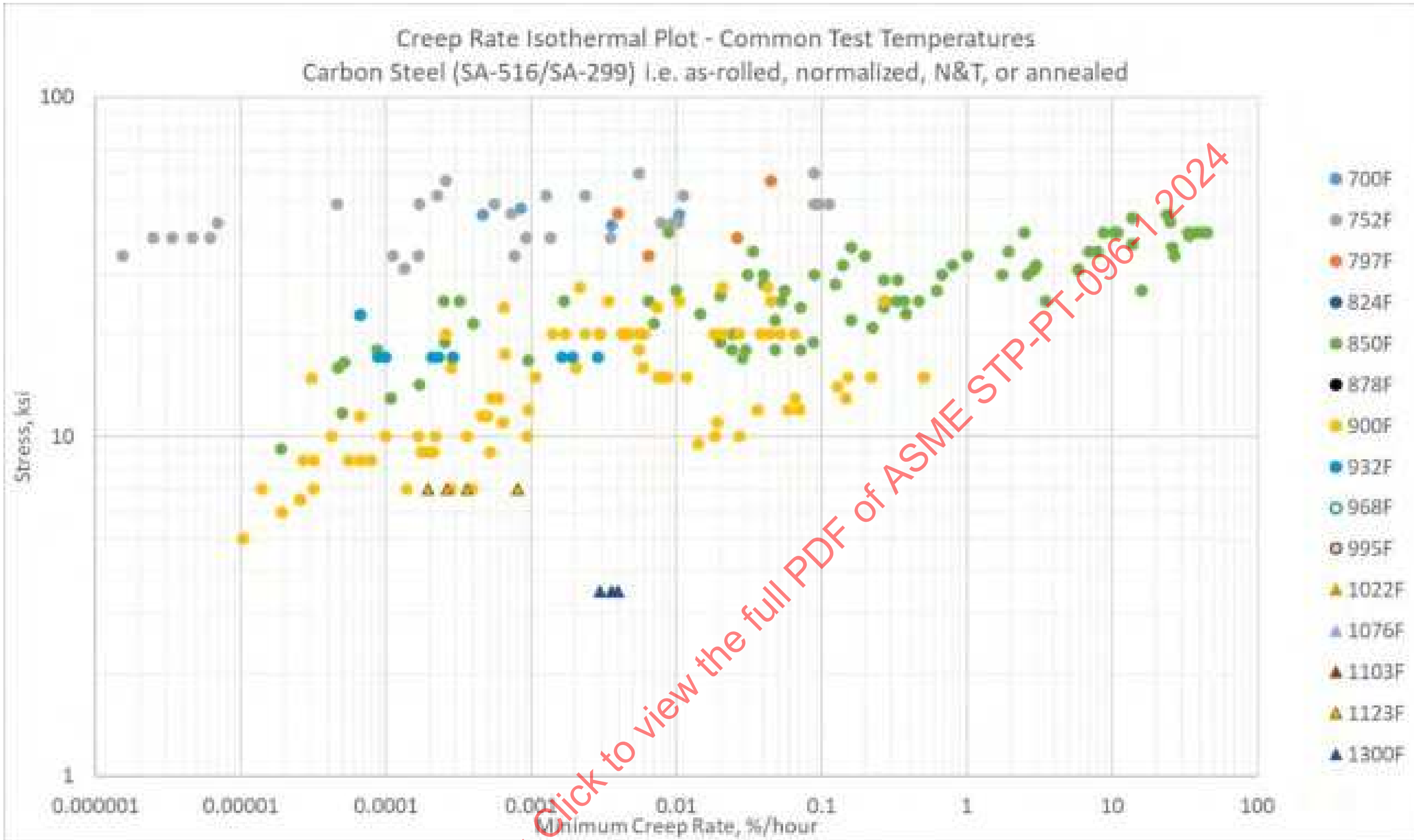


Figure 5-11: CS (516/299) Creep Strain Rate (MCR) Isotherm Curves, 2 of 3

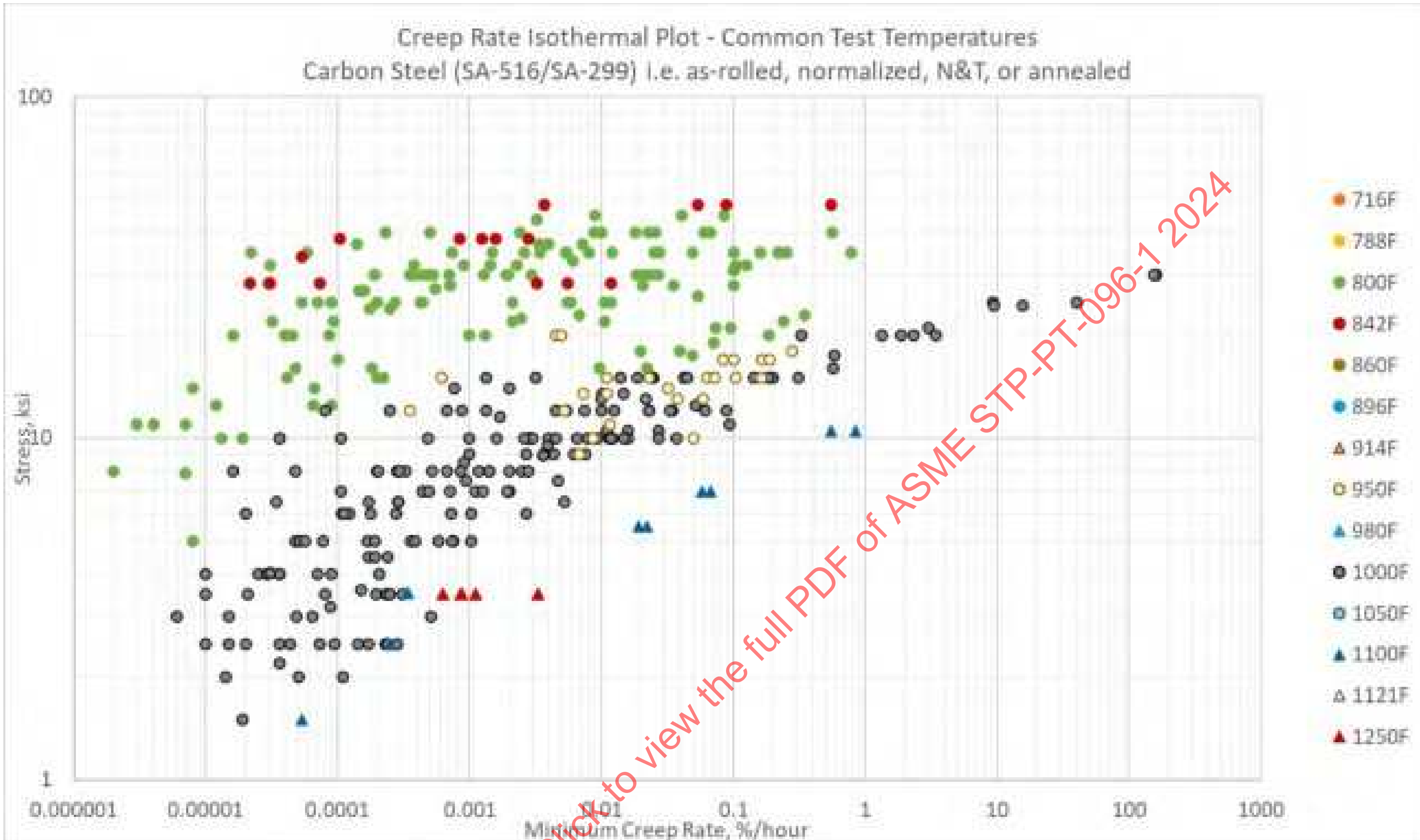


Figure 5-12: CS (516/299) Creep Strain Rate (MCR) Isotherm Curves, 3 of 3

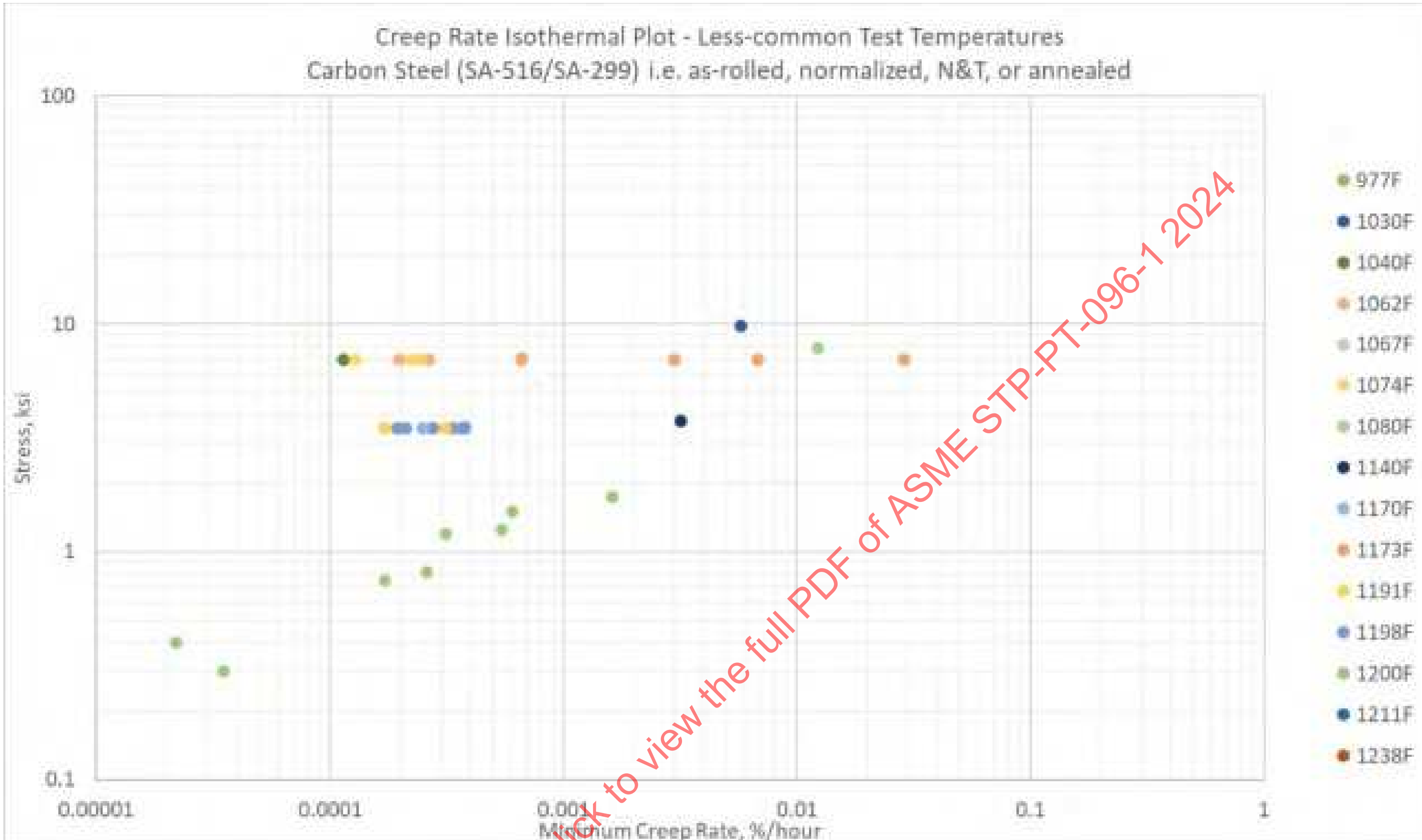


Figure 5-13: CS (516/299) Creep Ductility (% Elongation) Vs. Rupture Time Isotherms

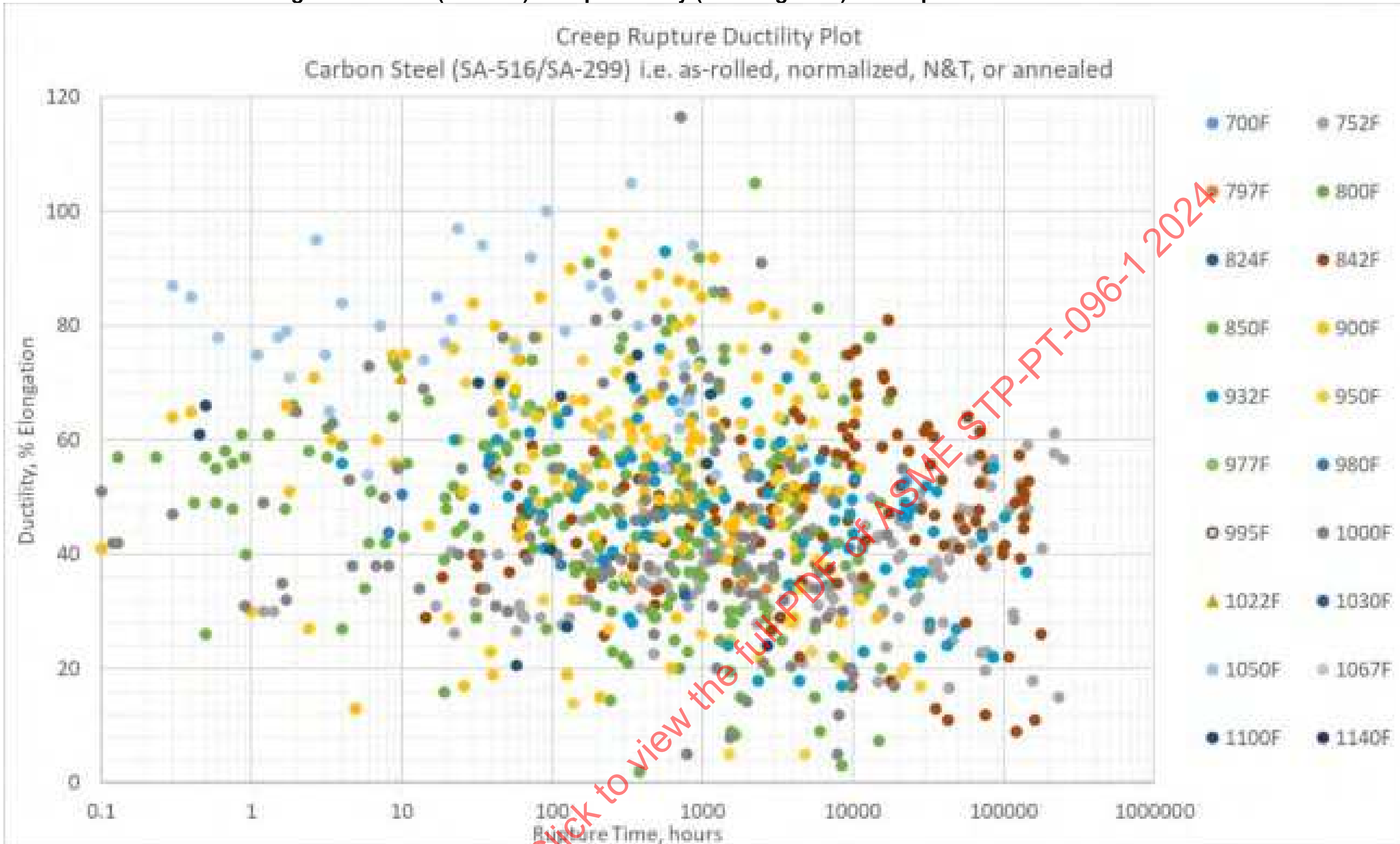


Figure 5-14: Calculated Allowable Stresses Based on Rupture and Creep Strain Rate and ASME II-D Appendix 1 Criteria (CS (516/299))

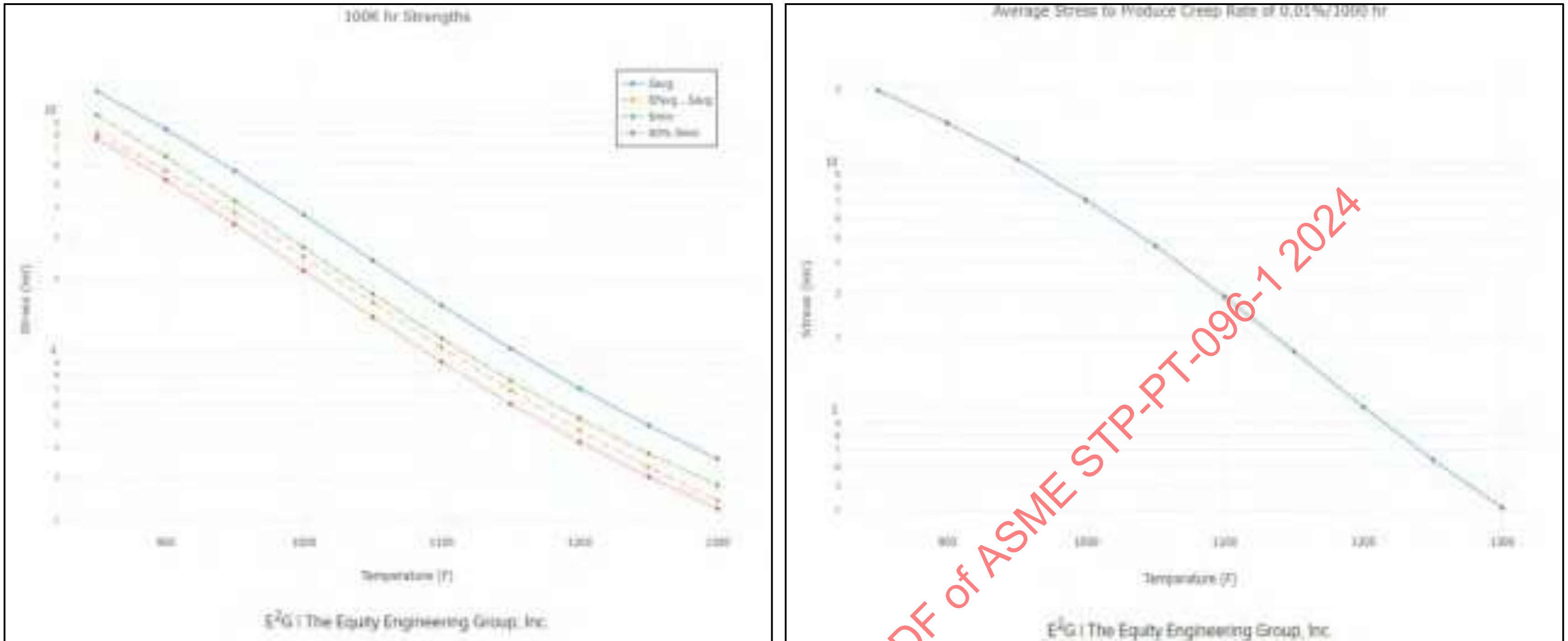


Figure 5-15: Comparison of Current CS (516/299) Allowable Stresses (Except Forgings) Vs. ASME II-D Appendix 1 Criteria Applied to Data

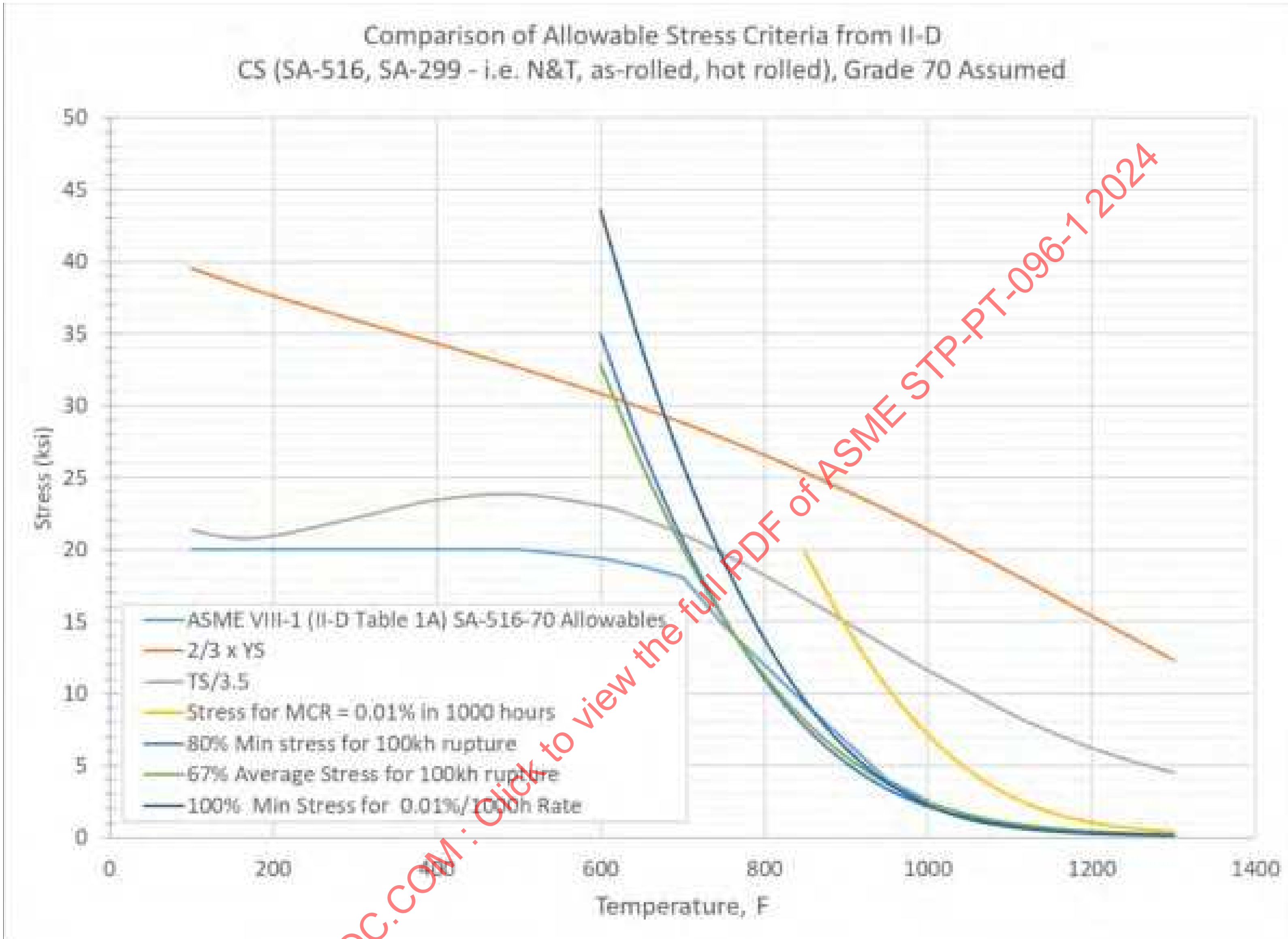


Figure 5-16: Strain Vs. Time Data, up to 2,500 Hour Test Durations – CS (516/299), 1 of 7

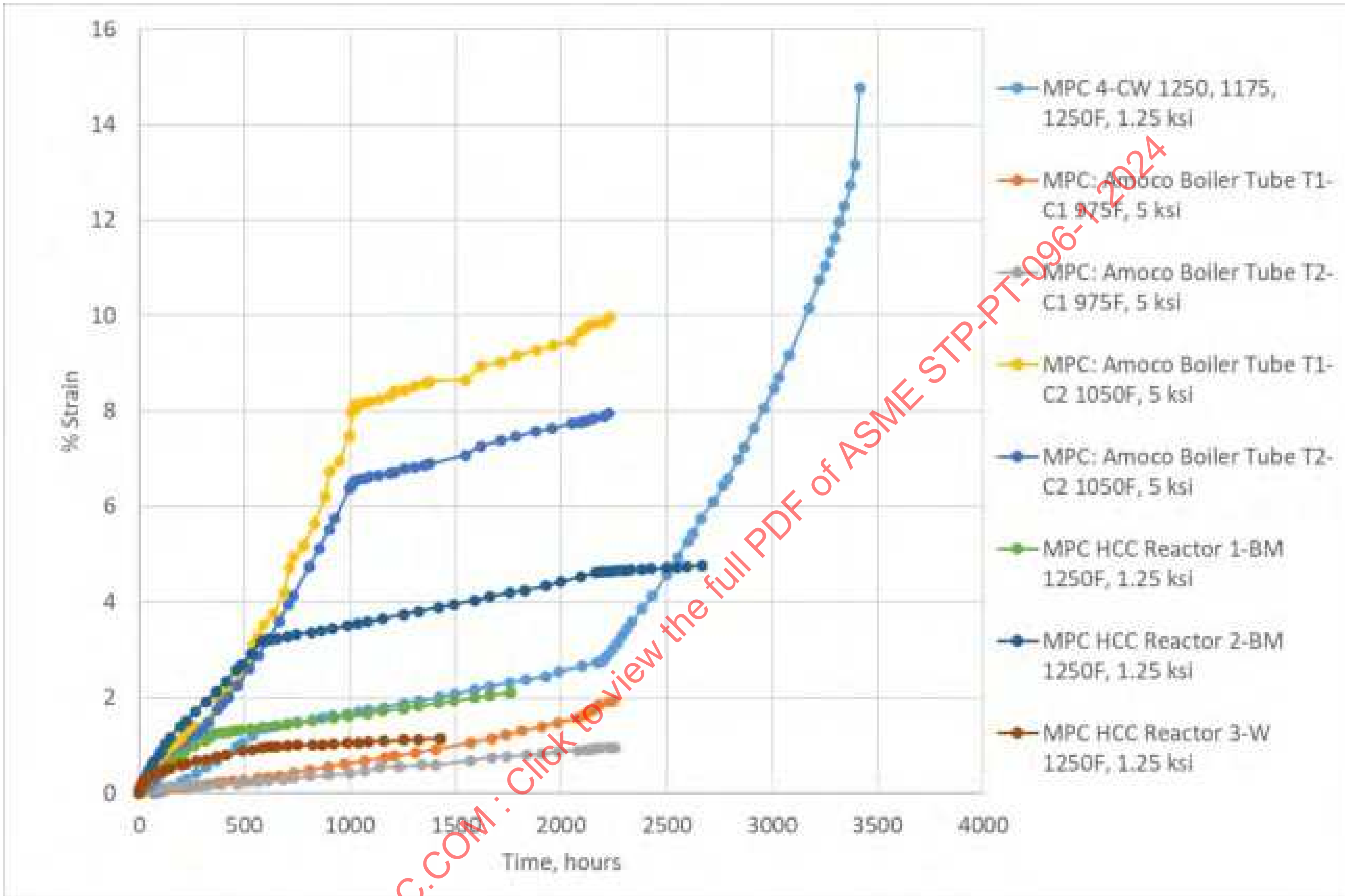


Figure 5-17: Strain Vs. Time Data, up to 2,500 Hour Test Durations – CS (516/299), 2 of 7

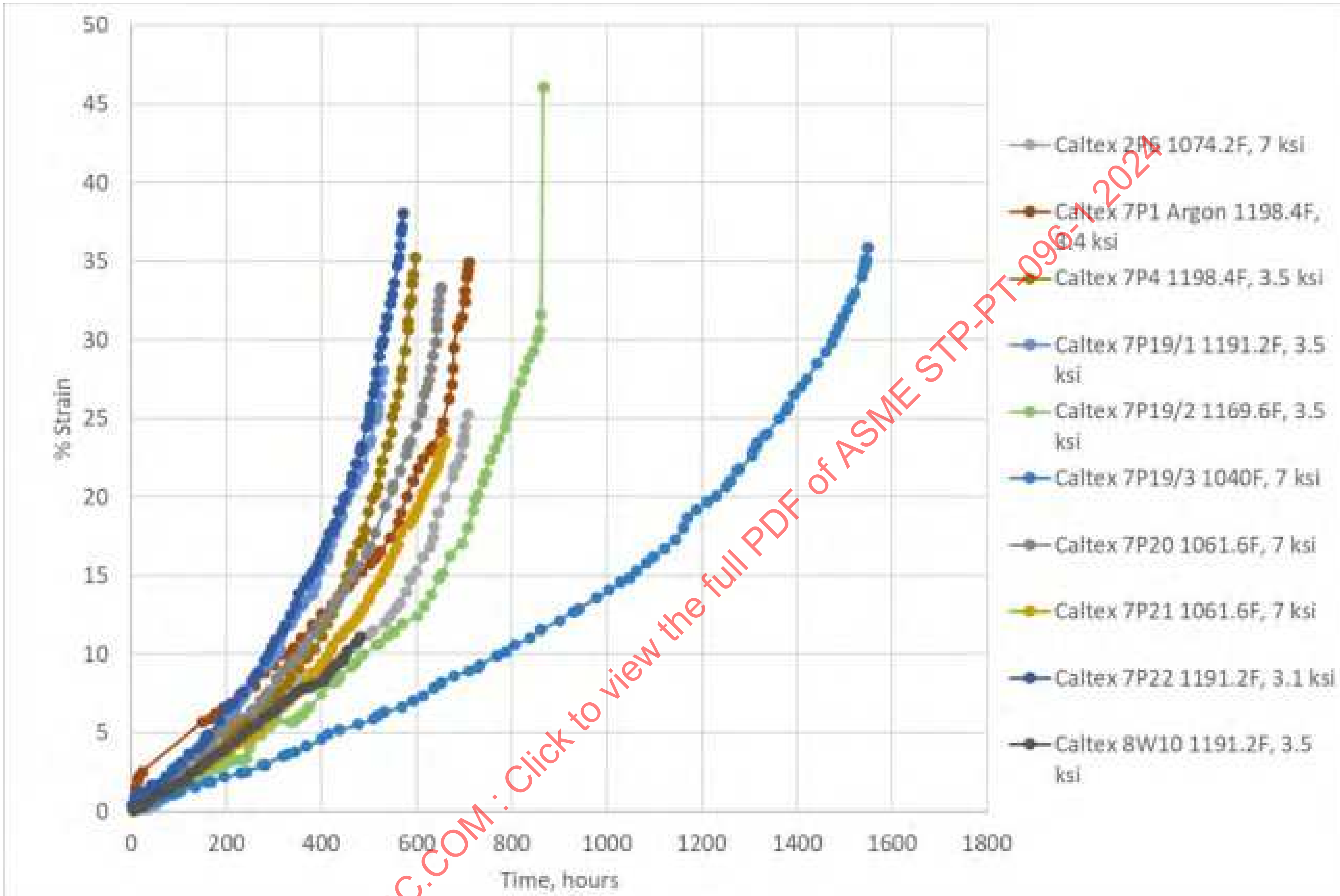


Figure 5-18: Strain Vs. Time Data, up to 2,500 Hour Test Durations – CS (516/299), 3 of 7

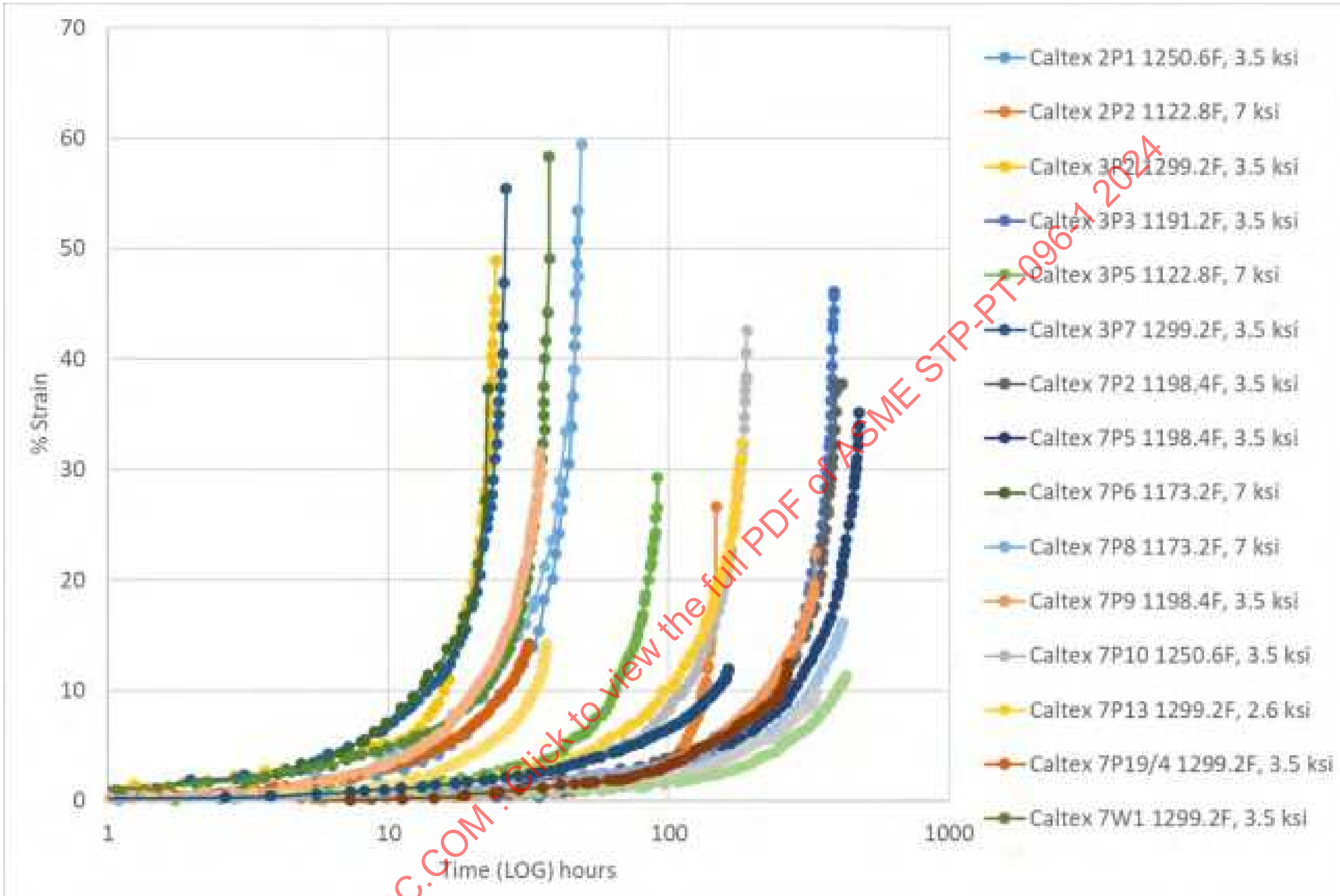


Figure 5-19: Strain Vs. Time Data, up to 2,500 Hour Test Durations – CS (516/299), 4 of 7

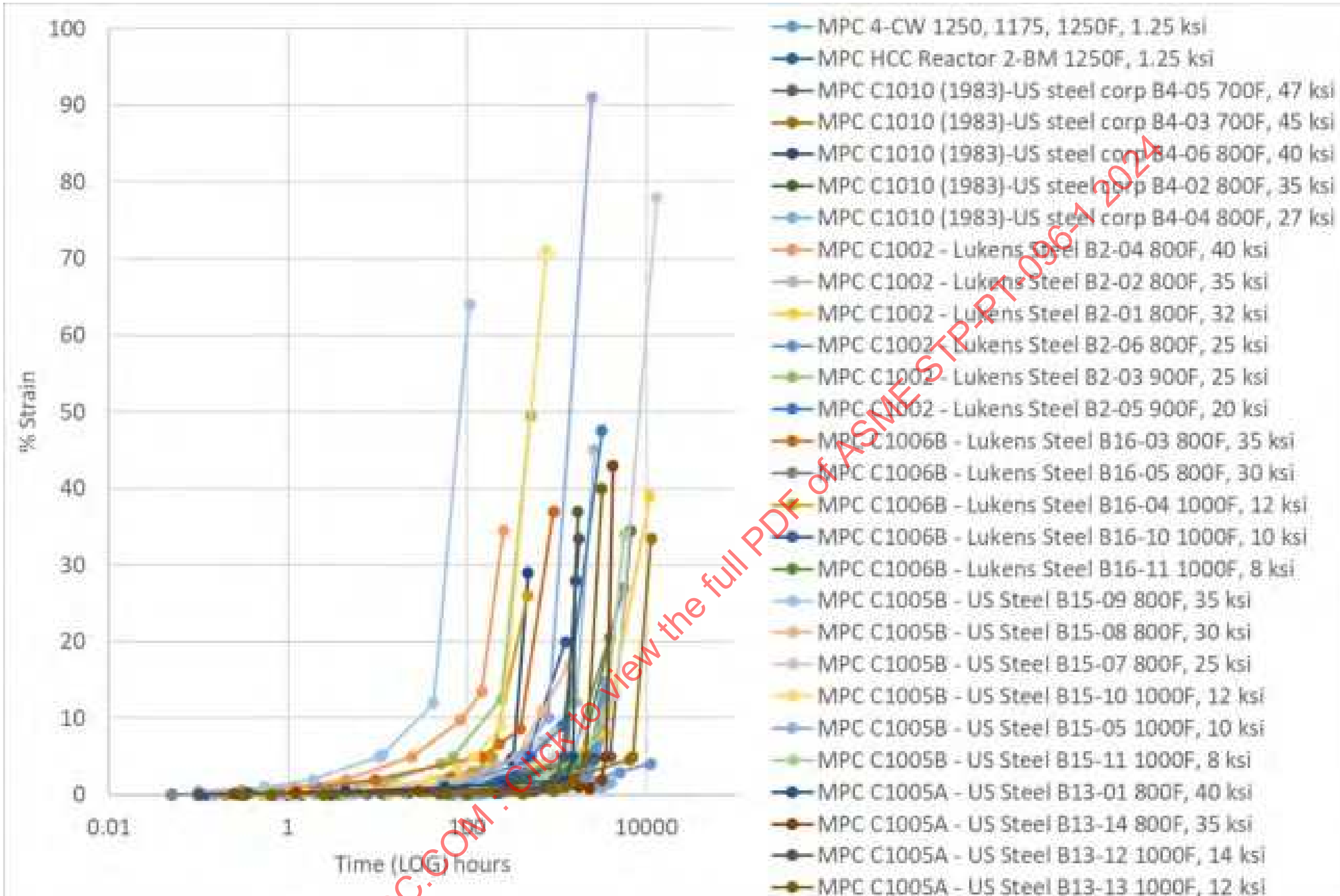


Figure 5-20: Strain Vs. Time Data, up to 2,500 Hour Test Durations – CS (516/299), 5 of 7

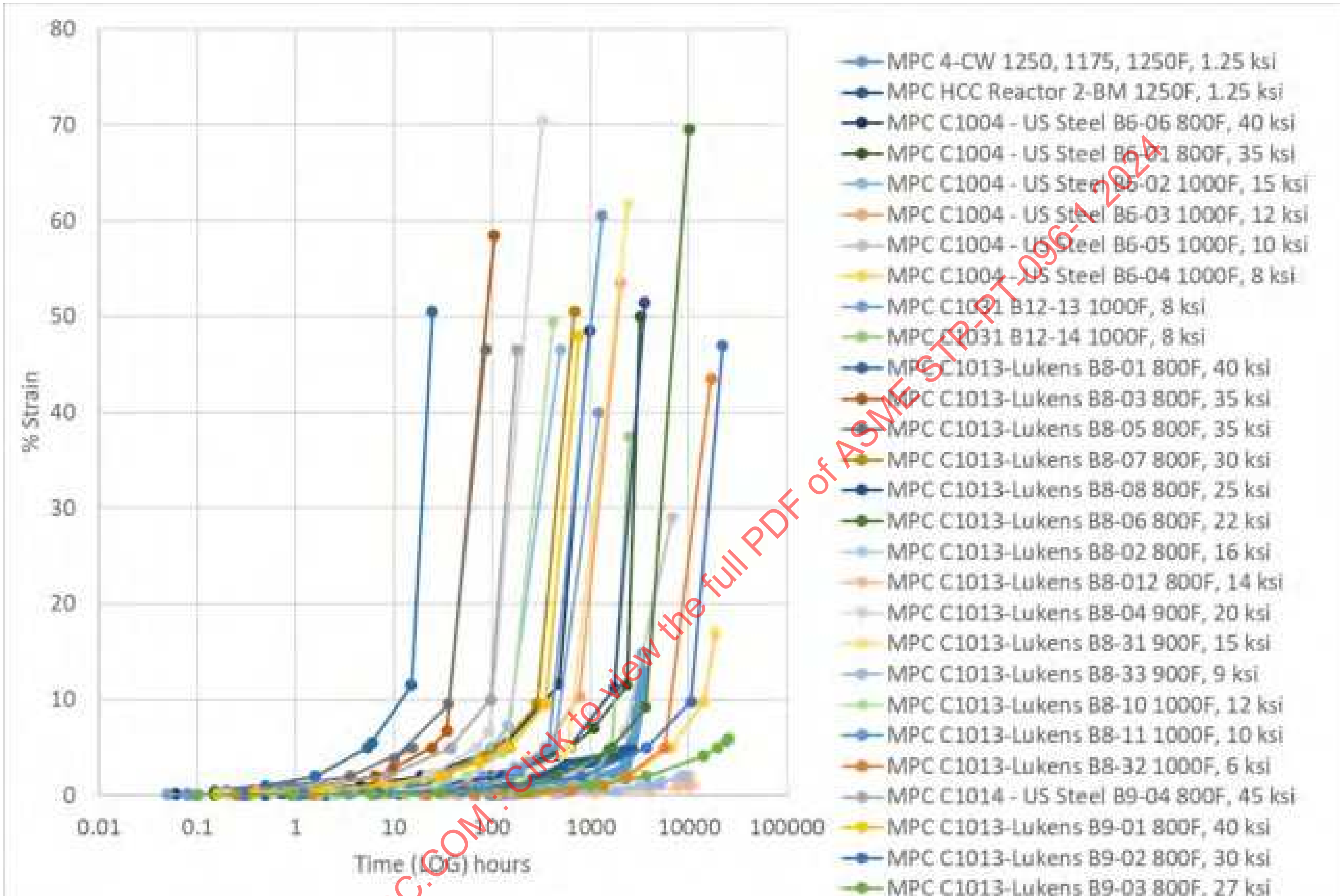


Figure 5-21: Strain Vs. Time Data, up to 2,500 Hour Test Durations – CS (516/299), 6 of 7

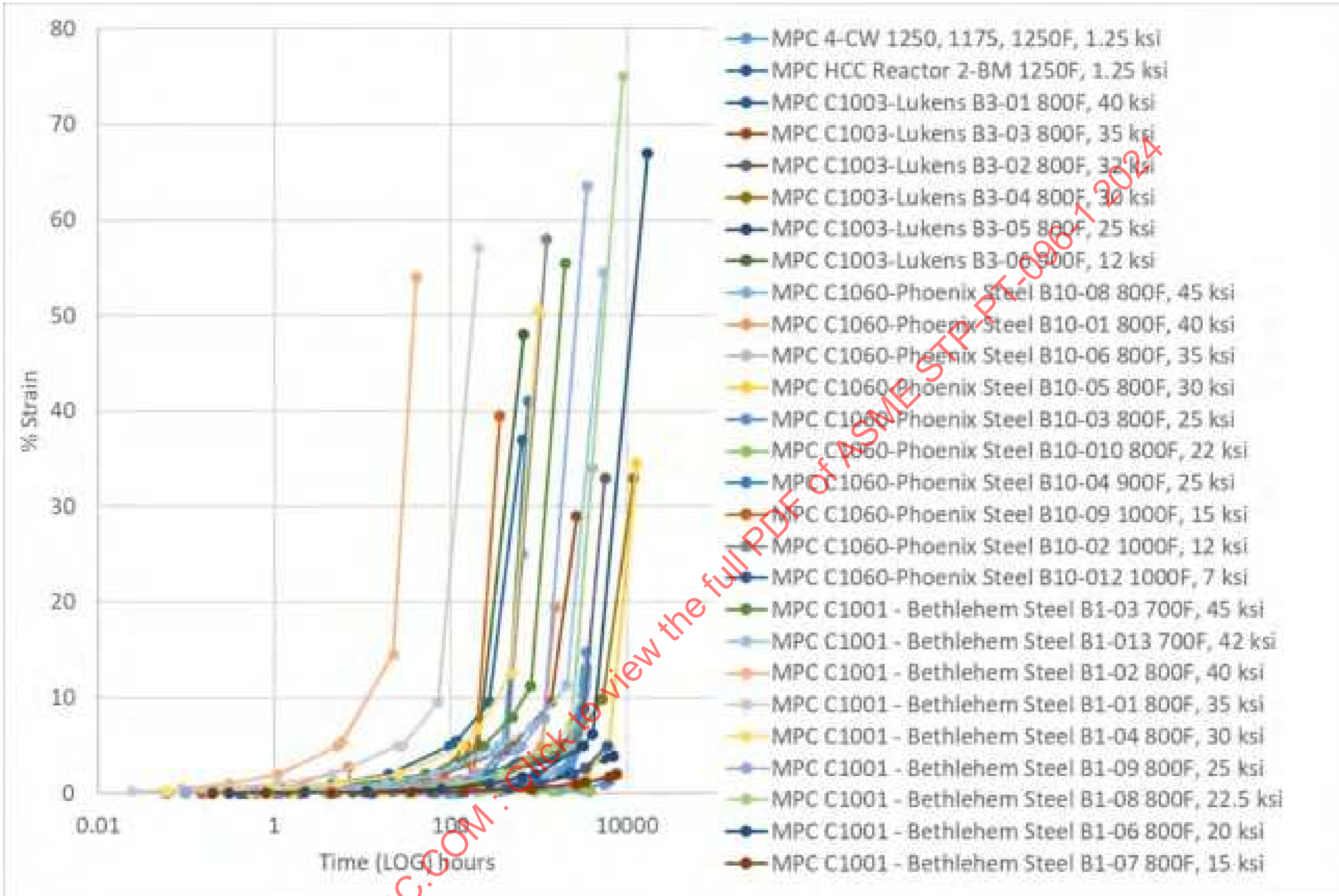


Figure 5-22: Strain Vs. Time Data, up to 2,500 Hour Test Durations – CS (516/299), 7 of 7

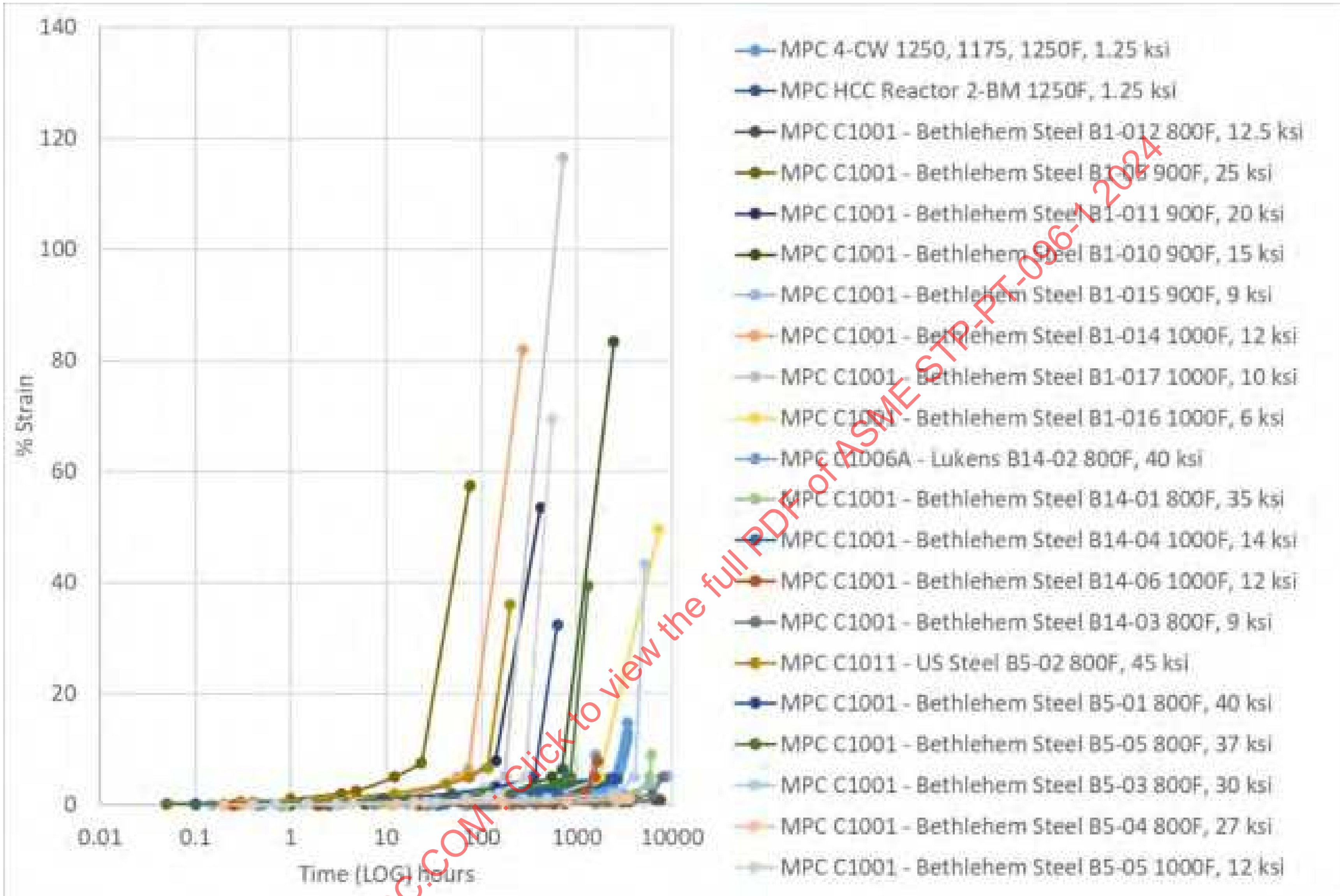


Figure 5-23: CS (516/299) Continuous Cycling Fatigue, Elevated Temperature Data

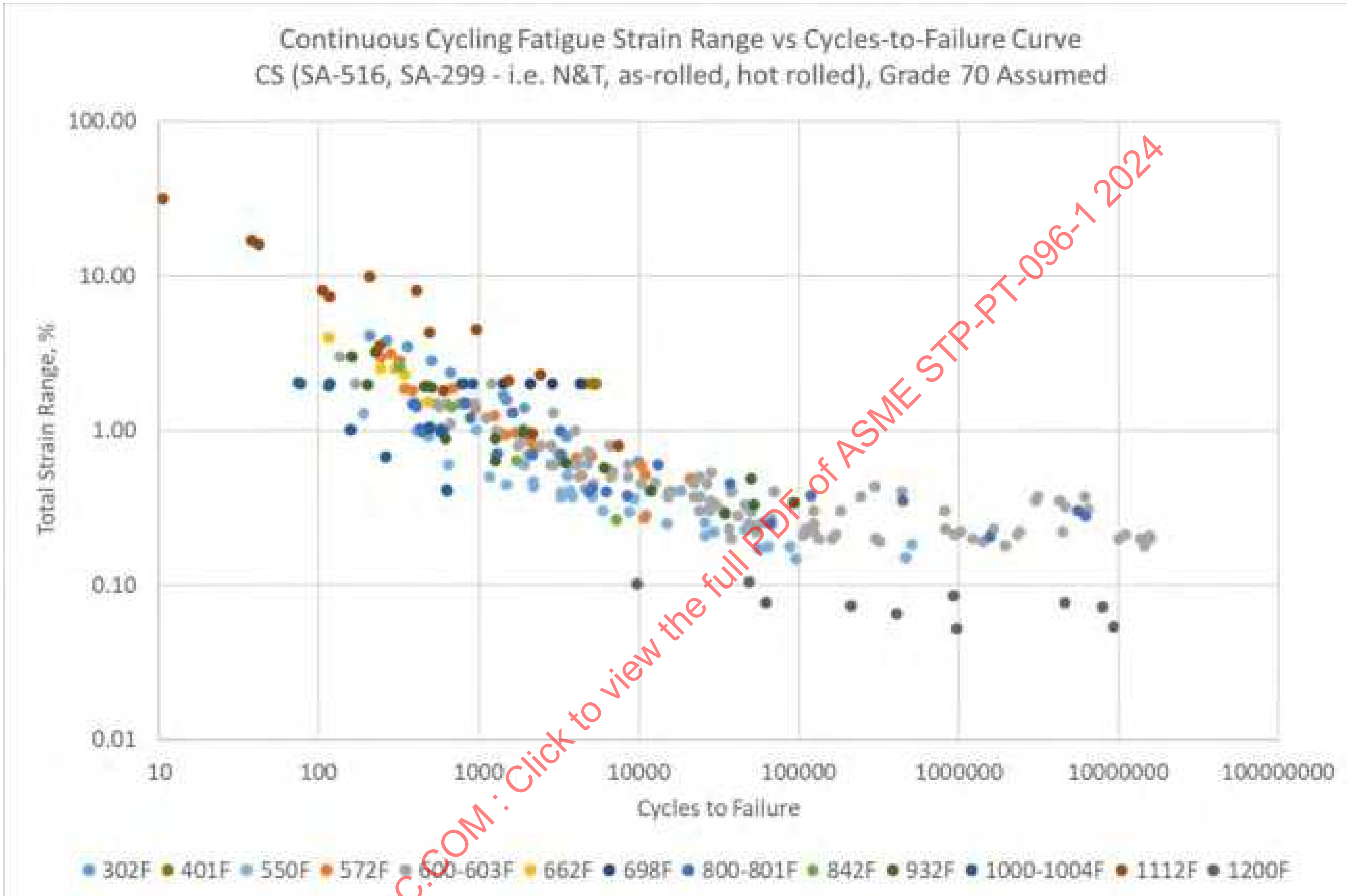


Figure 5-24: CS (516/299) Hold Time Data (Creep Fatigue)

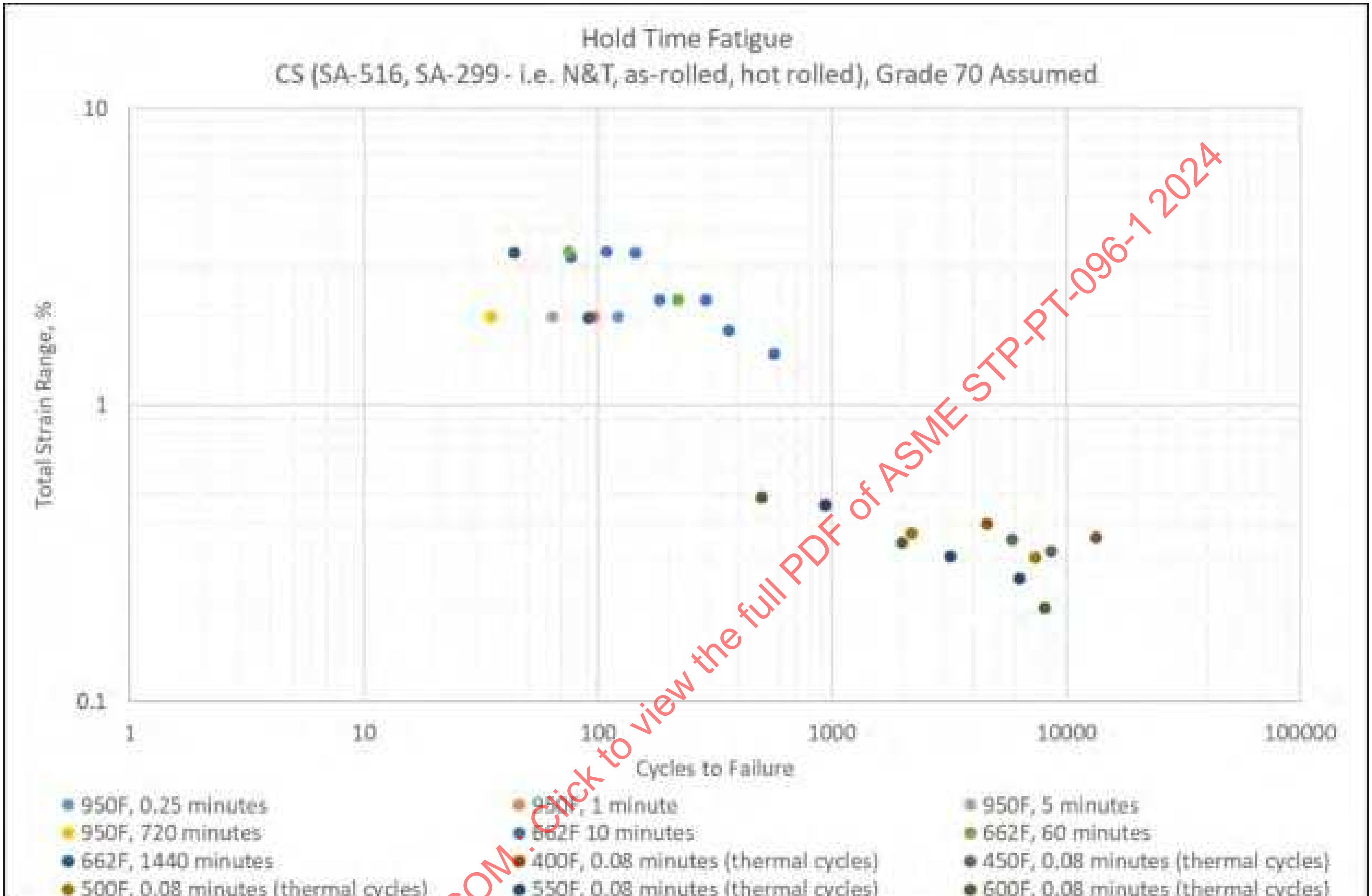
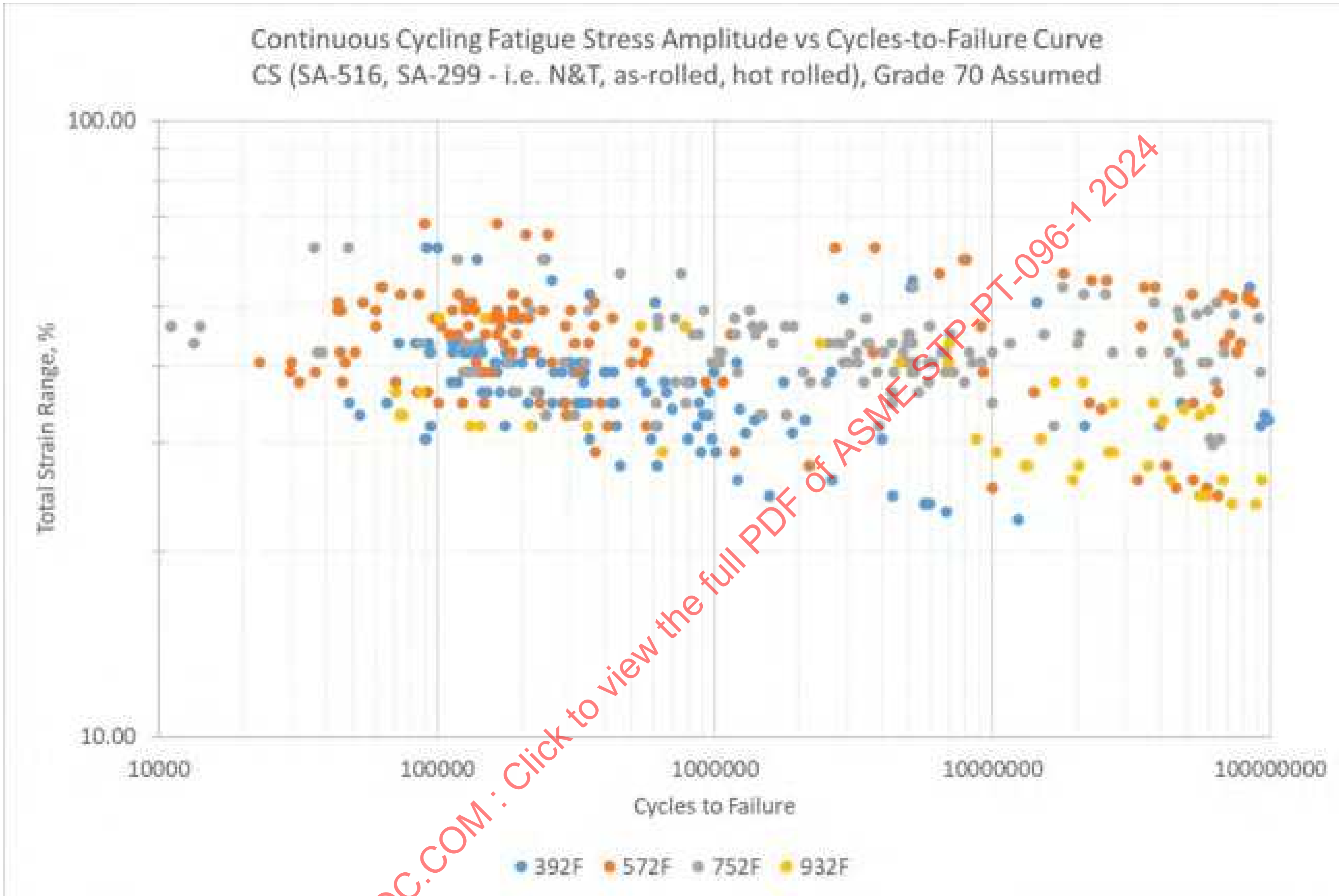


Figure 5-25: CS (516/299) Stress-Controlled Fatigue Data at Elevated Temperatures



Attachment 5: Carbon Steel (SA-516/SA-299, I.E., Normalized, N&T, AS-Rolled/Hot-Rolled Material) Property Data

If you want the referenced embedded spreadsheet with additional data, please email a request to research@asme.org.

6 CARBON STEEL (SA-508) AND SIMILAR

As explained in reference [2], material data for quenched and tempered carbon steels are included in the analysis, even if the specification of the material is not listed as SA-508. SA-508 is for quenched and tempered vacuum-treated carbon steel and low-alloy forgings, and contains multiple grades, many of which are not carbon steel (Ni or Ni-Cr steels, etc.). Initially, the search for materials data was limited to Grades 1 and 1A of SA-508. This was subsequently expanded to include all product forms, with quenched and tempered heat treatment. In addition, to increase the amount of data included, other grades of the SA-508 specification were included in the analysis. The spreadsheet containing data for this material, wherever possible, includes the chemical composition and heat treatment details for the data points listed, which can be used to verify that the material either does or does not meet the specification.

6.1 Physical Properties

Well-established physical properties were referenced from the BPVC Section II for this material. Physical property curves from *WRC Bulletin 503* were plotted for comparison. Figure 6-1 shows the trends of Elastic Modulus (E_y), Thermal Conductivity (k), Thermal Diffusivity (TD), and Thermal Expansion (α) with temperature. External data sources were not located specifically for this material.

6.2 Yield and Tensile Strength

Elevated temperature Yield and Tensile Strength were readily available up to approximately 1100°F, with limited data available above this temperature, as shown in Figures 6-2 and 6-3. The sources for both high-temperature yield and high-temperature tensile strength are provided in the embedded spreadsheet at the end of this section. One source identified the material as quenched and tempered carbon steel casting; however, the values of yield and tensile strength are significantly lower than other data sources.

To facilitate comparison of the data obtained to existing allowable stresses (Section II-D Table 1A), yield and tensile data were normalized on a heat-by-heat basis to express the ratio of yield or tensile strength at temperature to that measured for the heat at room temperature. For this material, data from some of the original sources could not be separated by heat. E2G understands that this approach is similar to the normalizing procedure performed by ASME in typical analysis of yield and tensile data to obtain Table Y and Table U (Section II-D) trend curves, as well as for the calculation of allowable stresses. Figures 6-4 and 6-5 show the heat-by-heat variation in yield and tensile strength ratios (respectively) as a function of temperature. It should be emphasized that even though the figure legends reference an entire source of data, the ratios were calculated on a heat-by-heat basis; this is evident in the embedded spreadsheet at the end of this section. Figures 6-6 and 6-7 contain all of the yield and tensile (respectively) ratios plotted together, to facilitate regression of a polynomial fits that are subsequently used for allowable stress comparison.

6.3 Creep Data (Creep Rupture, Minimum Creep Rate, and Ductility)

Creep Rupture data is shown in Figure 6-8, plotted as isotherms. Creep Minimum strain rates (%/hour) are shown in Figure 6-9, although the data for minimum creep rates is limited. Creep Ductility, as % elongation, is plotted in Figure 6-10. As is typical, the data show significant overlap, and it is difficult to observe clear trends in the ductility data. The data is not intended to be used as plotted but is available in the spreadsheet for additional analysis.

Creep data were analyzed using E2G's proprietary Lot-Centered Analysis web-based software tool (Mandel-Paule algorithm), according to a Larson-Miller 3rd-order polynomial of stress, assuming parallel behavior and a 95% predictive limit. This procedure was utilized to obtain the lower-bound (minimum LM constant for both rupture and strain rate) properties. The results of this analysis are summarized in Table 6-1 for rupture data and Table 6-2 for strain rate data. The Lot-Centered Analysis software tool generates property tables in the creep regime using the criteria outlined in Mandatory Appendix 1 of ASME Section II-D; the nomenclature of variables is consistent with II-D Appendix 1. For visualization of the allowable stress trends, Figure 6-11 is provided (for rupture allowable stresses and creep rate allowable stresses). Figure 6-12 shows a comparison of the various allowable stress criteria from Section II-D, Appendix 1, to the existing (2019) Section II-D Table 1A allowable stresses for SA-508 Grades 1 and 1A CS (Q&T) forgings; the maximum temperature for this specification and grade is 1000°F for VIII-1 designs.

Creep Strain vs. time data are shown in Figures 6.-13 and 6-14. Additional creep strain vs. time data are located in the embedded spreadsheet. Both creep rate and creep strain vs. time data are provided to satisfy ASME's request for creep strain vs. time curves, and both forms of data are applicable in developing allowable stresses. Although digitalization of creep curve data was not explicitly necessary per the project contract, E2G did perform digitalization of creep curves where only graphical data was available (as is often the case in the published literature).

6.4 Continuous Cycling Fatigue and Hold Time Fatigue Curves

Very few datapoints for continuous fatigue at elevated temperature were located for quenched and tempered carbon steel. Those data that were obtained are plotted in Figure 6-15. No hold time fatigue data was found. However, almost 1,000 data points of room temperature fatigue (continuous data) are tabulated in the embedded spreadsheet. It is theorized that the volume of room temperature data for quenched and tempered carbon steel is a result of the use of material in this condition for structural applications (conversely, pressure vessels for use at moderate or elevated temperatures often use hot rolled, normalized and tempered, or otherwise heat-treated materials). The lack of common application for quenched and tempered carbon steel at moderate or elevated temperatures means that there has not been significant research interest in the past for such materials at elevated temperatures.

Table 6-1: Model Parameters, Larson-Miller Property Results, and Allowable Stress (Rupture) Criteria, CS (SA-508)

Equation Format:

$$\log(t_r) = C_{avg} + \frac{1}{T+460}\left(b_1 + b_2\log(\sigma) + b_3(\log(\sigma))^2 + b_4(\log(\sigma))^3\right)$$

C_{avg}	**-19.04**
C_{min}	**-19.64**
b_1	**52286.5**
b_2	**-39543**
b_3	**29373.6**
b_4	**-8619.1**

Number Data Points	**492**
R^2	0.8814
V_w	0.1329
V_b	0.3533
SEE	0.3646

Properties provided are for T in °F, stress in ksi, and t_R in hours

Temp, °F	**S_{avg} (ksi)**	**n**	**F_{avg} (calc)**	**F_{avg} (used)**	**$F_{avg} \times S_{avg}$**	**S_{min} (ksi)**	**80% S_{min}**
850	20.61	5.339	0.6497	0.67	13.81	15.63	12.5
900	13.4	4.542	0.6023	0.67	8.981	9.963	7.97
950	8.763	5.065	0.6347	0.67	5.872	6.82	5.456
1000	6.221	6.302	0.694	0.67	4.168	5.086	4.069
1050	4.761	7.686	0.7411	0.67	3.19	4.028	3.222
1100	3.835	9.013	0.7746	0.67	2.569	3.32	2.656
1150	3.198	10.23	0.7985	0.67	2.143	2.814	2.251
1200	2.733	11.34	0.8162	0.67	1.831	2.433	1.946
1250	2.379	12.33	0.8297	0.67	1.594	2.137	1.709
1300	2.1	13.24	0.8403	0.67	1.407	1.899	1.519

Table 6-2: Model Parameters, Larson-Miller Property Results, and Allowable Stress (Strain Rate) Criteria, CS (SA-508)

Equation Format:

$$\log(\dot{\varepsilon}_0) = -C_{avg} - \frac{1}{T+460}\left(a_1 + a_2\log(\sigma) + a_3(\log(\sigma))^2 + a_4(\log(\sigma))^3\right)$$

C_{avg} (A_0)	**-13.64**
C_{min} ($A_0+\Delta_\Omega^{SR,LB}$)	**-14.34**
a_1	**30837.9**
a_2	**-4571.5**
a_3	**2868.2**
a_4	**-1883.2**

Number Data Points		**24**
Correlation Coefficient	R^2	0.5807
Average Variance within Heats	V_w	0.1797
Variance between Heats	V_b	0.3412
Standard Error of Estimate	SEE	0.4239

Properties provided are for T in °F, stress in ksi, and t_R in hours

Temperature, °F	**S_{CAVG}**
850	28.83
900	21.74
950	15.52
1000	10.19
1050	5.939
1100	3.062
1150	1.599
1200	0.950
1250	0.633
1300	0.456

Figure 6-1: CS (SA-508 & SA-533) Modulus (E_y), Thermal Conductivity (k), Thermal Diffusivity (TD), & Thermal Expansion (α) With Temperature

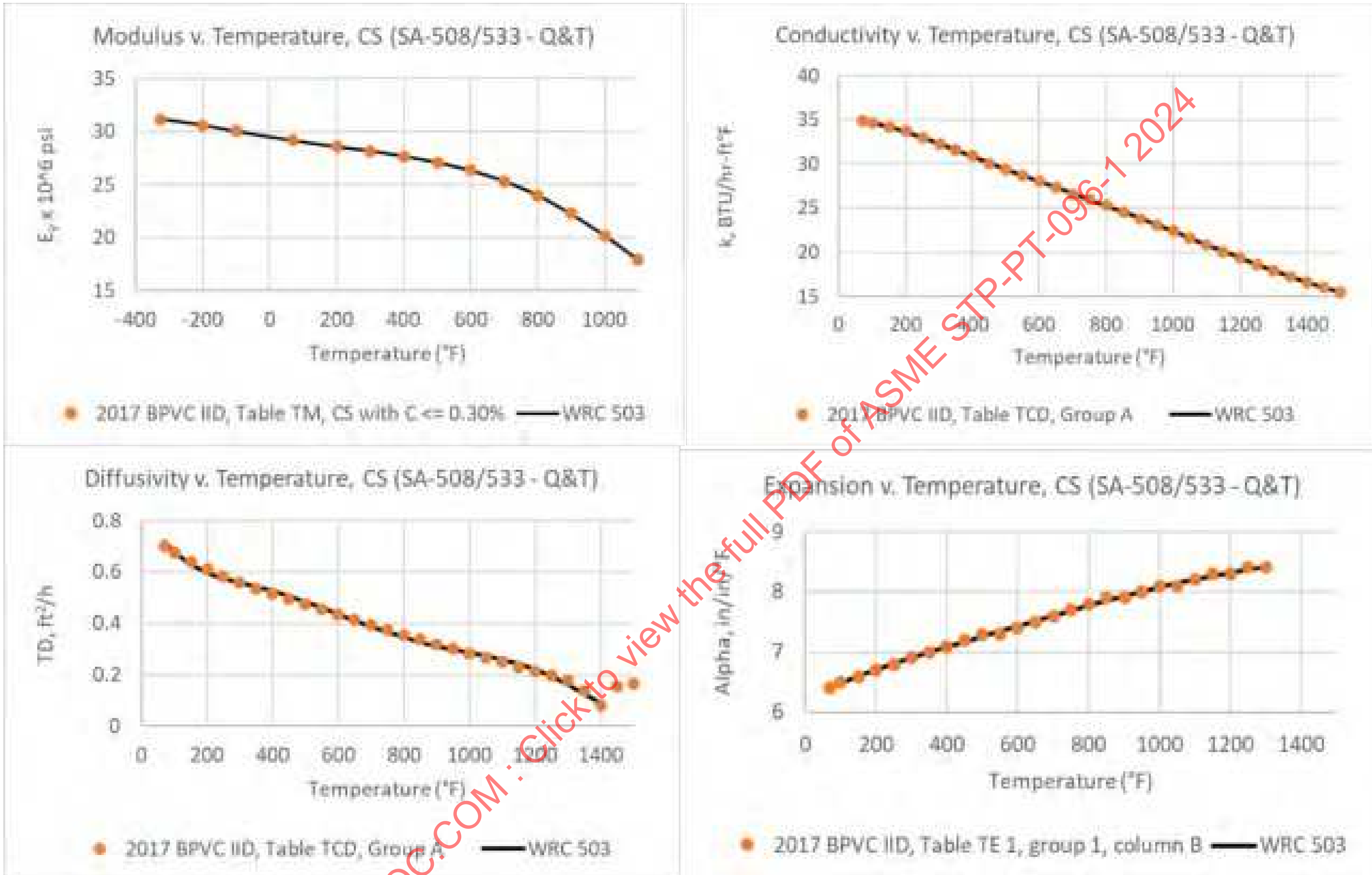


Figure 6-2: CS (SA-508) Yield Strength Vs. Temperature, By Data Source, Including Trend Curves

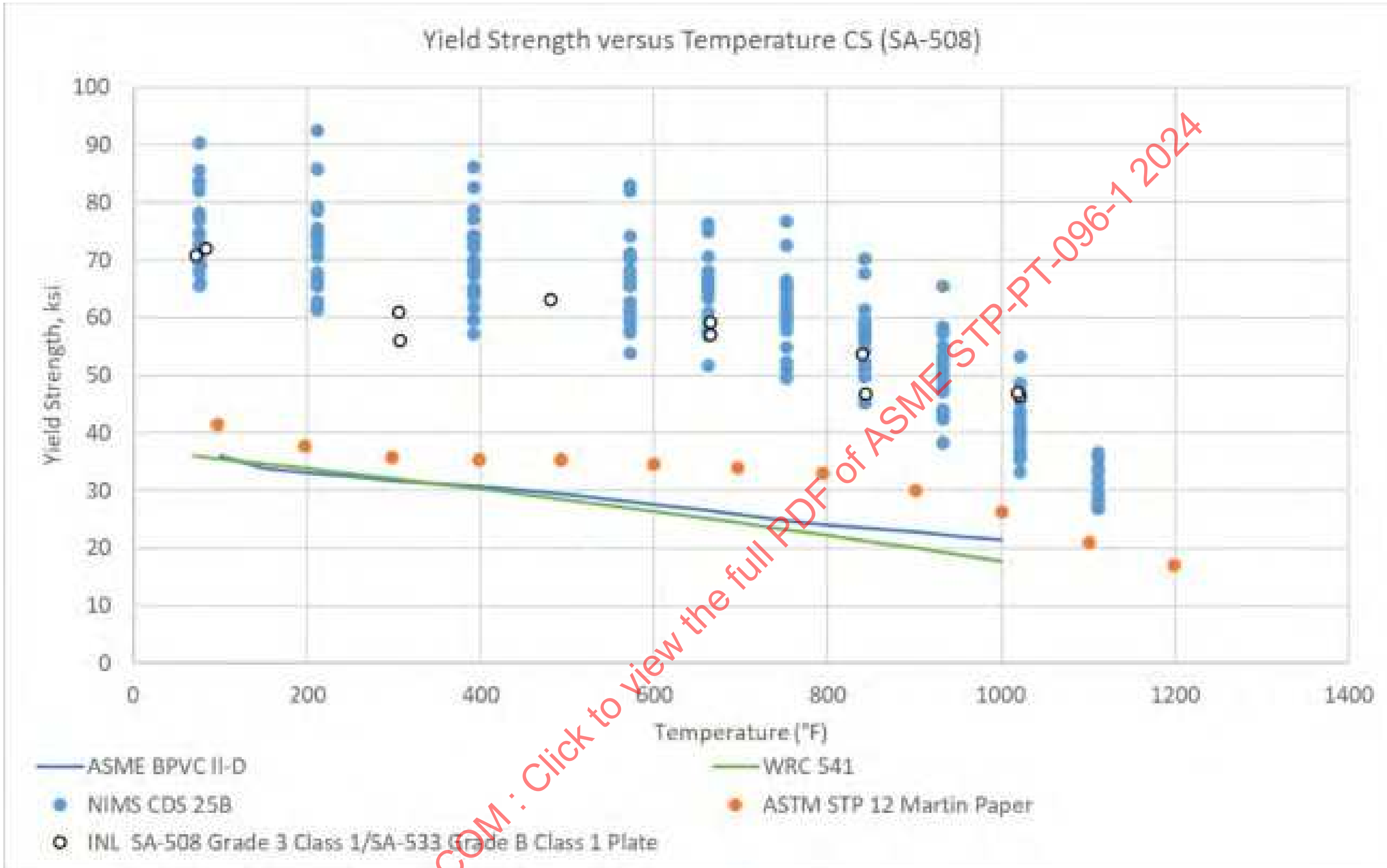


Figure 6-3: CS (SA-508) Tensile Strength Vs. Temperature, By Data Source, Including Trend Curves

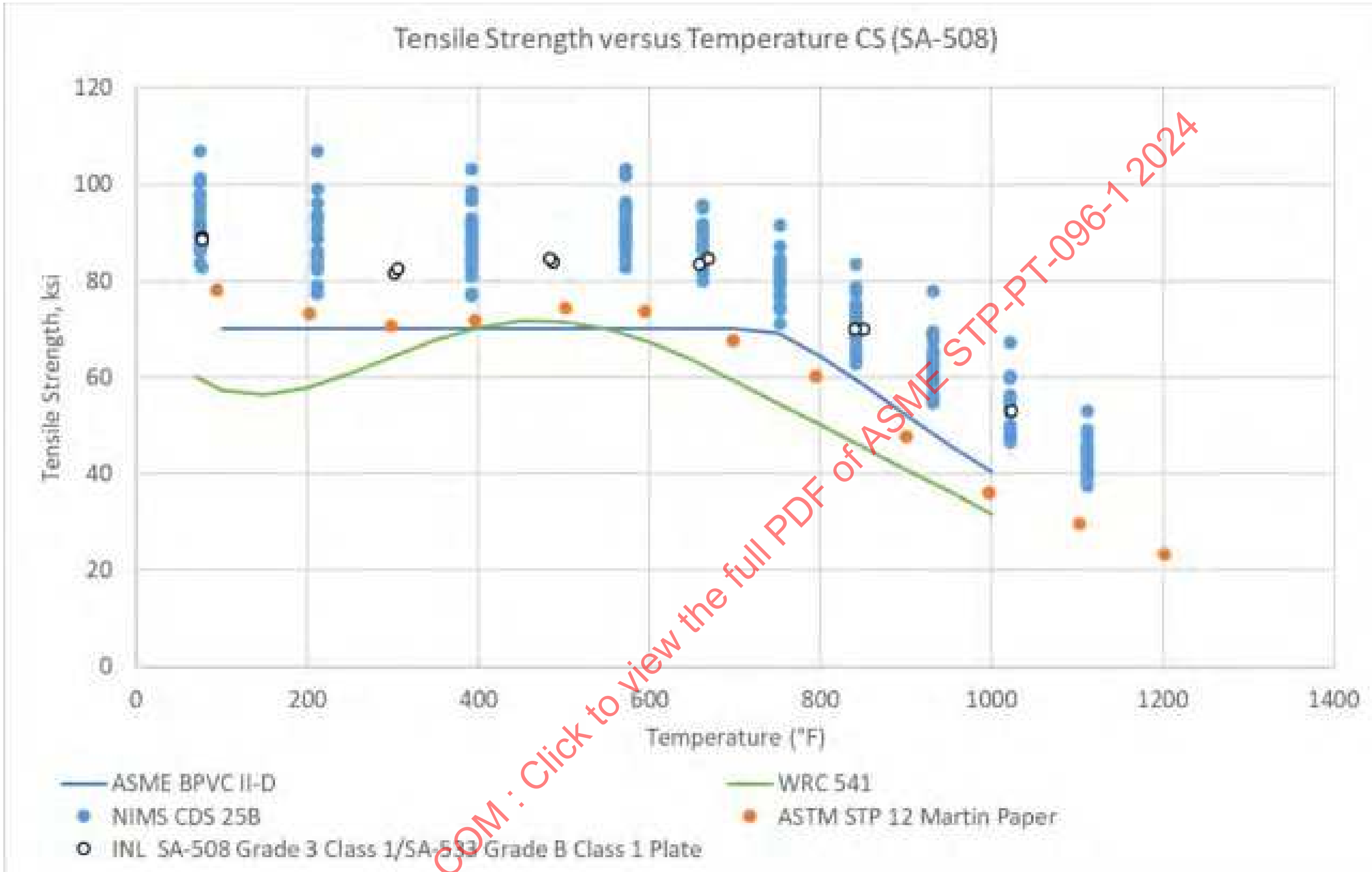


Figure 6-4: CS (SA-508) Yield Strength Ratios Vs. Temperature (Calculated on a Heat-By-Heat Basis, By Data Source)

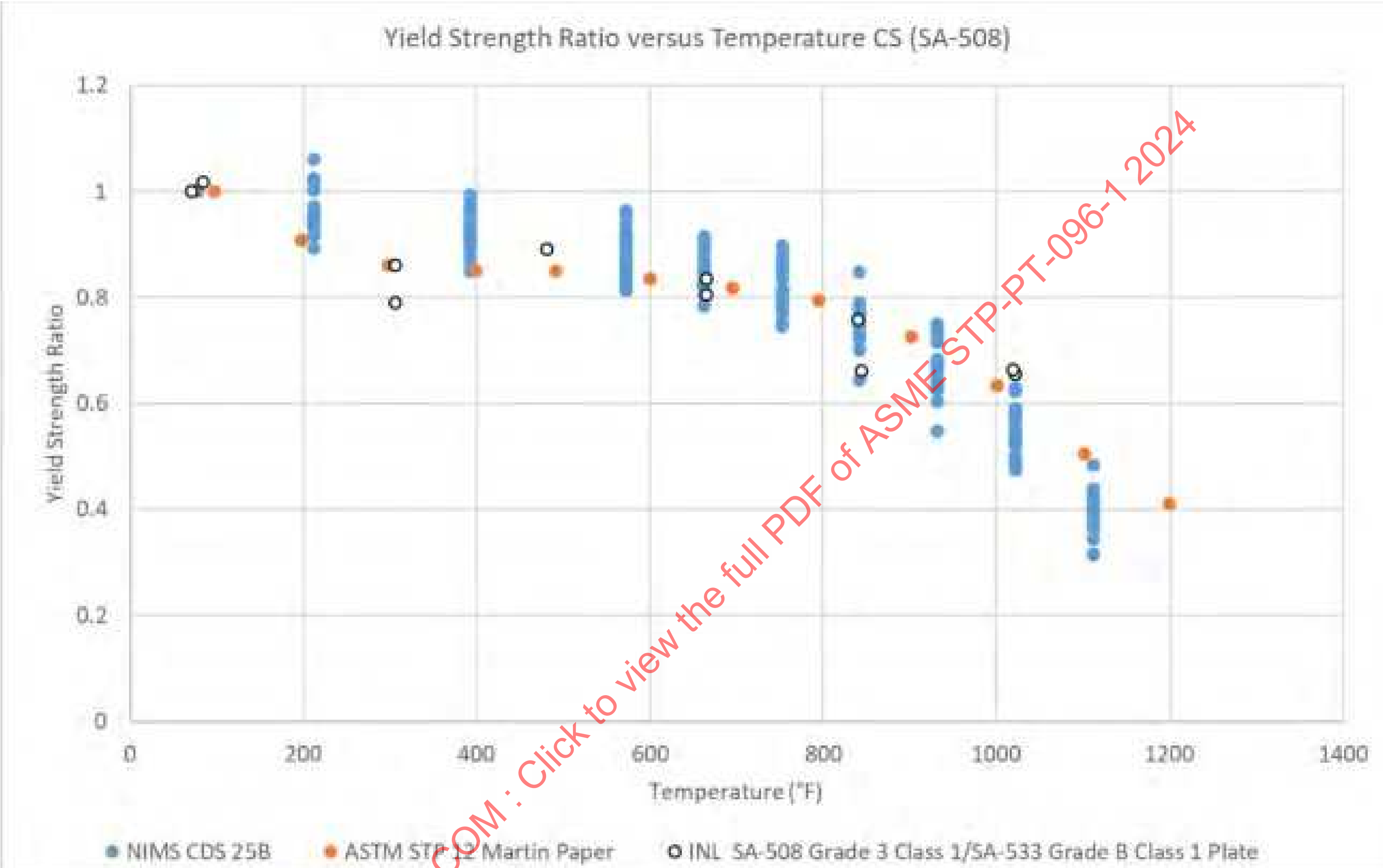


Figure 6-5: CS (SA-508) Tensile Strength Ratios Vs. Temperature (Calculated on a Heat-By-Heat Basis, By Data Source)

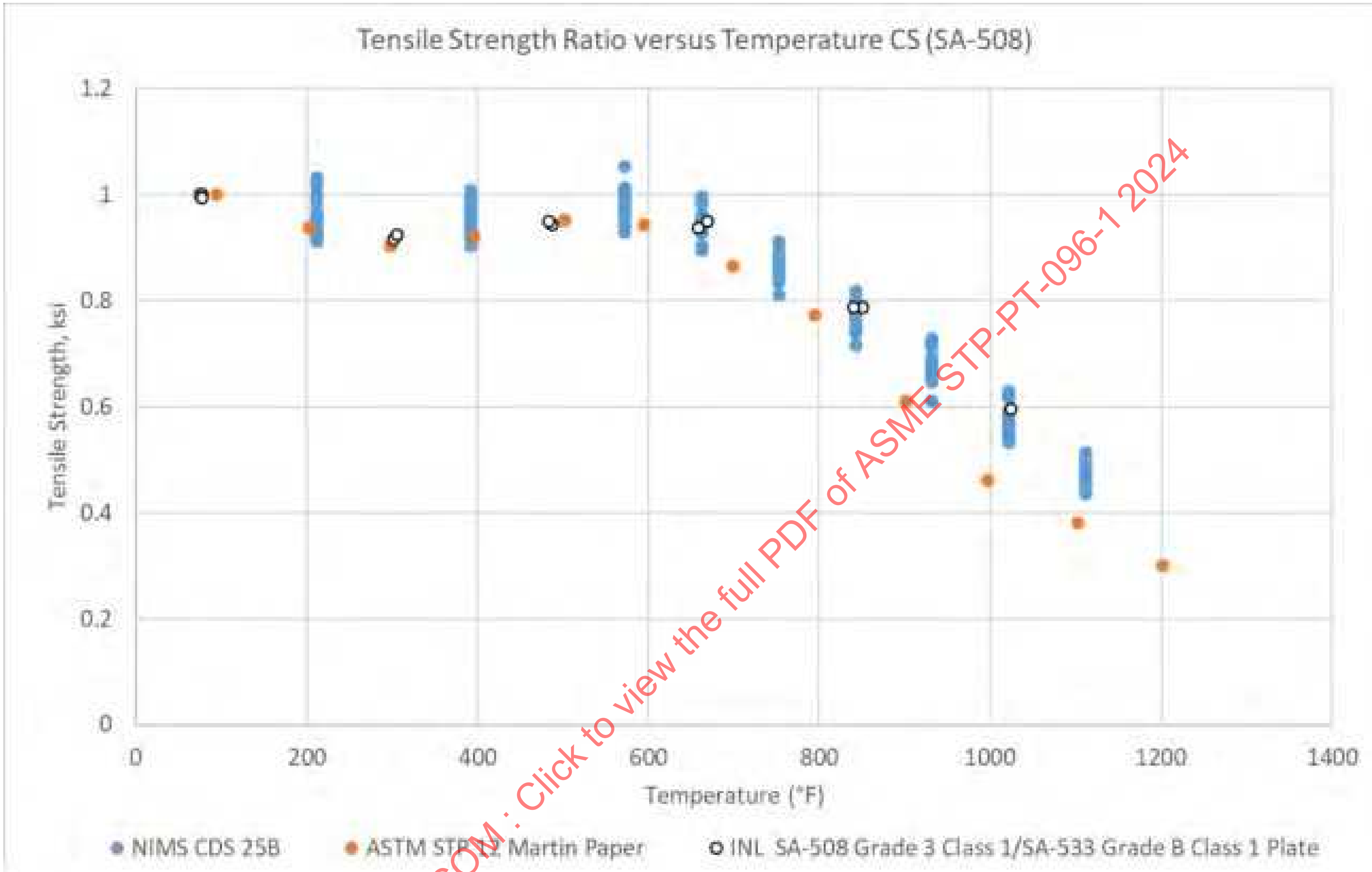


Figure 6-6: CS (SA-508) Yield Strength Ratios Vs. Temperature, All Combined Data, With Polynomial Regression

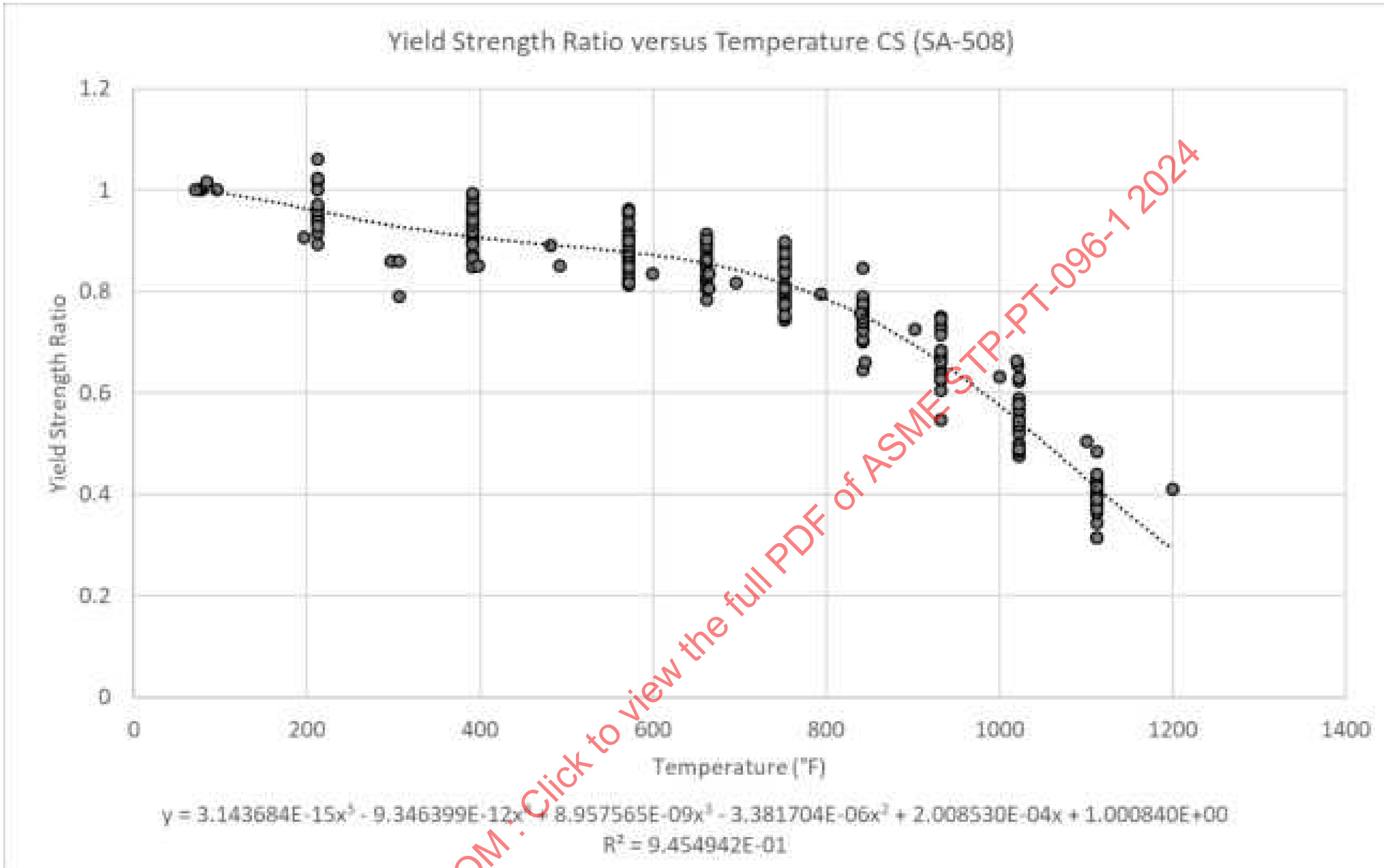


Figure 6-7: CS (SA-508) Tensile Strength Ratios Vs. Temperature, All Combined Data, With Polynomial Regression

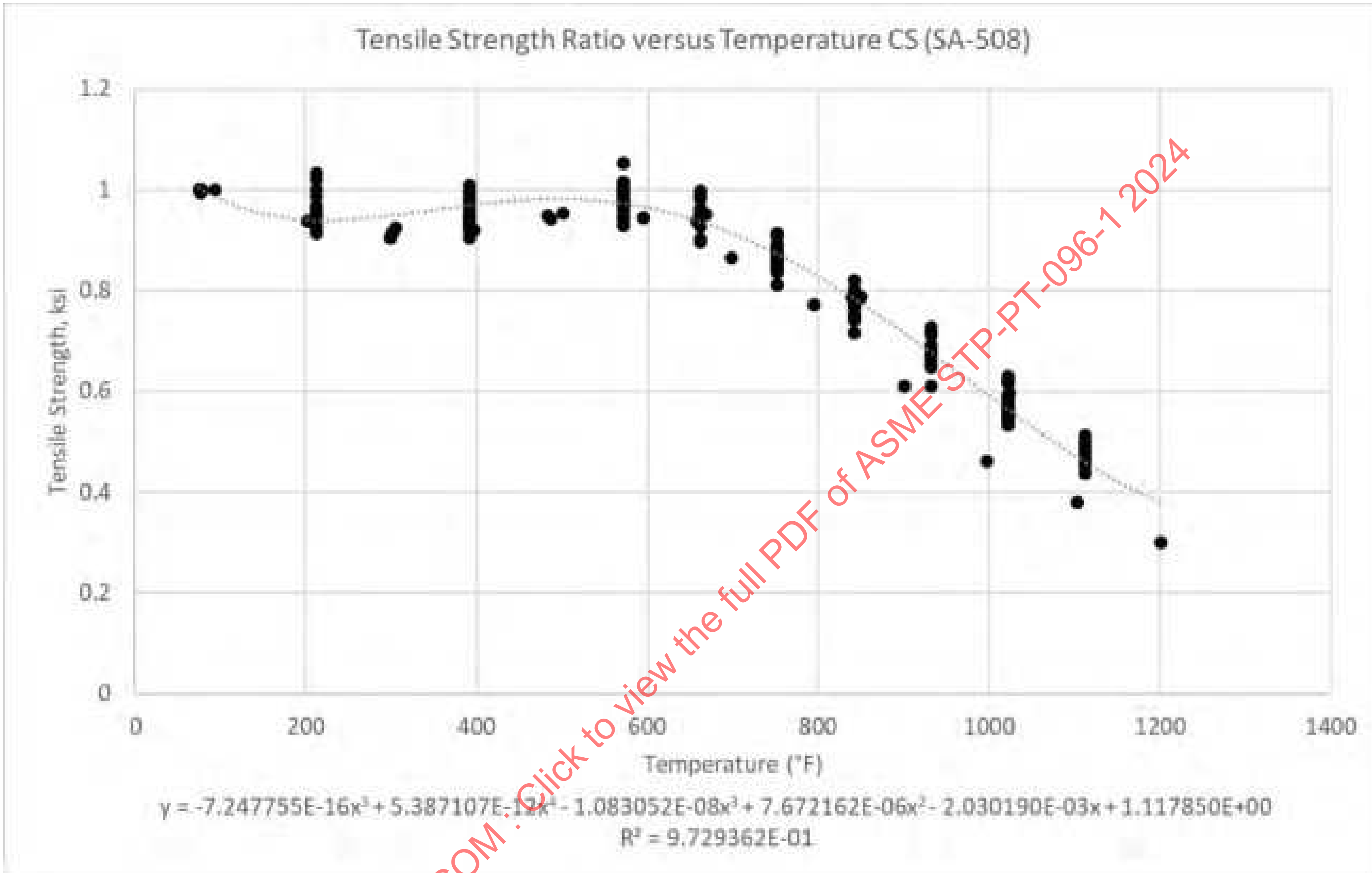


Figure 6-8: CS (SA-508) Creep Rupture Isotherm Curves, Temperatures with High Concentration of Data Points

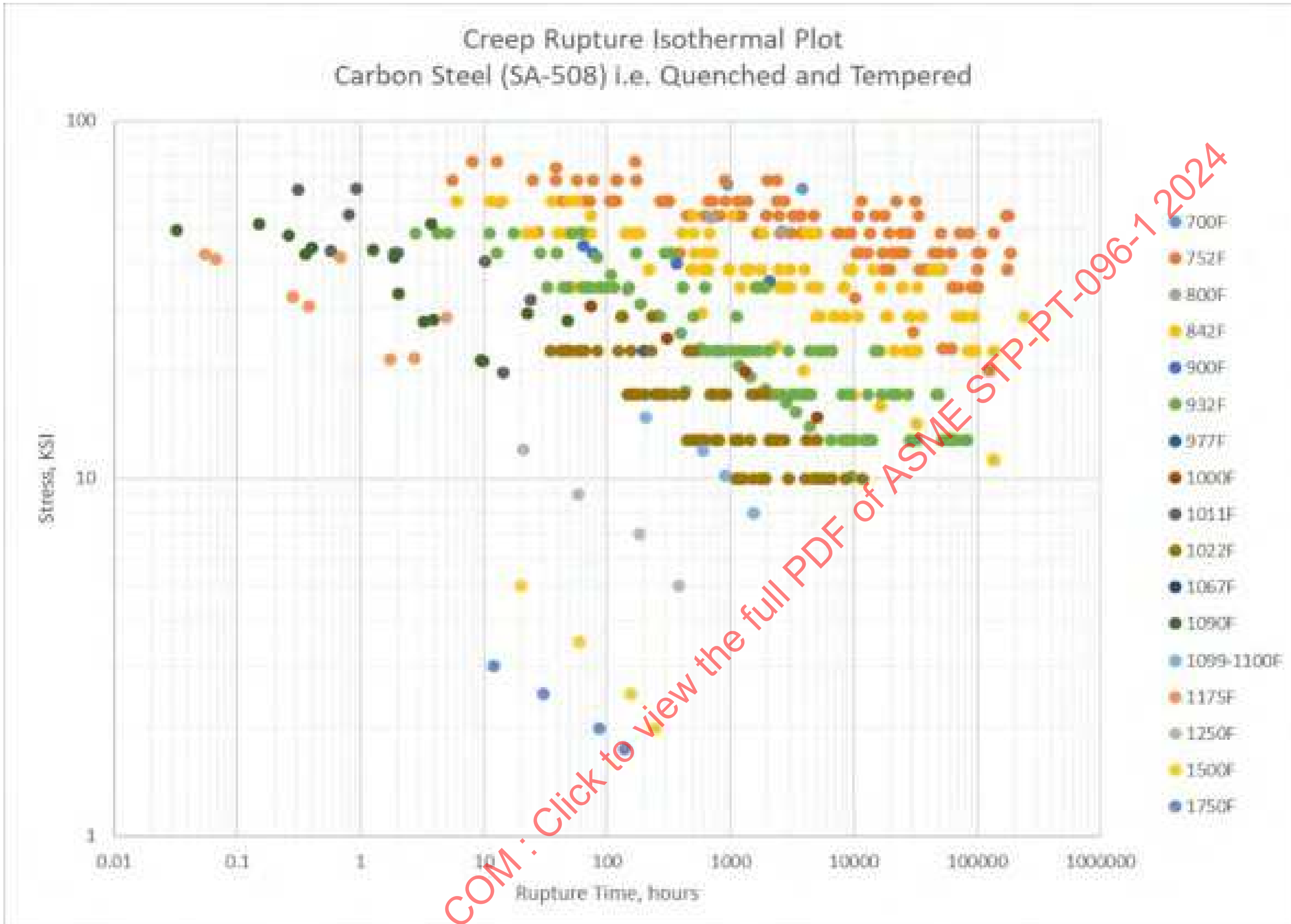


Figure 6-9: CS (SA-508) Creep Strain Rate (MCR) Isotherm Curves

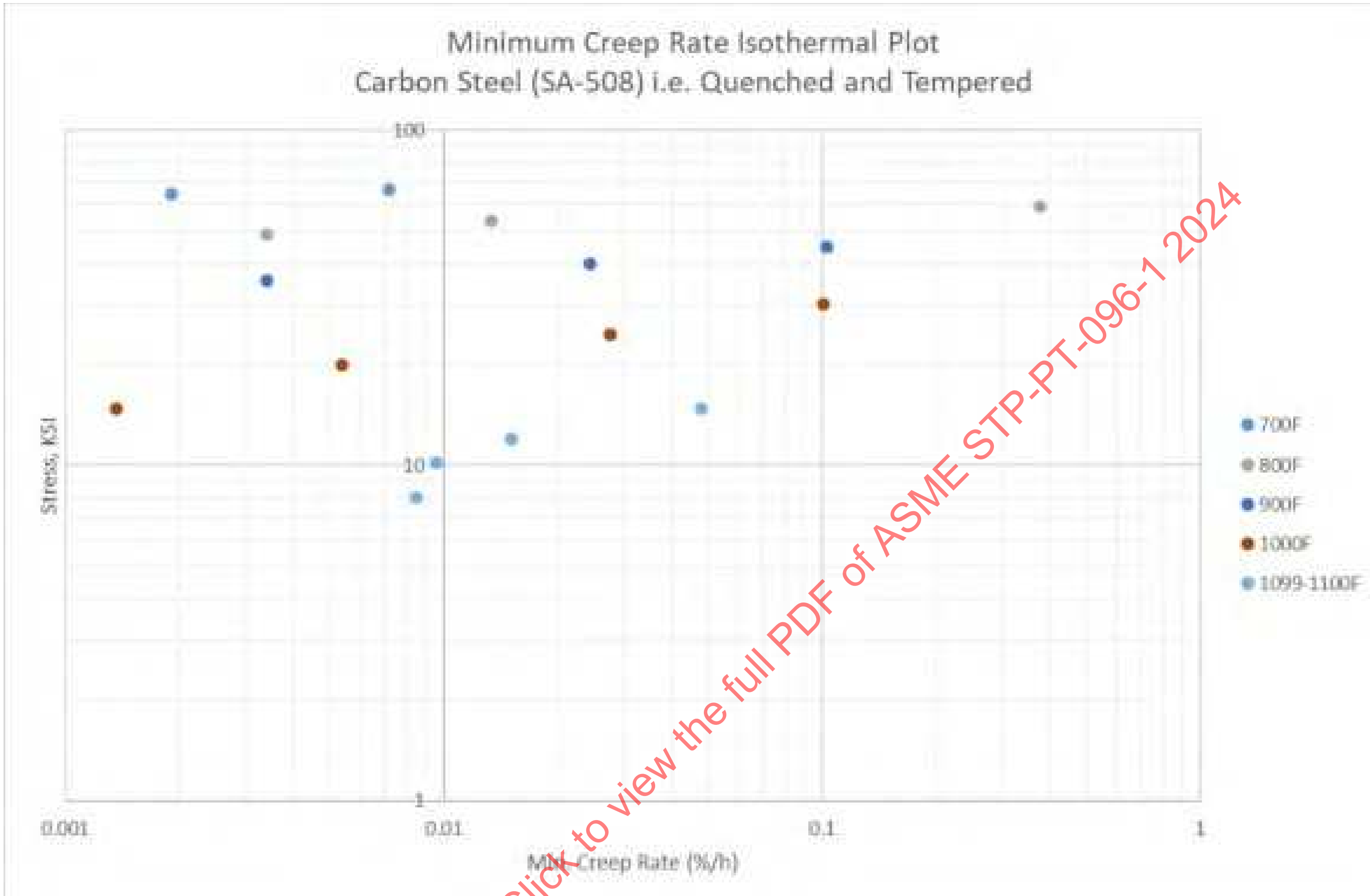


Figure 6-10: CS (SA-508) Creep Ductility (% Elongation) Vs. Rupture Time Isotherms

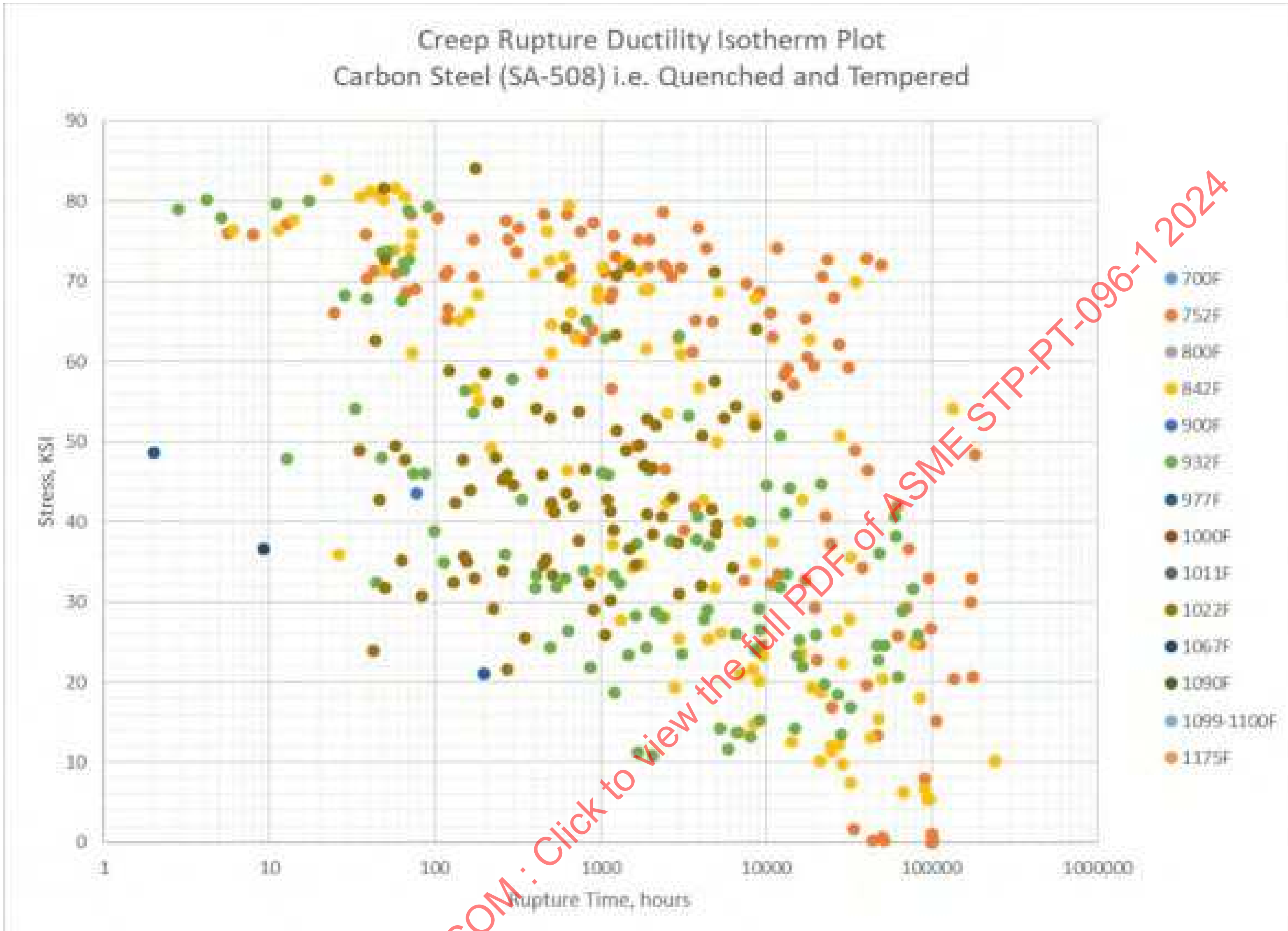
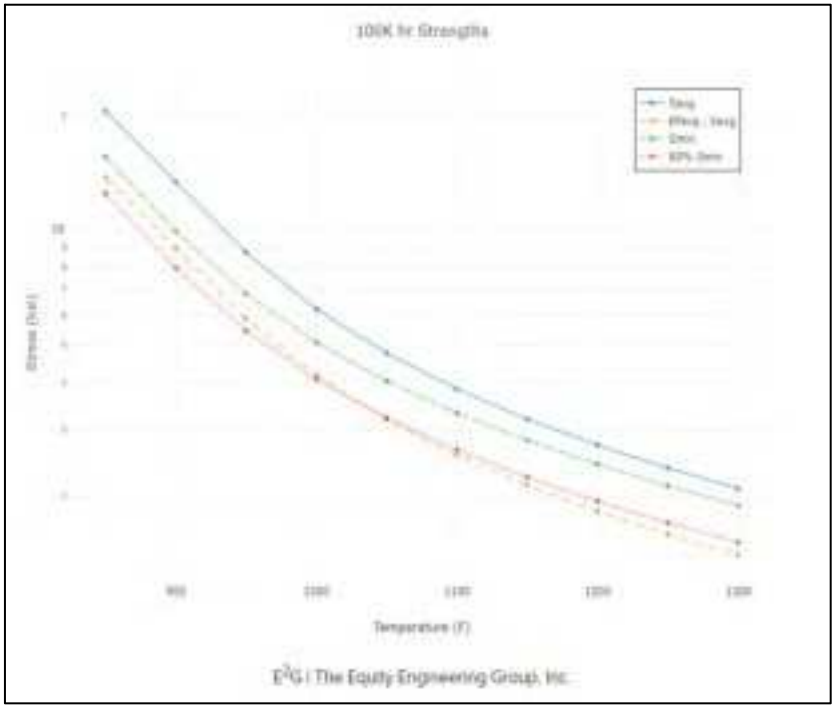


Figure 6-11: Calculated Allowable Stresses Based on Rupture and Creep Strain Rate and ASME II-D Appendix 1 Criteria (CS (SA-508))



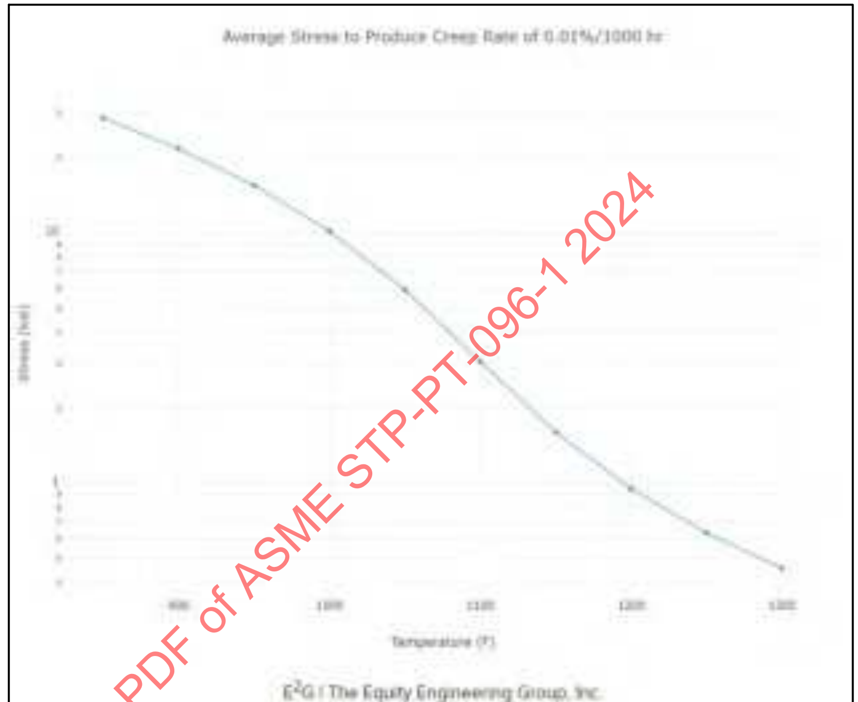


Figure 6-12: Comparison of Current CS (SA-508) Allowable Stresses Vs. ASME II-D Appendix 1 Criteria Applied to Data

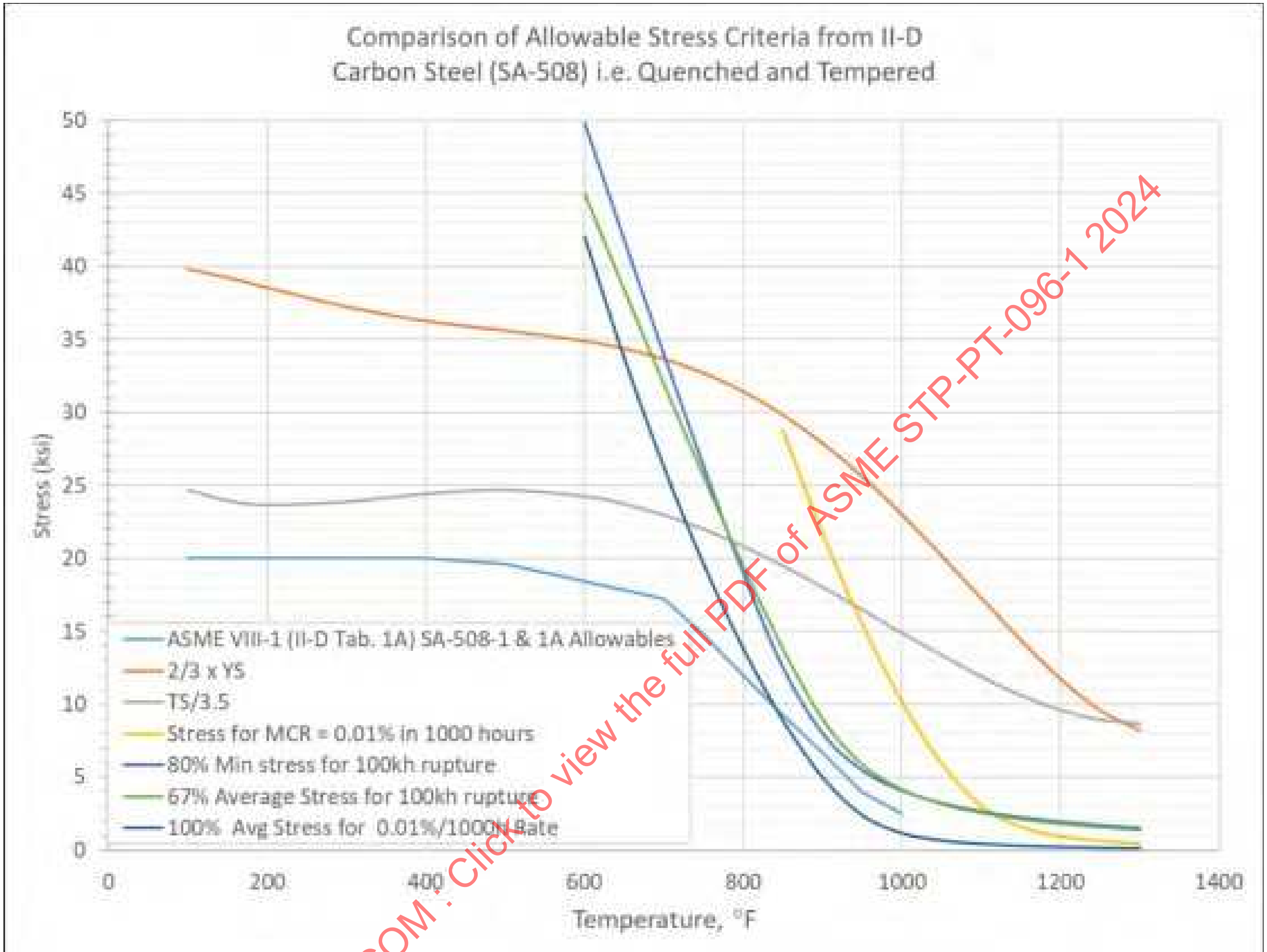


Figure 6-13: Strain Vs. Time Data – CS (SA-508), 1 of 2

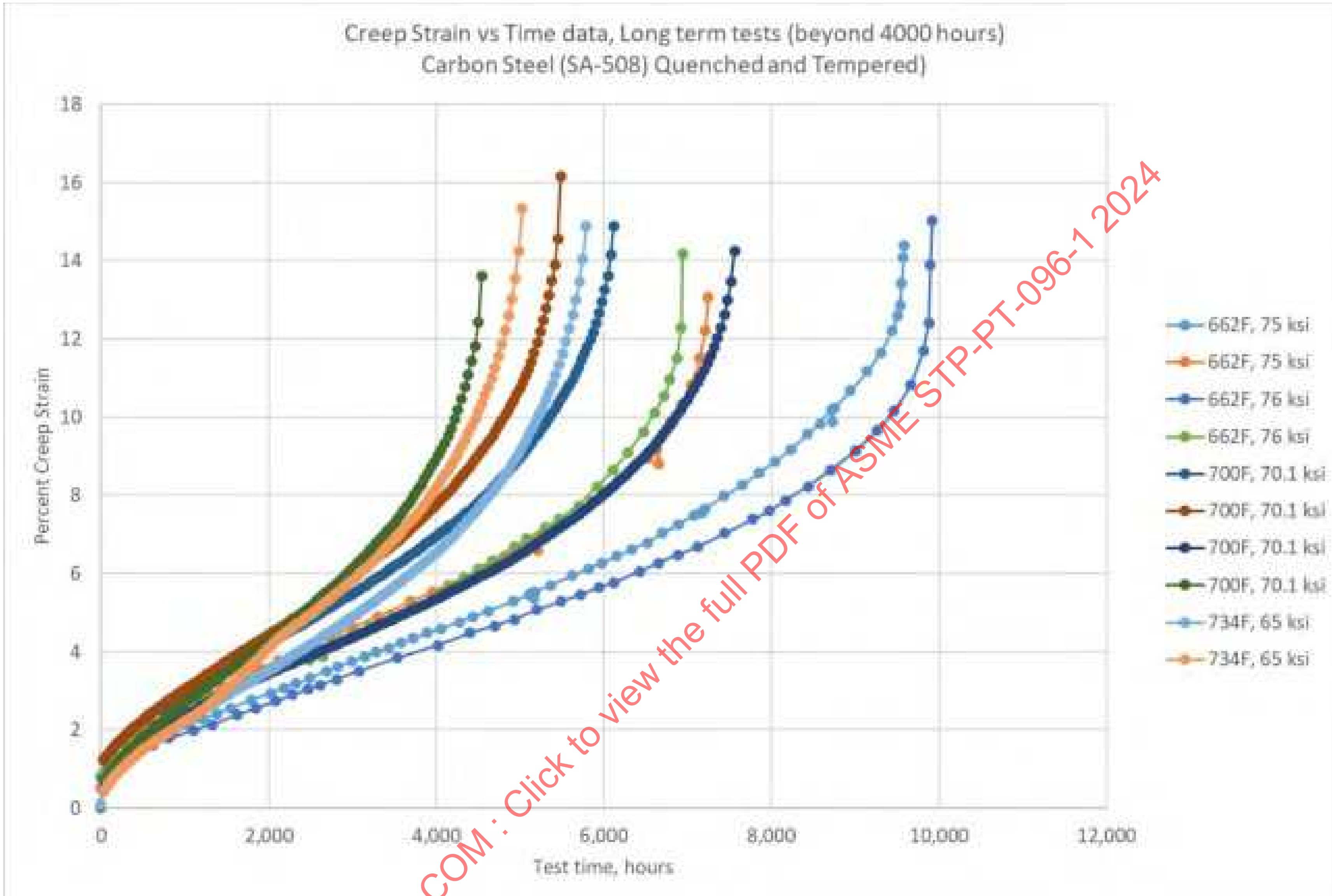


Figure 6-14: Strain Vs. Time Data – CS (SA-508), 2 of 2

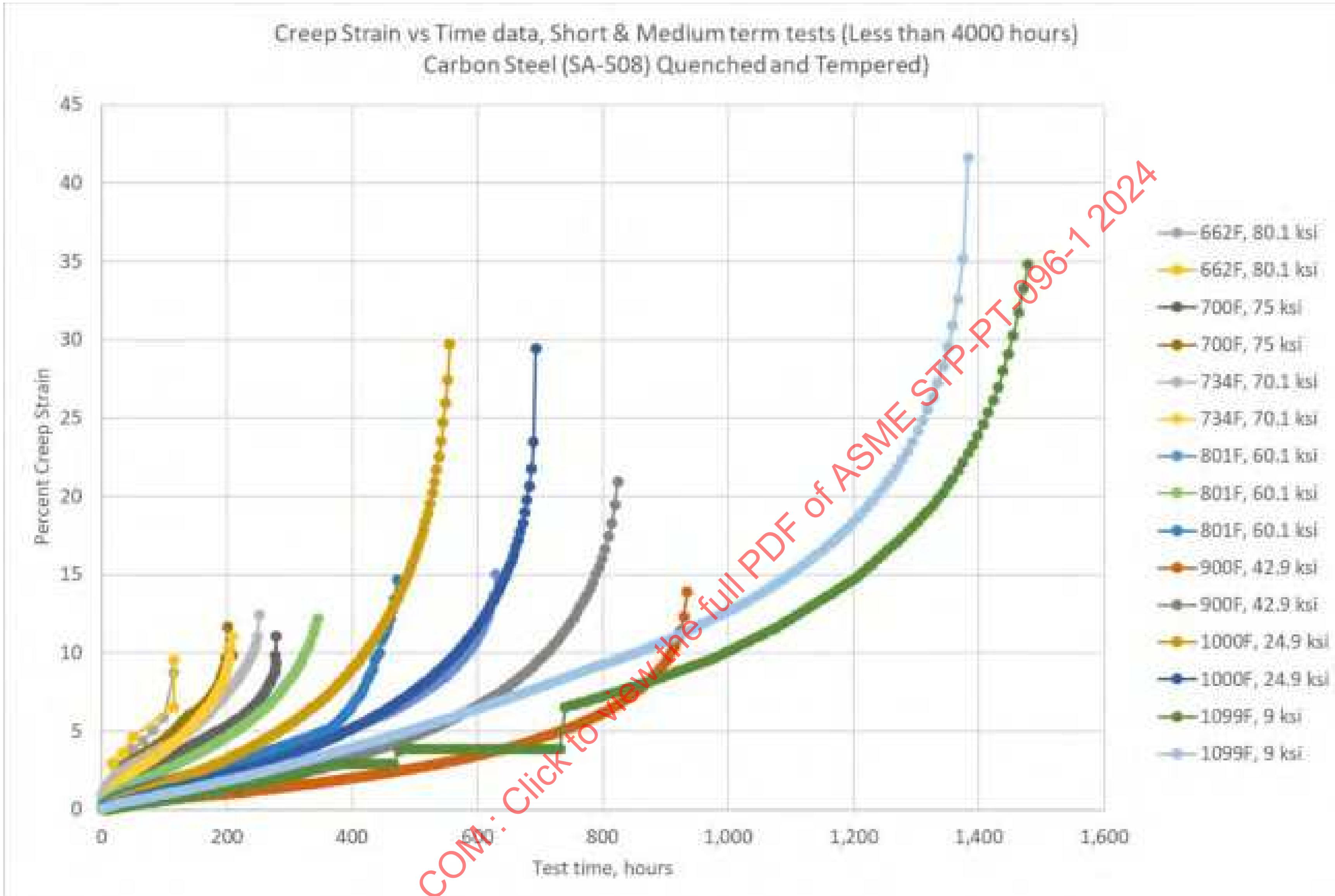
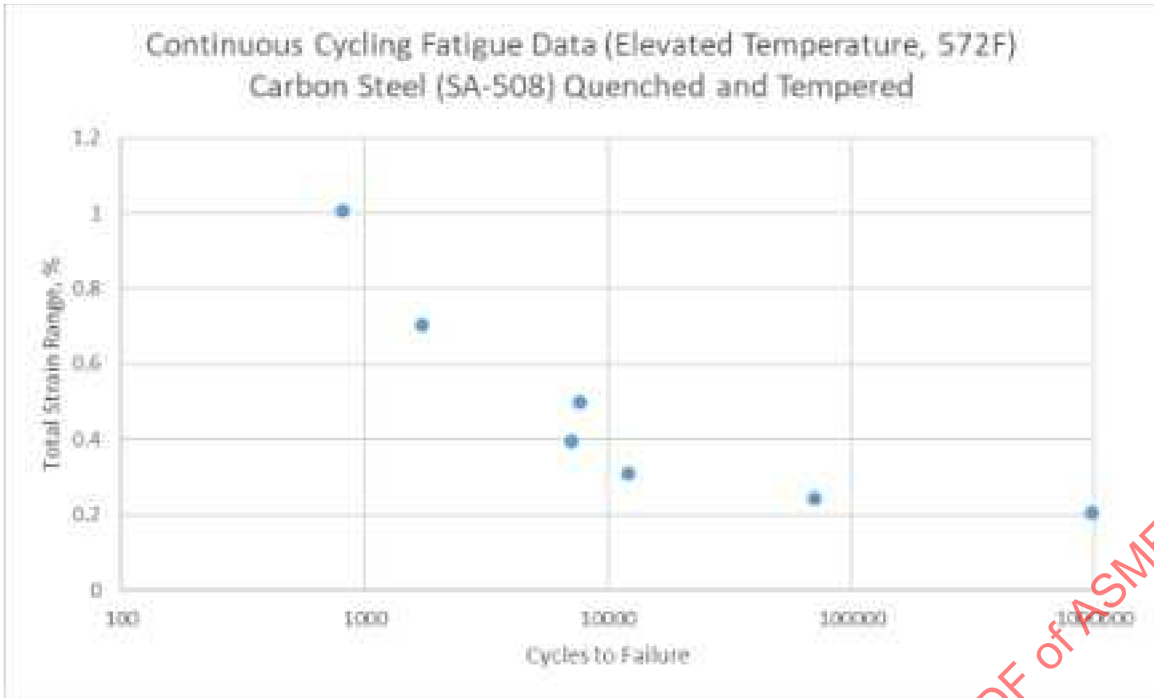


Figure 6-15: CS (SA-508) Continuous Cycling Fatigue, Elevated Temperature Data



Attachment 6: Carbon Steel (SA-508) Property Data

If you want the referenced embedded spreadsheet with additional data, please email a request to research@asme.org.

7 CARBON STEEL (SA-533) AND SIMILAR

As explained in reference [3], the search for SA-533 material data was initially expanded to include data for all quenched and tempered Mn-0.5Mo plate materials. Due to limited available data on the Mn-0.5Mo in this condition, the review was expanded to include materials meeting other grades of the SA-533 specification, including product forms besides plate. The spreadsheet containing data for this material, wherever possible, includes the chemical composition and heat treatment details for the data points listed, which can be used to verify that the material either does or does not meet the specification.

7.1 Physical Properties

Well-established physical properties were referenced from BPVC Section II for this material and are identical to those shown for SA-508 carbon steel in paragraph 6.1. As with SA-508, additional data sources beyond ASME Section II-D and WRC 503 were not located for this material.

7.2 Yield and Tensile Strength

Elevated temperature Yield and Tensile Strength were available from ASTM up to approximately 1100°F, with additional data extending well above this temperature obtained from a second published source, as shown in Figures 7-1 and 7-2. Notably, the second source has values at temperatures well into and above the critical region, where austenitic transformation would have occurred. These data are not generally applicable for design use, but are included in this analysis nonetheless.

To facilitate comparison of the data obtained to existing allowable stresses (Section II-D Table 1A), yield and tensile data were normalized on a heat-by-heat basis to express the ratio of yield or tensile strength at temperature to that measured for the heat at room temperature. For this material, data from some of the original sources could not be separated by heat. E^2G understands that this approach is similar to the normalizing procedure performed by ASME in typical analysis of yield and tensile data to obtain Table Y and Table U (Section II-D) trend curves, as well as for the calculation of allowable stresses. Figures 7-3 and 7-4 show the heat-by-heat variation in yield and tensile strength ratios (respectively) as a function of temperature. It should be emphasized that even though the figure legends reference an entire source of data, the ratios were calculated on a heat-by-heat basis; this is evident in the embedded spreadsheet at the end of this section. Figures 7-5 and 7-6 contain all of the yield and tensile (respectively) ratios plotted together, to facilitate regression of a polynomial fits that are subsequently used for allowable stress comparison.

7.3 Creep Data (Creep Rupture, Minimum Creep Rate, and Ductility)

Creep Rupture data is shown in Figure 7-7, plotted as isotherms. Creep Minimum strain rates (%/hour) are shown in Figure 7-8, although the data for minimum creep rates is limited. Creep Ductility, as % elongation, is plotted in Figure 7-9. The amount of data for SA-533 is relatively limited compared to many other Phase 1 materials.

Creep data were analyzed using E^2G's proprietary *Lot-Centered Analysis* web-based software tool (Mandel-Paule algorithm), according to a Larson-Miller 3rd-order polynomial of stress, assuming parallel behavior and a 95% predictive limit. This procedure was utilized to obtain the lower-bound (minimum LM constant for both rupture and strain rate) properties. The results of this analysis are summarized in Table 7-1 for rupture data and Table 7-2 for strain rate data. The *Lot-Centered Analysis* software tool generates property tables in the creep regime using the criteria outlined in Mandatory Appendix 1 of ASME Section II-D; the nomenclature of variables is consistent with II-D Appendix 1. It should be emphasized that for SA-533, the limited amount of data means that the properties obtained from lot-centered analysis may not accurately characterize the material. Additional testing is needed. For visualization of the allowable stress trends, Figure 7-10 is provided (for rupture allowable stresses and creep rate allowable stresses). Figure 7-11 shows a comparison of the various allowable stress criteria from Section II-D, Appendix 1, to the existing (2019) Section II-D Table 1A allowable stresses for SA-533 Grade A.

Creep Strain vs. time data are shown in Figure 7-12 and 7-13. Additional creep strain vs. time data are located in the embedded spreadsheet. Both creep rate and creep strain vs. time data are provided to satisfy ASME's request for creep strain vs. time curves, and both forms of data are applicable in developing allowable stresses. Although digitalization of creep curve data was not explicitly necessary per the project contract, E^2G did perform digitalization of creep curves where only graphical data was available (as is often the case in the published literature).

7.4 Continuous Cycling Fatigue and Hold Time Fatigue Curves

More data are shown for cyclic tests of SA-533 than SA-508. The continuous cycling data that were obtained are plotted in Figure 7-14, and the hold time fatigue data are shown in Figure 7-15. In a number of sources, grades of SA-508 and SA-533 other than those desired for this project (i.e., other than Grades 1 or 1A of SA-508, or other than Type A of SA-533) are presented. In such cases, the chemistry of the material in the source evaluated is a closer match to the chemistry of SA-533 than SA-508. This approach in grouping the data may have contributed to the increase in data for SA-533 compared to SA-508.

Table 7-1: Model Parameters, Larson-Miller Property Results, and Allowable Stress (Rupture) Criteria, SA-533

Equation Format:

$$\log(t_r) = C_{avg} + \frac{1}{T+460}\left(b_1 + b_2\log(\sigma) + b_3(\log(\sigma))^2 + b_4(\log(\sigma))^3\right)$$

C_{avg}	**-14.64**
C_{min}	**-15.33**
b_1	**35479.9**
b_2	**-14042.7**
b_3	**8889.6**
b_4	**-3247.5**

Number Data Points	**42**
R^2	0.8214
V_w	0.177
V_b	0.02851
SEE	0.4207

Properties provided are for T in °F, stress in ksi, and t_R in hours

Temp, °F	**S_{avg} (ksi)**	**n**	**F_{avg} (calc)**	**F_{avg} (used)**	**$F_{avg} \times S_{avg}$**	**S_{min} (ksi)**	**80% S_{min}**
850	16.33	5.199	0.6422	0.67	10.94	11.81	9.449
900	11.49	4.518	0.6007	0.67	7.701	8	6.4
950	7.883	4.208	0.5786	0.67	5.282	5.429	4.343
1000	5.423	4.275	0.5835	0.67	3.633	3.805	3.044
1050	3.844	4.621	0.6075	0.67	2.576	2.785	2.228
1100	2.838	5.12	0.6378	0.67	1.902	2.124	1.699
1150	2.178	5.68	0.6667	0.67	1.459	1.676	1.341
1200	1.727	6.248	0.6918	0.67	1.157	1.36	1.088
1250	1.406	6.799	0.7127	0.67	0.9419	1.127	0.9017
1300	1.169	7.32	0.7301	0.67	0.783	0.951	0.7608

Table 7-2: Model Parameters, Larson-Miller Property Results, and Allowable Stress (Strain Rate) Criteria, SA-533

Equation Format:

$$\log(\dot{\varepsilon}_0) = -C_{avg} - \frac{1}{T+460}\left(a_1 + a_2\log(\sigma) + a_3(\log(\sigma))^2 + a_4(\log(\sigma))^3\right)$$

C_{avg} (A_0)	**-21.71**
C_{min} ($A_0+\Delta_\Omega^{SR,LB}$)	**-22.16**
a_1	**47720.1**
a_2	**-13309.8**
a_3	**11137.7**
a_4	**-4985.6**

Number Data Points		**35**
Correlation Coefficient	R^2	0.9078
Average Variance within Heats	V_w	0.07614
Variance between Heats	V_b	0
Standard Error of Estimate	SEE	0.2759

Properties provided are for T in °F, stress in ksi, and t_R in hours

Temperature, °F	**S_{CAVG}**
850	37.12
900	29.83
950	23
1000	16.65
1050	10.91
1100	6.257
1150	3.459
1200	2.154
1250	1.508
1300	1.138

Figure 7-1: SA-533 (Q&T Mn-0.5Mo) Yield Strength Vs. Temperature, By Data Source, Including Trend Curves

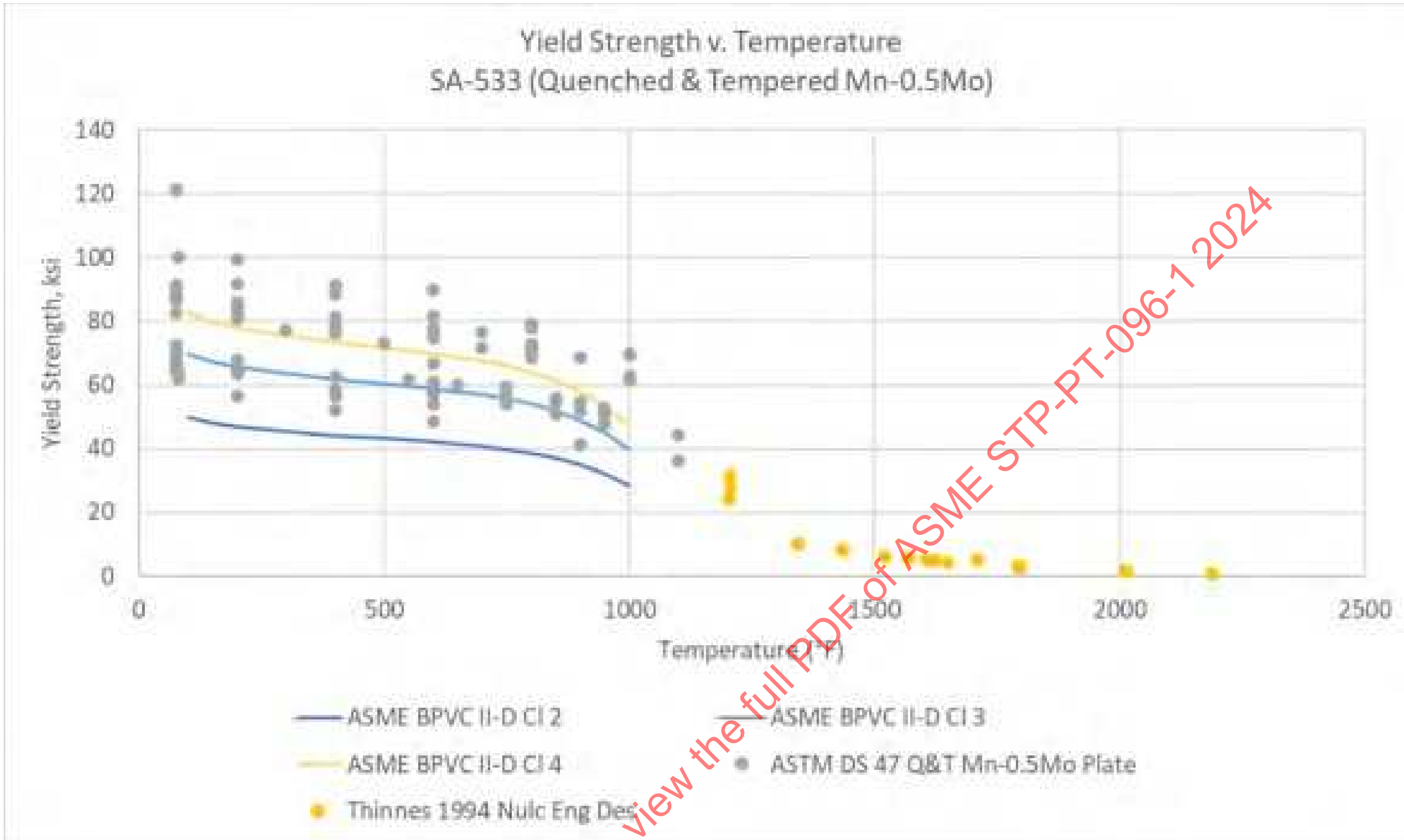


Figure 7-2: SA-533 (Q&T Mn-0.5Mo) Tensile Strength Vs. Temperature, By Data Source, Including Trend Curves

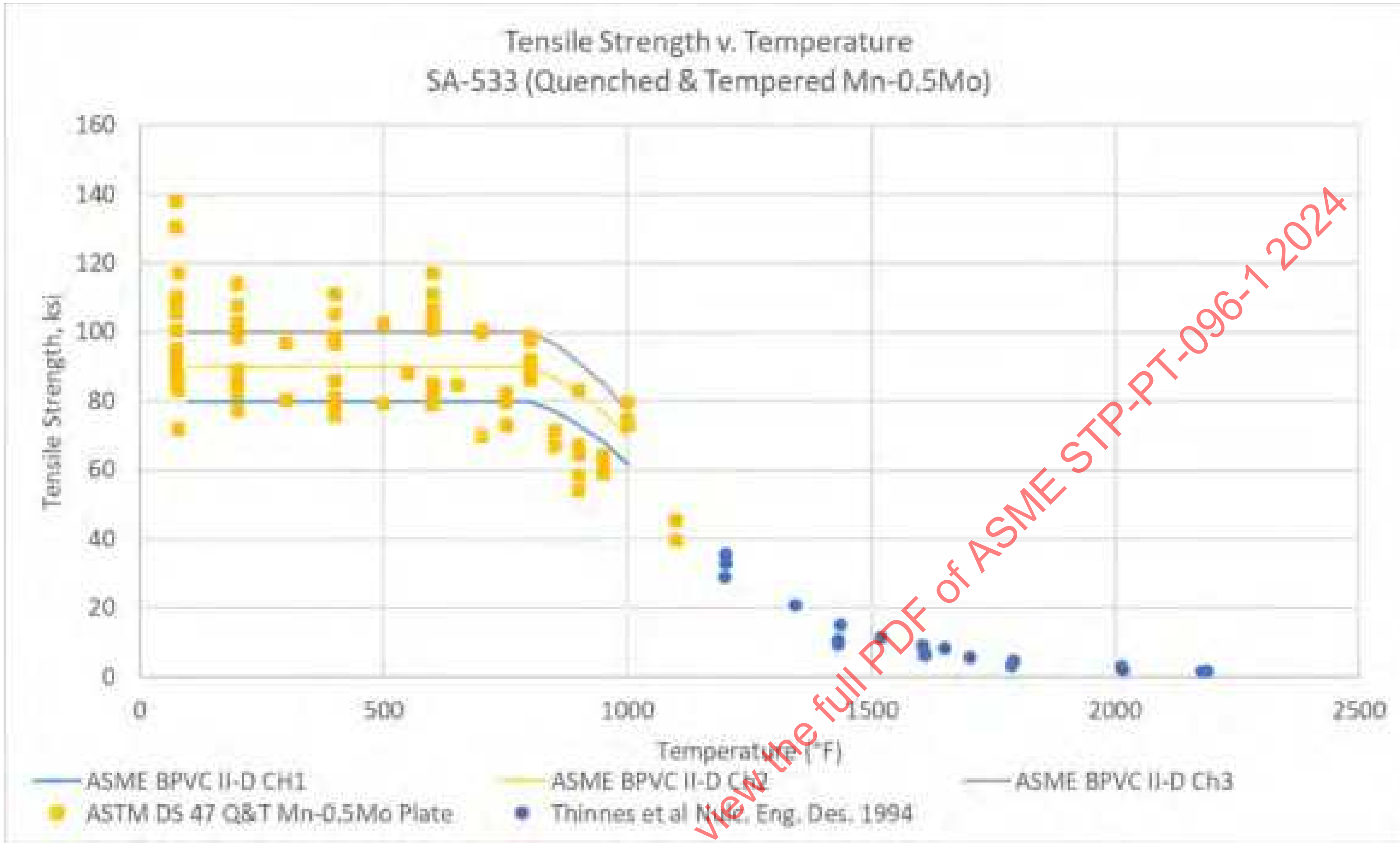


Figure 7-3: SA-533 (Q&T Mn-0.5Mo) Yield Strength Ratios Vs. Temperature (Calculated on a Heat-By-Heat Basis, By Data Source)

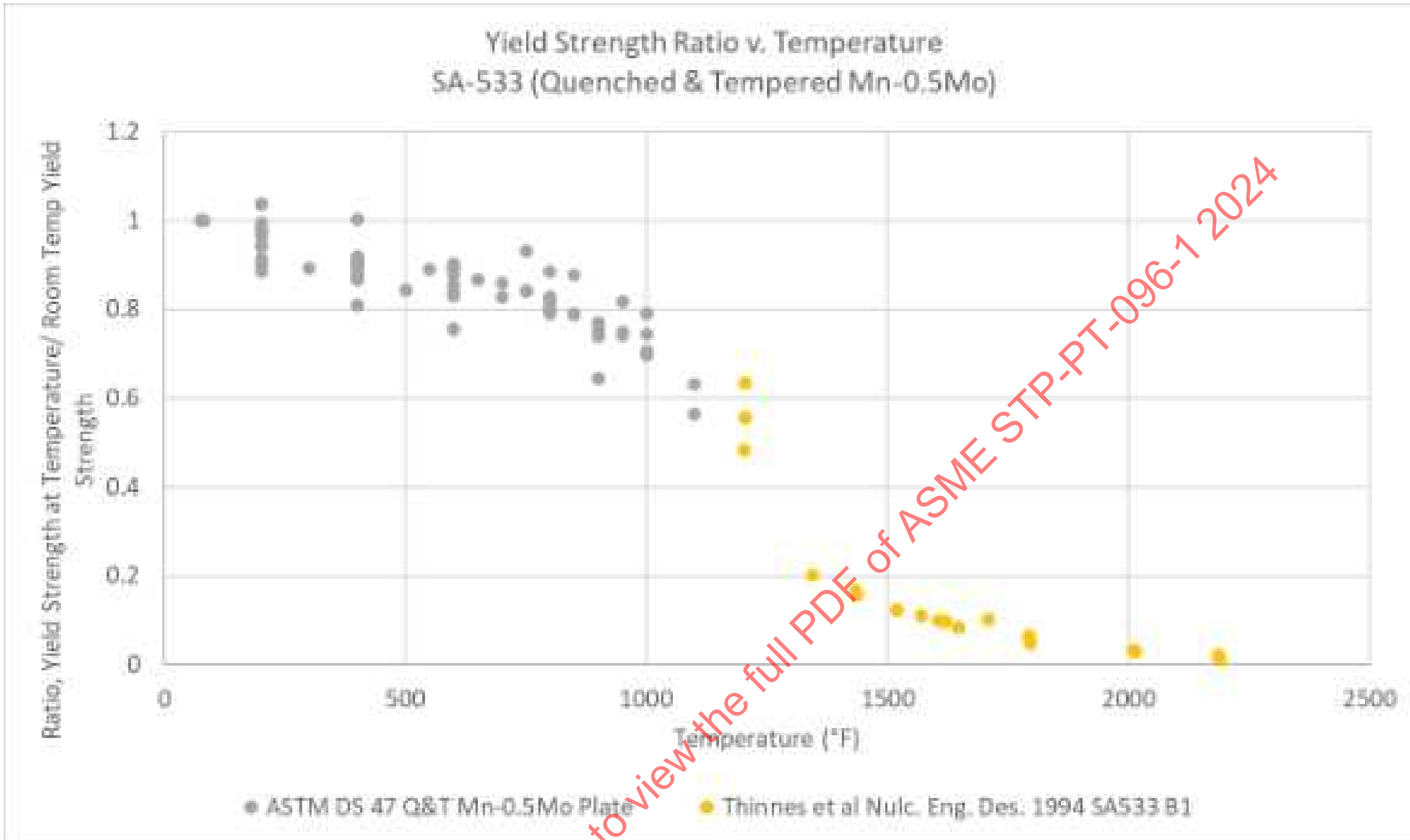


Figure 7-4: SA-533 (Q&T Mn-0.5Mo) Tensile Strength Ratios Vs. Temperature (Calculated on a Heat-By-Heat Basis, By Data Source)

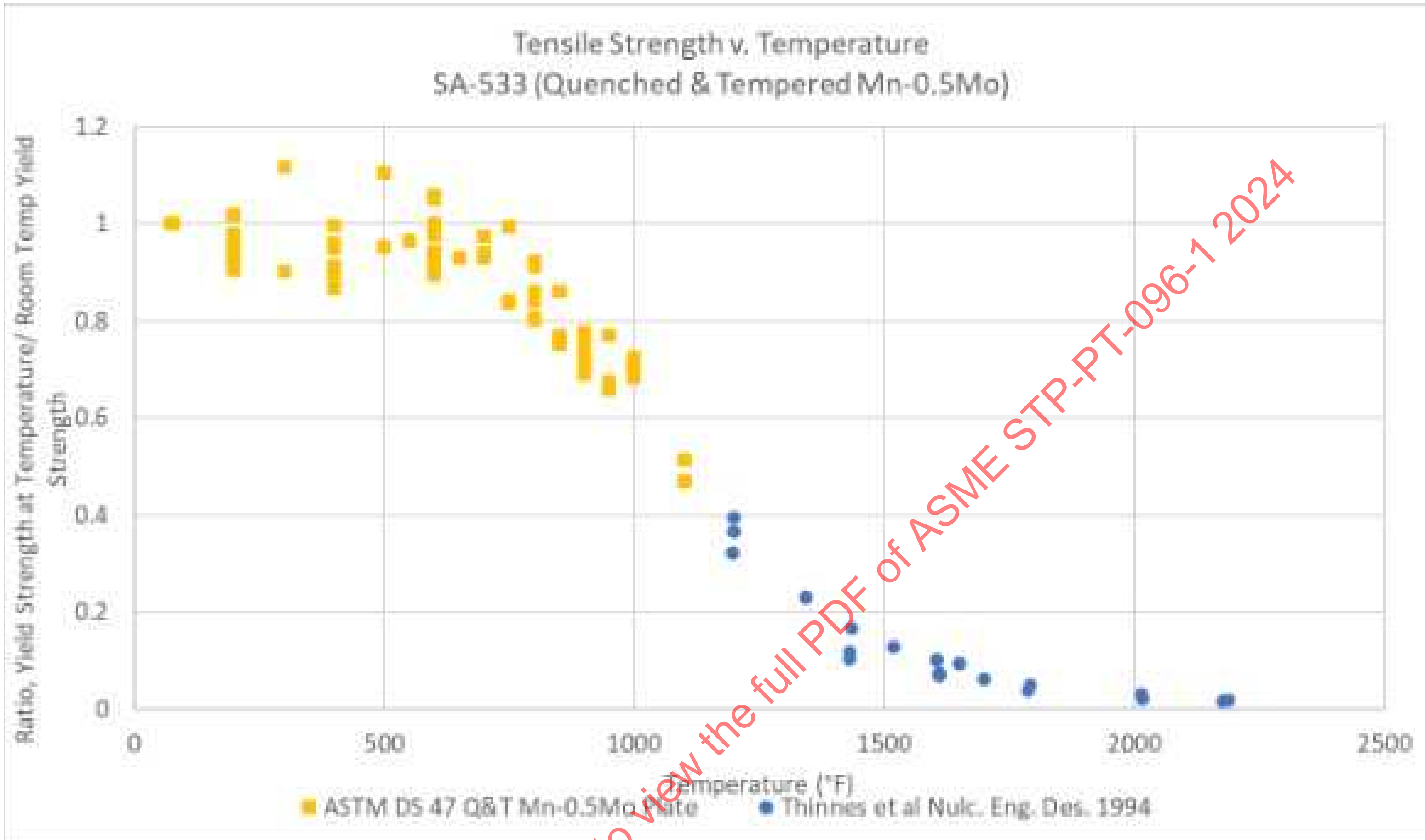


Figure 7-5: SA-533 (Q&T Mn-0.5Mo) Yield Strength Ratios Vs. Temperature, All Combined Data, With Polynomial Regression

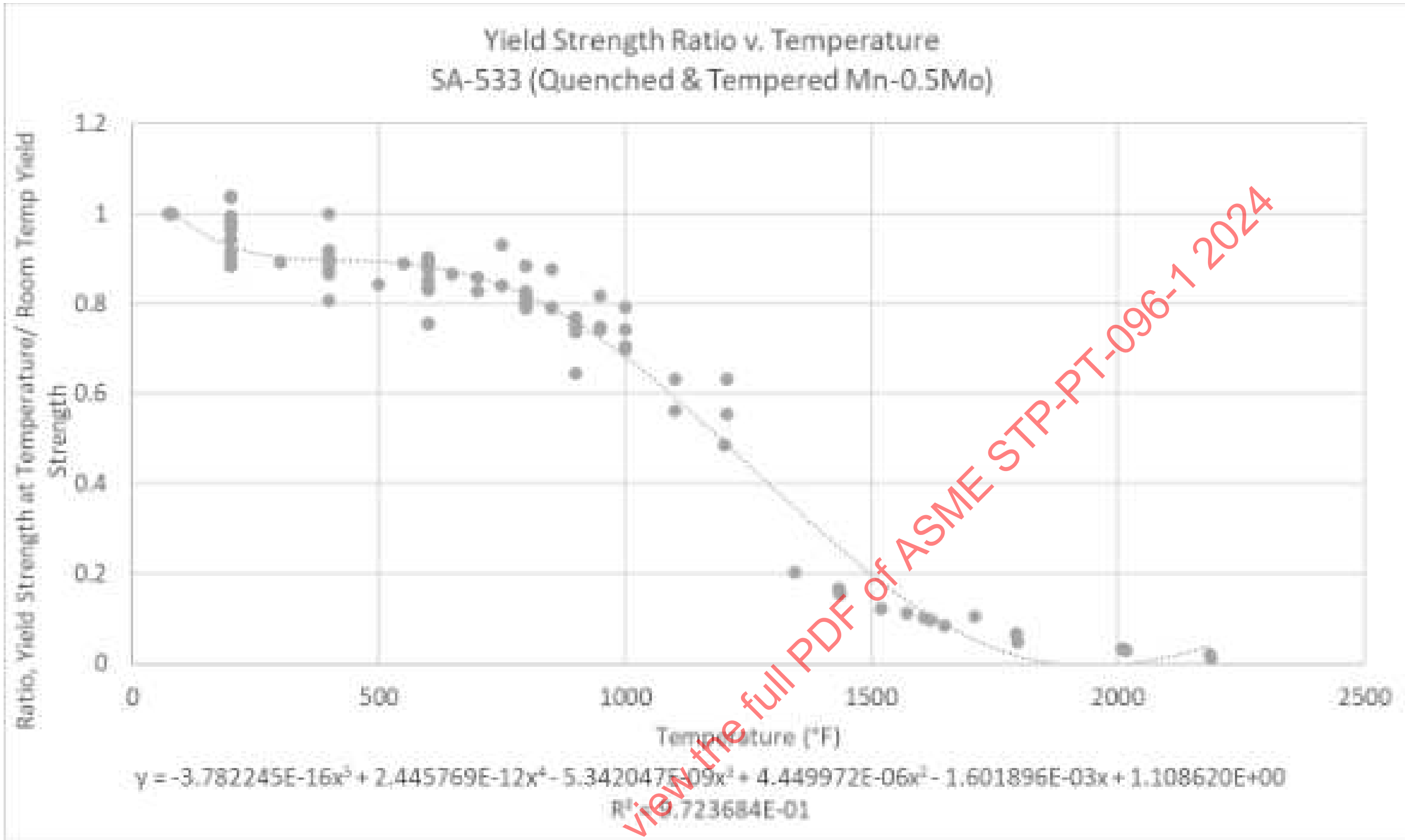


Figure 7-6: SA-533 (Q&T Mn-0.5Mo) Tensile Strength Ratios Vs. Temperature, All Combined Data, With Polynomial Regression

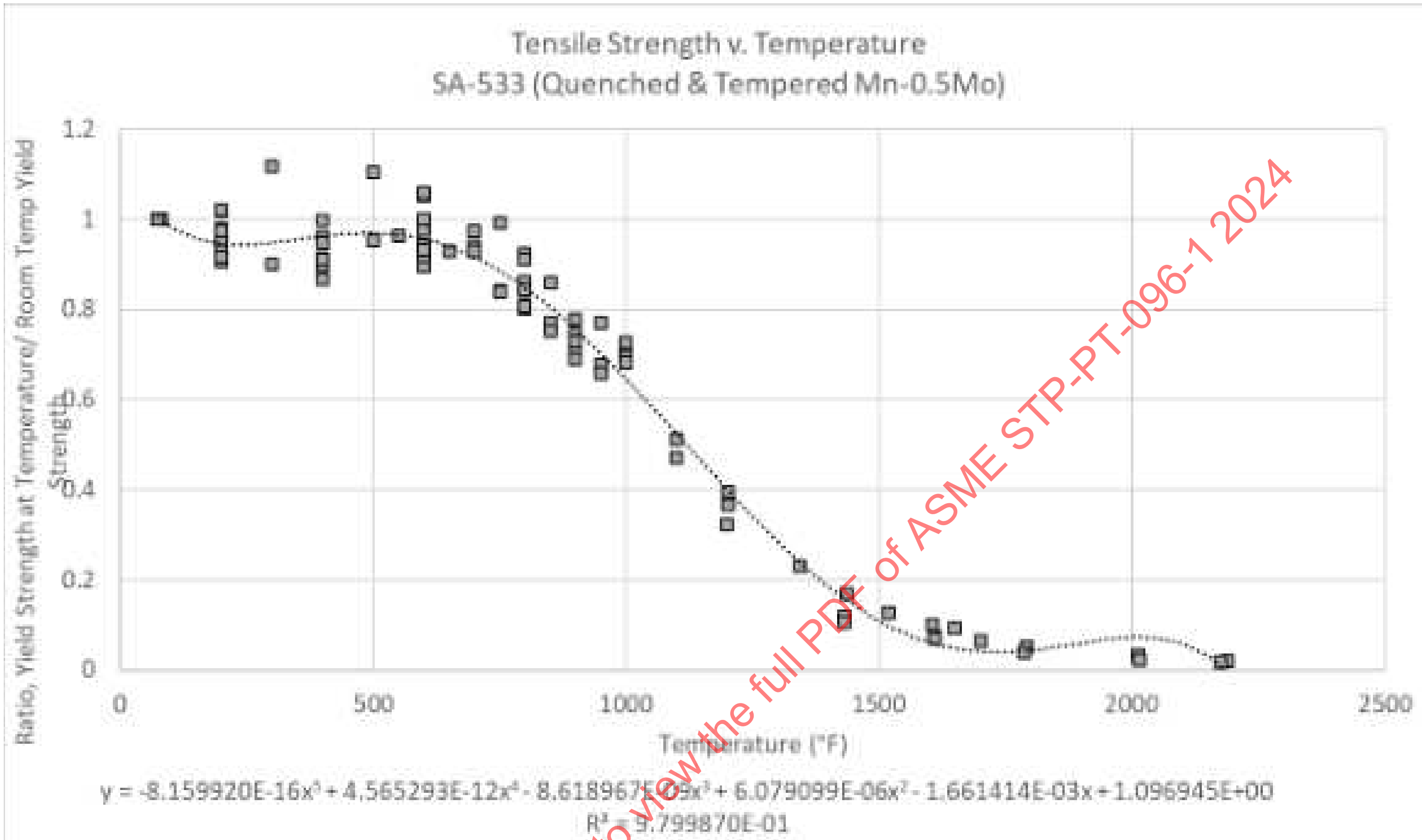


Figure 7-7: SA-533 (Q&T Mn-0.5Mo) Creep Rupture Isotherm Curves

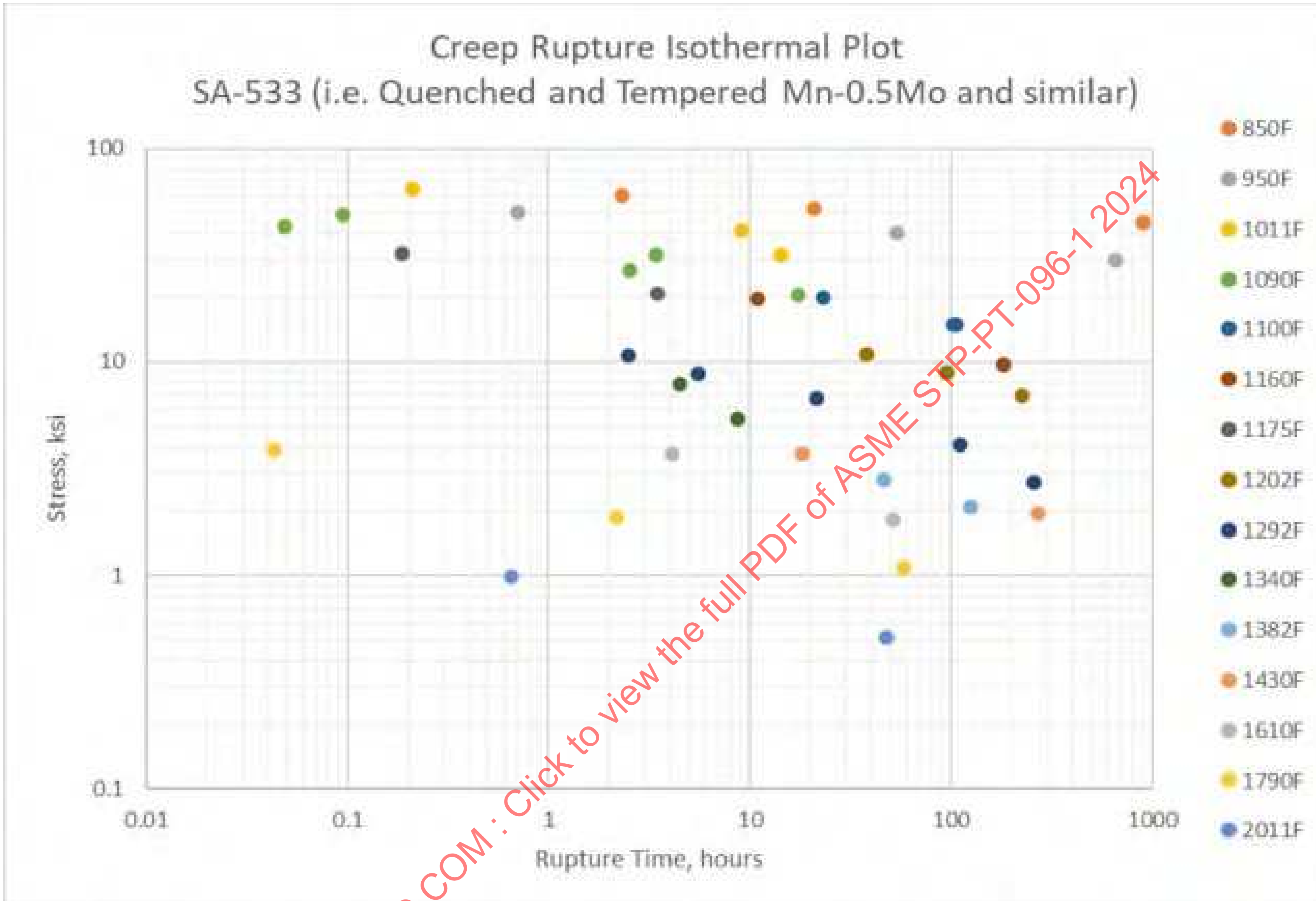


Figure 7-8: SA-533 (Q&T Mn-0.5Mo) Creep Strain Rate (MCR) Isotherm Curves

Figure 7-9: SA-533 (Q&T Mn-0.5Mo) Creep Ductility (% Elongation) Vs. Rupture Time Isotherms

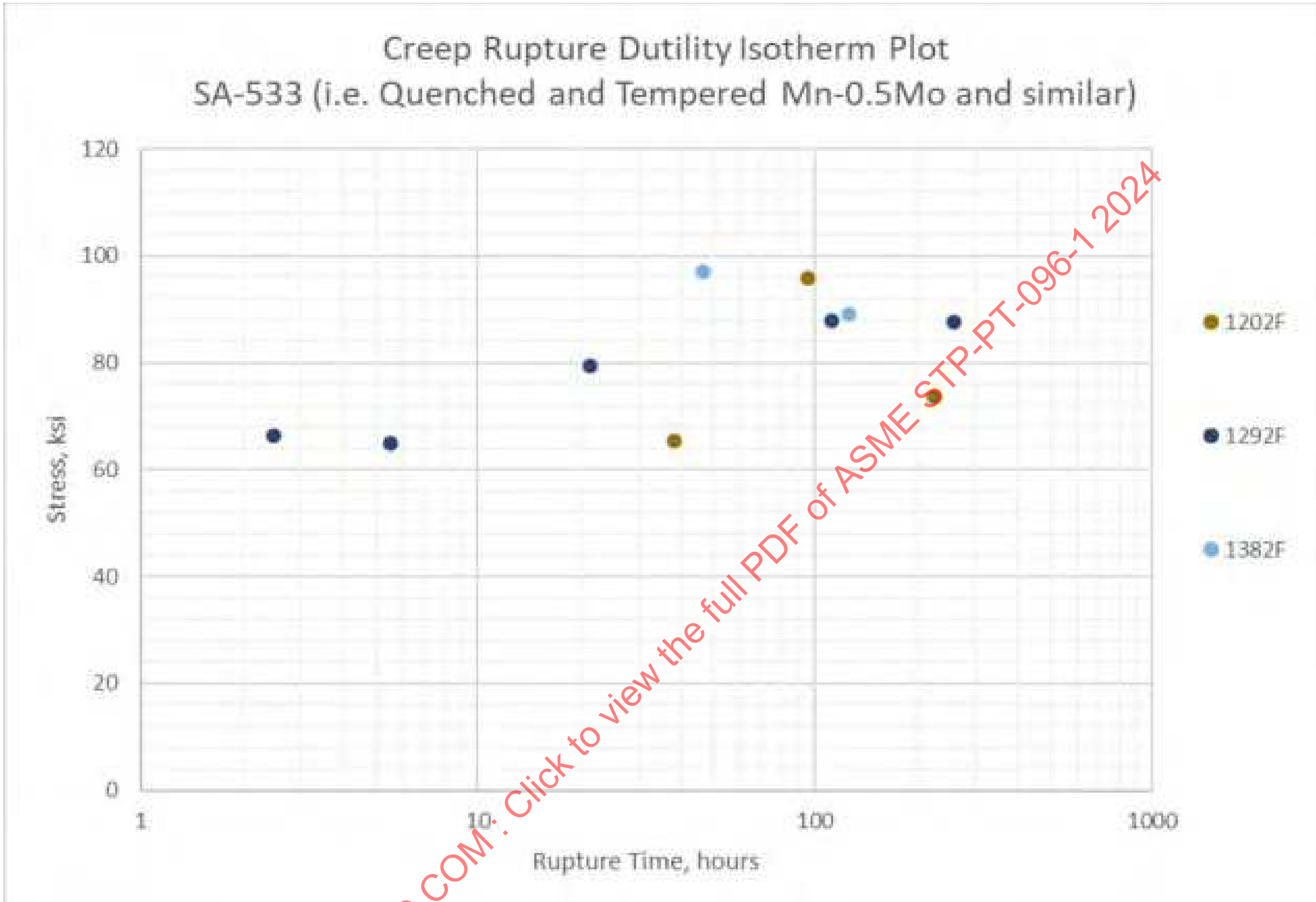
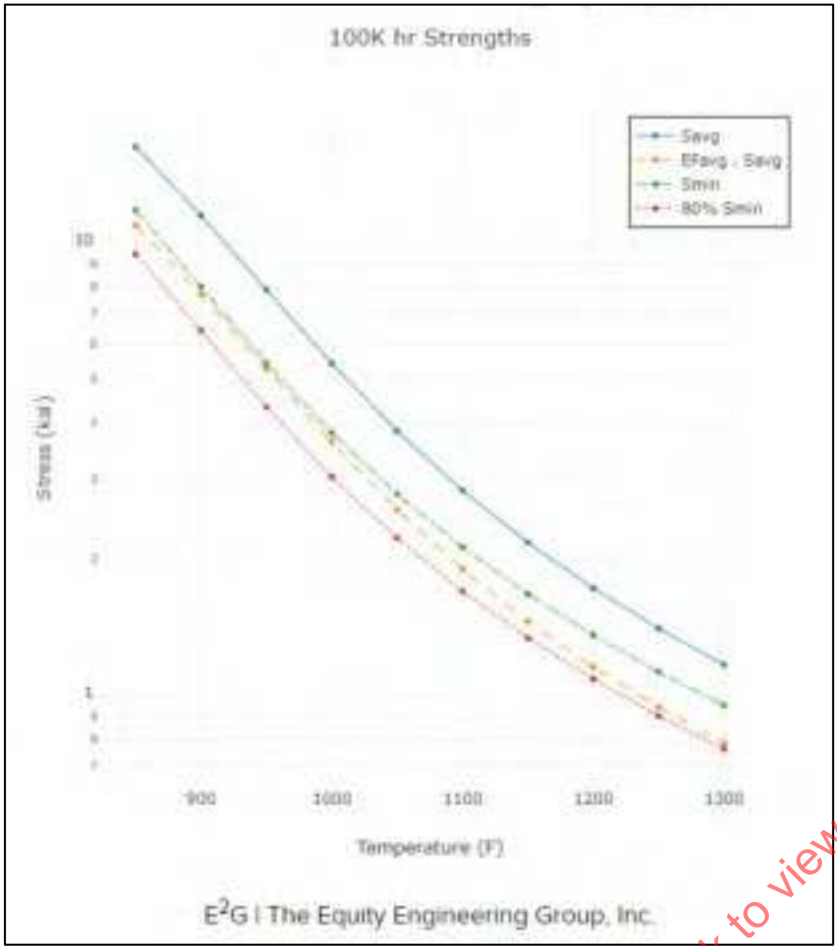


Figure 7-10: Calculated Allowable Stresses Based on Rupture and Creep Strain Rate and ASME II-D Appendix 1 Criteria (SA-533, Q&T Mn-0.5Mo)



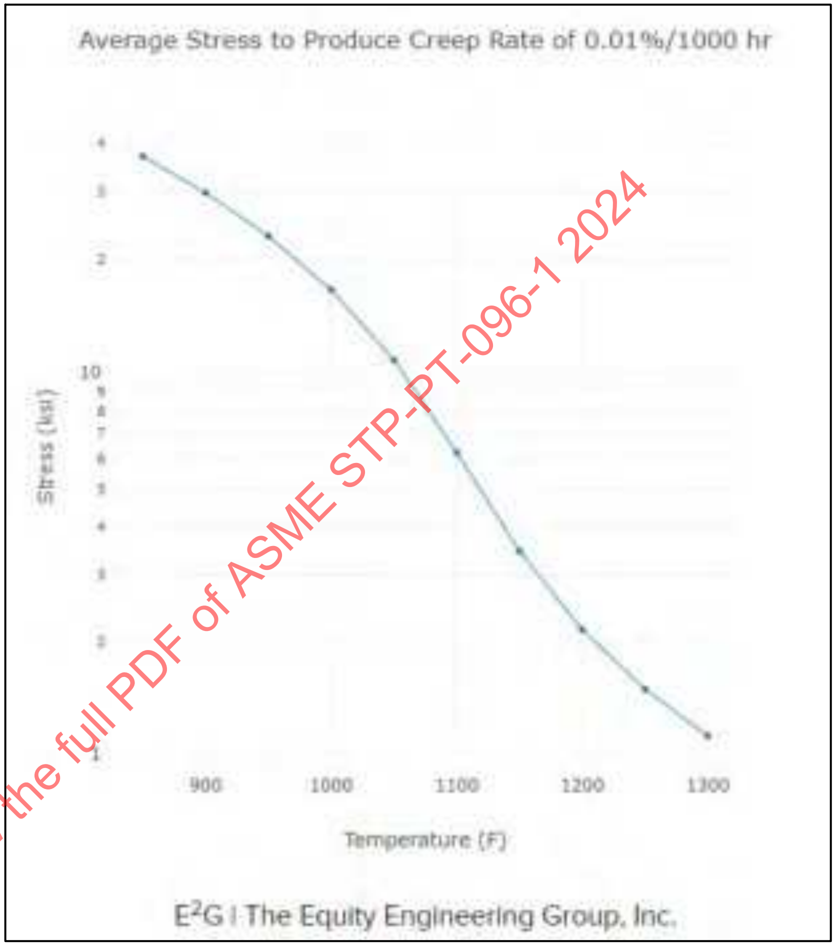


Figure 7-11: Comparison of Current SA-533 (Q&T Mn-0.5Mo) Allowable Stresses Vs. ASME II-D Appendix 1 Criteria Applied to Data

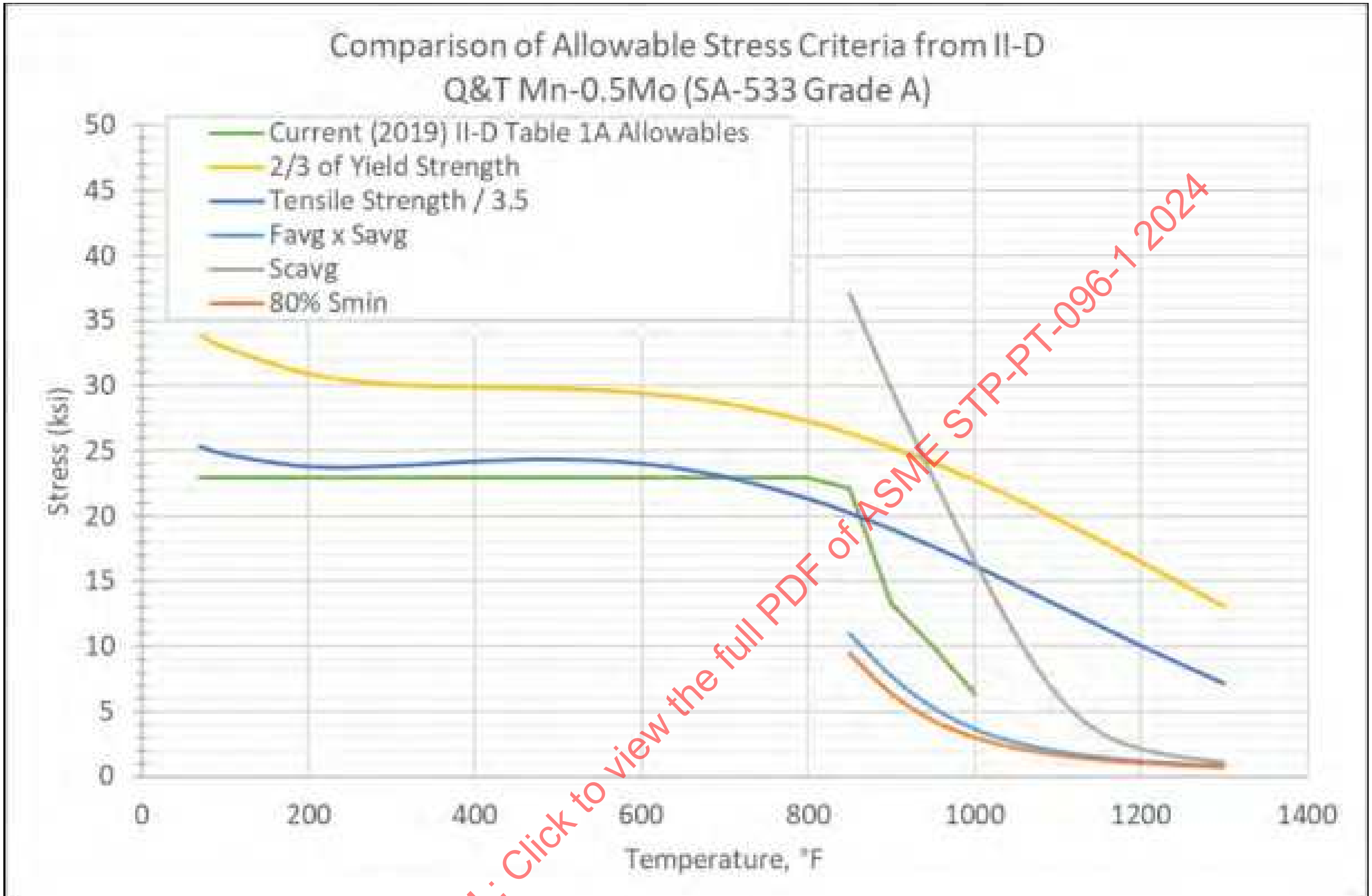


Figure 7-12: Strain Vs. Time Data – SA-533 (Q&T Mn-0.5Mo and Similar), 1 of 2

Figure 7-13: Strain Vs. Time Data – SA-533 (Q&T Mn-0.5Mo and Similar), 2 of 2

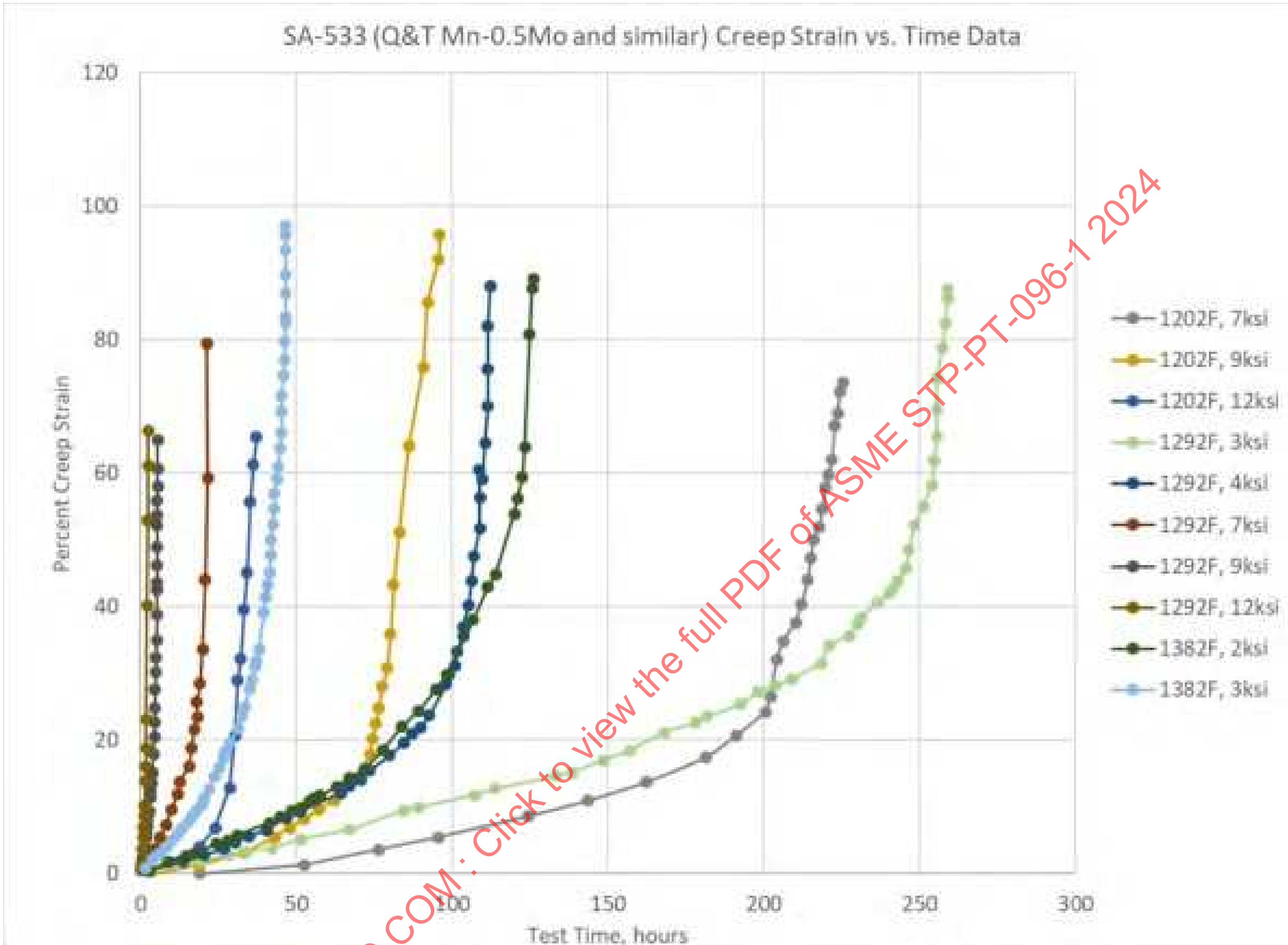


Figure 7-14: SA-533 (Q&T Mn-0.5Mo and Similar) Continuous Cycling Fatigue, Elevated Temperature Data

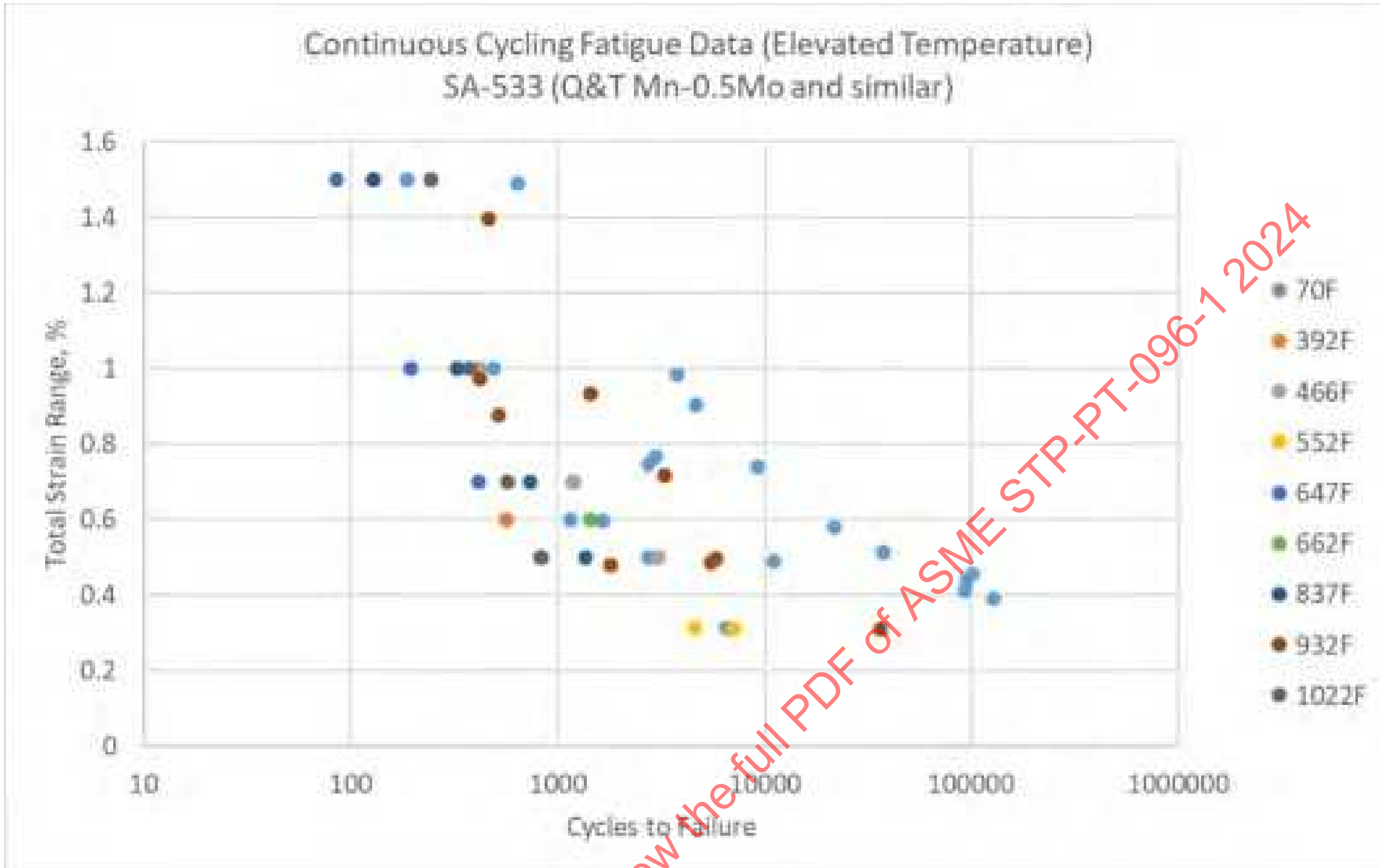
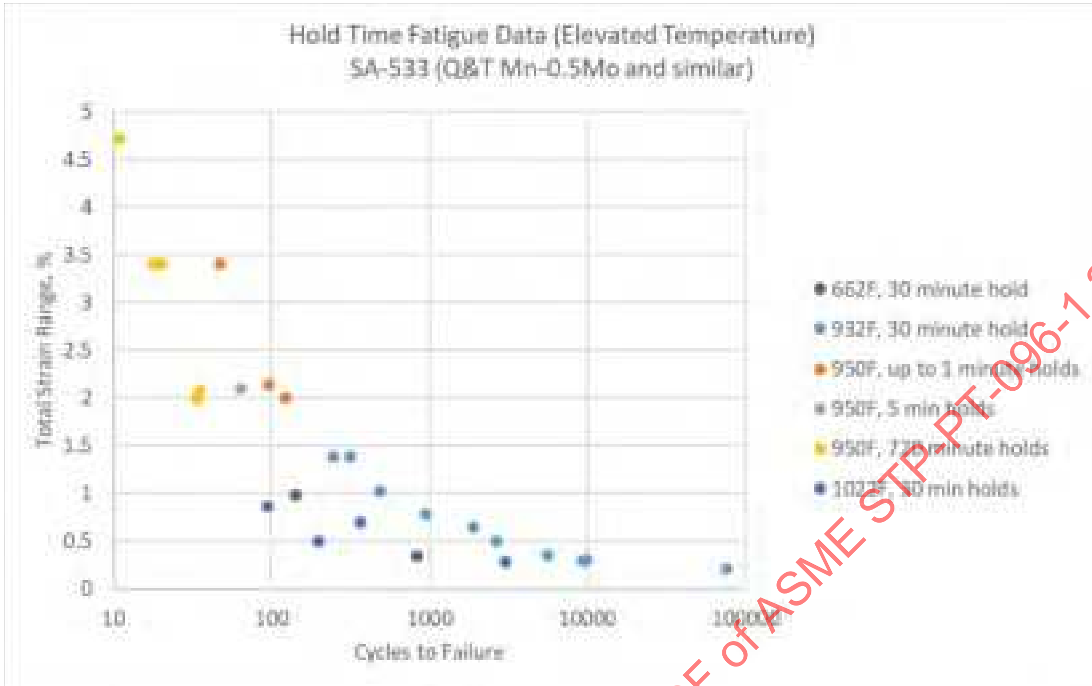


Figure 7-15: SA-533 (Q&T Mn-0.5Mo and Similar) Hold Time Fatigue, Elevated Temperature Data



Attachment 7: SA-533 (Quenched and Tempered Mn-0.5Mo Steel and Similar) Property Data

If you want the referenced embedded spreadsheet with additional data, please email a request to research@asme.org.

8 C-1/2MO

8.1 Physical Properties

Well-established physical properties were referenced from BPVC Section II for this material. Physical property curves from WRC Bulletin 503 were plotted for comparison as well. Figure 8-1 shows the trends of Elastic Modulus (Ey), Thermal Conductivity (k), Thermal Diffusivity (TD), and Thermal Expansion (α) with temperature.

8.2 Yield and Tensile Strength

Elevated temperature Yield and Tensile Strength over the range of existing allowable stresses (up to 1000°F) were readily available, including data beyond the current range of allowable stresses, up to approximately 1600°F, as shown in Figures 8-2 and 8-3. The sources for both high-temperature yield and high-temperature tensile strength are provided in the embedded spreadsheet at the end of this section. This spreadsheet also contains ductility data corresponding to the tensile test results presented in this report. Note that ductility (percent elongation and percent reduction in area) was not available for all sources referenced for the C-1/2Mo material.

To facilitate comparison of the data obtained to existing allowable stresses (Section II-D Table 1A), yield and tensile data were normalized on a heat-by-heat basis to express the ratio of yield or tensile strength at temperature to that measured for the heat at room temperature. In cases where data were not delineated by heats within a given source, or in cases where more than one room-temperature tensile test existed for a given heat of material, ratios are equal to the measured tensile or yield strength at temperature, divided by the average of all of the appropriate room-temperature values for the particular data source or heat of material. As a result of this approach, it is possible to have ratios in excess of 1.0. E^2G understands that this approach is similar to the normalizing procedure performed by ASME in typical analysis of yield and tensile data to obtain Table Y and Table U (Section II-D) trend curves, as well as for the calculation of allowable stresses. Figures 8-4 and 8-5 show the heat-by-heat variation in yield and tensile strength ratios (respectively) as a function of temperature. It should be emphasized that even though the figure legends reference an entire source of data, the ratios, wherever possible, were calculated on a heat-by-heat basis; this is evident in the embedded spreadsheet at the end of this section. Figures 8-6 and 8-7 contain all of the yield and tensile (respectively) ratios plotted together, to facilitate regression of a 5th-order polynomial that is subsequently used for allowable stress comparison.

8.3 Creep Data (Creep Rupture, Minimum Creep Rate, and Ductility)

Creep Rupture data is shown in Figures 8-8 and 8-9, plotted as isotherms. The temperatures have been separated onto separate plots to minimize data overlap, with Figure 8-8 showing those temperatures where most of the data were concentrated, and Figure 8-9 showing those temperatures with significantly less data. It should be emphasized that these plots contain data for all product forms of material classified in the referenced publications as "C-1/2Mo." This certainly includes material meeting the requirements of ASME BPVC Section II-A specifications (e.g., SA-204 Gr. A-C; SA-209; SA-250 Gr. T1b, T1, T1a, etc.). However, due to the diversity of data sources utilized for the compilation of the material property tables, it is likely that some of the material shown in Figures 8-8 and 8-9 may not meet existing specifications for this grade of material. Where older publications are referenced, the chemistry (and for that matter, manufacturing, processing, and heat treatment) corresponding to the heat of material in the original data source, may not be consistent with modern specifications. Where possible, E^2G has documented the chemical composition if contained within the original source. In many cases, the project team has also made efforts to trace cross-referenced data back to original test results to determine if the heat treatment, product form, chemistry, etc. details can be obtained. This information is provided with the embedded spreadsheet to facilitate additional analysis on the part of ASME.

Creep Minimum strain rates (%/hour) are shown in Figures 8-10 and 8-11, separated by temperature. As in the case of rupture data, temperatures of minimum creep rates have been separated onto separate plots to minimize data overlap, with Figure 8-10 showing those temperatures where most of the data were concentrated, and Figure 8-11 showing those temperatures with significantly less data. Creep Ductility, as % elongation, is plotted in Figure 8-12. As is typical, the data show significant overlap, and it is difficult to observe clear trends in the data. The data is not intended to be used as plotted but is available in the spreadsheet for additional analysis. Note that much of the data with less than 10% total elongation at failure corresponds to cross-weld specimens contained in the data.

Creep data were analyzed using E^2G's proprietary Lot-Centered Analysis web-based software tool, in order to obtain creep properties. This regression is based on a Mandel-Paule algorithm and considers the variation within individual heats of material (for both rupture and strain rate data) as well as the variation between heats. The weight assigned to each datapoint and each heat is scaled based on the relative variation. Both rupture and strain rate (minimum creep rate, expressed as true strain per hours) were regressed according to a Larson-Miller time-temperature-parameter model, with a 3rd-order polynomial of stress. Lot-specific constant behavior was accounted for in this analysis, but the variation of LMP with stress was assumed to be constant (no non-parallel terms were included in the analysis). A 95% predictive limit was utilized to obtain the lower-bound (minimum LM constant for both rupture and strain rate) properties. The results of this analysis are summarized in Table 8-1 for rupture data and Table 8-2 for strain rate data. The Lot-Centered Analysis software tool generates property tables in the creep regime using the criteria outlined in Mandatory Appendix 1 of ASME Section II-D; the nomenclature of variables is consistent with II-D Appendix 1. For visualization of the allowable stress trends, Figure 8-13 is provided (for rupture allowable stresses and creep rate allowable stresses). Figure 8-14 shows a comparison of the various allowable stress criteria from Section II-D, Appendix 1, to the existing (2019) Section II-D Table 1A allowable stresses for ASTM spec SA-204 Grade B C-1/2Mo (this spec aligned most closely with the average tensile/yield strengths accumulated in the data, and shares equivalent stresses in the creep regime as other specs of C-1/2Mo).

Creep Strain vs. time data are shown in Figure 8-15 for short-term data (up to 1,000 hour test durations); and Figure 8-16 for excess of 1,000 hour test durations. Curves are only plotted where more than 10 strain vs. time points are present for the test. Additional curves are available with fewer datapoints (typically obtained from data in the form of time-until-specified-strain, in the embedded spreadsheet. Both creep rate and creep strain vs. time data are provided to satisfy ASME's request for creep strain vs. time curves, and both forms of data are applicable in developing allowable stresses. Although digitalization of creep curve data was not explicitly necessary per the project contract, E^2G did perform digitalization of creep curves where only graphical data was available (as is often the case in the published literature).

8.4 Continuous Cycling Fatigue and Hold Time Fatigue Curves

A portion of the data obtained for continuous cycling fatigue data at elevated temperatures for C-1/2Mo is shown in Figure 8-17, which also includes an amount of room temperature data. Figure 8-17 only contains data for which total strain range was determined from the original source. Additional data points for continuous cycling fatigue data of C-1/2Mo are presented in the attached spreadsheet; however, due to the complexities of various forms of fatigue data, compatible plots for each type of data expression and failure criteria are not included in this report. Hold time fatigue data at high temperature is shown in Figure 8-18

(650°F, 850°F, 1000°F, and 1022°F) and Figure 8-19 (932°F, 950°F) with separate plots for temperatures at which at least a moderate collection of data points existed. Additional data is provided in the embedded spreadsheet.

Table 8-1: Model Parameters, Larson-Miller Property Results, and Allowable Stress (Rupture) Criteria, C-1/2Mo

Equation Format:

$$\log(t_r) = C_{avg} + \frac{1}{T+460}\left(b_1 + b_2\log(\sigma) + b_3(\log(\sigma))^2 + b_4(\log(\sigma))^3\right)$$

Cavg	**-21.52**
Cmin	**-22.16**
b_1	**84352.7**
b_2	**-1.06E+5**
b_3	**81100.9**
b_4	**-21559.1**

Number Data Points		**345**
Correlation Coefficient	R^2	0.8351
Average Variance within Heats	V_w	0.1503
Variance between Heats	V_b	0.09399
Standard Error of Estimate	SEE	0.3877

Properties provided are for T in °F, stress in ksi, and t_R in hours

Temperature, °F	**S_{avg} (ksi)**	***n***	**F_{avg} (calc)**	**F_{avg} (used)**	**Favg × Savg**	**S_{min} (ksi)**	**80% S_{min}**
850	35.76	7.636	0.7397	0.67	23.96	28.31	22.65
900	23.34	3.71	0.5376	0.67	15.64	14.84	11.88
950	12.16	4.291	0.5847	0.67	8.148	9.266	7.413
1000	8.431	7.647	0.74	0.67	5.649	7.129	5.703
1050	6.72	10.58	0.8044	0.67	4.503	5.92	4.736
1100	5.677	13.05	0.8382	0.67	3.804	5.111	4.089
1150	4.953	15.17	0.8592	0.67	3.318	4.519	3.615
1200	4.41	17.01	0.8734	0.67	2.955	4.061	3.249
1250	3.983	18.62	0.8837	0.67	2.669	3.693	2.954
1300	3.637	20.05	0.8915	0.67	2.437	3.389	2.711

Table 8-2: Model Parameters, Larson-Miller Property Results, and Allowable Stress (Strain Rate) Criteria, C-1/2Mo

Equation Format:

$$\log(\dot{\varepsilon}_0) = -C_{avg} - \frac{1}{T+460}\left(a_1 + a_2\log(\sigma) + a_3(\log(\sigma))^2 + a_4(\log(\sigma))^3\right)$$

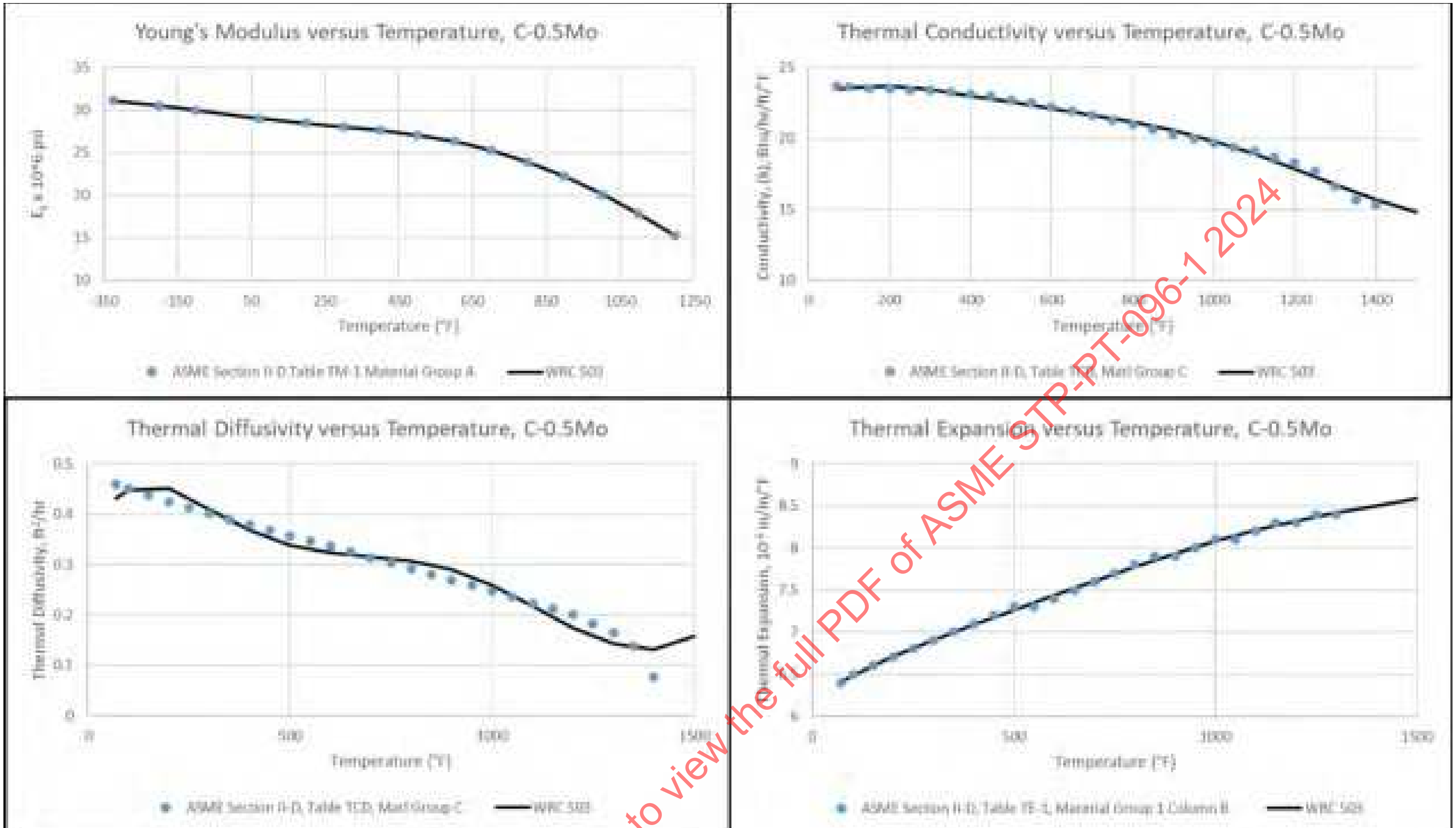
C_{avg} (A_0)	**-4.51**
Cmin (A0+ΔΩSR,LB)	**-5.004**
a_1	**18403.1**
a_2	**-3403.4**
a_3	**1207.2**
a_4	**-701.1**

Number Data Points		**171**
Correlation Coefficient	R2	0.5936
Average Variance within Heats	V_w	0.09014
Variance between Heats	V_b	0.2564
Standard Error of Estimate	SEE	0.3002

Properties provided are for T in °F, stress in ksi, and t_R in hours

Temperature, °F	**$S_{C,avg}$ (ksi)**
850	54.6
900	44.49
950	35.62
1000	27.95
1050	21.41
1100	15.95
1150	11.53
1200	8.069
1250	5.492
1300	3.677

Figure 8-1: C-1/2Mo Modulus (E_y), Thermal Conductivity (k), Thermal Diffusivity (TD), & Thermal Expansion (α) With Temperature



Note that WRC 503 material property fits for thermal diffusivity are currently being revised by WRC for release in a future edition of this bulletin.

Figure 8-2: C-1/2Mo Yield Strength Vs. Temperature, By Data Source, Including Trend Curves

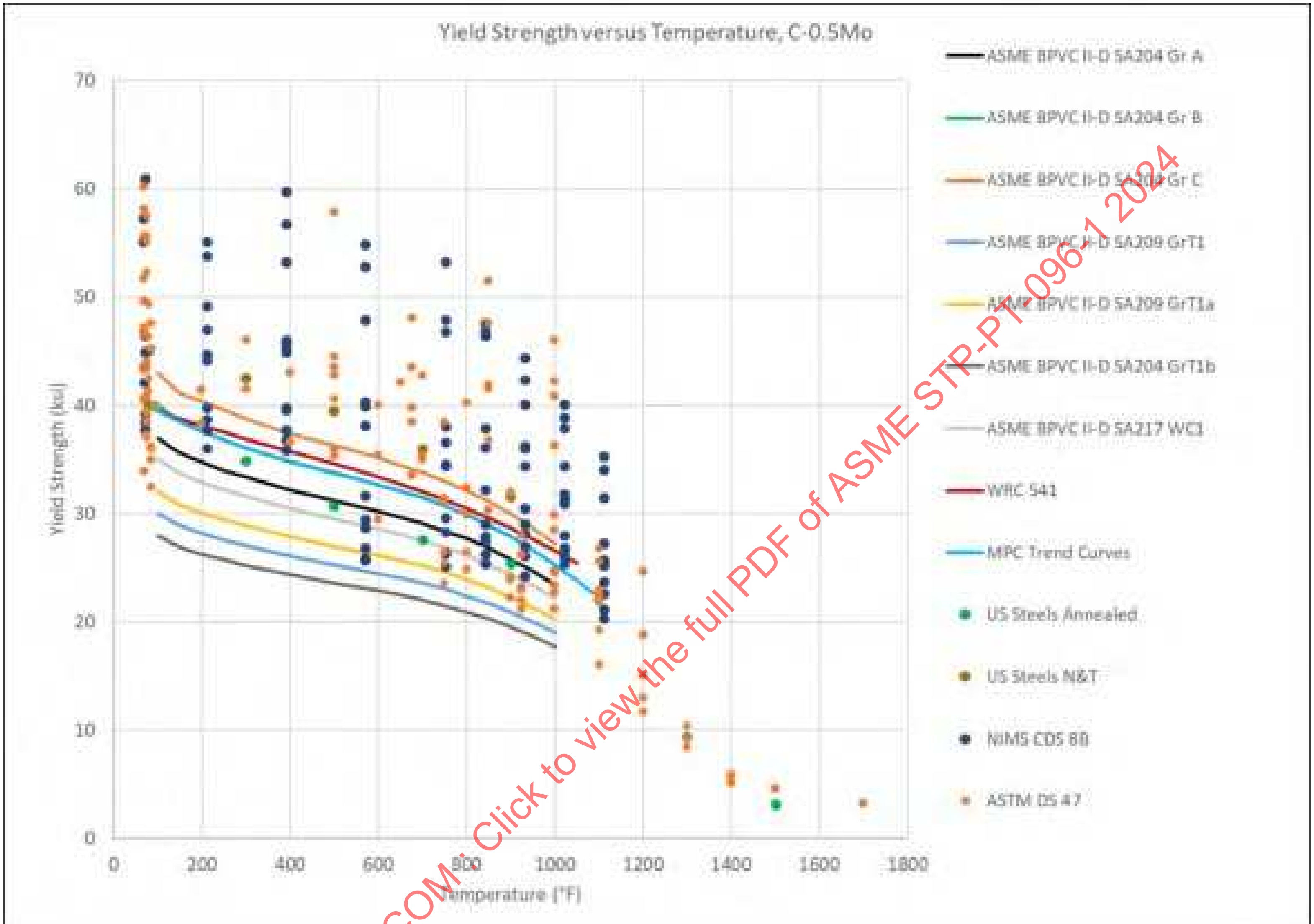


Figure 8-3: C-1/2Mo Tensile Strength Vs. Temperature, By Data Source, Including Trend Curves

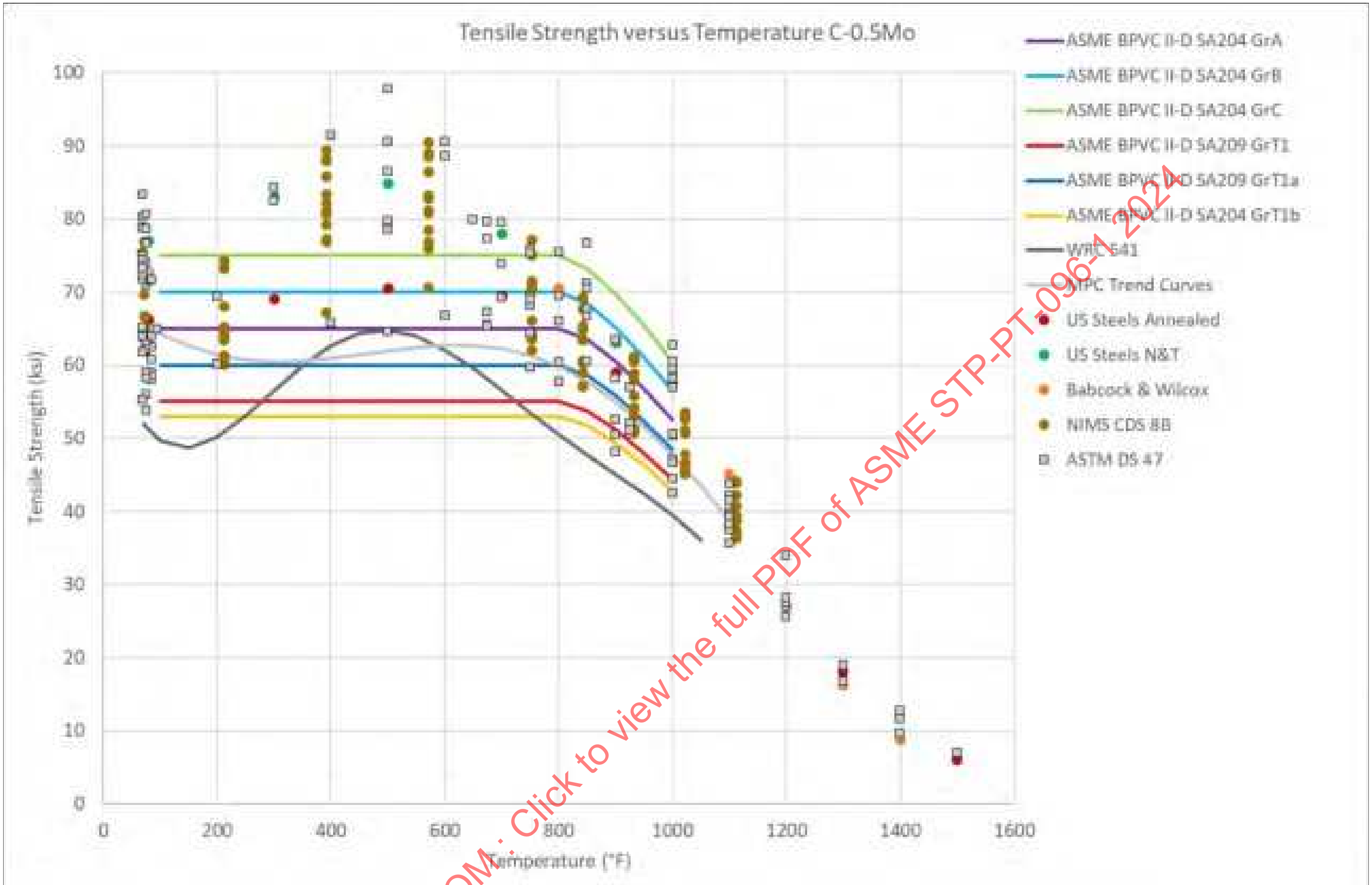


Figure 8-4: C-1/2Mo Yield Strength Ratios Vs. Temperature (Calculated on a Heat-By-Heat Basis, By Data Source)

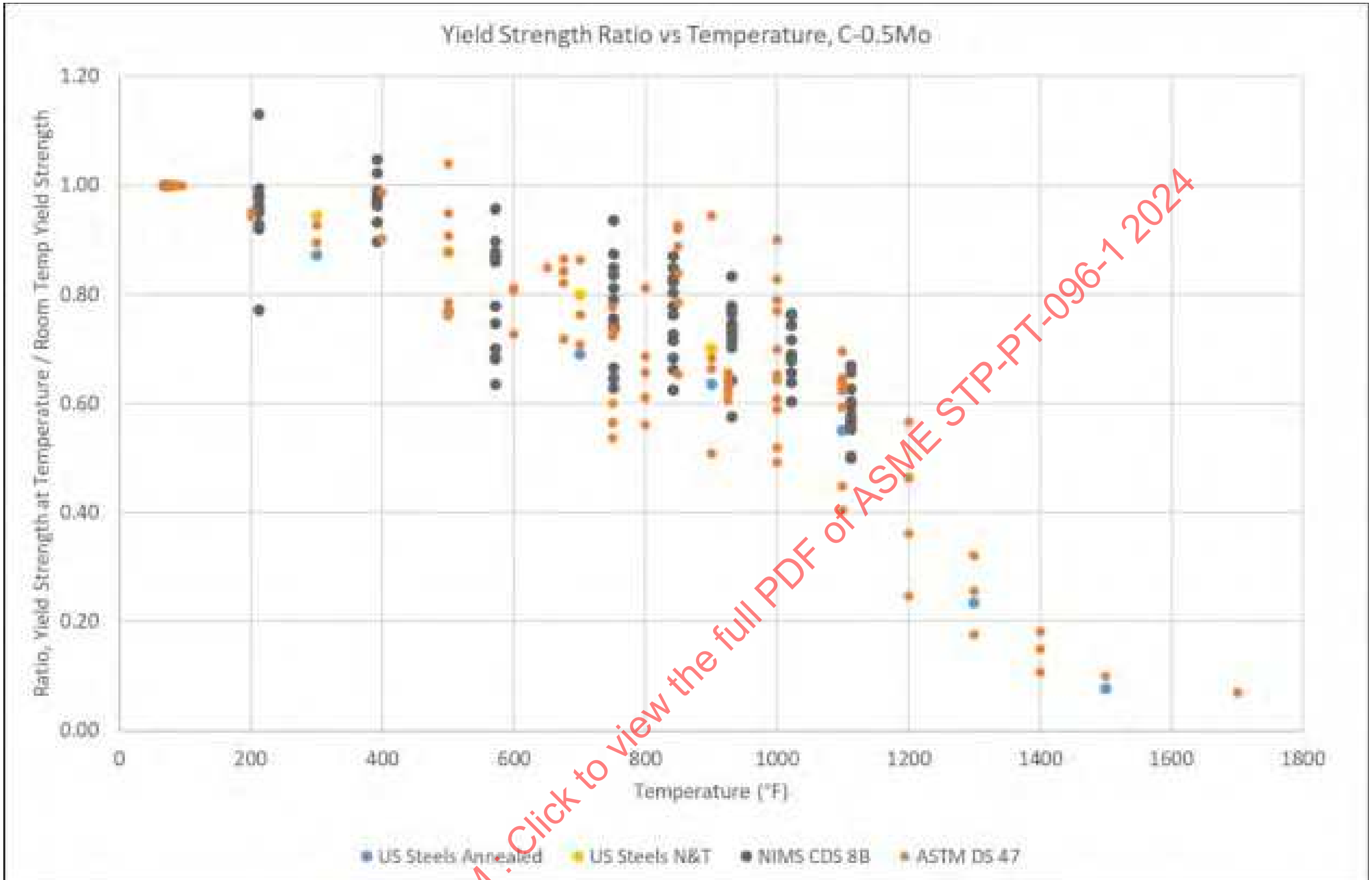


Figure 8-5: C-1/2Mo Tensile Strength Ratios Vs. Temperature (Calculated on a Heat-By-Heat Basis, By Data Source)

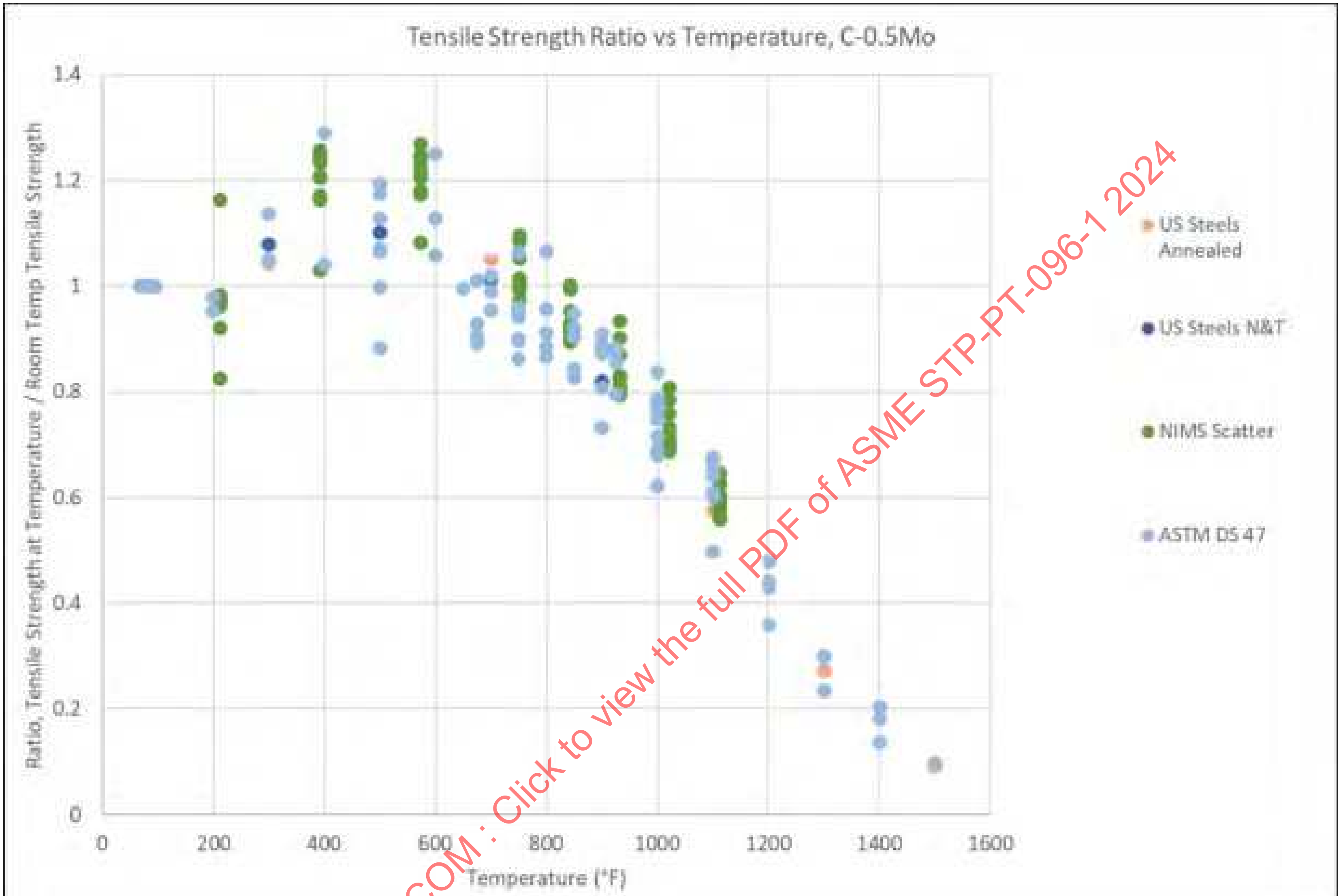


Figure 8-6: C-1/2Mo Yield Strength Ratios Vs. Temperature, All Combined Data, With Polynomial Regression

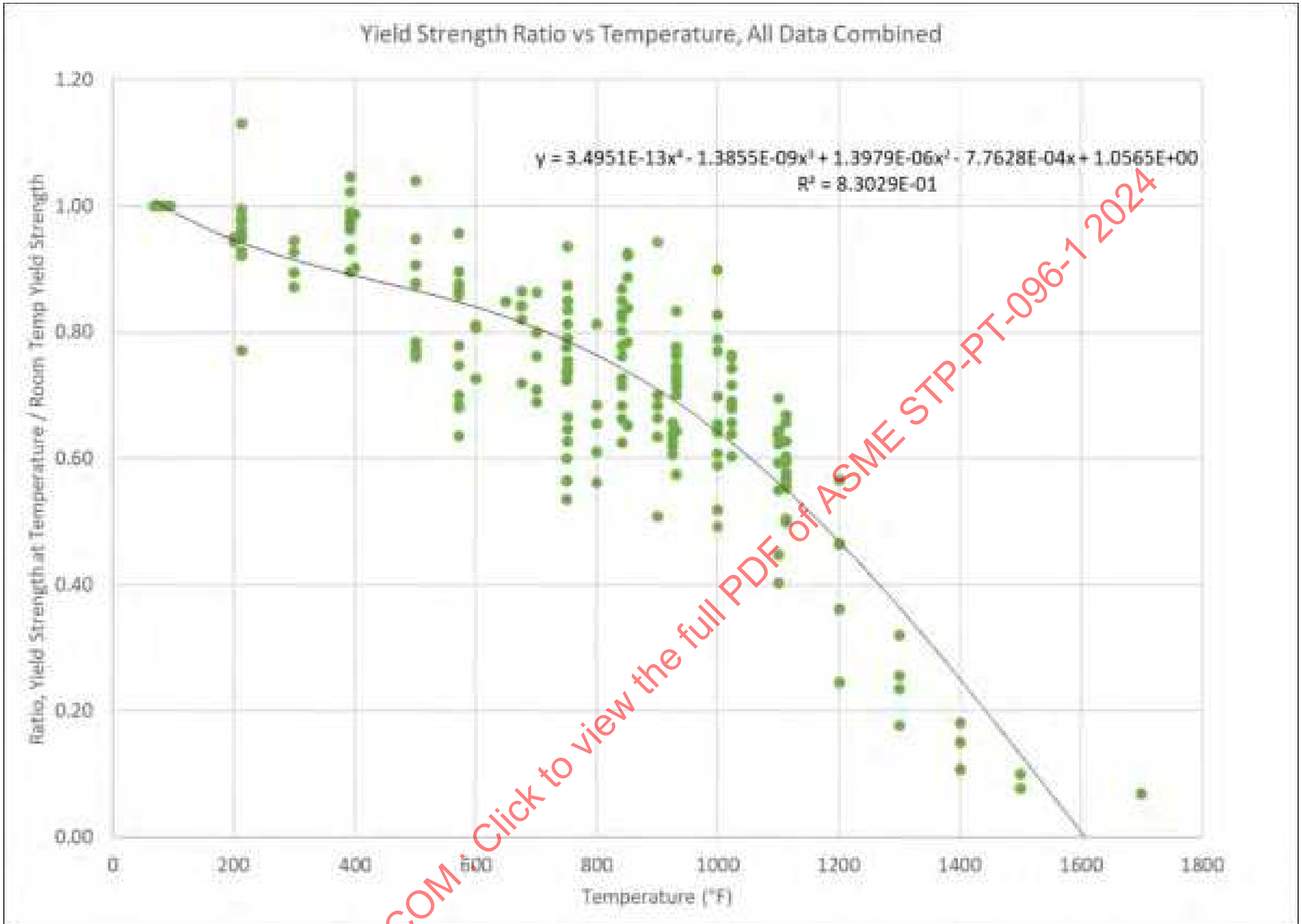


Figure 8-7: C-1/2Mo Tensile Strength Ratios Vs. Temperature, All Combined Data, With Polynomial Regression

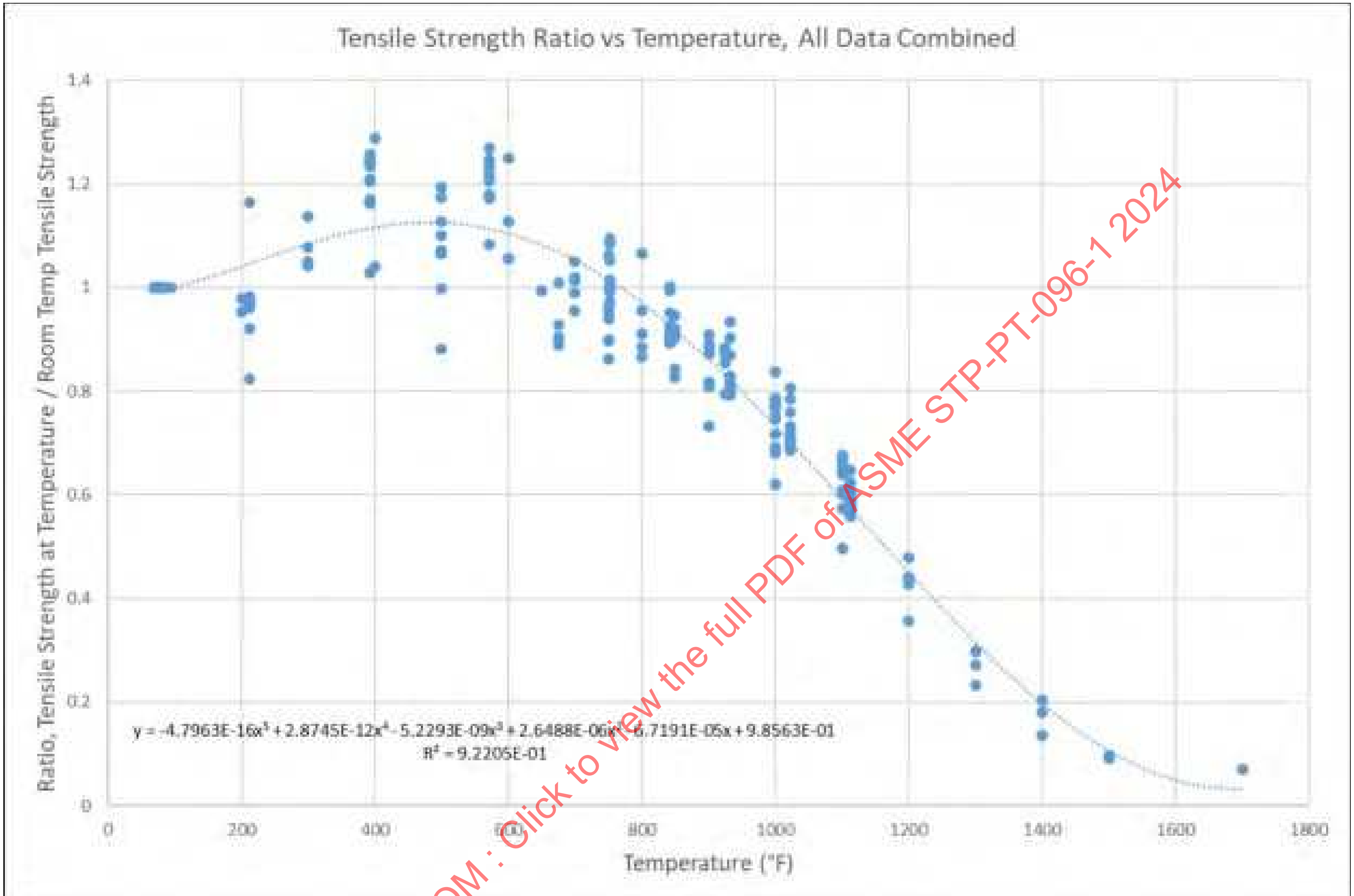


Figure 8-8: C-1/2Mo Creep Rupture Isotherm Curves, Temperatures With High Concentration of Data Points

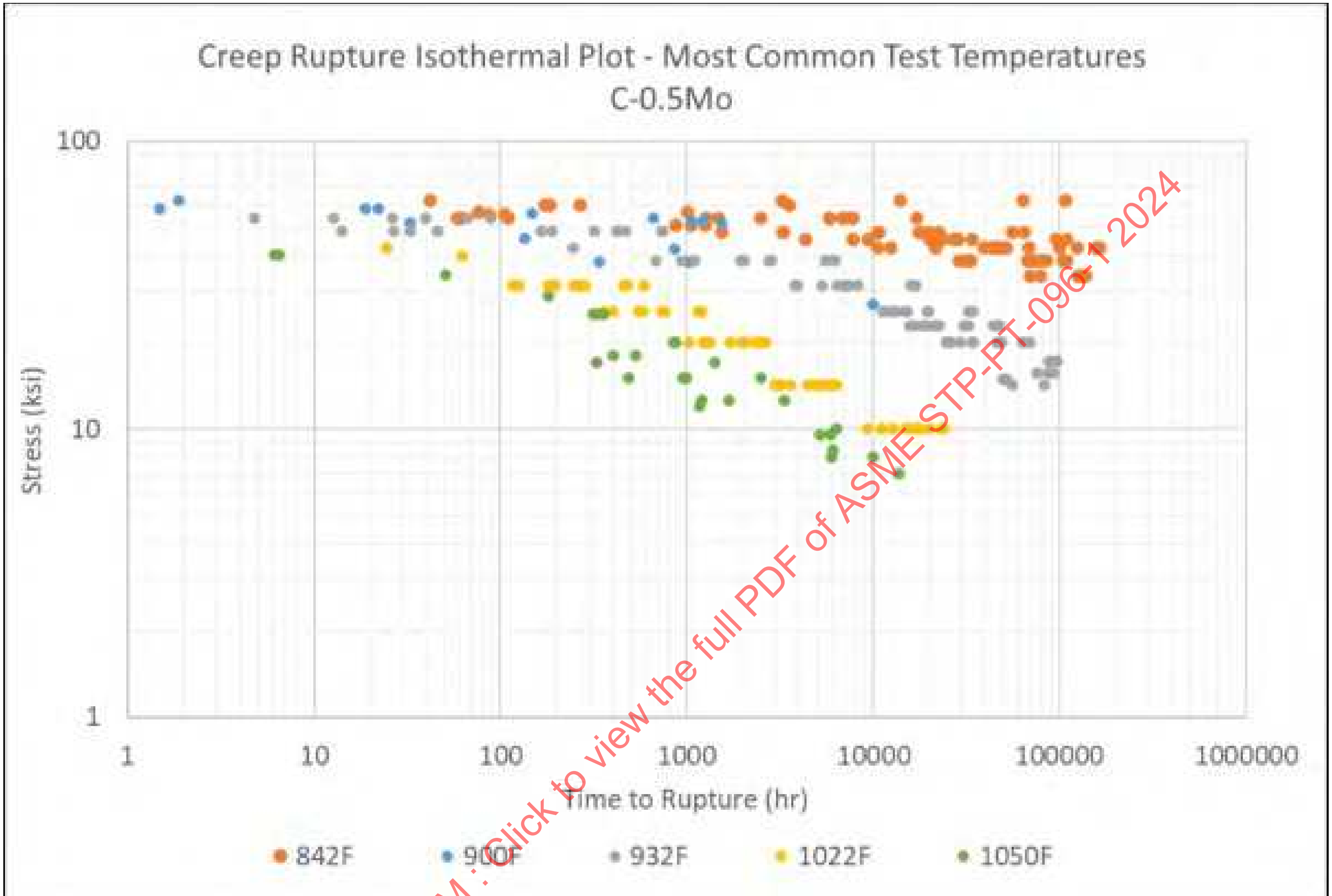


Figure 8-9: C-1/2Mo Creep Rupture Isotherm Curves for Additional and Intermediate Temperatures

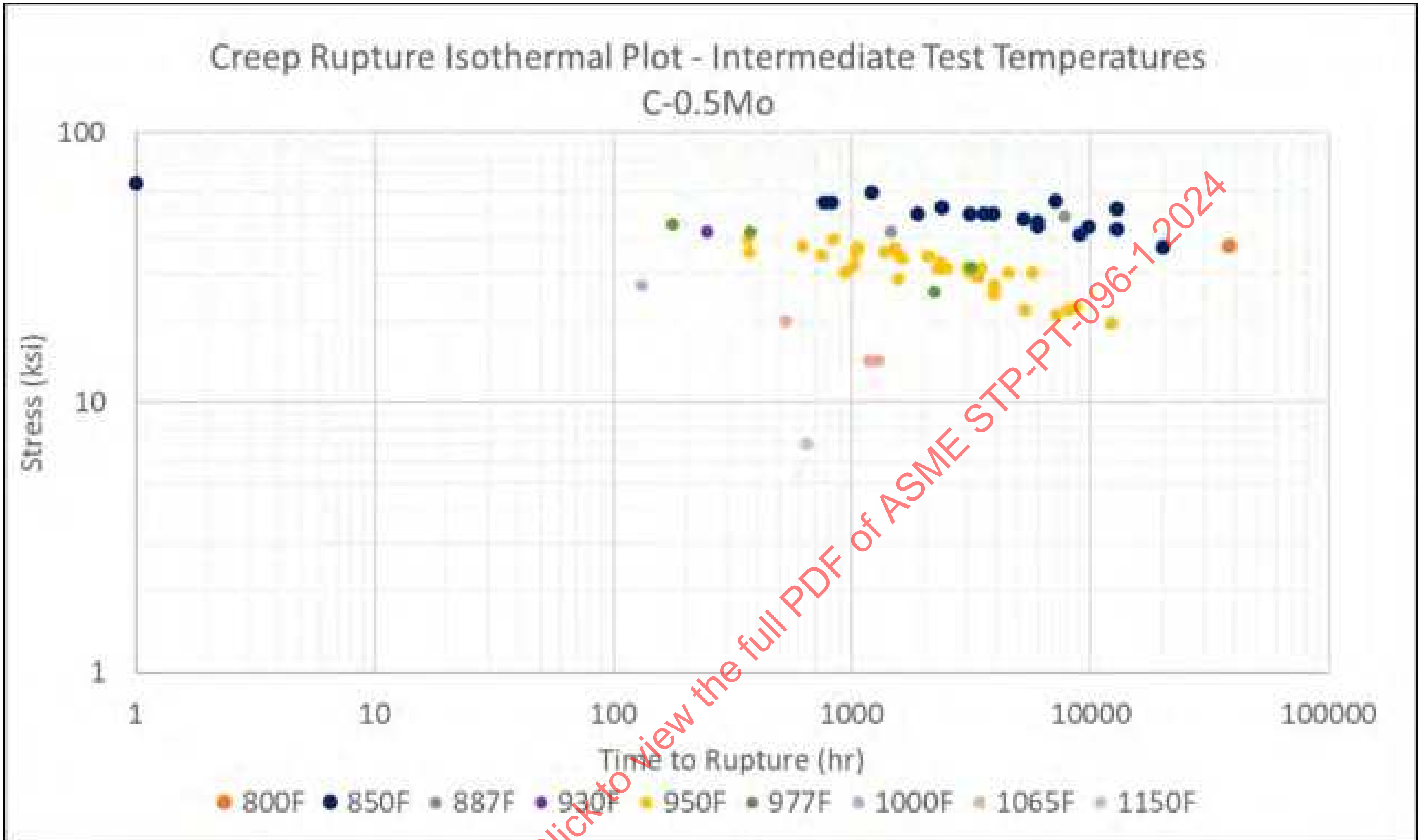


Figure 8-10: C-1/2Mo Creep Strain Rate (MCR) Isotherm Curves, Temperatures With High Concentration of Data Points

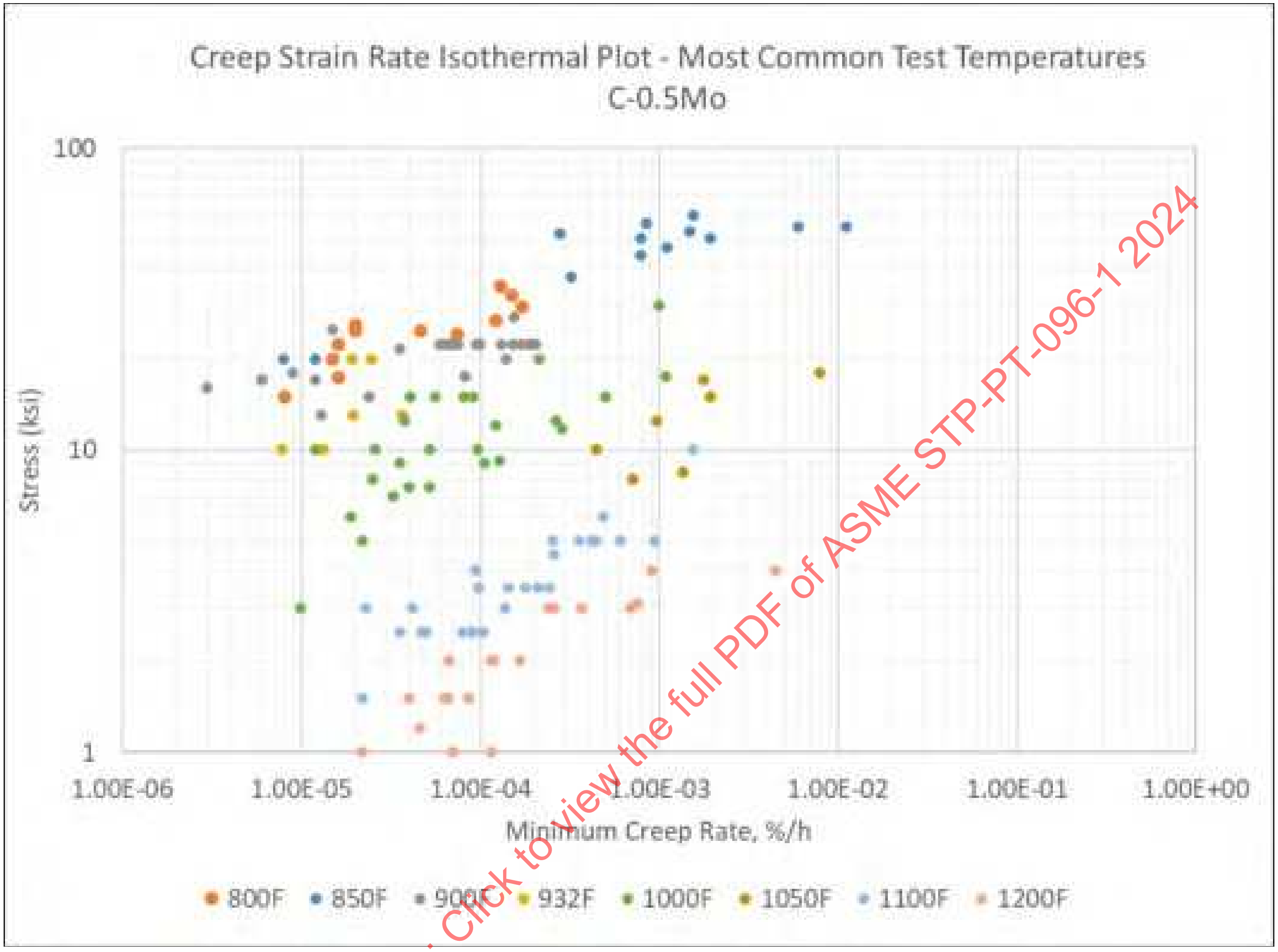


Figure 8-11: C-1/2Mo Creep Strain Rate (MCR) Isotherm Curves for Additional and Intermediate Temperatures

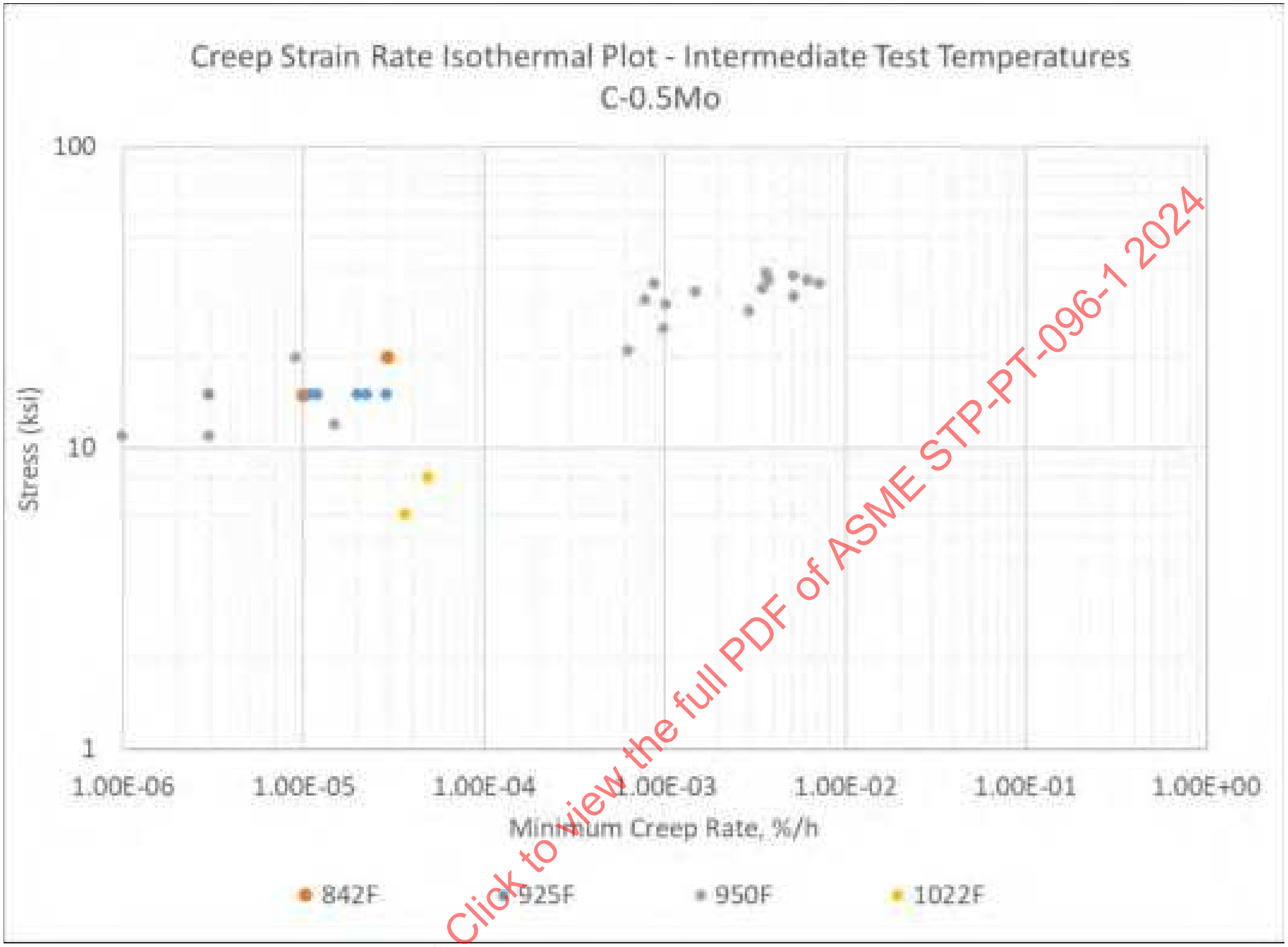


Figure 8-12: C-1/2Mo Creep Ductility (% Elongation) Vs. Rupture Time Isotherms

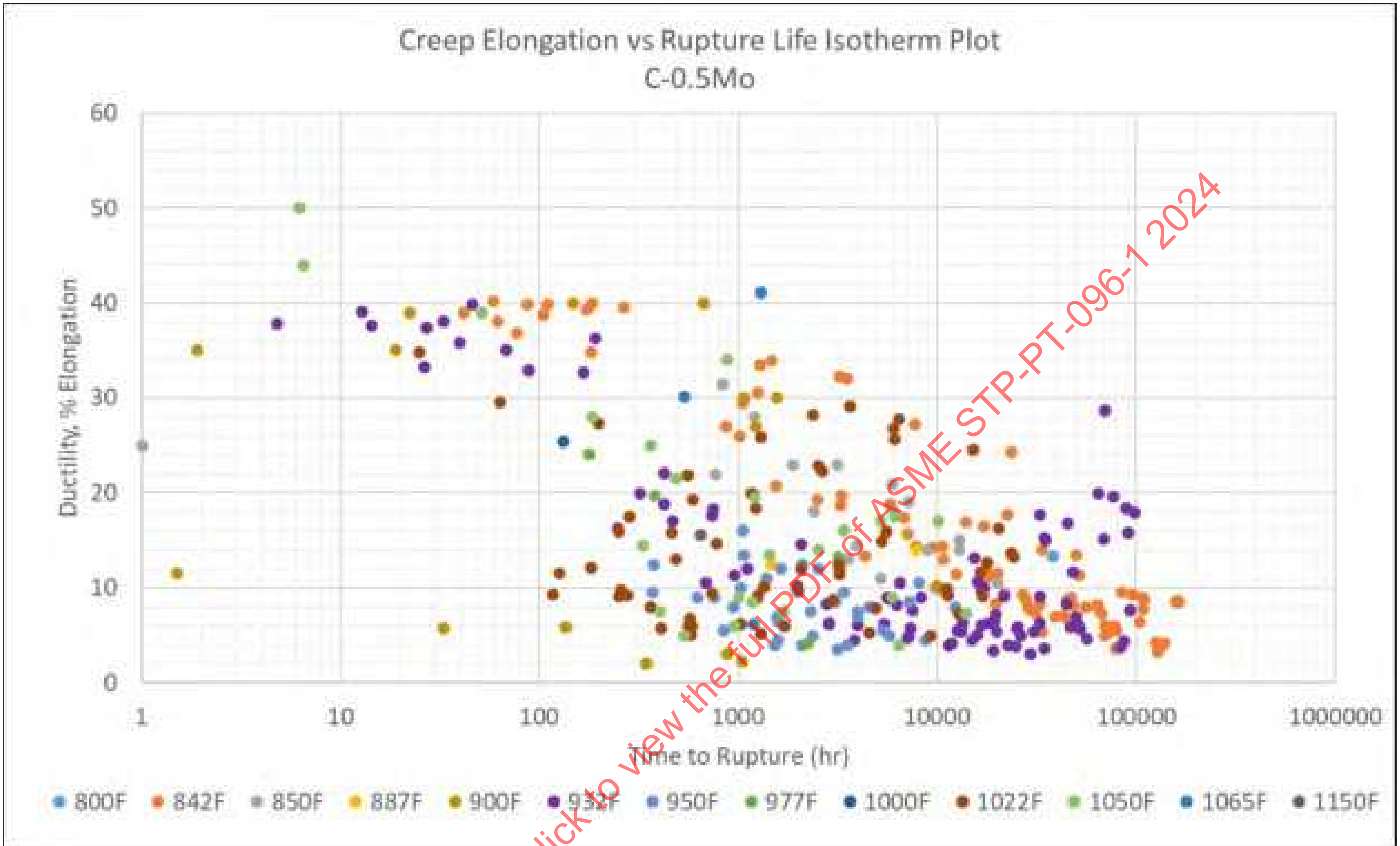


Figure 8-13: Calculated Allowable Stresses Based on Rupture and Creep Strain Rate and ASME II-D Appendix 1 Criteria (C-1/2Mo)

Figure 8-14: Comparison of Current C-1/2Mo Allowable Stresses (SA-204 Grade B) Vs. ASME II-D Appendix 1 Criteria Applied to Data

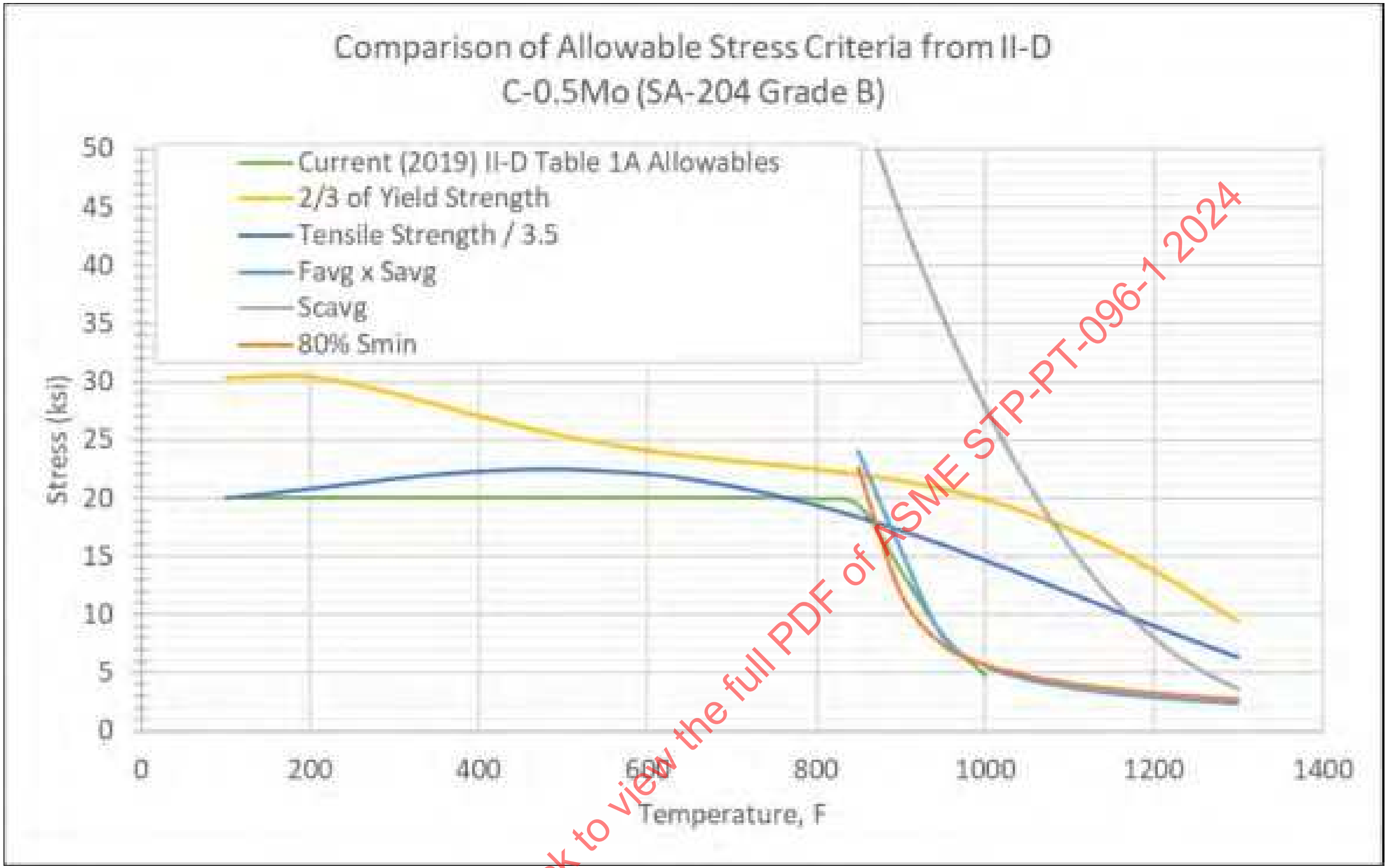


Figure 8-15: Short-Term Strain Vs. Time Data, up to 1,000 Hour Test Durations (C-1/2Mo)

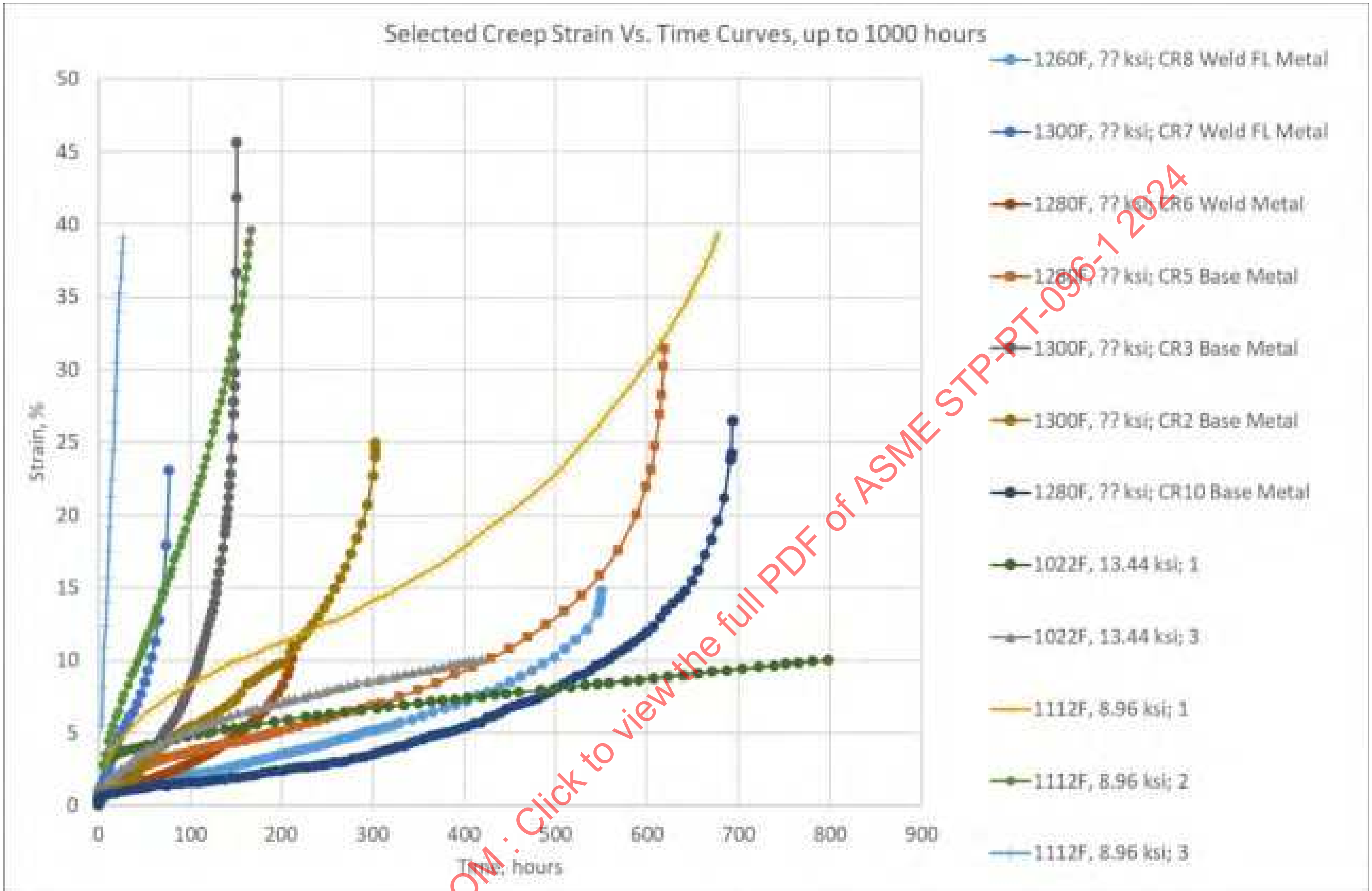


Figure 8-16: Long-Term Strain Vs. Time Data, in Excess of 1,000 Hour Test Durations (C-1/2Mo)

Figure 8-17: C-1/2Mo Continuous Cycling Fatigue (C-1/2Mo), Including Room Temperature and Elevated Temperature Data

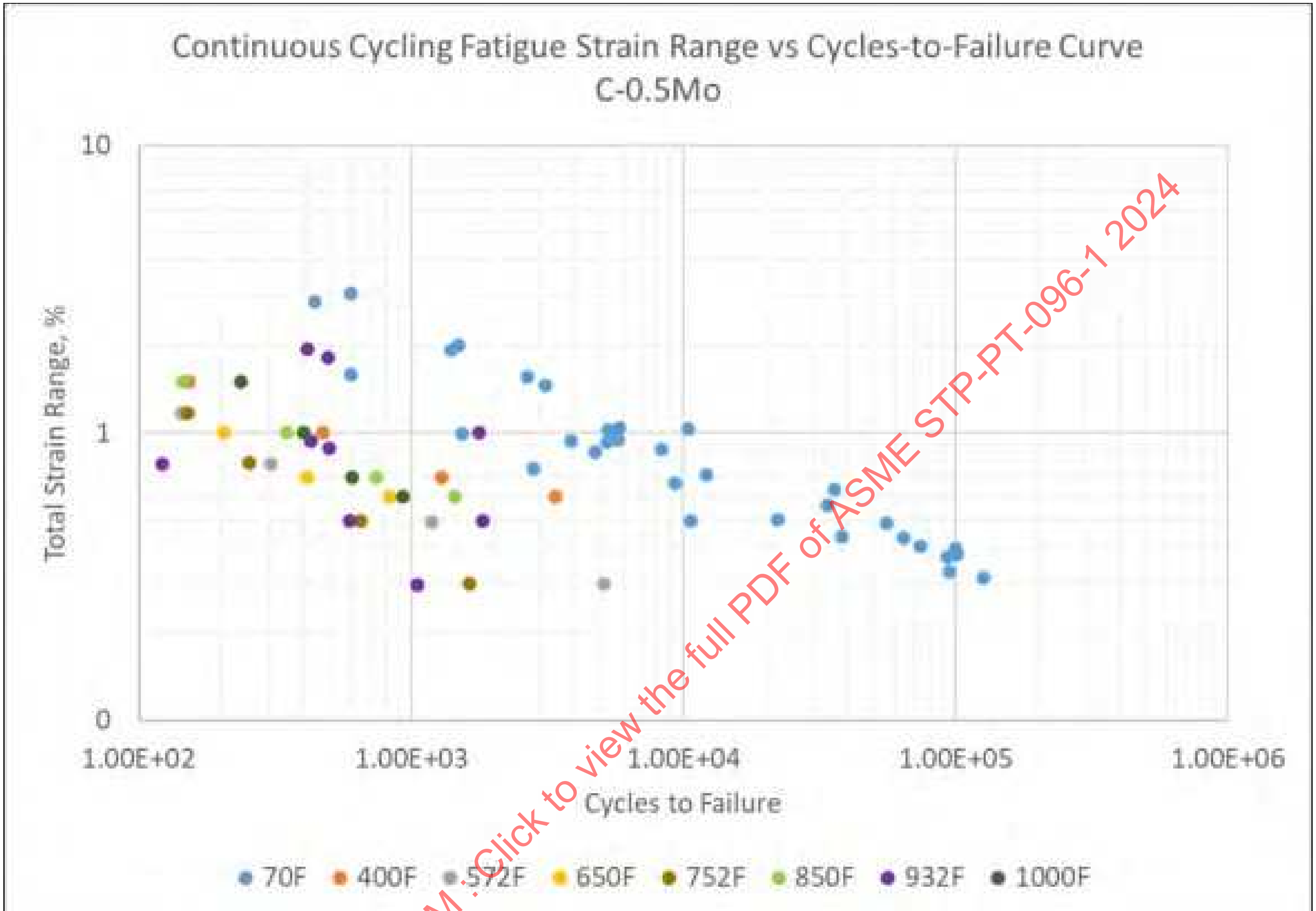


Figure 8-18: C-1/2Mo Hold Time Data (Creep Fatigue) for C-1/2Mo, Temperatures of 650°F, 850°F, 1000°F, 1022°F

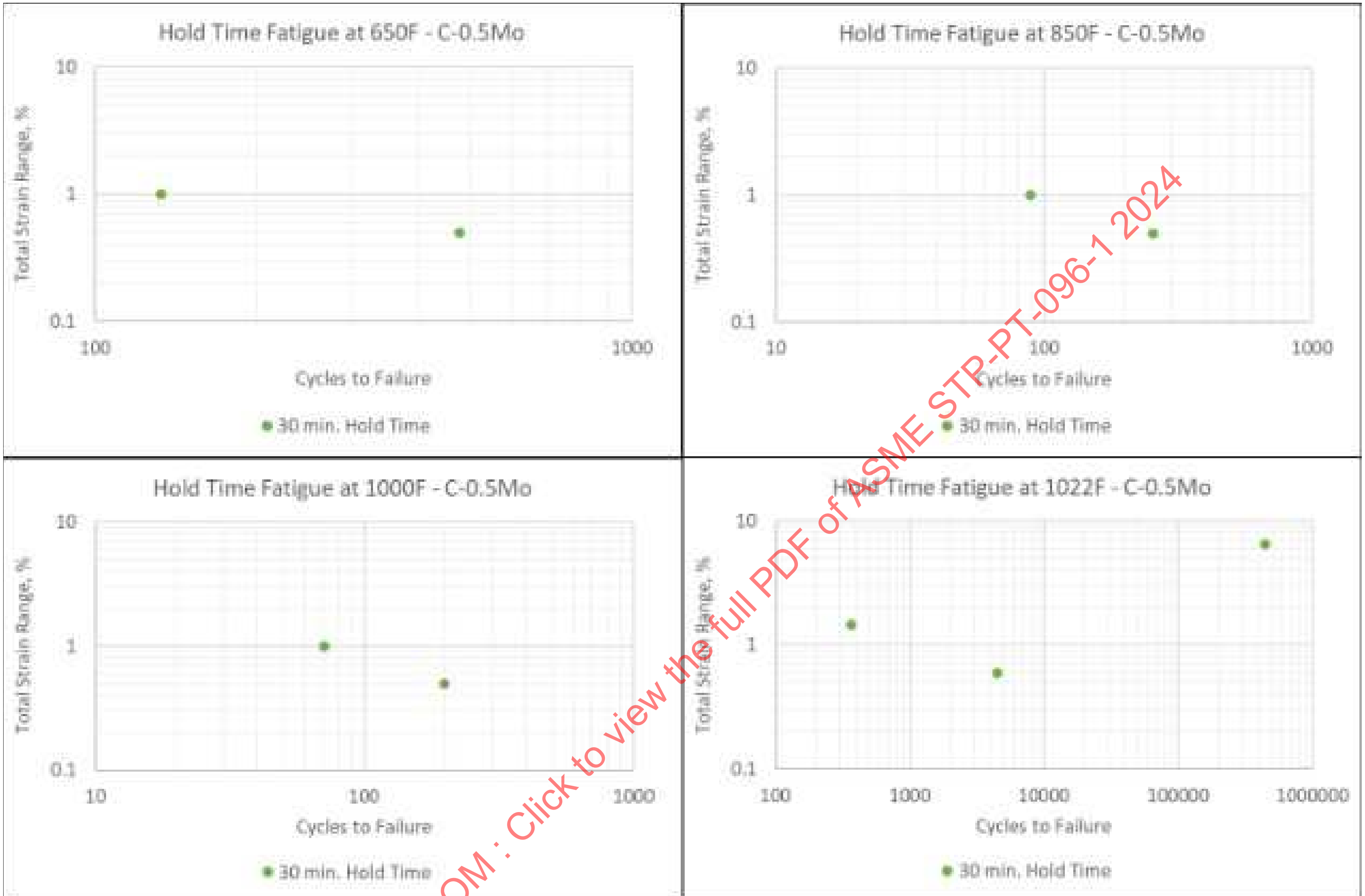
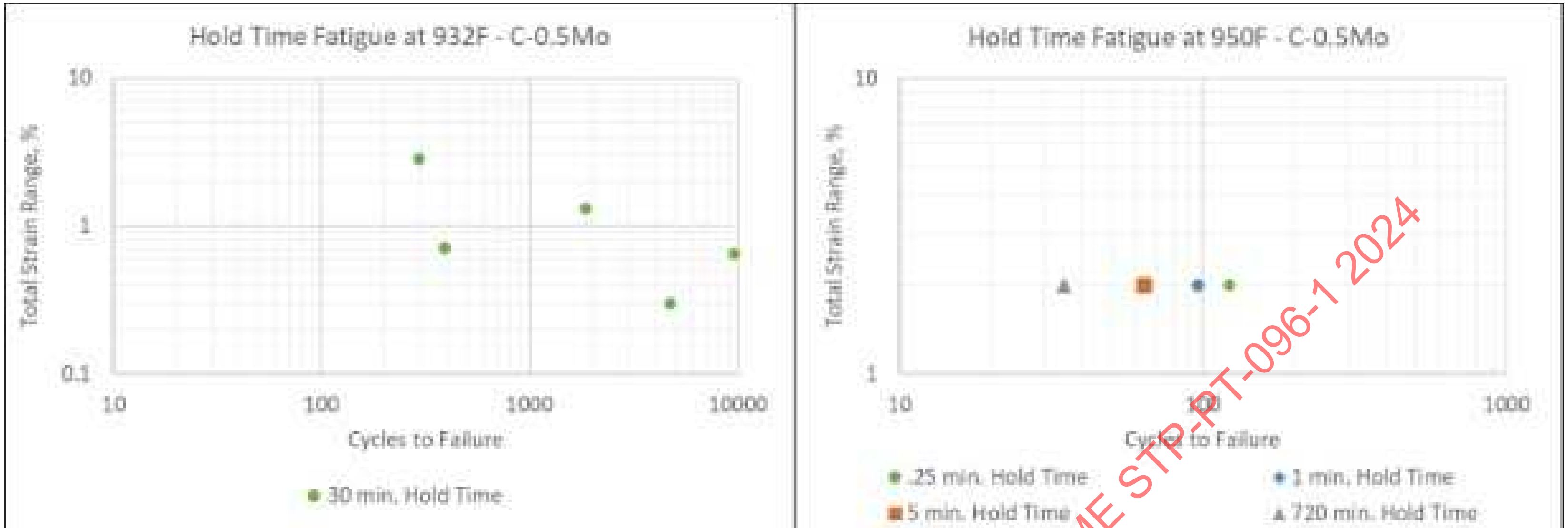


Figure 8-19: C-1/2Mo Hold Time Data (Creep Fatigue) for C-1/2Mo, Temperatures of 932°F and 950°F



Attachment 8: C-1/2Mo Property Data

If you want the referenced embedded spreadsheet with additional data, please email a request to research@asme.org.

9 GRADE 11, 1.25CR-0.5MO-SI

9.1 Physical Properties

Physical properties for this material were taken from the BPVC Section II. Additionally, physical property curves were plotted for comparison from WRC Bulletin 503. Figure 9-1 shows the plotted data and trends of Elastic Modulus (Ey), Thermal Conductivity (k), Thermal Diffusivity (TD), and Thermal Expansion (α) with temperature.

9.2 Yield and Tensile Strength

Elevated yield and tensile strength data for Grade 11 was initially split between Annealed and Normalized and Tempered (N&T) heat treatments to assess the effect of heat treatment on material strength properties. Upon review of the resulting fits, however, it was determined that the difference in the strength ratio trends was not significant. The sources for both high-temperature yield and high-temperature tensile strength are provided in the embedded spreadsheet at the end of this section. High-temperature yield and high-temperature tensile strength data are plotted, up approximately 1400°F, in Figures 9-2 and 9-3.

As with other materials, yield and tensile data were normalized on a heat-by-heat basis to express the ratio of yield or tensile strength at temperature to that measured for the heat at room temperature. In cases where data were not delineated by heats within a given source, or in cases where more than one room-temperature tensile test existed for a given heat of material, ratios are equal to the measured tensile or yield strength at temperature, divided by the average of all of the appropriate room-temperature values for the particular data source or heat of material. As a result of this approach, it is possible to have ratios in excess of 1.0. E^2G understands that this approach is similar to the normalizing procedure performed by ASME in typical analysis of yield and tensile data to obtain Table Y and Table U (Section II-D) trend curves, as well as for the calculation of allowable stresses. The heat-by-heat variation in yield strength ratio as a function of temperature for is shown in Figure 9-4. Similarly, the heat-by-heat variation in tensile strength as a function of temperature is depicted in Figure 9-5. Figures 9-6 and 9-7 respectively contain all of the yield and tensile ratios for all data points, as well as curves for only annealed and only N&T material, to facilitate regression of a 5th-order polynomial that is subsequently used for allowable stress comparison.

9.3 Creep Data (Creep Rupture, Minimum Creep Rate, and Ductility)

Plotted as isothermal figures, compiled Creep Rupture data can be seen in Figures 9-8 and 9-9. Similar to other materials, the data has been separated onto multiple plots in order to avoid data overlap, with the most concentrated data depicted in Figure 9-8 and the remaining data in Figure 9-9.

Creep Minimum strain rates (%/hour) can be seen in Figure 9-10, separated by temperature. Unlike creep rupture, a limited amount of strain rate data was found for this material. Similarly, creep ductility, as % elongation, is plotted in Figure 9-11.

Creep data were analyzed using E^2G's proprietary Lot-Centered Analysis web-based software tool, in order to obtain creep properties. This regression is based on a Mandel-Paule algorithm and considers the variation within individual heats of material (for both rupture and strain rate data) as well as the variation between heats. The weight assigned to each datapoint and each heat is scaled based on the relative variation. Both rupture and strain rate (minimum creep rate, expressed as true strain per hours) were regressed according to a Larson-Miller time-temperature-parameter model, with a 3rd-order polynomial of stress. Lot-specific constant behavior was accounted for in this analysis, but the variation of LMP with stress was assumed to be constant (no non-parallel terms were included in the analysis). A 95% predictive limit was utilized to obtain the lower-bound (minimum LM constant for both rupture and strain rate) properties. The results of this analysis are summarized in Table 9-1 for rupture data and Table 9-2 for strain rate data. The Lot-Centered Analysis software tool generates property tables in the creep regime using the criteria outlined in Mandatory Appendix 1 of ASME Section II-D; the nomenclature of variables is consistent with II-D Appendix 1. For visualization of the allowable stress trends, Figure 9-12 is provided (for rupture allowable stresses and creep rate allowable stresses). Figure 9-13 shows a comparison of the various allowable stress criteria from Section II-D, Appendix 1, to the existing (2019) Section II-D Table 1A allowable stresses for common grade 11 product forms (generally the same for seamless tubular product forms in the creep regime).

Creep Strain vs. time data are shown in Figures 9-14 and 9-15 for rupture times up to 3,000 hours and in excess of 3,000 hours, respectively. Both creep rate and creep strain vs. time data are provided to satisfy ASME's request for creep strain vs. time curves, and both forms of data are applicable in developing allowable stresses. Although digitalization of creep curve data was not explicitly necessary per the project contract, E^2G did perform digitalization of creep curves where only graphical data was available (as is often the case in the published literature).

9.4 Continuous Cycling Fatigue Curves

A limited amount of continuous cycling fatigue data was available for Grade 11 material. A plot of the continuous cycling fatigue strain range vs. cycles to failure is shown Figure 9-16 at elevated temperatures. This plot only contains data for which total strain range was determined from the original source. One source of hold time fatigue data was located for Grade 11 in Figure 9-17.

Table 9-1: Model Parameters, Larson-Miller Property Results, and Allowable Stress (Rupture) Criteria, Grade 11

Equation Format:

$$\log(t_r) = C_{avg} + \frac{1}{T+460}\left(b_1 + b_2\log(\sigma) + b_3(\log(\sigma))^2 + b_4(\log(\sigma))^3\right)$$

C_{avg}	**-19.76**
C_{min}	**-20.4**
b_1	**43126.9**
b_2	**-6477.7**
b_3	**-10.51**
b_4	**-106.3**

Number Data Points		**1888**
Correlation Coefficient	R^2	0.8878
Average Variance within Heats	V_w	0.06891
Variance between Heats	V_b	0.07378
Standard Error of Estimate	SEE	0.2625

Properties provided are for T in °F, stress in ksi, and t_R in hours

Temperature, °F	**S_{avg} (ksi)**	***n***	**F_{avg} (calc)**	**F_{avg} (used)**	**$F_{avg} \times S_{avg}$**	**S_{min} (ksi)**	**80% S_{min}**
850	35.01	5.55	0.6604	0.67	23.46	29.22	23.38
900	23.47	5.224	0.6436	0.67	15.72	19.37	15.5
950	15.59	4.934	0.6271	0.67	10.45	12.73	10.18
1000	10.27	4.675	0.6111	0.67	6.882	8.291	6.633
1050	6.717	4.446	0.5958	0.67	4.501	5.363	4.29
1100	4.364	4.245	0.5813	0.67	2.924	3.448	2.758
1150	2.82	4.069	0.5679	0.67	1.89	2.206	1.765
1200	1.816	3.918	0.5556	0.67	1.216	1.407	1.126
1250	1.166	3.79	0.5447	0.67	0.7812	0.8961	0.7169
1300	0.7482	3.682	0.5351	0.67	0.5013	0.5707	0.4566

Table 9-2: Model Parameters, Larson-Miller Property Results, and Allowable Stress (Strain Rate) Criteria, Grade 11

Equation Format:

$$\log(\dot{\varepsilon}_0) = -C_{avg} - \frac{1}{T+460}\left(a_1 + a_2\log(\sigma) + a_3(\log(\sigma))^2 + a_4(\log(\sigma))^3\right)$$

C_{avg} (A_0)	**-12.96**
C_{min} ($A_0+\Delta_\Omega^{SR,LB}$)	**-13.71**
a_1	**33046.9**
a_2	**-6637.3**
a_3	**668.8**
a_4	**-22.46**

Number Data Points		**380**
Correlation Coefficient	R^2	0.5182
Average Variance within Heats	V_w	0.2111
Variance between Heats	V_b	0.2369
Standard Error of Estimate	SEE	0.4594

Properties provided are for T in °F, stress in ksi, and t_R in hours

Temperature, °F	**$S_{C,avg}$ (ksi)**
850	51.68
900	33.13
950	21.66
1000	14.41
1050	9.742
1100	6.68
1150	4.641
1200	3.264
1250	2.321
1300	1.667

Figure 9-1: Grade 11 Modulus (E_y), Thermal Conductivity (k), Thermal Diffusivity (TD), & Thermal Expansion (α) With Temperature

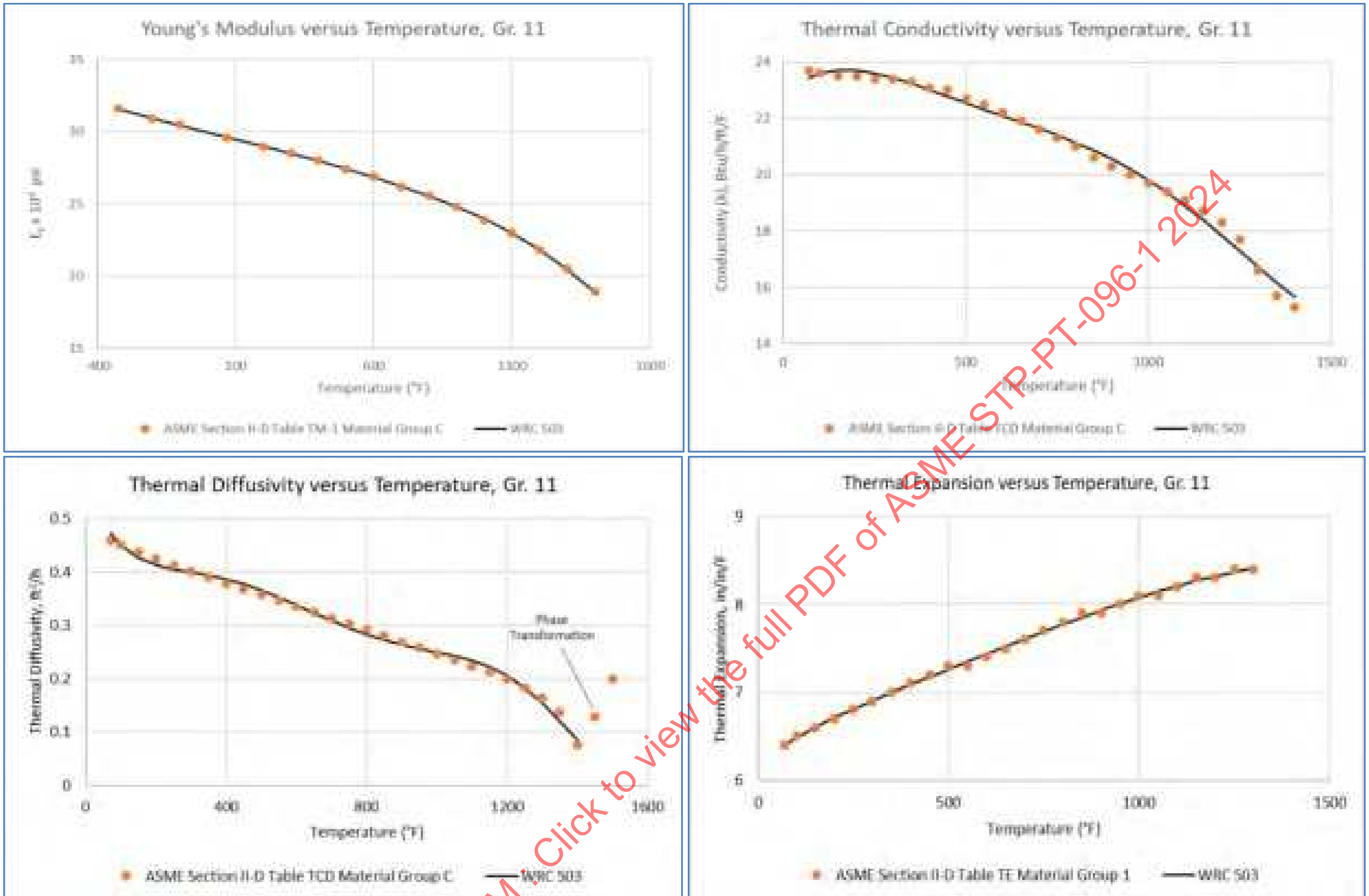


Figure 9-2: Grade 11 (All Heat Treatments) Yield Strength Vs. Temperature, By Data Source, Including Trend Curves

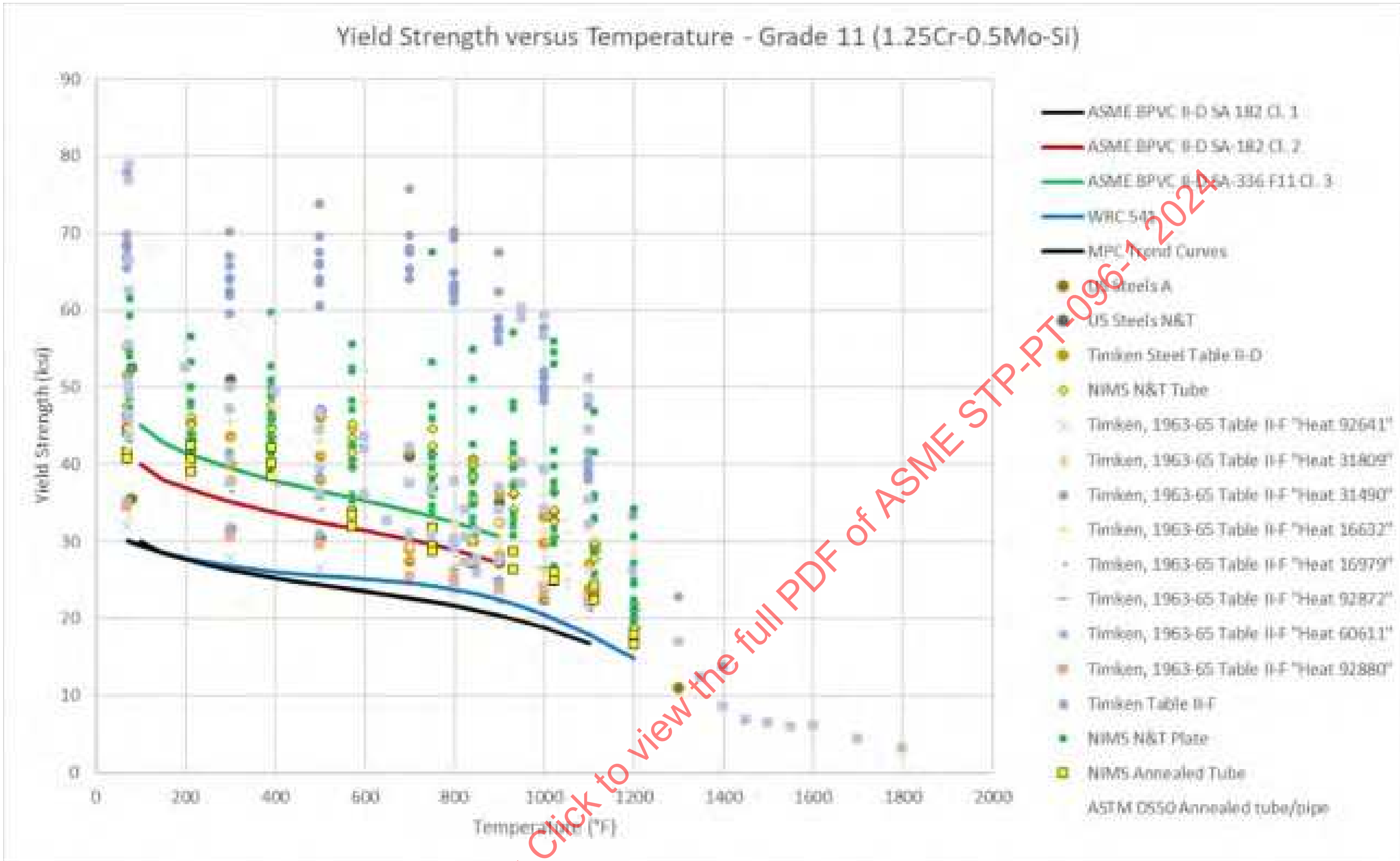


Figure 9-3: Grade 11 (All Heat Treatments) Tensile Strength Vs. Temperature, By Data Source, Including Trend Curves

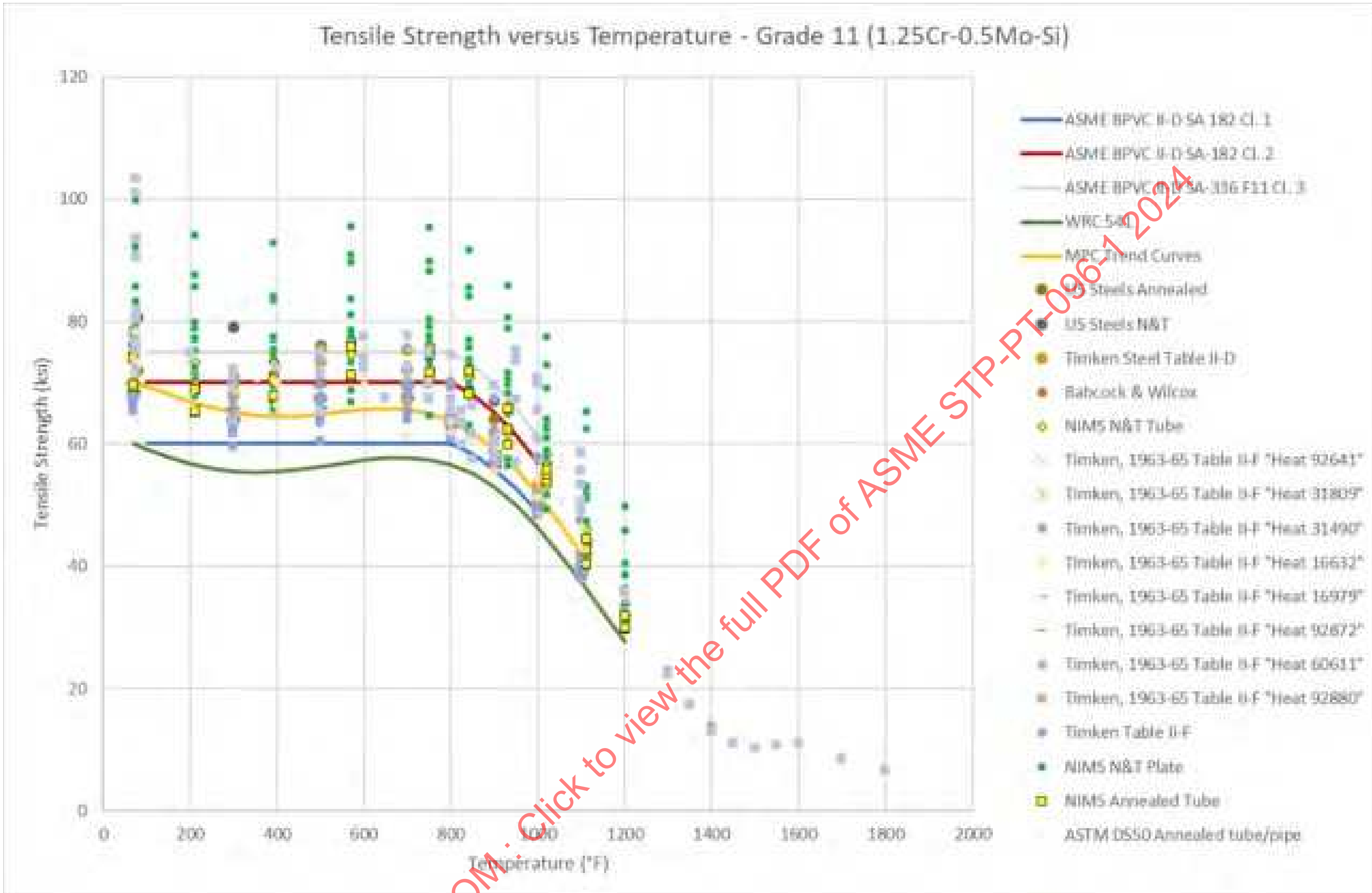


Figure 9-4: Grade 11 (All Heat Treatments) Yield Strength Ratios Vs. Temperature (Calculated on a Heat-By-Heat Basis)

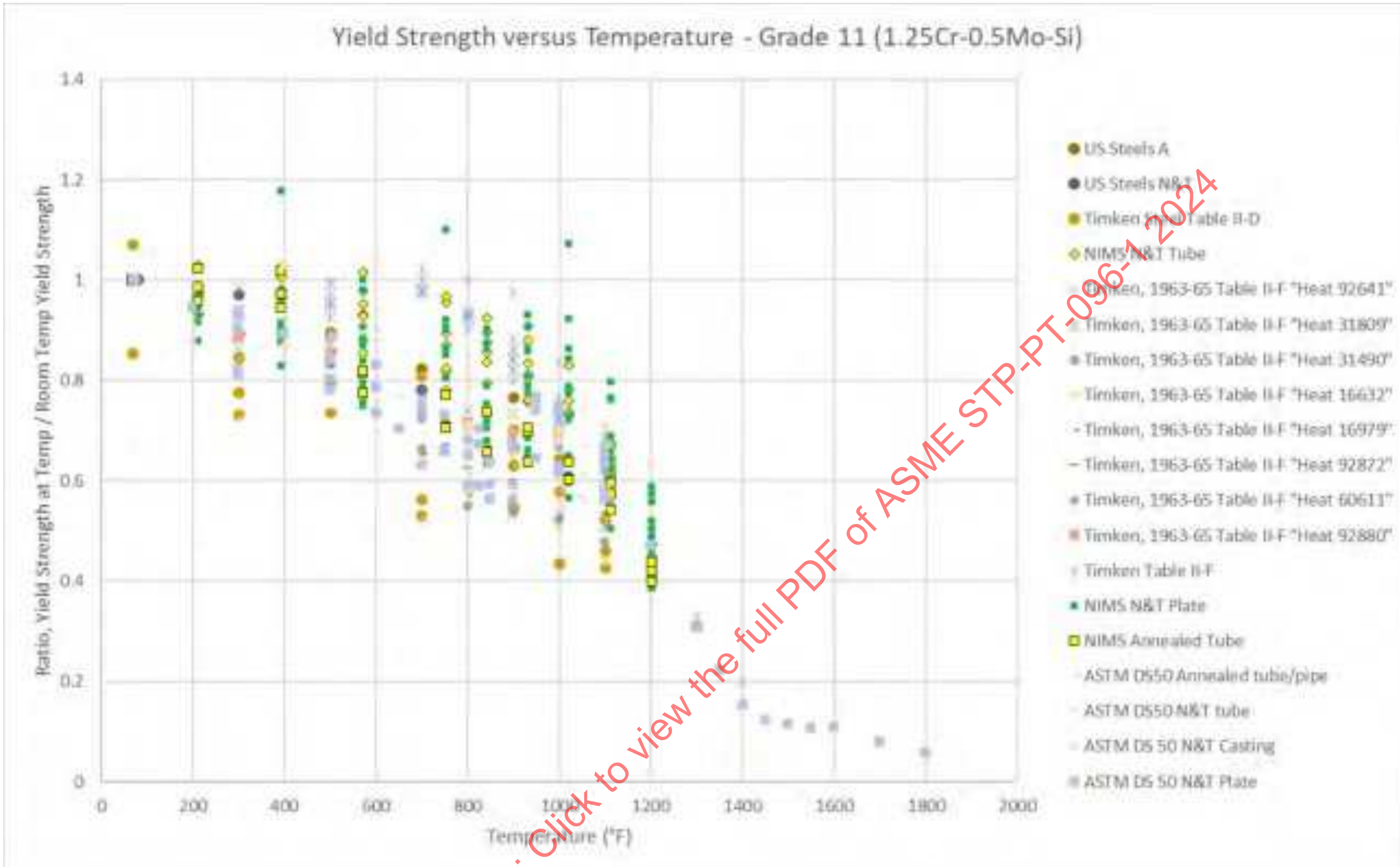


Figure 9-5: Grade 11 (All Heat Treatments) Tensile Strength Ratios Vs. Temperature (Calculated on a Heat-By-Heat Basis)

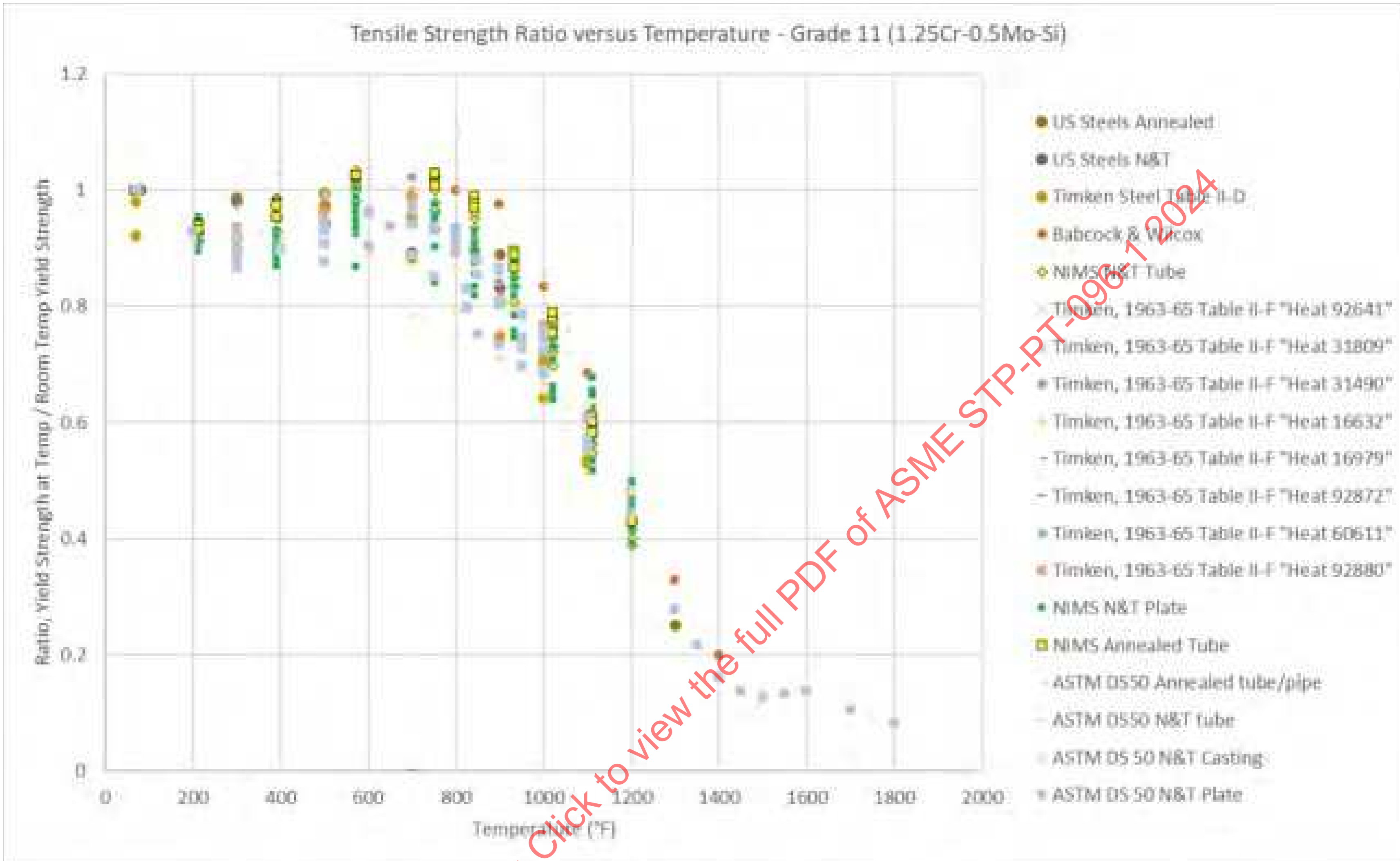


Figure 9-6: Grade 11 (All Heat Treatments) Yield Strength Ratios Vs. Temperature, All Combined Data, With Polynomial Regression

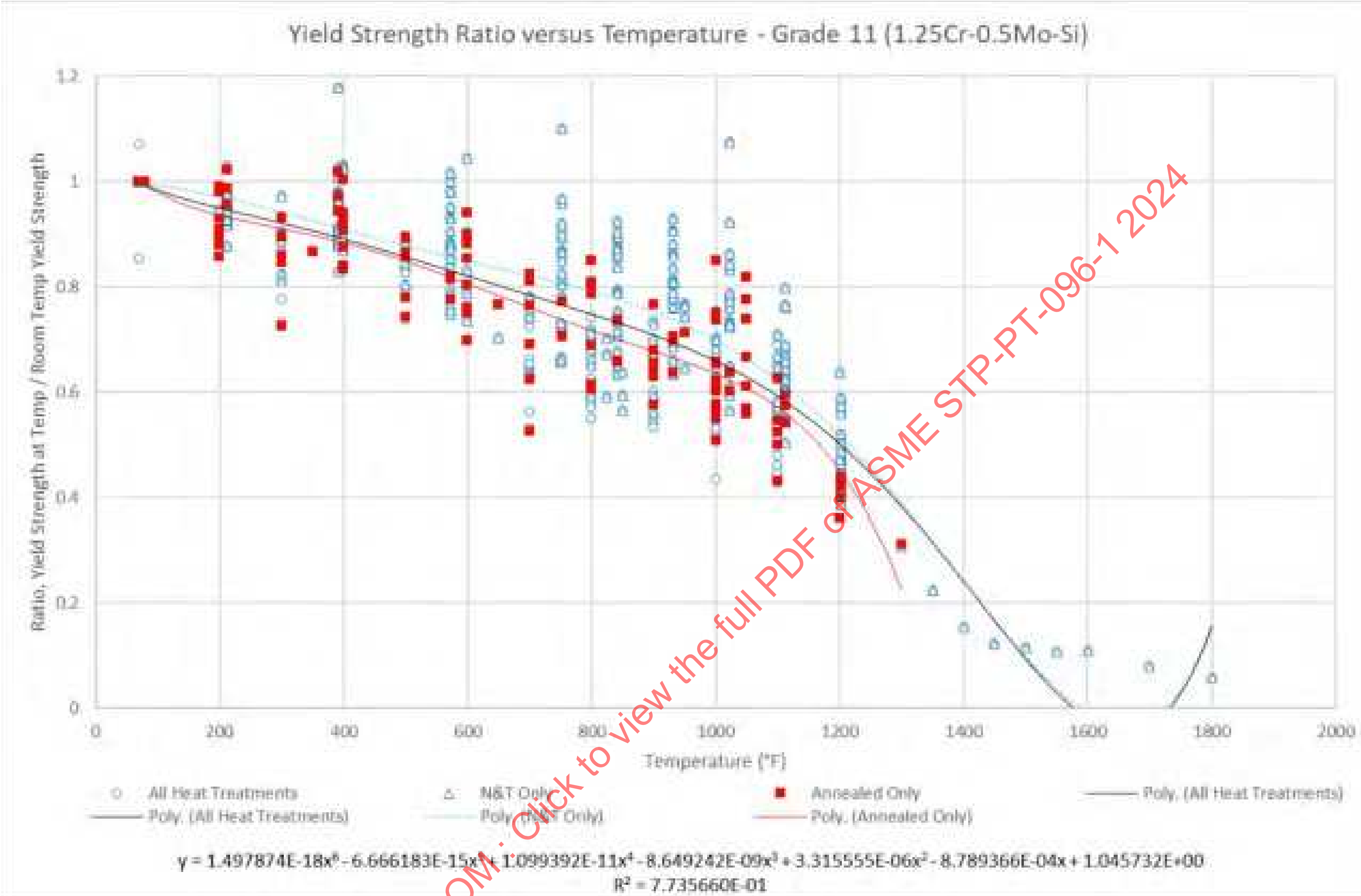


Figure 9-7: Grade 11 (All Heat Treatments) Tensile Strength Ratios Vs. Temperature, All Combined Data, With Polynomial Regression

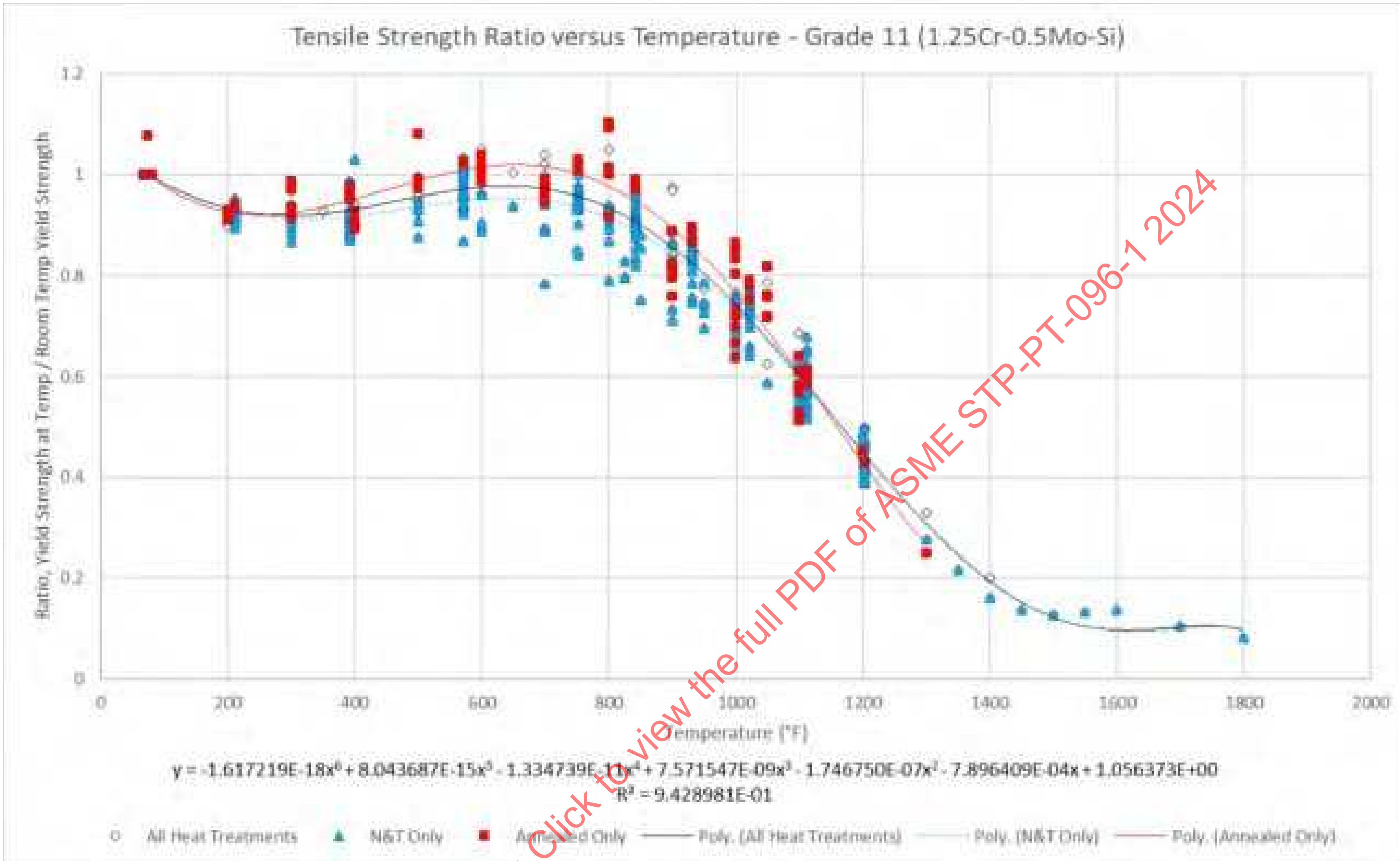


Figure 9-8: Grade 11 Creep Rupture Isotherm Curves, Temperatures With High Concentration of Data Points

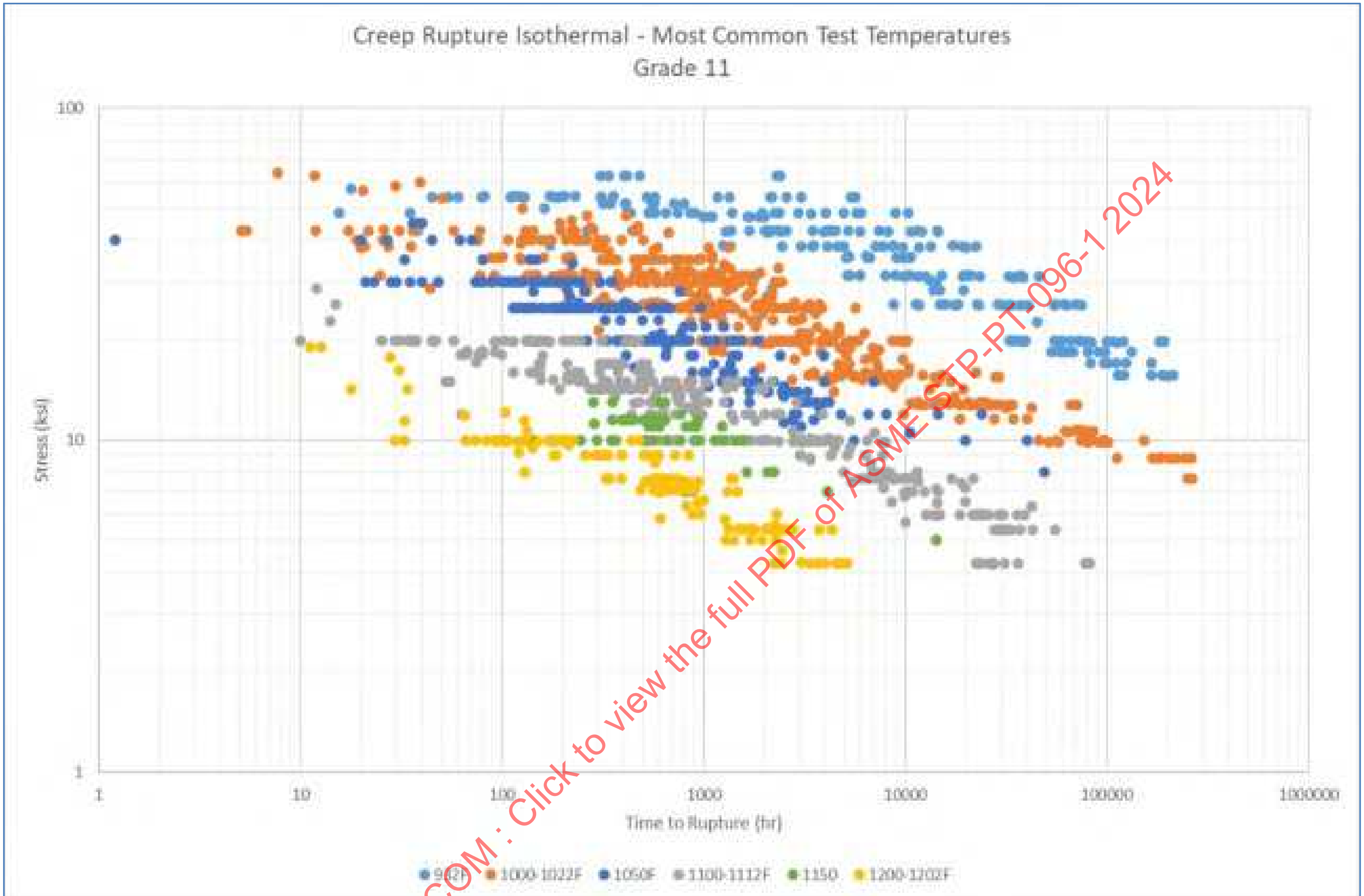


Figure 9-9: Grade 11 Creep Rupture Isotherm Curves for Additional and Intermediate Temperatures

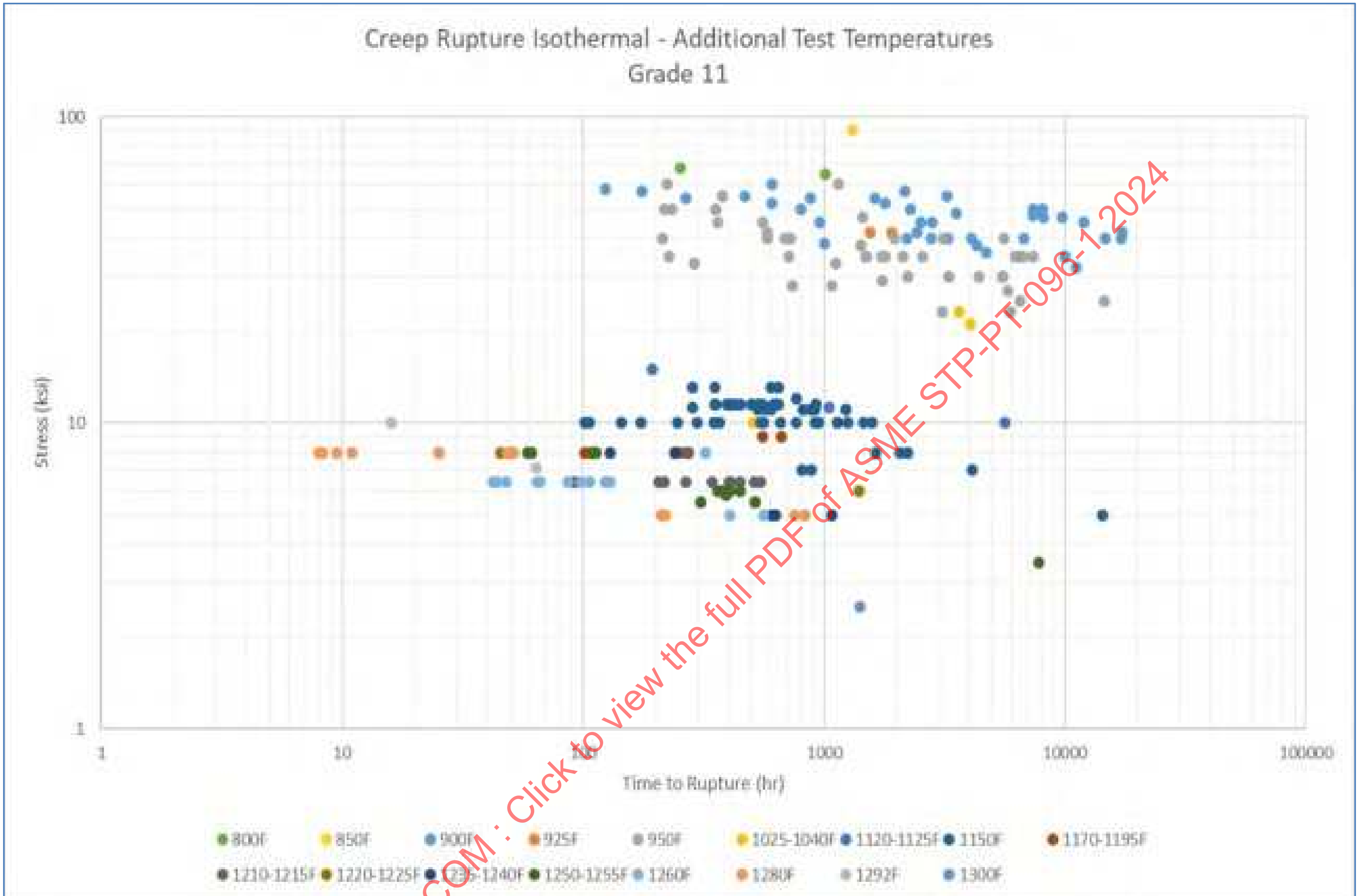


Figure 9-10: Grade 11 Creep Strain Rate (MCR) Isotherm Curves

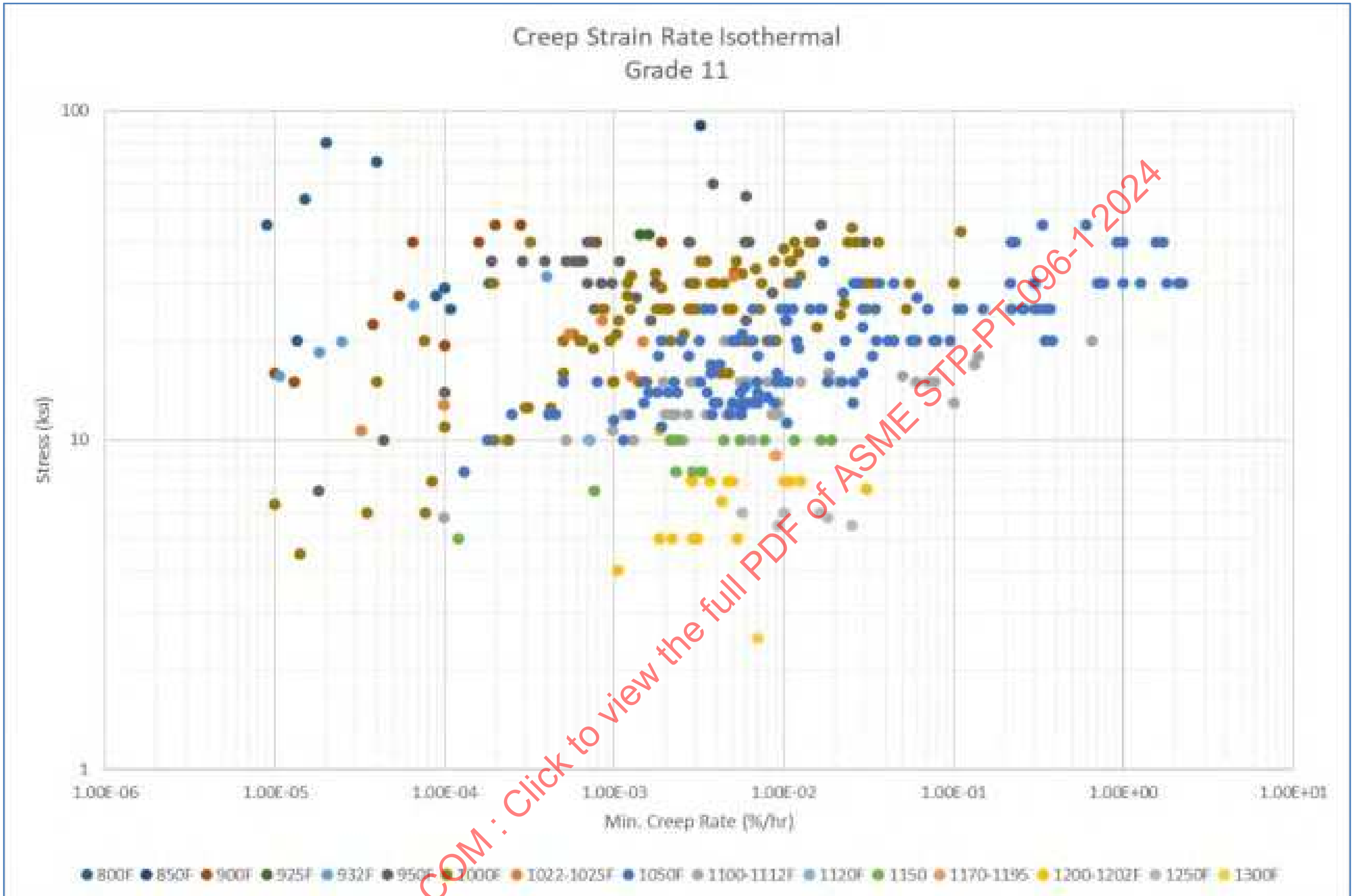


Figure 9-11: Grade 11 Creep Ductility (% Elongation) Vs. Rupture Time Isotherms

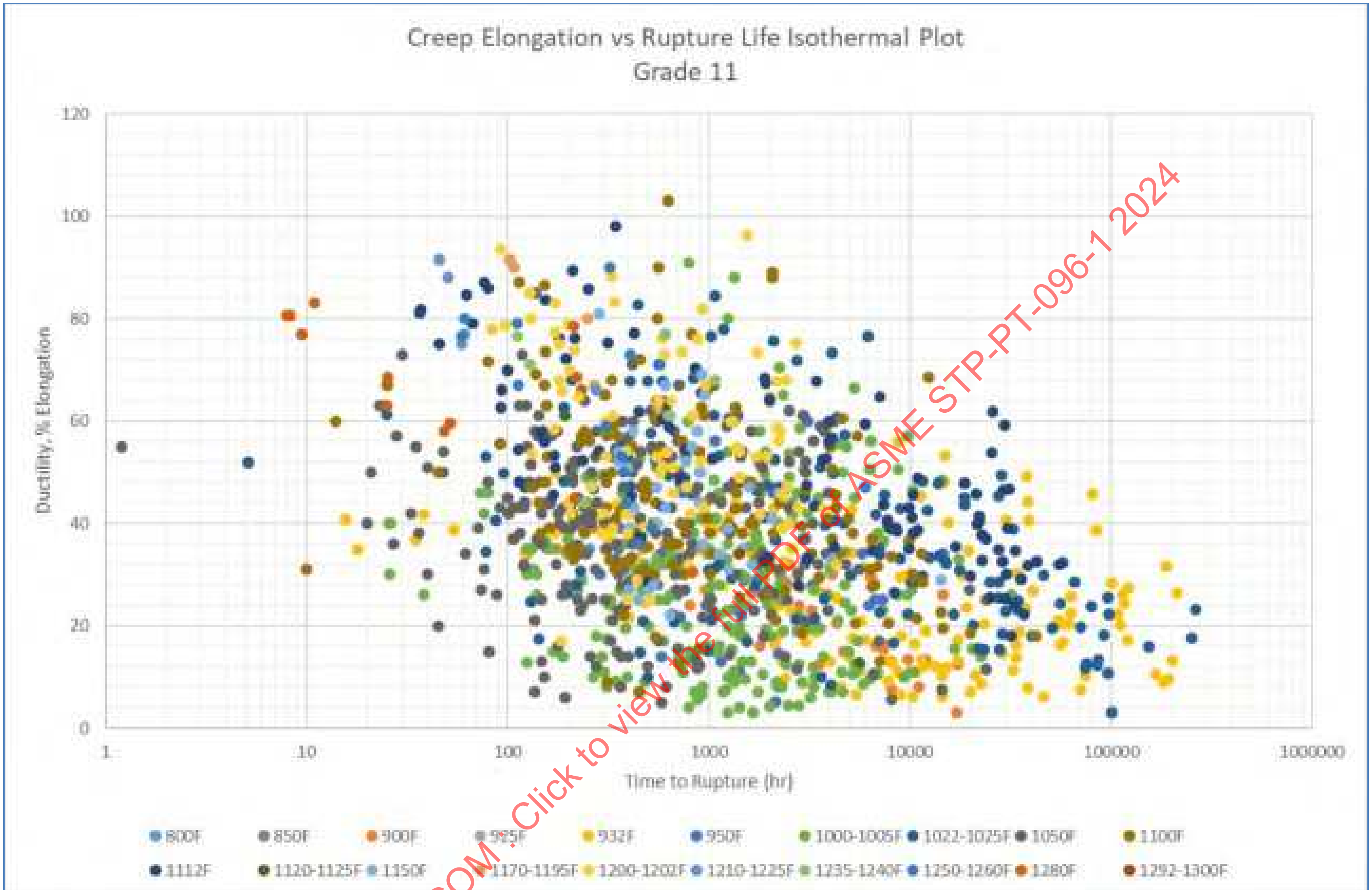


Figure 9-12: Calculated Allowable Stresses Based on Rupture and Creep Strain Rate and ASME II-D Appendix 1 Criteria (Grade 11)

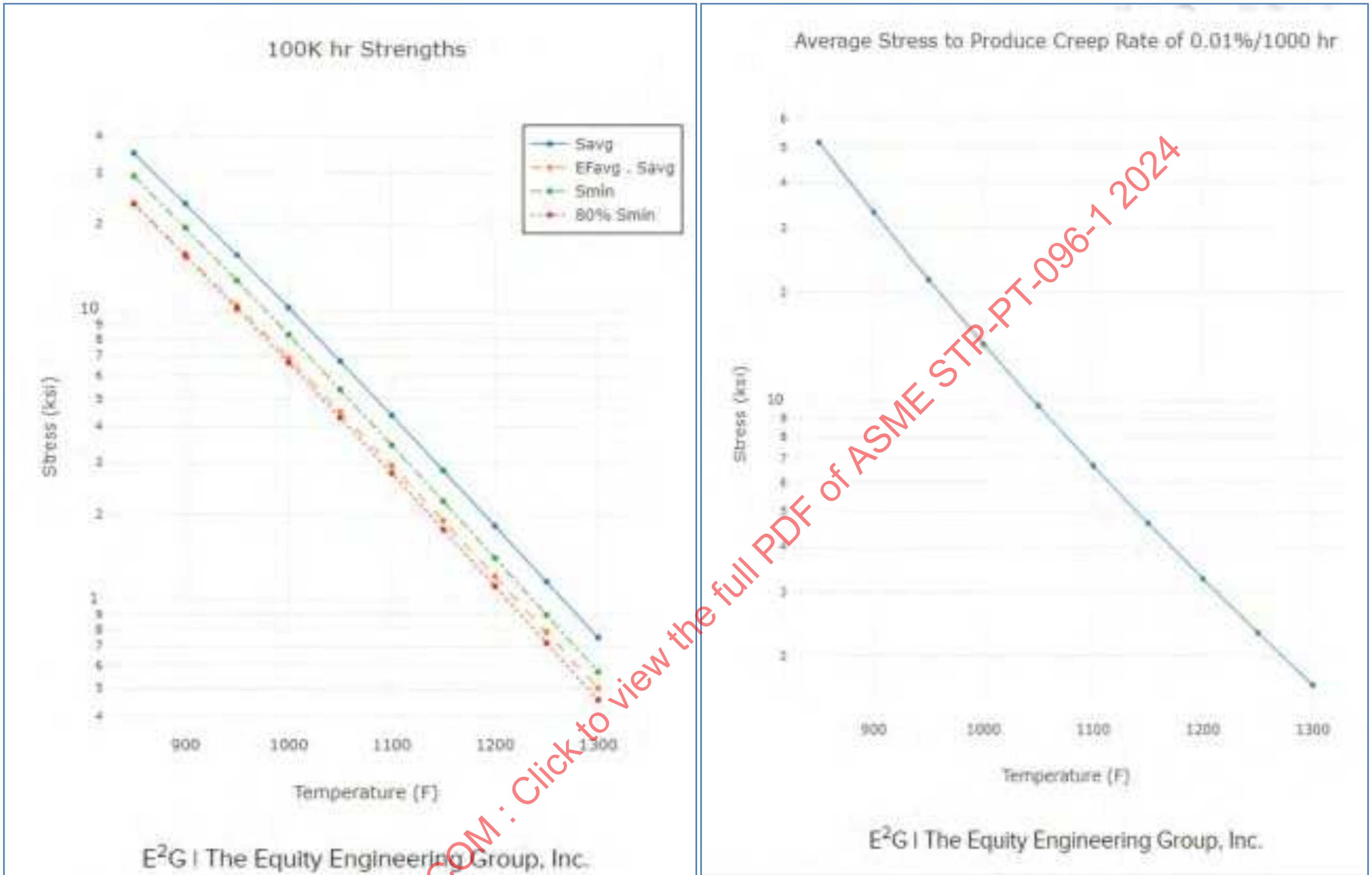


Figure 9-13: Comparison of Current Grade 11 Allowable Stresses Vs. ASME II-D Appendix 1 Criteria Applied to Data

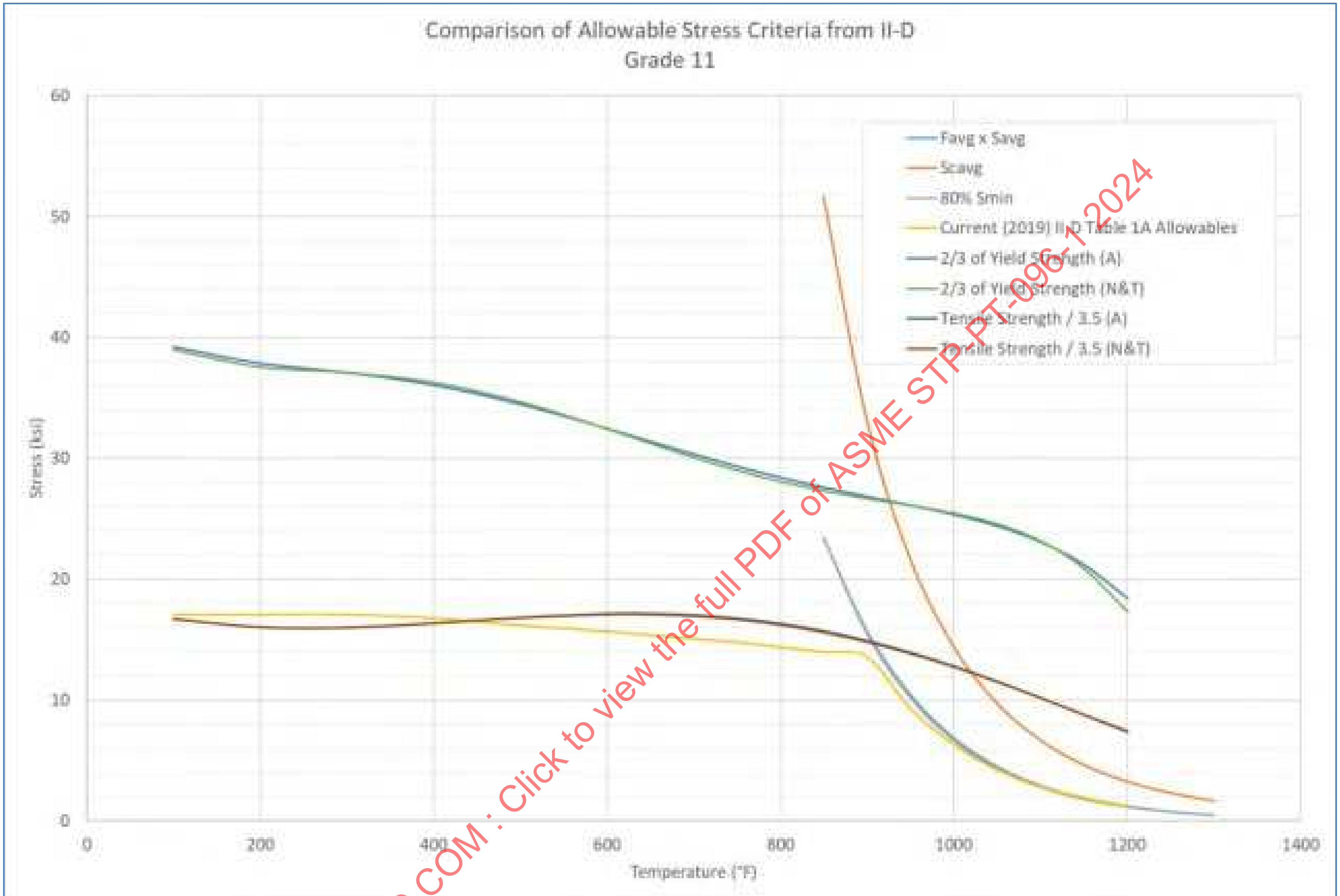


Figure 9-14: Creep Strain Vs. Time Data, up to 3,000 Hour Test Durations (Grade 11)

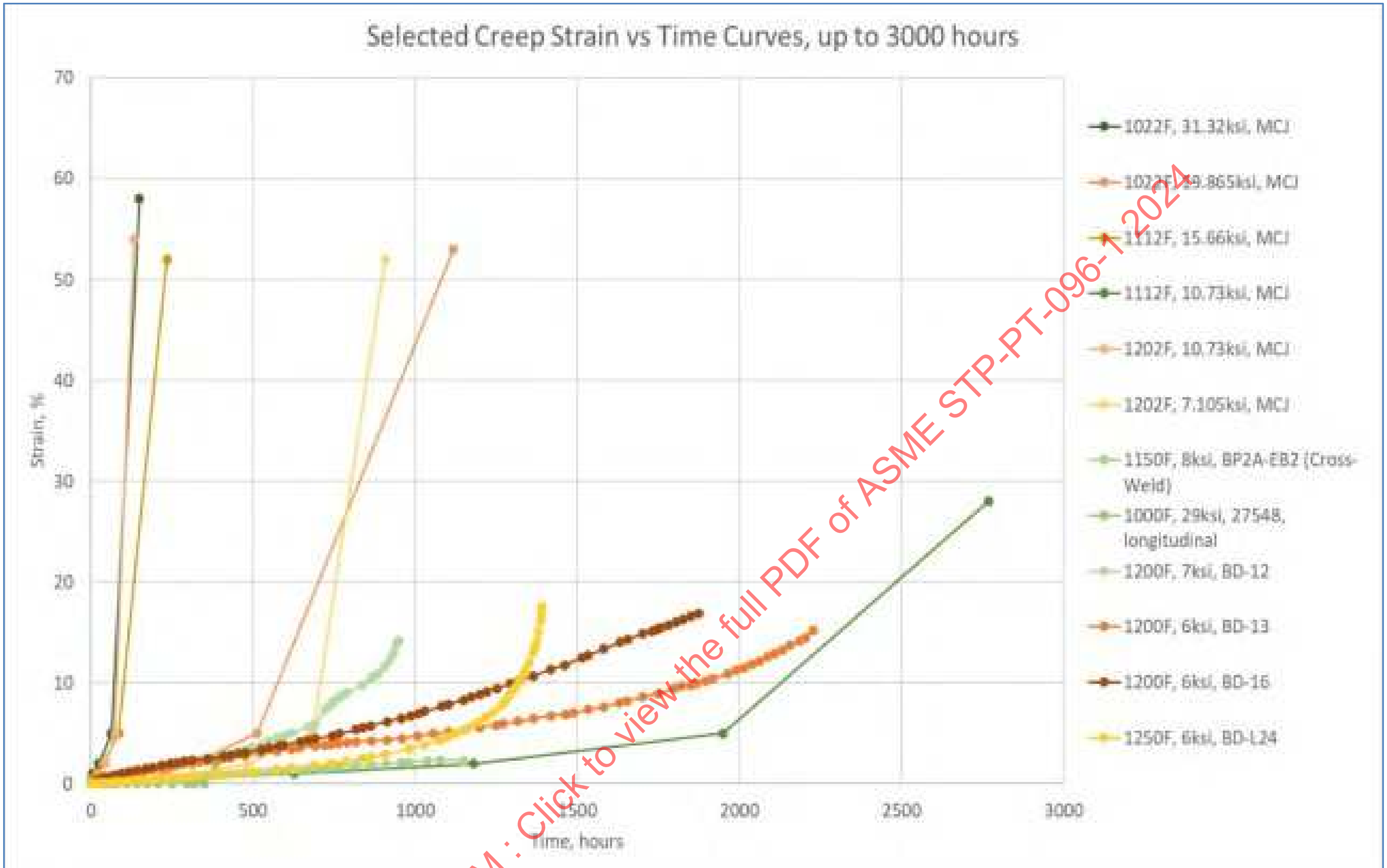


Figure 9-15: Creep Strain Vs. Time Data, In Excess of 3,000 Hours (Grade 11)

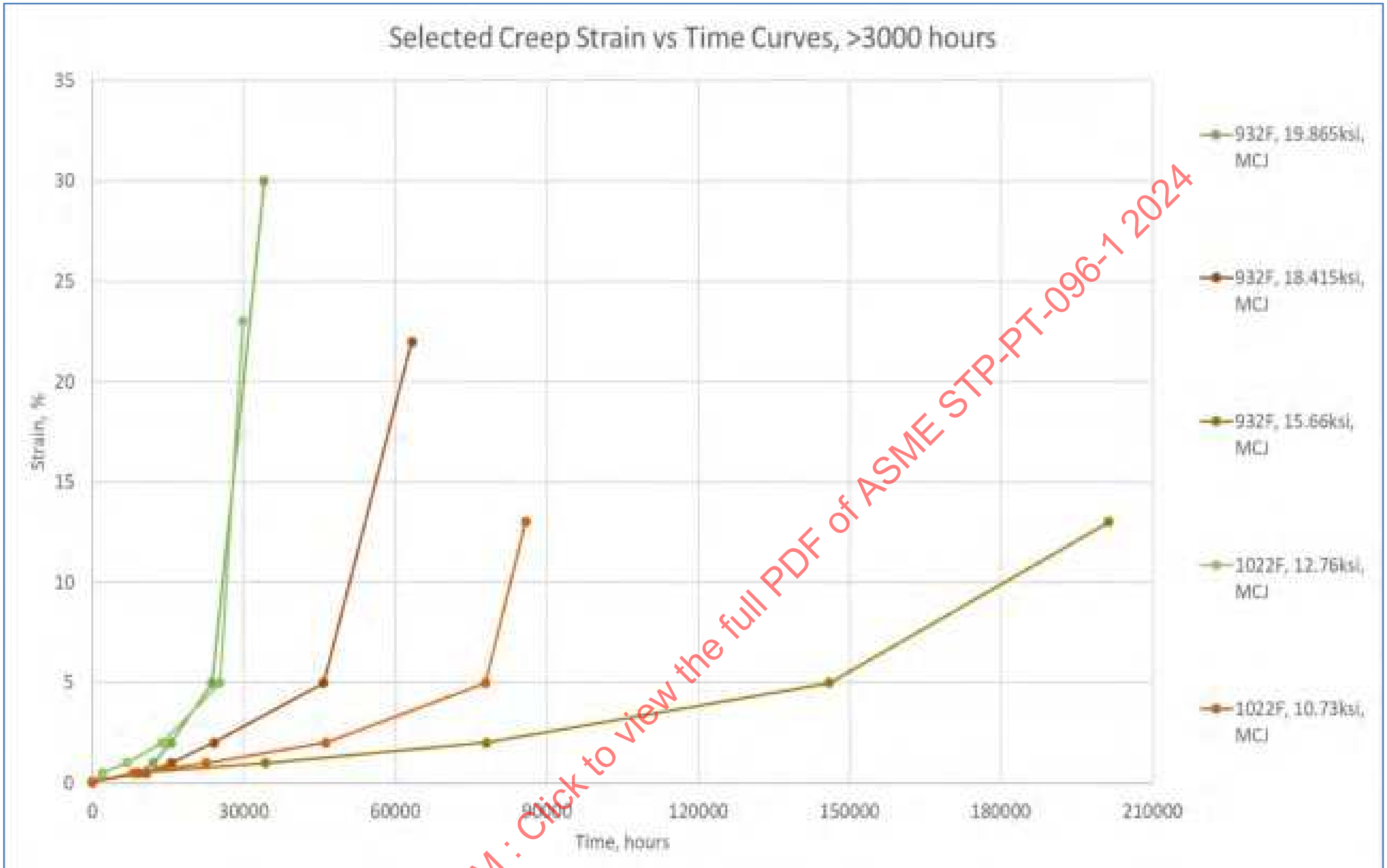


Figure 9-16: Grade 11 Continuous Cycling Fatigue, Including Room Temperature and Elevated Temperature Data

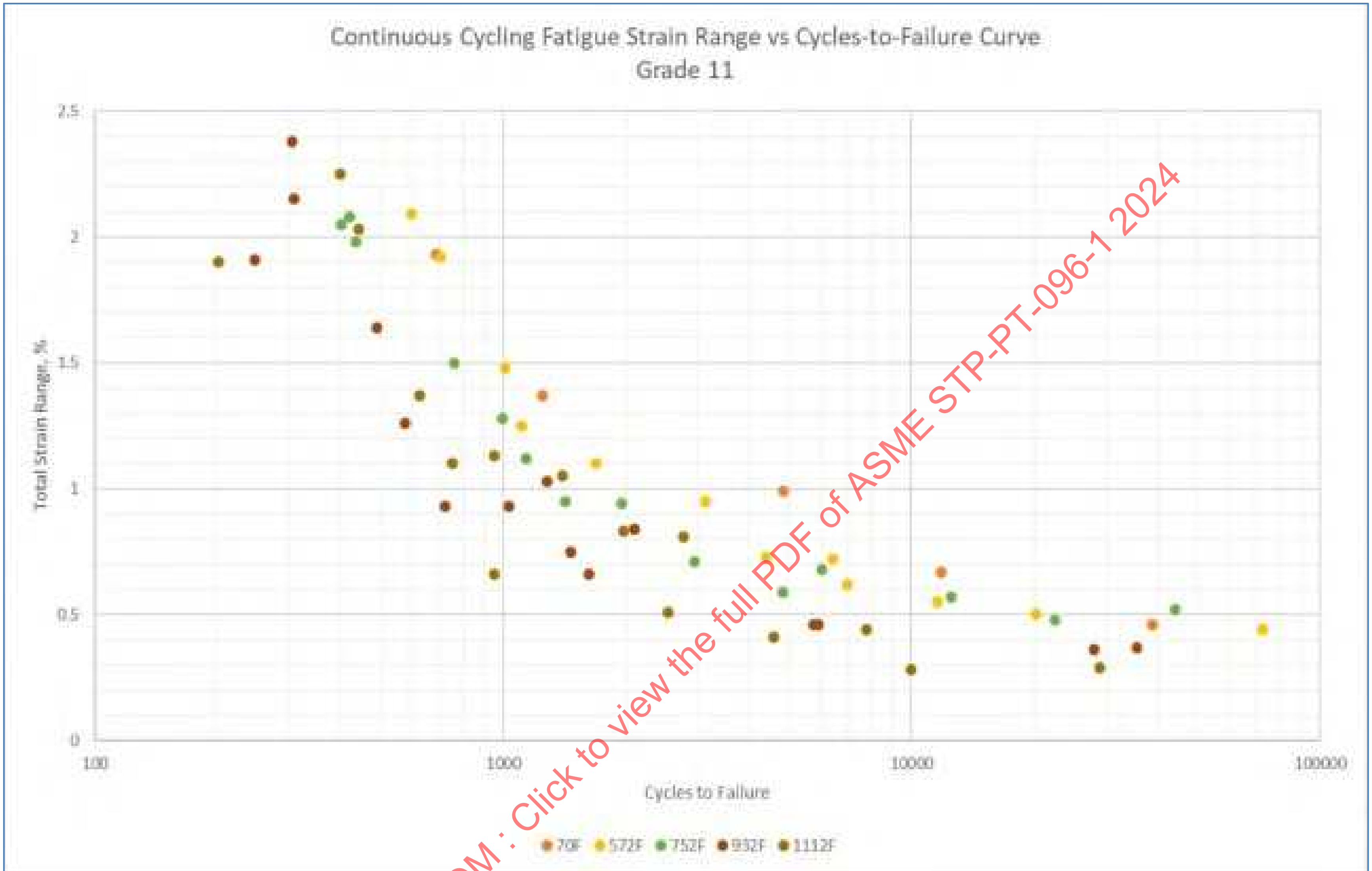
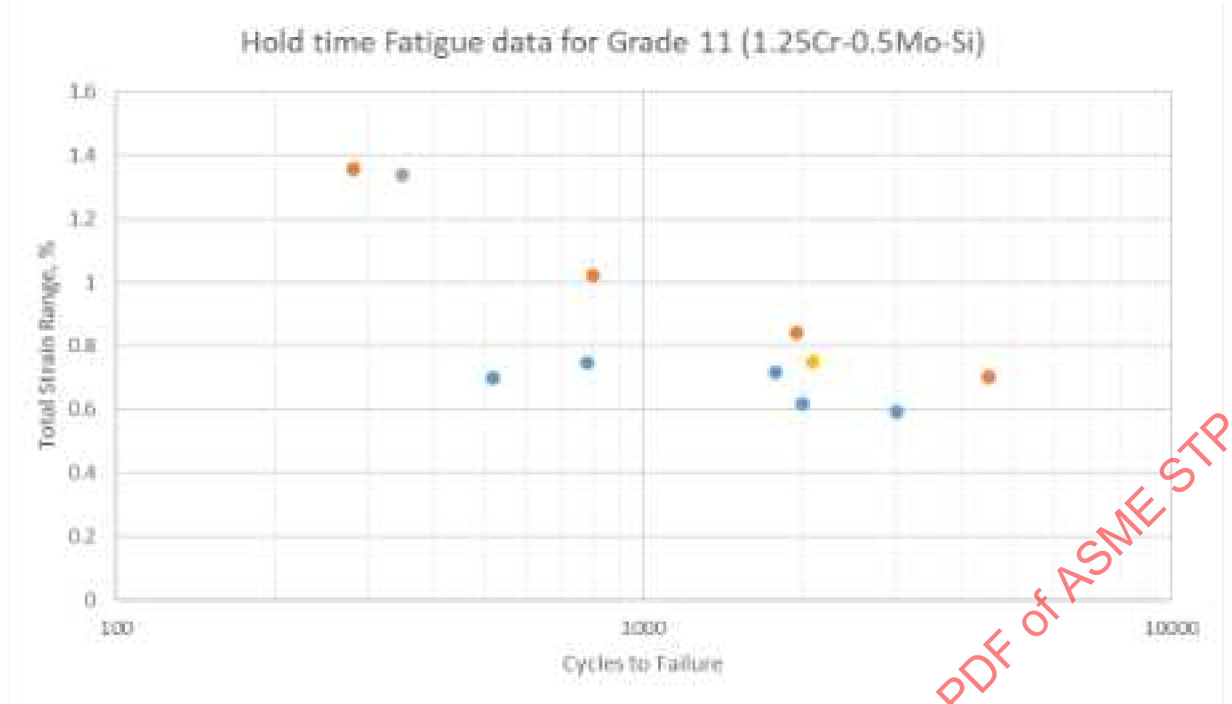


Figure 9-17: Grade 11 Continuous Cycling Fatigue, Including Room Temperature and Elevated Temperature Data



Attachment 9: Grade 11 Property Data

If you want the referenced embedded spreadsheet with additional data, please email a request to research@asme.org.

10 GRADE 22 (2.25CR-1MO)

10.1 Physical Properties

Physical properties for this material were taken from the BPVC Section II. Additionally, physical property curves were plotted for comparison from WRC Bulletin 503. No additional sources were sought for physical properties due to the existence of these well-established curves. Figure 10-1 shows the plotted data and trends of Elastic Modulus (Ey), Thermal Conductivity (k), Thermal Diffusivity (TD), and Thermal Expansion (α) with temperature.

10.2 Yield and Tensile Strength

Elevated yield and tensile strength data for Grade 22 was initially split by heat treatment, with Annealed, Normalized and Tempered (N&T), and Quenched and Tempered (Q&T) heat treatments separated to assess the effects of heat treatment on material strength properties. Upon review of the resulting fits, however, it was determined that the difference in the strength ratio trends was not significant. The sources for both high-temperature yield and high-temperature tensile strength are provided in the embedded spreadsheet at the end of this section. High-temperature yield and high-temperature tensile strength data are plotted, up to approximately 1300°F, in Figures 10-2 and 10-3.

As with other materials, yield and tensile data were normalized on a heat-by-heat basis to express the ratio of yield or tensile strength at temperature to that measured for the heat at room temperature. In cases where data were not delineated by heats within a given source, or in cases where more than one room-temperature tensile test existed for a given heat of material, ratios are equal to the measured tensile or yield strength at temperature, divided by the average of all of the appropriate room-temperature values for the particular data source or heat of material. As a result of this approach, it is possible to have ratios in excess of 1.0. E^2G understands that this approach is similar to the normalizing procedure performed by ASME in typical analysis of yield and tensile data to obtain Table Y and Table U (Section II-D) trend curves, as well as for the calculation of allowable stresses. The heat-by-heat variation in yield strength ratio as a function of temperature for is shown in Figure 10-4. Similarly, the heat-by-heat variation in tensile strength as a function of temperature is depicted in Figure 10-5. Figures 10-6 and 10-7 respectively contain all of the yield and tensile ratios for all data points, as well as curves for only annealed and only N&T material, to facilitate regression of a 5th-order polynomial that is subsequently used for allowable stress comparison.

10.3 Creep Data (Creep Rupture, Minimum Creep Rate, and Ductility)

Plotted as isothermal figures, compiled Creep Rupture data can be seen in Figures 10-8 and 10-9. Similar to other materials, the data has been separated onto multiple plots in order to avoid data overlap, with the most concentrated data depicted in Figure 10-8 and the remaining data in Figure 10-9.

Creep Minimum strain rates (%/hour) can be seen in Figures 10-10 and 10-11, separated by temperature. Unlike creep rupture, a limited amount of strain rate data was found for this material. Creep ductility, as % elongation, is plotted in Figure 10-12. Overall, grade 22 had a similar volume of data and variety of available sources to Grade 91 and carbon steel (SA-519/SA-299).

Creep data were analyzed using E^2G's proprietary Lot-Centered Analysis web-based software tool, in order to obtain creep properties. This regression is based on a Mandel-Paule algorithm and considers the variation within individual heats of material (for both rupture and strain rate data) as well as the variation between heats. The weight assigned to each datapoint and each heat is scaled based on the relative variation. Both rupture and strain rate (minimum creep rate, expressed as true strain per hours) were regressed according to a Larson-Miller time-temperature-parameter model, with a 3rd-order polynomial of stress. Lot-specific constant behavior was accounted for in this analysis, but the variation of LMP with stress was assumed to be constant (no non-parallel terms were included in the analysis). A 95% predictive limit was utilized to obtain the lower-bound (minimum LM constant for both rupture and strain rate) properties. The results of this analysis are summarized in Table 10-1 for rupture data and Table 10-2 for strain rate data. The Lot-Centered Analysis software tool generates property tables in the creep regime using the criteria outlined in Mandatory Appendix 1 of ASME Section II-D; the nomenclature of variables is consistent with II-D Appendix 1. For visualization of the allowable stress trends, Figure 10-13 is provided (for rupture allowable stresses and creep rate allowable stresses). Figure 10-14 shows a comparison of the various allowable stress criteria from Section II-D, Appendix 1, to the existing (2019) Section II-D Table 1A allowable stresses for SA-213 T22 seamless tube.

Creep Strain vs. time data are shown in Figures 10-15, 10-16, and 10-17. Both creep rate and creep strain vs. time data are provided to satisfy ASME's request for creep strain vs. time curves, and both forms of data are applicable in developing allowable stresses. Although digitalization of creep curve data was not explicitly necessary per the project contract, E^2G did perform digitalization of creep curves where only graphical data was available (as is often the case in the published literature).

10.4 Continuous Cycling Fatigue Curves

A limited amount of continuous cycling fatigue data was available for Grade 22 material. A plot of the continuous cycling fatigue strain range vs. cycles to failure is shown Figure 10-18 at elevated temperatures. This plot only contains data for which total strain range was determined from the original source. One source of hold time fatigue data was located for Grade 22, as shown in Figure 10-19 and Figure 10-20.

Table 10-1: Model Parameters, Larson-Miller Property Results, and Allowable Stress (Rupture) Criteria, Grade 22

Equation Format:

$$\log(t_r) = C_{avg} + \frac{1}{T+460}\left(b_1 + b_2\log(\sigma) + b_3(\log(\sigma))^2 + b_4(\log(\sigma))^3\right)$$

C_{avg}	**-16.85**
C_{min}	**-17.51**
b_1	**36564**
b_2	**-2468.9**
b_3	**-1655.1**
b_4	**-369.8**

Number Data Points		**3544**
Correlation Coefficient	R^2	0.7492
Average Variance within Heats	V_w	0.1601
Variance between Heats	V_b	0.3105
Standard Error of Estimate	SEE	0.4002

Properties provided are for T in °F, stress in ksi, and t_R in hours

Temperature, °F	**S_{avg} (ksi)**	***n***	**F_{avg} (calc)**	**F_{avg} (used)**	**$F_{avg} \times S_{avg}$**	**S_{min} (ksi)**	**80% S_{min}**
850	26.53	7.199	0.7263	0.67	17.77	21.33	17.06
900	20.08	6.371	0.6967	0.67	13.46	15.67	12.54
950	14.81	5.578	0.6618	0.67	9.924	11.13	8.905
1000	10.56	4.809	0.6195	0.67	7.076	7.553	6.043
1050	7.2	4.055	0.5667	0.67	4.824	4.805	3.844
1100	4.605	3.303	0.498	0.67	3.086	2.762	2.21
1150	2.667	2.535	0.4031	0.67	1.787	1.315	1.052
1200	1.284	1.712	0.2605	0.67	0.8605	0.3561	0.2848
1250	0.3584	0.71	0.03904	0.67	0.2401	0.1	0.08
1300	0.1	0.1524	2.75E-07	0.67	0.067	0.1	0.08

Table 10-2: Model Parameters, Larson-Miller Property Results, and Allowable Stress (Strain Rate) Criteria, Grade 22

Equation Format:

$$\log(\dot{\varepsilon}_0) = -C_{avg} - \frac{1}{T+460}\left(a_1 + a_2\log(\sigma) + a_3(\log(\sigma))^2 + a_4(\log(\sigma))^3\right)$$

C_{avg} (A_0)	**-17.08**
C_{min} ($A_0+\Delta_\Omega^{SR,LB}$)	**-17.94**
a_1	**44324.4**
a_2	**-7718**
a_3	**-180.6**
a_4	**-363.6**

Number Data Points		**767**
Correlation Coefficient	R^2	0.6302
Average Variance within Heats	V_w	0.2741
Variance between Heats	V_b	1.438
Standard Error of Estimate	SEE	0.5236

Properties provided are for T in °F, stress in ksi, and t_R in hours

Temperature, °F	**$S_{C,avg}$ (ksi)**
850	49.88
900	39.82
950	31.54
1000	24.77
1050	19.29
1100	14.89
1150	11.38
1200	8.626
1250	6.477
1300	4.819

Figure 10-1: Grade 22 Modulus (E_y), Thermal Conductivity (k), Thermal Diffusivity (TD), & Thermal Expansion (α) With Temperature

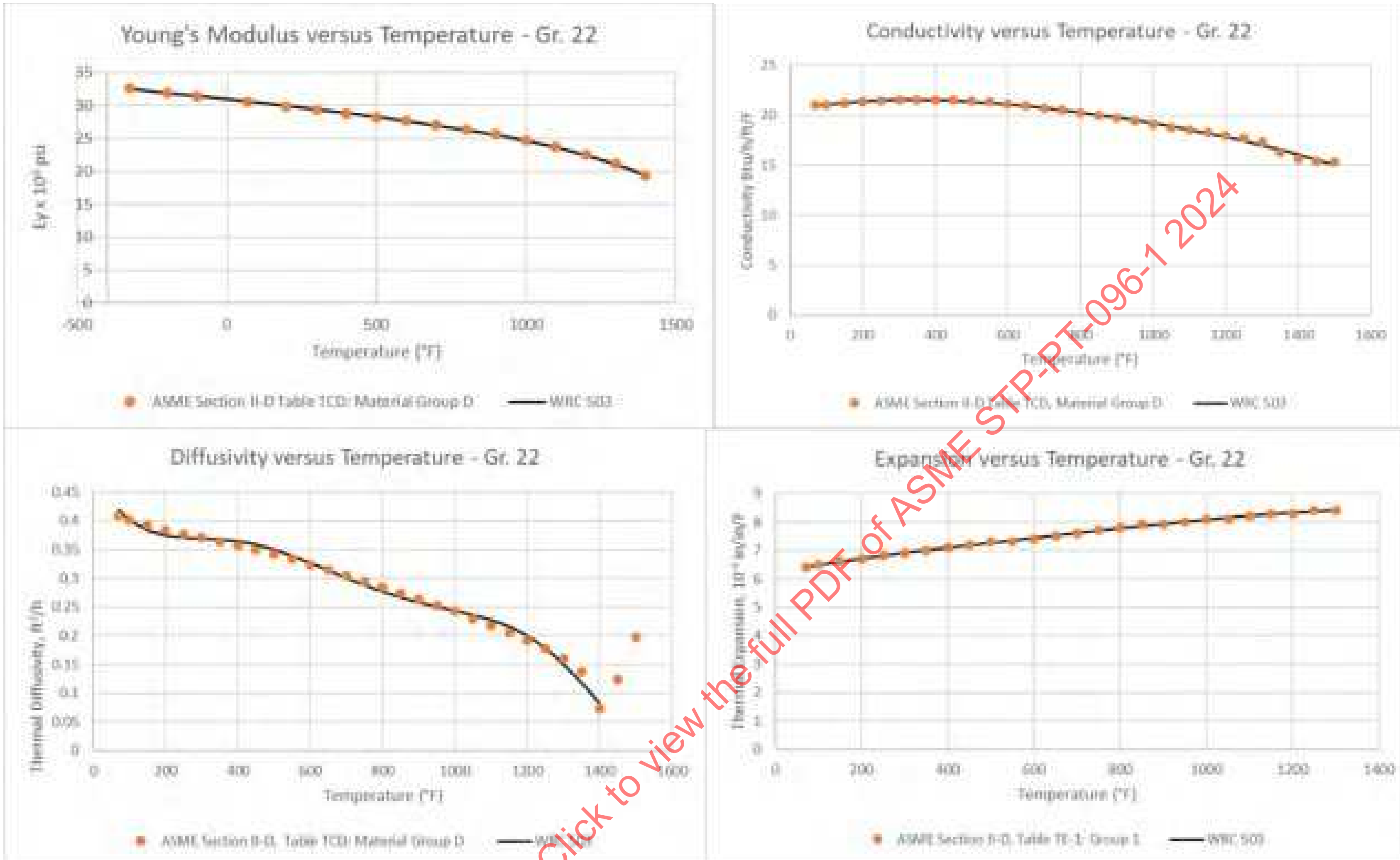


Figure 10-2: Grade 22 (All Heat Treatments) Yield Strength Vs. Temperature, By Data Source, Including Trend Curves

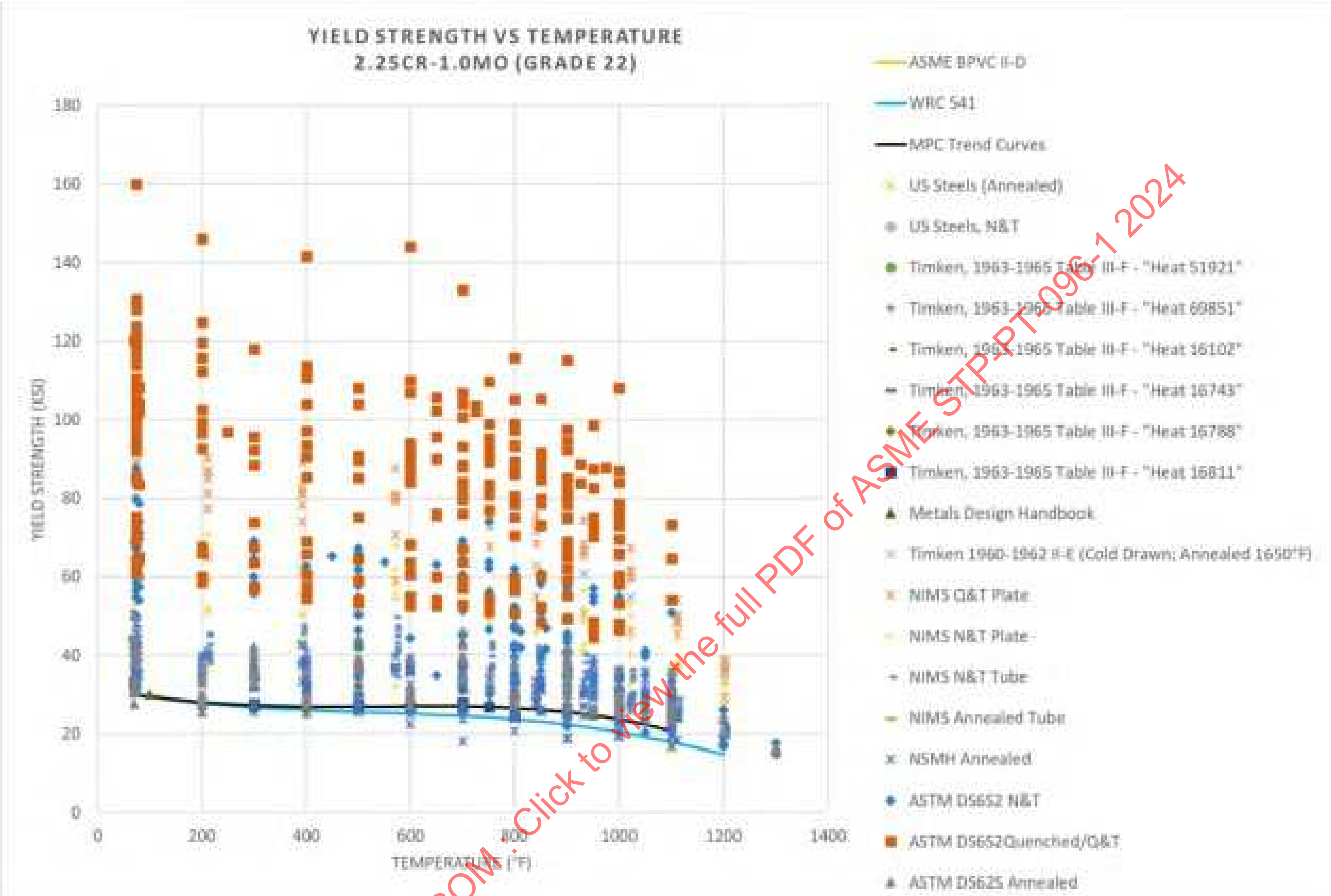


Figure 10-3: Grade 22 (All Heat Treatments) Tensile Strength Vs. Temperature, By Data Source, Including Trend Curves

Figure 10-4: Grade 22 (All Heat Treatments) Yield Strength Ratios Vs. Temperature (Calculated on a Heat-By-Heat Basis)

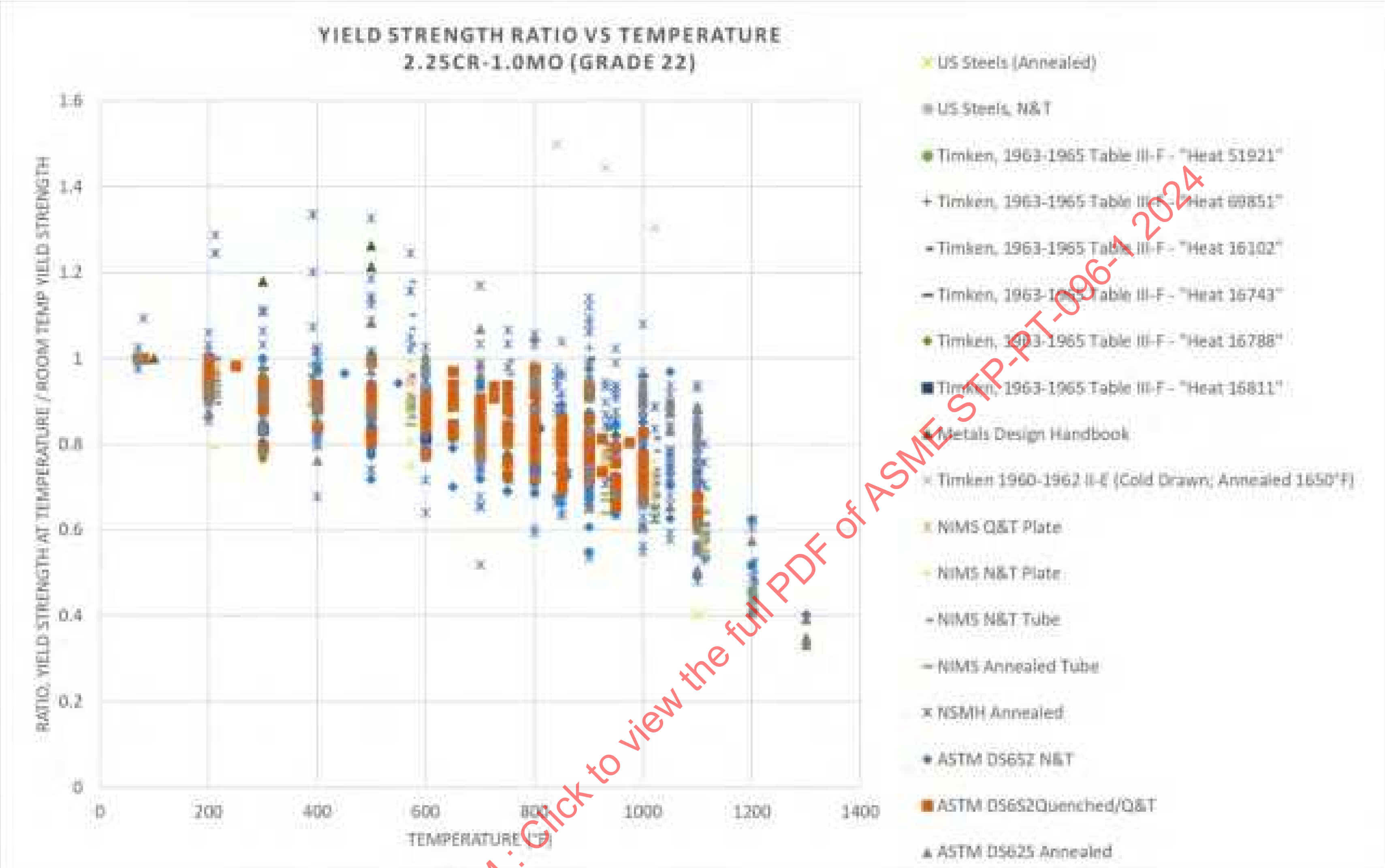


Figure 10-5: Grade 22 (All Heat Treatments) Tensile Strength Ratios Vs. Temperature (Calculated on a Heat-By-Heat Basis)

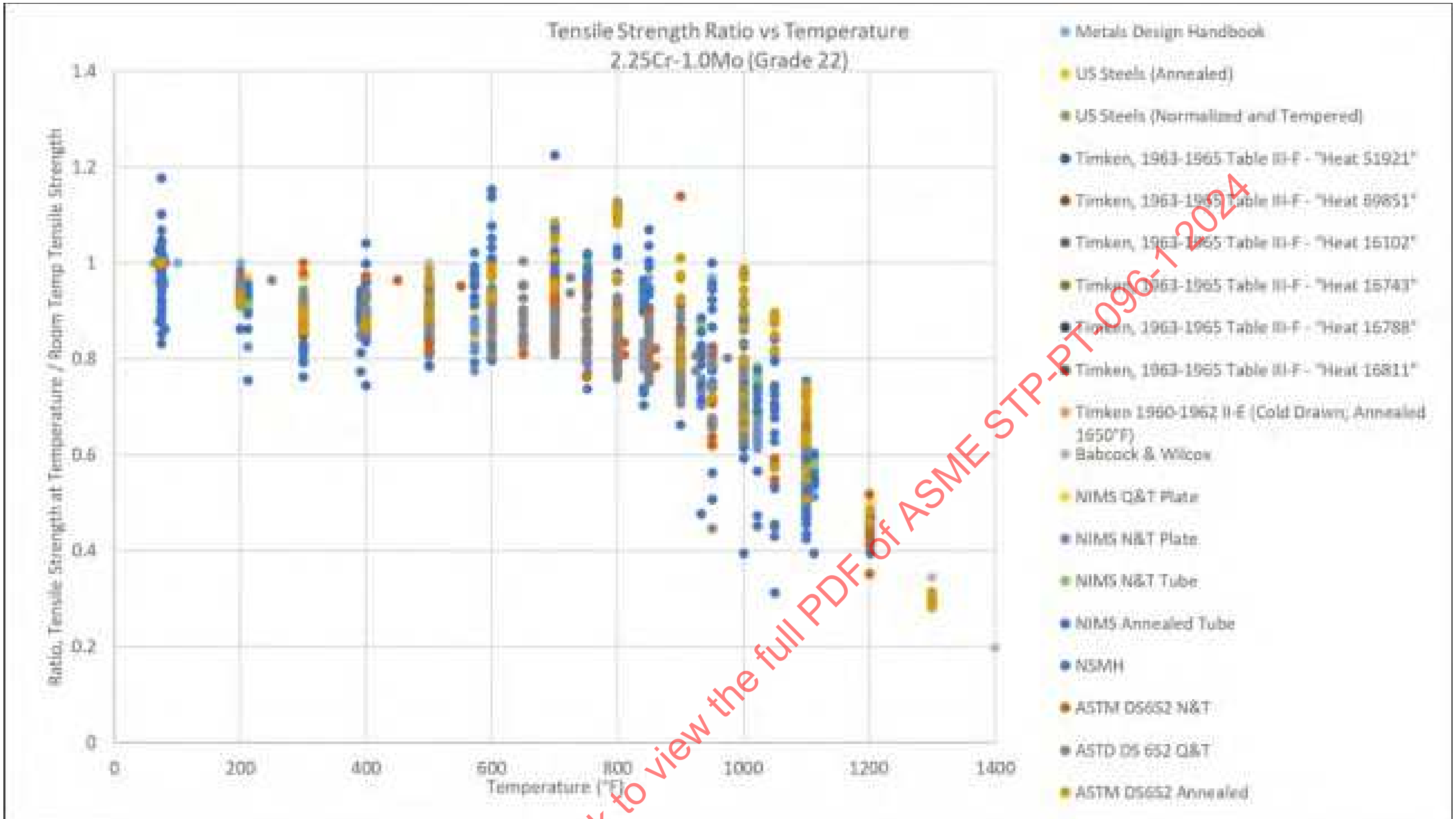


Figure 10-6: Grade 22 (All Heat Treatments) Yield Strength Ratios Vs. Temperature, All Combined Data, With Polynomial Regression

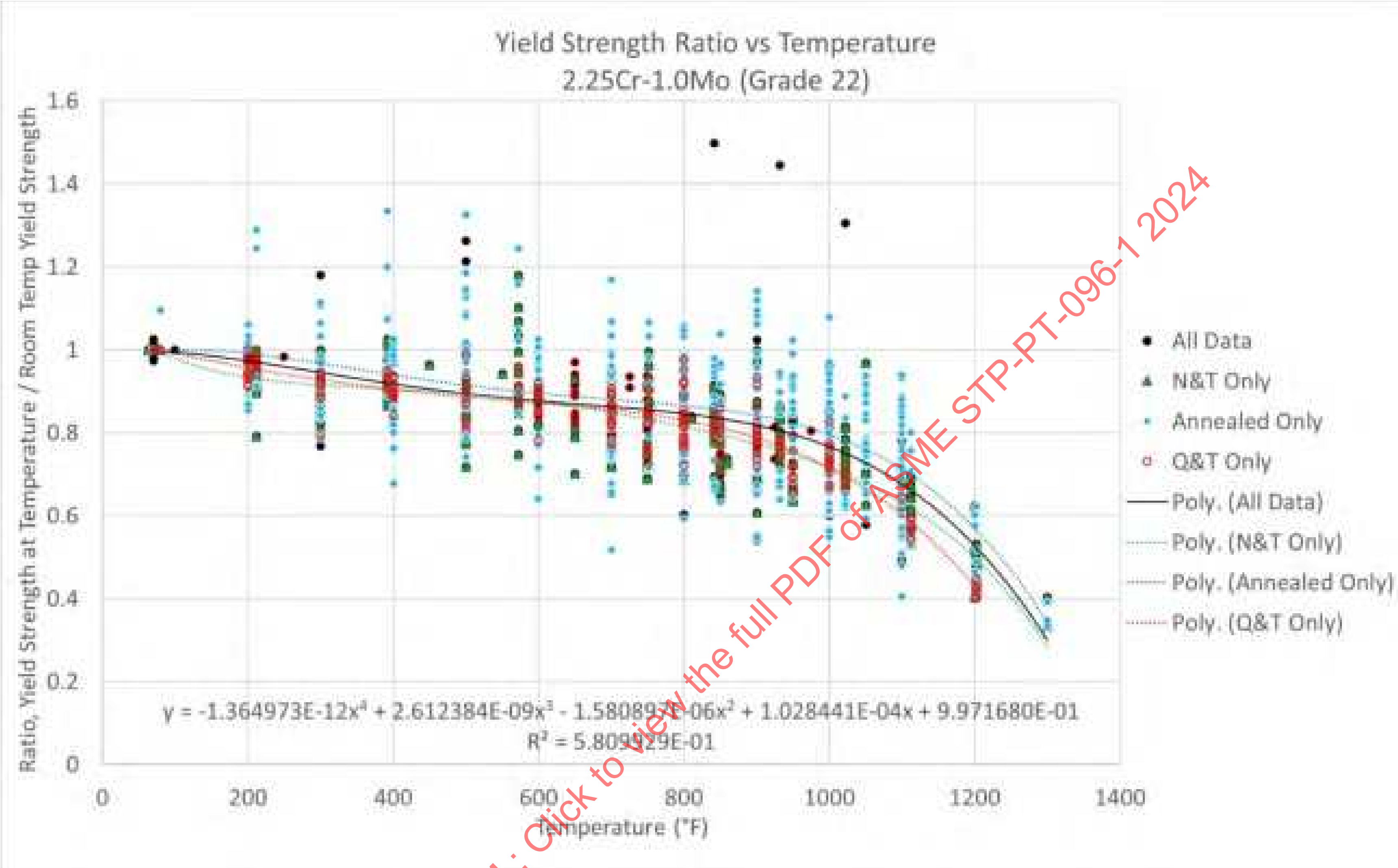


Figure 10-7: Grade 22 (All Heat Treatments) Tensile Strength Ratios Vs. Temperature, All Combined Data, With Polynomial Regression

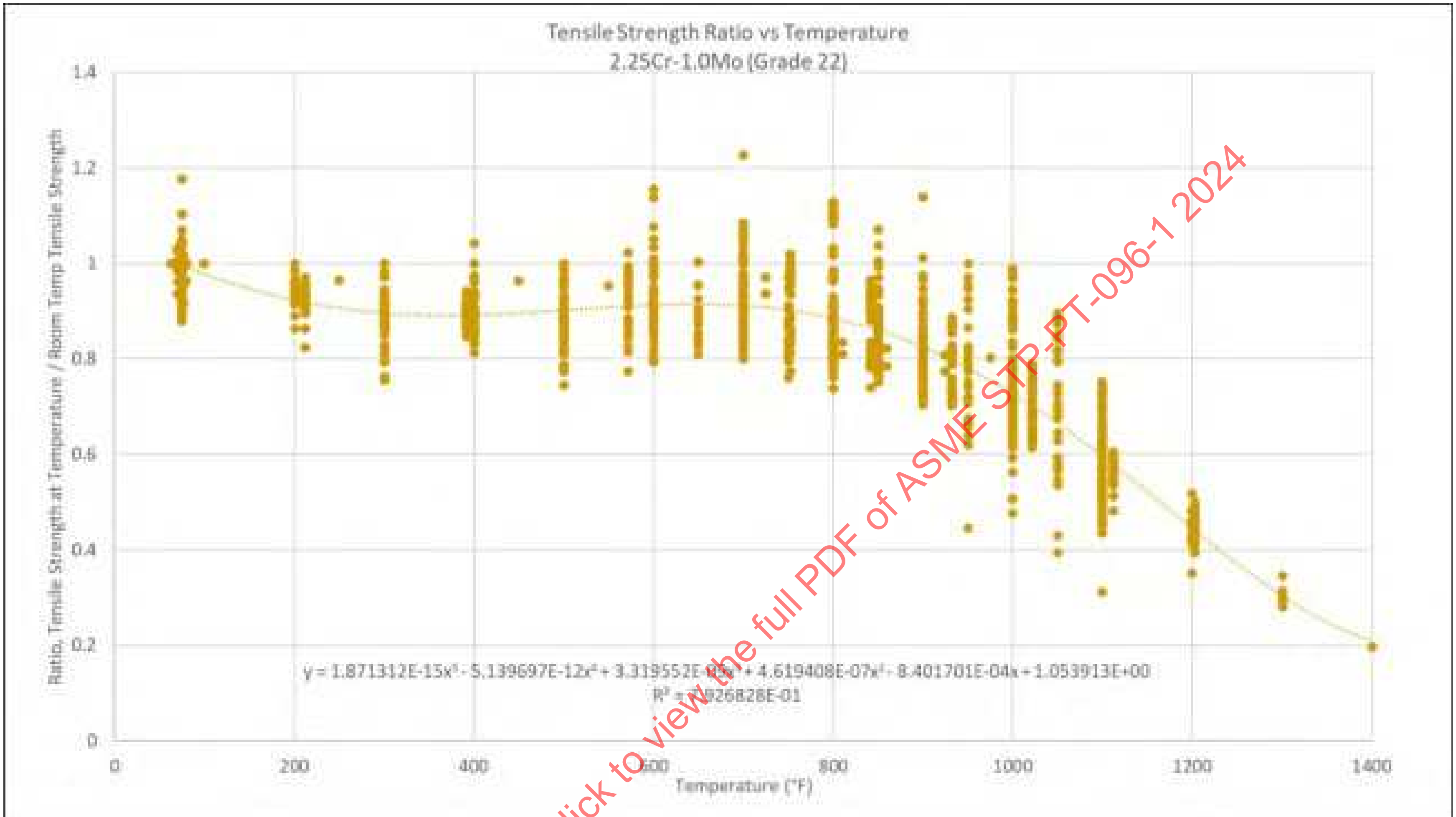


Figure 10-8: Grade 22 Creep Rupture Isotherm Curves, Temperatures With High Concentration of Data Points

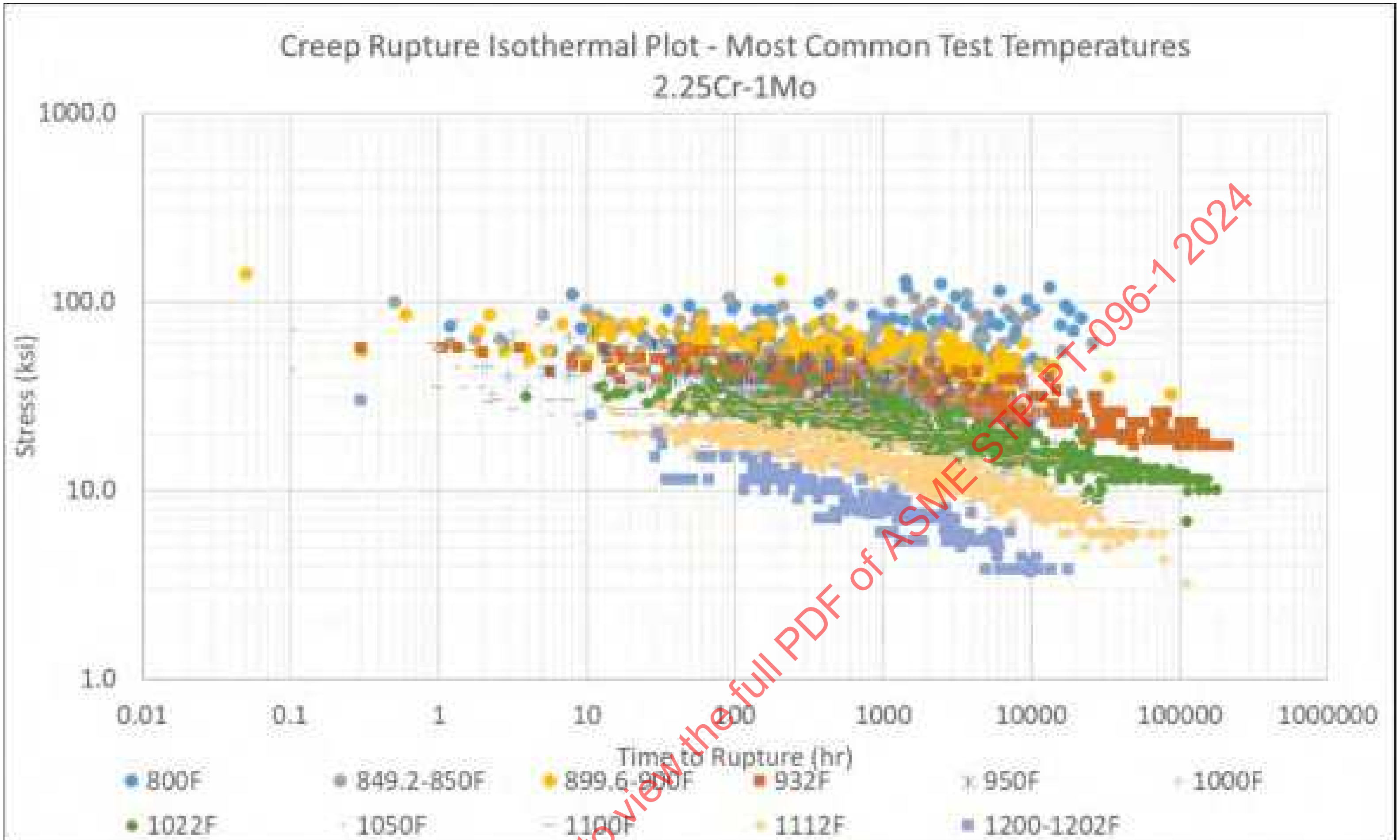


Figure 10-9: Grade 22 Creep Rupture Isotherm Curves for Additional and Intermediate Temperatures

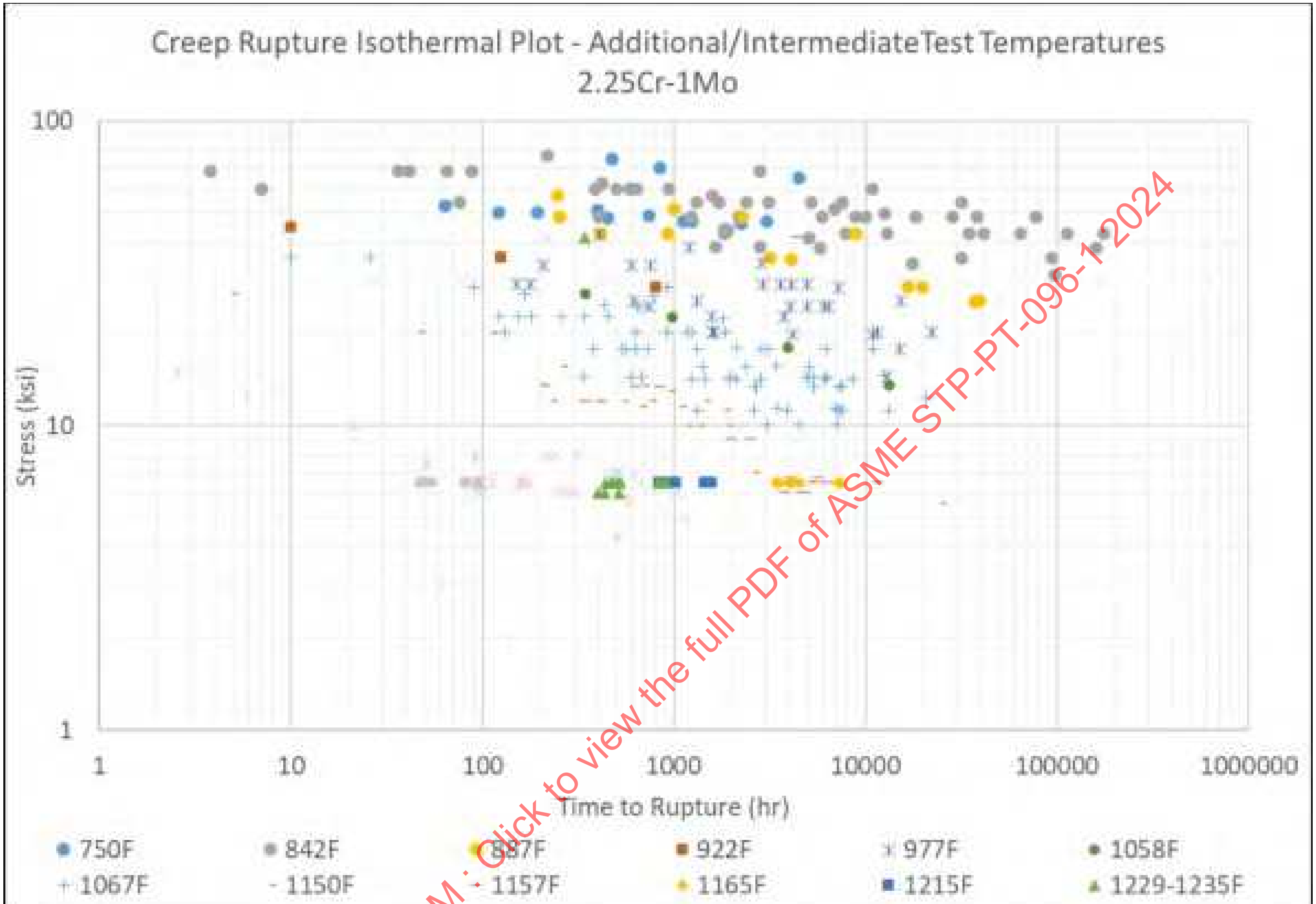


Figure 10-10: Grade 22 Creep Strain Rate (MCR) Isotherm Curves for Most Common Temperatures

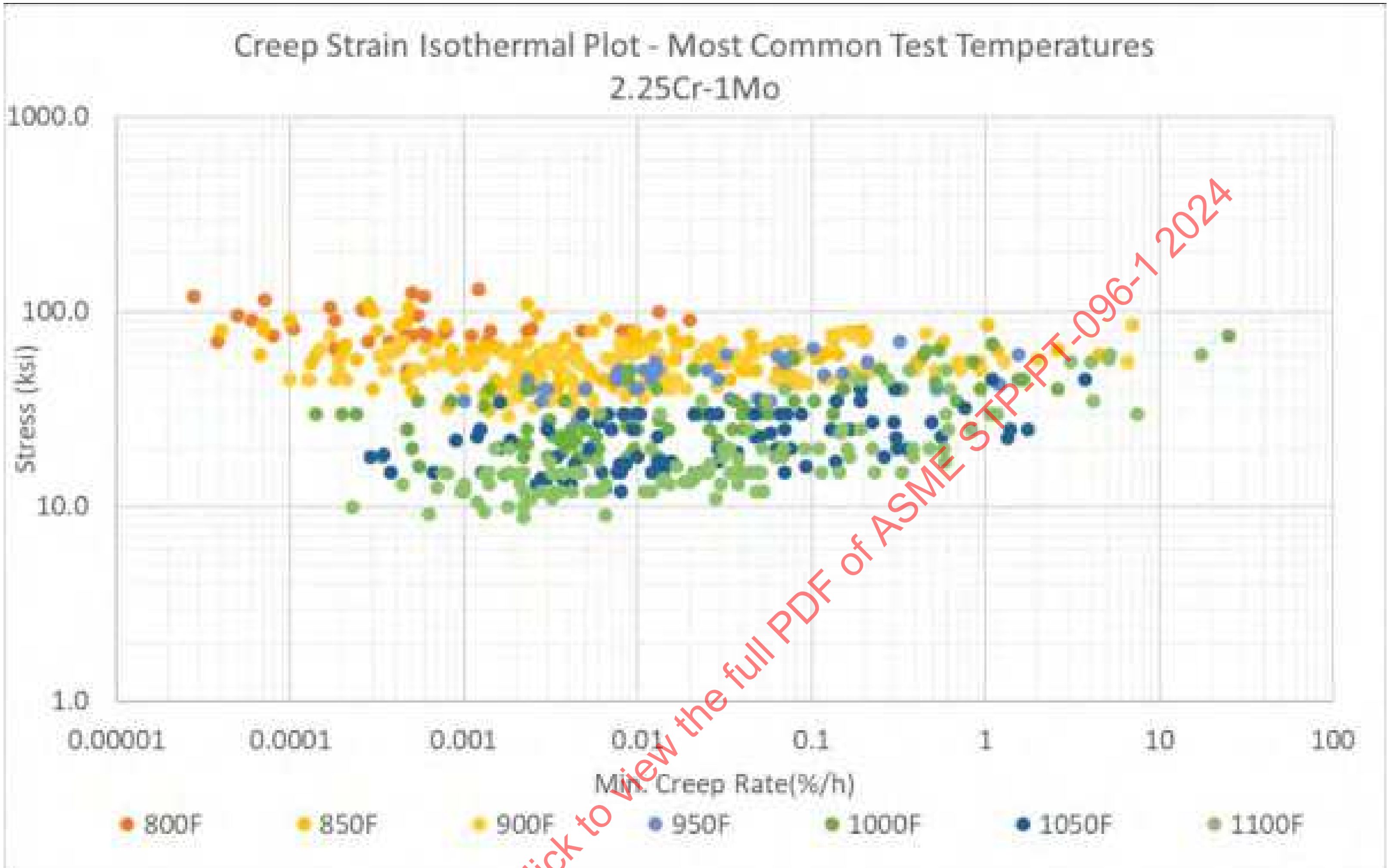


Figure 10-11: Grade 22 Creep Strain Rate (MCR) Isotherm Curves for Additional/Intermediate Temperatures

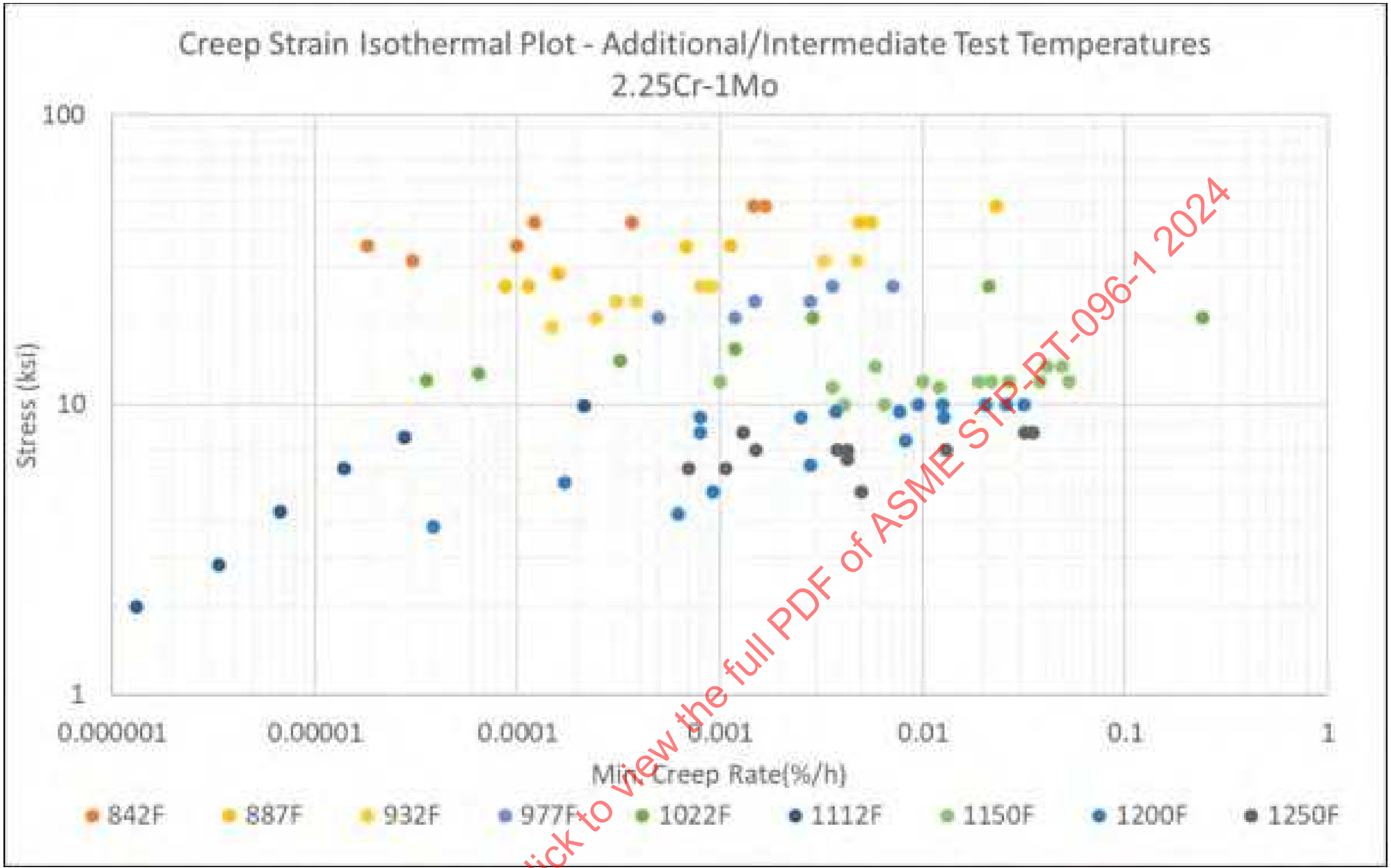


Figure 10-12: Grade 22 Creep Ductility (% Elongation) Vs. Rupture Time Isotherms

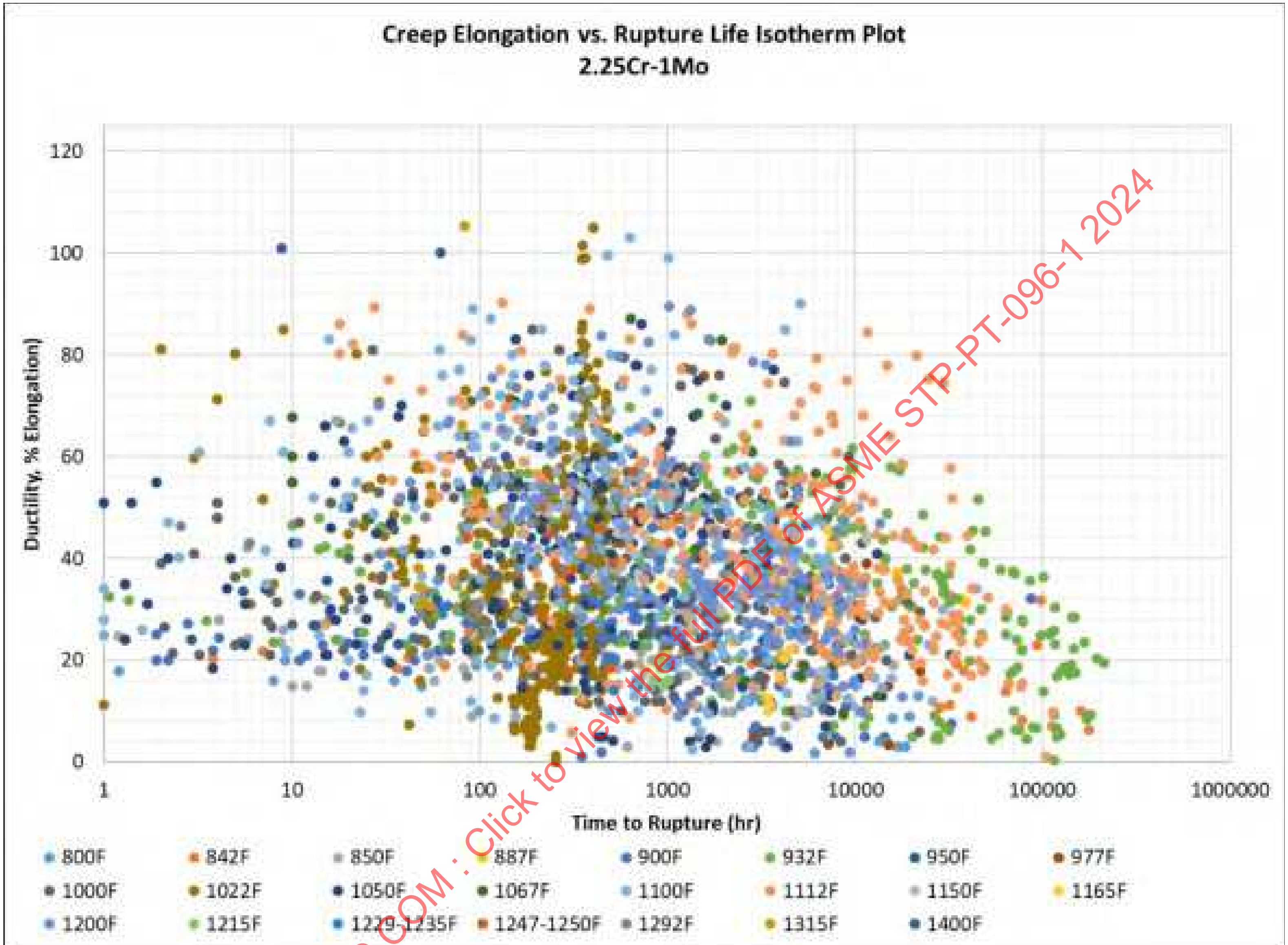


Figure 10-13: Calculated Allowable Stresses Based On Rupture and Creep Strain Rate and ASME II-D Appendix 1 Criteria (Grade 22)

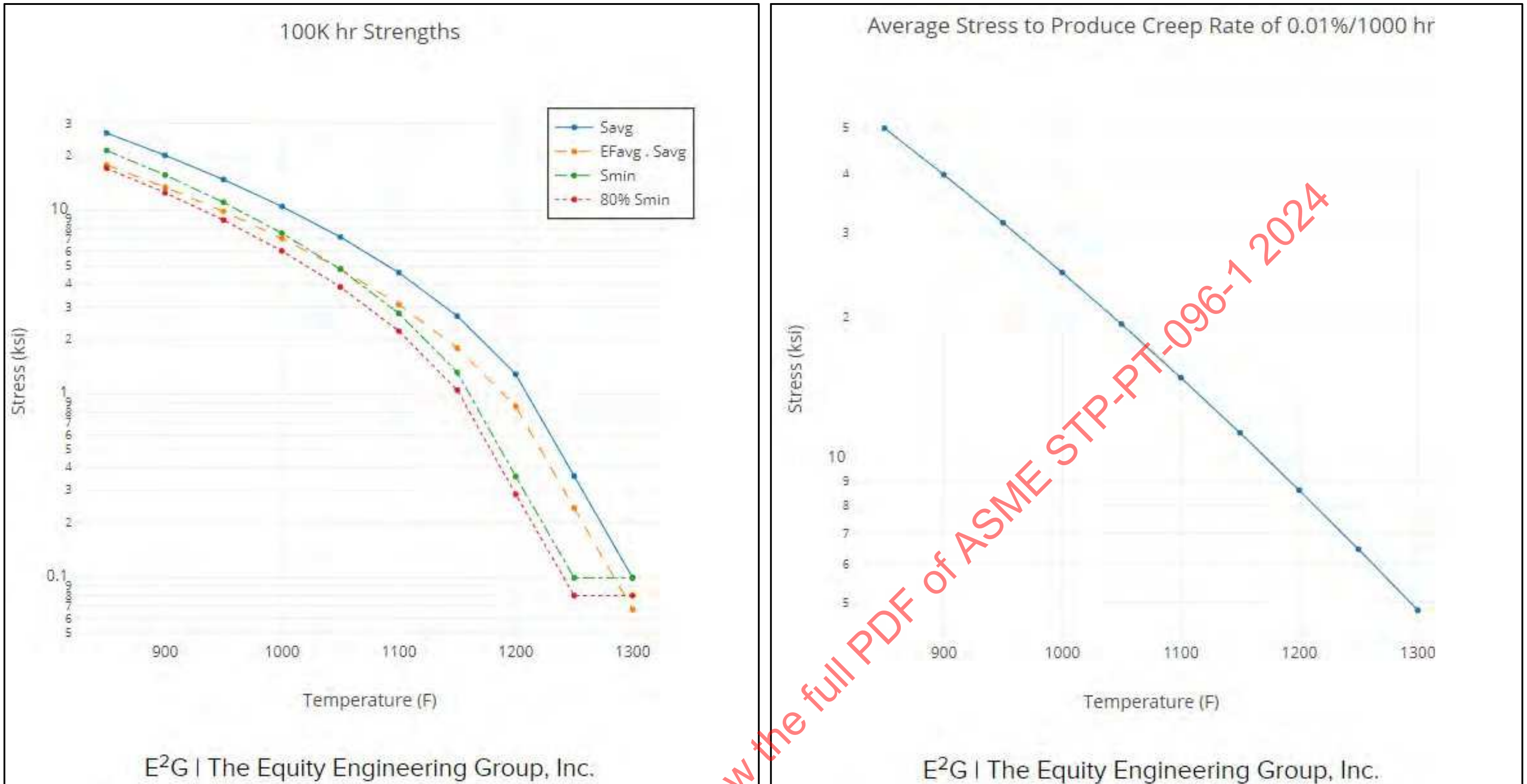


Figure 10-14: Comparison of Current Grade 22 Allowable Stresses Vs. ASME II-D Appendix 1 Criteria Applied to Data

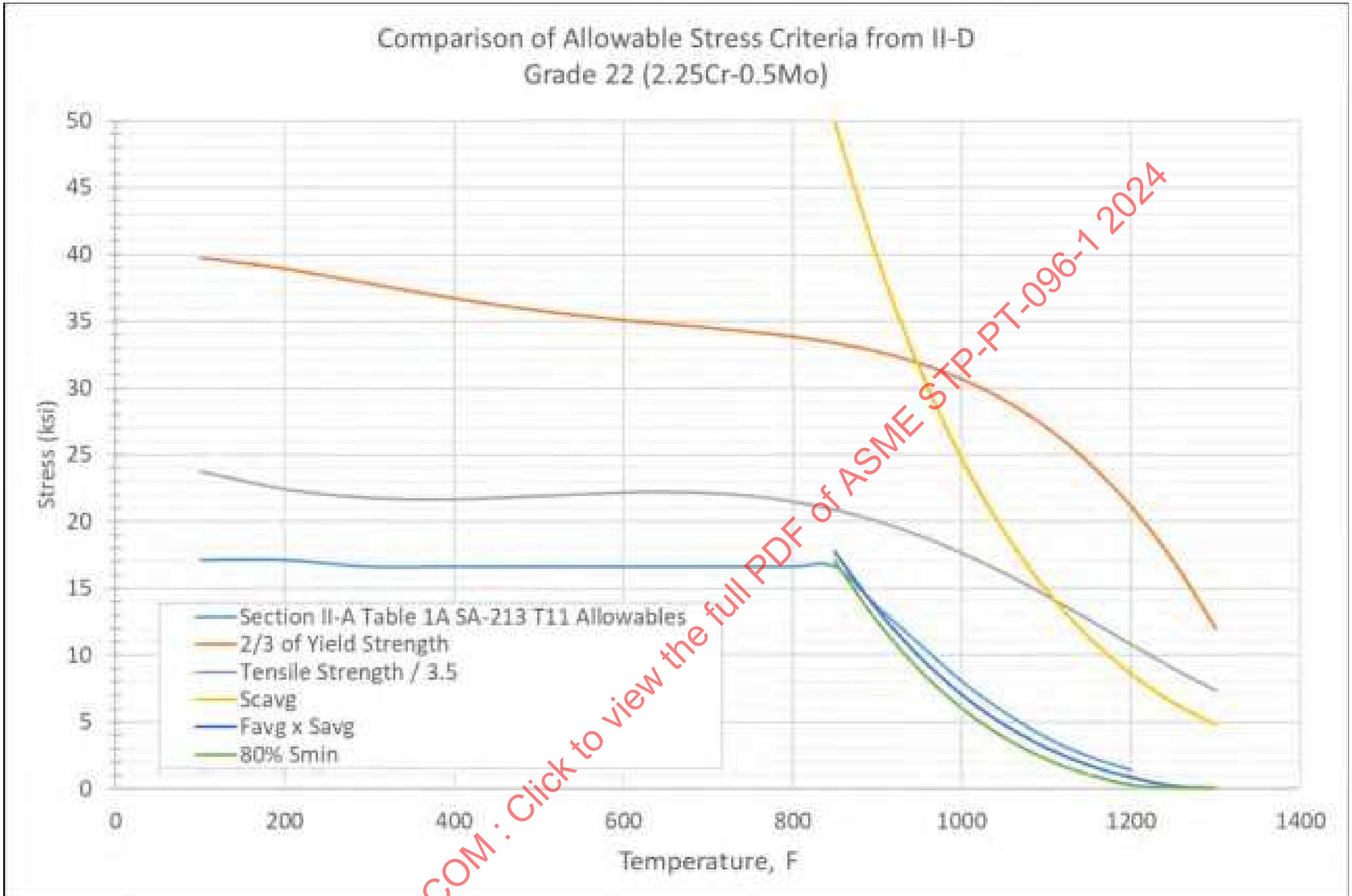


Figure 10-15: Creep Strain Vs. Time Data, (Grade 22) 1 of 3

Figure 10-16: Creep Strain Vs. Time Data, (Grade 22) 2 of 3

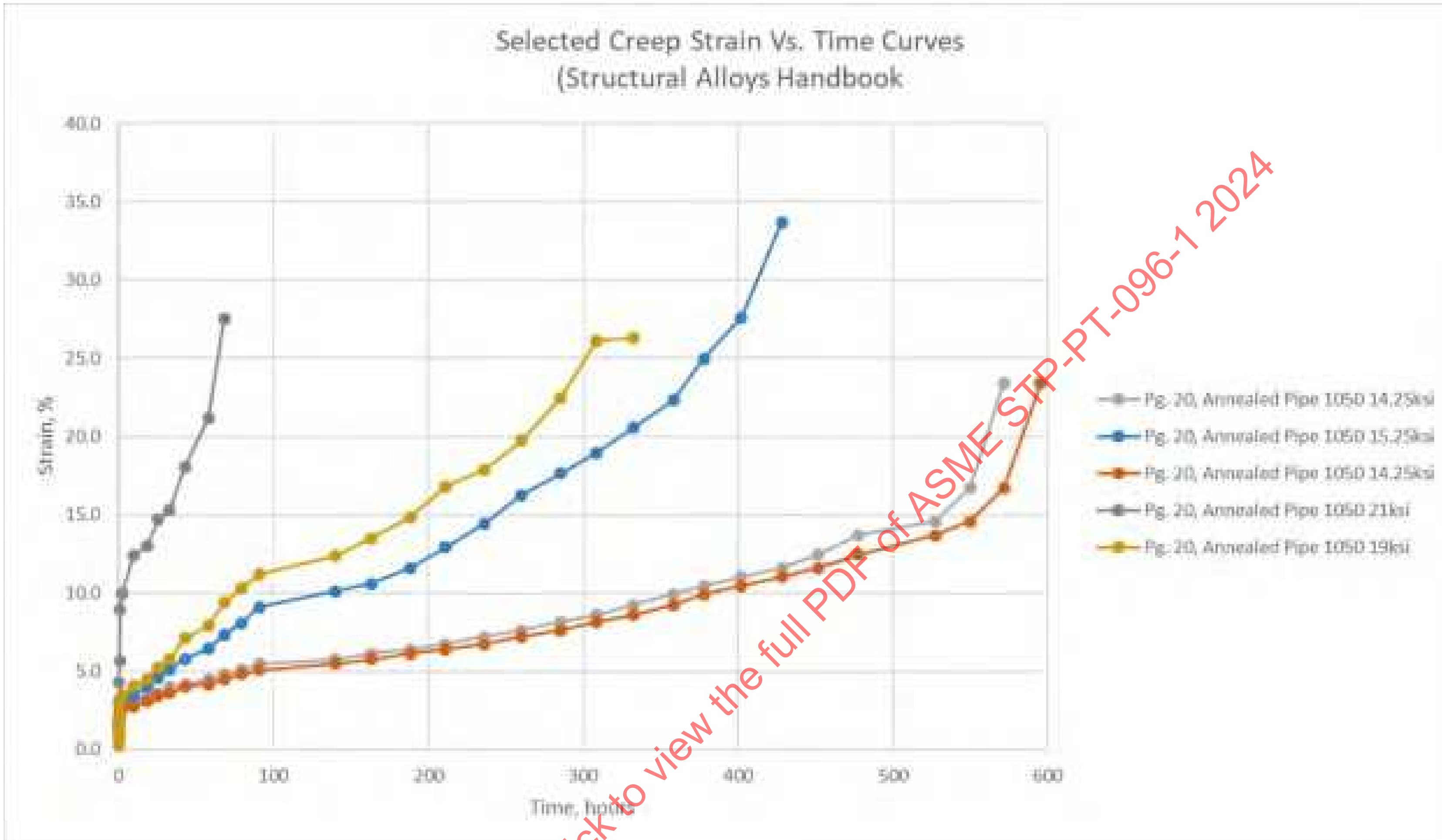


Figure 10-17: Creep Strain Vs. Time Data, (Grade 22) 3 of 3

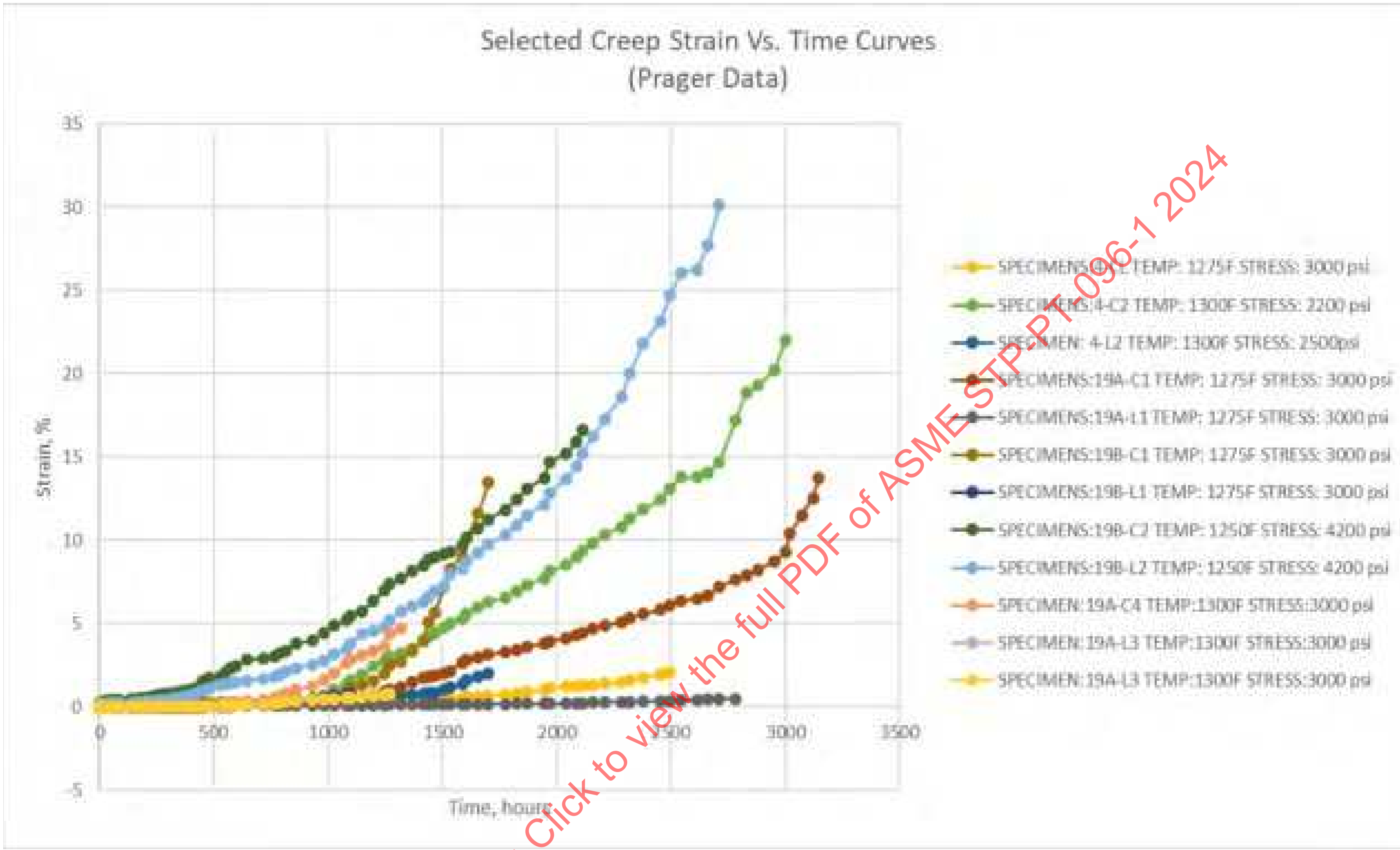


Figure 10-18: Grade 22 Continuous Cycling Fatigue, Including Room Temperature and Elevated Temperature Data

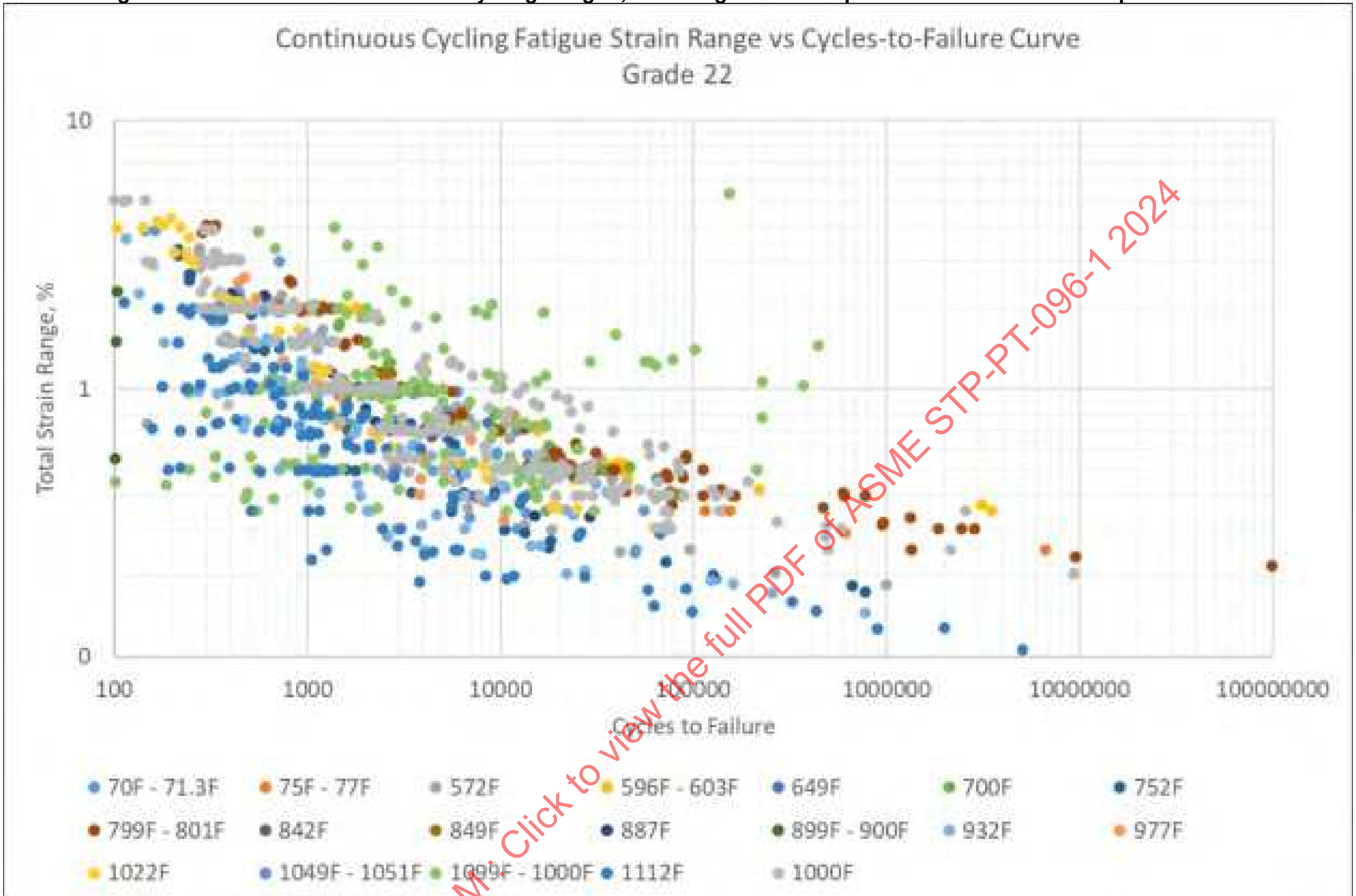


Figure 10-19: Grade 22 Hold Time Fatigue Data at Selected Elevated Temperatures, 1 of 2

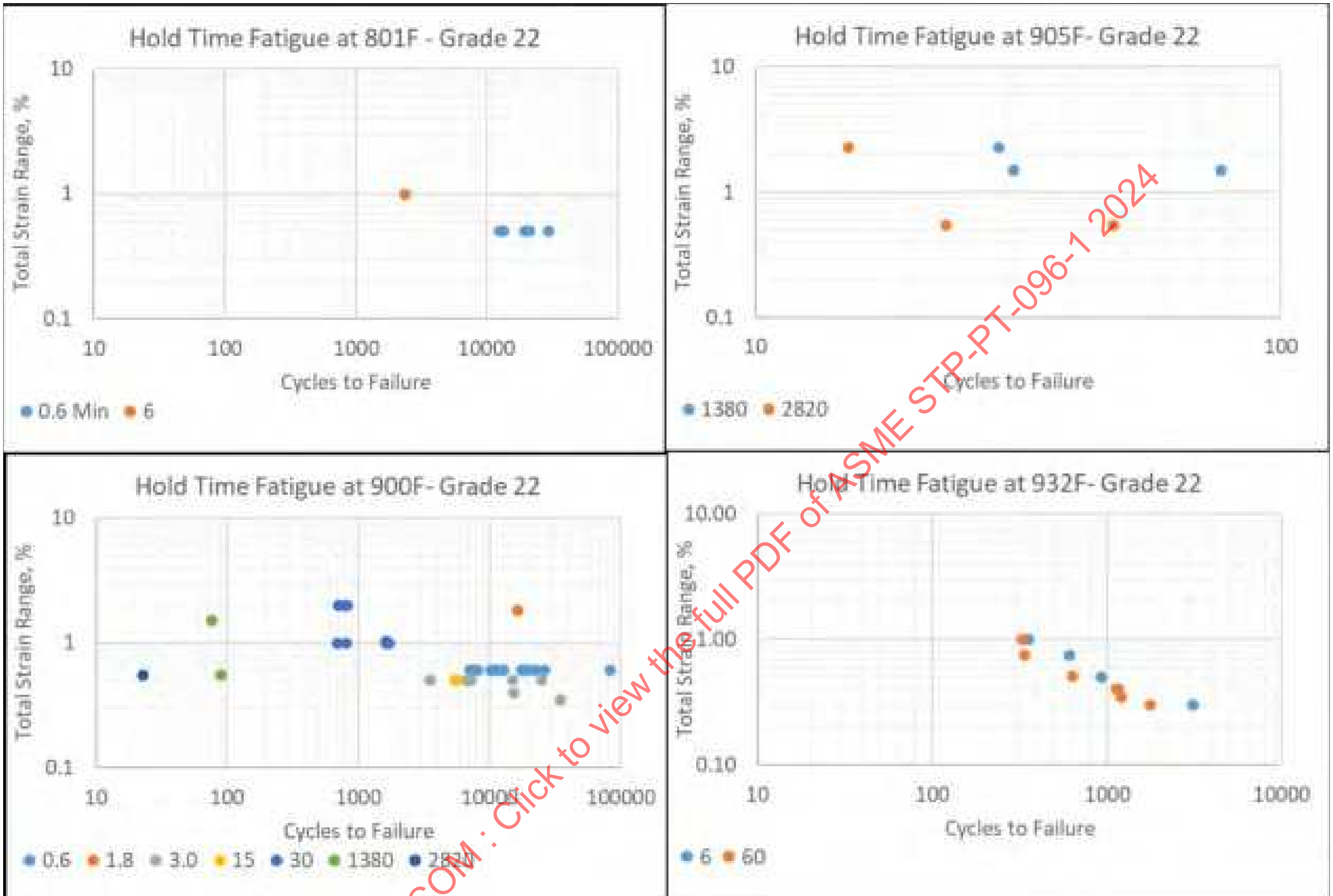
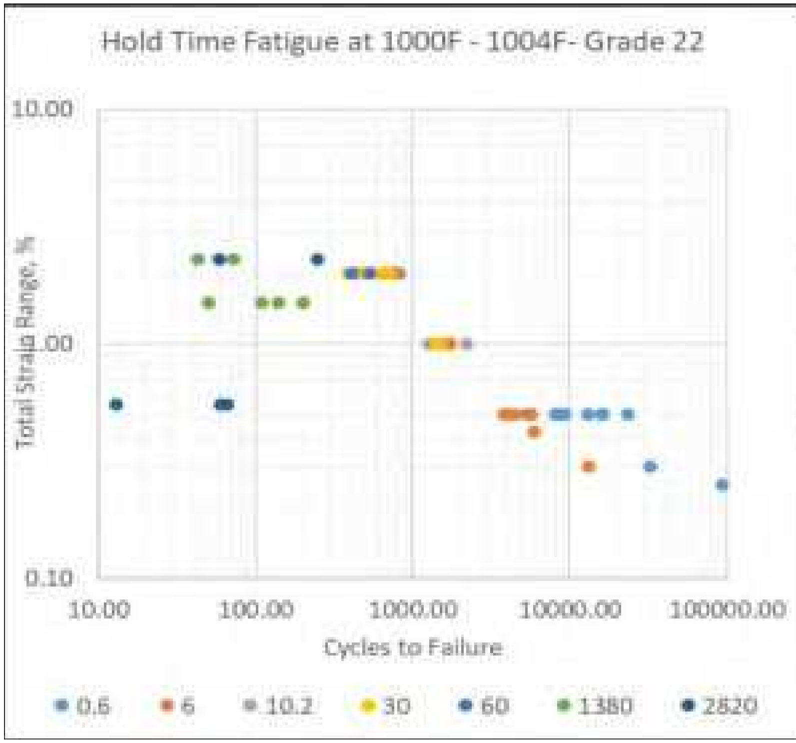
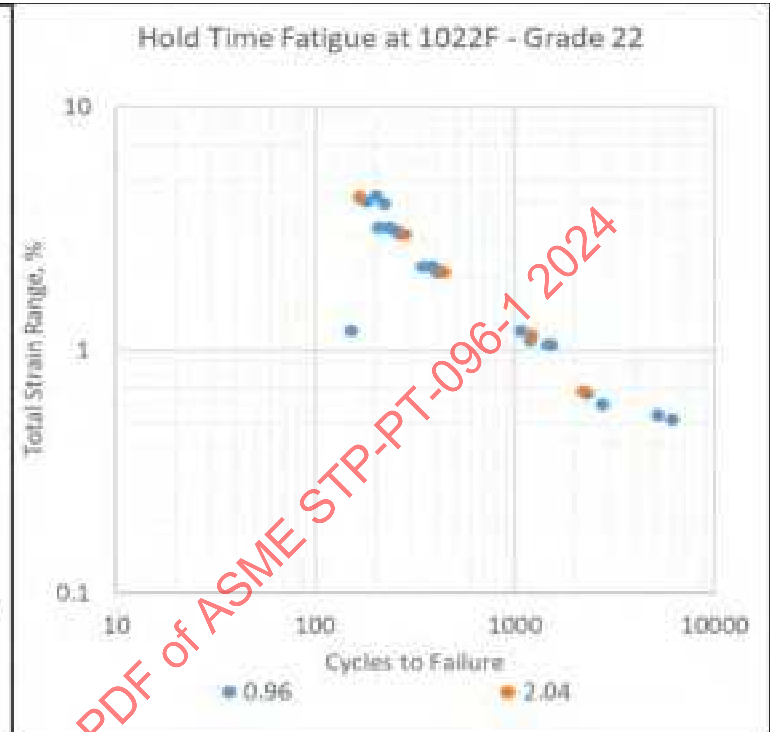


Figure 10-20: Grade 22 Hold Time Fatigue Data at Selected Elevated Temperatures, 2 of 2





Attachment 10: Grade 22 Property Data

If you want the referenced embedded spreadsheet with additional data, please email a request to research@asme.org.

11 GRADE 22V (2.25CR-1MO-V)

11.1 Physical Properties

Well-established physical properties were referenced from the BPVC Section II for this material. Physical property curves from WRC Bulletin 503 were plotted for comparison as well. Figure 11-1 shows the trends of Elastic Modulus (Ey), Thermal Conductivity (k), Thermal Diffusivity (TD), and Thermal Expansion (α) with temperature.

11.2 Yield and Tensile Strength

Elevated temperature Yield and Tensile Strength over the range of existing allowable stresses (up to 900°F) were readily available, including data beyond the current range of allowable stresses, up to approximately 1200°F, as shown in Figures 11-2 and 11-3. The sources for both high-temperature yield and high-temperature tensile strength are provided in the embedded spreadsheet at the end of this section. This spreadsheet also contains ductility data corresponding to the tensile test results presented in this report. Note that ductility (percent elongation and percent reduction in area) was not available for all sources referenced for the Grade 22V material.

To facilitate comparison of the data obtained to existing allowable stresses (Section II-D Table 1A), yield and tensile data were normalized on a heat-by-heat basis to express the ratio of yield or tensile strength at temperature to that measured for the heat at room temperature. In cases where data were not delineated by heats within a given source, or in cases where more than one room-temperature tensile test existed for a given heat of material, ratios are equal to the measured tensile or yield strength at temperature, divided by the average of all of the appropriate room-temperature values for the particular data source or heat of material. As a result of this approach, it is possible to have ratios in excess of 1.0. E^2G understands that this approach is similar to the normalizing procedure performed by ASME in typical analysis of yield and tensile data to obtain Table Y and Table U (Section II-D) trend curves, as well as for the calculation of allowable stresses. Figures 11-4 and 11-5 show the heat-by-heat variation in yield and tensile strength ratios (respectively) as a function of temperature. It should be emphasized that even though the figure legends reference an entire source of data, the ratios, wherever possible, were calculated on a heat-by-heat basis; this is evident in the embedded spreadsheet at the end of this section. Figures 11-6 and 11-7 contain all of the yield and tensile (respectively) ratios plotted together, to facilitate regression of a polynomial that is subsequently used for allowable stress comparison.

11.3 Creep Data (Creep Rupture, Minimum Creep Rate, and Ductility)

Creep Rupture data is shown in Figures 11-8 and 11-9, plotted as isotherms. The temperatures have been separated onto separate plots to minimize data overlap, with Figure 11-8 showing those temperatures where most of the data were concentrated, and Figure 11-9 showing those temperatures with significantly less data. It should be emphasized that these plots contain data for all product forms of material classified in the referenced publications as "Grade 22V." Where possible, E^2G has documented the chemical composition if contained within the original source. In many cases, the project team has also made efforts to trace cross-referenced data back to original test results to determine if the heat treatment, product form, chemistry, etc. details can be obtained. This information is provided with the embedded spreadsheet to facilitate additional analysis on the part of ASME.

Creep Minimum strain rates (%/hour) are shown in Figure 11-10 separated by temperature. Due to the minimum creep rate data acquired being limited to only a few different temperatures, all minimum creep rate data has been included on one plot. Creep Ductility, as % elongation, is plotted in Figure 11-11. As is typical, the data show significant overlap, and it is difficult to observe clear trends in the data. The data is not intended to be used as plotted but is available in the spreadsheet for additional analysis.

Creep data were analyzed using E^2G's proprietary Lot-Centered Analysis web-based software tool, in order to obtain creep properties. This regression is based on a Mandel-Paule algorithm and considers the variation within individual heats of material (for both rupture and strain rate data) as well as the variation between heats. The weight assigned to each datapoint and each heat is scaled based on the relative variation. Both rupture and strain rate (minimum creep rate, expressed as true strain per hours) were regressed according to a Larson-Miller time-temperature-parameter model, with a 3rd-order polynomial of stress. Lot-specific constant behavior was accounted for in this analysis, but the variation of LMP with stress was assumed to be constant (no non-parallel terms were included in the analysis). A 95% predictive limit was utilized to obtain the lower-bound (minimum LM constant for both rupture and strain rate) properties. The results of this analysis are summarized in Table 11.1 for rupture data and Table 11.2 for strain rate data. The Lot-Centered Analysis software tool generates property tables in the creep regime using the criteria outlined in Mandatory Appendix 1 of ASME Section II-D; the nomenclature of variables is consistent with II-D Appendix 1. For visualization of the allowable stress trends, Figure 11-12 is provided (for rupture allowable stresses and creep rate allowable stresses). Figure 11-13 shows a comparison of the various allowable stress criteria from Section II-D, Appendix 1, to the existing (2019) Section II-D Table 1A allowable stresses for all product forms of Grade 22V (up to the Table 1A limit of 900°F).

Creep Strain vs. time data are shown in Figures 11-14 through 11-20. Both creep rate and creep strain vs. time data are provided to satisfy ASME's request for creep strain vs. time curves, and both forms of data are applicable in developing allowable stresses. Although digitalization of creep curve data was not explicitly necessary per the project contract, E^2G did perform digitalization of creep curves where only graphical data was available (as is often the case in the published literature).

11.4 Continuous Cycling Fatigue and Hold Time Fatigue Curves

A portion of the data obtained for continuous cycling fatigue data at elevated temperatures for Grade 22V is shown in Figure 11-21 only contains data for which total strain range was determined from the original source. Hold time fatigue data at high temperature is shown in Figure 11-22 (850°F). Due to the acquired hold time fatigue data for Grade 22V all being at the same temperature (850°F), only one plot including the several different hold times has been included. Additional data is provided in the embedded spreadsheet.

Table 11-1: Model Parameters, Larson-Miller Property Results, and Allowable Stress (Rupture) Criteria, Grade 22V

Equation Format:

$$\log(t_r) = C_{avg} + \frac{1}{T+460}\left(b_1 + b_2\log(\sigma) + b_3(\log(\sigma))^2 + b_4(\log(\sigma))^3\right)$$

Cavg	**-19.18**
Cmin	**-19.55**
b_1	**127000**
b_2	**-170000**
b_3	**109700**
b_4	**-25492.6**

Number Data Points		**320**
Correlation Coefficient	R^2	0.8556
Average Variance within Heats	V_w	0.0492
Variance between Heats	V_b	0.1931
Standard Error of Estimate	SEE	0.2218

Properties provided are for T in °F, stress in ksi, and t_R in hours

Temperature, °F	**S_{avg} (ksi)**	***n***	**F_{avg} (calc)**	**F_{avg} (used)**	**Favg × Savg**	**S_{min} (ksi)**	**80% S_{min}**
850	41.95	11.75	0.8221	0.67	28.11	38.97	31.18
900	34.56	9.934	0.7931	0.67	23.16	31.7	25.36
950	27.89	8.998	0.7742	0.67	18.69	25.4	20.32
1000	22.45	9.045	0.7752	0.67	15.04	20.5	16.4
1050	18.39	9.855	0.7916	0.67	12.32	16.93	13.54
1100	15.45	11.08	0.8123	0.67	10.35	14.36	11.49
1150	13.31	12.45	0.8311	0.67	8.915	12.46	9.971
1200	11.69	13.83	0.8466	0.67	7.83	11.02	8.813
1250	10.43	15.16	0.8591	0.67	6.986	9.879	7.903
1300	9.419	16.41	0.8691	0.67	6.311	8.959	7.167

Table 11-2: Model Parameters, Larson-Miller Property Results, and Allowable Stress (Strain Rate) Criteria, Grade 22V

Equation Format:

$$\log(\dot{\varepsilon}_0) = -C_{avg} - \frac{1}{T+460}\left(a_1 + a_2\log(\sigma) + a_3(\log(\sigma))^2 + a_4(\log(\sigma))^3\right)$$

C_{avg} (A_0)	**-30.7**
Cmin (A0+ΔΩSR,LB)	**-31.12**
a_1	**8.94E+05**
a_2	**-1.534E+06**
a_3	**9.375E+05**
a_4	**-1.926E+05**

Number Data Points		**139**
Correlation Coefficient	R^2	0.8135
Average Variance within Heats	V_w	0.06498
Variance between Heats	V_b	0.31680
Standard Error of Estimate	SEE	0.25490

Properties provided are for T in °F, stress in ksi, and t_R in hours

Temperature, °F	$S_{C,avg}$ **(ksi)**
850	61.93
900	51.94
950	39.08
1000	30.89
1050	26.79
1100	24.19
1150	22.32
1200	20.87
1250	19.7
1300	18.71

Figure 11-1: Grade 22V Modulus (E_y), Thermal Conductivity (k), Thermal Diffusivity (TD), & Thermal Expansion (α) With Temperature

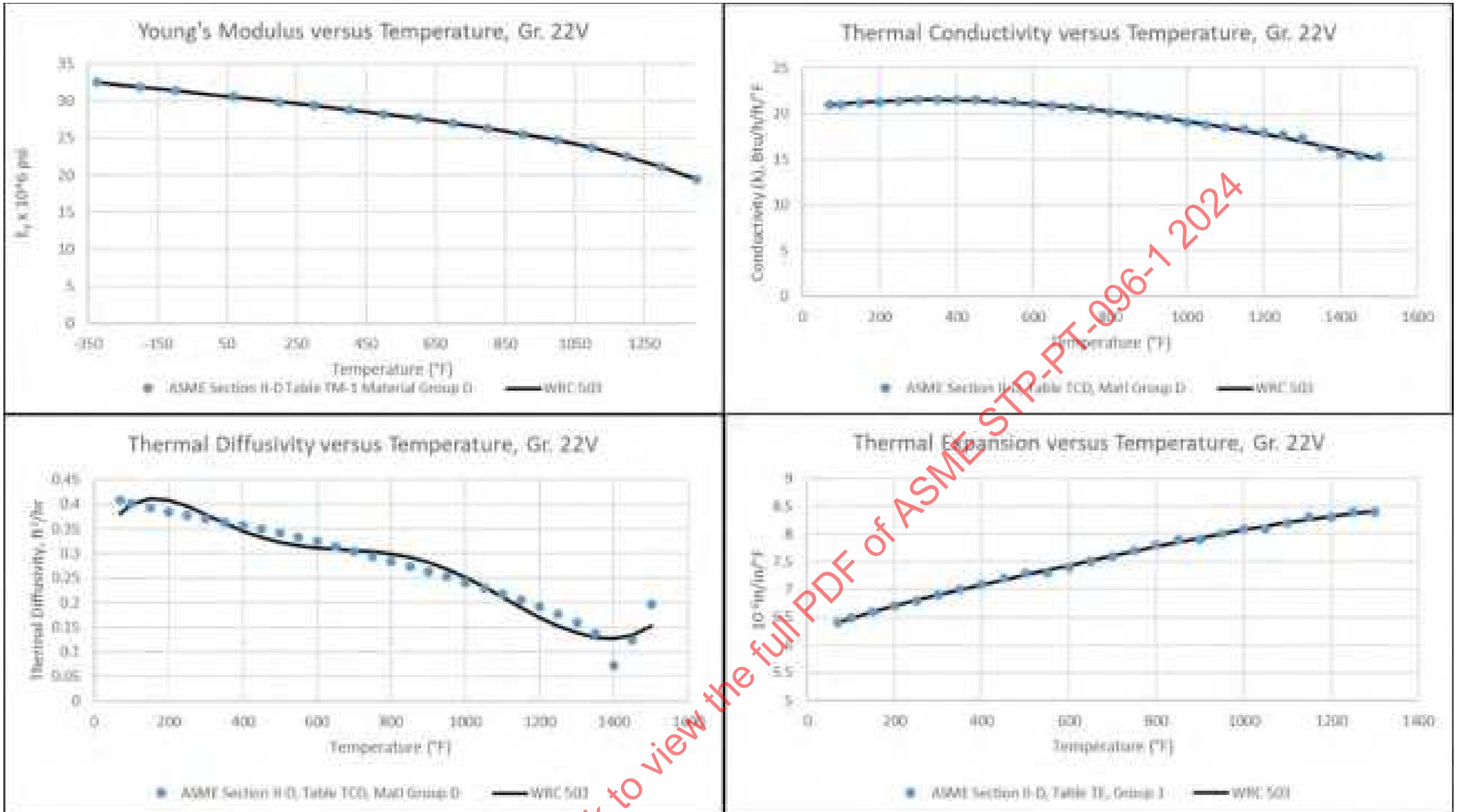


Figure 11-2: Grade 22V Yield Strength Vs. Temperature, By Data Source, Including Trend Curves

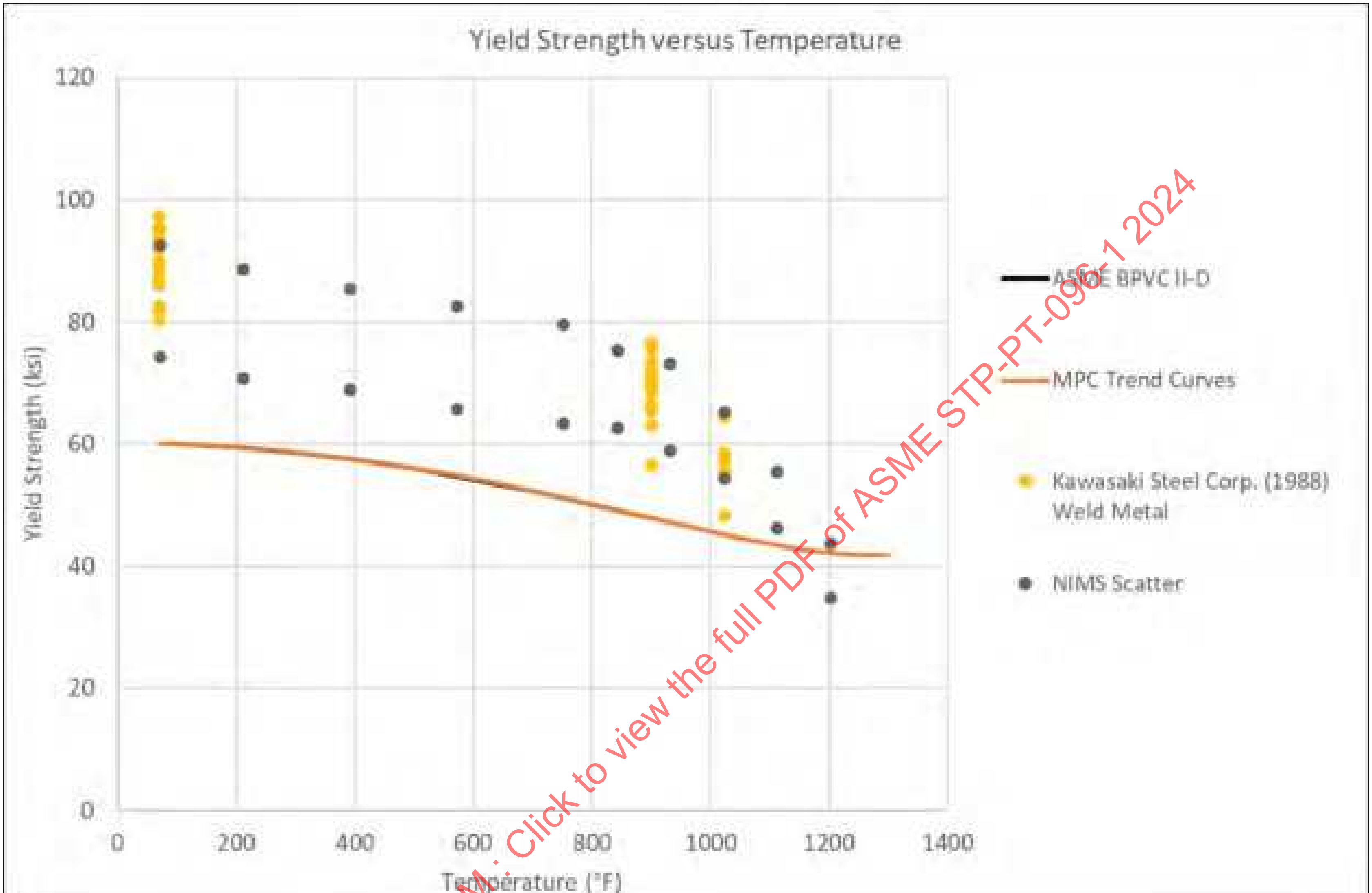


Figure 11-3: Grade 22V Tensile Strength Vs. Temperature, By Data Source, Including Trend Curves

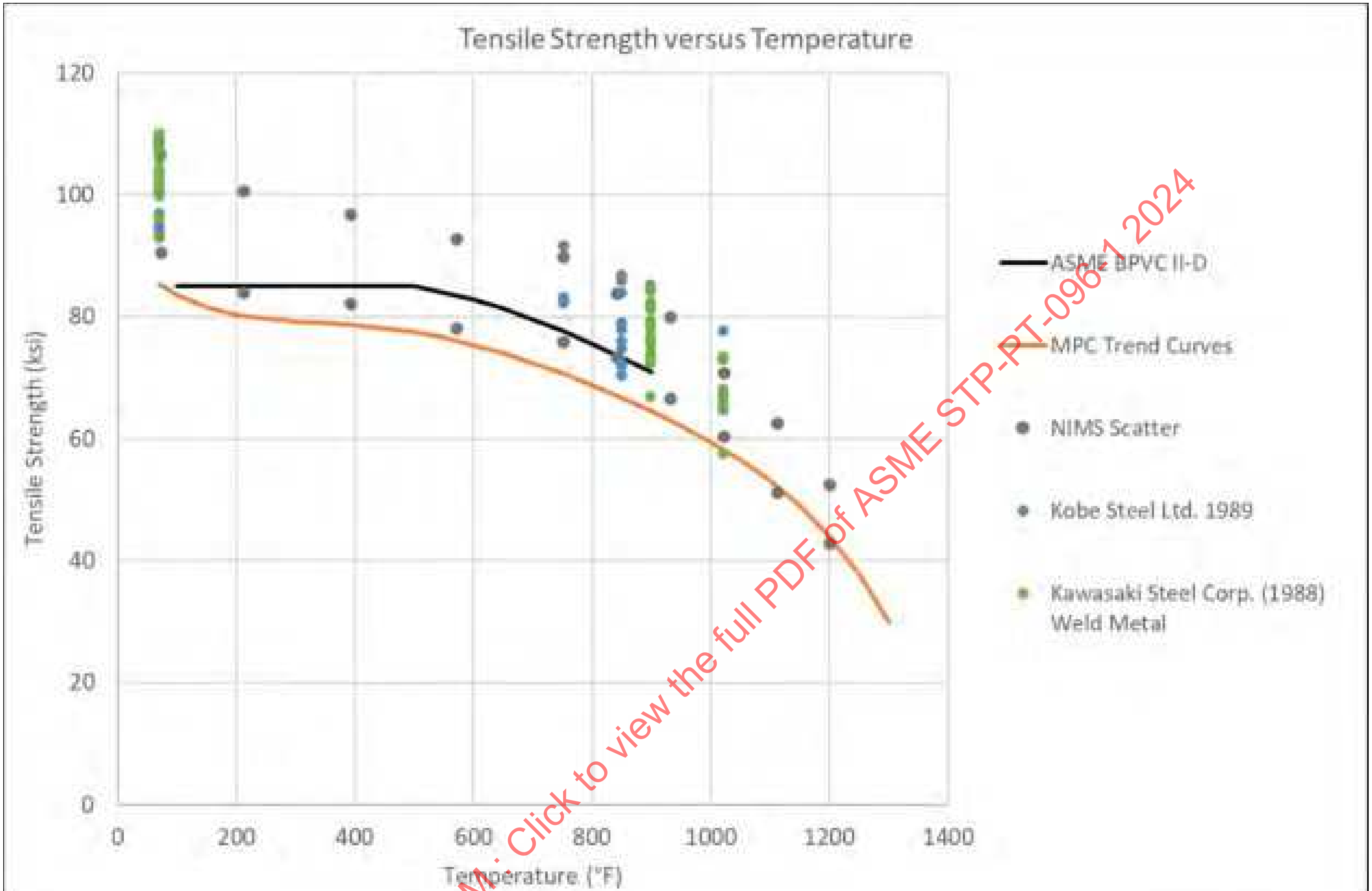


Figure 11-4: Grade 22V Yield Strength Ratios Vs. Temperature (Calculated on a Heat-By-Heat Basis, By Data Source)

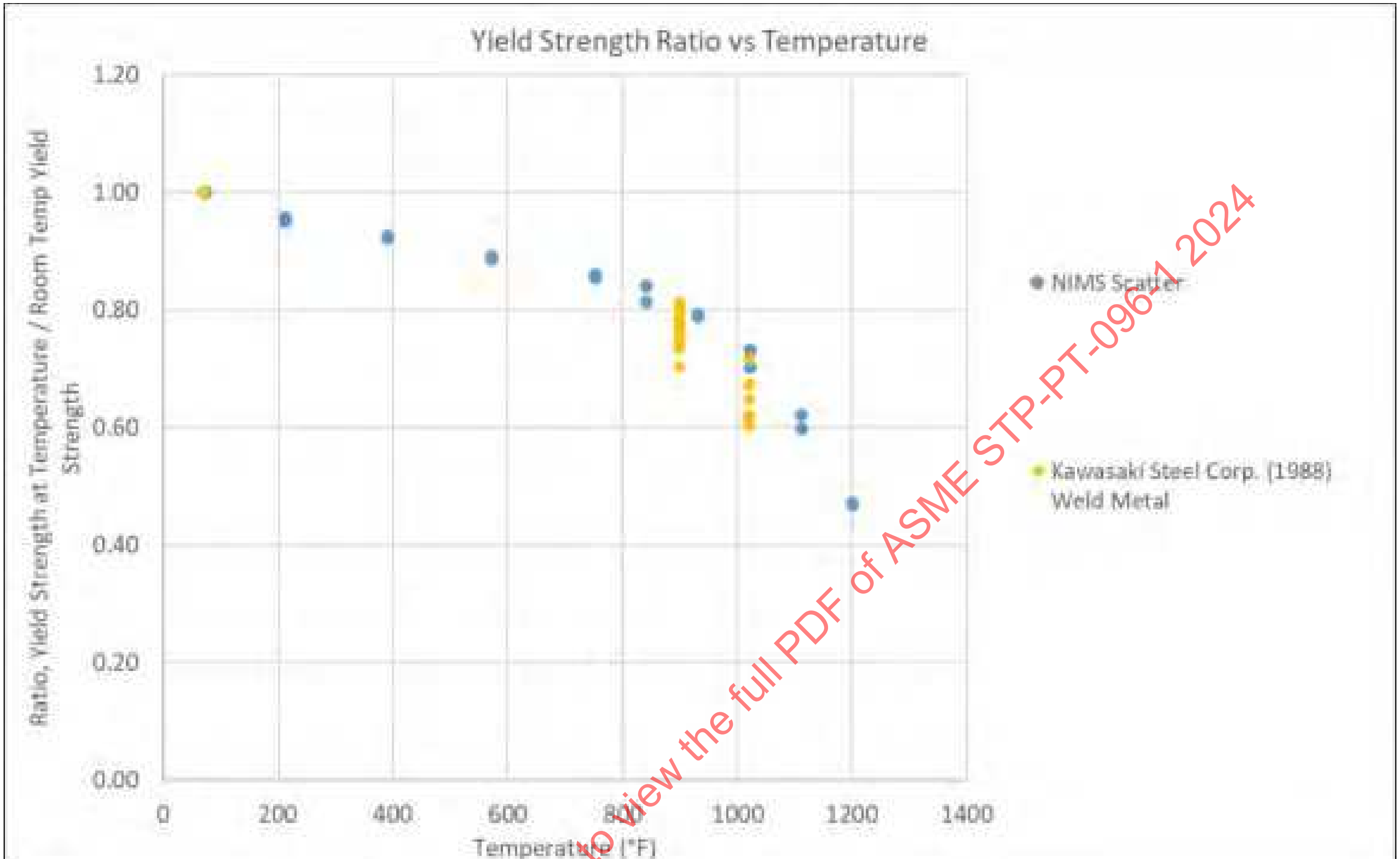


Figure 11-5: Grade 22V Tensile Strength Ratios Vs. Temperature (Calculated on a Heat-By-Heat Basis, By Data Source)

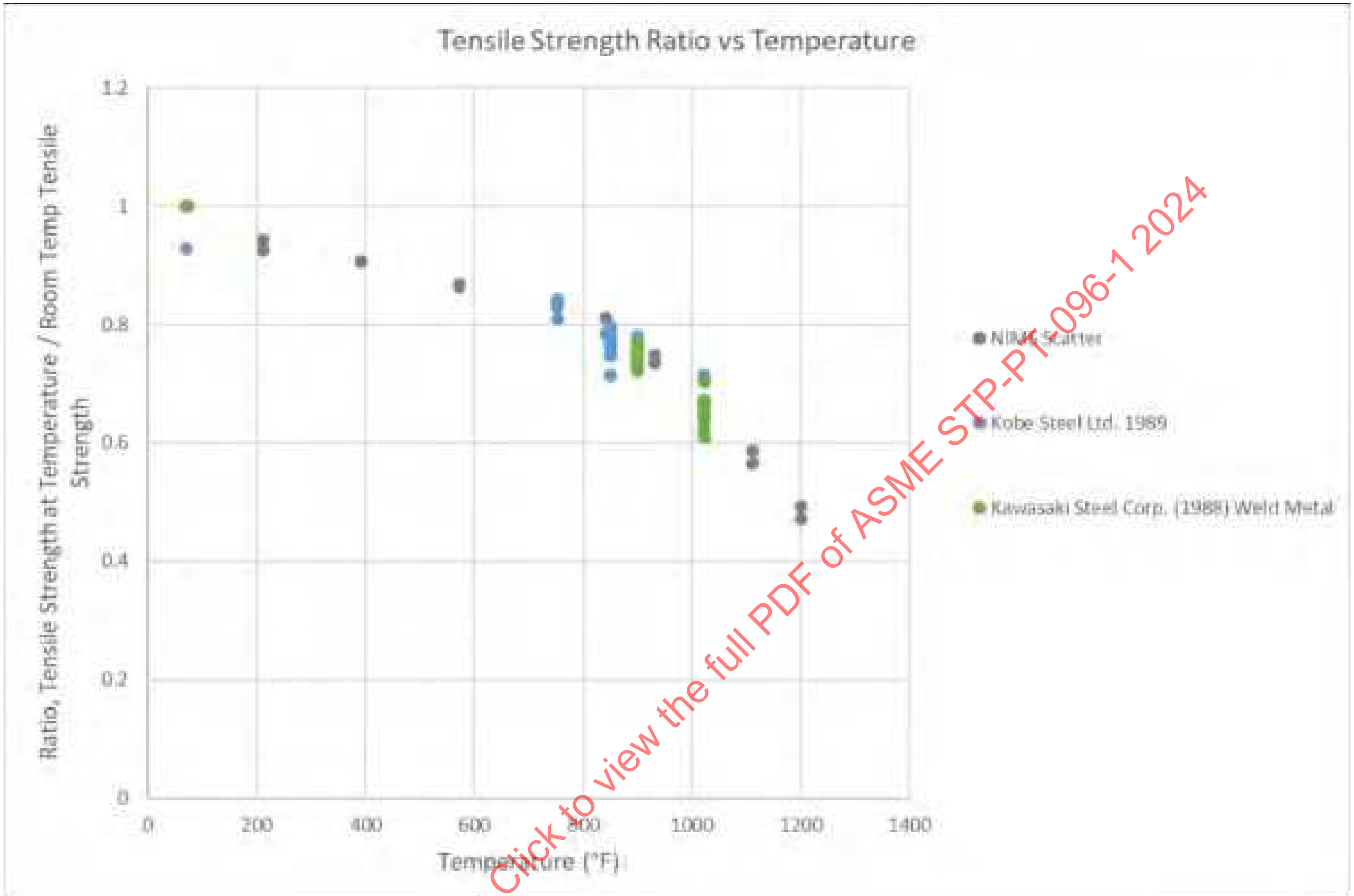


Figure 11-6: Grade 22V Yield Strength Ratios Vs. Temperature, All Combined Data, With Polynomial Regression

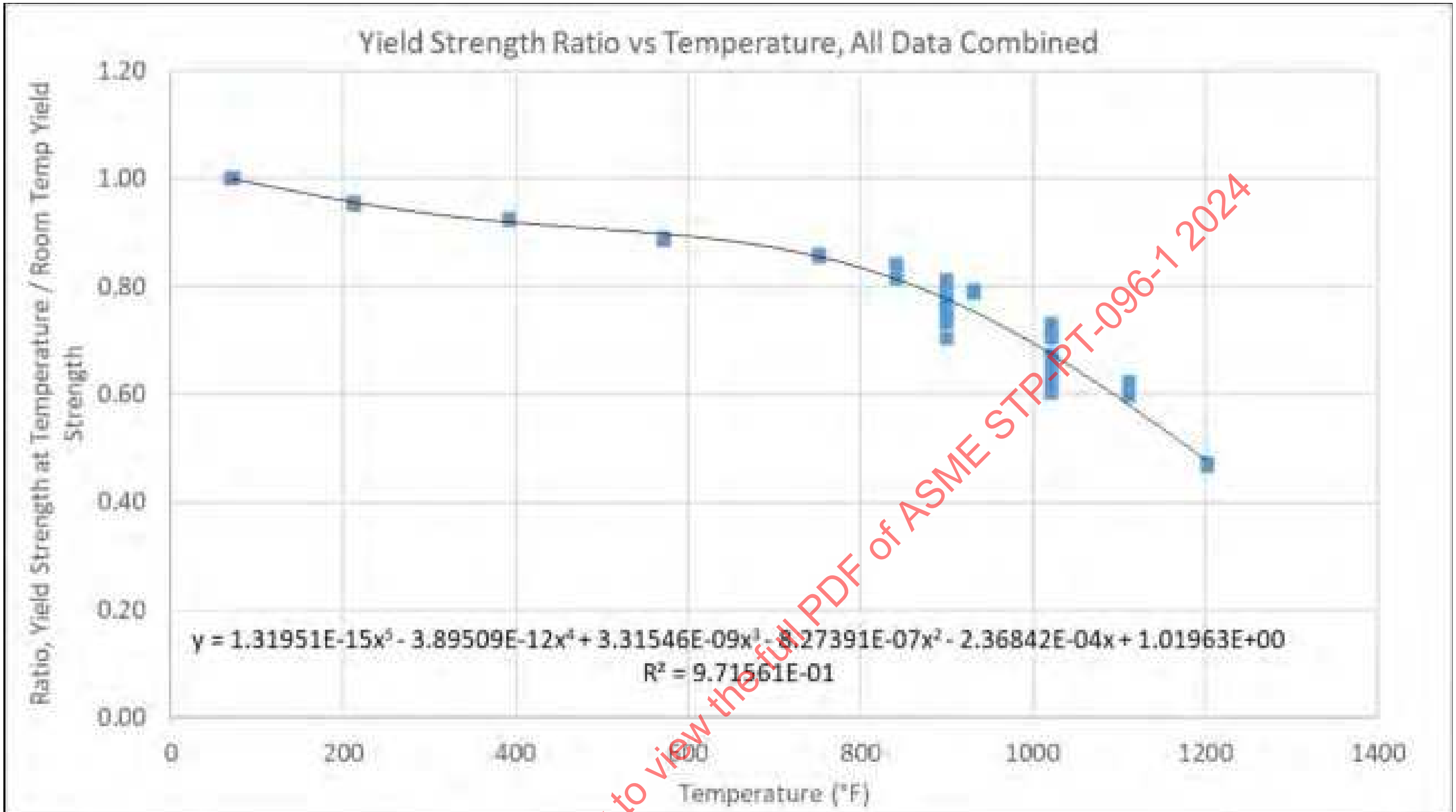


Figure 11-7: Grade 22V Tensile Strength Ratios Vs. Temperature, All Combined Data, With Polynomial Regression

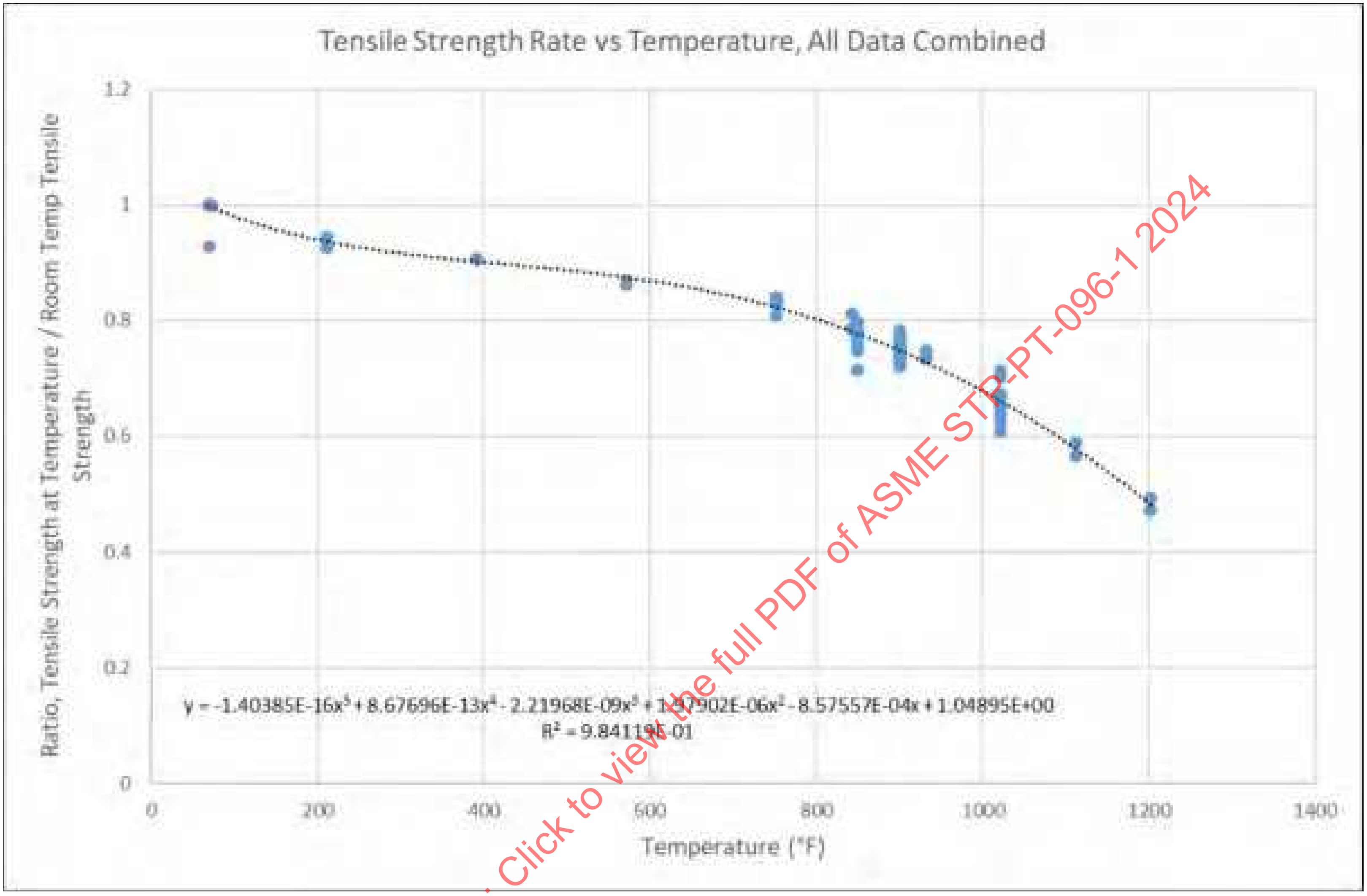


Figure 11-8: Grade 22V Creep Rupture Isotherm Curves, Temperatures With High Concentration of Data Points

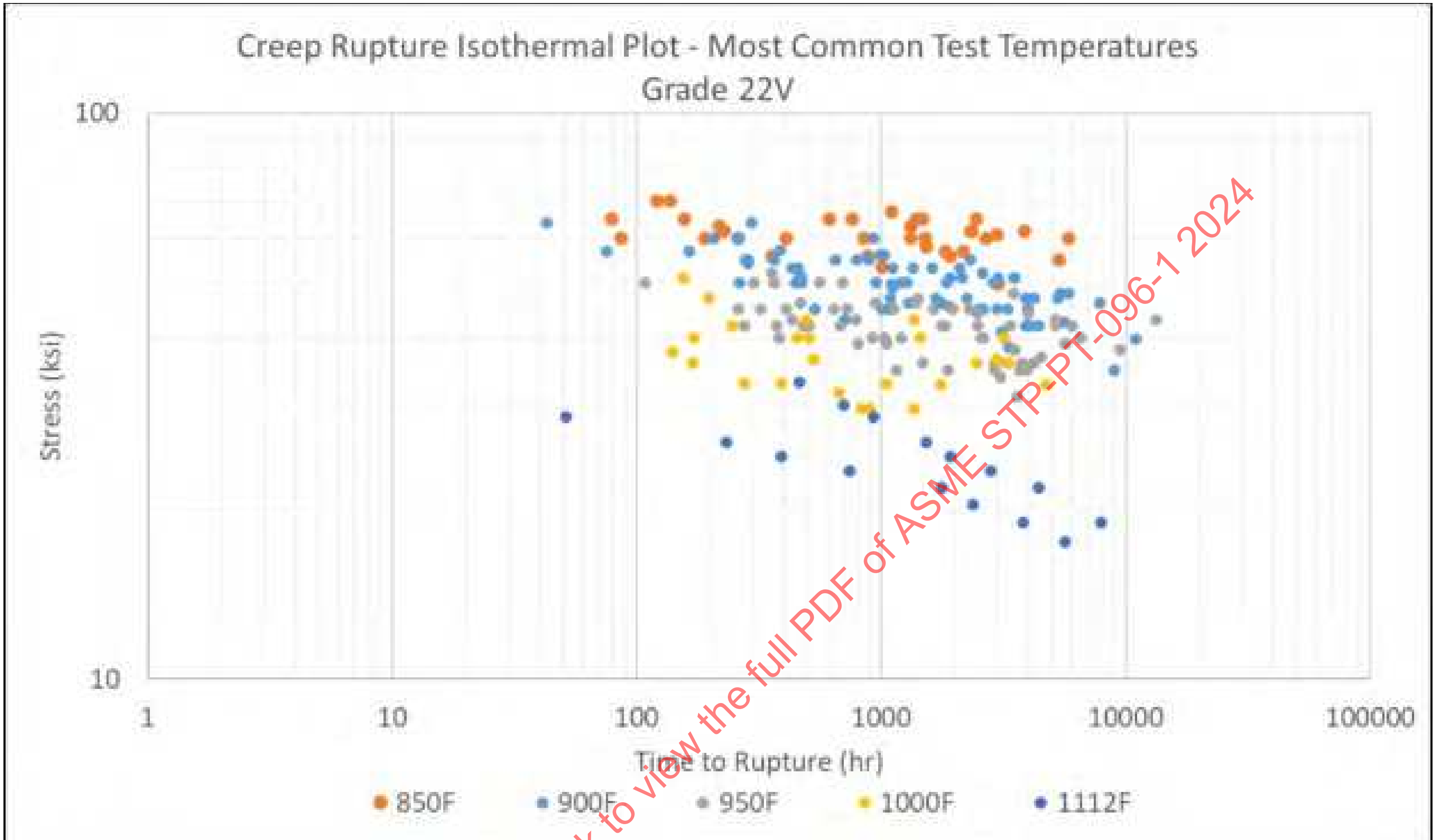


Figure 11-9: Grade 22V Creep Rupture Isotherm Curves for Additional and Intermediate Temperatures

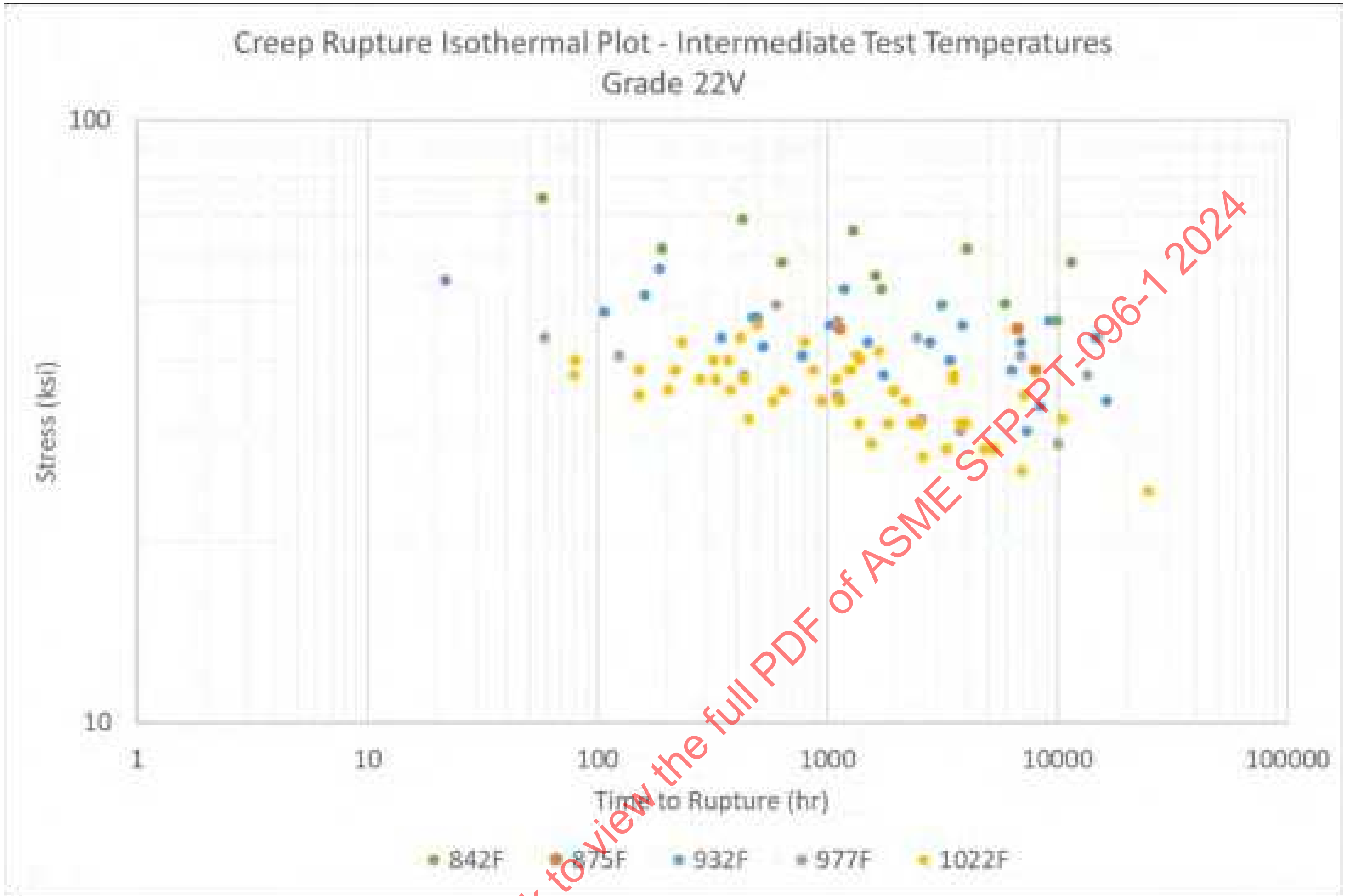


Figure 11-10: Grade 22V Creep Strain Rate (MCR) Isotherm Curves, Temperatures With High Concentration of Data Points

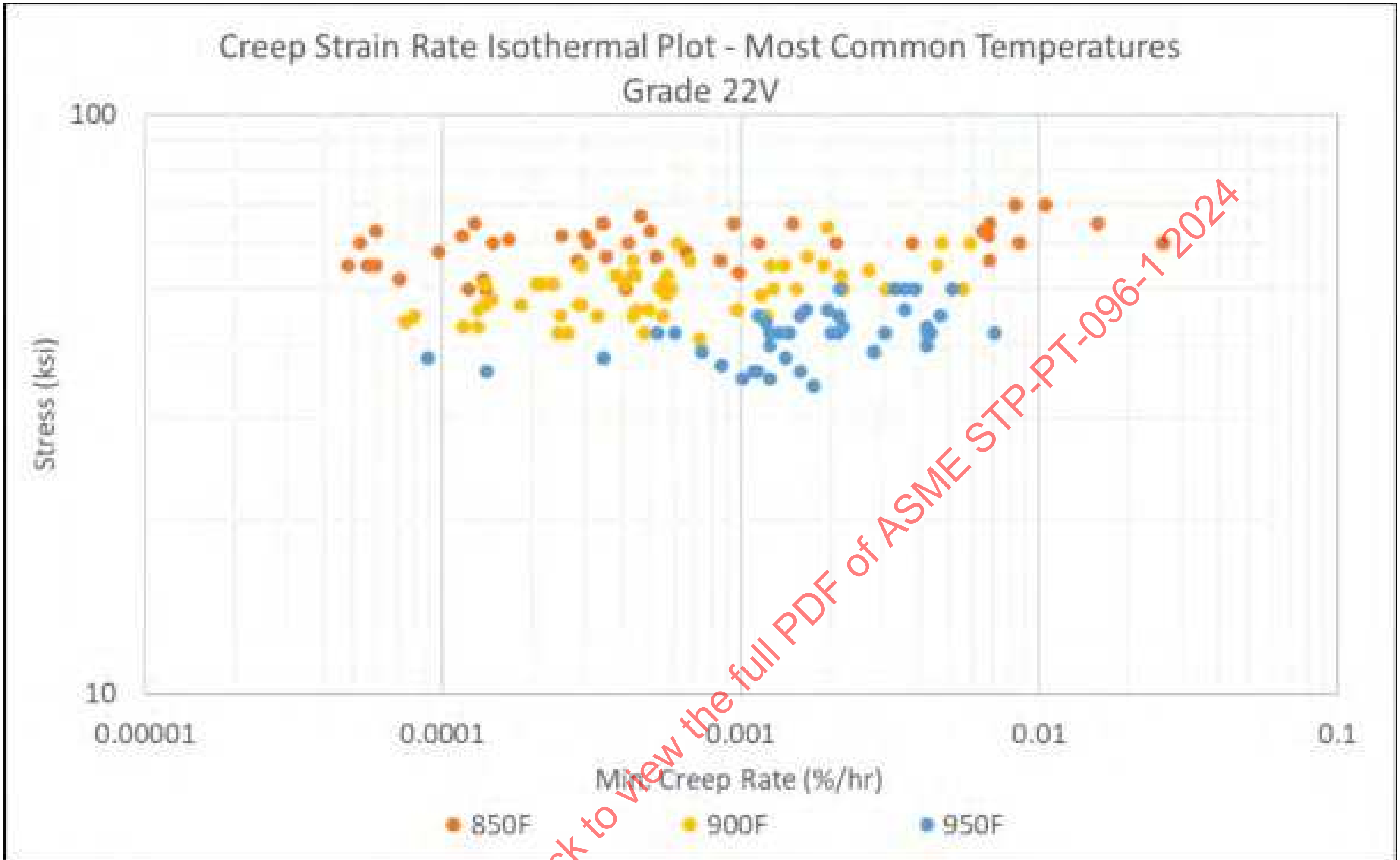


Figure 11-11: Grade 22V Creep Ductility (% Elongation) Vs. Rupture Time Isotherms

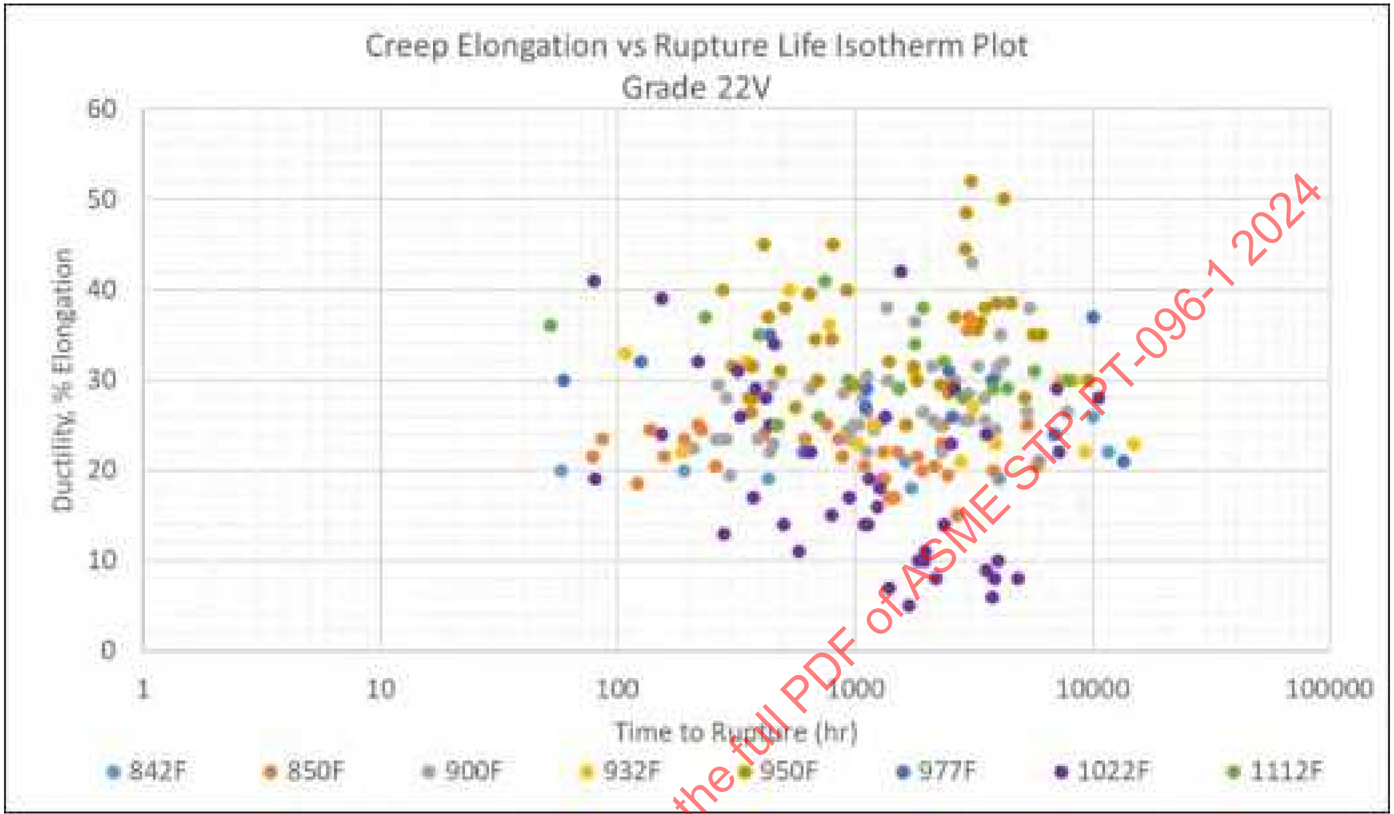


Figure 11-12: Calculated Allowable Stresses Based on Rupture and Creep Strain Rate and ASME II-D Appendix 1 Criteria (Grade 22V)

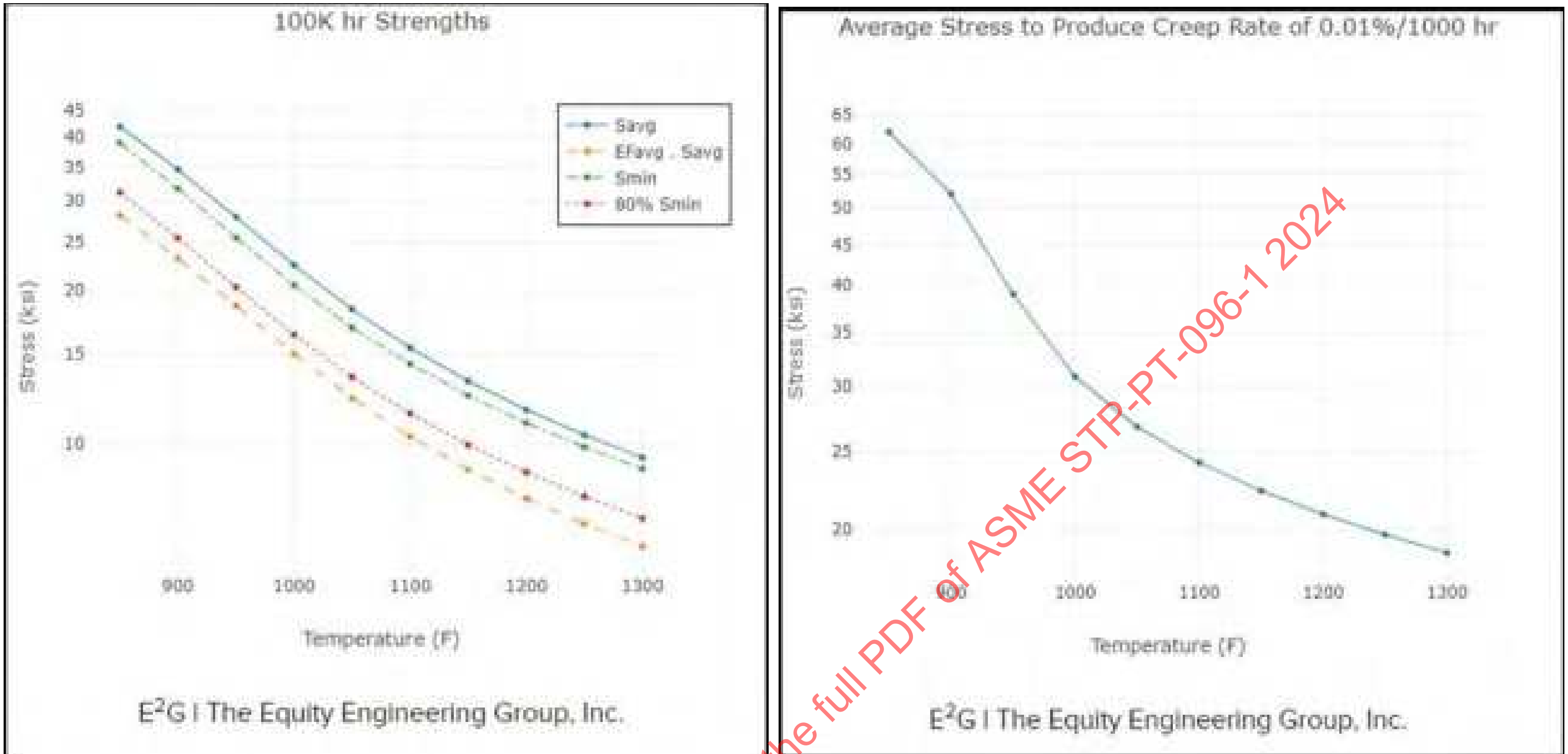


Figure 11-13: Comparison of Current Grade 22V Allowable Stresses (All Product Forms) Vs. ASME II-D Appendix 1 Criteria Applied to Data

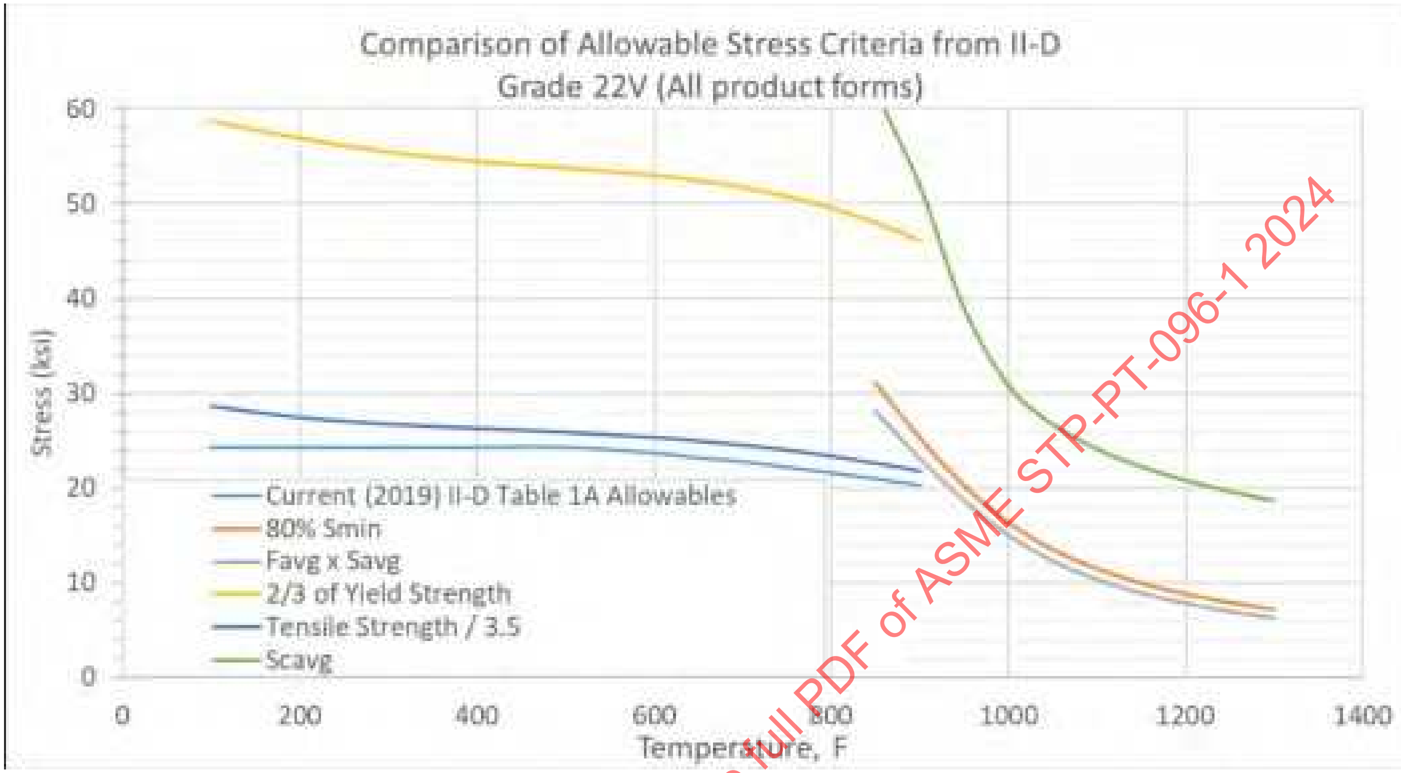


Figure 11-14: Short-Term Strain Vs. Time Data, up to 1,000 Hour Test Durations (Grade 22V), 1 of 2

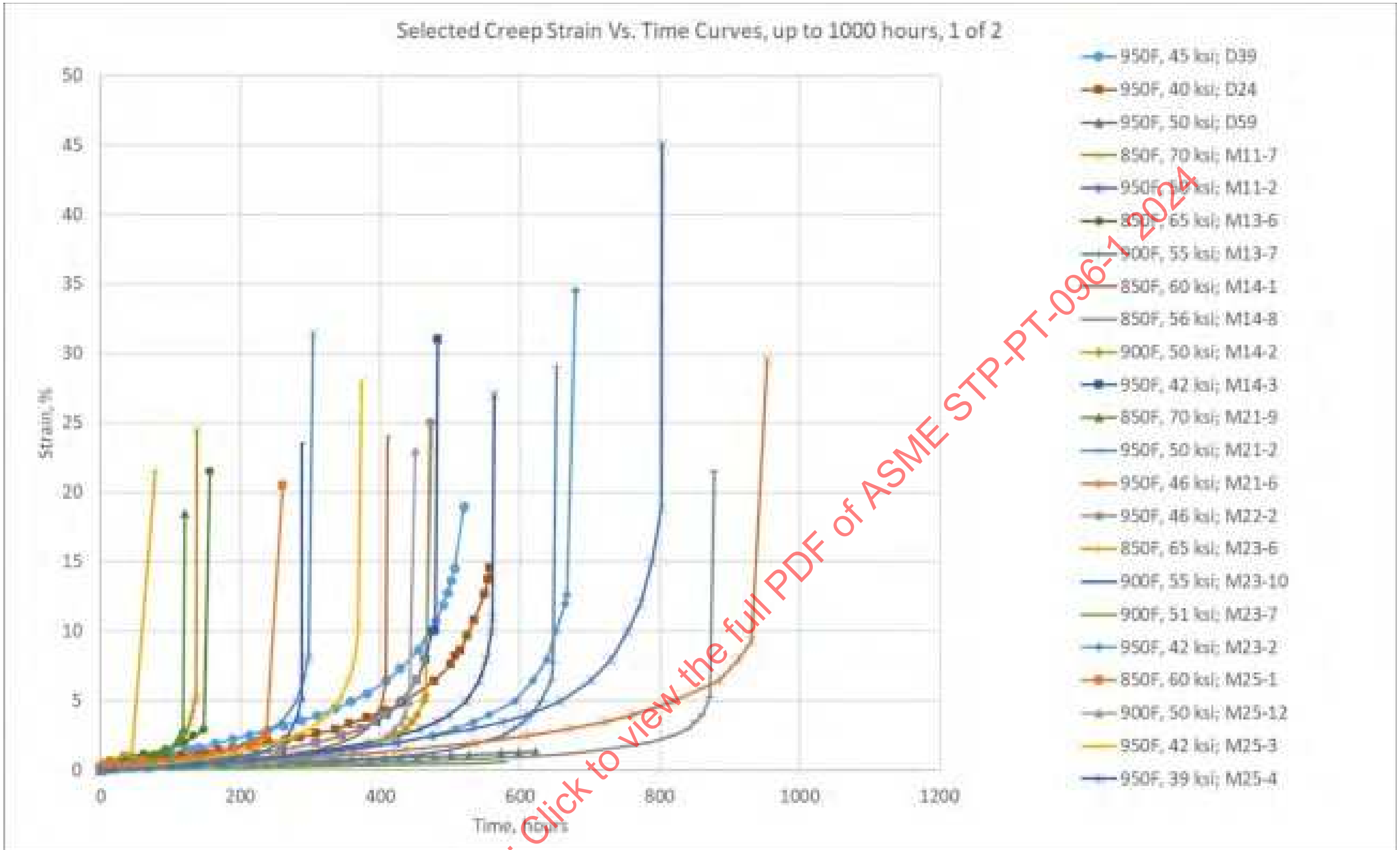


Figure 11-15: Short-Term Strain Vs. Time Data, up to 1,000 Hour Test Durations (Grade 22V), 2 of 2

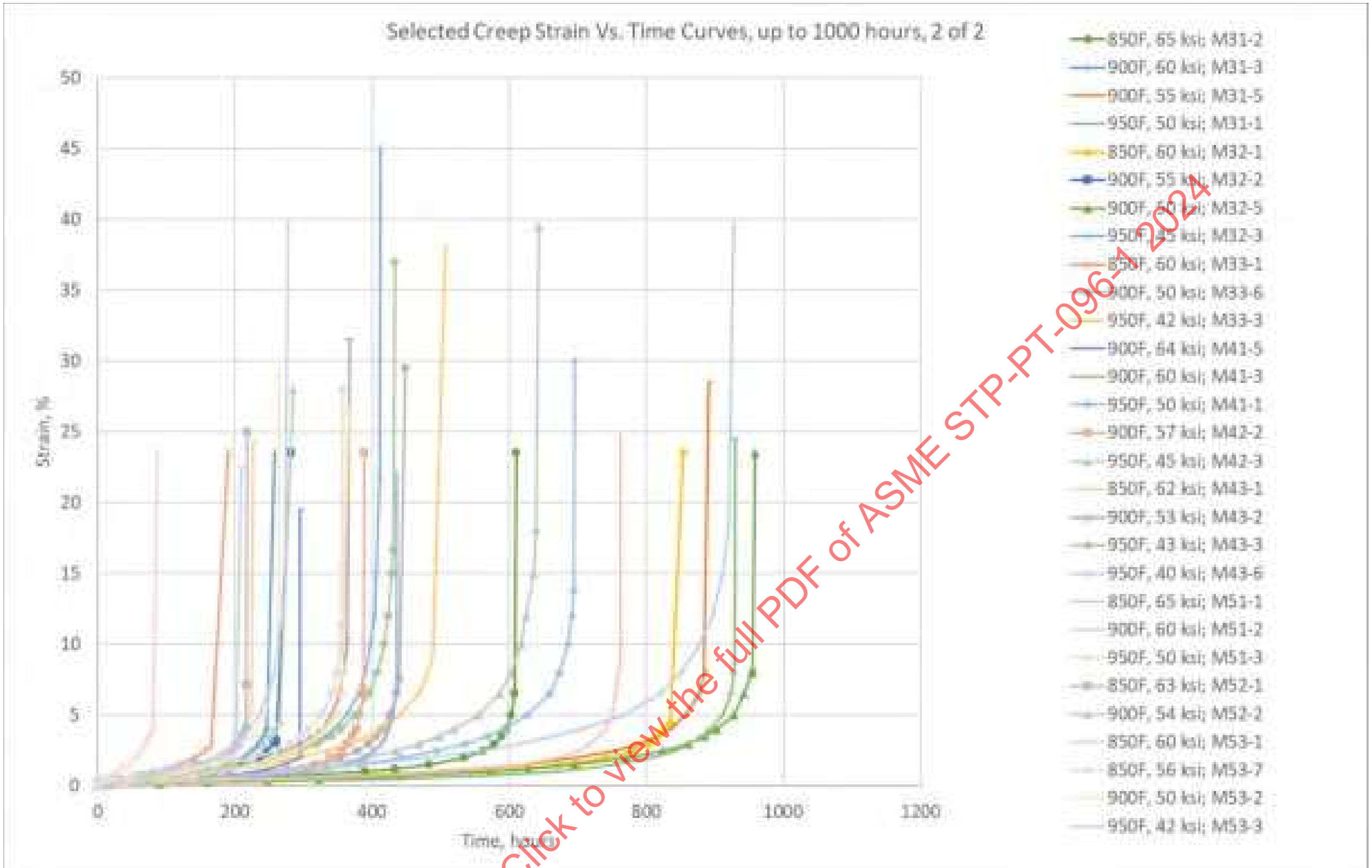


Figure 11-16: Medium-Term Strain Vs. Time Data, 1,000 to 2,500 Hour Test Durations (Grade 22V), 1 of 2

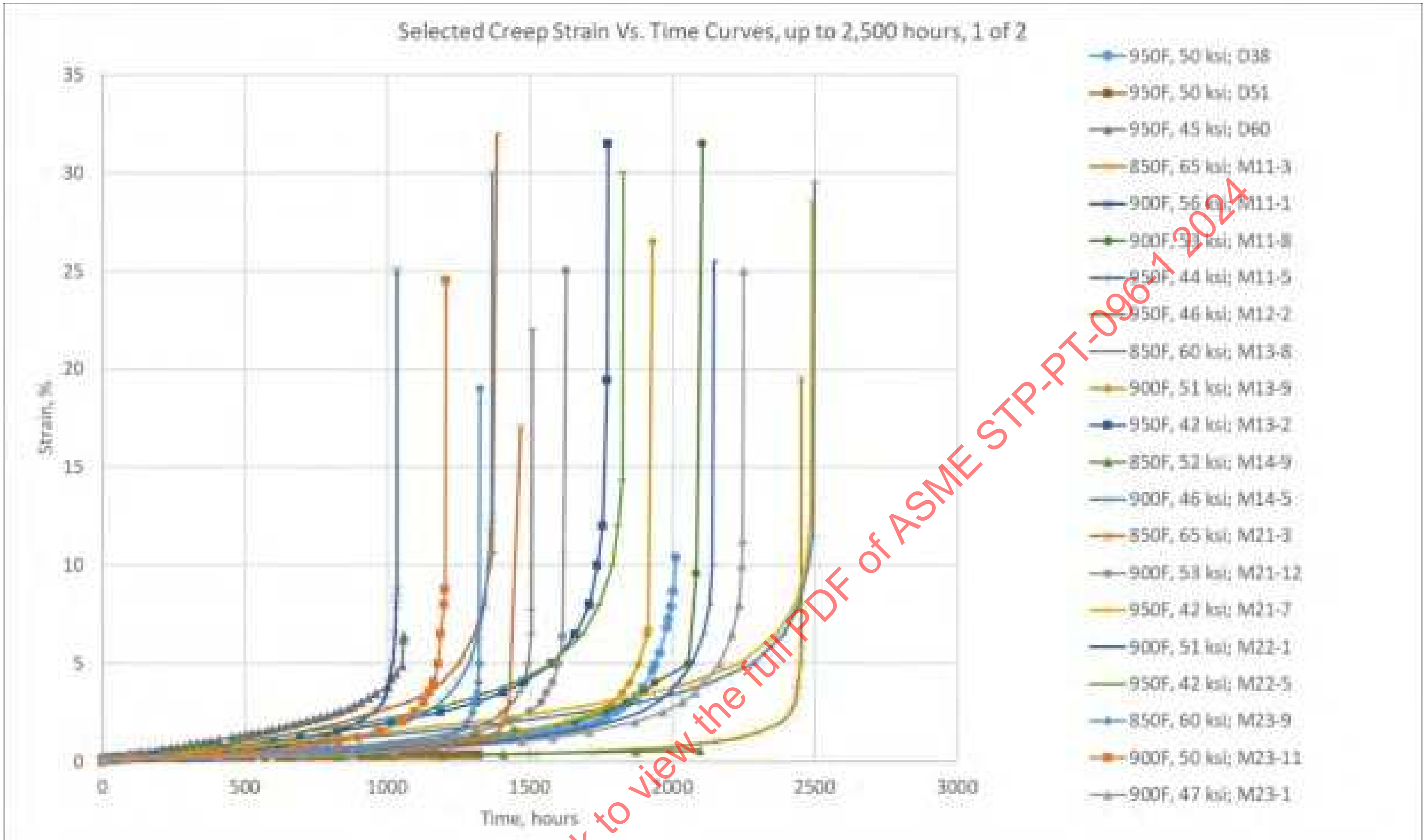


Figure 11-17: Medium-Term Strain Vs. Time Data, up to 2,500 Hour Test Durations (Grade 22V), 2 of 2

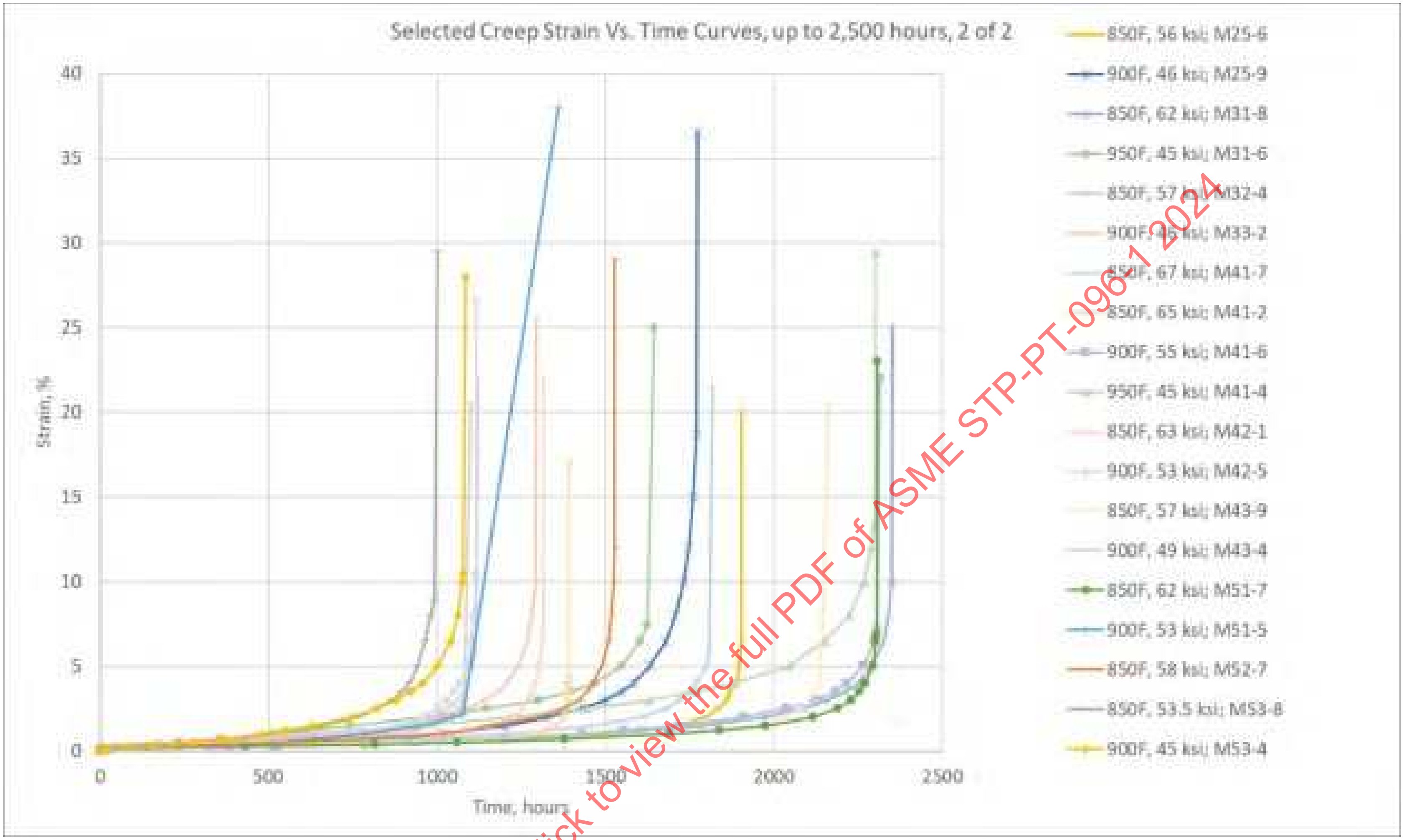


Figure 11-18: Long-Term Strain Vs. Time Data, up to 5,000 Hour Test Durations (Grade 22V)

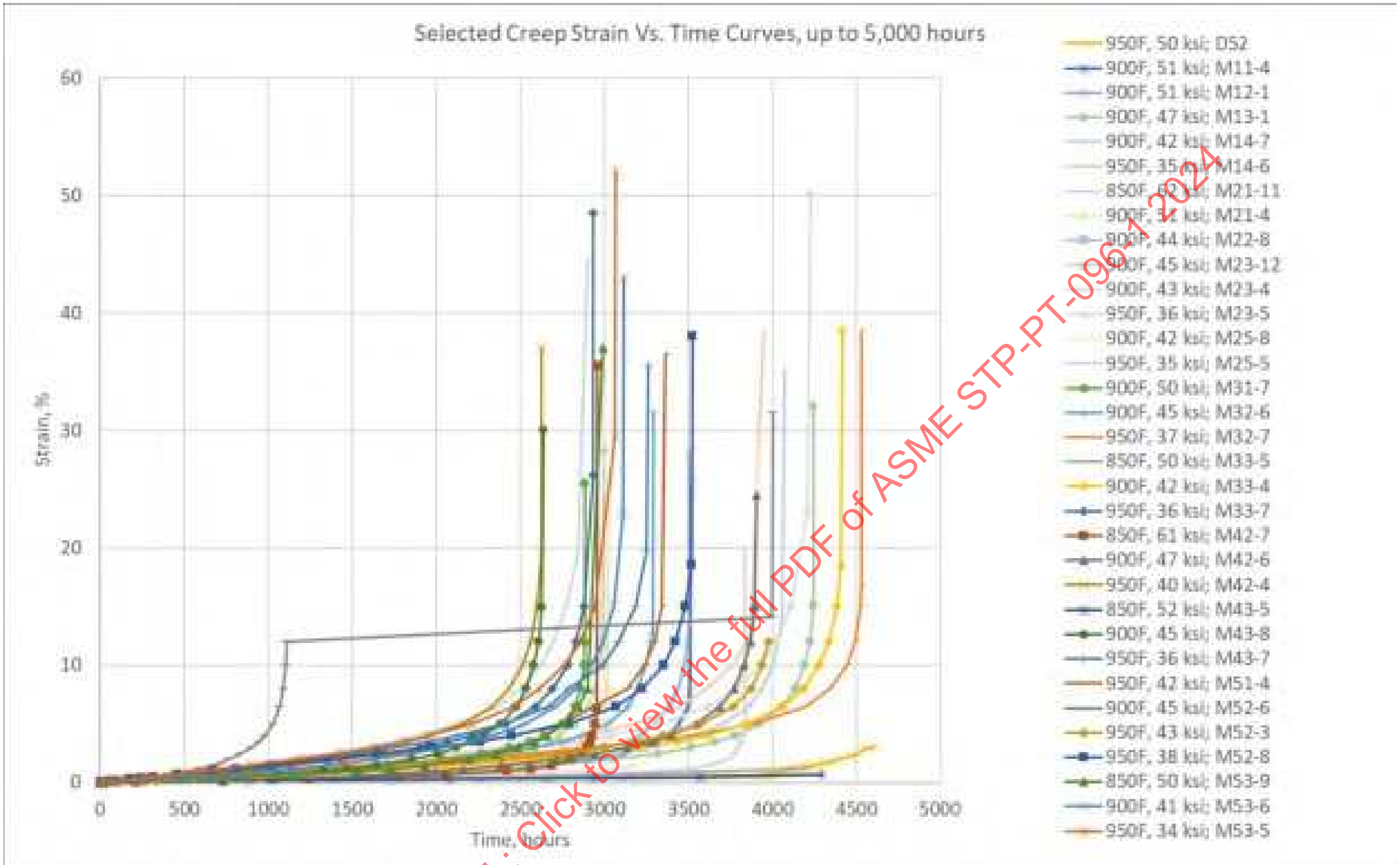


Figure 11-19: Long-Term Strain Vs. Time Data, up to 5,000 Hour Test Durations (Grade 22V)

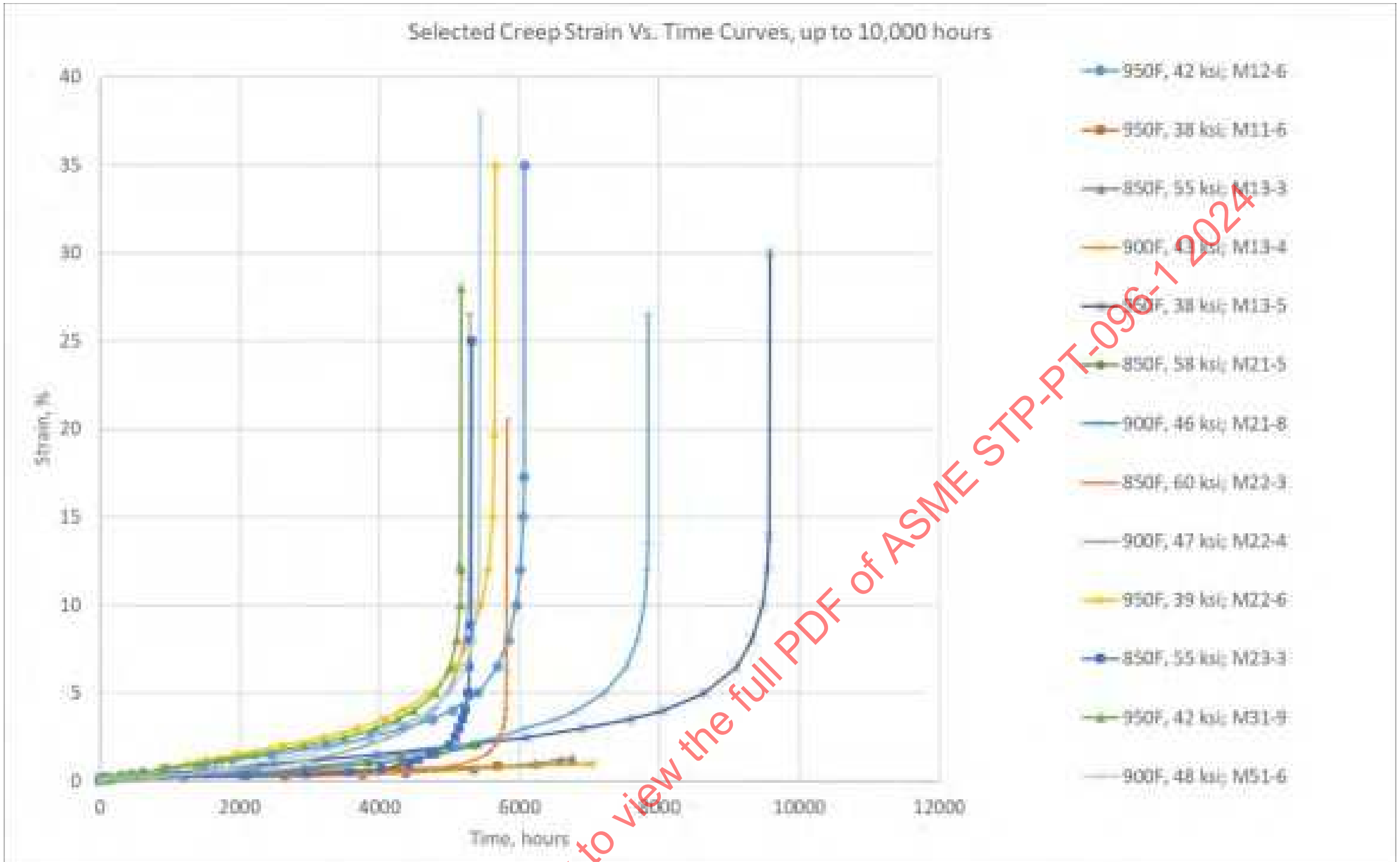


Figure 11-20: Long-Term Strain Vs. Time Data, in Excess of 10,000 Hour Test Durations (Grade 22V)

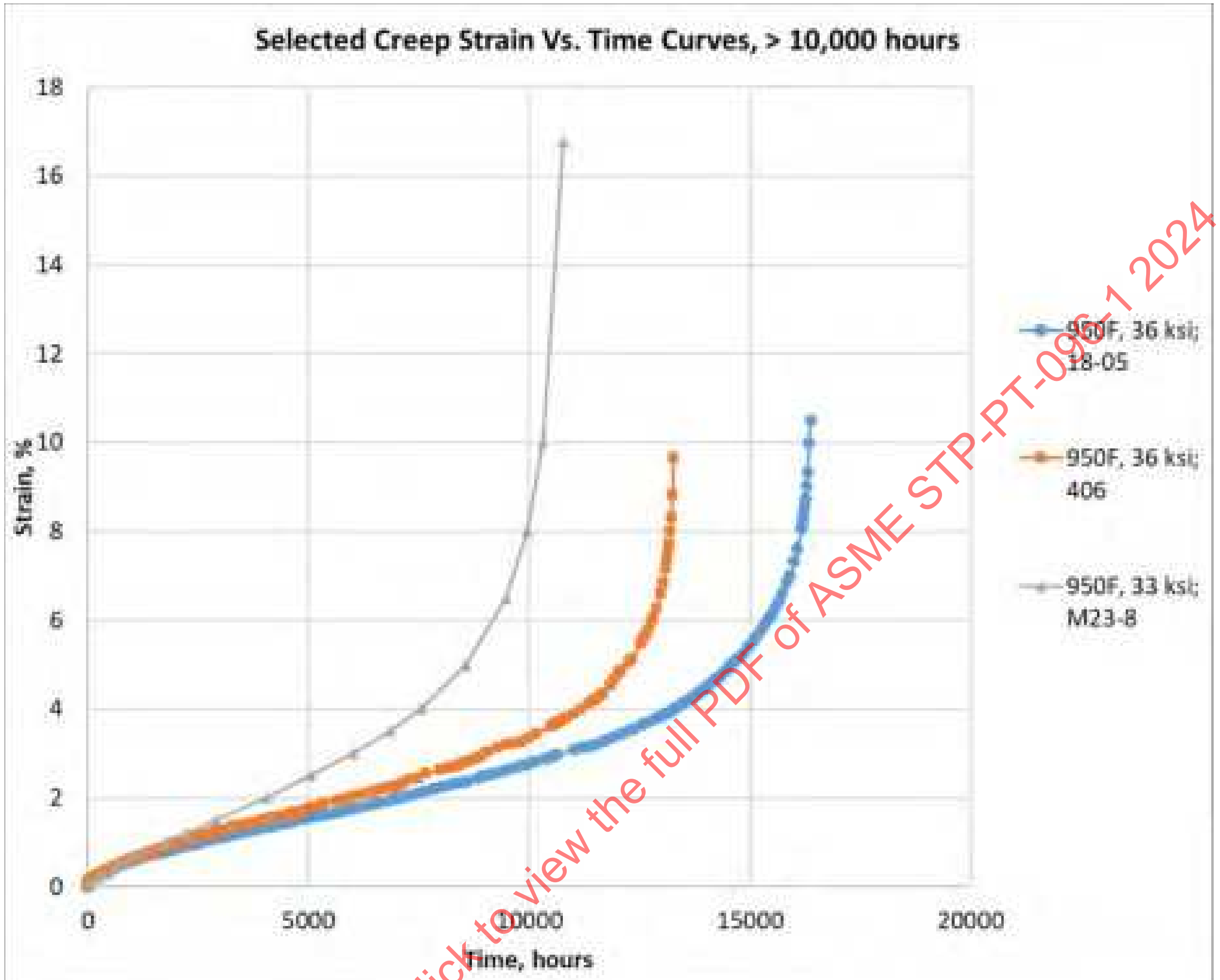


Figure 11-21: Grade 22V Continuous Cycling Fatigue (Grade 22V), Including Elevated Temperature Data

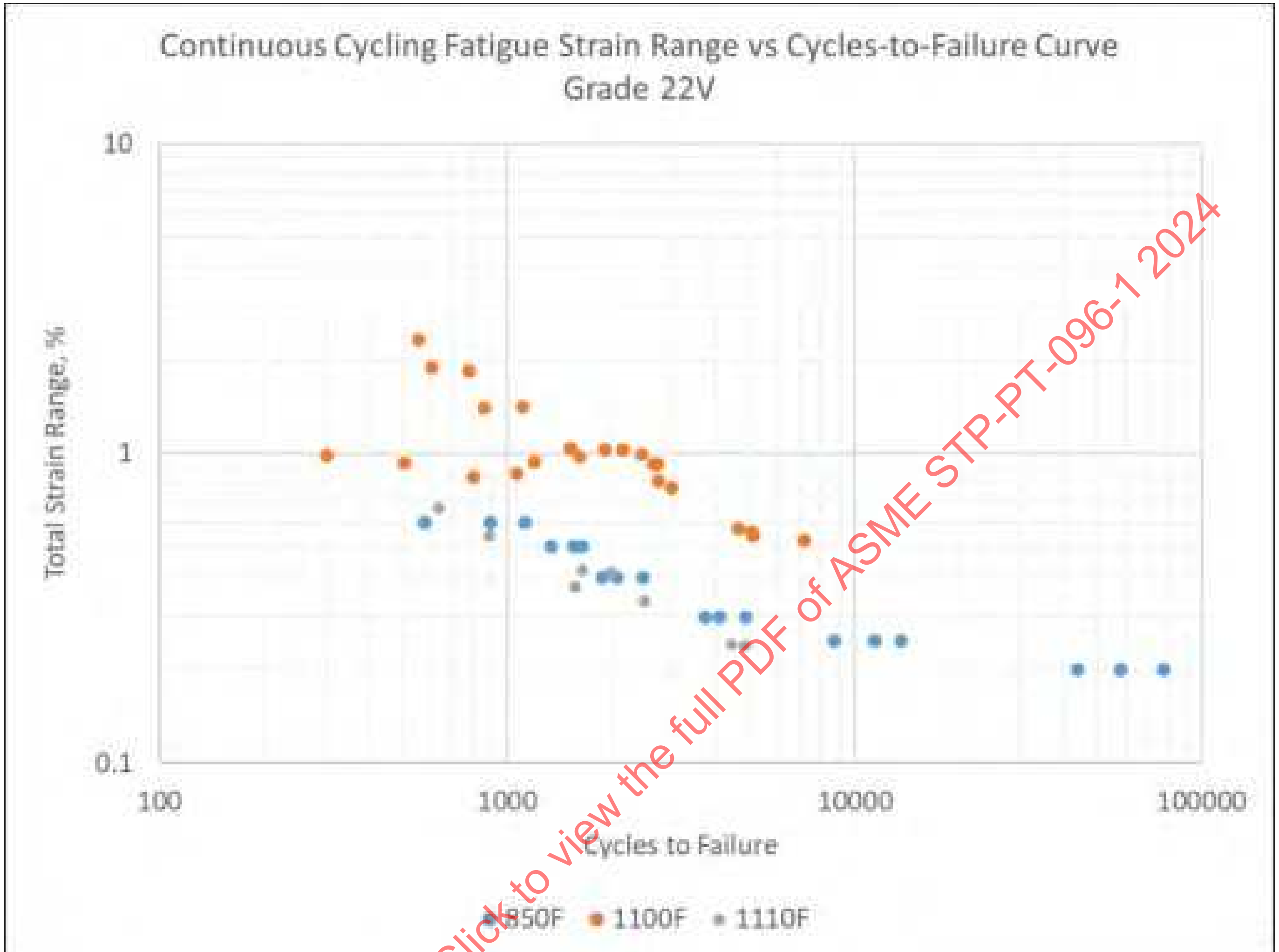


Figure 11-22: Grade 22V Hold Time Data (Creep Fatigue) for Grade 22V, Temperature of 850°F

Attachment 11: Grade 22V Property Data

If you want the referenced embedded spreadsheet with additional data, please email a request to research@asme.org.

12 5CR-0.5MO (GRADE 5)

12.1 Physical Properties

Well-established physical properties were referenced from the BPVC Section II for this material. Physical property curves from WRC Bulletin 503 were plotted for comparison. Note, these physical properties apply to both common heat treatments of the 5Cr-0.5Mo material (Normalized and Tempered [N&T] or Annealed). Figure 12-1 shows the trends of Elastic Modulus (E_y), Thermal Conductivity (k), Thermal Diffusivity (TD), and Thermal Expansion (α) with temperature.

12.2 Yield and Tensile Strength

Elevated temperature Yield and Tensile Strength over the range of existing allowable stresses (up to 1200°F) were readily available, including data beyond the current range of allowable stresses, up to approximately 1500°F, as shown in Figures 12-2 and 12-3 for the Annealed heat treatment, and Figures 12-4 and 12-5 for the N&T heat treatment. The sources for both high-temperature yield and high-temperature tensile strength are provided in the embedded spreadsheet at the end of this section.

To facilitate comparison of the data obtained to existing allowable stresses (Section II-D Table 1A), yield and tensile data were normalized on a heat-by-heat basis to express the ratio of yield or tensile strength at temperature to that measured for the heat at room temperature. In cases where data were not delineated by heats within a given source, or in cases where more than one room-temperature tensile test existed for a given heat of material, ratios are equal to the measured tensile or yield strength at temperature, divided by the average of all of the appropriate room-temperature values for the particular data source or heat of material. As a result of this approach, it is possible to have ratios in excess of 1.0 (although this did not occur for this particular material). E^2G understands that this approach is similar to the normalizing procedure performed by ASME in typical analysis of yield and tensile data to obtain Table Y and Table U (Section II-D) trend curves, as well as for the calculation of allowable stresses. Figures 12-6 and 12-7 (Annealed) and Figures 12-8 and 12-9 (N&T) show the heat-by-heat variation in yield and tensile strength ratios (respectively) as a function of temperature. It should be emphasized that even though the figure legends reference an entire source of data, the ratios, wherever possible, were calculated on a heat-by-heat basis; this is evident in the embedded spreadsheet at the end of this section. Figures 12-10 and 12-11 (Annealed) and Figures 12-12 and 12-13 (N&T) contain all of the yield and tensile (respectively) ratios plotted together, to facilitate regression of a 5th-order polynomial that is subsequently used for allowable stress comparison.

12.3 Creep Data (Creep Rupture, Minimum Creep Rate, and Ductility)

Creep Rupture data is shown in Figure 12-14, plotted as isotherms. It should be emphasized that these plots contain data for all product forms of material classified in the referenced publications as "5Cr-0.5Mo" material. This certainly includes material meeting the requirements of current ASME BPVC Section II-A specifications (e.g., SA-213 T5, SA-217 C5, SA-335 P5, etc.). However, due to the diversity of data sources utilized for the compilation of the material property tables, it is likely that some of the material data shown in Figure 12-14 may not meet existing specifications for this grade of material. Where possible, E^2G has documented the chemical composition if contained within the original source. In many cases, the project team has also made efforts to trace cross-referenced data back to original test results to determine if the heat treatment, product form, chemistry, etc. details can be obtained. This information is provided with the embedded spreadsheet to facilitate additional analysis on the part of ASME.

Creep Minimum strain rates (%/hour) are shown in Figure 12-15, again, separated by temperature. Creep Ductility, as % elongation, is plotted in Figure 12-16. As is typical, the data show significant overlap, and it is difficult to observe clear trends in the data. The data is not intended to be used as plotted but is available in the spreadsheet for additional analysis.

Creep data were analyzed using E^2G's proprietary Lot-Centered Analysis web-based software tool, in order to obtain creep properties. This regression is based on a Mandel-Paule algorithm and considers the variation within individual heats of material (for both rupture and strain rate data) as well as the variation between heats. The weight assigned to each datapoint and each heat is scaled based on the relative variation. Both rupture and strain rate (minimum creep rate, expressed as true strain per hours) were regressed according to a Larson-Miller time-temperature-parameter model, with a 3rd-order polynomial of stress. Lot-specific constant behavior was accounted for in this analysis, but the variation of LMP with stress was assumed to be constant (no non-parallel terms were included in the analysis). A 95% predictive limit was utilized to obtain the lower-bound (minimum LM constant for both rupture and strain rate) properties. The results of this analysis are summarized in Table 12-1 for rupture data and Table 12-2 for strain rate data. The Lot-Centered Analysis software tool generates property tables in the creep regime using the criteria outlined in Mandatory Appendix 1 of ASME Section II-D; the nomenclature of variables is consistent with II-D Appendix 1. For visualization of the allowable stress trends, Figure 12-17 summarizes the rupture allowable stresses. The creep rate allowable stresses are illustrated in Figure 12-18. Figure 12-19 displays a comparison of the various allowable stress criteria from Section II-D, Appendix 1, to the existing (2019) Section II-D Table 1A allowable stresses for all product forms of 5Cr-0.5Mo. Note, the allowable stress criteria based on Yield (2/3 of Yield) and Tensile Strength (Tensile / 3.5) is illustrated for both common heat treatments of 5Cr-0.5Mo material (Annealed and N&T).

Creep Strain vs. time data (at 1300°F) for several selected tests is shown in Figure 12-20. Note that the majority of the creep strain vs. time data that was identified included a test condition change, either varying stress or temperature during the test. Consequently, only the tests with constant test conditions over the duration of the test were included in Figure 12-20. The remainder of the creep strain vs. time data are included in the embedded spreadsheet for this material.

Both creep rate and creep strain vs. time data are provided to satisfy ASME's request for creep strain vs. time curves, and both forms of data are applicable in developing allowable stresses. Although digitalization of creep curve data was not explicitly necessary per the project contract, E^2G did perform digitalization of creep curves where only graphical data was available (as is often the case in the published literature).

12.4 Continuous Cycling Fatigue and Hold Time Fatigue Curves

No elevated temperature continuous cycling or hold time fatigue data was located for 5Cr-0.5Mo.

Table 12-1: Model Parameters, Larson-Miller Property Results, and Allowable Stress (Rupture) Criteria, Grade 5

Equation Format:

$$\log(t_r) = C_{avg} + \frac{1}{T+460}\left(b_1 + b_2\log(\sigma) + b_3(\log(\sigma))^2 + b_4(\log(\sigma))^3\right)$$

C_{avg}	**-19.74**
C_{min}	**-20.13**
b_1	**44305.3**
b_2	**-6572.6**
b_3	**-1492.1**
b_4	**-112.9**

Number Data Points		**473**
Correlation Coefficient	R^2	0.9439
Average Variance within Heats	V_w	0.05711
Variance between Heats	V_b	0.2944
Standard Error of Estimate	SEE	0.239

Properties provided are for T in °F, stress in ksi, and t_R in hours

Temperature, °F	**S_{avg} (ksi)**	***n***	**F_{avg} (calc)**	**F_{avg} (used)**	**$F_{avg} \times S_{avg}$**	**S_{min} (ksi)**	**80% S_{min}**
850	22.53	8.572	0.764	0.67	15.10	20.25	16.20
900	17.40	7.938	0.748	0.67	11.66	15.50	12.40
950	13.29	7.343	0.731	0.67	8.905	11.73	9.384
1000	10.03	6.781	0.712	0.67	6.722	8.762	7.010
1050	7.473	6.250	0.692	0.67	5.007	6.451	5.161
1100	5.483	5.746	0.670	0.67	3.674	4.672	3.737
1150	3.955	5.264	0.646	0.67	2.650	3.320	2.656
1200	2.798	4.803	0.619	0.67	1.874	2.308	1.846
1250	1.934	4.360	0.590	0.67	1.296	1.564	1.251
1300	1.301	3.931	0.557	0.67	0.872	1.027	0.822

Table 12-2: Model Parameters, Larson-Miller Property Results, and Allowable Stress (Strain Rate) Criteria, Grade 5

Equation Format:

$$\log(\dot{\varepsilon}_0) = -C_{avg} - \frac{1}{T+460}\left(a_1 + a_2\log(\sigma) + a_3(\log(\sigma))^2 + a_4(\log(\sigma))^3\right)$$

C_{avg} (A_0)	**-12.41**
C_{min} ($A_0+\Delta_\Omega^{SR,LB}$)	**-13.07**
a_1	**32184**
a_2	**-4481.5**
a_3	**-1266.3**
a_4	**-119.3**

Number Data Points		**186**
Correlation Coefficient	R^2	0.8038
Average Variance within Heats	V_w	0.1639
Variance between Heats	V_b	0.1739
Standard Error of Estimate	SEE	0.4049

Properties provided are for T in °F, stress in ksi, and t_R in hours

Temperature, °F	**$S_{C,avg}$ (ksi)**
850	27.17
900	21.56
950	16.94
1000	13.17
1050	10.11
1100	7.650
1150	5.697
1200	4.164
1250	2.977
1300	2.073

Figure 12-1: Grade 5 Modulus (E_y), Thermal Conductivity (k), Thermal Diffusivity (TD), & Thermal Expansion (α) With Temperature

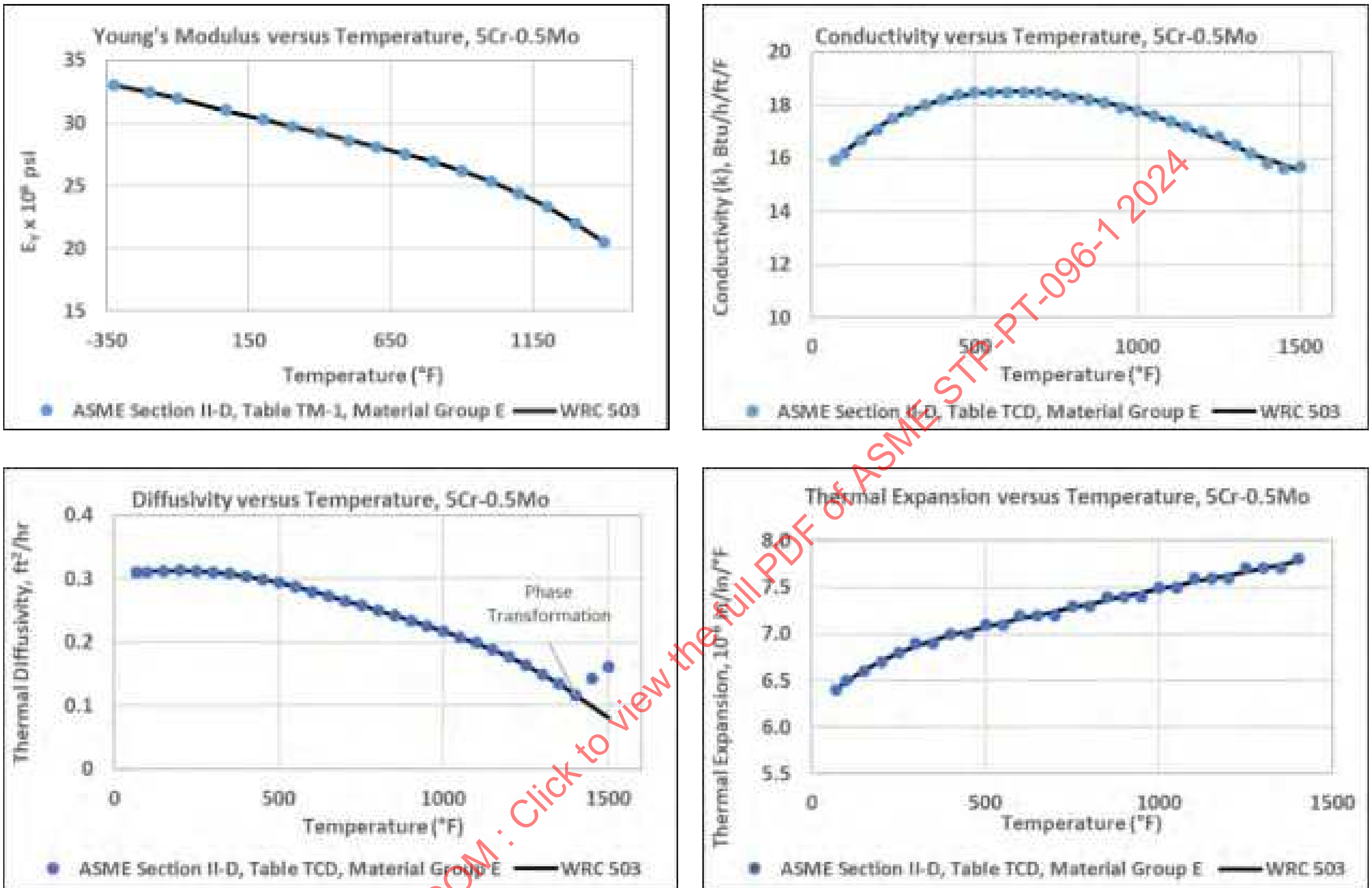


Figure 12-2: Grade 5 (Annealed) Yield Strength Vs. Temperature, By Data Source, Including Trend Curves

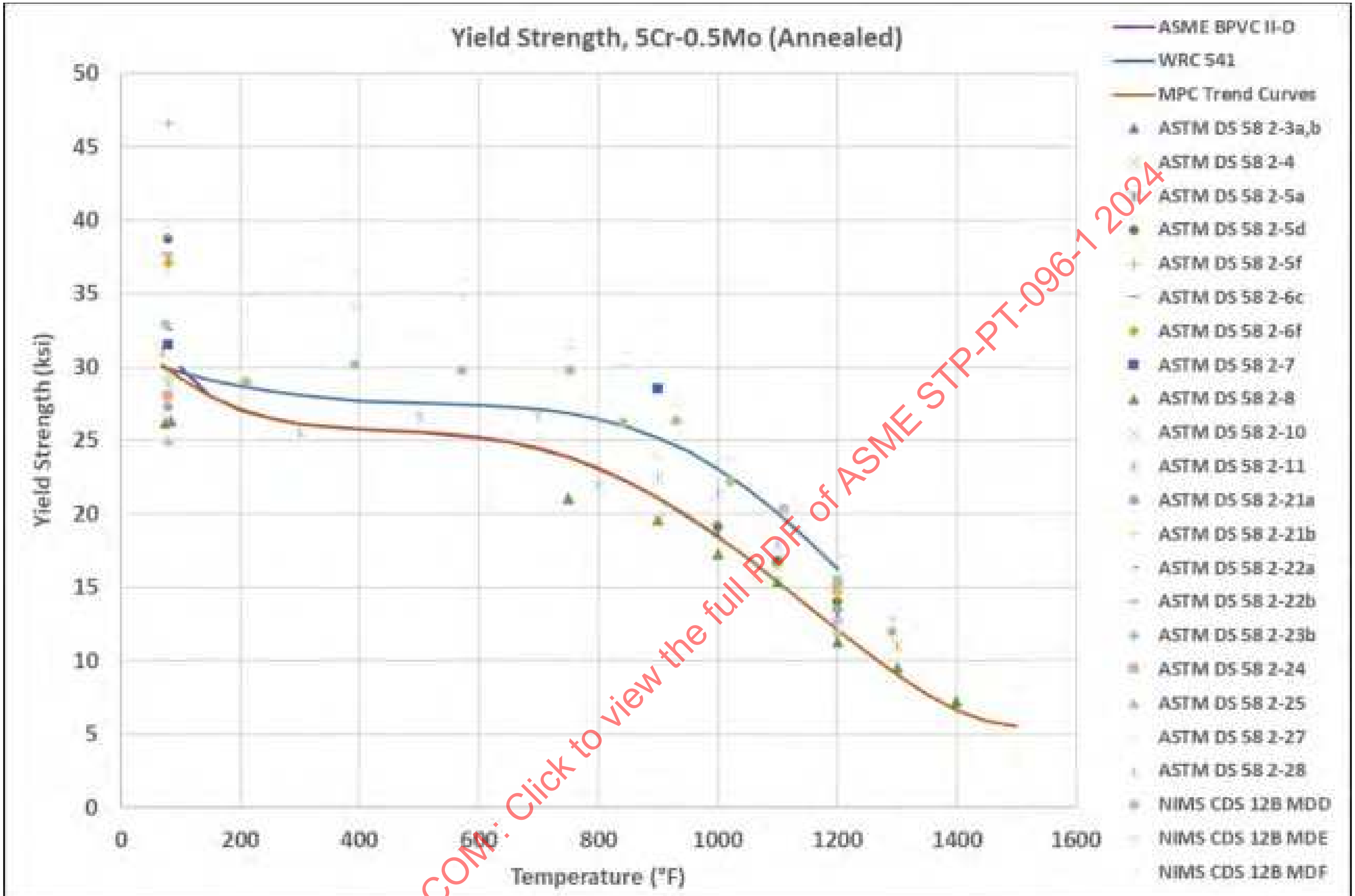


Figure 12-3: Grade 5 (Annealed) Strength Vs. Temperature, By Data Source, Including Trend Curves

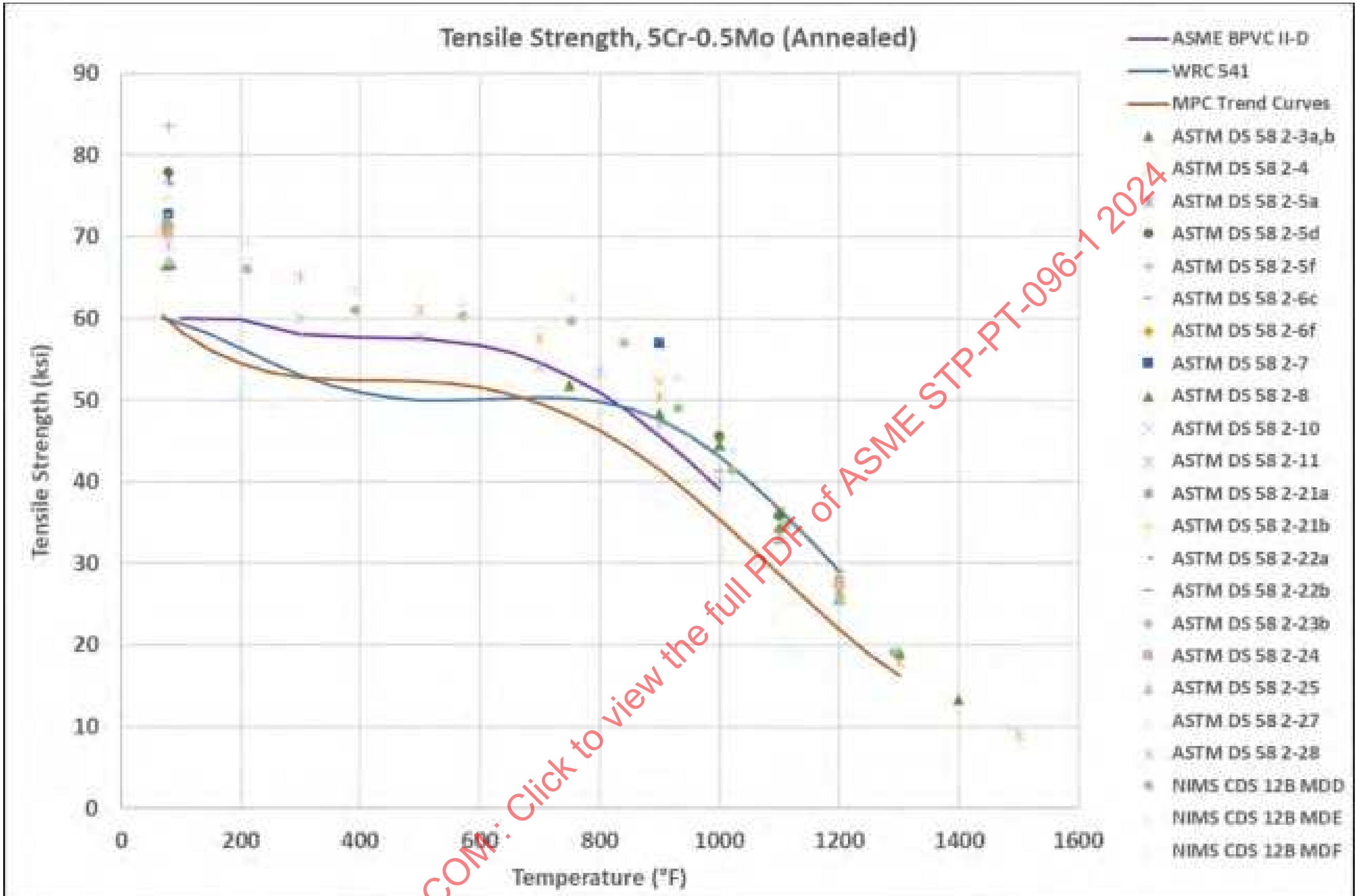


Figure 12-4: Grade 5 (N&T) Yield Strength Vs. Temperature, By Data Source, Including Trend Curves

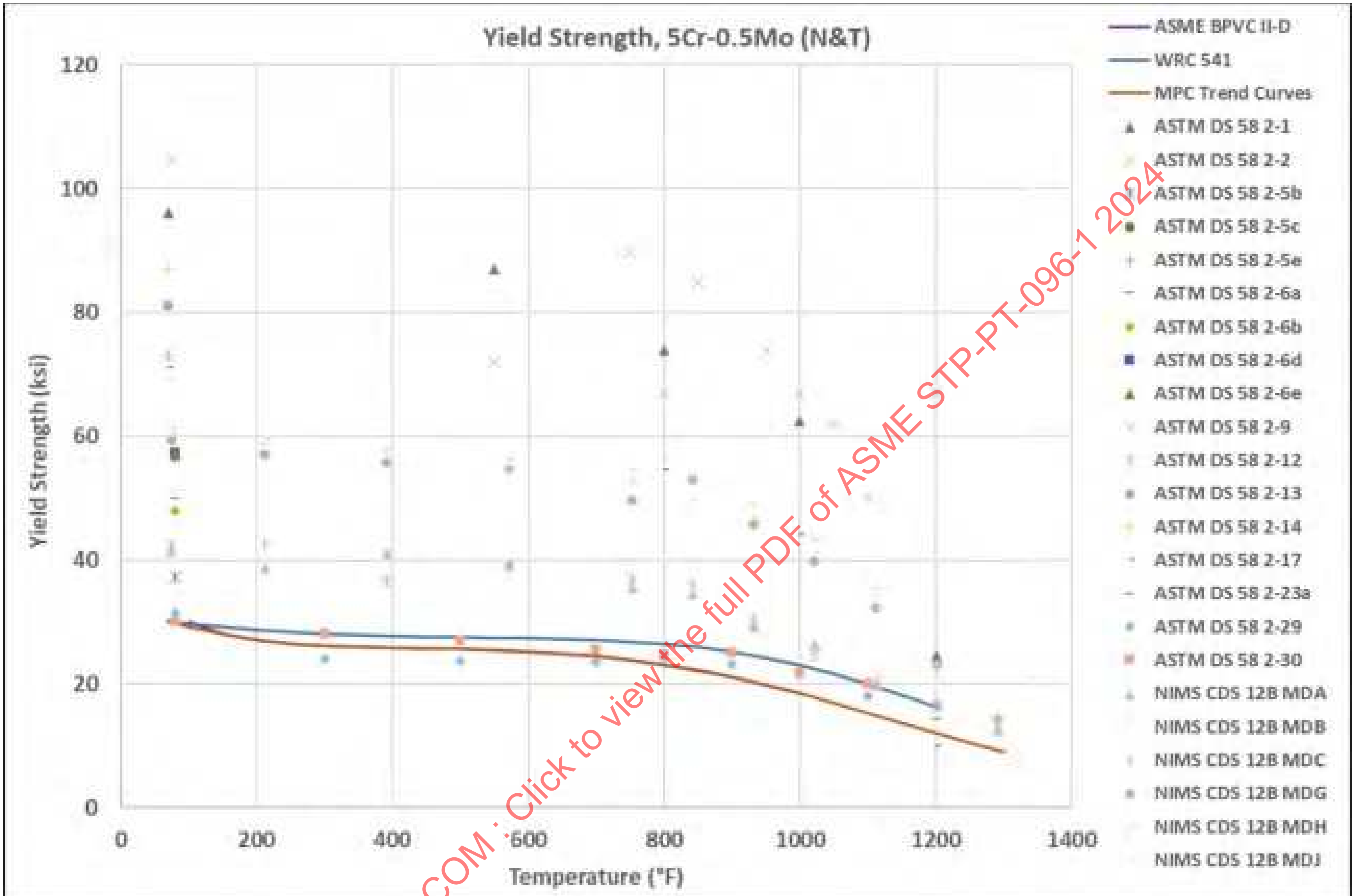


Figure 12-5: Grade 5 (N&T) Tensile Strength Vs. Temperature, By Data Source, Including Trend Curves

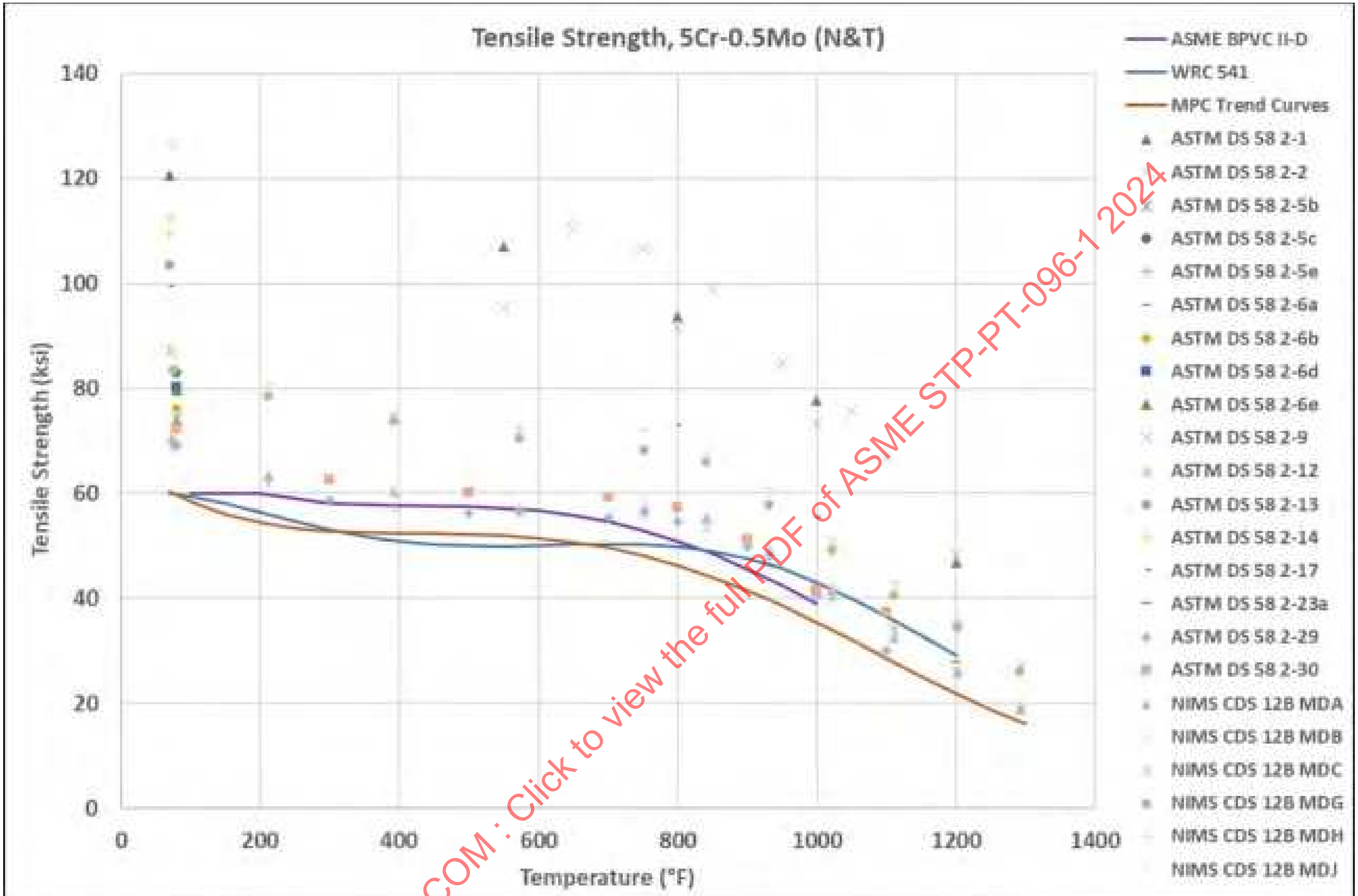


Figure 12-6: Grade 5 (Annealed) Yield Strength Ratios Vs. Temperature (Calculated on a Heat-By-Heat Basis, By Data Source)

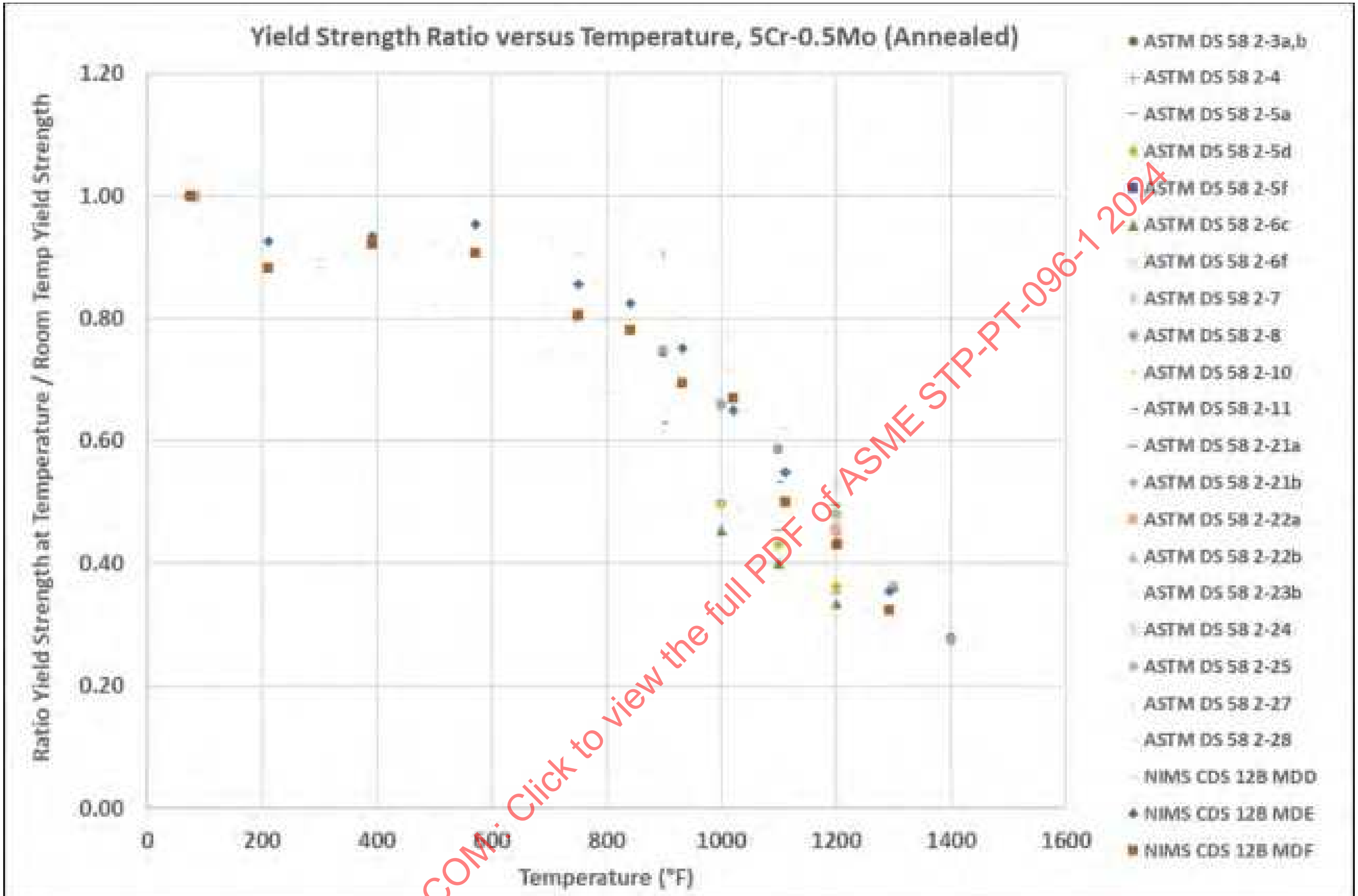


Figure 12-7: Grade 5 (Annealed) Tensile Strength Ratios Vs. Temperature (Calculated on a Heat-By-Heat Basis, By Data Source)

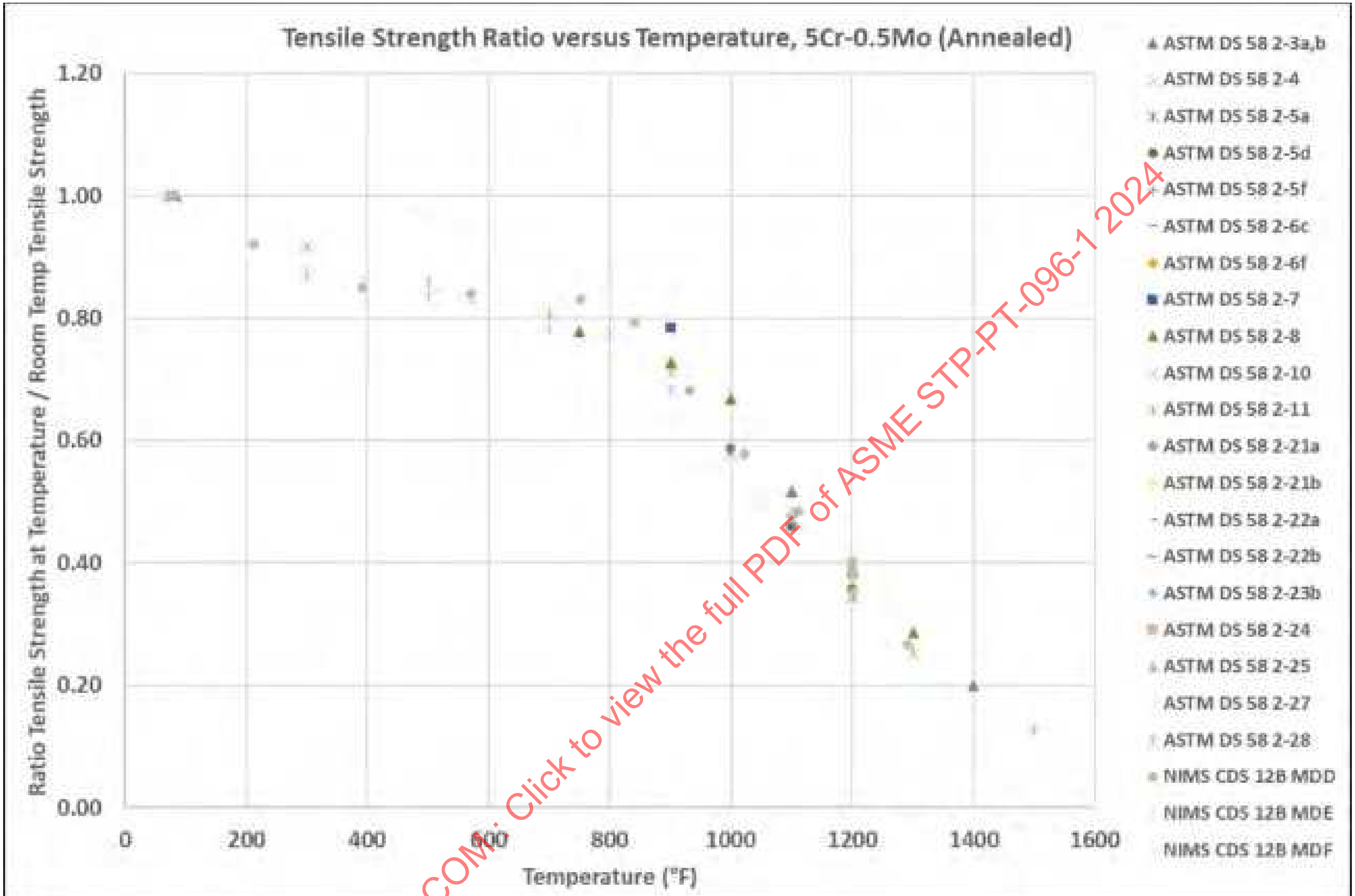


Figure 12-8: Grade 5 (N&T) Yield Strength Ratios Vs. Temperature (Calculated on a Heat-By-Heat Basis, By Data Source)

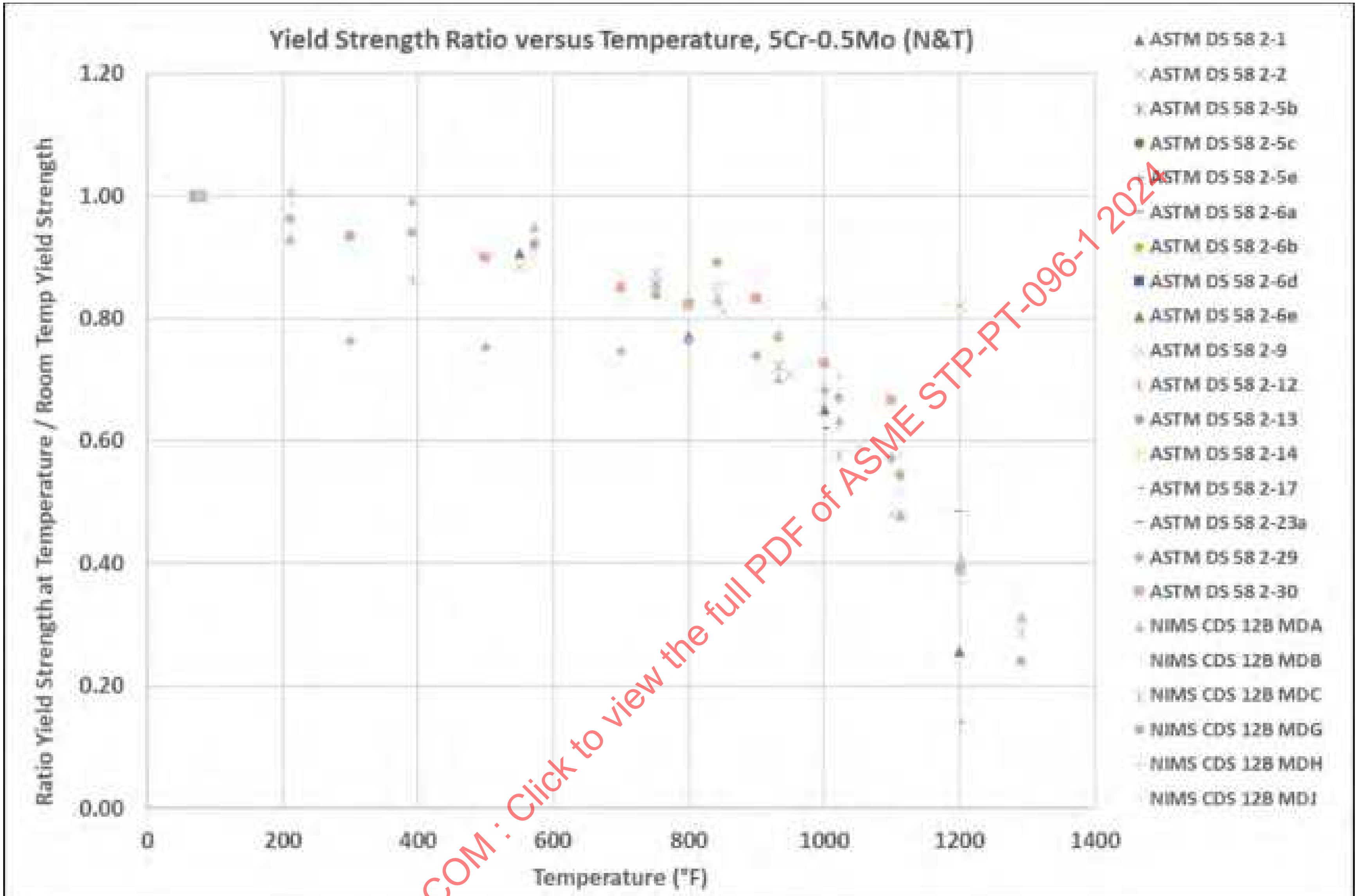


Figure 12-9: Grade 5 (N&T) Tensile Strength Ratios Vs. Temperature (Calculated on a Heat-By-Heat Basis, By Data Source)

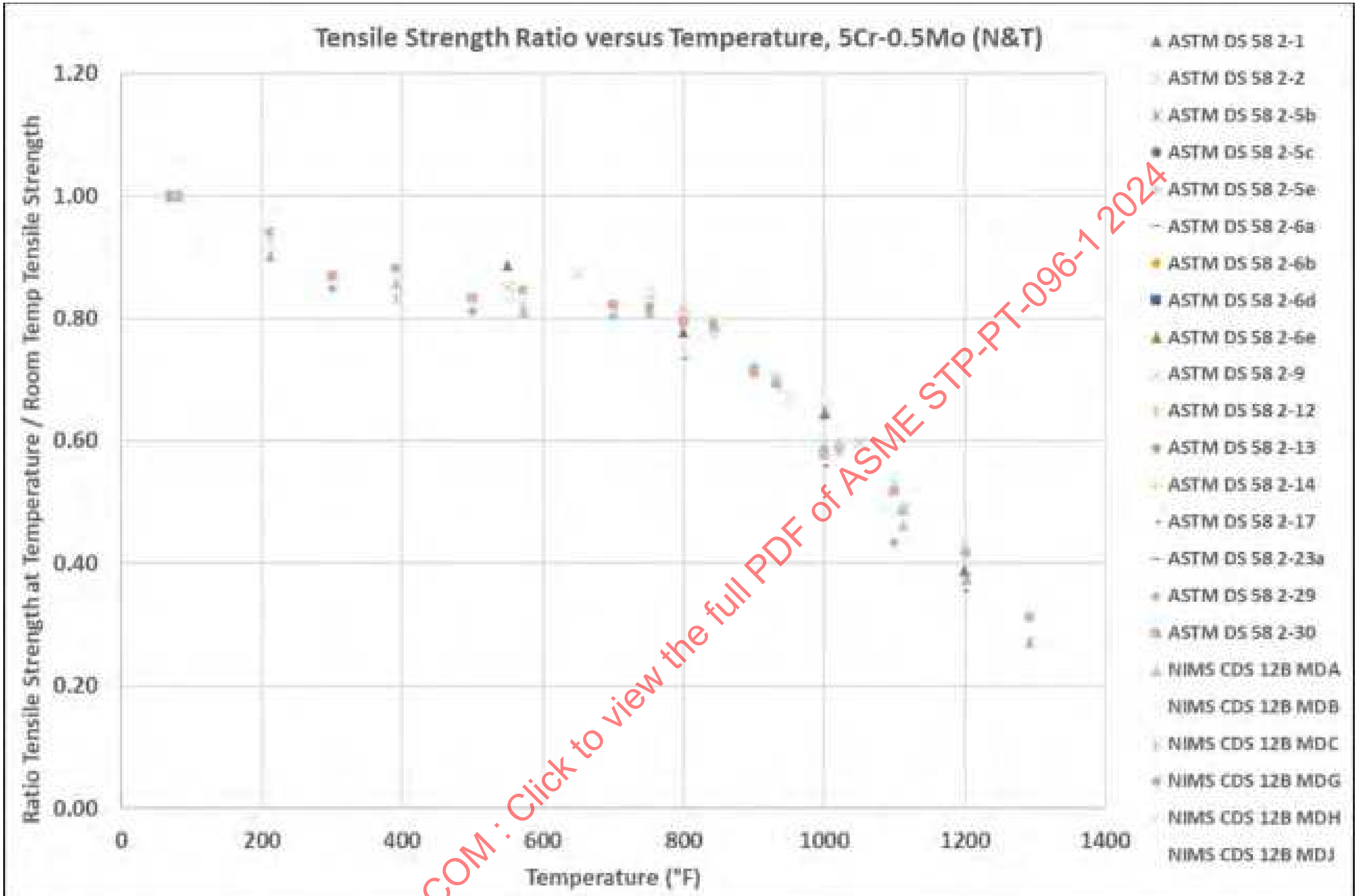


Figure 12-10: Grade 5 (Annealed) Yield Strength Ratios Vs. Temperature, All Combined Data, With Polynomial Regression

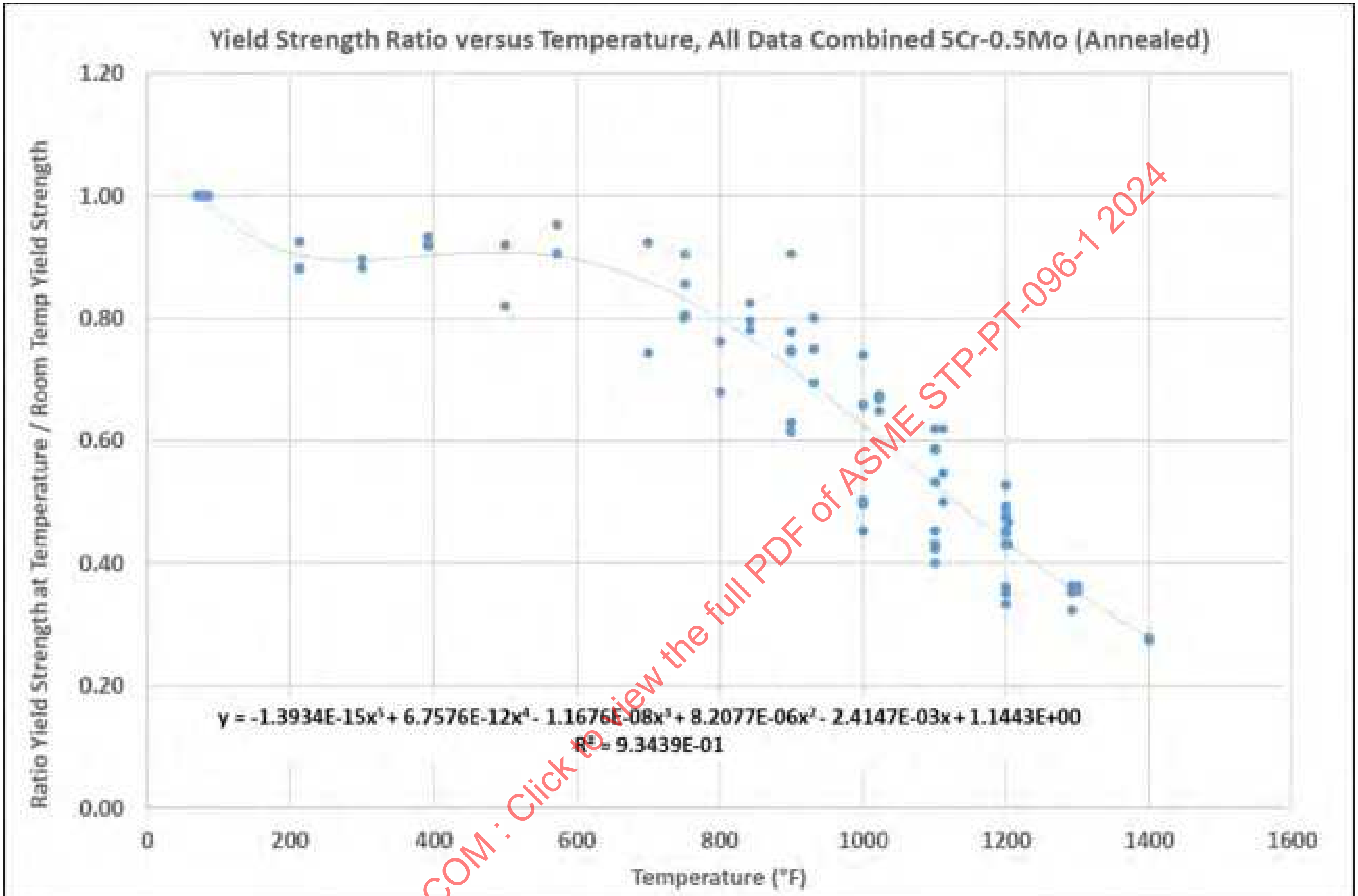


Figure 12-11: Grade 5 (Annealed) Tensile Strength Ratios Vs. Temperature, All Combined Data, With Polynomial Regression

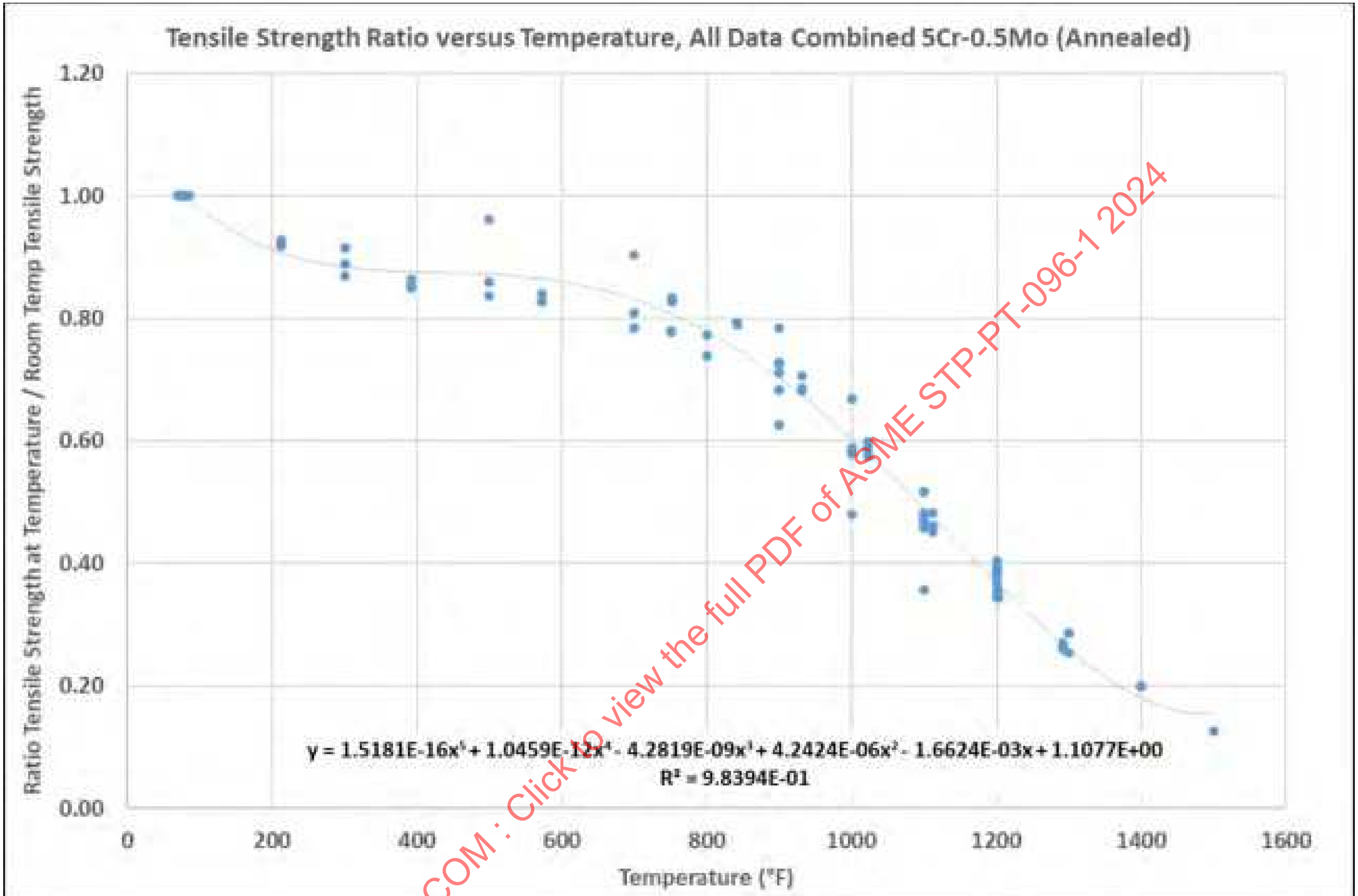


Figure 12-12: Grade 5 (N&T) Yield Strength Ratios Vs. Temperature, All Combined Data, With Polynomial Regression

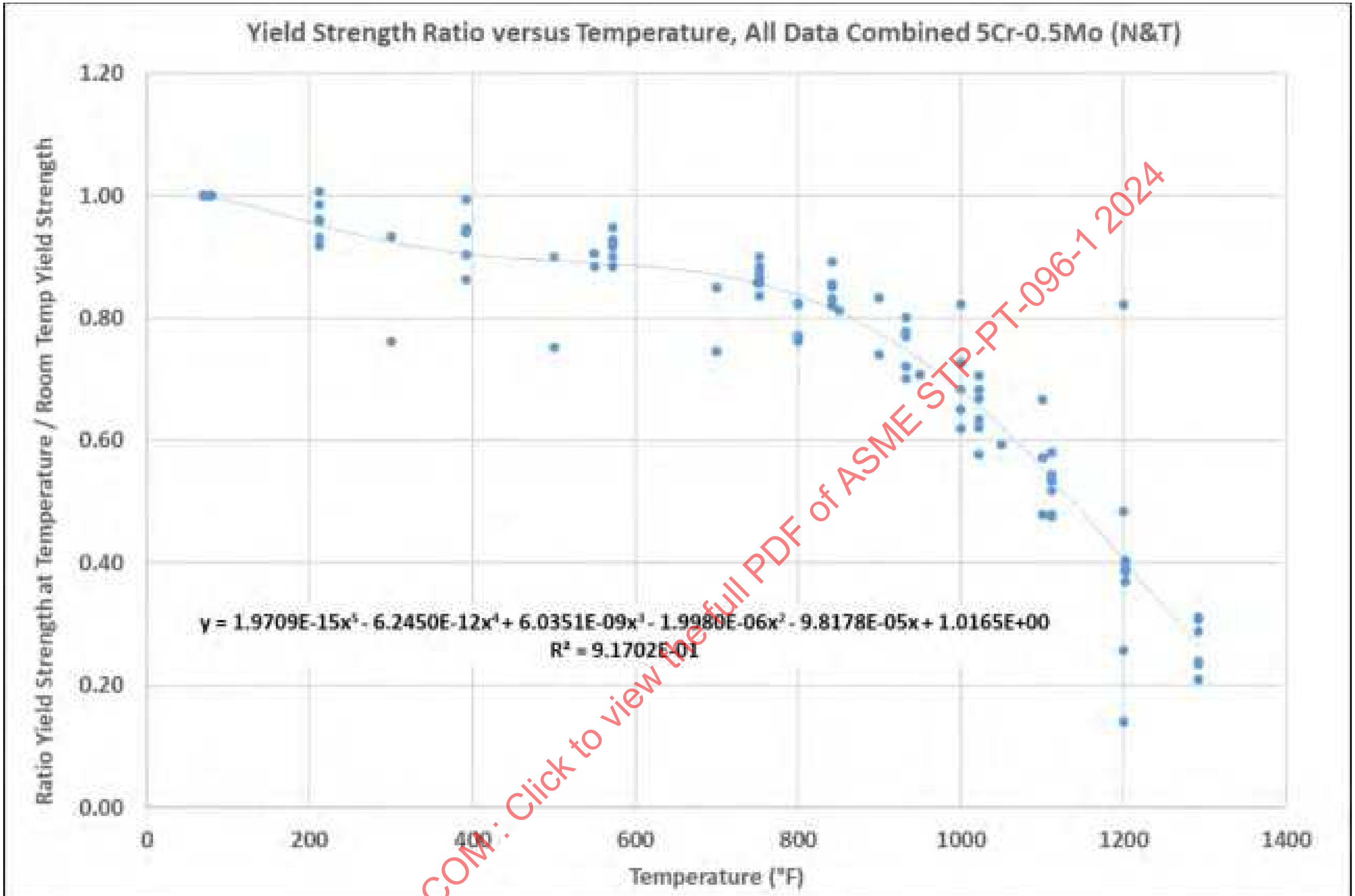


Figure 12-13: Grade 5 (N&T) Tensile Strength Ratios Vs. Temperature, All Combined Data, With Polynomial Regression

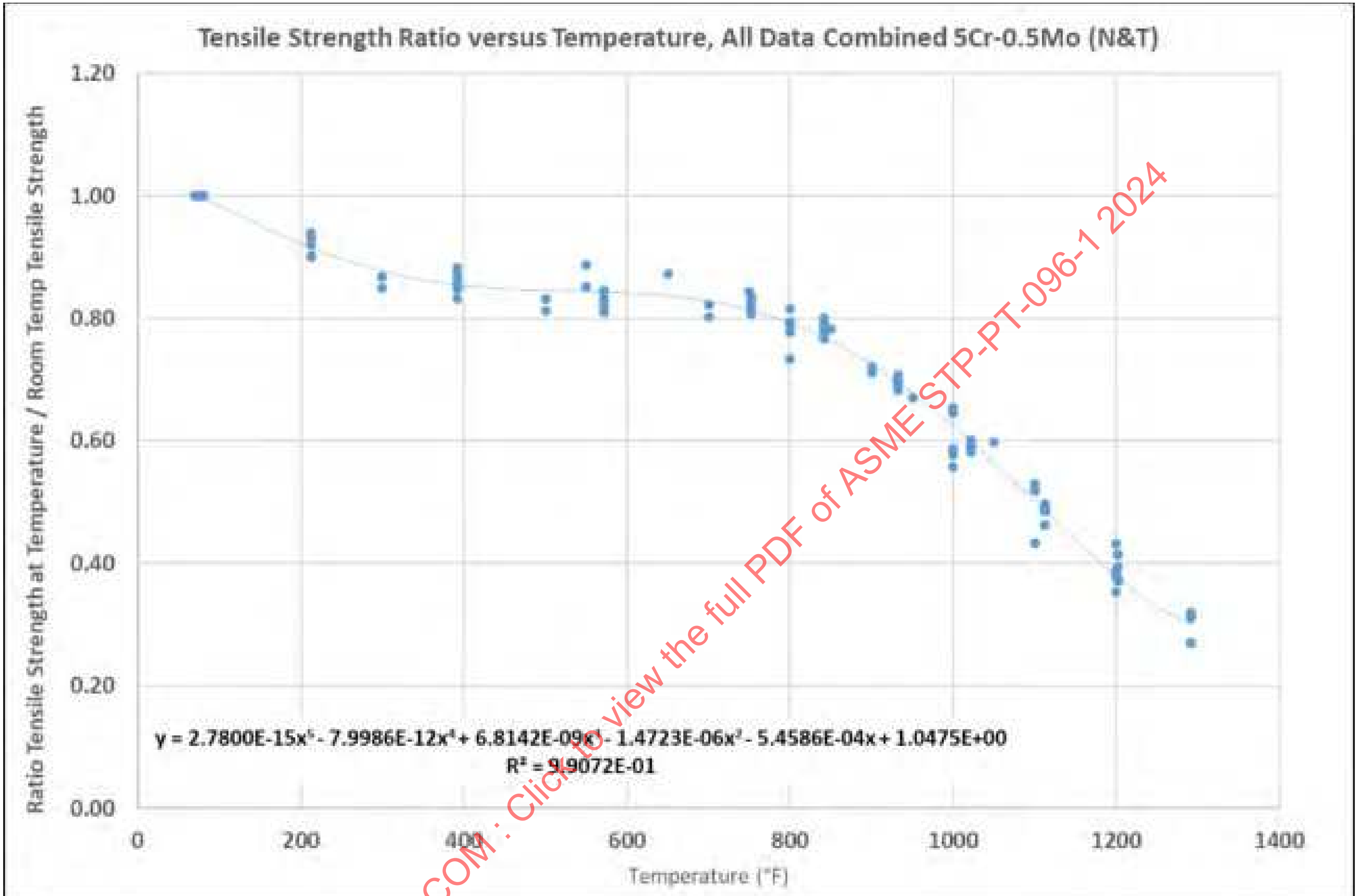


Figure 12-14: Grade 5 Creep Rupture Isotherm Curves

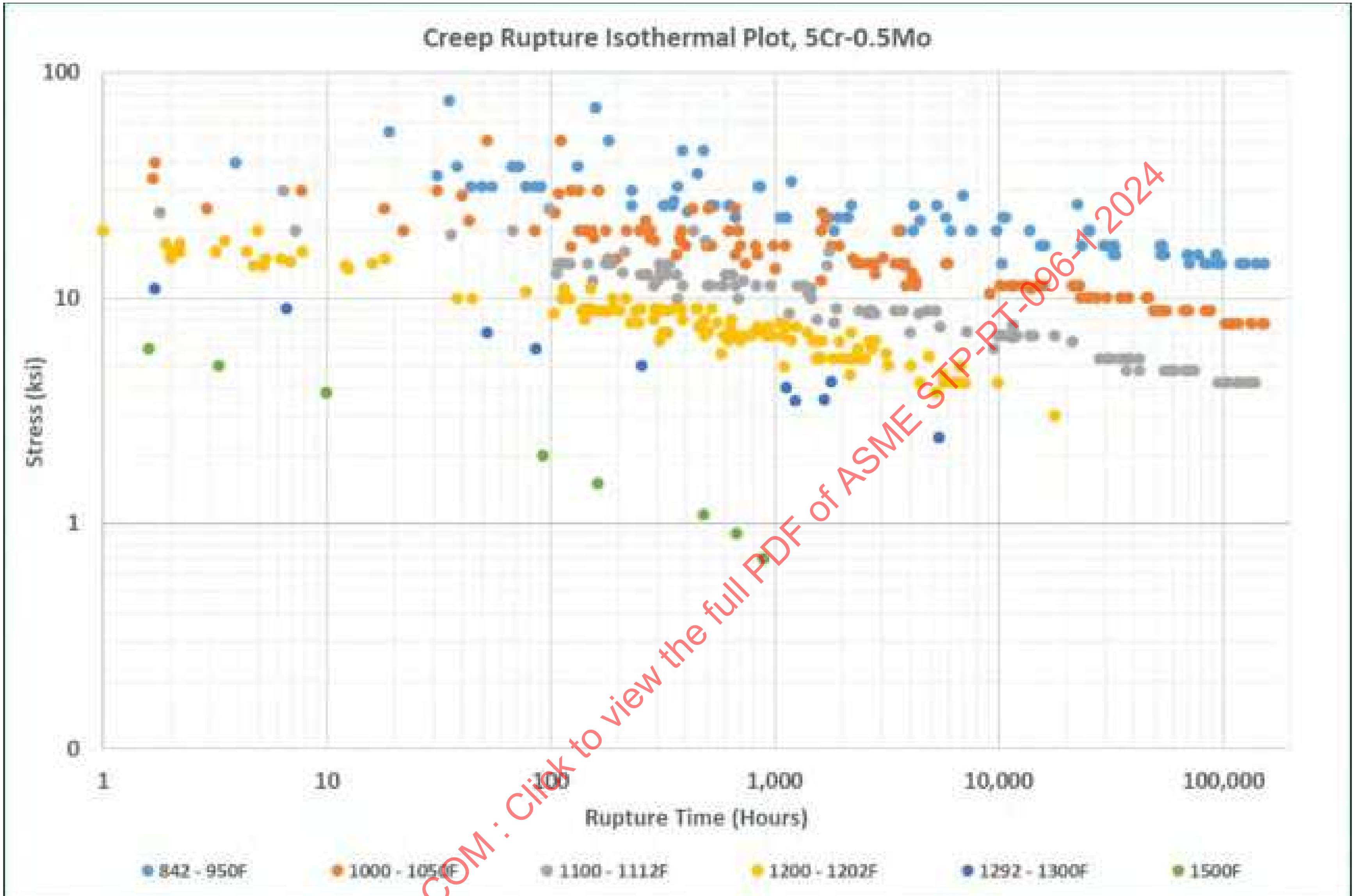


Figure 12-15: Grade 5 Creep Strain Rate (MCR) Isotherm Curves

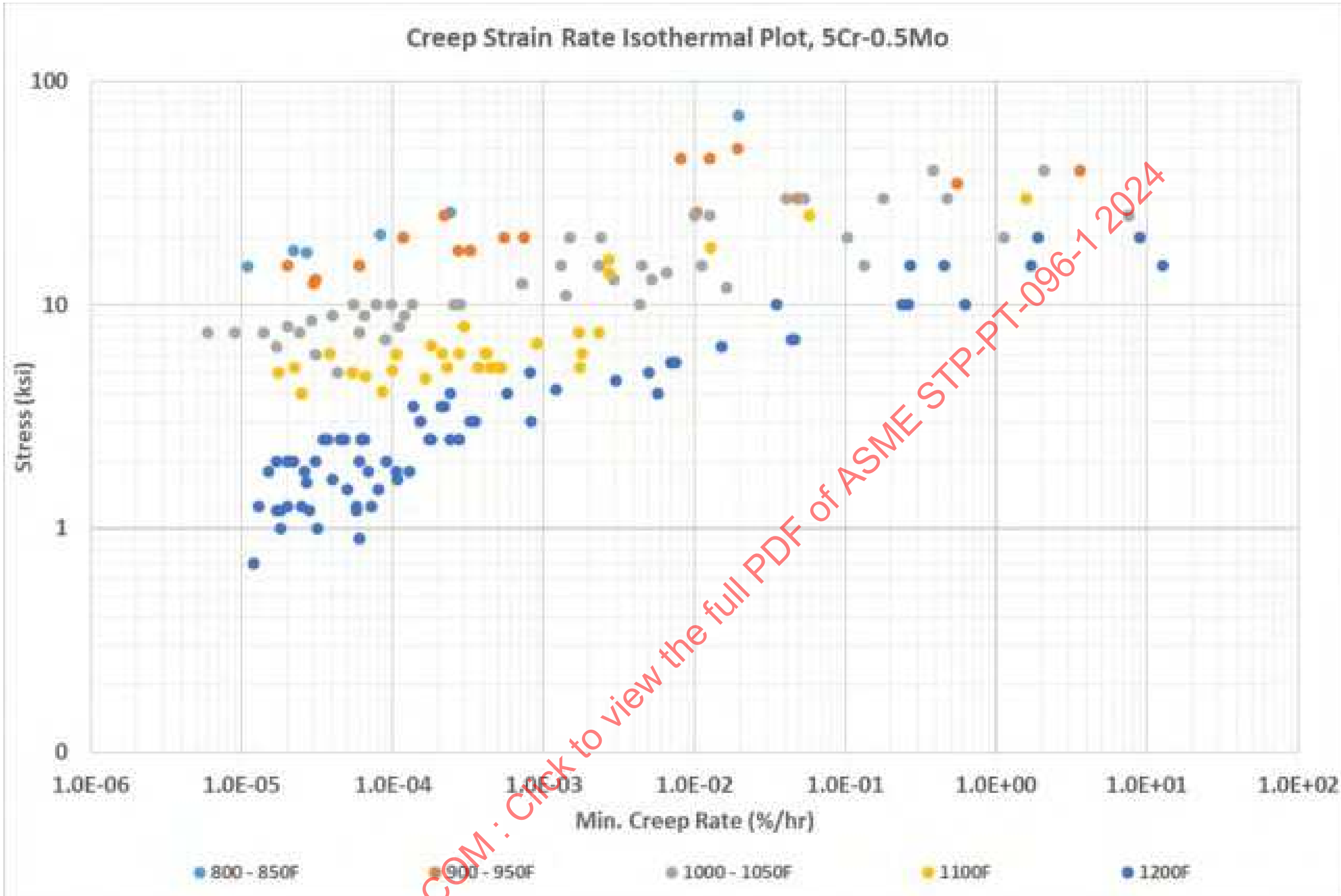


Figure 12-16: Grade 5 Creep Ductility (% Elongation) Vs. Rupture Time Isotherms

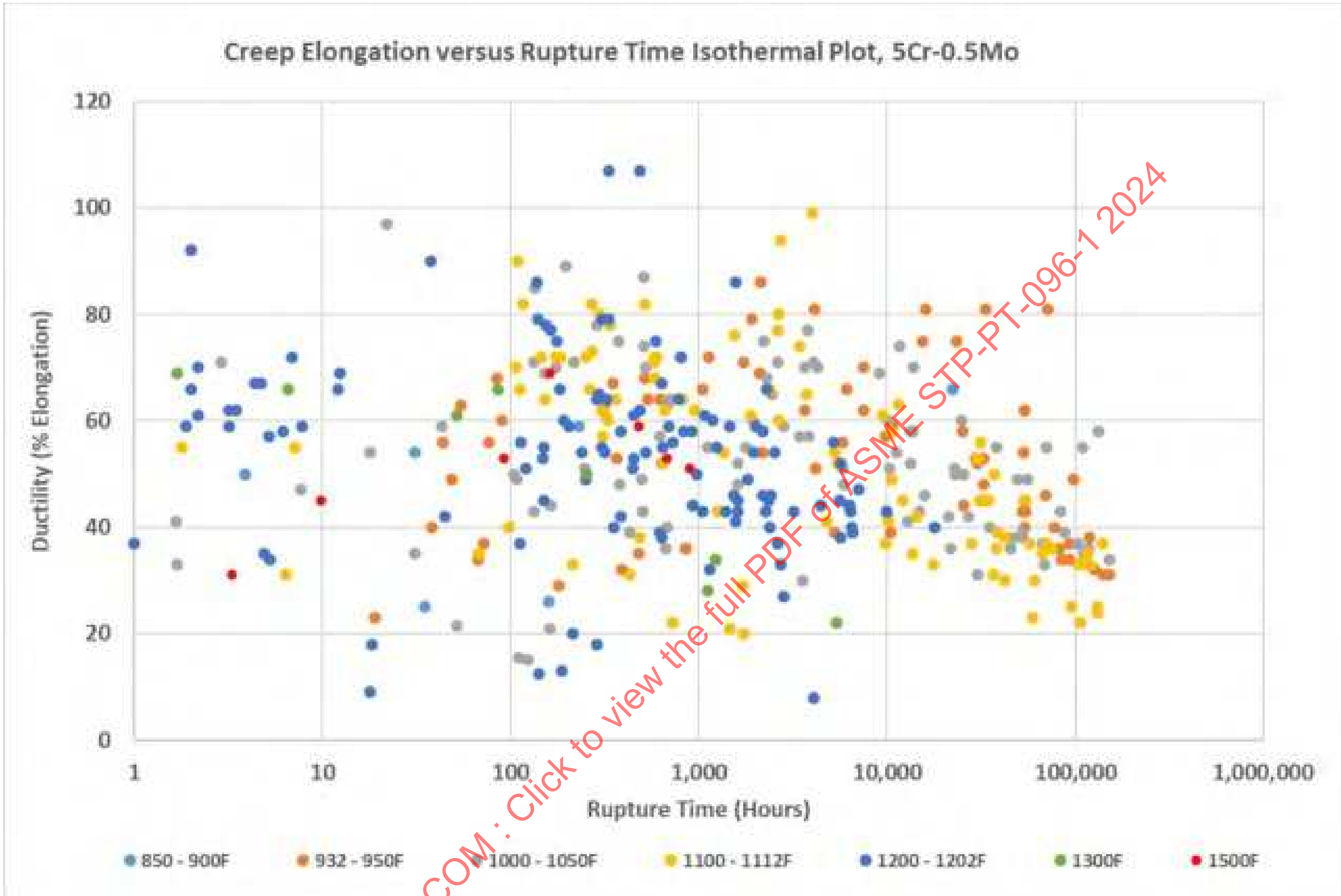


Figure 12-17: Calculated Allowable Stresses Based on Rupture Time and ASME II-D Appendix 1 Criteria (Grade 5)

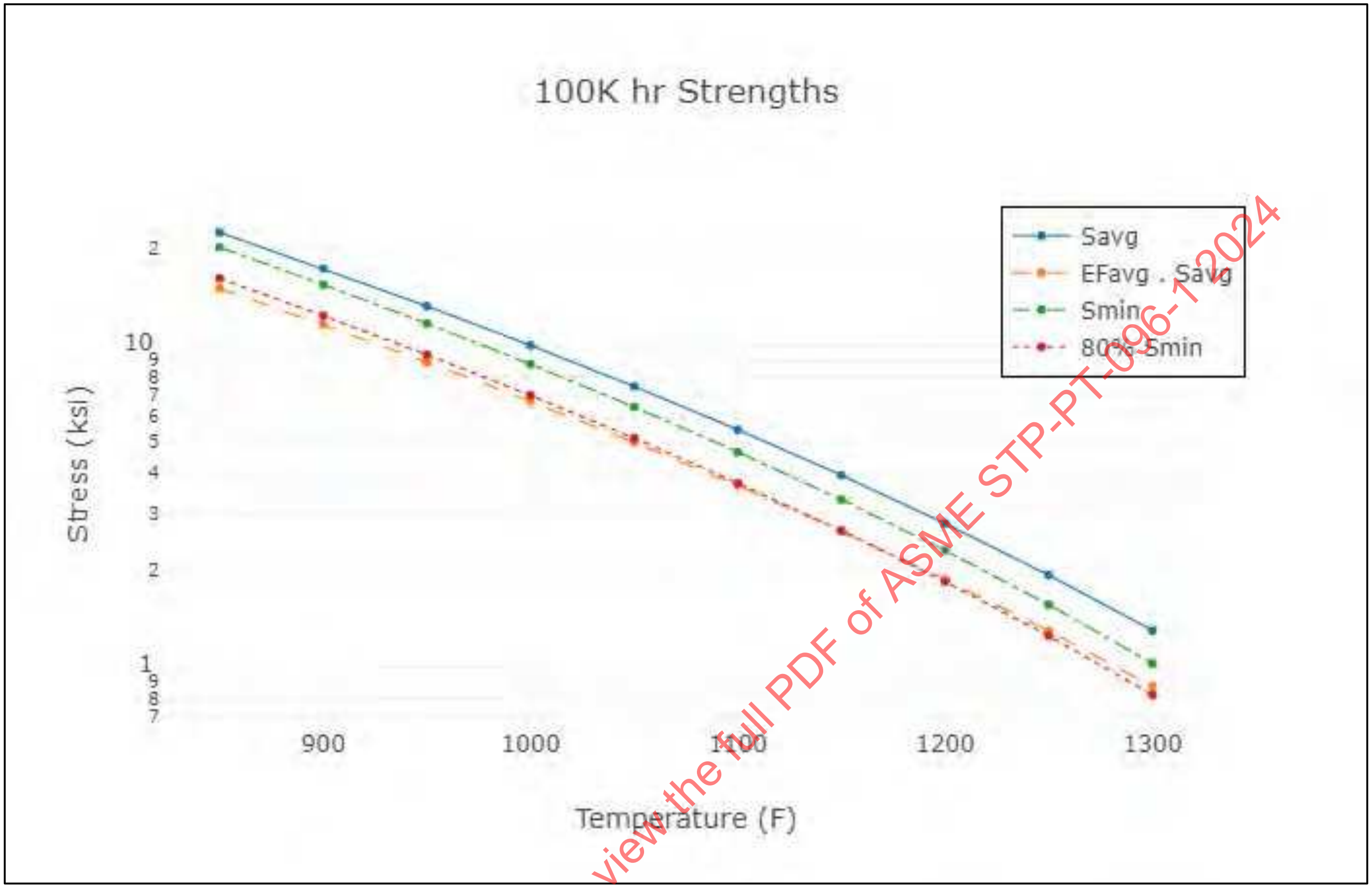


Figure 12-18: Calculated Allowable Stresses Based on Creep Strain Rate and ASME II-D Appendix 1 Criteria (Grade 5)

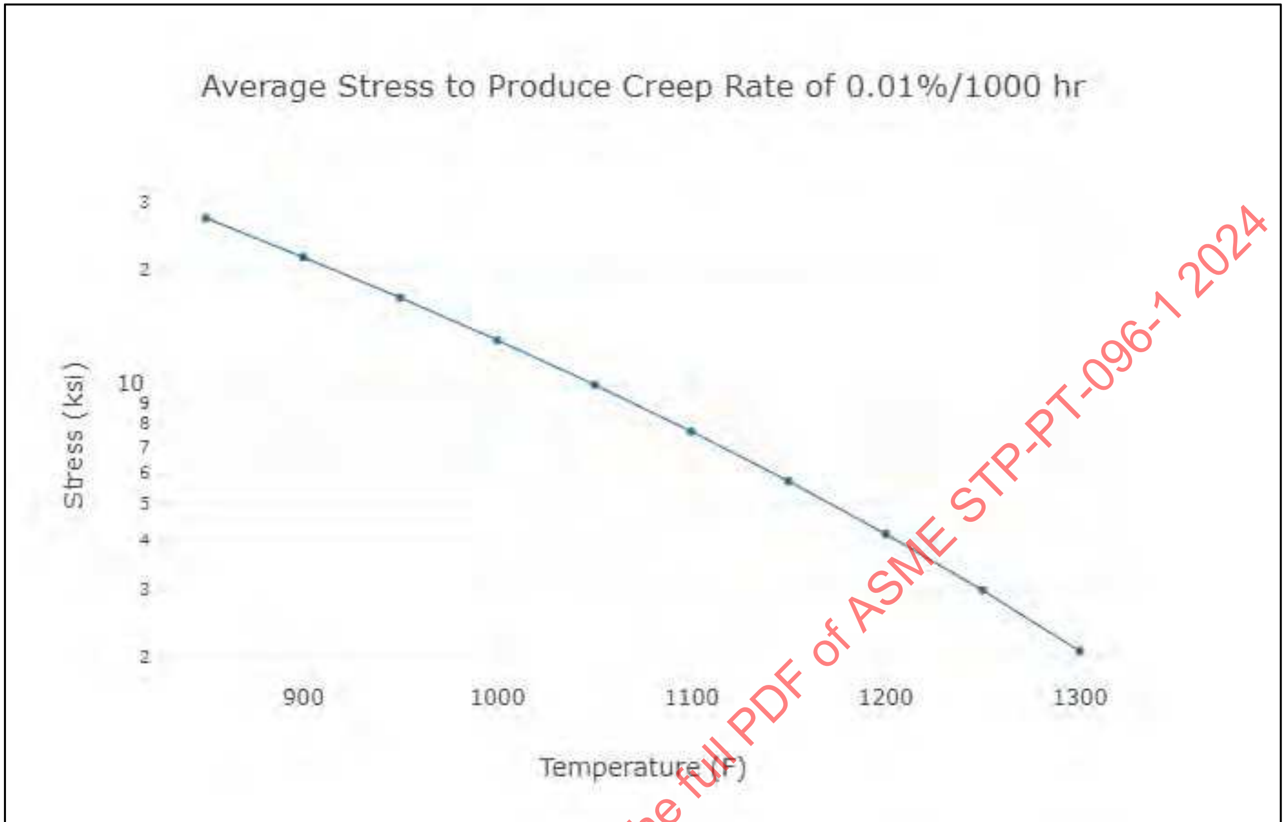


Figure 12-19: Comparison of Current Grade 5 Allowable Stresses Vs. ASME II-D Appendix 1 Criteria Applied to Data

Figure 12-20: Selected Strain Vs. Time Data (Grade 5 at 1300°F), All Tests Terminated Prior to Rupture

Attachment 12: Grade 5 Property Data

If you want the referenced embedded spreadsheet with additional data, please email a request to research@asme.org.

13 5CR-0.5MO-SI (GRADE 5A)

13.1 Physical Properties

Well-established physical properties were referenced from the BPVC Section II for this material. Physical property curves from WRC Bulletin 503 were plotted for comparison. Note, these physical properties apply to both common heat treatments of the 5Cr-0.5Mo-Si material (Normalized and Tempered [N&T] or Annealed). Figure 13-1 shows the trends of Elastic Modulus (E_y), Thermal Conductivity (k), Thermal Diffusivity (TD), and Thermal Expansion (α) with temperature.

13.2 Yield and Tensile Strength

Elevated temperature Yield and Tensile Strength over the range of existing allowable stresses (up to 1200°F) were readily available, including data beyond the current range of allowable stresses, up to approximately 1500°F, as shown in Figures 13-2 and 13-3 for the Annealed heat treatment, and Figures 13-4 and 13-5 for the N&T heat treatment. The sources for both high-temperature yield and high-temperature tensile strength are provided in the embedded spreadsheet at the end of this section.

To facilitate comparison of the data obtained to existing allowable stresses (Section II-D Table 1A), yield and tensile data were normalized on a heat-by-heat basis to express the ratio of yield or tensile strength at temperature to that measured for the heat at room temperature. In cases where data were not delineated by heats within a given source, or in cases where more than one room-temperature tensile test existed for a given heat of material, ratios are equal to the measured tensile or yield strength at temperature, divided by the average of all of the appropriate room-temperature values for the particular data source or heat of material. As a result of this approach, it is possible to have ratios in excess of 1.0 (although this did not occur for this particular material). E^2G understands that this approach is similar to the normalizing procedure performed by ASME in typical analysis of yield and tensile data to obtain Table Y and Table U (Section II-D) trend curves, as well as for the calculation of allowable stresses. Figures 13-6 and 13-7 (Annealed) and Figures 13-8 and 13-9 (N&T) show the heat-by-heat variation in yield and tensile strength ratios (respectively) as a function of temperature. It should be emphasized that even though the figure legends reference an entire source of data, the ratios, wherever possible, were calculated on a heat-by-heat basis; this is evident in the embedded spreadsheet at the end of this section. Figures 13-10 and 13-11 (Annealed) and Figures 13-12 and 13-13 (N&T) contain all of the yield and tensile (respectively) ratios plotted together, to facilitate regression of a 5th-order polynomial that is subsequently used for allowable stress comparison.

13.3 Creep Data (Creep Rupture, Minimum Creep Rate, and Ductility)

Creep Rupture data is shown in Figure 13-14, plotted as isotherms. It should be emphasized that these plots contain data for all product forms of material classified in the referenced publications as "5Cr-0.5Mo-Si" material. This certainly includes material meeting the requirements of current ASME BPVC Section II-A specifications (e.g., SA-213 T5b and SA-335 P5b). However, due to the diversity of data sources utilized for the compilation of the material property tables, it is likely that some of the material data shown in Figure 13-14 may not meet existing specifications for this grade of material. For example, several data points in the creep data shown in Figure 13-14 includes "bar" or "cast" product forms of 5Cr-0.5Mo-Si, which are not included in the current code book. Where possible, E^2G has documented the chemical composition if contained within the original source. In many cases, the project team has also made efforts to trace cross-referenced data back to original test results to determine if the heat treatment, product form, chemistry, etc.

details can be obtained. This information is provided with the embedded spreadsheet to facilitate additional analysis on the part of ASME.

Creep Minimum strain rates (%/hour) are shown in Figure 13-15, again, separated by temperature. Creep Ductility, as % elongation, is plotted in Figure 13-16. As is typical, the data show significant overlap, and it is difficult to observe clear trends in the data. The data is not intended to be used as plotted but is available in the spreadsheet for additional analysis.

Creep data were analyzed using E^2G's proprietary Lot-Centered Analysis web-based software tool, in order to obtain creep properties. This regression is based on a Mandel-Paule algorithm and considers the variation within individual heats of material (for both rupture and strain rate data) as well as the variation between heats. The weight assigned to each datapoint and each heat is scaled based on the relative variation. Both rupture and strain rate (minimum creep rate, expressed as true strain per hours) were regressed according to a Larson-Miller time-temperature-parameter model, with a 3rd-order polynomial of stress. Lot-specific constant behavior was accounted for in this analysis, but the variation of LMP with stress was assumed to be constant (no non-parallel terms were included in the analysis). A 95% predictive limit was utilized to obtain the lower-bound (minimum LM constant for both rupture and strain rate) properties. The results of this analysis are summarized in Table 13-1 for rupture data and Table 13-2 for strain rate data. The Lot-Centered Analysis software tool generates property tables in the creep regime using the criteria outlined in Mandatory Appendix 1 of ASME Section II-D; the nomenclature of variables is consistent with II-D Appendix 1. For visualization of the allowable stress trends, Figure 13-17 summarizes the rupture allowable stresses. The creep rate allowable stresses are illustrated in Figure 13-18. Figure 13-19 displays a comparison of the various allowable stress criteria from Section II-D, Appendix 1, to the existing (2019) Section II-D Table 1A allowable stresses for all product forms of 5Cr-0.5Mo-Si (seamless tube or pipe). Note, the allowable stress criteria based on Yield (2/3 of Yield) and Tensile Strength (Tensile / 3.5) is illustrated for both common heat treatments of 5Cr-0.5Mo-Si material (Annealed and N&T).

13.4 Continuous Cycling Fatigue and Hold Time Fatigue Curves

No elevated temperature continuous cycling or hold time fatigue data was located for 5Cr-0.5Mo-Si.

Table 13-1: Model Parameters, Larson-Miller Property Results, and Allowable Stress (Rupture) Criteria, 5Cr-0.5Mo-Si

Equation Format:

$$\log(t_r) = C_{avg} + \frac{1}{T+460}\left(b_1 + b_2\log(\sigma) + b_3(\log(\sigma))^2 + b_4(\log(\sigma))^3\right)$$

C_{avg}	**-8.061**
C_{min}	**-9.662**
b_1	**19499.3**
b_2	**-6180**
b_3	**4488.9**
b_4	**-2176.7**

Number Data Points		**99**
Correlation Coefficient	R^2	0.181
Average Variance within Heats	V_w	0.9468
Variance between Heats	V_b	0.205
Standard Error of Estimate	SEE	0.973

Properties provided are for T in °F, stress in ksi, and t_R in hours

Temperature, °F	**S_{avg} (ksi)**	***n***	**F_{avg} (calc)**	**F_{avg} (used)**	**$F_{avg} \times S_{avg}$**	**S_{min} (ksi)**	**80% S_{min}**
850	3.514	2.462	0.393	0.67	2.354	1.117	0.893
900	2.280	2.797	0.439	0.67	1.527	0.854	0.683
950	1.592	3.285	0.496	0.67	1.067	0.678	0.543
1000	1.184	3.806	0.546	0.67	0.793	0.555	0.444
1050	0.922	4.307	0.586	0.67	0.618	0.463	0.371
1100	0.743	4.773	0.617	0.67	0.498	0.394	0.315
1150	0.614	5.200	0.642	0.67	0.412	0.339	0.272
1200	0.518	5.588	0.662	0.67	0.347	0.296	0.237
1250	0.444	5.942	0.679	0.67	0.297	0.260	0.208
1300	0.385	6.263	0.692	0.67	0.258	0.231	0.185

Table 13-2: Model Parameters, Larson-Miller Property Results, and Allowable Stress (Strain Rate) Criteria, 5Cr-0.5Mo-Si

Equation Format:

$$\log(\dot{\varepsilon}_0) = -C_{avg} - \frac{1}{T+460}\left(a_1 + a_2\log(\sigma) + a_3(\log(\sigma))^2 + a_4(\log(\sigma))^3\right)$$

C_{avg} (A_0)	**-16.76**
C_{min} ($A_0+\Delta_\Omega^{SR,LB}$)	**-17.26**
a_1	**40676.7**
a_2	**-8553.6**
a_3	**2052.2**
a_4	**-1246**

Number Data Points		**81**
Correlation Coefficient	R^2	0.9521
Average Variance within Heats	V_w	0.0941
Variance between Heats	V_b	0.4158
Standard Error of Estimate	SEE	0.3068

Properties provided are for T in °F, stress in ksi, and t_R in hours

Temperature, °F	**$S_{C,avg}$ (ksi)**
850	29.99
900	23.51
950	18.12
1000	13.72
1050	10.20
1100	7.461
1150	5.383
1200	3.851
1250	2.750
1300	1.974

Figure 13-1: 5Cr-0.5Mo-Si Modulus (E_y), Thermal Conductivity (k), Thermal Diffusivity (TD), & Thermal Expansion (α) With Temperature

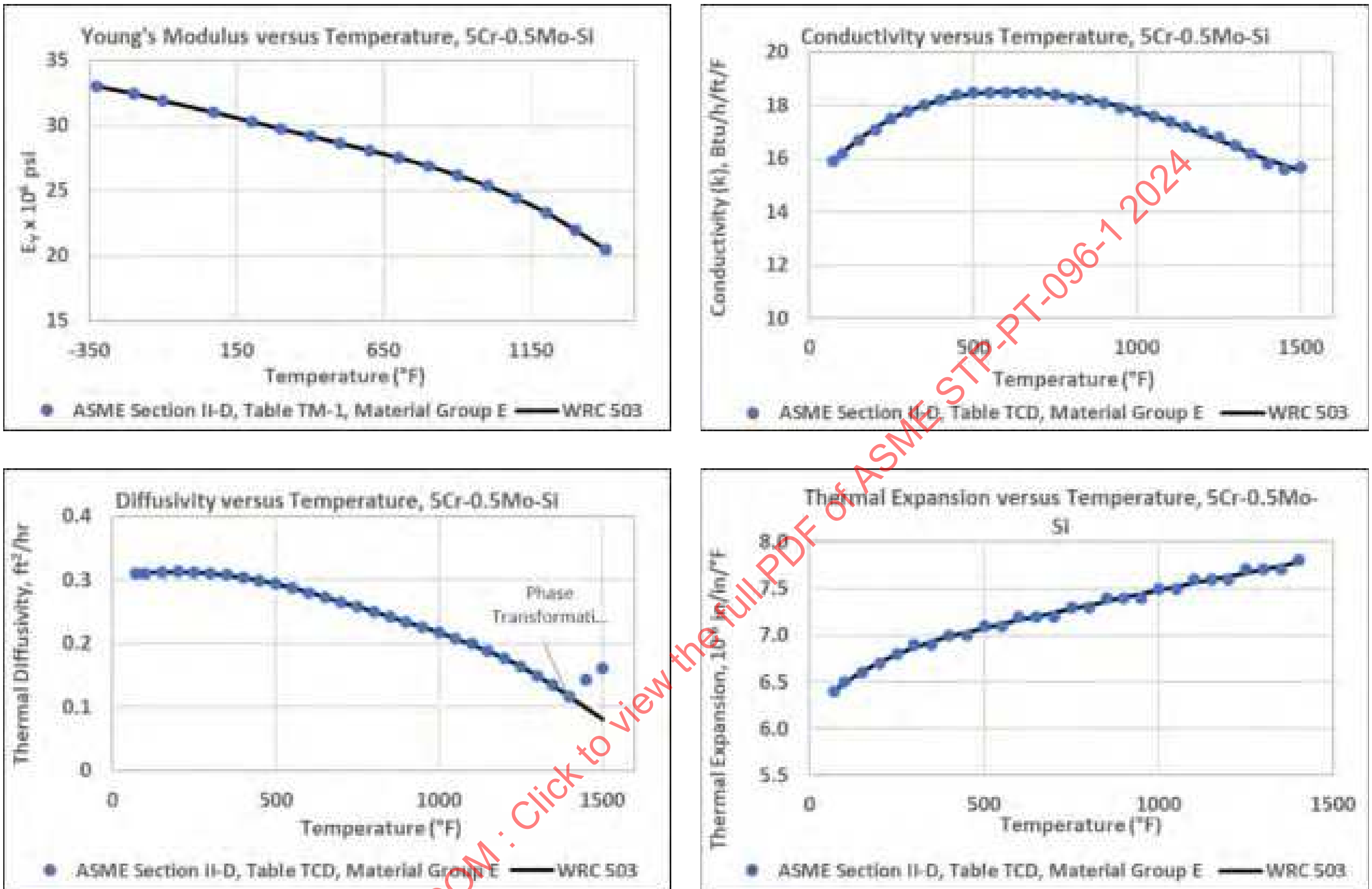


Figure 13-2: 5Cr-0.5Mo-Si (Annealed) Yield Strength Vs. Temperature, By Data Source, Including Trend Curves

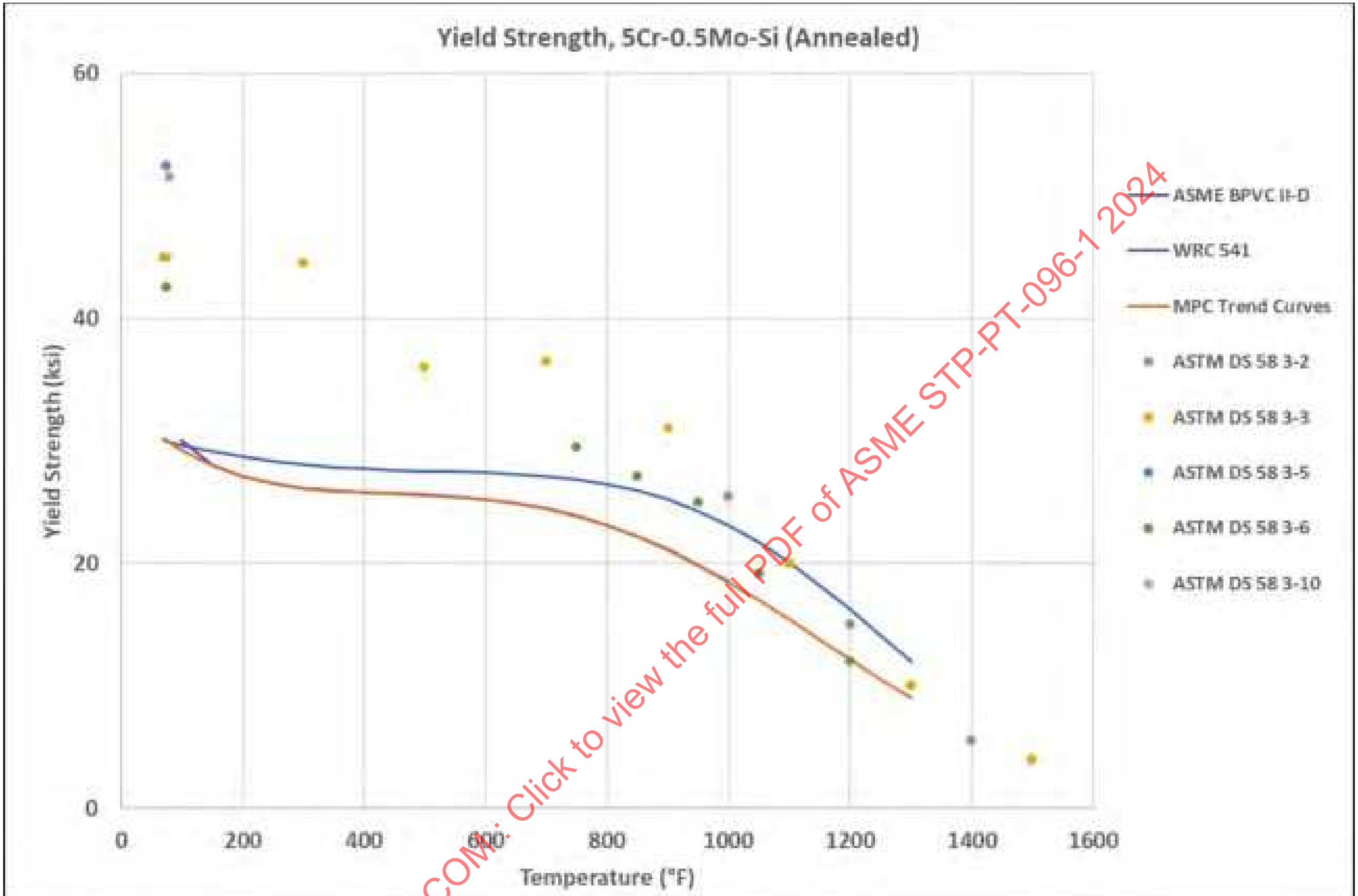


Figure 13-3: 5Cr-0.5Mo-Si (Annealed) Strength Vs. Temperature, By Data Source, Including Trend Curves

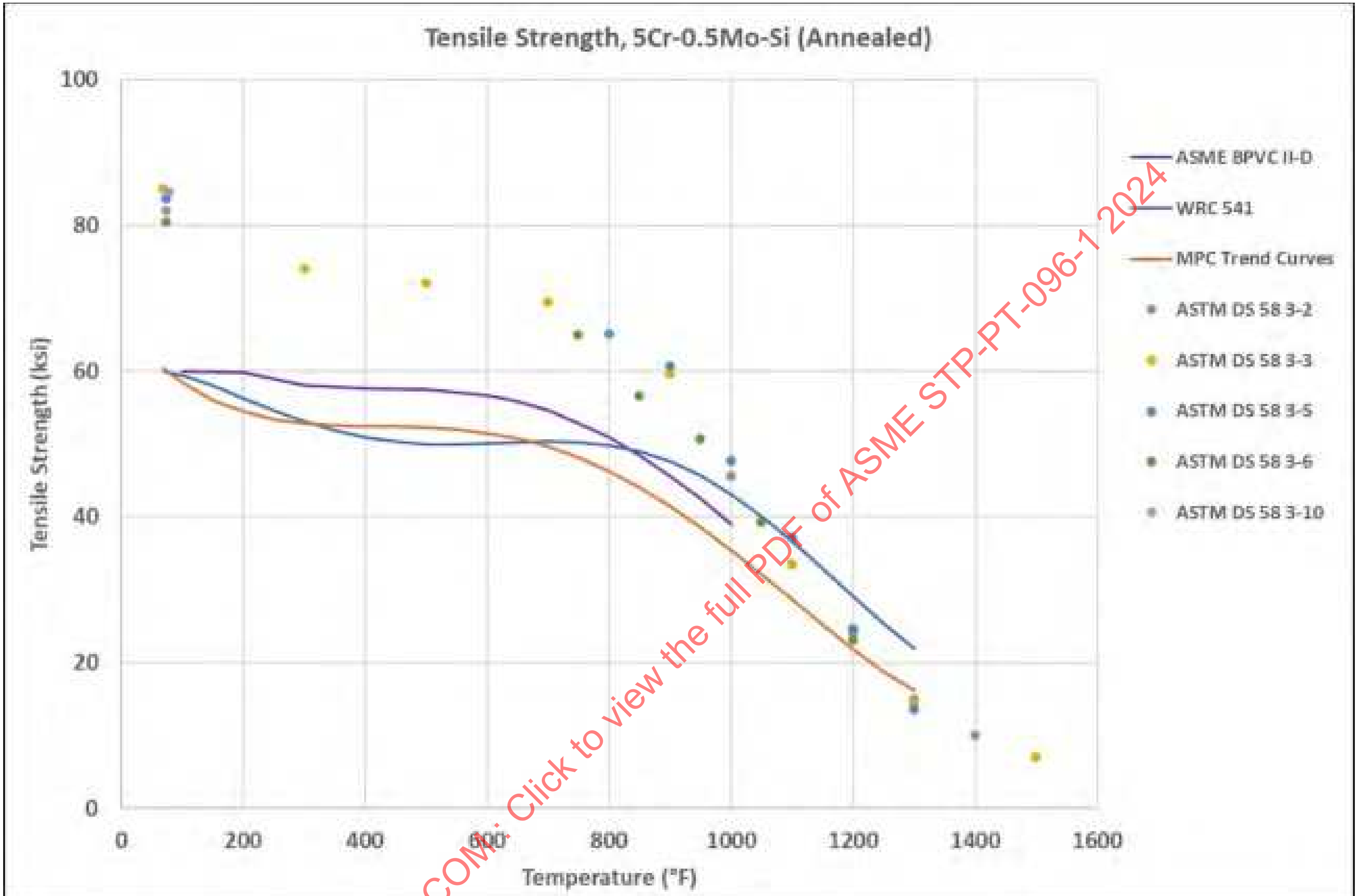


Figure 13-4: 5Cr-0.5Mo-Si (N&T) Yield Strength Vs. Temperature, By Data Source, Including Trend Curves

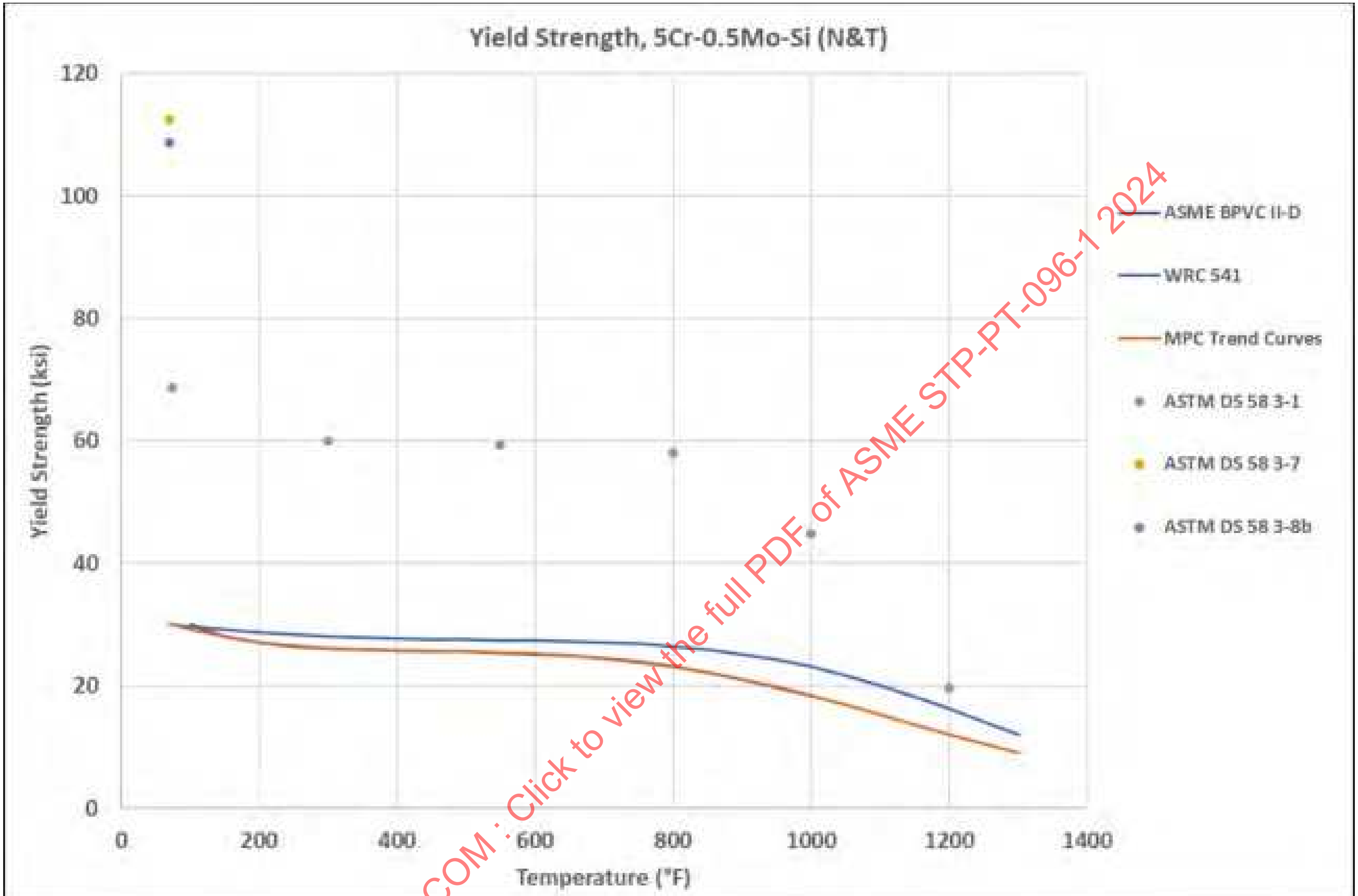


Figure 13-5: 5Cr-0.5Mo-Si (N&T) Tensile Strength Vs. Temperature, By Data Source, Including Trend Curves

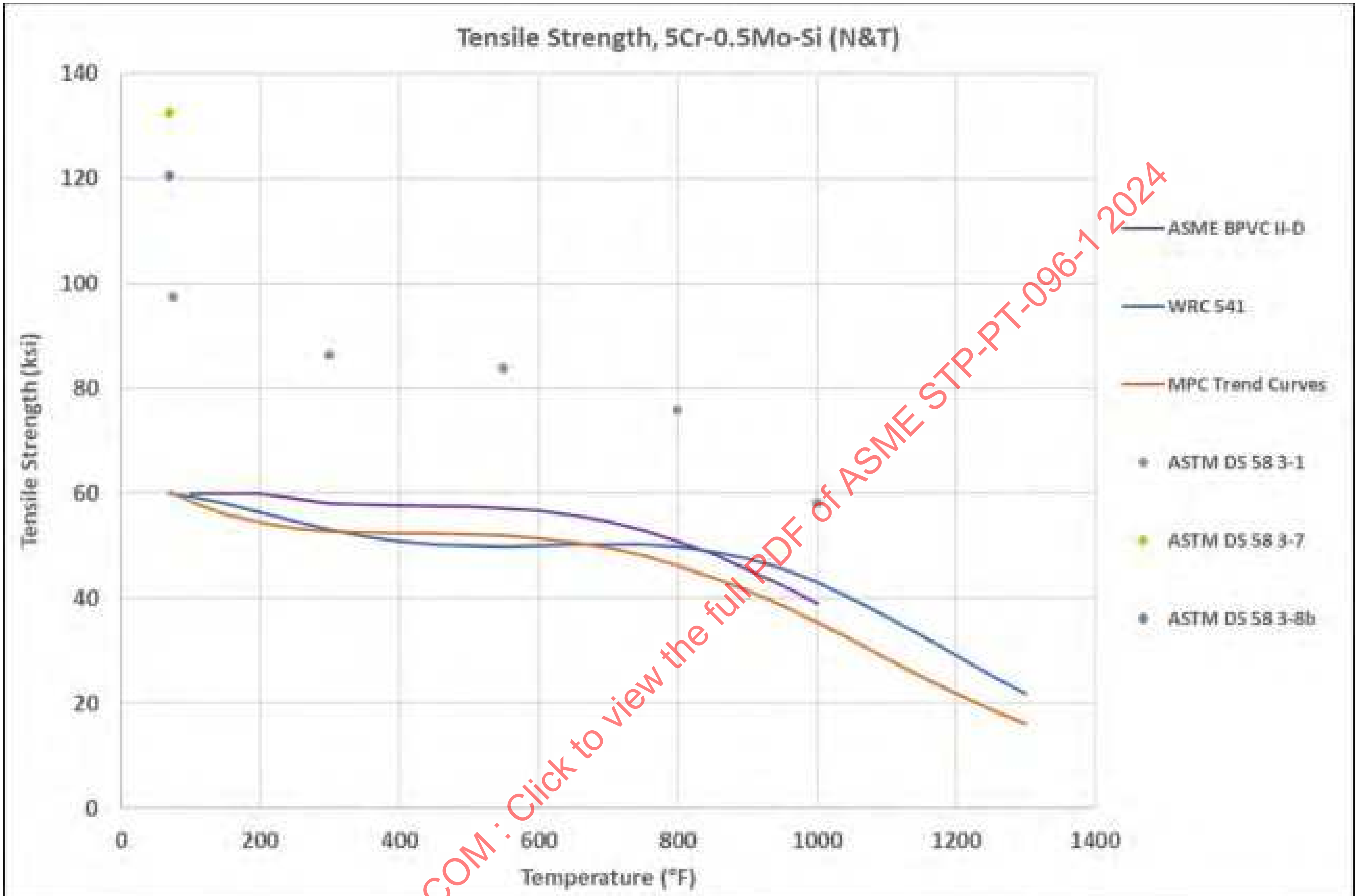


Figure 13-6: 5Cr-0.5Mo-Si (Annealed) Yield Strength Ratios Vs. Temperature (Calculated on a Heat-By-Heat Basis, By Data Source)

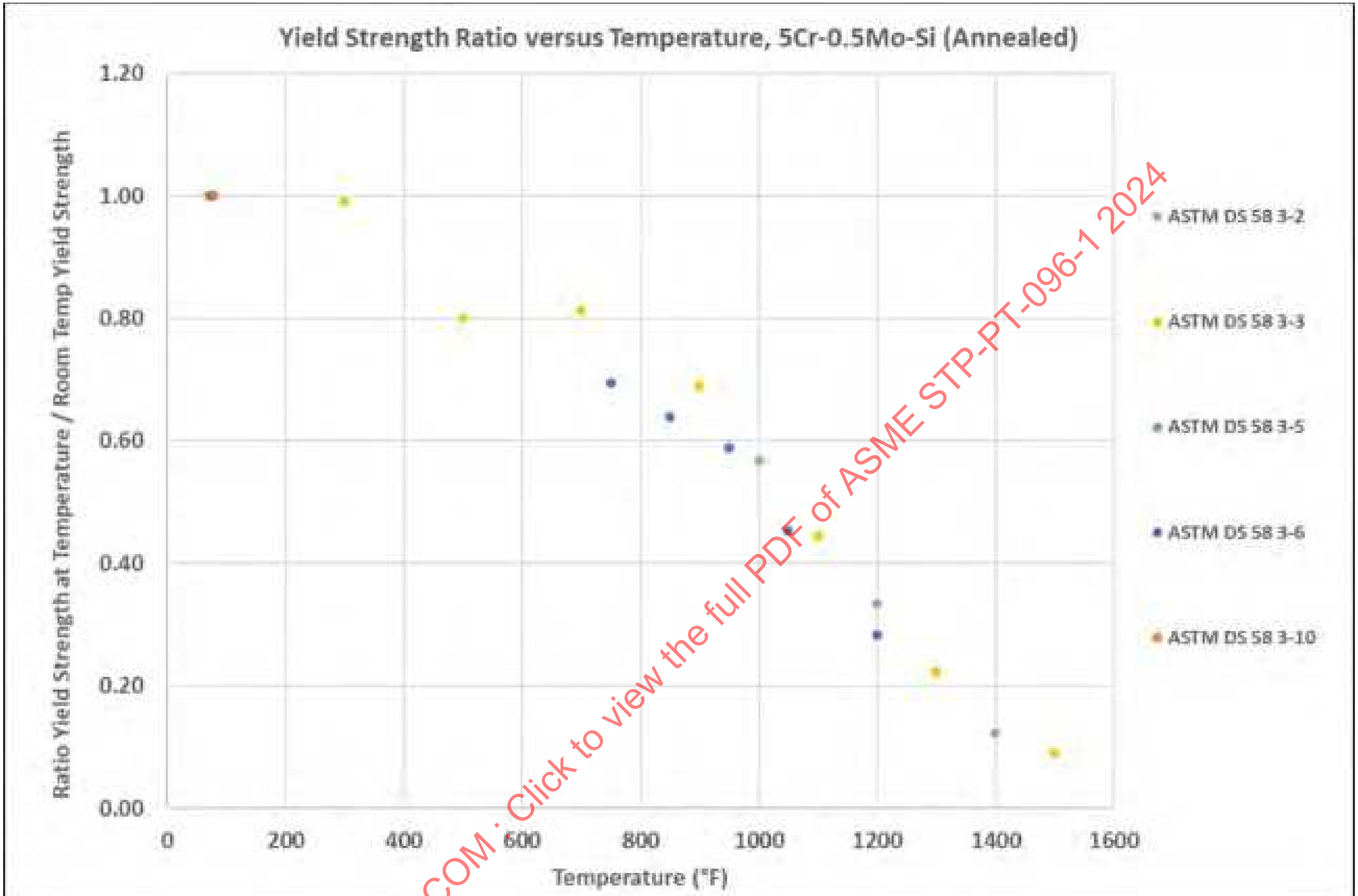


Figure 13-7: 5Cr-0.5Mo-Si (Annealed) Tensile Strength Ratios Vs. Temperature (Calculated on a Heat-By-Heat Basis, By Data Source)

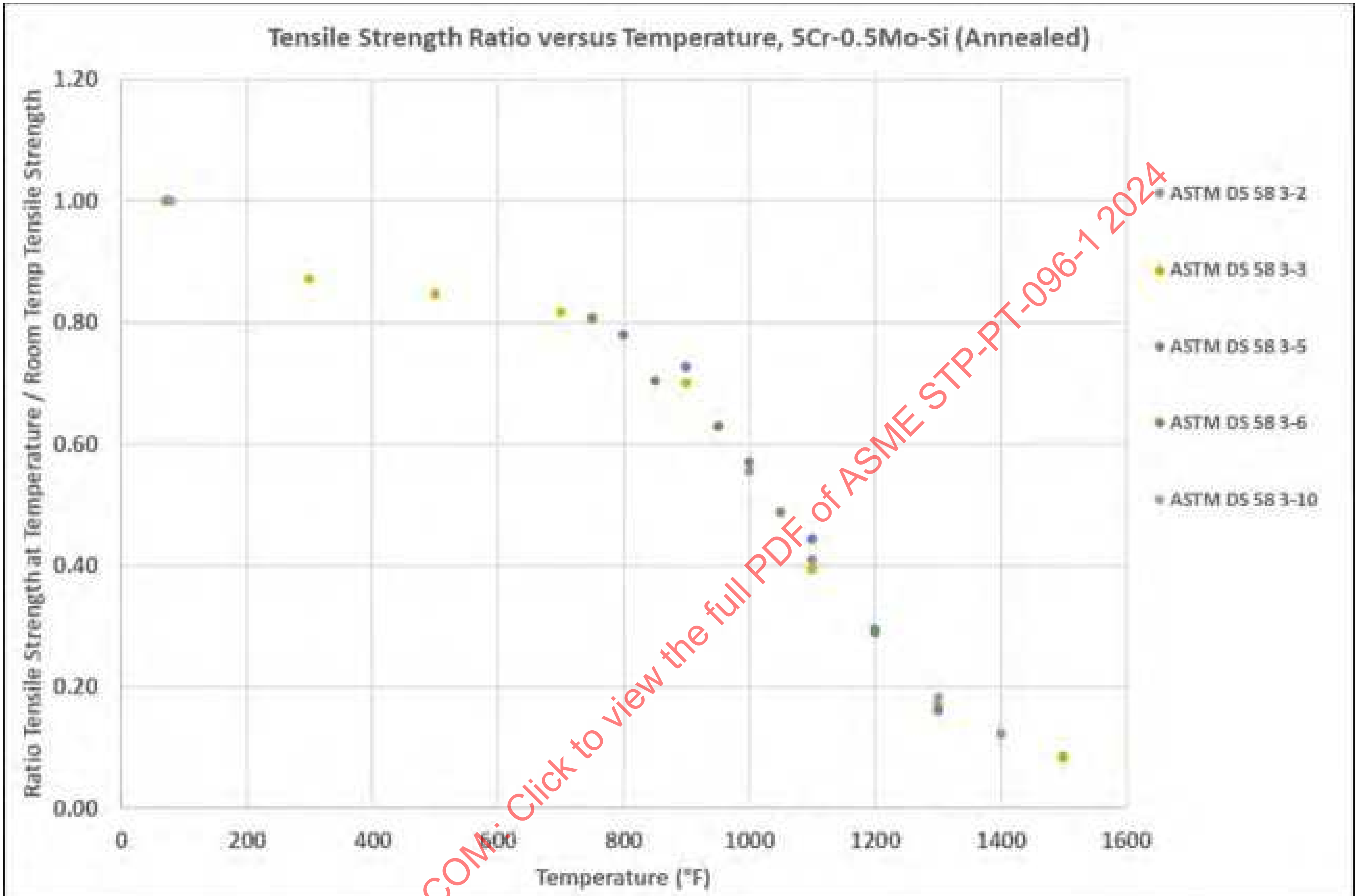


Figure 13-8: 5Cr-0.5Mo-Si (N&T) Yield Strength Ratios Vs. Temperature (Calculated on a Heat-By-Heat Basis, By Data Source)

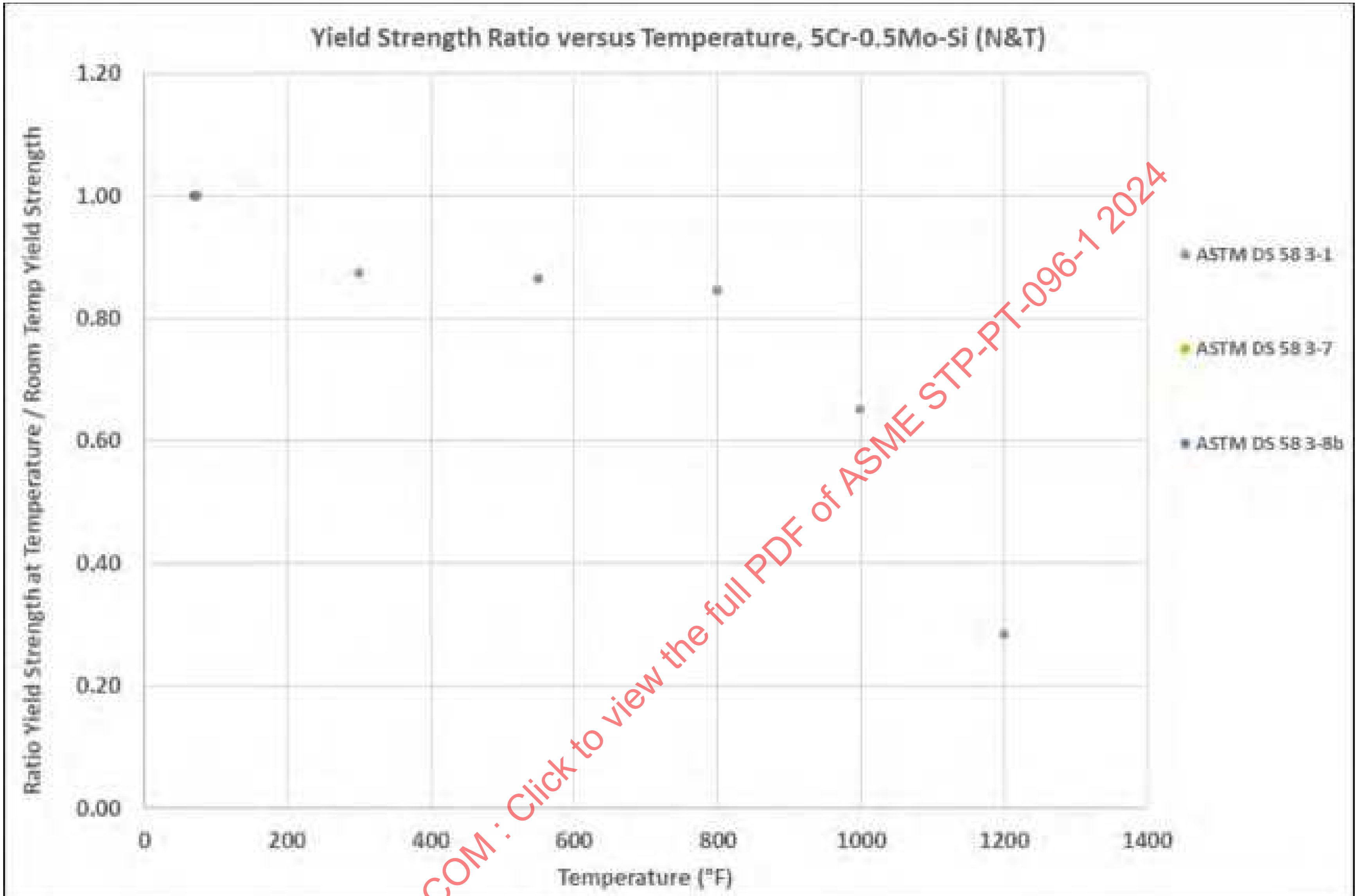


Figure 13-9: 5Cr-0.5Mo-Si (N&T) Tensile Strength Ratios Vs. Temperature (Calculated on a Heat-By-Heat Basis, By Data Source)

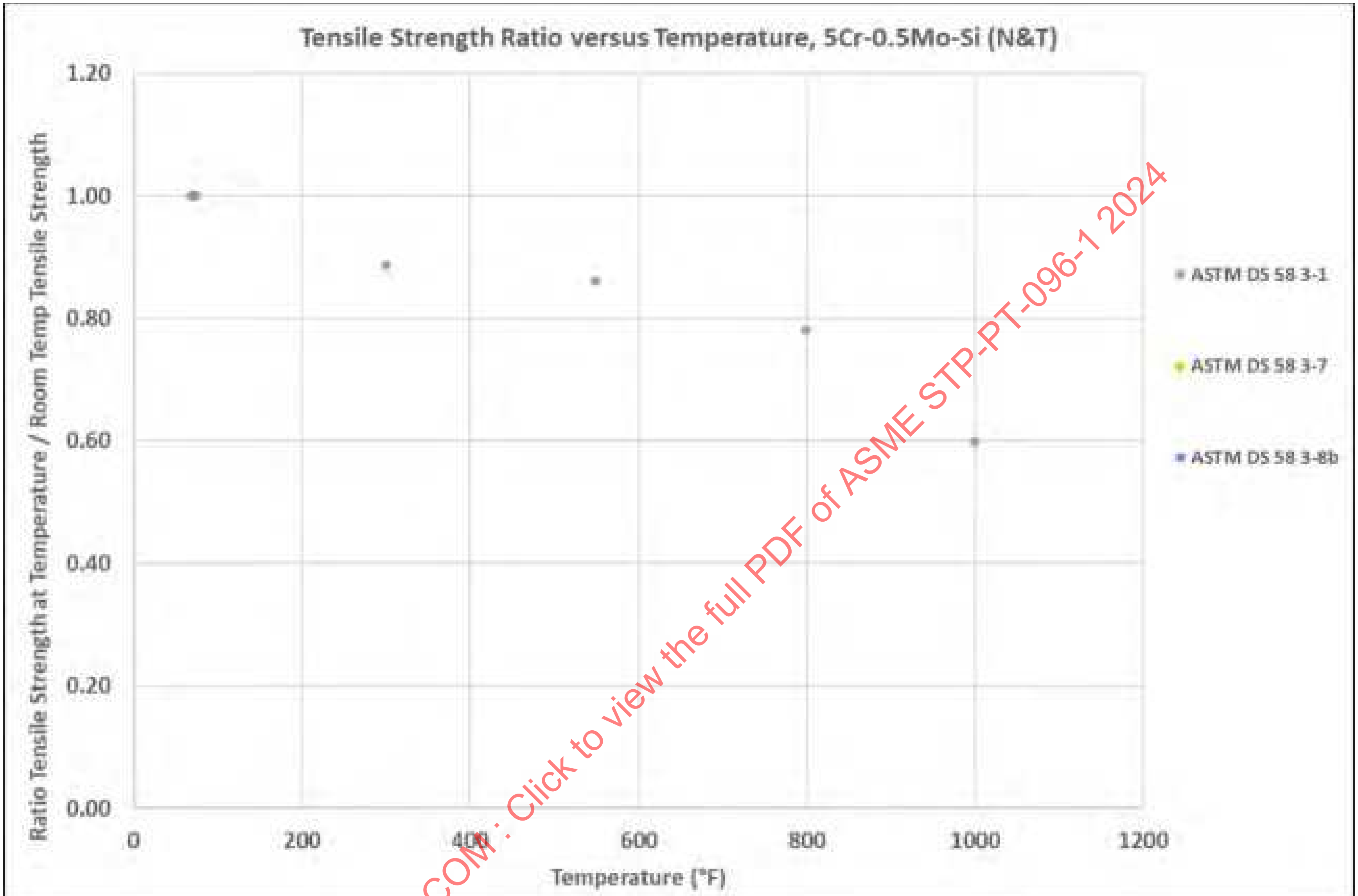


Figure 13-10: 5Cr-0.5Mo-Si (Annealed) Yield Strength Ratios Vs. Temperature, All Combined Data, With Polynomial Regression

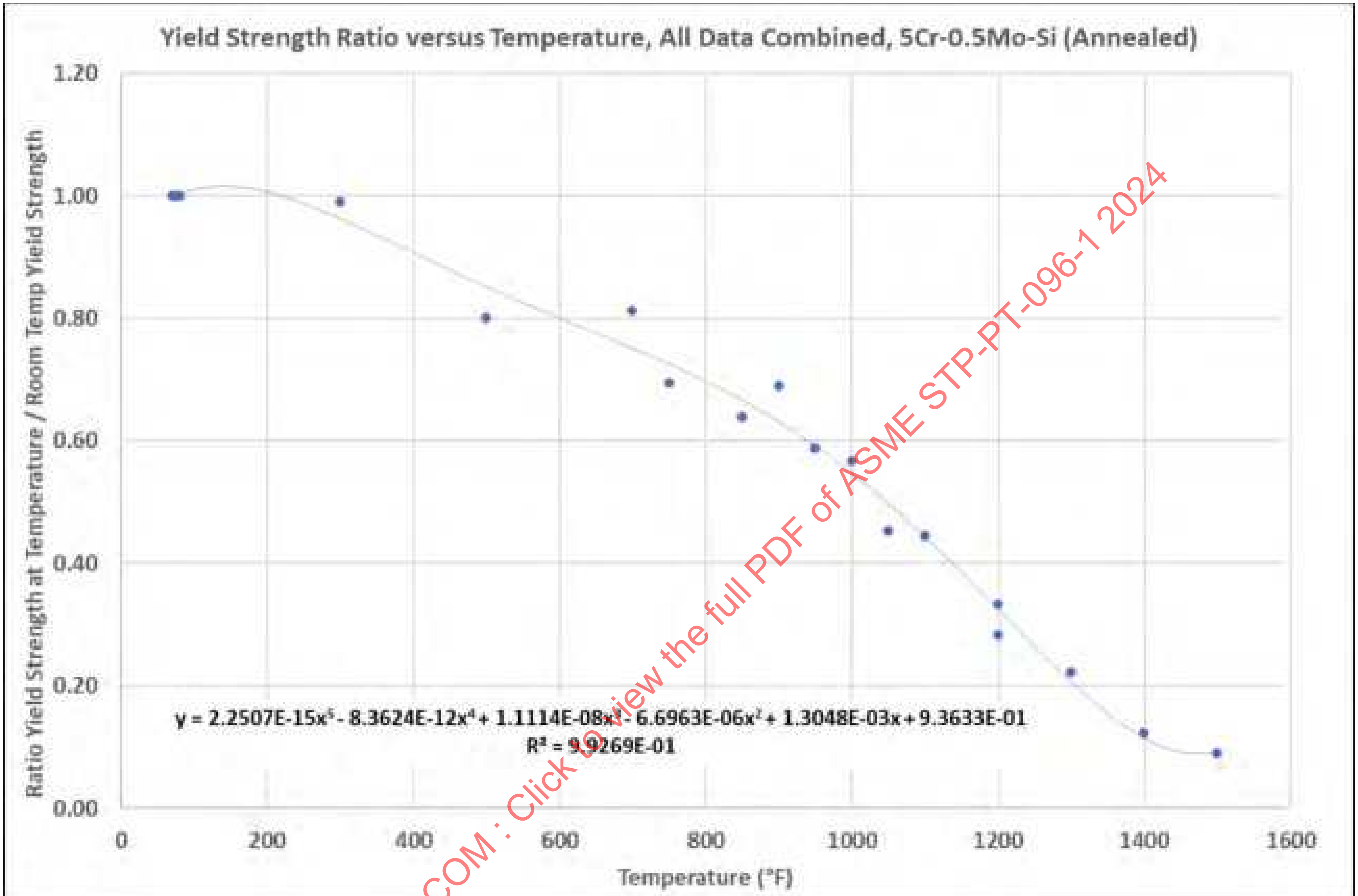


Figure 13-11: 5Cr-0.5Mo-Si (Annealed) Tensile Strength Ratios Vs. Temperature, All Combined Data, With Polynomial Regression

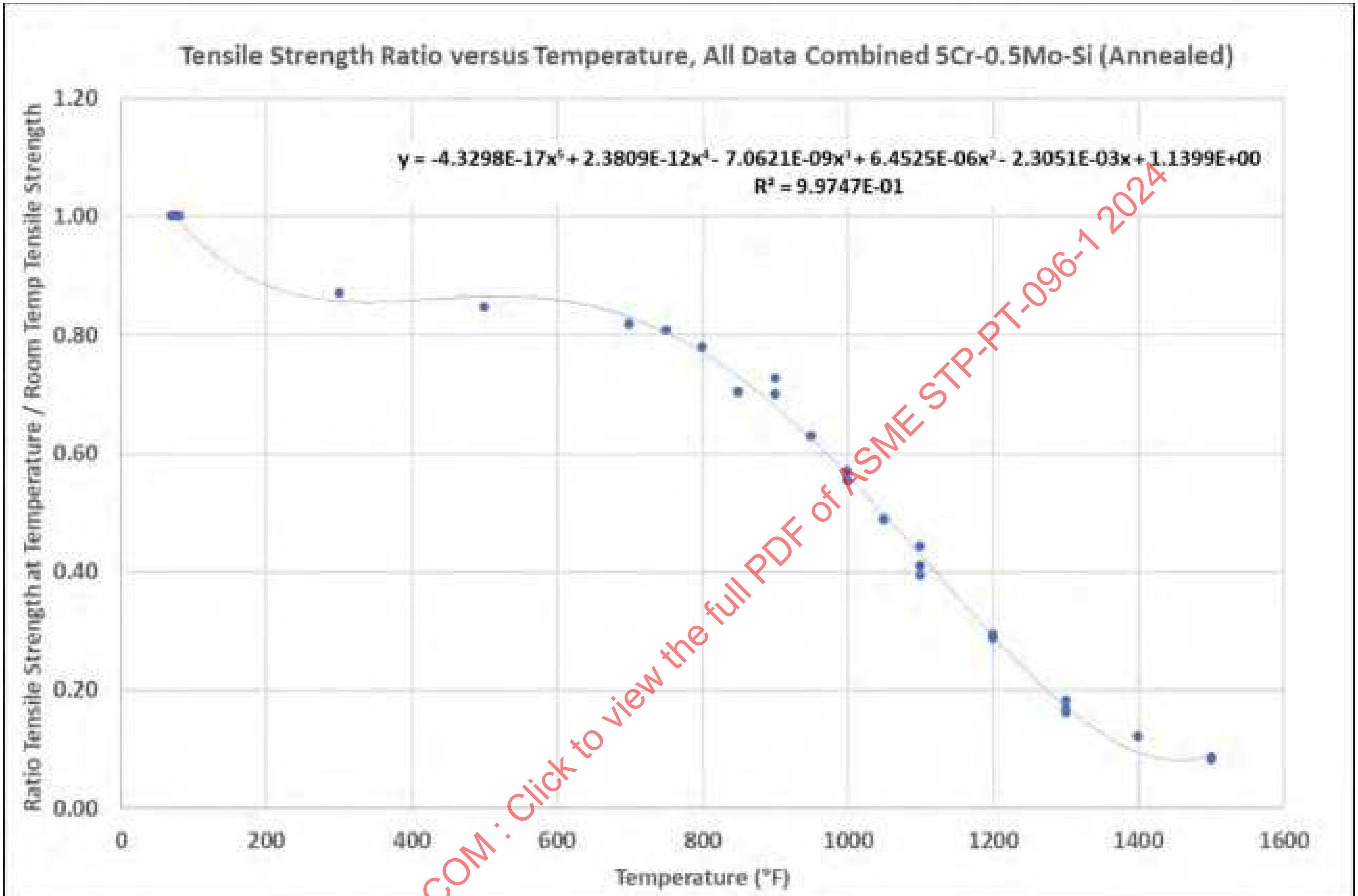


Figure 13-12: 5Cr-0.5Mo-Si (N&T) Yield Strength Ratios Vs. Temperature, All Combined Data, With Polynomial Regression

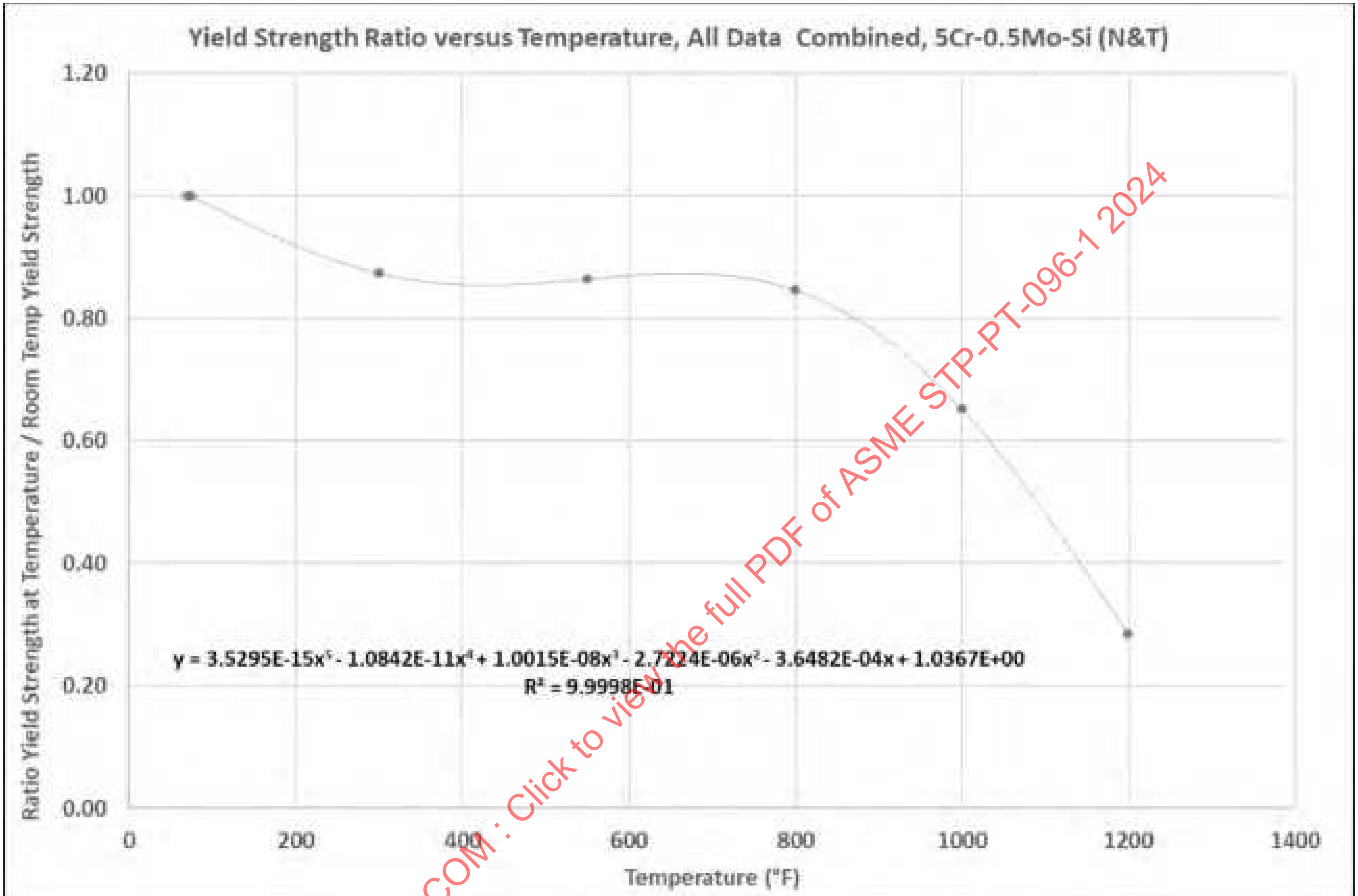


Figure 13-13: 5Cr-0.5Mo-Si (N&T) Tensile Strength Ratios Vs. Temperature, All Combined Data, With Polynomial Regression

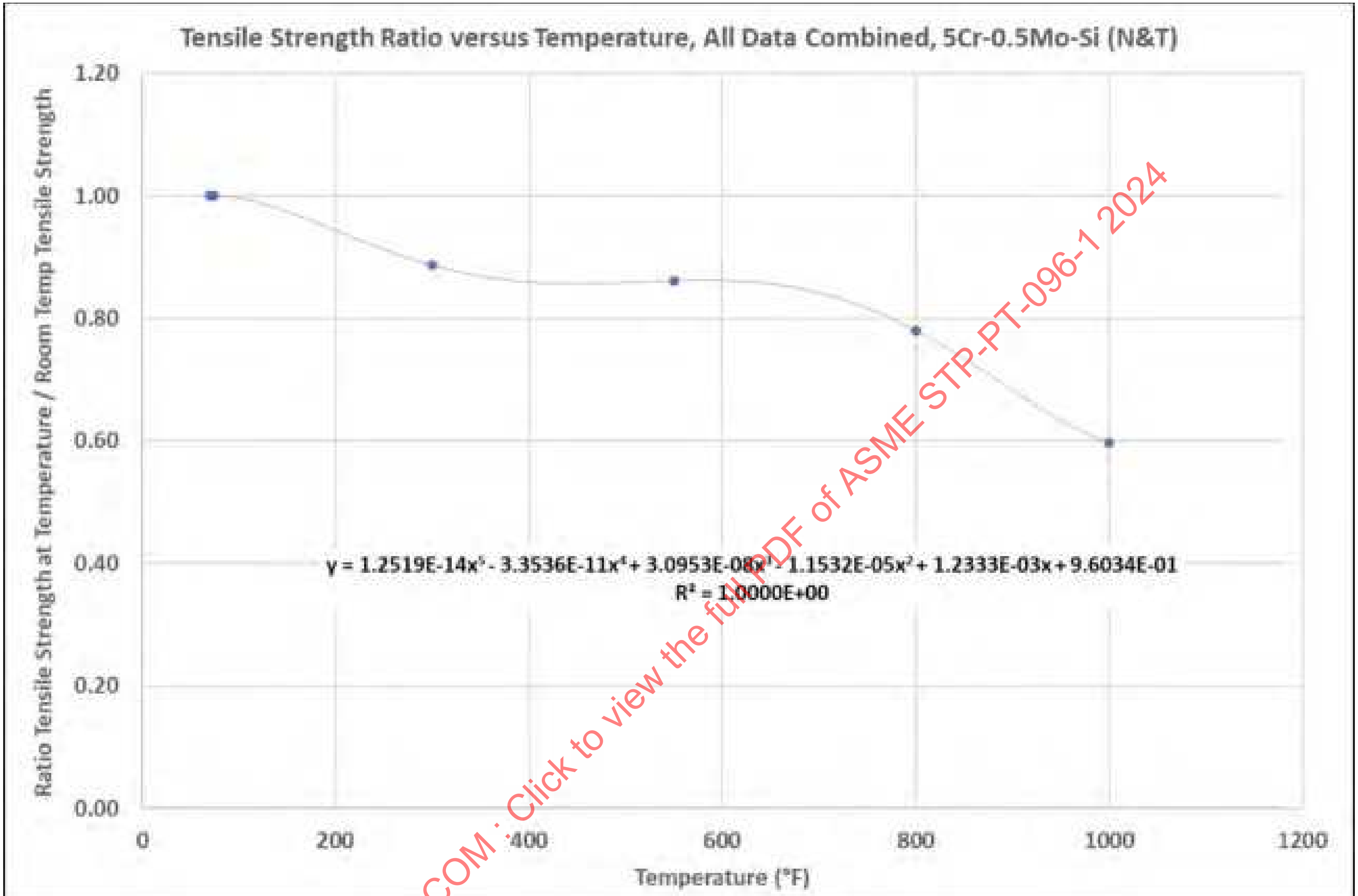


Figure 13-14: 5Cr-0.5Mo-Si Creep Rupture Isotherm Curves

Figure 13-15: 5Cr-0.5Mo-Si Creep Strain Rate (MCR) Isotherm Curves

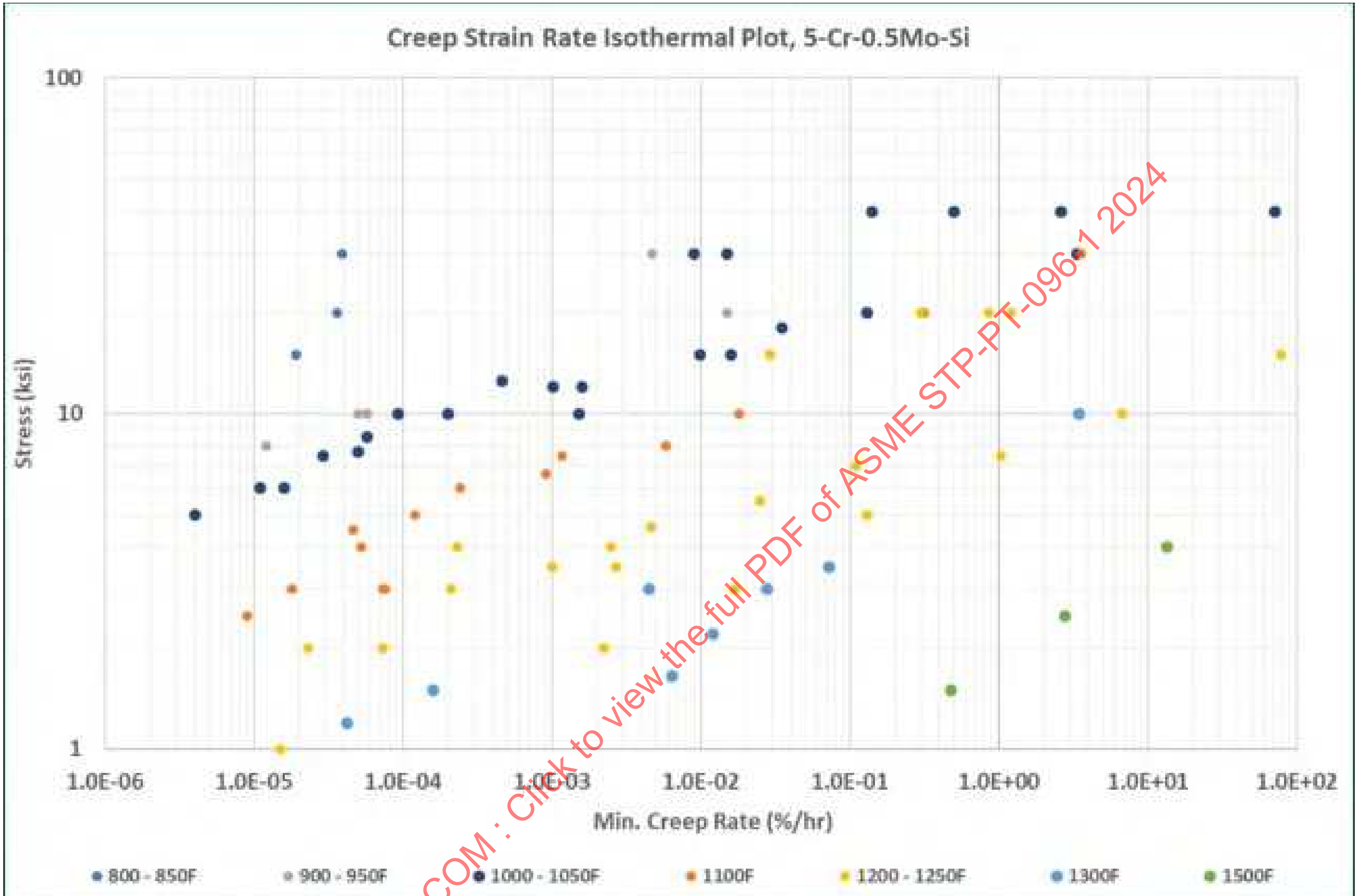


Figure 13-16: 5Cr-0.5Mo-Si Creep Ductility (% Elongation) Vs. Rupture Time Isotherms

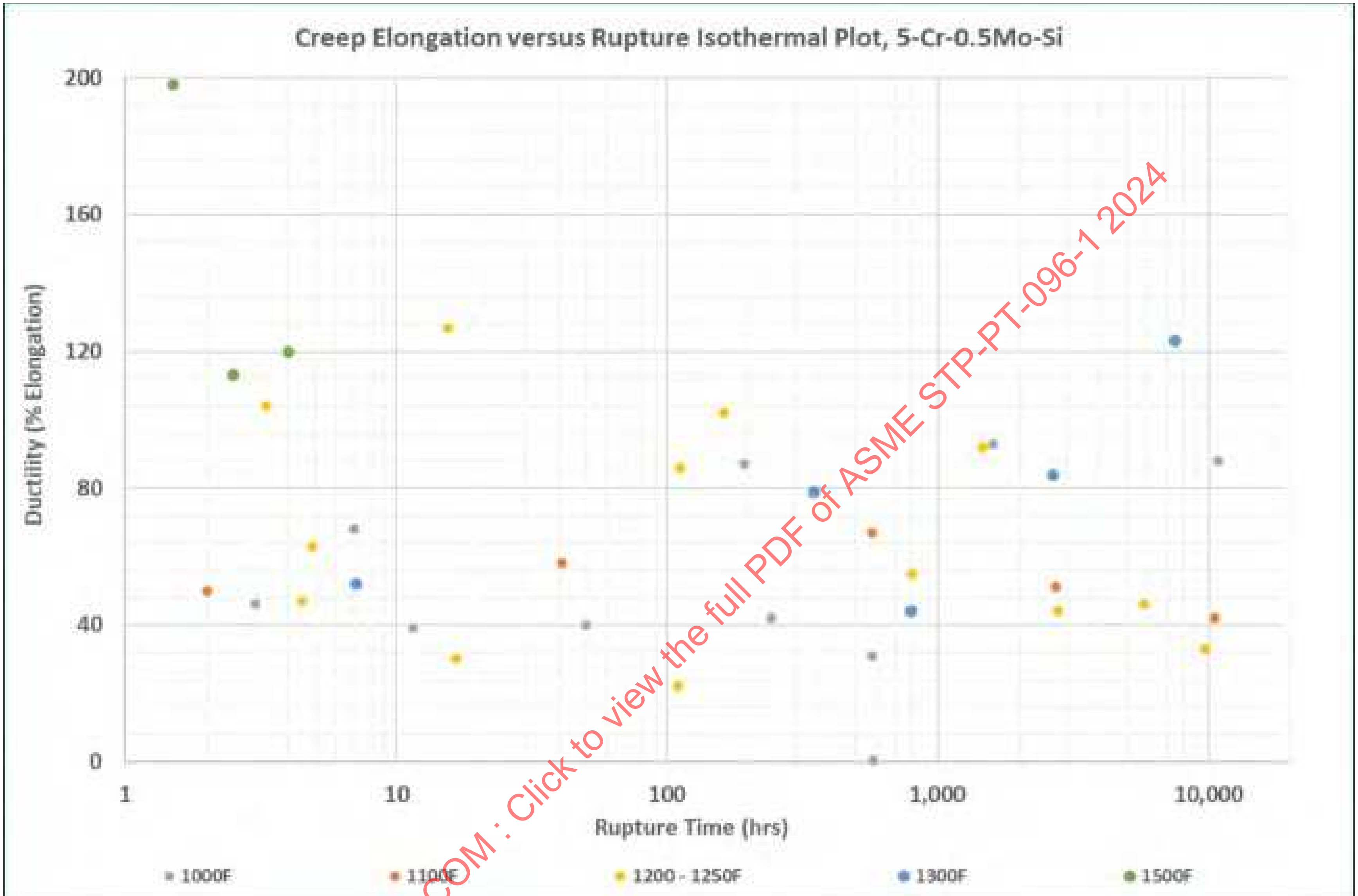


Figure 13-17: Calculated Allowable Stresses Based on Rupture Time and ASME II-D Appendix 1 Criteria (5Cr-0.5Mo-Si)

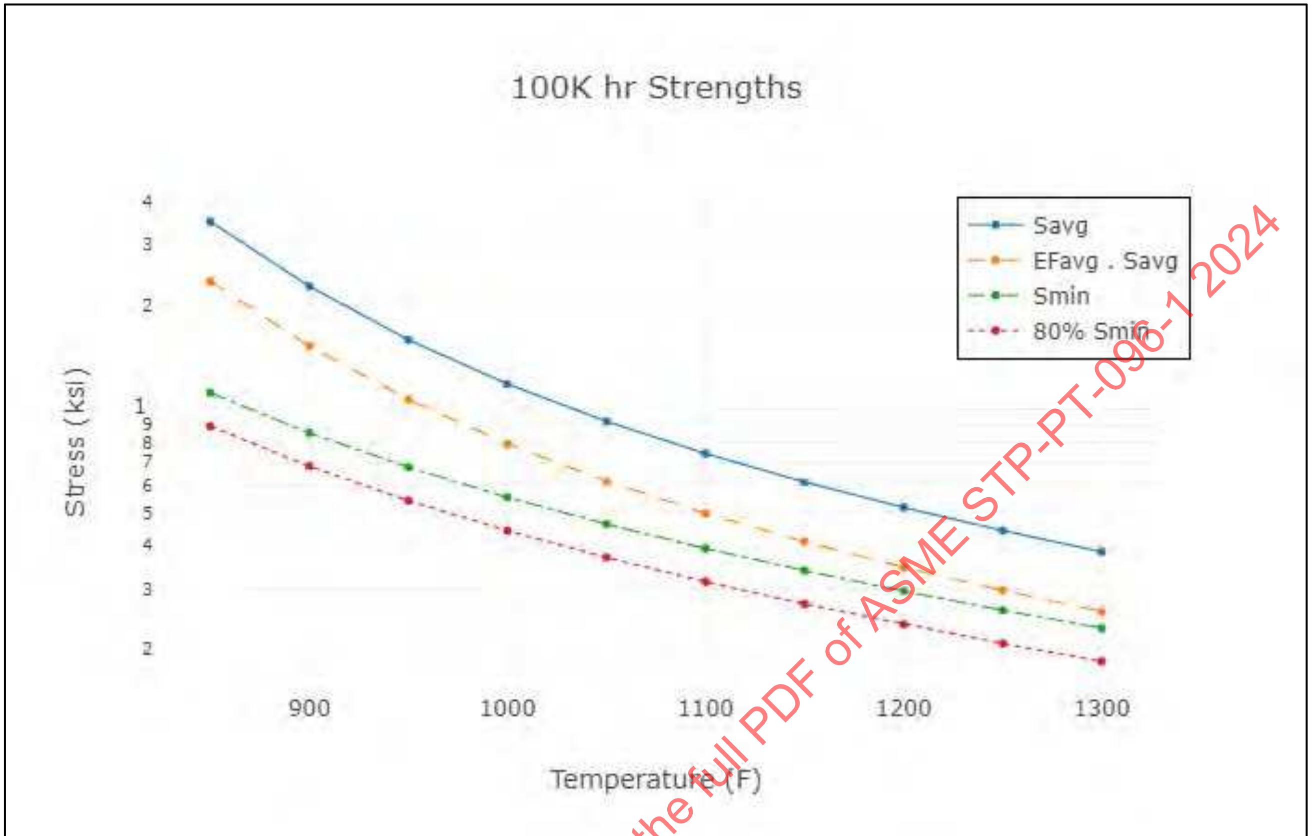


Figure 13-18: Calculated Allowable Stresses Based on Creep Strain Rate and ASME II-D Appendix 1 Criteria (5Cr-0.5Mo-Si)

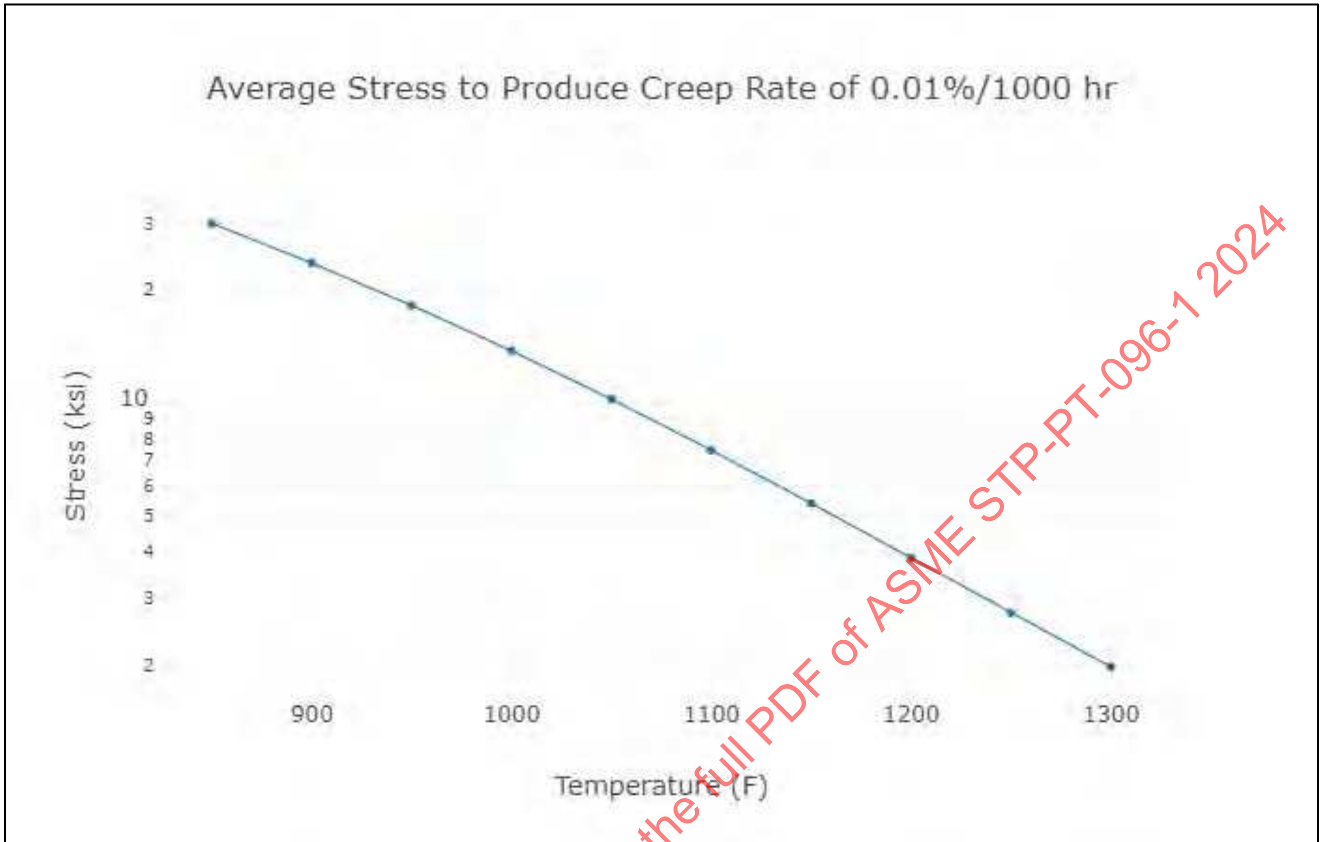
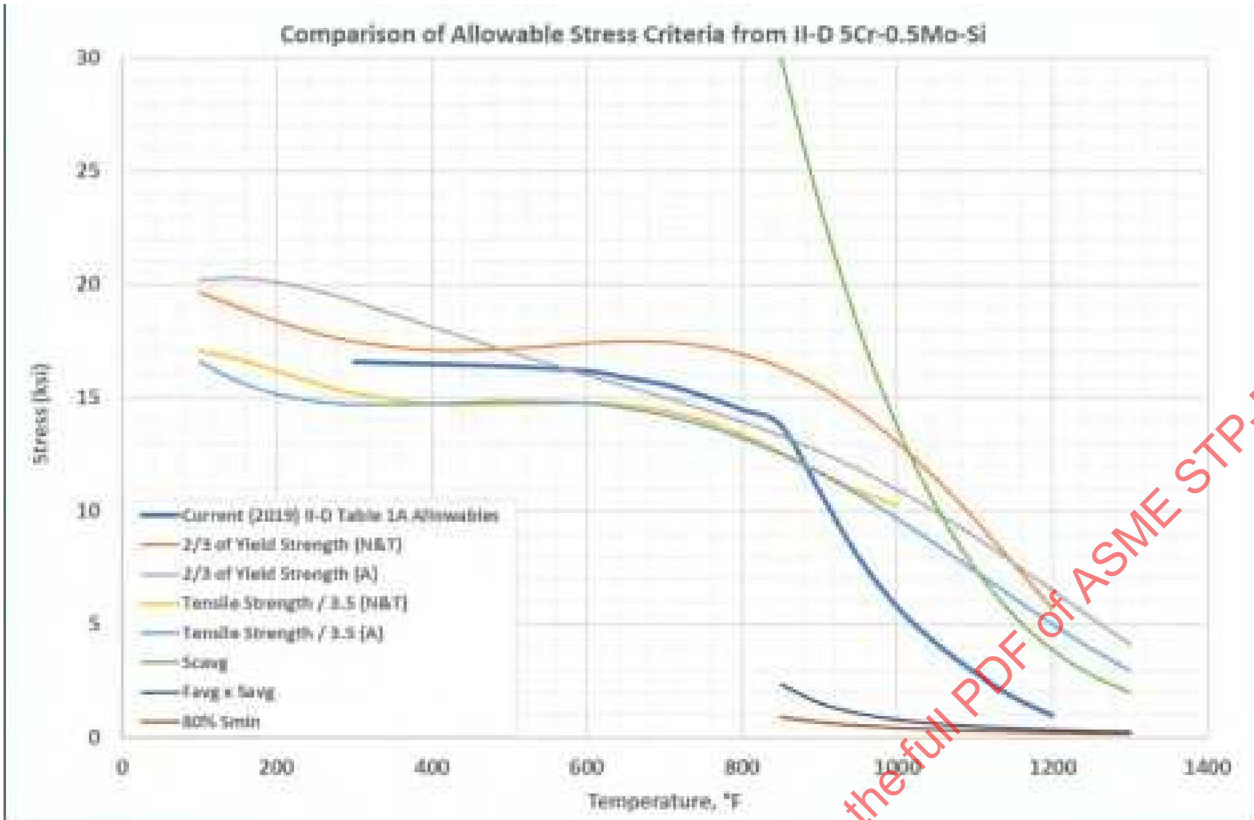


Figure 13-19: Comparison of Current 5Cr-0.5Mo-Si Allowable Stresses Vs. ASME II-D Appendix 1 Criteria Applied to Data



Attachment 13: Grade 5A (5Cr-0.5Mo-Si) Property Data

If you want the referenced embedded spreadsheet with additional data, please email a request to research@asme.org.

14 GRADE 9, 9CR-1MO

14.1 Physical Properties

Well-established Grade 9 physical properties were referenced from the BPVC Section II for this material as well as the curves from WRC Bulletin 503. Both sources were plotted for comparison. It should be noted that the thermal diffusivity plot includes data after a phase transformation has taken place. Figure 14-1 shows the trends of Elastic Modulus (E_y), Thermal Conductivity (k), Thermal Diffusivity (TD), and Thermal Expansion (α) with temperature.

14.2 Yield and Tensile Strength

Elevated temperature Yield and Tensile Strength over the range of existing allowable stresses (up to 1200°F) were readily available, including data beyond the current range of allowable stresses, up to approximately 1300°F, as shown in Figures 14-2 and 14-3. All sources for both high-temperature yield and high-temperature tensile strength are provided in the embedded spreadsheet at the end of this section. This spreadsheet also contains ductility data corresponding to the tensile test results presented in this report. Note that ductility (percent elongation and percent reduction in area) was not available for all sources referenced for the Grade 9 material.

To facilitate comparison of the data obtained to existing allowable stresses (Section II-D Table 1A), yield and tensile data were normalized on a heat-by-heat basis to express the ratio of yield or tensile strength at temperature to that measured for the heat at room temperature. In cases where data were not delineated by heats within a given source, or in cases where more than one room-temperature tensile test existed for a given heat of material, ratios are equal to the measured tensile or yield strength at temperature, divided by the average of all of the appropriate room-temperature values for the particular data source or heat of material. As a result of this approach, it is possible to have ratios in excess of 1.0. E^2G understands that this approach is similar to the normalizing procedure performed by ASME in typical analysis of yield and tensile data to obtain Table Y and Table U (Section II-D) trend curves, as well as for the calculation of allowable stresses. Figures 14-4 and 14-5 show the heat-by-heat variation in yield and tensile strength ratios (respectively) as a function of temperature. It should be emphasized that even though the figure legends reference an entire source of data, the ratios, wherever possible, were calculated on a heat-by-heat basis; this is evident in the embedded spreadsheet at the end of this section. Figures 14-6 and 14-7 contain all of the yield and tensile (respectively) ratios plotted together, to facilitate regression of a 5th-order polynomial that is subsequently used for allowable stress comparison.

14.3 Creep Data (Creep Rupture, Minimum Creep rate, and Ductility)

Creep Rupture data, plotted as isotherms, is shown in Figures 14-8 and 14-9. The temperatures have been separated onto separate plots to minimize data overlap, with Figure 14-8 showing the temperatures that had large amounts of data, and Figure 14-9 showing the temperatures with less data. This allows for gaps between the bands of data, increasing visual clarity. It should be emphasized that these plots contain data for all product forms of material classified in the referenced publications as "Grade 9." This certainly includes material meeting the requirements of ASME BPVC Section II-A specifications (e.g., SA-182 F9, SA-199 T9, SA-213 T9, SA-335 P9, etc.). However, due to the diversity of data sources utilized for the compilation of the material property tables, it is likely that some of the material shown in Figures 14-8 and 14-9 may not meet existing specifications for this grade of material. Where older publications are referenced, the chemistry (and for that matter, manufacturing, processing, and heat treatment) corresponding to the heat of material in the original data source may not be consistent with modern specifications. Where possible, E^2G has documented the chemical composition if contained within the original source. In many cases, the project team has also made efforts to trace cross-referenced data back to original test results to determine if the heat treatment, product form, chemistry, etc. details can be obtained. This information is provided with the embedded spreadsheet to facilitate additional analysis on the part of ASME.

Creep Minimum strain rates (%/hour) are shown in Figures 14-10 and 14-11, separated by temperature. As in the case of rupture data, temperatures of minimum creep rates have been separated onto separate plots to minimize data overlap, with Figure 14-10 including the temperatures with abundant data, and Figure 14-11 including additional temperatures with significantly less data. Creep Ductility, as % elongation, is plotted in Figure 14-12. As is typical, the data show significant overlap, and it is difficult to observe clear trends in the data. The data is not intended to be used as plotted but is available in the spreadsheet for additional analysis.

Creep data were analyzed using E^2G's proprietary Lot-Centered Analysis web-based software tool, in order to obtain creep properties. This regression is based on a Mandel-Paule algorithm and considers the variation within individual heats of material (for both rupture and strain rate data) as well as the variation between heats. The weight assigned to each datapoint and each heat is scaled based on the relative variation. Both rupture and strain rate (minimum creep rate, expressed as true strain per hours) were regressed according to a Larson-Miller time-temperature-parameter model, with a 3rd-order polynomial of stress. Lot-specific constant behavior was accounted for in this analysis, but the variation of LMP with stress was assumed to be constant (no non-parallel terms were included in the analysis). A 95% predictive limit was utilized to obtain the lower-bound (minimum LM constant for both rupture and strain rate) properties. The results of this analysis are summarized in Table 14-1 for rupture data and Table 14-2 for strain rate data. The Lot-Centered Analysis software tool generates property tables in the creep regime using the criteria outlined in Mandatory Appendix 1 of ASME Section II-D; the nomenclature of variables is consistent with II-D Appendix 1. For visualization of the allowable stress trends, Figure 14-13 is provided (for rupture allowable stresses and creep rate allowable stresses). Figure 14-14 shows a comparison of the various allowable stress criteria from Section II-D, Appendix 1, to the existing (2019) Section II-D Table 1A allowable stresses for all forms of Grade 9 with a minimum specified tensile strength of 60 ksi (higher 85 and 90 ksi minimum specified tensile strength allowable stresses are not shown).

Creep Strain vs. time data are shown in Figure 14-15 for short-term data (up to 2,500 hour test durations); Figure 14-16 for 2,500 to 5,000 hour test durations; Figure 14-17 for 5,000 to 10,000 hour test durations; and Figure 14-18 for tests exceeding 10,000 hour test durations. Curves are only plotted where 10 or more strain vs. time points are present for the test. Both creep rate and creep strain vs. time data are provided to satisfy ASME's request for creep strain vs. time curves, and both forms of data are applicable in developing allowable stresses. Although digitalization of creep curve data was not explicitly necessary per the project contract, E^2G did perform digitalization of creep curves where only graphical data was available (as is often the case in the published literature).

14.4 Continuous Cycling Fatigue and Hold Time Curves

The data obtained for continuous cycling fatigue data at elevated temperatures for Grade 9 is shown in Figure 14-19, which does not include any room-temperature data. It was found that ample room-temperature data was not contained in sources that also present high-temperature data. Figure 14-19 only contains data for which total strain range was determined from the original source. Hold time fatigue data at high temperature is shown in Figure 14-20 (1000°F, 1099°F). Additional data is provided in the embedded spreadsheet.

Table 14-1: Model Parameters, Larson-Miller Property Results, and Allowable Stress (Rupture) Criteria, Grade 9

Equation Format:

$$\log(t_r) = C_{avg} + \frac{1}{T+460}\left(b_1 + b_2\log(\sigma) + b_3(\log(\sigma))^2 + b_4(\log(\sigma))^3\right)$$

Cavg	**-24.29**
Cmin	**-24.83**
b_1	**52584**
b_2	**-7971**
b_3	**-1139**
b_4	**-54.28**

Number Data Points		**839**
Correlation Coefficient	R^2	0.8464
Average Variance within Heats	V_w	0.1093
Variance between Heats	V_b	0.3332
Standard Error of Estimate	SEE	0.3306

Properties provided are for T in °F, stress in ksi, and t_R in hours

Temperature, °F	**S_{avg} (ksi)**	***n***	**F_{avg} (calc)**	**F_{avg} (used)**	**Favg × Savg**	**S_{min} (ksi)**	**80% S_{min}**
850	28.73	8.886	0.7717	0.67	19.25	24.92	19.94
900	21.41	8.302	0.7578	0.67	14.35	18.38	14.71
950	15.81	7.756	0.7431	0.67	10.59	13.43	10.74
1000	11.55	7.244	0.7277	0.67	7.741	9.699	7.759
1050	8.353	6.761	0.7114	0.67	5.596	6.923	5.538
1100	5.966	6.305	0.6941	0.67	3.997	4.878	3.902
1150	4.206	5.873	0.6757	0.67	2.818	3.387	2.71
1200	2.922	5.462	0.656	0.67	1.958	2.315	1.852
1250	1.998	5.07	0.635	0.67	1.339	1.554	1.243
1300	1.342	4.696	0.6124	0.67	0.8989	1.022	0.8177

Table 14-2: Model Parameters, Larson-Miller Property Results, and Allowable Stress (Strain Rate) Criteria, Grade 9

Equation Format:

$$\log(\dot{\varepsilon}_0) = -C_{avg} - \frac{1}{T+460}\left(a_1 + a_2\log(\sigma) + a_3(\log(\sigma))^2 + a_4(\log(\sigma))^3\right)$$

C_{avg} (A_0)	**-26.67**
Cmin (A0+ΔΩSR,LB)	**-27.07**
a_1	**59933.4**
a_2	**-6856.1**
a_3	**-2200.5**
a_4	**-235.4**

Number Data Points		**39**
Correlation Coefficient	R2	0.927
Average Variance within Heats	V_w	0.0587
Variance between Heats	V_b	4.627
Standard Error of Estimate	SEE	0.2423

Properties provided are for T in °F, stress in ksi, and t_R in hours

Temperature, °F	**$S_{C,avg}$ (ksi)**
850	45.18
900	35.83
950	28.13
1000	21.82
1050	16.71
1100	12.6
1150	9.337
1200	6.779
1250	4.805
1300	3.306

Figure 14-1: Grade 9 Modulus (E_y), Thermal Conductivity (k), Thermal Diffusivity (TD), & Thermal Expansion (α) With Temperature

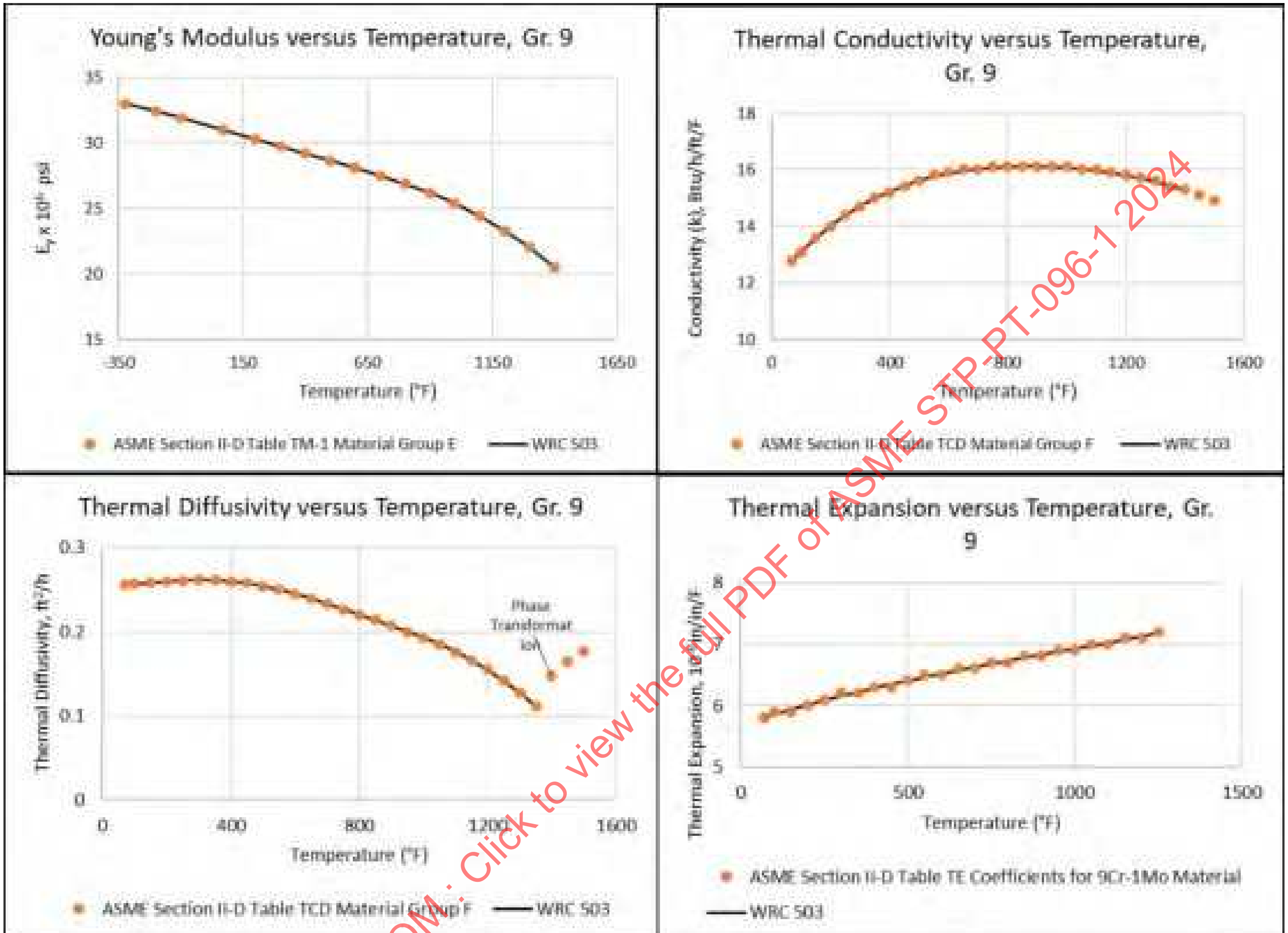


Figure 14-2: Grade 9 Yield Strength Vs. Temperature, By Data Source, Including Trend Curves

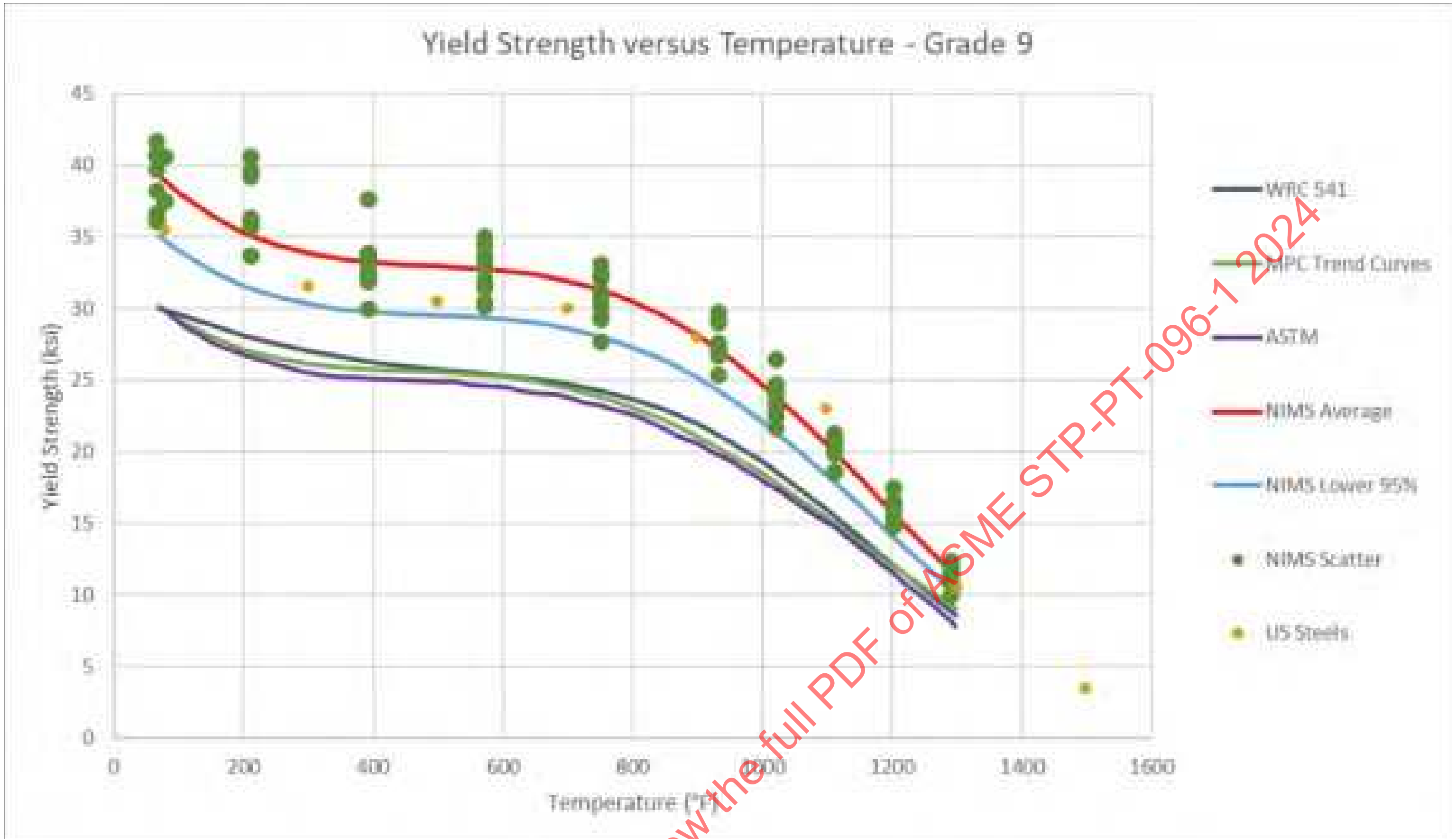


Figure 14-3: Grade 9 Tensile Strength Vs. Temperature, By Data Source, Including Trend Curves

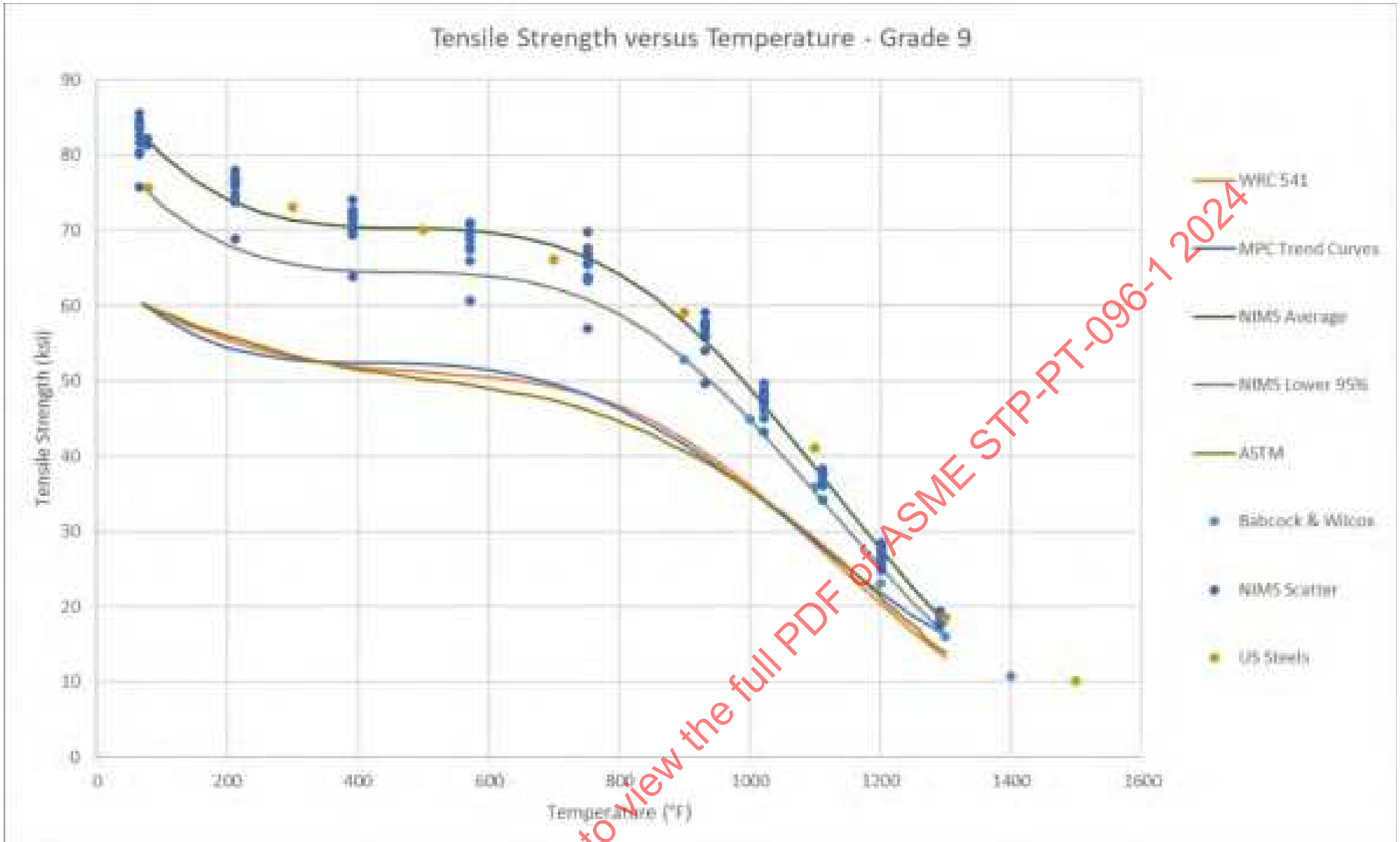


Figure 14-4: Grade 9 Yield Strength Ratios Vs. Temperature (Calculated on a Heat-By-Heat Basis, By Data Source)

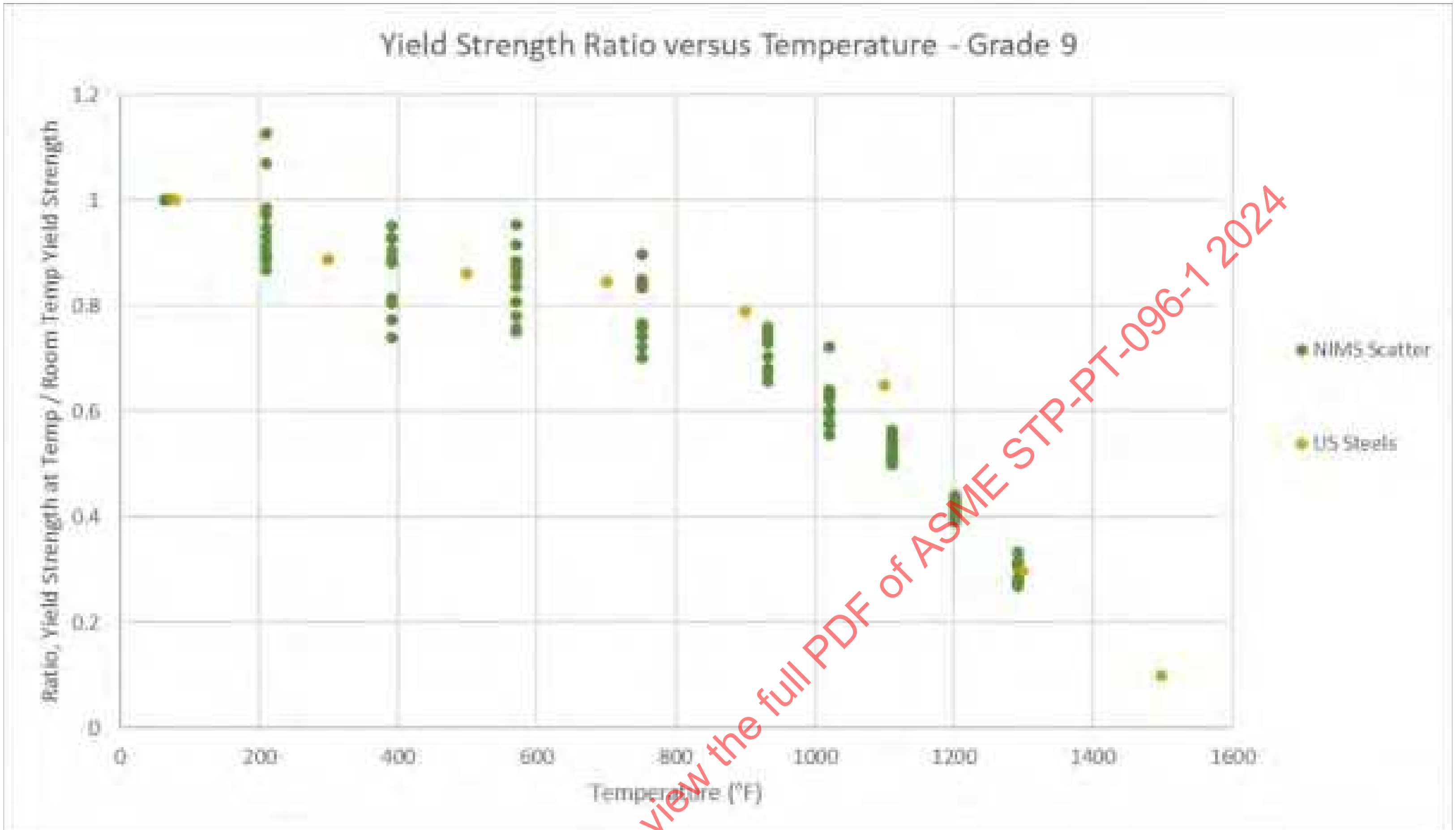


Figure 14-5: Grade 9 Tensile Strength Ratios Vs. Temperature (Calculated on a Heat-By-Heat Basis, By Data Source)

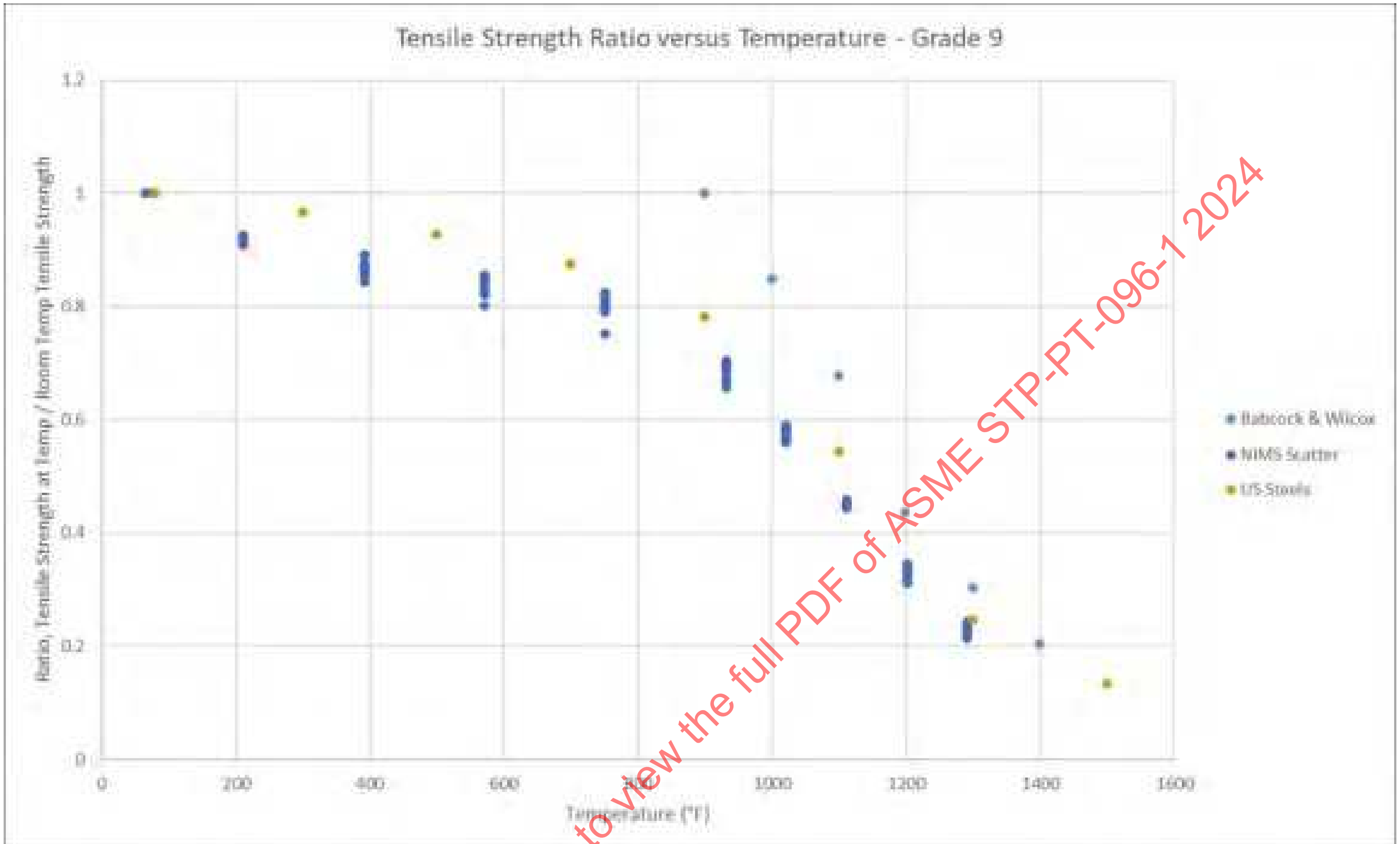


Figure 14-6: Grade 9 Yield Strength Ratios Vs. Temperature, All Combined Data, With Polynomial Regression

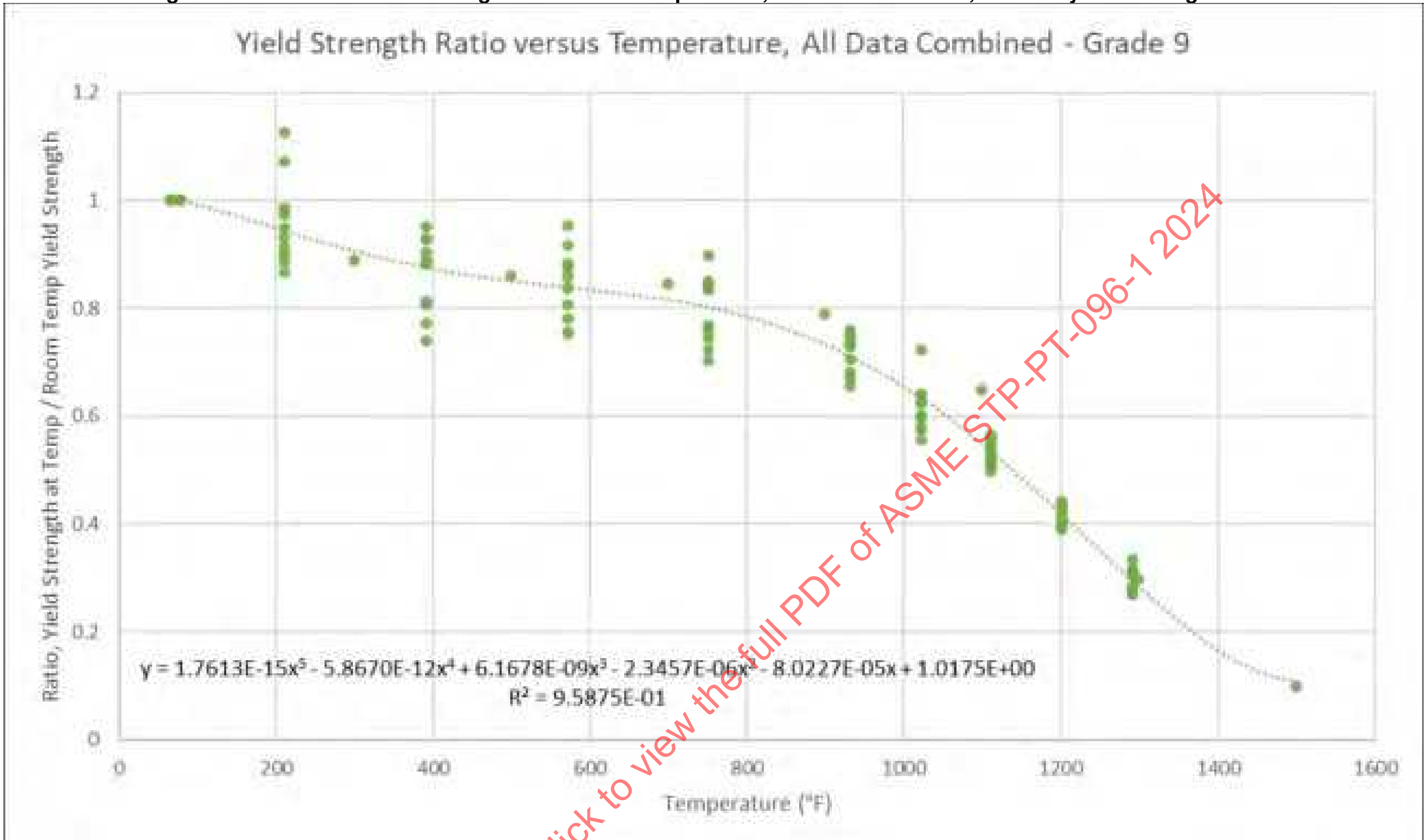


Figure 14-7: Grade 9 Tensile Strength Ratios Vs. Temperature, All Combined Data, With Polynomial Regression

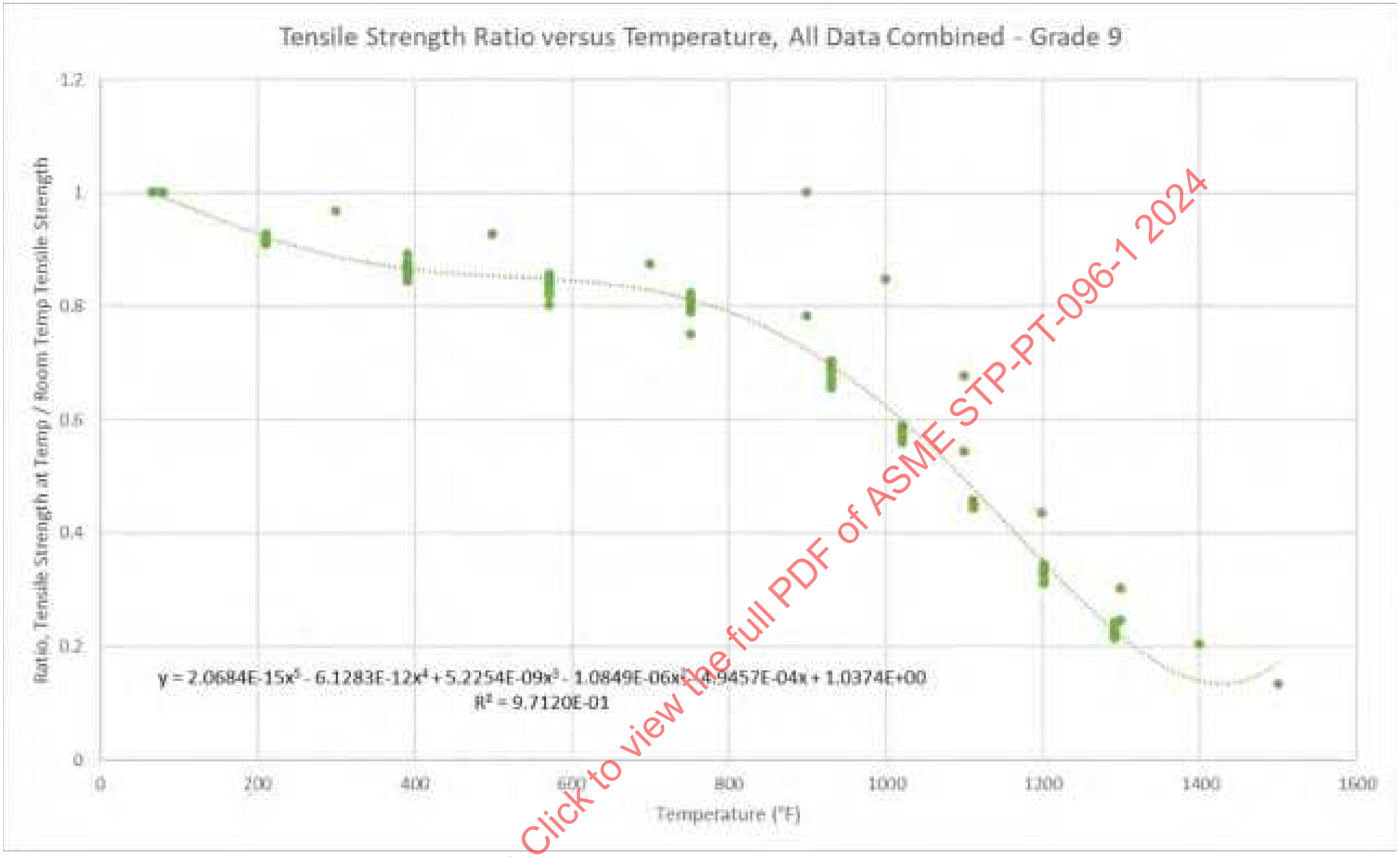


Figure 14-8: Grade 9 Creep Rupture Isotherm Curves, Most Common Test Temperatures

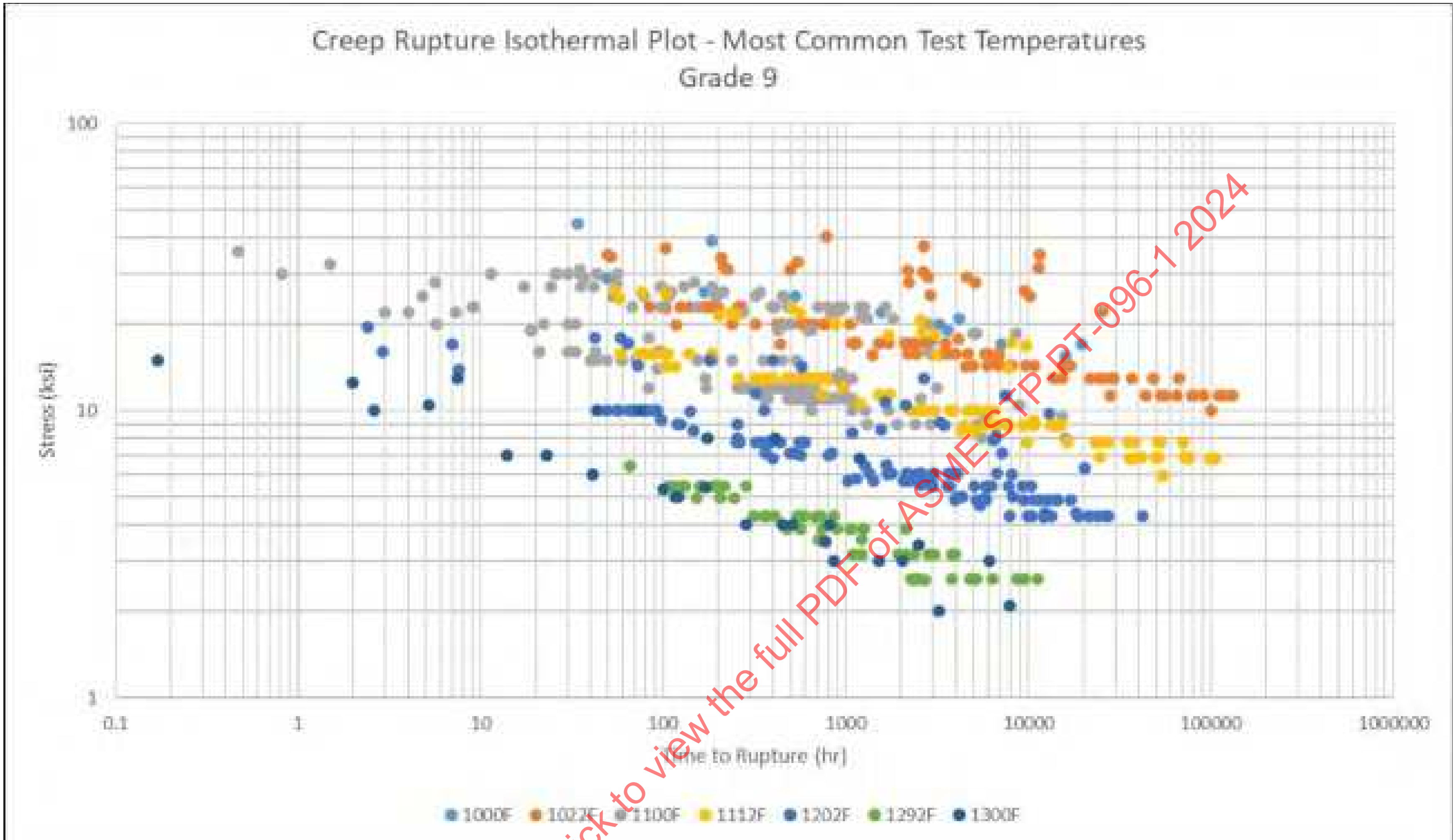


Figure 14-9: Grade 9 Creep Rupture Isotherm Curves, Additional Test Temperatures

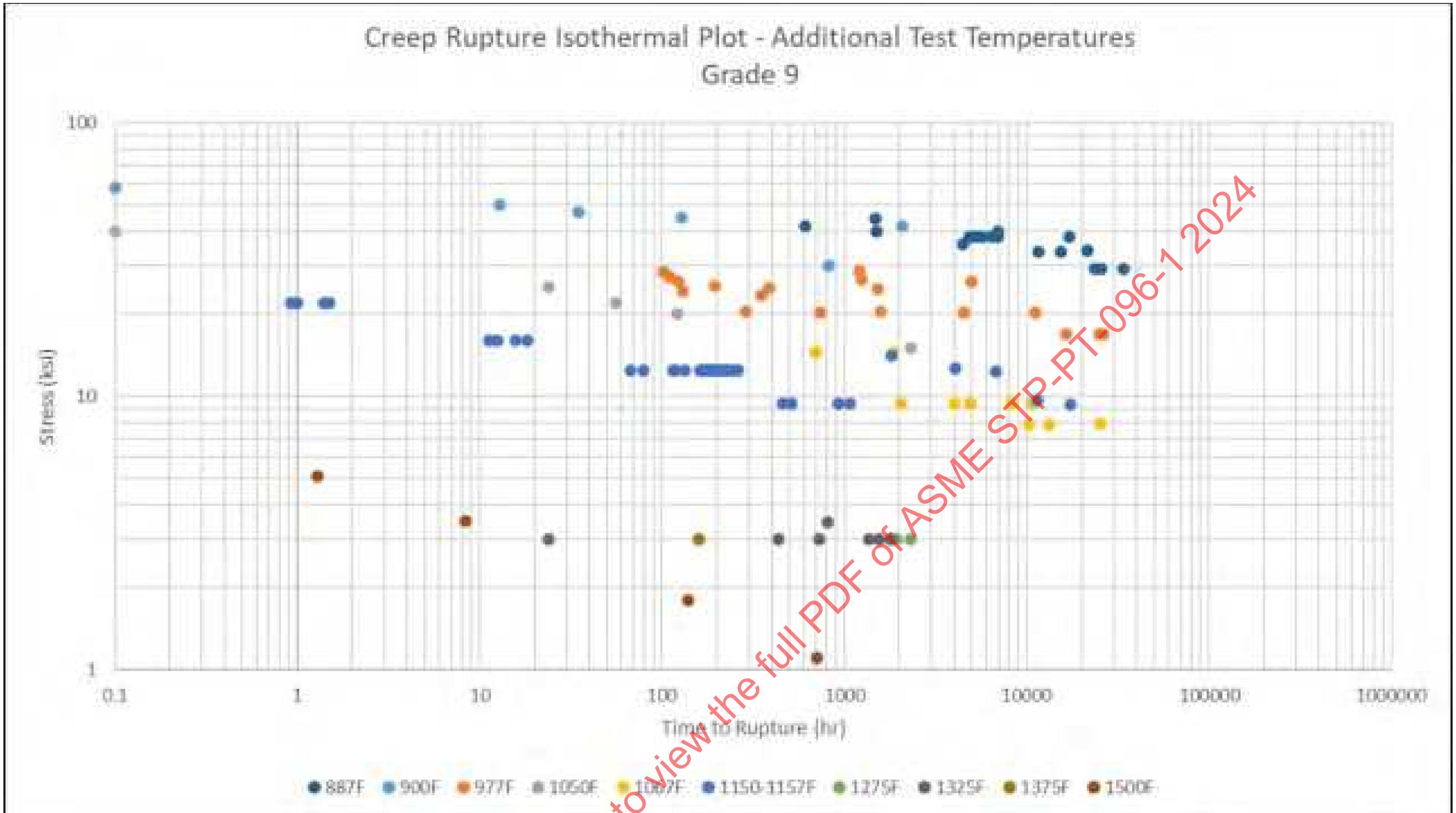


Figure 14-10: Grade 9 Creep Strain Rate (MCR) Isotherm Curves, First Lot of Temperatures

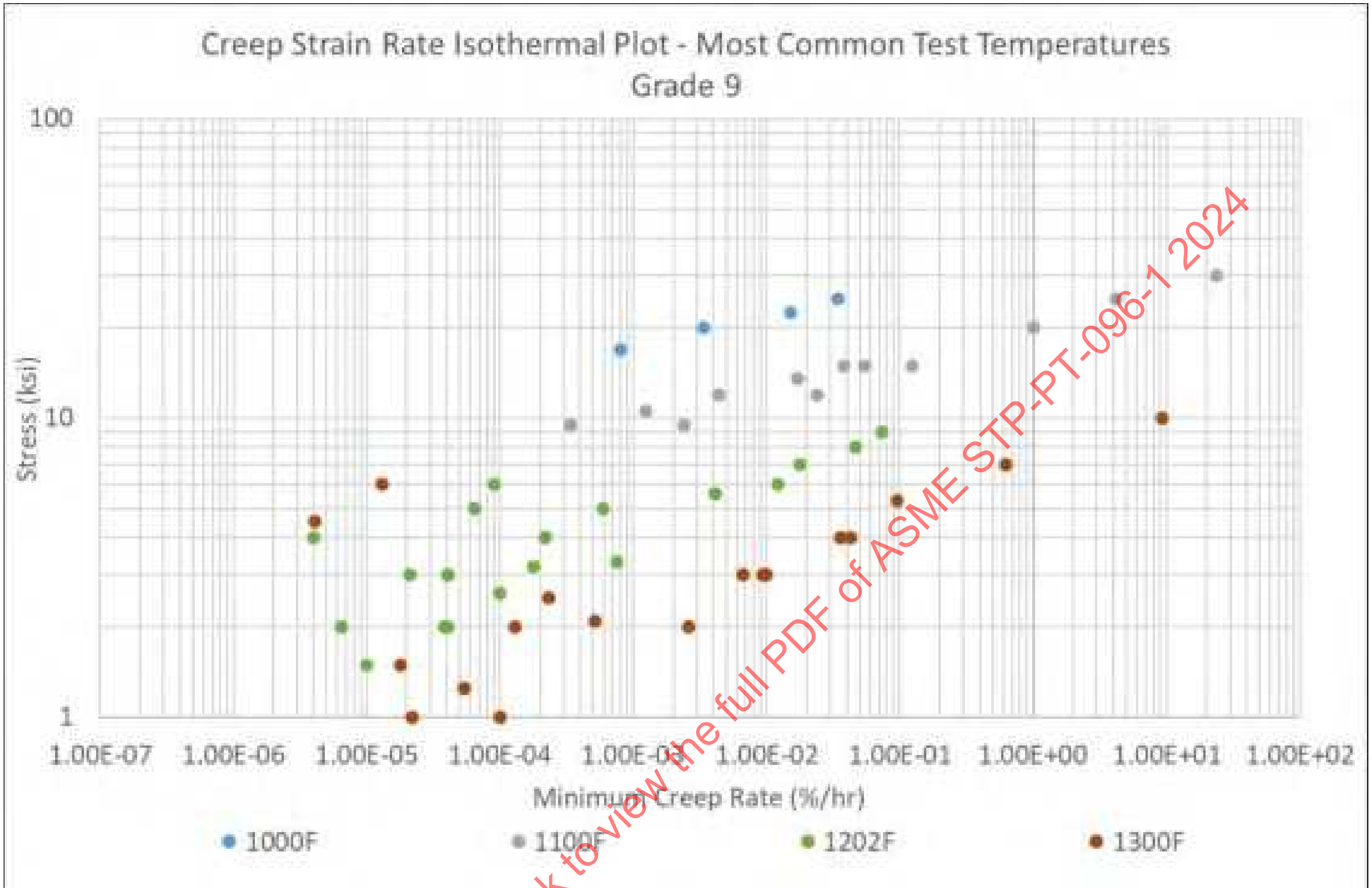


Figure 14-11: Grade 9 Creep Strain Rate (MCR) Isotherm Curves, Second Lot of Temperatures

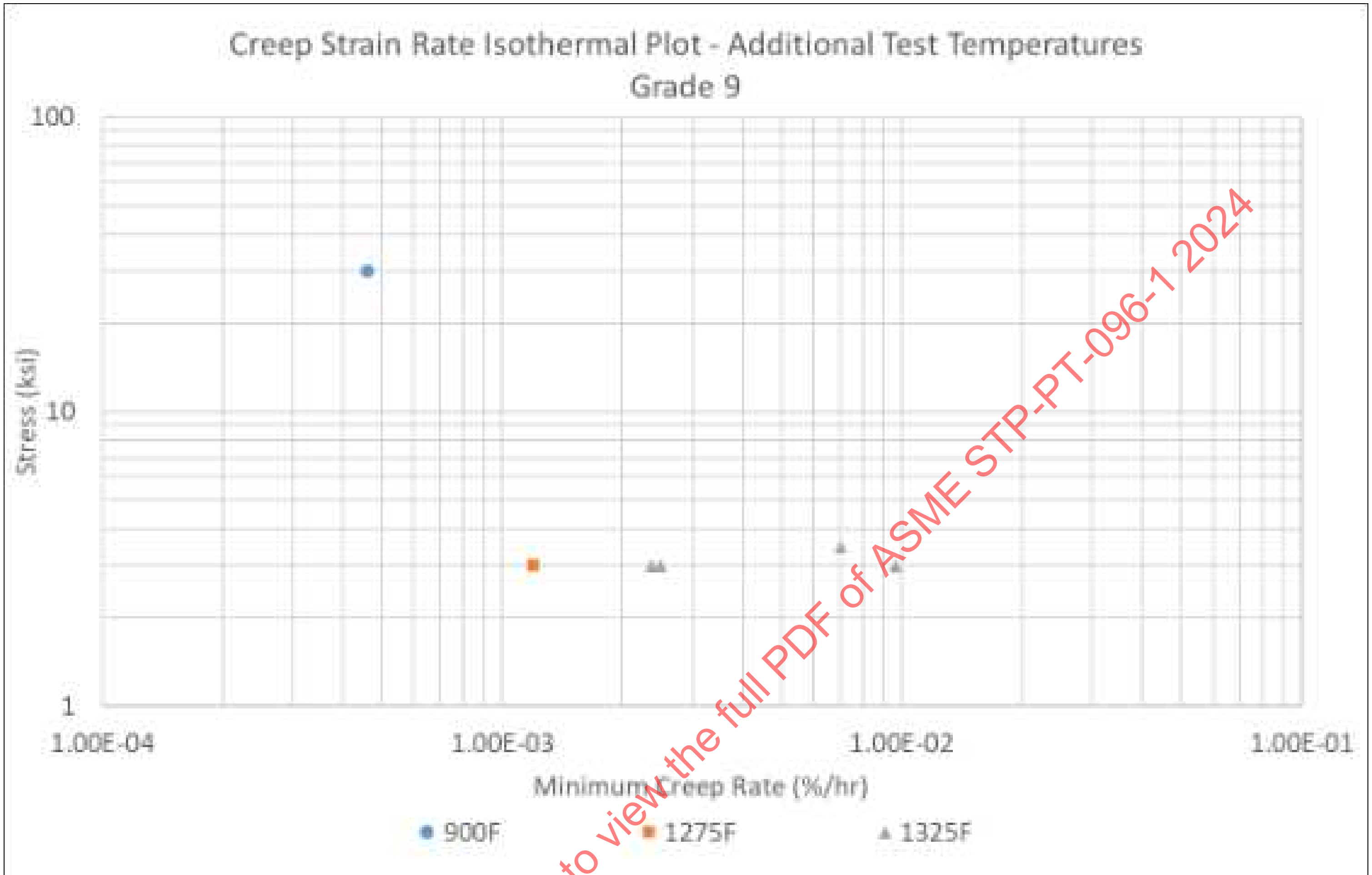


Figure 14-12: Grade 9 Creep Ductility (% Elongation) Vs. Rupture Time Isotherms

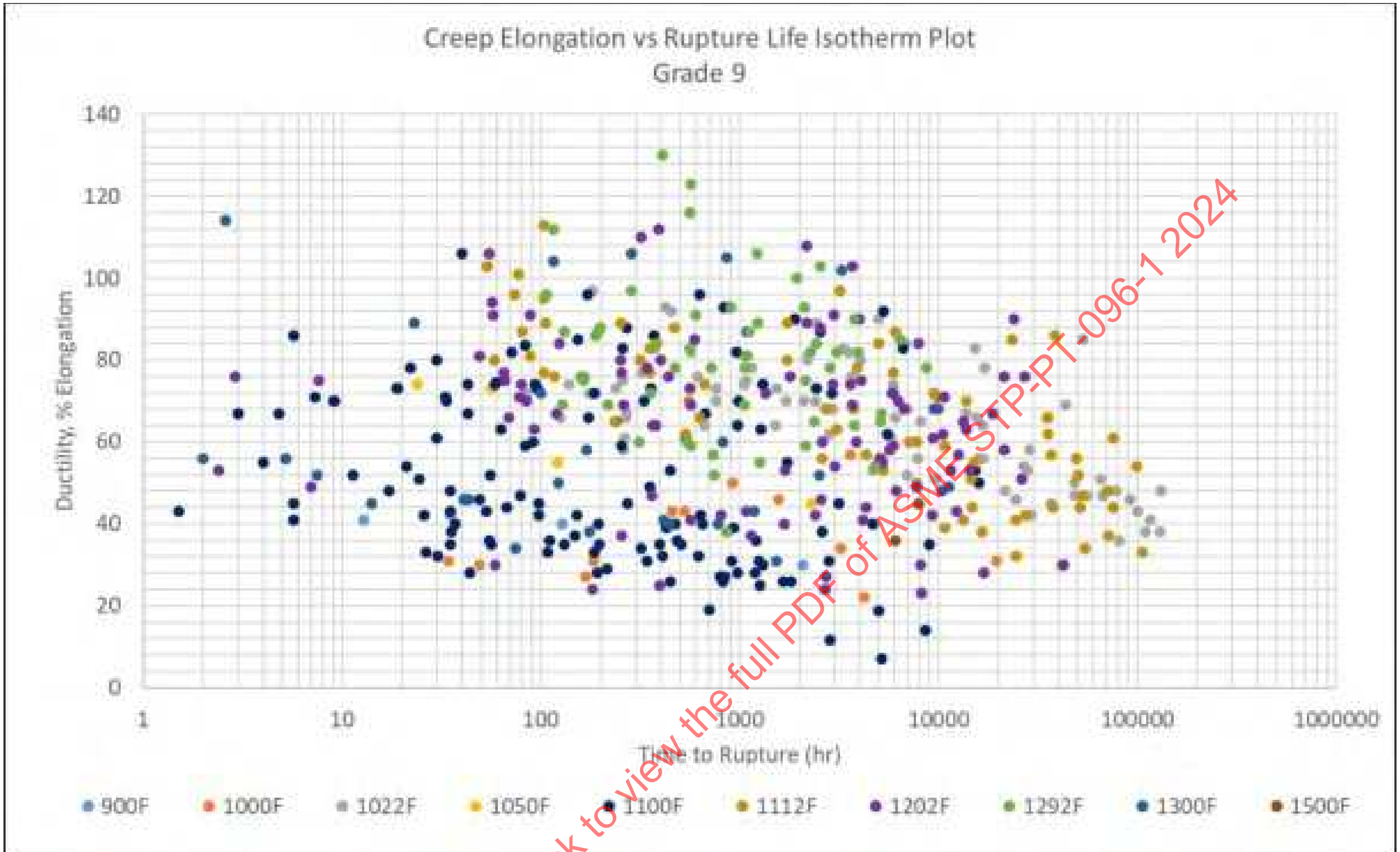


Figure 14-13: Calculated Allowable Stresses Based on Rupture and Creep Strain Rate and ASME II-D Appendix 1 Criteria (Grade 9)

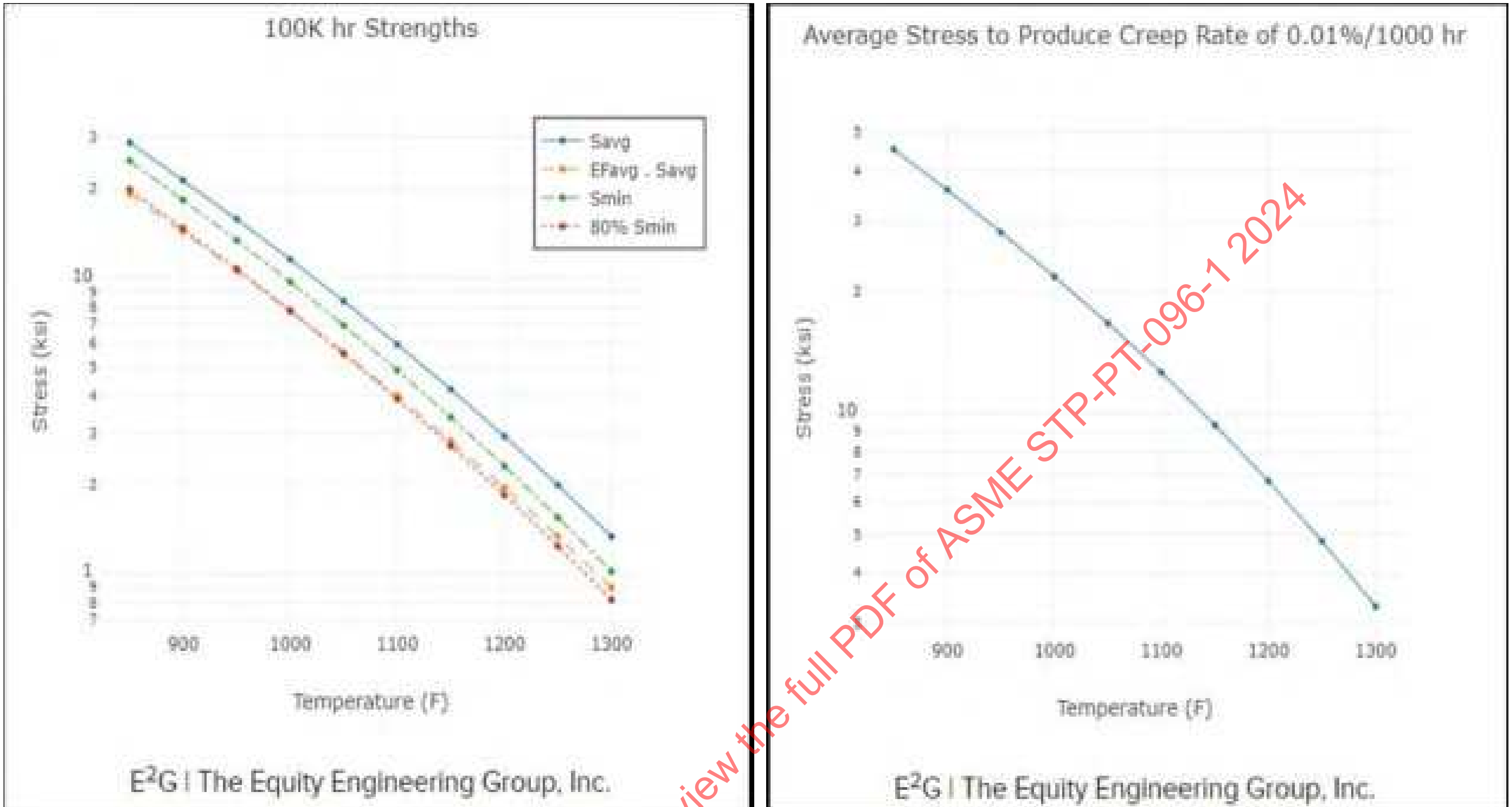


Figure 14-14: Comparison of Current Grade 9 Allowable Stresses (Annealed) Vs. ASME II-D Appendix 1 Criteria Applied to Data

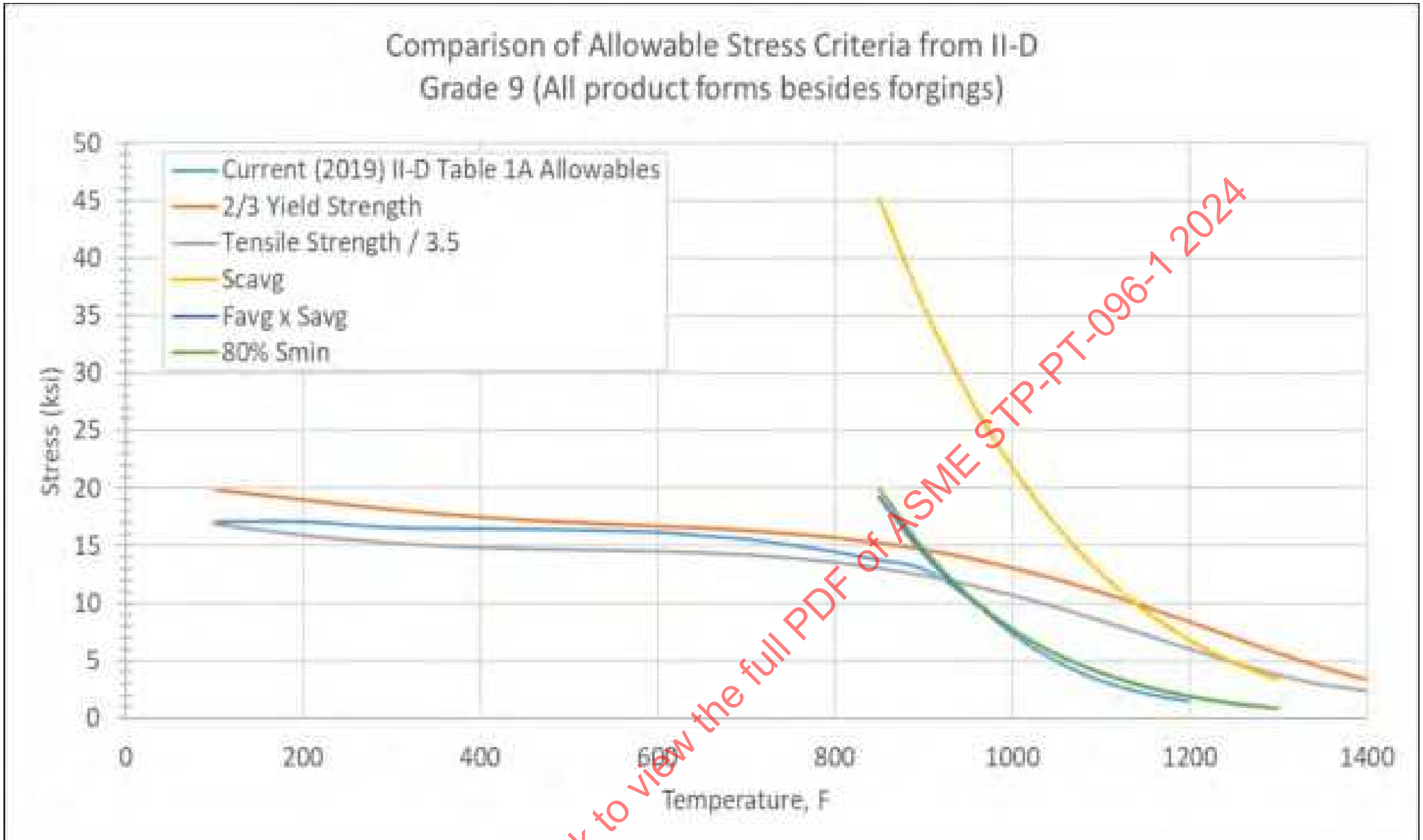


Figure 14-15: Short-Term Strain Vs. Time Data, up to 2,500 Hour Test Durations (Grade 9)

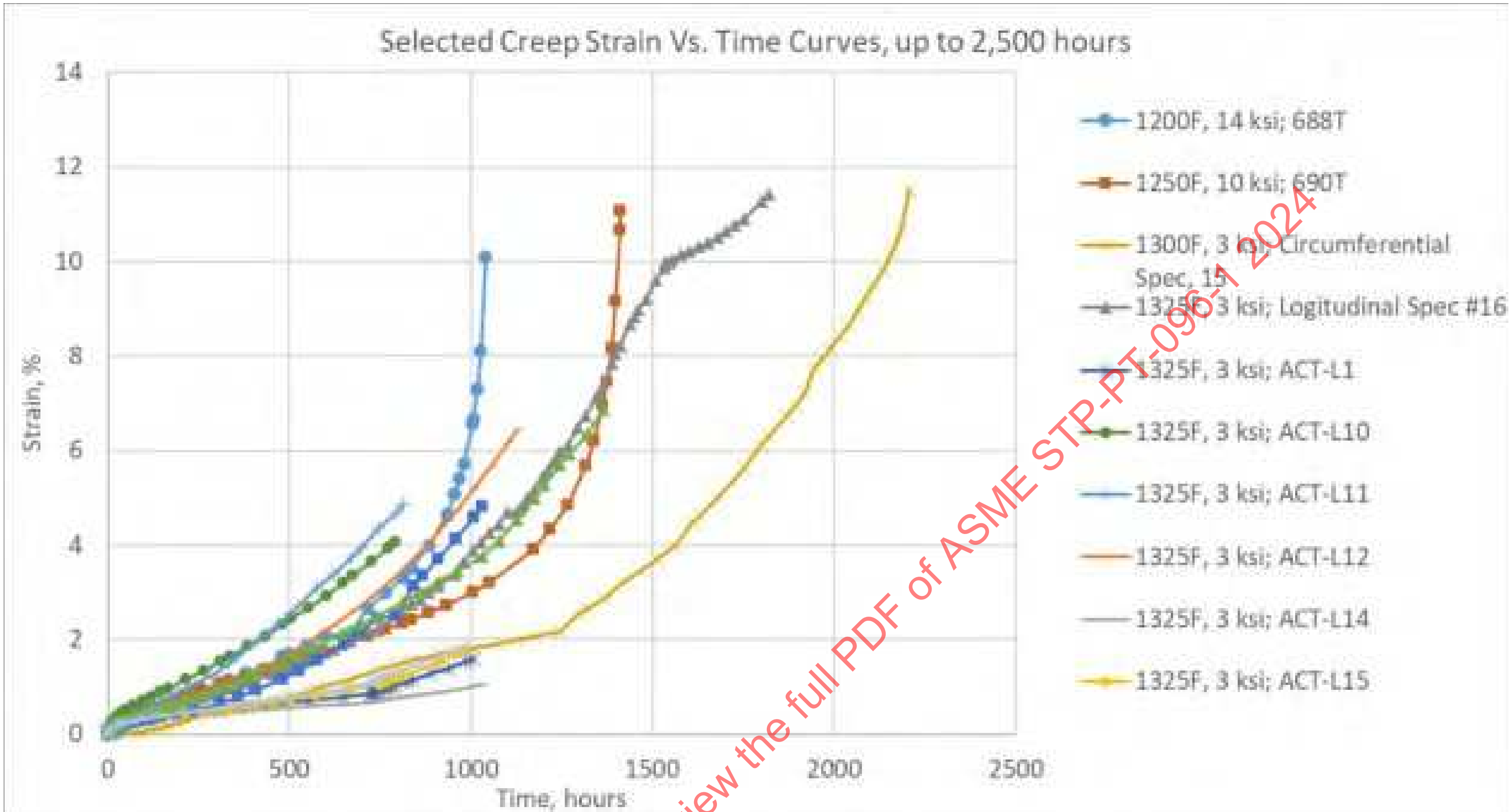


Figure 14-16: Medium-Term Strain Vs. Time Data, 2,500 to 5,000 Hour Test Durations (Grade 9)

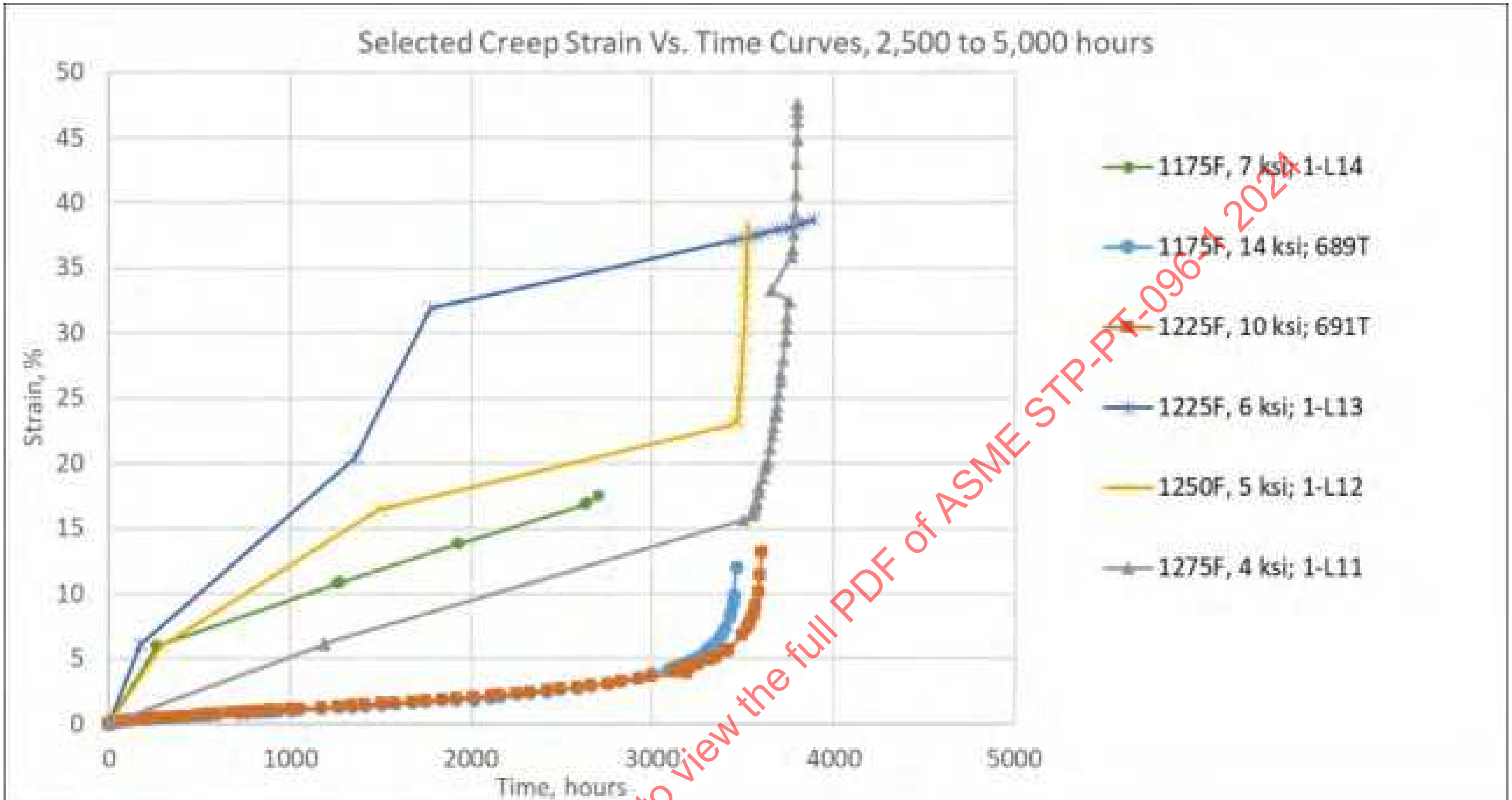


Figure 14-17: Long-Term Strain Vs. Time Data, 5,000 to 10,000 Hour Test Durations (Grade 9)

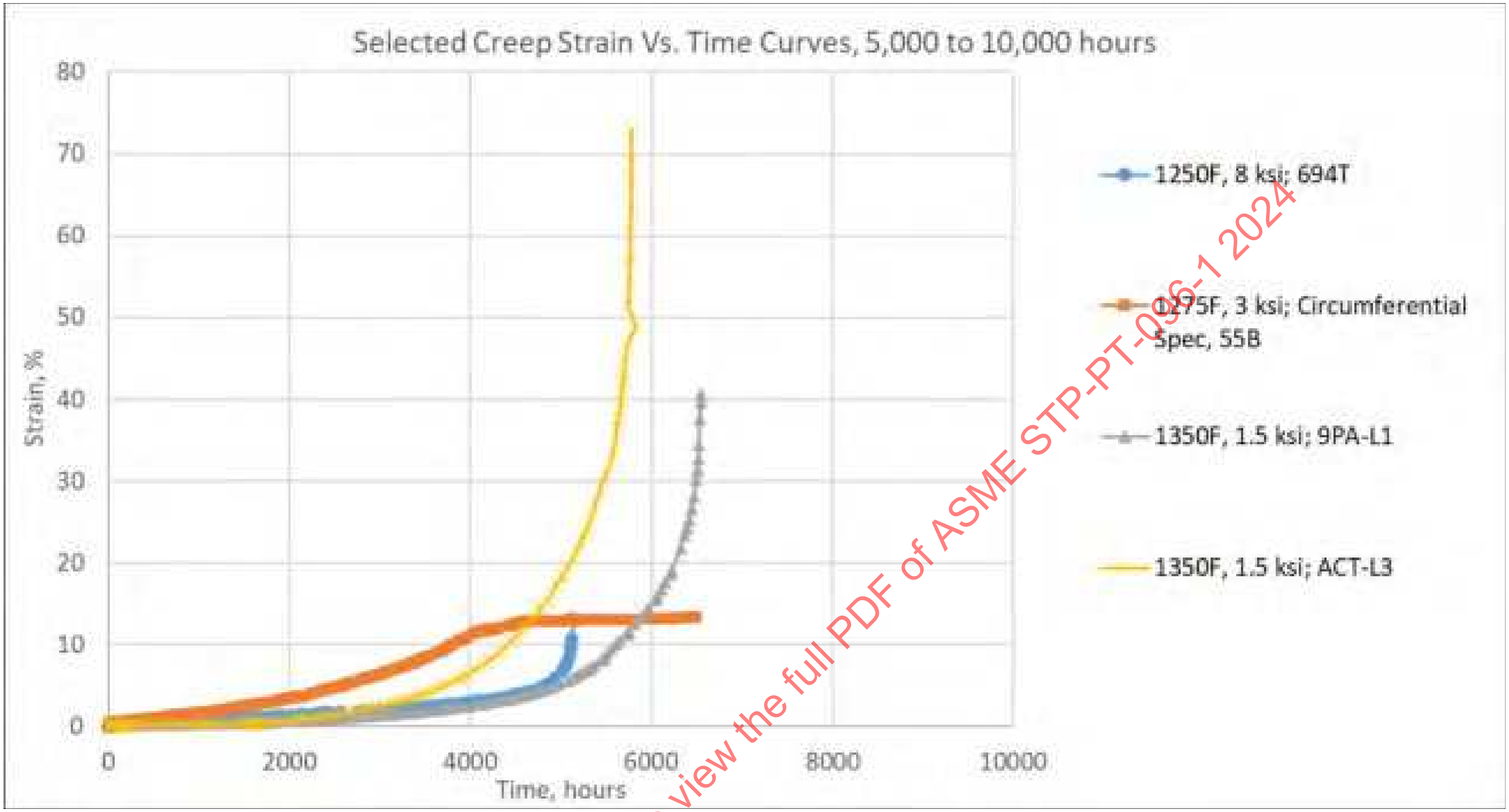


Figure 14-18: Long-Term Strain Vs. Time Data, In Excess of 10,000 Hour Test Durations (Grade 9)

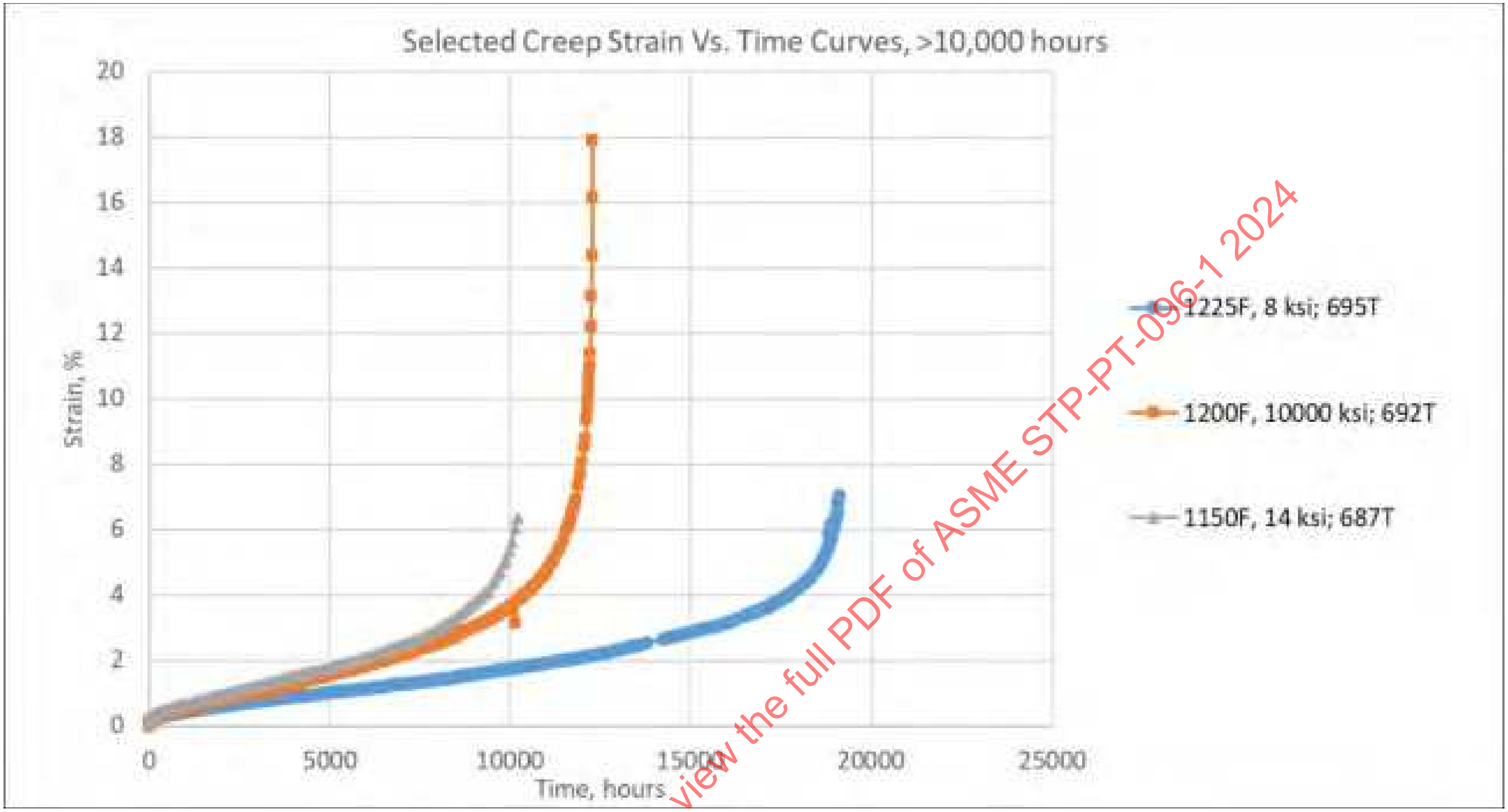


Figure 14-19: Grade 9 Continuous Cycling Fatigue Data, Including Elevated Temperature Data

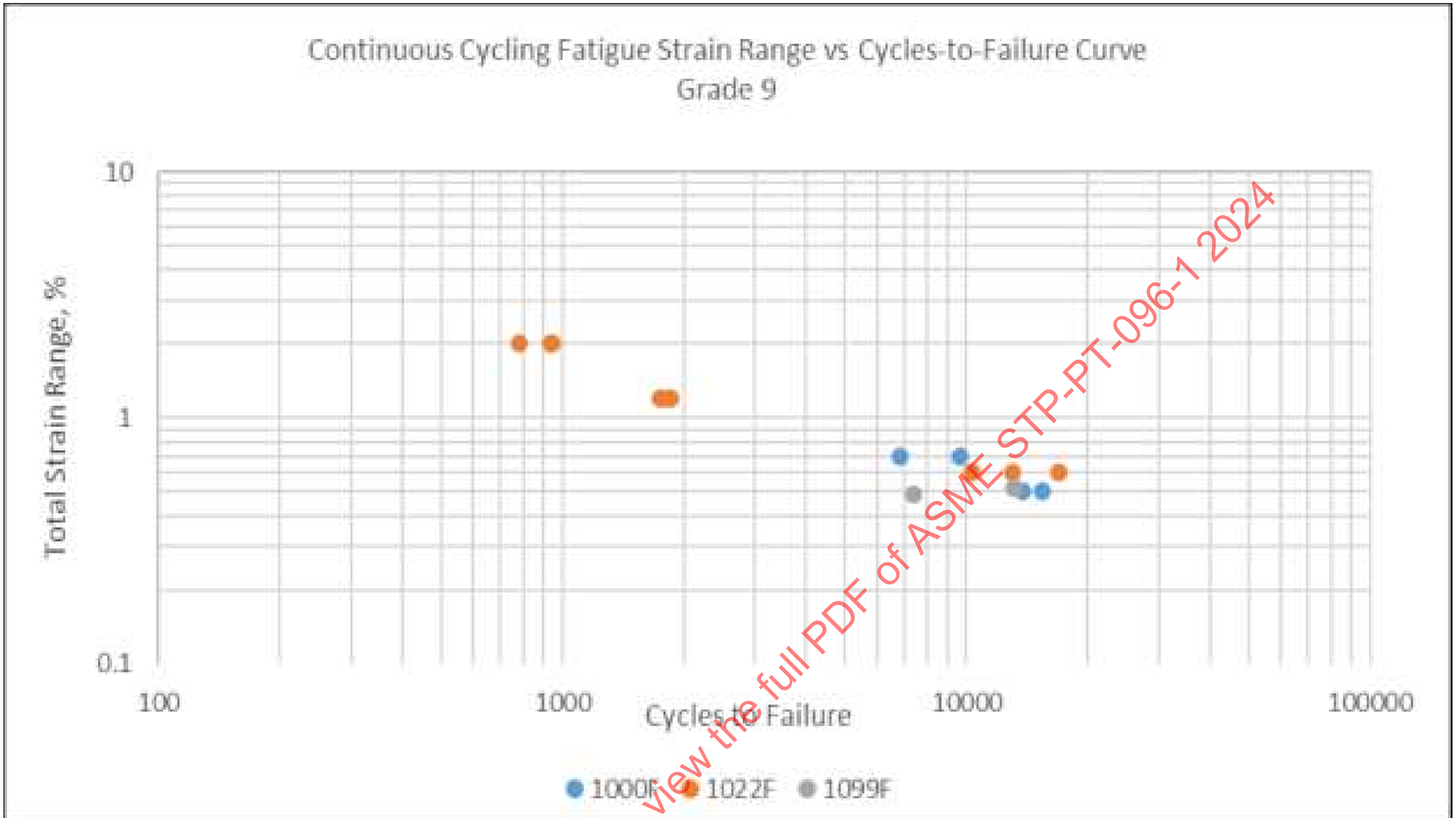
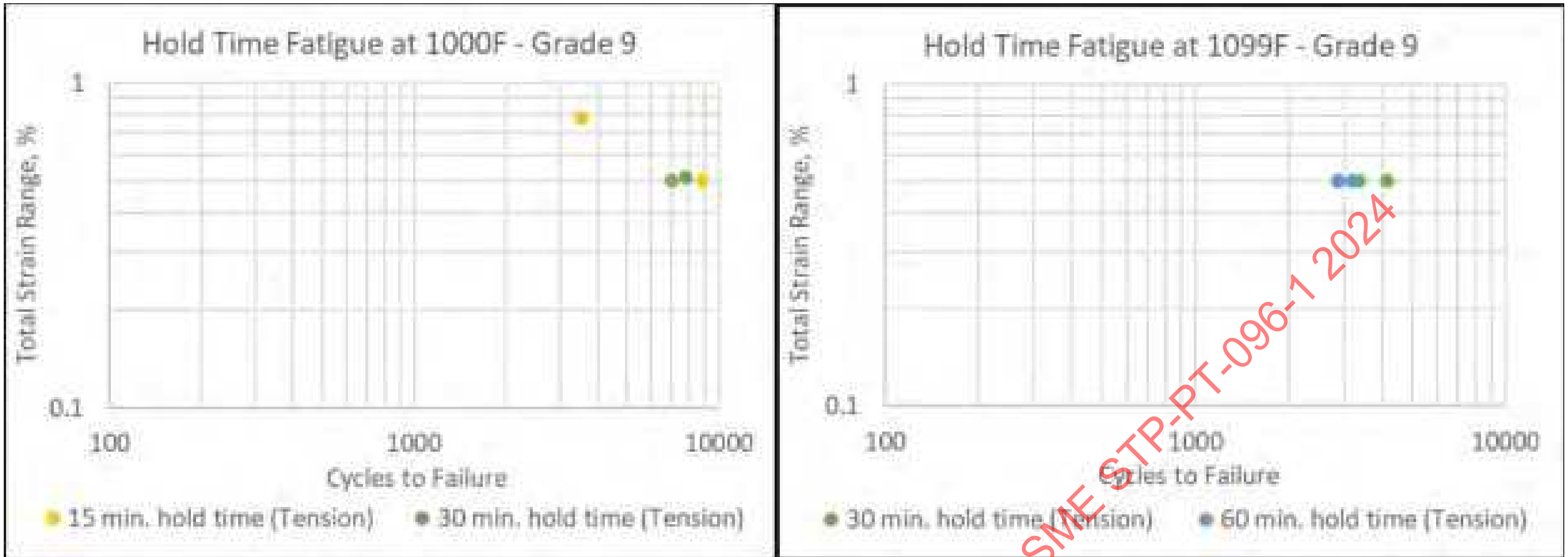


Figure 14-20: Grade 9 Hold Time Data (Creep Fatigue) for Grade 9, Temperatures of 1000°F & 1099°F



Attachment 14: Grade 9 Property Data

If you want the referenced embedded spreadsheet with additional data, please email a request to research@asme.org.

15 GRADE 92 (9CR-2W)

15.1 Physical Properties

Well-established physical properties were referenced from the BPVC Section II for this material. Physical property curves from WRC Bulletin 503 were plotted for comparison, and data from Vallourec & Mannesmann The T92/P92 Book were obtained. Figure 15-1 shows the trends of Elastic Modulus (E_y), Thermal Conductivity (k), Thermal Diffusivity (TD), and Thermal Expansion (α) with temperature.

15.2 Yield and Tensile Strength

Elevated temperature Yield and Tensile Strength over the range of existing allowable stresses (up to 1200°F) were readily available, including data beyond the current range of allowable stresses, up to approximately 1400°F, as shown in Figures 15-2 and 15-3. The sources for both high-temperature yield and high-temperature tensile strength are provided in the embedded spreadsheet at the end of this section. This spreadsheet also contains ductility data corresponding to the tensile test results presented in this report. Note that ductility (percent elongation and percent reduction in area) was not available for all sources referenced for the Grade 92 material.

To facilitate comparison of the data obtained to existing allowable stresses (obtained from ASME BPVC Code Case 2179-8), yield and tensile data were normalized on a heat-by-heat basis to express the ratio of yield or tensile strength at temperature to that measured for the heat at room temperature. In cases where data were not delineated by heats within a given source, or in cases where more than one room-temperature tensile test existed for a given heat of material, ratios are equal to the measured tensile or yield strength at temperature, divided by the average of all of the appropriate room-temperature values for the particular data source or heat of material. As a result of this approach, it is possible to have ratios in excess of 1.0. E^{2}G understands that this approach is similar to the normalizing procedure performed by ASME in typical analysis of yield and tensile data to obtain trend curves, as well as for the calculation of allowable stresses. Figures 15-4 and 15-5 show the heat-by-heat variation in yield and tensile strength ratios (respectively) as a function of temperature. It should be emphasized that even though the figure legends reference an entire source of data, the ratios, wherever possible, were calculated on a heat-by-heat basis; this is evident in the embedded spreadsheet at the end of this section. Figures 15-6 and 15-7 contain all of the yield and tensile (respectively) ratios plotted together, to facilitate regression of a 5th-order polynomial that is subsequently used for allowable stress comparison.

15.3 Creep Data (Creep Rupture, Minimum Creep Rate, and Ductility)

Creep Rupture data is shown in Figures 15-8 and 15-9, plotted as isotherms. The temperatures have been separated onto separate plots to minimize data overlap, with Figure 15-8 showing those temperatures where most of the data were concentrated, and Figure 15-9 showing those temperatures with significantly less data. It should be emphasized that these plots contain data for all product forms of material classified in the referenced publications as "Grade 92." This certainly includes material meeting the requirements of ASME BPVC Section II-A specifications. However, due to the diversity of data sources utilized for the compilation of the material property tables, it is likely that some of the material shown in Figures 15-8 and 15-9 may not meet existing specifications for this grade of material. Especially for Grade 92, recent publications by ASME, EPRI, ETD, and other entities, have demonstrated the importance of chemistry control for certain elements and certain ratios of elements (e.g., N:Al). Where older publications are referenced, the chemistry (and for that matter, manufacturing, processing, and heat treatment) corresponding to the heat of material in the original data source may not be consistent with modern specifications. Where possible, E^{2}G has documented the chemical composition if contained within the original source. In many cases, the project team has also made efforts to trace cross-referenced data back to original test results to determine if the heat treatment, product form, chemistry, etc. details can be obtained. This information is provided with the embedded spreadsheet to facilitate additional analysis on the part of ASME.

Creep Minimum strain rates (%/hour) are shown in Figure 15-10, separated by temperature Creep Ductility, as % elongation, is plotted in Figure 15-11. As is typical, the data show significant overlap, and it is difficult to observe clear trends in the data. The data is not intended to be used as plotted but is available in the spreadsheet for additional analysis. Note that much of the data with less than 10% total elongation at failure corresponds to cross-weld specimens contained in the data.

Creep data were analyzed using E^{2}G's proprietary Lot-Centered Analysis web-based software tool, in order to obtain creep properties. This regression is based on a Mandel-Paule algorithm and considers the variation within individual heats of material (for both rupture and strain rate data) as well as the variation between heats. The weight assigned to each datapoint and each heat is scaled based on the relative variation. Both rupture and strain rate (minimum creep rate, expressed as true strain per hours) were regressed according to a Larson-Miller time-temperature-parameter model, with a 3rd-order polynomial of stress. Lot-specific constant behavior was accounted for in this analysis, but the variation of LMP with stress was assumed to be constant (no non-parallel terms were included in the analysis). A 95% predictive limit was utilized to obtain the lower-bound (minimum LM constant for both rupture and strain rate) properties. The results of this analysis are summarized in Table 15-1 for rupture data and Table 15-2 for strain rate data. The Lot-Centered Analysis software tool generates property tables in the creep regime using the criteria outlined in Mandatory Appendix 1 of ASME Section II-D; the nomenclature of variables is consistent with II-D Appendix 1. For visualization of the allowable stress trends, Figure 15-12 is provided (for rupture allowable stresses and creep rate allowable stresses). Figure 15-13 shows a comparison of the various allowable stress criteria from Section II-D, Appendix 1, to the allowable stresses listed in code case 2179-8 for grade 92 tubes.

Creep Strain vs. time data are shown in Figure 15-14 for short-term data (up to 250 hour test durations); Figure 15-15 for 250 to 5,000 hour test durations; and Figure 15-16 for up to 5,000 hour test durations. Curves are only plotted where more than 10 strain vs. time points are present for the test. Additional curves are available with fewer datapoints (typically obtained from data in the form of time-until-specified-strain, in the embedded spreadsheet. Both creep rate and creep strain vs. time data are provided to satisfy ASME's request for creep strain vs. time curves, and both forms of data are applicable in developing allowable stresses. Although digitalization of creep curve data was not explicitly necessary per the project contract, E^{2}G did perform digitalization of creep curves where only graphical data was available (as is often the case in the published literature).

15.4 Continuous Cycling and Hold Time Fatigue Data

Continuous Cycling elevated temperature fatigue data is provided in Figure 15-17. Hold time fatigue data at high temperature is shown in Figure 15-18 (600°F). Additional detail is provided in the embedded spreadsheet.

Table 15-1: Model Parameters, Larson-Miller Property Results, and Allowable Stress (Rupture) Criteria, Grade 92

Equation Format:

$$\log(t_r) = C_{avg} + \frac{1}{T+460}\left(b_1 + b_2\log(\sigma) + b_3(\log(\sigma))^2 + b_4(\log(\sigma))^3\right)$$

C_{avg}	**-33.37**
C_{min}	**-33.95**
b_1	**78096.8**
b_2	**-26792.9**
b_3	**21016.9**
b_4	**-8743.3**

Number Data Points		
Correlation Coefficient	R^2	0.8995
Average Variance within Heats	V_w	0.1269
Variance between Heats	V_b	0.1013
Standard Error of Estimate	SEE	0.3562

Properties provided are for T in °F, stress in ksi, and t_R in hours

Temperature, °F	**S_{avg} (ksi)**	***n***	**F_{avg} (calc)**	**F_{avg} (used)**	**$F_{avg} \times S_{avg}$**	**S_{min} (ksi)**	**80% S_{min}**
850	50.38	23.85	0.908	0.67	33.75	47.55	38.04
900	43.43	20.81	0.8953	0.67	29.1	40.64	32.51
950	36.83	17.94	0.8796	0.67	24.67	34.08	27.27
1000	30.57	15.22	0.8596	0.67	20.48	27.89	22.31
1050	24.68	12.66	0.8337	0.67	16.54	22.09	17.67
1100	19.18	10.28	0.7993	0.67	12.85	16.71	13.37
1150	14.15	8.172	0.7545	0.67	9.481	11.89	9.512
1200	9.765	6.557	0.7039	0.67	6.543	7.884	6.308
1250	6.351	5.82	0.6733	0.67	4.255	5.043	4.034
1300	4.127	6.168	0.6885	0.67	2.765	3.347	2.678

Table 15-2: Model Parameters, Larson-Miller Property Results, and Allowable Stress (Strain Rate) Criteria, Grade 92

Equation Format:

$$\log(\dot{\varepsilon}_0) = -C_{avg} - \frac{1}{T+460}\left(a_1 + a_2\log(\sigma) + a_3(\log(\sigma))^2 + a_4(\log(\sigma))^3\right)$$

C_{avg} (A_0)	**-14.27**
C_{min} ($A_0+\Delta_\Omega^{SR,LB}$)	**-15.84**
a_1	**38728.1**
a_2	**-26712.7**
a_3	**29730.5**
a_4	**-11029.7**

Number Data Points		**694**
Correlation Coefficient	R^2	0.3312
Average Variance within Heats	V_w	0.9044
Variance between Heats	V_b	0.8139
Standard Error of Estimate	SEE	0.951

Properties provided are for T in °F, stress in ksi, and t_R in hours

Temperature, °F	**$S_{C,avg}$ (ksi)**
850	49.04
900	43.76
950	38.37
1000	32.76
1050	26.71
1100	19.5
1150	3.955
1200	2.586
1250	2.049
1300	1.726

Figure 15-1: Grade 92 Modulus (E_y), Thermal Conductivity (k), Thermal Diffusivity (TD), & Thermal Expansion (α) With Temperature

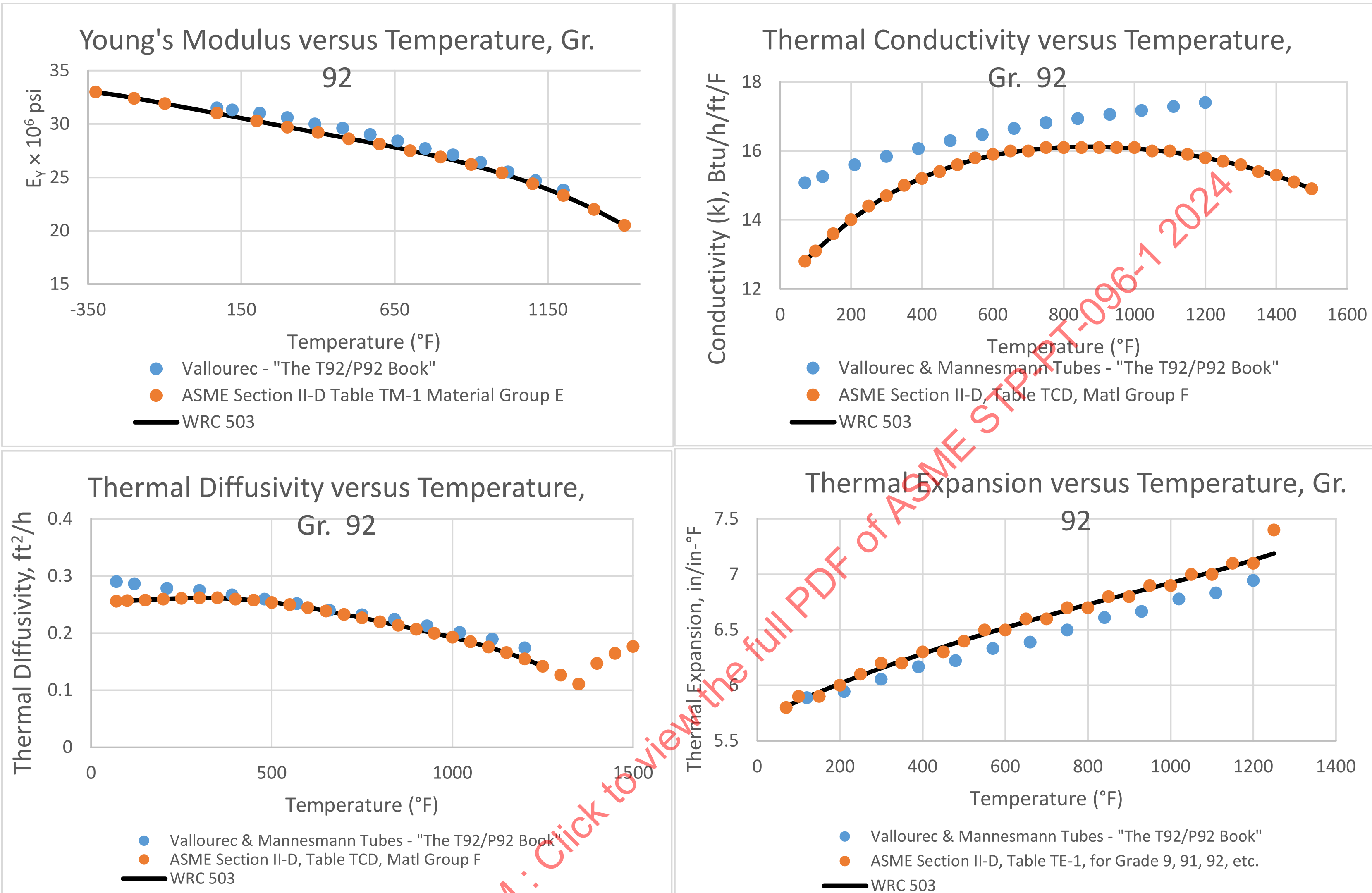


Figure 15-2: Grade 92 Yield Strength Vs. Temperature, By Data Source, Including Trend Curves

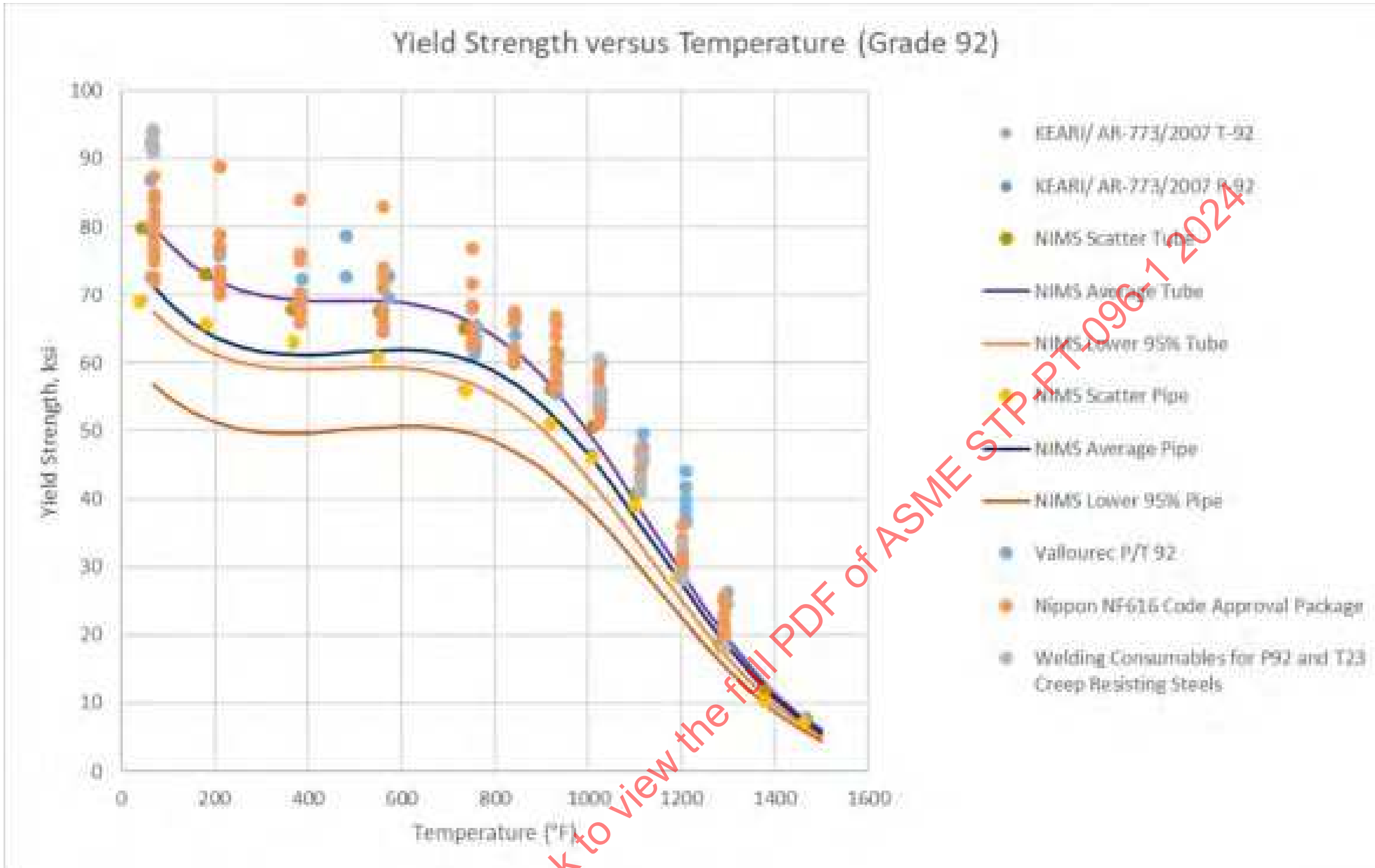


Figure 15-3: Grade 92 Tensile Strength Vs. Temperature, By Data Source, Including Trend Curves

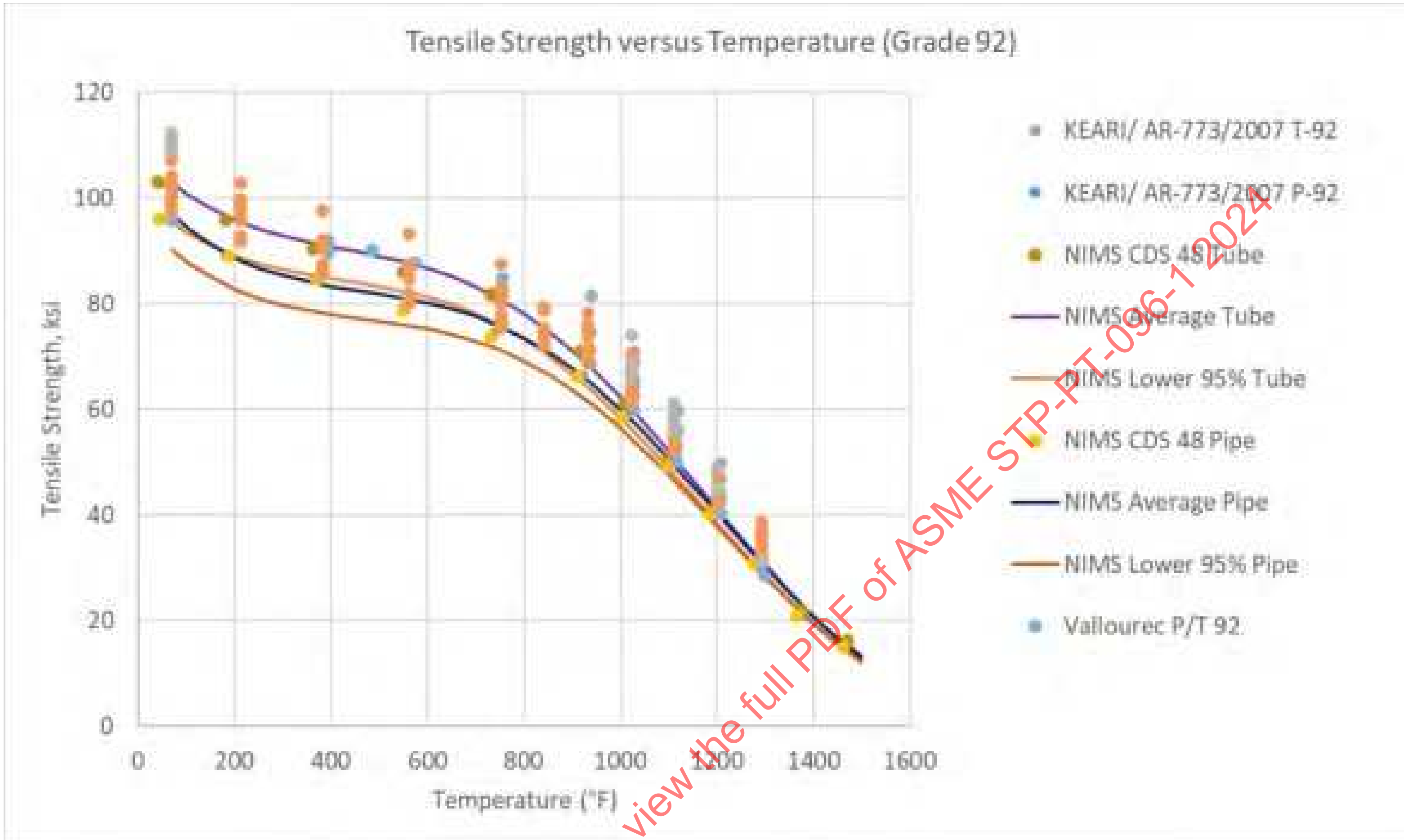


Figure 15-4: Grade 92 Yield Strength Ratios Vs. Temperature (Calculated on a Heat-By-Heat Basis, By Data Source)

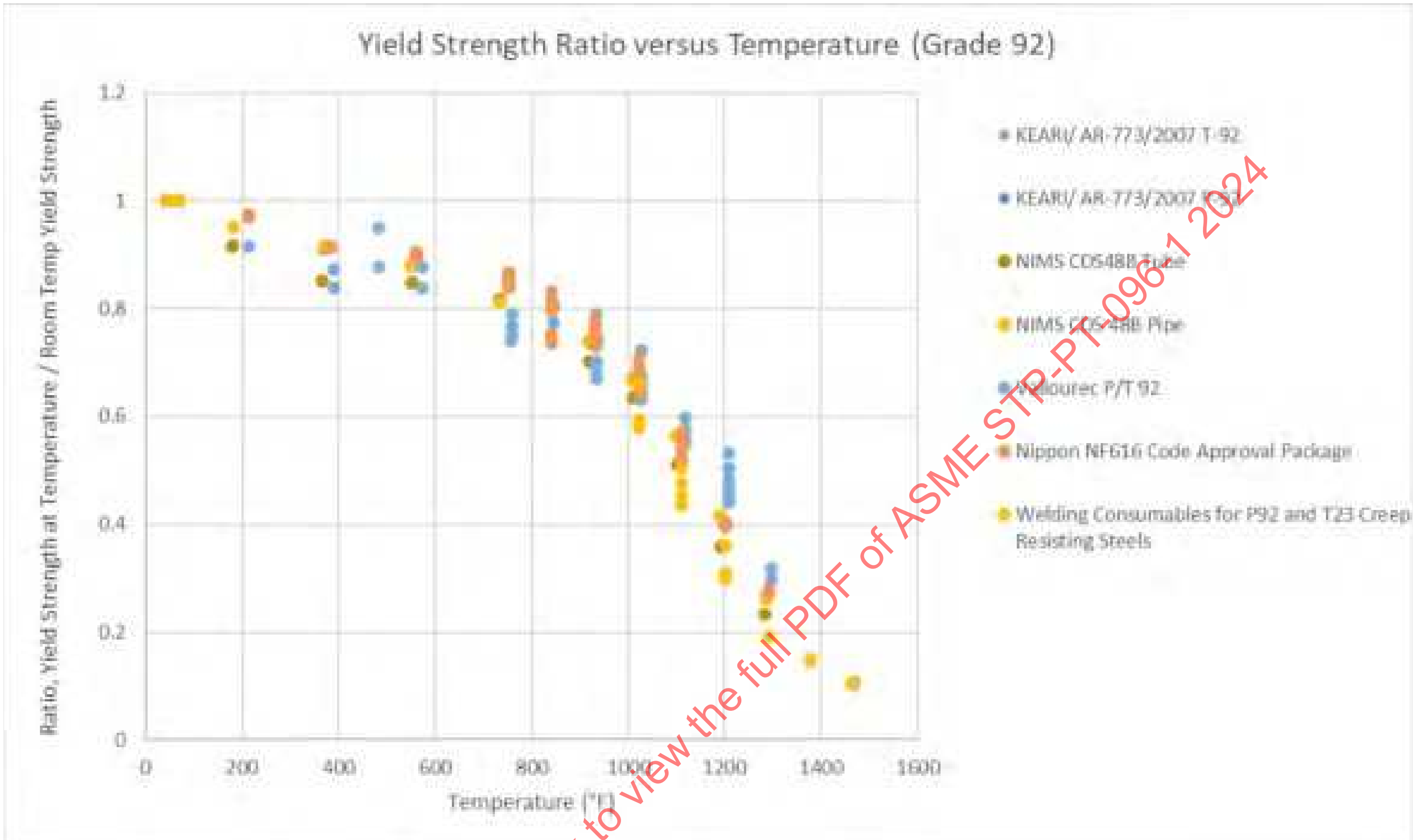


Figure 15-5: Grade 92 Tensile Strength Ratios Vs. Temperature (Calculated on a Heat-By-Heat Basis, By Data Source)

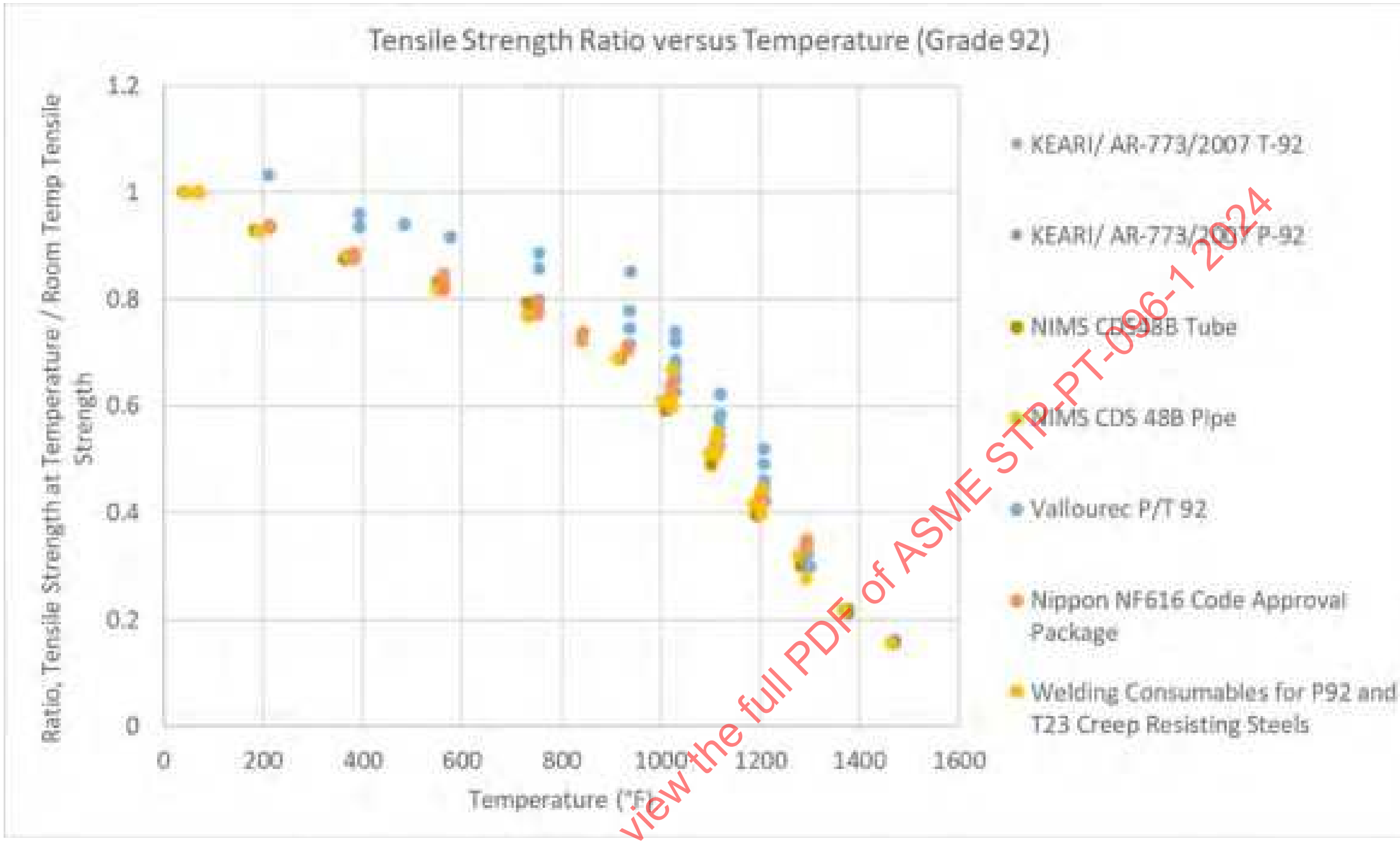


Figure 15-6: Grade 92 Yield Strength Ratios Vs. Temperature, All Combined Data, With Polynomial Regression

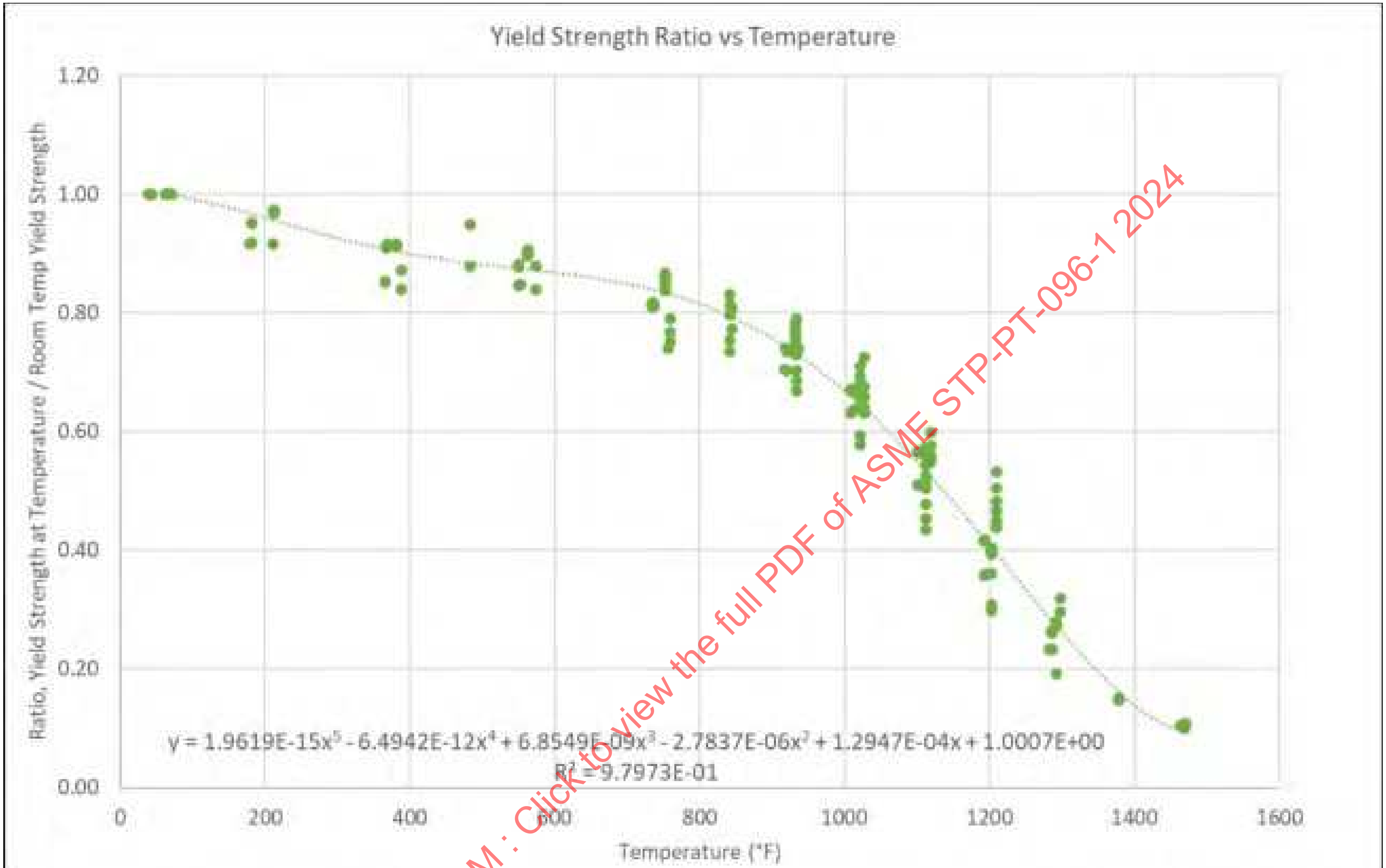


Figure 15-7: Grade 92 Tensile Strength Ratios Vs. Temperature, All Combined Data, With Polynomial Regression

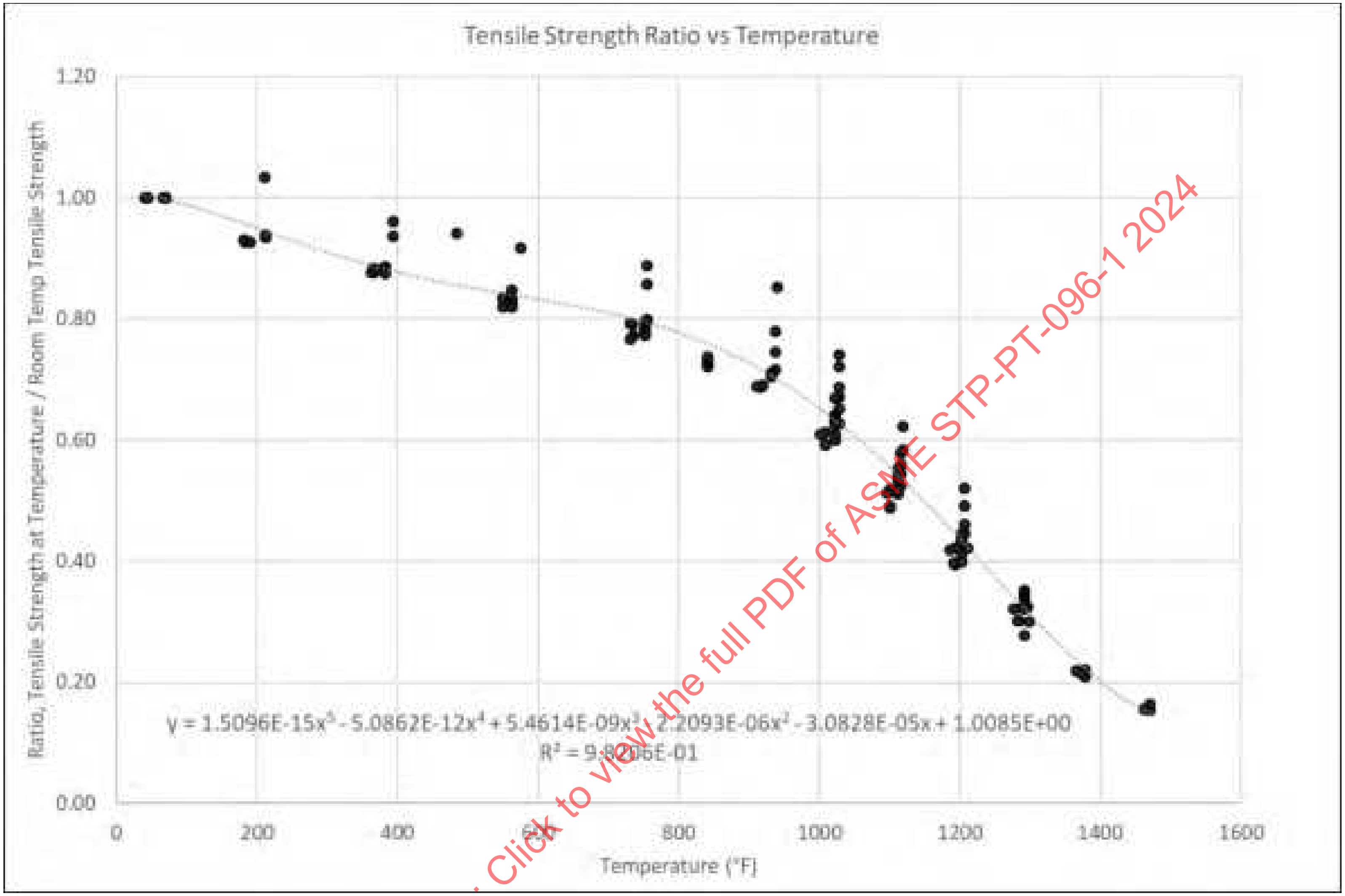


Figure 15-8: Grade 92 Creep Rupture Isotherm Curves, Temperatures With High Concentration of Data Points

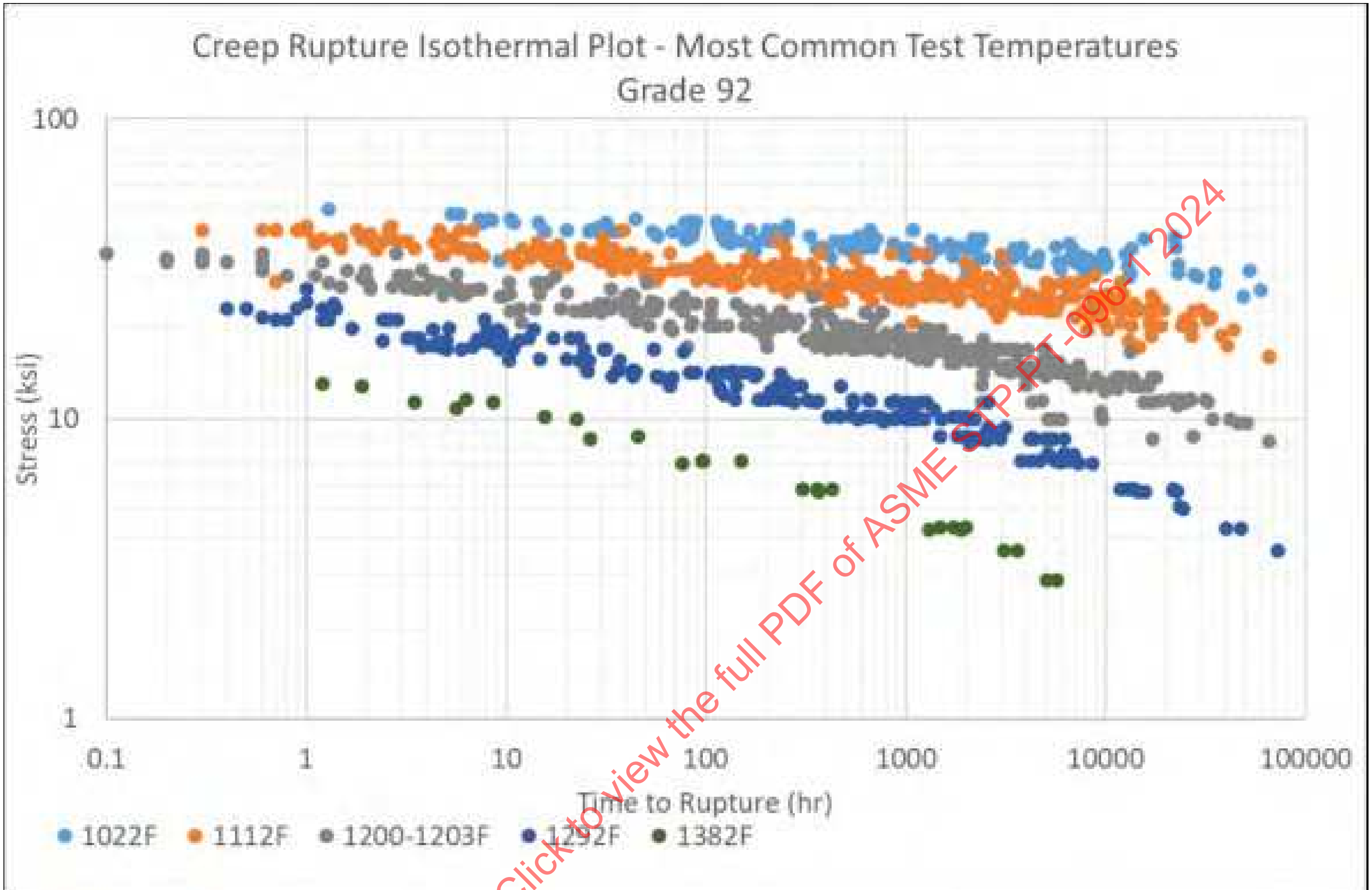


Figure 15-9: Grade 92 Creep Rupture Isotherm Curves for Additional and Intermediate Temperatures

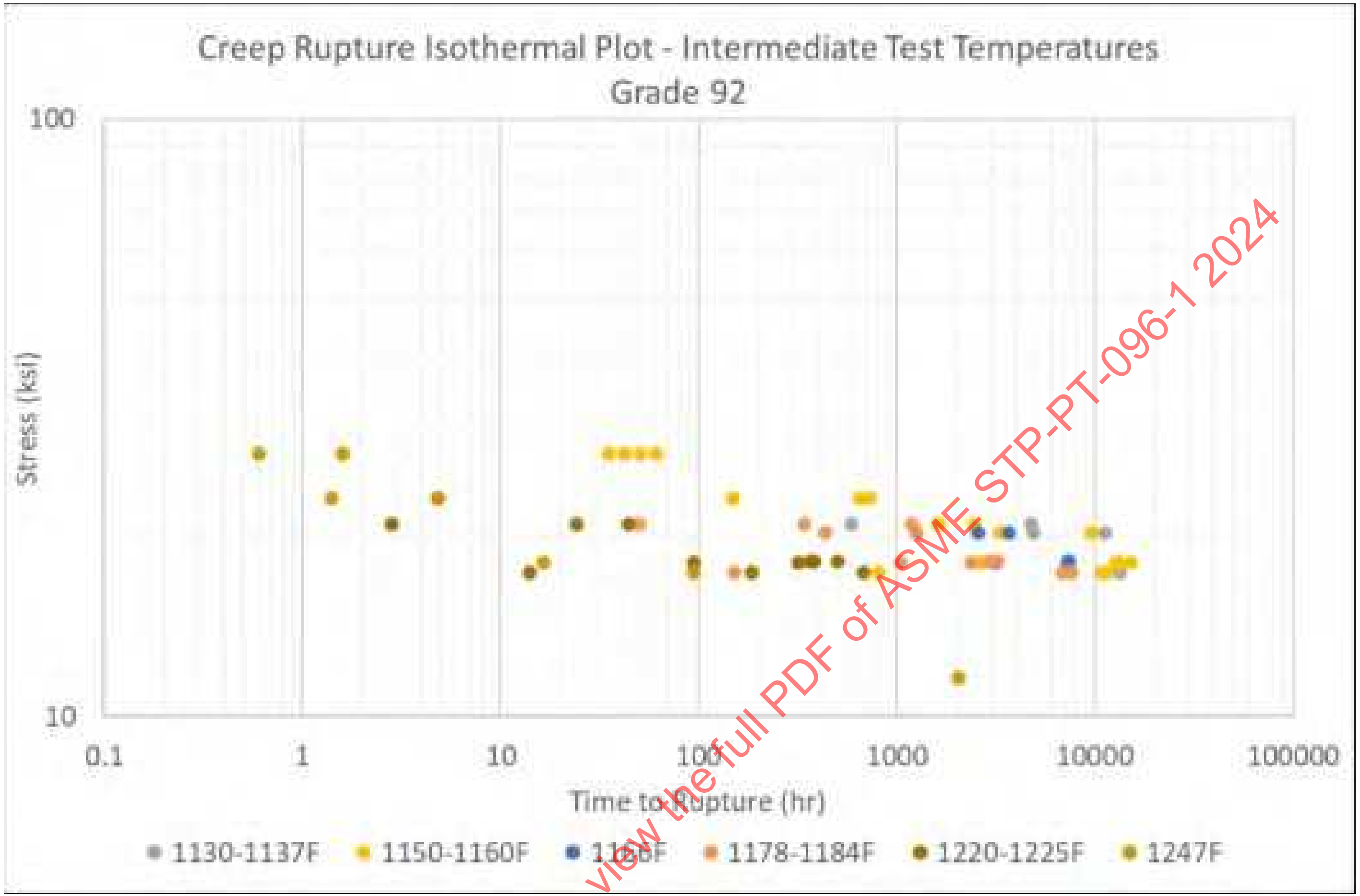


Figure 15-10: Grade 92 Creep Strain Rate (MCR) Isotherm Curves, Temperatures With High Concentration of Data Points

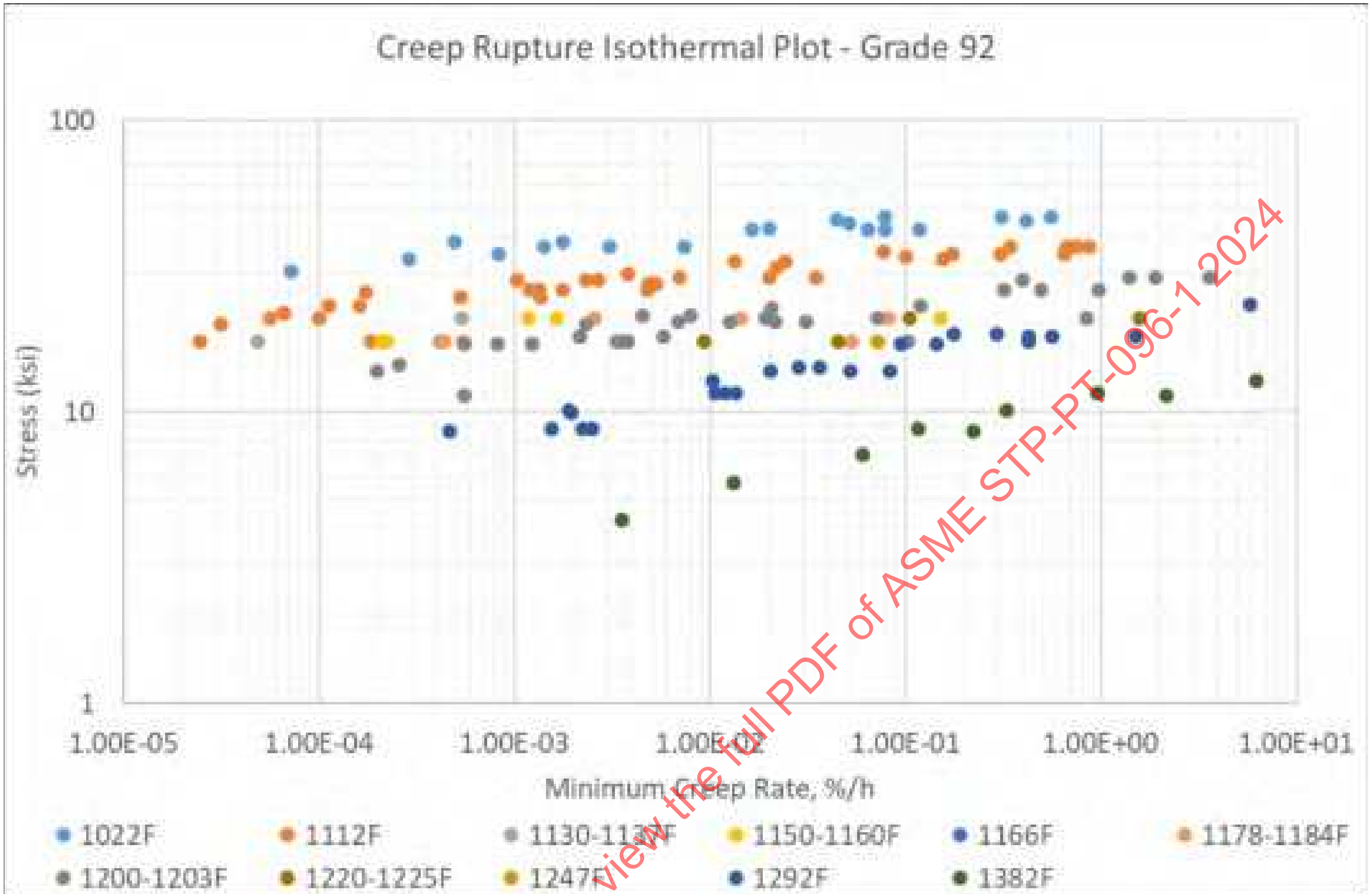


Figure 15-11: Grade 92 Creep Ductility (% Elongation) Vs. Rupture Time Isotherms

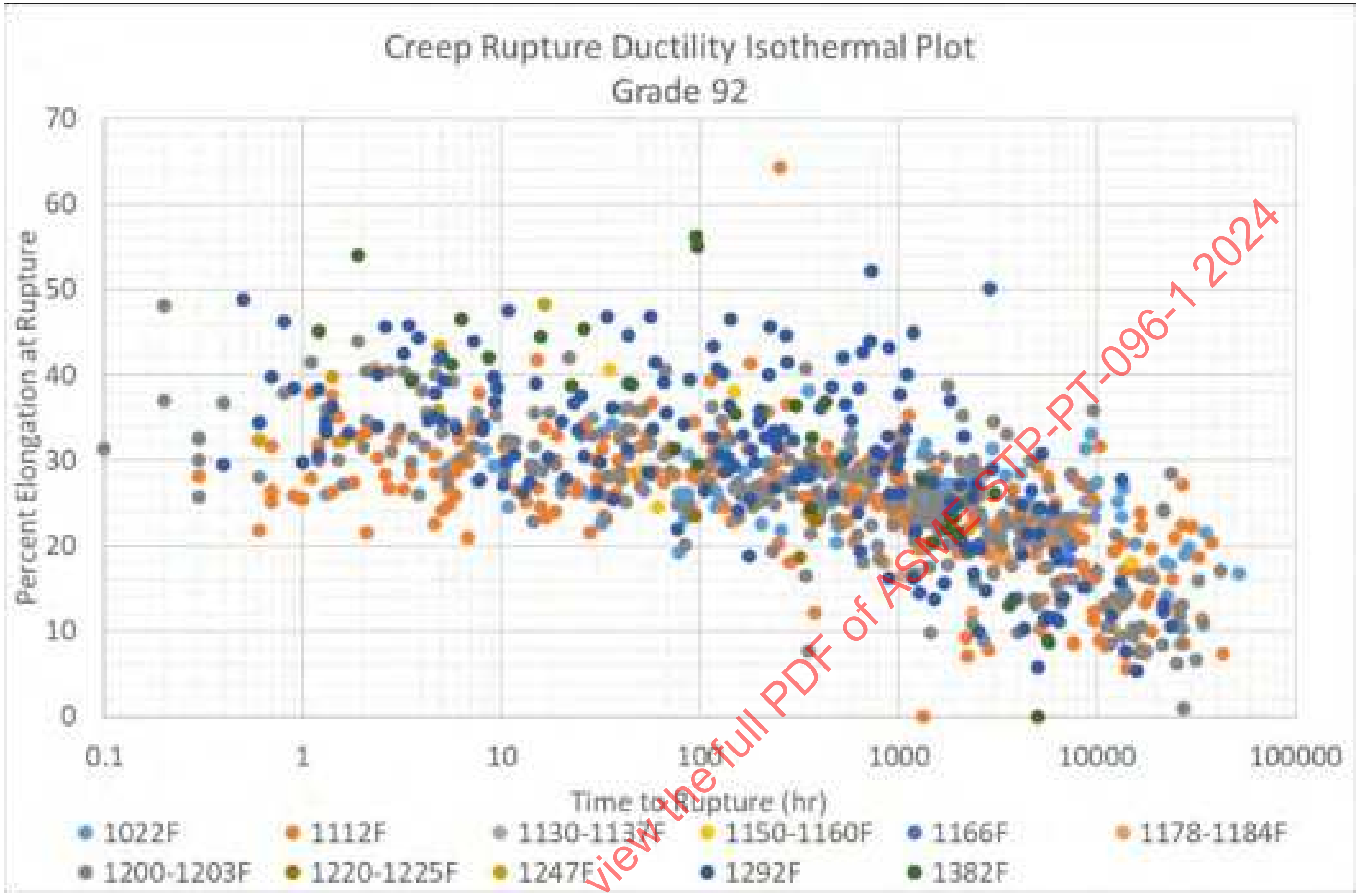


Figure 15-12: Calculated Allowable Stresses Based on Rupture and Creep Strain Rate and ASME II-D Appendix 1 Criteria (Grade 92)

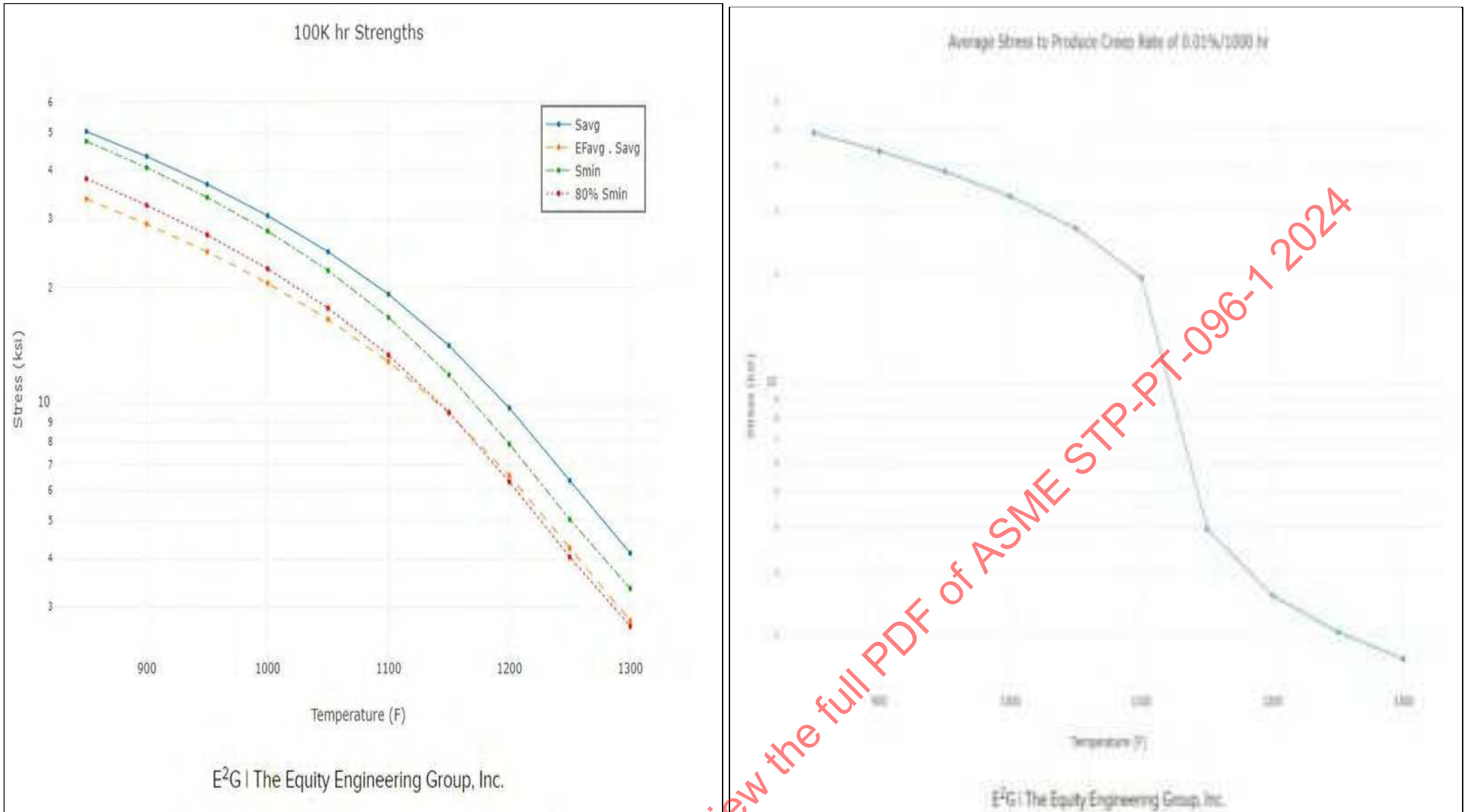


Figure 15-13: Comparison of Current Grade 92 Allowable Stresses (Except Forgings) Vs. ASME II-D Appendix 1 Criteria Applied to Data

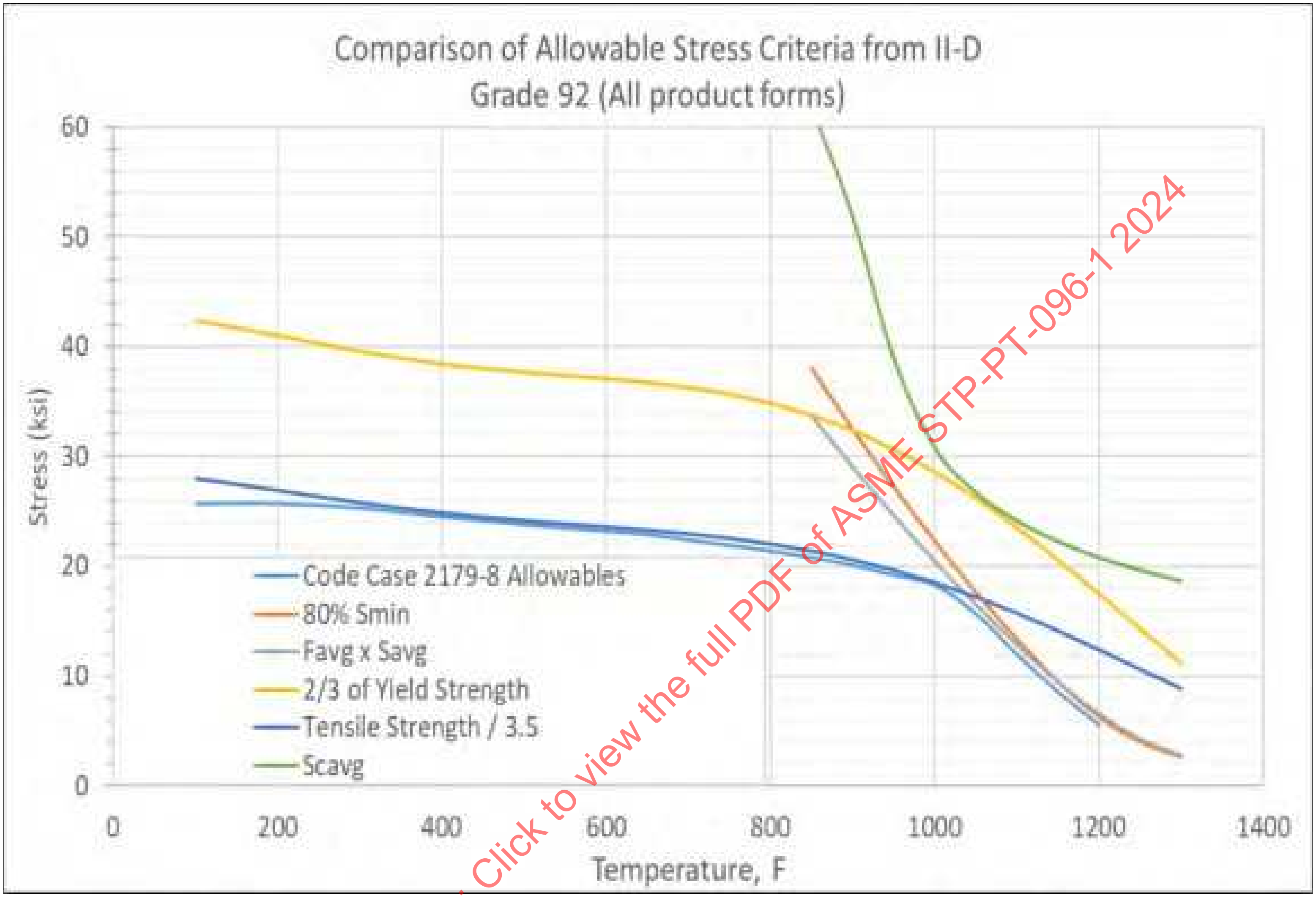


Figure 15-14: Short-Term Strain Vs. Time Data, Up to 250 Hour Test Durations (Grade 92)

Figure 15-15: Medium-Term Strain Vs. Time Data, 250 to 5,000 Hour Test Durations (Grade 92)

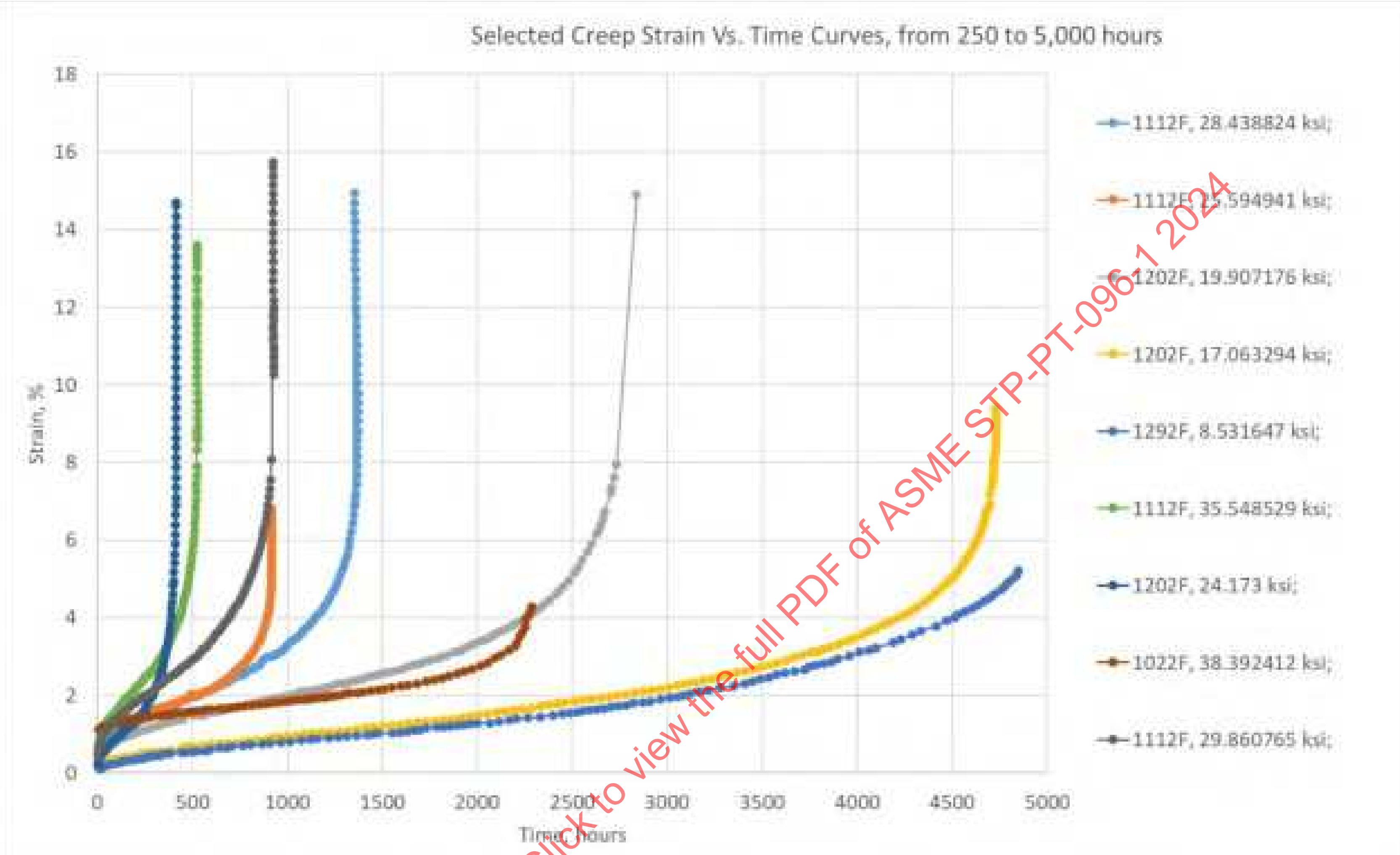


Figure 15-16: Long-Term Strain Vs. Time Data, in Excess of 5,000 Hour Test Durations (Grade 92)

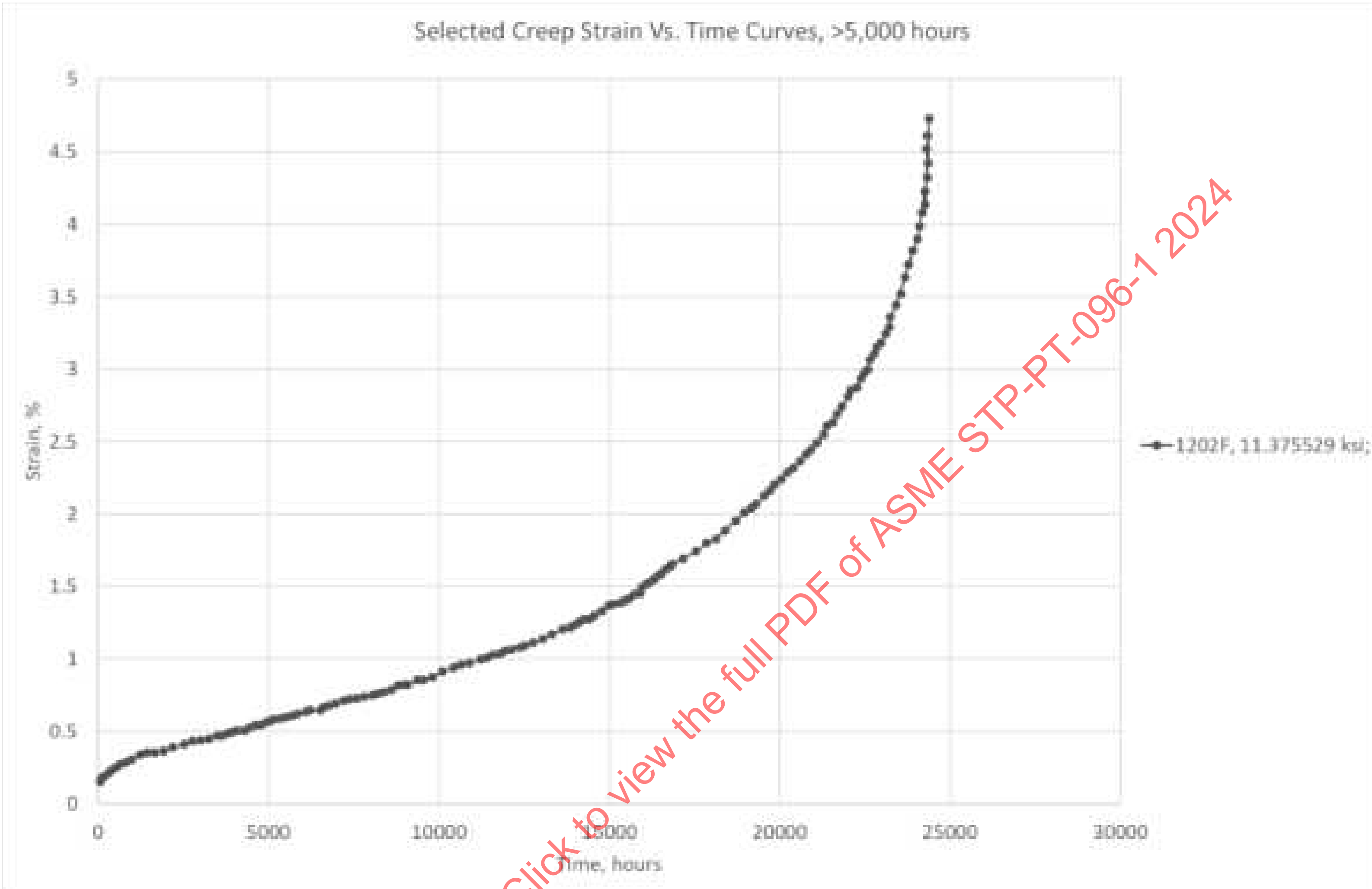


Figure 15-17: Grade 92 Continuous Cycling High Temperature Fatigue Data for Grade 92

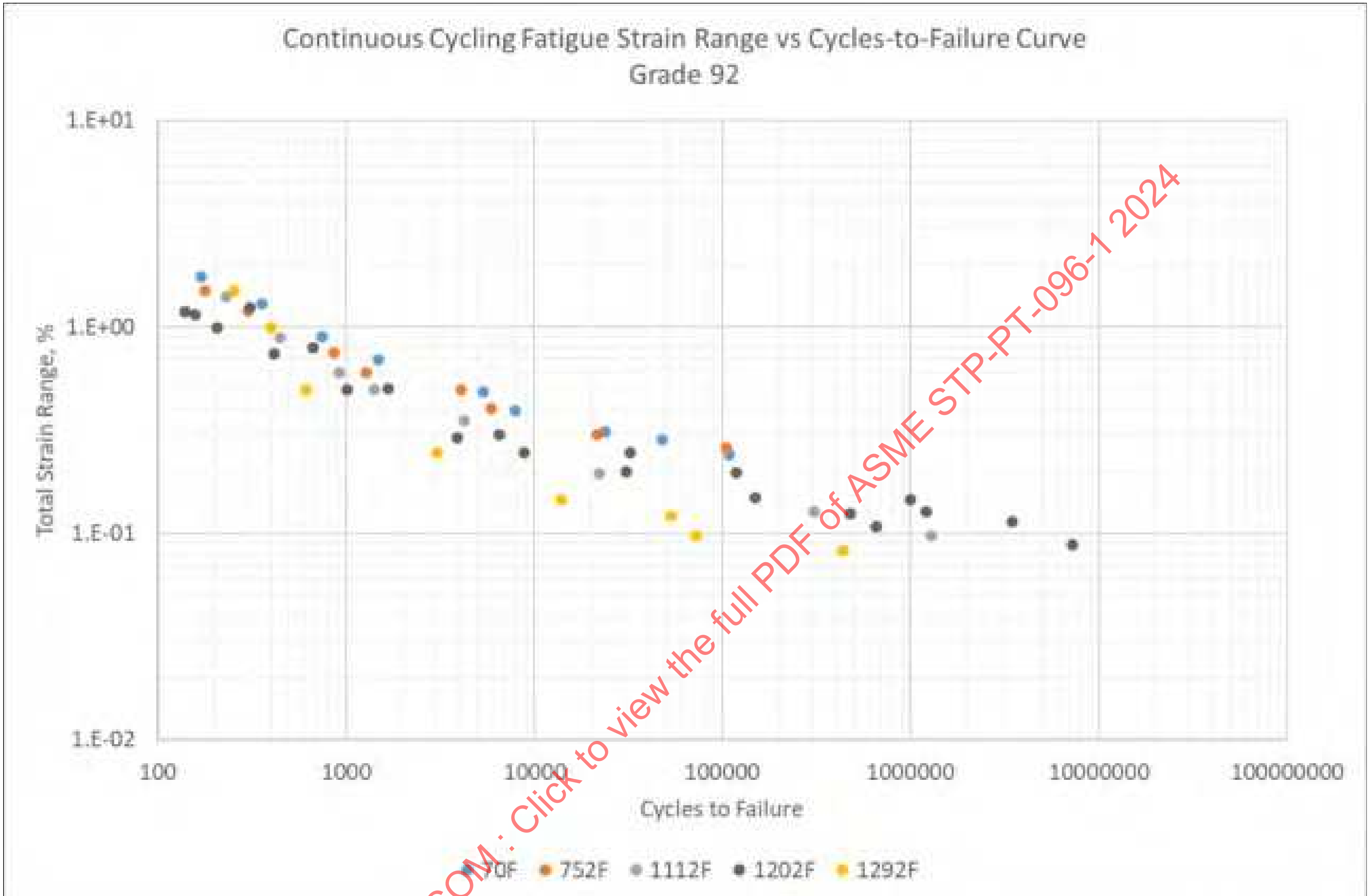
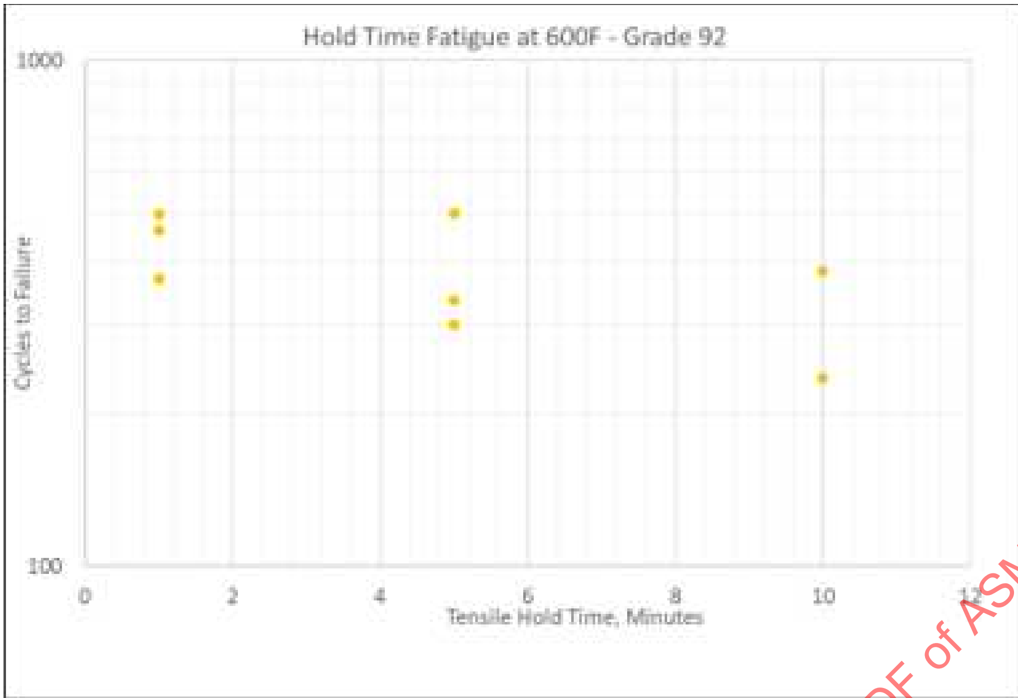


Figure 15-18: Grade 92 Hold Time Data (Creep Fatigue) for Grade 92, Temperature of 600°F



Attachment 15: Grade 92 Property Data

If you want the referenced embedded spreadsheet with additional data, please email a request to research@asme.org.

16 TYPE 304H (AND 304) STAINLESS STEEL

16.1 Physical Properties

Well-established physical properties were referenced from the BPVC Section II for this material. Physical property curves from WRC Bulletin 503 were plotted for comparison, and data from two literature sources (ASTM STP 124 and the Nuclear Systems Materials Handbook) were obtained. Figure 16-1 shows the trends of Elastic Modulus (E_y), Thermal Conductivity (k), Thermal Diffusivity (TD), and Thermal Expansion (α) with temperature.

16.2 Yield and Tensile Strength

Elevated temperature Yield and Tensile Strength over the range of existing allowable stresses (up to 1200°F) were readily available, including data beyond the current range of allowable stresses, up to approximately 1800°F, as shown in Figures 16-2 and 16-3. The sources for both high-temperature yield and high-temperature tensile strength are provided in the embedded spreadsheet at the end of this section. This spreadsheet also contains ductility data corresponding to the tensile test results presented in this report. Note that ductility (percent elongation and percent reduction in area) was not available for all sources referenced for the 304H material.

To facilitate comparison of the data obtained to existing allowable stresses (Section II-D Table 1A), yield and tensile data were normalized on a heat-by-heat basis to express the ratio of yield or tensile strength at temperature to that measured for the heat at room temperature. In cases where data were not delineated by heats within a given source, or in cases where more than one room-temperature tensile test existed for a given heat of material, ratios are equal to the measured tensile or yield strength at temperature, divided by the average of all of the appropriate room-temperature values for the particular data source or heat of material. As a result of this approach, it is possible to have ratios in excess of 1.0. E^2G understands that this approach is similar to the normalizing procedure performed by ASME in typical analysis of yield and tensile data to obtain Table Y and Table U (Section II-D) trend curves, as well as for the calculation of allowable stresses. Figures 16-4 and 16-5 show the heat-by-heat variation in yield and tensile strength ratios (respectively) as a function of temperature. It should be emphasized that even though the figure legends reference an entire source of data, the ratios, wherever possible, were calculated on a heat-by-heat basis; this is evident in the embedded spreadsheet at the end of this section. Figures 16-6 and 16-7 contain all of the yield and tensile (respectively) ratios plotted together, to facilitate regression of a polynomial that is subsequently used for allowable stress comparison.

16.3 Creep data (Creep Rupture, Minimum Creep Rate, and Ductility)

Creep Rupture data is shown in Figures 16-8 and 16-9, plotted as isotherms. The temperatures have been separated onto separate plots to minimize data overlap, with Figure 16-8 showing those temperatures where most of the data were concentrated, and Figure 16-9 showing those temperatures with significantly less data. It should be emphasized that these plots contain data for all product forms of material classified in the referenced publications as "304, 304H or 304L." This certainly includes material meeting the requirements of ASME BPVC Section II-A specifications (e.g., SA-182 F304H, SA-213 TP304H, SA-249 TP304H, etc.). However, due to the diversity of data sources utilized for the compilation of the material property tables, it is likely that some of the material shown in Figures 16-8 and 16-9 may not meet existing specifications for this grade of material. Where older publications are referenced, the chemistry (and for that matter, manufacturing, processing, and heat treatment) corresponding to the heat of material in the original data source may not be consistent with modern specifications. Where possible, E^2G has documented the chemical composition if contained within the original source. In many cases, the project team has also made efforts to trace cross-referenced data back to original test results to determine if the heat treatment, product form, chemistry, etc. details can be obtained. This information is provided with the embedded spreadsheet to facilitate additional analysis on the part of ASME.

Creep Minimum strain rates (%/hour) are shown in Figure 16-10 separated by temperature. Creep Ductility, as % elongation, is plotted in Figure 16-11. As is typical, the data show significant overlap, and it is difficult to observe clear trends in the data. The data is not intended to be used as plotted but is available in the spreadsheet for additional analysis.

Creep data were analyzed using E^2G's proprietary Lot-Centered Analysis web-based software tool, in order to obtain creep properties. This regression is based on a Mandel-Paule algorithm and considers the variation within individual heats of material (for both rupture and strain rate data) as well as the variation between heats. The weight assigned to each datapoint and each heat is scaled based on the relative variation. Both rupture and strain rate (minimum creep rate, expressed as true strain per hours) were regressed according to a Larson-Miller time-temperature-parameter model, with a 3rd-order polynomial of stress. Lot-specific constant behavior was accounted for in this analysis, but the variation of LMP with stress was assumed to be constant (no non-parallel terms were included in the analysis). A 95% predictive limit was utilized to obtain the lower-bound (minimum LM constant for both rupture and strain rate) properties. The results of this analysis are summarized in Table 16-1 for rupture data and Table 16-2 for strain rate data. The Lot-Centered Analysis software tool generates property tables in the creep regime using the criteria outlined in Mandatory Appendix 1 of ASME Section II-D; the nomenclature of variables is consistent with II-D Appendix 1. For visualization of the allowable stress trends, Figure 16-12 is provided (for rupture allowable stresses and creep rate allowable stresses). Figure 16-13 shows a comparison of the various allowable stress criteria from Section II-D, Appendix 1, to the existing (2019) Section II-D Table 1A allowable stresses for typical product forms of 304H (67% yield basis as opposed to 90% basis).

Creep Strain vs. time data are shown in Figures 16-14 and 16-15 for two different sources, NRIM 4B and the Nuclear Systems Material Handbook. Both creep rate and creep strain vs. time data are provided to satisfy ASME's request for creep strain vs. time curves, and both forms of data are applicable in developing allowable stresses. Although digitalization of creep curve data was not explicitly necessary per the project contract, E^2G did perform digitalization of creep curves where only graphical data was available (as is often the case in the published literature).

16.4 Continuous Cycling Fatigue and Hold Time Fatigue Curves

A portion of the data obtained for continuous cycling fatigue data at elevated temperatures for 304H is shown in Figure 16-16, includes a limited amount of room temperature data contained in sources which also present high-temperature data. Figure 16-16 only contains data for which total strain range was determined from the original source. Additional data points for continuous cycling fatigue data of 304H are presented in the attached spreadsheet; however, due to the complexities of various forms of fatigue data, compatible plots for each type of data expression and failure criteria are not included in this report. Hold time fatigue data at high temperature is shown in Figure 16-17 (1022°F), Figure 16-18 (1100-1012°F), and Figure 16-19 (1200-1202°F) with separate plots for temperatures at which at least a moderate collection of data points existed. Additional data is provided in the embedded spreadsheet.

Table 16-1: Model Parameters, Larson-Miller Property Results, and Allowable Stress (Rupture) Criteria, 304H

Equation Format:

$$\log(t_r) = C_{avg} + \frac{1}{T+460}\left(b_1 + b_2\log(\sigma) + b_3(\log(\sigma))^2 + b_4(\log(\sigma))^3\right)$$

C_{avg}	**8.87**
C_{min}	**9.899**
b_1	**26601.5**
b_2	**-7387.7**
b_3	**3595.6**
b_4	**-1650.3**

Number Data Points		**2164**
Correlation Coefficient	**R^2**	0.4891
Average Variance within Heats	**V_w**	0.3915
Variance between Heats	**V_b**	0.3007
Standard Error of Estimate	**SEE**	0.6257

Properties provided are for T in °F, stress in ksi, and t_R in hours

Temperature, °F	**S_{avg} (ksi)**	***n***	**F_{avg} (calc)**	**F_{avg} (used)**	**$F_{avg} \times S_{avg}$**	**S_{min} (ksi)**	**80% S_{min}**
850	30.42	5.81	0.6729	0.67	20.38	19.43	15.54
900	24.42	5.11	0.637	0.67	16.36	14.61	11.69
950	19.19	4.48	0.5978	0.67	12.85	10.67	8.539
1000	14.71	3.93	0.5568	0.67	9.858	7.595	6.076
1050	11	3.49	0.5168	0.67	7.37	5.319	4.255
1100	8.036	3.16	0.4829	0.67	5.384	3.725	2.98
1150	5.779	2.97	0.4606	0.67	3.872	2.651	2.121
1200	4.141	2.91	0.4536	0.67	2.774	1.937	1.549
1250	2.998	2.97	0.461	0.67	2.009	1.457	1.165
1300	2.215	3.12	0.4783	0.67	1.484	1.127	0.9014

** E²G's proprietary *Lot-Centered Analysis* web-based software tool only provides results up to 1300°F, but it should be noted that Type 304H allowable stress properties are observed above 1300°F.

Table 16-2: Model Parameters, Larson-Miller Property Results, and Allowable Stress (Strain Rate) Criteria, 304H

Equation Format:

$$\log(\dot{\varepsilon}_0) = -C_{avg} - \frac{1}{T+460}\left(a_1 + a_2\log(\sigma) + a_3(\log(\sigma))^2 + a_4(\log(\sigma))^3\right)$$

C_{avg} (A_0)	**9.907**
C_{min} ($A_0+\Delta_\Omega^{SR,LB}$)	**10.91**
a_1	**32415.3**
a_2	**-6984.2**
a_3	**-202.2**
a_4	**-316.8**

Number Data Points		**346**
Correlation Coefficient	R^2	0.696
Average Variance within Heats	V_w	0.3683
Variance between Heats	V_b	1.164
Standard Error of Estimate	SEE	0.6068

Properties provided are for T in °F, stress in ksi, and t_R in hours

Temperature, °F	**$S_{C,avg}$ (ksi)**
850	38.88
900	32.7
950	27.37
1000	22.8
1050	18.91
1100	15.61
1150	12.81
1200	10.47
1250	8.51
1300	6.882

** E²G's proprietary *Lot-Centered Analysis* web-based software tool only provides results up to 1300°F, but it should be noted that Type 304H allowable stress properties are observed above 1300°F.

Figure 16-1: 304H Modulus (E_y), Thermal Conductivity (k), Thermal Diffusivity (TD), & Thermal Expansion (α) With Temperature

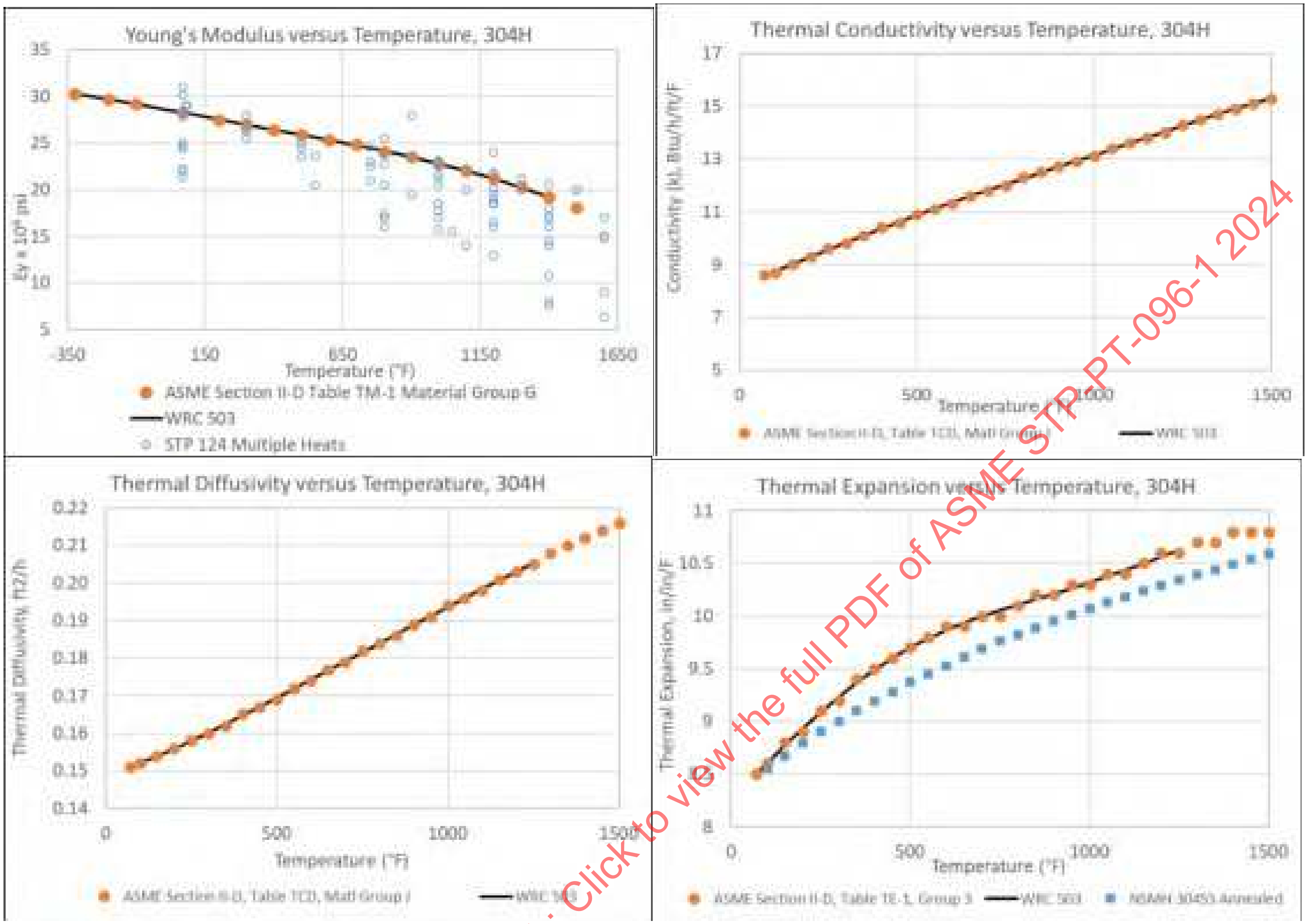


Figure 16-2: 304H Yield Strength Vs. Temperature, By Data Source, Including Trend Curves

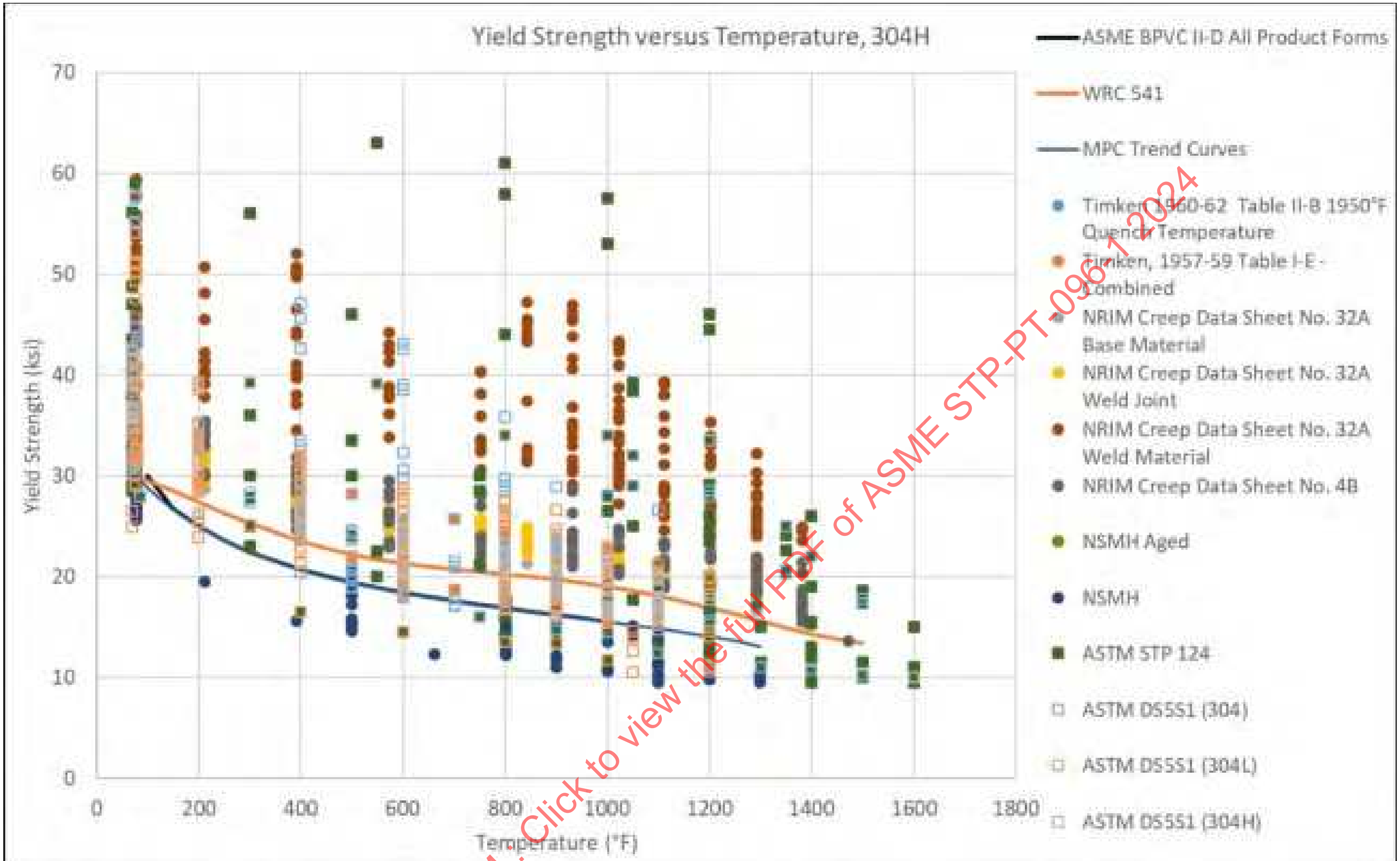


Figure 16-3: 304H Tensile Strength Vs. Temperature, By Data Source, Including Trend Curves

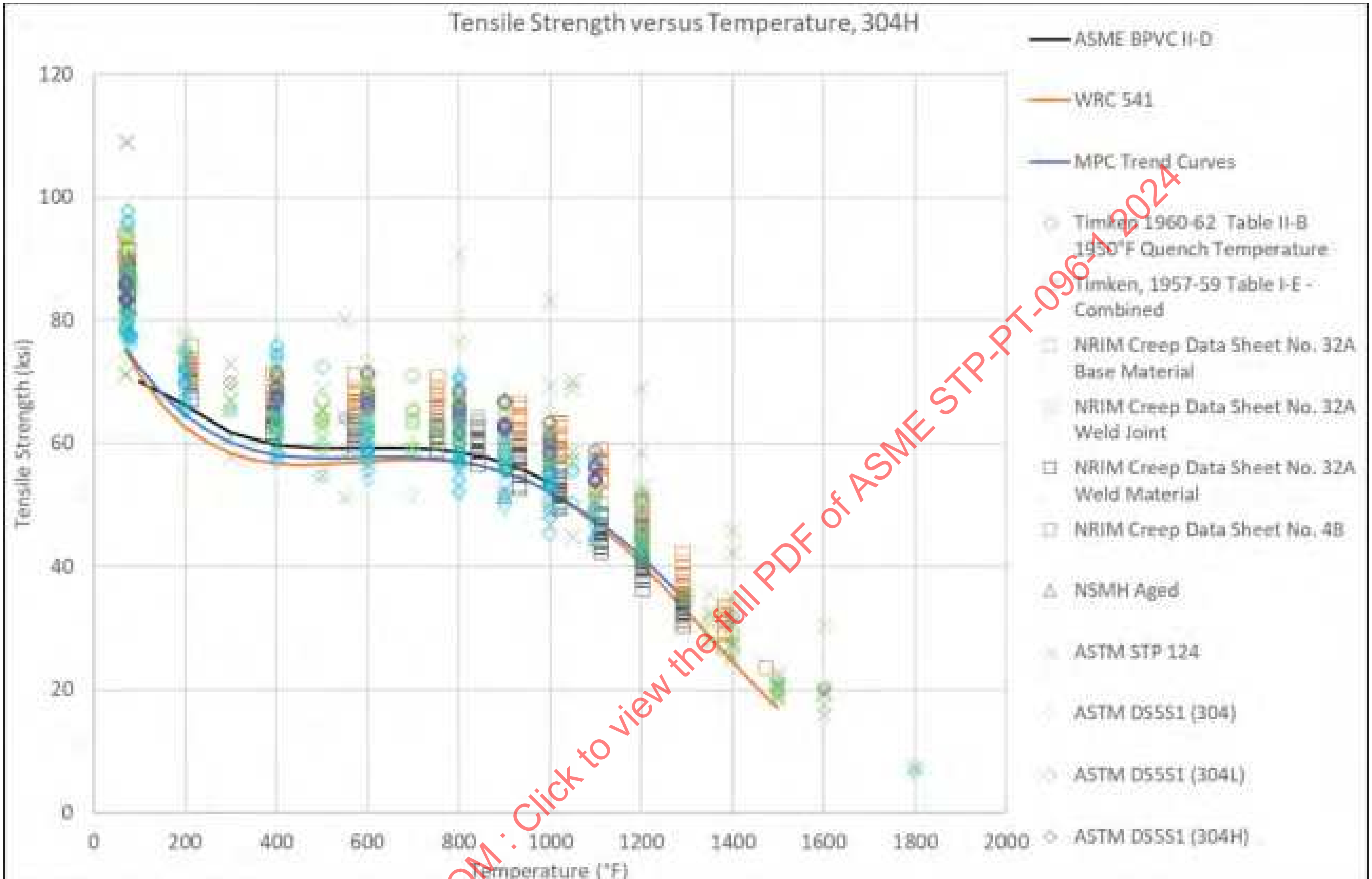


Figure 16-4: 304H Yield Strength Ratios Vs. Temperature (Calculated on a Heat-By-Heat Basis, By Data Source)

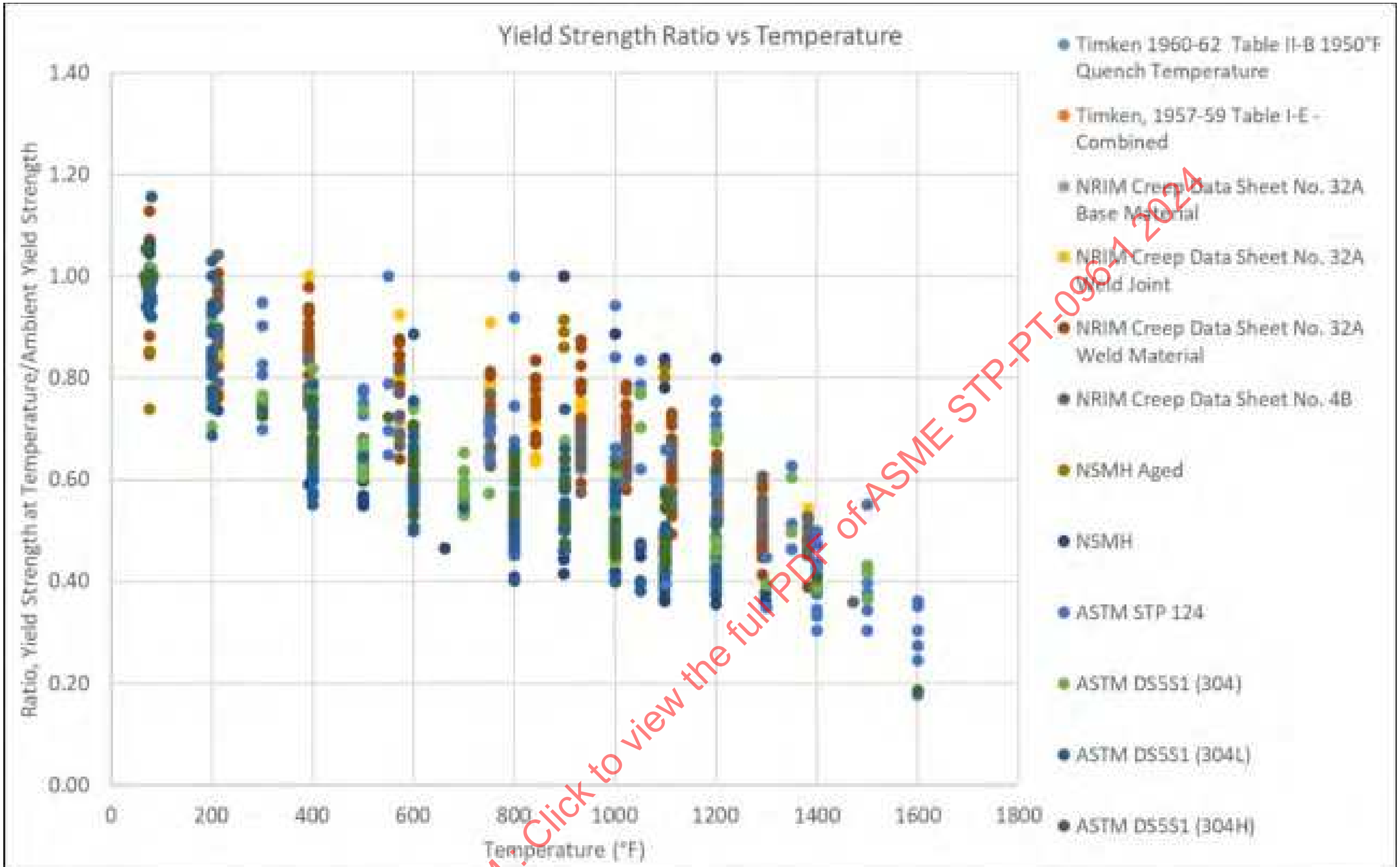


Figure 16-5: 304H Tensile Strength Ratios Vs. Temperature (Calculated on a Heat-By-Heat Basis, By Data Source)

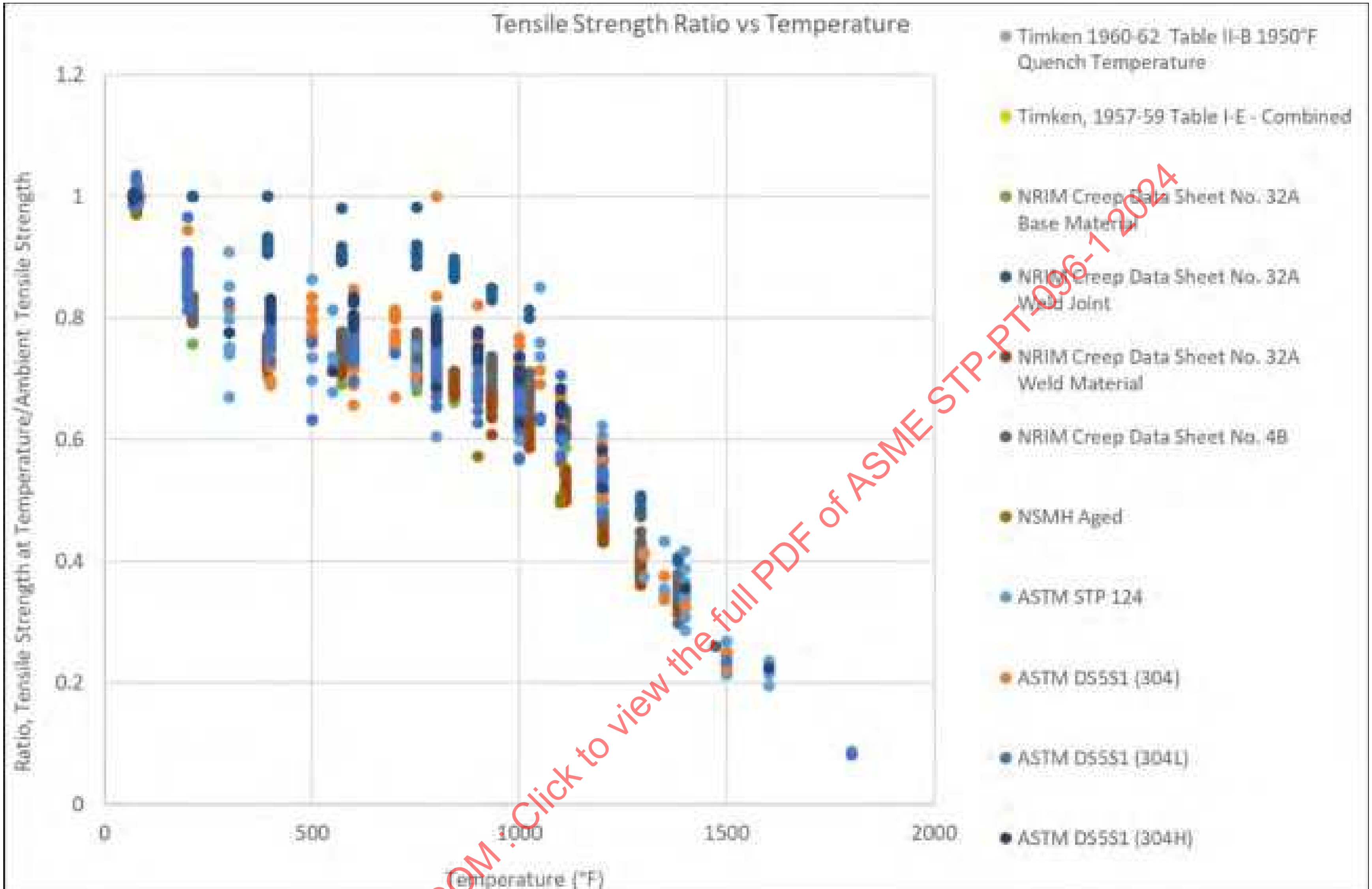


Figure 16-6: 304H Yield Strength Ratios Vs. Temperature, All Combined Data, With Polynomial Regression

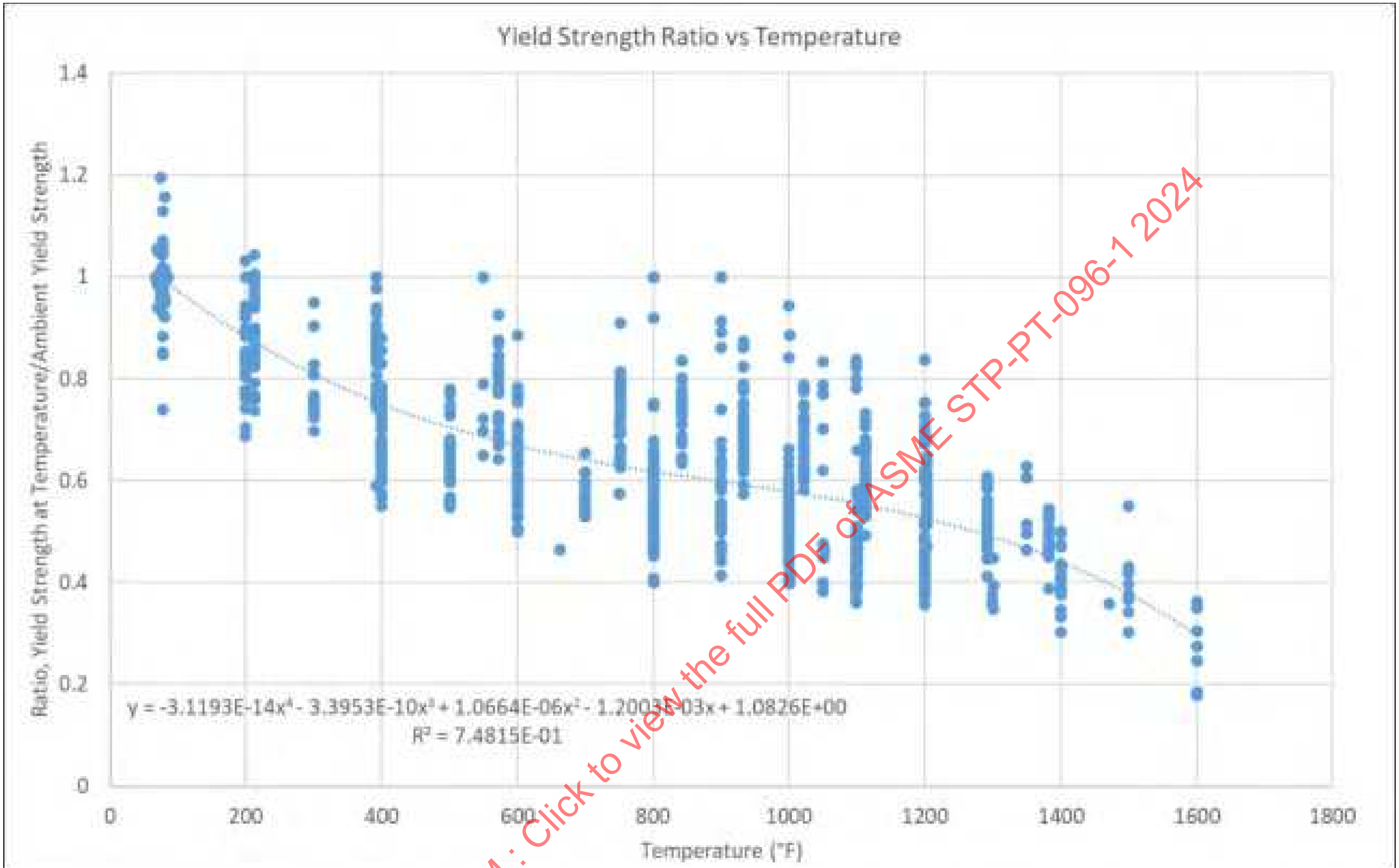


Figure 16-7: 304H Tensile Strength Ratios Vs. Temperature, All Combined Data, With Polynomial Regression

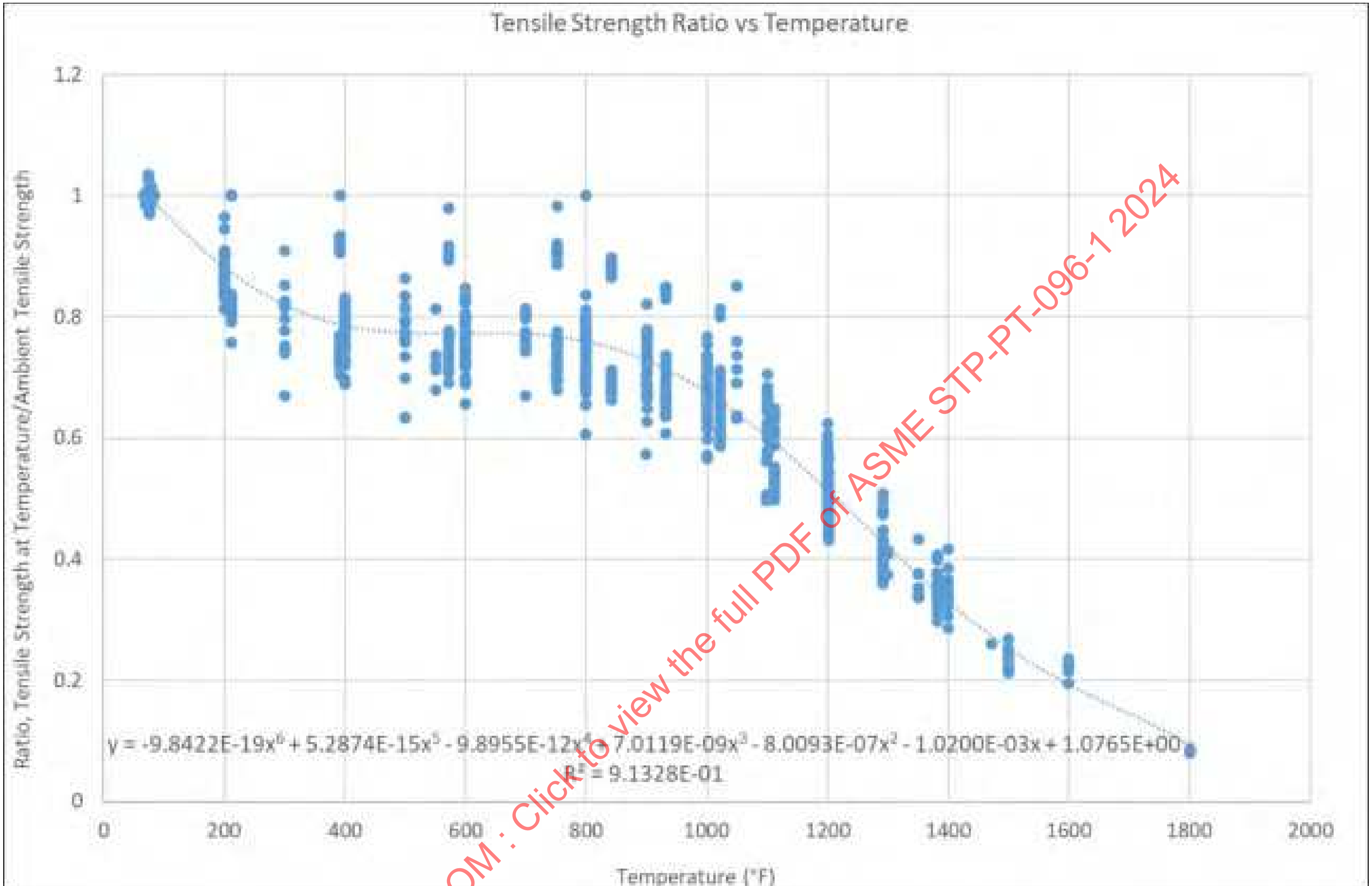


Figure 16-8: 304H Creep Rupture Isotherm Curves, Temperatures With High Concentration of Data Points

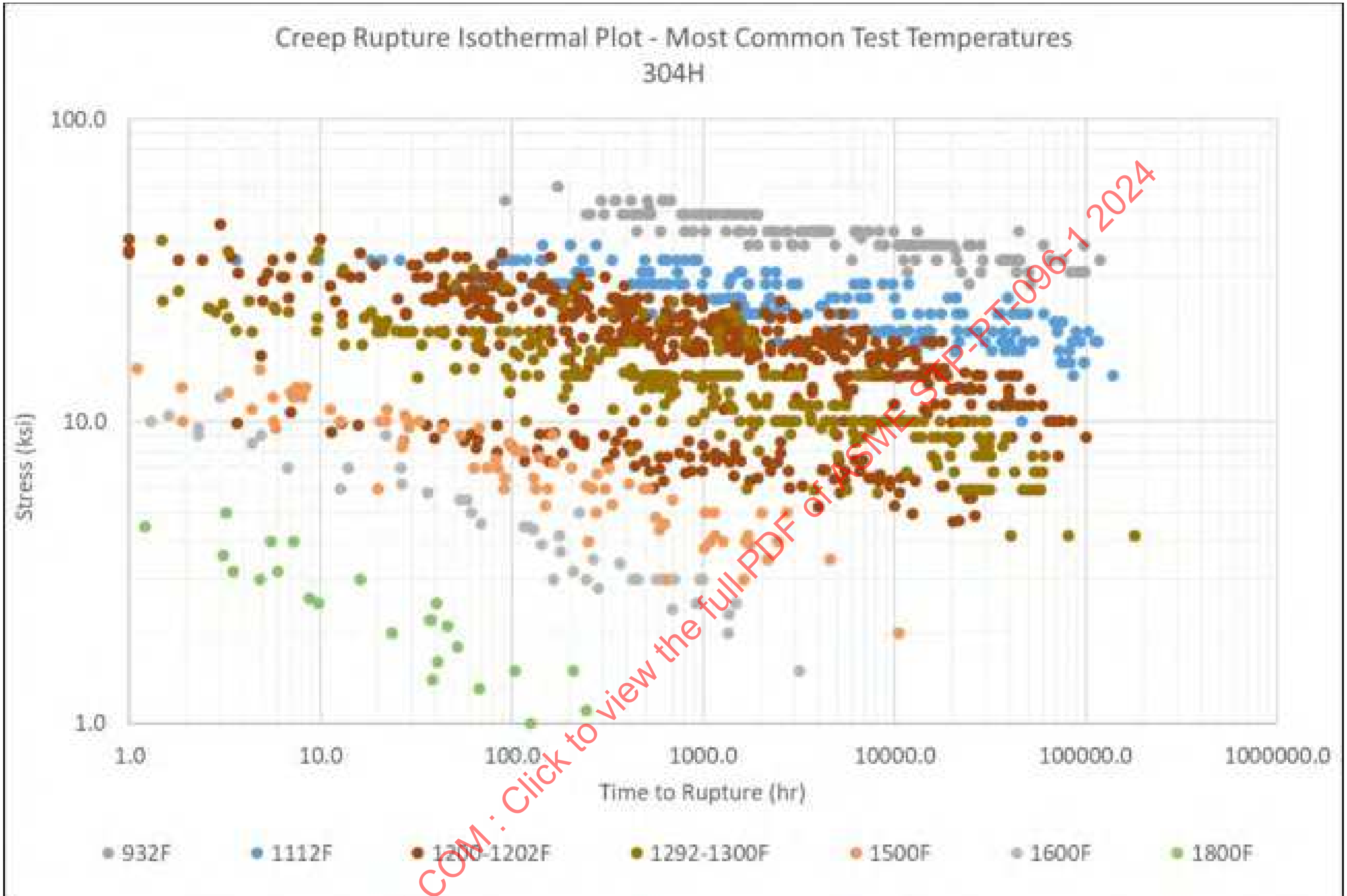


Figure 16-9: 304H Creep Rupture Isotherm Curves for Additional and Intermediate Temperatures

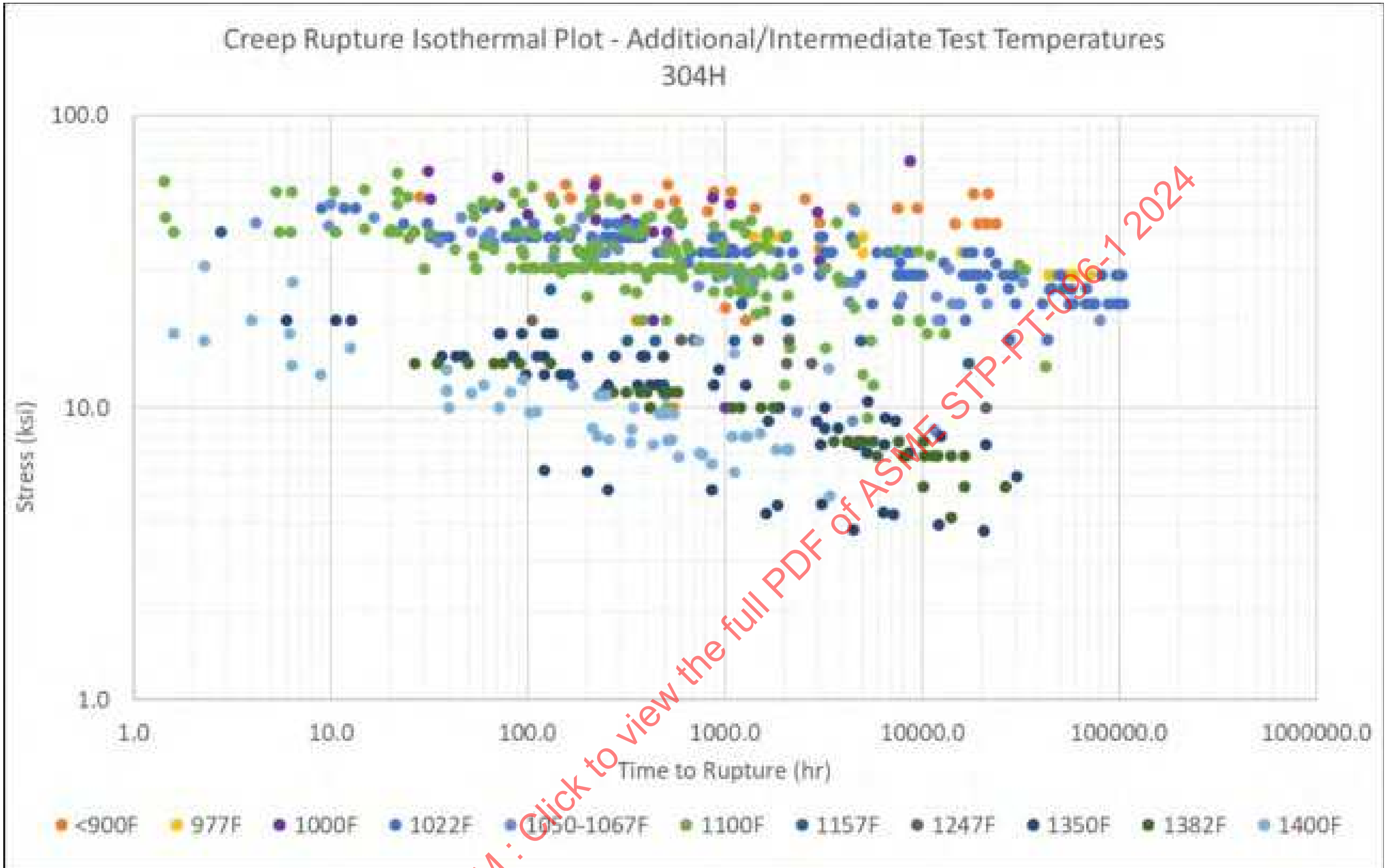


Figure 16-10: 304H Creep Strain Rate (MCR) Isotherm Curves, Temperatures with High Concentration of Data Points

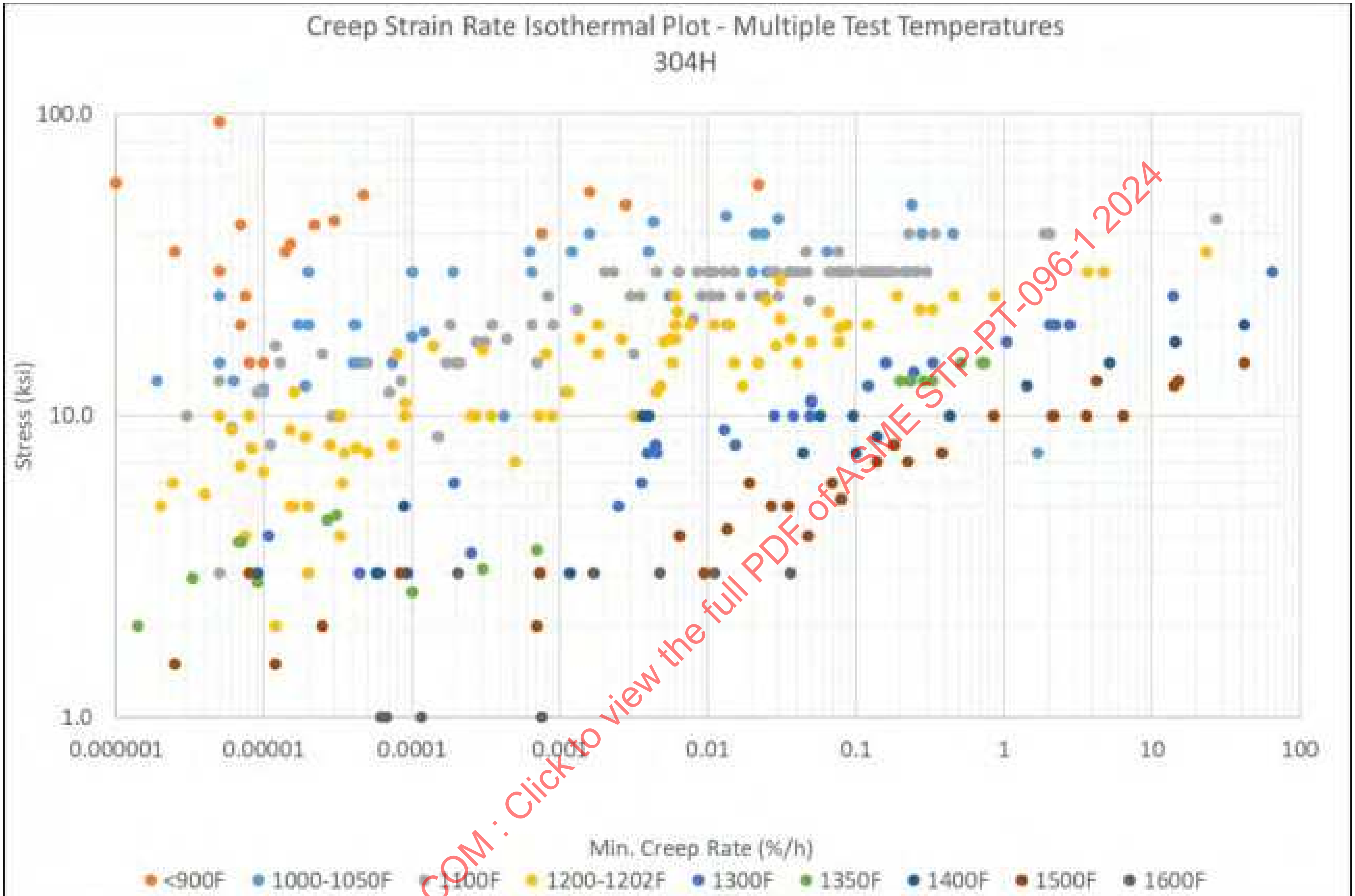


Figure 16-11: 304H Creep Ductility (% Elongation) Vs. Rupture Time Isotherms

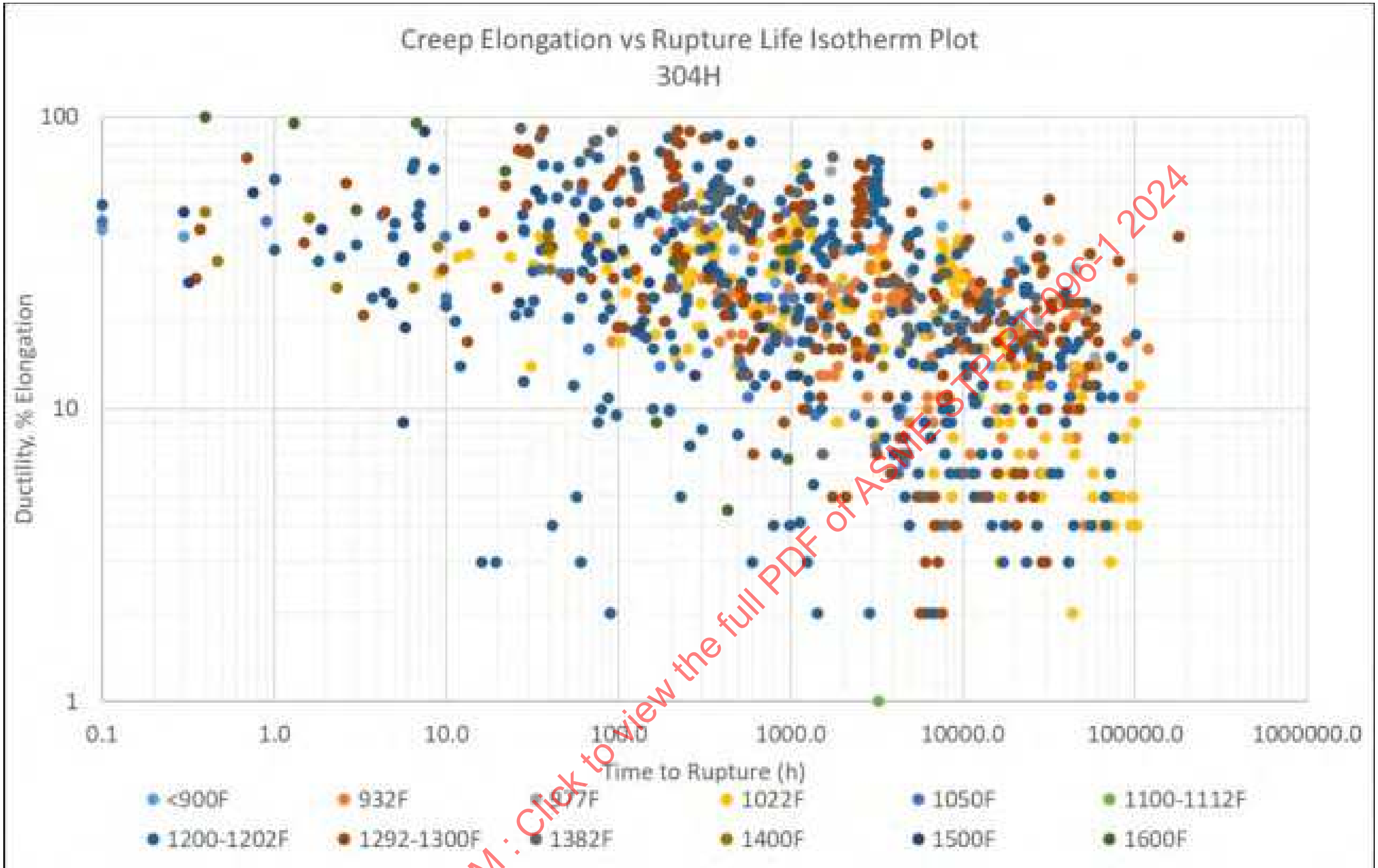


Figure 16-12: Calculated Allowable Stresses Based on Rupture and Creep Strain Rate and ASME II-D Appendix 1 Criteria (304H)

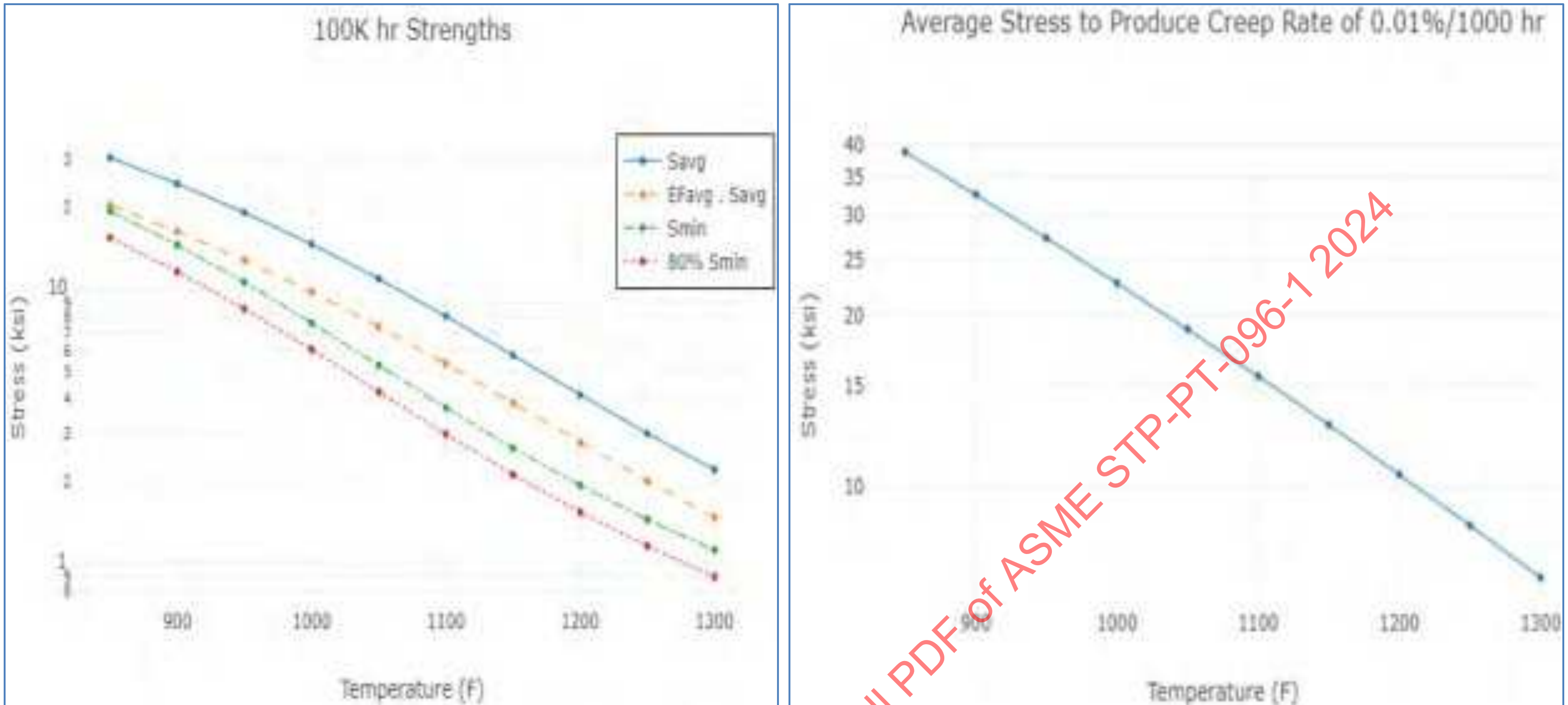


Figure 16-13: Comparison of Current 304H Allowable Stresses Vs. ASME II-D Appendix 1 Criteria Applied to Data; Note That These Curves Reflect Properties Regressed to Non-H Grades of 304 (I.E., Less Than 0.04 WT% Carbon)

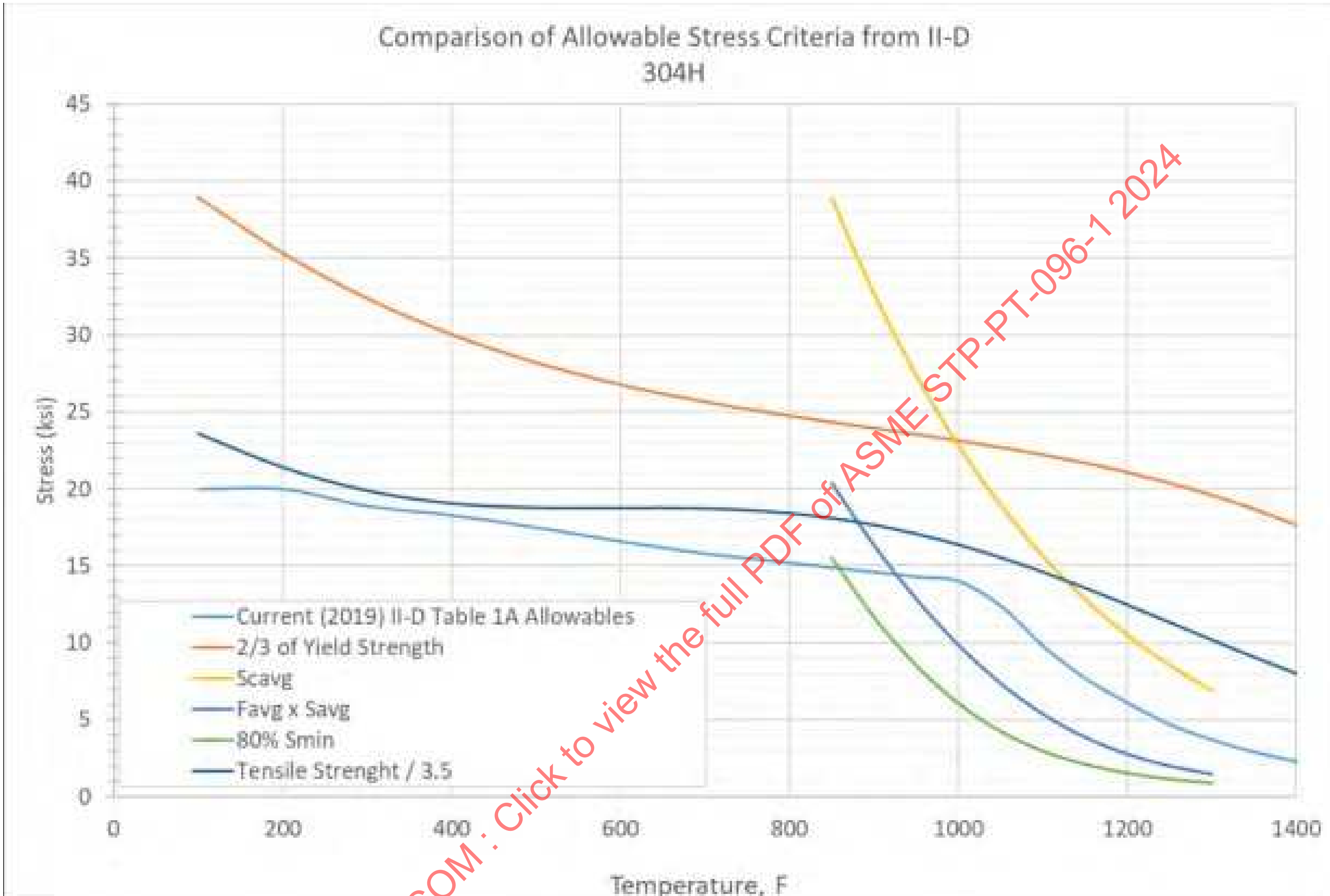


Figure 16-14: Strain Vs. Time Data at Multiple Temperatures From NRIM 4B (304H)

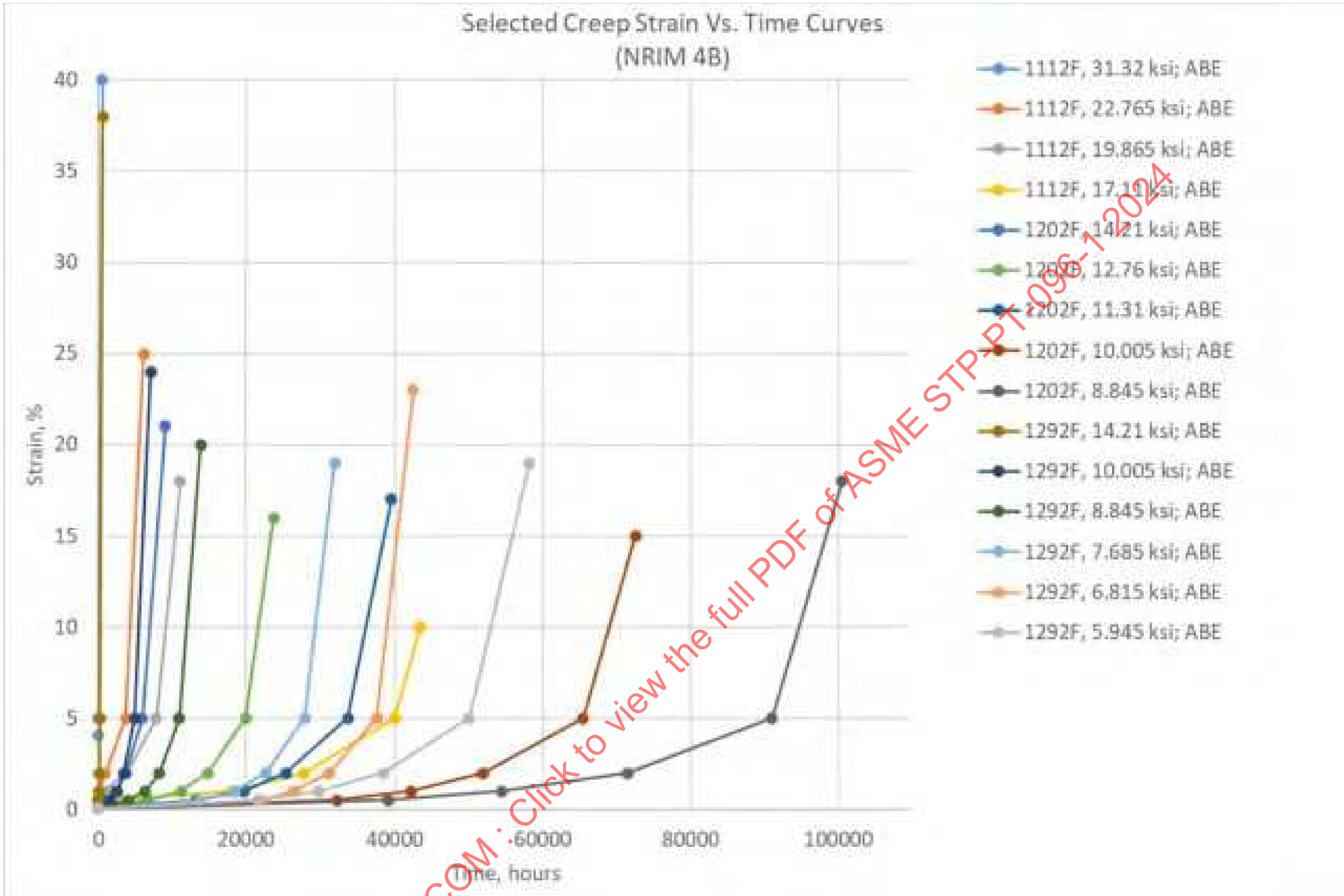


Figure 16-15: Strain Vs. Time Data at 1099°F From NSMH (304H)

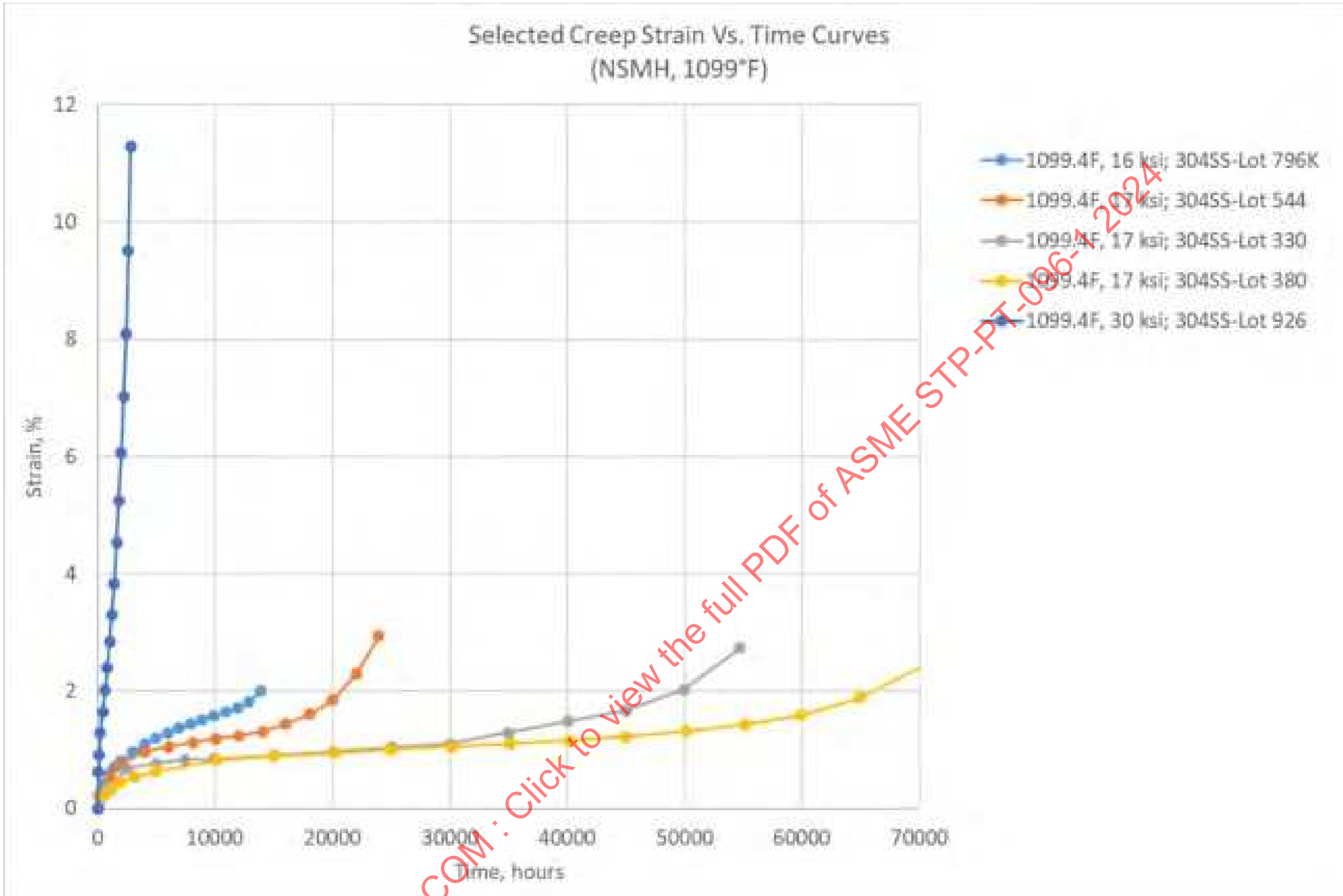


Figure 16-16: Continuous Cycling Fatigue (304H), Including Room Temperature and Elevated Temperature Data

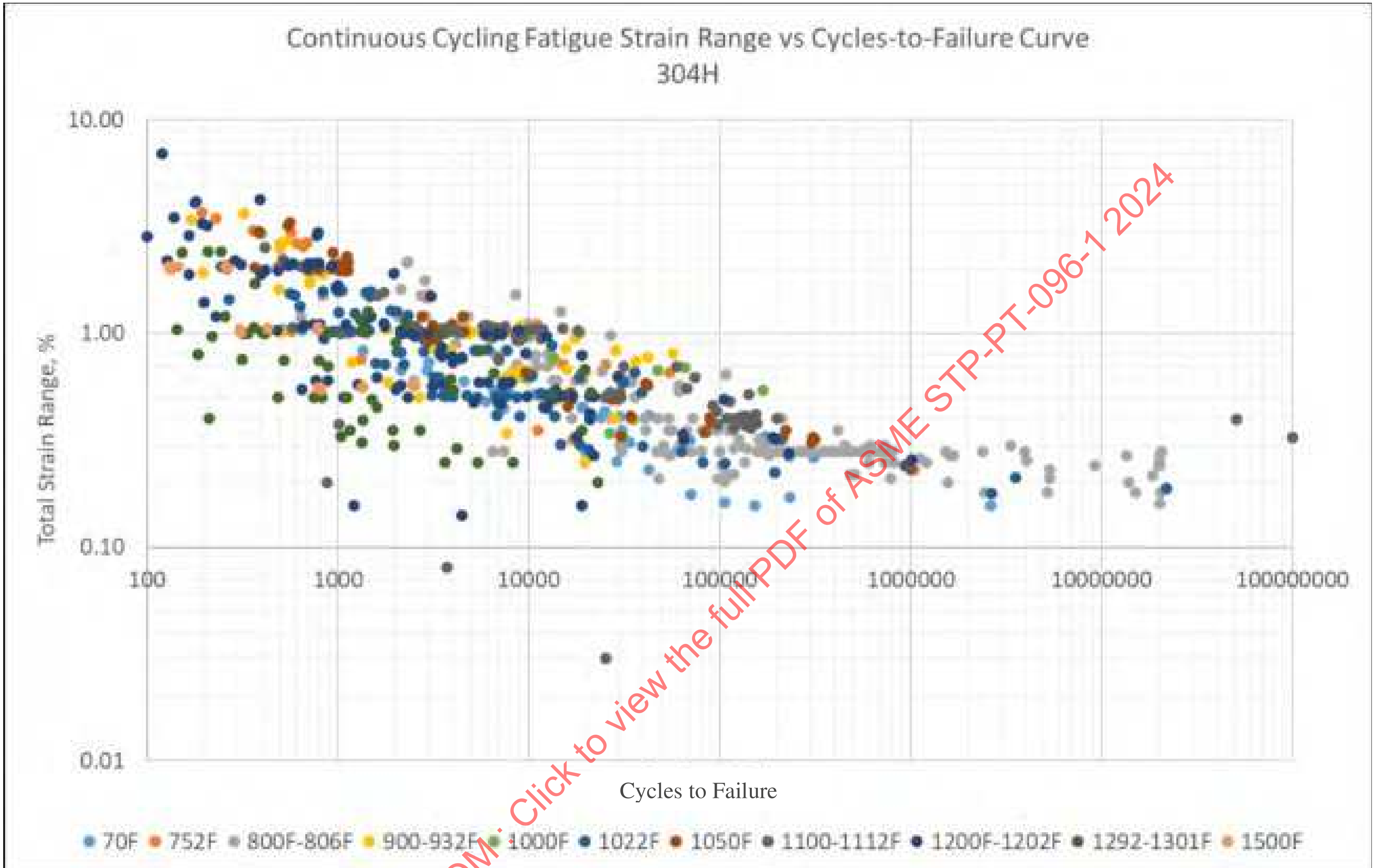


Figure 16-17: Hold Time Data (Creep Fatigue) for 304H, Temperature of 1022°F

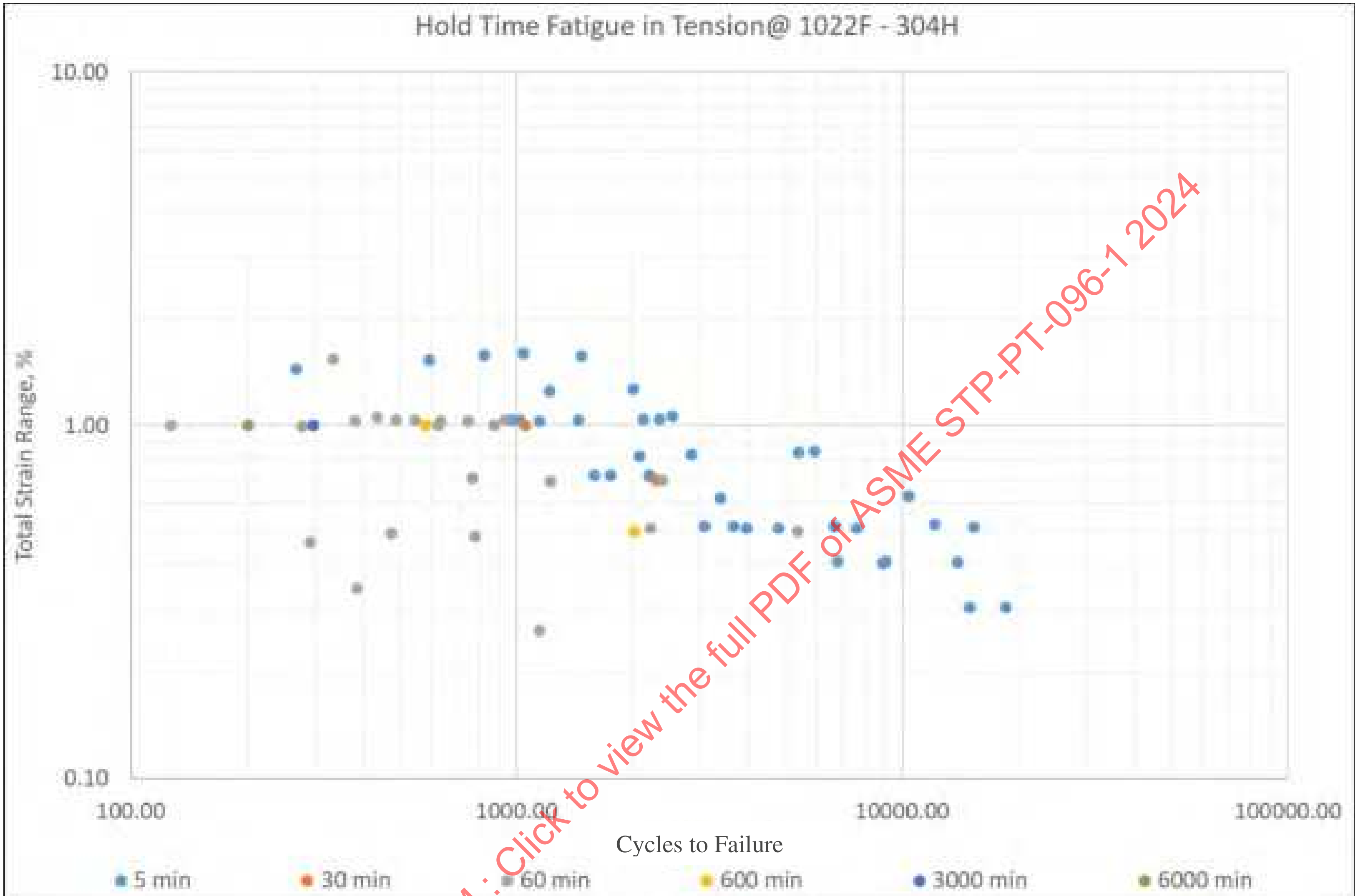


Figure 16-18: Hold Time Data (Creep Fatigue) for 304H, Temperature of 1100°F - 1112°F

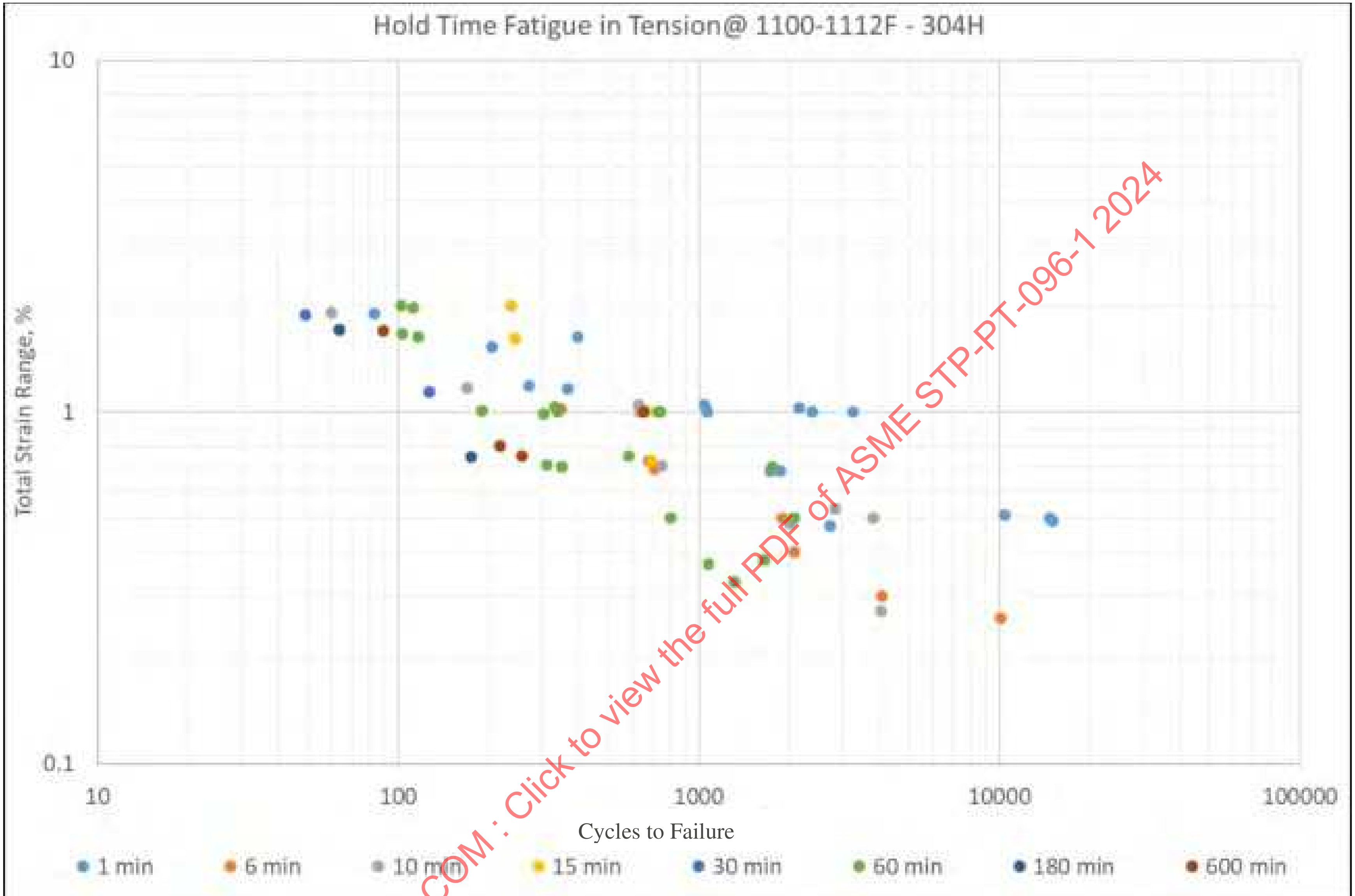
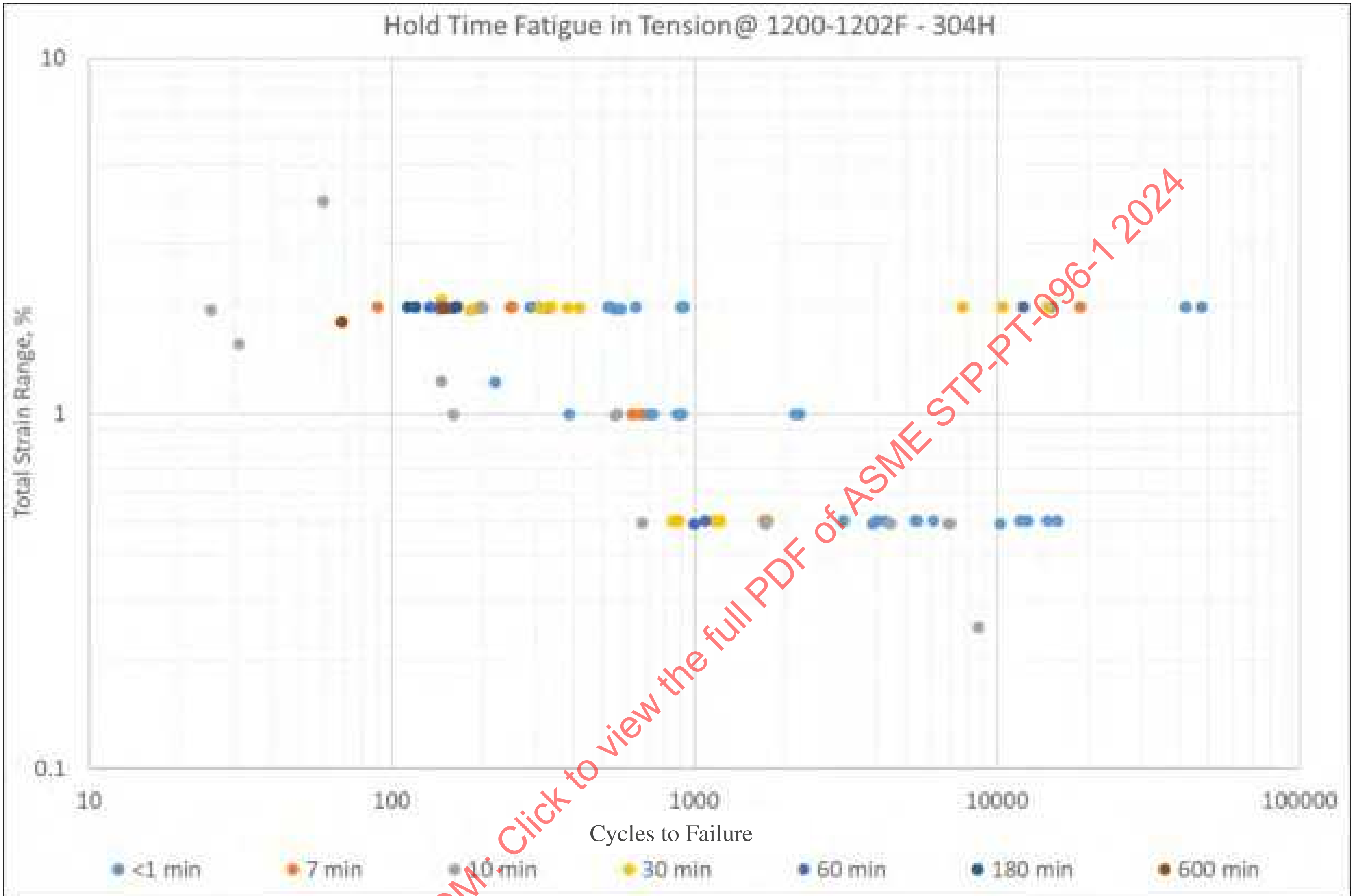


Figure 16-19: Hold Time Data (Creep Fatigue) for 304H, Temperature of 1200-1202°F



Attachment 16: 304H Property Data

If you want the referenced embedded spreadsheet with additional data, please email a request to research@asme.org.

17 TYPE 316H (AND 316) STAINLESS STEEL

17.1 Physical Properties

Well-established physical properties were referenced from the BPVC Section II for this material. Physical property curves from WRC Bulletin 503 were also plotted for comparison. Figure 17-1 shows the trends of Elastic Modulus (E_y), Thermal Conductivity (k), Thermal Diffusivity (TD), and Thermal Expansion (α) with temperature.

17.2 Yield and Tensile Strength

Elevated temperature Yield and Tensile Strength over the range of existing allowable stresses (up to 1500°F) were readily available, including data beyond the current range of allowable stresses, up to approximately 2300°F, as shown in Figures 17-2 and 17-3. The sources for both high-temperature yield and high-temperature tensile strength are provided in the embedded spreadsheet at the end of this section. This spreadsheet also contains ductility data corresponding to the tensile test results presented in this report. Note that ductility (percent elongation and percent reduction in area) was not available for all sources referenced for the Grade 91 material.

To facilitate comparison of the data obtained to existing allowable stresses (Section II-D Table 1A), yield and tensile data were normalized on a heat-by-heat basis to express the ratio of yield or tensile strength at temperature to that measured for the heat at room temperature. In cases where data were not delineated by heats within a given source, or in cases where more than one room-temperature tensile test existed for a given heat of material, ratios are equal to the measured tensile or yield strength at temperature, divided by the average of all of the appropriate room-temperature values for the particular data source or heat of material. As a result of this approach, it is possible to have ratios in excess of 1.0. E^2G understands that this approach is similar to the normalizing procedure performed by ASME in typical analysis of yield and tensile data to obtain Table Y and Table U (Section II-D) trend curves, as well as for the calculation of allowable stresses. Figures 17-4 and 17-5 show the heat-by-heat variation in yield and tensile strength ratios (respectively) as a function of temperature. It should be emphasized that even though the figure legends reference an entire source of data, the ratios, wherever possible, were calculated on a heat-by-heat basis; this is evident in the embedded spreadsheet at the end of this section. Figures 17-6 and 17-7 contain all of the yield and tensile (respectively) ratios plotted together, to facilitate regression of a 5th-order polynomial that is subsequently used for allowable stress comparison.

17.3 Creep Data (Creep Rupture, Minimum Creep Rate, and Ductility)

Creep Rupture data is shown in Figures 17-8 and 17-9, plotted as isotherms. The temperatures have been separated onto separate plots to minimize data overlap, with Figure 17-8 showing those temperatures where most of the data were concentrated, and Figure 17-9 showing those temperatures with significantly less data. It should be emphasized that these plots contain data for all product forms of material classified in the referenced publications as "316 or 316H." This certainly includes material meeting the requirements of ASME BPVC Section II-A specifications (e.g., SA-213 TP316H, SA-182 F316H, SA-249 TP316H, etc.). However, due to the diversity of data sources utilized for the compilation of the material property tables, it is likely that some of the material shown in Figures 17-8 and 17-9 may not meet existing specifications for this grade of material. Where older publications are referenced, the chemistry (and for that matter, manufacturing, processing, and heat treatment) corresponding to the heat of material in the original data source, may not be consistent with modern specifications. Where possible, E^2G has documented the chemical composition if contained within the original source. In many cases, the project team has also made efforts to trace cross-referenced data back to original test results to determine if the heat treatment, product form, chemistry, etc. details can be obtained. This information is provided with the embedded spreadsheet to facilitate additional analysis on the part of ASME.

Creep Minimum strain rates (%/hour) are shown in Figures 17-10 and 17-11, separated by temperature. As in the case of rupture data, temperatures of minimum creep rates have been separated onto separate plots to minimize data overlap, with Figure 17-10 showing those temperatures where most of the data were concentrated, and Figure 17-11 showing those temperatures with significantly less data. Creep Ductility, as % elongation, is plotted in Figure 17-12. As is typical, the data show significant overlap, and it is difficult to observe clear trends in the data. The data is not intended to be used as plotted but is available in the spreadsheet for additional analysis.

Creep data were analyzed using E^{2}G's proprietary Lot-Centered Analysis web-based software tool, in order to obtain creep properties. This regression is based on a Mandel-Paule algorithm and considers the variation within individual heats of material (for both rupture and strain rate data) as well as the variation between heats. The weight assigned to each datapoint and each heat is scaled based on the relative variation. Both rupture and strain rate (minimum creep rate, expressed as true strain per hours) were regressed according to a Larson-Miller time-temperature-parameter model, with a 3rd-order polynomial of stress. Lot-specific constant behavior was accounted for in this analysis, but the variation of LMP with stress was assumed to be constant (no non-parallel terms were included in the analysis). A 95% predictive limit was utilized to obtain the lower-bound (minimum LM constant for both rupture and strain rate) properties. The results of this analysis are summarized in Table 17-1 for rupture data and Table 17-2 for strain rate data. The Lot-Centered Analysis software tool generates property tables in the creep regime using the criteria outlined in Mandatory Appendix 1 of ASME Section II-D; the nomenclature of variables is consistent with II-D Appendix 1. For visualization of the allowable stress trends, Figure 17-13 is provided (for rupture allowable stresses and creep rate allowable stresses). Figure 17-14 shows a comparison of the various allowable stress criteria from Section II-D, Appendix 1, to the existing (2019) Section II-D Table 1A allowable stresses for all product forms of 316H.

Creep Strain vs. time data are shown in Figure 17-15 for short-term data (up to 2,500 hour test durations); Figure 17-16 for 2,500 to 19,000 hour test durations; and Figure 17-17 for excess of 19,000 hour test durations. Curves are only plotted where more than 10 strain vs. time points are present for the test. Additional curves are available with fewer datapoints (typically obtained from data in the form of time-until-specified-strain) in the embedded spreadsheet. Both creep rate and creep strain vs. time data are provided to satisfy ASME's request for creep strain vs. time curves, and both forms of data are applicable in developing allowable stresses. Although digitalization of creep curve data was not explicitly necessary per the project contract, E^{2}G did perform digitalization of creep curves where only graphical data was available (as is often the case in the published literature).

17.4 Continuous Cycling Fatigue and Hold Time Fatigue Curves

A portion of the data obtained for continuous cycling fatigue data at elevated temperatures for 316H is shown in Figure 17-18, includes a limited amount of room temperature data contained in sources which also present high-temperature data. Figure 17-18 only contains data for which total strain range was determined from the original source. Additional data points for continuous cycling fatigue data of 316H are presented in the attached spreadsheet; however, due to the complexities of various forms of fatigue data, compatible plots for each type of data expression and failure criteria are not included in this report. Hold time fatigue data at high temperature is shown in Figure 17-19 (1050°F), Figure 17-20 (1100°F), Figure 17-21 (1112°F), and Figure 17-22 (1200°F) with separate plots for temperatures at which at least a moderate collection of data points existed. Additional data is provided in the embedded spreadsheet.

Table 17-1: Model Parameters, Larson-Miller Property Results, and Allowable Stress (Rupture) Criteria, 316H

Equation Format:

$$\log(t_r) = C_{avg} + \frac{1}{T+460}\left(b_1 + b_2\log(\sigma) + b_3(\log(\sigma))^2 + b_4(\log(\sigma))^3\right)$$

C_{avg}	**14.79**
C_{min}	**15.5**
b_1	**39470**
b_2	**-6862**
b_3	**816.4**
b_4	**-958.8**

Number Data Points		**3014**
Correlation Coefficient	R^2	0.7652
Average Variance within Heats	V_w	0.1879
Variance between Heats	V_b	0.2353
Standard Error of Estimate	SEE	0.4335

Properties provided are for T in °F, stress in ksi, and t_R in hours

Temperature, °F	**S_{avg} (ksi)**	***n***	**F_{avg} (calc)**	**F_{avg} (used)**	**$F_{avg} \times S_{avg}$**	**S_{min} (ksi)**	**80% S_{min}**
850	45.92	9.232	0.7792	0.67	30.76	38.23	30.59
900	37.83	8.417	0.7607	0.67	25.35	30.94	24.75
950	30.83	7.665	0.7405	0.67	20.66	24.7	19.76
1000	24.81	6.972	0.7187	0.67	16.62	19.44	15.55
1050	19.7	6.336	0.6953	0.67	13.2	15.05	12.04
1100	15.41	5.756	0.6703	0.67	10.32	11.45	9.161
1150	11.86	5.233	0.6441	0.67	7.943	8.554	6.843
1200	8.969	4.769	0.6171	0.67	6.009	6.272	5.017
1250	6.668	4.368	0.5903	0.67	4.468	4.518	3.615
1300	4.876	4.034	0.5651	0.67	3.267	3.208	2.566

** E^2G's proprietary *Lot-Centered Analysis* web-based software tool only provides results up to 1300°F, but it should be noted that Type 316H allowable stress properties are observed above 1300°F.

Table 17-2: Model Parameters, Larson-Miller Property Results, and Allowable Stress (Strain Rate) Criteria, 316H

Equation Format:

$$\log(\dot{\varepsilon}_0) = -C_{avg} - \frac{1}{T+460}\left(a_1 + a_2\log(\sigma) + a_3(\log(\sigma))^2 + a_4(\log(\sigma))^3\right)$$

C_{avg} (A_0)	**13.14**
C_{min} ($A_0+\Delta_\Omega^{SR,LB}$)	**14.91**
a_1	**48200**
a_2	**-19951.9**
a_3	**4294.4**
a_4	**-308.1**

Number Data Points		**349**
Correlation Coefficient	R^2	0.569
Average Variance within Heats	V_w	1.149
Variance between Heats	V_b	0.4955
Standard Error of Estimate	SEE	1.072

Properties provided are for T in °F, stress in ksi, and t_R in hours

Temperature, °F	**$S_{C,avg}$ (ksi)**
850	77.15
900	58.07
950	44.7
1000	35.05
1050	27.92
1100	22.53
1150	18.39
1200	15.17
1250	12.62
1300	10.58

** E²G's proprietary *Lot-Centered Analysis* web-based software tool only provides results up to 1300°F, but it should be noted that Type 316H allowable stress properties are observed above 1300°F.

Figure 17-1: 316H Modulus (E_y), Thermal Conductivity (k), Thermal Diffusivity (TD), & Thermal Expansion (α) With Temperature

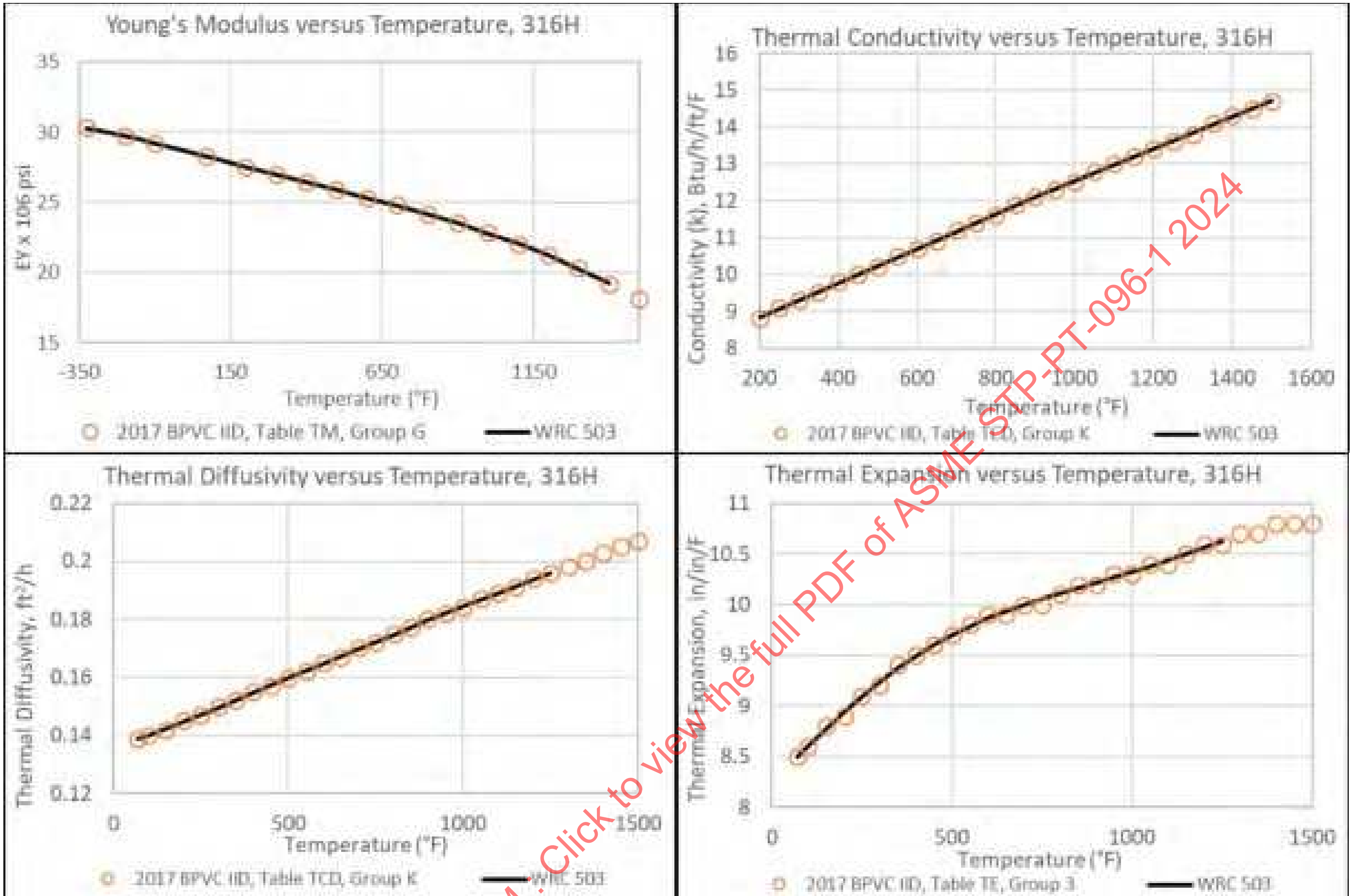


Figure 17-2: 316H Yield Strength Vs. Temperature, By Data Source, Including Trend Curves

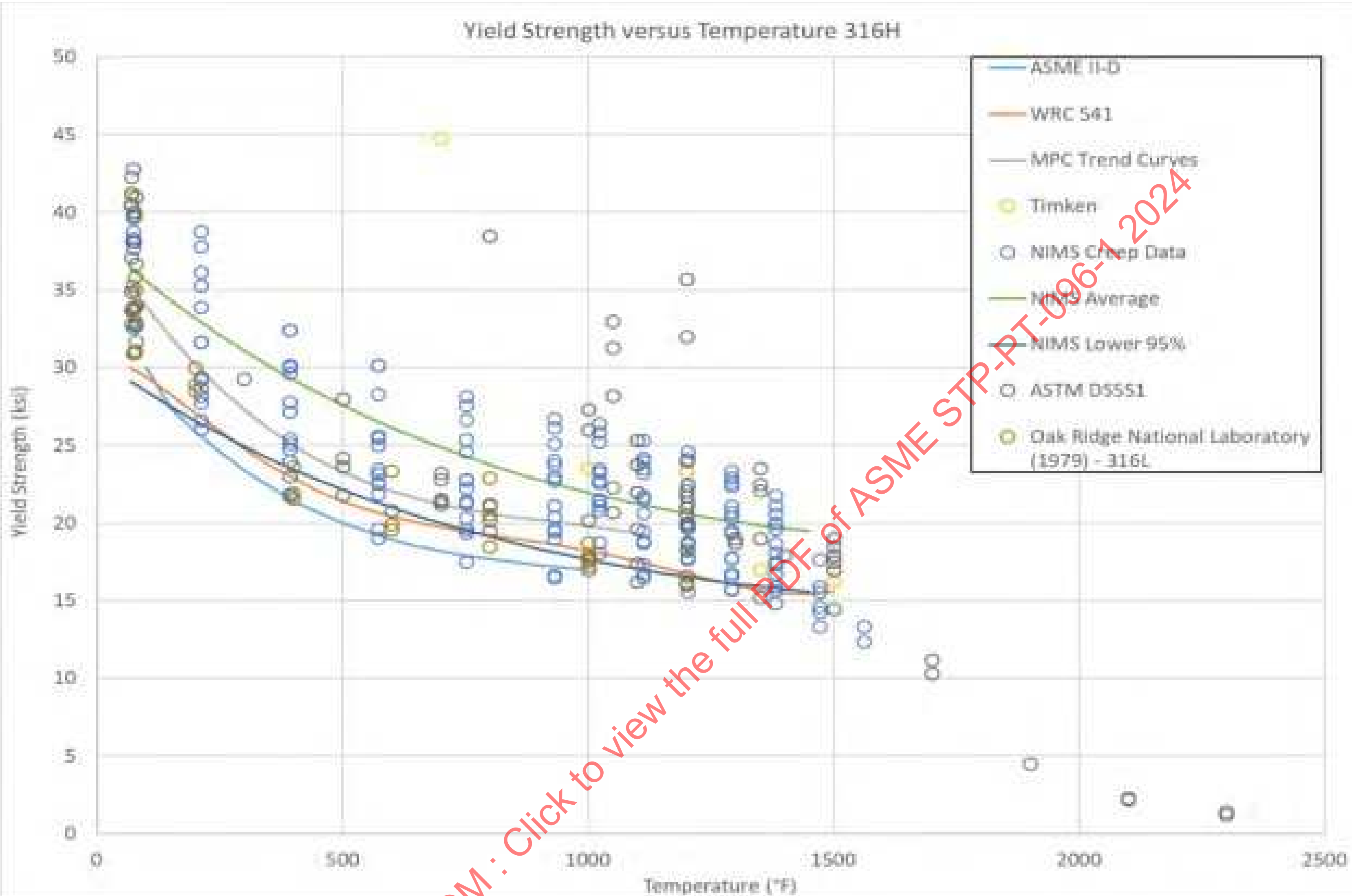


Figure 17-3: 316H Tensile Strength Vs. Temperature, By Data Source, Including Trend Curves

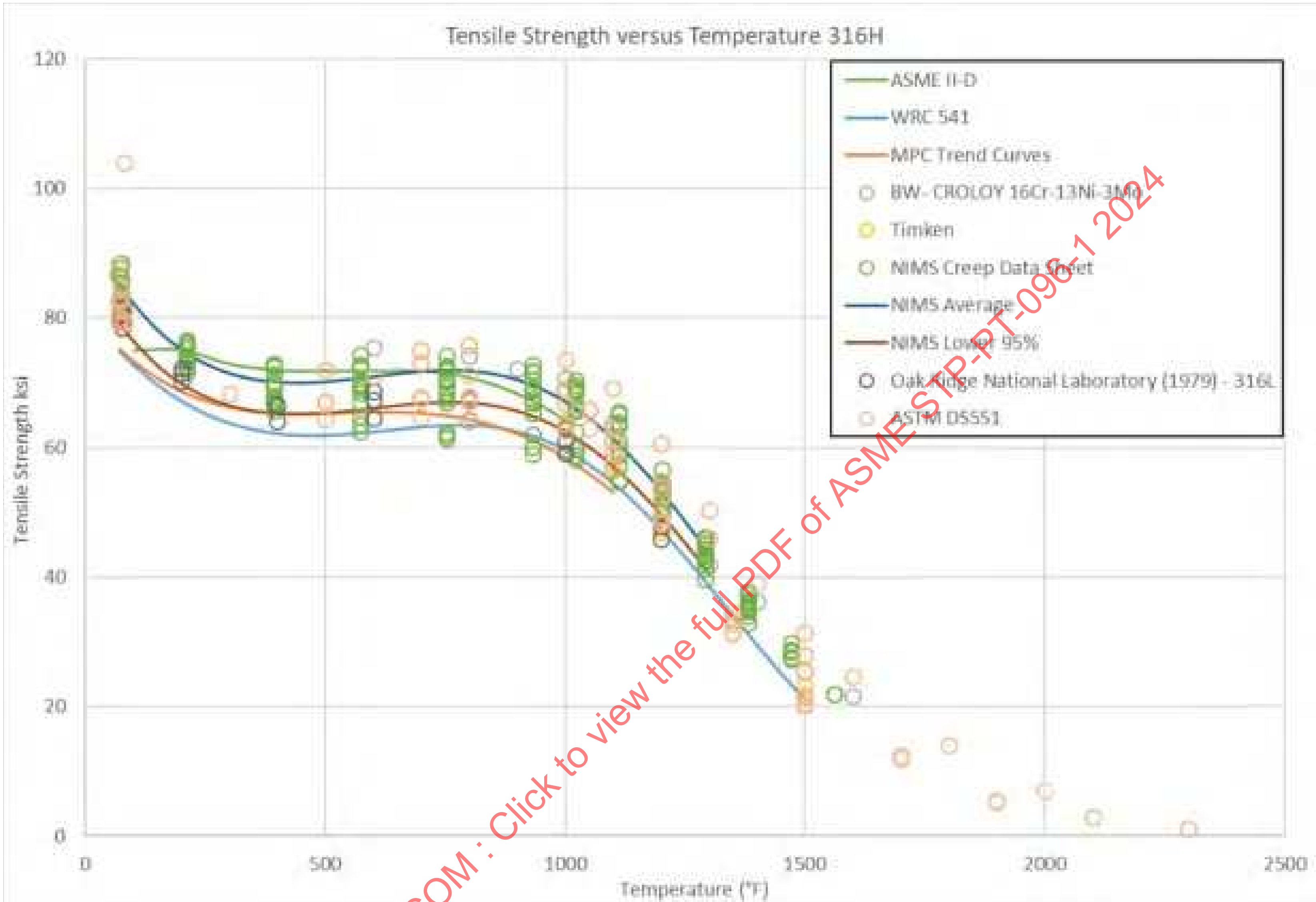


Figure 17-4: 316H Yield Strength Ratios Vs. Temperature (Calculated on a Heat-By-Heat Basis, By Data Source)

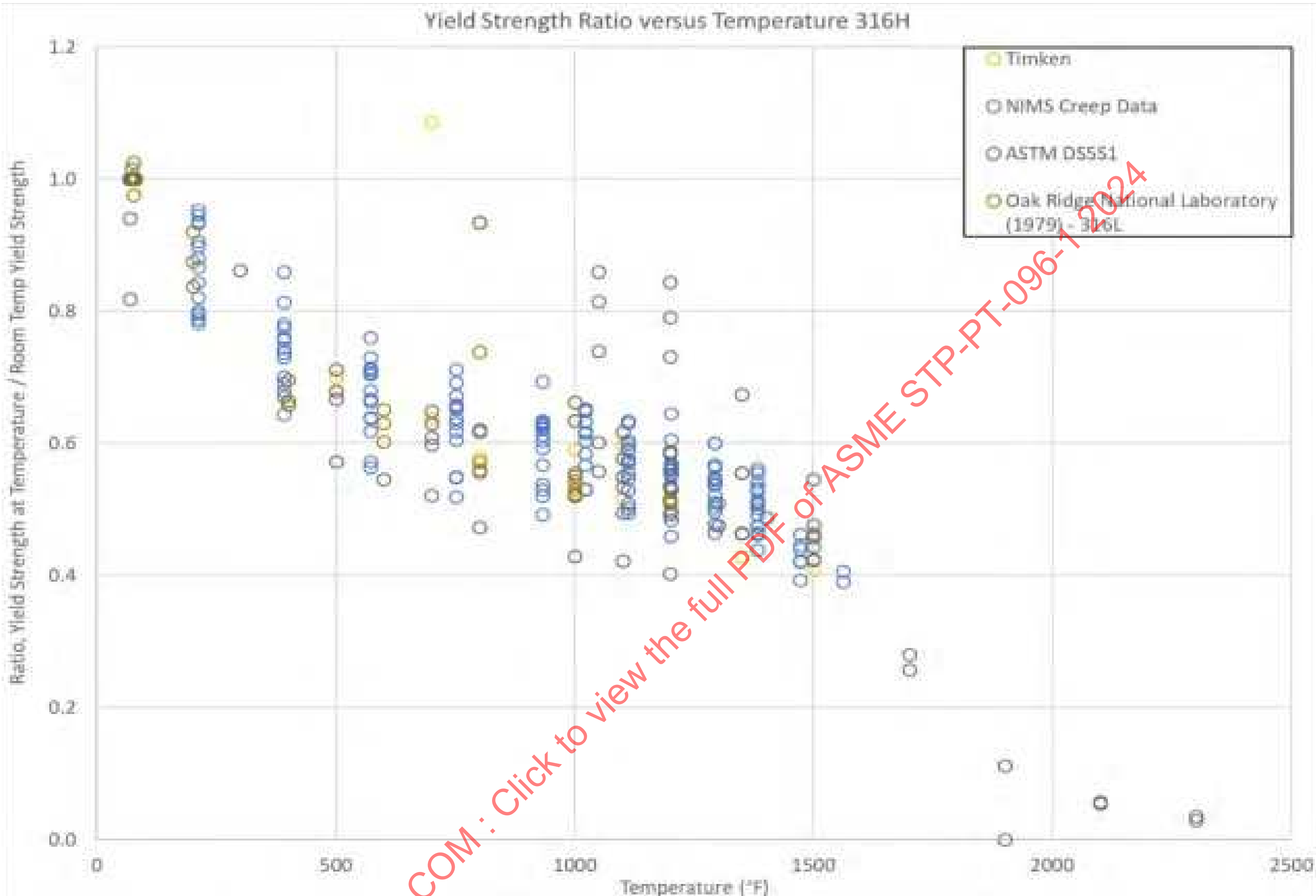


Figure 17-5: 316H Tensile Strength Ratios Vs. Temperature (Calculated on a Heat-By-Heat Basis, By Data Source)

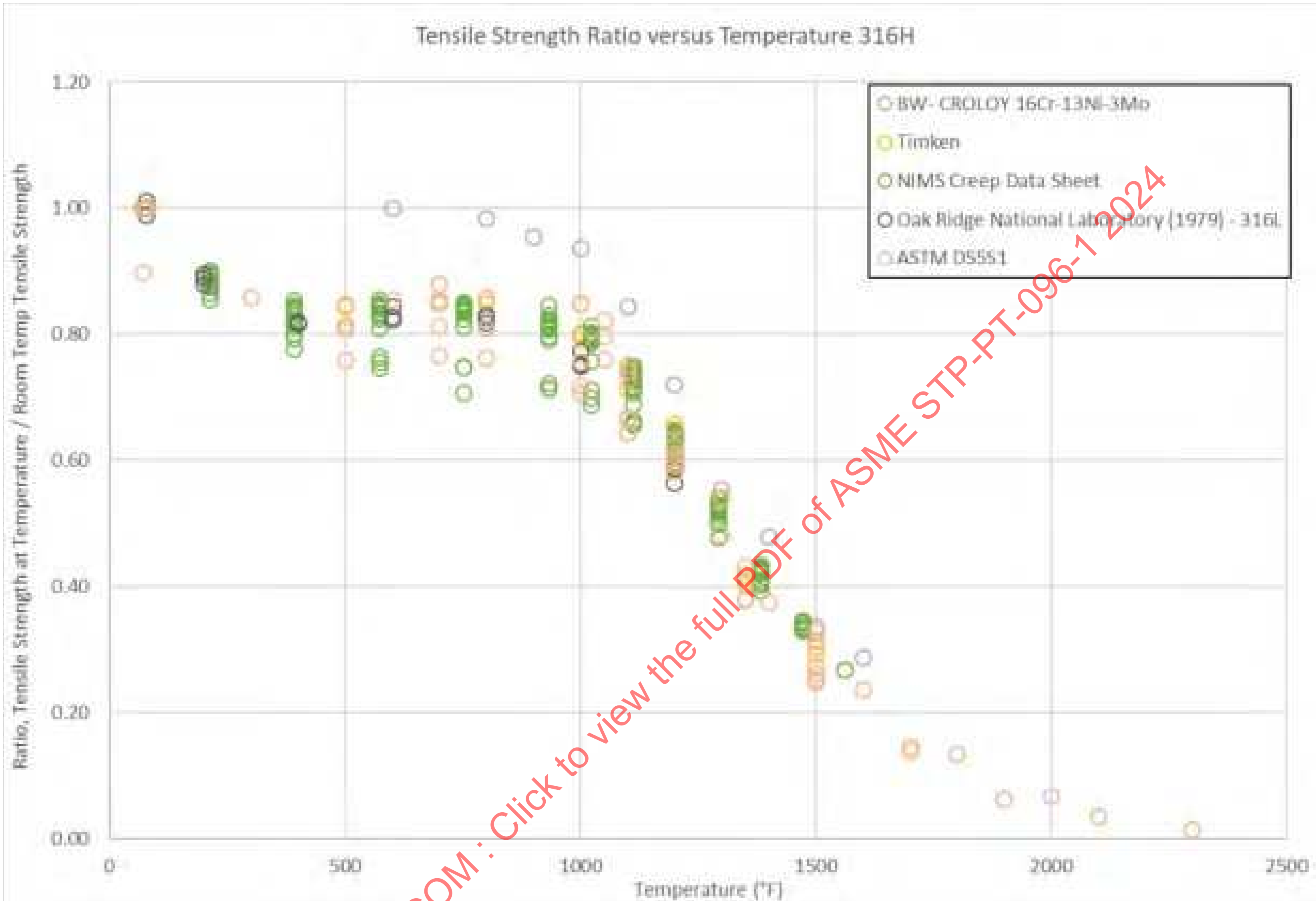


Figure 17-6: 316H Yield Strength Ratios Vs. Temperature, All Combined Data, With Polynomial Regression

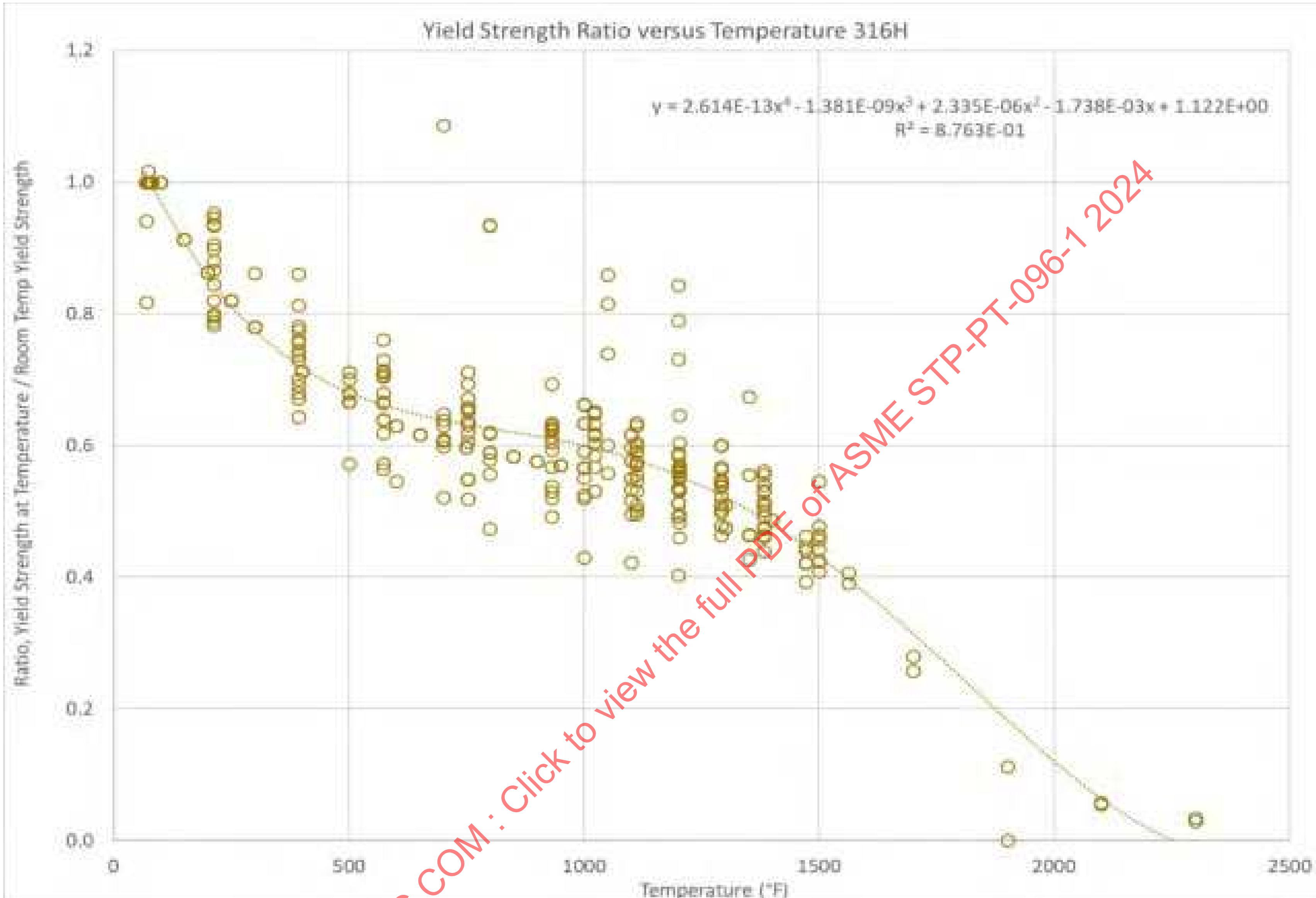


Figure 17-7: 316H Tensile Strength Ratios Vs. Temperature, All Combined Data, With Polynomial Regression

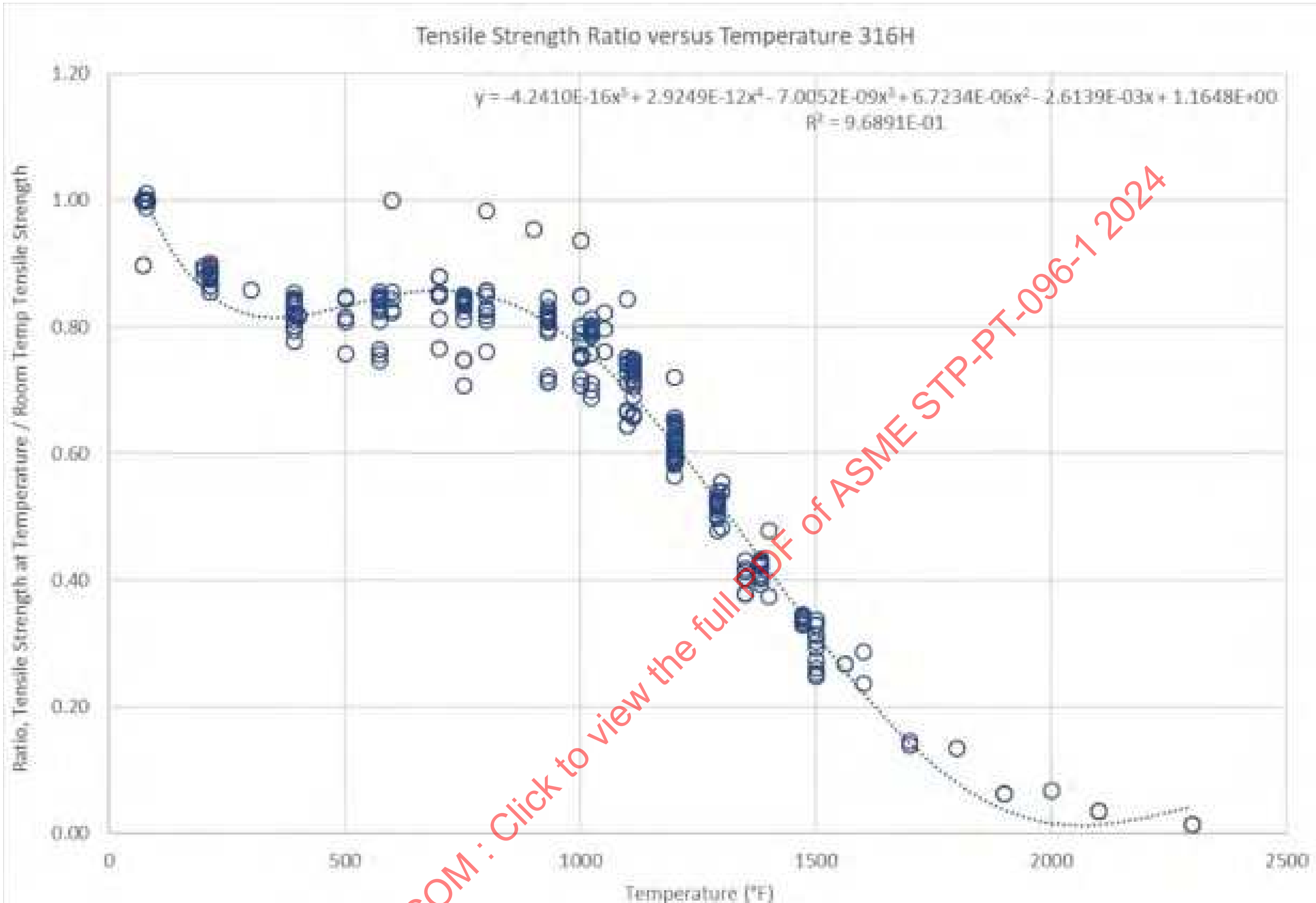


Figure 17-8: 316H Creep Rupture Isotherm Curves, Temperatures With High Concentration of Data Points

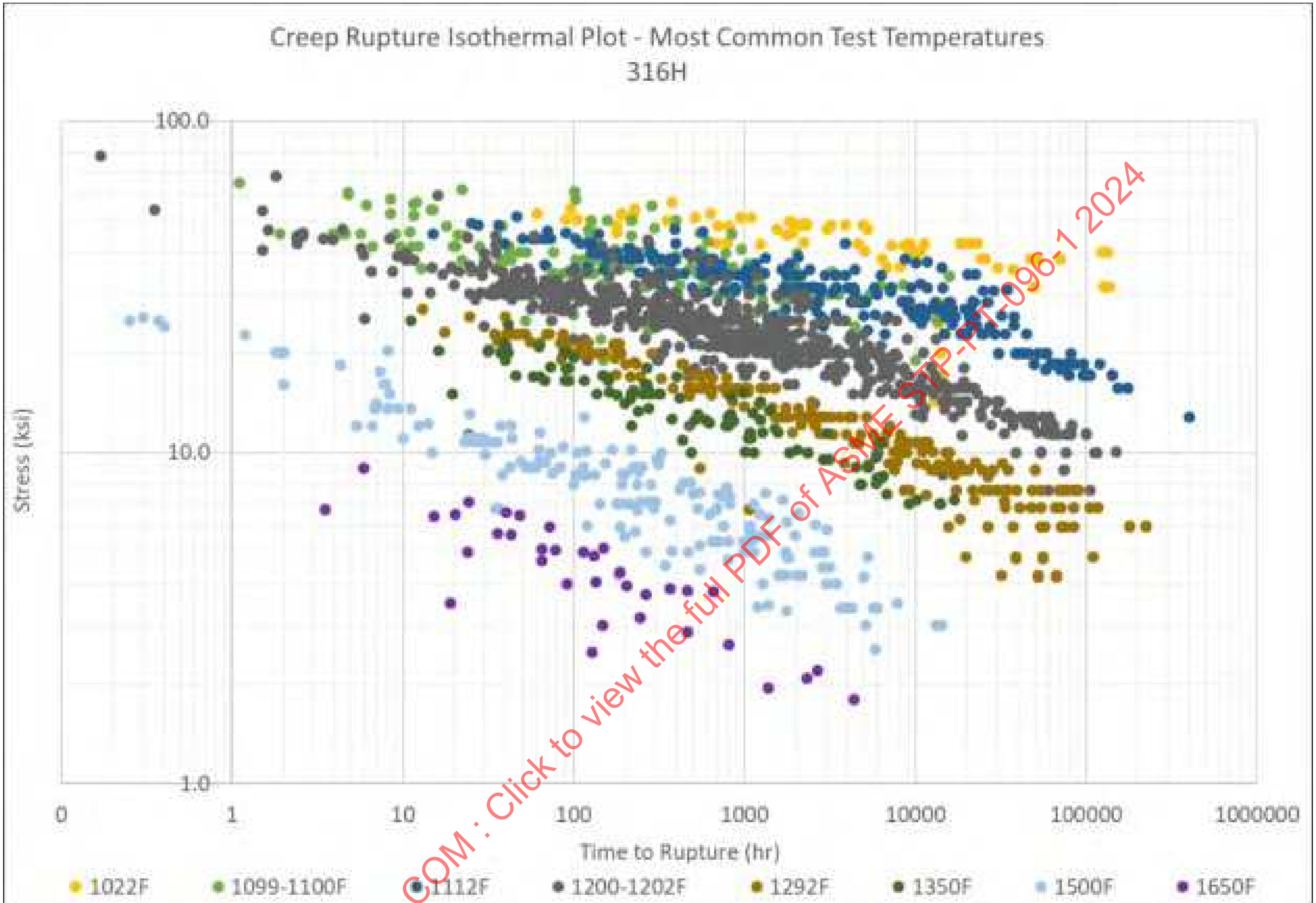


Figure 17-9: 316H Creep Rupture Isotherm Curves for Additional and Intermediate Temperatures

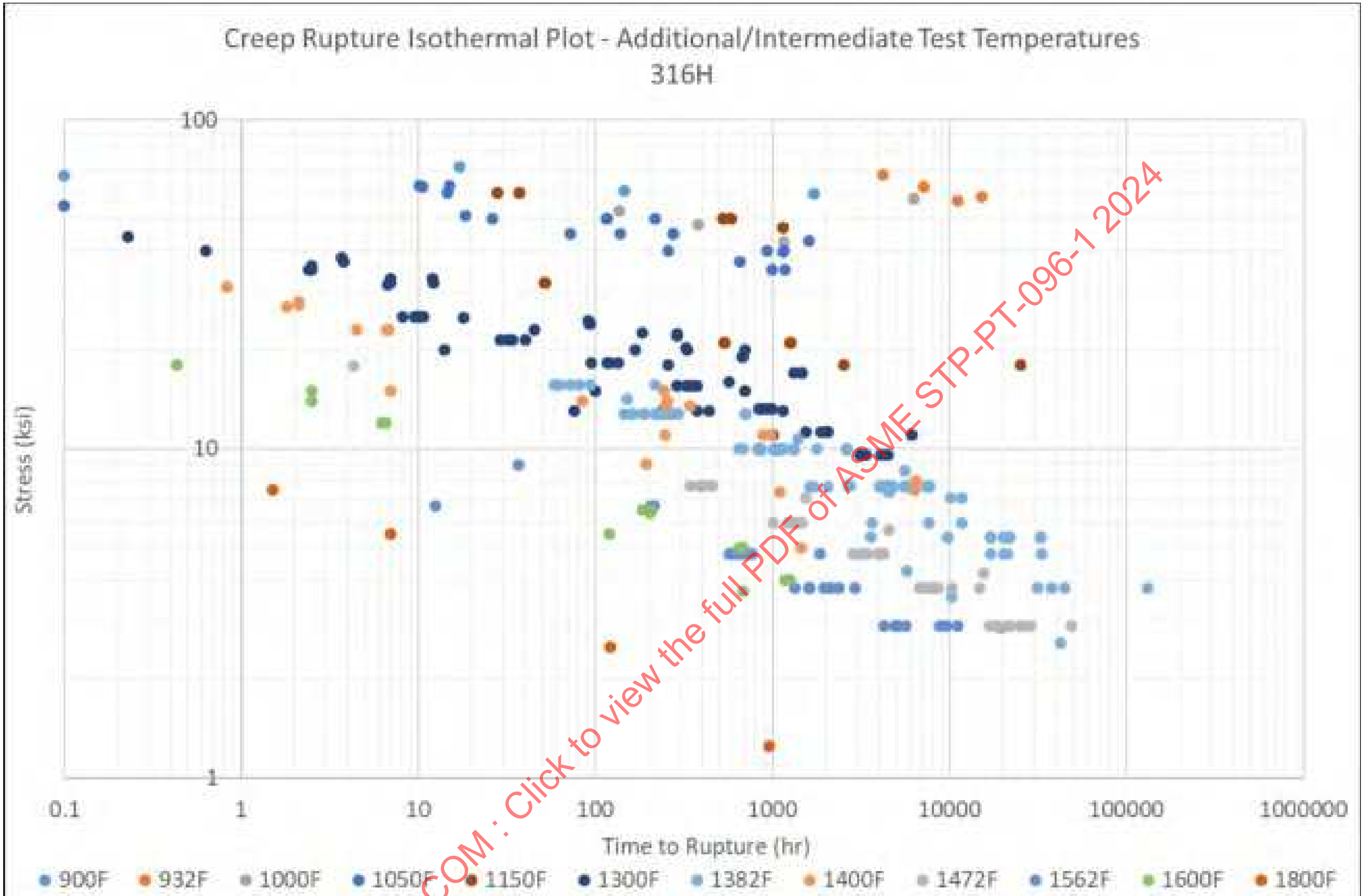


Figure 17-10: 316H Creep Strain Rate (MCR) Isotherm Curves, Temperatures With High Concentration of Data Points

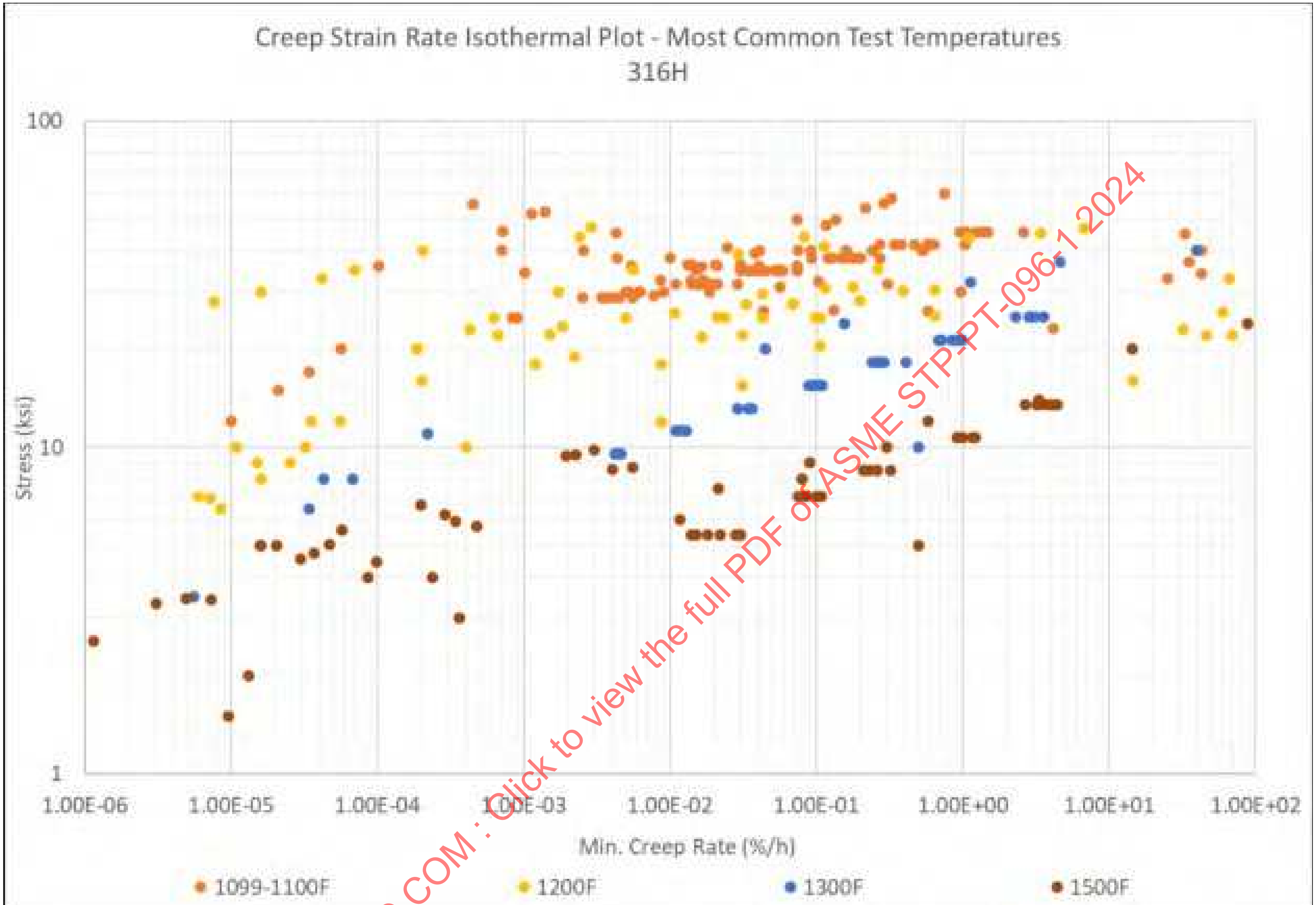


Figure 17-11: 316H Creep Strain Rate (MCR) Isotherm Curves for Additional and Intermediate Temperatures

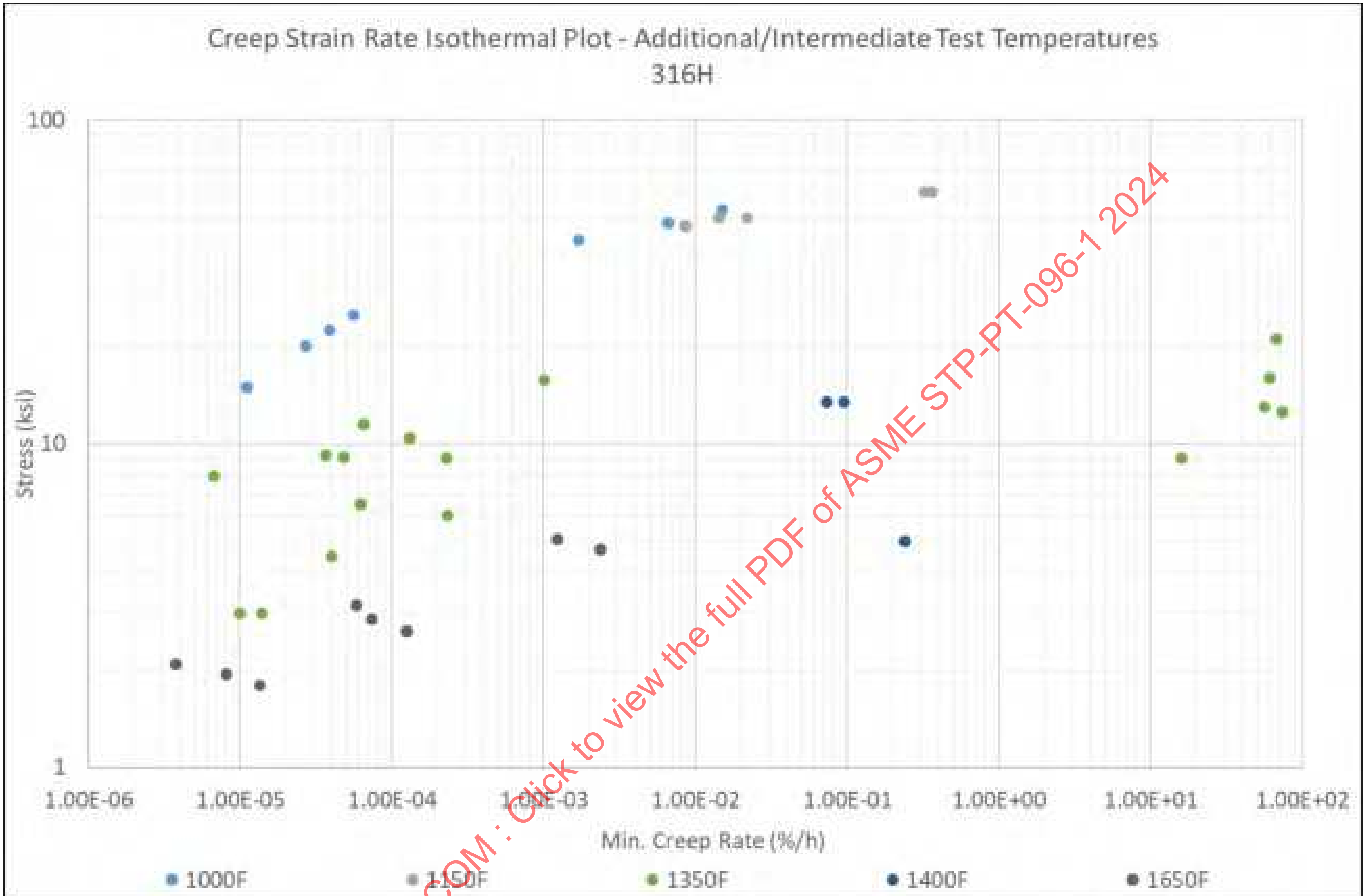


Figure 17-12: 316H Creep Ductility (% Elongation) Vs. Rupture Time Isotherms

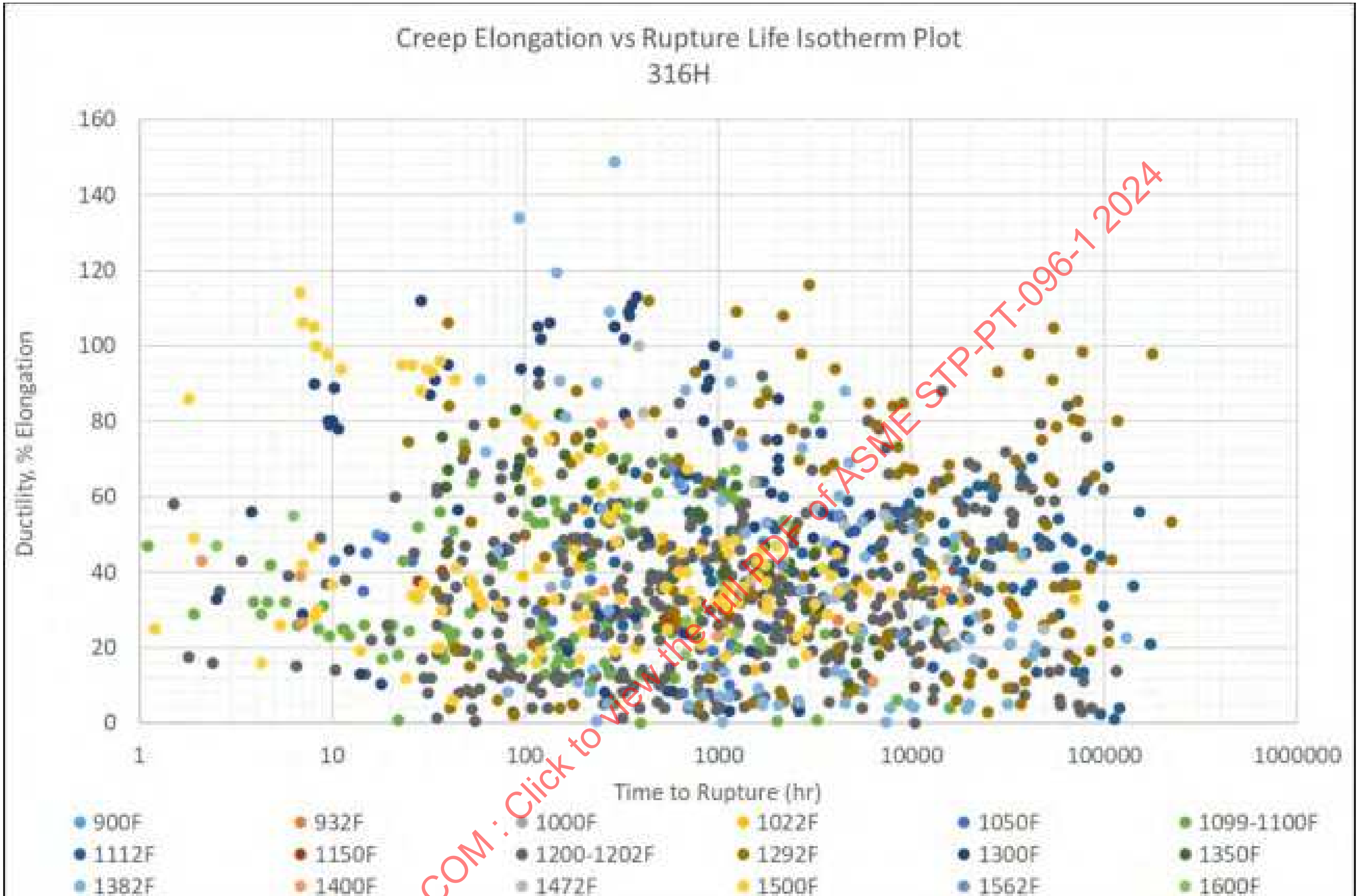


Figure 17-13: Calculated Allowable Stresses Based on Rupture and Creep Strain Rate and ASME II-D Appendix 1 Criteria (316H)

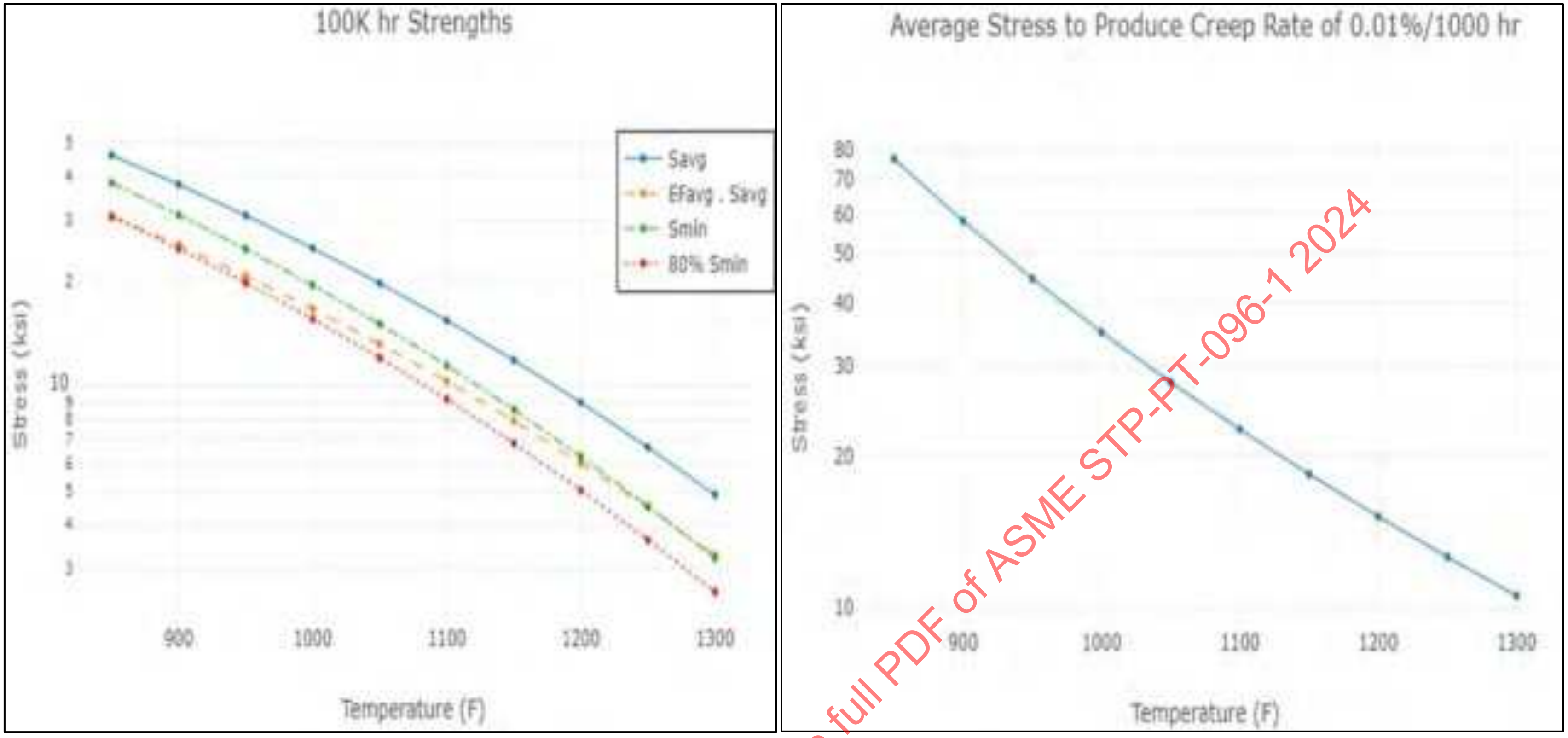


Figure 17-14: Comparison of Current 316H Allowable Stresses (Except Forgings) Vs. ASME II-D Appendix 1 Criteria Applied to Data; Note That These Curves Reflect Properties Regressed to Non-H-Grades of 316 (I.E., Less Than 0.04 WT% Carbon)

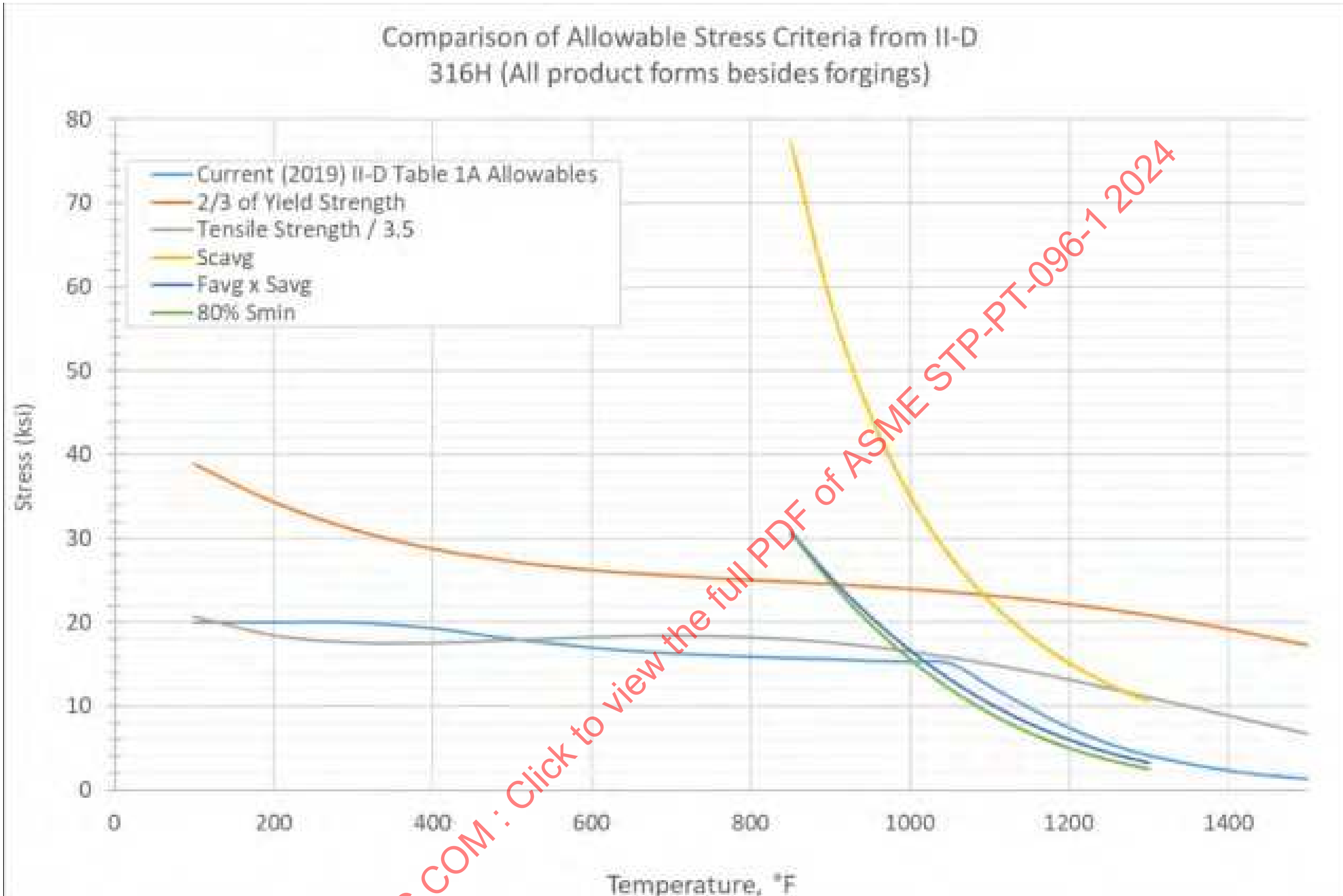


Figure 17-15: Short-Term Strain Vs. Time Data, up to 2,500 Hour Test Durations (316H)

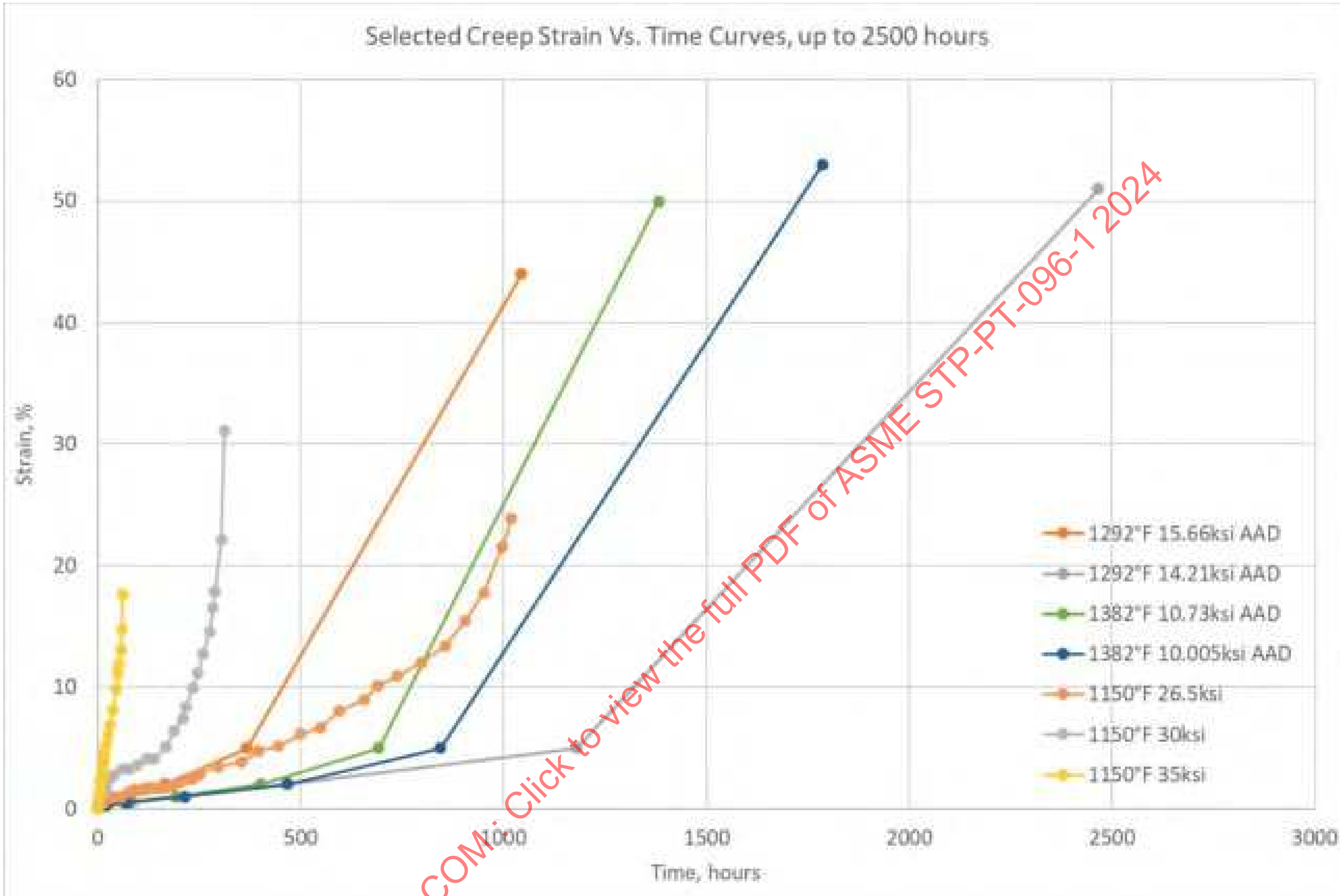


Figure 17-16: Medium-Term Strain Vs. Time Data, 2,500 to 19,000 Hour Test Durations (316H)

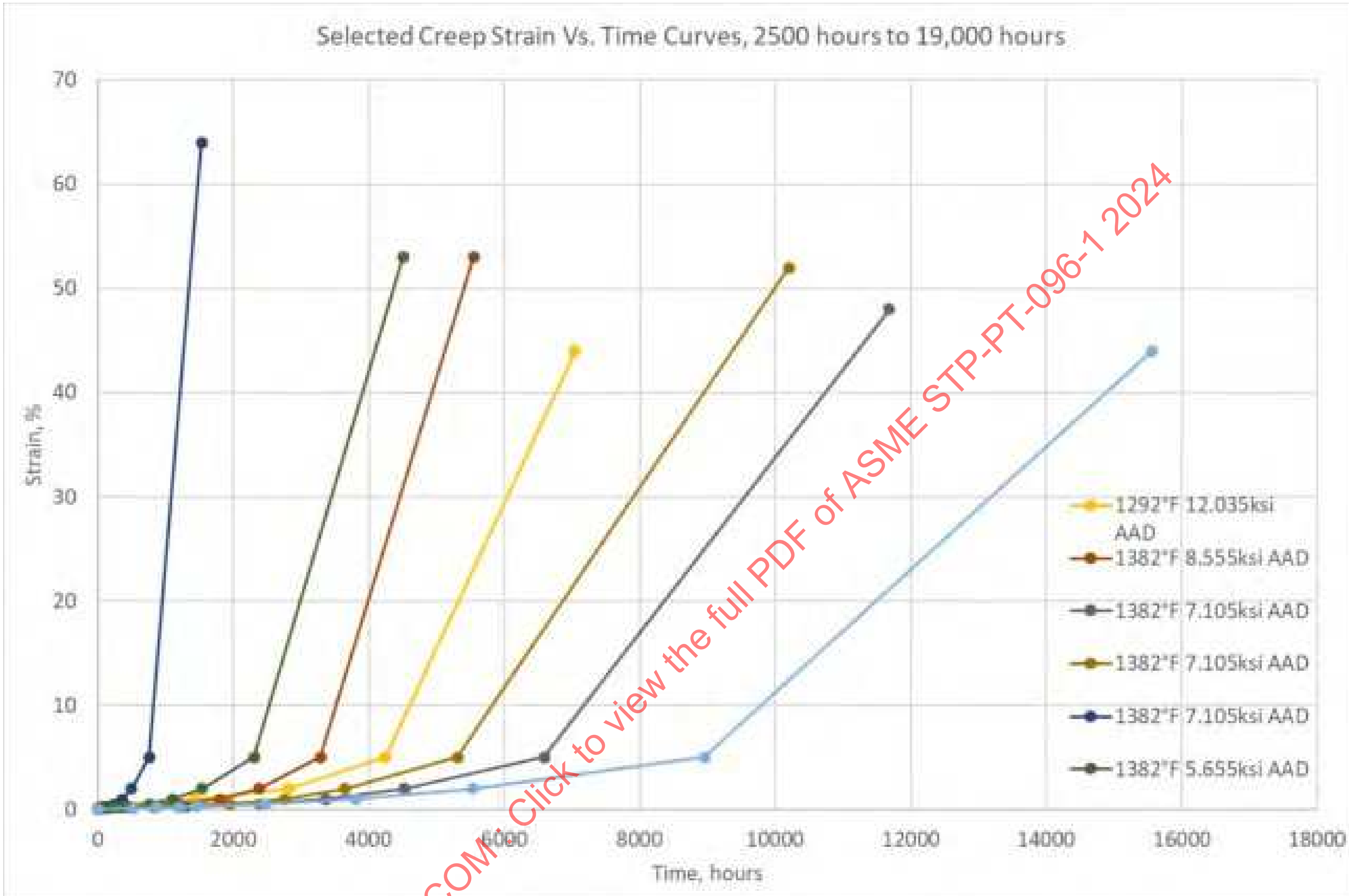


Figure 17-17: Long-Term Strain Vs. Time Data, 19,000+ Hour Test Durations (316H)

Figure 17-18: Continuous Cycling Fatigue (316H), Including Room Temperature and Elevated Temperature Data

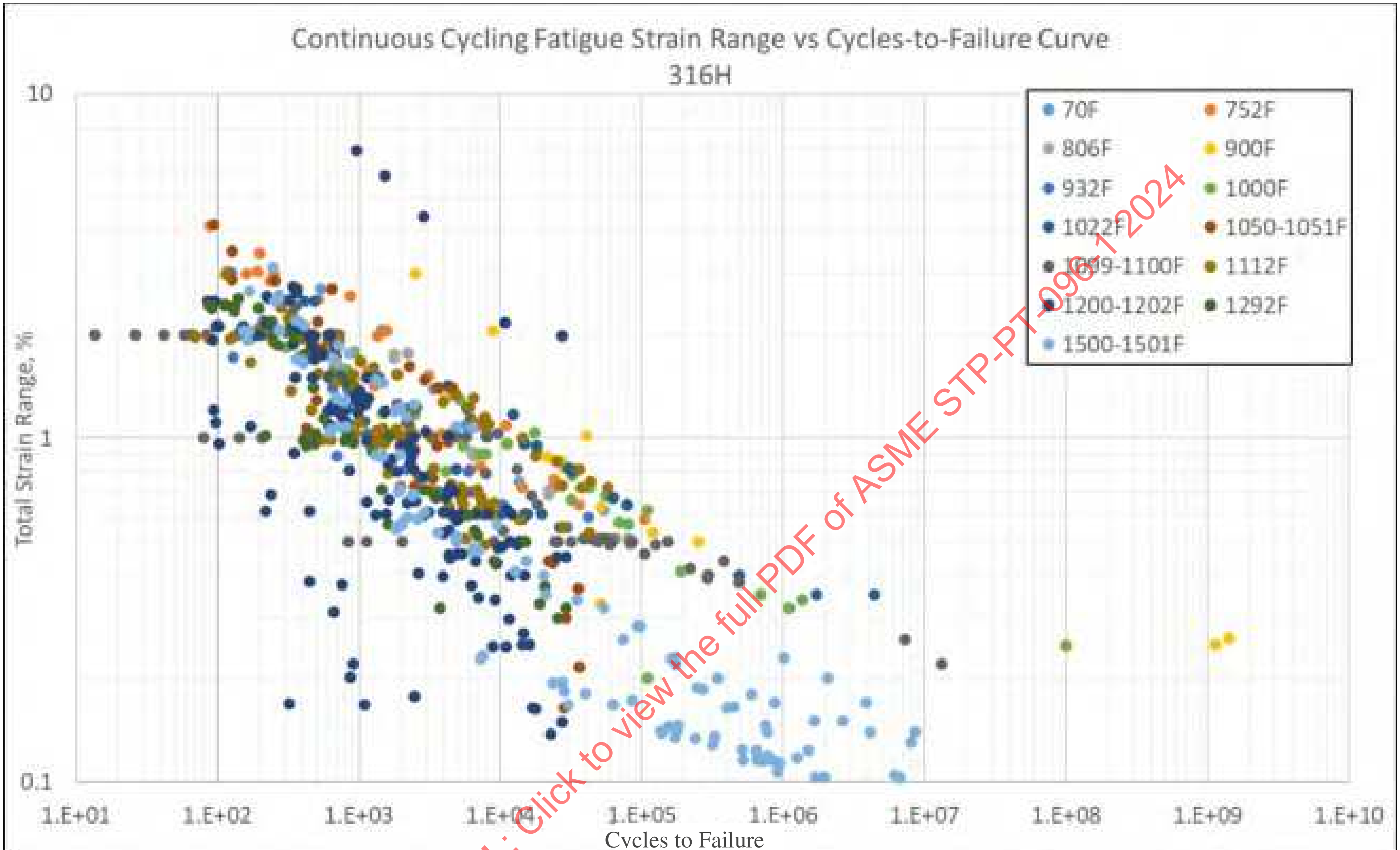


Figure 17-19: Hold Time Data (Creep Fatigue) for 316H, Temperature of 1050°F

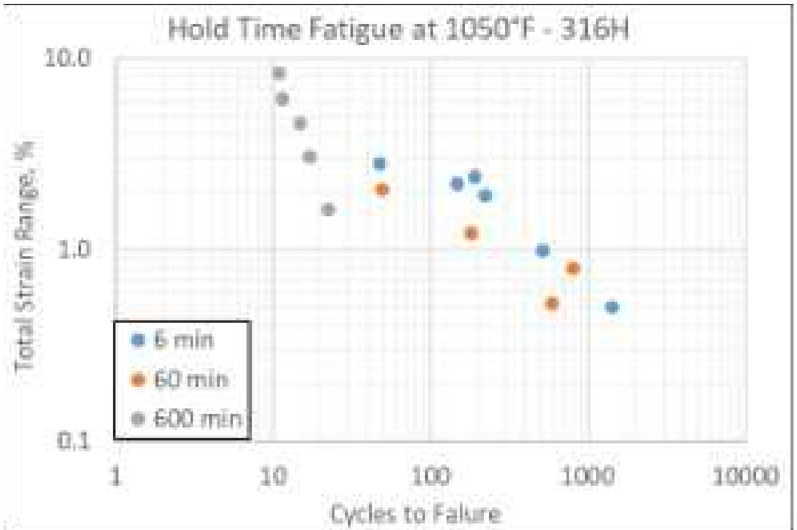


Figure 17-20: Hold Time Data (Creep Fatigue) for 316H, Temperature of 1100°F

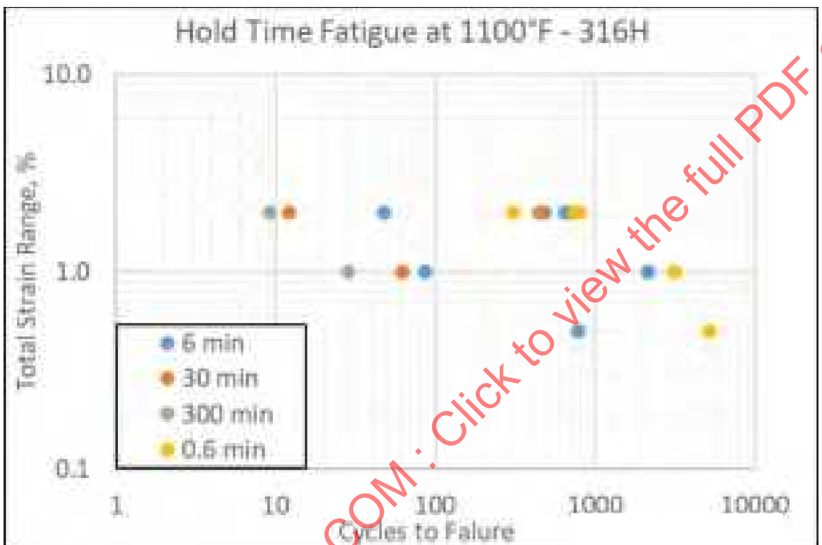


Figure 17-21: Hold Time Data (Creep Fatigue) for 316H, Temperature of 1112°F

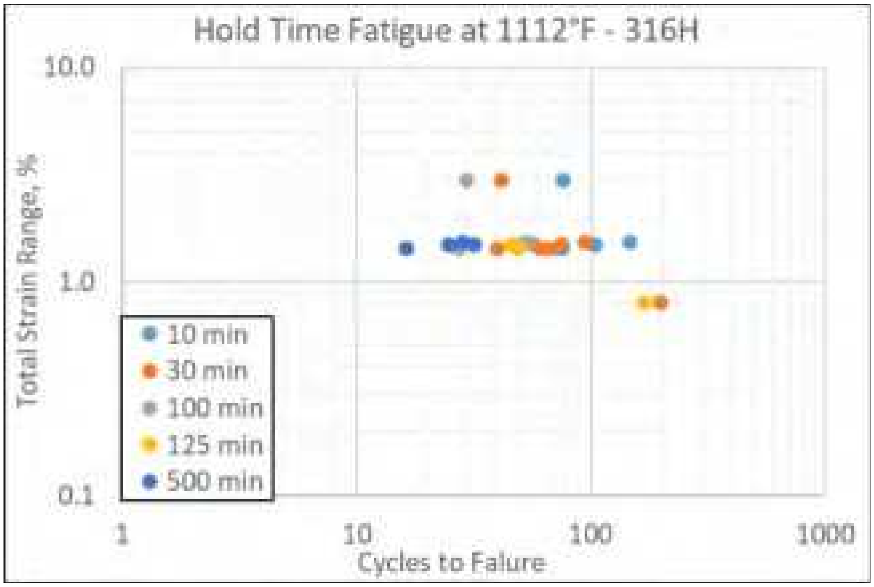
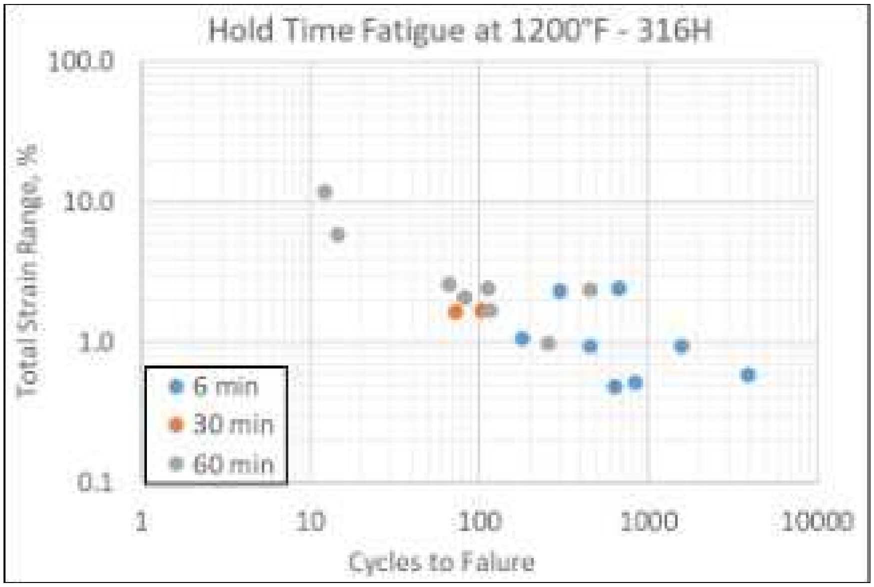


Figure 17-22: Hold Time Data (Creep Fatigue) for 316H, Temperature of 1200°F



Attachment 17: 316H Property Data

If you want the referenced embedded spreadsheet with additional data, please email a request to research@asme.org.

18 TYPE 347H (AND 347) STAINLESS STEEL

18.1 Physical Properties

Physical properties for this material were taken from the BPVC Section II. Additionally, physical property curves were plotted for comparison from WRC Bulletin 503. Figure 18-1 shows the plotted data and trends of Elastic Modulus (E_y), Thermal Conductivity (k), Thermal Diffusivity (TD), and Thermal Expansion (α) with temperature.

18.2 Yield and Tensile Strength

The sources for both high-temperature yield and high-temperature tensile strength are provided in the embedded spreadsheet at the end of this section. High-temperature yield and high-temperature tensile strength data are plotted as shown in Figures 18-2 and 18-3.

As with other materials, yield and tensile data were normalized on a heat-by-heat basis to express the ratio of yield or tensile strength at temperature to that measured for the heat at room temperature. In cases where data were not delineated by heats within a given source, or in cases where more than one room-temperature tensile test existed for a given heat of material, ratios are equal to the measured tensile or yield strength at temperature, divided by the average of all of the appropriate room-temperature values for the particular data source or heat of material. As a result of this approach, it is possible to have ratios in excess of 1.0. E^2G understands that this approach is similar to the normalizing procedure performed by ASME in typical analysis of yield and tensile data to obtain Table Y and Table U (Section II-D) trend curves, as well as for the calculation of allowable stresses. The heat-by-heat variation in yield strength ratio as a function of temperature is shown in Figure 18-4. Similarly, the heat-by-heat variation in tensile strength as a function of temperature is depicted in Figure 18-5. Figures 18-6 and 18-7 contain all of the yield and tensile ratios plotted together, respectively, to facilitate regression of a 5th-order polynomial that is subsequently used for allowable stress comparison.

18.3 Creep Data (Creep Rupture, Minimum Creep Rate, and Ductility)

Plotted as isothermal figures, compiled Creep Rupture data can be seen in Figures 18-8 and 18-9. Similar to other materials, the data has been separated onto multiple plots in order to avoid data overlap, with the most concentrated data depicted in Figure 18-8 and the remaining data in Figure 18-9.

Creep Minimum strain rates (%/hour) can be seen in Figure 18-10, separated by temperature. A limited amount of strain rate data was found for this material. Similar to creep rupture, creep ductility, as % elongation, is plotted in Figures 18-11 and 18-12 and is separated onto multiple plots to avoid data overlap.

Creep data were analyzed using E^2G's proprietary Lot-Centered Analysis web-based software tool, in order to obtain creep properties. This regression is based on a Mandel-Paule algorithm and considers the variation within individual heats of material (for both rupture and strain rate data) as well as the variation between heats. The weight assigned to each datapoint and each heat is scaled based on the relative variation. Both rupture and strain rate (minimum creep rate, expressed as true strain per hours) were regressed according to a Larson-Miller time-temperature-parameter model, with a 3rd-order polynomial of stress. Lot-specific constant behavior was accounted for in this analysis, but the variation of LMP with stress was assumed to be constant (no non-parallel terms were included in the analysis). A 95% predictive limit was utilized to obtain the lower-bound (minimum LMP constant for both rupture and strain rate) properties. The results of this analysis are summarized in Table 18-1 for rupture data and Table 18-2 for strain rate data. The Lot-

Centered Analysis software tool generates property tables in the creep regime using the criteria outlined in Mandatory Appendix 1 of ASME Section II-D; the nomenclature of variables is consistent with II-D Appendix 1. Figure 18-13 is provided for visualization of the rupture allowable stresses and creep rate allowable stresses. In a similar vein, Figure 18-14 shows a comparison of the various allowable stress criteria from Section II-D, Appendix 1, to the existing (2019) Section II-D Table 1A allowable stresses for all product forms of 347H other than forgings.

Creep Strain vs. time data are shown in Figures 18-15 and 18-16 for rupture times up to 2,000 hours and in excess of 2,000 hours, respectively. Both creep rate and creep strain vs. time data are provided to satisfy ASME's request for creep strain vs. time curves, and both forms of data are applicable in developing allowable stresses. Although digitalization of creep curve data was not explicitly necessary per the project contract, E^2G did perform digitalization of creep curves where only graphical data was available (as is often the case in the published literature).

18.4 Continuous Cycling Fatigue Curves

A limited amount of continuous cycling fatigue data was available for 347H material. A plot of the continuous cycling fatigue strain range vs. cycles to failure is shown Figure 18-17 at elevated temperatures. This plot only contains data for which total strain range was determined from the original source. No hold time fatigue data was available for 347H.

Table 18-1: Model Parameters, Larson-Miller Property Results, and Allowable Stress (Rupture) Criteria, 347H

Equation Format:

$$\log(t_r) = C_{avg} + \frac{1}{T+460}\left(b_1 + b_2\log(\sigma) + b_3(\log(\sigma))^2 + b_4(\log(\sigma))^3\right)$$

C_{avg}	**-14.71**
C_{min}	**-15.37**
b_1	**38488.3**
b_2	**-12.491**
b_3	**7719.8**
b_4	**-3191.9**

Number Data Points		**2144**
Correlation Coefficient	R^2	0.7978
Average Variance within Heats	V_w	0.1581
Variance between Heats	V_b	0
Standard Error of Estimate	SEE	0.3976

Properties provided are for T in °F, stress in ksi, and t_R in hours

Temperature, °F	**S_{avg} (ksi)**	***n***	**F_{avg} (calc)**	**F_{avg} (used)**	**$F_{avg} \times S_{avg}$**	**S_{min} (ksi)**	**80% S_{min}**
850	35.23	8.796	0.7697	0.67	23.6	29.42	23.54
900	28.61	7.587	0.7382	0.67	19.17	23.19	18.55
950	22.65	6.492	0.7014	0.67	15.18	17.7	14.16
1000	17.4	5.53	0.6594	0.67	11.66	13.02	10.41
1050	12.9	4.739	0.6151	0.67	8.643	9.223	7.378
1100	9.239	4.174	0.576	0.67	6.19	6.374	5.1
1150	6.464	3.893	0.5536	0.67	4.331	4.407	3.526
1200	4.519	3.908	0.5548	0.67	3.027	3.125	2.5
1250	3.231	4.159	0.5749	0.67	2.165	2.3	1.84
1300	2.391	4.556	0.6033	0.67	1.602	1.757	1.405

** E²G's proprietary *Lot-Centered Analysis* web-based software tool only provides results up to 1300°F, but it should be noted that Type 347H allowable stress properties are observed above 1300°F.

Table 18-2: Model Parameters, Larson-Miller Property Results, and Allowable Stress (Strain Rate) Criteria, 347H

Equation Format:

$$\log(\dot{\varepsilon}_0) = -C_{avg} - \frac{1}{T+460}\left(a_1 + a_2\log(\sigma) + a_3(\log(\sigma))^2 + a_4(\log(\sigma))^3\right)$$

C_{avg} (A_0)	**-15.84**
C_{min} ($A_0+\Delta_\Omega^{SR,LB}$)	**-16.94**
a_1	**49180.2**
a_2	**-22322.6**
a_3	**16506.3**
a_4	**-5666.2**

Number Data Points		**214**
Correlation Coefficient	R^2	0.7363
Average Variance within Heats	V_w	0.4471
Variance between Heats	V_b	1.806
Standard Error of Estimate	SEE	0.6687

Properties provided are for T in °F, stress in ksi, and t_R in hours

Temperature, °F	**$S_{C,avg}$ (ksi)**
850	81.08
900	72.1
950	63.49
1000	55.23
1050	47.33
1100	39.8
1150	32.66
1200	25.96
1250	19.78
1300	14.32

** E[2]G's proprietary *Lot-Centered Analysis* web-based software tool only provides results up to 1300°F, but it should be noted that Type 347H allowable stress properties are observed above 1300°F.

Figure 18-1: 347H Modulus (E_y), Thermal Conductivity (k), Thermal Diffusivity (TD), & Thermal Expansion (α) with Temperature

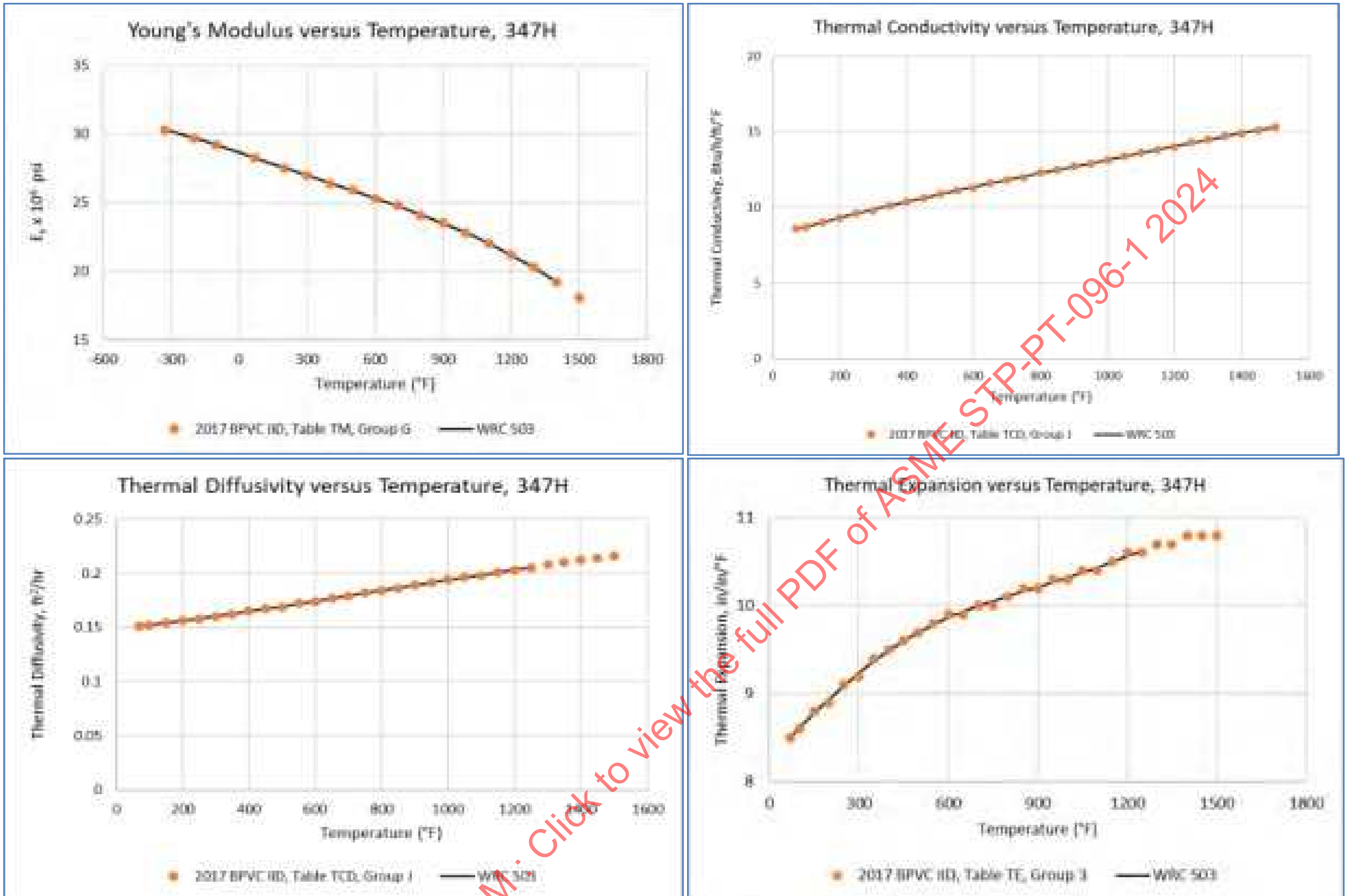


Figure 18-2: 347H Yield Strength Vs. Temperature, By Data Source, Including Trend Curves

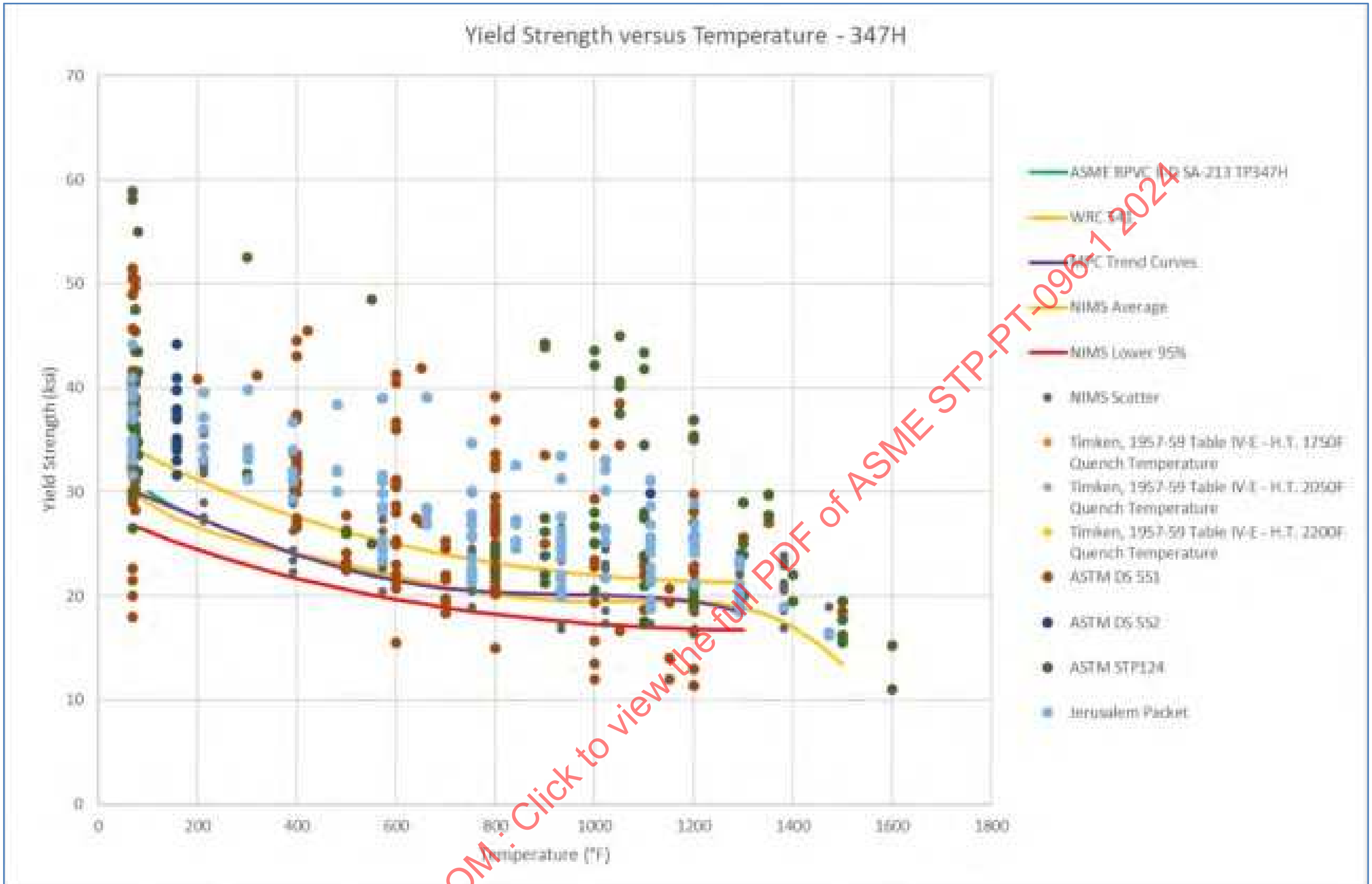


Figure 18-3: 347H Tensile Strength Vs. Temperature, By Data Source, Including Trend Curves

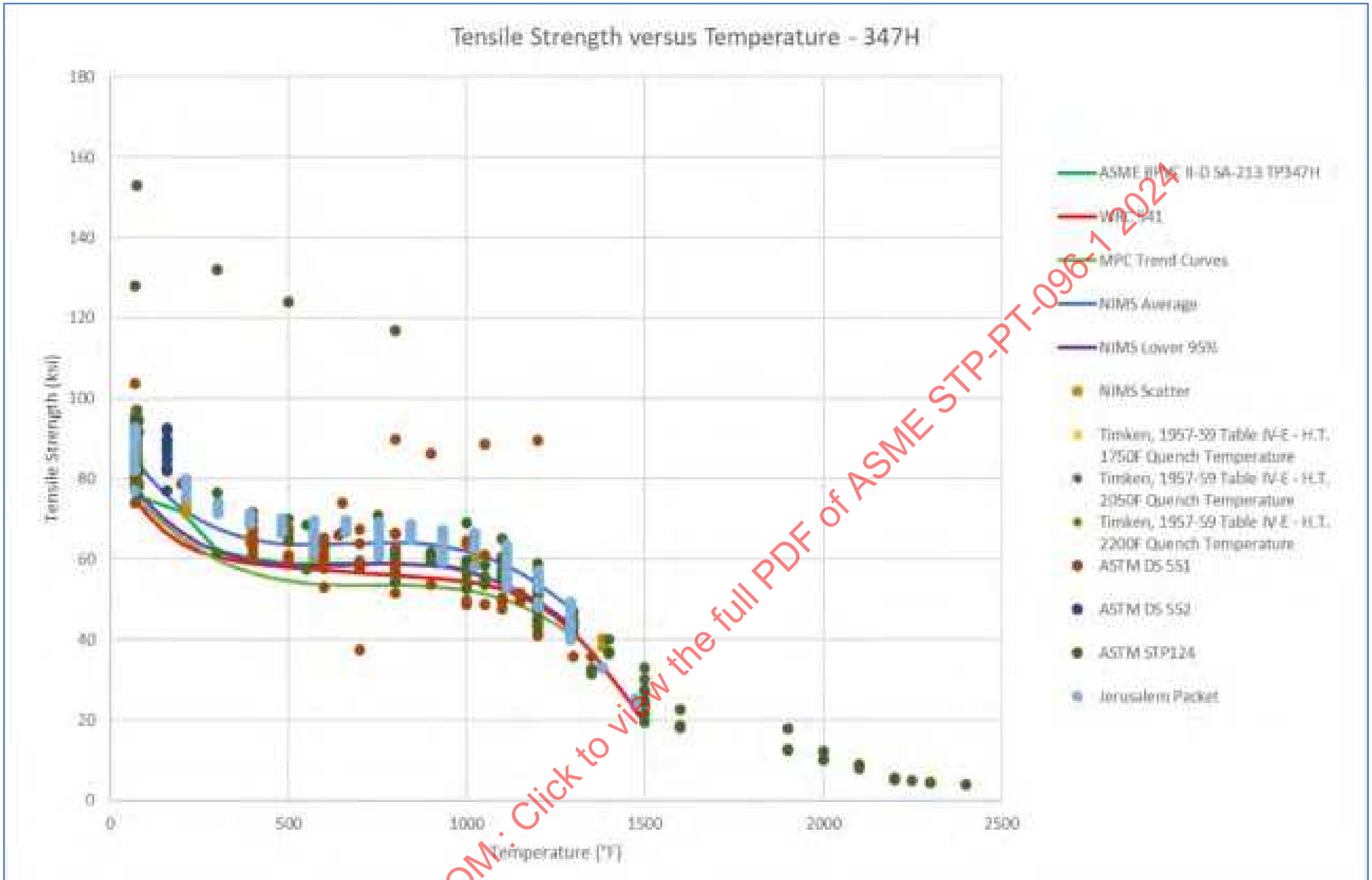


Figure 18-4: 347H Yield Strength Ratios Vs. Temperature (Calculated on a Heat-By-Heat Basis, By Data Source)

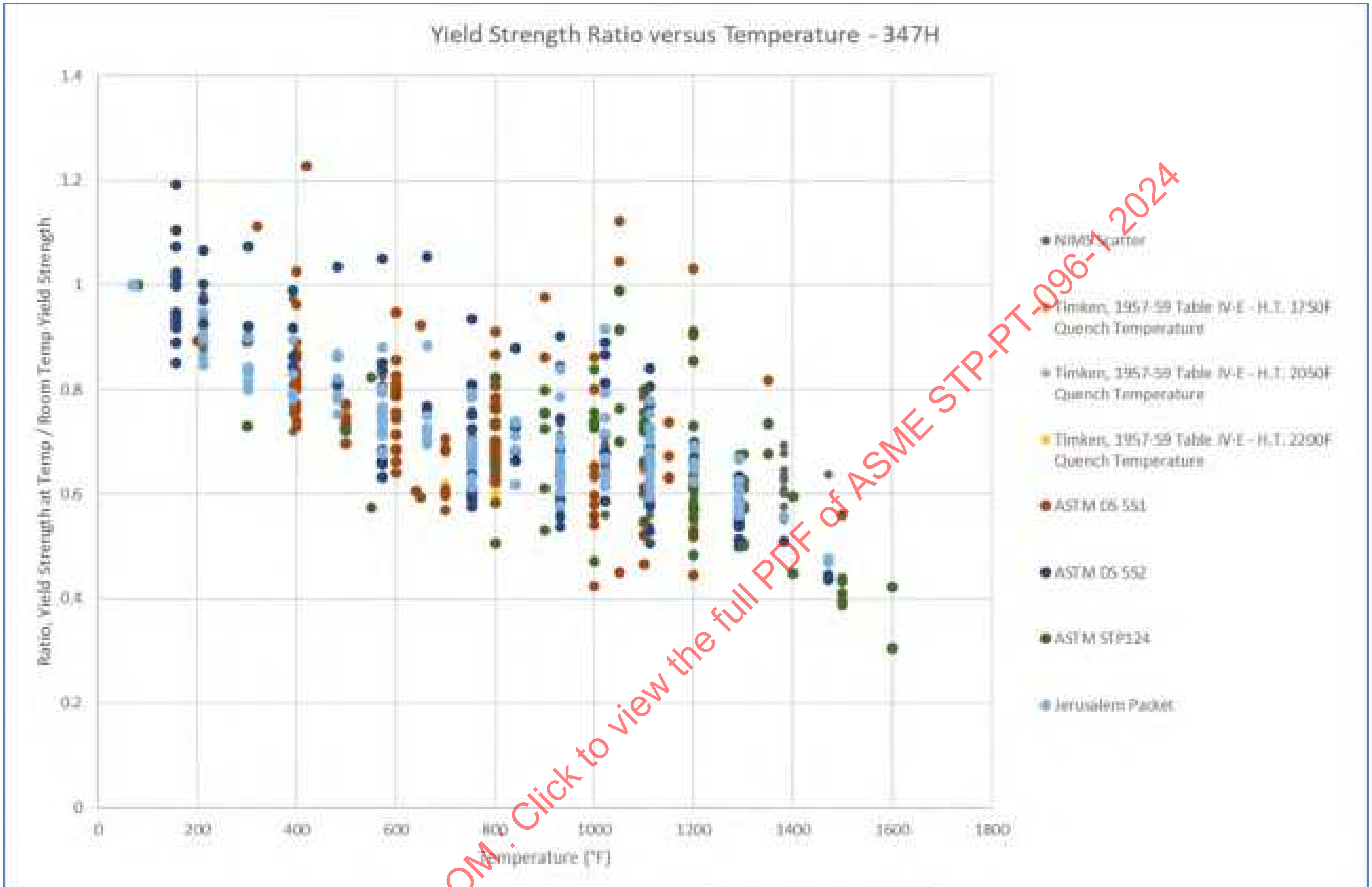


Figure 18-5: 347H Tensile Strength Ratios Vs. Temperature (Calculated on a Heat-By-Heat Basis, By Data Source)

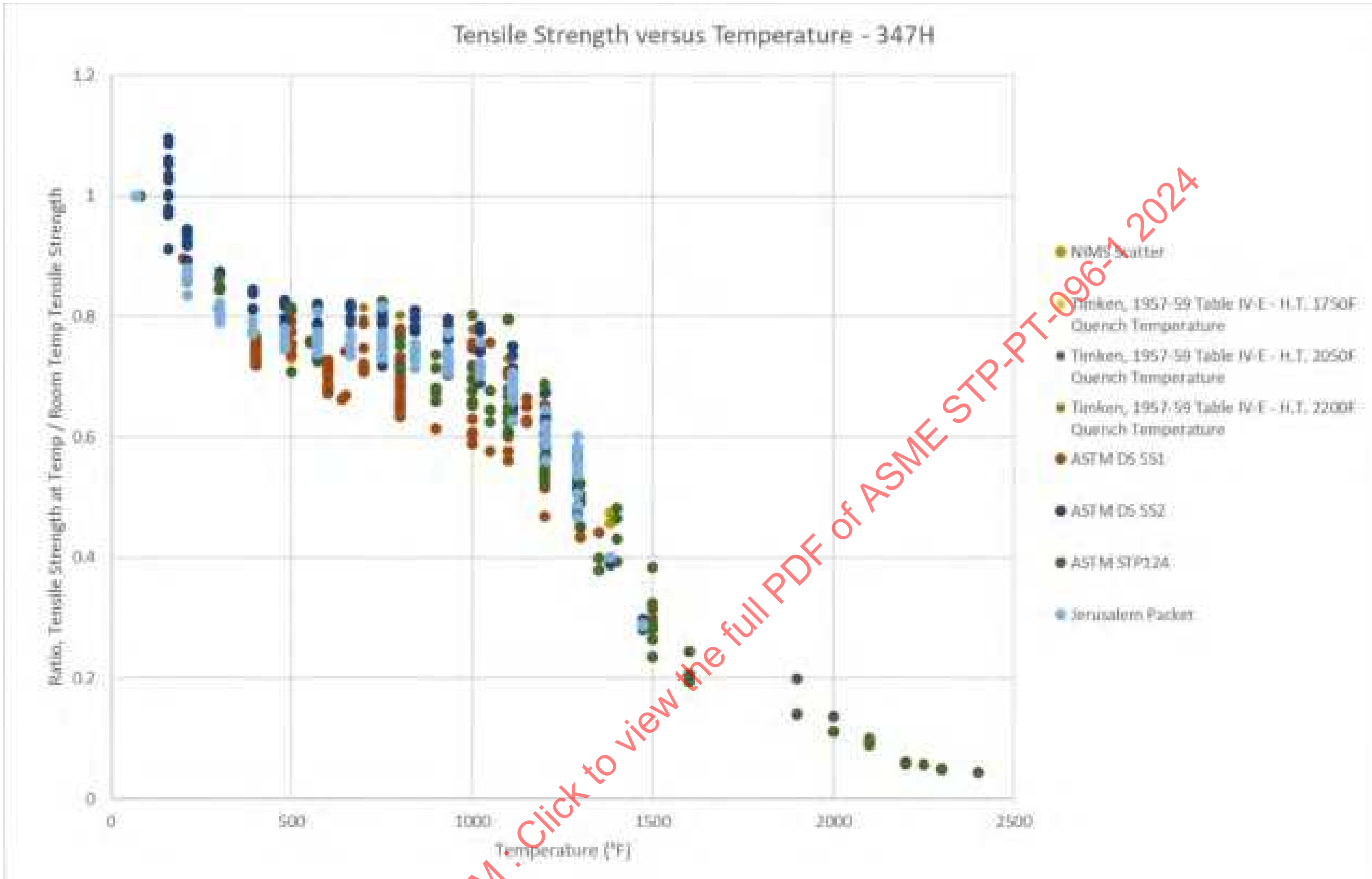


Figure 18-6: 347H Yield Strength Ratios Vs. Temperature, All Combined Data, With Polynomial Regression

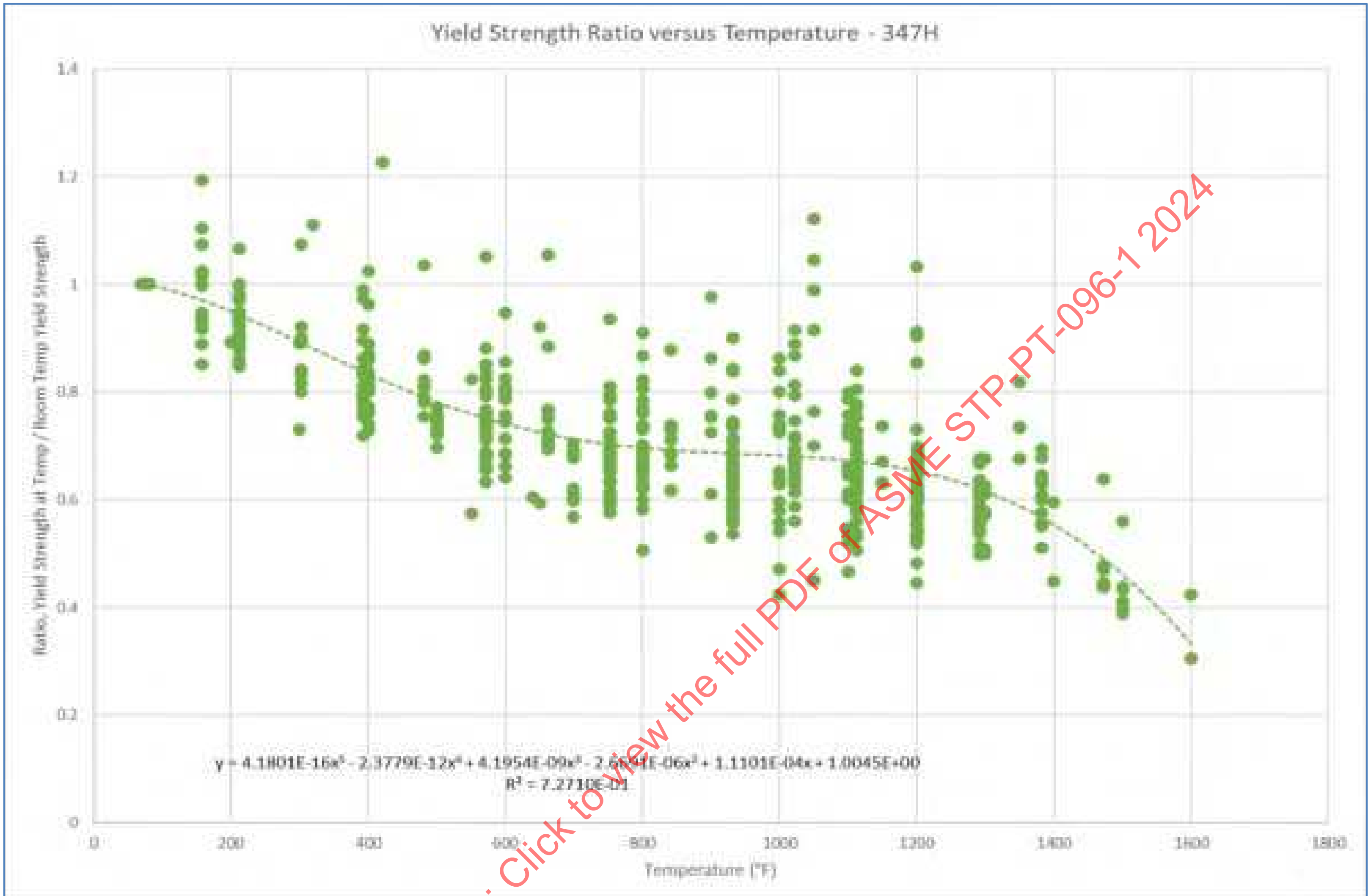


Figure 18-7: 347H Tensile Strength Ratios Vs. Temperature, All Combined Data, With Polynomial Regression

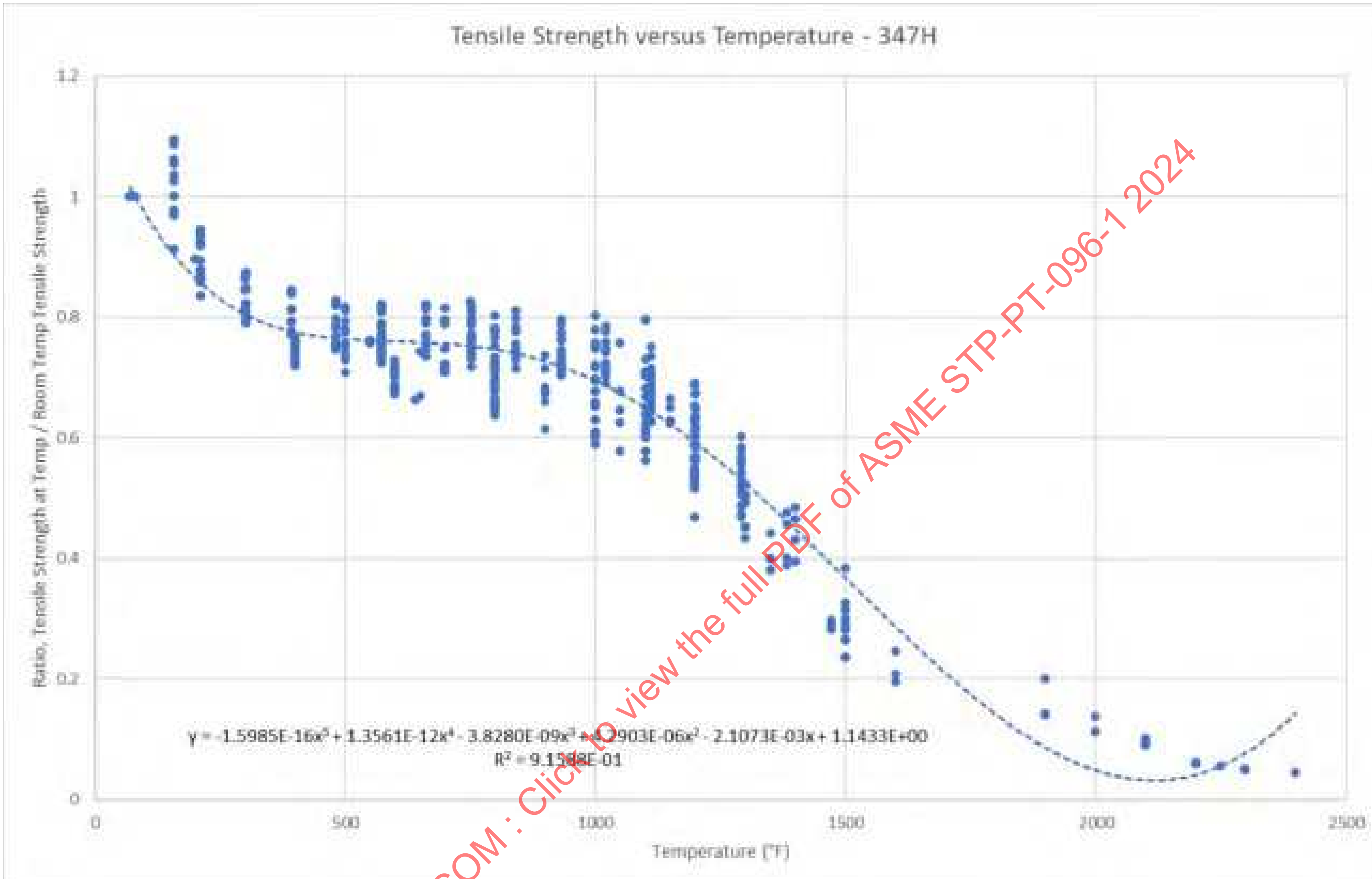


Figure 18-8: 347H Creep Rupture Isotherm Curves, Temperatures With High Concentration of Data Points

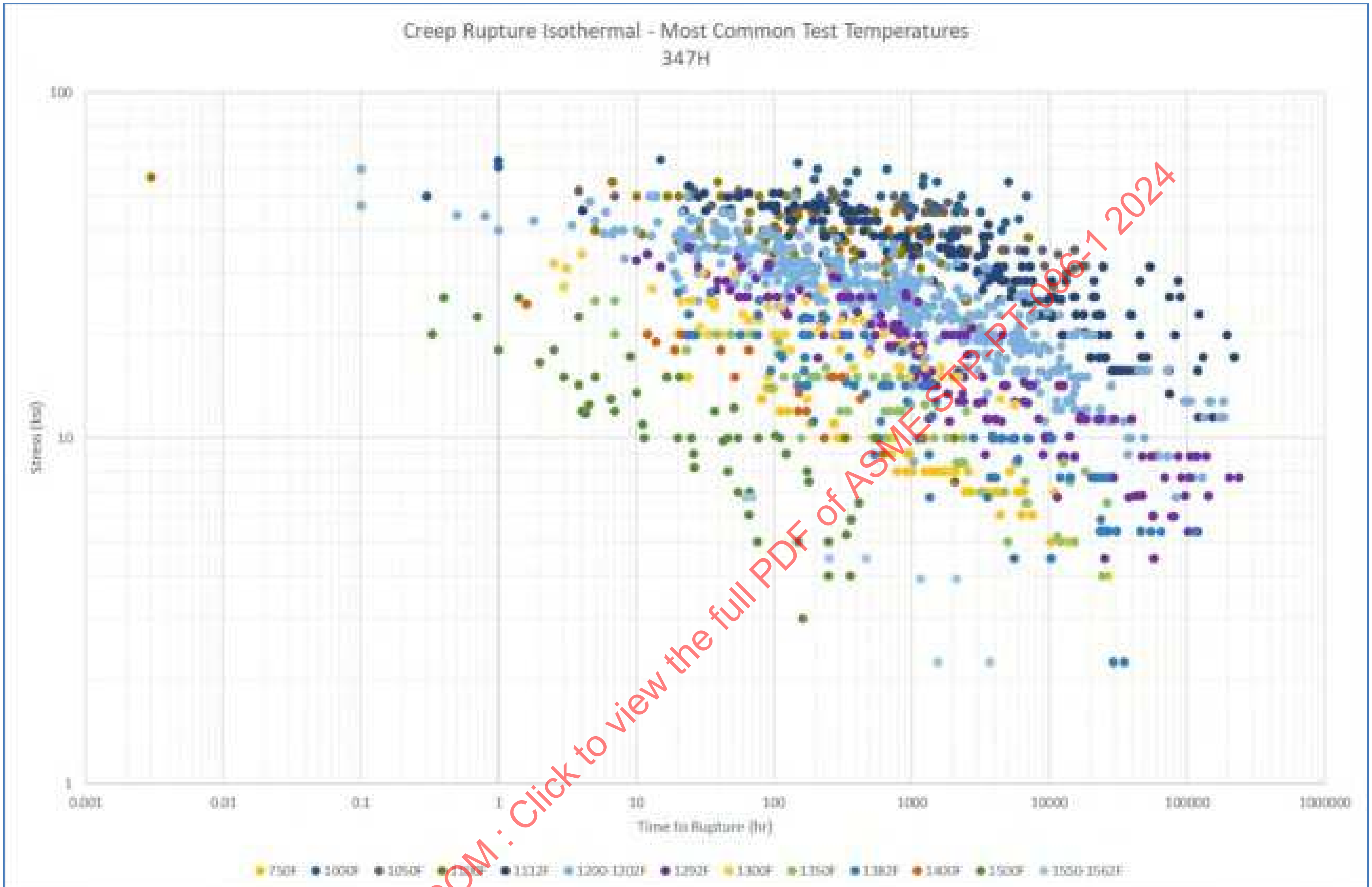


Figure 18-9: 347H Creep Rupture Isotherm Curves, Additional and Intermediate Temperatures

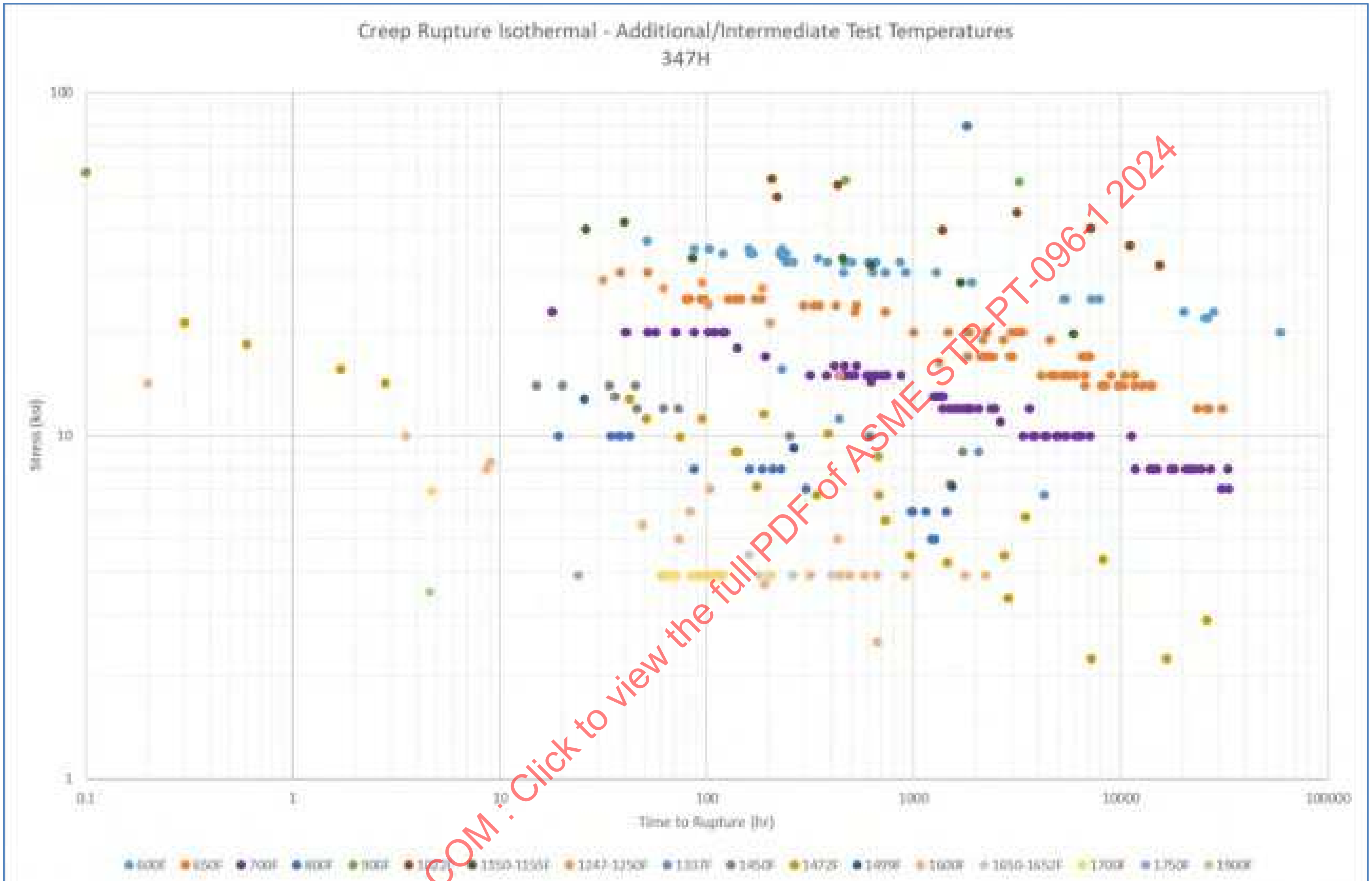


Figure 18-10: 347H Creep Strain Rate (MCR) Isotherm Curves

Figure 18-11: 347H Creep Ductility (% Elongation) Vs. Rupture Time Isotherms, Most Common Test Temperatures

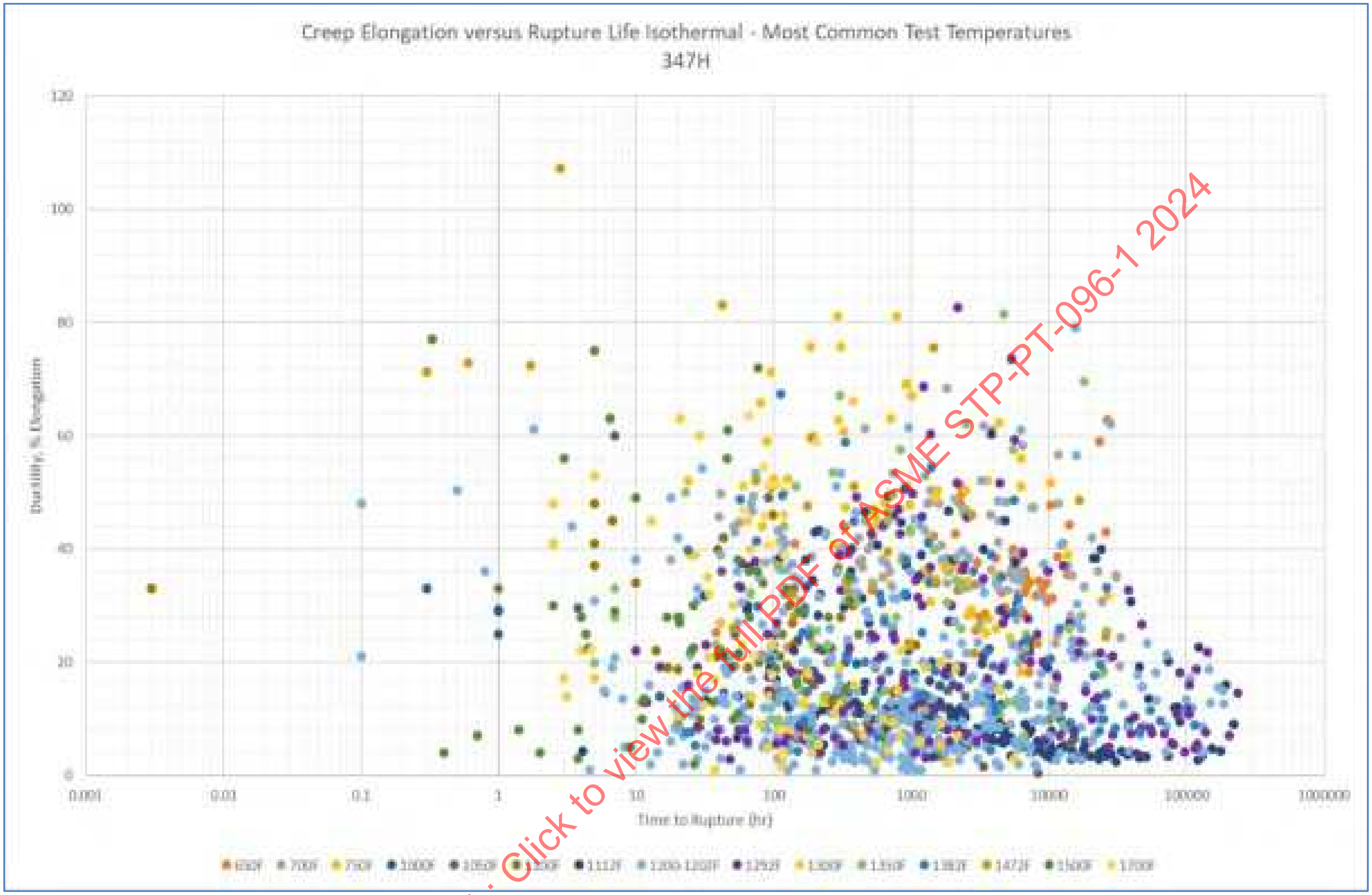


Figure 18-12: 347H Creep Ductility (% Elongation) Vs. Rupture Time Isotherms, Additional and Intermediate Test Temperature

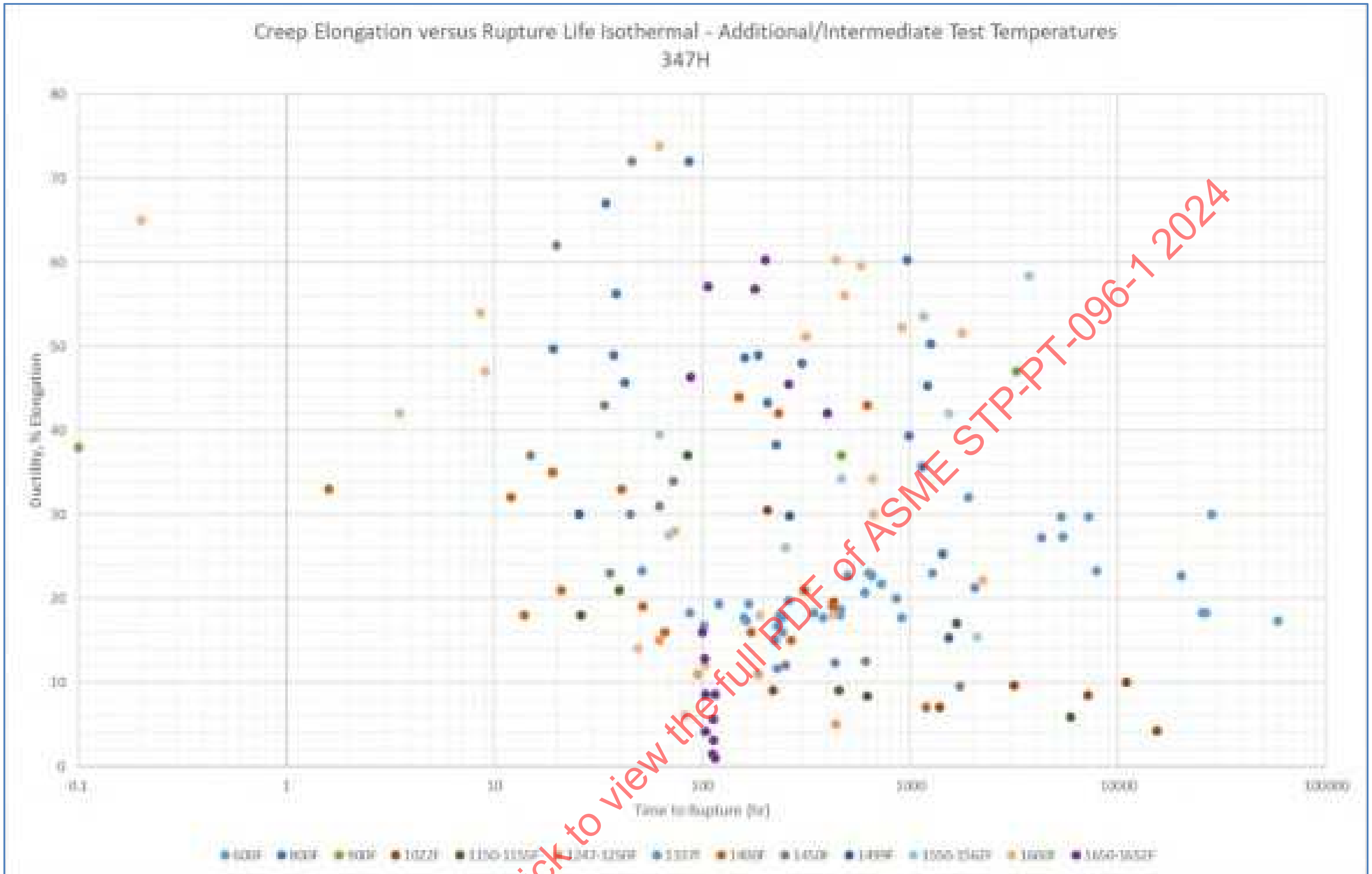


Figure 18-13: Calculated Allowable Stresses Based on Rupture and Creep Strain Rate and ASME II-D Appendix 1 Criteria (347H)

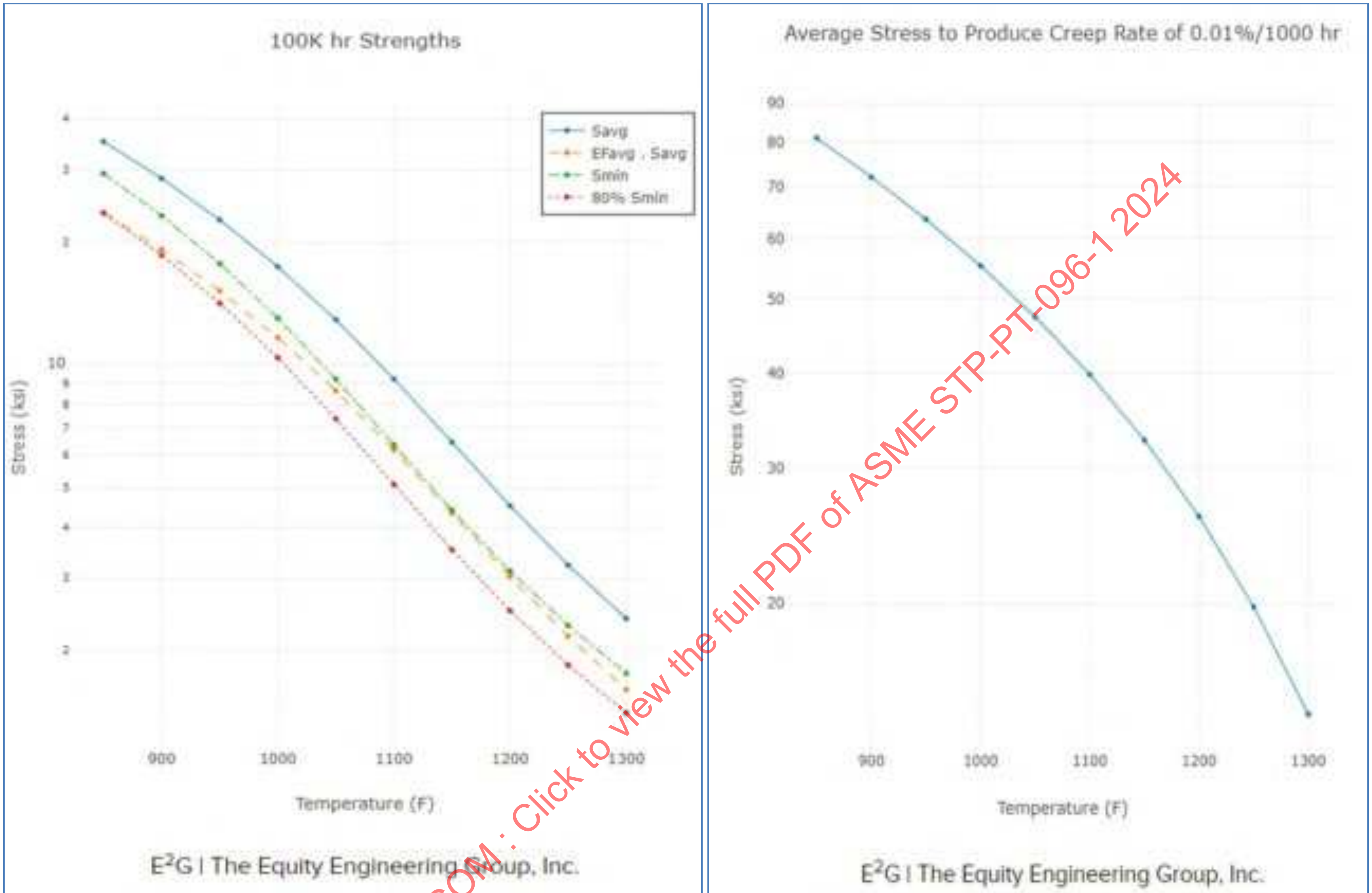


Figure 18-14: Comparison of Current 347H Allowable Stresses Vs. ASME II-D Appendix 1 Criteria Applied to Data; Note That These Curves Reflect Properties Regressed to Non-H Grades of 347 (I.E, Less Than 0.04 WT% Carbon)

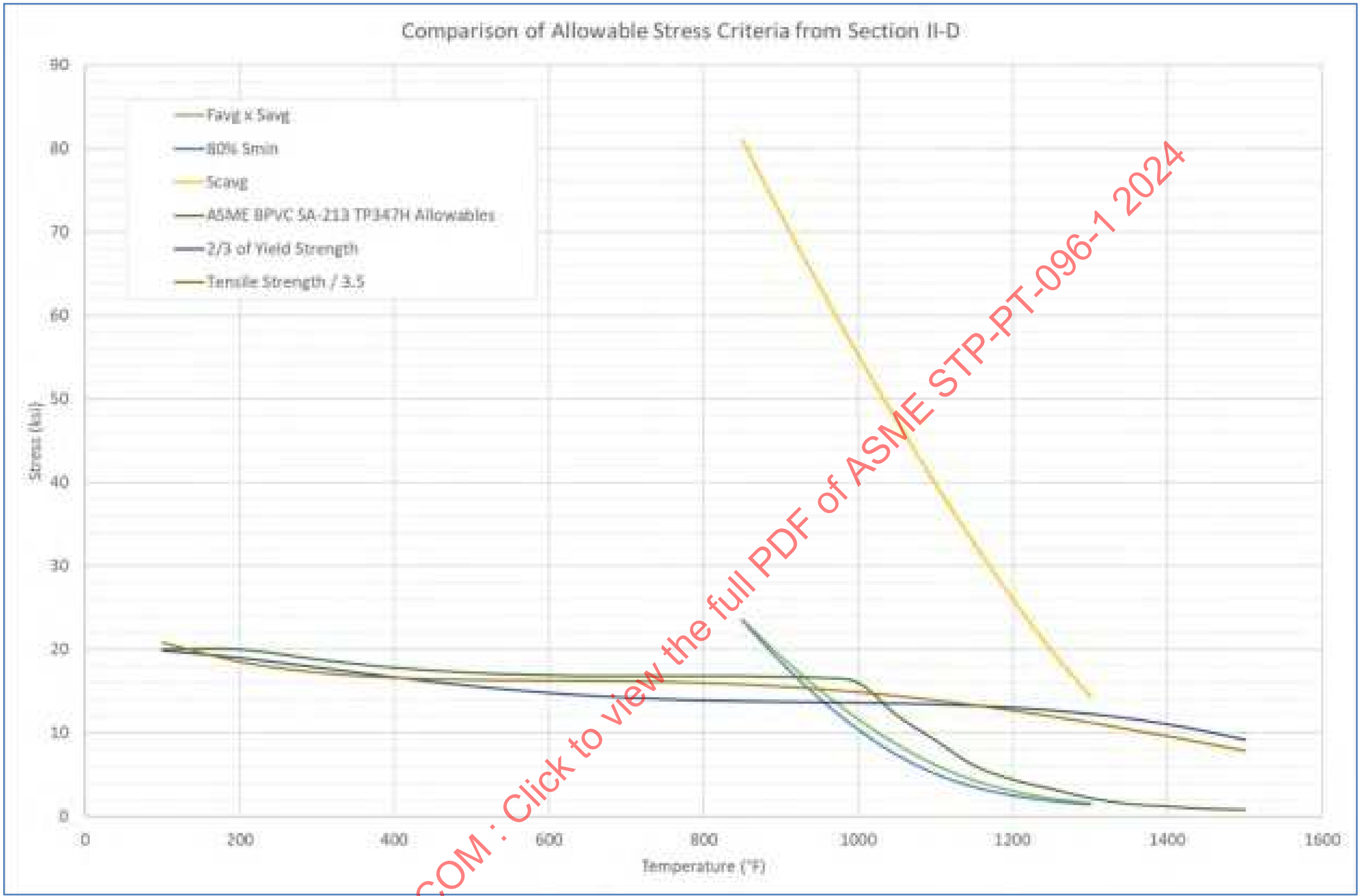


Figure 18-15: Creep Strain Vs. Time Data, up to 2,000 Hour Test Durations (347H)

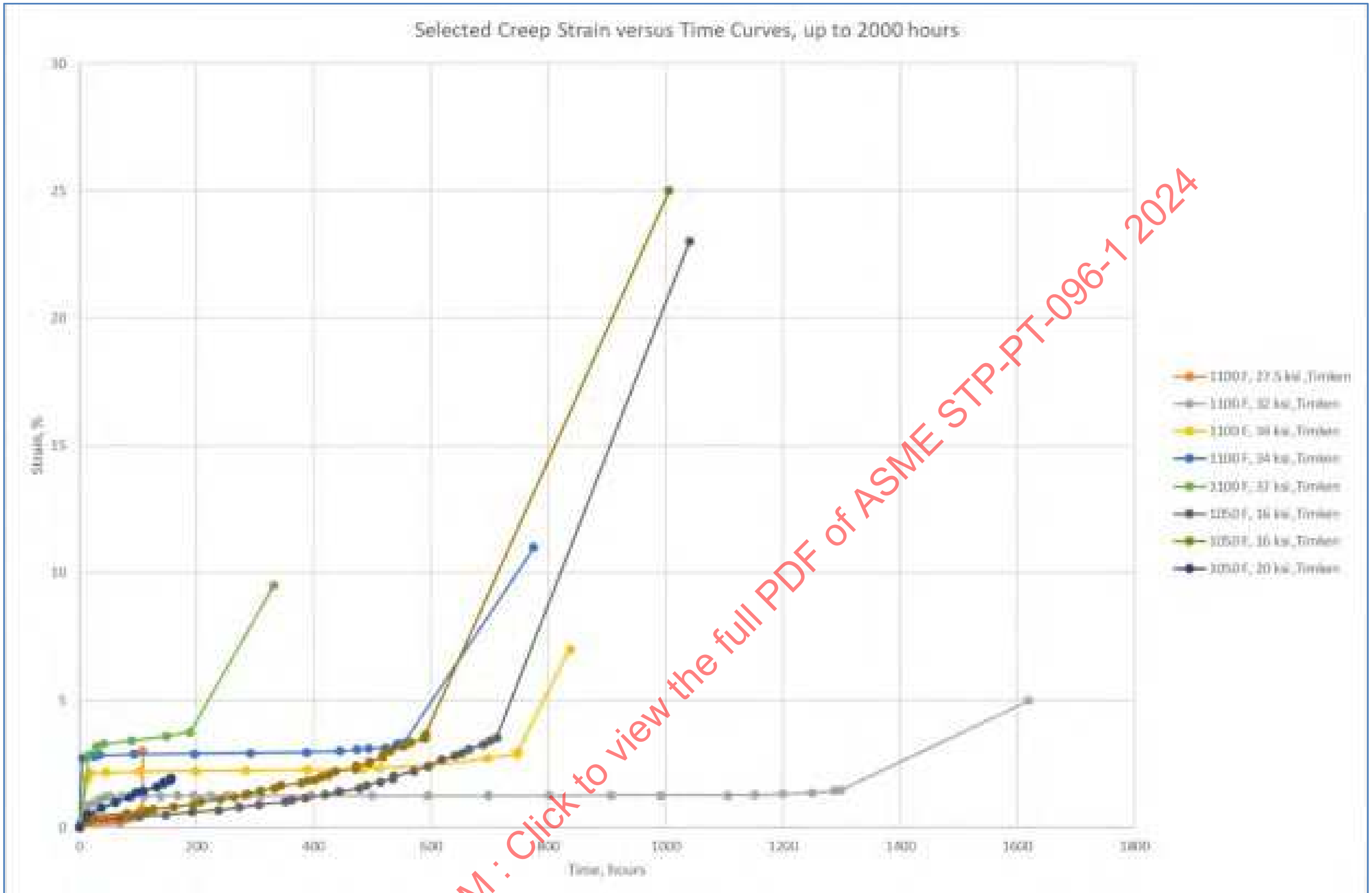


Figure 18-16: Creep Strain Vs. Data, in Excess of 2,000 Hour Test Durations (374H)

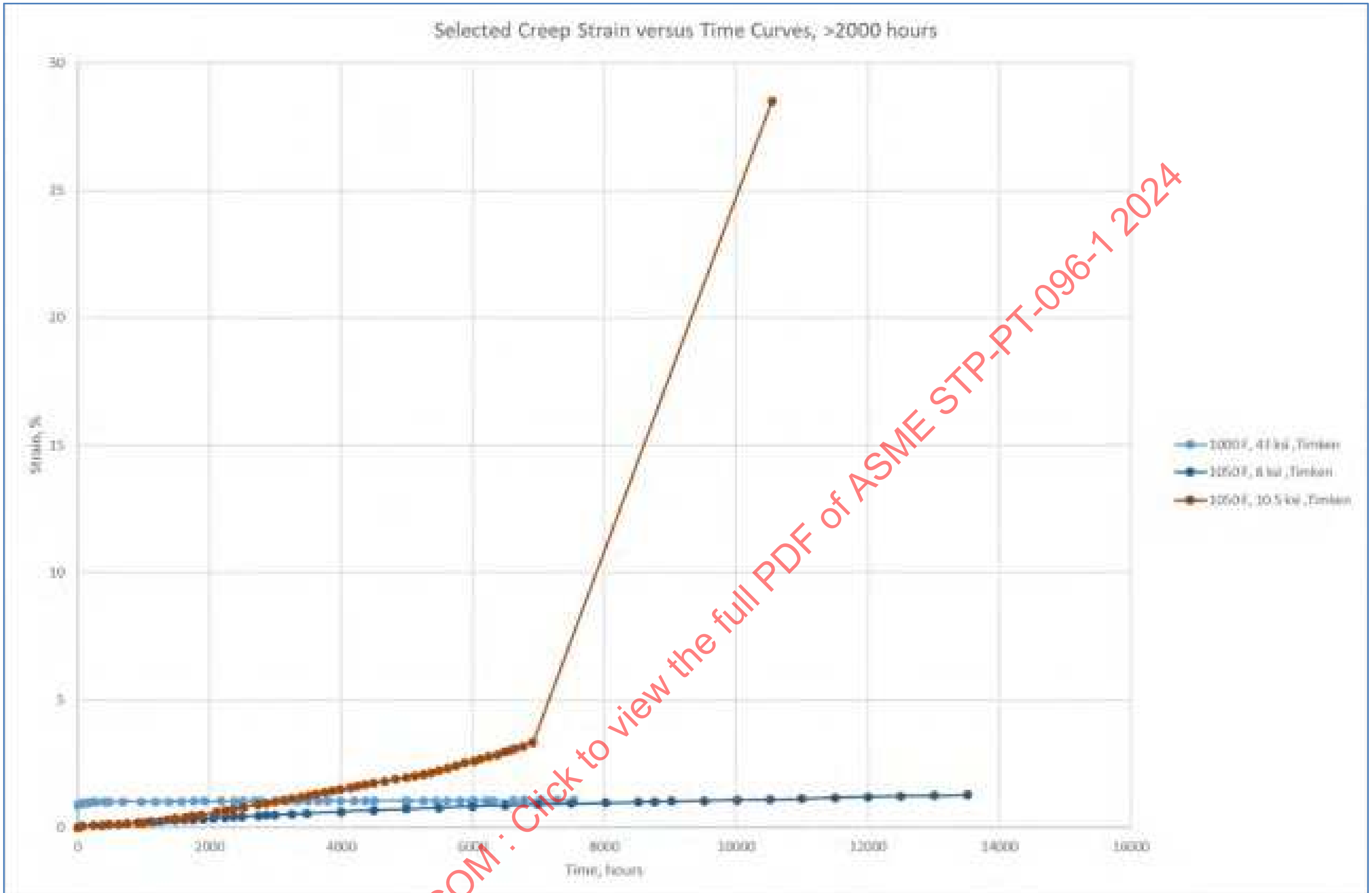
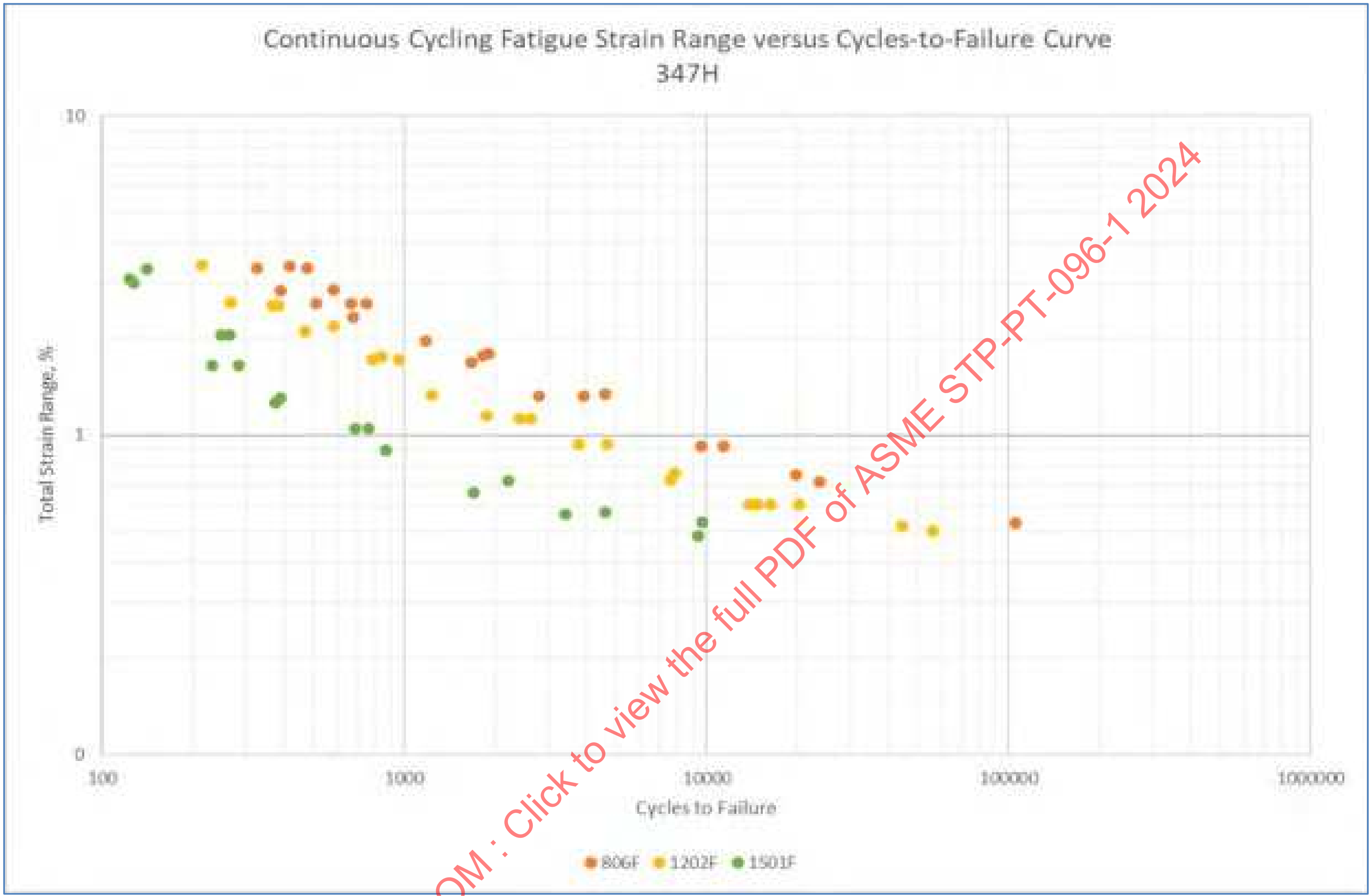


Figure 18-17: 347H Continuous Cycling Fatigue Strain Range Vs. Cycles to Failure



Attachment 18: 347H Property Data

If you want the referenced embedded spreadsheet with additional data, please email a request to research@asme.org.

19 ALLOY 617, 52NI-22CR-13CO-9MO

19.1 Physical Properties

Alloy 617 physical properties were referenced from the BPVC Section II for this material as well as the curves from WRC Bulletin 503. Both sources were plotted for comparison. The Idaho National Labs also provided property data from the 2015 draft code case. VDM Metals material data was also sourced for multiple physical properties. Data for thermal expansion and thermal conductivity published by Haynes was also included in the comparison. Figure 19-1 shows the trends of Elastic Modulus (E_y), Thermal Conductivity (k), Thermal Diffusivity (TD), and Thermal Expansion (α) with temperature.

19.2 Yield and Tensile Strength

Elevated temperature Yield and Tensile Strength over the range of existing allowable stresses (up to 1800°F) were readily available, including data beyond the current range of allowable stresses, up to approximately 2000°F, as shown in Figures 19-2 and 19-3. All sources for both high-temperature yield and high-temperature tensile strength are provided in the embedded spreadsheet at the end of this section. This spreadsheet also contains ductility data corresponding to the tensile test results presented in this report. Note that ductility (percent elongation and percent reduction in area) was not available for all sources referenced for the Alloy 617 material.

To facilitate comparison of the data obtained to existing allowable stresses (Section II-D Table 1B), yield and tensile data were normalized on a heat-by-heat basis to express the ratio of yield or tensile strength at temperature to that measured for the heat at room temperature. In cases where data were not delineated by heats within a given source, or in cases where more than one room-temperature tensile test existed for a given heat of material, ratios are equal to the measured tensile or yield strength at temperature, divided by the average of all of the appropriate room-temperature values for the particular data source or heat of material. As a result of this approach, it is possible to have ratios in excess of 1.0. E^2G understands that this approach is similar to the normalizing procedure performed by ASME in typical analysis of yield and tensile data to obtain Table Y and Table U (Section II-D) trend curves, as well as for the calculation of allowable stresses. Figures 19-4 and 19-5 show the heat-by-heat variation in yield and tensile strength ratios (respectively) as a function of temperature. It should be emphasized that even though the figure legends reference an entire source of data, the ratios, wherever possible, were calculated on a heat-by-heat basis; this is evident in the embedded spreadsheet at the end of this section. Figures 19-6 and 19-7 contain all of the yield and tensile (respectively) ratios plotted together, to facilitate regression of a 5th-order polynomial that is subsequently used for allowable stress comparison.

19.3 Creep Data (Creep Rupture, Minimum Creep Rate, and Ductility)

Creep Rupture data, plotted as isotherms, is shown in Figures 19-8 and 19-9. The temperatures have been separated onto separate plots to minimize data overlap, with Figure 19-8, including those temperatures where most of the data were concentrated, and Figure 19-9 including those intermediate temperatures with significantly less data. This allows for gaps between the bands of data, increasing visual clarity. It should be emphasized that these plots contain data for all product forms of material classified in the referenced publications as "Alloy 617." This certainly includes material meeting the requirements of ASME BPVC Section II-B specifications (e.g., SB-166, SB-167, SB-168, SB-564, etc.). However, due to the diversity of data sources utilized for the compilation of the material property tables, it is likely that some of the material shown in Figures 19-8 and 19-9 may not meet existing specifications for this grade of material. Where older publications are referenced, the chemistry (and for that matter, manufacturing, processing, and heat treatment) corresponding to the heat of material in the original data source, may not be consistent with modern specifications. Where possible, E^2G has documented the chemical composition if contained within the original source. In many cases, the project team has also made efforts to trace cross-referenced data back to original test results to determine if the heat treatment, product form, chemistry, etc. details can be obtained. This information is provided with the embedded spreadsheet to facilitate additional analysis on the part of ASME.

Creep Minimum strain rates (%/hour) are shown in Figures 19-10 and 19-11, separated by temperature. As in the case of rupture data, temperatures of minimum creep rates have been separated onto separate plots to minimize data overlap, with Figure 19-10, including those temperatures where most of the data were concentrated, and Figure 19-11 showing those intermediate temperatures with significantly less data. Creep Ductility, as % elongation, is plotted in Figure 19-12. As is typical, the data show significant overlap, and it is difficult to observe clear trends in the data. The data is not intended to be used as plotted but is available in the spreadsheet for additional analysis.

Creep data were analyzed using E^2G's proprietary Lot-Centered Analysis web-based software tool, in order to obtain creep properties. This regression is based on a Mandel-Paule algorithm and considers the variation within individual heats of material (for both rupture and strain rate data) as well as the variation between heats. The weight assigned to each datapoint and each heat is scaled based on the relative variation. Both rupture and strain rate (minimum creep rate, expressed as true strain per hours) were regressed according to a Larson-Miller time-temperature-parameter model, with a 3rd-order polynomial of stress. Lot-specific constant behavior was accounted for in this analysis, but the variation of LMP with stress was assumed to be constant (no non-parallel terms were included in the analysis). A 95% predictive limit was utilized to obtain the lower-bound (minimum LM constant for both rupture and strain rate) properties. The results of this analysis are summarized in Table 19-1 for rupture data and Table 19-2 for strain rate data. The Lot-Centered Analysis software tool generates property tables in the creep regime using the criteria outlined in Mandatory Appendix 1 of ASME Section II-D; the nomenclature of variables is consistent with II-D Appendix 1. For visualization of the allowable stress trends, Figure 19-13 is provided (for rupture allowable stresses and creep rate allowable stresses). Figure 19-14 shows a comparison of the various allowable stress criteria from Section II-D, Appendix 1, to the existing (2019) Section II-D Table 1B allowable stresses for annealed forms of Alloy 617 (which are the most conservative in the temperature-dependent range and equal to other forms in the time dependent range).

Creep Strain vs. time data are shown in Figure 19-15 for short-term data (up to 1,000 hour test durations), and 19-16 for long-term data (exceeding 1,000 hour test durations). Curves are only plotted where more than 10 strain vs. time points are present for the test. Additional curves are available with fewer datapoints (typically obtained from data in the form of time-until-specified-strain, in the embedded spreadsheet. Both creep rate and creep strain vs. time data are provided to satisfy ASME's request for creep strain vs. time curves, and both forms of data are applicable in developing allowable stresses. Although digitalization of creep curve data was not explicitly necessary per the project contract, E^2G did perform digitalization of creep curves where only graphical data was available (as is often the case in the published literature).

19.4 Continuous Cycling Fatigue and Hold Time Fatigue Curves

A portion of the data obtained for continuous cycling fatigue data at elevated temperatures for Alloy 617 is shown in Figure 19-17, which includes a limited amount of room temperature data contained in sources which also present high-temperature data. Figure 19-17 only contains data for which total strain range was determined from the original source. Additional data points for continuous cycling fatigue data of Alloy 617 are presented in the attached spreadsheet; however, due to the complexities of various forms of fatigue data, compatible plots for each type of data expression and failure criteria are not included in this report.

Hold time fatigue data at high temperature is shown in Figure 19-18 (1472°F, 1652°F, 1750-60°F, and 1832°F), Figure 19-19 (1292°F), Figure 19-20 (1562°F), and Figure 19-21 (1742°F) with separate plots for temperatures at which at least a moderate collection of data points existed. Additional data is provided in the embedded spreadsheet.

Table 19-1: Model Parameters, Larson-Miller Property Results, and Allowable Stress (Rupture) Criteria, Alloy 617

Equation Format:

$$\log(t_r) = C_{avg} + \frac{1}{T+460}\left(b_1 + b_2\log(\sigma) + b_3(\log(\sigma))^2 + b_4(\log(\sigma))^3\right)$$

Cavg	**-17.61**
Cmin	**-18.14**
b_1	**50738.4**
b_2	**-7581.2**
b_3	**-1430**
b_4	**-89.91**

Number Data Points		**677**
Correlation Coefficient	R^2	0.8538
Average Variance within Heats	V_w	0.1038
Variance between Heats	V_b	0.1161
Standard Error of Estimate	SEE	0.3221

Properties provided are for T in °F, stress in ksi, and t_R in hours

Temperature, °F	**S_{avg} (ksi)**	***n***	**F_{avg} (calc)**	**F_{avg} (used)**	**Favg × Savg**	**S_{min} (ksi)**	**80% S_{min}**
850	92.59	10.88	0.8092	0.67	62.04	82.67	66.14
900	76.98	10.25	0.7987	0.67	51.57	68.25	54.6
950	63.72	9.659	0.7879	0.67	42.7	56.09	44.87
1000	52.52	9.109	0.7766	0.67	35.19	45.87	36.69
1050	43.08	8.593	0.7649	0.67	28.86	37.31	29.85
1100	35.16	8.107	0.7528	0.67	23.56	30.19	24.15
1150	28.54	7.649	0.7401	0.67	19.12	24.28	19.42
1200	23.04	7.216	0.7268	0.67	15.43	19.41	15.52
1250	18.48	6.805	0.7129	0.67	12.38	15.4	12.32
1300	14.73	6.415	0.6984	0.67	9.866	12.14	9.71

** E^2G's proprietary *Lot-Centered Analysis* web-based software tool only provides results up to 1300°F, but it should be noted that Alloy 617 allowable stress properties are observed above 1300°F.

Table 19-2: Model Parameters, Larson-Miller Property Results, and Allowable Stress (Strain Rate) Criteria, Alloy 617

Equation Format:

$$\log(\dot{\varepsilon}_0) = -C_{avg} - \frac{1}{T+460}\left(a_1 + a_2\log(\sigma) + a_3(\log(\sigma))^2 + a_4(\log(\sigma))^3\right)$$

C_{avg} (A_0)	**-23.33**
Cmin (A0+ΔΩSR,LB)	**-24.17**
a_1	**66409.5**
a_2	**-21815.2**
a_3	**9936.3**
a_4	**-3039.1**

Number Data Points		**348**
Correlation Coefficient	R2	0.7587
Average Variance within Heats	V_w	0.2629
Variance between Heats	V_b	0.9028
Standard Error of Estimate	SEE	0.5128

Properties provided are for T in °F, stress in ksi, and t_R in hours

Temperature, °F	**$S_{C,avg}$ (ksi)**
850	114.2
900	96.11
950	79.87
1000	65.46
1050	52.82
1100	41.9
1150	32.66
1200	25.01
1250	18.86
1300	14.07

** E^2G's proprietary *Lot-Centered Analysis* web-based software tool only provides results up to 1300°F, but it should be noted that Alloy 617 allowable stress properties are observed above 1300°F.

Figure 19-1: Alloy 617 Modulus (E_y), Thermal Conductivity (k), Thermal Diffusivity (TD), & Thermal Expansion (α) With Temperature

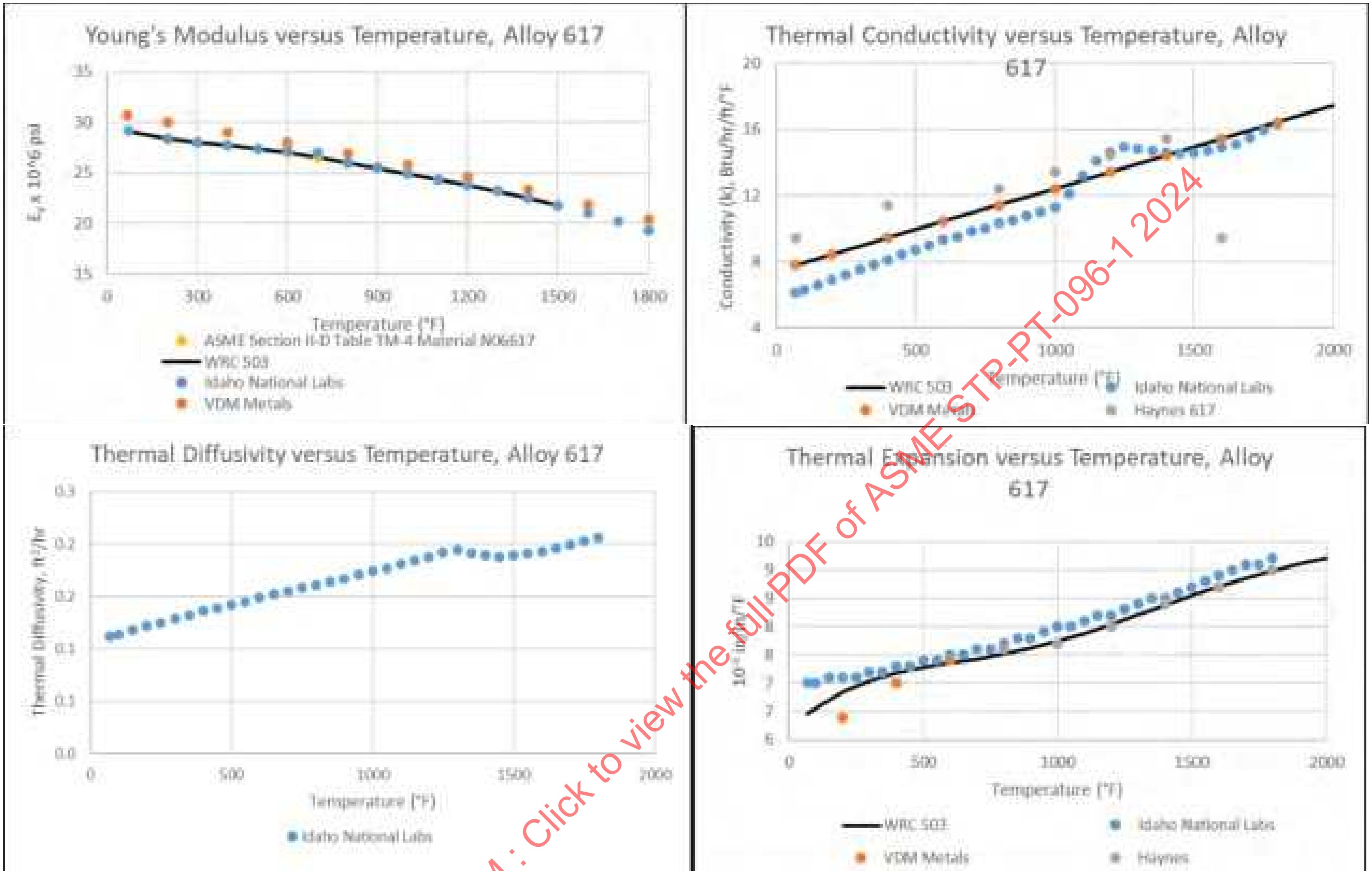


Figure 19-2: Alloy 617 Yield Strength Vs. Temperature, By Data Source, Including Trend Curves

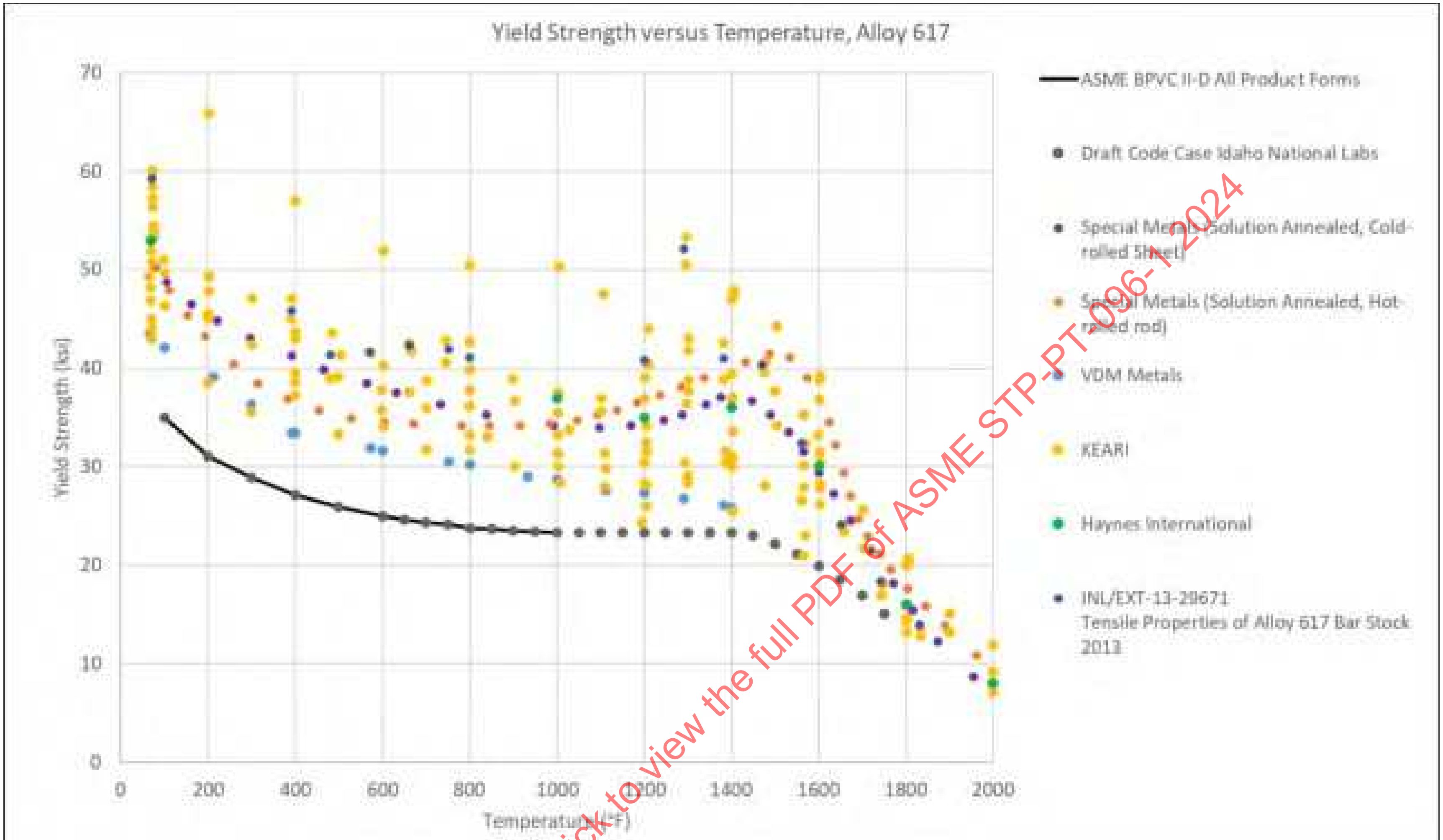


Figure 19-3: Alloy 617 Tensile Strength Vs. Temperature, By Data Source, Including Trend Curves

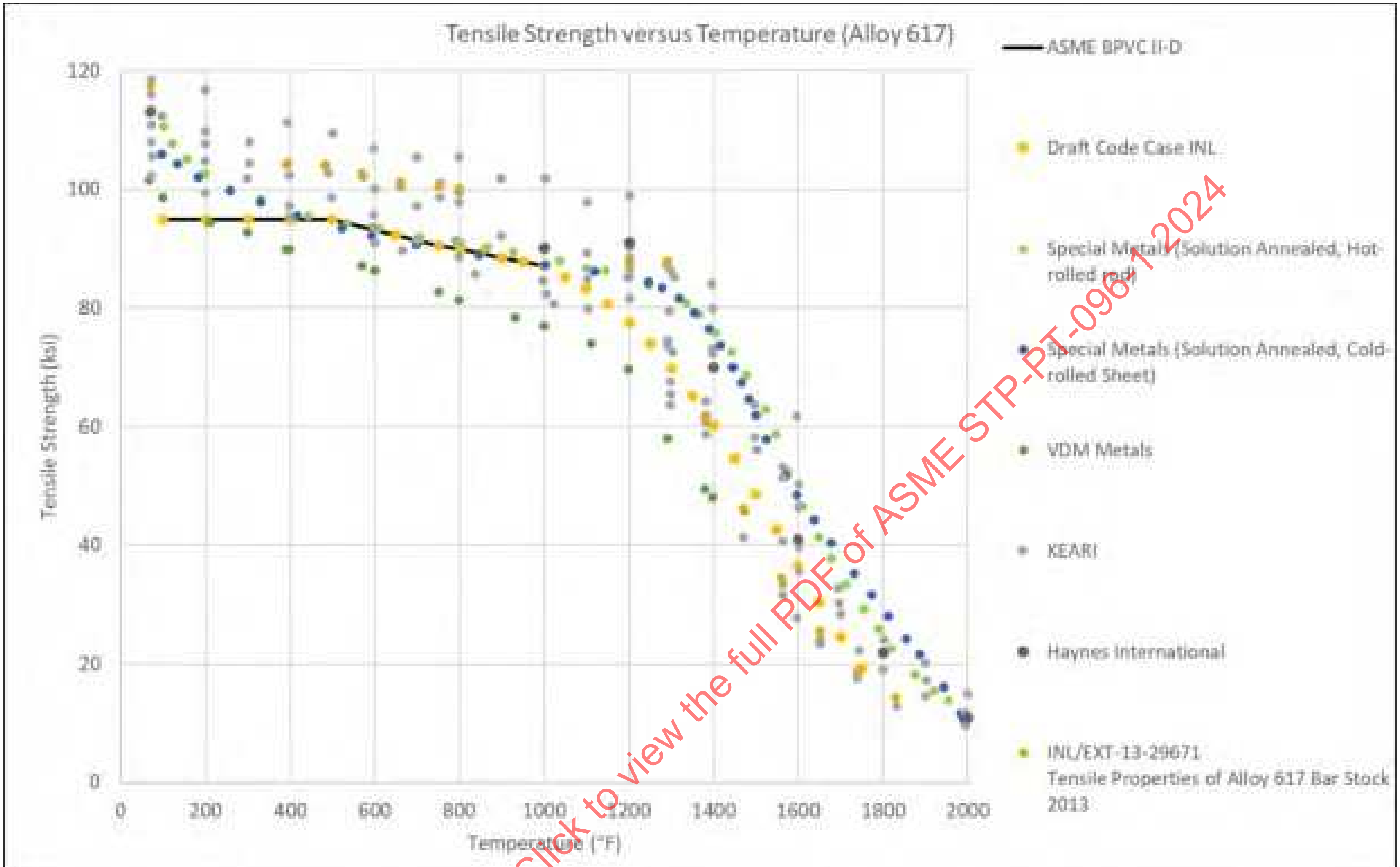


Figure 19-4: Alloy 617 Yield Strength Ratios Vs. Temperature (Calculated on a Heat-By-Heat Basis, By Data Source)

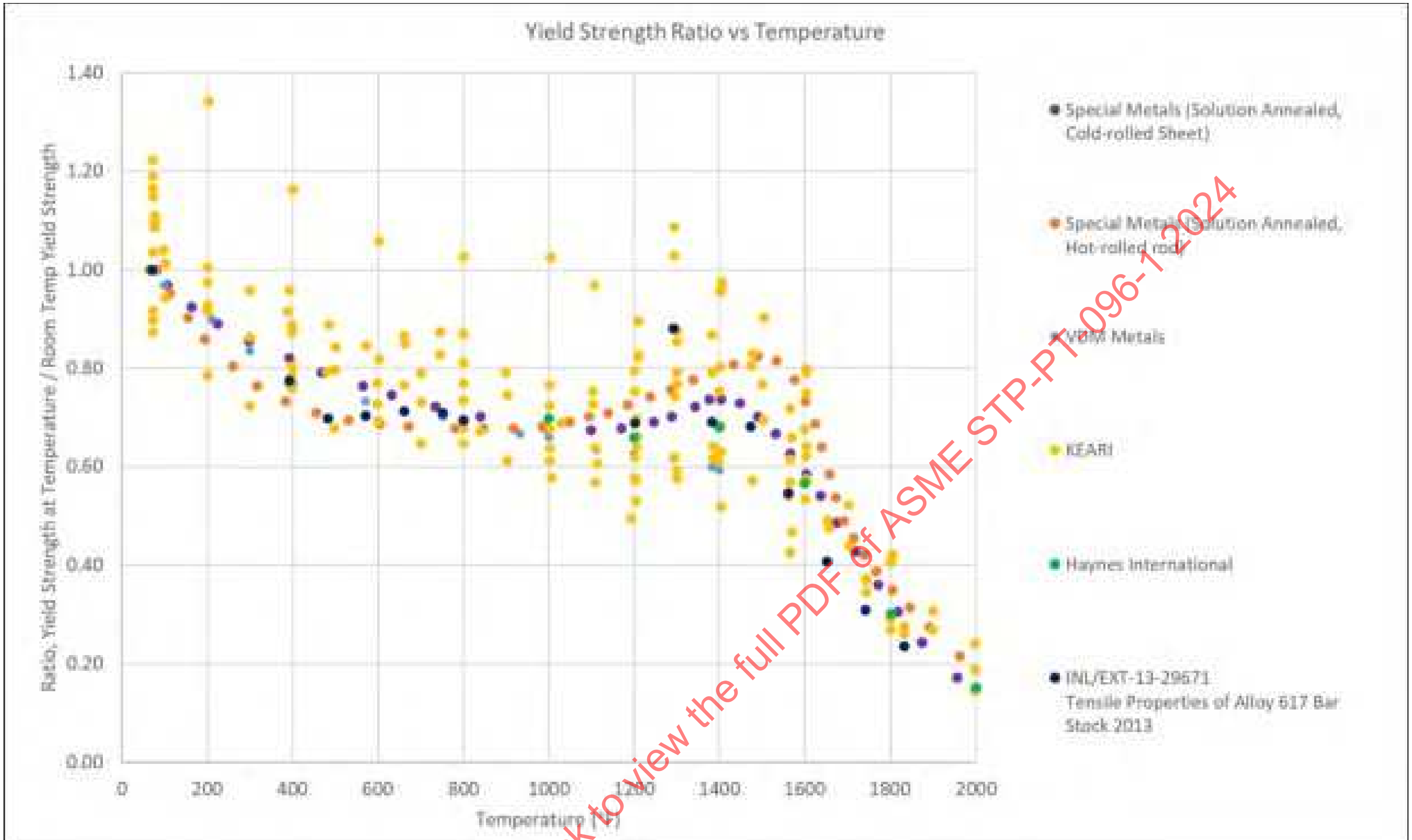


Figure 19-5: Alloy 617 Tensile Strength Ratios Vs. Temperature (Calculated on a Heat-By-Heat Basis, By Data Source)

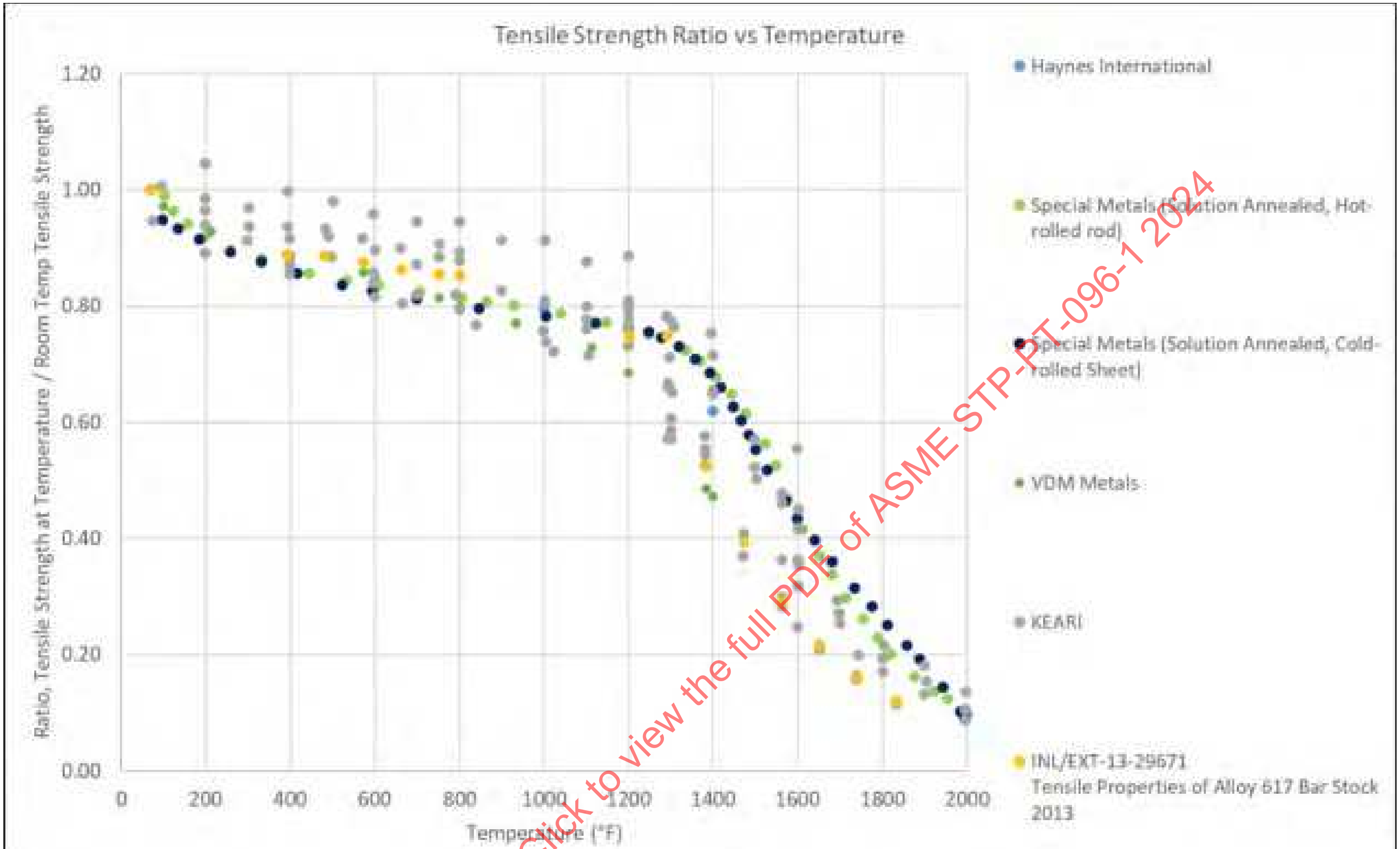


Figure 19-6: Alloy 617 Yield Strength Ratios Vs. Temperature, All Combined Data, With Polynomial Regression

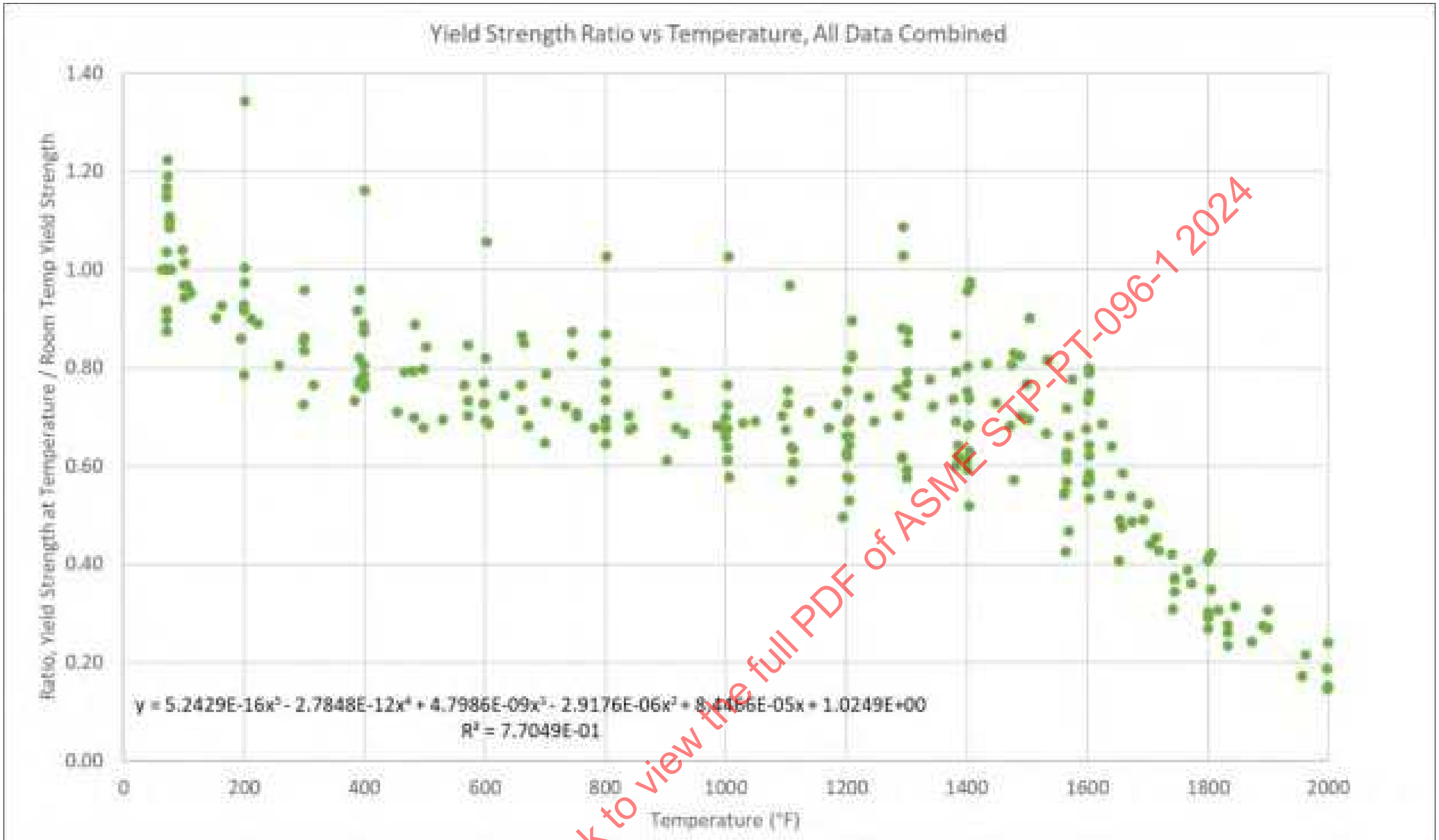


Figure 19-7: Alloy 617 Tensile Strength Ratios Vs. Temperature, All Combined Data, With Polynomial Regression

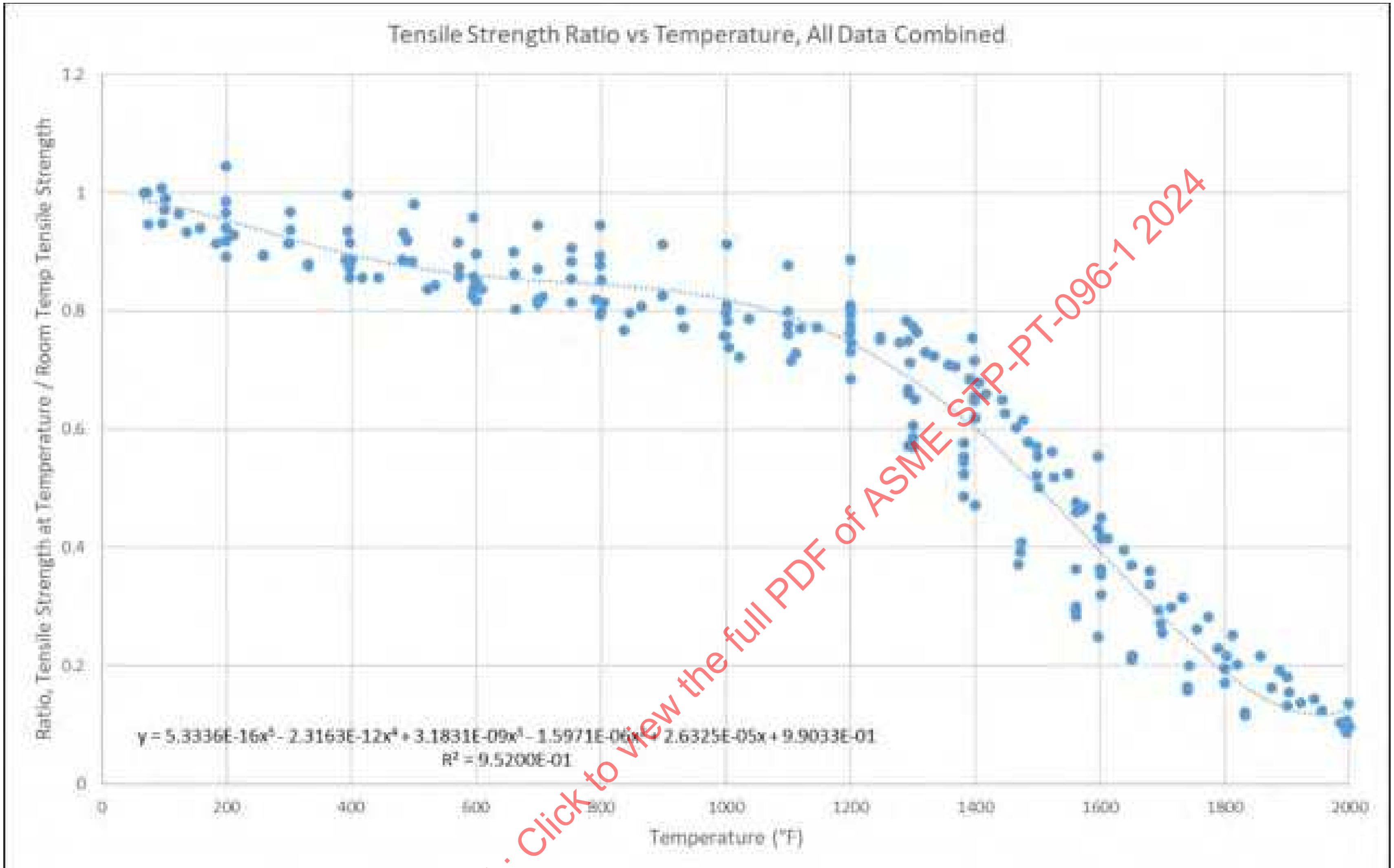


Figure 19-8: Alloy 617 Creep Rupture Isotherm Curves, Most Common Temperatures

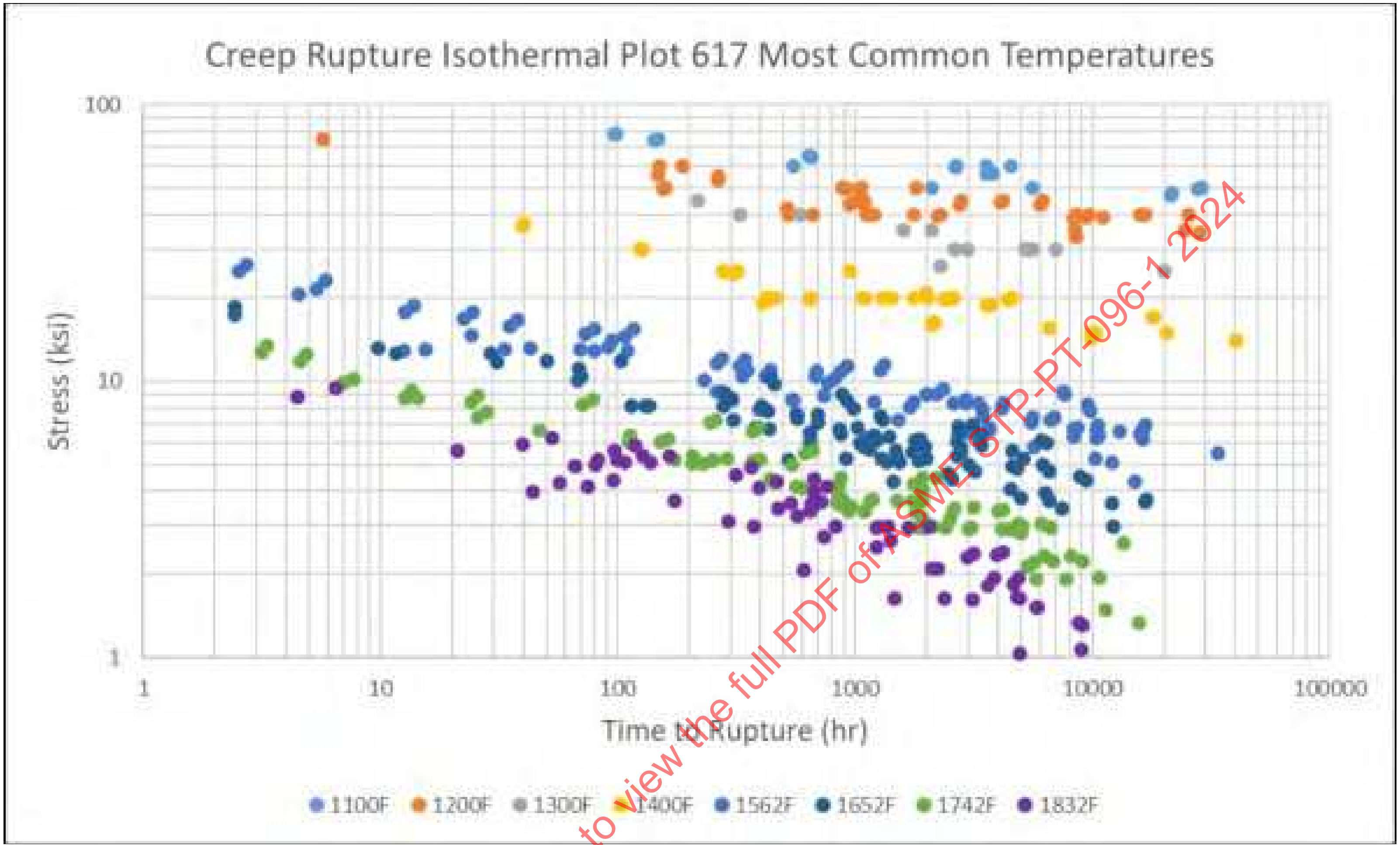


Figure 19-9: Alloy 617 Creep Rupture Isotherm Curves, Intermediate Temperatures

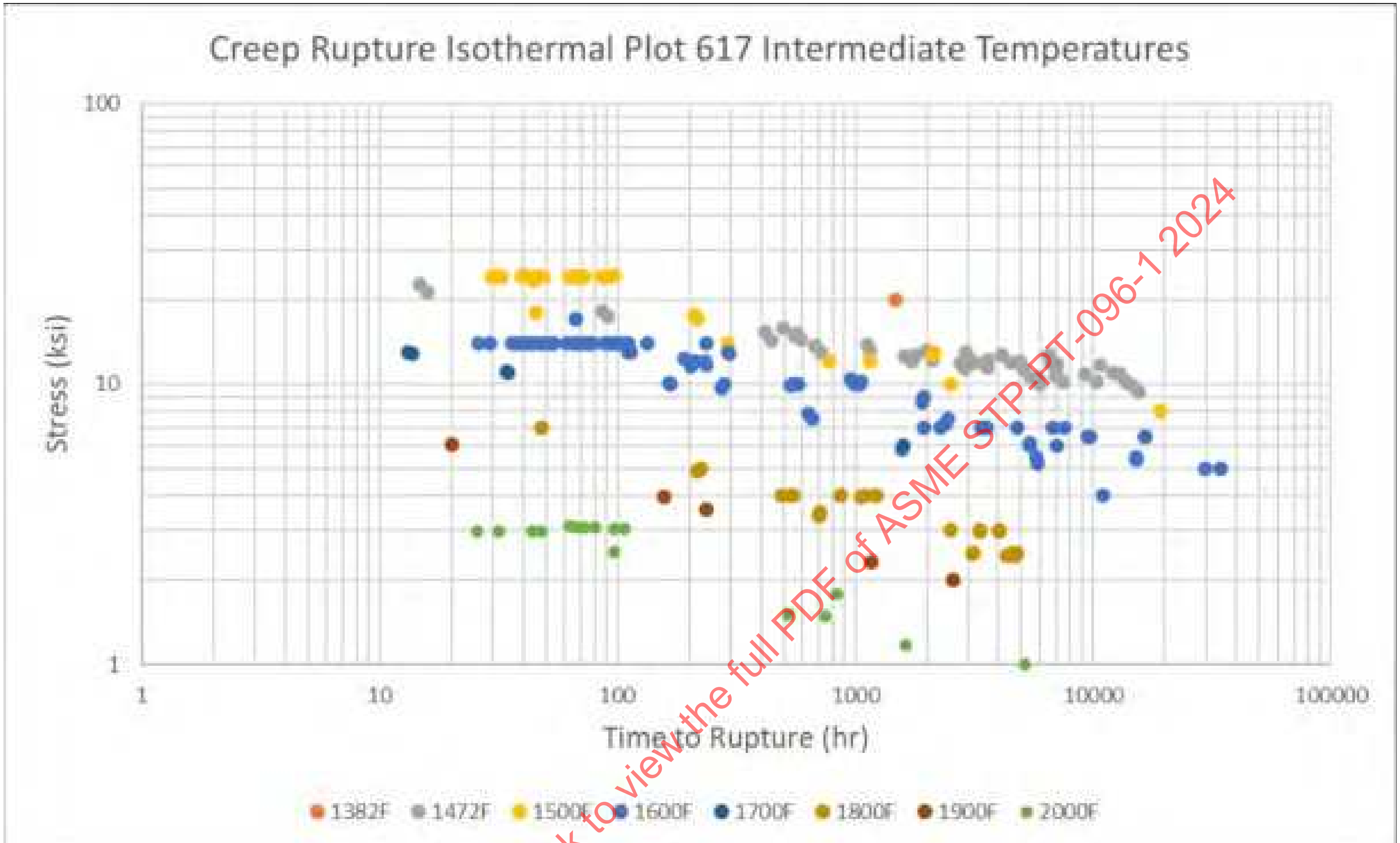


Figure 19-10: Alloy 617 Creep Strain Rate (MCR) Isotherm Curves, Most Common Temperatures

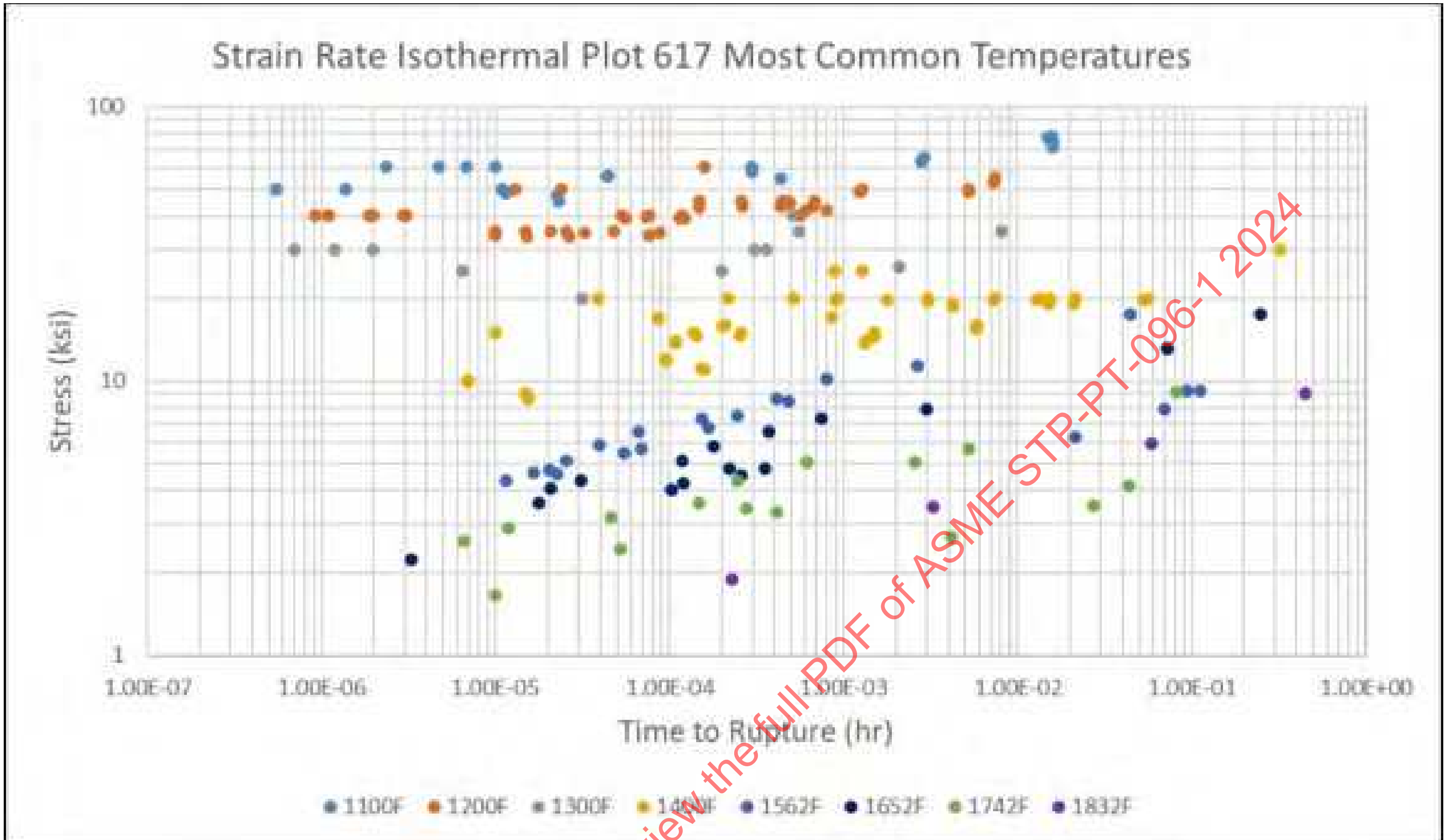


Figure 19-11: Alloy 617 Creep Strain Rate (MCR) Isotherm Curves, Intermediate Temperatures

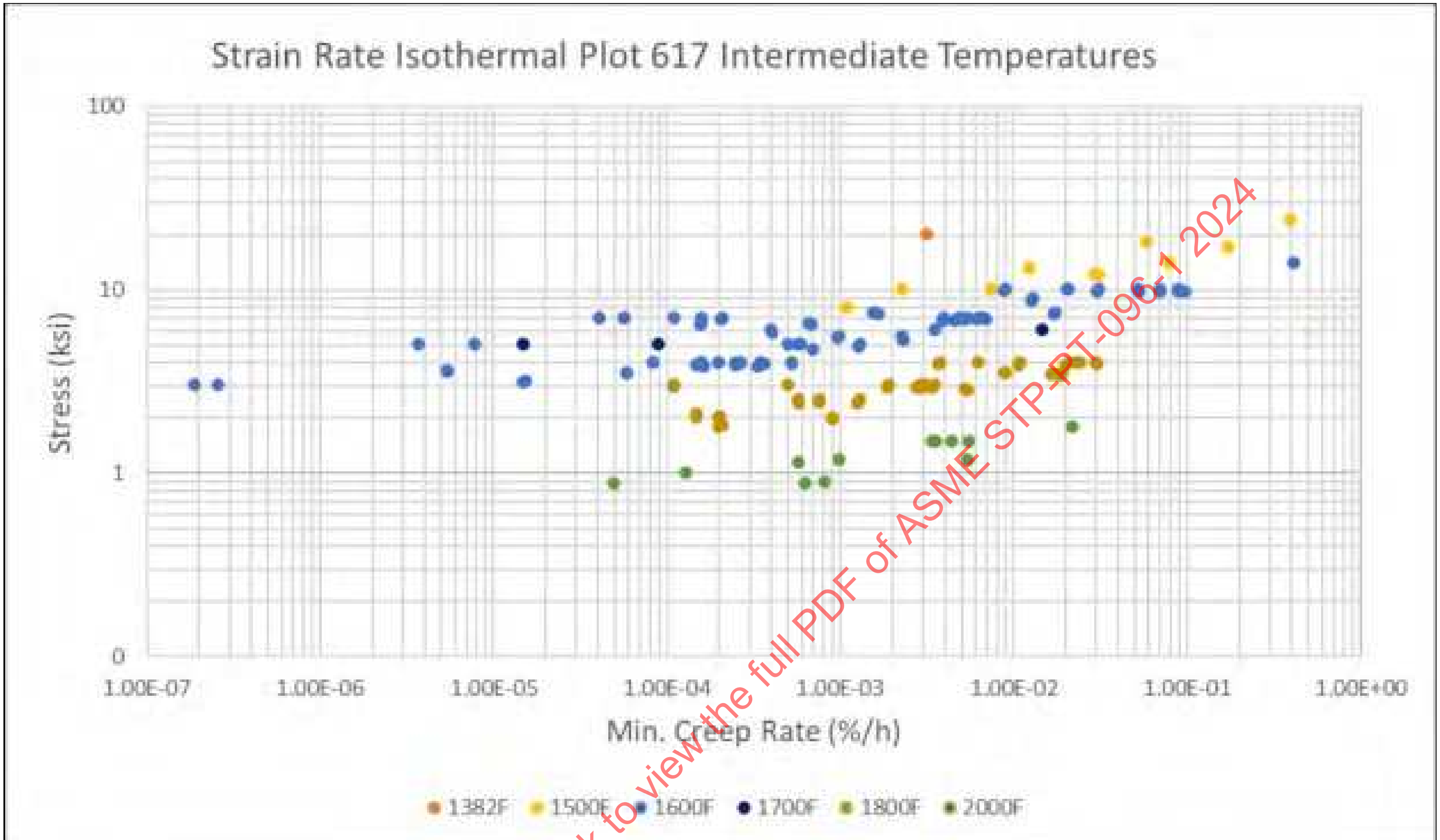


Figure 19-12: Alloy 617 Creep Ductility (% Elongation) Vs. Rupture Time Isotherms

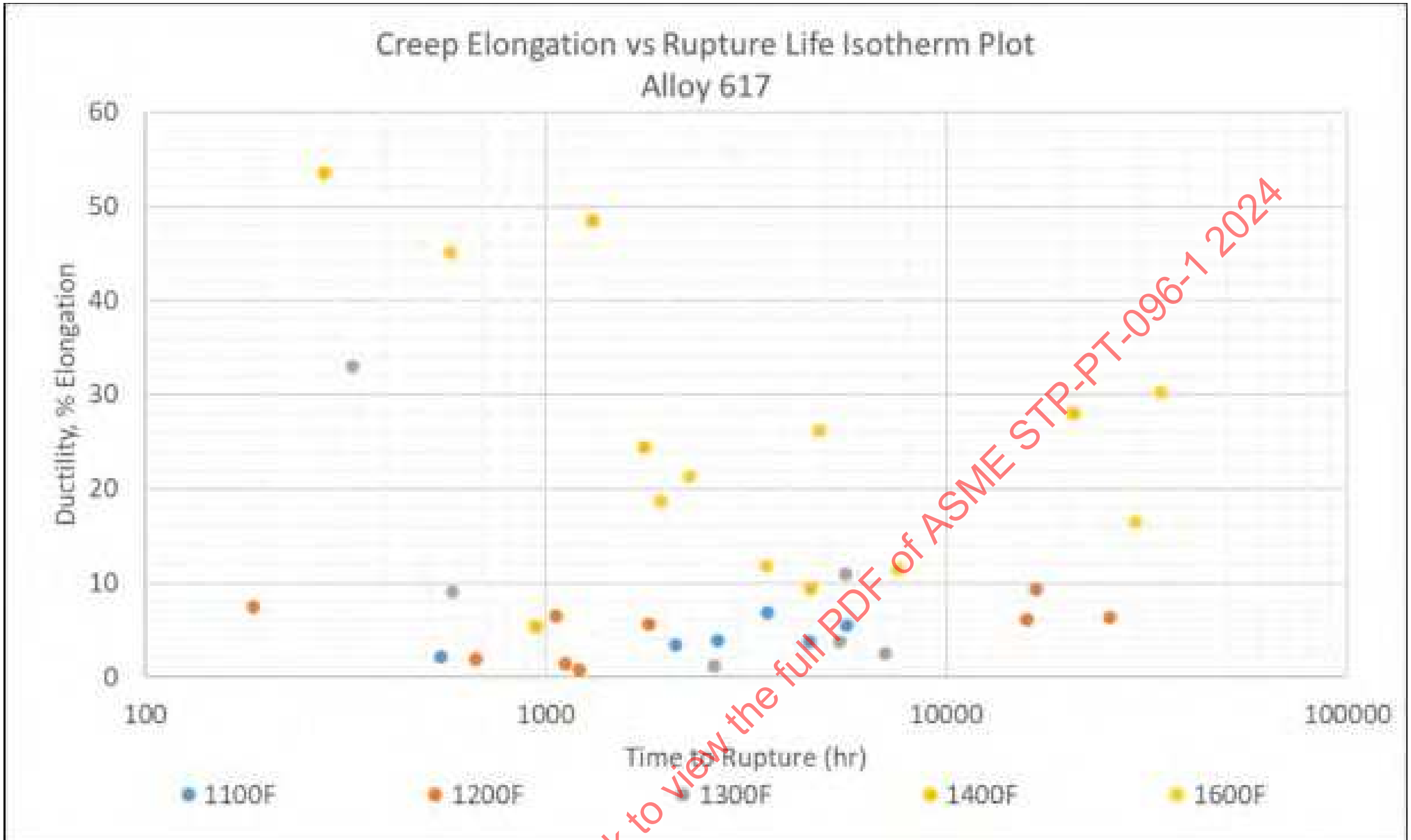


Figure 19-13: Calculated Allowable Stresses Based on Rupture and Creep Strain Rate and ASME II-D Appendix 1 Criteria (Alloy 617)

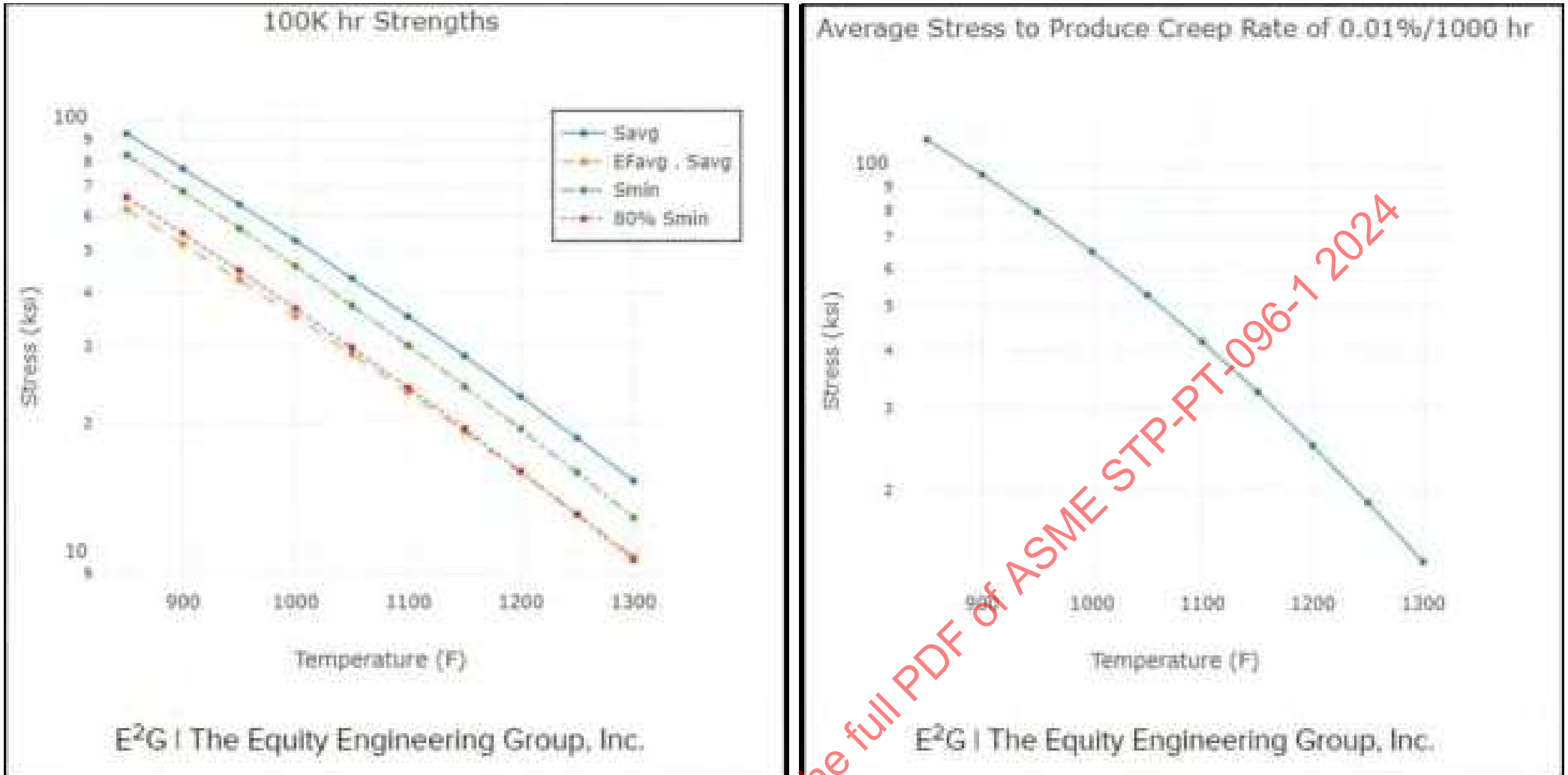


Figure 19-14: Comparison of Current Alloy 617 Allowable Stresses (Annealed) Vs. ASME II-D Appendix 1 Criteria Applied to Data

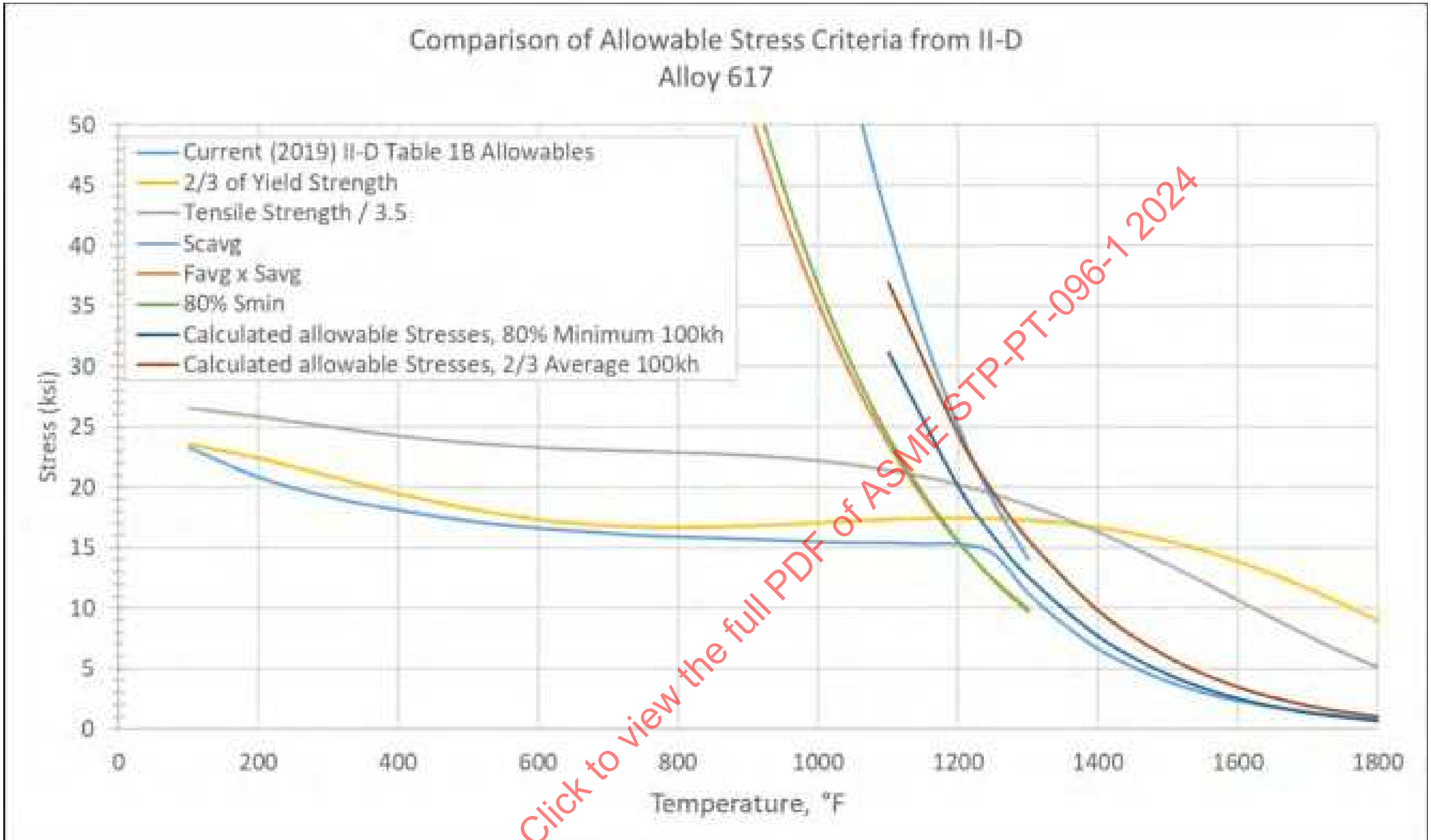


Figure 19-15: Short-Term Strain Vs. Time Data, up to 1,000 Hour Test Durations (Alloy 617)

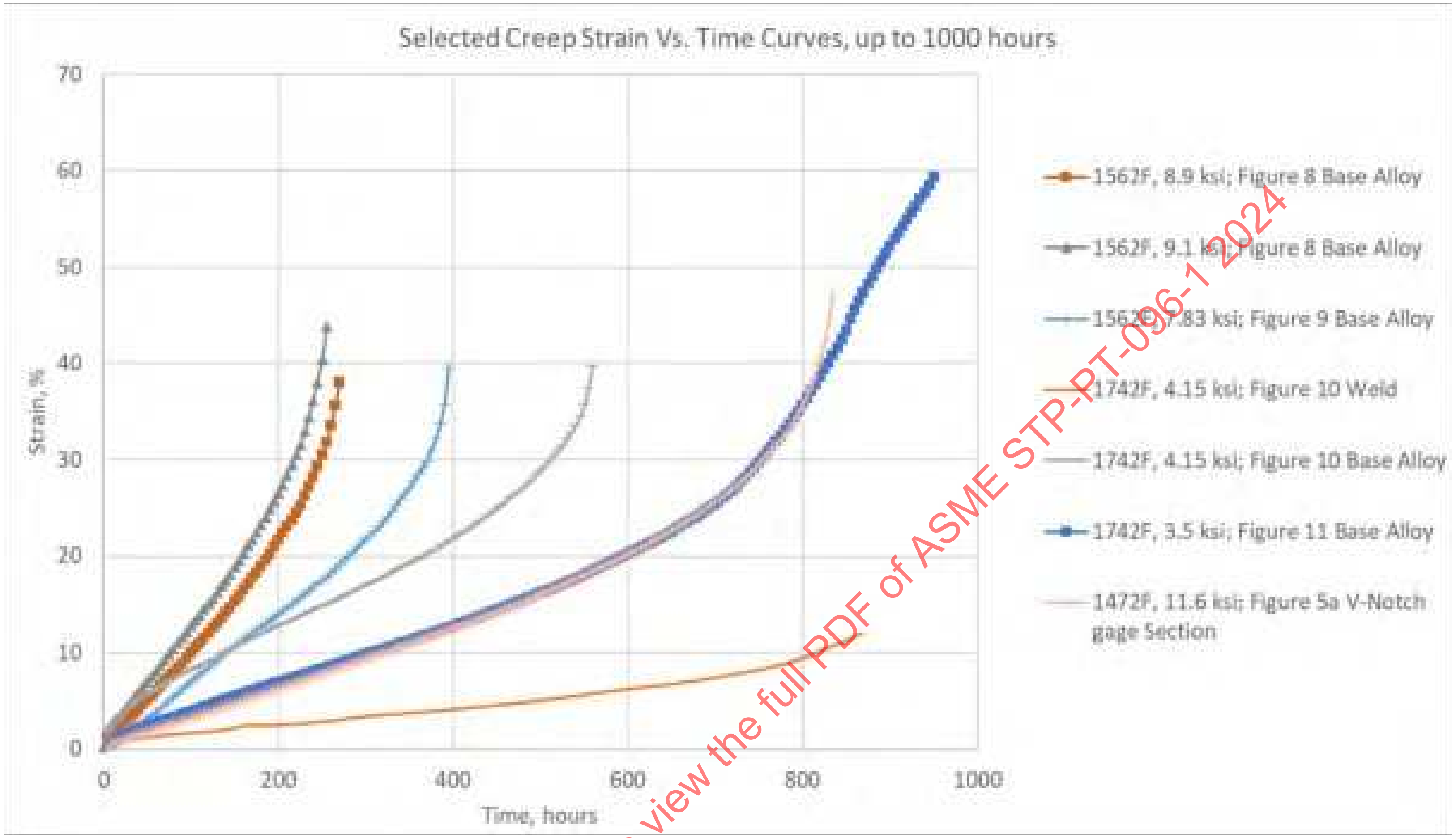


Figure 19-16: Short-Term Strain Vs. Time Data, In Excess of 1,000 Hour Test Durations (Alloy 617)

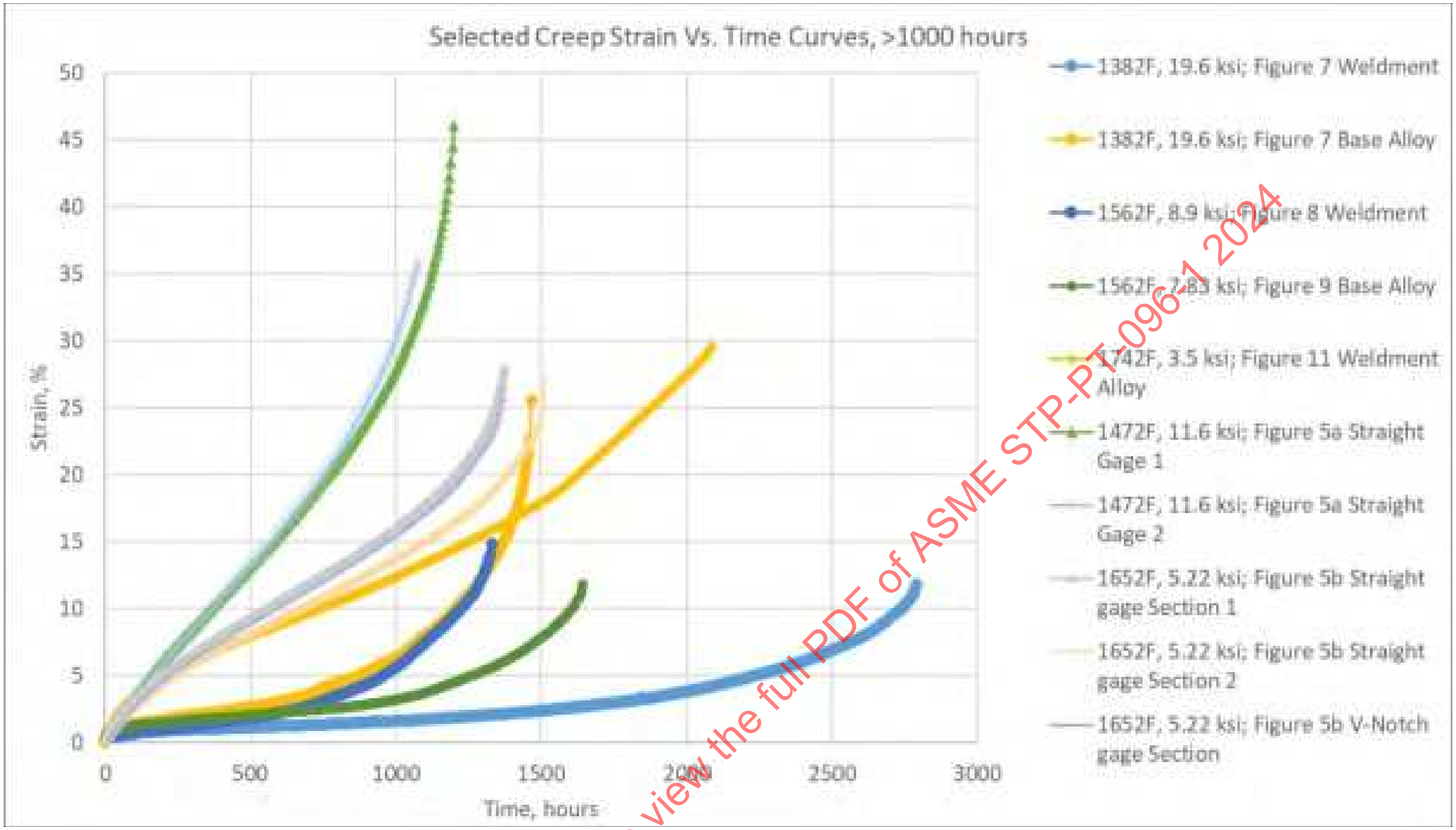


Figure 19-17: Alloy 617 Continuous Cycling Fatigue, Including Room Temperature and Elevated Temperature Data

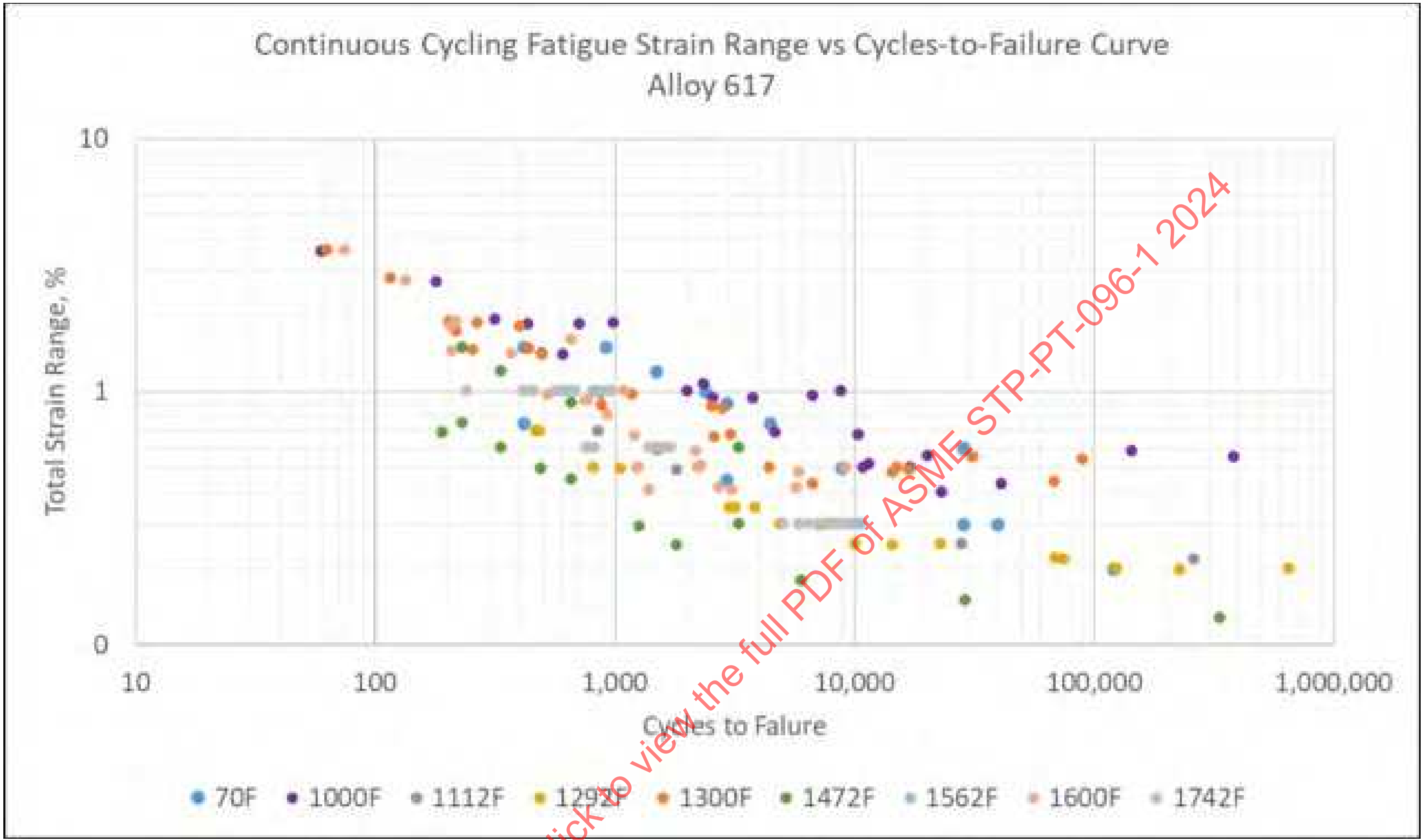


Figure 19-18: Alloy 617 Hold Time Data (Creep Fatigue) for Alloy 617, Temperatures of 1472°F, 1652°F, 1750-60°F, & 1832°F

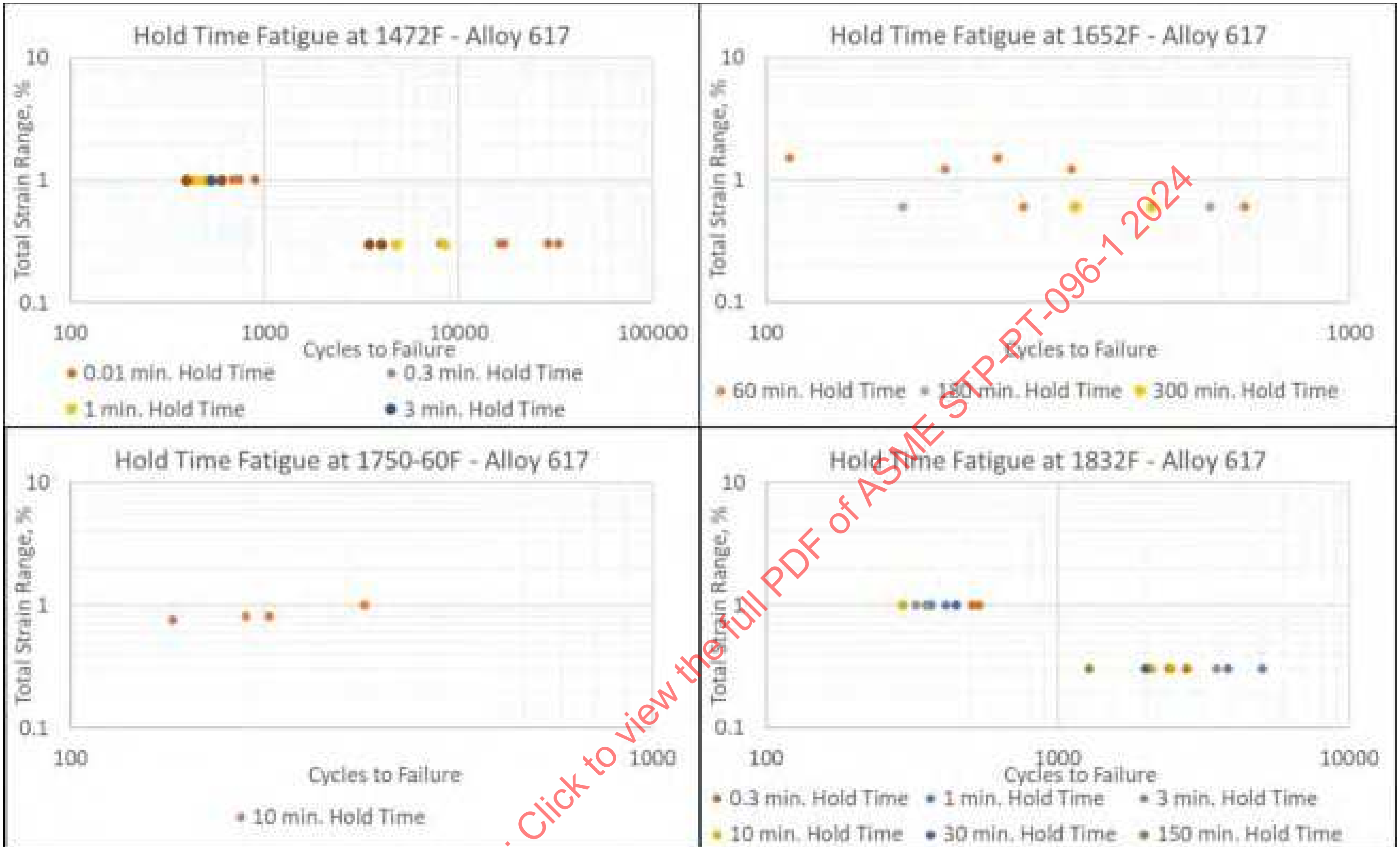


Figure 19-19: Alloy 617 Hold Time Data (Creep Fatigue) for Alloy 617, Temperature of 1292°F

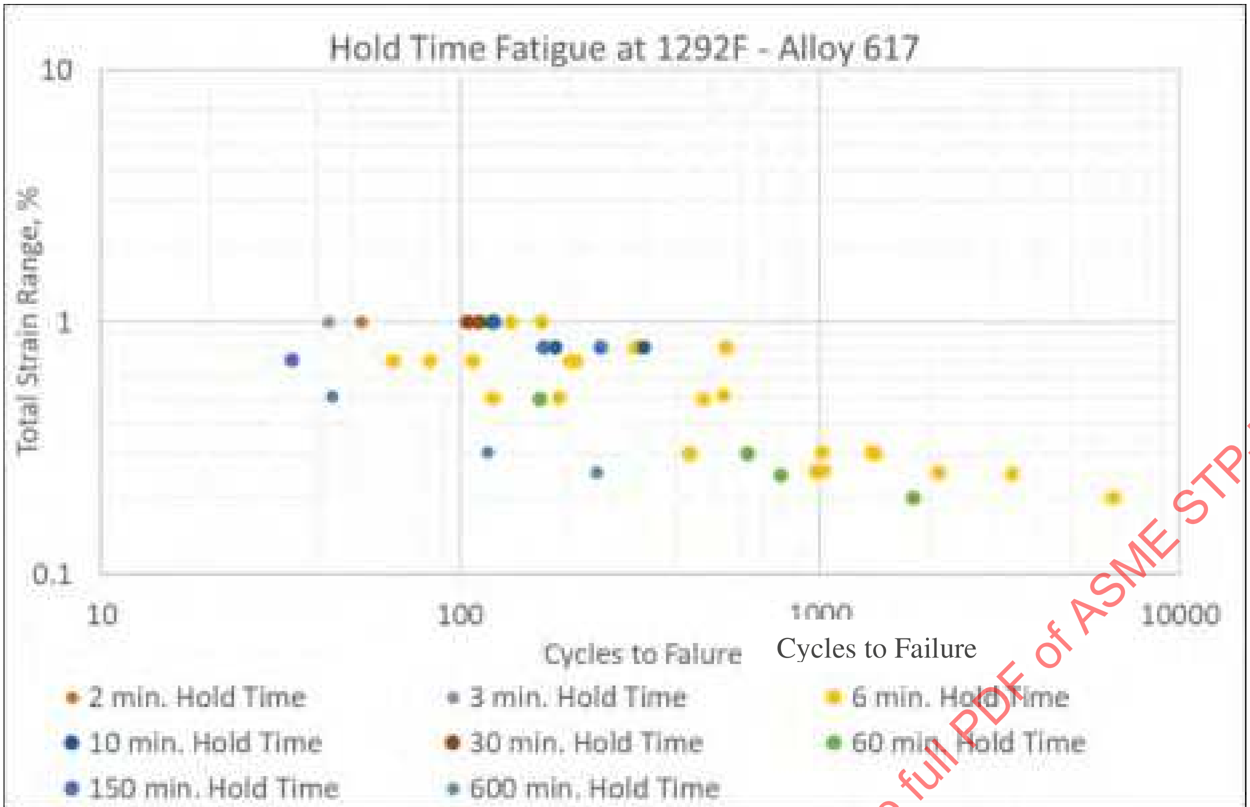


Figure 19-20: Alloy 617 Hold Time Data (Creep Fatigue) for Alloy 617, Temperature of 1562°F

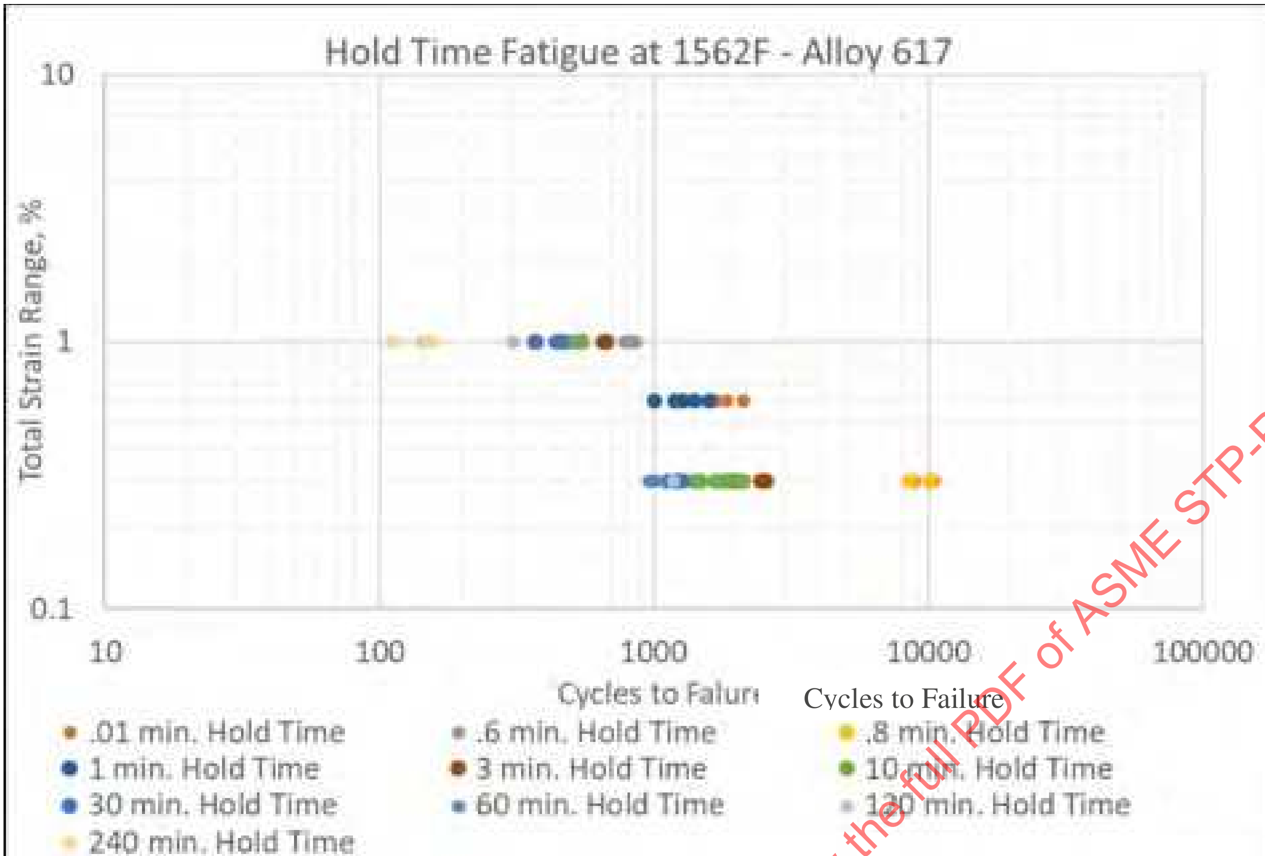
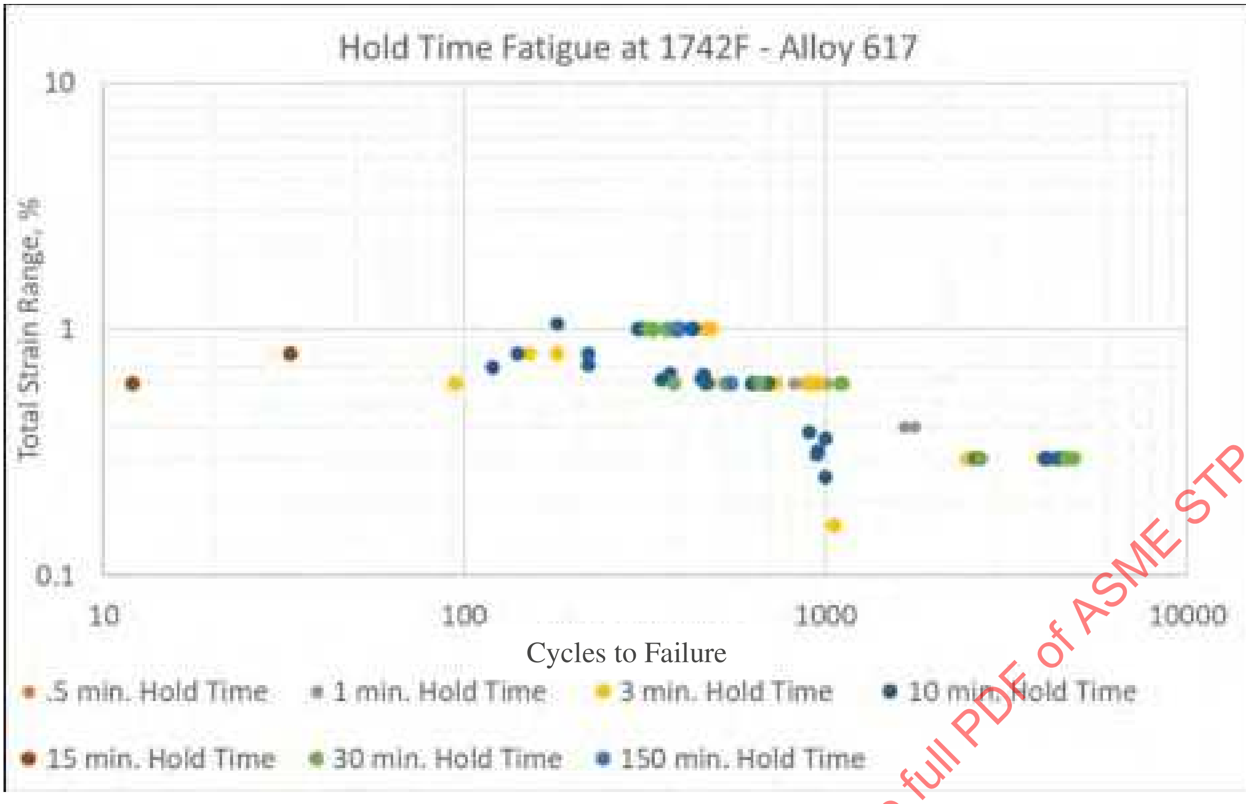


Figure 19-21: Alloy 617 Hold Time Data (Creep Fatigue) For Alloy 617, Temperature of 1742°F



Attachment 19: Alloy 617 Property Data

If you want the referenced embedded spreadsheet with additional data, please email a request to research@asme.org.

20 INCONEL 740H

20.1 Physical Properties

Physical properties for this material were taken from the ASME BPVC CC BPV 2017 Code Case 2702 (N07740). Additionally, physical property curves were plotted for comparison from WRC Bulletin 503. Figure 20-1 shows the plotted data and trends of Elastic Modulus (E_y), Thermal Conductivity (k), Thermal Diffusivity (TD), and Thermal Expansion (α) with temperature.

20.2 Yield and Tensile Strength

The sources for both high-temperature yield and high-temperature tensile strength are provided in the embedded spreadsheet at the end of this section. High-temperature yield and high-temperature tensile strength data are plotted, up to approximately 1800°F, as shown in Figures 20-2 and 20-3. As with other materials, yield and tensile data were normalized on a heat-by-heat basis to express the ratio of yield or tensile strength at temperature to that measured for the heat at room temperature. In cases where data were not delineated by heats within a given source, or in cases where more than one room-temperature tensile test existed for a given heat of material, ratios are equal to the measured tensile or yield strength at temperature, divided by the average of all of the appropriate room-temperature values for the particular data source or heat of material. As a result of this approach, it is possible to have ratios in excess of 1.0. E^2G understands that this approach is similar to the normalizing procedure performed by ASME in typical analysis of yield and tensile data to obtain Table Y and Table U (Section II-D) trend curves, as well as for the calculation of allowable stresses. The heat-by-heat variation in yield strength ratio as a function of temperature is shown in Figure 20-4. Similarly, the heat-by-heat variation in tensile strength as a function of temperature is depicted in Figure 20-5. Figures 20-6 and 20-7 contain all of the yield and tensile ratios plotted together, respectively, to facilitate regression of a 5th-order polynomial that is subsequently used for allowable stress comparison.

20.3 Creep Data (Creep Rupture, Minimum Creep Rate, and Ductility)

Plotted as isothermal figures, compiled Creep Rupture data can be seen in Figure 20-8. Creep Minimum strain rates (%/hour) can be seen in Figure 20-9, separated by temperature. Unlike creep rupture, a limited amount of strain rate data was found for this material. Similarly, creep ductility, as % elongation, is plotted in Figure 20-10. Creep data were analyzed using E^2G's proprietary Lot-Centered Analysis web-based software tool, in order to obtain creep properties. This regression is based on a Mandel-Paule algorithm and considers the variation within individual heats of material (for both rupture and strain rate data) as well as the variation between heats. The weight assigned to each datapoint and each heat is scaled based on the relative variation. Both rupture and strain rate (minimum creep rate, expressed as true strain per hours) were regressed according to a Larson-Miller time-temperature-parameter model, with a 3rd-order polynomial of stress. Lot-specific constant behavior was accounted for in this analysis, but the variation of LMP with stress was assumed to be constant (no non-parallel terms were included in the analysis). A 95% predictive limit was utilized to obtain the lower-bound (minimum LM constant for both rupture and strain rate) properties. The results of this analysis are summarized in Table 20-1 for rupture data and Table 20-2 for strain rate data. The Lot-Centered Analysis software tool generates property tables in the creep regime using the criteria outlined in Mandatory Appendix 1 of ASME Section II-D; the nomenclature of variables is consistent with II-D Appendix 1. For visualization of the allowable stress trends, Figure 20-11 is provided (for rupture allowable stresses and creep rate allowable stresses). Figure 20-12 shows a comparison of the various allowable stress criteria from Section II-D, Appendix 1, to the existing BPVC CC 2017 BPV Code Case 2702 allowable stresses.

No creep strain vs. time data was available for 740H.

20.4 Continuous Cycling Fatigue Curves

No continuous cycling or hold time fatigue data was available for 740H.

Table 20-1: Model Parameters, Larson-Miller Property Results, and Allowable Stress (Rupture) Criteria, 740H

Equation Format:

$$\log(t_r) = C_{avg} + \frac{1}{T+460}\left(b_1 + b_2\log(\sigma) + b_3(\log(\sigma))^2 + b_4(\log(\sigma))^3\right)$$

C_{avg}	-15.93
C_{min}	-16.45
b_1	40853
b_2	-176.9
b_3	-714.6
b_4	-962.5

Number Data Points		250
Correlation Coefficient	R^2	0.7888
Average Variance within Heats	V_w	0.0987
Variance between Heats	V_b	0.1147
Standard Error of Estimate	SEE	0.3142

Properties provided are for T in °F, stress in ksi, and t_R in hours

Temperature, °F	S_{avg} (ksi)	*n*	F_{avg} (calc)	F_{avg} (used)	$F_{avg} \times S_{avg}$	S_{min} (ksi)	80% S_{min}
850	144.8	12.79	0.8352	0.67	97.04	131.7	105.4
900	124.9	11.67	0.8209	0.67	83.71	112.6	90.05
950	106.9	10.61	0.8049	0.67	71.59	95.25	76.2
1000	90.48	9.608	0.7869	0.67	60.62	79.66	63.73
1050	75.73	8.65	0.7663	0.67	50.74	65.7	52.56
1100	62.51	7.729	0.7424	0.67	41.88	53.27	42.62
1150	50.72	6.838	0.7141	0.67	33.98	42.29	33.83
1200	40.27	5.97	0.68	0.67	26.98	32.64	26.11
1250	31.1	5.114	0.6375	0.67	20.84	24.26	19.41
1300	23.11	4.259	0.5824	0.67	15.48	17.04	13.63

Table 20-2: Model Parameters, Larson-Miller Property Results, and Allowable Stress (Strain Rate) Criteria, 740H

Equation Format:

$$\log(\dot{\varepsilon}_0) = -C_{avg} - \frac{1}{T+460}\left(a_1 + a_2\log(\sigma) + a_3(\log(\sigma))^2 + a_4(\log(\sigma))^3\right)$$

C_{avg} (A_0)	**327.6**
C_{min} ($A_0+\Delta_\Omega^{SR,LB}$)	**327.3**
a_1	**0**
a_2	**-1.12E+06**
a_3	**7.12E+05**
a_4	**-1.52E+05**

Number Data Points		**8**
Correlation Coefficient	R^2	0.9698
Average Variance within Heats	V_w	0.04057
Variance between Heats	V_b	0
Standard Error of Estimate	SEE	0.2014

Properties provided are for T in °F, stress in ksi, and t_R in hours

Temperature, °F	**$S_{C,avg}$ (ksi)**
850	3.488
900	3.777
950	4.115
1000	4.514
1050	4.996
1100	5.592
1150	6.354
1200	7.373
1250	8.839
1300	11.25

Figure 20-1: 740 Modulus (E_y), Thermal Conductivity (k), Thermal Diffusivity (TD), & Thermal Expansion (α) With Temperature

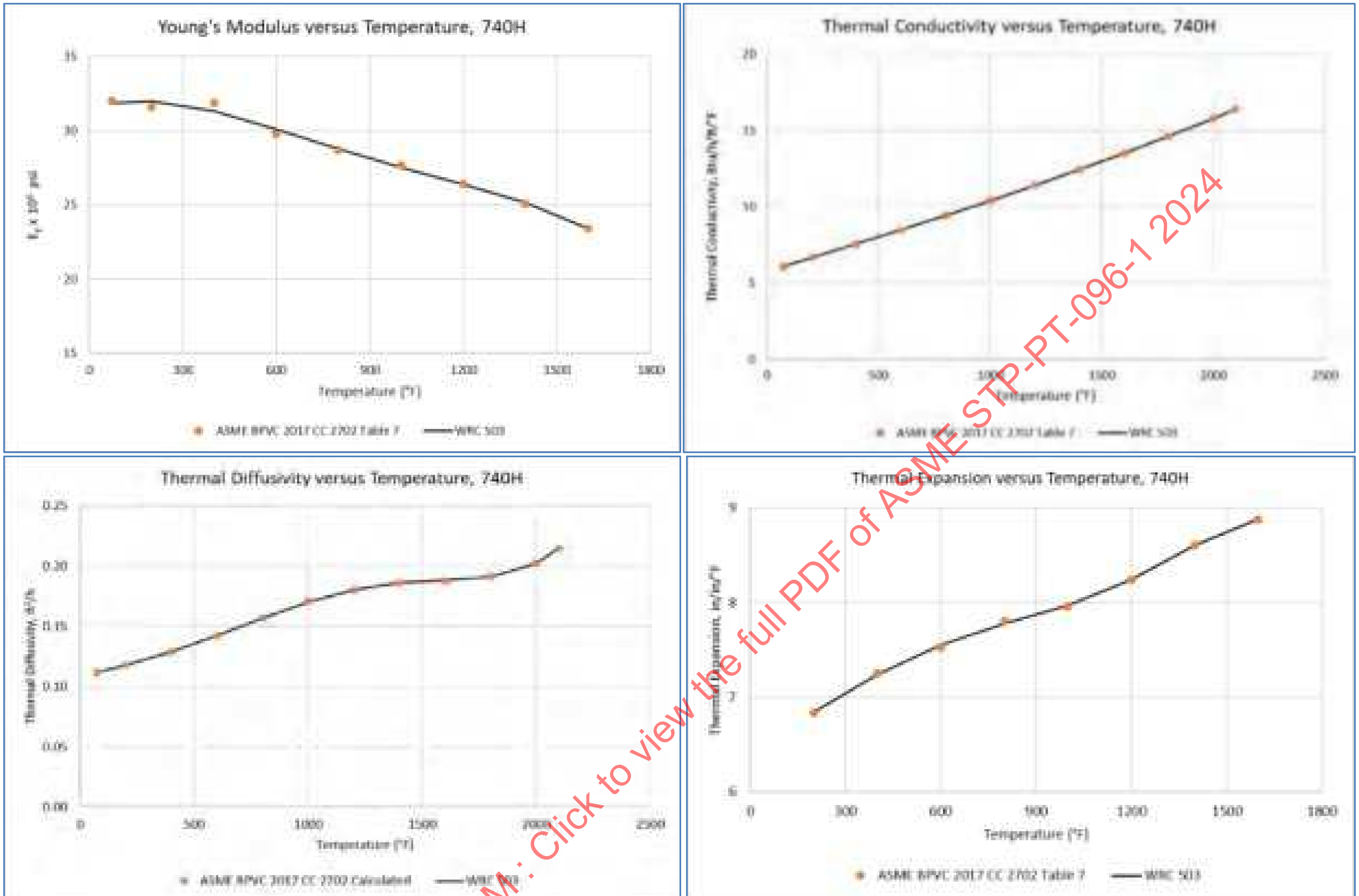


Figure 20-2: 740H Yield Strength Vs. Temperature, By Data Source, Including Trend Curves

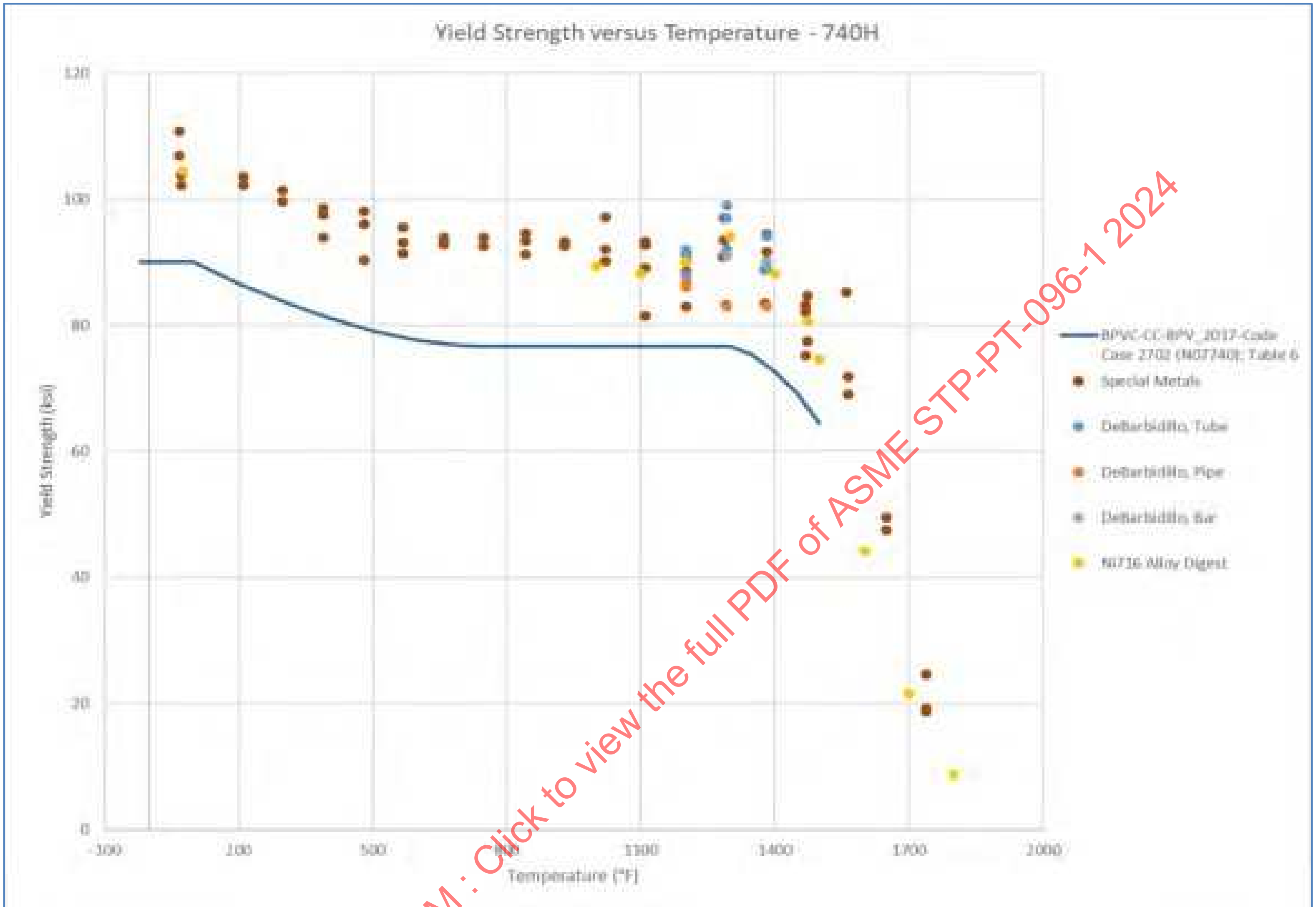


Figure 20-3: 740H Tensile Strength Vs. Temperature, By Data Source, Including Trend Curves

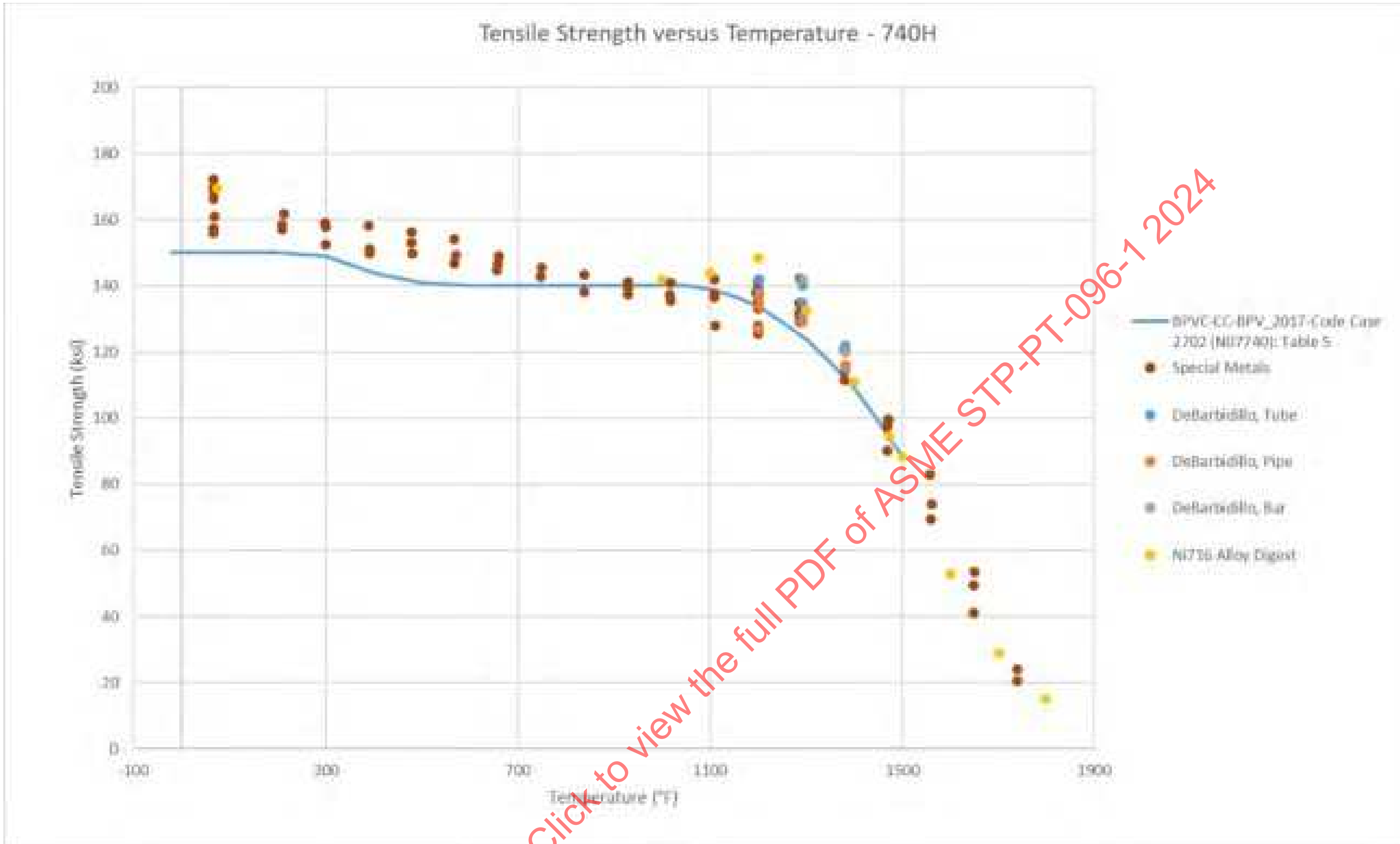


Figure 20-4: 740H Yield Strength Ratios Vs. Temperature (Calculated on a Heat-By-Heat Basis, By Data Source)

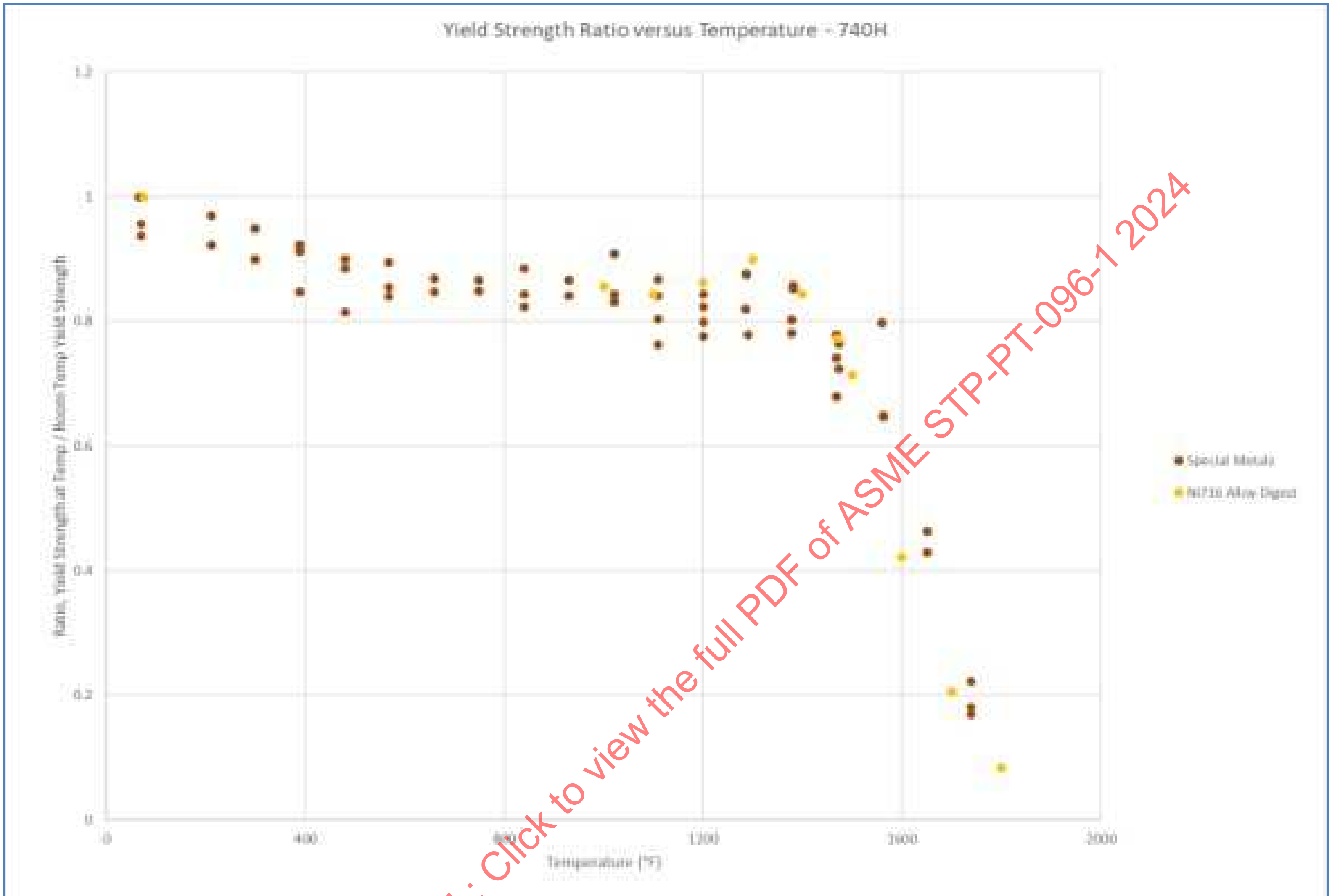


Figure 20-5: 740H Tensile Strength Ratios Vs. Temperature (Calculated on a Heat-By-Heat Basis, By Data Source)

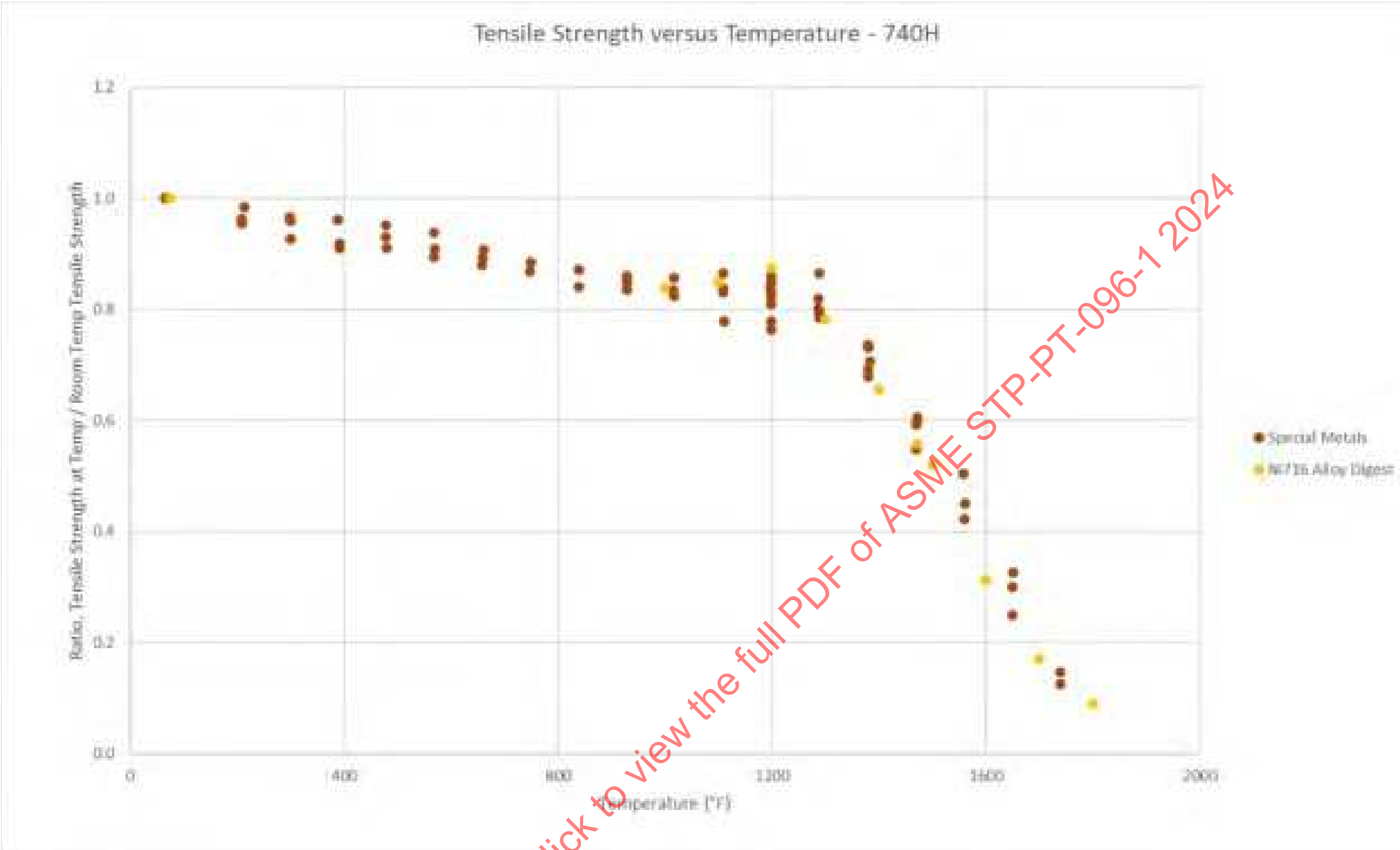


Figure 20-6: 740H Yield Strength Ratios Vs. Temperature, All Combined Data, With Polynomial Regression

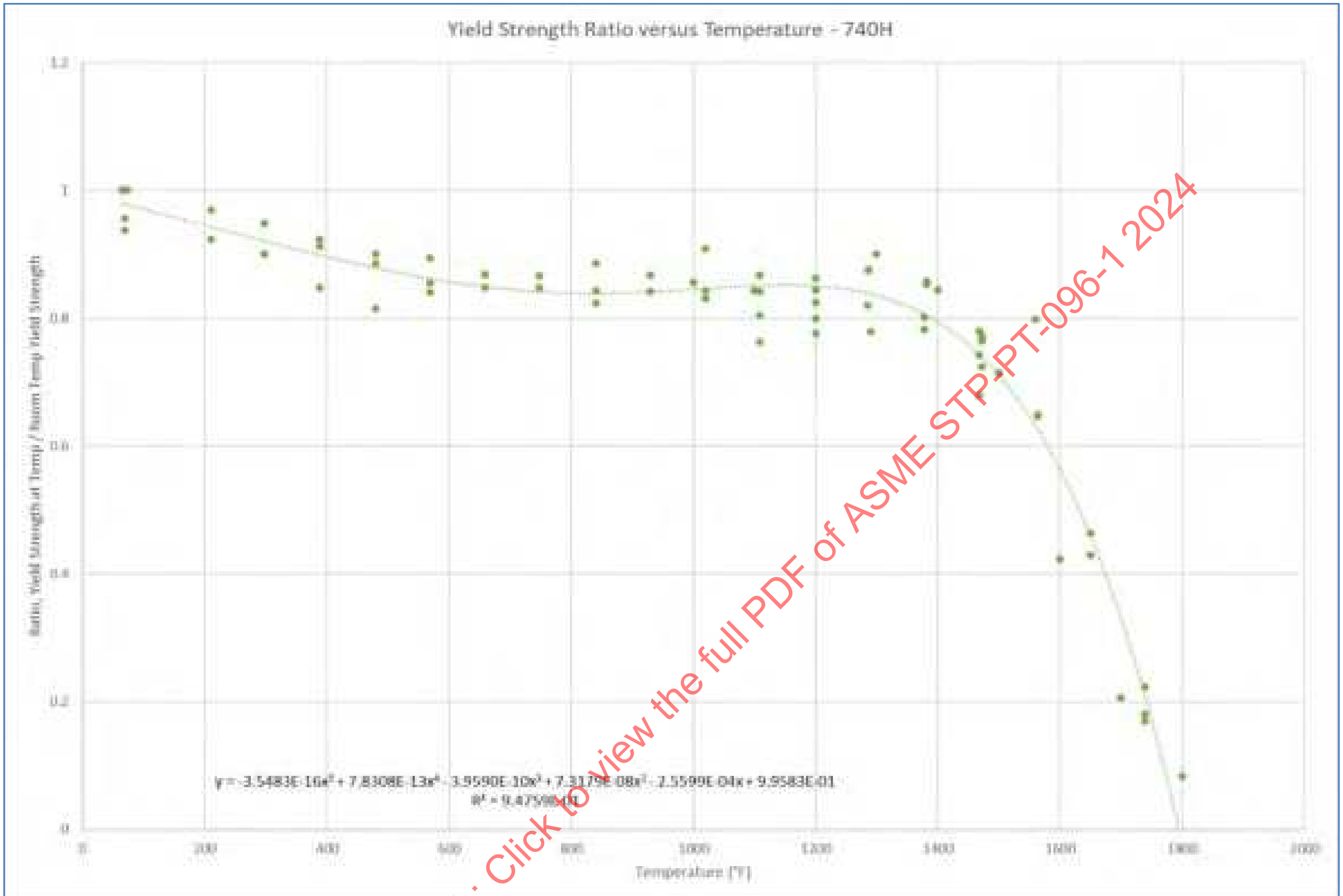


Figure 20-7: 740H Tensile Strength Ratios Vs. Temperature, All Combined Data, With Polynomial Regression

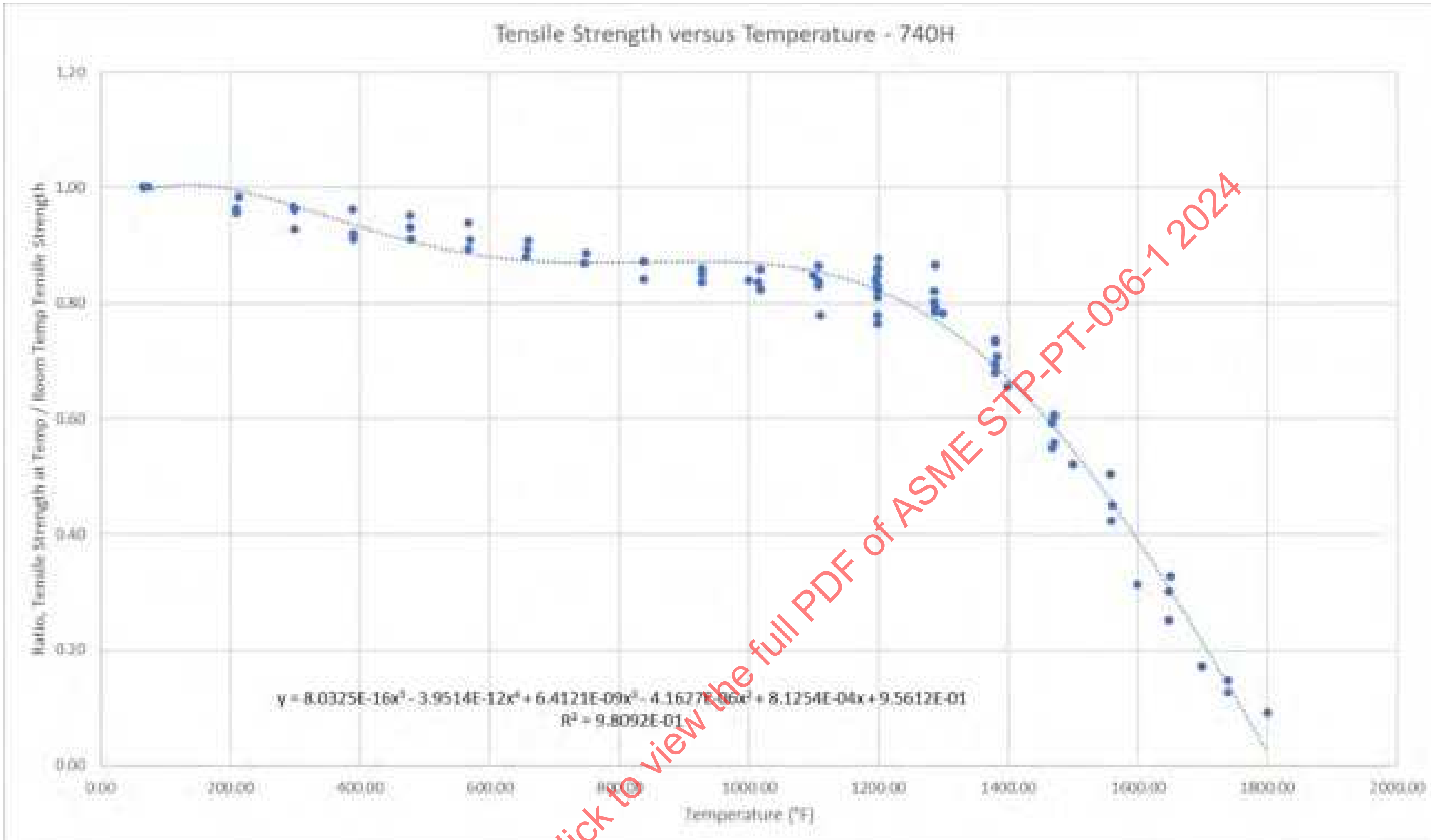


Figure 20-8: 740H Creep Rupture Isotherm Curves

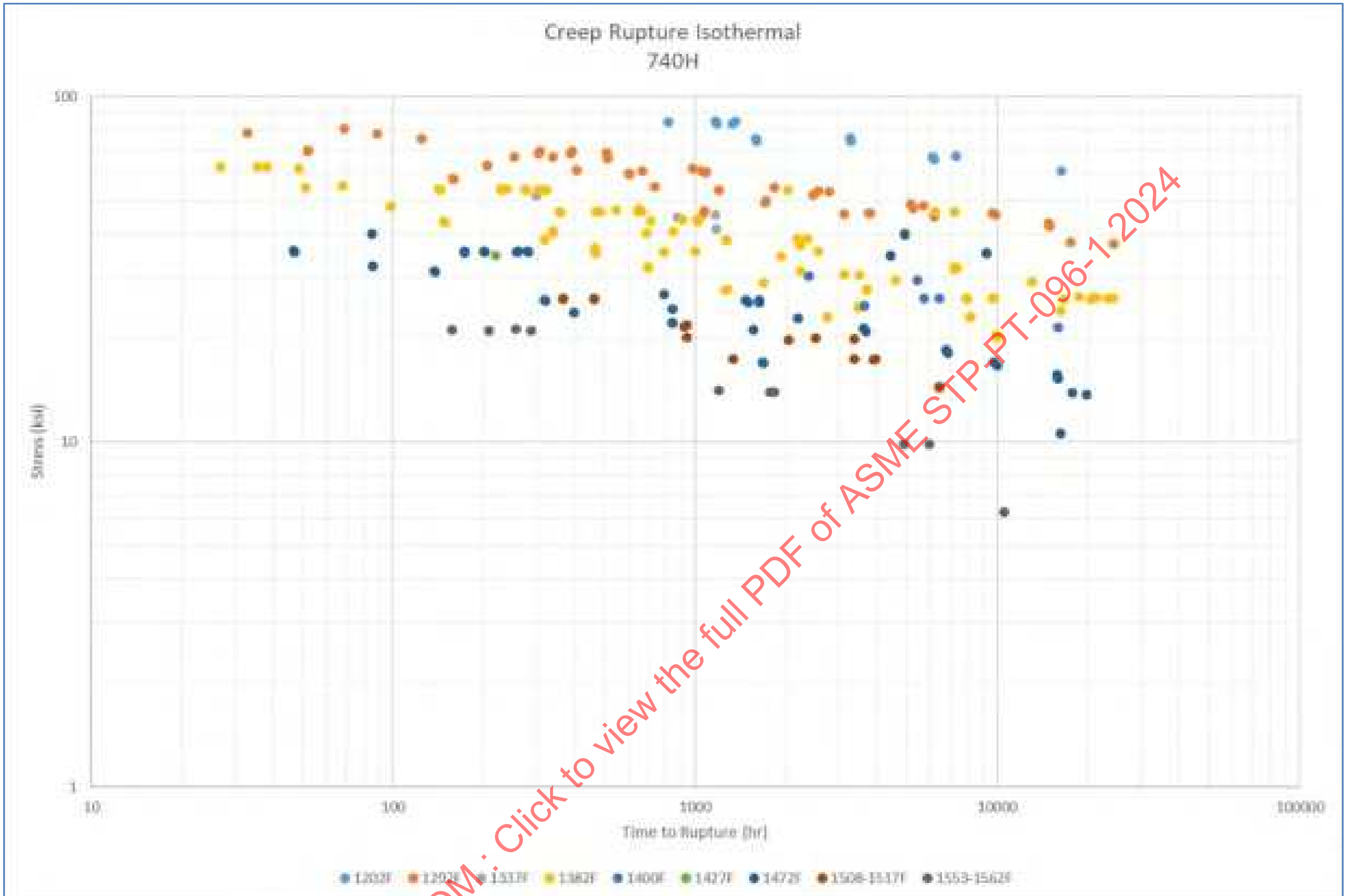


Figure 20-9: 740H Creep Strain Rate (MCR) Isotherm Curves

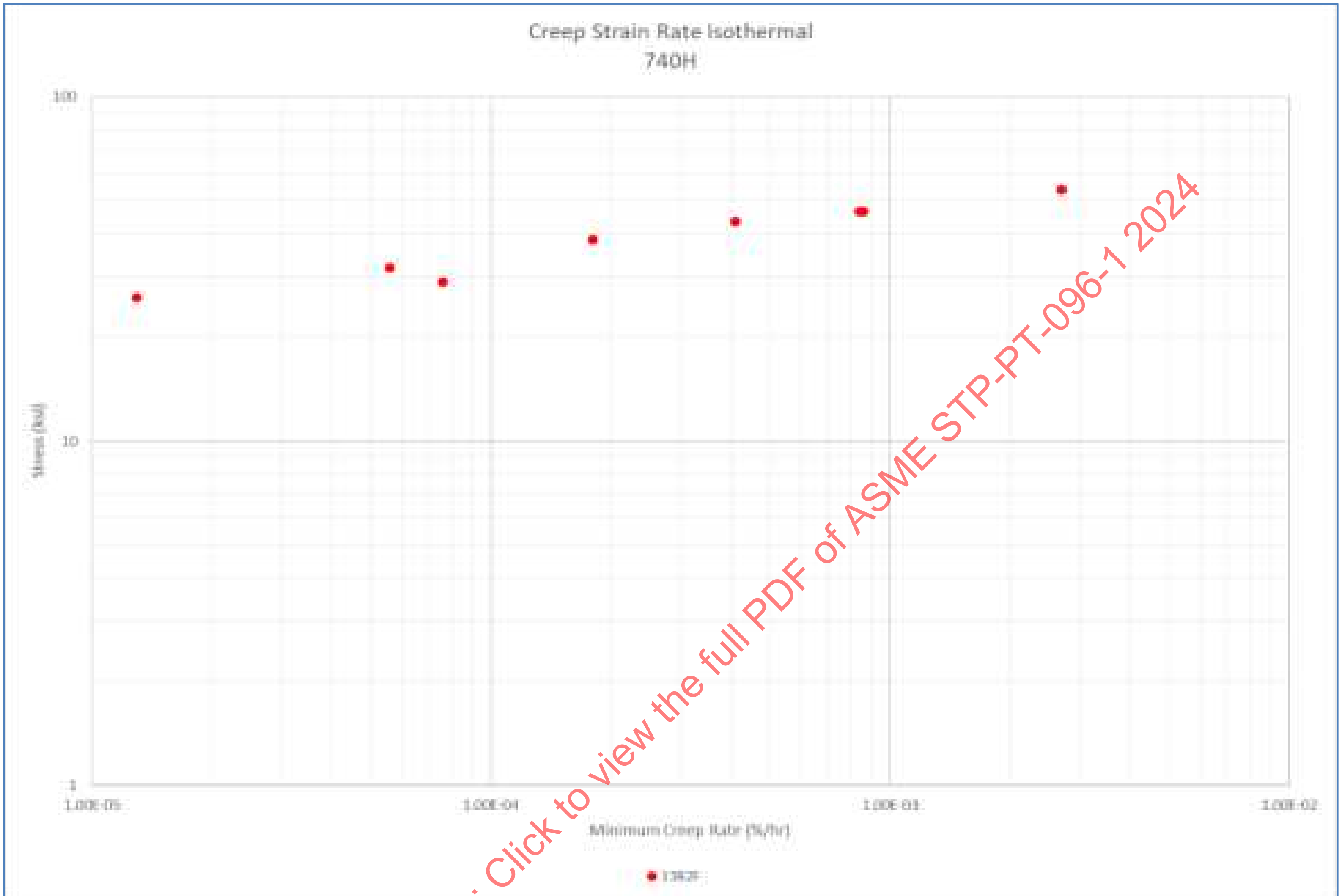


Figure 20-10: 740H Creep Ductility (% Elongation) Vs. Rupture Time Isotherms

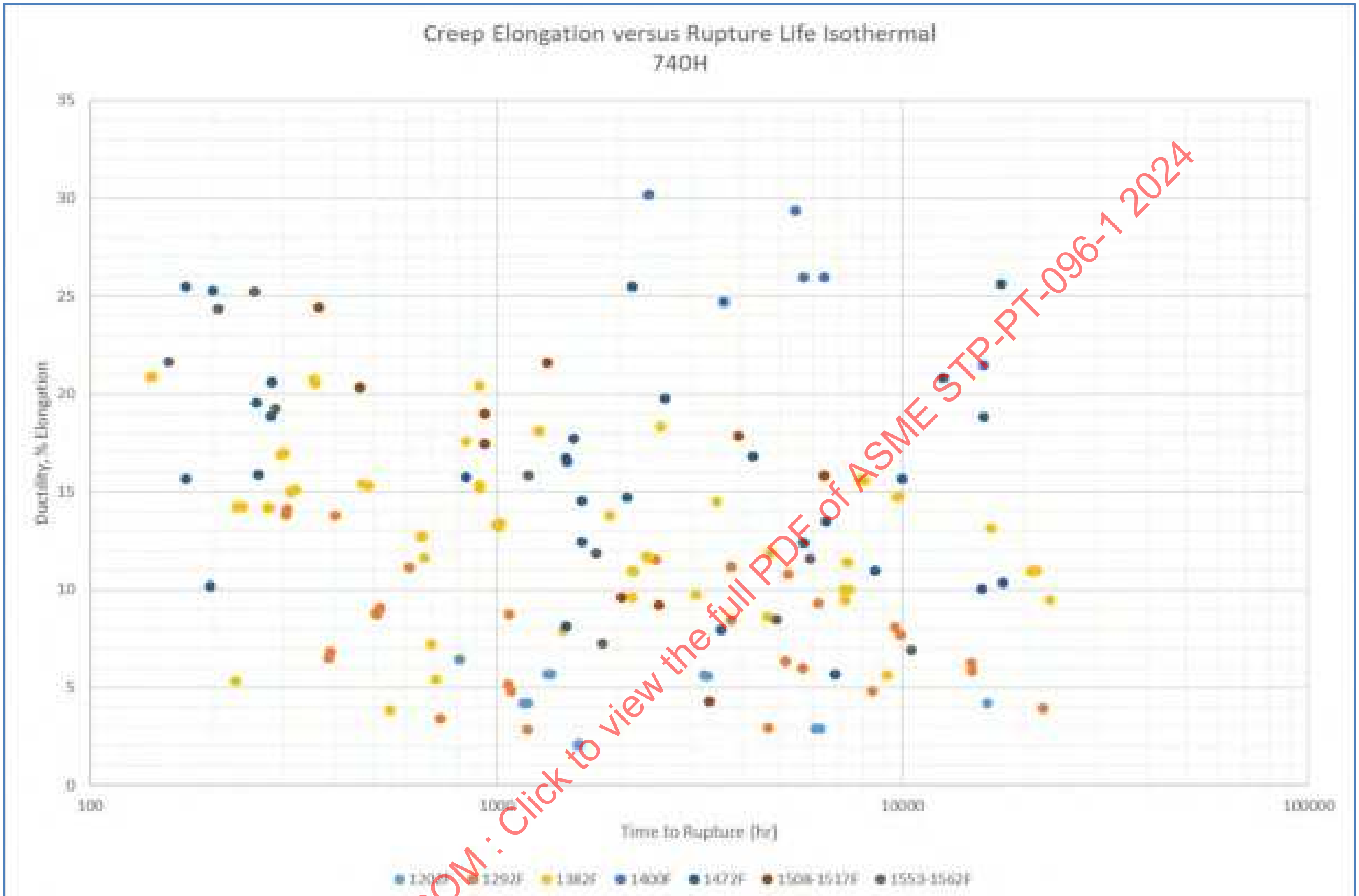


Figure 20-11: Calculated Allowable Stresses Based on Rupture and Creep Strain Rate and ASME II-D Appendix 1 Criteria (740H)

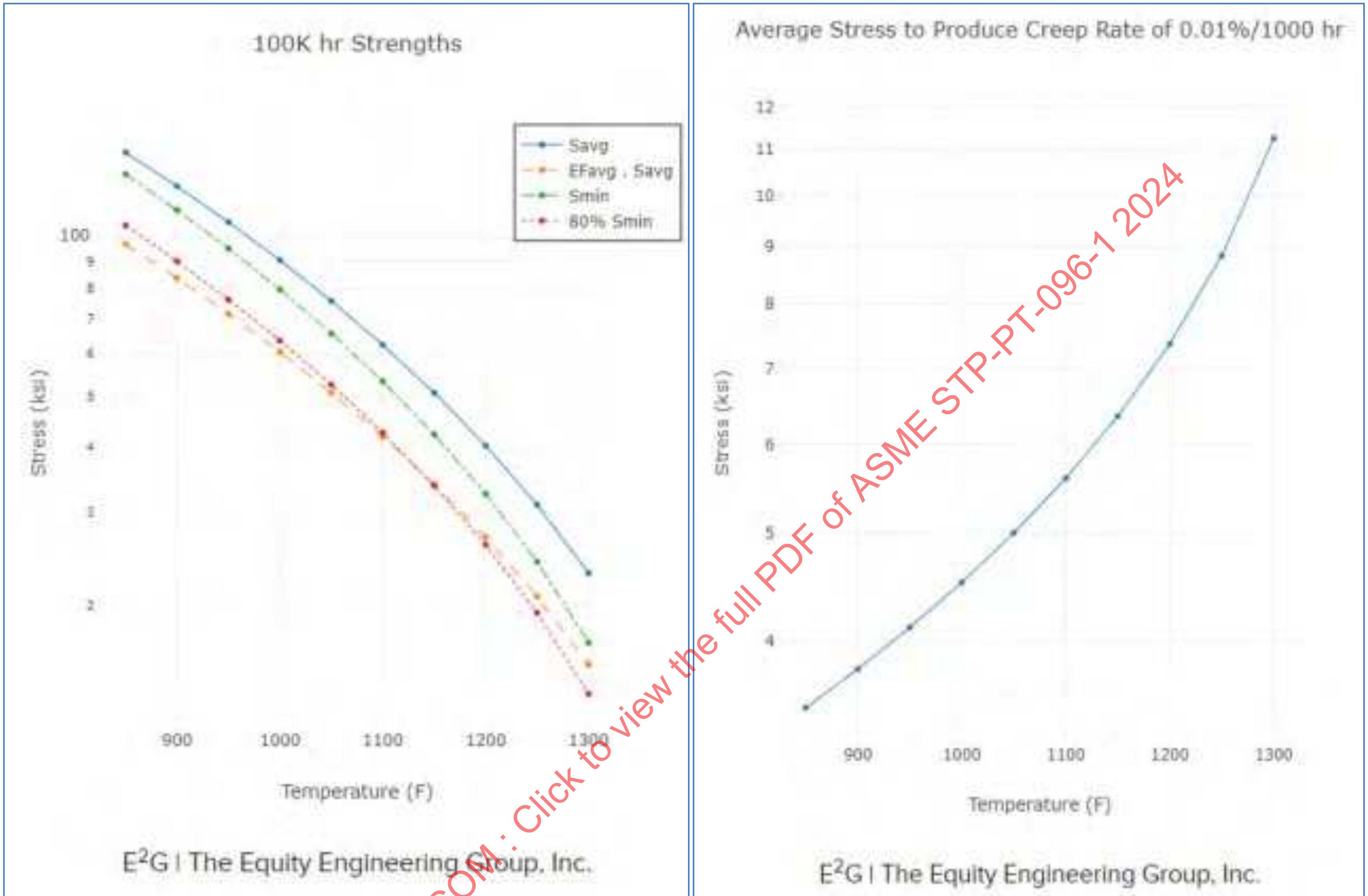
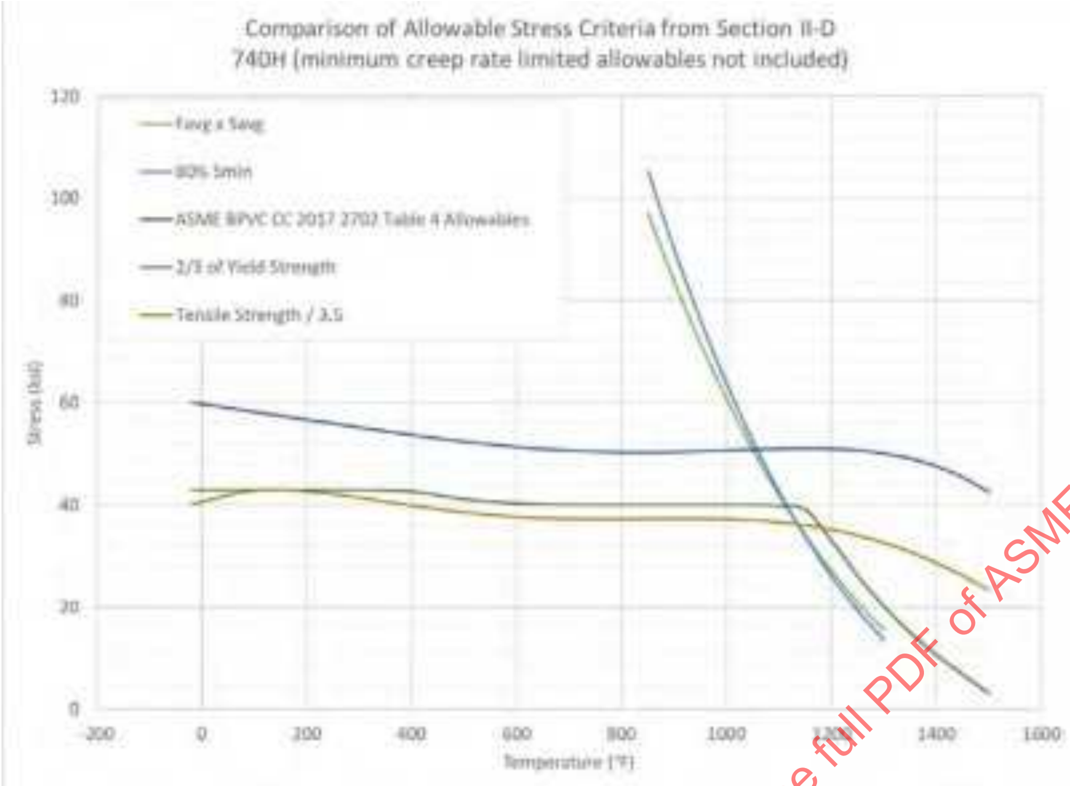


Figure 20-12: Comparison of Current 740H Allowable Stresses Vs. ASME II-D Appendix 1 Criteria Applied to Data



Attachment 20: Grade 740H Property Data

If you want the referenced embedded spreadsheet with additional data, please email a request to research@asme.org.

21 ALLOY 800H, 33NI-42FE-21CR

21.1 Physical Properties

Alloy 800H physical properties were referenced from the BPVC Section II for this material as well as the curves from WRC Bulletin 503. Both sources were plotted for comparison. The Aerospace Structural Metals Handbook also provided property data including Thermal Conductivity and Thermal Expansion. Additional Thermal Expansion data was included from the Materials Design Handbook source. Figure 21-1 shows the trends of Elastic Modulus (E_y), Thermal Conductivity (k), Thermal Diffusivity (TD), and Thermal Expansion (α) with temperature.

21.2 Yield and Tensile Strength

Elevated temperature Yield and Tensile Strength over the range of existing allowable stresses (up to 1652°F) were readily available, including data beyond the current range of allowable stresses, up to approximately 2000°F, as shown in Figures 21-2 and 21-3. All sources for both high-temperature yield and high-temperature tensile strength are provided in the embedded spreadsheet at the end of this section. This spreadsheet also contains ductility data corresponding to the tensile test results presented in this report. Note that ductility (percent elongation and percent reduction in area) was not available for all sources referenced for the Alloy 800 material.

To facilitate comparison of the data obtained to existing allowable stresses (Section II-D Table 1B), yield and tensile data were normalized on a heat-by-heat basis to express the ratio of yield or tensile strength at temperature to that measured for the heat at room temperature. In cases where data were not delineated by heats within a given source, or in cases where more than one room-temperature tensile test existed for a given heat of material, ratios are equal to the measured tensile or yield strength at temperature, divided by the average of all of the appropriate room-temperature values for the particular data source or heat of material. As a result of this approach, it is possible to have ratios in excess of 1.0. E^2G understands that this approach is similar to the normalizing procedure performed by ASME in typical analysis of yield and tensile data to obtain Table Y and Table U (Section II-D) trend curves, as well as for the calculation of allowable stresses. Figures 21-4 and 21-5 show the heat-by-heat variation in yield and tensile strength ratios (respectively) as a function of temperature. It should be emphasized that even though the figure legends reference an entire source of data, the ratios, wherever possible, were calculated on a heat-by-heat basis; this is evident in the embedded spreadsheet at the end of this section. Figures 21-6 and 21-7 contain all of the yield and tensile (respectively) ratios plotted together, to facilitate regression of a 5th-order polynomial that is subsequently used for allowable stress comparison.

21.3 Creep Data (Creep Rupture, Minimum Creep Rate, and Ductility)

Creep Rupture data, plotted as isotherms, is shown in Figures 21-8 and 21-9. The temperatures have been separated onto separate plots to minimize data overlap. This was done by plotting "every other" temperature starting at 842°F on Figure 21-8, and starting at 900°F on Figure 21-9. This allows for gaps between the bands of data, increasing visual clarity. It should be emphasized that these plots contain data for all product forms of material classified in the referenced publications as "Alloy 800H." This certainly includes material meeting the requirements of ASME BPVC Section II-A specifications (e.g., SA-240 800, SA-240 800H, Alloy 800HT etc.). However, due to the diversity of data sources utilized for the compilation of the material property tables, it is likely that some of the material shown in Figures 21-8 and 21-9 may not meet existing specifications for this grade of material. Where older publications are referenced, the chemistry (and for that matter, manufacturing, processing, and heat treatment) corresponding to the heat of material in the original data source, may not be consistent with modern specifications. Where possible, E^2G has documented the chemical composition if contained within the original source. In many cases, the project team has also made efforts to trace cross-referenced data back to original test results to determine if the heat treatment, product form, chemistry, etc. details can be obtained. This information is provided with the embedded spreadsheet to facilitate additional analysis on the part of ASME.

Creep Minimum strain rates (%/hour) are shown in Figures 21-10 and 21-11, separated by temperature. As in the case of rupture data, temperatures of minimum creep rates have been separated onto separate plots to minimize data overlap, with Figure 21-10 starting at 900°F and continuing with every other temperature, and Figure 21-11 starting at 950°F and including every other temperature. Creep Ductility, as % elongation, is plotted in Figure 21-12. As is typical, the data show significant overlap, and it is difficult to observe clear trends in the data. The data is not intended to be used as plotted but is available in the spreadsheet for additional analysis.

Creep data were analyzed using E^2G's proprietary Lot-Centered Analysis web-based software tool, in order to obtain creep properties. This regression is based on a Mandel-Paule algorithm and considers the variation within individual heats of material (for both rupture and strain rate data) as well as the variation between heats. The weight assigned to each datapoint and each heat is scaled based on the relative variation. Both rupture and strain rate (minimum creep rate, expressed as true strain per hours) were regressed according to a Larson-Miller time-temperature-parameter model, with a 3rd-order polynomial of stress. Lot-specific constant behavior was accounted for in this analysis, but the variation of LMP with stress was assumed to be constant (no non-parallel terms were included in the analysis). A 95% predictive limit was utilized to obtain the lower-bound (minimum LM constant for both rupture and strain rate) properties. The results of this analysis are summarized in Table 21-1 for rupture data and Table 21-2 for strain rate data. The Lot-Centered Analysis software tool generates property tables in the creep regime using the criteria outlined in Mandatory Appendix 1 of ASME Section II-D; the nomenclature of variables is consistent with II-D Appendix 1. For visualization of the allowable stress trends, Figure 21-13 is provided (for rupture allowable stresses and creep rate allowable stresses). Figure 21-14 shows a comparison of the various allowable stress criteria from Section II-D, Appendix 1, to the existing (2019) Section II-D Table 1B allowable stresses for annealed forms of Alloy 800H (which are the most conservative in the temperature-dependent range and equal to other forms in the time dependent range).

Creep Strain vs. time data are shown in Figures 21-15 and 21-16 for short-term data (up to 2,500 hour test durations); Figure 21-17 for 2,500 to 5,000 hour test durations; Figure 21-18 for 5,000 to 10,000 hour test durations; Figure 21-19 for 10,000 to 100,000 hour test durations, and Figure 21-20 for durations exceeding 100,000 hours. Curves are only plotted where 3 or more strain vs. time points are present for the test. Additional curves are available with fewer datapoints (typically obtained from data in the form of time-until-specified-strain) in the embedded spreadsheet. Both creep rate and creep strain vs. time data are provided to satisfy ASME's request for creep strain vs. time curves, and both forms of data are applicable in developing allowable stresses. Although digitalization of creep curve data was not explicitly necessary per the project contract, E^2G did perform digitalization of creep curves where only graphical data was available (as is often the case in the published literature).

21.4 Continuous Cycling Fatigue and Hold Time Fatigue Curves

A portion of the data obtained for continuous cycling fatigue data at elevated temperatures for Alloy 800H is shown in Figure 21-21, which includes a limited amount of room temperature data contained in sources which also present high-temperature data. Figure 21-21 only contains data for which total strain range was determined from the original source. Additional data points for continuous cycling fatigue data of Alloy 800H are presented in the attached spreadsheet; however, due to the complexities of various forms of fatigue data, compatible plots for each type of data expression and failure criteria are not included in this report. Hold time fatigue data at high temperature is shown in Figure 21-22 (1000°F, 1292°F, 1400°F, and 1472°F), Figure 21-23 (1112°F), Figure 21-24 (1200°F), and Figure 21-25 (1526°F) with separate plots for temperatures at which at least a moderate collection of data points existed. Additional data is provided in the embedded spreadsheet.

Table 21-1: Model Parameters, Larson-Miller Property Results, and Allowable Stress (Rupture) Criteria, Alloy 800H

Equation Format:

$$\log(t_r) = C_{avg} + \frac{1}{T+460}\left(b_1 + b_2\log(\sigma) + b_3(\log(\sigma))^2 + b_4(\log(\sigma))^3\right)$$

Cavg	**-15.07**
Cmin	**-15.63**
b_1	**43473.2**
b_2	**-9404.2**
b_3	**-341**
b_4	**-4.122**

Number Data Points		**2092**
Correlation Coefficient	R^2	0.8064
Average Variance within Heats	V_w	0.1131
Variance between Heats	V_b	0.06813
Standard Error of Estimate	SEE	0.3363

Properties provided are for T in °F, stress in ksi, and t_R in hours

Temperature, °F	**S_{avg} (ksi)**	***n***	**F_{avg} (calc)**	**F_{avg} (used)**	**Favg × Savg**	**S_{min} (ksi)**	**80% S_{min}**
850	52.15	8.101	0.7526	0.67	34.94	44.52	35.62
900	41.91	7.752	0.743	0.67	28.08	35.53	28.42
950	33.64	7.429	0.7335	0.67	22.54	28.31	22.65
1000	26.96	7.127	0.7239	0.67	18.06	22.52	18.02
1050	21.57	6.845	0.7143	0.67	14.45	17.89	14.31
1100	17.24	6.581	0.7048	0.67	11.55	14.19	11.35
1150	13.75	6.333	0.6952	0.67	9.213	11.23	8.986
1200	10.95	6.1	0.6856	0.67	7.339	8.878	7.102
1250	8.712	5.881	0.676	0.67	5.837	7.005	5.604
1300	6.917	5.674	0.6664	0.67	4.635	5.518	4.415

** E^2G's proprietary *Lot-Centered Analysis* web-based software tool only provides results up to 1300°F, but it should be noted that Alloy 800H allowable stress properties are observed above 1300°F.

Table 21-2: Model Parameters, Larson-Miller Property Results, and Allowable Stress (Strain Rate) Criteria, Alloy 800H

Equation Format:

$$\log(\dot{\varepsilon}_0) = -C_{avg} - \frac{1}{T+460}\left(a_1 + a_2\log(\sigma) + a_3(\log(\sigma))^2 + a_4(\log(\sigma))^3\right)$$

C_{avg} (A_0)	**-17.39**
Cmin (A0+ΔΩSR,LB)	**-18.67**
a_1	**52536**
a_2	**-15012.3**
a_3	**4020.2**
a_4	**-1151**

Number Data Points		**248**
Correlation Coefficient	R2	0.5758
Average Variance within Heats	V_w	0.6032
Variance between Heats	V_b	0.5246
Standard Error of Estimate	SEE	0.7766

Properties provided are for T in °F, stress in ksi, and t_R in hours

Temperature, °F	**$S_{C,avg}$ (ksi)**
850	101
900	82.16
950	66.33
1000	53.13
1050	42.24
1100	33.36
1150	26.19
1200	20.48
1250	15.97
1300	12.44

** E²G's proprietary *Lot-Centered Analysis* web-based software tool only provides results up to 1300°F, but it should be noted that Alloy 800H allowable stress properties are observed above 1300°F.

Figure 21-1: Alloy 800H Modulus (E_y), Thermal Conductivity (k), Thermal Diffusivity (TD), & Thermal Expansion (α) With Temperature

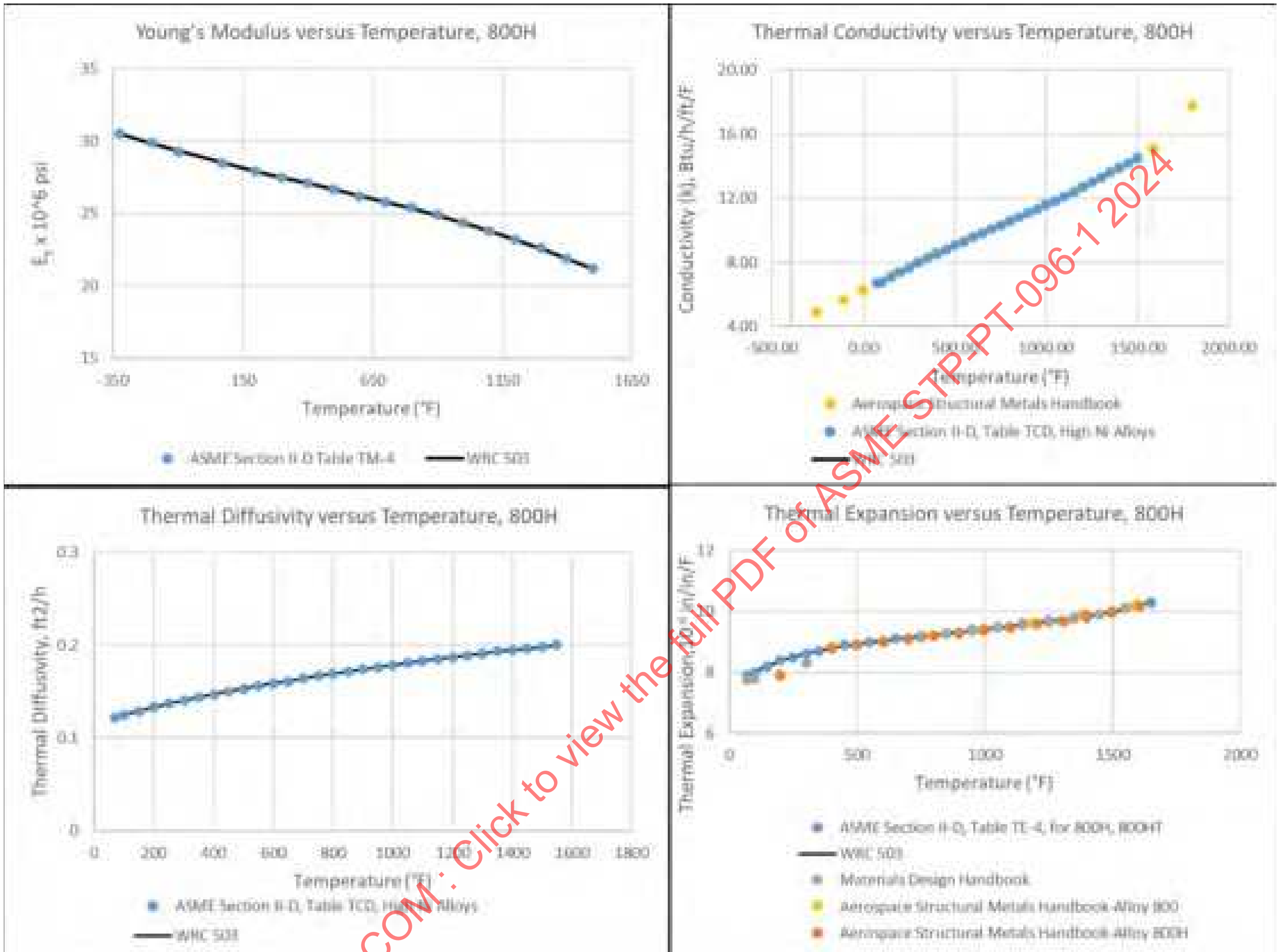


Figure 21-2: Alloy 800H Yield Strength Vs. Temperature, By Data Source, Including Trend Curves

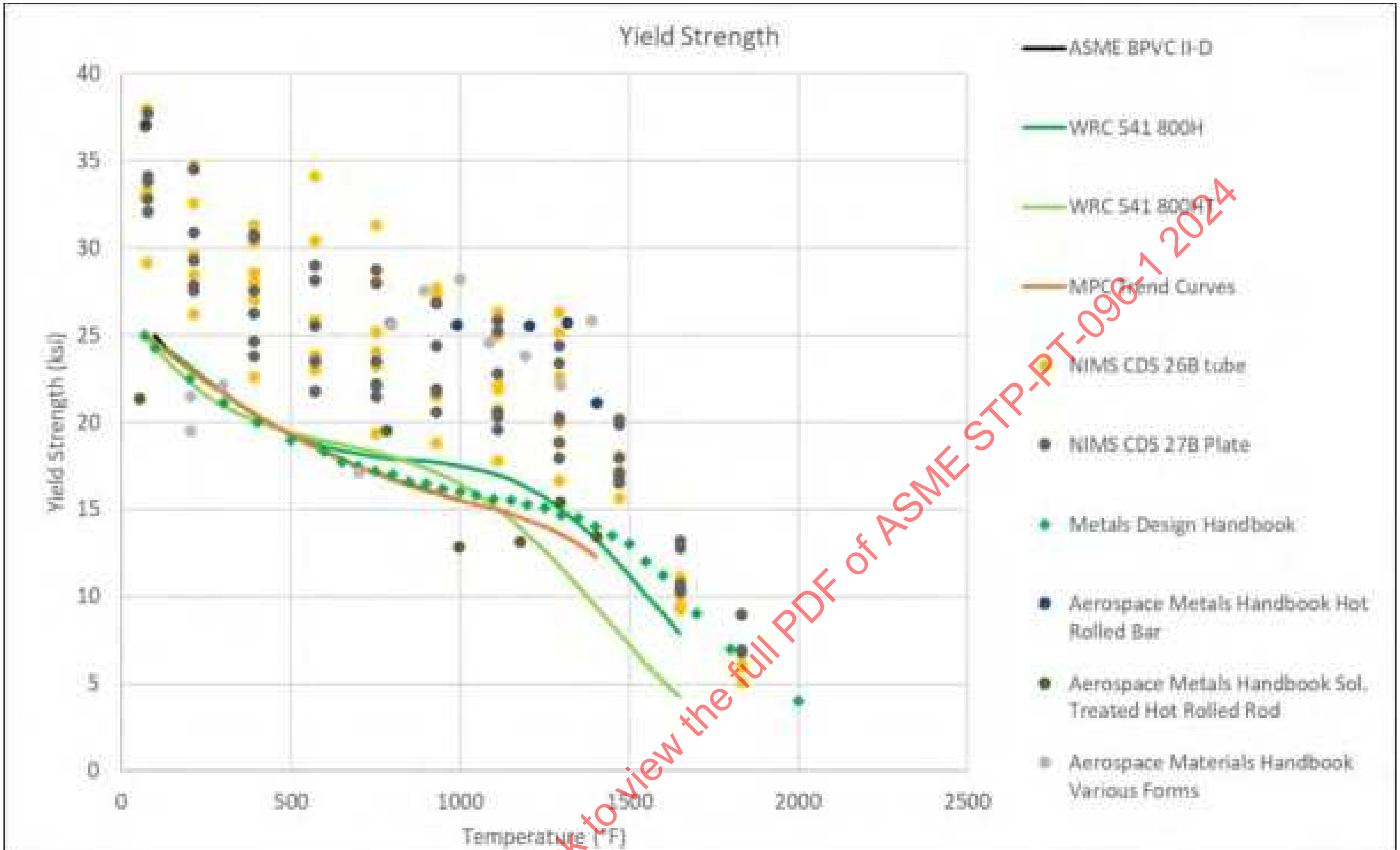


Figure 21-3: Alloy 800H Tensile Strength Vs. Temperature, By Data Source, Including Trend Curves

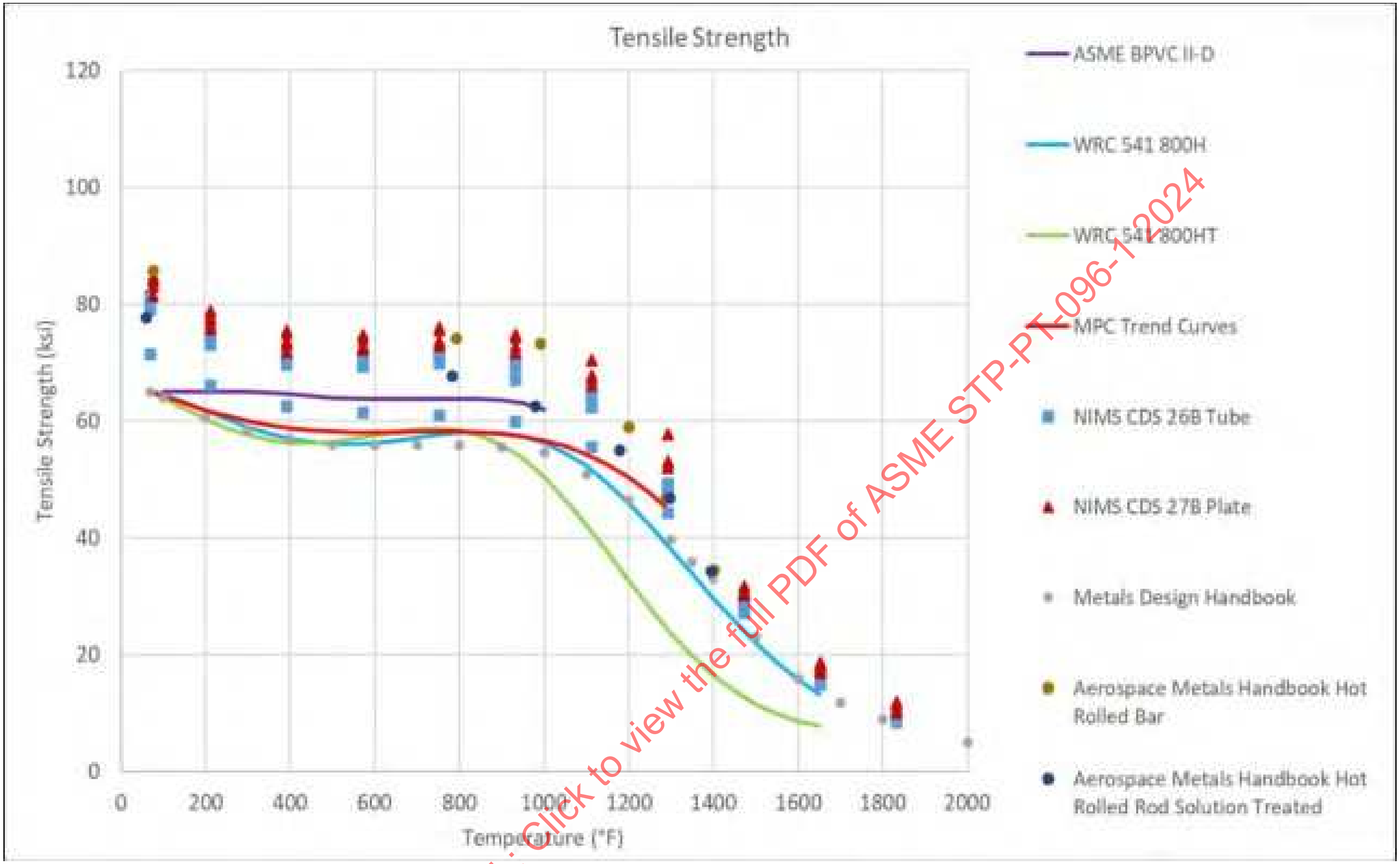


Figure 21-4: Alloy 800H Yield Strength Ratios Vs. Temperature (Calculated on a Heat-By-Heat Basis, By Data Source)

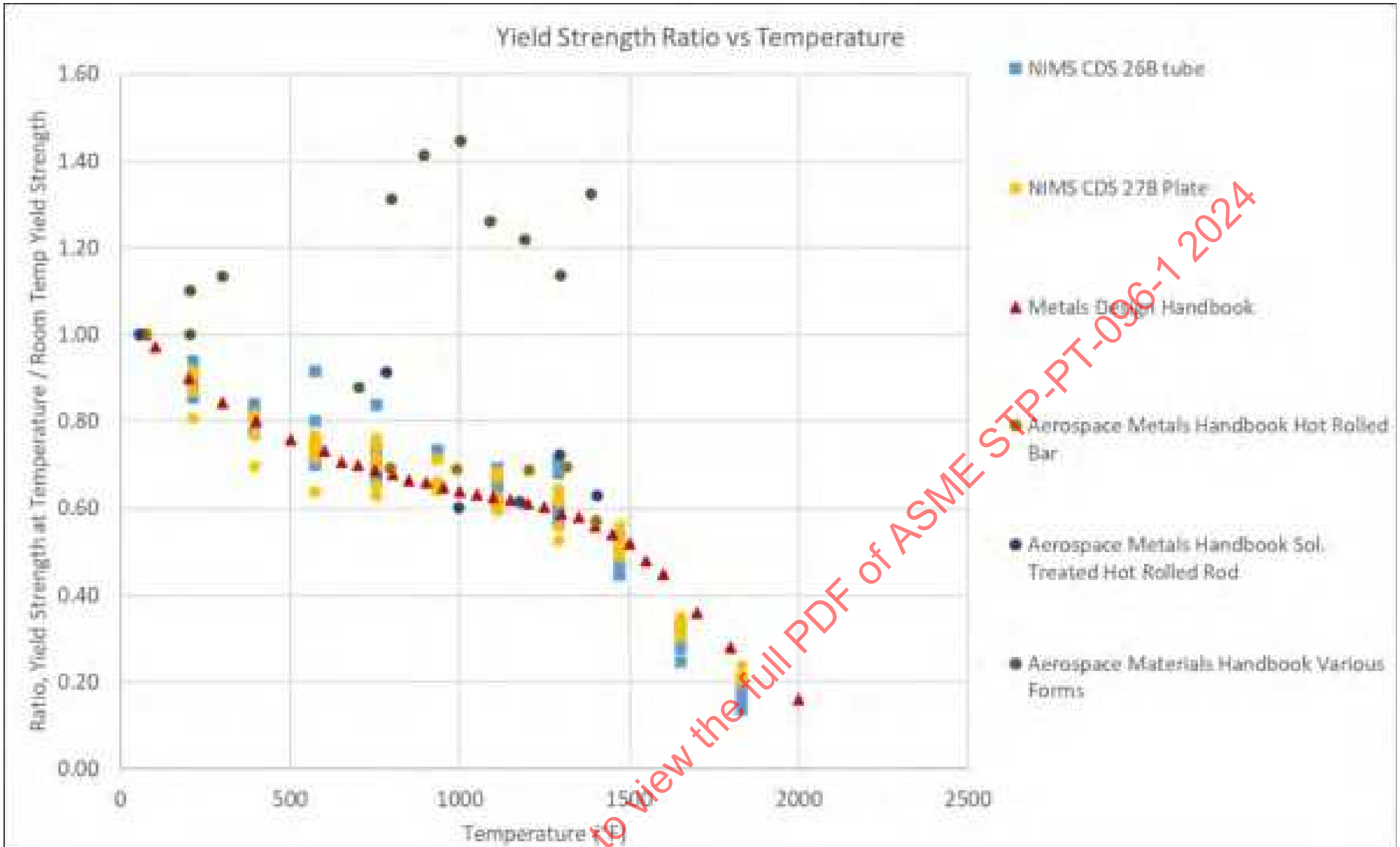


Figure 21-5: Alloy 800H Tensile Strength Ratios Vs. Temperature (Calculated on a Heat-By-Heat Basis, By Data Source)

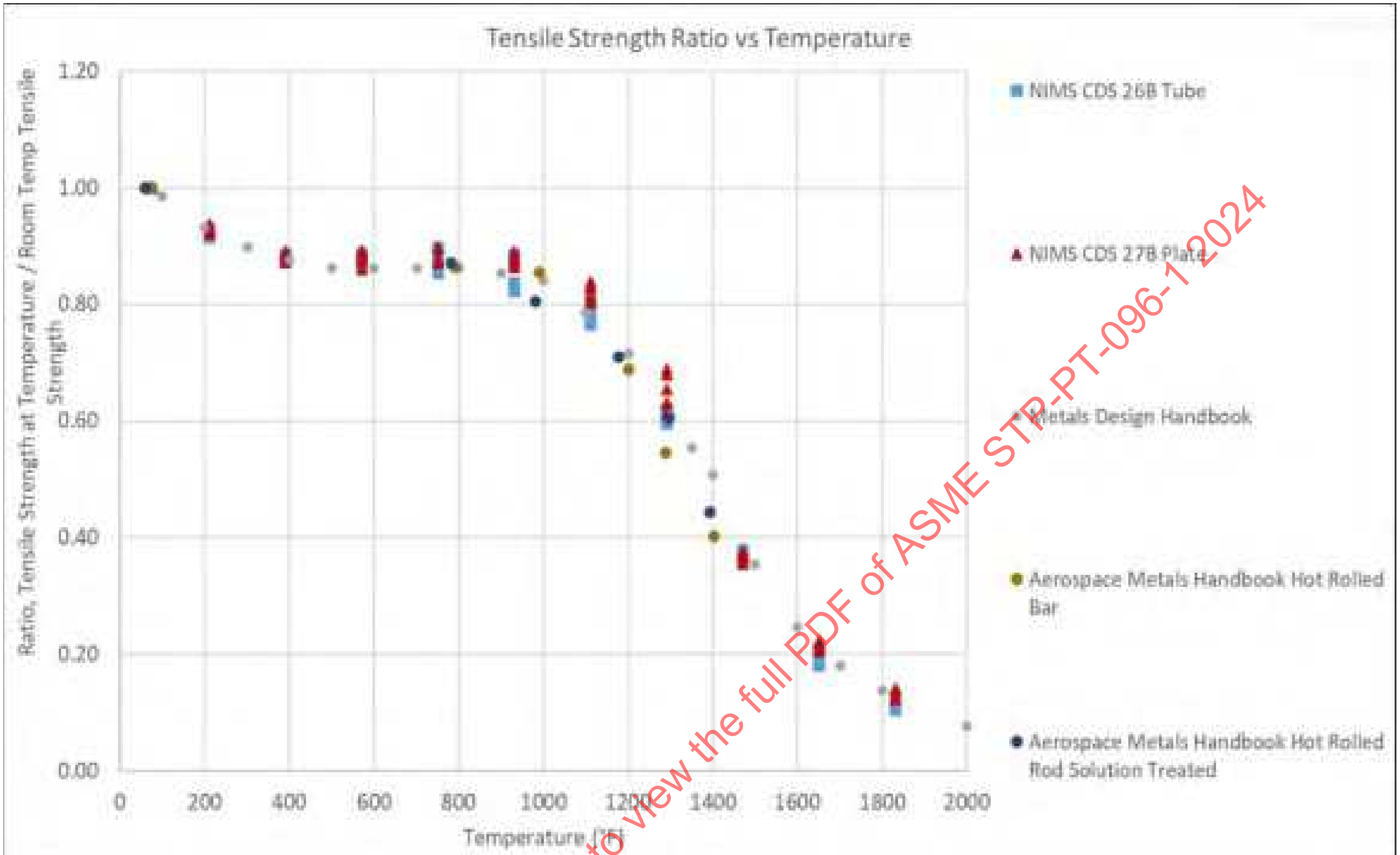


Figure 21-6: Alloy 800H Yield Strength Ratios Vs. Temperature, All Combined Data, With Polynomial Regression

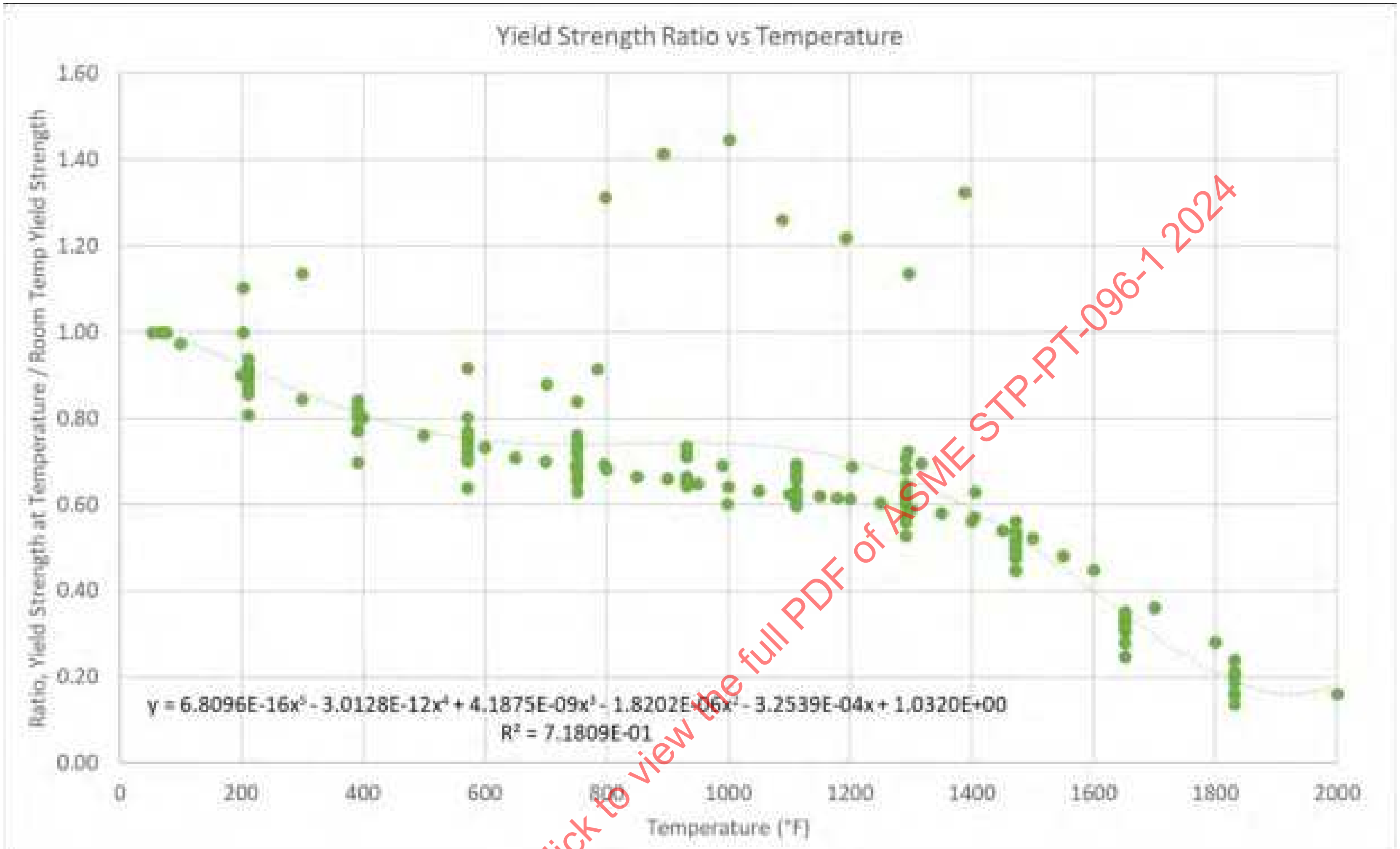


Figure 21-7: Alloy 800H Tensile Strength Ratios Vs. Temperature, All Combined Data, With Polynomial Regression

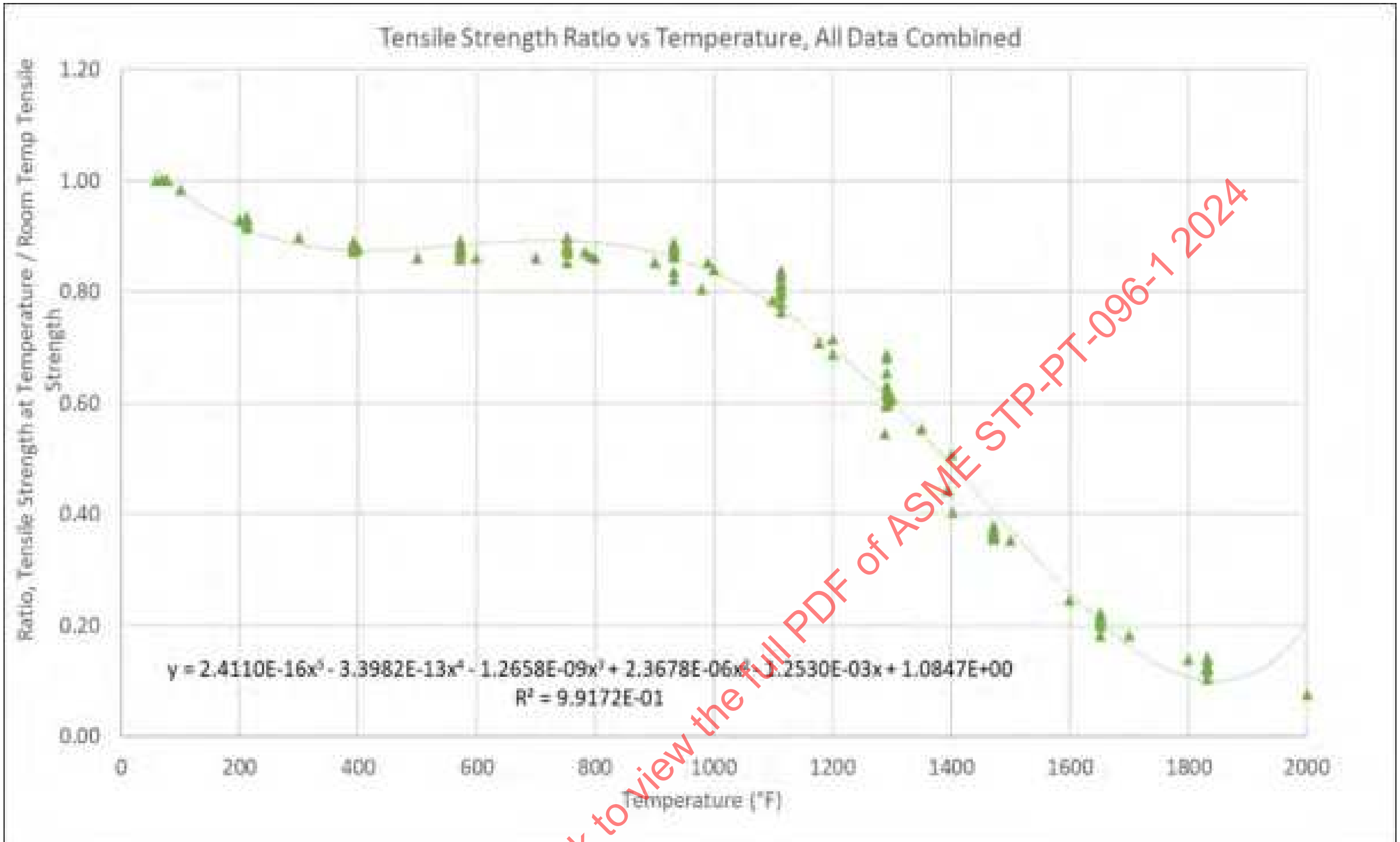


Figure 21-8: Alloy 800H Creep Rupture Isotherm Curves, First Lot of Temperatures

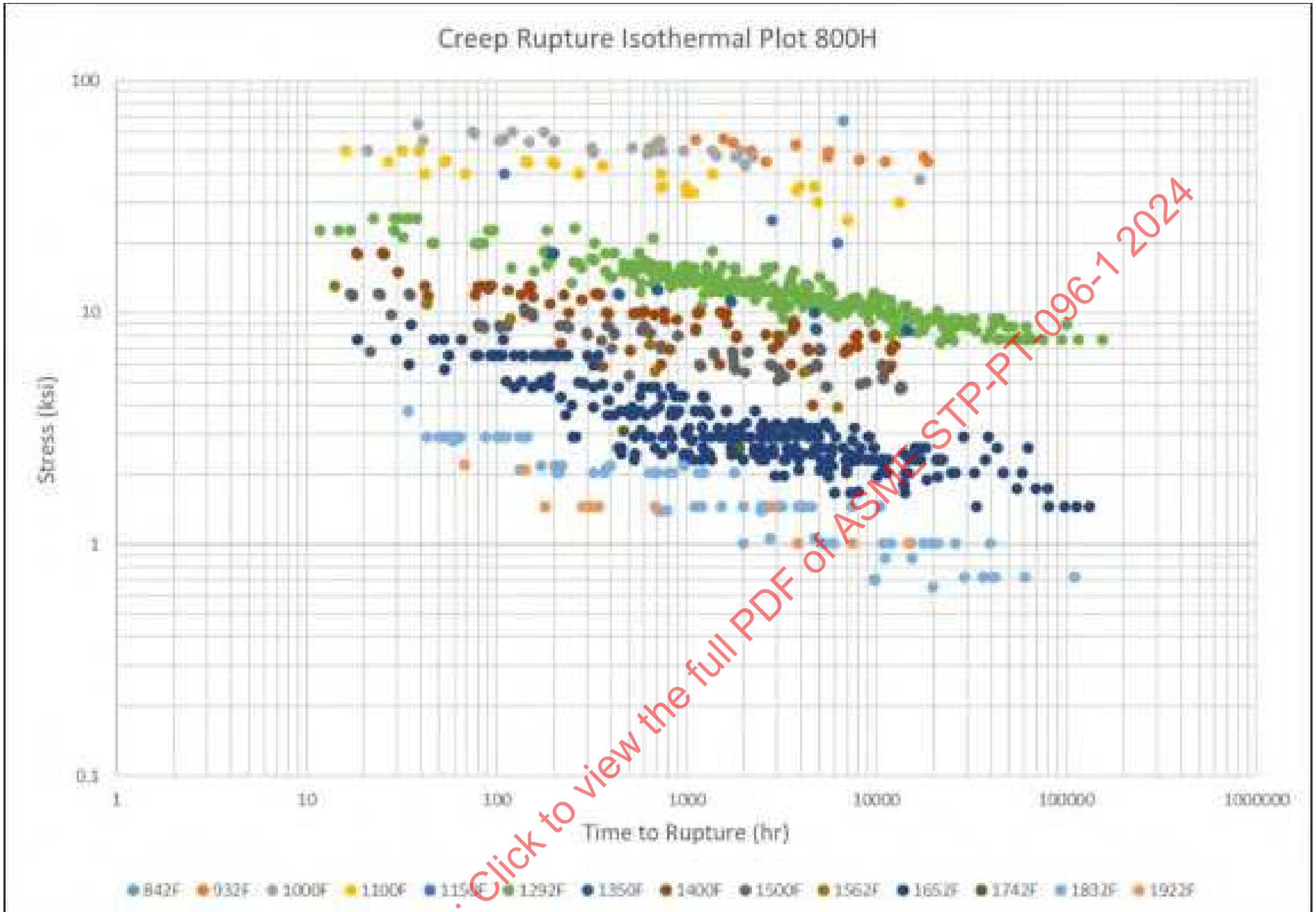


Figure 21-9: Alloy 800H Creep Rupture Isotherm Curves, Second Lot of Temperatures

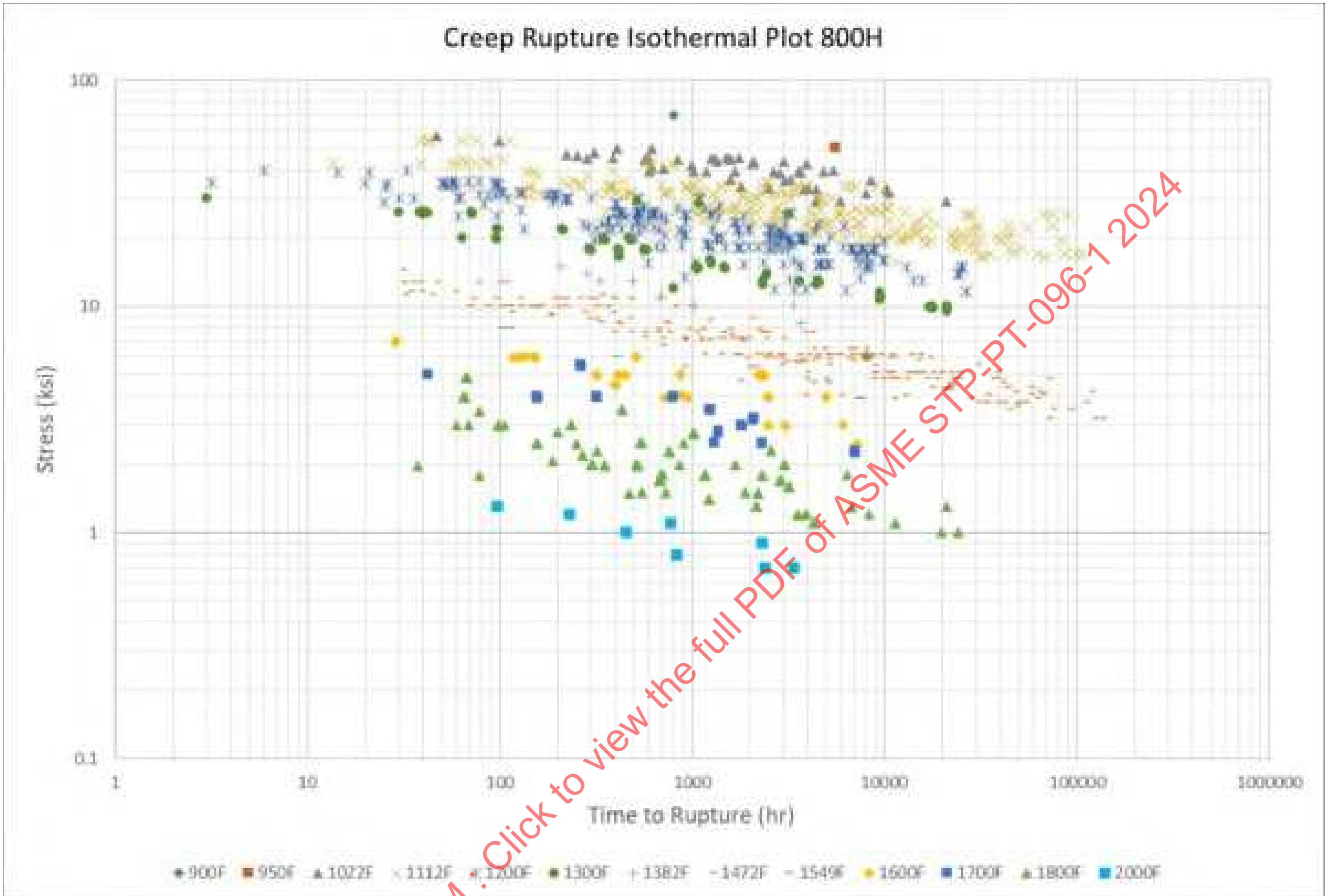


Figure 21-10: Alloy 800H Creep Strain Rate (MCR) Isotherm Curves, First Lot of Temperatures

Figure 21-11: Alloy 800H Creep Strain Rate (MCR) Isotherm Curves, Second Lot of Temperatures

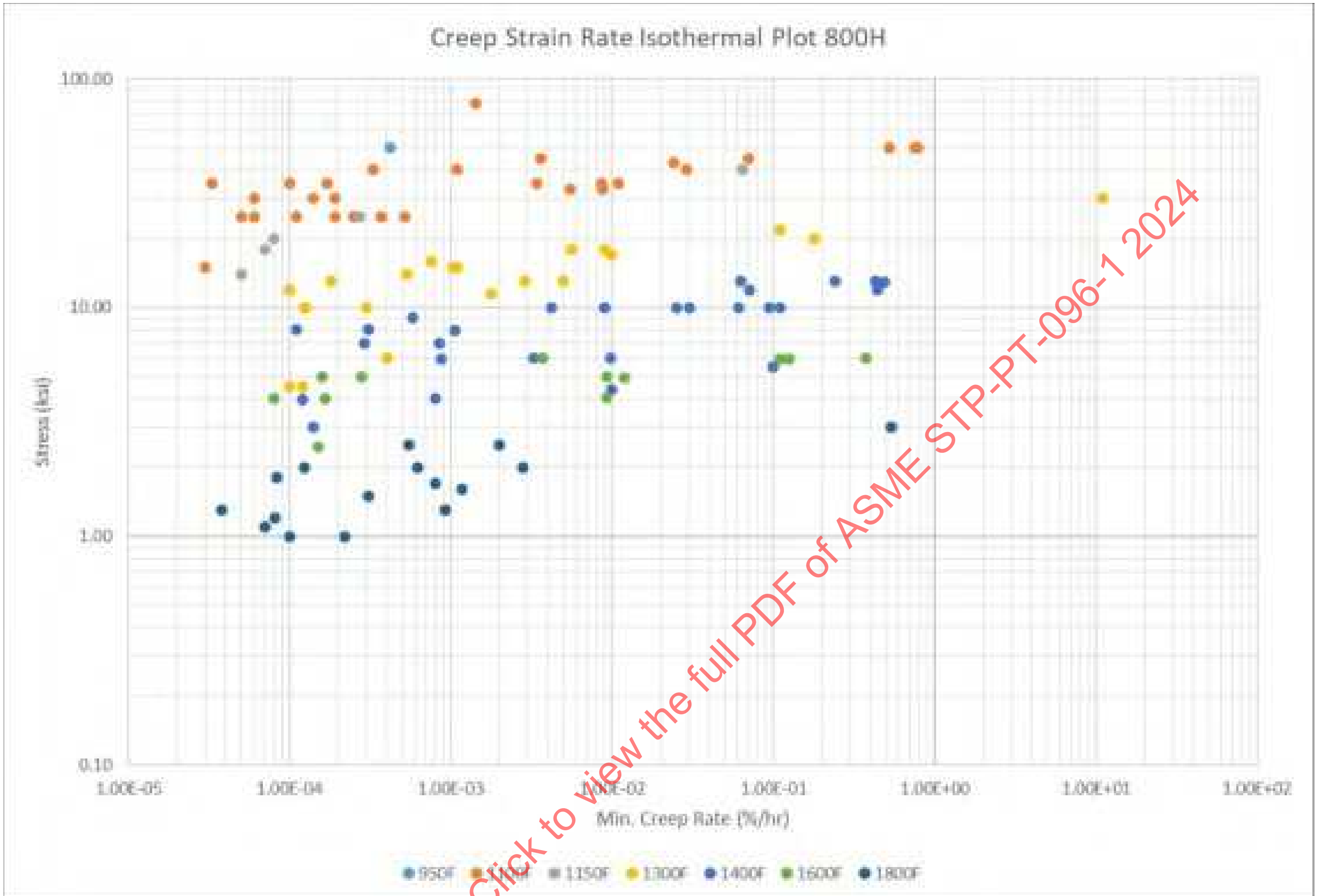


Figure 21-12: Alloy 800H Creep Ductility (% Elongation) Vs. Rupture Time Isotherms

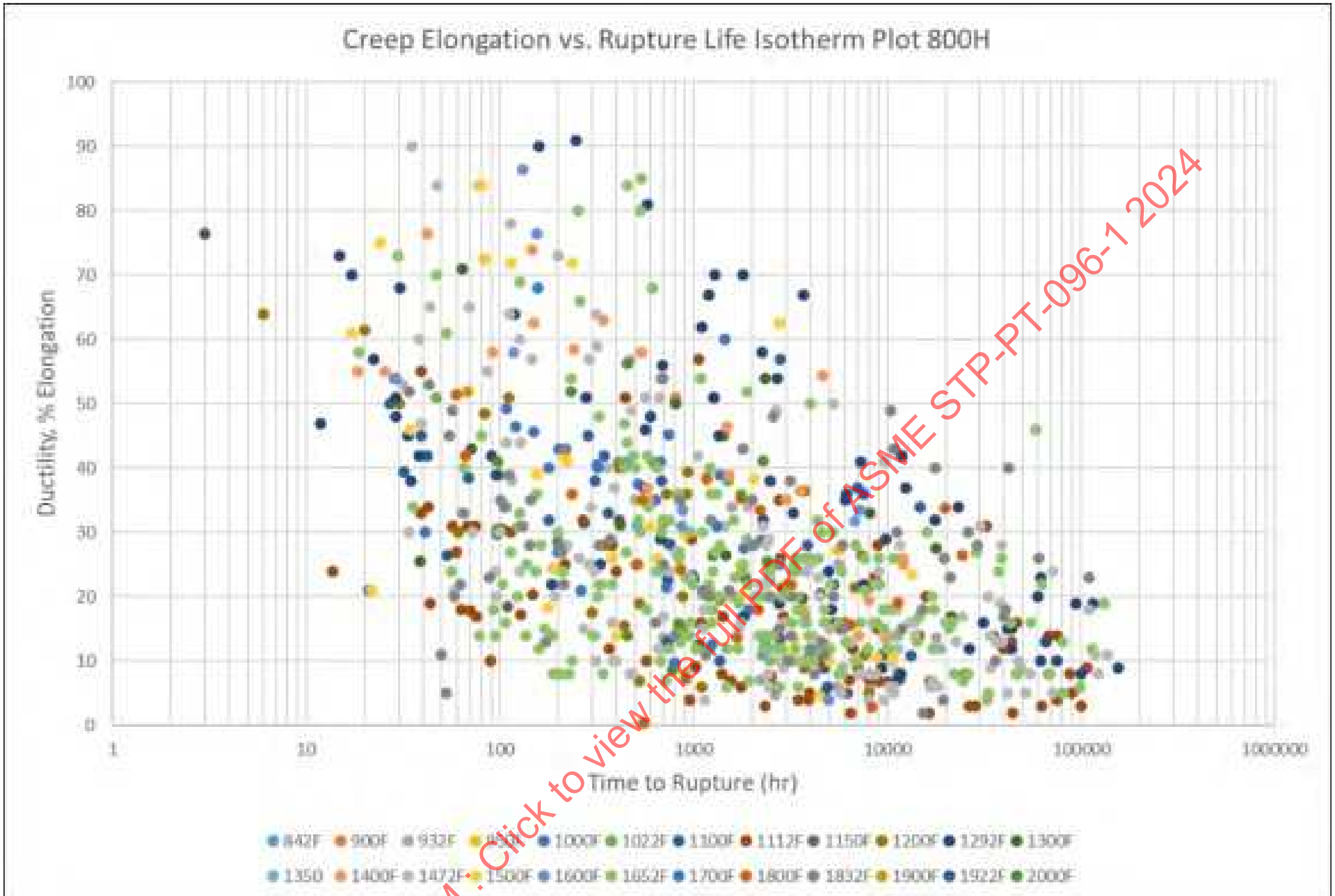


Figure 21-13: Calculated Allowable Stresses Based on Rupture and Creep Strain Rate and ASME II-D Appendix 1 Criteria (Alloy 800H)

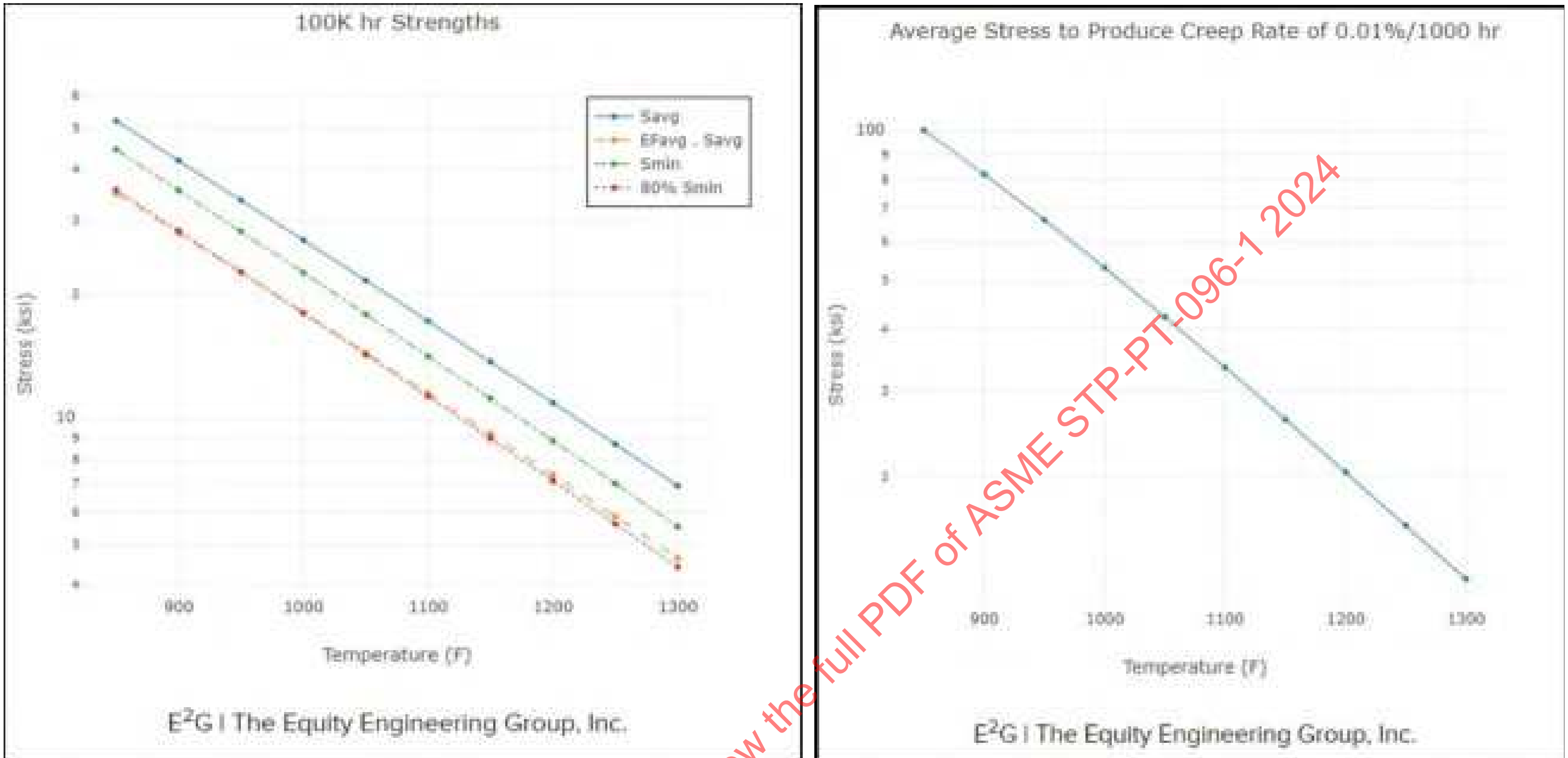


Figure 21-14: Comparison of Current Alloy 800H Allowable Stresses (Annealed) Vs. ASME II-D Appendix 1 Criteria Applied to Data

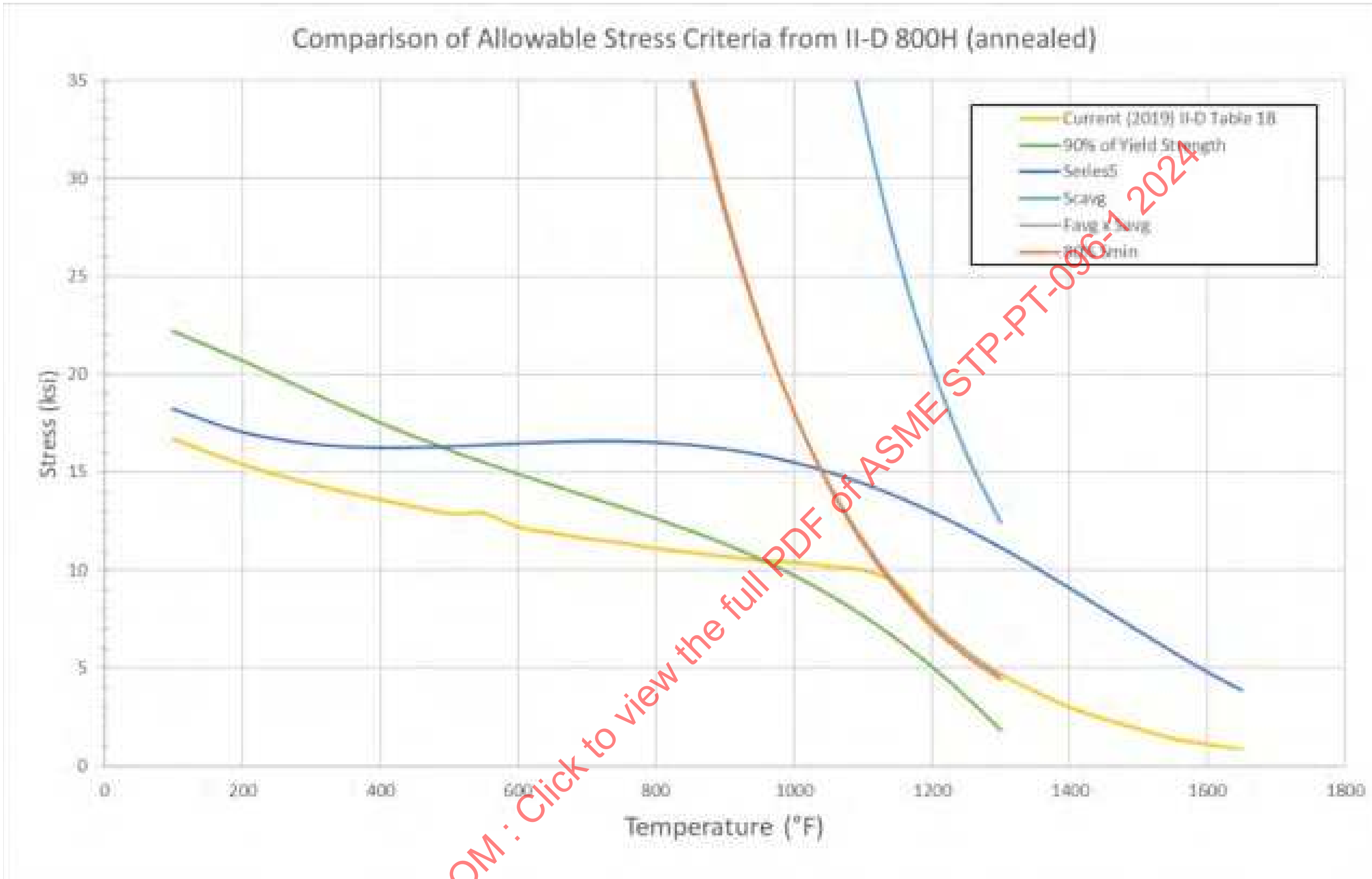


Figure 21-15: Short-Term Strain Vs. Time Data, up to 2,500 Hour Test Durations (Alloy 800H), 1 of 2

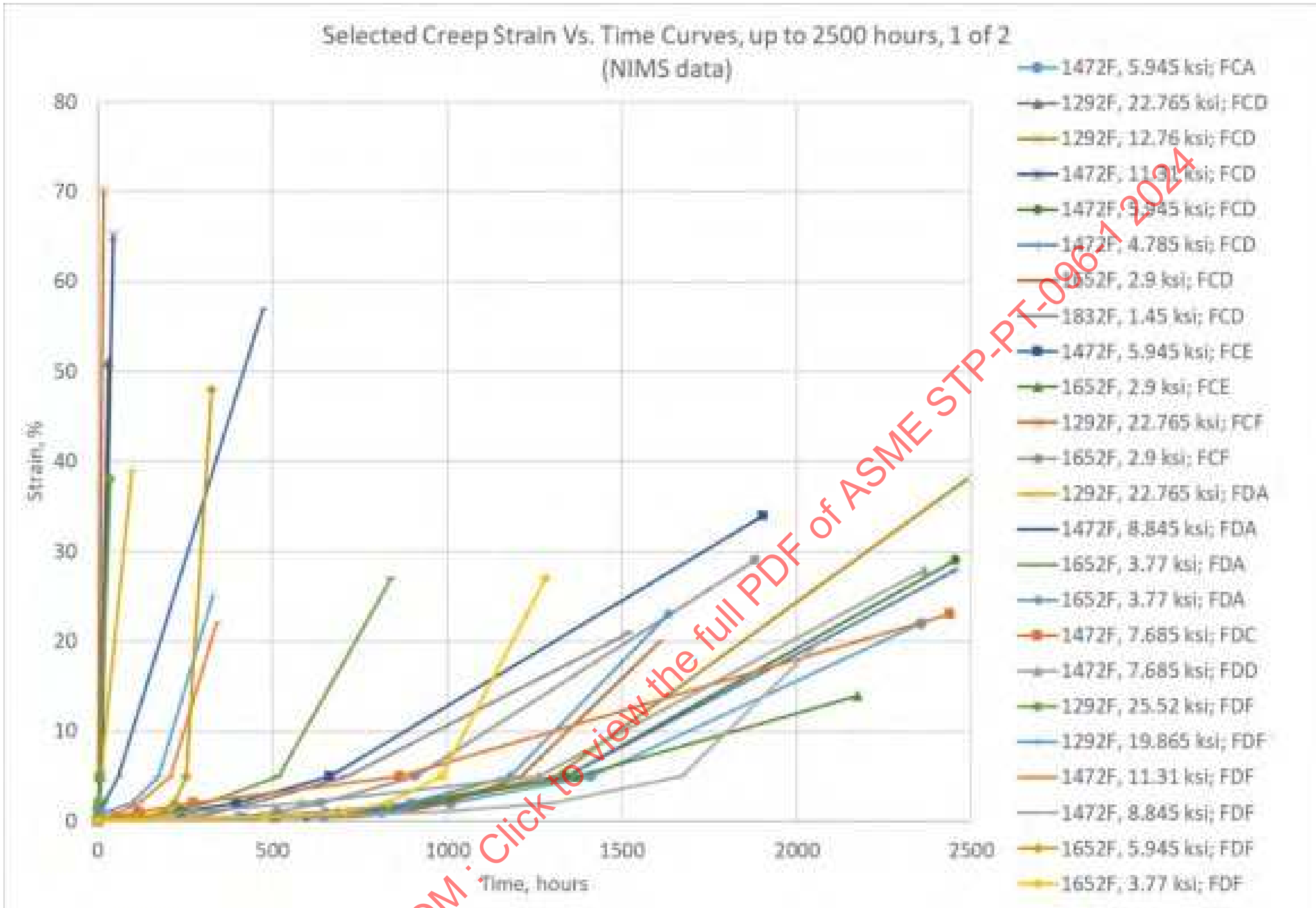


Figure 21-16: Short-Term Strain Vs. Time Data, up to 2,500 Hour test Durations (Alloy 800H), 2 of 2

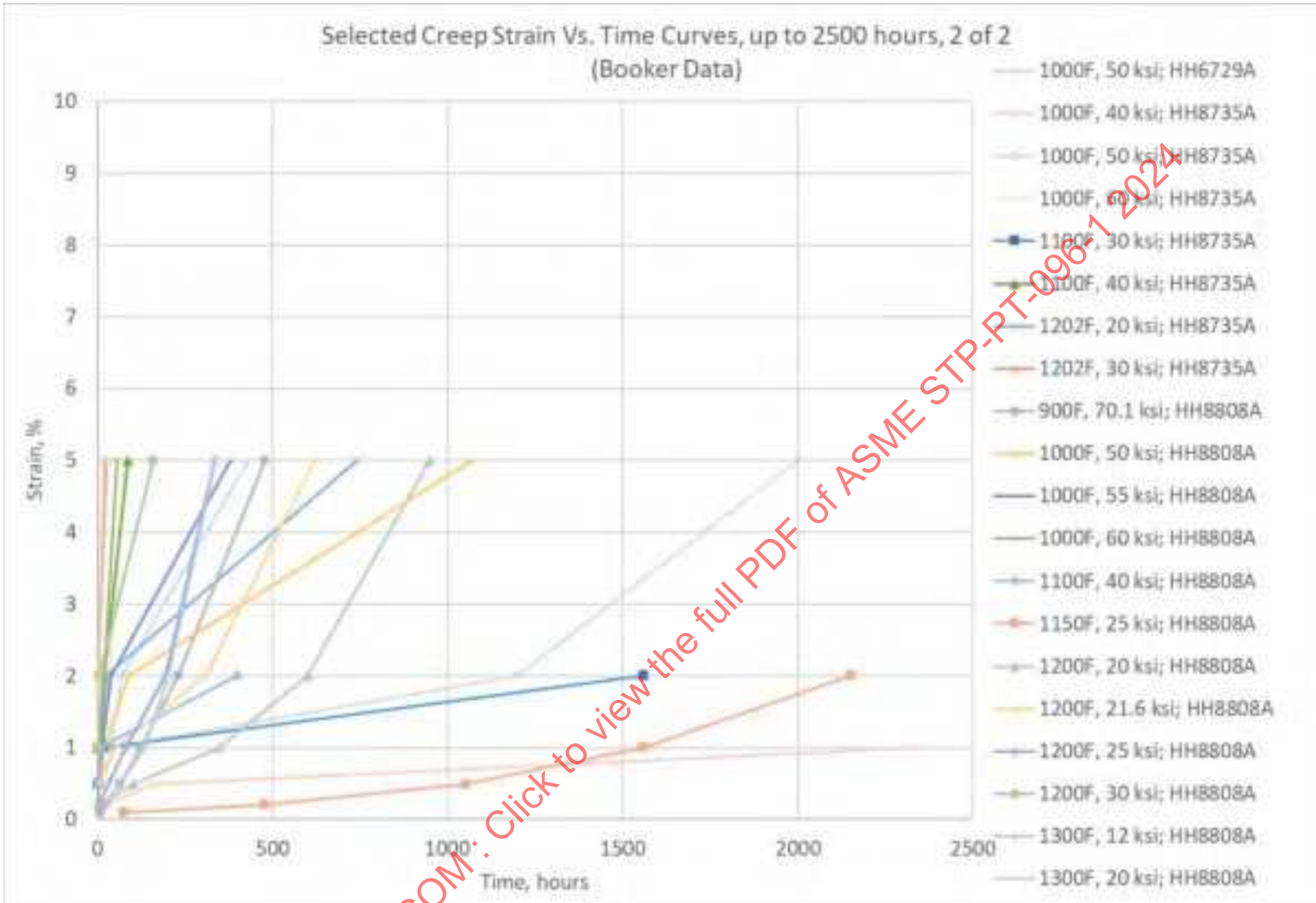


Figure 21-17: Medium-Term Strain Vs. Time Data, 2,500 to 5,000 Hour Test Durations (Alloy 800H)

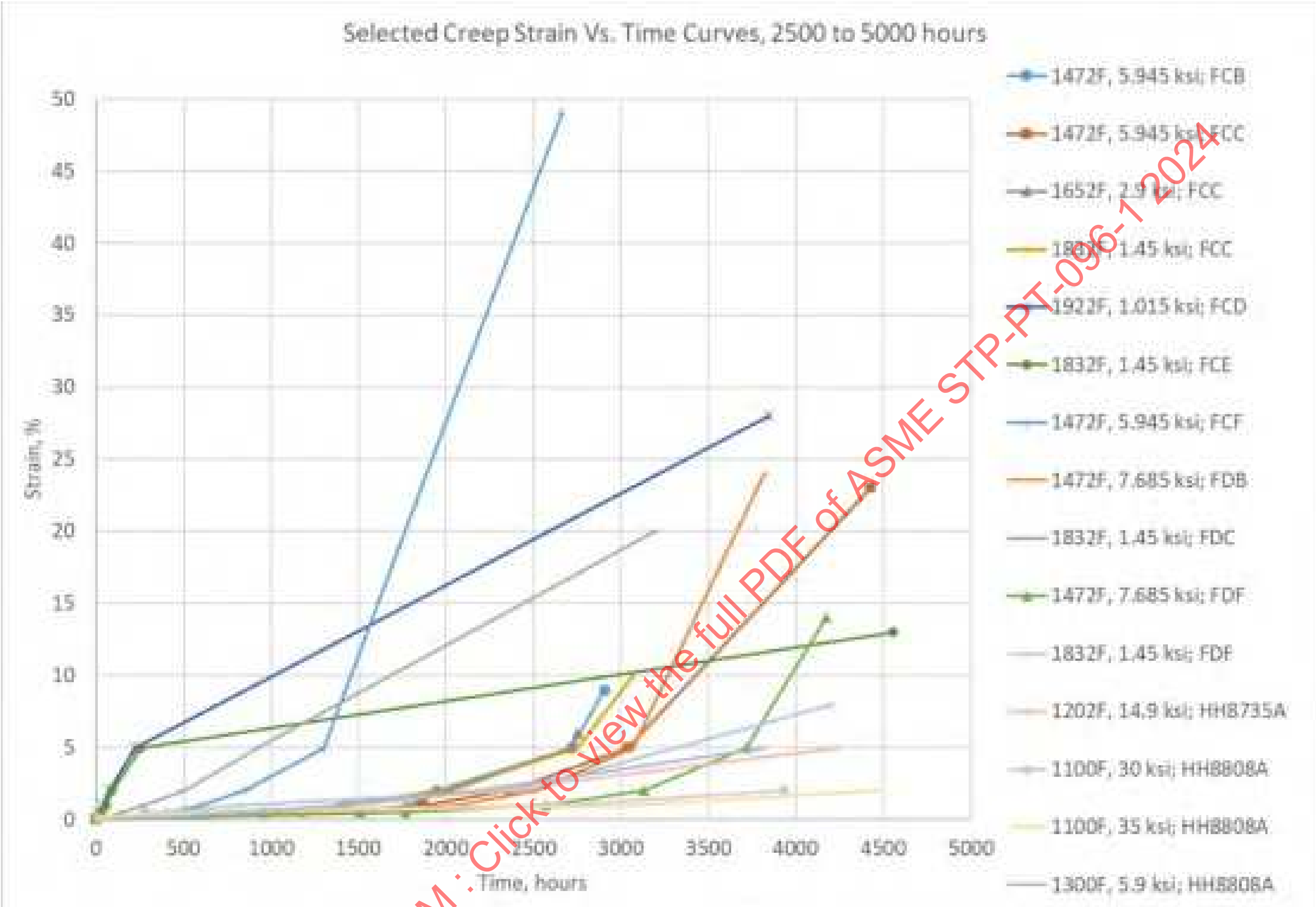


Figure 21-18: Long-Term Strain Vs. Time Data, 5,000 to 10,000 Hour Test Durations (Alloy 800H)

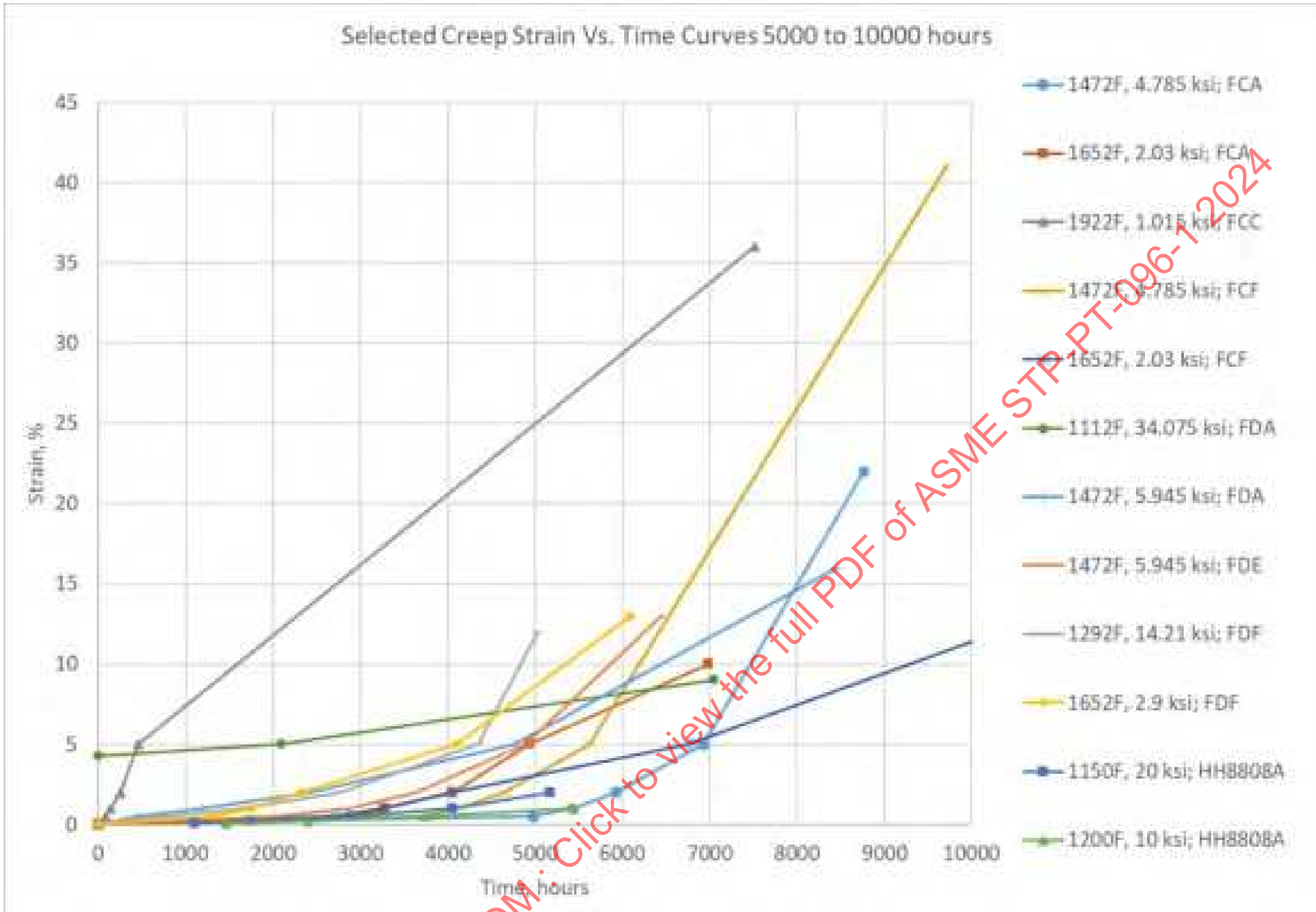


Figure 21-19: Long-Term Strain Vs. Time Data, 10,000 to 100,000 Hour Test Durations (Alloy 800H)

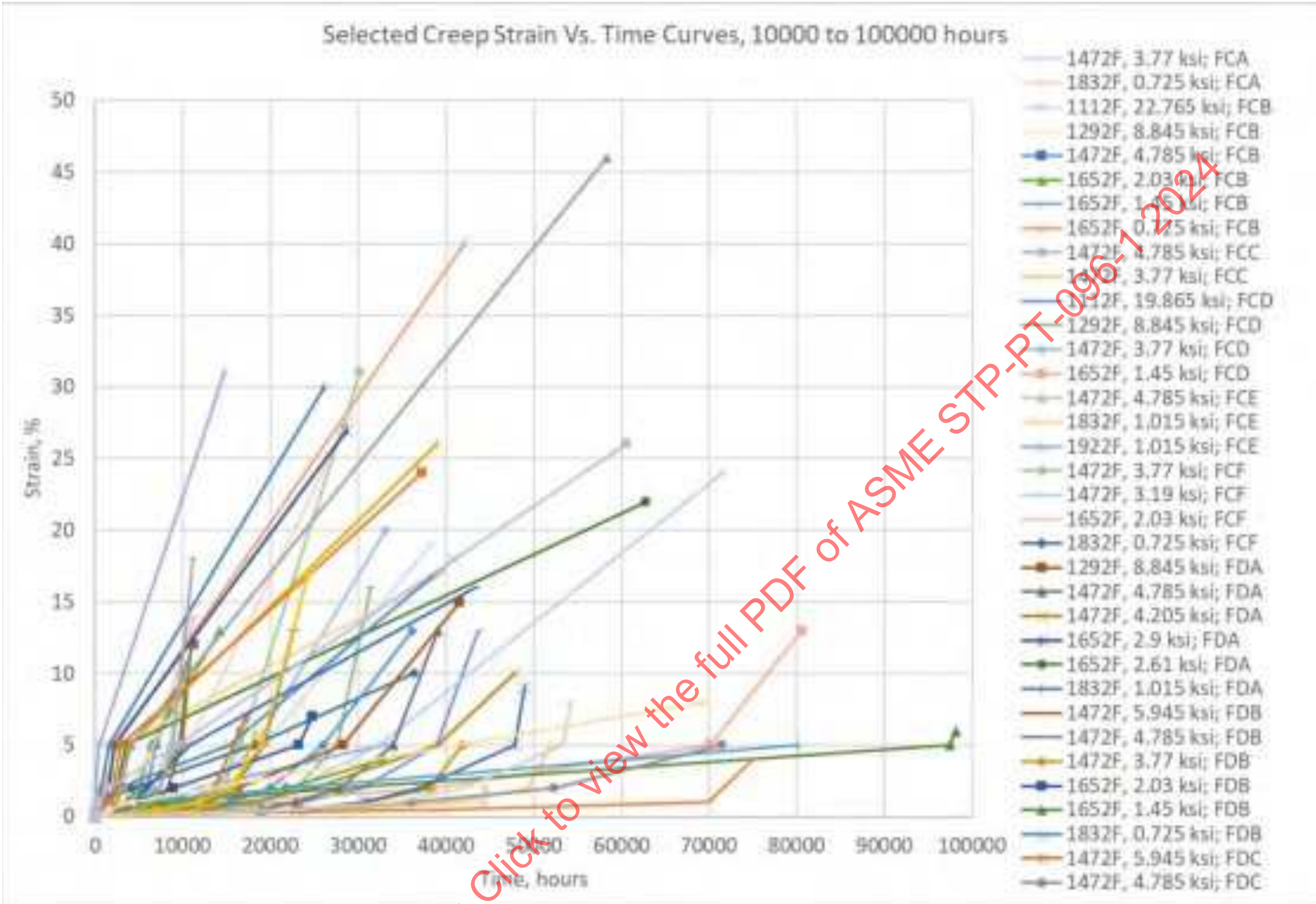


Figure 21-20: Long-Term Strain Vs. Time Data, 10,000 to 100,000 Hour Test Durations (Alloy 800H)

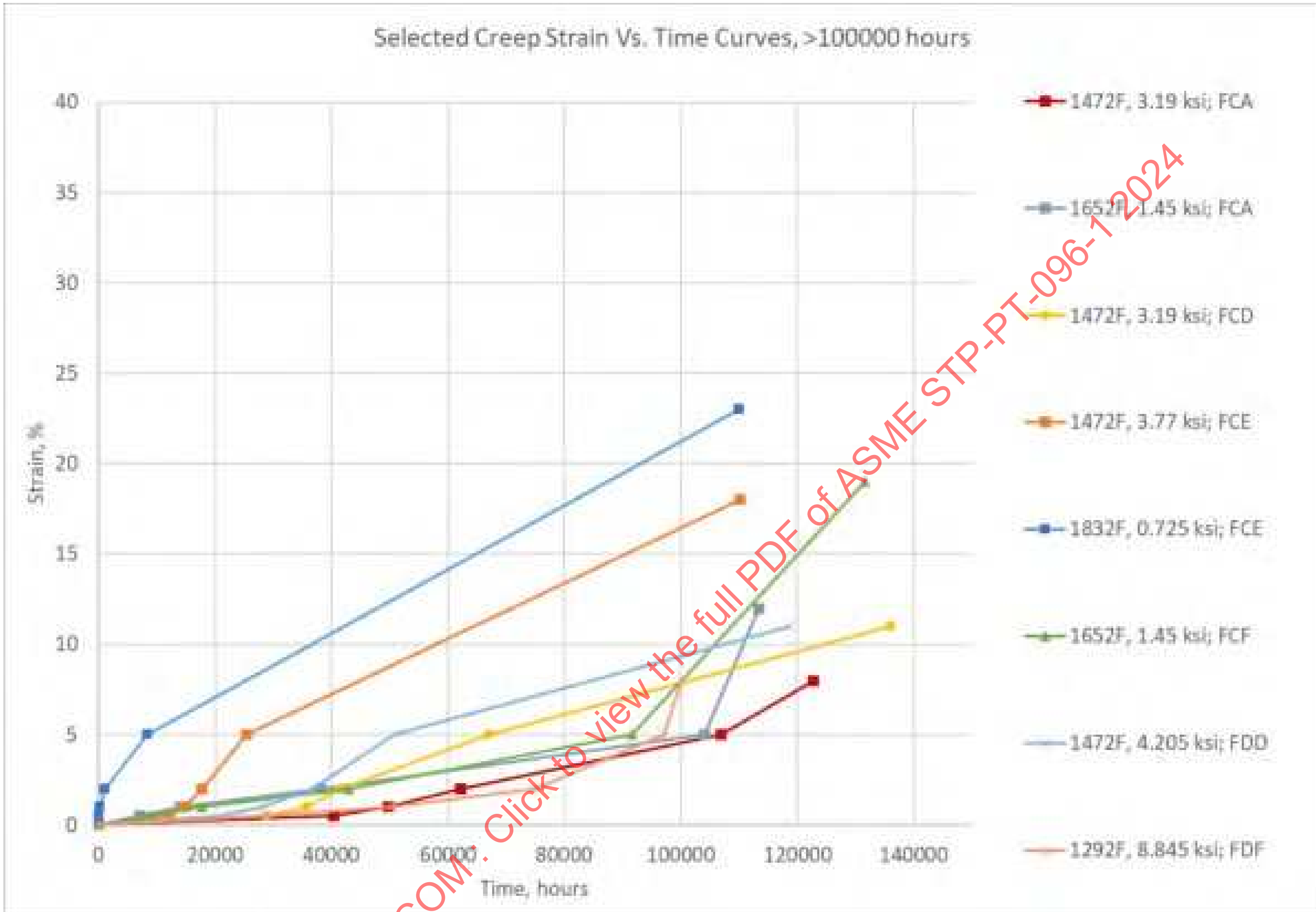


Figure 21-21: Alloy 800H Continuous Cycling Fatigue Including Room Temperature and Elevated Temperature Data

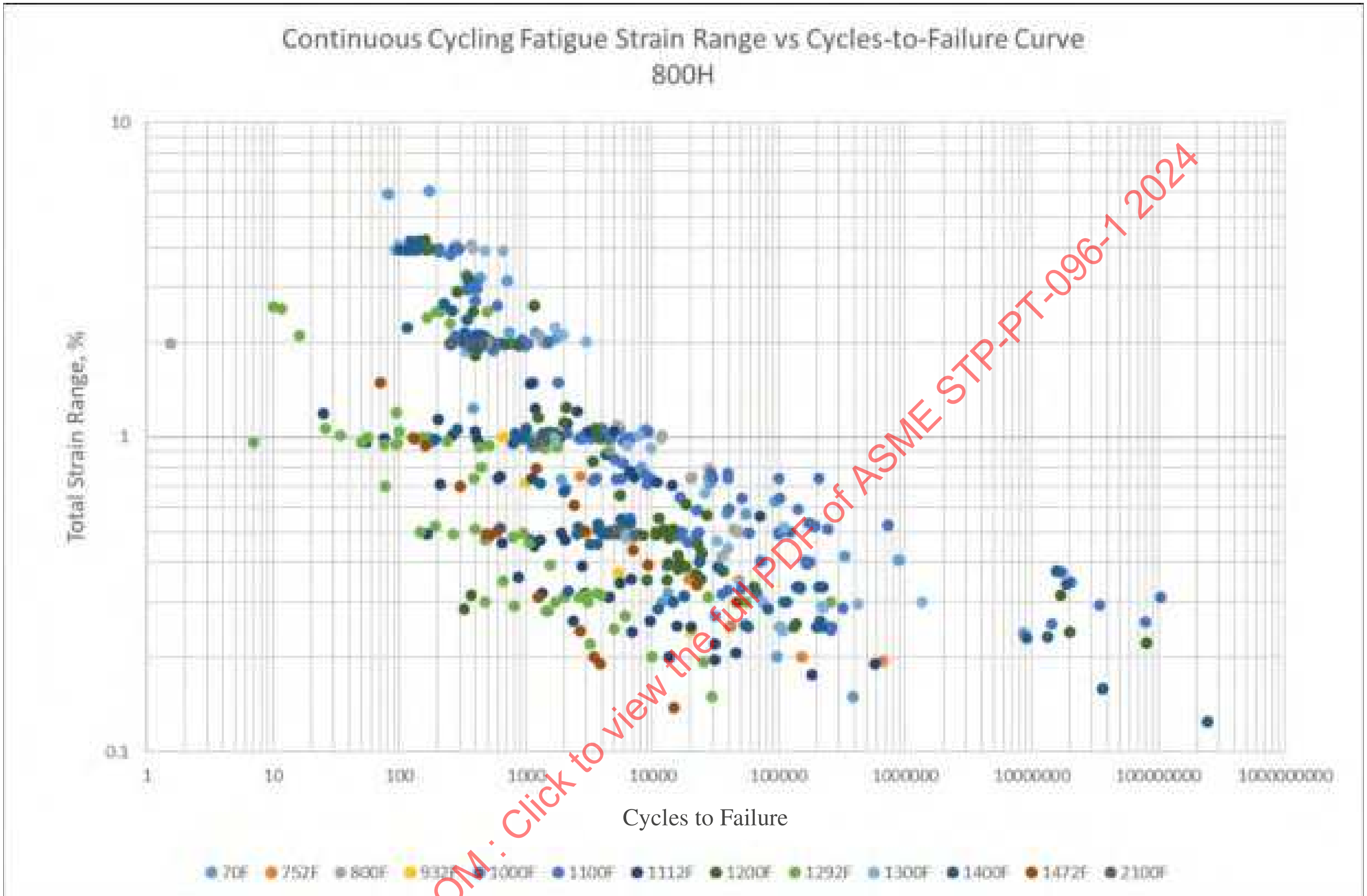


Figure 21-22: Alloy 800H Hold Time Data (Creep Fatigue) for Alloy 800H, Temperatures of 1000°F, 1292°F, 1400°F, and 1472°F

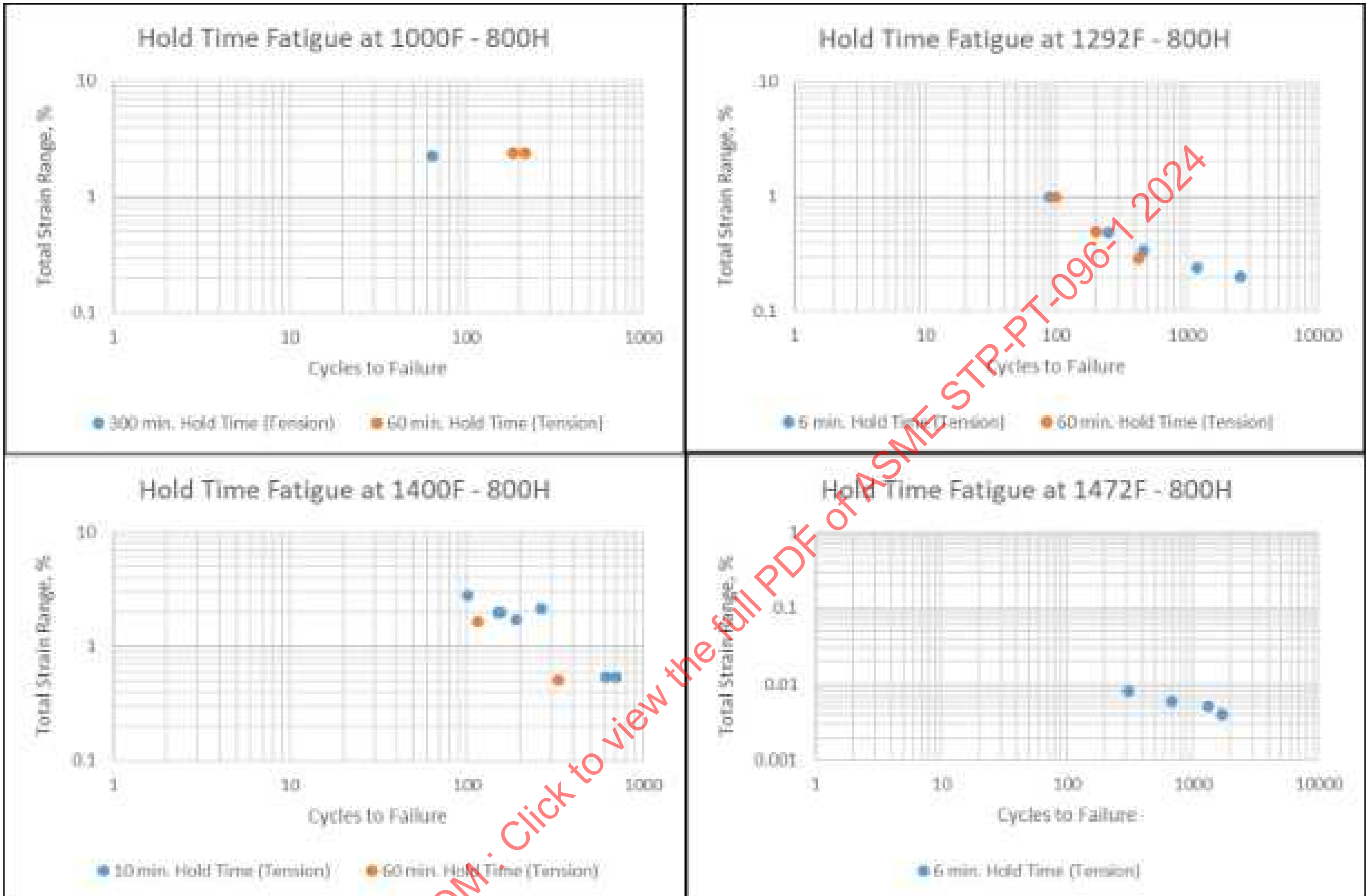


Figure 21-23: Alloy 800H Hold Time Data (Creep Fatigue) for Alloy 800H, Temperature of 1112°F

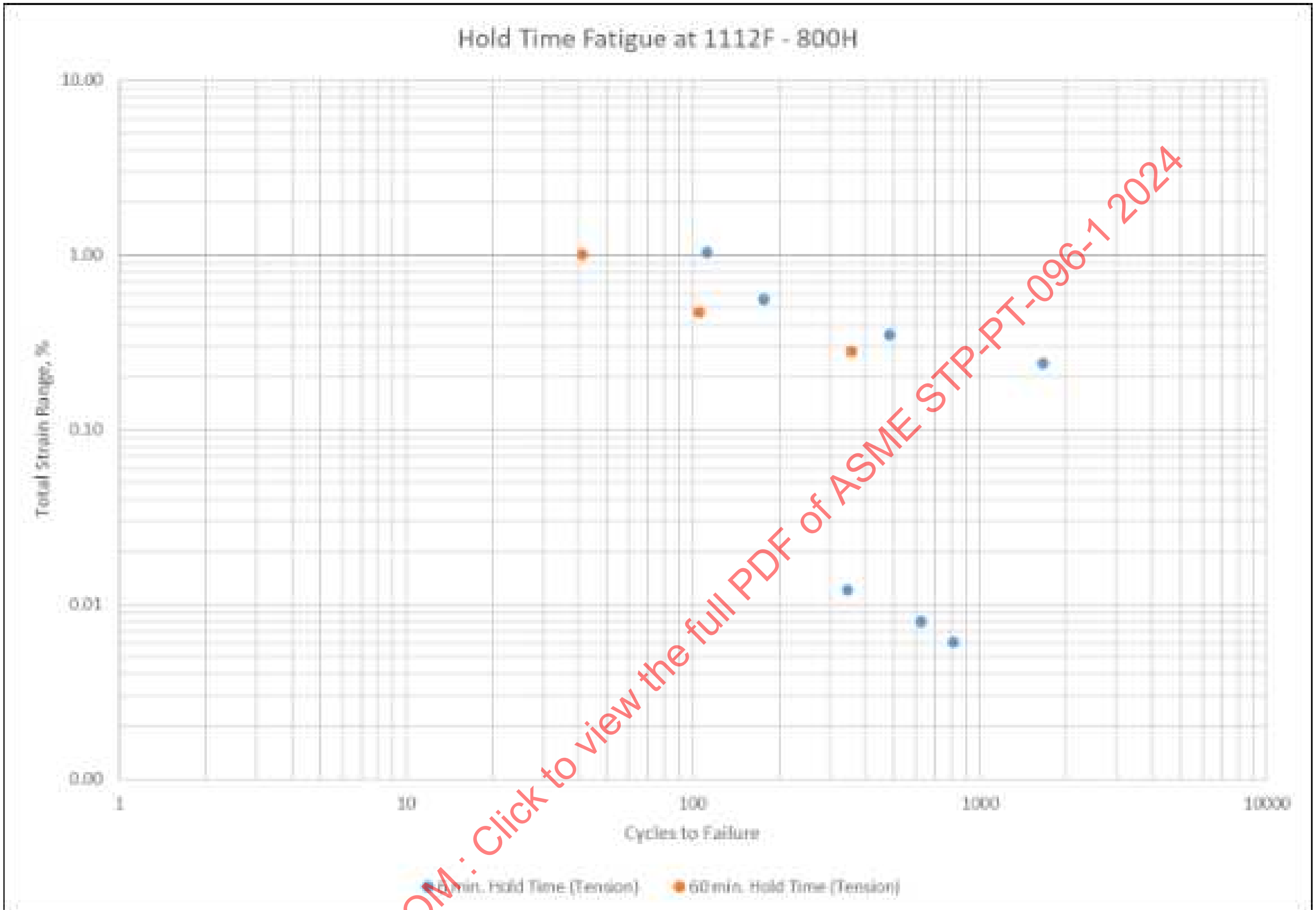


Figure 21-24: Alloy 800H Hold Time Data (Creep Fatigue) For Alloy 800H, Temperature of 1200°F

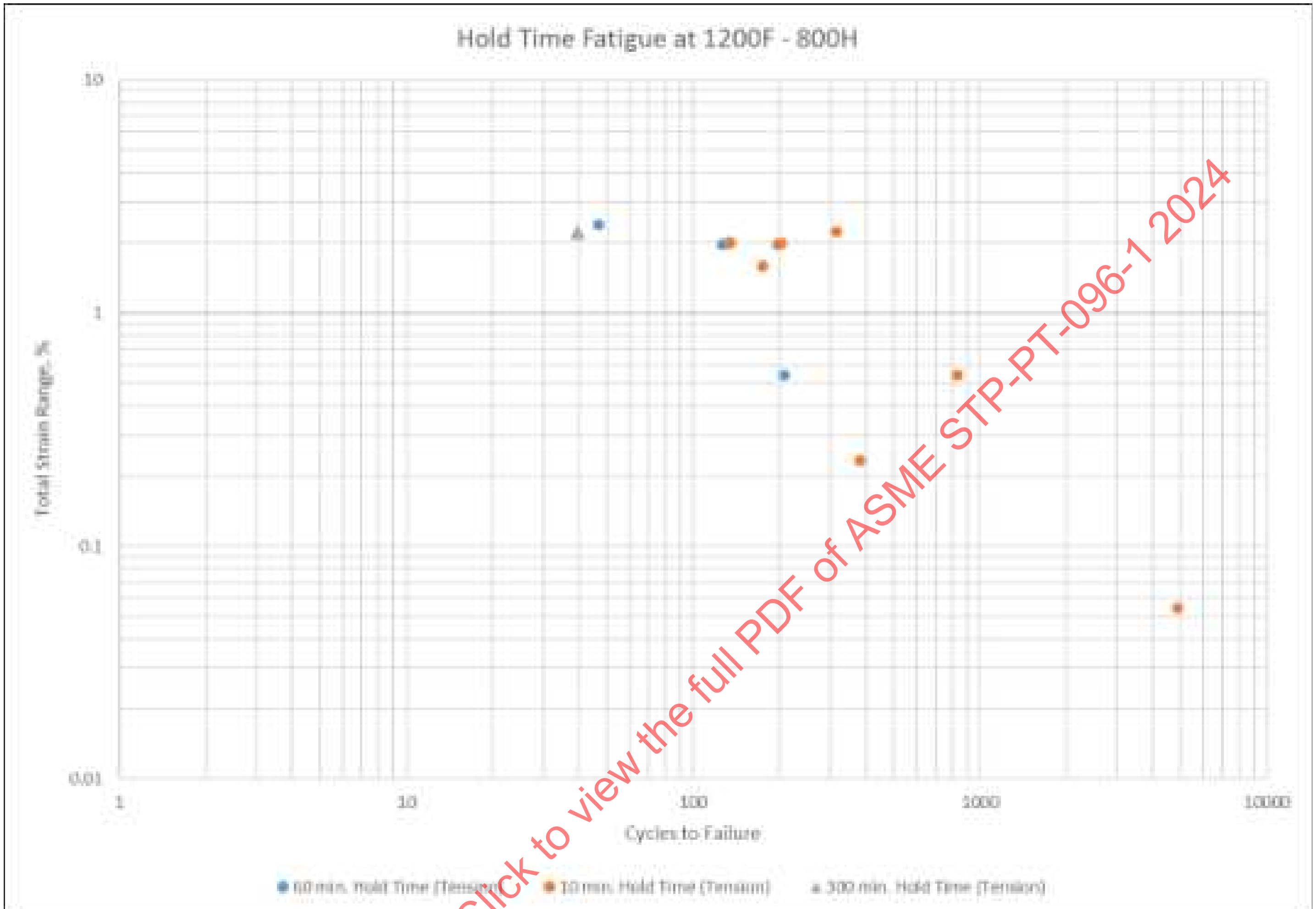
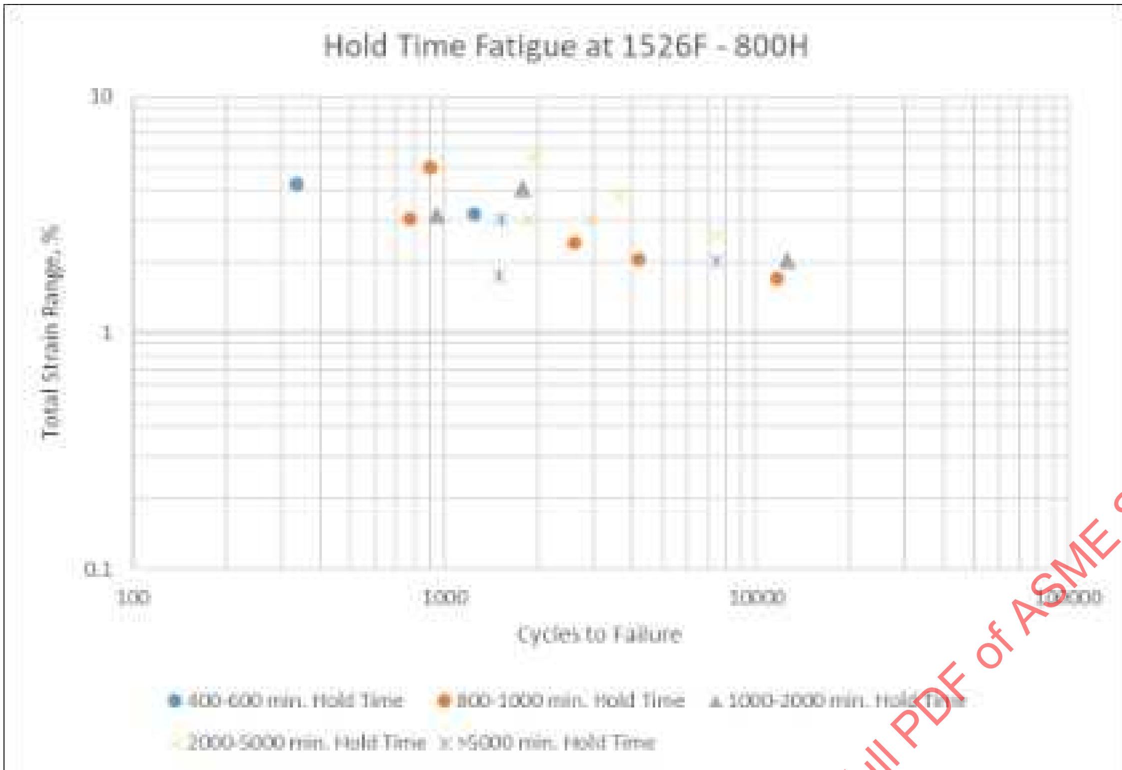


Figure 21-25: Alloy 800H Hold Time Data (Creep Fatigue) for Alloy 800H, Temperature of 1526°F



Attachment 21: Alloy 800H Property Data

If you want the referenced embedded spreadsheet with additional data, please email a request to research@asme.org.

22 GRADE 12, 1CR-0.5MO

22.1 Physical Properties

Well-established physical properties were referenced from the BPVC Section II for this material. Physical property curves from WRC Bulletin 503 were plotted for comparison. Figure 22-1 shows the trends of Elastic Modulus (E_y), Thermal Conductivity (k), Thermal Diffusivity (TD), and Thermal Expansion (α) with temperature.

22.2 Yield and Tensile Strength

Elevated temperature Yield and Tensile Strength over the range of existing allowable stresses (up to 1200°F) were readily available, including data beyond the current range of allowable stresses, up to approximately 1400°F, as shown in Figures 22-2 and 22-3. The sources for both high-temperature yield and high-temperature tensile strength are provided in the embedded spreadsheet at the end of this section. This spreadsheet also contains ductility data corresponding to the tensile test results presented in this report. Note that ductility (percent elongation and percent reduction in area) was not available for all sources referenced for the Grade 12 material.

To facilitate comparison of the data obtained to existing allowable stresses (Section II-D Table 1A), yield and tensile data were normalized on a heat-by-heat basis to express the ratio of yield or tensile strength at temperature to that measured for the heat at room temperature. In cases where data were not delineated by heats within a given source, or in cases where more than one room-temperature tensile test existed for a given heat of material, ratios are equal to the measured tensile or yield strength at temperature, divided by the average of all of the appropriate room-temperature values for the particular data source or heat of material. As a result of this approach, it is possible to have ratios in excess of 1.0. E^2G understands that this approach is similar to the normalizing procedure performed by ASME in typical analysis of yield and tensile data to obtain Table Y and Table U (Section II-D) trend curves, as well as for the calculation of allowable stresses. Figures 22-4 and 22-5 show the heat-by-heat variation in yield and tensile strength ratios (respectively) as a function of temperature. It should be emphasized that even though the figure legends reference an entire source of data, the ratios, wherever possible, were calculated on a heat-by-heat basis; this is evident in the embedded spreadsheet at the end of this section. Figures 22-6 and 22-7 contain all of the yield and tensile (respectively) ratios plotted together, to facilitate regression of a 5th-order polynomial that is subsequently used for allowable stress comparison.

22.3 Creep Data (Creep Rupture, Minimum Creep Rate, and Ductility)

Creep Rupture data is shown in Figure 22-8 and 22-9, plotted as isotherms. The temperatures have been separated onto separate plots to minimize data overlap, with Figure 22-8 showing those temperatures where most of the data were concentrated, and Figure 22-9 showing those temperatures with significantly less data. It should be emphasized that these plots contain data for all product forms of material classified in the referenced publications as "Grade 12." This certainly includes material meeting the requirements of ASME BPVC Section II-A specifications. However, due to the diversity of data sources utilized for the compilation of the material property tables, it is likely that some of the material shown in Figures 22-8 and 22-9 may not meet existing specifications for this grade of material. Where older publications are referenced, the chemistry (and for that matter, manufacturing, processing, and heat treatment) corresponding to the heat of material in the original data source, may not be consistent with modern specifications. Where possible, E^2G has documented the chemical composition if contained within the original source. In many cases, the project team has also made efforts to trace cross-referenced data back to original test results to determine if the heat treatment, product form, chemistry, etc. details can be obtained. This information is provided with the embedded spreadsheet to facilitate additional analysis on the part of ASME.

Creep Minimum strain rates (%/hour) are shown in Figure 22-10, separated by temperature. Creep Ductility, as % elongation, is plotted in Figure 22-11. As is typical, the data show significant overlap, and it is difficult to observe clear trends in the data. The data is not intended to be used as plotted but is available in the spreadsheet for additional analysis. Note that much of the data with less than 10% total elongation at failure corresponds to cross-weld specimens contained in the data.

Creep data were analyzed using E^2G's proprietary Lot-Centered Analysis web-based software tool, in order to obtain creep properties. This regression is based on a Mandel-Paule algorithm and considers the variation within individual heats of material (for both rupture and strain rate data) as well as the variation between heats. The weight assigned to each datapoint and each heat is scaled based on the relative variation. Both rupture and strain rate (minimum creep rate, expressed as true strain per hours) were regressed according to a Larson-Miller time-temperature-parameter model, with a 3rd-order polynomial of stress. Lot-specific constant behavior was accounted for in this analysis, but the variation of LMP with stress was assumed to be constant (no non-parallel terms were included in the analysis). A 95% predictive limit was utilized to obtain the lower-bound (minimum LM constant for both rupture and strain rate) properties. The results of this analysis are summarized in Table 22-1 for rupture data and Table 22-2 for strain rate data. The Lot-Centered Analysis software tool generates property tables in the creep regime using the criteria outlined in Mandatory Appendix 1 of ASME Section II-D; the nomenclature of variables is consistent with II-D Appendix 1. For visualization of the allowable stress trends, Figure 22-12 is provided (for rupture allowable stresses and creep rate allowable stresses). Figure 22-13 shows a comparison of the various allowable stress criteria from Section II-D, Appendix 1, to the existing (2019) Section II-D Table 1A allowable stresses for all product forms of Grade 12.

Creep Strain vs. time data are shown in Figure 22-14 for short-term data (up to 1,000 hour test durations); Figure 22-15 for 1,000 to 25,000 hour test durations, and Figure 22-16 for tests exceeding 25,000 hour test durations. Curves are only plotted where more than 5 strain vs. time points are present for the test. Additional curves are available with fewer datapoints (typically obtained from data in the form of time-until-specified-strain) in the embedded spreadsheet. Both creep rate and creep strain vs. time data are provided to satisfy ASME's request for creep strain vs. time curves, and both forms of data are applicable in developing allowable stresses. Although digitalization of creep curve data was not explicitly necessary per the project contract, E^2G did perform digitalization of creep curves where only graphical data was available (as is often the case in the published literature).

22.4 Hold Time Fatigue Curves

A portion of the data obtained for continuous cycling fatigue data at elevated temperatures for Grade 12 is shown in Figure 22-17, which includes room temperature data contained in sources which also present high-temperature data. Figure 22-17 only contains data for which total strain range was determined from the original source. Additional data points for continuous cycling fatigue data of Grade 12 are presented in the attached spreadsheet; however, due to the complexities of various forms of fatigue data, compatible plots for each type of data expression and failure criteria are not included in this report.

Table 22-1: Model Parameters, Larson-Miller Property Results, and Allowable Stress (Rupture) Criteria, Grade 12

Equation Format:

$$\log(t_r) = C_{avg} + \frac{1}{T+460}\left(b_1 + b_2\log(\sigma) + b_3(\log(\sigma))^2 + b_4(\log(\sigma))^3\right)$$

C_{avg}	**-19.24**
C_{min}	**-19.94**
b_1	**43557.3**
b_2	**-14568.5**
b_3	**9971.3**
b_4	**-3489.1**

Number Data Points		**931**
Correlation Coefficient	R^2	0.7845
Average Variance within Heats	V_w	0.181
Variance between Heats	V_b	0.0632
Standard Error of Estimate	SEE	0.4254

Properties provided are for T in °F, stress in ksi, and t_R in hours

Temperature, °F	**S_{avg} (ksi)**	***n***	**F_{avg} (calc)**	**F_{avg} (used)**	**$F_{avg} \times S_{avg}$**	**S_{min} (ksi)**	**80% S_{min}**
850	37.18	6.919	0.7169	0.67	24.91	28.9	23.12
900	26.44	5.425	0.6541	0.67	17.71	19.09	15.27
950	17.31	4.202	0.5781	0.67	11.6	11.44	9.15
1000	10.35	3.501	0.518	0.67	6.937	6.531	5.224
1050	6.022	3.565	0.5242	0.67	4.035	3.962	3.169
1100	3.753	4.21	0.5787	0.67	2.514	2.65	2.12
1150	2.563	5.072	0.6351	0.67	1.717	1.916	1.533
1200	1.879	5.958	0.6794	0.67	1.259	1.463	1.17
1250	1.449	6.8	0.7127	0.67	0.9709	1.161	0.9287
1300	1.158	7.578	0.738	0.67	0.7762	0.9478	0.7583

Table 22-2: Model Parameters, Larson-Miller Property Results, and Allowable Stress (Strain Rate) Criteria, Grade 12

Equation Format:

$$\log(\dot{\varepsilon}_0) = -C_{avg} - \frac{1}{T+460}\left(a_1 + a_2\log(\sigma) + a_3(\log(\sigma))^2 + a_4(\log(\sigma))^3\right)$$

C_{avg} (A_0)	**-16.64**
C_{min} ($A_0+\Delta_\Omega^{SR,LB}$)	**-17.71**
a_1	**40049.1**
a_2	**-11688.8**
a_3	**8260.3**
a_4	**-3046.7**

Number Data Points		**120**
Correlation Coefficient	R^2	0.6259
Average Variance within Heats	V_w	0.3424
Variance between Heats	V_b	0.144
Standard Error of Estimate	SEE	0.5851

Properties provided are for T in °F, stress in ksi, and t_R in hours

Temperature, °F	**$S_{C,avg}$ (ksi)**
850	58.76
900	46.1
950	34.6
1000	24.36
1050	15.63
1100	9.021
1150	5.068
1200	3.111
1250	2.118
1300	1.553

Figure 22-1: Grade 12 Modulus (E_y), Thermal Conductivity (k), Thermal Diffusivity (TD), & Thermal Expansion (α) With Temperature

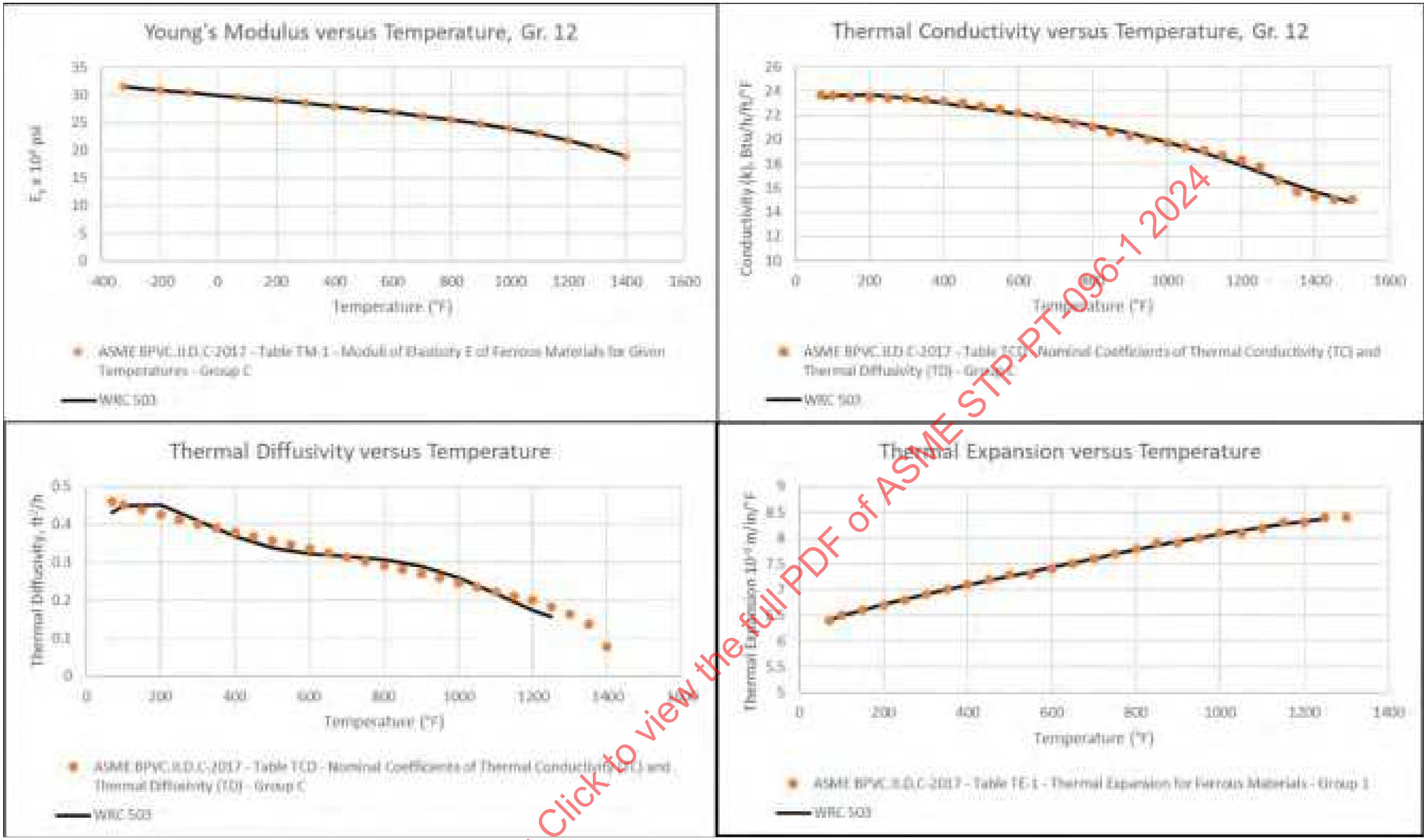


Figure 22-2: Grade 12 Yield Strength Vs. Temperature, By Data Source, Including Trend Curves

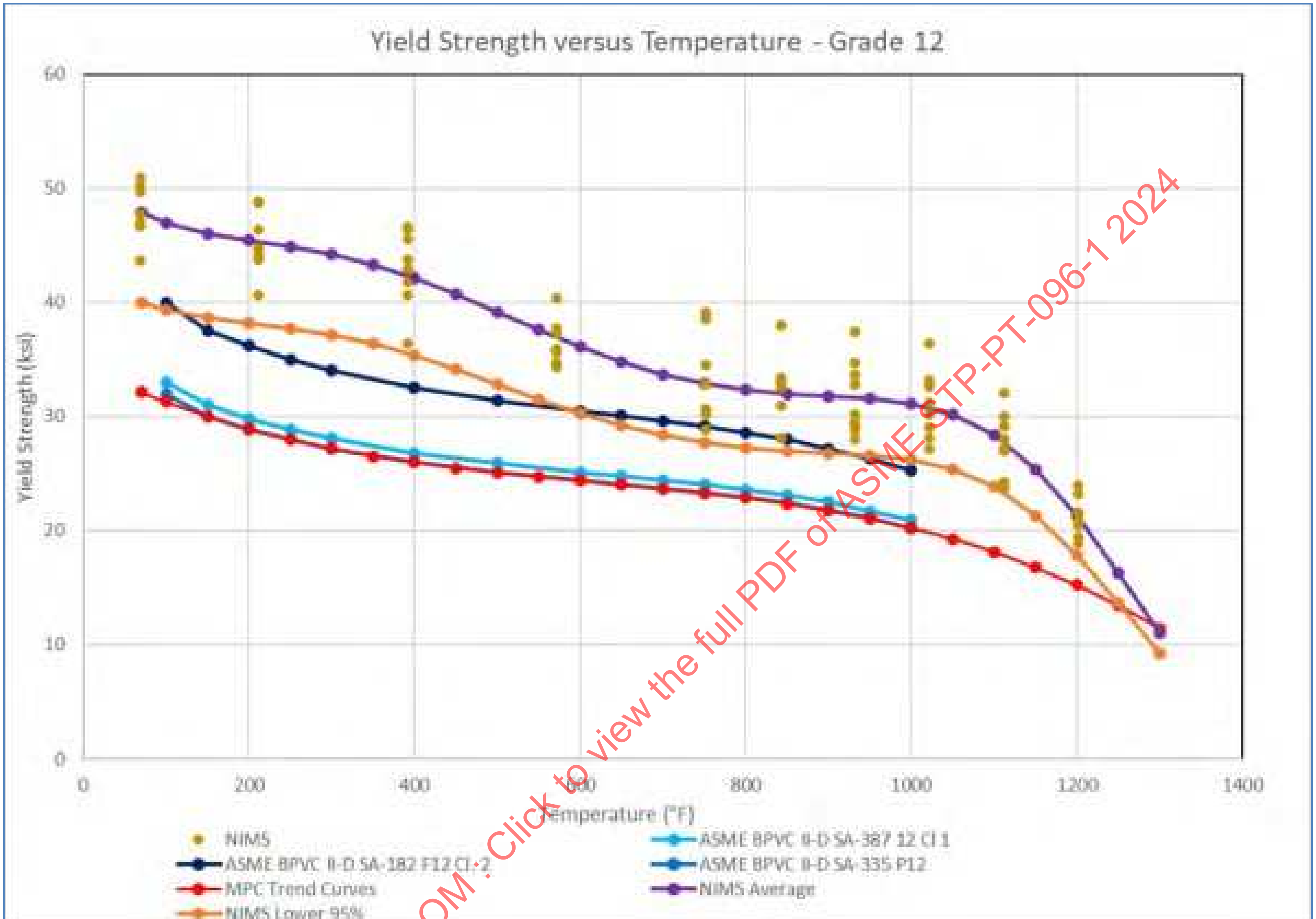


Figure 22-3: Grade 12 Tensile Strength Vs. Temperature, By Data Source, Including Trend Curves

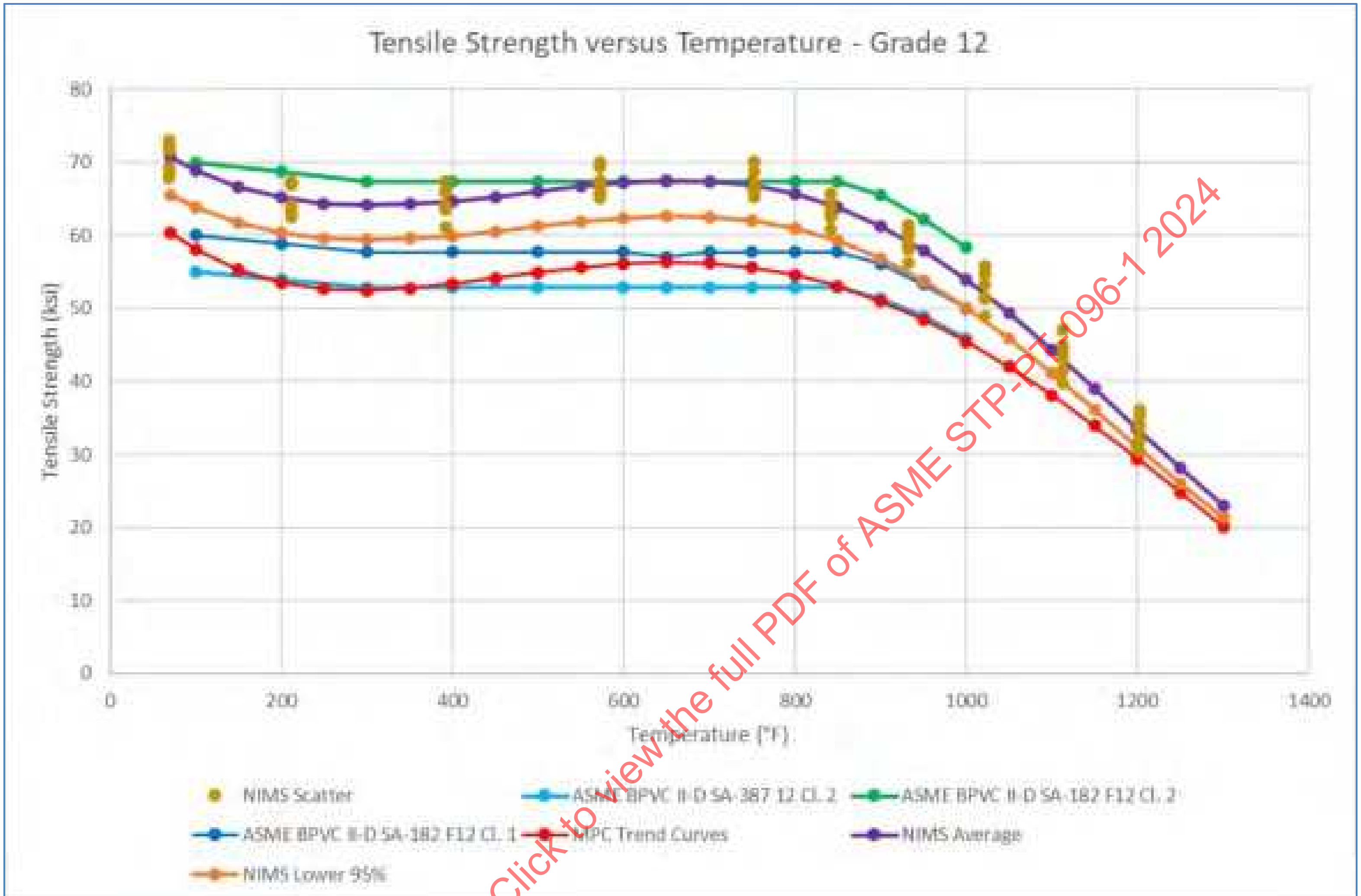


Figure 22-4: Grade 12 Yield Strength Ratios Vs. Temperature (Calculated on a Heat-By-Heat Basis, By Data Source)

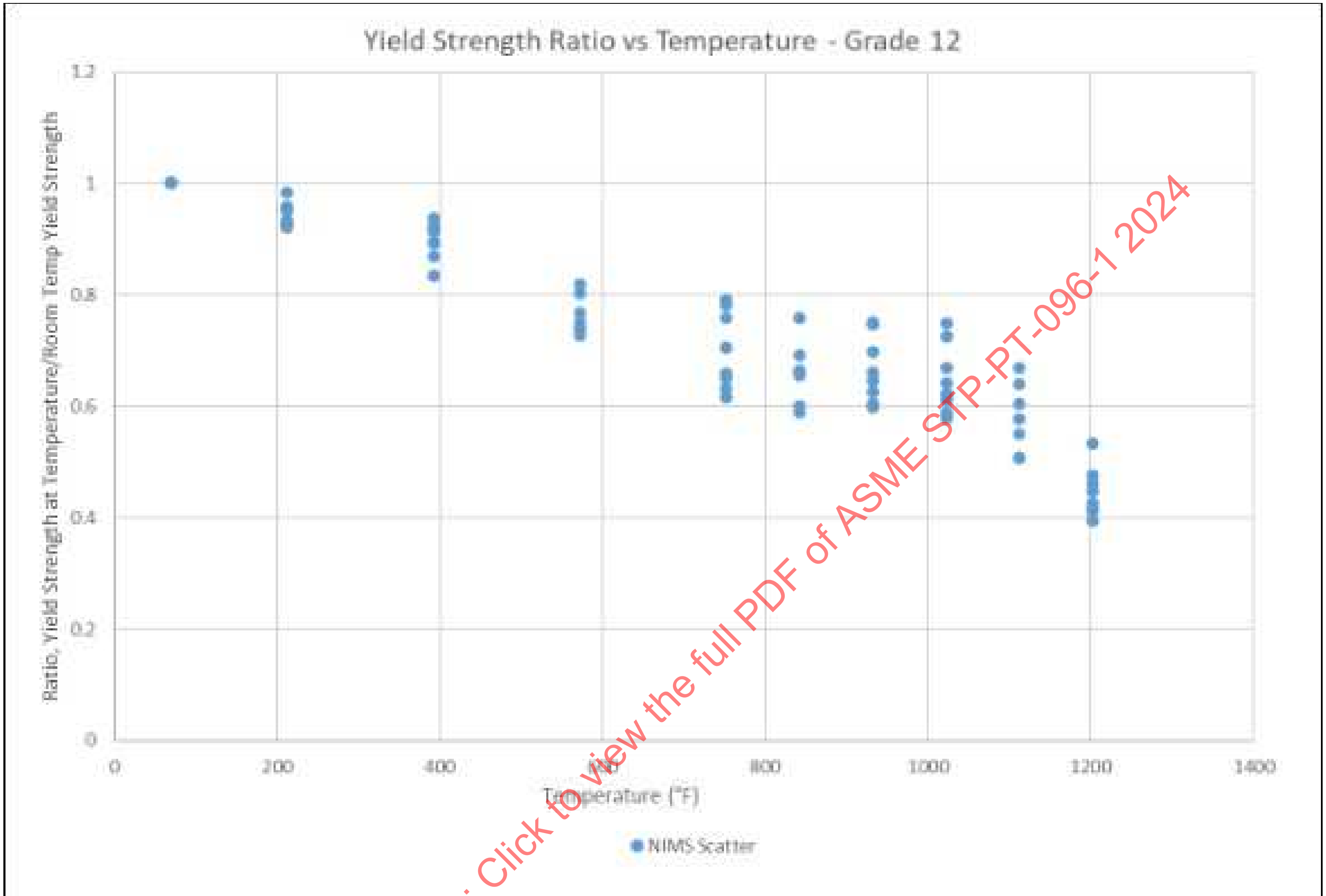


Figure 22-5: Grade 12 Tensile Strength Ratios Vs. Temperature (Calculated on a Heat-By-Heat Basis, By Data Source)

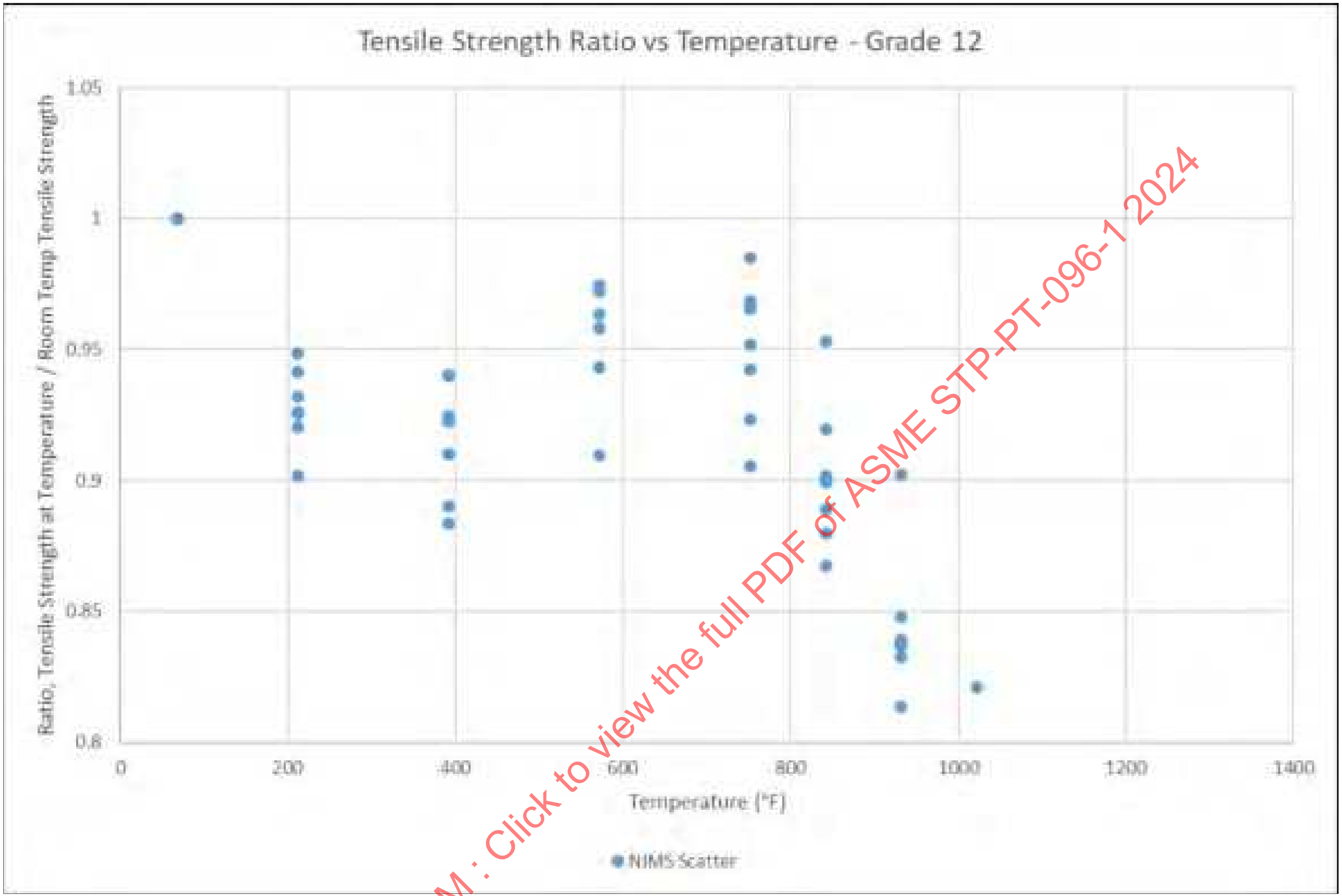


Figure 22-6: Grade 12 Yield Strength Ratios Vs. Temperature, All Combined Data, With Polynomial Regression

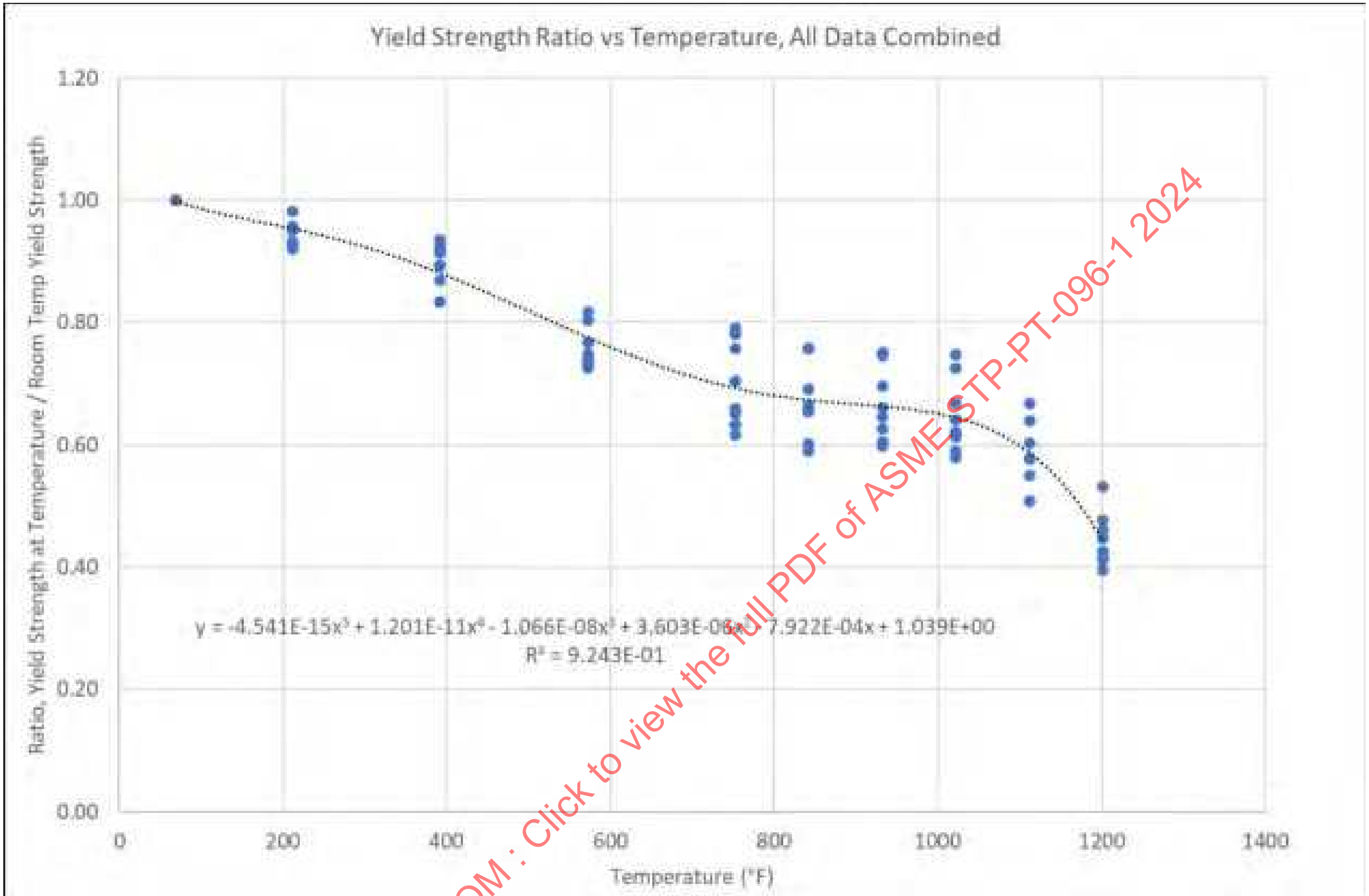


Figure 22-7: Grade 12 Tensile Strength Ratios Vs. Temperature, All Combined Data, With Polynomial Regression

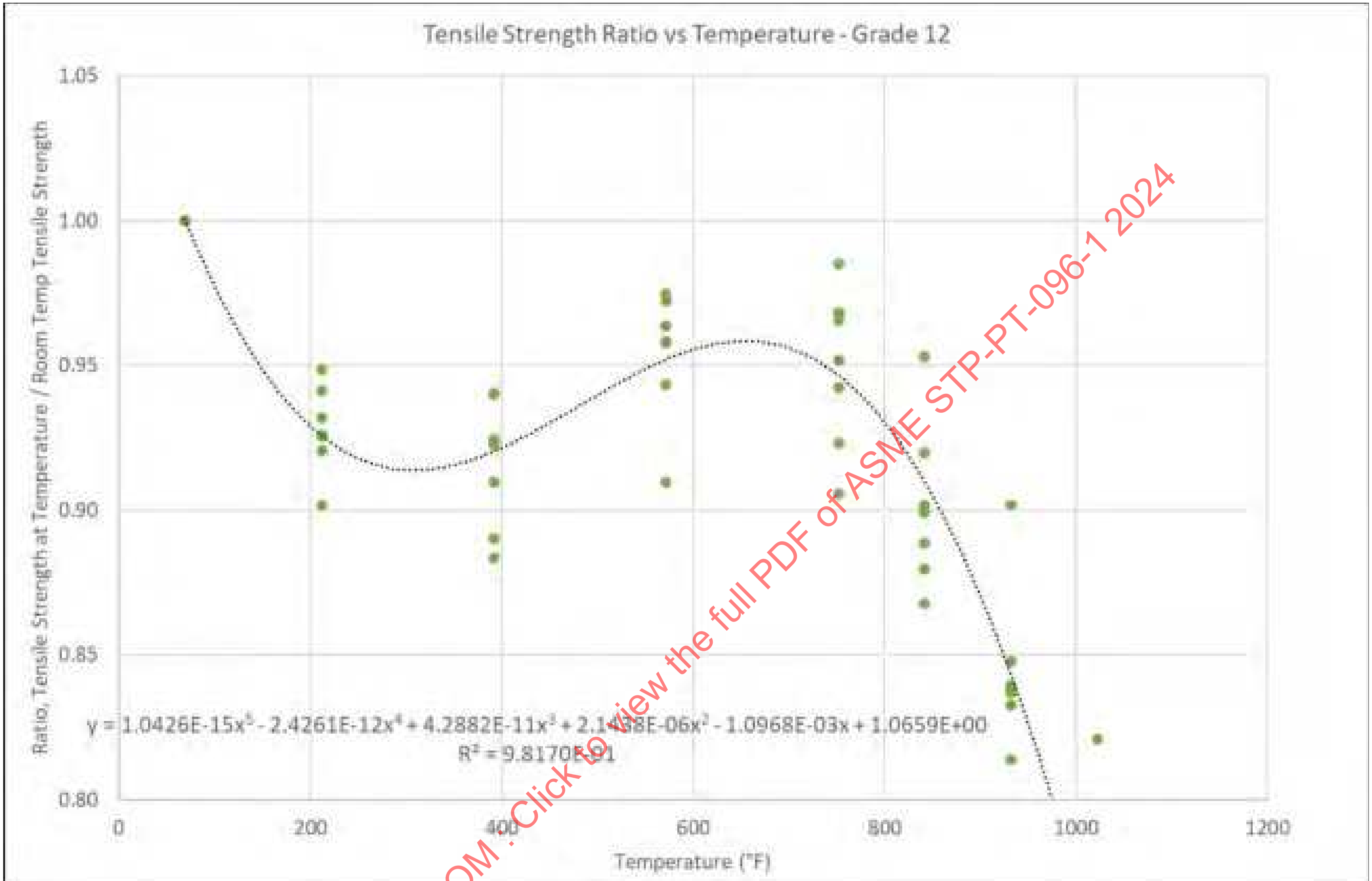


Figure 22-8: Grade 12 Creep Rupture Isotherm Curves, Temperatures With High Concentration of Data Points

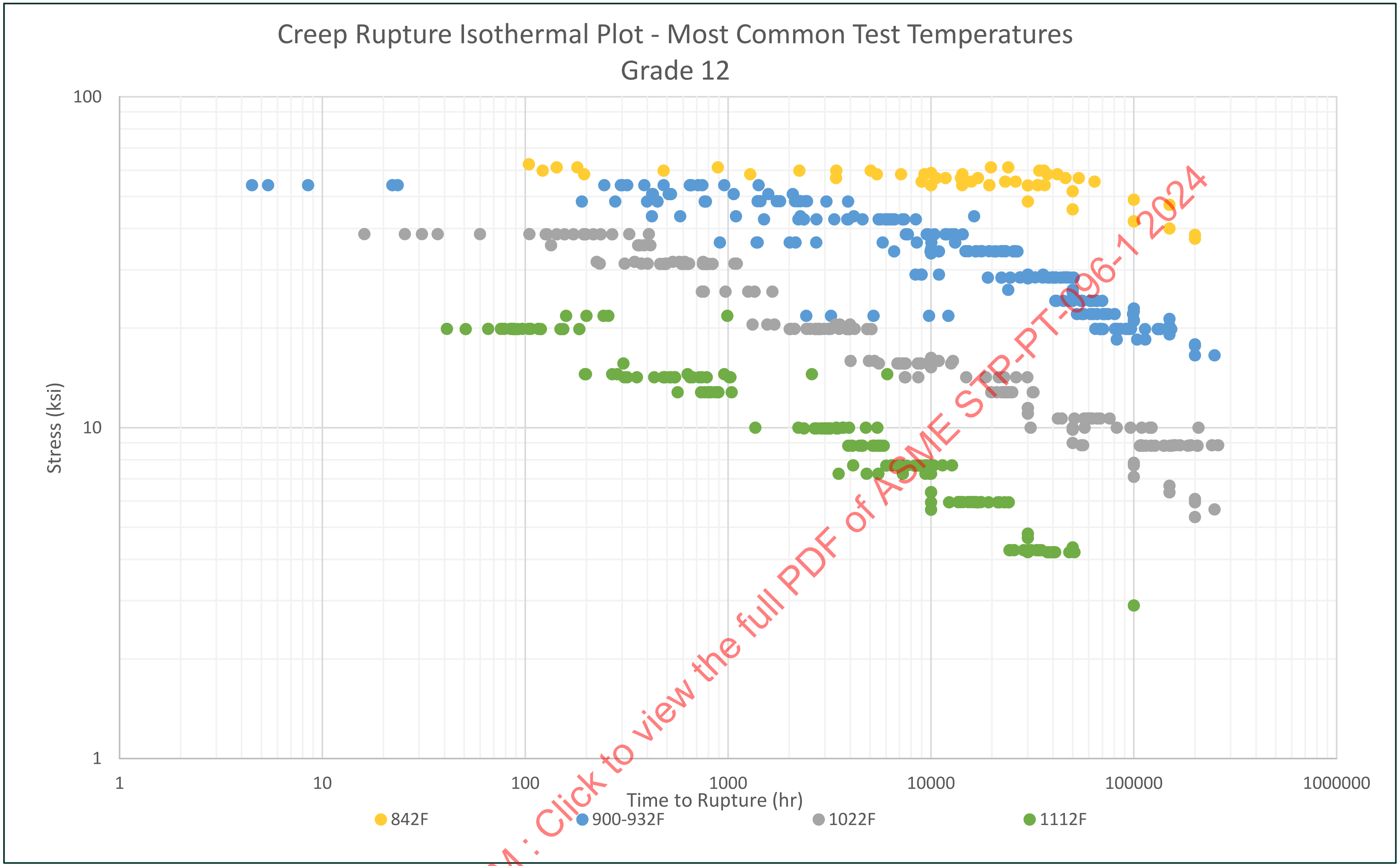


Figure 22-9: Grade 12 Creep Rupture Isotherm Curves for Additional and Intermediate Temperatures

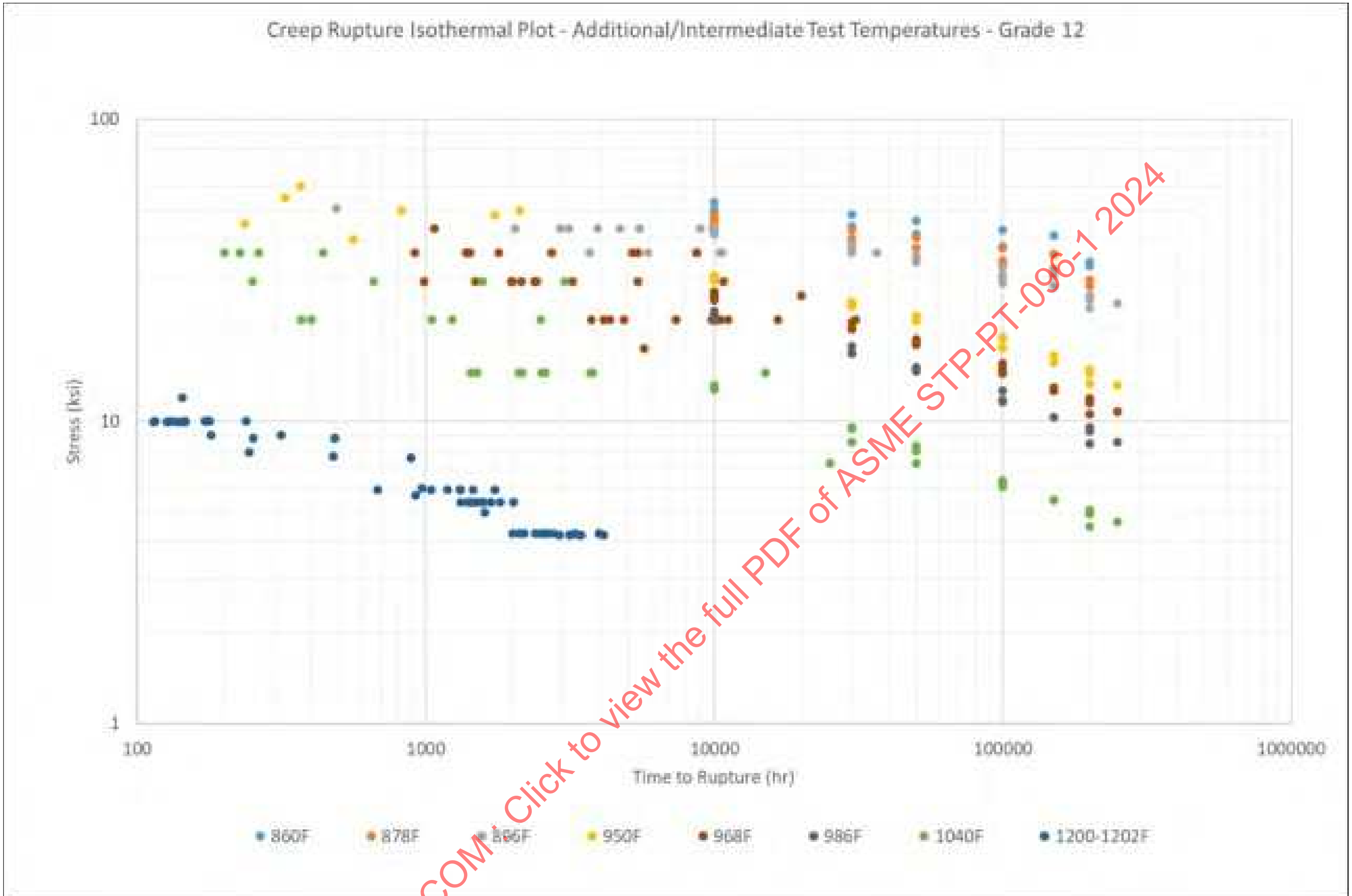


Figure 22-10: Grade 12 Creep Strain Rate (MCR) Isotherm Curves, Temperatures With High Concentration of Data Points

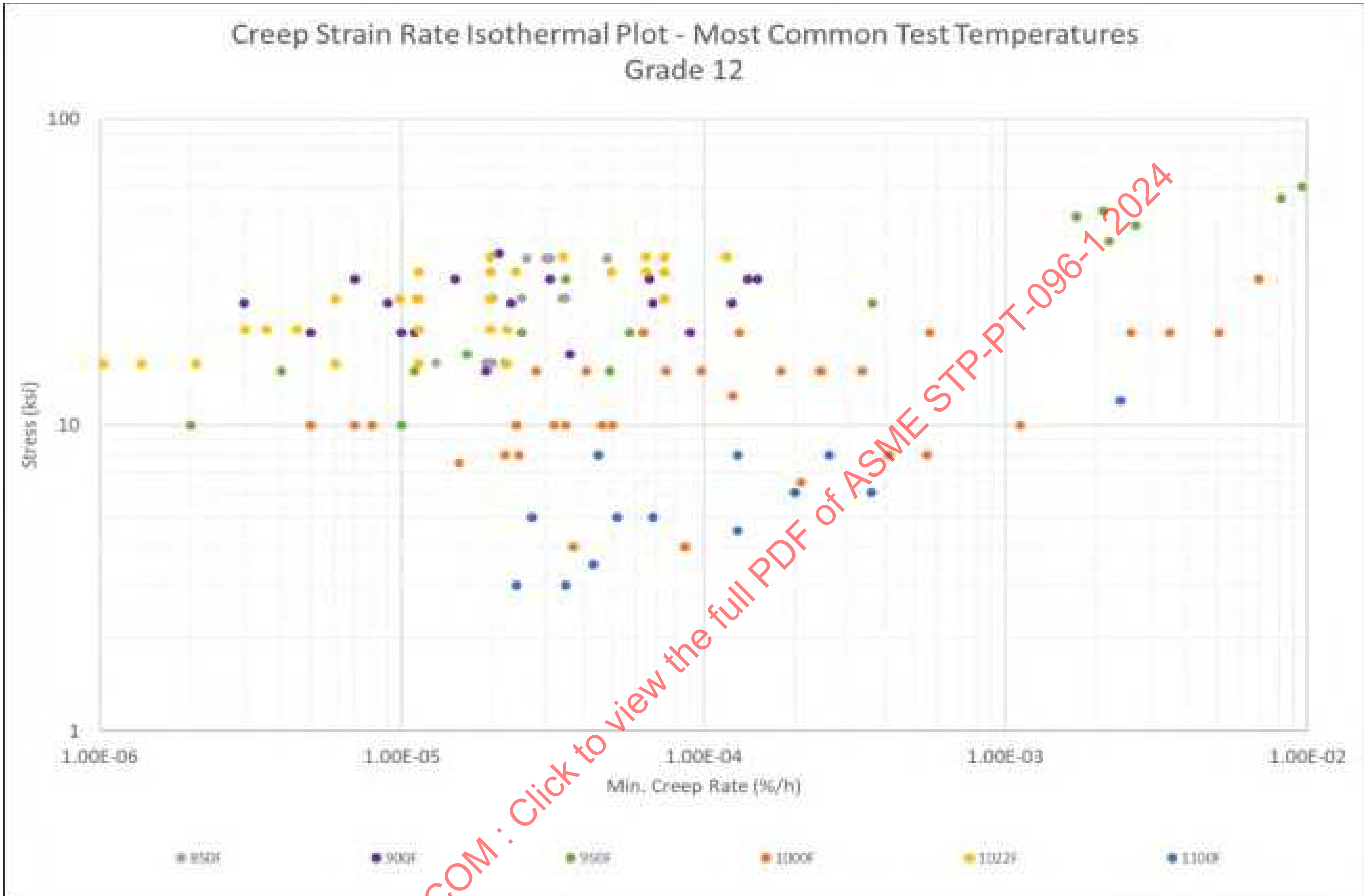


Figure 22-11: Grade 12 Creep Ductility (% Elongation) Vs. Rupture Time Isotherms

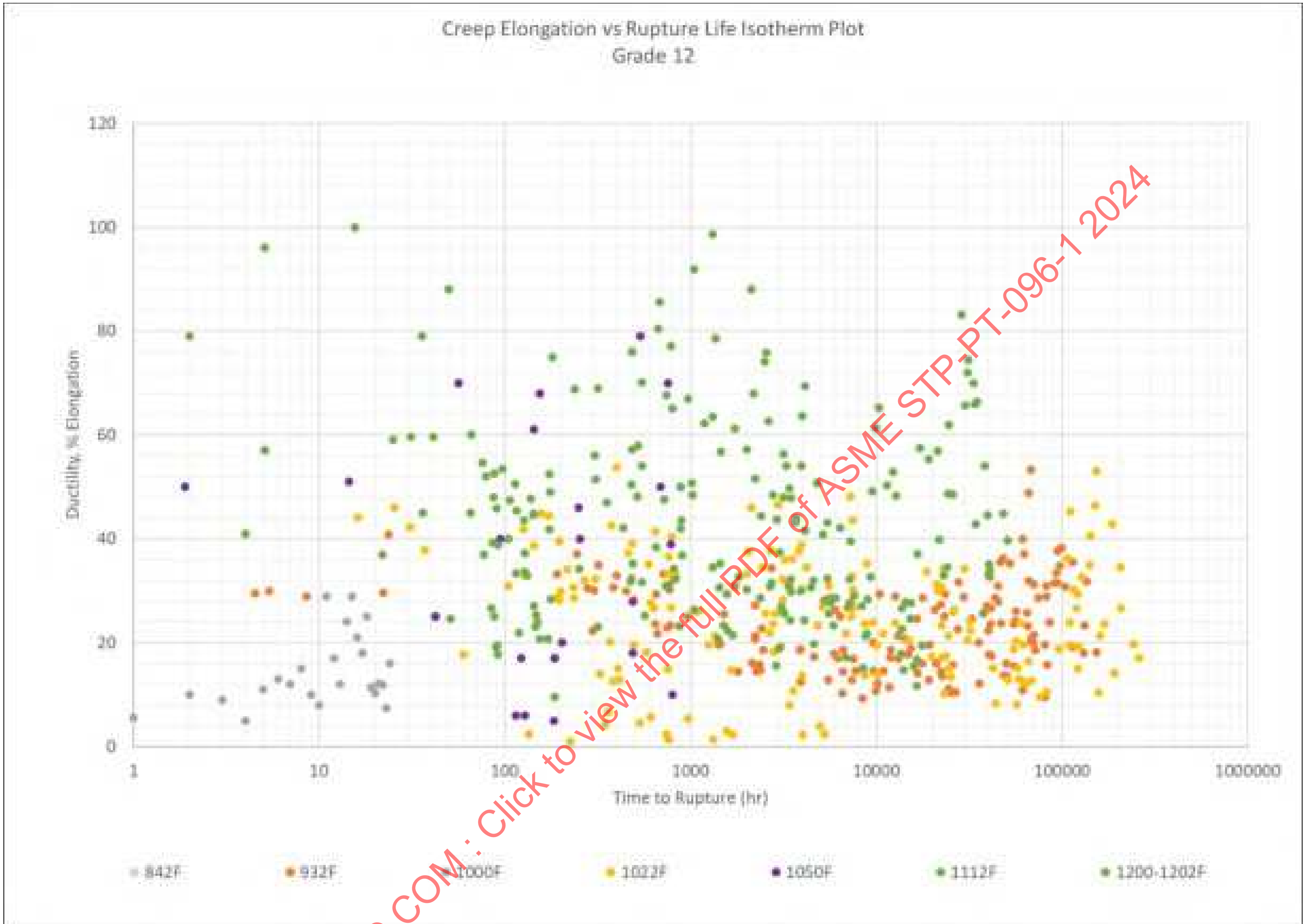


Figure 22-12: Calculated Allowable Stresses Based on Rupture and Creep Strain Rate and ASME II-D Appendix 1 Criteria (Grade 12)

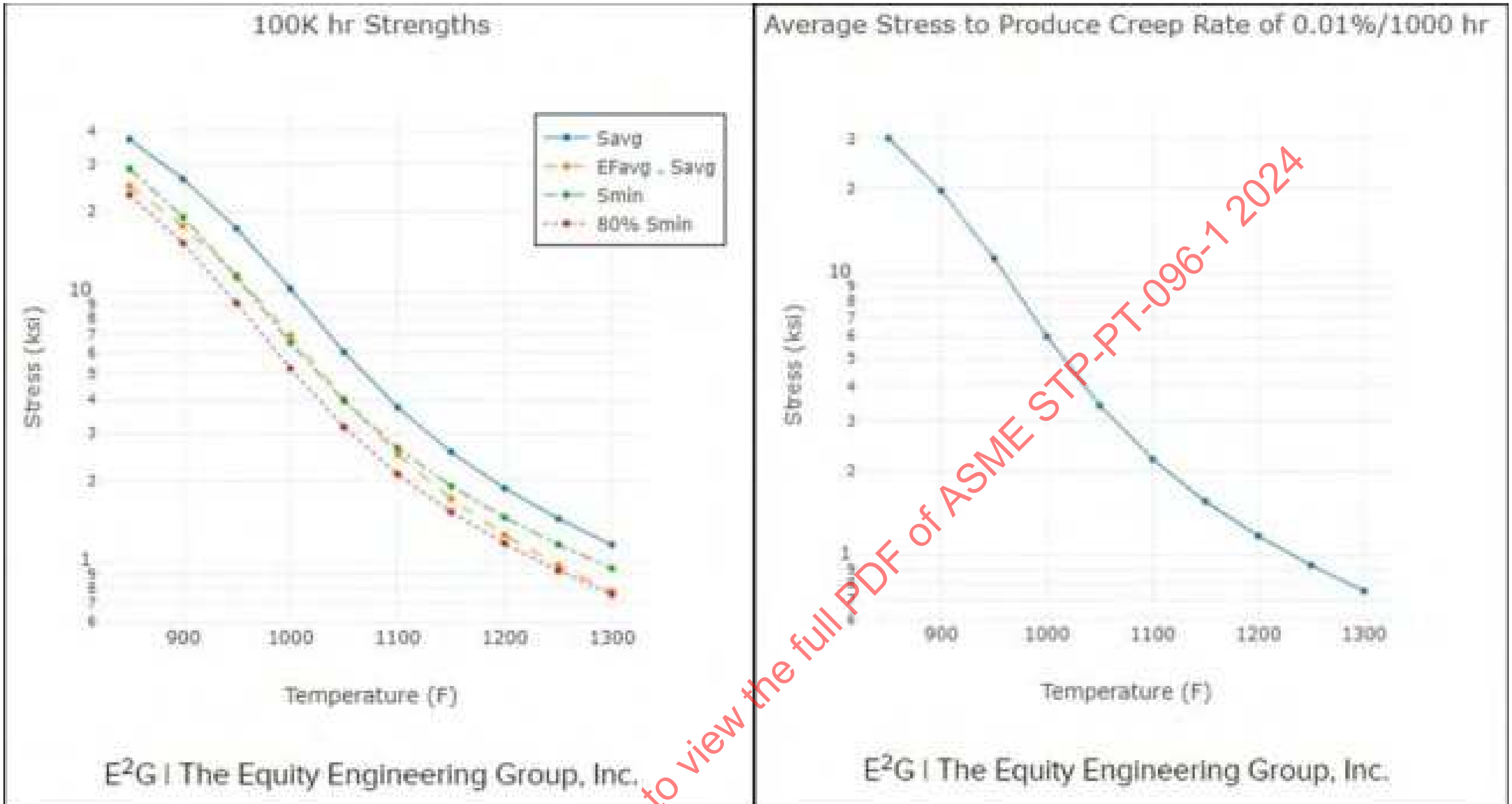


Figure 22-13: Comparison of Current Grade 12 Allowable Stresses Vs. ASME II-D Appendix 1 Criteria Applied to Data

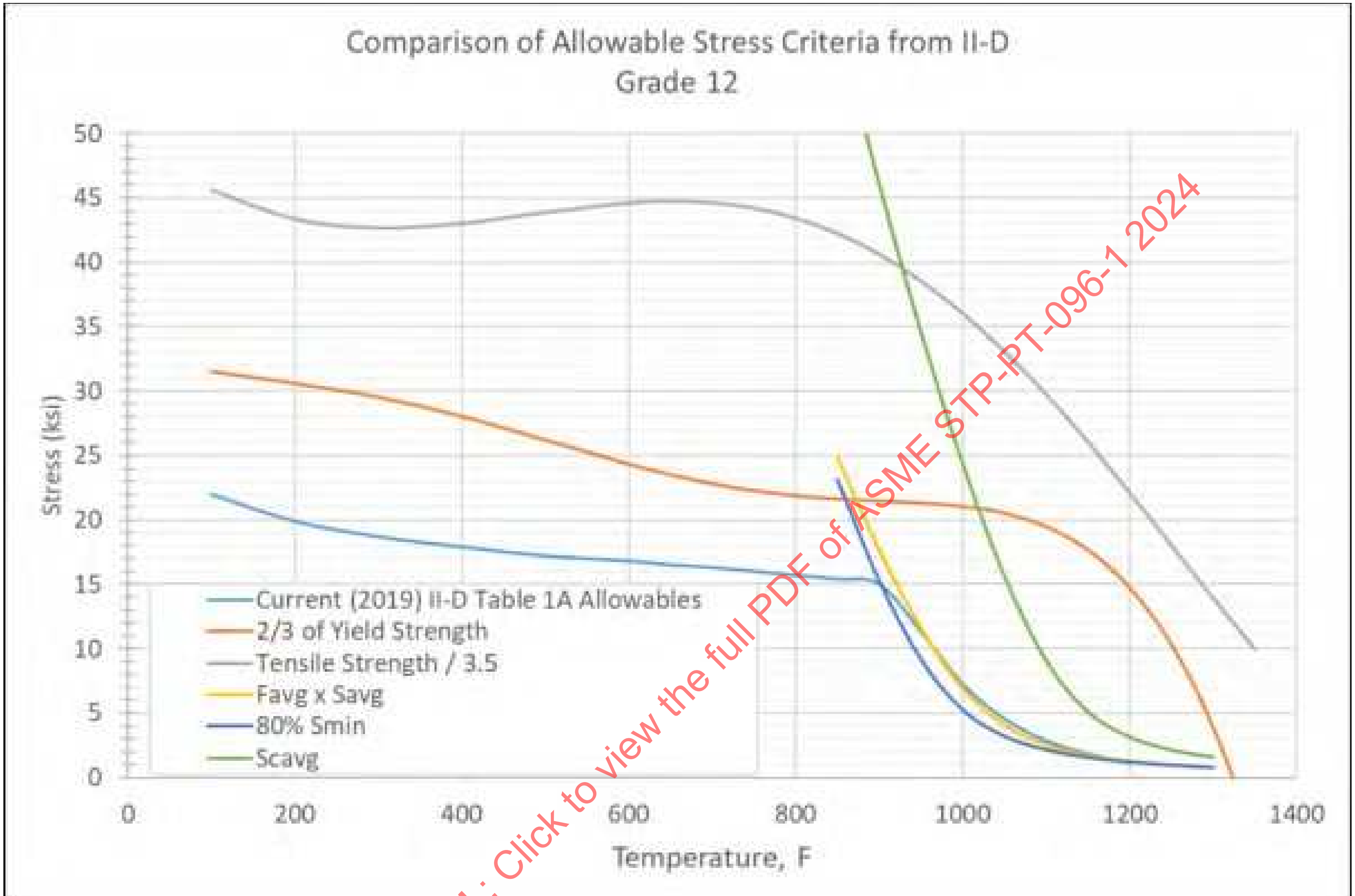


Figure 22-14: Short-Term Strain Vs. Time data, up to 1,000 Hour Test Durations (Grade 12)

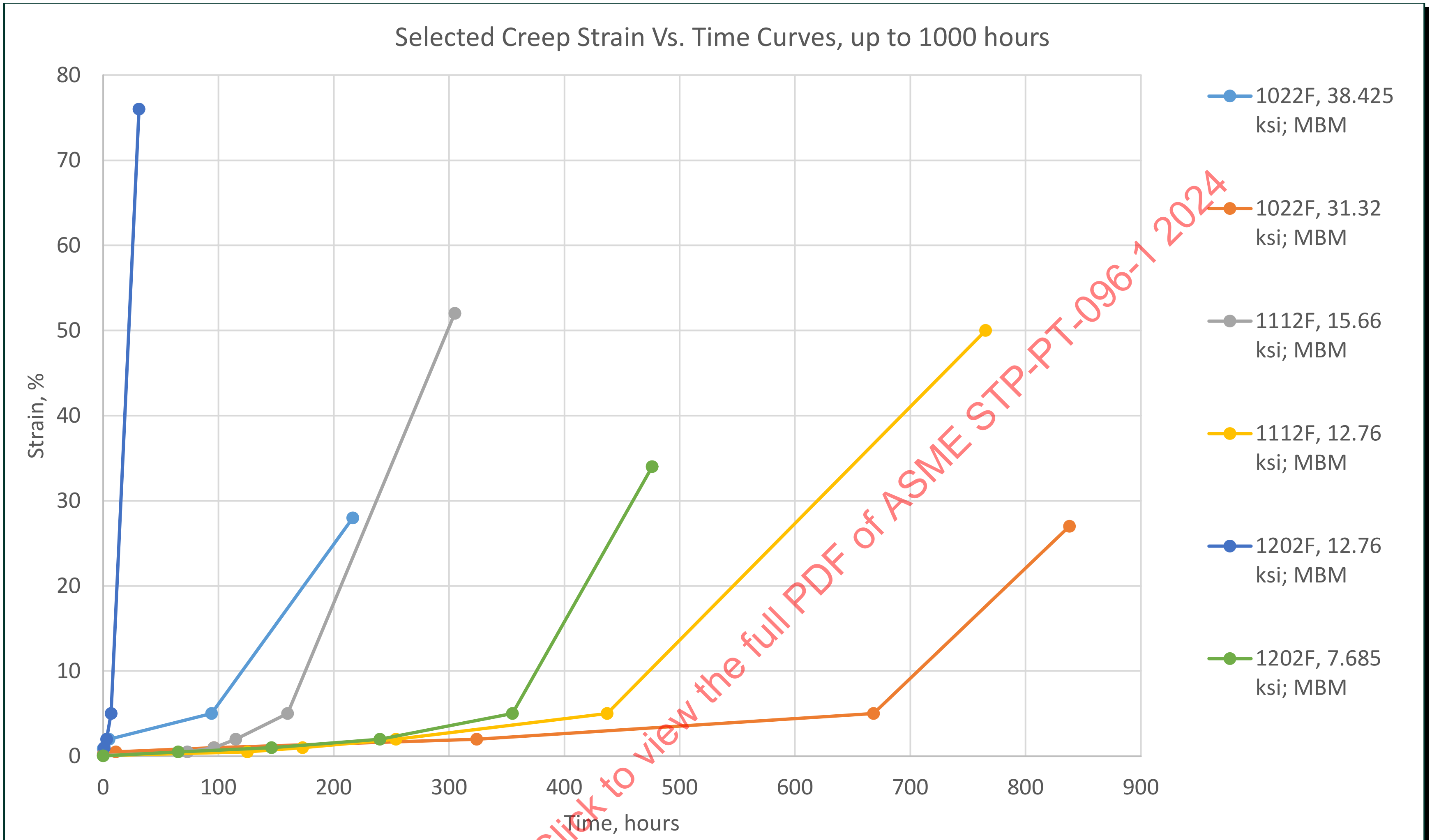


Figure 22-15: Medium-Term Strain Vs. Time Data, 1,000 to 25,000 Hour Test Durations (Grade 12)

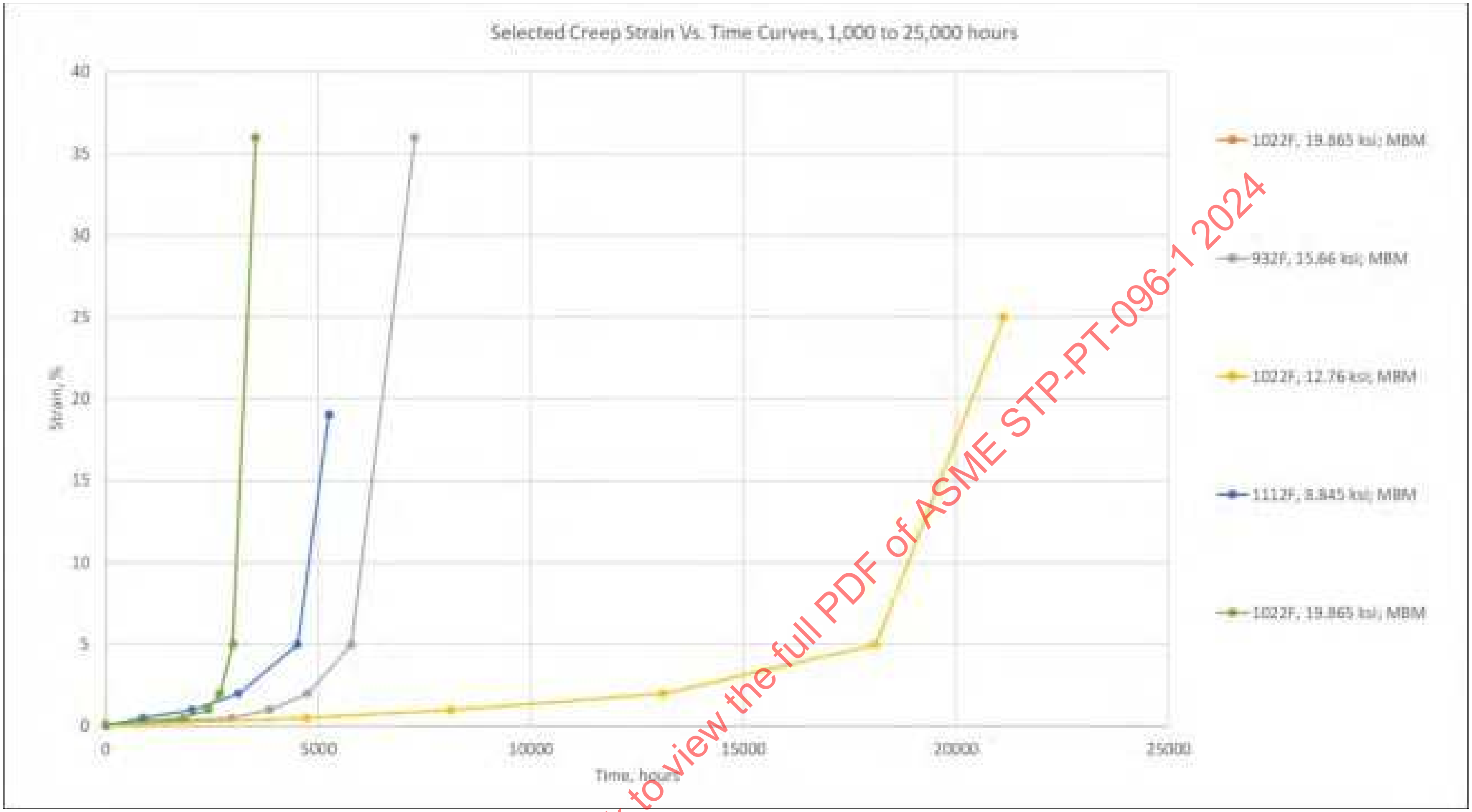


Figure 22-16: Long-Term Strain Vs. Time Data, in Excess of 25,000 Hour Test Durations (Grade 12)

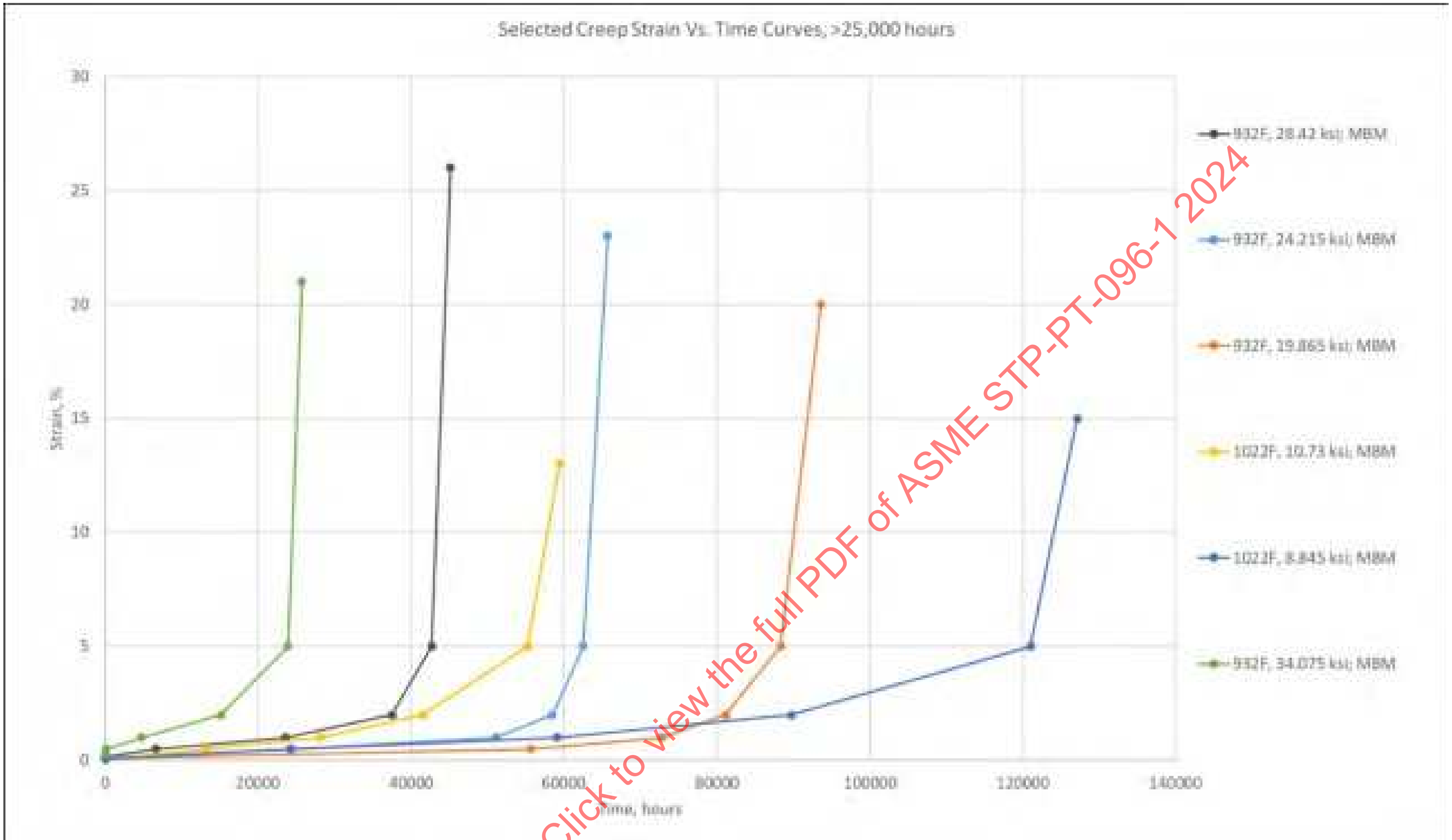
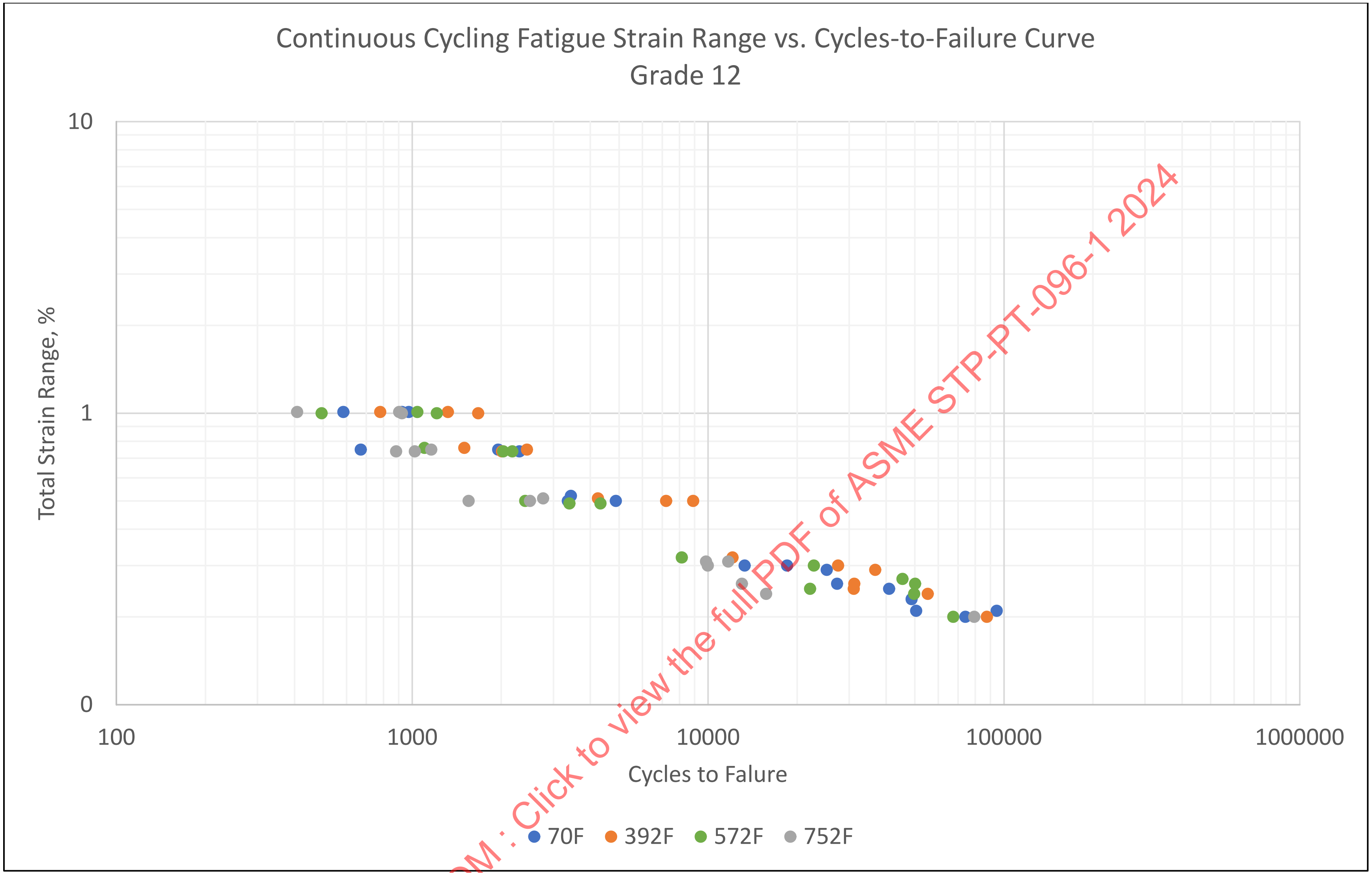


Figure 22-17: Continuous Cycling Fatigue Strain Range Data (Creep Fatigue) for Grade 12, Temperature of 70°F, 392°F, 572°F, and 752°F



Attachment 22: Grade 12 Property Data

If you want the referenced embedded spreadsheet with additional data, please email a request to research@asme.org.

23 GRADE 23

23.1 Physical Properties

Physical property data or physical property curves for Grade 23 are currently not available in 2019 BPVC Section II-D or WRC Bulletin 503. Rather, physical properties for Grade 23 were sourced from Vallourec's The T23/P23 Book. Figure 23-1 shows the data of Elastic Modulus (E_y), Thermal Conductivity (k), Thermal Diffusivity (TD), and Thermal Expansion (α) with temperature from this data source.

23.2 Yield and Tensile Strength

Similar to physical properties, yield and tensile strength data for Grade 23 does not exist in 2019 BPVC Section II-D. Several data sources containing elevated temperature yield and tensile strength data (up to 1200°F) of Grade 23 were identified. These data are plotted in Figures 23-2 and 23-3. The sources for both high-temperature yield and high-temperature tensile strength are provided in the embedded spreadsheet at the end of this section. Although comparison of the data to existing allowable stresses (Section II-D Table 1A) was not possible, the yield and tensile data were normalized on a heat-by-heat basis to express the ratio of yield or tensile strength at temperature to that measured for the heat at room temperature. In cases where data were not delineated by heats within a given source, or in cases where more than one room-temperature tensile test existed for a given heat of material, ratios are equal to the measured tensile or yield strength at temperature, divided by the average of all of the appropriate room-temperature values for the particular data source or heat of material. As a result of this approach, it is possible to have ratios in excess of 1.0. E^2G understands that this approach is similar to the normalizing procedure performed by ASME in typical analysis of yield and tensile data to obtain Table Y and Table U (Section II-D) trend curves, as well as for the calculation of allowable stresses. Figures 23-4 and 23-5 show the heat-by-heat variation in yield and tensile strength ratios (respectively) as a function of temperature. It should be emphasized that even though the figure legends reference an entire source of data, the ratios, wherever possible, were calculated on a heat-by-heat basis; this is evident in the embedded spreadsheet at the end of this section. Figures 23-6 and 23-7 contain all of the yield and tensile (respectively) ratios plotted together, to facilitate regression of a 5th-order polynomial that is subsequently used for allowable stress comparison.

23.3 Creep Data (Creep Rupture, Minimum Creep Rate, and Ductility)

Creep Rupture data is shown in Figure 23-8, plotted as isotherms. Where possible, E^2G has documented the chemical composition if contained within the original source. In many cases, the project team has also made efforts to trace cross-referenced data back to original test results to determine if the heat treatment, product form, chemistry, etc. details can be obtained. This information is provided with the embedded spreadsheet to facilitate additional analysis on the part of ASME. Creep Minimum strain rates (%/hour) are shown in Figure 23-9, again, separated by temperature. Creep Ductility, as % elongation, is plotted in Figure 23-10. As is typical, the data show significant overlap, and it is difficult to observe clear trends in the data. The data is not intended to be used as plotted but is available in the spreadsheet for additional analysis.

Creep data were analyzed using E^2G's proprietary Lot-Centered Analysis web-based software tool, in order to obtain creep properties. This regression is based on a Mandel-Paule algorithm and considers the variation within individual heats of material (for both rupture and strain rate data) as well as the variation between heats. The weight assigned to each datapoint and each heat is scaled based on the relative variation. Both rupture and strain rate (minimum creep rate, expressed as true strain per hours) were regressed according to a Larson-Miller time-temperature-parameter model, with a 3rd-order polynomial of stress. Lot-specific constant behavior was accounted for in this analysis, but the variation of LMP with stress was assumed to be constant (no non-parallel terms were included in the analysis). A 95% predictive limit was utilized to obtain the lower-bound (minimum LM constant for both rupture and strain rate) properties. The results of this analysis are summarized in Table 23-1 for rupture data and Table 23-2 for strain rate data. The Lot-Centered Analysis software tool generates property tables in the creep regime using the criteria outlined in Mandatory Appendix 1 of ASME Section II-D; the nomenclature of variables is consistent with II-D Appendix 1. For visualization of the allowable stress trends, Figure 23-11 summarizes the rupture allowable stresses. The creep rate allowable stresses are illustrated in Figure 23-12. Figure 23-13 displays a comparison of the various allowable stress criteria from Section II-D, Appendix 1.

23.4 Continuous Cycling Fatigue and Hold Time Fatigue Curves

Conventional elevated continuous cycling fatigue data and hold time fatigue data were not identified for Grade 23. However, cycling fatigue crack growth data was identified from one source. This testing was performed on welded specimens via cyclic strain-controlled experiments, with cycles to initiation (of a flaw) and cycles to failure being recorded. Since this data is not "conventional" fatigue testing, figures are not included in this report, but this data is provided in the embedded spreadsheet at the end of this section.

Table 23-1: Model Parameters, Larson-Miller Property Results, and Allowable Stress (Rupture) Criteria, Grade 23

Equation Format:

$$\log(t_r) = C_{avg} + \frac{1}{T+460}\left(b_1 + b_2\log(\sigma) + b_3(\log(\sigma))^2 + b_4(\log(\sigma))^3\right)$$

C_{avg}	**-20.34**
C_{min}	**-20.97**
b_1	**43808.8**
b_2	**-352.5**
b_3	**-1344.2**
b_4	**-1708.4**

Number Data Points		**1067**
Correlation Coefficient	R^2	0.8108
Average Variance within Heats	V_w	0.1462
Variance between Heats	V_b	0.07352
Standard Error of Estimate	SEE	0.3824

Properties provided are for T in °F, stress in ksi, and t_R in hours

Temperature, °F	**S_{avg} (ksi)**	***n***	**F_{avg} (calc)**	**F_{avg} (used)**	**$F_{avg} \times S_{avg}$**	**S_{min} (ksi)**	**80% S_{min}**
850	37.80	13.24	0.840	0.67	25.33	33.77	27.02
900	31.72	11.72	0.822	0.67	21.25	27.91	22.33
950	26.18	10.26	0.799	0.67	17.54	22.60	18.08
1000	21.15	8.85	0.771	0.67	14.17	17.81	14.25
1050	16.61	7.46	0.735	0.67	11.13	13.51	10.81
1100	12.54	6.08	0.685	0.67	8.40	9.67	7.74
1150	8.89	4.67	0.611	0.67	5.96	6.24	4.99
1200	5.61	3.16	0.482	0.67	3.76	3.07	2.46
1250	2.52	1.32	0.175	0.67	1.69	0.11	0.09
1300	0.10	1.59	0.234	0.67	0.07	0.10	0.08

Table 23-2: Model Parameters, Larson-Miller Property Results, and Allowable Stress (Strain Rate) Criteria, Grade 23

Equation Format:

$$\log(\dot{\varepsilon}_0) = -C_{avg} - \frac{1}{T+460}\left(a_1 + a_2\log(\sigma) + a_3(\log(\sigma))^2 + a_4(\log(\sigma))^3\right)$$

C_{avg} (A_0)	**-4.615**
C_{min} ($A_0+\Delta_\Omega^{SR,LB}$)	**-6.236**
a_1	**26123.3**
a_2	**-8480.8**
a_3	**-155.5**
a_4	**-0.951**

Number Data Points	**38**
Correlation Coefficient	0.2291
Average Variance within Heats	0.9705
Variance between Heats	0
Standard Error of Estimate	0.9851

Properties provided are for T in °F, stress in ksi, and t_R in hours

Temperature, °F	**$S_{C,avg}$ (ksi)**
850	35.52
900	31.40
950	27.74
1000	24.51
1050	21.64
1100	19.11
1150	16.87
1200	14.89
1250	13.13
1300	11.59

Figure 23-1: Grade 23 Modulus (E_y), Thermal Conductivity (k), Thermal Diffusivity (TD), & Thermal Expansion (α) With Temperature

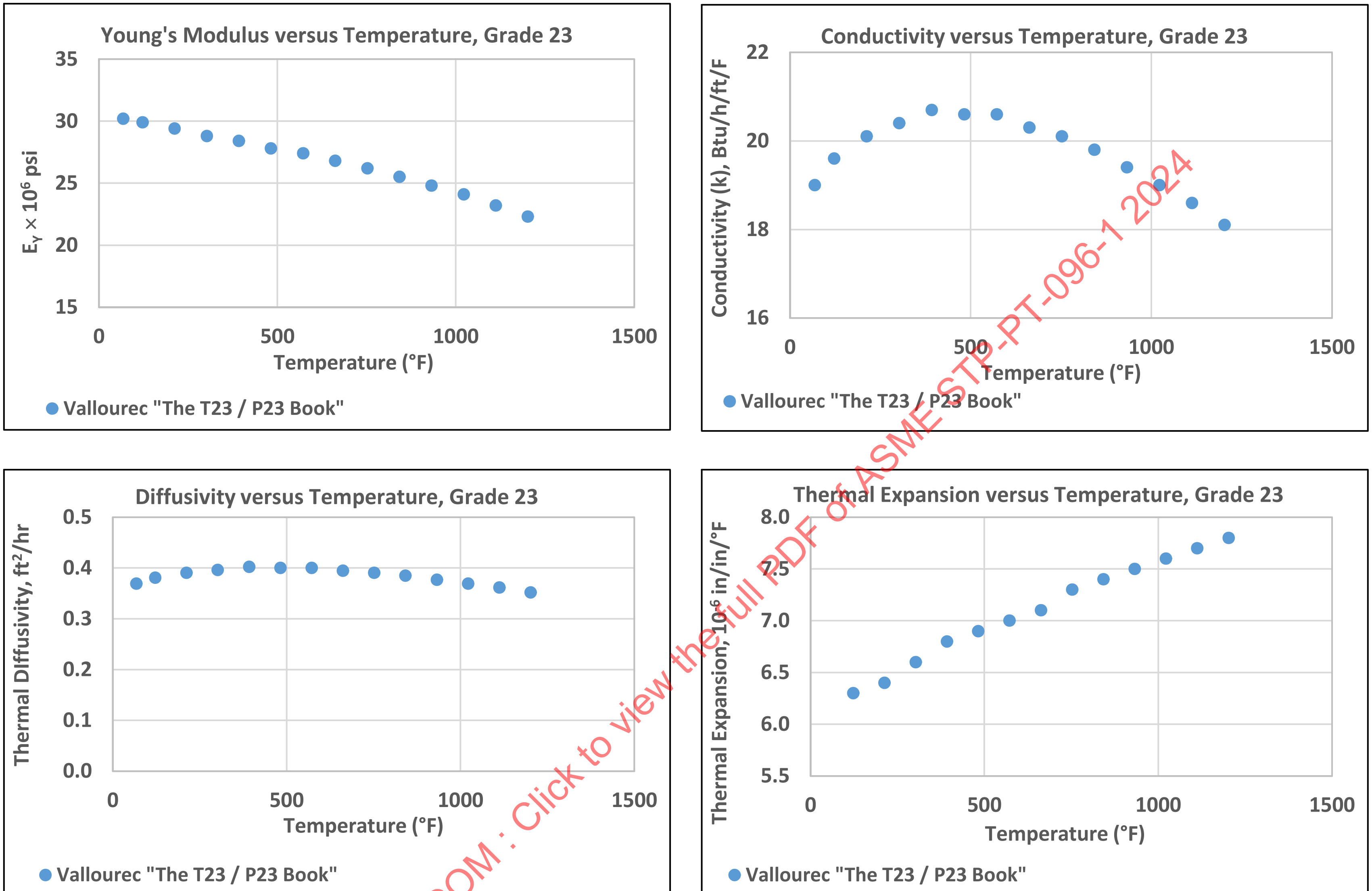


Figure 23-2: Grade 23 Yield Strength Vs. Temperature, By Data Source

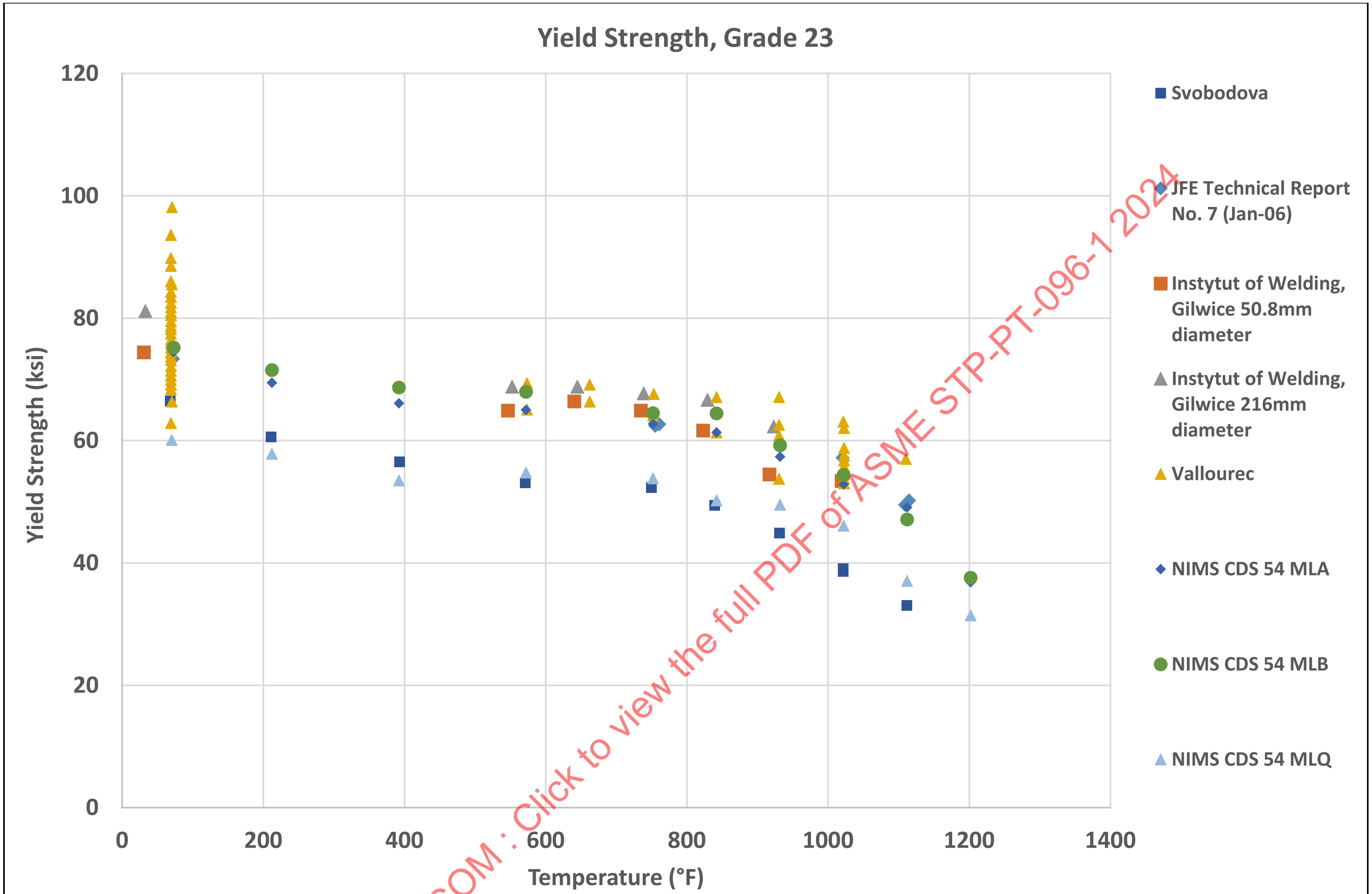


Figure 23-3: Grade 23 Tensile Strength Vs. Temperature, By Data Source

Figure 23-4: Grade 23 Yield Strength Ratios Vs. Temperature (Calculated on a Heat-By-Heat Basis, By Data Source)

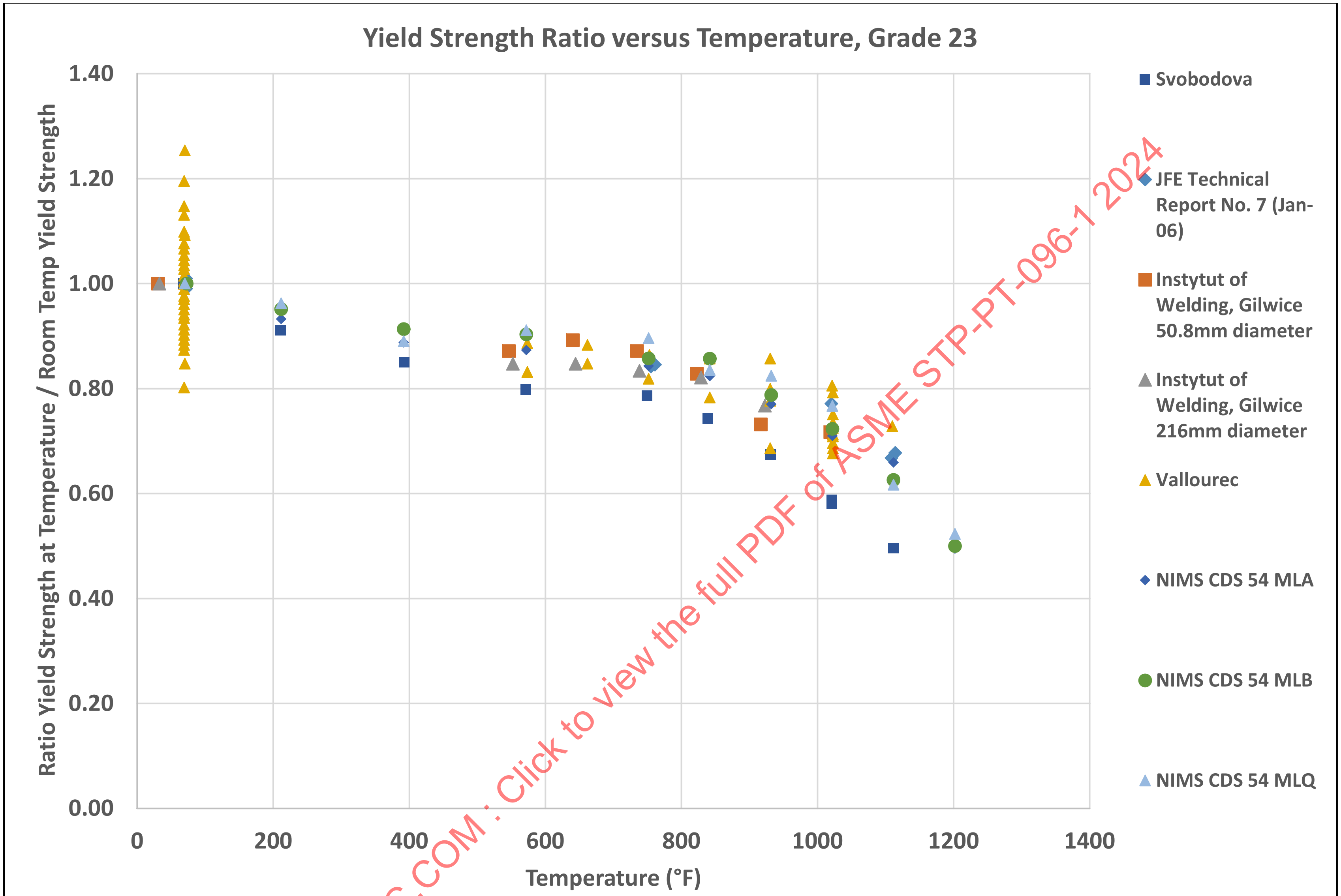


Figure 23-5: Grade 23 Tensile Strength Ratios Vs. Temperature (Calculated on a Heat-By-Heat Basis, By Data Source)

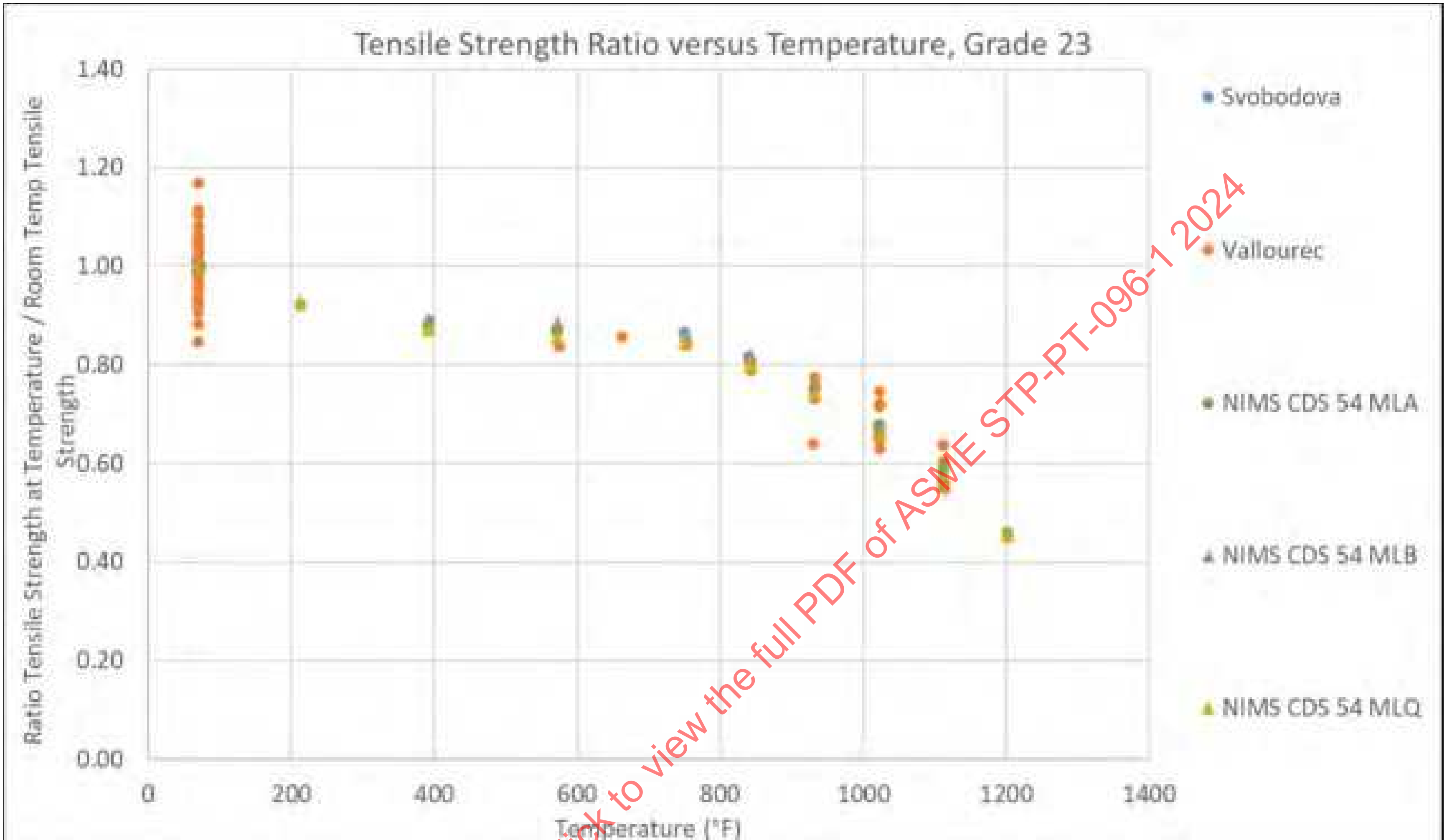


Figure 23-6: Grade 23 Yield Strength Ratios Vs. Temperature, All Combined Data, With Polynomial Regression

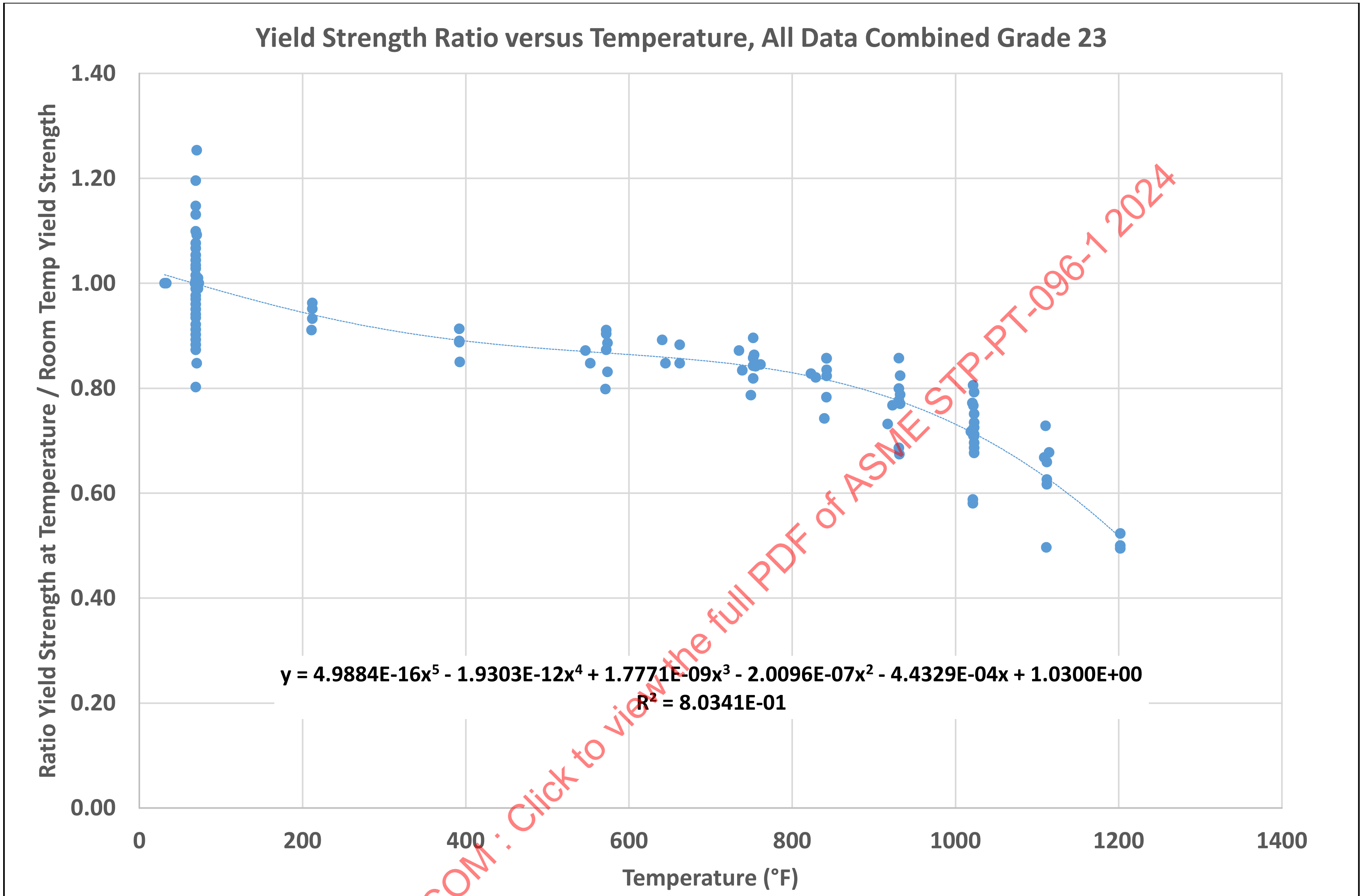


Figure 23-7: Grade 23 Tensile Strength Ratios Vs. Temperature, All Combined Data, With Polynomial Regression

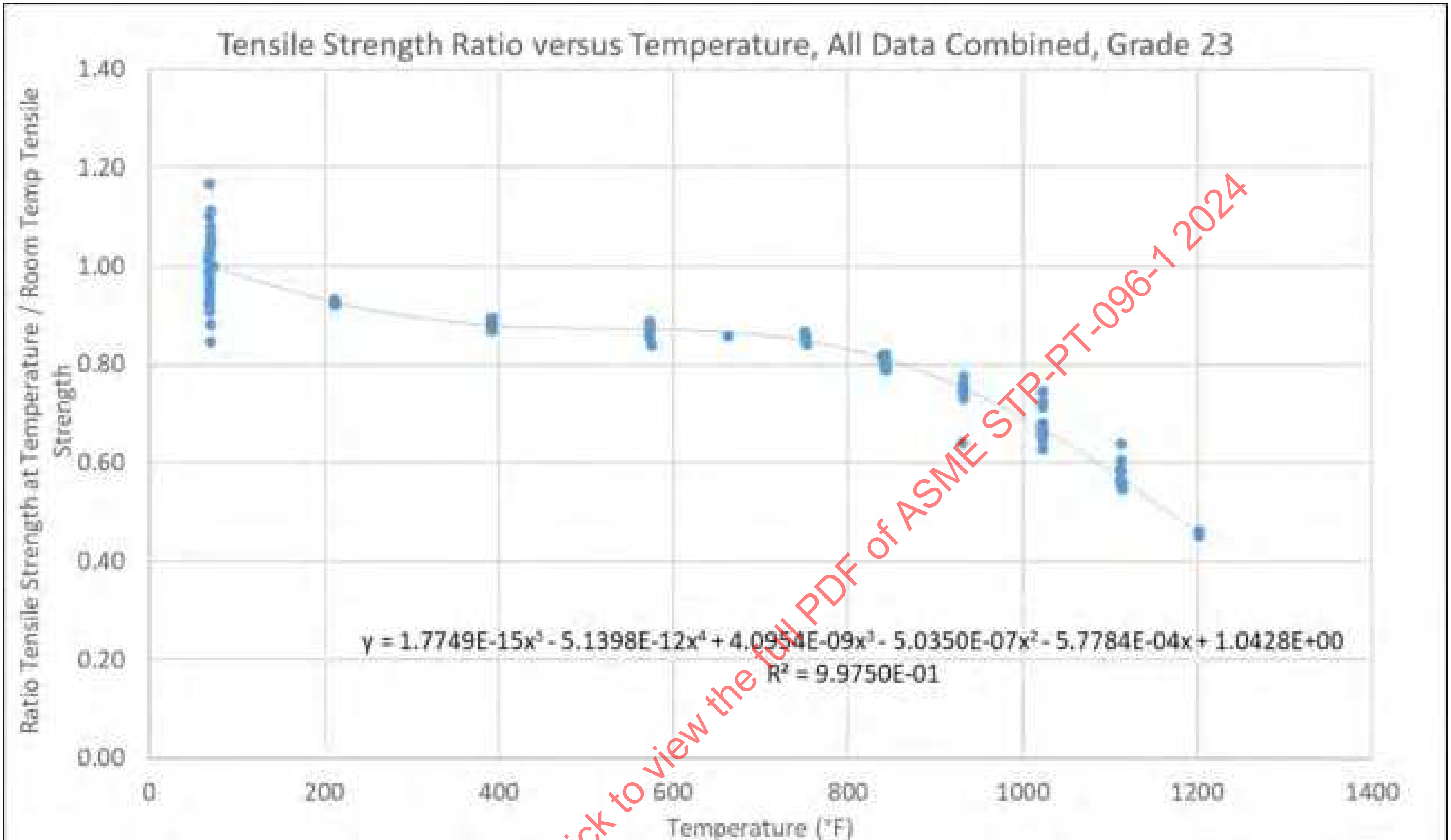


Figure 23-8: Grade 23 Creep Rupture Isotherm Curves

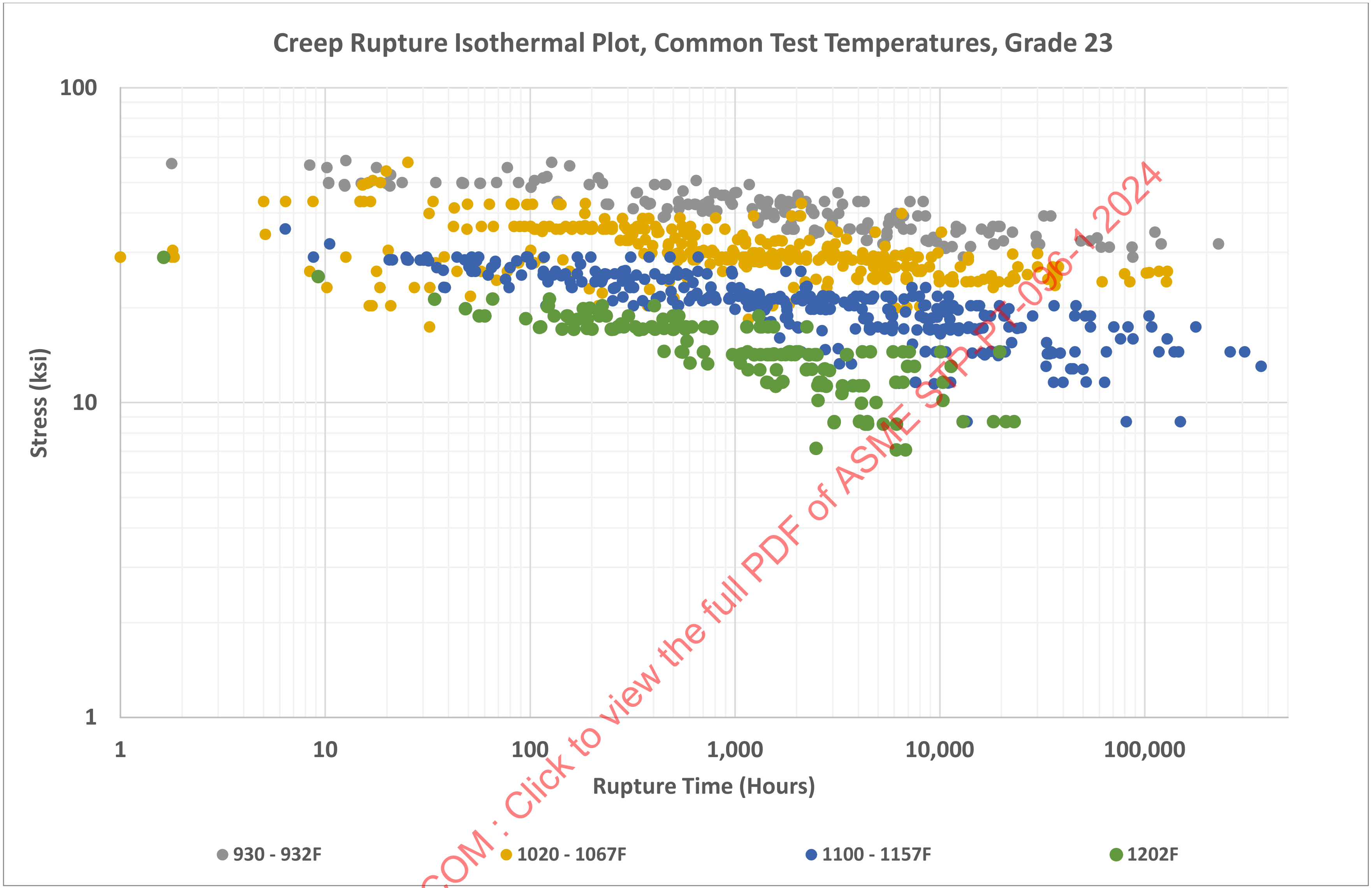


Figure 23-9: Grade 23 Creep Strain Rate (MCR) Isotherm Curves

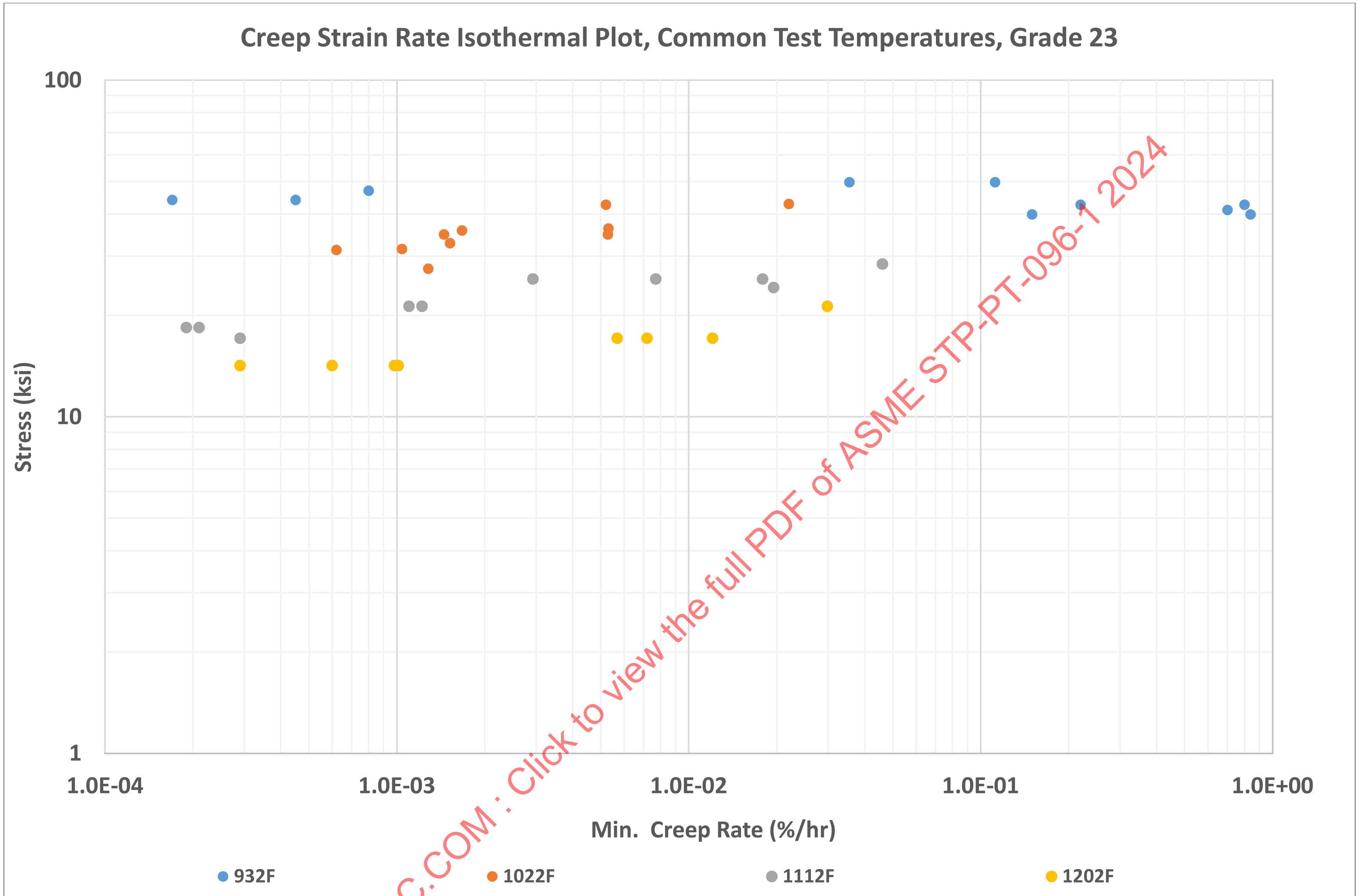


Figure 23-10: Grade 23 Creep Ductility (% Elongation) Vs. Rupture Time Isotherms

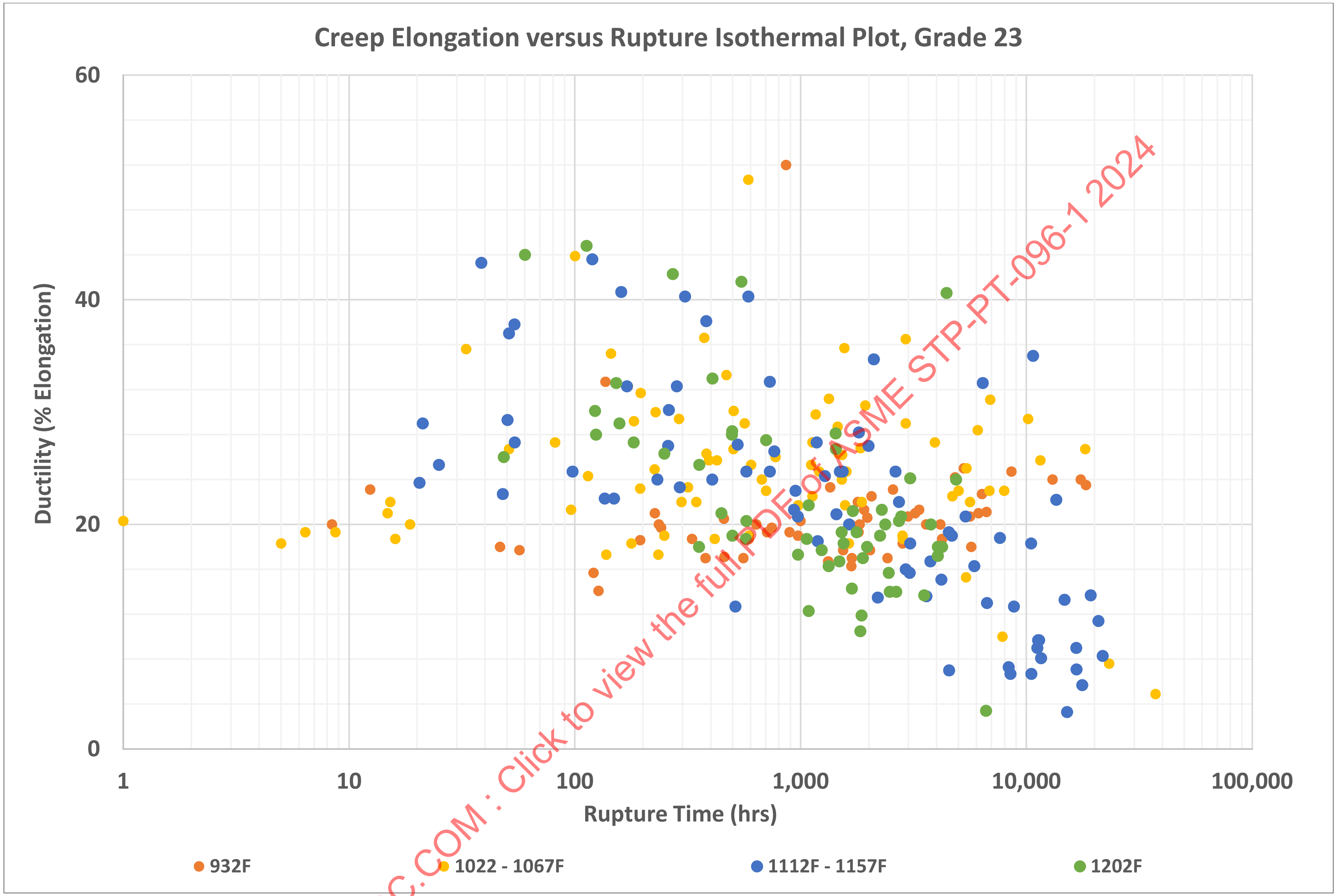


Figure 23-11: Calculated Allowable Stresses Based on Rupture Time and ASME II-D Appendix 1 Criteria (Grade 23)

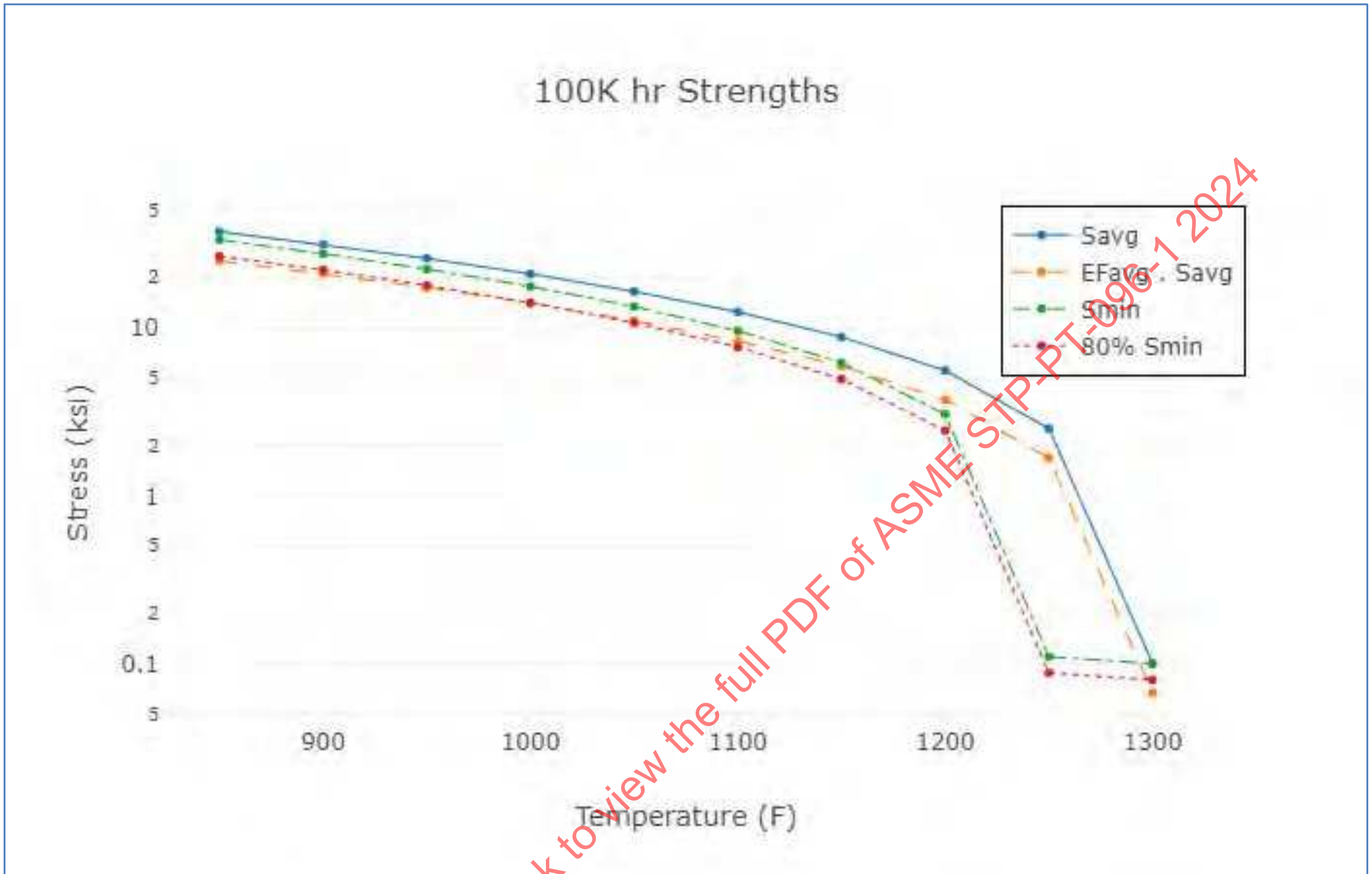


Figure 23-12: Calculated Allowable Stresses Based on Creep Strain Rate and ASME II-D Appendix 1 Criteria (Grade 23)

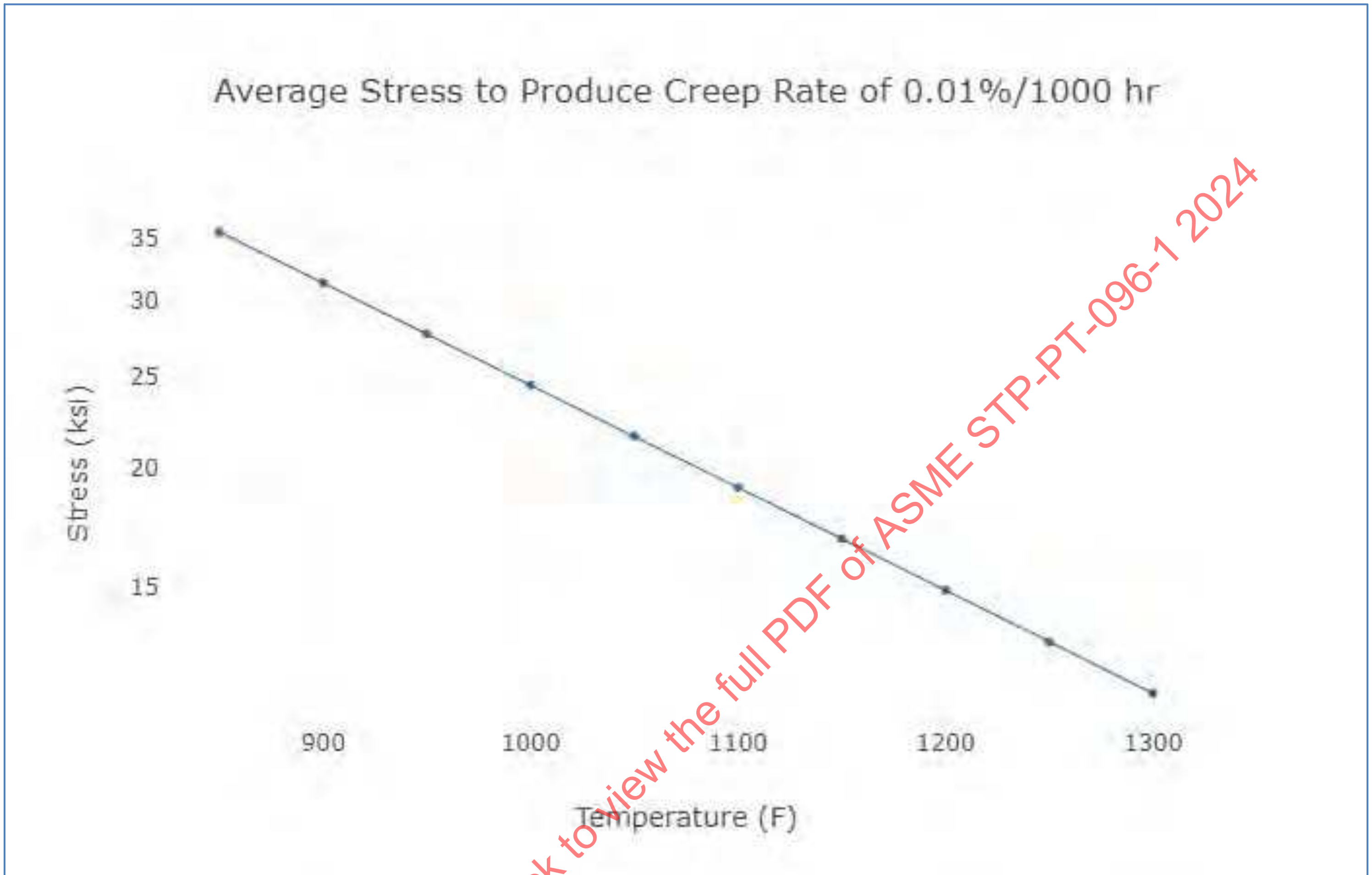
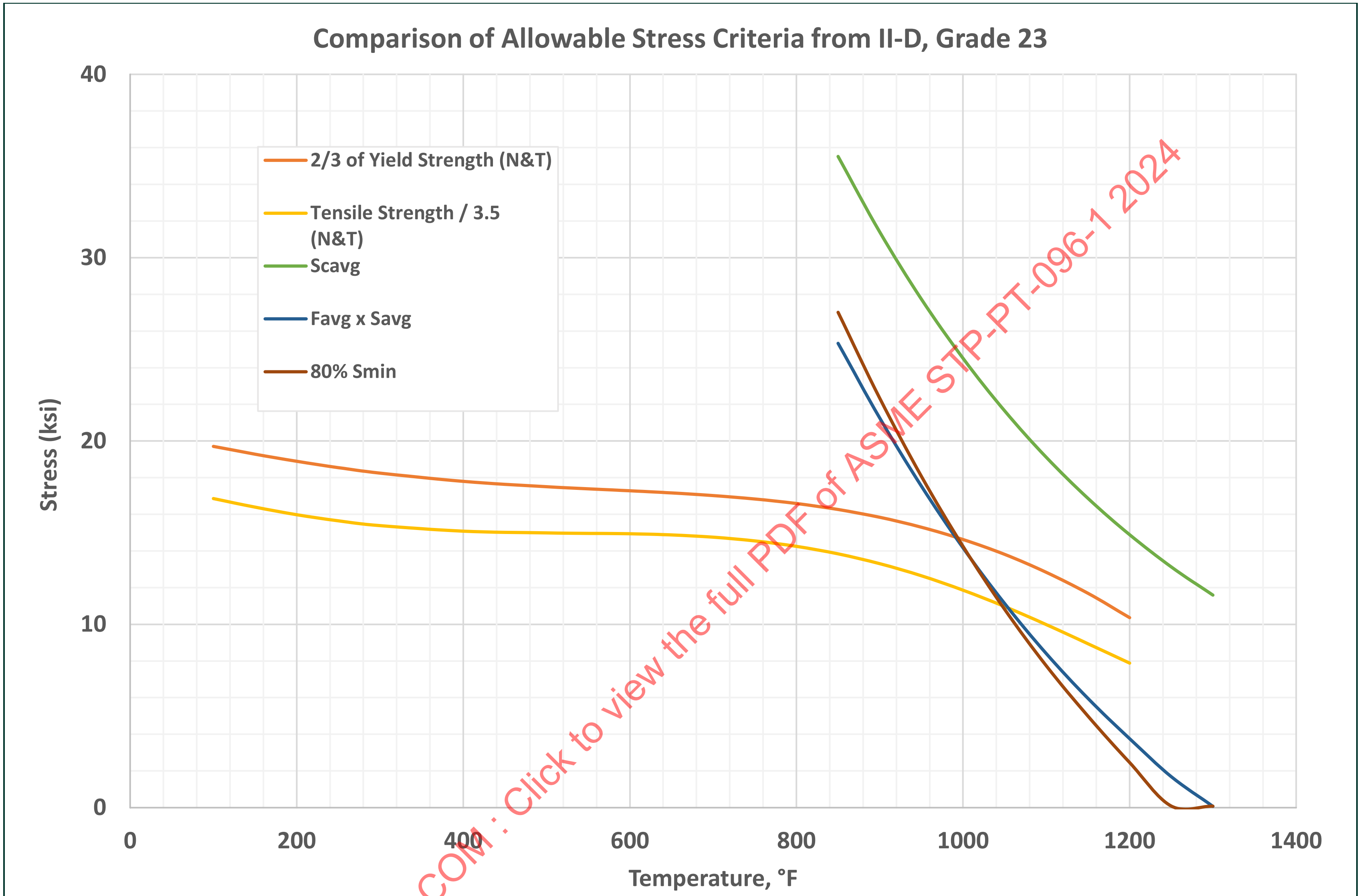


Figure 23-13: Comparison of ASME II-D Appendix 1 Criteria Applied to Grade 23 Data



Attachment 23: Grade 23 Property Data

If you want the referenced embedded spreadsheet with additional data, please email a request to research@asme.org.

24 GRADE 21 (3CR)

24.1 Physical Properties

Well-established physical properties were referenced from the BPVC Section II for this material. Physical property curves from WRC Bulletin 503 were also plotted for comparison. Figure 24-1 shows the trends of Elastic Modulus (E_y), Thermal Conductivity (k), Thermal Diffusivity (TD), and Thermal Expansion (α) with temperature.

24.2 Yield and Tensile Strength

Elevated temperature Yield and Tensile Strength over the range of existing allowable stresses (up to 1200°F) were readily available, including data beyond the current range of allowable stresses, up to approximately 1400°F, as shown in Figures 24-2 and 24-3. The sources for both high-temperature yield and high-temperature tensile strength are provided in the embedded spreadsheet at the end of this section. This spreadsheet also contains ductility data corresponding to the tensile test results presented in this report. Note that ductility (percent elongation and percent reduction in area) was not available for all sources referenced for the Grade 21 material.

To facilitate comparison of the data obtained to existing allowable stresses (Section II-D Table 1A), yield and tensile data were normalized on a heat-by-heat basis to express the ratio of yield or tensile strength at temperature to that measured for the heat at room temperature. In cases where data were not delineated by heats within a given source, or in cases where more than one room-temperature tensile test existed for a given heat of material, ratios are equal to the measured tensile or yield strength at temperature, divided by the average of all of the appropriate room-temperature values for the particular data source or heat of material. As a result of this approach, it is possible to have ratios in excess of 1.0. E^2G understands that this approach is similar to the normalizing procedure performed by ASME in typical analysis of yield and tensile data to obtain Table Y and Table U (Section II-D) trend curves, as well as for the calculation of allowable stresses. Figures 24-4 and 24-5 show the heat-by-heat variation in yield and tensile strength ratios (respectively) as a function of temperature. It should be emphasized that even though the figure legends reference an entire source of data, the ratios, wherever possible, were calculated on a heat-by-heat basis; this is evident in the embedded spreadsheet at the end of this section. Figures 24-6 and 24-7 contain all of the yield and tensile (respectively) ratios plotted together, to facilitate regression of a 5th-order polynomial that is subsequently used for allowable stress comparison.

24.3 Creep Data (Creep Rupture, Minimum Creep Rate, and Ductility)

Creep Rupture data is shown in Figures 24-8 and 24-9, plotted as isotherms. The temperatures have been separated onto separate plots to minimize data overlap, with Figure 24-8 showing those temperatures where most of the data were concentrated, and Figure 24-9 showing those temperatures with significantly less data. It should be emphasized that these plots contain data for all product forms of material classified in the referenced publications as "3Cr-1Mo or Grade 21." This certainly includes material meeting the requirements of ASME BPVC Section II-A specifications (e.g., SA-213 T21, SA-336 F21, SA-335 P21, etc.). However, due to the diversity of data sources utilized for the compilation of the material property tables, it is likely that some of the material shown in Figures 24-8 and 24-9 may not meet existing specifications for this grade of material. Where older publications are referenced, the chemistry (and for that matter, manufacturing, processing, and heat treatment) corresponding to the heat of material in the original data source, may not be consistent with modern specifications. Where possible, E^2G has documented the chemical composition if contained within the original source. In many cases, the project team has also made efforts to trace cross-referenced data back to original test results to determine if the heat treatment, product form, chemistry, etc. details can be obtained. This information is provided with the embedded spreadsheet to facilitate additional analysis on the part of ASME.

Creep Minimum strain rates (%/hour) are shown in Figures 24-10 and 24-11, separated by temperature. As in the case of rupture data, temperatures of minimum creep rates have been separated onto separate plots to minimize data overlap, with Figure 24-10 showing those temperatures where most of the data were concentrated, and Figure 24-11 showing those temperatures with significantly less data. Creep Ductility, as % elongation, is plotted in Figure 24-12. As is typical, the data show significant overlap, and it is difficult to observe clear trends in the data. The data is not intended to be used as plotted but is available in the spreadsheet for additional analysis.

Creep data were analyzed using E^2G's proprietary Lot-Centered Analysis web-based software tool, in order to obtain creep properties. This regression is based on a Mandel-Paule algorithm and considers the variation within individual heats of material (for both rupture and strain rate data) as well as the variation between heats. The weight assigned to each datapoint and each heat is scaled based on the relative variation. Both rupture and strain rate (minimum creep rate, expressed as true strain per hours) were regressed according to a Larson-Miller time-temperature-parameter model, with a 3rd-order polynomial of stress. Lot-specific constant behavior was accounted for in this analysis, but the variation of LMP with stress was assumed to be constant (no non-parallel terms were included in the analysis). A 95% predictive limit was utilized to obtain the lower-bound (minimum LM constant for both rupture and strain rate) properties. The results of this analysis are summarized in Table 24-1 for rupture data and Table 24-2 for strain rate data. The Lot-Centered Analysis software tool generates property tables in the creep regime using the criteria outlined in Mandatory Appendix 1 of ASME Section II-D; the nomenclature of variables is consistent with II-D Appendix 1. For visualization of the allowable stress trends, Figure 24-13 is provided (for rupture allowable stresses and creep rate allowable stresses). Figure 24-14 shows a comparison of the various allowable stress criteria from Section II-D, Appendix 1, to the existing (2019) Section II-D Table 1A allowable stresses for common product forms of 3Cr.

Creep Strain vs. time data are shown in Figure 24-15. A single curve was identified containing 31 points in the literature search. Both creep rate and creep strain vs. time data are provided to satisfy ASME's request for creep strain vs. time curves, and both forms of data are applicable in developing allowable stresses. Although digitalization of creep curve data was not explicitly necessary per the project contract, E^2G did perform digitalization of creep curves where only graphical data was available (as is often the case in the published literature).

24.4 Continuous Cycling Fatigue and Hold Time Fatigue Curves

No continuous cycling or hold time fatigue data was identified for Grade 21 (3Cr) during this literature search.

Table 24-1: Model Parameters, Larson-Miller Property Results, and Allowable Stress (Rupture) Criteria, Gr. 21

Equation Format:

$$\log(t_r) = C_{avg} + \frac{1}{T+460}\left(b_1 + b_2\log(\sigma) + b_3(\log(\sigma))^2 + b_4(\log(\sigma))^3\right)$$

C_{avg}	**-9.691**
C_{min}	**-10.62**
b_1	**22670.5**
b_2	**-1201.8**
b_3	**-1063.9**
b_4	**-313.9**

Number Data Points		**340**
Correlation Coefficient	R^2	0.5649
Average Variance within Heats	V_w	0.3205
Variance between Heats	V_b	0.2597
Standard Error of Estimate	SEE	0.5661

Properties provided are for T in °F, stress in ksi, and t_R in hours

Temperature, °F	**S_{avg} (ksi)**	***n***	**F_{avg} (calc)**	**F_{avg} (used)**	**$F_{avg} \times S_{avg}$**	**S_{min} (ksi)**	**80% S_{min}**
850	15.21	3.842	0.5492	0.67	10.19	8.083	6.466
900	10.61	3.217	0.4888	0.67	7.109	4.831	3.865
950	6.962	2.598	0.4122	0.67	4.665	2.429	1.943
1000	4.145	1.969	0.3105	0.67	2.777	0.7355	0.5884
1050	2.049	1.295	0.1691	0.67	1.373	0.1	0.08
1100	0.5471	0.4545	0.00631	0.67	0.3666	0.1	0.08
1150	0.1	0.009833	2.00E-102	0.67	0.067	0.1	0.08
1200	0.1	0.009537	1.39E-105	0.67	0.067	0.1	0.08
1250	0.1	0.009258	9.62E-109	0.67	0.067	0.1	0.08
1300	0.1	0.008995	6.68E-112	0.67	0.067	0.1	0.08

Table 24-2: Model Parameters, Larson-Miller Property Results, and Allowable Stress (Strain Rate) Criteria, Gr. 21

Equation Format:

$$\log(\dot{\varepsilon}_0) = -C_{avg} - \frac{1}{T+460}\left(a_1 + a_2\log(\sigma) + a_3(\log(\sigma))^2 + a_4(\log(\sigma))^3\right)$$

C_{avg} (A_0)	**-9.94**
C_{min} ($A_0+\Delta_\Omega^{SR,LB}$)	**-11.17**
a_1	**27527.4**
a_2	**-9580.7**
a_3	**6844.2**
a_4	**-2459.2**

Number Data Points		**180**
Correlation Coefficient	R^2	0.3863
Average Variance within Heats	V_w	0.5588
Variance between Heats	V_b	0.4237
Standard Error of Estimate	SEE	0.7475

Properties provided are for T in °F, stress in ksi, and t_R in hours

Temperature, °F	**$S_{C,avg}$ (ksi)**
850	40.87
900	30.82
950	21.84
1000	14.2
1050	8.508
1100	5.092
1150	3.306
1200	2.339
1250	1.762
1300	1.388

Figure 24-1: 3Cr Modulus (E_y), Thermal Conductivity (k), Thermal Diffusivity (TD), & Thermal Expansion (α) With Temperature

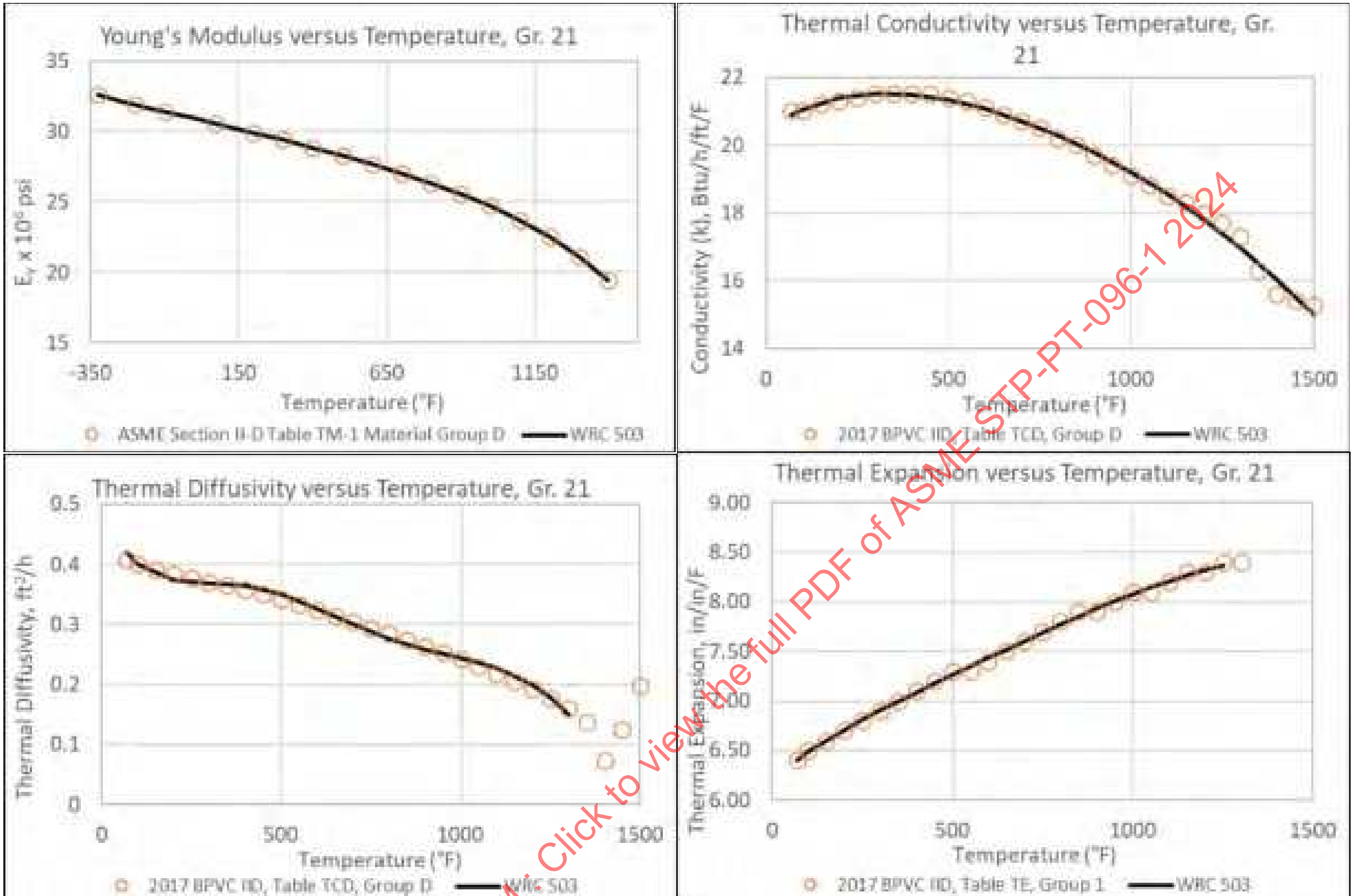


Figure 24-2: 3Cr Yield Strength Vs. Temperature, By Data Source, Including Trend Curves

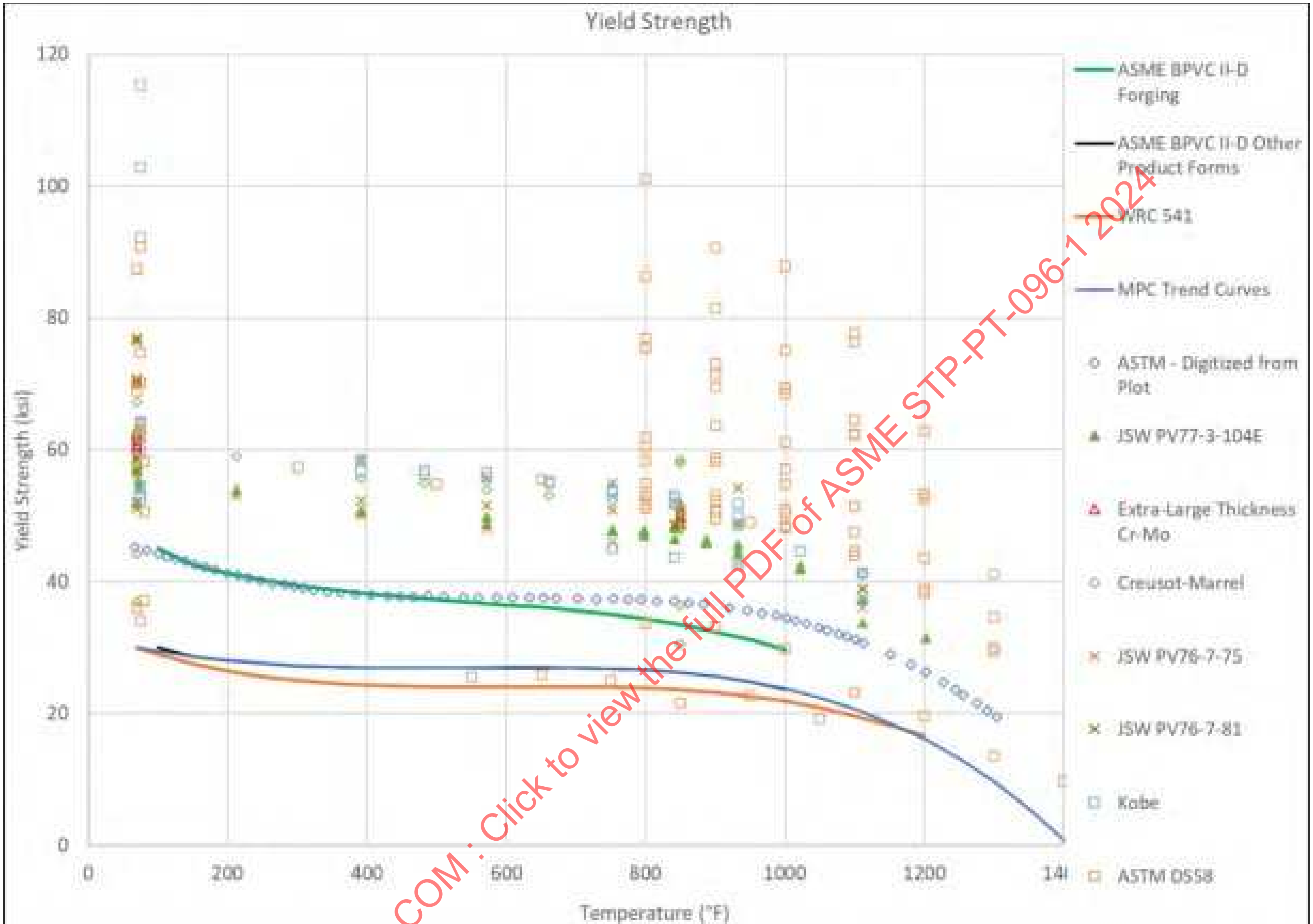


Figure 24-3: 3Cr Tensile Strength Vs. Temperature, By Data Source, Including Trend Curves

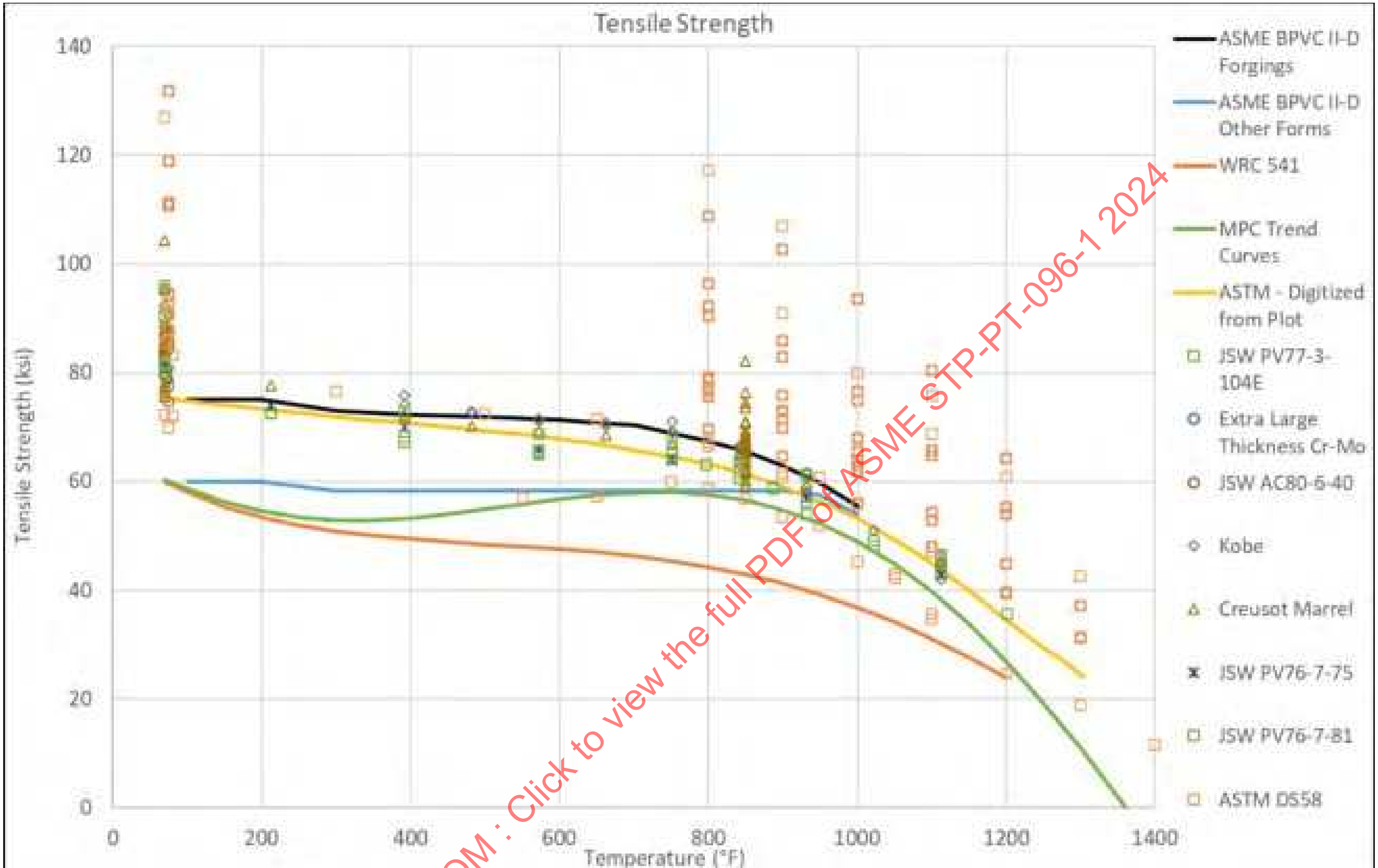


Figure 24-4: 3Cr Yield Strength Ratios Vs. Temperature (Calculated on a Heat-By-Heat Basis, By Data Source)

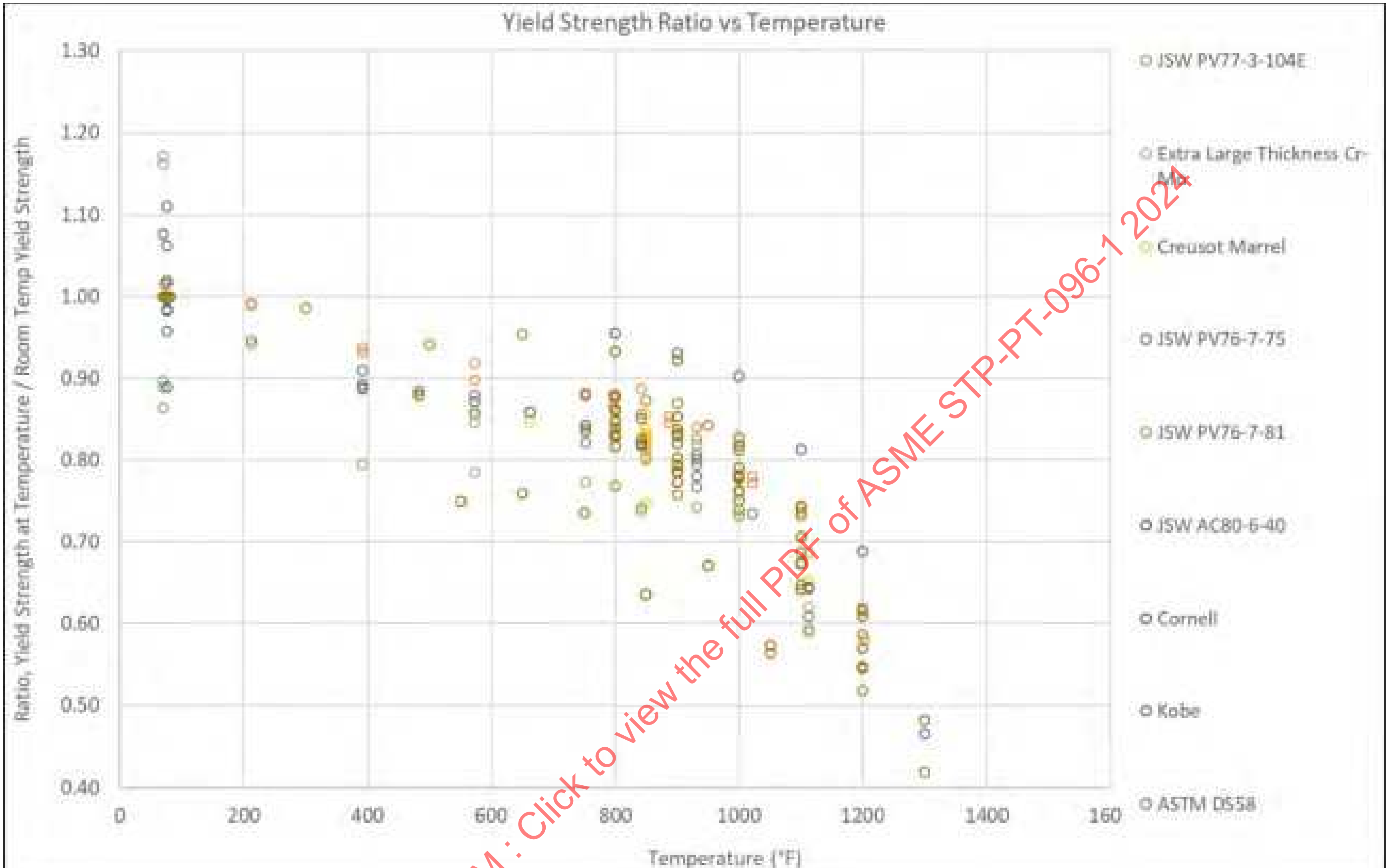


Figure 24-5: 3Cr Tensile Strength Ratios Vs. Temperature (Calculated on a Heat-By-Heat Basis, By Data Source)

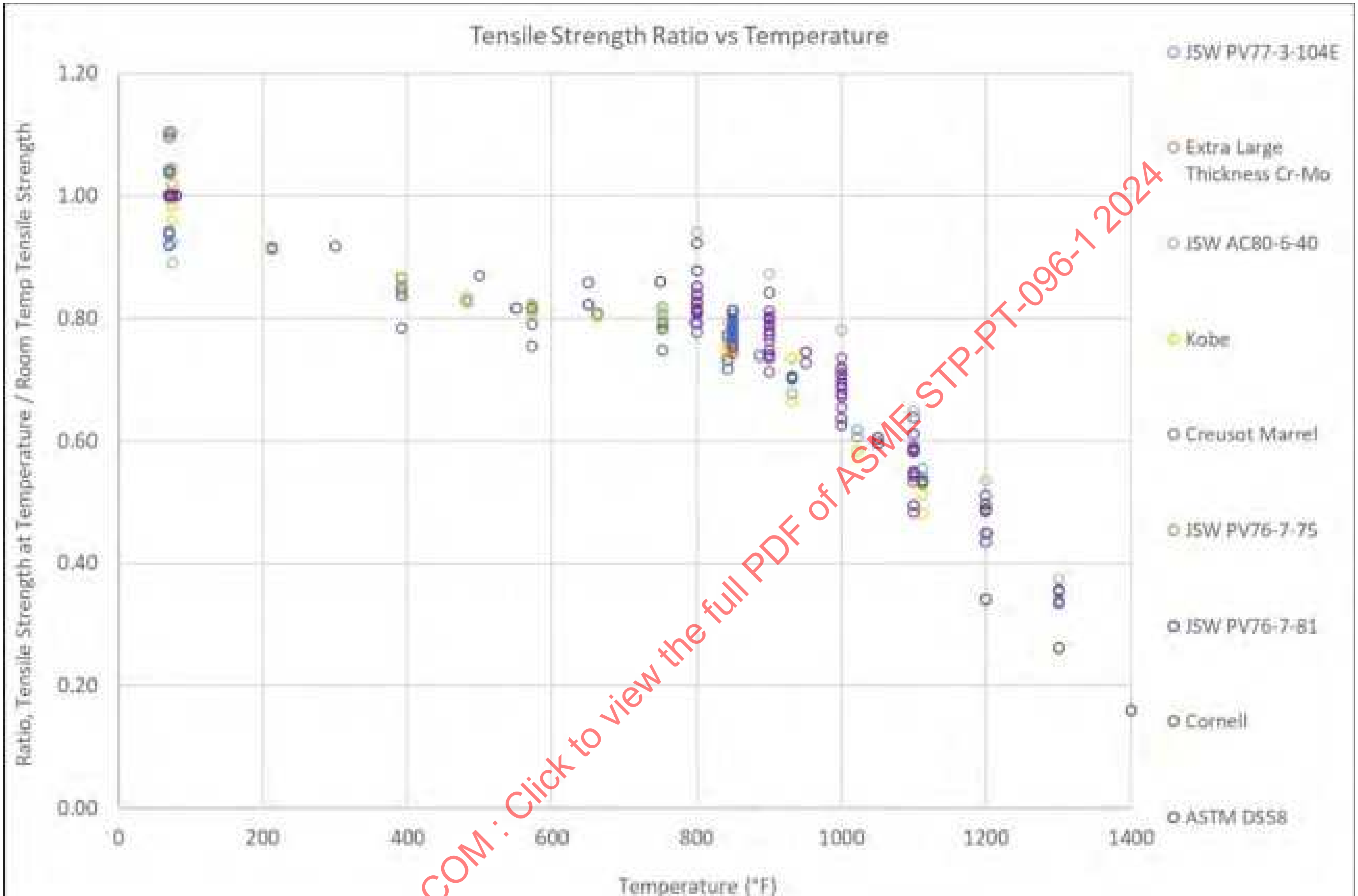


Figure 24-6: 3Cr Yield Strength Ratios Vs. Temperature, All Combined Data, With Polynomial Regression

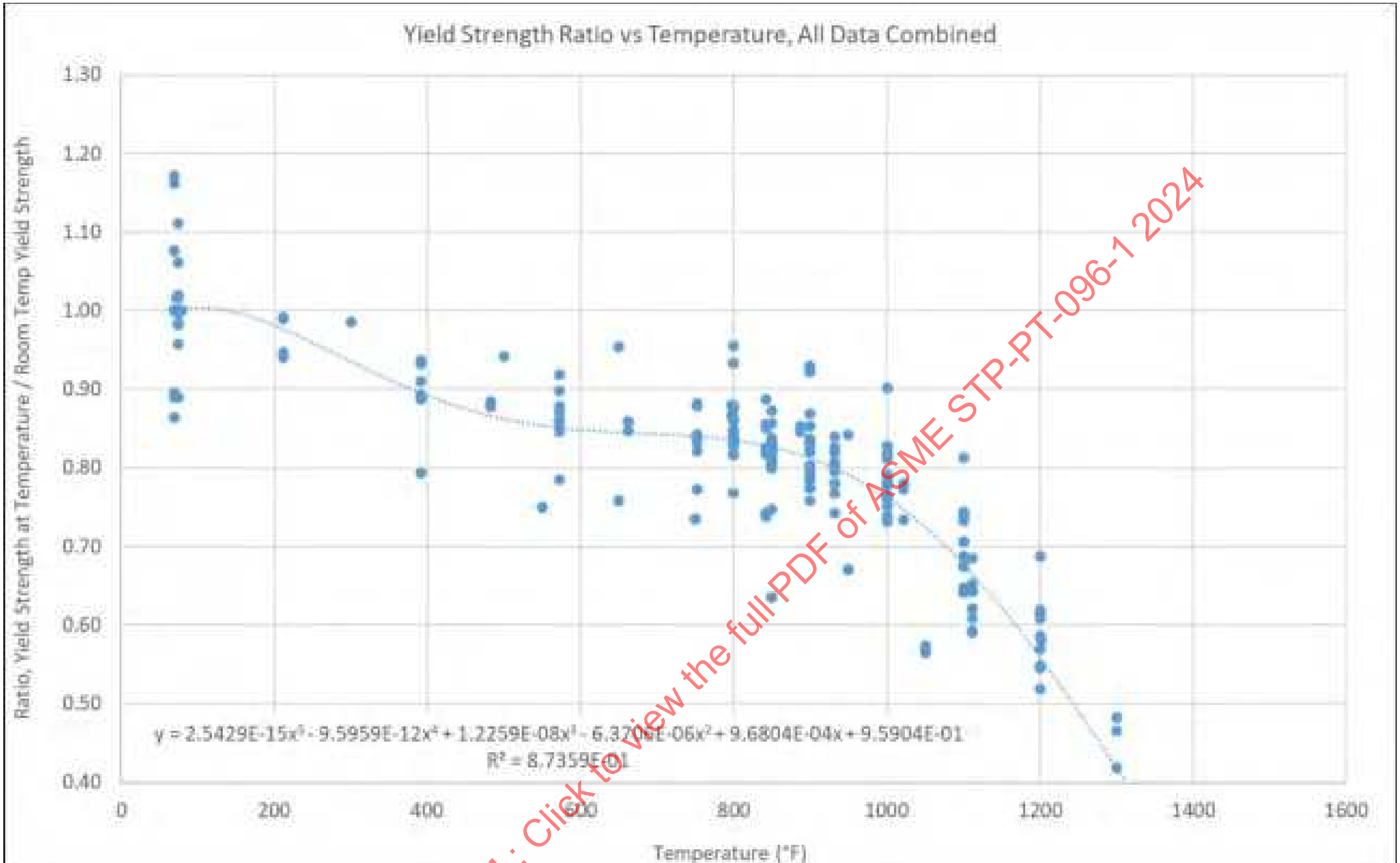


Figure 24-7: 3Cr Tensile Strength Ratios Vs. Temperature, All Combined Data, With Polynomial Regression

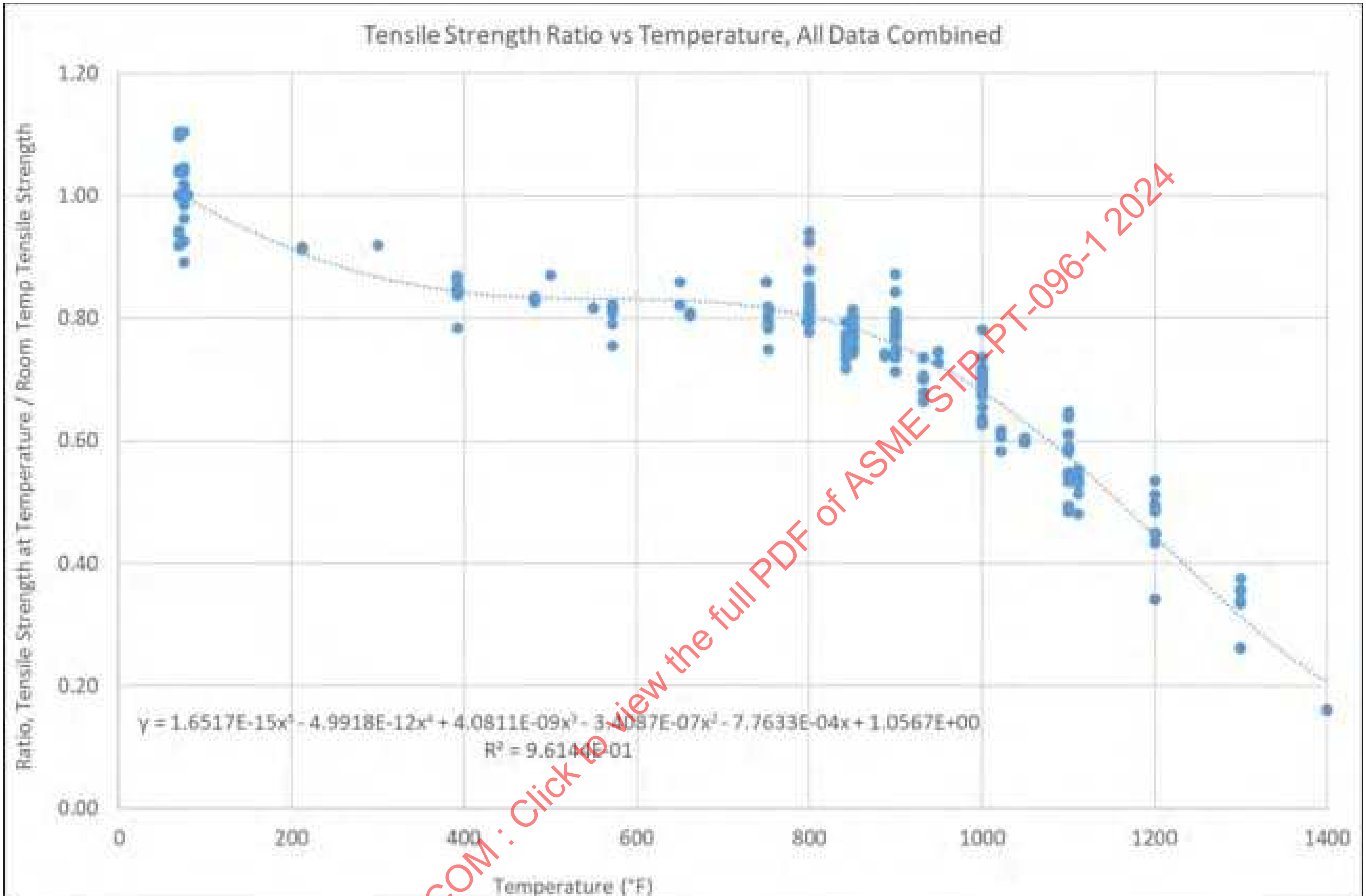


Figure 24-8: 3Cr Creep Rupture Isotherm Curves, Temperatures With High Concentration of Data Points

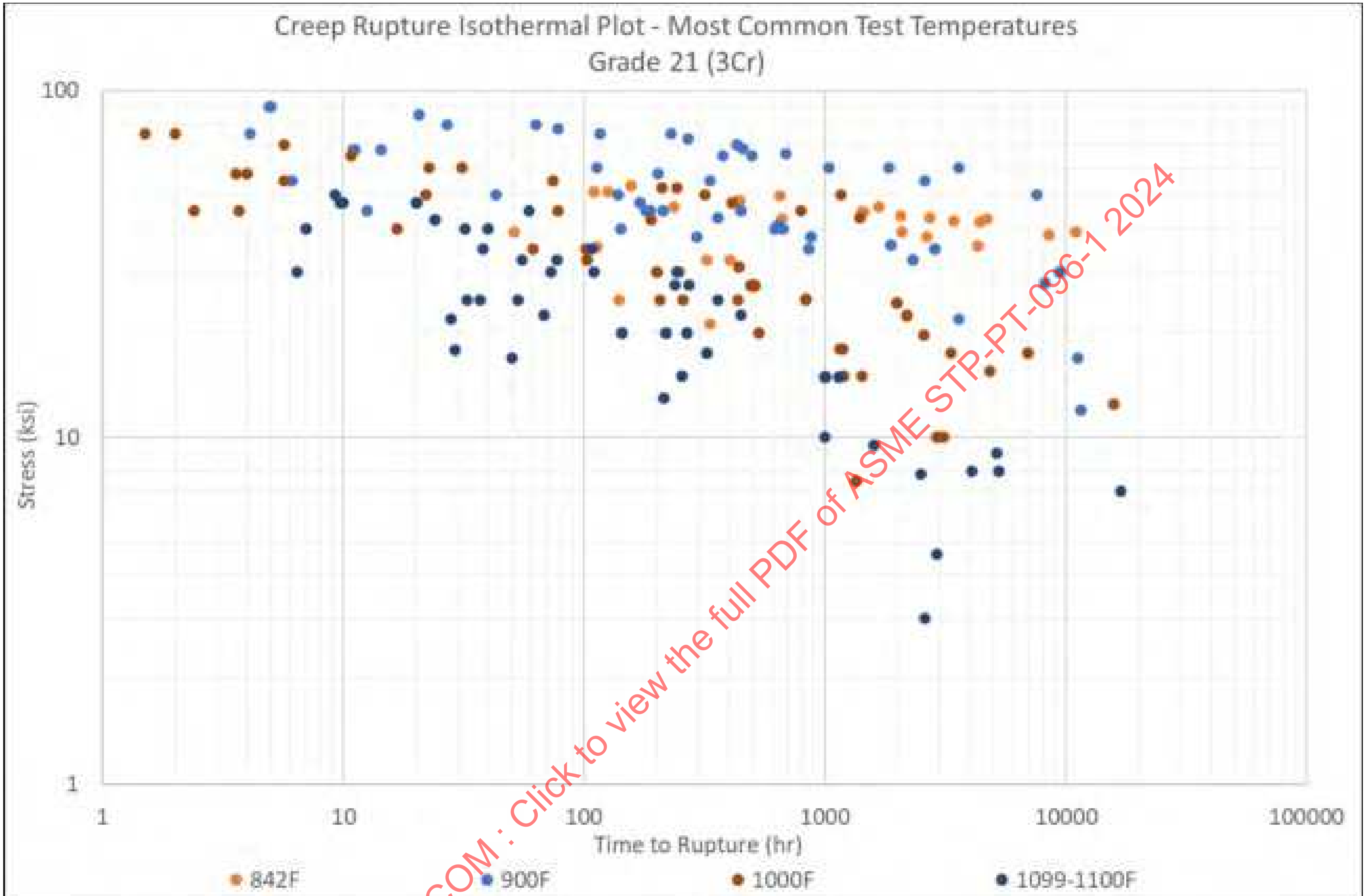


Figure 24-9: 3Cr Creep Rupture Isotherm Curves for Additional and Intermediate Temperatures

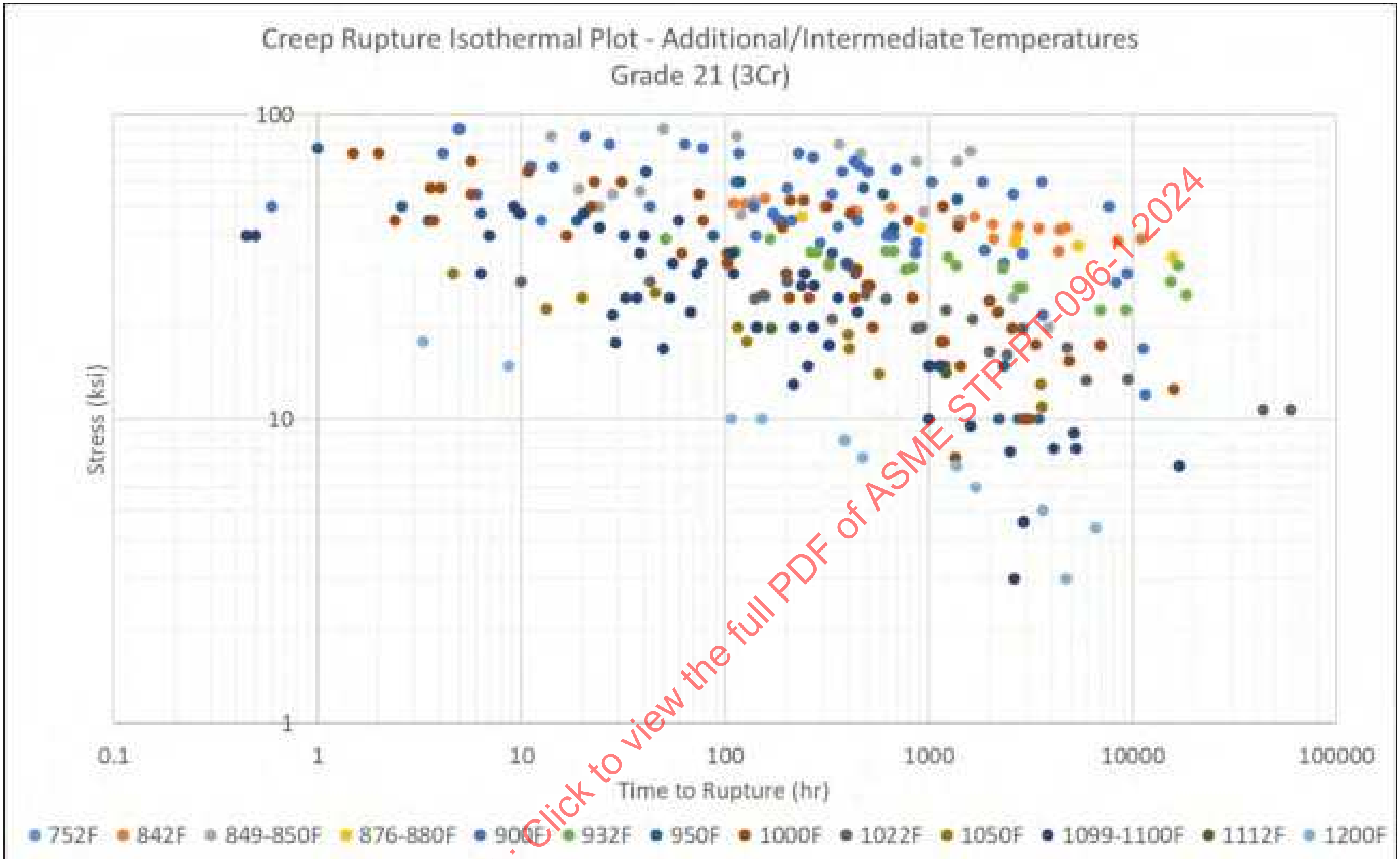


Figure 24-10: 3Cr Creep Strain Rate (MCR) Isotherm Curves, Temperatures With High Concentration of Data Points

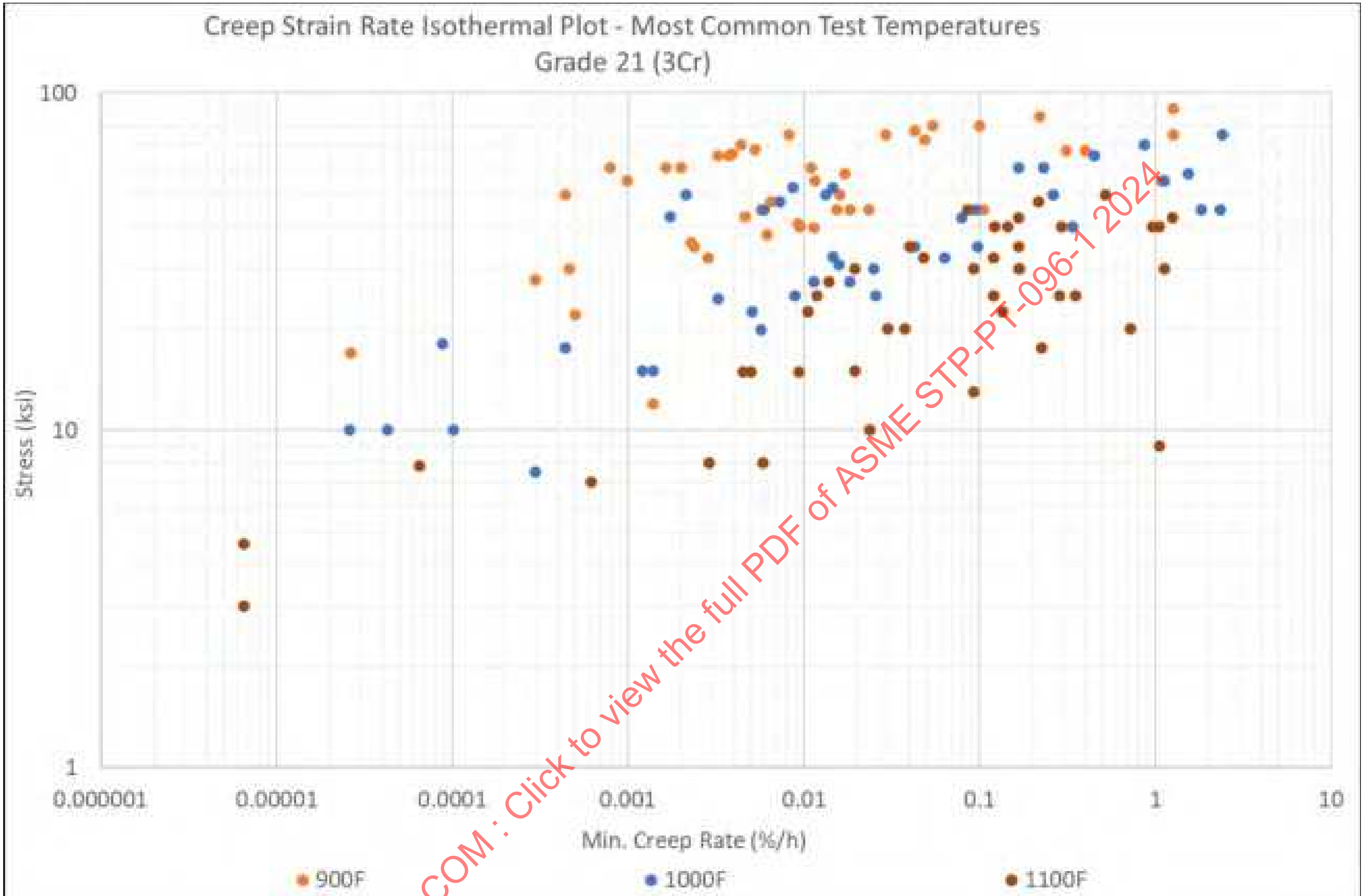


Figure 24-11: 3Cr Creep Strain Rate (MCR) Isotherm Curves for Additional and Intermediate Temperatures

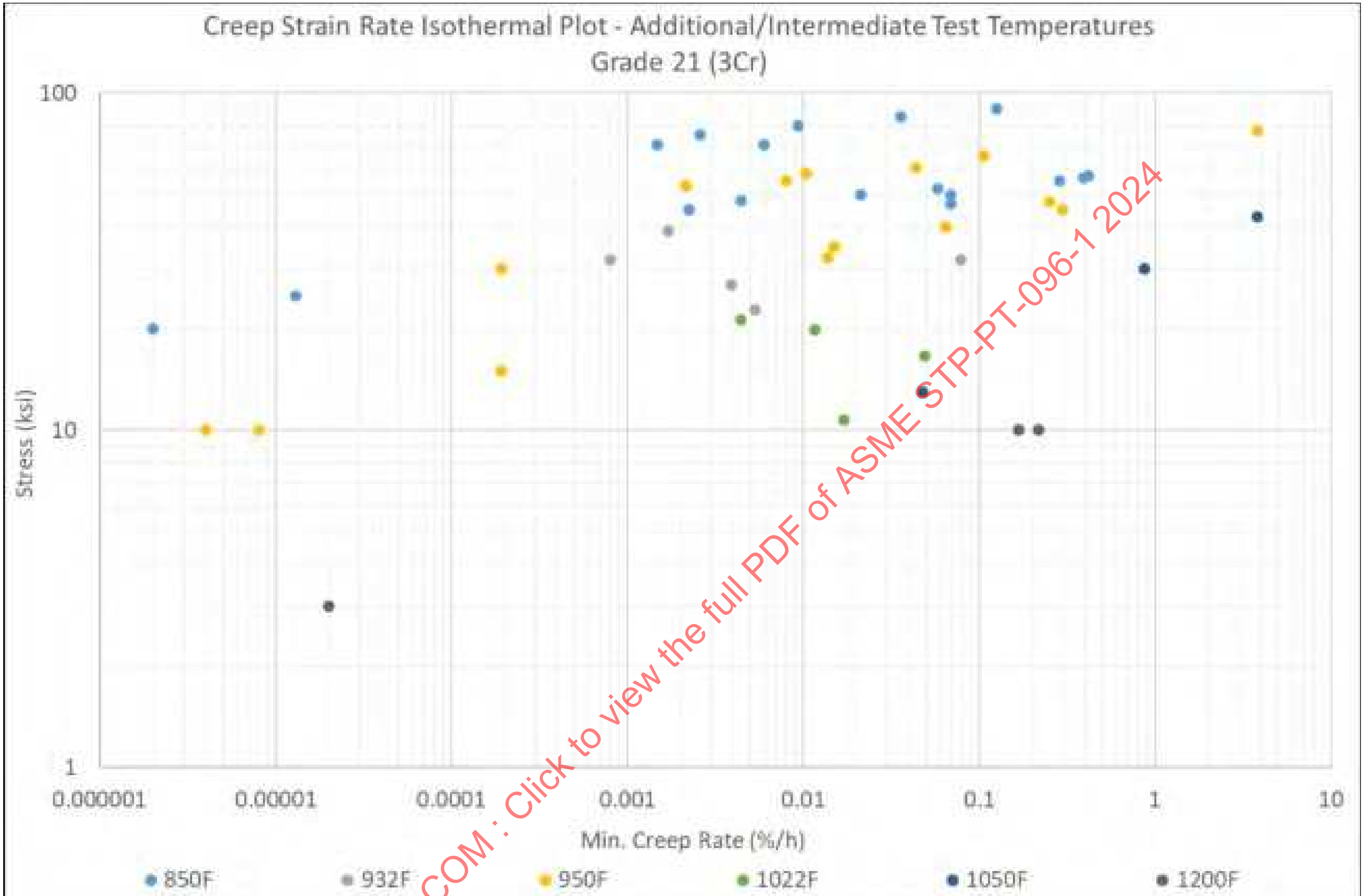


Figure 24-12: 3Cr Creep Ductility (% Elongation) Vs. Rupture Time Isotherms

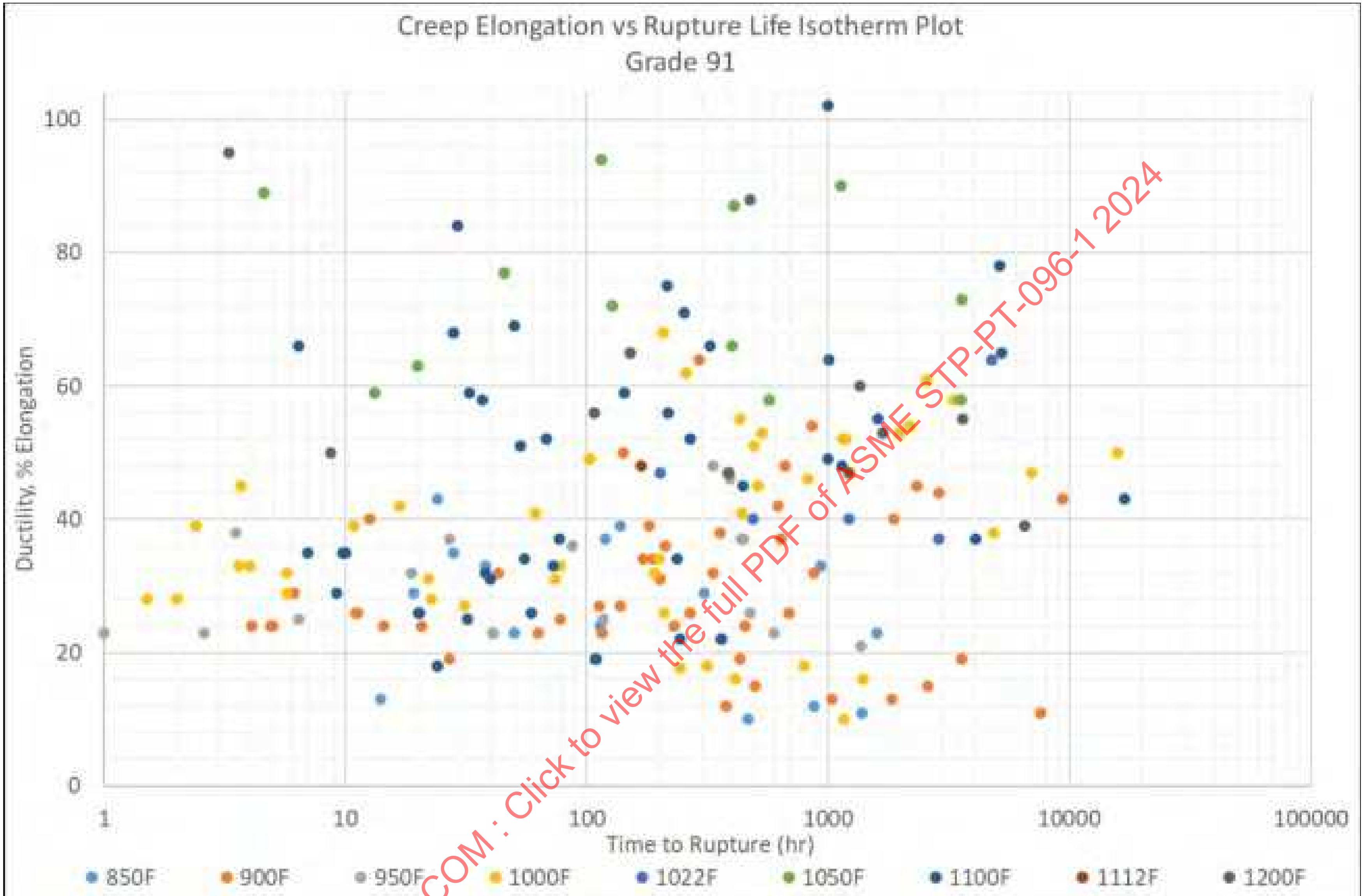
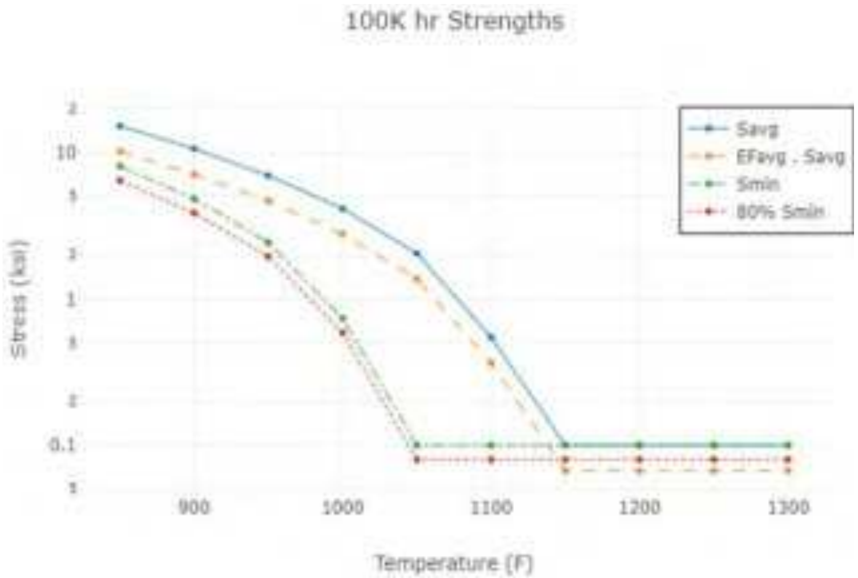


Figure 24-13: Calculated Allowable Stresses Based on Rupture and Creep Strain Rate and ASME II-D Appendix 1 Criteria (3Cr)



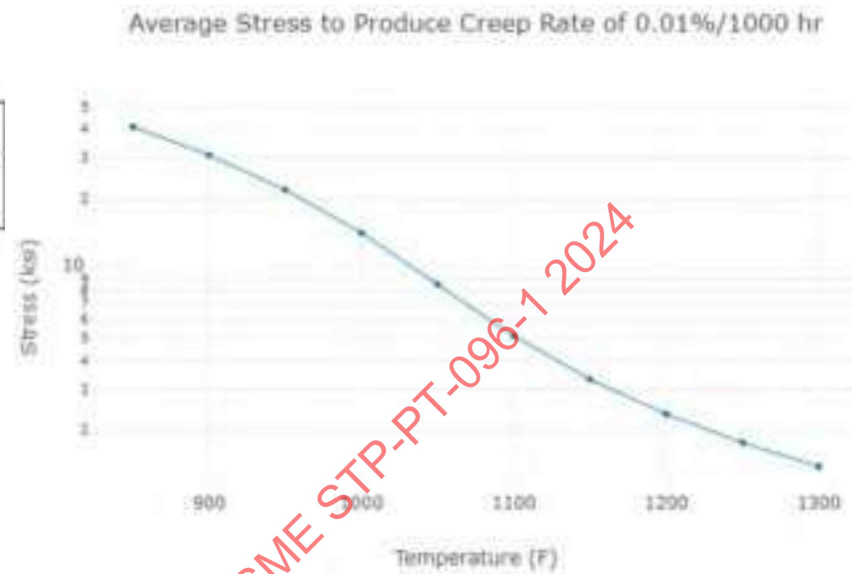


Figure 24-14: Comparison of Current 316H Allowable Stresses (Except Forgings) Vs. ASME II-D Appendix 1 Criteria Applied to Data

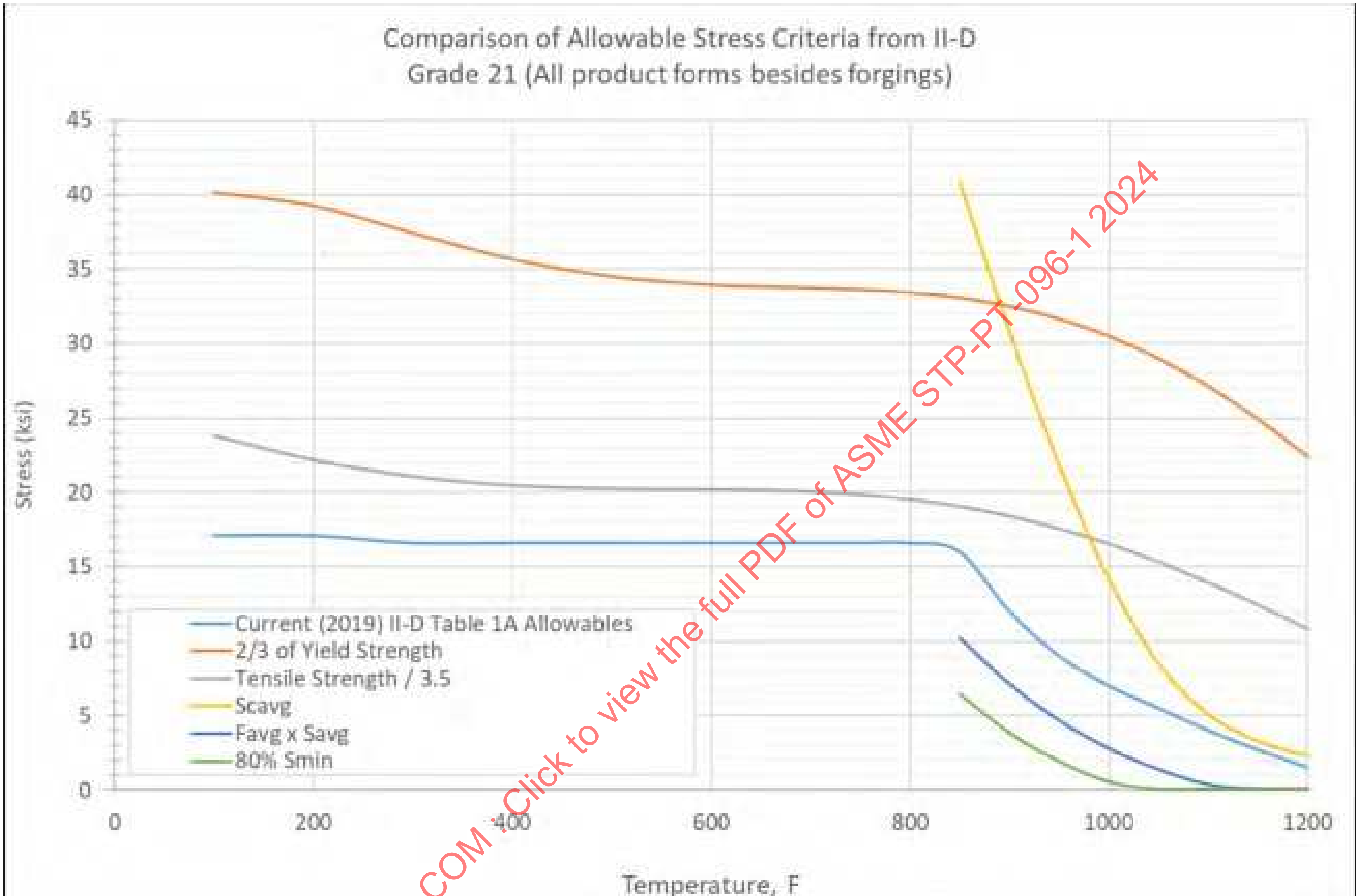


Figure 24-15: Short-Term Strain Vs. Time Data, (3Cr)

Attachment 24: 3Cr Property Data

If you want the referenced embedded spreadsheet with additional data, please email a request to research@asme.org.

25 TYPE 410 (13CR)/12CR

25.1 Physical Properties

Well-established physical properties were referenced from the BPVC Section II for this material. Physical property curves were plotted throughout the temperature range noted in Section II, Part D. Figure 25-1 shows the trends of Elastic Modulus (E_y), Thermal Conductivity (k), Thermal Diffusivity (TD), and Thermal Expansion (α) with temperature.

25.2 Yield and Tensile Strength

Elevated temperature Yield and Tensile Strength over the range of existing allowable stresses (up to 1200°F) were readily available, including data beyond the current range of allowable stresses, up to approximately 1600°F, as shown in Figures 25-2 and 25-3. The sources for both high-temperature yield and high-temperature tensile strength are provided in the embedded spreadsheet at the end of this section. This spreadsheet also contains ductility data corresponding to the tensile test results presented in this report. Note that ductility (percent elongation and percent reduction in area) was not available for all sources referenced for the Type 410/12Cr materials.

To facilitate comparison of the data obtained to existing allowable stresses (Section II-D Table 1A), yield and tensile data were normalized on a heat-by-heat basis to express the ratio of yield or tensile strength at temperature to that measured for the heat at room temperature. In cases where data were not delineated by heats within a given source, or in cases where more than one room-temperature tensile test existed for a given heat of material, ratios are equal to the measured tensile or yield strength at temperature, divided by the average of all of the appropriate room-temperature values for the particular data source or heat of material. As a result of this approach, it is possible to have ratios in excess of 1.0. E^2G understands that this approach is similar to the normalizing procedure performed by ASME in typical analysis of yield and tensile data to obtain Table Y and Table U (Section II-D) trend curves, as well as for the calculation of allowable stresses. Figures 25-4 and 25-5 show the heat-by-heat variation in yield and tensile strength ratios (respectively) as a function of temperature. It should be emphasized that even though the figure legends reference an entire source of data, the ratios, wherever possible, were calculated on a heat-by-heat basis; this is evident in the embedded spreadsheet at the end of this section. Figures 25-6 and 25-7 contain all of the yield and tensile (respectively) ratios plotted together, to facilitate regression of a 5th-order polynomial that is subsequently used for allowable stress comparison.

25.3 Creep Data (Creep Rupture, Minimum Creep Rate, and Ductility)

Creep Rupture data is shown in Figures 25-8 and 25-9, plotted as isotherms. The temperatures have been separated onto separate plots to minimize data overlap, with Figure 25-8 showing those temperatures where most of the data were concentrated, and Figure 25-9 showing those temperatures with significantly less data. It should be emphasized that these plots contain data for all product forms of material classified in the referenced publications as "Type 410" and "12Cr." This certainly includes material meeting the requirements of ASME BPVC Section II-A specifications (e.g., SA-182 F6a, Cl. 1&2, SA-240 Type 410, SA-479 Grade 403, etc.). However, due to the diversity of data sources utilized for the compilation of the material property tables, it is likely that some of the material shown in Figures 25-8 and 25-9 may not meet existing specifications for this grade of material. Where older publications are referenced, the chemistry (and for that matter, manufacturing, processing, and heat treatment) corresponding to the heat of material in the original data source, may not be consistent with modern specifications. Where possible, E^2G has documented the chemical composition if contained within the original source. In many cases, the project team has also made efforts to trace cross-referenced data back to original test results to determine if the heat treatment, product form, chemistry, etc. details can be obtained. This information is provided with the embedded spreadsheet to facilitate additional analysis on the part of ASME.

Creep Minimum strain rates (%/hour) are shown in Figures 25-10 and 25-11, separated by temperature. As in the case of rupture data, temperatures of minimum creep rates have been separated onto separate plots to minimize data overlap, with Figure 25-10 showing those temperatures where most of the data were concentrated, and Figure 25-11 showing those temperatures with significantly less data. Creep Ductility, as % elongation, is plotted in Figure 25-12. As is typical, the data show significant overlap, and it is difficult to observe clear trends in the data. The data is not intended to be used as plotted but is available in the spreadsheet for additional analysis. Note that much of the data with less than 10% total elongation at failure corresponds to cross-weld specimens contained in the data.

Creep data were analyzed using E^2G's proprietary Lot-Centered Analysis web-based software tool, in order to obtain creep properties. This regression is based on a Mandel-Paule algorithm and considers the variation within individual heats of material (for both rupture and strain rate data) as well as the variation between heats. The weight assigned to each datapoint and each heat is scaled based on the relative variation. Both rupture and strain rate (minimum creep rate, expressed as true strain per hours) were regressed according to a Larson-Miller time-temperature-parameter model, with a 3rd-order polynomial of stress. Lot-specific constant behavior was accounted for in this analysis, but the variation of LMP with stress was assumed to be constant (no non-parallel terms were included in the analysis). A 95% predictive limit was utilized to obtain the lower-bound (minimum LM constant for both rupture and strain rate) properties. The results of this analysis are summarized in Table 25-1 for rupture data and Table 25-2 for strain rate data. The Lot-Centered Analysis software tool generates property tables in the creep regime using the criteria outlined in Mandatory Appendix 1 of ASME Section II-D; the nomenclature of variables is consistent with II-D Appendix 1. For visualization of the allowable stress trends, Figure 25-13 is provided (for rupture allowable stresses and creep rate allowable stresses). Figure 25-14 shows a comparison of the various allowable stress criteria from Section II-D, Appendix 1, to the existing (2019) Section II-D Table 1A allowable stresses for Plate & Forgings of Type 410.

Creep Strain vs. time data are shown in Figures 25-15 and 25-16 for short-term data (up to 2,500 hour test durations); Figure 25-17 for 2,500 to 5,000 hour test durations; Figure 25-18 for 5,000 to 10,000 hour test durations, Figure 25-19 for 10,000 to 100,000 hour test durations, and Figure 25-20 for durations in excess of 100,000 hours. Curves are only plotted where more than 6 strain vs. time points are present for the test. Additional curves are available with fewer datapoints (typically obtained from data in the form of time-until-specified-strain, in the embedded spreadsheet. Both creep rate and creep strain vs. time data are provided to satisfy ASME's request for creep strain vs. time curves, and both forms of data are applicable in developing allowable stresses. Although digitalization of creep curve data was not explicitly necessary per the project contract, E^2G did perform digitalization of creep curves where only graphical data was available (as is often the case in the published literature).

25.4 Continuous Cycling Fatigue and Hold Time Fatigue Curves

A portion of the data obtained for continuous cycling fatigue data at elevated temperatures for Type 410/12Cr is shown in Figure 25-21, which includes room temperature data contained in sources which also present high-temperature data. Figure 25-21 only contains data for which total strain range was determined from the original source. Another portion of the continuous cyclic fatigue data obtained is included in Figure 25-22. This data is presented as stress amplitude vs. the amount of cycles to failure. Additional data points for continuous cycling fatigue data of Type 410/12Cr are presented in the attached spreadsheet; however, due to the complexities of various forms of fatigue data, compatible plots for each type of data expression and failure criteria are not included in this report. Hold time fatigue data at high temperature is shown in Figure 25-23 (950°F) and Figure 25-24 (1202°F). Additional data is provided in the embedded spreadsheet.

Table 25-1: Model Parameters, Larson-Miller Property Results, and Allowable Stress (Rupture) Criteria, Type 410/12Cr

Equation Format:

$$\log(t_r) = C_{avg} + \frac{1}{T+460}\left(b_1 + b_2\log(\sigma) + b_3(\log(\sigma))^2 + b_4(\log(\sigma))^3\right)$$

Cavg	**-12.96**
Cmin	**-14.03**
b_1	**32984.3**
b_2	**-8432.8**
b_3	**3072.8**
b_4	**-1286.7**

Number Data Points		**861**
Correlation Coefficient	R^2	0.5088
Average Variance within Heats	V_w	0.4216
Variance between Heats	V_b	0.6733
Standard Error of Estimate	SEE	0.6493

Properties provided are for T in °F, stress in ksi, and t_R in hours

Temperature, °F	**S_{avg} (ksi)**	***n***	**F_{avg} (calc)**	**F_{avg} (used)**	**Favg × Savg**	**S_{min} (ksi)**	**80% S_{min}**
850	26.21	5.711	0.6682	0.67	17.56	16.58	13.26
900	19.67	5.105	0.637	0.67	13.18	11.81	9.449
950	14.45	4.608	0.6067	0.67	9.68	8.269	6.615
1000	10.42	4.23	0.5803	0.67	6.98	5.739	4.591
1050	7.413	3.979	0.5606	0.67	4.967	3.994	3.195
1100	5.25	3.852	0.55	0.67	3.517	2.817	2.254
1150	3.736	3.838	0.5489	0.67	2.503	2.028	1.622
1200	2.694	3.917	0.5555	0.67	1.805	1.495	1.196
1250	1.98	4.064	0.5675	0.67	1.327	1.128	0.9024
1300	1.486	4.255	0.5821	0.67	0.9958	0.8706	0.6965

Table 25-2: Model Parameters, Larson-Miller Property Results, and Allowable Stress (Strain Rate) Criteria, Type 410/12Cr

Equation Format:

$$\log(\dot{\varepsilon}_0) = -C_{avg} - \frac{1}{T+460}\left(a_1 + a_2\log(\sigma) + a_3(\log(\sigma))^2 + a_4(\log(\sigma))^3\right)$$

C_{avg} (A_0)	**-23.7**
Cmin (A0+ΔΩSR,LB)	**-24.93**
a_1	**54814.6**
a_2	**-12184.2**
a_3	**4091.5**
a_4	**-1925.7**

Number Data Points		**136**
Correlation Coefficient	R2	0.6377
Average Variance within Heats	V_w	0.5591
Variance between Heats	V_b	0.0994
Standard Error of Estimate	SEE	0.7477

Properties provided are for T in °F, stress in ksi, and t_R in hours

Temperature, °F	**$S_{C,avg}$ (ksi)**
850	41.9
900	32.85
950	25.25
1000	18.99
1050	13.97
1100	10.06
1150	7.125
1200	4.999
1250	3.51
1300	2.49

Figure 25-1: Type 410/12Cr Modulus (E_y), Thermal Conductivity (k), Thermal Diffusivity (TD), & Thermal Expansion (α) With Temperature

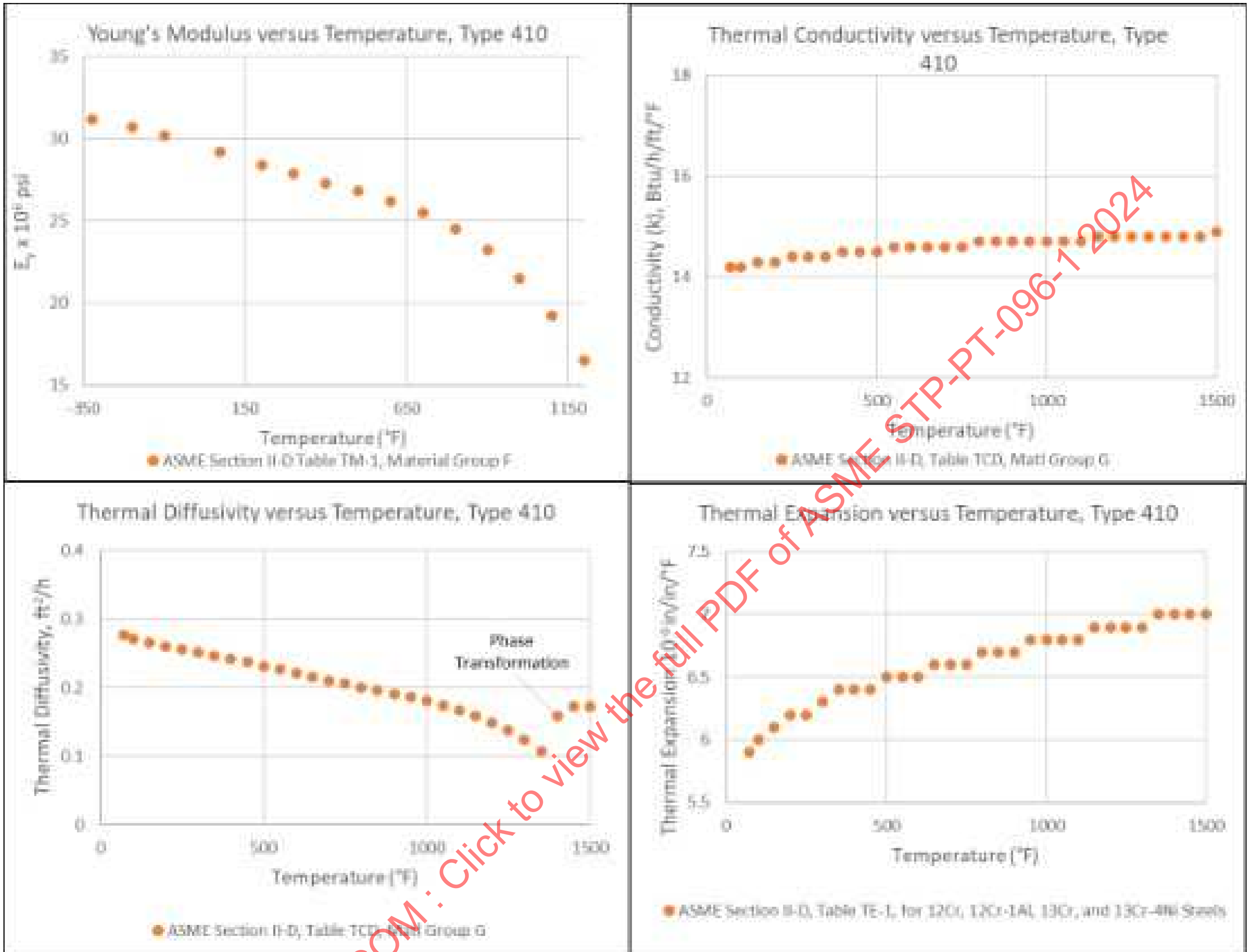


Figure 25-2: Type 410/12Cr Yield Strength Vs. Temperature, By Data Source, Including Trend Curves

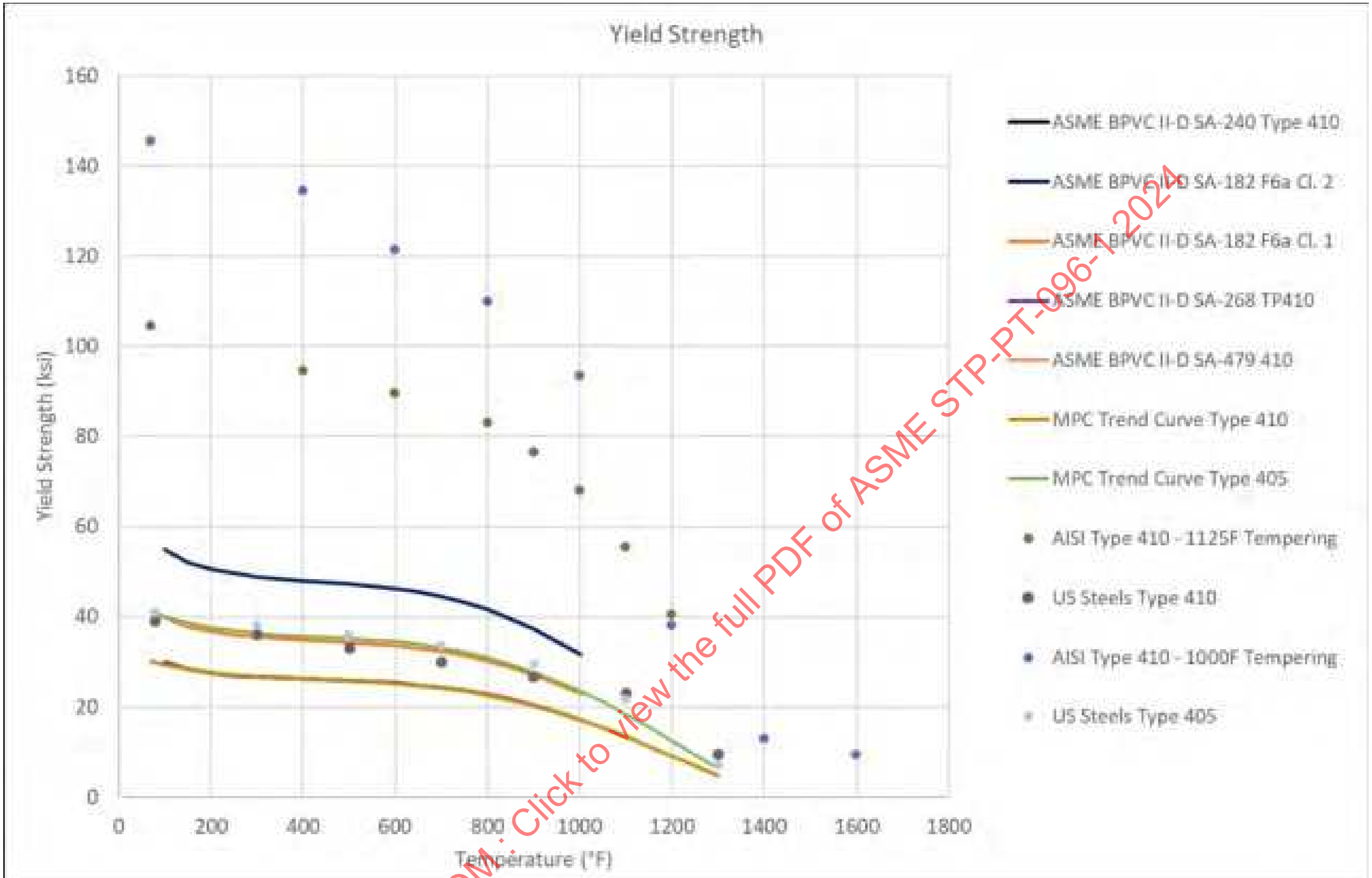


Figure 25-3: Type 410/12Cr Tensile Strength Vs. Temperature, By Data Source, Including Trend Curves

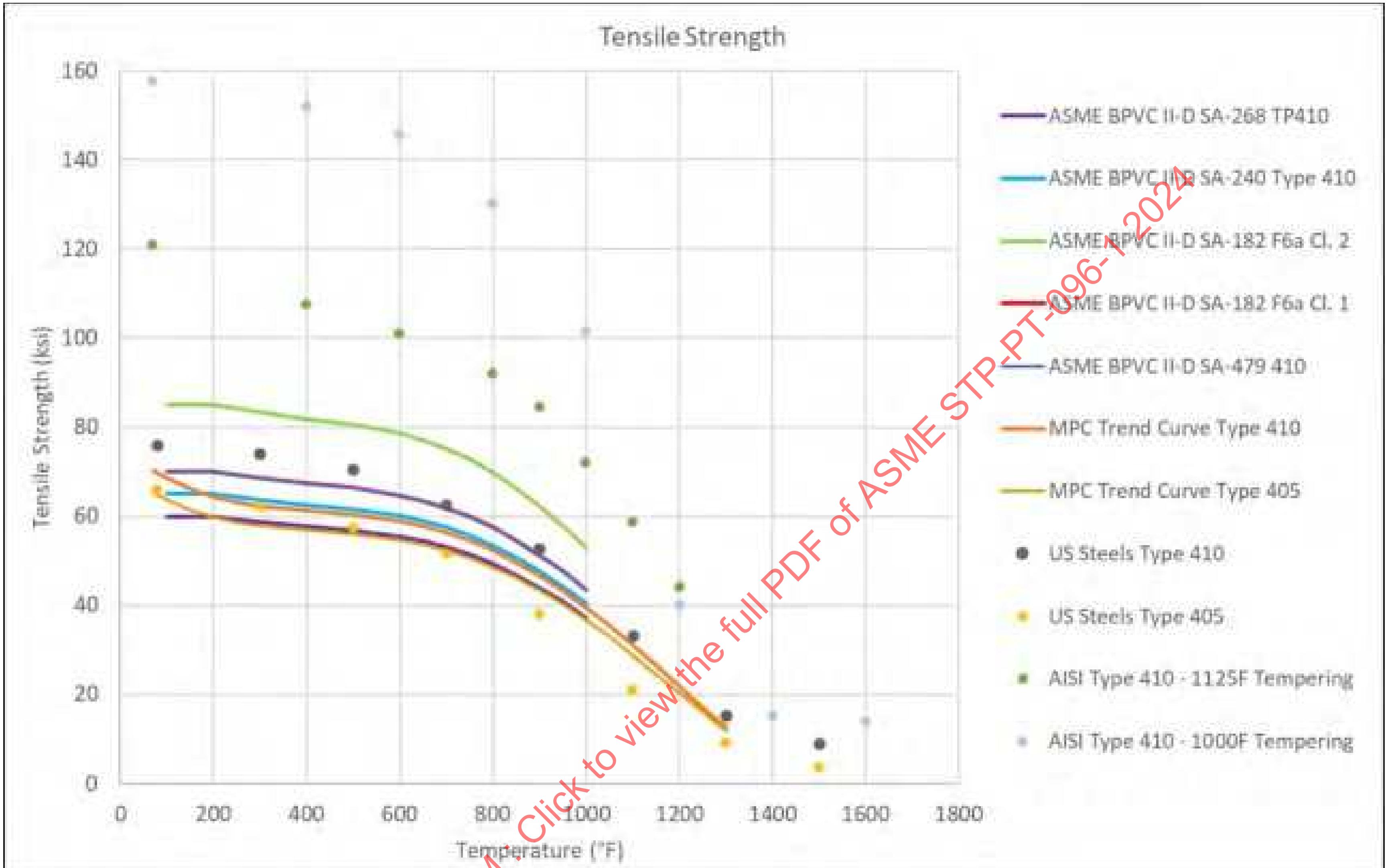


Figure 25-4: Type 410/12Cr Yield Strength Ratios Vs. Temperature (Calculated on a Heat-By-Heat Basis, By Data Source)

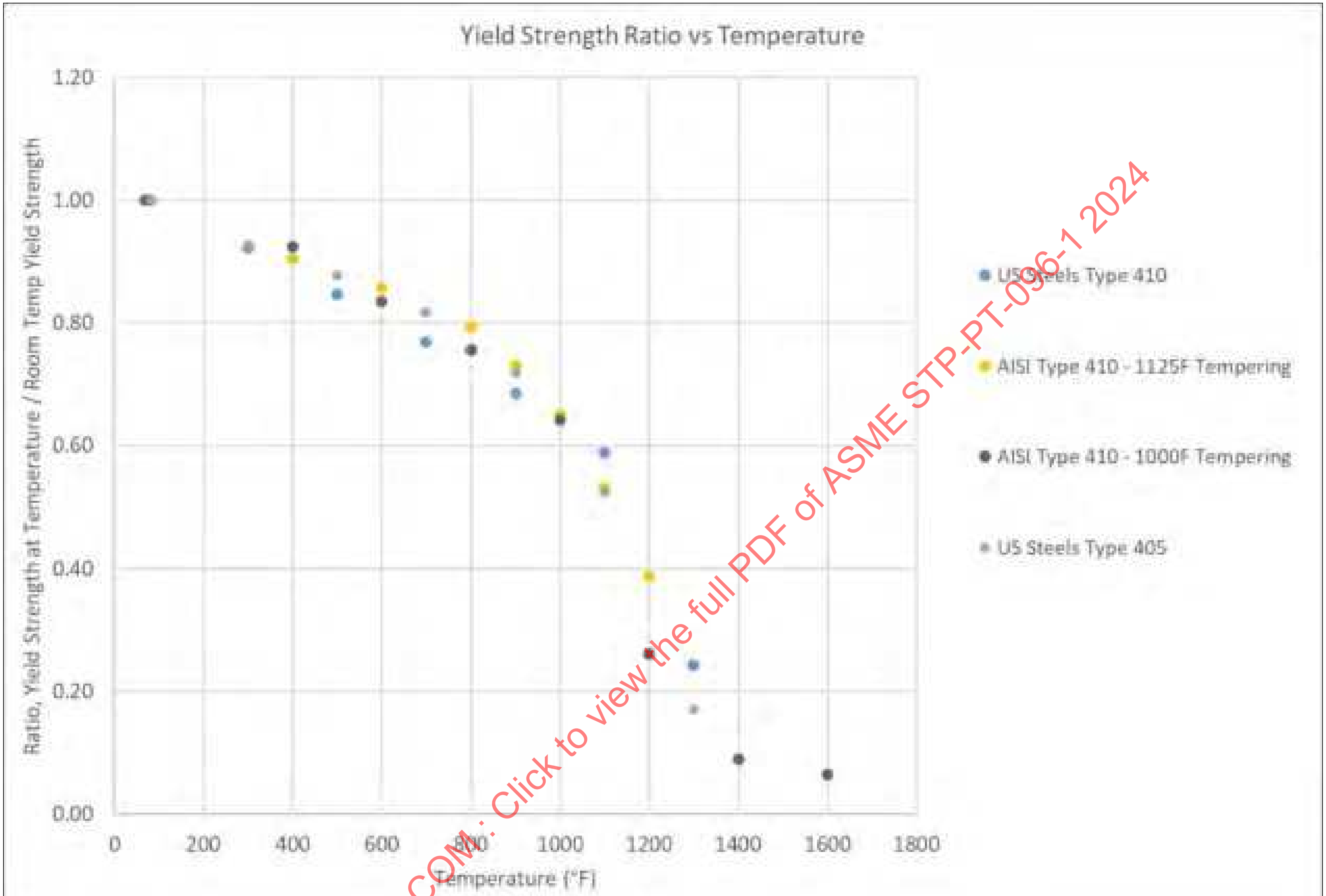


Figure 25-5: Type 410/12Cr Tensile Strength Ratios Vs. Temperature (Calculated on a Heat-By-Heat Basis, By Data Source)

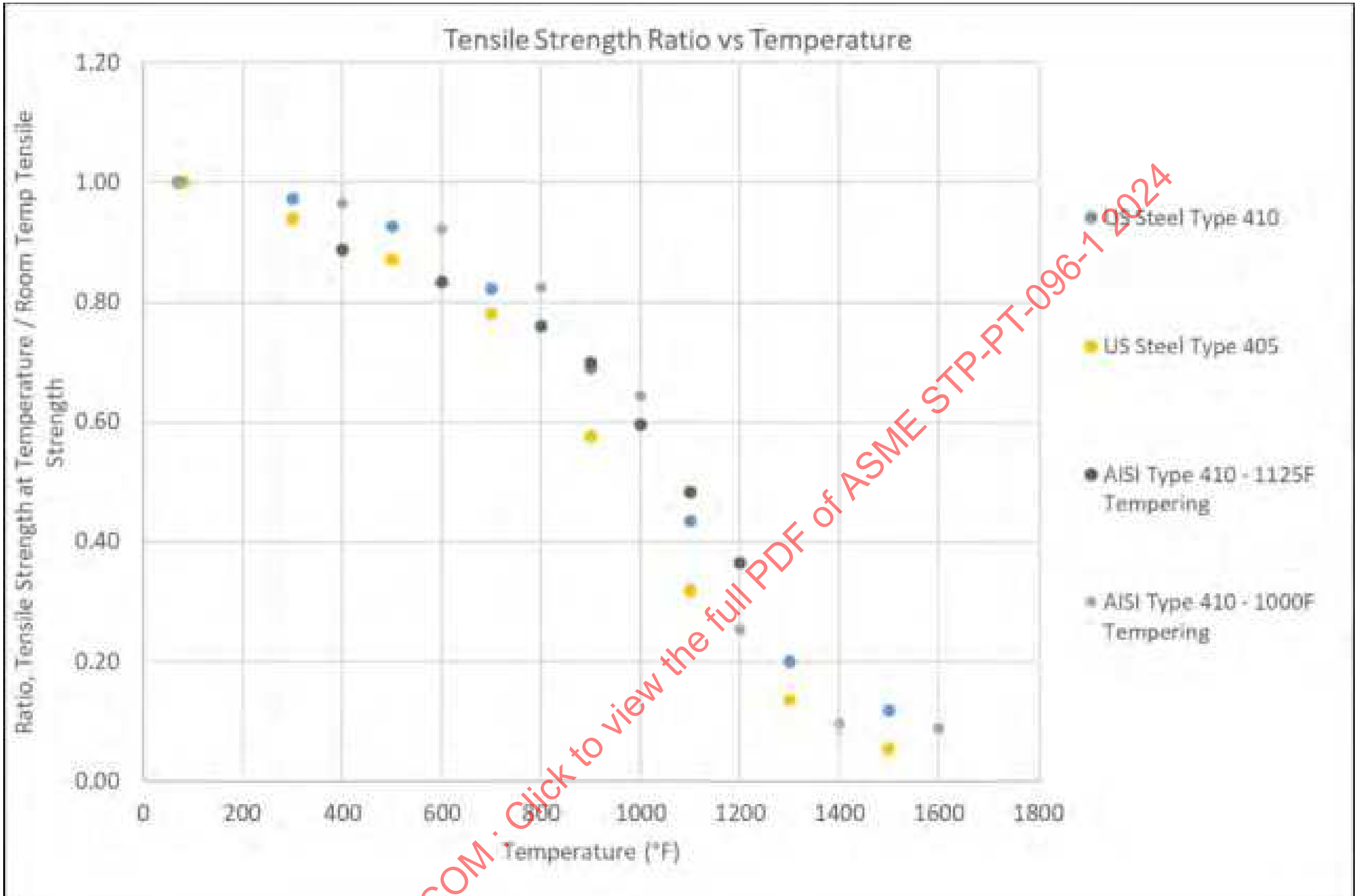


Figure 25-6: Type 410/12Cr Yield Strength Ratios Vs. Temperature, All Combined data, With Polynomial Regression

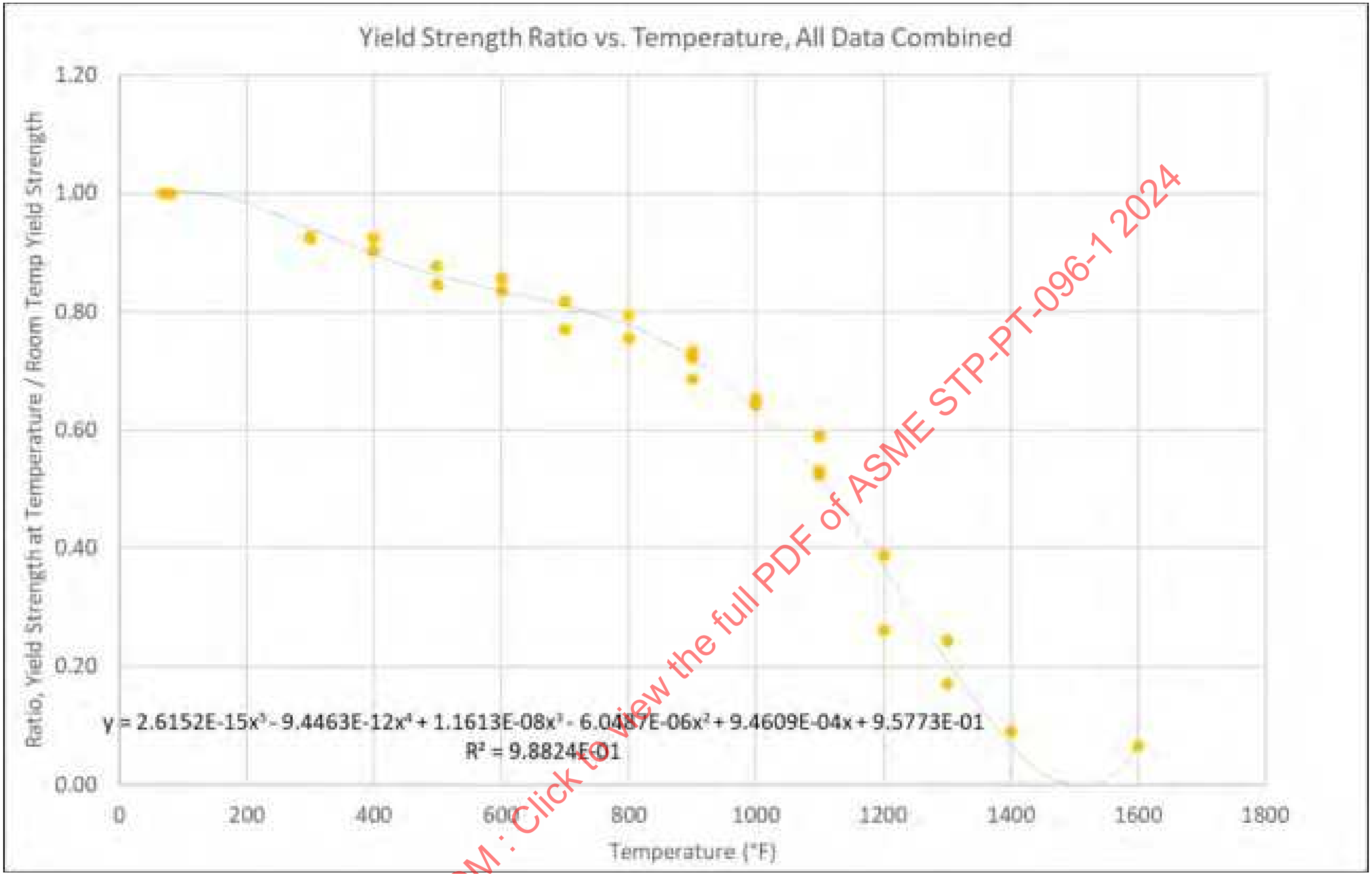


Figure 25-7: Type 410/12Cr Tensile Strength Ratios Vs. Temperature, All Combined Data, With Polynomial Regression

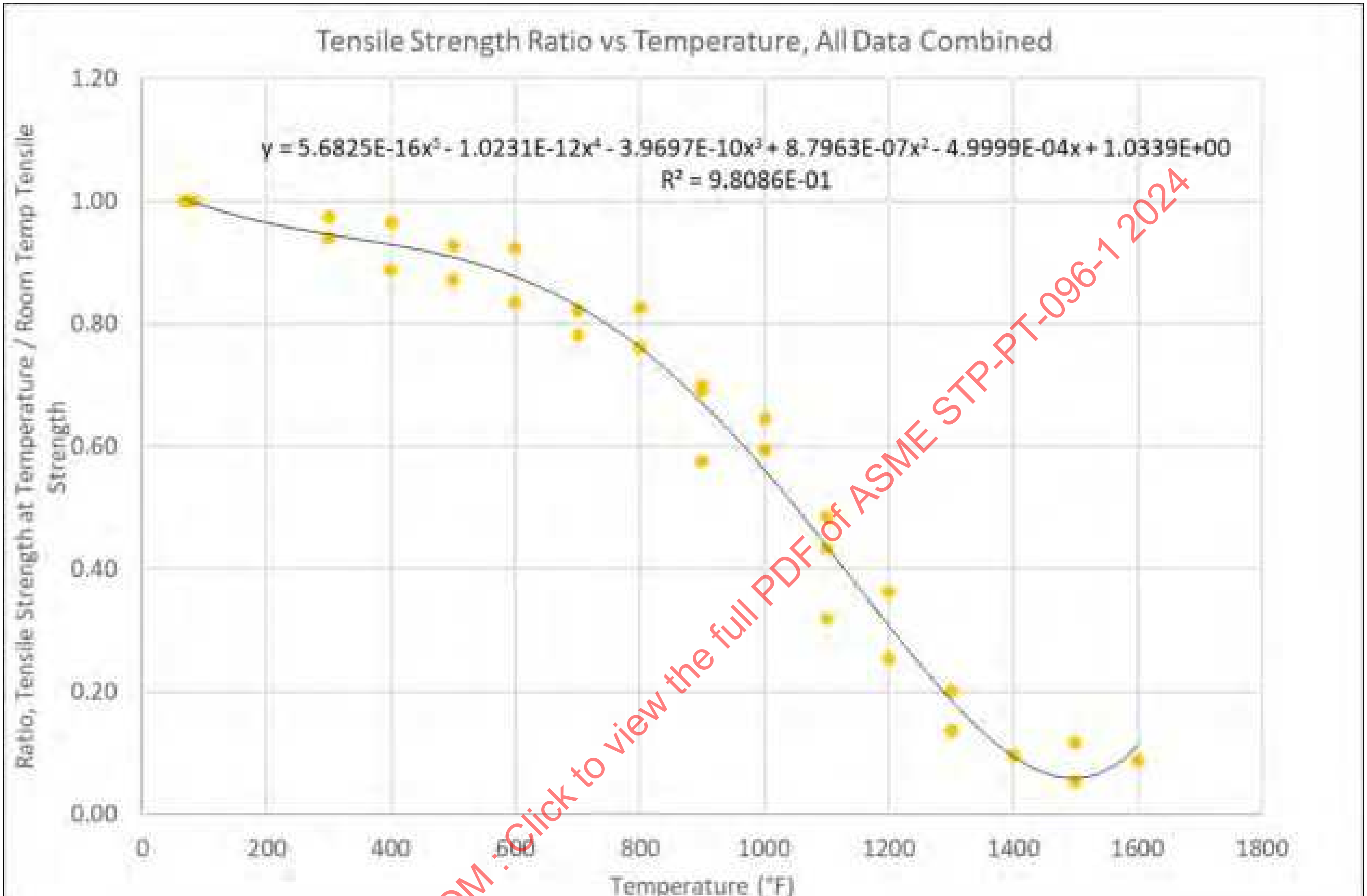


Figure 25-8: Type 410/12Cr Creep Rupture Isotherm Curves, Temperatures With High Concentration of Data Points

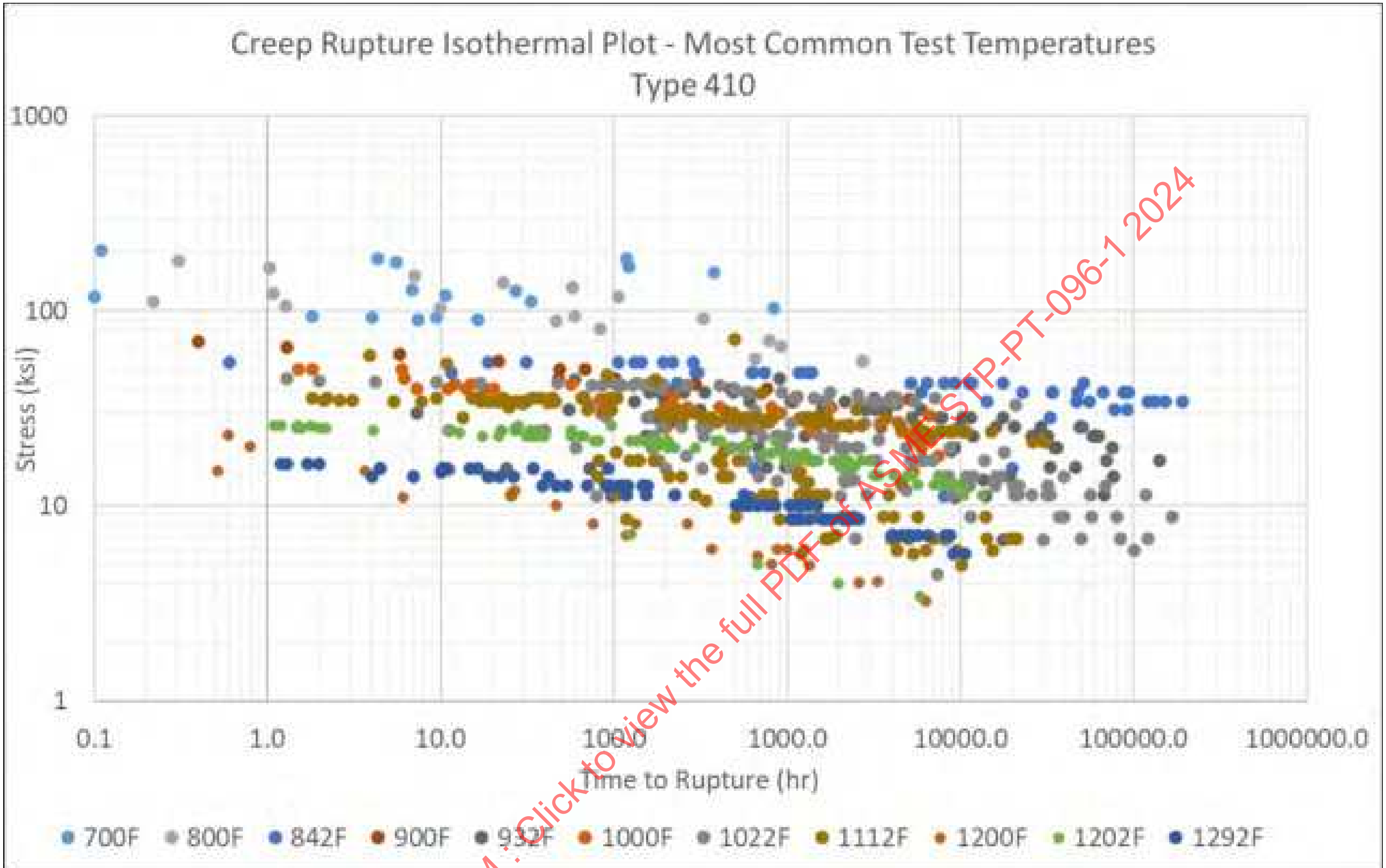


Figure 25-9: Type 410/12Cr Creep Rupture Isotherm Curves for Additional and Intermediate Temperatures

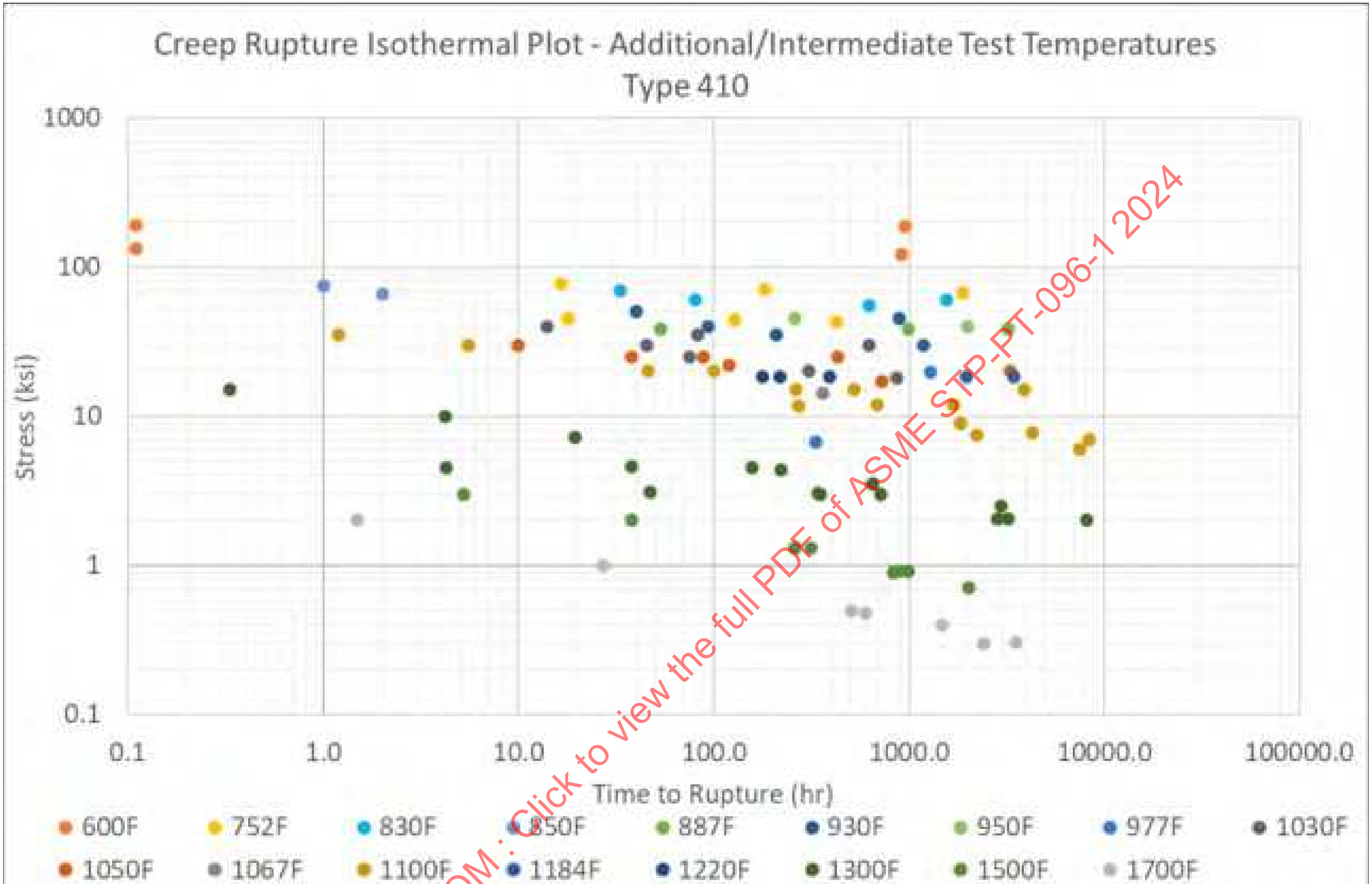


Figure 25-10: Type 410/12Cr Creep Strain Rate (MCR) Isotherm Curves, Temperatures With High Concentration of Data Points

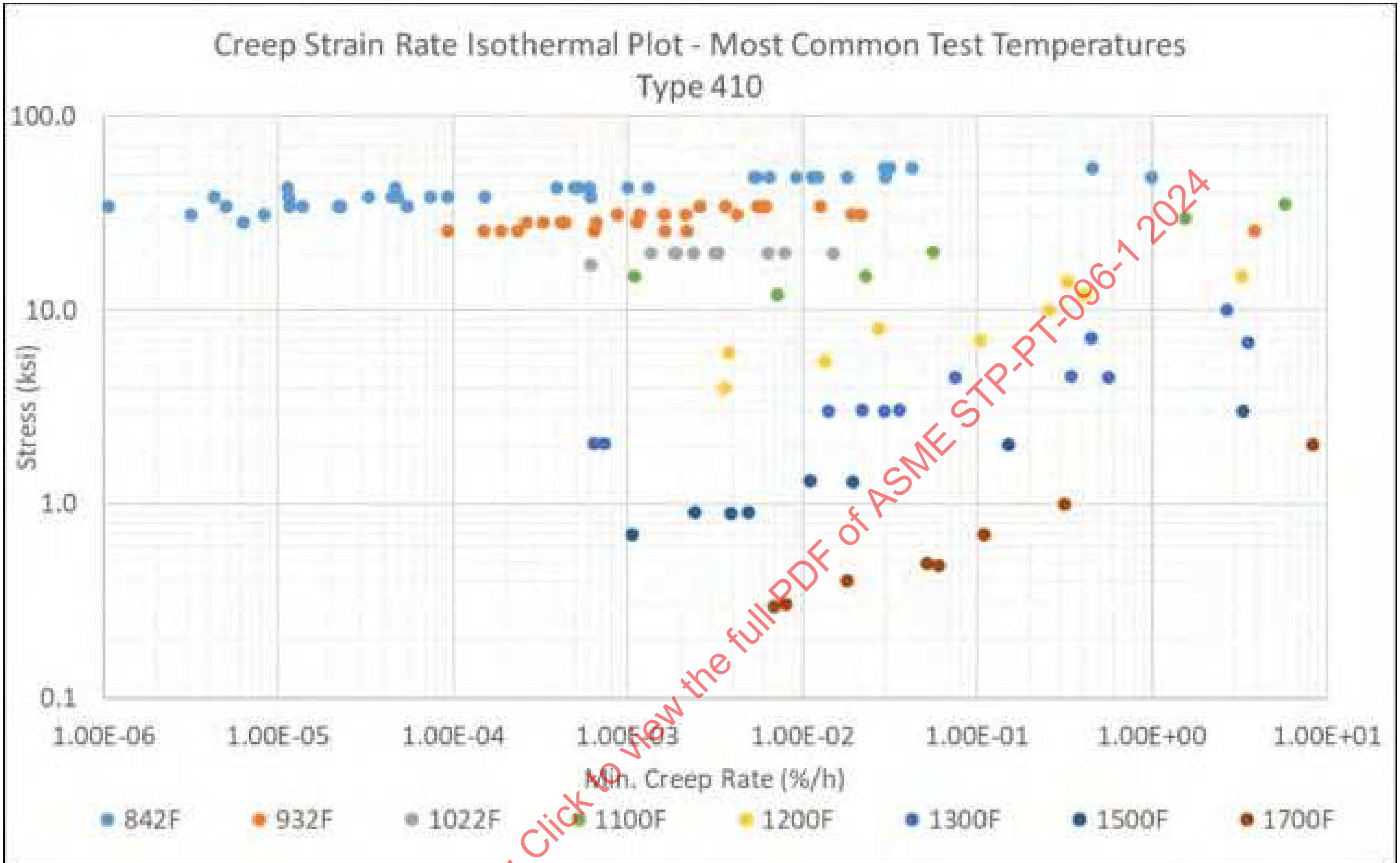


Figure 25-11: Type 410/12Cr Creep Strain Rate (MCR) Isotherm Curves for Additional and Intermediate Temperatures

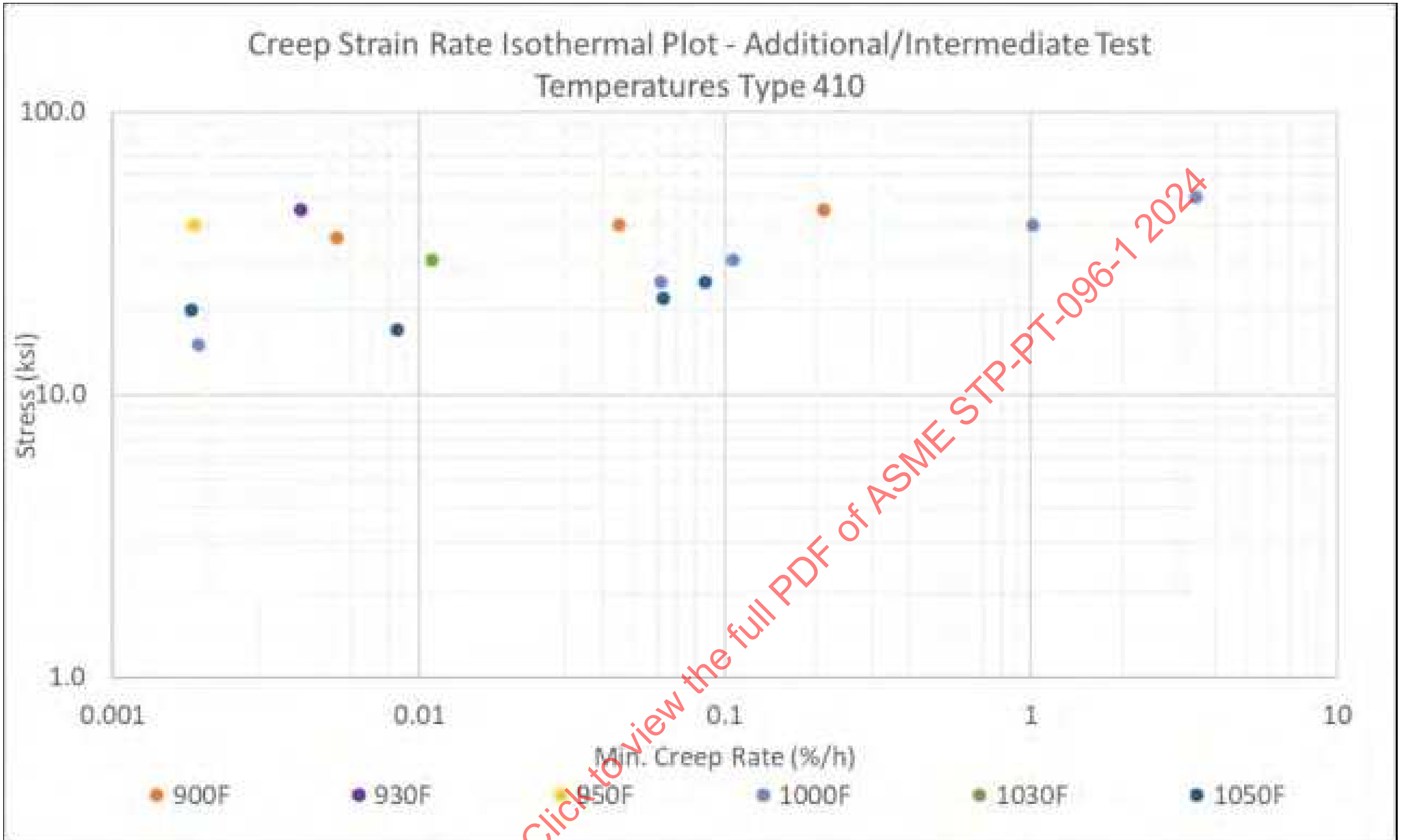


Figure 25-12: Type 410/12Cr Creep Ductility (% Elongation) Vs. Rupture Time Isotherms

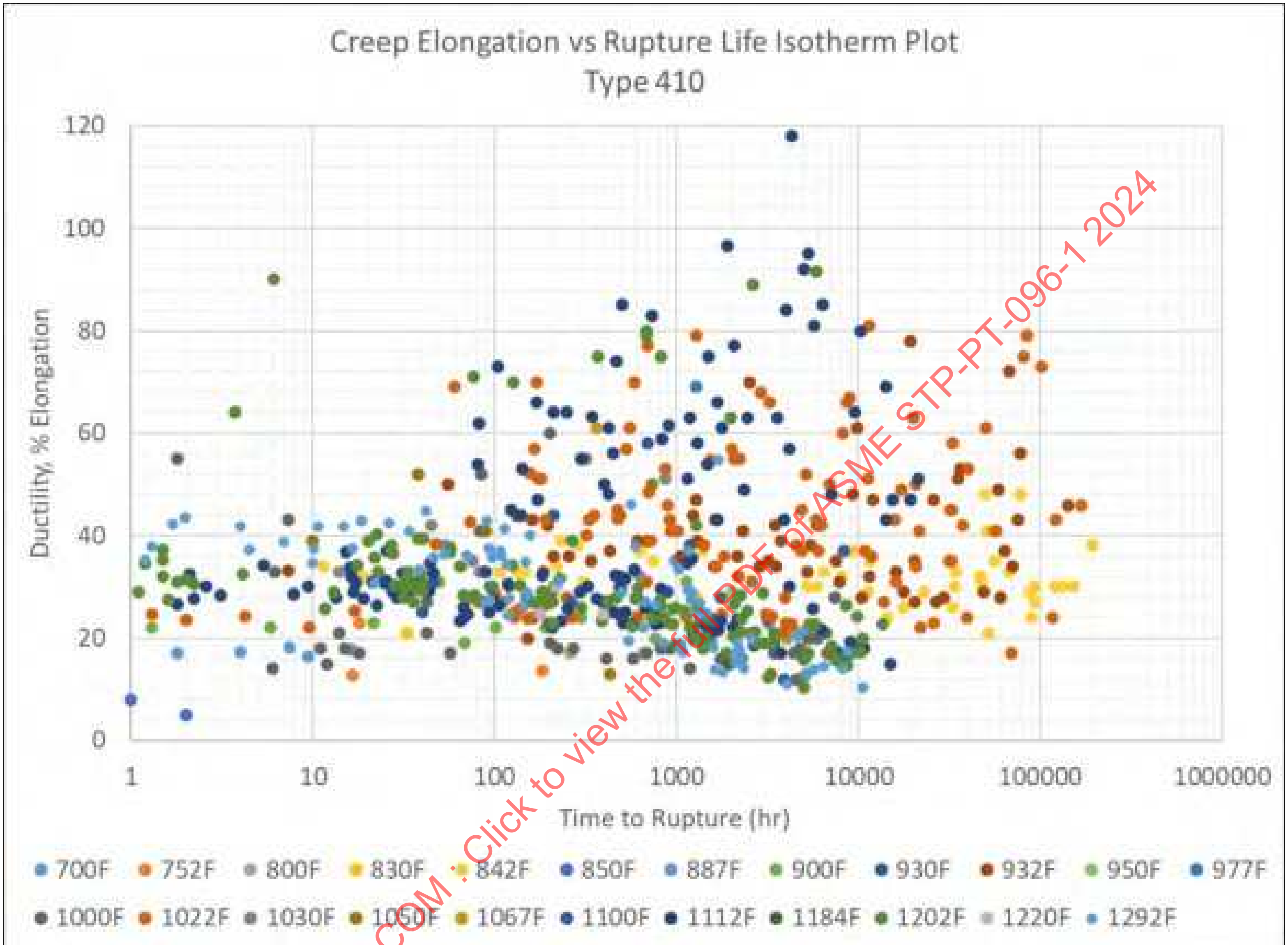


Figure 25-13: Calculated Allowable Stresses Based on Rupture and Creep Strain Rate and ASME II-D Appendix 1 Criteria (Type 410/12Cr)

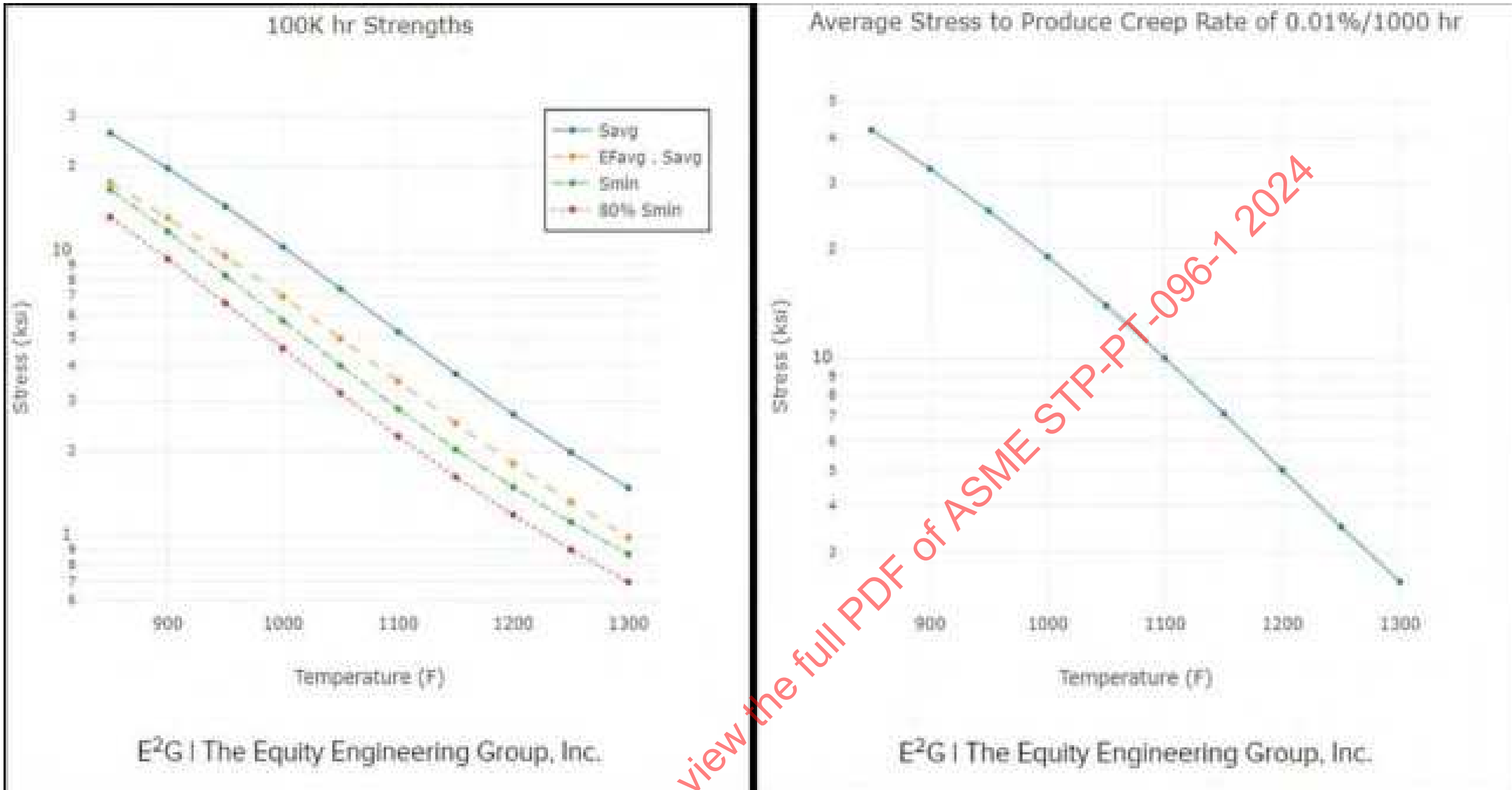


Figure 25-14: Comparison of Current Type 410 Allowable Stresses (Plate & Forgings) Vs. ASME II-D Appendix 1 Criteria Applied to Data

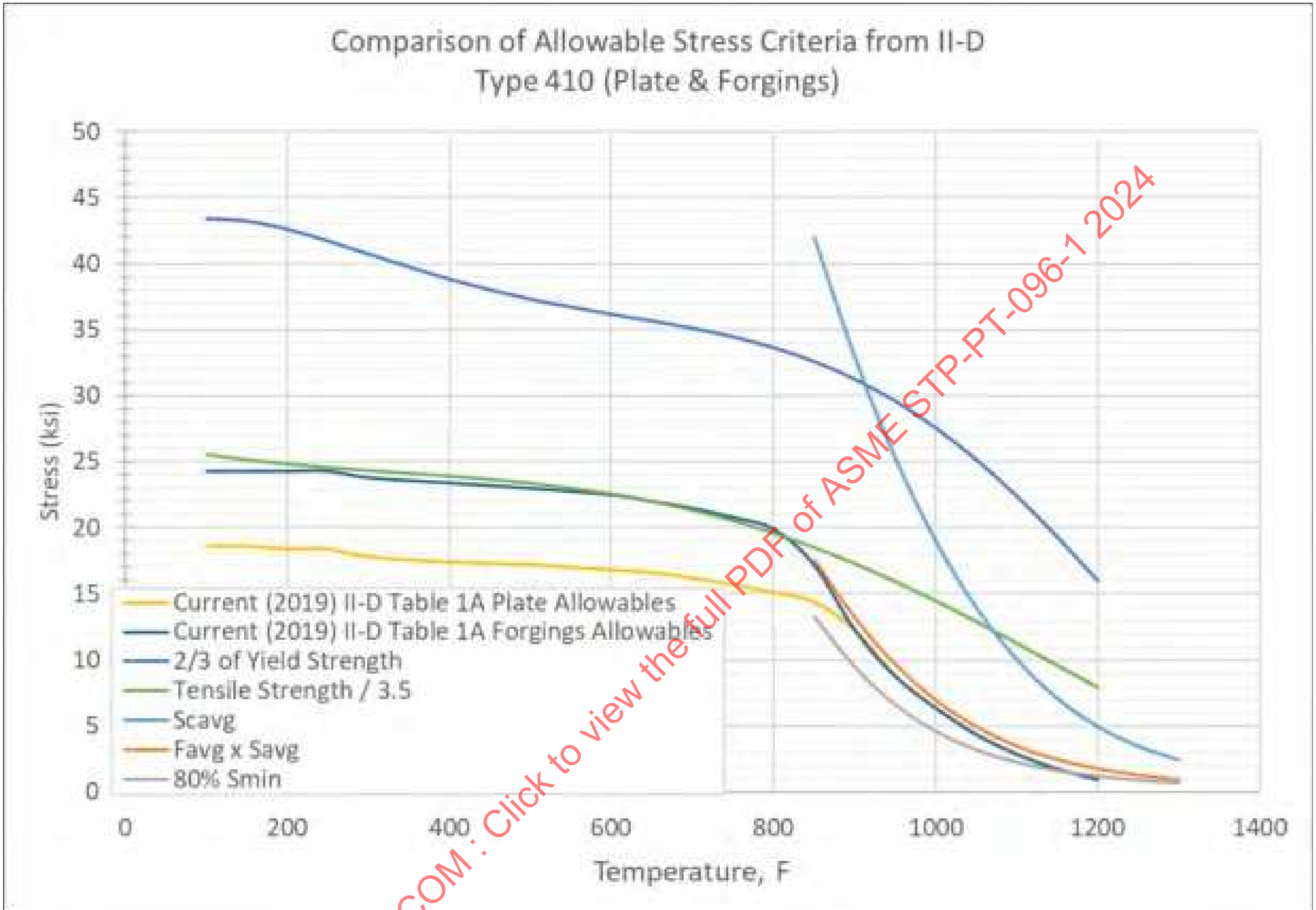


Figure 25-15: Short-Term Strain Vs. Time Data, up to 2,500 Hour Test Durations (Type 410/12Cr), 1 of 2

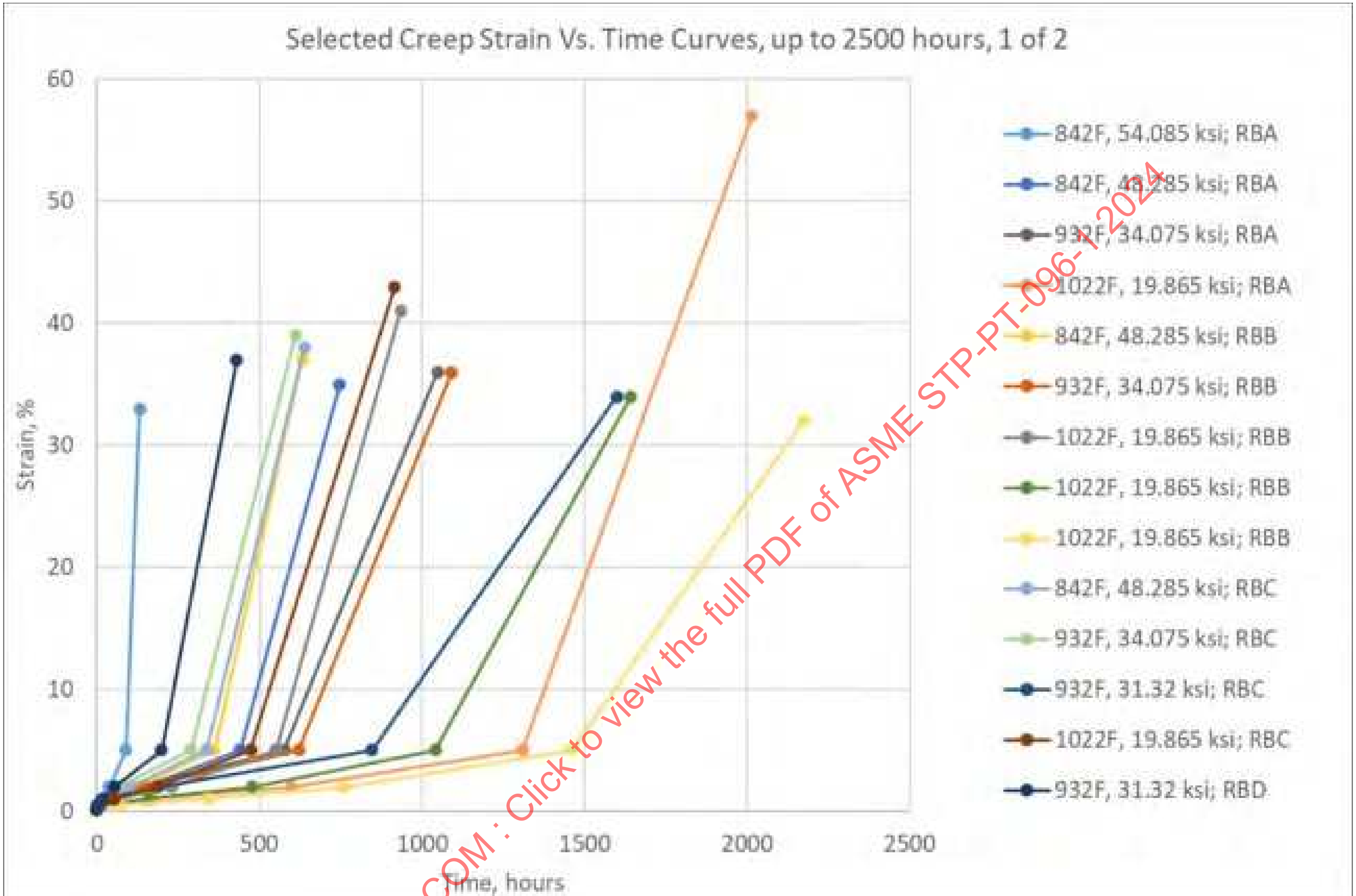


Figure 25-16: Short-Term Strain Vs. Time Data, up to 2,500 Hour Test Durations (Type 410/12Cr), 2 of 2

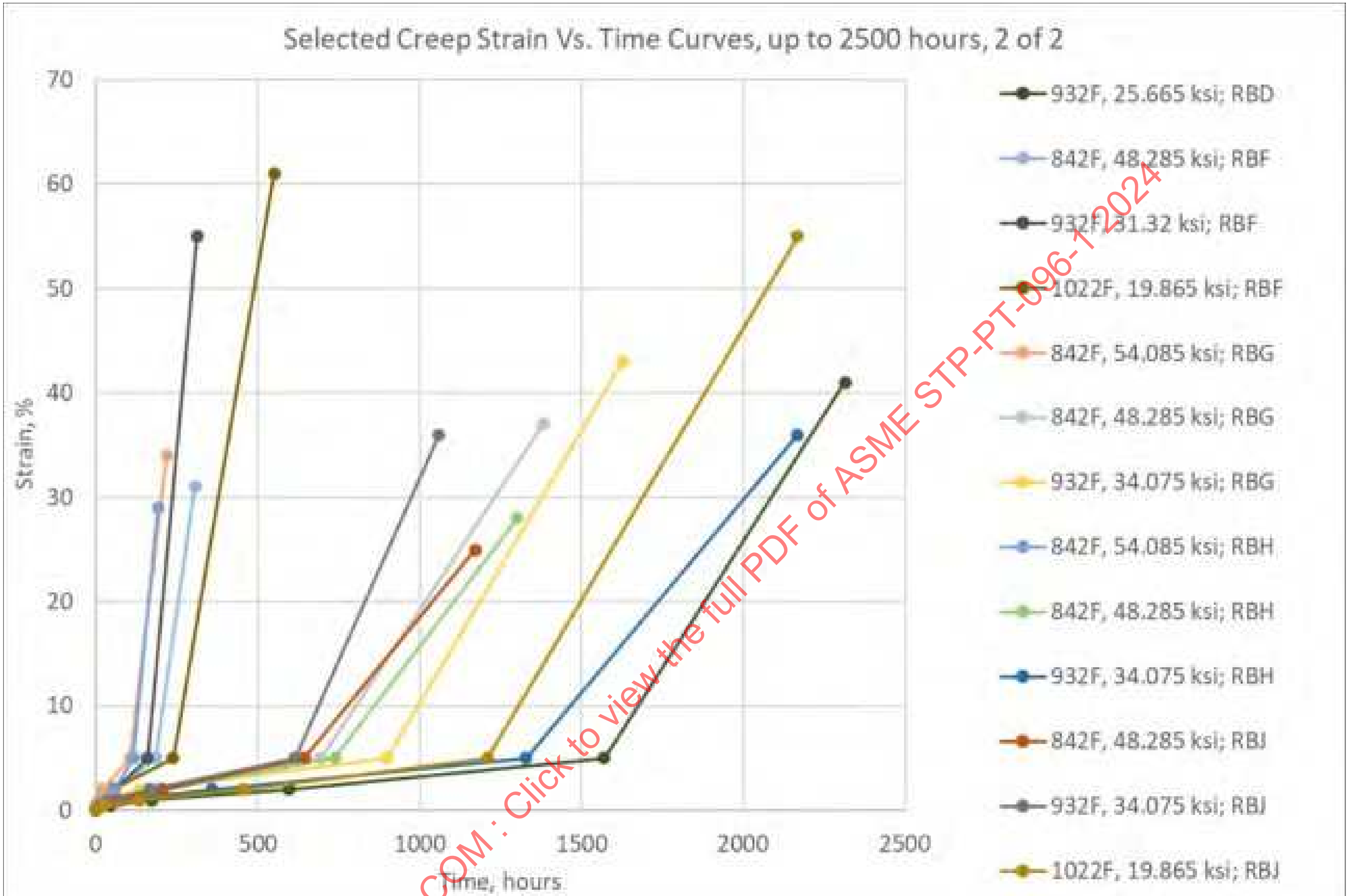


Figure 25-17: Medium-Term Strain Vs. Time Data, 2,500 to 5,000 Hour Test Durations (Type 410/12Cr)

Figure 25-18: Long-Term Strain Vs. Time Data, up to 10,000 Hour Test Durations (Type 410/12Cr)

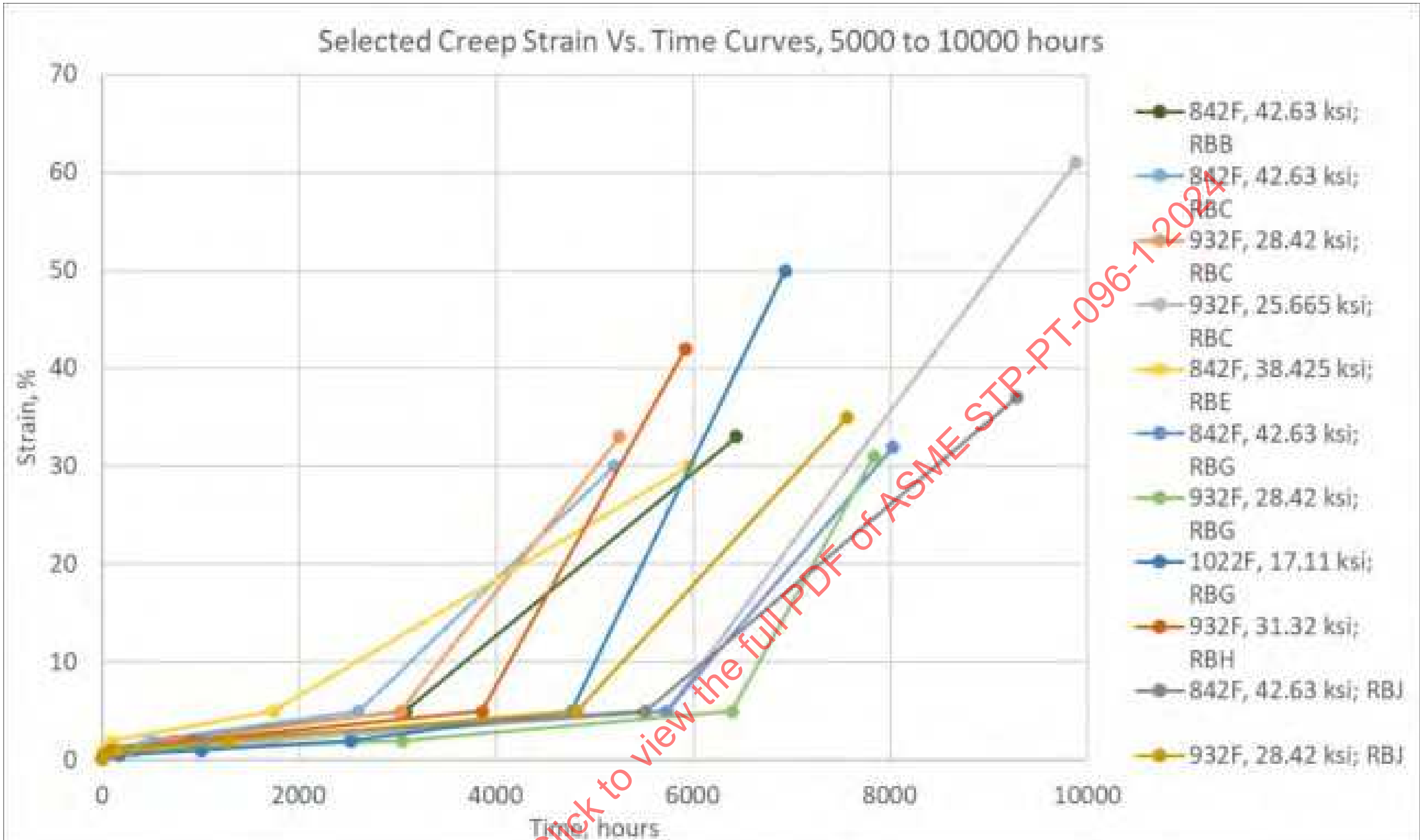


Figure 25-19: Long-Term Strain Vs. Time Data, 10,000 to 100,000 Hour Test Durations (Type 410/12Cr)

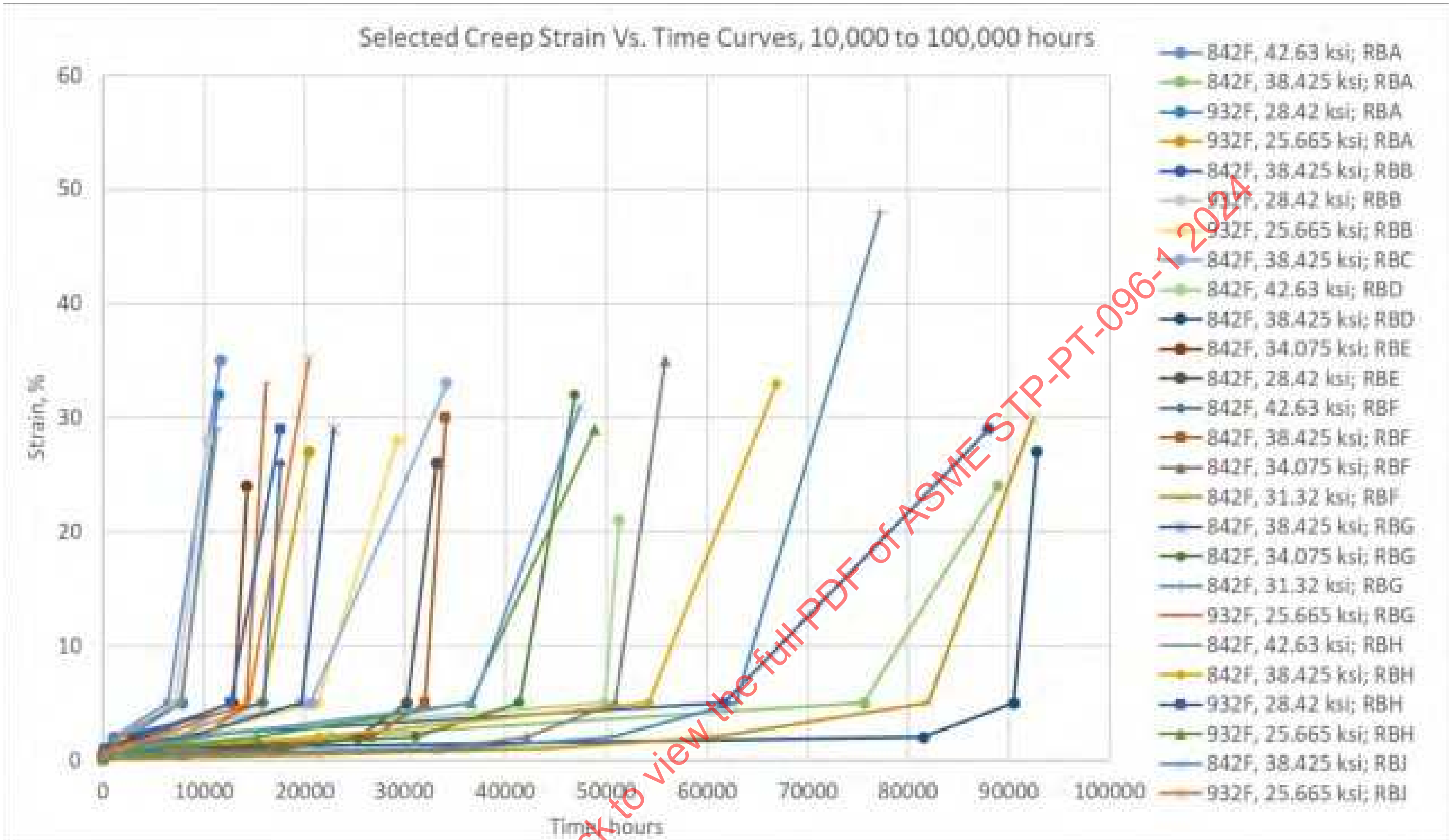


Figure 25-20: Long-Term Strain Vs. Time Data, in Excess of 100,000 Hour Test Durations (Type 410/12Cr)

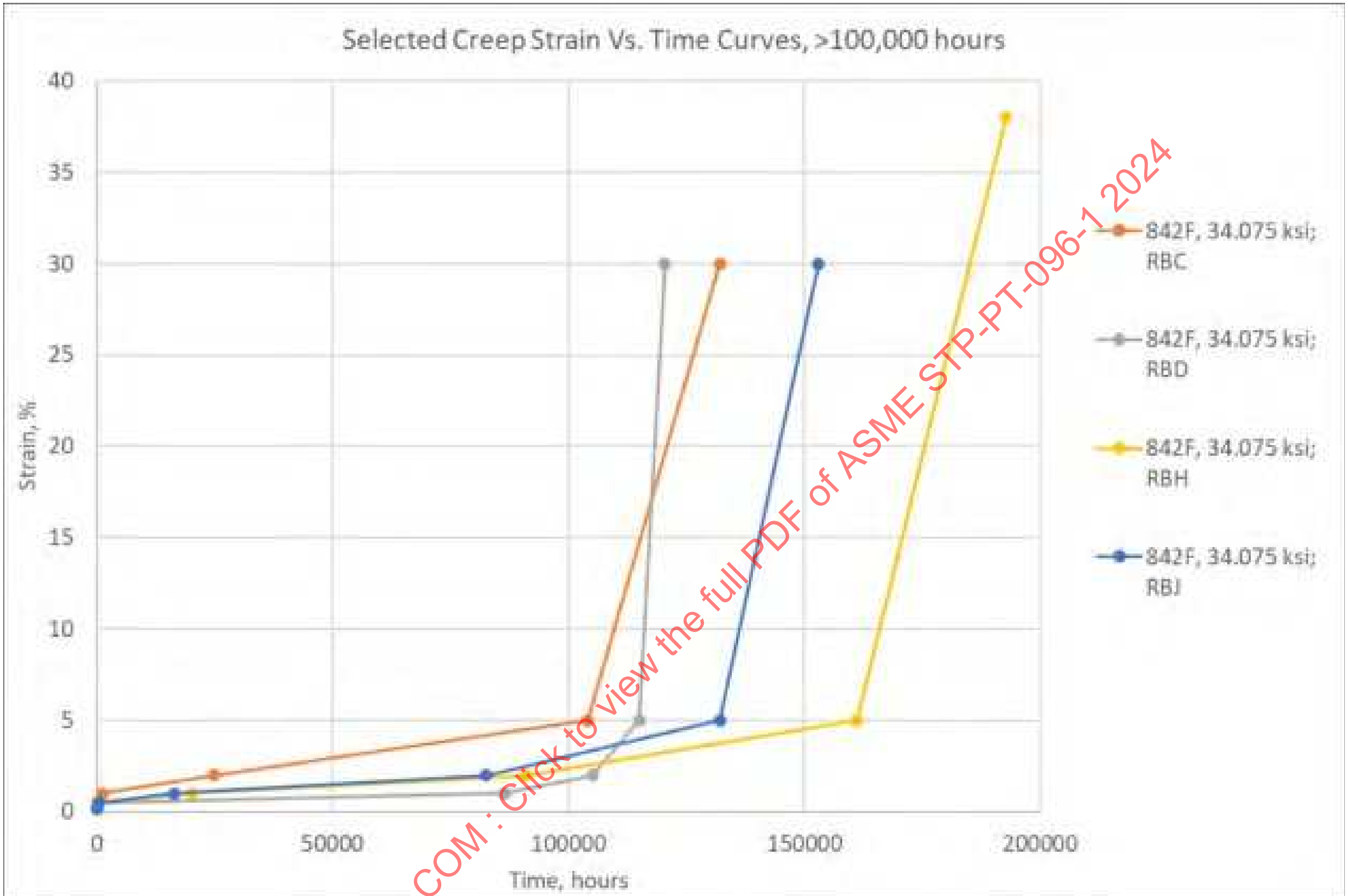


Figure 25-21: Type 410/12Cr Continuous Cycling Fatigue (Type 410/12Cr), Including Room Temperature and Elevated Temperature Data

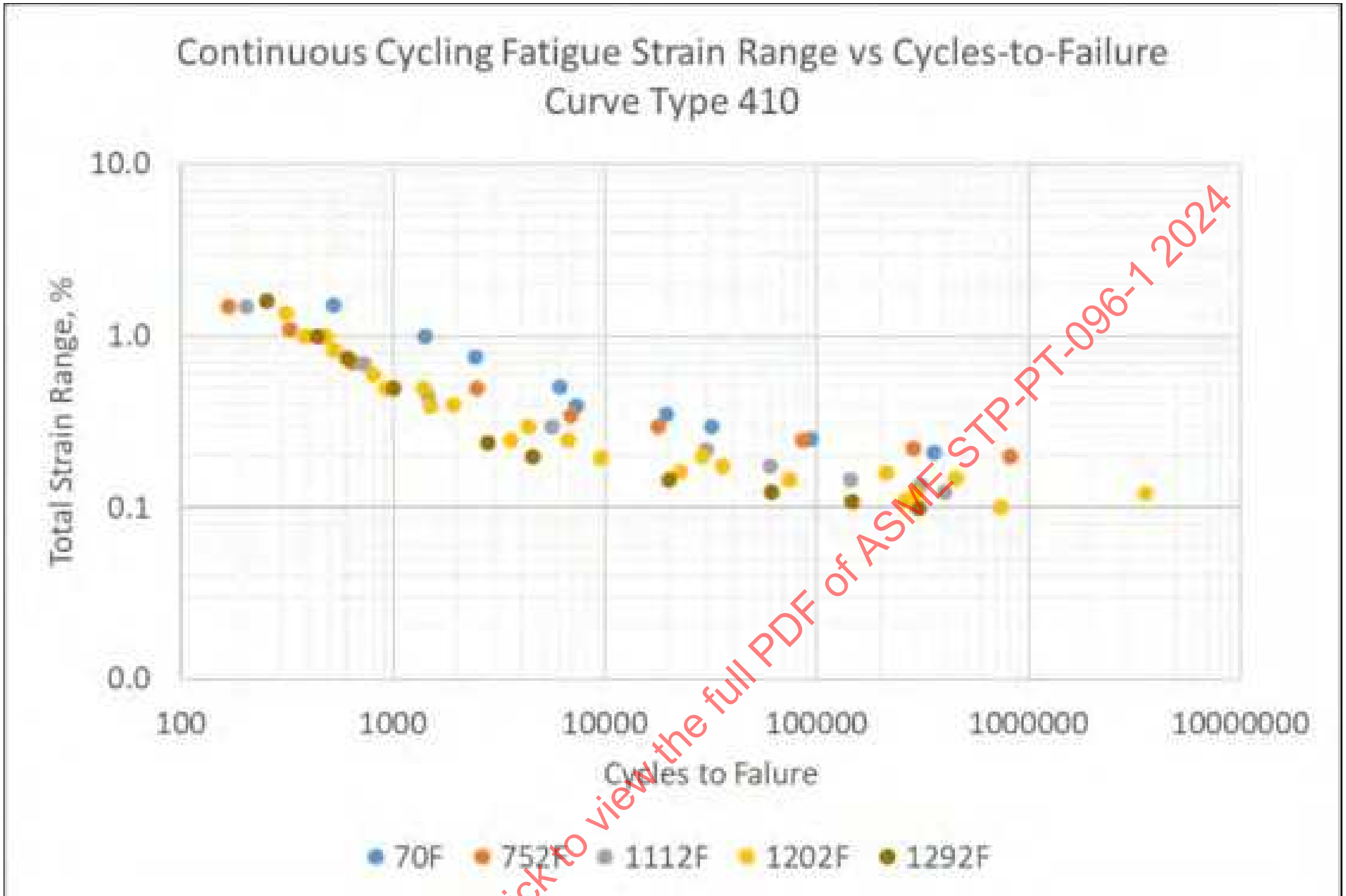


Figure 25-22: Type 410/12Cr Continuous Cycling Fatigue Stress Amplitude Vs. Cycles to Failure Data

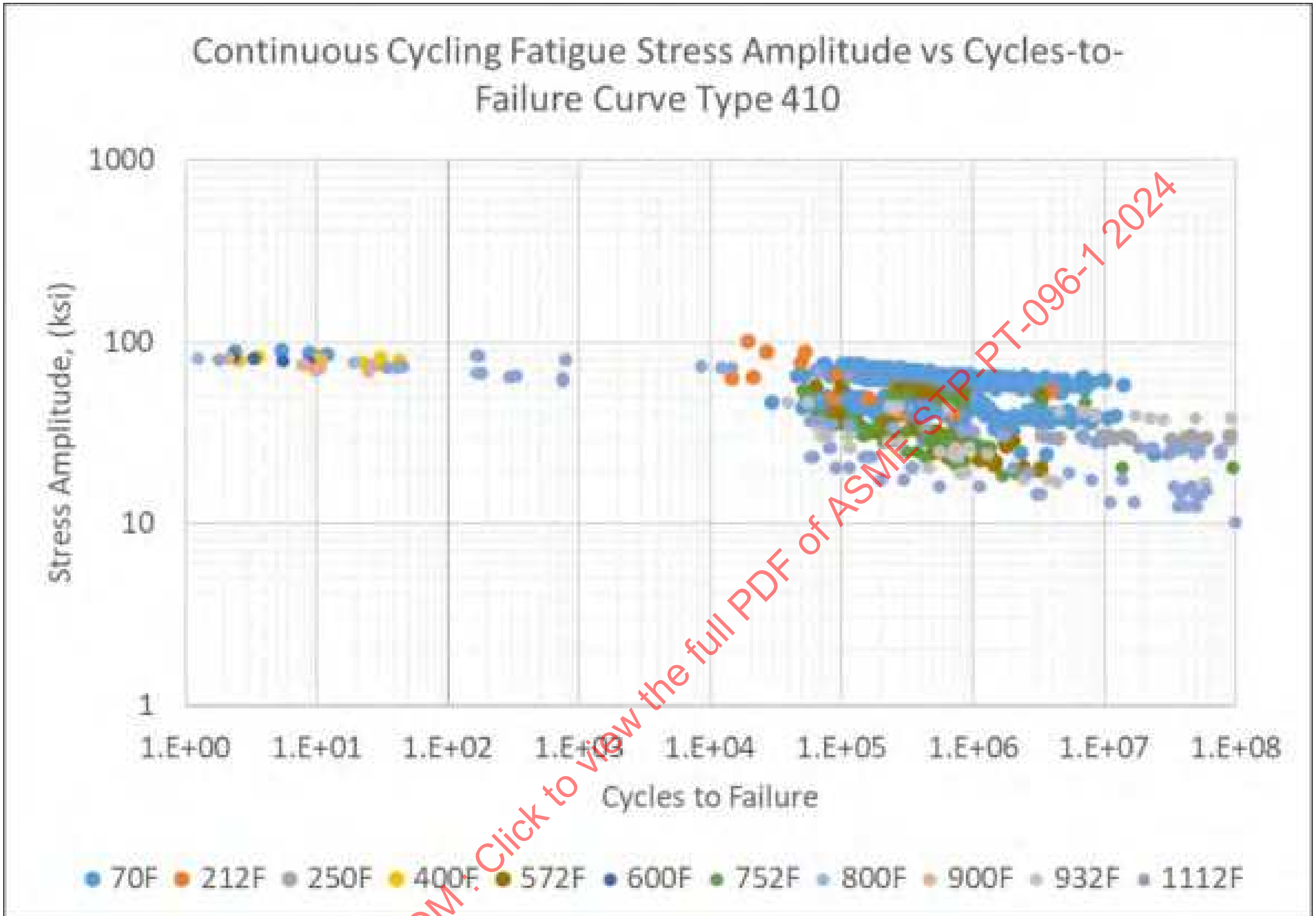


Figure 25-23: Type 410/12Cr Hold Time Data (Creep Fatigue) for Type 410/12Cr, Temperature of 950°F

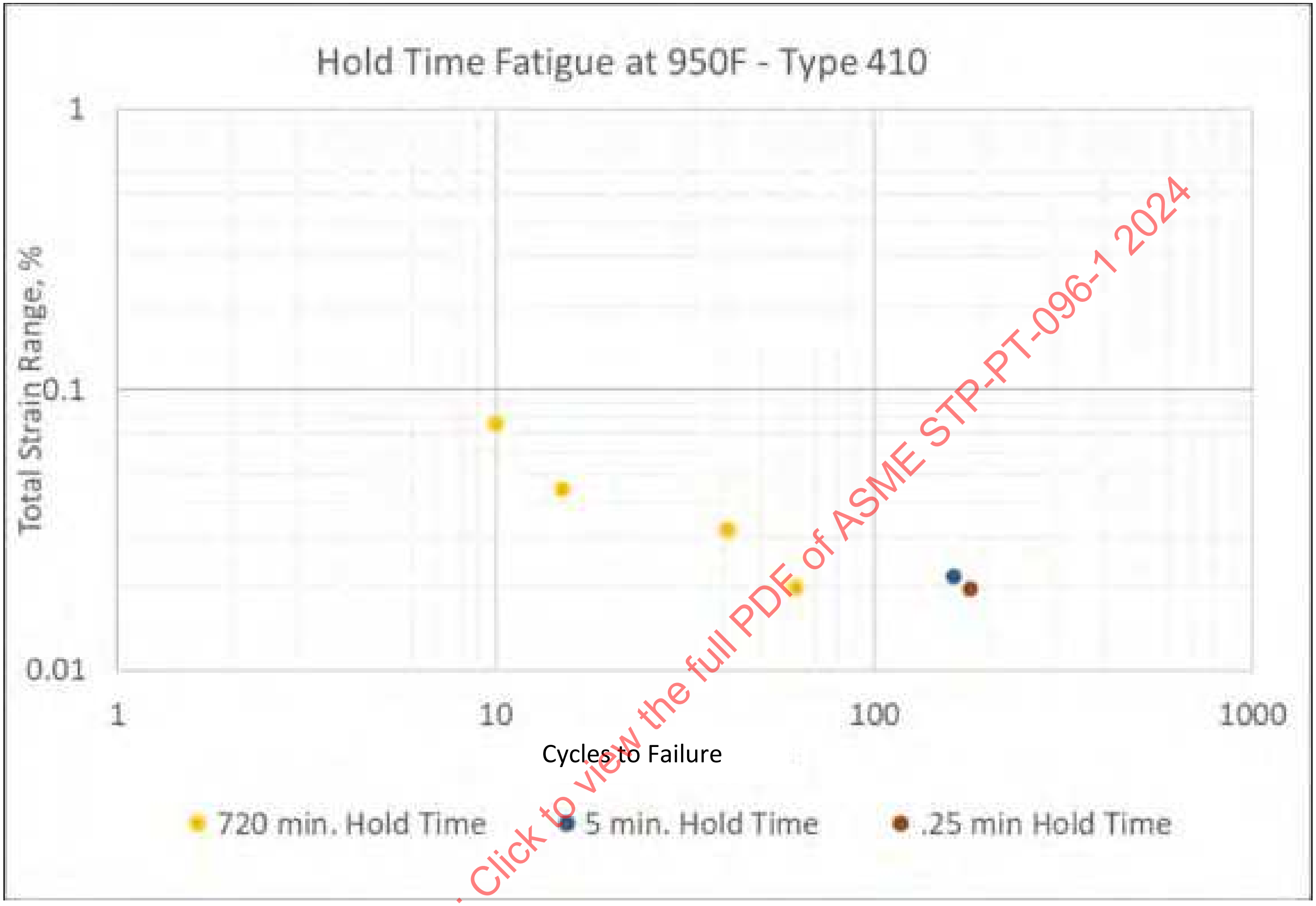
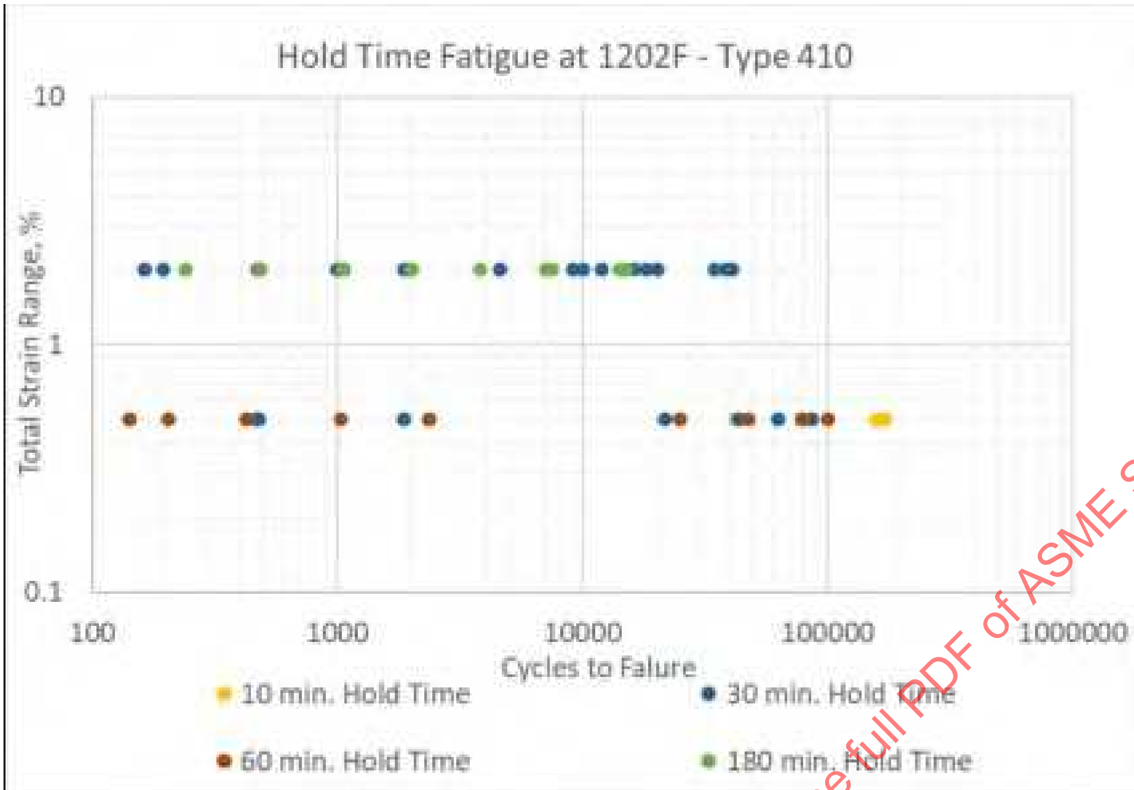


Figure 25-24: Type 410/12Cr Hold Time Data (Creep Fatigue) for Type 410/12Cr, Temperature of 1202°F



Attachment 25: Type 410/12Cr Property Data

If you want the referenced embedded spreadsheet with additional data, please email a request to research@asme.org.

26 321H 18CR-10NI-TI

26.1 Physical Properties

Well-established physical properties were referenced from the BPVC Section II for this material. Physical property curves from WRC Bulletin 503 were also plotted for comparison. Figure 26-1 shows the trends of Elastic Modulus (E_y), Thermal Conductivity (k), Thermal Diffusivity (TD), and Thermal Expansion (α) with temperature.

26.2 Yield and Tensile Strength

Elevated temperature Yield and Tensile Strength over the range of existing allowable stresses (up to 1500°F) were readily available, including data beyond the current range of allowable stresses, as shown in Figures 26-2 and 26-3. The sources for both high-temperature yield and high-temperature tensile strength are provided in the embedded spreadsheet at the end of this section. This spreadsheet also contains ductility data corresponding to the tensile test results presented in this report. Note that ductility (percent elongation and percent reduction in area) was not available for all sources referenced for the 321H material.

To facilitate comparison of the data obtained to existing allowable stresses (Section II-D Table 1A), yield and tensile data were normalized on a heat-by-heat basis to express the ratio of yield or tensile strength at temperature to that measured for the heat at room temperature. In cases where data were not delineated by heats within a given source, or in cases where more than one room-temperature tensile test existed for a given heat of material, ratios are equal to the measured tensile or yield strength at temperature, divided by the average of all of the appropriate room-temperature values for the particular data source or heat of material. As a result of this approach, it is possible to have ratios in excess of 1.0. E^2G understands that this approach is similar to the normalizing procedure performed by ASME in typical analysis of yield and tensile data to obtain Table Y and Table U (Section II-D) trend curves, as well as for the calculation of allowable stresses. Figures 26-4 and 26-5 show the heat-by-heat variation in yield and tensile strength ratios (respectively) as a function of temperature. It should be emphasized that even though the figure legends reference an entire source of data, the ratios, wherever possible, were calculated on a heat-by-heat basis; this is evident in the embedded spreadsheet at the end of this section. Figures 26-6 and 26-7 contain all of the yield and tensile (respectively) ratios plotted together, to facilitate regression of a 5th-order polynomial that is subsequently used for allowable stress comparison.

26.3 Creep Data (Creep Rupture, Minimum Creep Rate, and Ductility)

Creep Rupture data is shown in Figures 26-8 and 26-9, plotted as isotherms. The temperatures have been separated onto separate plots to minimize data overlap, with Figure 26-8 showing those temperatures where most of the data were concentrated, and Figure 26-9 showing those temperatures with significantly less data. It should be emphasized that these plots contain data for all product forms of material classified in the referenced publications as "321" or "321H." This certainly includes material meeting the requirements of ASME BPVC Section II-A specifications (e.g., SA-312 TP321H, SA-182 F321H, SA-240 321H, etc.). However, due to the diversity of data sources utilized for the compilation of the material property tables, it is likely that some of the material shown in Figures 26-8 and 26-9 may not meet existing specifications for this grade of material. Where older publications are referenced, the chemistry (and for that matter, manufacturing, processing, and heat treatment) corresponding to the heat of material in the original data source, may not be consistent with modern specifications. Where possible, E^2G has documented the chemical composition if contained within the original source. In many cases, the project team has also made efforts to trace cross-referenced data back to original test results to determine if the heat treatment, product form, chemistry, etc. details can be obtained. This information is provided with the embedded spreadsheet to facilitate additional analysis on the part of ASME.

Creep Minimum strain rates (%/hour) are shown in Figures 26-10 and 26-11, separated by temperature. As in the case of rupture data, temperatures of minimum creep rates have been separated onto separate plots to minimize data overlap, with Figure 26-10 showing those temperatures where most of the data were concentrated, and Figure 26-11 showing those temperatures with significantly less data. Creep Ductility, as % elongation, is plotted in Figure 26-12. As is typical, the data show significant overlap, and it is difficult to observe clear trends in the data. The data is not intended to be used as plotted but is available in the spreadsheet for additional analysis.

Creep data were analyzed using E^2G's proprietary Lot-Centered Analysis web-based software tool, in order to obtain creep properties. This regression is based on a Mandel-Paule algorithm and considers the variation within individual heats of material (for both rupture and strain rate data) as well as the variation between heats. The weight assigned to each datapoint and each heat is scaled based on the relative variation. Both rupture and strain rate (minimum creep rate, expressed as true strain per hours) were regressed according to a Larson-Miller time-temperature-parameter model, with a 3rd-order polynomial of stress. Lot-specific constant behavior was accounted for in this analysis, but the variation of LMP with stress was assumed to be constant (no non-parallel terms were included in the analysis). A 95% predictive limit was utilized to obtain the lower-bound (minimum LM constant for both rupture and strain rate) properties. The results of this analysis are summarized in Table 26-1 for rupture data and Table 26-2 for strain rate data. The Lot-Centered Analysis software tool generates property tables in the creep regime using the criteria outlined in Mandatory Appendix 1 of ASME Section II-D; the nomenclature of variables is consistent with II-D Appendix 1. For visualization of the allowable stress trends, Figure 26-13 is provided (for rupture allowable stresses and creep rate allowable stresses). Figure 26-14 shows a comparison of the various allowable stress criteria from Section II-D, Appendix 1, to the existing (2019) Section II-D Table 1A allowable stresses for common product forms of 321H.

Creep Strain vs. time data are shown in Figure 26-15 for short-term data (up to 1,000 hour test durations); Figure 26-16 for 1,000 to 5,000 hour test durations; Figure 26-17 for 5,000 to 20,000 hour test durations; and Figure 26-18 for tests with durations in excess of 20,000 hours. Curves are only plotted where more than 6 strain vs. time points are present for the test. Additional curves are available with fewer datapoints (typically obtained from data in the form of time-until-specified-strain) in the embedded spreadsheet. Both creep rate and creep strain vs. time data are provided to satisfy ASME's request for creep strain vs. time curves, and both forms of data are applicable in developing allowable stresses. Although digitalization of creep curve data was not explicitly necessary per the project contract, E^2G did perform digitalization of creep curves where only graphical data was available (as is often the case in the published literature).

26.4 Continuous Cycling Fatigue and Hold Time Fatigue Curves

A portion of the data obtained for continuous cycling fatigue data at elevated temperatures for 321H is shown in Figure 26-19, which includes a limited amount of room temperature data contained in sources which also present high-temperature data. Figure 26-19 only contains data for which total strain range was determined from the original source. Data points for continuous cycling fatigue data of 321H are presented in the attached spreadsheet; however, due to the complexities of various forms of fatigue data, compatible plots for each type of data expression and failure criteria are not included in this report. Hold time fatigue data at high temperature is shown in Figure 26-20 (1112°F).

Table 26-1: Model Parameters, Larson-Miller Property Results, and Allowable Stress (Rupture) Criteria, 321H

Equation Format:

$$\log(t_r) = C_{avg} + \frac{1}{T+460}\left(b_1 + b_2\log(\sigma) + b_3(\log(\sigma))^2 + b_4(\log(\sigma))^3\right)$$

C_{avg}	**-15.04**
C_{min}	**-15.56**
b_1	**41900.8**
b_2	**-15969**
b_3	**10877.7**
b_4	**-4181.5**

Number Data Points		**1413**
Correlation Coefficient	R^2	0.8425
Average Variance within Heats	V_w	0.1017
Variance between Heats	V_b	0.1342
Standard Error of Estimate	SEE	0.3189

Properties provided are for T in °F, stress in ksi, and t_R in hours

Temperature, °F	**S_{avg} (ksi)**	***n***	**F_{avg} (calc)**	**F_{avg} (used)**	**$F_{avg} \times S_{avg}$**	**S_{min} (ksi)**	**80% S_{min}**
850	45.63	11	0.8111	0.67	30.57	40.71	32.57
900	38.56	9.575	0.7862	0.67	25.83	33.8	27.04
950	31.97	8.253	0.7565	0.67	21.42	27.42	21.93
1000	25.89	7.039	0.721	0.67	17.35	21.6	17.28
1050	20.36	5.95	0.6791	0.67	13.64	16.42	13.14
1100	15.46	5.025	0.6324	0.67	10.36	12	9.598
1150	11.31	4.33	0.5876	0.67	7.575	8.467	6.773
1200	8.02	3.948	0.5581	0.67	5.373	5.904	4.723
1250	5.648	3.92	0.5558	0.67	3.784	4.194	3.355
1300	4.061	4.19	0.5772	0.67	2.721	3.092	2.473

** E[2]G's proprietary *Lot-Centered Analysis* web-based software tool only provides results up to 1300°F, but it should be noted that Type 321H allowable stress properties are observed above 1300°F.

Table 26-2: Model Parameters, Larson-Miller Property Results, and Allowable Stress (Strain Rate) Criteria, 321H

Equation Format:

$$\log(\dot{\varepsilon}_0) = -C_{avg} - \frac{1}{T+460}\left(a_1 + a_2\log(\sigma) + a_3(\log(\sigma))^2 + a_4(\log(\sigma))^3\right)$$

C_{avg} (A_0)	**-12.06**
C_{min} ($A_0+\Delta_\Omega^{SR,LB}$)	**-12.92**
a_1	**34833.9**
a_2	**-6044.4**
a_3	**3325.1**
a_4	**-2187.8**

Number Data Points		**286**
Correlation Coefficient	R^2	0.7069
Average Variance within Heats	V_w	0.2772
Variance between Heats	V_b	0.2700
Standard Error of Estimate	SEE	0.5265

Properties provided are for T in °F, stress in ksi, and t_R in hours

Temperature, °F	**$S_{C,avg}$ (ksi)**
850	40.87
900	30.82
950	21.84
1000	14.2
1050	8.508
1100	5.092
1150	3.306
1200	2.339
1250	1.762
1300	1.388

** E²G's proprietary *Lot-Centered Analysis* web-based software tool only provides results up to 1300°F, but it should be noted that Type 321H allowable stress properties are observed above 1300°F.

Figure 26-1: 321H Modulus (E_y), Thermal Conductivity (k), Thermal Diffusivity (TD), & Thermal Expansion (α) With Temperature

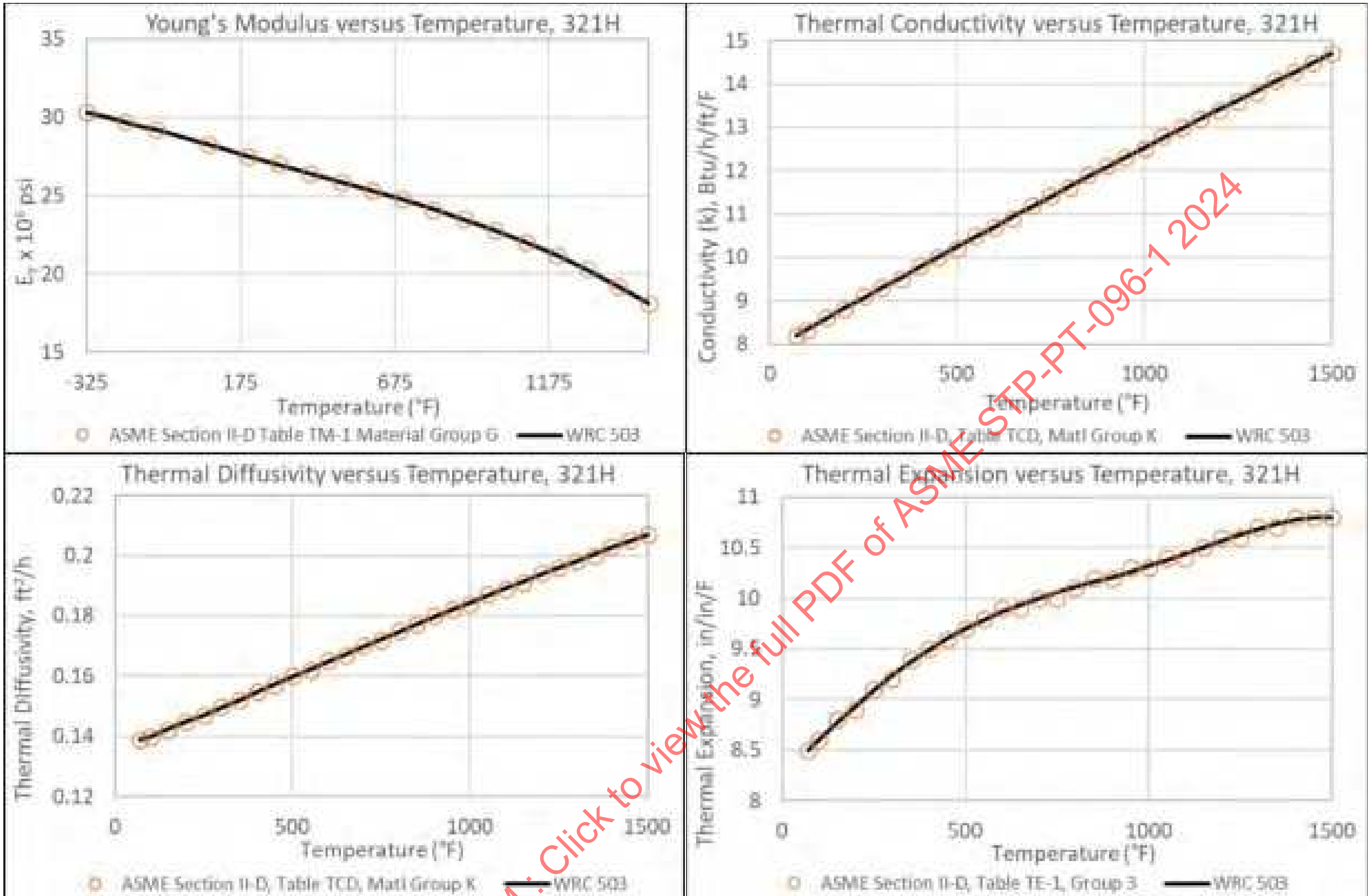


Figure 26-2: 321H Yield Strength Vs. Temperature, By Data Source, Including Trend Curves

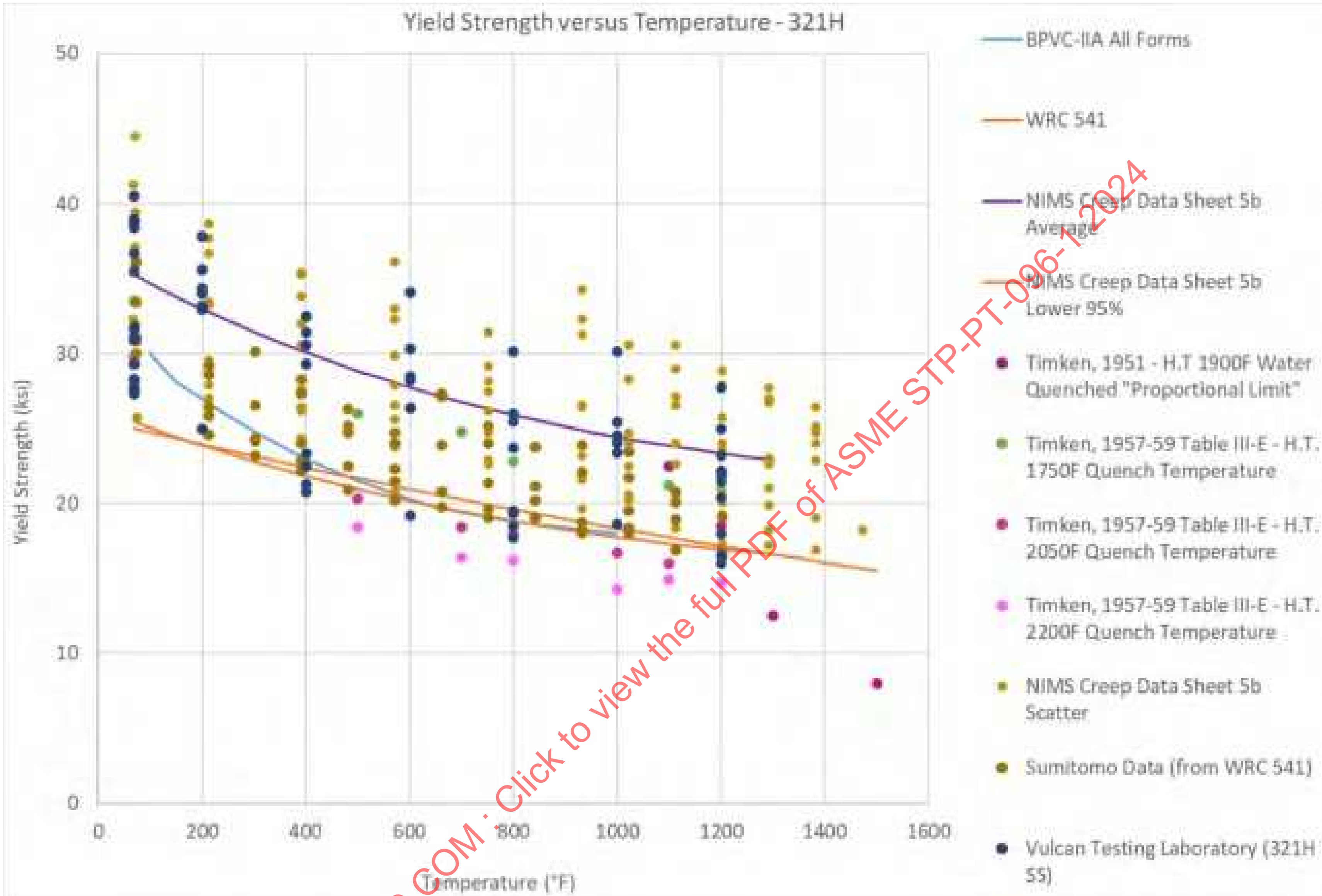


Figure 26-3: 321H Tensile Strength Vs. Temperature, By Data Source, Including Trend Curves

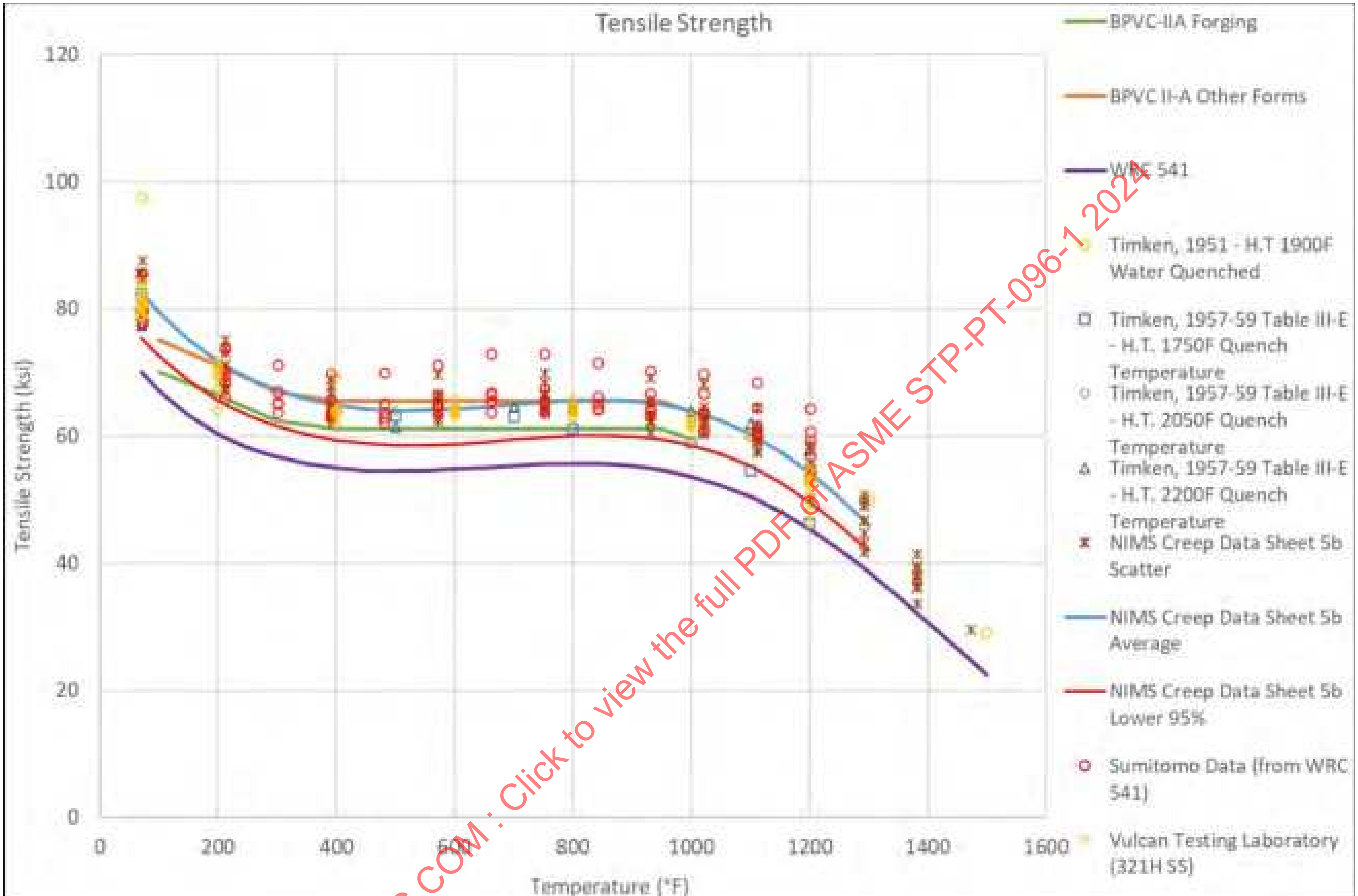


Figure 26-4: 321H Yield Strength Ratios Vs. Temperature (Calculated on a Heat-By-Heat Basis, By Data Source)

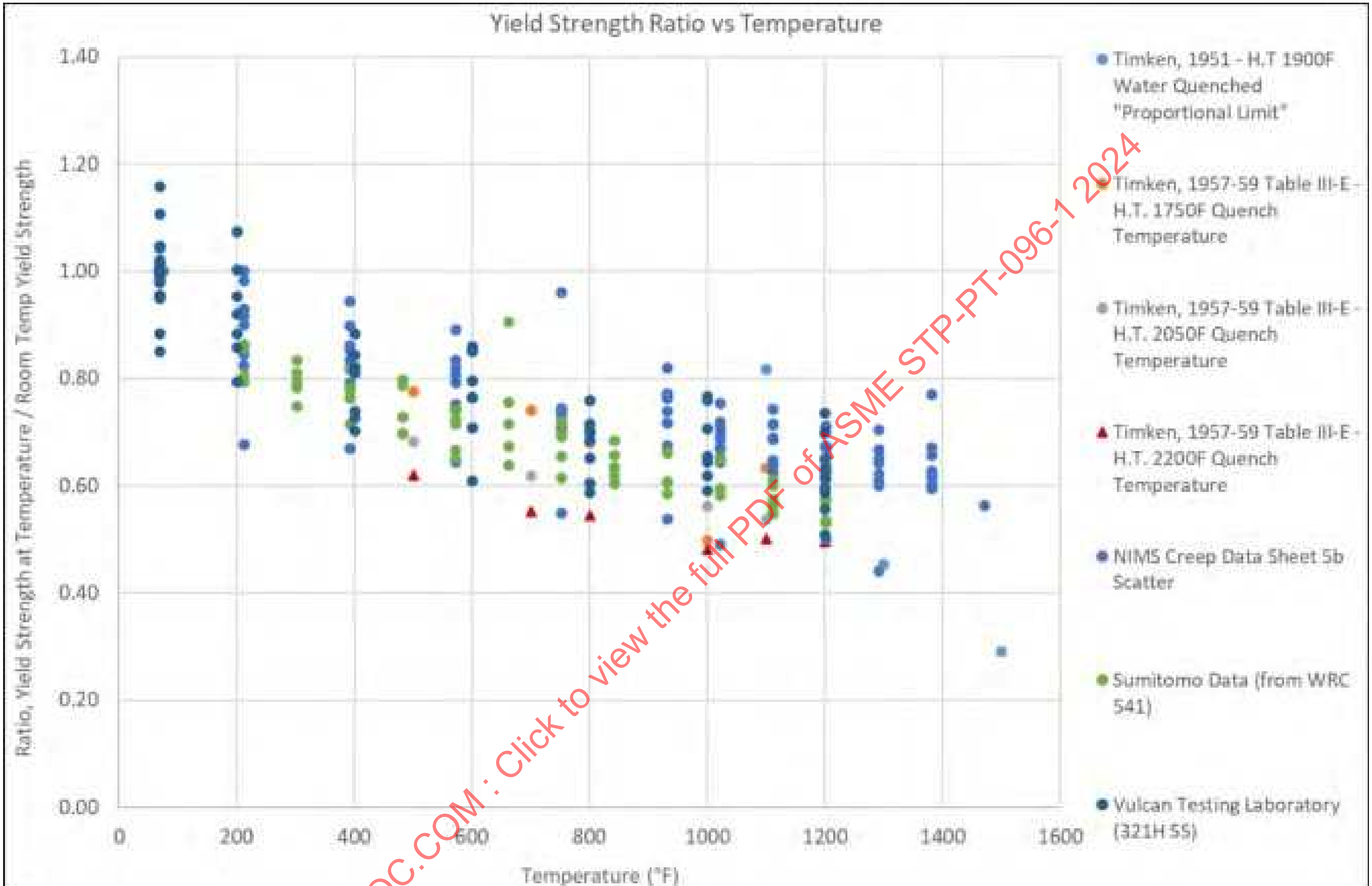


Figure 26-5: 321H Tensile Strength Ratios Vs. Temperature (Calculated on a Heat-By-Heat Basis, By Data Source)

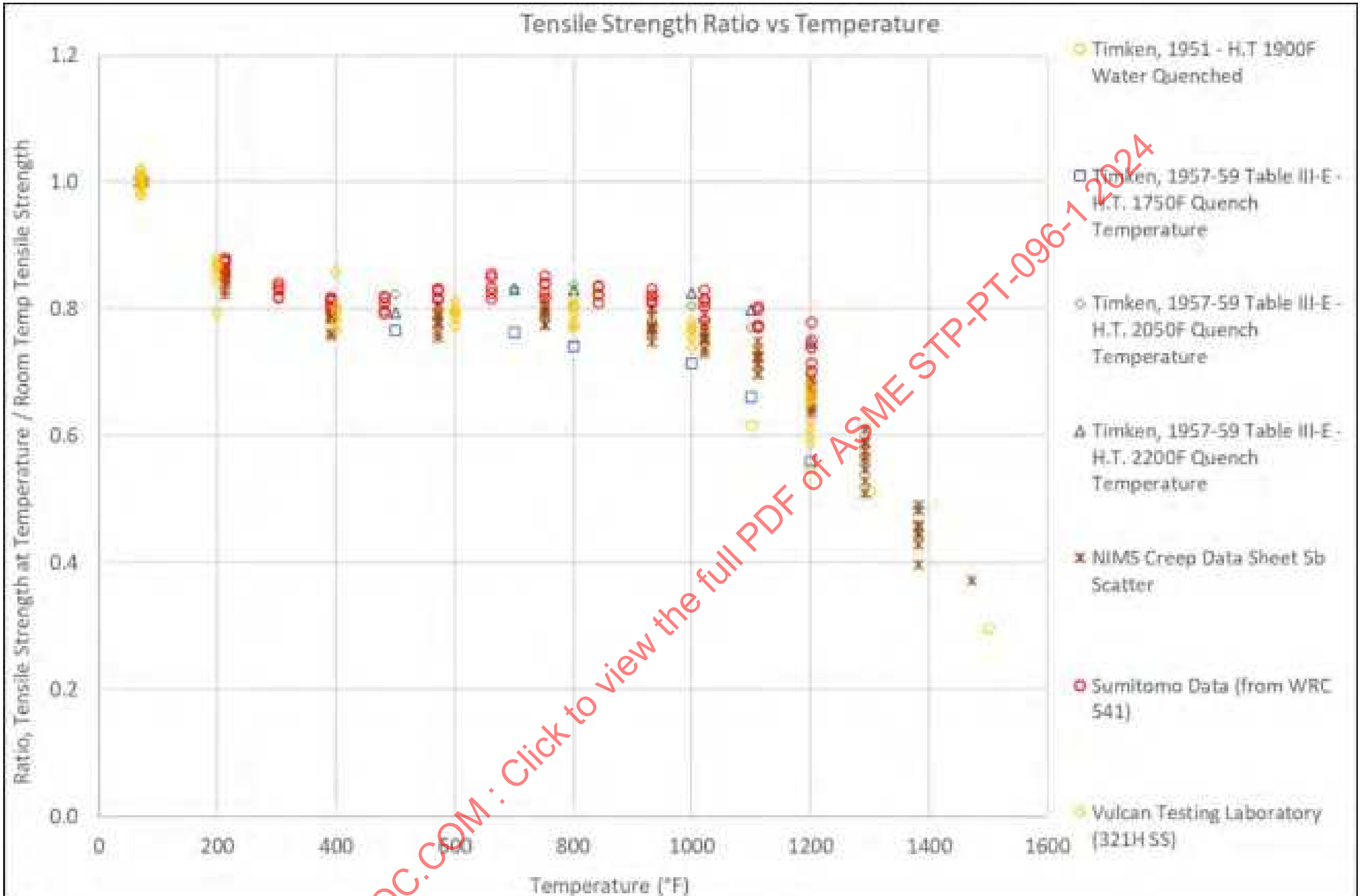


Figure 26-6: 321H Yield Strength Ratios Vs. Temperature, All Combined Data, With Polynomial Regression

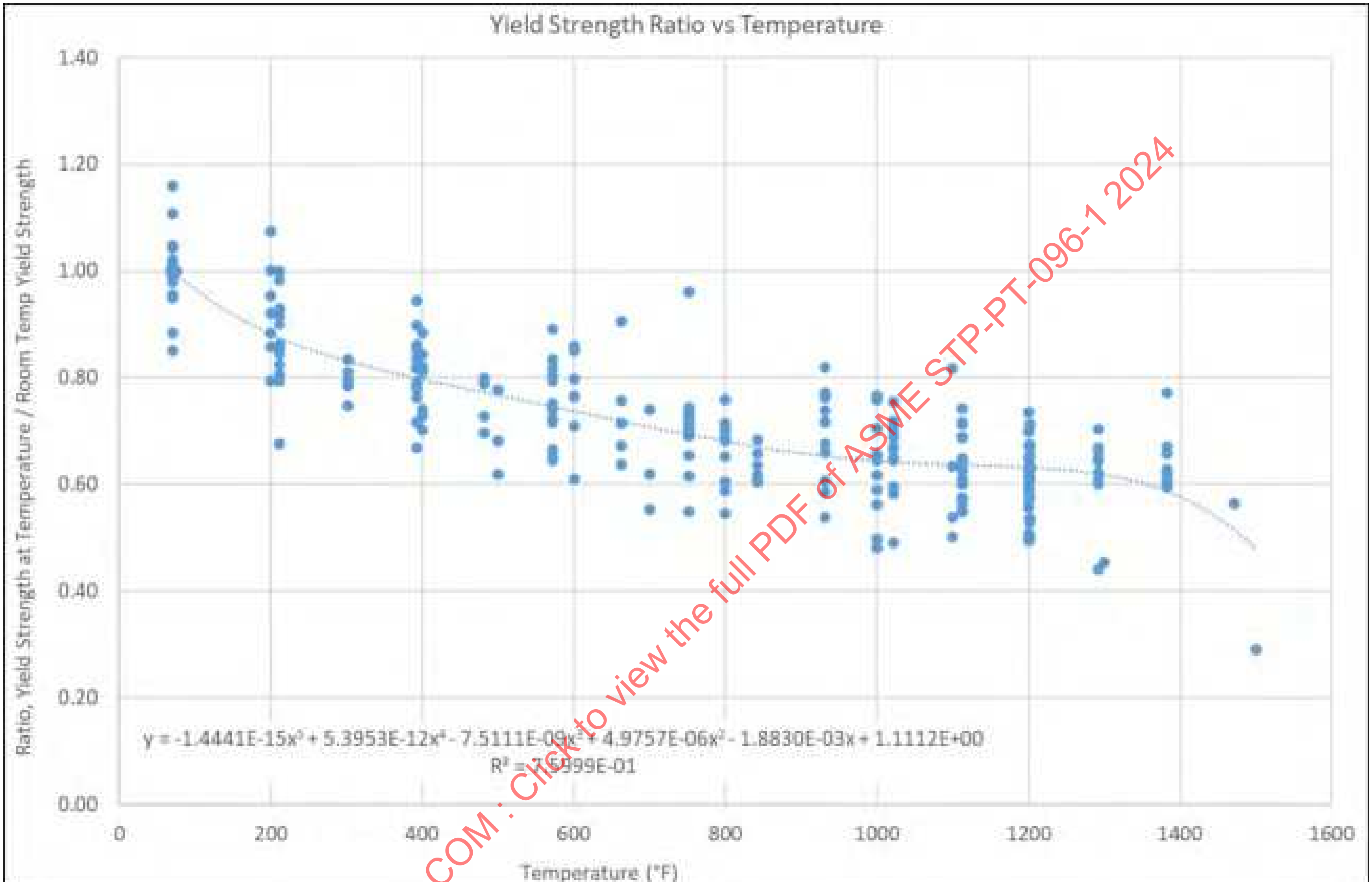


Figure 26-7: 321H Tensile Strength Ratios Vs. Temperature, All Combined Data, With Polynomial Regression

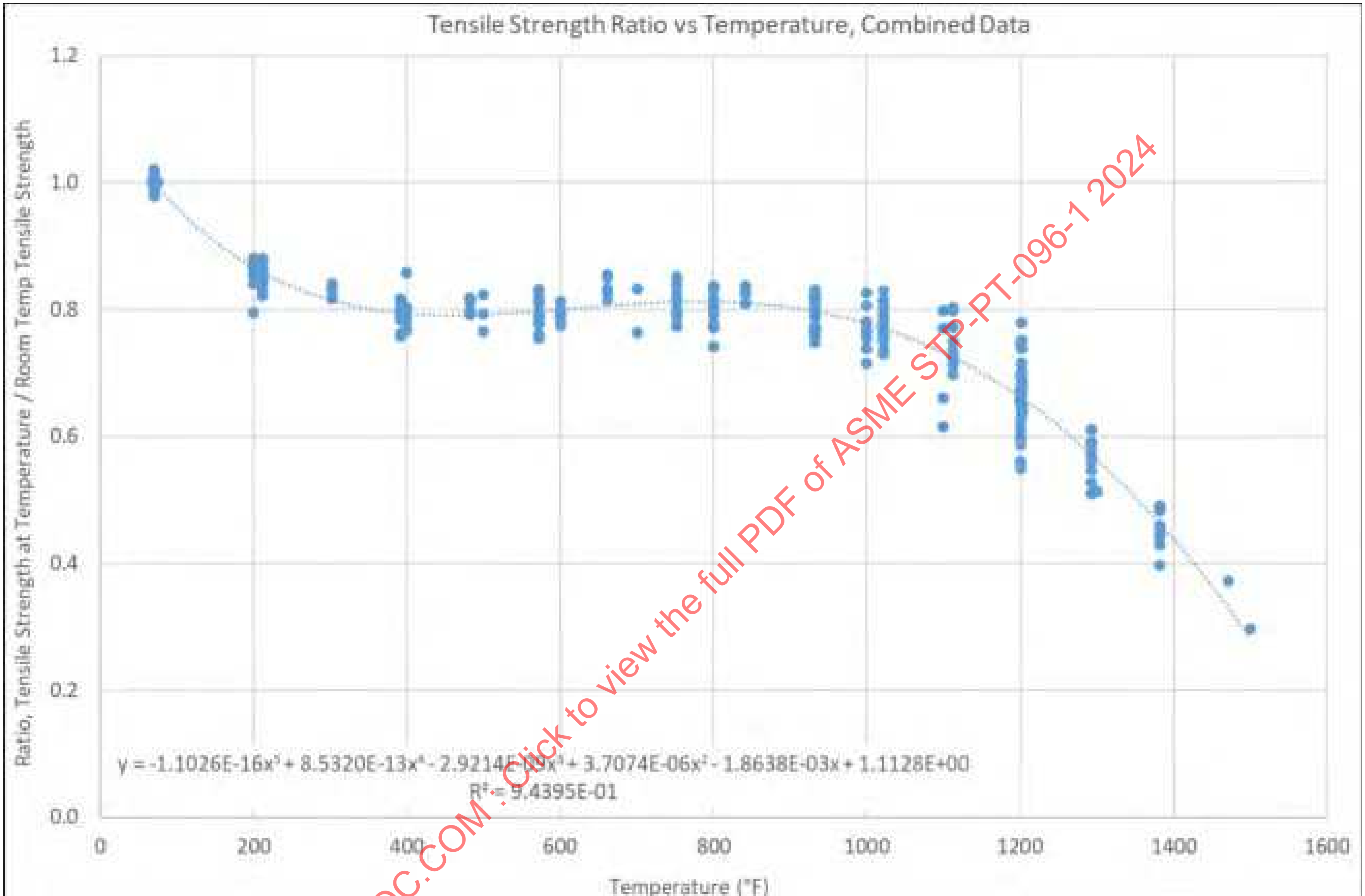


Figure 26-8: 321H Creep Rupture Isotherm Curves, Temperatures With High Concentration of Data Points

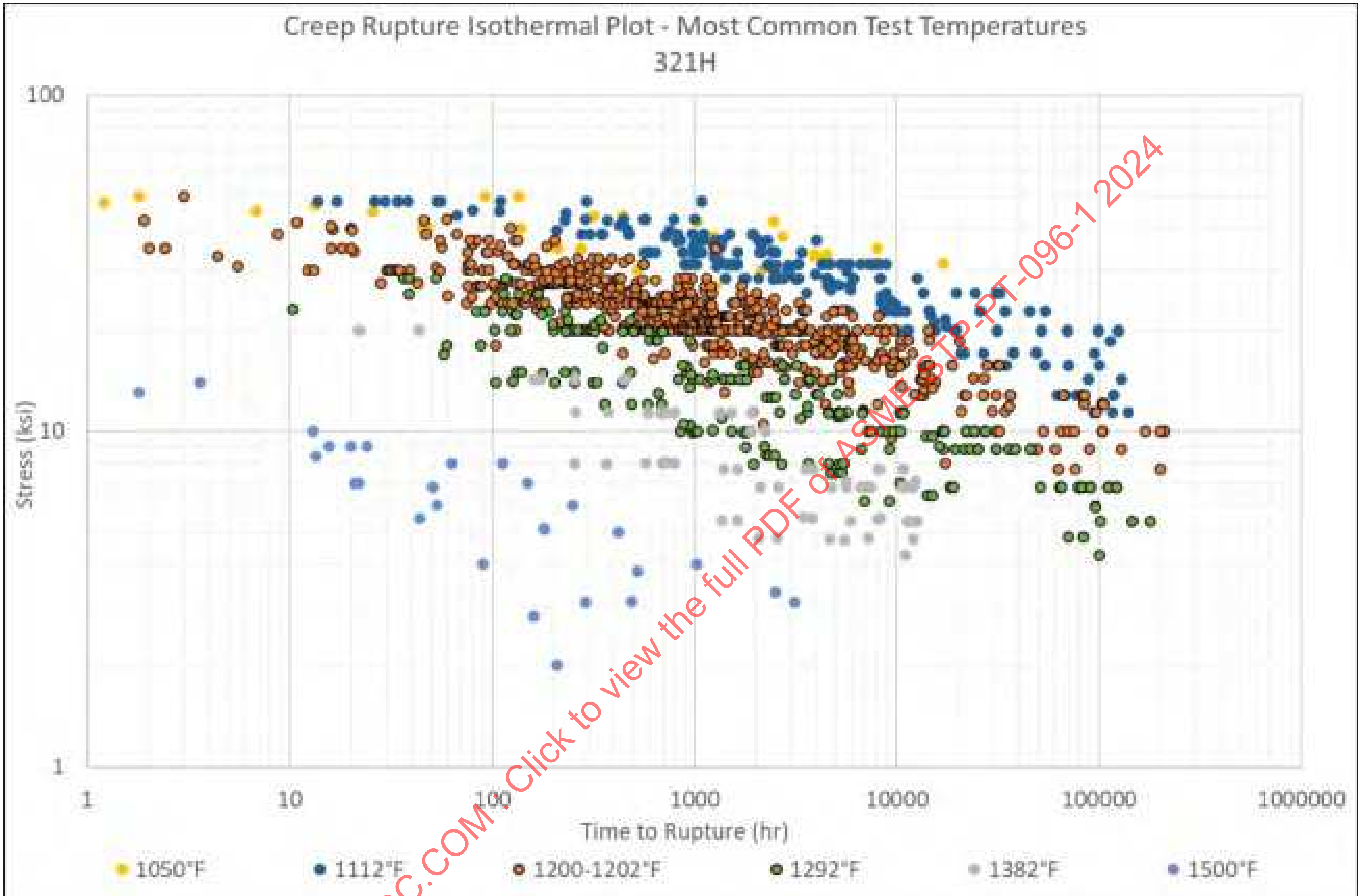


Figure 26-9: 321H Creep Rupture Isotherm Curves for Additional and Intermediate Temperatures

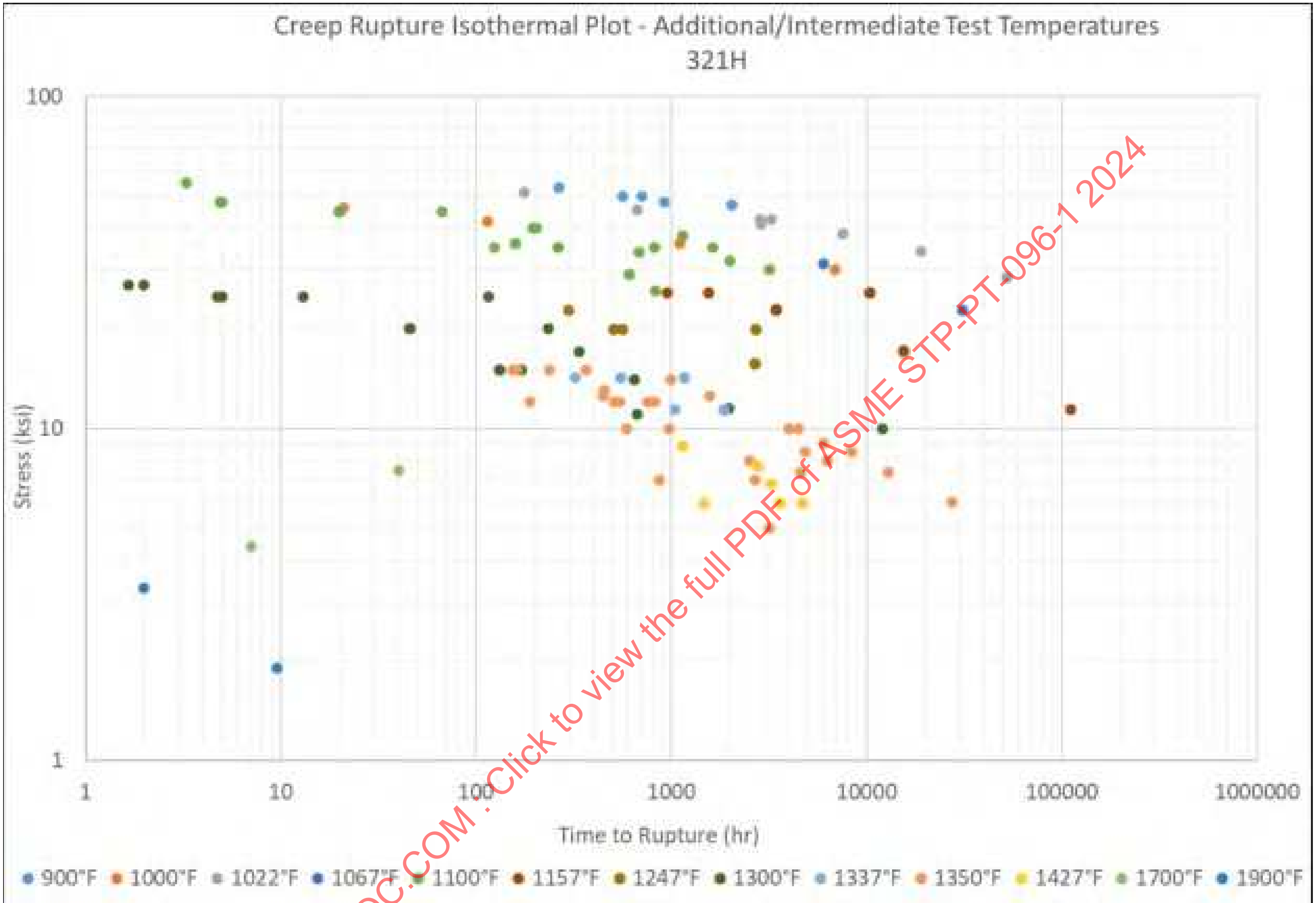


Figure 26-10: 321H Creep Strain Rate (MCR) Isotherm Curves, Temperatures With High Concentration of Data Points

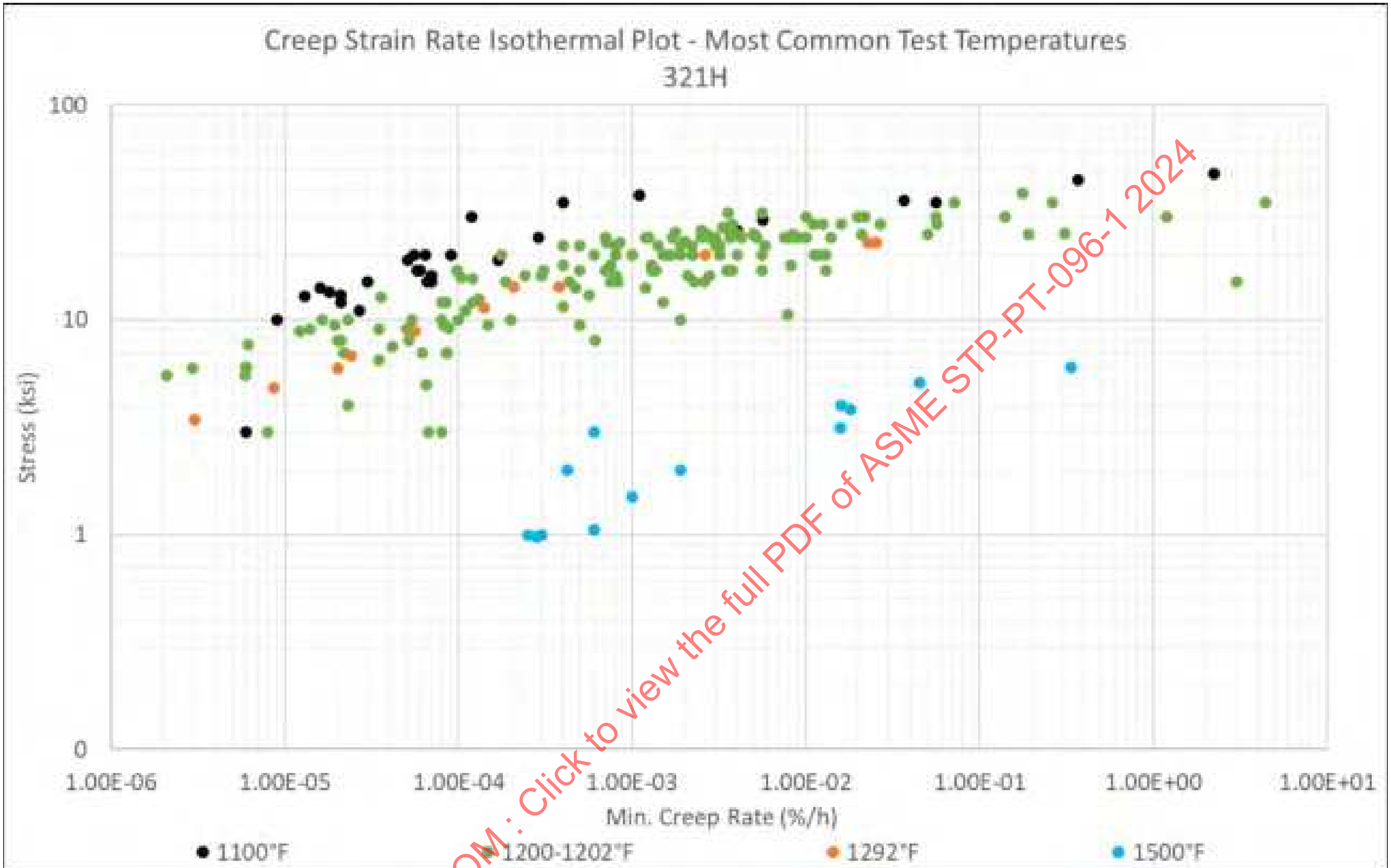


Figure 26-11: 321H Creep Strain Rate (MCR) Isotherm Curves for Additional and Intermediate Temperatures

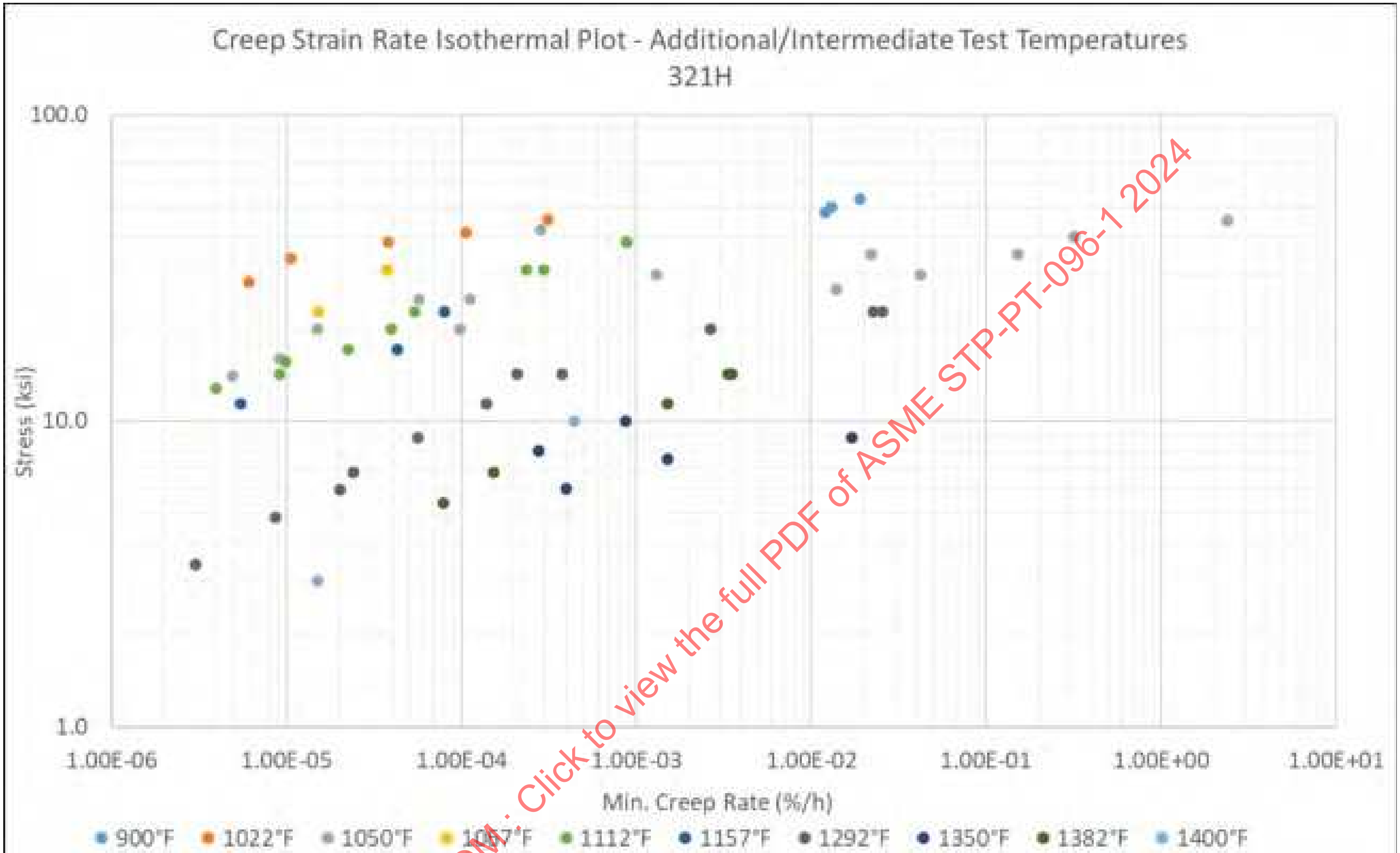


Figure 26-12: 321H Creep Ductility (% Elongation) Vs. Rupture Time Isotherms

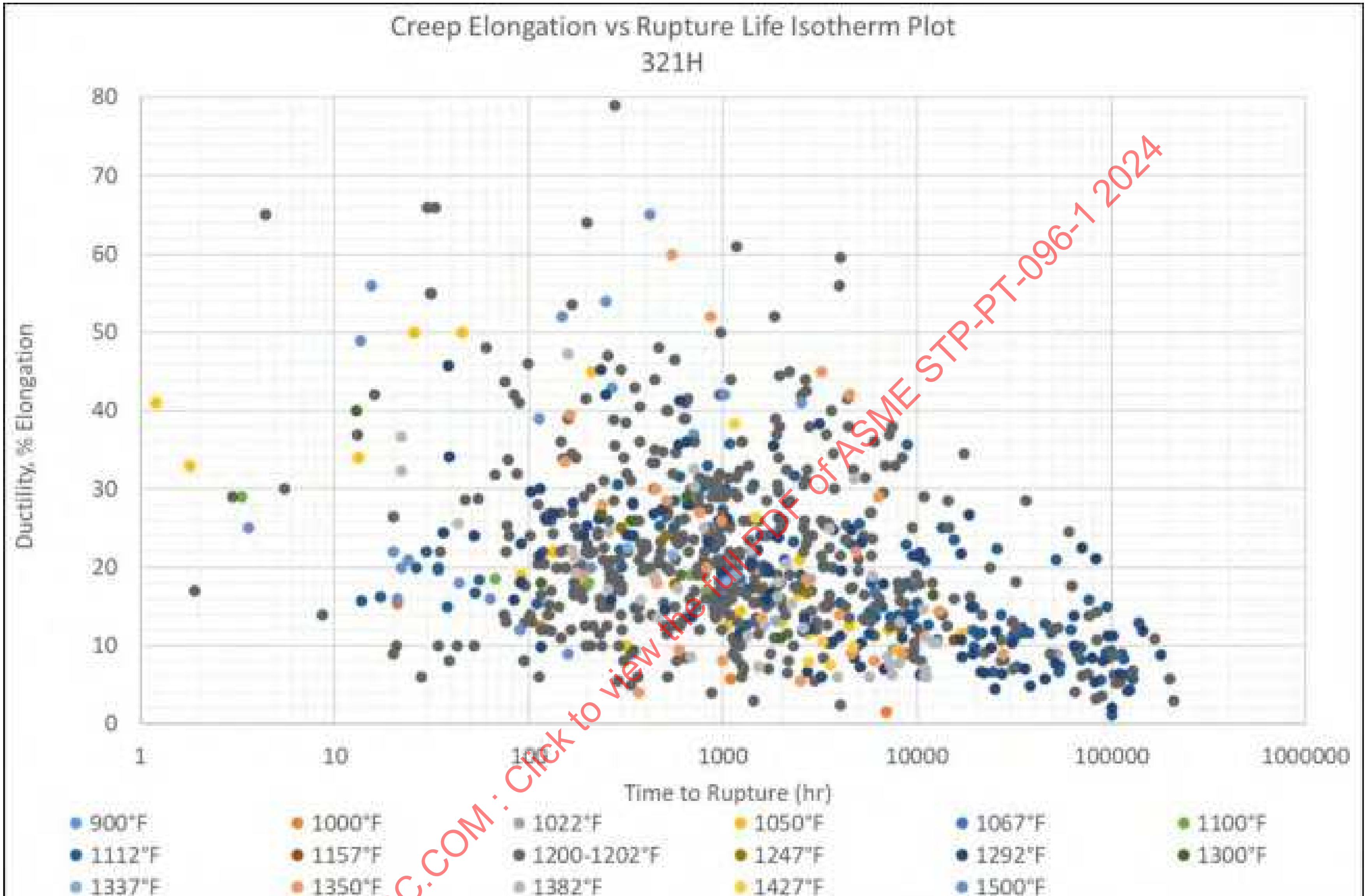


Figure 26-13: Calculated Allowable Stresses Based on Rupture and Creep Strain Rate and ASME II-D Appendix 1 Criteria (321H)

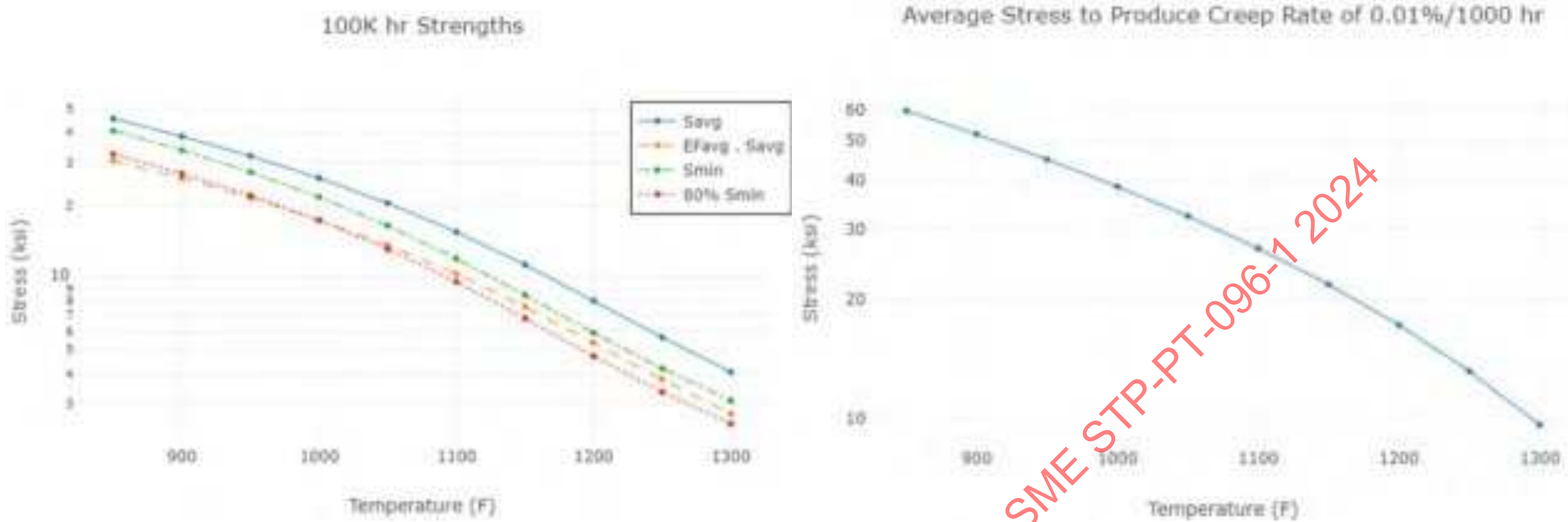


Figure 26-14: Comparison of Current 321H Allowable Stresses (Except Forgings) Vs. ASME II-D Appendix 1 Criteria Applied to Data

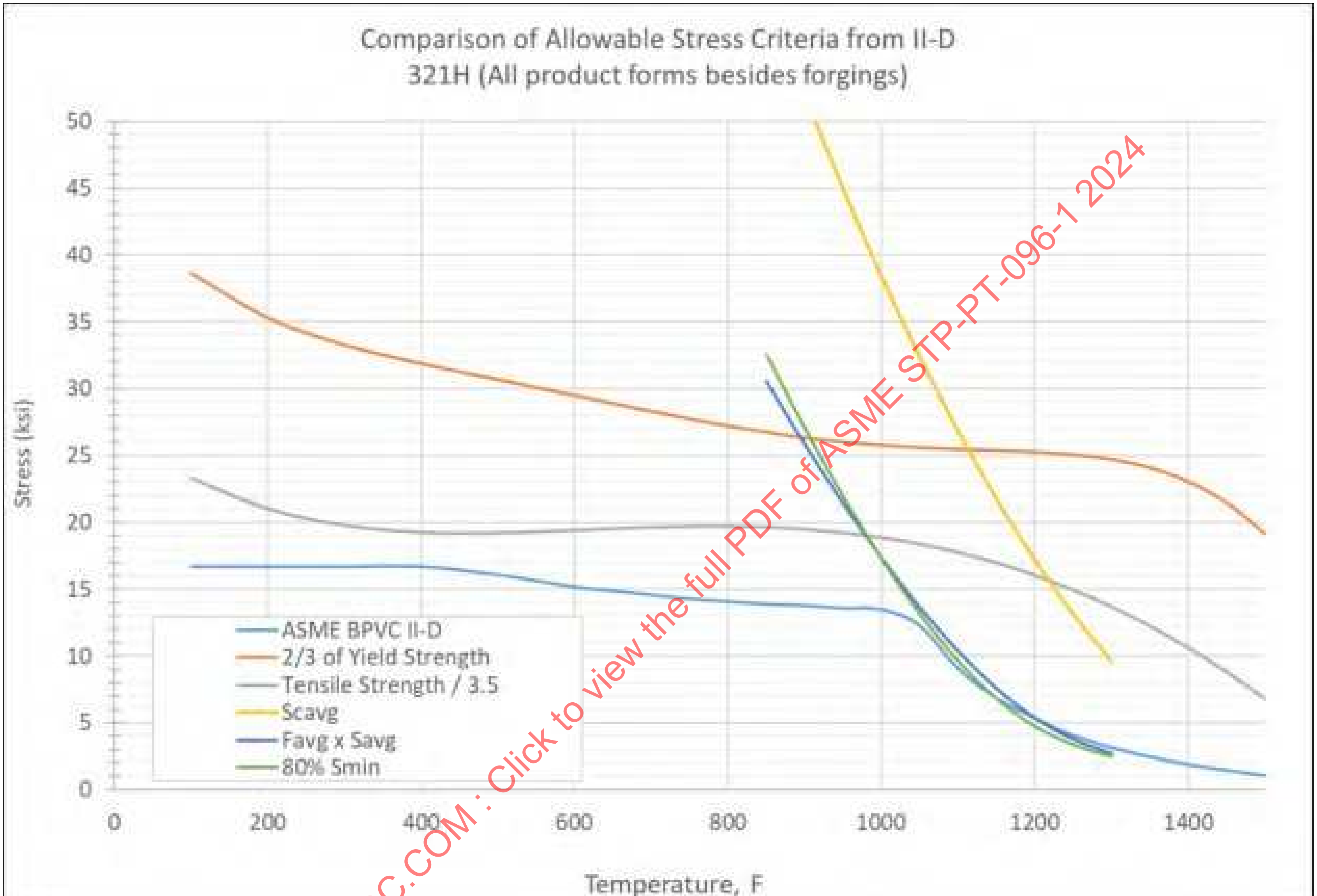


Figure 26-15: Short-Term Strain Vs. Time Data, up to 1,000 Hours (321H)

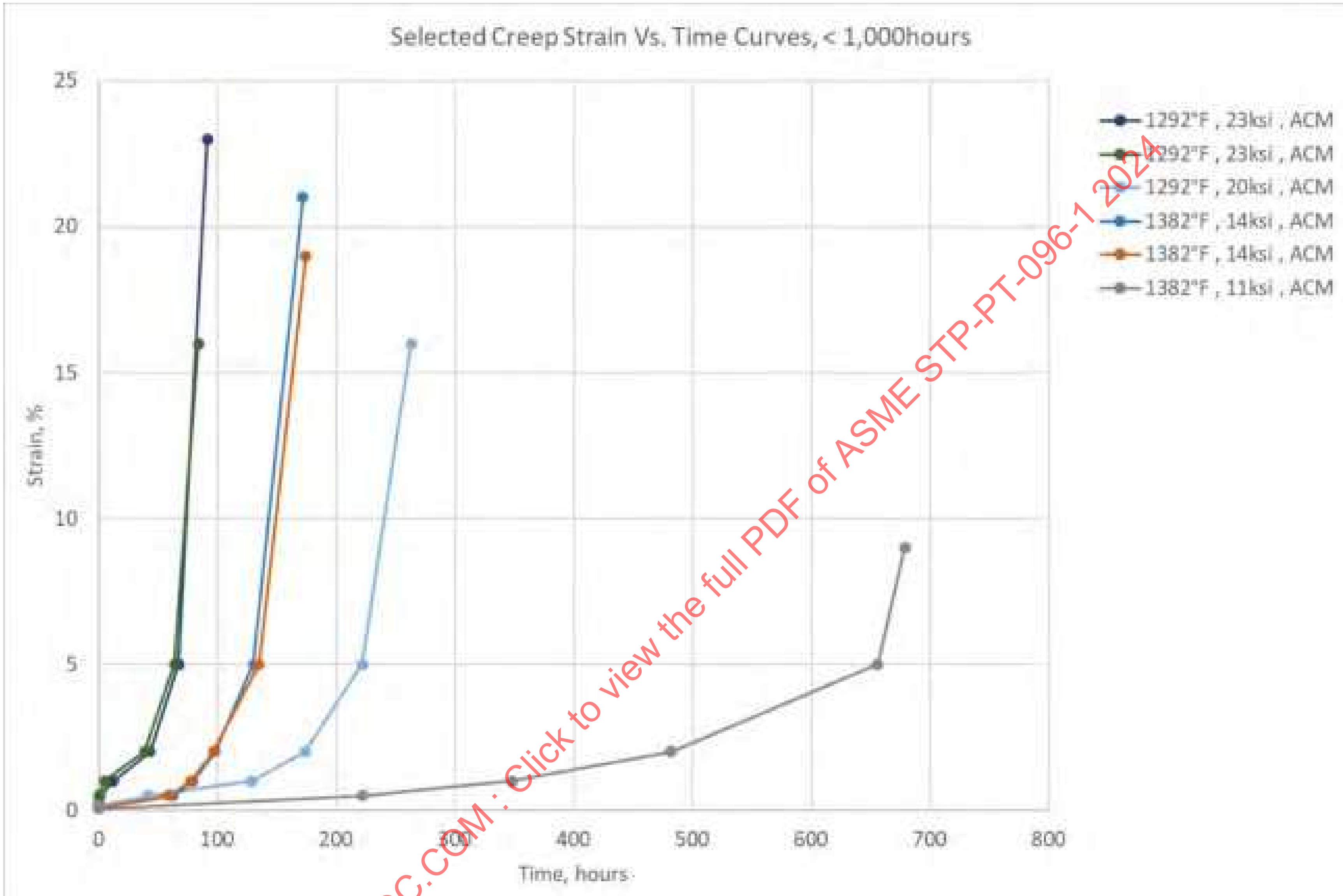


Figure 26-16: Short-Term Strain Vs. Time Data, 1,000 to 5,000 Hours (321H)

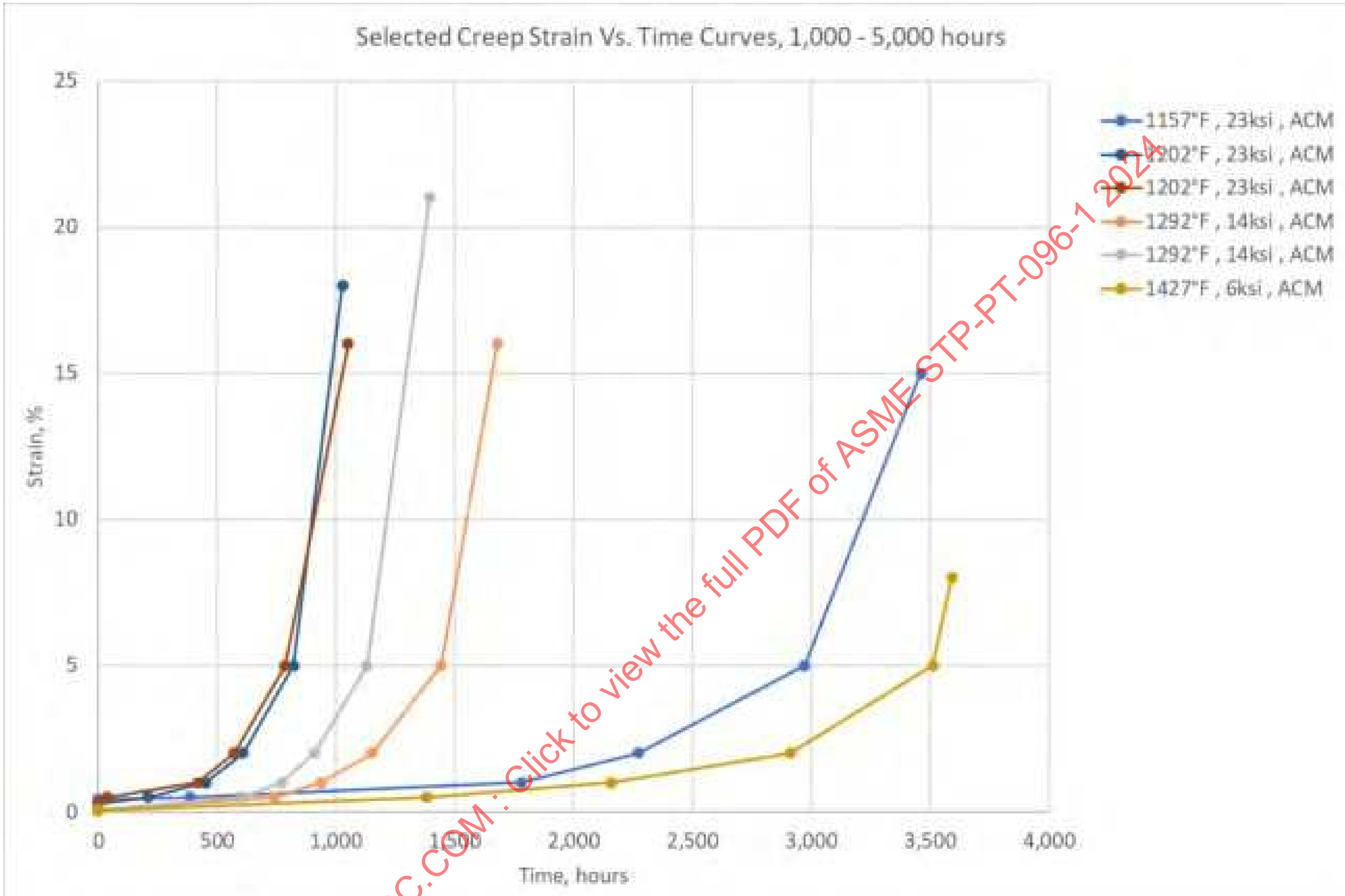


Figure 26-17: Short-Term Strain Vs. Time Data, 5,000 to 20,000 Hours (321H)