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ST-23

SPACE NUCLEAR PROPULSION (SNP)

MATERIAL PROPERTY HANDBOOK

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I REVISION AND HISTORY PAGE

Document Revision	Revision Date	Description
0	08/05/2020	Initial SNP Material Property Databook
1	08/02/2021	• Inclusion of Section 8 Composites and Structures • Format change
2	04/26/2023	• Update to Section 3.1.2 Mo-30W • Inclusion of Section 3.1.3 Titanium-Zirconium-Molybdenum (TZM) • Inclusion of Section 3.3.1 Rhenium (Re) • Update to elastic properties of Section 6.2.2 Beryllium (Be) • Switch from SBU to CUI designation • Minor technical fixes • Minor formatting changes
2.1	08/25/2023	Units fixed in room temperature tables – Young's modulus and Shear modulus values are in [GPa], not [MPa]
3	01/25/2024	• Inclusion of Section 6.1.3 • Inclusion of Section IV Preface • Inclusion of Section V Introduction • Inclusion of Section VI Front Matter References • Phase diagrams in Sections 6.1.1 Uranium Nitride (UN) and 6.1.2 Uranium Carbide (UC) were replaced for readability • Removed the incorrect reference to "S-basis tubing" in figure captions of Section 2.1.1 Inconel 718 (IN718) • Altered Figure 6.2.1-3 to include phase information and an explanation of the inflection point • Added a trend for the specific heat of ZrHx below 300 K in Figure 6.2.1-8 • Formatting fixes to various material property tables • All front matter is numbered with Roman numerals and is now included in Section II Table of Contents • Updated Section I Revision and History Page to include more details in the Description column
3.1	08/05/2024	• Switch from CUI//SP-EXPT to Uncontrolled Unclassified Information (UUI) designation • Updated the title page and added an acknowledgement • Phrasing changes to Section IV Preface and Section V Introduction • Moved Section 6.1.3 to a new, controlled annex of the handbook • Removed stress rupture data from Section 2.1.1

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III PROPERTY LIST

IV PREFACE

The National Aeronautics and Space Administration's (NASA's) Space Nuclear Propulsion (SNP) project aims to demonstrate the feasibility of nuclear thermal propulsion (NTP) as a thrust mechanism for spacecraft. An initial Demonstration Rocket for Agile Cislunar Operations (DRACO) launch will serve as a test of the technology in Earth's orbit [1]. Future work may involve the development of an NTP engine and spacecraft design with the capability to transport astronauts from Earth to Mars and back safely, though NTP has other potential uses too.

A large team of experts is required to accomplish these lofty goals. While NASA's Marshall Space Flight Center (MSFC) leads engine and nuclear reactor work, the Department of Defense's (DOD's) Defense Advanced Research Projects Agency (DARPA) controls development of the rest of the spacecraft for DRACO [1]. There are many contributors to this project beyond MSFC and DARPA, including other NASA centers, Department of Energy (DOE) national laboratories, researchers at universities, and industry design teams, among others. A list of contributors to the project can be found on the SNP SharePoint site [2].

Several materials under active consideration by the SNP project, including materials in this handbook, will operate in extreme environments should they ever be incorporated into spacecraft. While any rocket must contend with cryogenic temperatures, vacuum pressures, and the cosmic radiation imposed by outer space, NTP brings its own suite of challenges to the table. Since the specific impulse of an NTP-propelled spacecraft is dependent on nuclear reactor temperatures, engineers are incentivized to design a reactor that functions at the highest temperatures possible. Simultaneously, other components must have a low temperature due to their environments or for operational reasons. Radiation builds on the dangers of the wide-ranging temperatures and vacuum exposure. While cosmic radiation imposed by space is always an external threat, the reactors aboard NTP rockets simultaneously produce radiation from within, albeit for a limited duration.

For any engineering project, designers must ensure that materials – and the components that use them – can function in their anticipated operating environments without cracking, improperly deforming, or otherwise compromising the integrity of the structure created.

To predict whether a material will function properly in its application environment, one can look to a material's standardized properties. Various properties are important for SNP modelers and designers, such as physical, thermal, and mechanical properties. SNP-HDBK-0008, referred to as "the handbook" going forward, was created to consolidate data on solid materials of interest to SNP across a wide range of temperatures, thereby improving access to the data throughout the project. Simultaneously, the handbook serves to standardize values across the project, which aids in modeling and review activities.

Mechanical properties often exhibit a greater dependency on a material's composition, processing methods, grain size, and geometry than thermophysical properties do. Since this handbook is primarily built from historical literature data with limited traceability, thermophysical properties are provided more frequently than mechanical properties. For mechanical properties to be better understood, experiments should be devised for key materials while keeping geometries, manufacturing methods, and other factors as consistent as possible.

Peer reviews by experts are a key aspect of the scientific method, and they help to locate and address technical issues. Therefore, beginning with Revision 3 of this handbook, the SNP Materials Characterization Working Group (MCWG) community examined new additions to the handbook and provided their feedback. With each potential change to the handbook, the MCWG board was given an opportunity for review and the authority to prevent alterations. Changes range from handbook formatting improvements to material and material property additions. For more details on the SNP MCWG, the MCWG board, and the SNP-HDBK-0008 review process, please refer to the MCWG Charter [3].

All readers are recommended to read Section V.4 *Using the Material Property Handbook* for techniques to make the most of this handbook. Other areas of Section V *Introduction* are useful for gaining a basic understanding of material properties and learning how this handbook was created. In addition, technical experience and engineering judgement will aid readers in using SNP material property data correctly. When using the data from this handbook in their own work, readers should think about the real-world situations that the data represents. Errors are constantly tracked down and removed from the handbook, but readers' additional diligence will help them maintain high quality designs and models.

Most of the trends in this handbook are created through the average value curve fitting process illustrated in Section V.3.2. This quality of data may be acceptable for spaceflight applications, but it is dependent on both the individual material property and the project's risk posture. NASA-STD-6016, Standard Materials and Processes Requirements for Spacecraft, directs designers to use the Metallic Materials Properties Development and Standardization Handbook (MMPDS) for determining data accuracy requirements or tolerance levels [4, 5]. Unless a project is willing to take on a considerable amount of risk, the materials used in spaceflight systems must be well understood.

Of course, the two NTP systems envisioned by the SNP project have different risk profiles – one is intended to prove that humanity can build upon the successes of NTP seen in the 1960s, and this mission has a relatively short duration. The second mission will pose a greater challenge due to many factors. Increased mission duration and the need to one day support crew on the spacecraft expand on and introduce new engineering constraints. These constraints result in new problems for the materials science community to solve.

Beginning with Revision 3.1, this handbook is no longer subject to export control restrictions. Instead, an SNP-HDBK-0008 Annex document will contain all data evaluated as Controlled Unclassified Information (CUI). Material sections located in the Annex are denoted in Section II *Table of Contents* by the marking "*See Annex*".

It is hoped that the following handbook helps address readers' material property data needs. If readers have any questions or comments on the SNP Material Property Handbook, then they may contact the SNP MCWG coordinator, Peter Karkos (peter.d.karkos@nasa.gov). All feedback is welcome.

V INTRODUCTION

This section serves to heighten readers' understanding of this handbook. Those who wish to learn more about material properties, data generation, the analytical methods used to create trends, and methods for using the handbook to its full potential should read on.

The material property handbook is divided into broad sections primarily based on material composition. Dividing the handbook by material use in parts and components was contemplated, but rarely pursued, due to overlapping use cases for the various materials and the export control requirements that would be imposed. At present, the primary categories of materials for SNP applications are as follows: light metal alloys, nickel-base alloys, refractory metals and alloys, other nonferrous metals and alloys, ferrous alloys, nuclear materials, refractory ceramics, and composites and structures.

The broad, primary sections are broken down once again by composition. From there, individual material chapters are listed within the resulting subsections. For example, light metal alloys are one primary section, consisting of aluminum and titanium alloy secondary sections. In this example, aluminum 7075 (Al7075) and titanium – 6Al – 4V (Ti64) are the material sections (or chapters) within these two secondary subsections, respectively. This style of section division was inspired not only by several modern, digitized handbooks in MSFC's Materials and Processes Technical Information System (MAPTIS) [6], but also by Rover / Nuclear Engine for Rocket Vehicle Application (NERVA) documentation from the 1960s [7]. NERVA achieved many important milestones in the name of space nuclear propulsion [8], so the project is a regular topic of discussion for this handbook's design team.

Across the handbook, a focus is placed on thermophysical properties, but mechanical properties appear as well. Thermophysical properties plotted include density, thermal conductivity, linear thermal expansion, the mean coefficient of linear thermal expansion, thermal diffusivity, specific heat capacity (specific heat), and electrical resistivity. Mechanical properties like Young's modulus (elastic modulus), shear modulus (modulus of rigidity), Poisson's ratio, offset yield strength, and tensile strength are included for several materials, though a wide data spread is often observed for the reasons mentioned in Section IV *Preface*.

V.1 Applicable Documents

The documents listed in Table V-1 contain requirements and guidance that can aid in the use of this handbook. Note that this table is not all-inclusive. Further, the sources that material property data was extracted from can be found separately in the *References* subsection of each material section. A list of commonly used data sources is provided in Table V-2 of Section V.3.1. The most recent versions of government standards, as well as many commercial standards, can be found at https://standards.nasa.gov.

Table V-1: Applicable Documents and References.

Reference	Title
MAPTIS [6]	Materials and Processes Technical Information System
MMPDS [5]	The Metallic Materials Properties Development and Standardization Handbook
NASA-STD-6016 [4]	Standard Materials and Processes Requirements for Spacecraft
SNPP MDB [9]	Space Nuclear Power and Propulsion Materials Database; unavailable – in development
SNP-PLAN-0010 [10]	Nuclear Thermal Propulsion Fuel and Moderator Development Plan

V.2 Overview of Material Properties

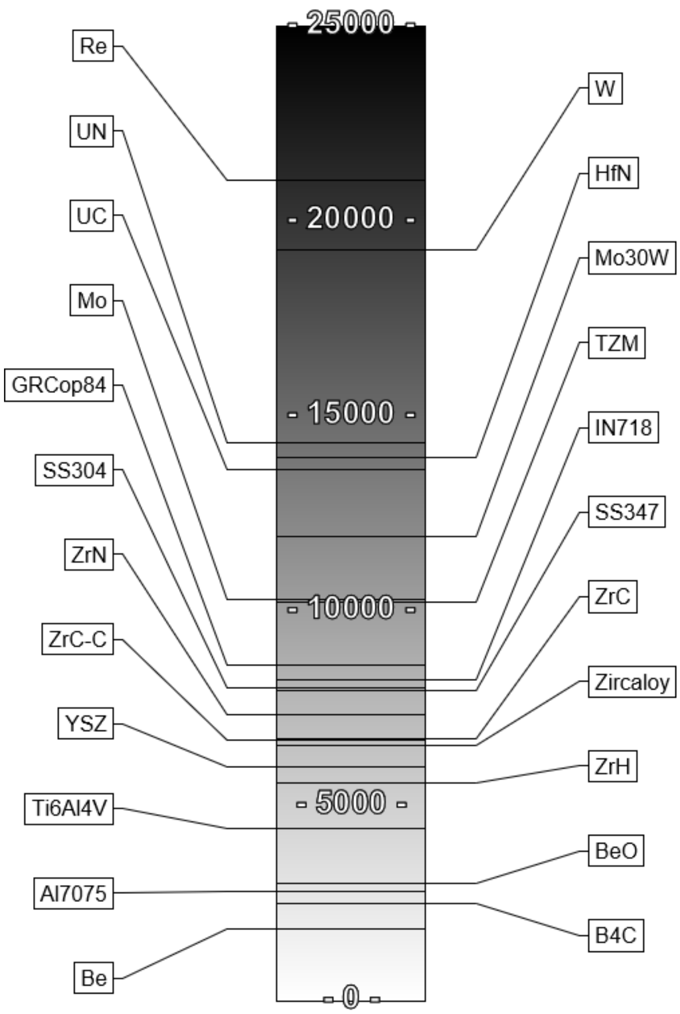

Figure V-1: Room temperature densities of select materials in kg/m^3.

V.2.1 Density

Materials' density, or mass per unit volume, is calculated for most materials using the general formula of Equation (V-1).

$$\rho(T) = \rho_{RT}/(1 + dL/L_0(T)/100)^3 \qquad \text{(V-1)}$$

$\rho(T) = Density\ [kg/m^3]$

$\rho_{RT} = Room\ Temperature\ Density\ [kg/m^3]$

$dL/L_0\ (T) = Linear\ Thermal\ Expansion\ [\%]$

$T = Temperature\ [K]$

In these equations, $dL/L_0\ (T)$ represents the material's corresponding linear thermal expansion trend, which can be found in the same section as all the other material's properties. Section V.2.5 discusses thermal expansion in greater detail.

Density is an incredibly important property for spaceflight applications since it is used to evaluate hardware weights. The greater the weight of a spacecraft, the more thrust is required during launch. Additionally, for a given thrust, a rocket with greater mass will experience less acceleration than a rocket with a lesser mass. Therefore, using materials with low densities is a high priority for spaceflight projects.

To the left, Figure V-1 illustrates the densities of several SNP materials at room temperature (RT), in units of kg/m^3. While common aerospace materials – like aluminum alloy 7075 – will often be found at the lower end of the density scale, refractory metals occupy the higher tiers. Despite their many beneficial properties, materials like tungsten and rhenium are used sparingly in aerospace applications due to their high densities.

Density is often treated as a constant for a given material, but it does change with temperature. As temperatures rise, most materials expand, leading to a slight drop in density. Densities within this handbook will often be described as "theoretical densities" (TD), which correspond to the theoretical maximum density of a material, and "bulk densities", which are the actual real-world densities of samples.

V.2.2 Melting Point

Material melting points are also an important property, noting the temperature – or temperature range – where a material transitions from a solid to a liquid. See Figure V-2 for a visual representation of several materials' melting points. But this property has additional uses too. Materials regularly become weaker and more ductile as temperatures climb, so their effectiveness is reduced well before their melting point is reached.

Melting points are dependent on pressure and impurity concentrations in a material. Therefore, when a high accuracy melting point is needed, one should perform testing at the desired pressure and with the material processing method of interest. Unless otherwise specified, melting points are provided at atmospheric pressure.

Some materials lack clearly defined melting points. Or a material could be considered for use at various stoichiometries, as is the case with zirconium hydride (ZrH_x). When possible, phase diagrams have been provided for these materials. Phase diagrams illustrate the different states a material will attain at different temperature and pressure combinations. Though harder to work with than single value melting points, phase diagrams better explain the hazards associated with changing environmental conditions. An example phase diagram is provided in Figure V-3.

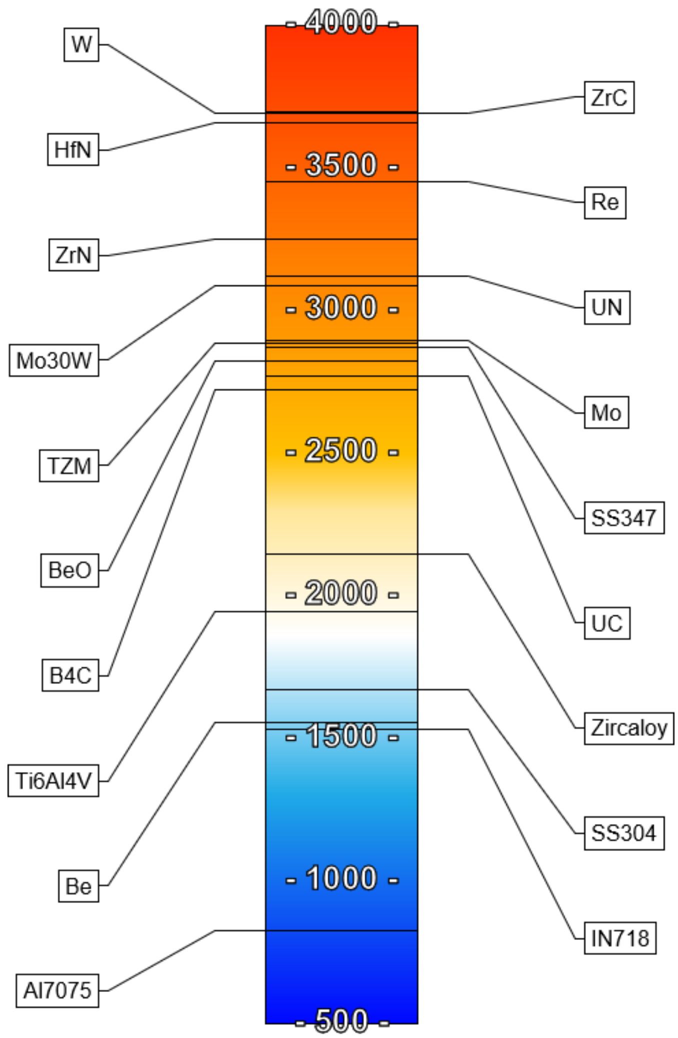

Figure V-2: Melting points of select materials in K.

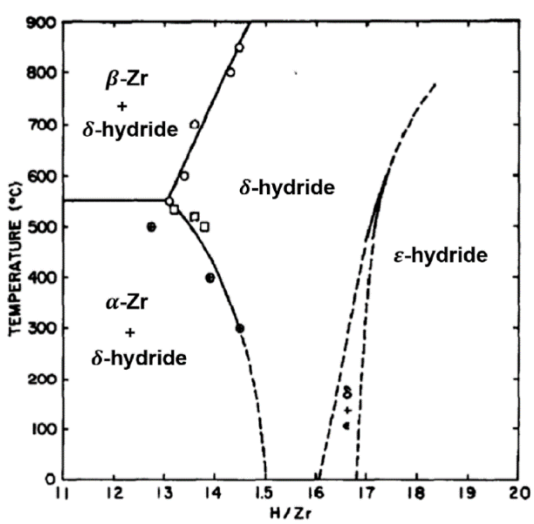

Figure V-3: Example phase diagram for zirconium hydride. See Section 6.2.1 for details.

For nuclear thermal propulsion to be function at the desired efficiency, certain components will be exposed to very high operating temperatures. Fuel and thermal insulator materials are expected to experience particularly high temperatures. Melting points can aid in quickly identifying ill-suited materials for different tasks, though other properties must be tested to understand the details of a material's performance at temperature.

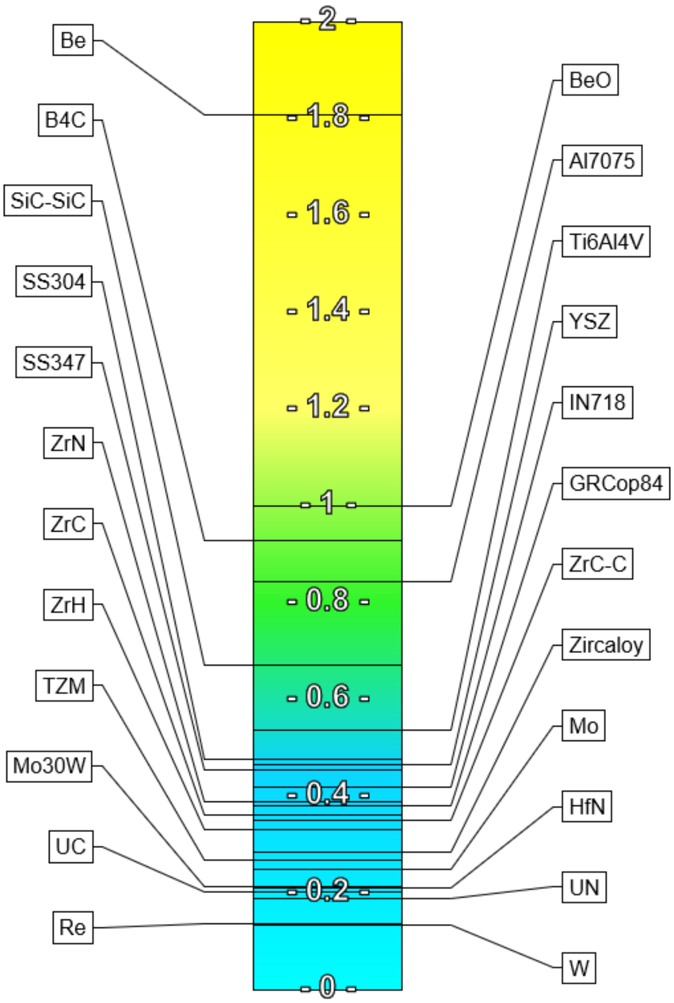

Figure V-4: Room temperature specific heat capacities of select materials in J/(g-K).

V.2.3 Specific Heat Capacity

A material's specific heat capacity is a measure of its ability to store energy without experiencing a change in temperature. Within this handbook, that ability is often stated in terms of joules required to increase a gram of a material by one Kelvin. Figure V-4 contains the RT specific heat values for several materials.

Knowing the specific heat of a material is important when questioning the amount of energy to provide to or extract from a component to alter its temperature by a desired amount.

Heat transfer calculations are dependent on specific heat, including heat conduction, convection, and radiation scenarios. A material's ability to expand or contract is tied to its specific heat, as are its phase changes.

For most materials, specific heat increases with temperature, though the relationship is not a simple one. The Shomate style of equation employed by NIST, an example of which is provided in Table V-3 of Section V.3.2, typically provides good correlations for specific heat. This property benefits from small uncertainties during testing.

This handbook only concerns solid materials; therefore, only specific heat capacities at constant pressure are provided.

V.2.4 Thermal Conductivity

Thermal conductivity represents the rate at which thermal energy passes through a material. It is often a calculated property; Equation (V-2) is used throughout this handbook to determine a material's thermal conductivity when its density, specific heat, and thermal diffusivity are known. The thermal conductivity of several materials at RT is provided in Figure V-5.

Metals are extremely good thermal and electrical conductors, with copper and its alloys having exceptional conductivity. Conversely, nonmetals are poor conductors, with conductivity values sometimes orders of magnitude lower than metals. Conductivity of metals is tied to the mobility of free electrons, and above cryogenic temperatures, it is roughly proportional to the product of electrical conductivity and the metal's absolute temperature [11]. Non-metals, on the other hand, lack a "sea" of valence electrons [12], and their conductivity is due to lattice vibrations and phonons [11].

In solid-fuel nuclear thermal propulsion, it is important that the fuel be sufficiently thermally conductive to avoid building up too much heat – the fuel must remain solid and stable to function correctly. Besides, the heat transferred out of nuclear fuel is needed to energize the propellant and create thrust for the rocket.

$$k(T) = \alpha(T)\rho(T)C_p(T) \quad \text{(V-2)}$$

$k(T) = Thermal\ Conductivity$
$\alpha(T) = Thermal\ Diffusivity$
$\rho(T) = Density$
$C_p(T) = Specific\ Heat$
$T = Temperature$

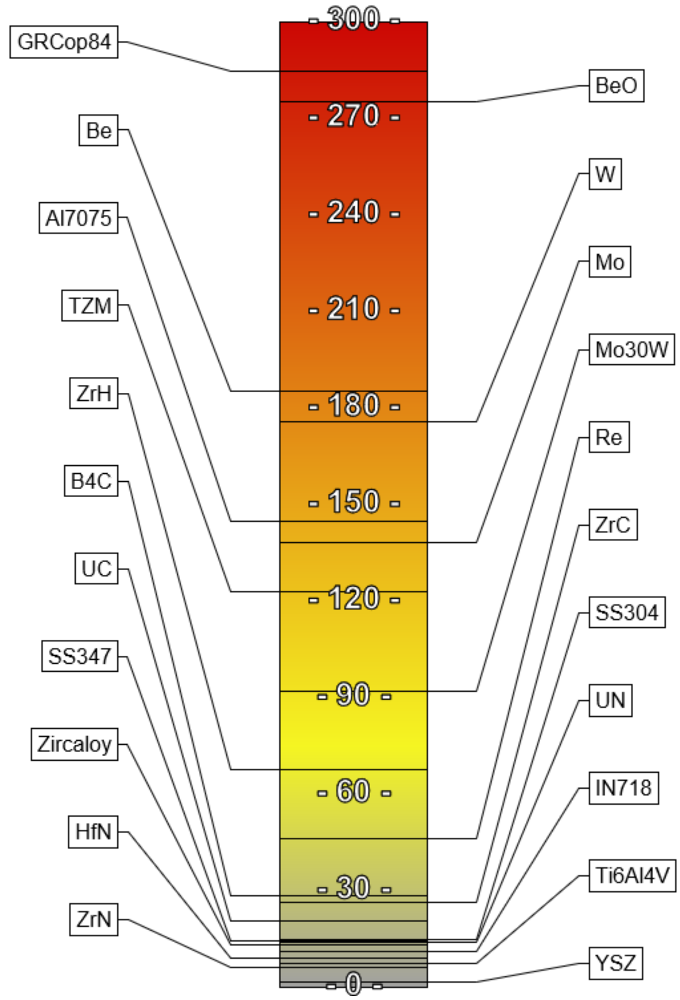

Figure V-5: Room temperature thermal conductivity for select materials in W/(m-K).

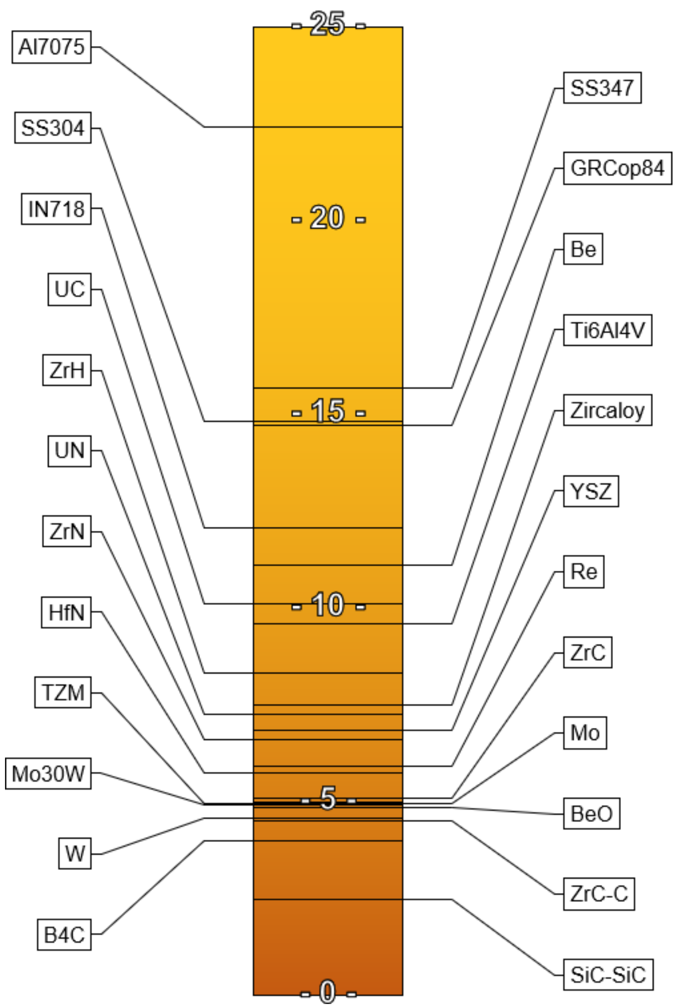

Figure V-6: Room temperature mean coefficients of linear thermal expansion for select materials in μm/(m-K).

V.2.5 Mean Coefficient of Thermal Expansion

When a material changes temperature, it will shrink or expand. In some systems – where temperature changes are minimal – these size fluctuations may be insignificant. But for nuclear systems, the opposite is true. Here, the large temperature changes experienced by materials make thermal expansion effects noteworthy. The transient periods of NTP have the potential for rapid temperature changes, compounding the issue. It is important that materials in contact can expand or contract without causing cracking.

Linear thermal expansion – or the one-dimensional change in a material when heated – is often measured through dilatometry. This data can be represented by the change in a material's length divided by the original length of the material, expressed as a percentage.

Coefficients of thermal expansion (CTEs) can be calculated from linear thermal expansion data. There are two types – the instantaneous CTE and mean (secant) CTE. The first represents how a material expands at a particular temperature when the temperature rises slightly. With the second term, one considers how a material expands due to a change in temperature from a fixed reference temperature to a new temperature it attains [13]. Unless otherwise specified, all the CTE data in this handbook is mean CTE data with RT as the reference temperature. The mean CTE reporting format was chosen due to its usefulness in computing thermal strains – no integration is required to perform these calculations.

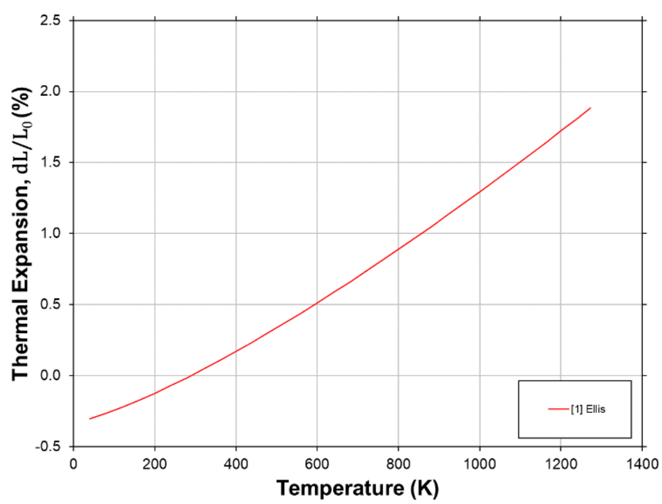

Figure V-7: Example GRCop84 thermal expansion plot. Note the symbol and units of the y-axis. See Section 4.1.1 for references and details on GRCop84.

Mean CTE values, like the ones shown in Figure V-6, are calculated from linear thermal expansion with the expression shown in Equation (V-3). For an example of a linear thermal expansion trend, see Figure V-7.

$$\bar{\alpha}(T) = \frac{\frac{dL}{L_0}(T)/100}{T - T_{ref}} * 10^6 \qquad \text{(V-3)}$$

$\bar{\alpha}(T) = Mean\ Coefficient\ of\ Thermal\ Expansion\ [\mu m/(m \cdot K)]$

$\frac{dL}{L_0}(T) = Linear\ Thermal\ Expansion\ [\%]$

$T = Temperature\ [K]$

$T_{ref} = Reference\ Temperature\ [K]$, usually RT

V.2.6 Electrical Resistivity

As discussed along with thermal conductivity in Section V.1.4, electrical conductivity reflects the mobility of electrons within a material [14]. Electrical resistivity is the inverse of electrical conductivity, demonstrating how electrically insulating a material can be. A plot of the RT electrical resistivity for multiple materials is shown in Figure V-8.

Various quantum mechanics models can be combined to understand electron motion and electron energy levels. However, this information is not required for the use of electrical resistivity at the macroscopic level – as a material property.

Ultimately, resistivity increases with atomic displacements, crystal lattice imperfections, and foreign atom substitution [14]. A material's composition, temperature, and radiation exposure affect these events, thereby influencing electrical resistivity.

Besides it's occasional usefulness in the estimation of thermal conductivity, electrical resistivity aids in the design of systems from an electrical standpoint. Various components are used in spacecraft, each with its own electricity (or protection from electricity) requirements. For example, since the 1970's, spacecraft surface charging became an issue for the spaceflight industry [15]. Projects have experienced part degradation, part failure, mission redesign, and mission loss due to charging. The number of modern charging-related issues has dropped due to improved design practices and material choices [16].

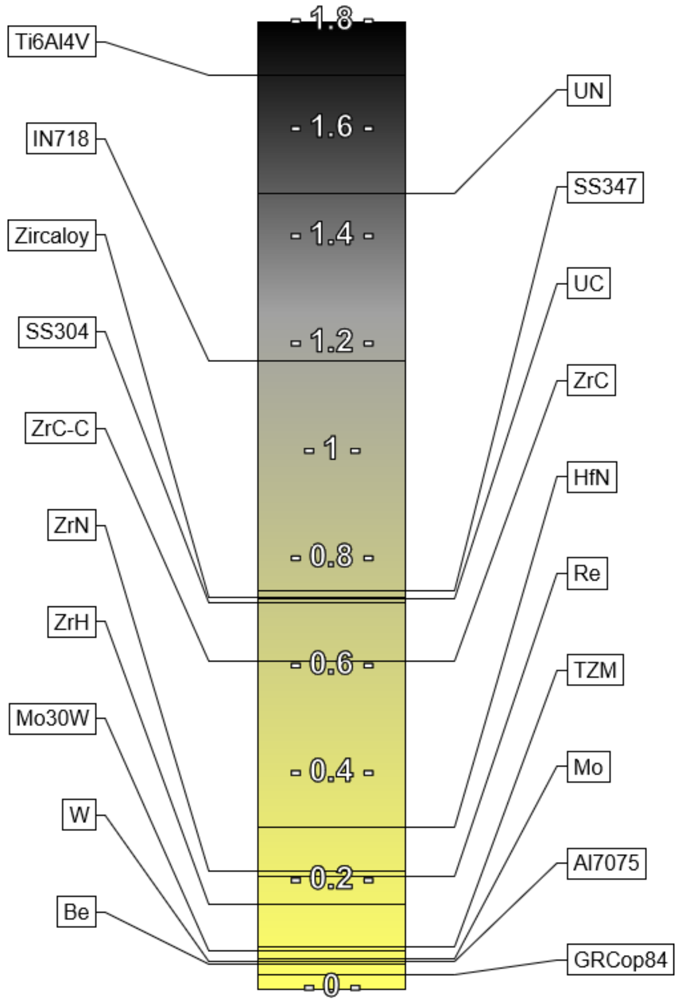

Figure V-8: Room temperature electrical resistivity for select materials in μΩ-m.

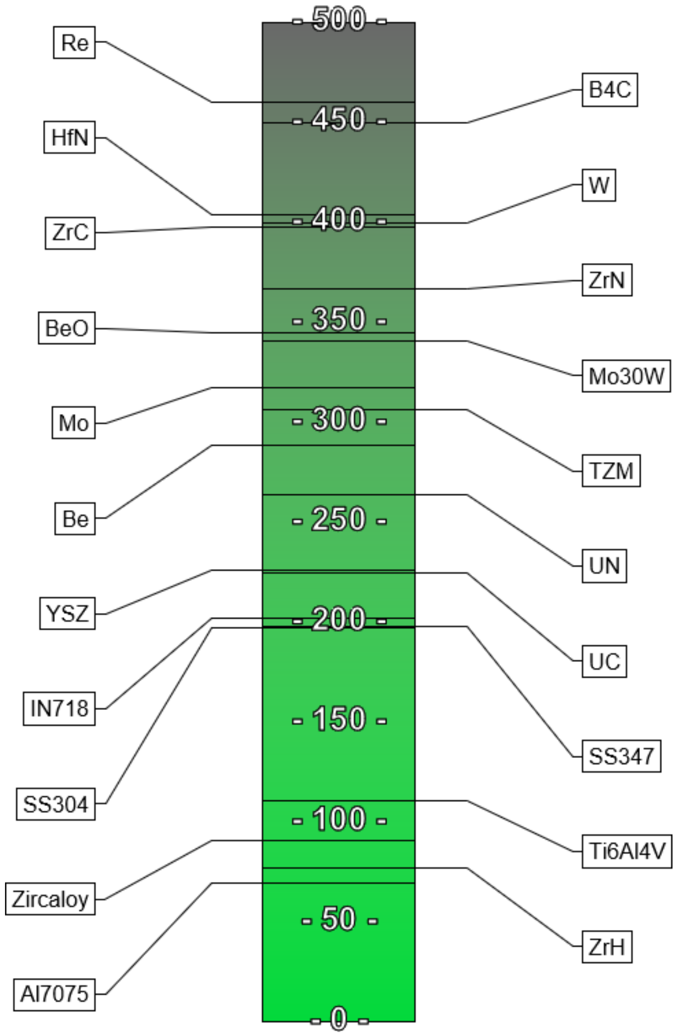

Figure V-9: Room temperature Young's modulus for select materials in GPa.

V.2.7 Young's Modulus

The modulus of elasticity, also known as Young's modulus, is important for determining how a material will elastically deform when exposed to a force. Other elastic properties like the shear modulus and Poisson's ratio, which are described in Sections V.1.8 and V.1.9 respectively, are also involved in elastic behavior. Figure V-9 contains Young's modulus values for various materials at RT.

When a material is exposed to a tensile or compressive force, the Young's modulus recognizes the deformation the material should experience *parallel* to the applied force. Some tests – tensile and compressive tests – do exactly this, applying a force and marking down stress-strain curves. The initial, relatively constant slope of these curves is the Young's modulus. From a theoretical perspective, the tensile Young's modulus and compressive variant should be equal, though residual stresses can cause a discrepancy [17].

The *static modulus* is the material property being measured by tensile and compressive testing in the elastic region. Unfortunately, a wide uncertainty band is often observed for static modulus results.

Dynamic modulus testing, however, provides data of greater consistency, and the property involves vibration testing. While the static modulus arises from a sample deforming under an increasing stress, the dynamic modulus is found through the application of an oscillatory stress. Ultimately, dynamic modulus testing can be faster, lower cost, and nondestructive in comparison to static modulus testing [18].

Note that static and dynamic moduli values are often similar but not identical. Researchers have proposed different theories on the difference between the moduli. Some state that static loading provides isothermal elastic constants, while dynamic loading yields adiabatic elastic constants. Alternatively, the varying atomic displacements due to the different magnitudes of strain could explain the discrepancy [18]. Another researcher noted:

"*At temperatures where time dependent deformation is absent the static and dynamic moduli are essentially equal with the dynamic value in some materials being slightly lower than the static value. At temperatures where time dependent deformation would occur in static tests the dynamic modulus is useful where vibratory loads accompany creep deformation*" [17].

When materials are known to have significantly different static and dynamic moduli values, equations can be used to convert between the two moduli [19].

V.2.8 Shear Modulus

Dividing shear stress by shear strain yields the modulus of rigidity, or the shear modulus. This property represents a material's elastic shear stiffness.

The deformation of a solid resulting from a force parallel to one of its surfaces is characterized by the shear modulus. See Figure V-10 for the shear modulus values of several materials at RT.

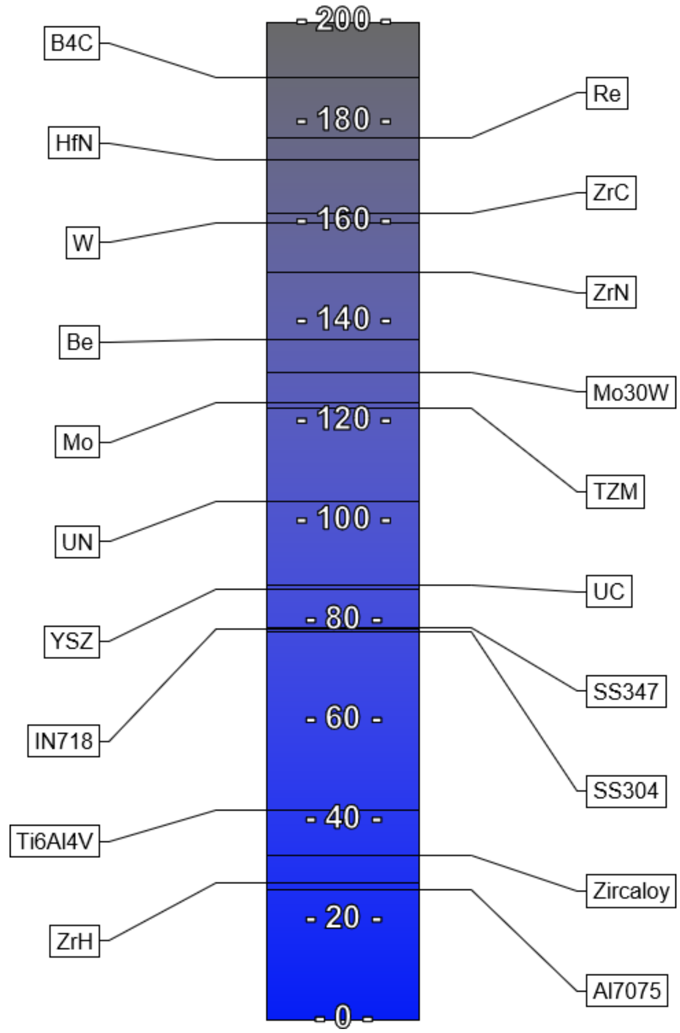

Figure V-10: Room temperature shear modulus for select materials in GPa.

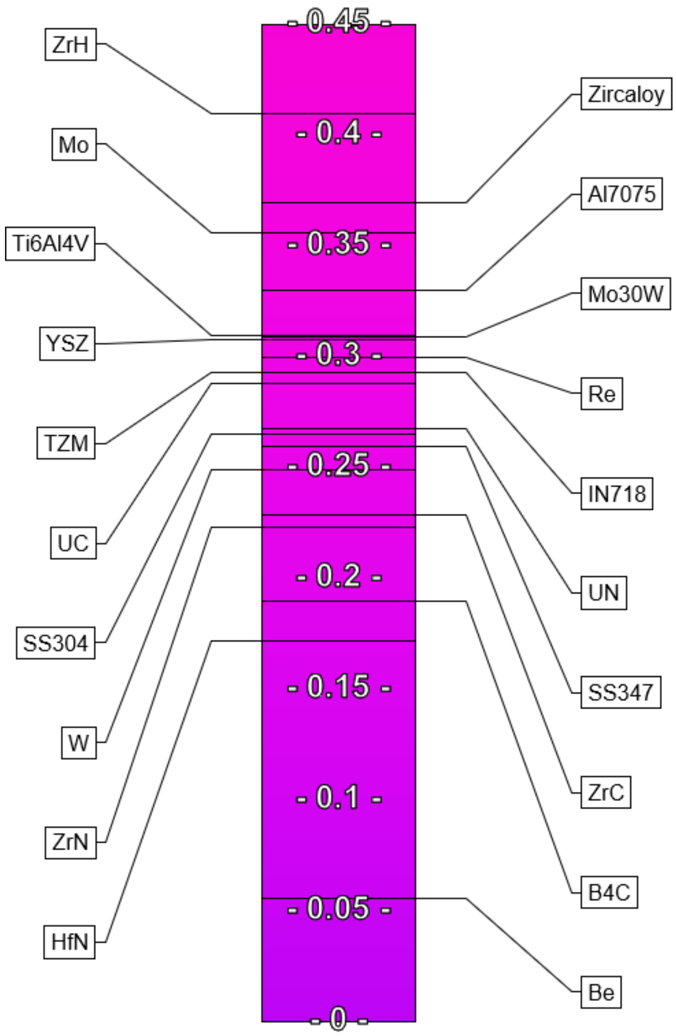

Figure V-11: Room temperature Poisson's ratio [-] for select materials.

V.2.9 Poisson's Ratio

Young's modulus, shear modulus, and Poisson's ratio are related properties. They have a simple relationship within isotropic materials, as demonstrated in Equation (V-4). This equation is regularly used in this handbook, since literature data on Poisson's ratio is rarer than data on Young's modulus and shear modulus. However, on rare occasions when Poisson's ratio data is more readily available than shear modulus data, Equation (V-4) is rearranged to calculate the shear modulus.

$$\nu(T) = \frac{E(T)}{2G(T)} - 1 \qquad \text{(V-4)}$$

$\nu(T) = Poisson's\ ratio$ [-]

$E(T) = Young's\ modulus\ [GPa]$

$G(T) = Shear\ modulus\ [GPa]$

$T = Temperature\ [K]$

Poisson's ratio represents deformation of a material in perpendicular directions to an applied load. For example, for a rod lengthening due to a tensile force, the change in the rod's cross-sectional area can be predicted via the Poisson's ratio of the material. In Figure V-11, the RT Poisson's ratio values for multiple materials are provided.

Most materials have a positive Poisson's ratio, meaning that the material's cross section shrinks as its length expands, and vice versa. Some materials have a negative Poisson's ratio, and their cross sections increase with increasing length. Note that this requires a density change, assuming the material's mass is held constant as its volume fluctuates. Finally, materials of near-zero Poisson's ratio experience no cross-sectional area change when their lengths are altered.

Isotropic material relationships are used in the handbook. But to have their elastic behavior characterized in a way that captures their full, real-world behavior, anisotropic materials require tensor expressions of their elastic constants. Anisotropic material testing and data acquisition is substantially more involved than isotropic material testing; as a result, tensor expressions are outside of the current scope of this handbook. These tensors are also more difficult for modelers and designers to work with, even if they improve the accuracy of results.

V.3 Handbook Development Methodology

Here, the process used to modify this handbook is outlined. Modelers and designers should consult the information to follow when details on data generation, curve fitting, or the models used in the handbook are needed. This section largely exists for traceability purposes. The major strengths and limitations of this handbook's development can be discerned from the following explanations.

V.3.1 Data Generation and Literature Searches

The data used in this handbook stems from two sources – SNP material property testing campaigns and historical literature.

Details on SNP testing campaigns vary and are held within different planning documents. The Fuel and Moderator Development Plan (FMDP) [10] currently covers the bulk of SNP material testing work. Please also see SNP-PLAN-0021, Space Nuclear Propulsion Task 1.10 Materials & Process Mapping Documentation Recommendations [20], which aids readers in understanding the intent of the FMDP and applying the document in their own testing efforts. Data originating from SNP testing campaigns is considered "internal" data, whereas data acquired from other programs and projects is considered "external".

Literature searches vary in duration – from a couple days to about a week – but are intended to be exhaustive. The searches typically include most databases in MAPTIS, with particular emphasis placed on MMPDS, Aerospace Structural Metals Handbook, and Material Universe. The results of past NASA, DOE, DOD, and industry aerospace efforts are examined during each literature search. Table V-2 is an incomplete list of important sources of material property data. Note that databases of academic journals and internet searches are also utilized when seeking historical literature data. The table is sorted alphabetically.

Numerous reports and handbooks from key projects have also been added to the table. Contact the SNP Material Property Handbook team for an index document noting the materials and properties included within past nuclear projects' data books. An avid reader will find that a tremendous amount of information on nuclear systems has been gathered by the references of Table V-2.

Table V-2: Frequently used handbooks, databases, and services for literature searches.

Title	Description
Aerospace Structural Metals Handbook (ASMH)	Contains data on metals and alloys from AMS, federal, and industry sources, with a focus on physical properties, mechanical properties, and factors limiting the load carrying capacity of each material
AFCI Materials Handbook – Materials Data for Particle Accelerator Applications	Provides data on materials applicable to nuclear transmutation and Gen IV fast neutron spectrum systems, originally created by various DOE national labs to support the Accelerator Production of Tritium Project
Comprehensive Nuclear Materials	Set of volumes encompassing various nuclear fuel systems, spent fuel processes, modeling nuclear systems, radiation effects in materials, and other material properties
Defense Technical Information Center – Technical Reports	Contains technical reports funded by the DOD
DOE Data Explorer (DDE)	Tool for locating data records resulting from DOE funding
DOE Office of Scientific and Technical Information – OSTI.GOV	Collection of research and technology information funded by the DOE
DOE Public Access Gateway for Energy and Science (DOE PAGES)	Tool for locating peer-reviewed publications founded upon DOE research

Table V-2: Frequently used handbooks, databases, and services for literature searches.

Title	Description
IAEA Thermo-Physical Materials Properties Database (IAEA THERPRO)	Digital database of thermophysical materials data resulting from IAEA coordinated research projects
Materials and Processes Technical Information System (MAPTIS)	Houses many databases, which in turn provide physical, mechanical, and environmental properties of materials
MaterialUniverse	Database of material properties, environmental data, and costs, as well as information on many manufacturing processes – produced by ANSYS Granta
Metallic Materials Properties Development and Standardization (MMPDS)	Source of design data for many aerospace materials, as well as for different material geometries (fasteners, etc.)
NASA Glenn Library	Provides reference books in a physical and virtual collection
NASA Technical Reports Server (NTRS)	A repository of scientific and technical information created or funded by NASA
NERVA Program – Materials Properties Data Book	An Aerojet Nuclear Systems Company and Westinghouse Astronuclear Laboratory publication which was used to provide basic design criteria – including property data – for materials within the NERVA Program
NIST Chemistry WebBook	Source of chemical and physical property data, as maintained by the NIST Standard Reference Data Program
SNAP Technology Handbook	Handbook including data and descriptions regarding liquid metals, hydride fuels and claddings, and refractory fuels and claddings for use in the SNAP Program
SP-100 Materials Handbook	Compilation of data on Re, BeO, Nb-1Zr, PWC-11, Li, and UN for use in the SP-100 Program
SP-100 PCA Materials Properties Database	Compilation of data on SiGe/GaP, GS-526, Al2O3, W, graphite, Nb, and Cu – originally intended for inclusion in the SP-100 Materials Handbook
Thermophysical Properties of Matter – The TPRC Data Series	Set of volumes on the thermophysical properties of over 5,000 materials; experimental data and trends are both provided

Once data is gathered through a comprehensive literature search and from new testing, it is housed in “Excel Database” files. Important details about the data, such as the material manufacturing method and specimen geometry are also stored here. Data is plotted to quickly assess its variance. Outlier datasets – or individual data points – are investigated to determine why discrepancies exist. When issues with experimental methods or conditions are identified, the data may be discarded, adjusted through a correction factor, or marked with a note on its irregularity, whichever is most applicable. Note that data that is “discarded” is merely hidden from view in plots and is held separate from trend creation – it can still be found in the Excel Database if the data is later determined to be useful. After the initial vetting of the data, correlations can be developed.

V.3.2 The Curve Fitting Process

Matrix Laboratory (MATLAB) and the MATLAB curve fitting tool [21] were used to develop material property trends. These trends are empirical and based on test data, rather than scientific theory. For chapters introduced in SNP-HDBK-0008 Rev. 2 and onwards, including the rhenium and TZM sections, note that an open-source code [22] was used to create polynomial curve fits for the thermal expansion property. This code allowed for trends to demonstrate zero thermal expansion at RT, which previously needed to be accounted for manually.

To develop a new trend, the data gathered through the process of Section V.3.1 is copied from Excel into MATLAB. When all datasets are approximately the same size – or when the data shows little variation when plotted – the data can be pooled together into a single matrix in MATLAB. From there, a trendline encapsulating all the data can be created.

However, sometimes datasets vary notably and have different numbers of data points. In these cases, pooling the data would lead to some datasets having greater influence over the trend than other datasets. If all else is held equal – such as equipment being of similar quality and testing procedures being equivalent – then the datasets should have equal influence on the eventual trendline. The issue can be visualized in Figure V-12A. To avoid this issue, techniques like overfitting, underfitting, and extrapolating can be employed. See Figure V-12B for an example of mitigating the problem posed by differing amounts of data.

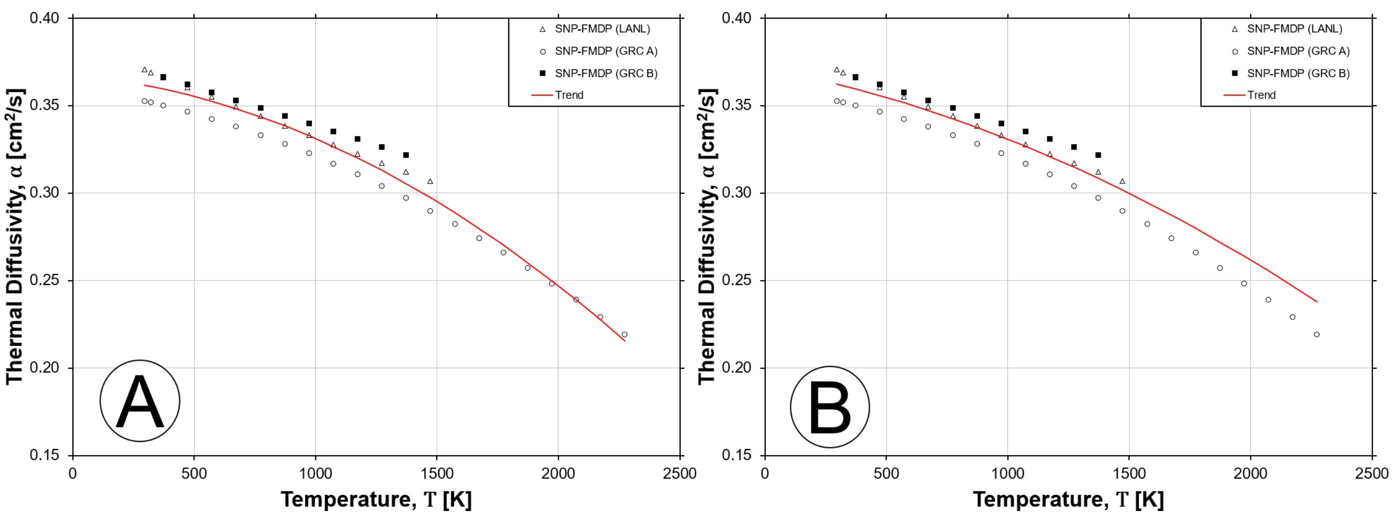

Figure V-12: Example of generating curve fits when datasets have varying numbers of data points *or* different maximum or minimum independent variable values. This Mo30W thermal diffusivity data and its references can be found in Section 3.1.2. In (A), the data is pooled together, while in (B), overfitting is used to produce a more realistic trend. Note that the high temperature data of SNP-FMDP (GRC A) pulls the trend downwards, while we would expect – if the other two datasets were to continue to higher temperatures – that the resulting trend would have its values slightly elevated at these temperatures.

For overfitting and underfitting, a separate trend is first created for each individual dataset. These trends are then evaluated for the same series of independent variable values – or the same set of temperatures. Previously large datasets have now been condensed into smaller datasets, whereas originally small datasets end up with more values than they started out with.

An extra level of complexity is introduced when the datasets have wildly different maximum and minimum independent variable values. If a trend is generated for pooled data, it will favor areas with greater numbers of data points – even if that causes the trend to skew away from a realistic trajectory. Again, see Figure V-12A. To show caution, the trend can be cut off early. But the SNP project requires trends that reach extremes. Thus, trends can be extrapolated to higher and lower independent variable values. Since trends exist for individual datasets, those trends may be evaluated at values outside of their preexisting maximums and minimums. Within plots, this may be referred to as either “extrapolation” or as an “extended temperature range”. By contrast, a “valid temperature range” involves no extrapolation.

When datasets exhibit consistent patterns, this turns out well. But sometimes a dataset’s individual trend will exhibit abnormalities at its extremes. If this were extrapolated and incorporated into the trendline of the material property as a whole, it could lead to an unrealistic trend shape. See Figure V-13 for an example.

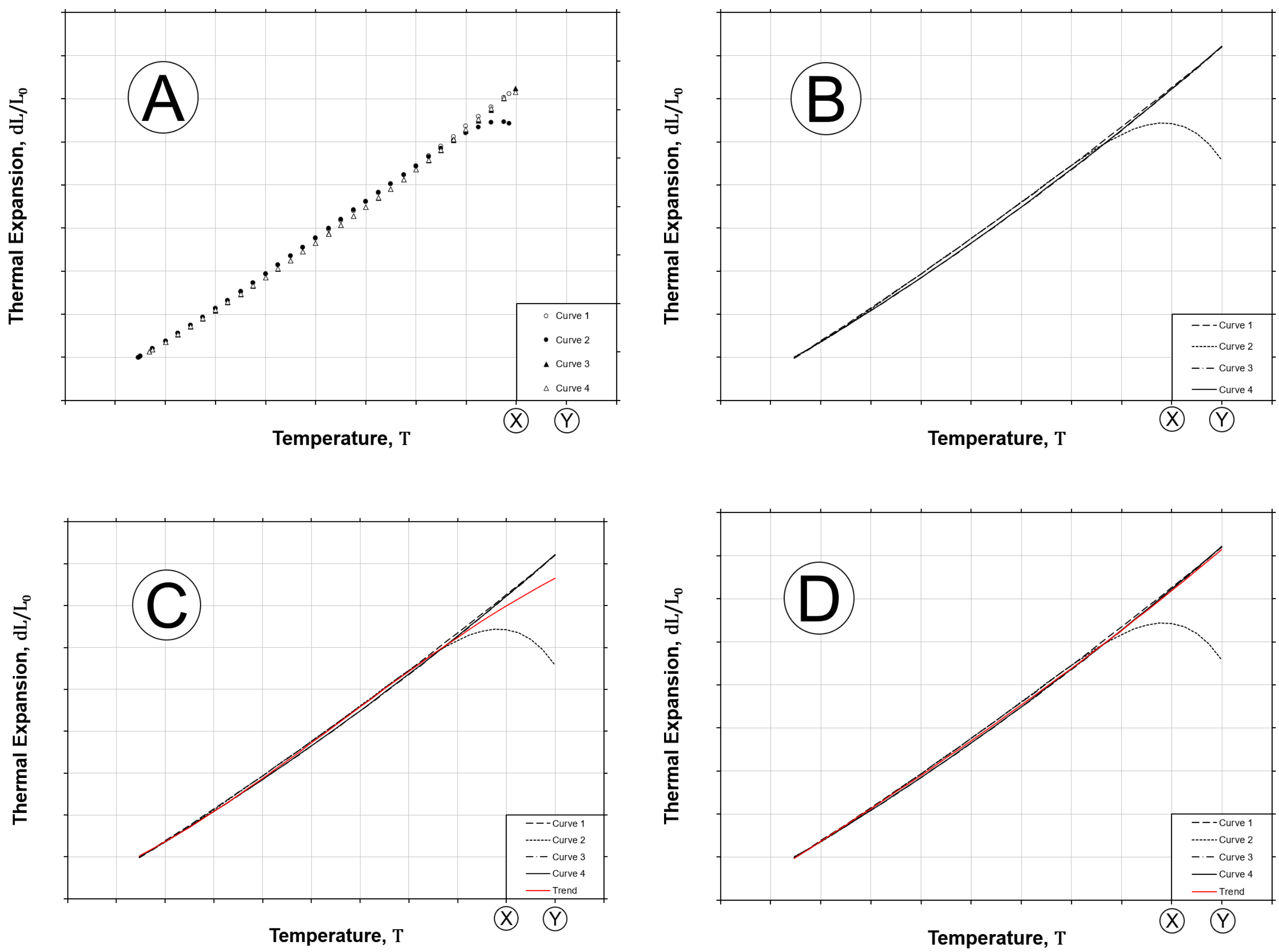

Figure V-13: Exemplifying a risk of extrapolation. (A) Four reduced datasets are shown, each of which ends near temperature X. (B) Trends are created for the individual datasets, and the trends are extrapolated to temperature Y. Note how low Curve 2 drops. (C) Using each of the individual trendlines, a generalized trend is created for the material. This new trend is lower than expected at temperature Y. (D) If the extrapolated portion of Curve 2 is removed from the trend generation, a more realistic trend is obtained.

Again, NTP conditions expose materials to a wide range of temperatures. Sometimes a single trend cannot capture the changing patterns in experimental material property data. These shifting patterns are a regular occurrence in this handbook, but phase changes in materials provide the most notable examples – please see Figure V-14. This figure illustrates the specific heat of zircaloy. Due to the material's phase change at around 1200 K, one can see a significant spike in specific heat. In situations like this one, piecewise trend equations are used in place of single trends. Reusing data close to where the piecewise trends meet allows for the piecewise equations to intersect. However, the slopes of the piecewise trends are not guaranteed to be equal at the intersection point. Caution is advised for modelers who work with models that incorporate material property trends *and* require differentiability.

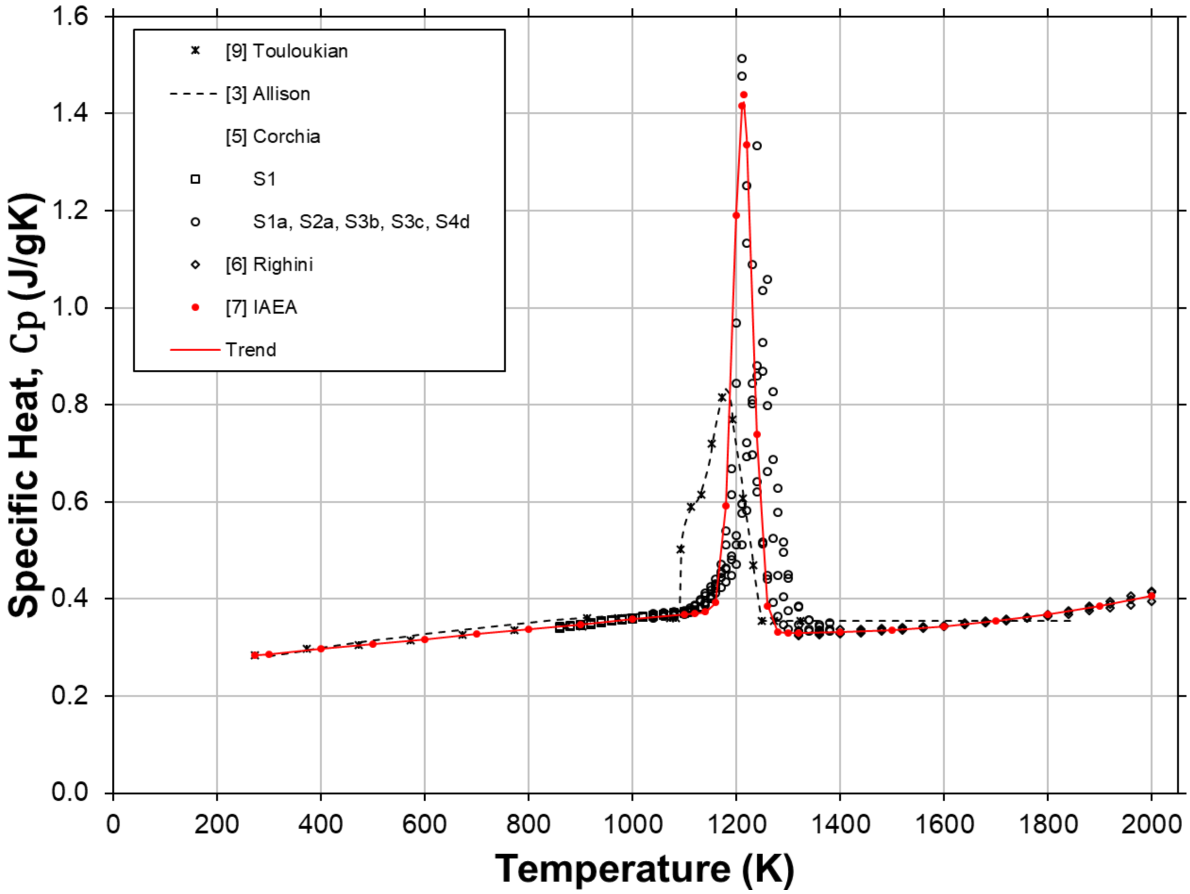

Figure V-14: Impact of a phase change on a material's properties. This plot captures specific heat data on zircaloy. See Section 4.2.1 for the data and its references. The large spike in specific heat around 1200 K is atypical, and it is due to a phase change.

Several types of curve fits are used for trend development. Since the trends are experimental rather than theoretical, there are no real-world physics or thermodynamics driving the use of one fit type over any other. MATLAB's curve fitting tool automatically calculates the sum of squared errors, an R^2 value, and other statistical measures for each curve fit. To be incorporated in the handbook, a given fit must surpass the other fits tested when these statistical measures are taken into consideration.

The primary fit types used to develop this handbook are listed in Table V-3. Equations in the table serve as generic examples – actual fit equations elsewhere in the handbook have different numbers of terms. For example, some polynomial fits of material properties may be linear, quadratic, or quartic – forms that vary from the cubic shown in the table. When developing a curve fit for a material property and the different curve fit options have approximately equivalent merit based on statistical measures, the simplest of the acceptable curve fits is chosen. That is, curve fits with fewer coefficients are given preference over those with many coefficients. Similarly, curve fits that involve the basic addition and multiplication of terms are prioritized over those with complex numerator and denominator terms. It is hoped that the extra simplicity benefits the modelers and designers who translate trend equations into their own work.

Table V-3: Categories of curve fits.

Generic Equation	Fit Name / Description
$y(T) = A0 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2 + A3 \cdot \left(\frac{T}{1000}\right)^3$	Polynomial
$y(T) = \left[A0 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2\right] / \left[B0 + B1 \cdot \left(\frac{T}{1000}\right)\right]$	Rational
$y(T) = A0 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2 + A3 \cdot \left(\frac{T}{1000}\right)^3 + A\_2/\left(\frac{T}{1000}\right)^2$	Shomate
$y(T) = AN \cdot \left(\frac{T}{1000}\right)^N + A0 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2$	Power fit with a polynomial addition
$y(T) = AN \cdot \left(\frac{T}{1000}\right)^N / \left[A0 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2\right]$	Power fit divided by polynomial
$y(T) = \frac{AN}{\left(\frac{T}{1000}\right)^N} + A0 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2$	Polynomial fit with a rational addition

Most trends in this handbook represent a curve fit of average values. That is, they pass through the “center” of clusters of data points, rather than being offset to indicate maximums, minimums, or other kinds of upper and lower bounds. Fits of average values are labeled “typical basis” fits, according to MMPDS [5] – and NASA often utilizes the MMPDS method of basis designation [4]. Unless otherwise specified, assume the trend for each plot is a typical basis trend. Even when multiple trends are provided – such as “minimum” and “high” trends – readers should continue to make the typical basis assumption until explicitly told otherwise. As stated in Table 9.2.4 of MMPDS-2023, typical basis values are often suitable for thermophysical properties [5].

The design basis associated with a trend is an indicator of the trend’s reliability. Typical basis trends have no statistical significance – that is, the risk associated with using the trend is unknown. Other basis designations include S-basis, B-basis, and A-basis, listed in order of increasing reliability. NASA strongly prefers A-basis values for use in the design of “primary structures”, or components intended to sustain significant applied loads and lead to catastrophic hazards when they fail. Redundant structures, on the other hand, are often designed with B-basis values [4]. But note that both A- and B-basis trend generation require a substantial amount of data, depending on the material property of interest. According to Table 9.2.4 of MMPDS-2023, applying an A- or B-basis designation to certain mechanical properties can require hundreds of samples [5].

This handbook contains material property data that spans vast temperature regimes. With current cost and schedule constraints, acquiring A- and B-basis trends for all materials of interest for SNP applications is impractical. It is advised that future testing and literature search campaigns be used to determine A- and/or B-basis values for material properties and materials when designs or models require the heightened level of fidelity. However, even small-scale test series can be used to strengthen the accuracy of typical basis trends. Table 9.2.3 in MMPDS-2023 provides a list of industry testing standards that accounts for each of the material properties in the database [5].

V.3.3 The Use of Models

On occasion, theoretical equations are provided alongside the experimental data and trends within property plots. These models can serve multiple functions. At times when data is limited – or the quality of datasets is unknown – models can be used to provide clarity and increase one’s confidence that experimental data or trends are valid. Alternatively, the reverse situation may occur, and a theoretical model may be of unknown reliability, while experimental data has well-defined accuracy. In these cases, comparing the experimental and theoretical trends can provide insights for those who wish to use models – or extrapolate those models to extreme temperatures, different materials, etc. – in the future.

A commonly used model methodology is the rule of mixtures (ROM). This weighted mean serves to predict material properties for composite materials and alloys based on their constituent materials.

Unless explicitly stated otherwise, designers should only use the experimental trends provided in this handbook. See Sections V.4.3, V.4.4, and V.4.5 for guidance on using the three distinct forms of data provided.

V.4 Using the Material Property Handbook

V.4.1 Definitions

Table V-4 defines the acronyms, abbreviations, and several technical terms used in this handbook, while Table V-5 includes a list of common symbols. Materials with their own sections in the handbook have already been defined in Section III, and they are not included in the table. However, materials referenced in the text that do not have corresponding sections in the handbook are still shown.

The symbols' definitions are also provided alongside each fit equation to aid in readers' understanding of the equations. Note that Greek letters within phase diagrams refer to different phases of materials, rather than to the definitions provided in Table V-5.

Table V-4: Acronyms, Abbreviations, and Terminology.

Term	Definition
AM	Additive manufacturing *or* additively manufactured
As – [manufacturing method]	For example, "As – wrought"; indicates that measurements were taken on material samples in the same condition that they were manufactured in, without further treatment or processing
at%	Atomic percent
basis (A-, B-, S-, typical)	A designation for data and trends that indicates statistical significance; NASA uses the MMPDS method of basis determination; see Section V.3.2 for details
bcc	Body-centered cubic crystal structure
BP	Boiling point
cercer	Composite material consisting of ceramic particles in a ceramic matrix
cermet	Composite material consisting of ceramic particles in a metallic matrix
correlation	See "trend"
CTE	Mean coefficient of thermal expansion [a]
CUI	Controlled unclassified information
Curve [number]	For example, "Curve 2"; used to designate between different datasets in plots; for more details on a given curve, please see its associated reference
curve fit	See "trend"
CVI	Chemical vapor infiltration *or* chemically vapor-infiltrated

Table V-4: Acronyms, Abbreviations, and Terminology.

Term	Definition
DARPA	Defense Advanced Research Projects Agency
DFT	Density functional theory
DOD	Department of Defense
DOE	Department of Energy
DRACO	Demonstration Rocket for Agile Cislunar Operations
EAR	Export Administration Regulations
extended temperature range	A temperature range for which a trend is supported by limited data; see “extrapolation”
external data	Material property data produced by programs and projects other than the SNP project
extrapolation	Method for predicting material property values outside the ranges for which data exists; see Section V.3.2 for details
fcc	Face-centered cubic crystal structure
FMDP	Fuel and Moderator Development Plan
FSP	Fission surface power
GRC	NASA John H. Glenn Research Center
hcp	Hexagonal close packed crystal structure
high (trend)	One of multiple trends – this trend expresses higher values than the others; it should be treated as a typical basis trend unless otherwise stated
HNLS	Hi-Nicalon Type S SiC fibers by Nippon Carbon Co., Tokyo, Japan
INL	Idaho National Laboratory
internal data	Material property data produced by the SNP project
ITAR	International Traffic in Arms Regulations
LANL	Los Alamos National Laboratory
LaRC	NASA Langley Research Center
MAPTIS	Materials and Processes Technical Information Center
MATLAB	Matrix Laboratory; a programming language by MathWorks
MCWG	Materials Characterization Working Group
minimum (trend)	One of multiple trends – this trend expresses lower values than the others; it should be treated as a typical basis trend unless otherwise stated
MMPDS	Metallic Materials Properties Development and Standardization
mol%	Mole percent, equivalent to at%
MP	Melting point
MSFC	NASA George C. Marshall Space Flight Center

Table V-4: Acronyms, Abbreviations, and Terminology.

Term	Definition
MST	Missouri University of Science and Technology
MW	Molecular weight
NASA	The National Aeronautics and Space Administration
NEP	Nuclear electric propulsion
NERVA	Nuclear Engine for Rocket Vehicle Application
NTP	Nuclear thermal propulsion
ORNL	Oak Ridge National Laboratory
PIP	Polymer impregnation and pyrolysis
PLS	Proportional limit stress
PyC	Pyrolytic carbon
ROM	Rule of mixtures; a model for predicting material property values; see Section V.3.3 for details
RT	Room temperature
SA3	Tyranno 3 SiC fibers by Ube Industries, Ltd., Ube, Japan
SI units	International System of Units
SNP	Space nuclear propulsion
SNPP DB	Space Nuclear Power and Propulsion Materials Database
SPS	Spark plasma sintering *or* spark plasma sintered
SSC	Solid solution carbide
TD	Theoretical density; materials with zero porosity
temp.	Temperature
trend	The general course of a material's given material property data; the values composing the trend should be used by modelers and designers; see V.3.2 for background on how trends are formed and V.4.3 to V.4.5 for a discussion on making use of trends
trendline	The red line in a material property plot that represents the trend of experimental data
valid temperature range	A temperature range for which a trend is supported by sufficient data; see "extrapolation"
vol%	Percent by volume
w/o	see "wt%"
wt%	Percent by weight

[a] Also known as the average coefficient of thermal expansion or the linear expansion coefficient

Table V-5: Symbols.

Symbol	Definition
ρ	Density – assume TD unless otherwise stated
ρ_{bulk}	Bulk density, or the density of real-world, porous material
ρ_e	Electrical resistivity
P	Fractional porosity
K_{ic}	Fracture toughness
dL/L_0	Linear thermal expansion
$\bar{\alpha}$	Mean coefficient of thermal expansion [a]
M	Modulus of rupture
ν	Poisson's ratio
x	Ratio of one material to another material
T_{ref}	Reference temperature
ρ_{RT}	Room temperature density
G	Shear modulus
C_p	Specific heat
T	Temperature
k	Thermal conductivity for perfectly dense material
λ	See "k"
k_p	Thermal conductivity for porous material; an equation relating k and k_p is often provided for readers who wish to perform porosity conversions
α	Thermal diffusivity
δ	See "α"
UTS	Ultimate tensile strength
TS	See "UTS"
YS	Yield strength
E	Young's modulus [b]

[a] Also known as the average coefficient of thermal expansion or the linear expansion coefficient

[b] Also known as the modulus of elasticity

V.4.2 Navigation

Following this introductory section of the handbook, readers will find sections on materials and their properties. A tiered structure is used to categorize materials, and the organization resembles the format used by the NERVA Program in their own Materials Properties Data Book [7]. The Table of Contents provides a good visualization of the high-level structure, while Figure V-15 expands the breakdown to show the individual subsections within a given material's section.

Given the size of the handbook, readers are encouraged to use built-in mechanisms to quickly navigate the document. First, the Table of Contents and the Property List are composed of links; in the Portable Document Format (PDF) version of the handbook, one can click on the links to jump to sections and subsections of interest.

However, readers may need to jump between areas of the handbook – and constantly returning to the Table of Contents takes time. Therefore, making use of Word's Navigation Pane, Adobe Reader's (or Acrobat's) Bookmarks side panel, or browser-based equivalents (i.e., the document outline in Google Chrome) is highly recommended. In each case, a sidebar appears that allows readers to switch between the different materials and material properties at will.

Each material section begins with room temperature and single-value properties, as well as any applicable composition or phase information. From there, material properties are each typically given two sheets each to relay data through plots, tables, and equations. Additional application notes sheets follow the material properties in cases where paragraph-style explanations would assist readers in making use of the data. Next comes a summary table of the most common thermophysical properties within the handbook. Finally, the material section ends with a reference list. All data sources used to develop the handbook section can be found within the list.

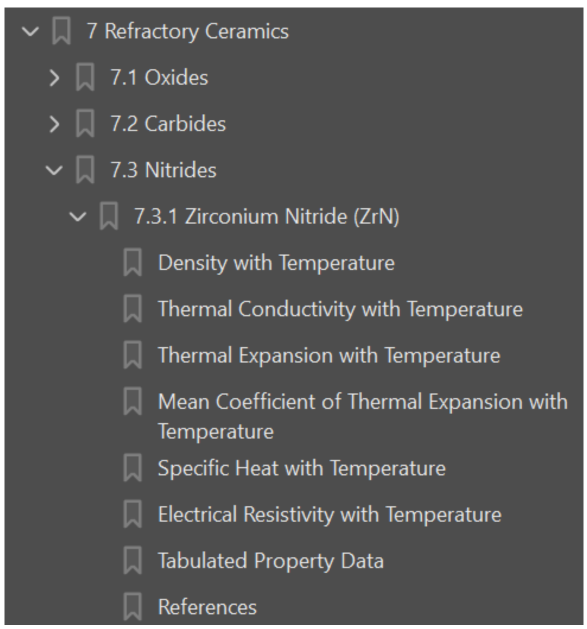

Figure V-15: Material section breakdown for zirconium nitride. Most subsections correspond with material properties, but the Tabulated Property Data and References subsections are exceptions.

V.4.3 How to Use Material Property Plots

Within each material's section, a set of material property trends are provided. For each property, a plot of trendlines and data points is first to appear. An example can be seen in Figure V-16. Individual data points are indicated by black data markers and are either hollow or filled. The dashed line from reference [1] (*of Section 2.1.1)* indicates a trend, though since it is black, it was not generated by the SNP Material Property Handbook team. Those trends appear red instead. Sometimes data or trends from references will be shown in a plot but were not used in trend formulation. Theoretical models are occasionally provided, and these likewise do not contribute to experimental, red trends. The application notes for a property, which are almost always found on the page following the plot, provide clarity on how a trend was generated. Additionally, the reference numbers listed in each plot, plot caption, and application note correspond with the sources listed in the References subsection at the end of each material's section. Figure V-15 in Section V.4.2 is a screenshot showing the generic breakdown of a material section.

Modelers and designers are advised to glance over the plots of relevance to their work before extracting information from the handbook. Visualizing the data in this way can serve as a helpful check – both that the reader has interpreted the information correctly, and that the handbook author did not err when adding data into the handbook. Plots are also useful for providing quick, rough estimates of property values at key temperatures of interest.

Readers are not advised to take data from the plots directly, though it is possible. Web plot digitizer [23] exemplifies an online tool that enables the conversion of trendlines and data markers into a series of tabulated values. Please obtain approval to use external software from the appropriate authority at your organization before utilizing browser-based tools like these. Each page following a property plot contains tabulated data and a fit equation – and these two tools are superior methods for incorporating material property values into models and designs than using the material property plots directly.

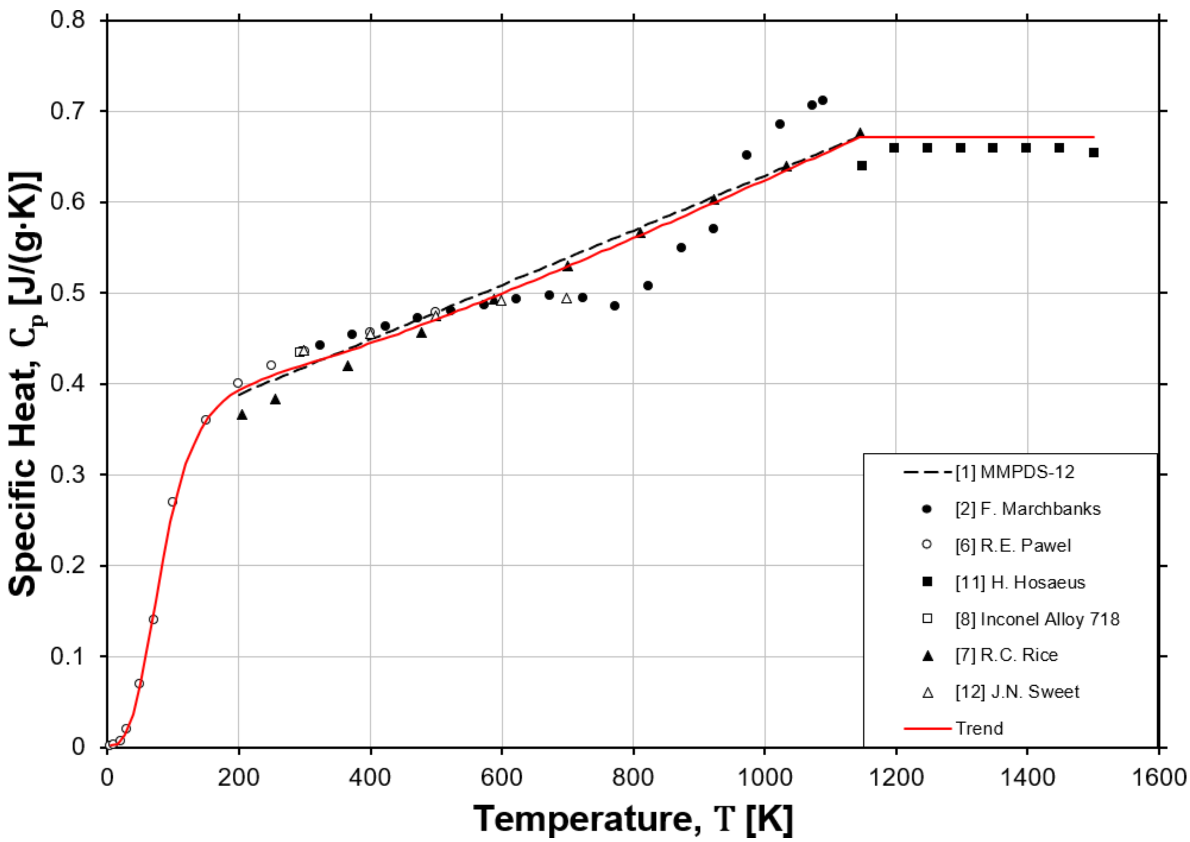

Figure V-16: Example of a material property plot. This plot captures specific heat data on IN718 from references [2, 6-8, 11, 12] *of Section 2.1.1* as black data points, shows a red trendline of the data, and compares that trend with a trend found in reference [1] *of Section 2.1.1*.

V.4.4 How to Use Material Property, Room Temperature, Composition, and Summary Tables

Tables are used in several ways within the handbook. The primary use is as a material property table, or the tabular counterpart of the red trends provided in material property plots. Table V-6 is one such table. These tables serve to capture the values of a property trend at different intervals. The tables typically begin at the trend's minimum defined temperature and extend up to the maximum temperature. When using these tables, note that the intervals between temperature values are not uniform, particularly near the extremes of the trend. For that reason, copying and pasting data from these tables is recommended. Double checking that values have been transferred correctly is also useful for verification.

Temperatures are listed in both Kelvin and degrees Fahrenheit within these tables. Likewise, both metric and English units are provided for the corresponding material property. To aid in differentiating between the unit systems, English units are always surrounded by parentheses.

Table V-6: Example of a material property table. This table contains values for the beryllium electrical resistivity trend with temperature.

Temperature (T)		Electrical Resistivity (ρ_e)		Temperature (T)		Electrical Resistivity (ρ_e)	
K	(°F)	μΩ-m	(μΩ-in)	K	(°F)	μΩ-m	(μΩ-in)
79	(-317.5)	0.010	(0.39)	800	(980.3)	0.190	(7.48)
100	(-279.7)	0.012	(0.47)	850	(1070.3)	0.207	(8.14)
150	(-189.7)	0.018	(0.70)	900	(1160.3)	0.224	(8.82)
200	(-99.7)	0.026	(1.02)	950	(1250.3)	0.242	(9.53)
250	(-9.7)	0.035	(1.39)	1000	(1340.3)	0.261	(10.28)
300	(80.3)	0.046	(1.82)	1050	(1430.3)	0.281	(11.08)
350	(170.3)	0.058	(2.29)	1100	(1520.3)	0.303	(11.94)
400	(260.3)	0.071	(2.79)	1150	(1610.3)	0.327	(12.87)
450	(350.3)	0.084	(3.32)	1200	(1700.3)	0.353	(13.89)
500	(440.3)	0.098	(3.88)	1250	(1790.3)	0.381	(15.01)
550	(530.3)	0.113	(4.44)	1300	(1880.3)	0.413	(16.25)
600	(620.3)	0.128	(5.03)	1329	(1932.5)	0.433	(17.03)
650	(710.3)	0.143	(5.62)				
700	(800.3)	0.158	(6.23)				
750	(890.3)	0.174	(6.85)				

Another commonly used table type is the room temperature properties table, as illustrated by Table V-7. As stated in the table's name, these tables contain data at RT. For the purposes of this handbook, RT corresponds with temperatures from 288 to 298 K, or 59 to 77 °F. Metric units are used in this table type, and International System of Units (SI units) are preferred.

Property values at RT are often derived directly from the material property trends stemming from other subsections in the handbook. When property values at RT cannot be provided, values may be taken at different temperatures, and notes are used to call out the discrepancy. Alternatively, values at RT can be found by extrapolating material property trends. But see Section V.3.2 to learn more about the dangers of extrapolation.

Table V-7: Example of a room temperature properties table. This table contains single-point values for several properties of zirconium carbide. Note the units in square brackets and the melting point tolerance.

Molar Mass, [g/mol]	103.23
Theoretical Density, [kg/m^3]	6,730
Melting Point, [K]	3693±30
Specific Heat, [J/(g-K)]	0.363
Thermal Conductivity, [W/(m-K)]	26.3
Linear expansion coefficient, [μm/(m-K)]	5.10
Electrical resistivity, [μΩ-m]	0.61
Young's Modulus, [GPa]	397.9
Shear Modulus, [GPa]	161.8
Poisson’s Ratio, [-]	0.229

Not all properties in the RT properties table are truly “room temperature properties”. For example, a material’s melting point is not taken at RT – it is evaluated at the temperature for which a solid material experiences a phase change to become liquid. Regardless, these single-value properties are still presented in these RT properties tables for ease of organization.

Following the RT properties tables are composition tables, such as Table V-8. These tables show the elemental constituents within a material. Values are provided in wt% unless otherwise specified. Minimums and maximums compositions for each element are regularly listed. Dashes reflect compositions of zero wt%, while the word “balance” reveals the element making up the remainder of the material once all the other elemental composition percentages are considered. When different grades – or designations – of materials are under consideration, composition tables can reflect the varying compositions. Unless stated otherwise, the material property values in the rest of a material section correspond with the composition(s) provided in the composition table.

Table V-8: Example composition table. Here, the elemental breakdown for SS304 is provided in wt%. Dashes are used to indicate zero or unavailable compositions.

Grade		Fe	Cr	Ni	C	Mn	Si	P	S	N
304	Min.	Balance	18.0	8.0	-	-	-	-	-	-
	Max.		20.0	10.5	0.08	2.0	0.75	0.045	0.030	0.10
304L	Min.	Balance	18.0	8.0	-	-	-	-	-	-
	Max.		20.0	12	0.03	2.0	0.75	0.045	0.030	0.10
304H	Min.	Balance	18.0	8.0	0.04	-	-	-	-	-
	Max.		20.0	10.5	0.10	2.0	0.75	0.045	0.030	

At the end of each material section, immediately before the References subsection, comes the Tabulated Property Data subsection. These subsections consist entirely of material property summary tables. See Table V-9 for an example. Much like the material property tables, these summary tables are founded on the red trends of various material property plots. The unique aspect of these summary tables is the fact that material property values for several different properties are collected in a single location. Those who use the handbook regularly and require rapid access to data on several properties for a material may find these tables useful.

Additionally, since the summary tables are built from trends, the tables can also be used to determine the range of temperatures for which a given trend exists.

Table V-9: Example of a material property summary table. This example corresponds with the property values for TZM. Note that the temperatures in the leftmost column correspond with the property values in all the other columns.

Temp.	Physical and Electrical		Thermal				Elastic		
Temp. (T) K	Density (ρ) kg/m³	Electrical Resistivity (ρ_e) μΩ-m	Thermal Conductivity (k) W/(m-K)	Thermal Expansion (dL/L_0) %	Mean CTE ($\bar{\alpha}$) 10^{-6}/K	Specific Heat (C_p) J/(g-K)	Young's Modulus (E) GPa	Shear Modulus (G) GPa	Poisson's Ratio (ν)
200	-	-	-	-	-	-	314.04	-	-
293	10220	0.079	123.22	0.000	4.97	0.269	306.31	122.7	0.293
300	10219	0.081	122.94	0.004	4.99	0.268	305.71	-	-
400	10201	0.106	119.40	0.062	5.18	0.265	297.09	-	-
500	10184	0.132	116.55	0.119	5.32	0.265	288.17	-	-
600	10166	0.157	114.20	0.176	5.43	0.267	278.95	-	-
700	10149	0.182	112.22	0.233	5.51	0.269	269.43	-	-
800	10131	0.207	110.46	0.291	5.58	0.272	259.62	-	-
900	10114	0.233	108.80	0.349	5.65	0.276	249.51	-	-
1000	10096	0.258	107.16	0.409	5.72	0.281	239.10	-	-
1100	10077	0.283	105.44	0.470	5.79	0.287	228.39	-	-
1200	10058	-	103.57	0.534	5.86	0.293	217.39	-	-
1300	10038	-	101.52	0.599	5.95	0.301	206.09	-	-
1400	10018	-	99.25	0.668	6.03	0.309	194.49	-	-
1500	9997	-	96.74	0.739	6.13	0.317	182.60	-	-
1600	9975	-	94.00	0.814	6.24	0.327	170.40	-	-
1700	9951	-	91.06	0.892	6.36	0.337	157.91	-	-
1800	9927	-	87.94	0.975	6.49	0.348	145.13	-	-
1900	9901	-	84.71	1.062	6.63	0.360	132.04	-	-
2000	9874	-	81.43	1.155	6.78	0.372	118.66	-	-
2100	9846	-	78.20	1.252	6.94	0.386	104.98	-	-
2200	9816	-	75.13	1.355	7.11	0.399	91.00	-	-
2300	9784	-	72.34	1.464	7.30	0.414	76.73	-	-
2500	9716	-	68.19	1.702	7.71	0.446	47.29	-	-
2700	9640	-	-	1.968	8.16	0.480	-	-	-

V.4.5 How to Use Fit Equations

Fit equations are equivalent to the red trends of material property plots – but they take the form of mathematical expressions. Various symbols are used in the equations. Symbols representing material properties are defined in Table V-5 of Section V.4.1, and they are often functions of temperature, as exemplified in Figure V-17 below. Most of the remaining symbols in fit equations are constants. The symbols for these constants are composed of a letter at a minimum, though they often include a number as well, as in the case of “A0”, “B_2”, etc. At present, the symbol composition is multifaceted. Sometimes the letters of coefficients are used to differentiate between multiple piecewise equations, while in other situations, the letters might distinguish between the numerator and denominator of a single equation. Readers are advised to pay close attention to the full expression provided in the upper left corner of each fit equation listing.

Below the mathematical expression of the fit equation, brief definitions of the independent and dependent variables are given. For example, in Figure V-17, T corresponds with temperature, the independent variable, and $G(T)$ is shear modulus, the dependent variable. Units are provided for these variables, and fit equations *must* be used with matching units. Various conversions are required to use the fit equations with units they were not built around.

Ranges of the independent variables for which the fit equation can be used are also listed, though these ranges can be stated in either the left or right half of the fit equation figure, as space allows. Using the expression outside of such a range may be permissible, though the act is an extrapolation, and it should be documented as such.

Constants are defined in the right half of the fit equation figure. The units associated with the constants vary greatly and are not necessary for modelers and designers – for that reason, they are not included. Please contact the SNP Material Property Handbook team if the units for fit equation constants are desired and cannot be calculated by the reader. When multiple trends are used to characterize a material property, coefficients can be given multiple values to define the different equations. For example, in Figure V-17, coefficients are given different values depending on whether the reader wishes to use the "minimum" or the "high" trend for tungsten's shear modulus. In either case, the reader only needs to take the appropriate values from the right half of the fit equation figure and substitute them into the mathematical expression of the upper left part of the fit equation figure. While Figure V-17 applies for two distinct curves with the same temperature range, the process for using fit equations is identical for scenarios involving piecewise equations with multiple temperature ranges.

Note that temperatures are regularly divided by a thousand, as shown in Figure V-17. This adjustment is a form of scaling that helps manage the magnitudes of constants. In addition, this scaling aids MATLAB – the curve fitting software described in Section V.3.2 – in avoiding rounding errors [24]. Within MATLAB's curve fitting tool, one can detect the threat of rounding errors by the presence of an "equation is badly conditioned" warning.

Fit Equations:

$$G(T) = A0 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2 + A3 \cdot \left(\frac{T}{1000}\right)^3$$

$G(T) = Shear\ Modulus\ [GPa]$

$T = Temperature\ [K]$

T Range [K]: $273 \leq T \leq 2873$

Constants:

Curve:	Minimum	High
A0 =	158.4	163.5
A1 =	-16.99	-11.98
A2 =	6.101	-3.414
A3 =	-3.92	0

Figure V-17: Example of a fit equation, including the definition of constants. This equation applies to the shear modulus of tungsten.

VI FRONT MATTER REFERENCES

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1 Light Metal Alloys

1.1 Aluminum Alloys

Room Temperature Properties

Density, [kg/m^3]	2,800
Melting Point, [K]	745 to 910
Specific Heat, [J/(g-K)]	0.845
Thermal Conductivity, [W/(m-K)]	144.7
Linear expansion coefficient, [μm/(m-K)]	22.44
Electrical resistivity, [μΩ-m]	0.05
Young's Modulus, [GPa]	69.4
Shear Modulus, [GPa]	26.1
Poisson’s Ratio, [-]	0.330

Composition

Table 1.1.1-1: Typical Composition ranges for Aluminum 7075 alloy (percent by weight).

Grade		Al	Zn	Cr	Cu	Fe	Mg	Mn	Si	Ti	Other
Al7075	Min.	87.1	5.1	0.18	1.2		2.1				
	Max.	91.4	6.1	0.28	2.0	0.50	2.9	0.30	0.4	0.2	0.15

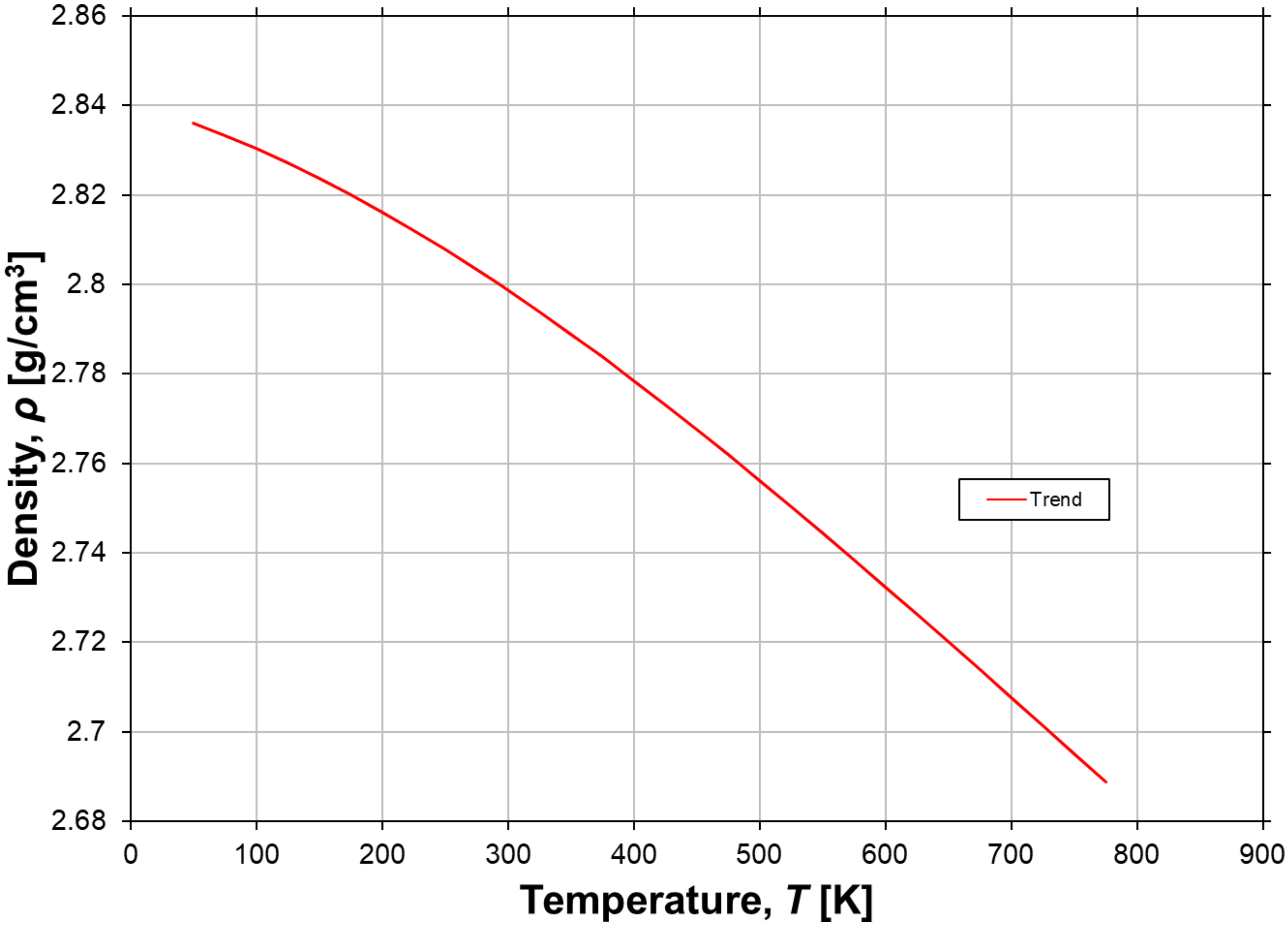

Figure 1.1.1-1: Density versus Temperature for Aluminum 7075. Calculated from fitted trend of Thermal Expansion data.

100% Theoretical Density

Temperature (T)		Density (ρ)		Temperature (T)		Density (ρ)	
K	(°F)	kg/m³	(lb/ft³)	K	(°F)	kg/m³	(lb/ft³)
50	(-369.7)	2836	(177.1)	425	(305.3)	2773	(173.1)
75	(-324.7)	2833	(176.9)	450	(350.3)	2768	(172.8)
100	(-279.7)	2830	(176.7)	475	(395.3)	2762	(172.4)
125	(-234.7)	2827	(176.5)	500	(440.3)	2756	(172.1)
150	(-189.7)	2824	(176.3)	525	(485.3)	2750	(171.7)
175	(-144.7)	2820	(176.1)	550	(530.3)	2744	(171.3)
200	(-99.7)	2816	(175.8)	575	(575.3)	2738	(171.0)
225	(-54.7)	2812	(175.6)	600	(620.3)	2732	(170.6)
250	(-9.7)	2808	(175.3)	625	(665.3)	2726	(170.2)
275	(35.3)	2803	(175.0)	650	(710.3)	2720	(169.8)
300	(80.3)	2799	(174.7)	675	(755.3)	2714	(169.4)
325	(125.3)	2794	(174.4)	700	(800.3)	2708	(169.0)
350	(170.3)	2789	(174.1)	725	(845.3)	2701	(168.6)
375	(215.3)	2784	(173.8)	750	(890.3)	2695	(168.3)
400	(260.3)	2778	(173.5)	775	(935.3)	2689	(167.9)

Application Notes: Density is calculated as a function of thermal expansion as seen in the equation below to approximate property trend with respect to temperature.

Density Calculation:

$\rho(T) = \rho_{RT}/(1 + dL/L_0(T)/100)^3$

$\rho(T) = Density\ [kg/m^3]$

$Room\ Temperature\ Density\ (\rho_{RT}) = 2800\ [kg/m^3]$

$T = Temperature\ [K]$

Temperature Range: $50 \leq T \leq 775$

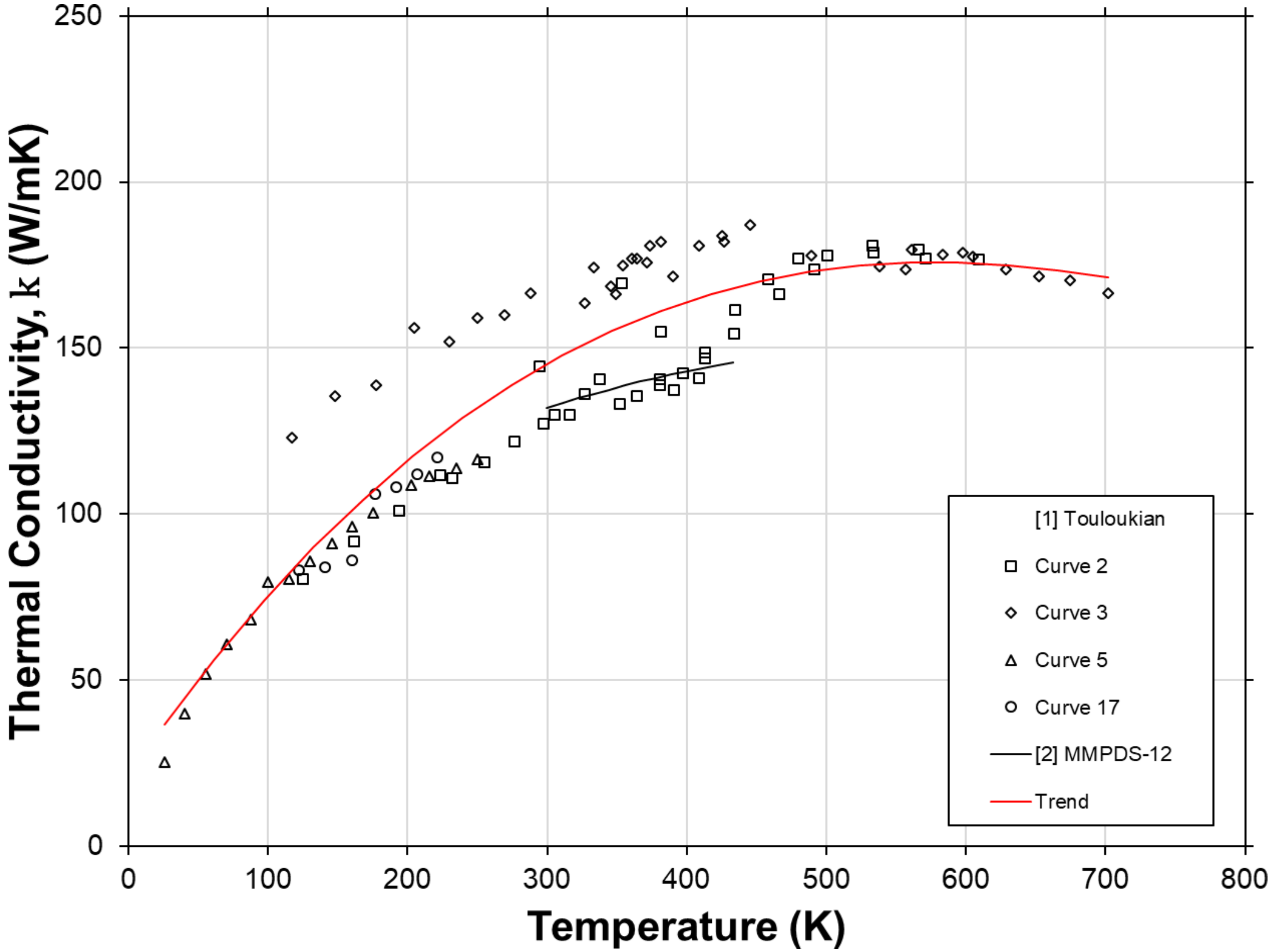

Figure 1.1.1-2: Thermal Conductivity versus Temperature for Aluminum 7075, compared to trend from MMPDS-12, Al 7075, T-6, A Basis.

100% Theoretical Density

Temperature (T)		Thermal Conductivity (k)		Temperature (T)		Thermal Conductivity (k)	
K	(°F)	W/(m-K)	((Btu·in)/(ft²·hr·°F))	K	(°F)	W/(m-K)	((Btu·in)/(ft²·hr·°F))
25	(-414.7)	36.17	(250.93)	375	(215.3)	160.17	(1111.31)
50	(-369.7)	50.03	(347.12)	400	(260.3)	163.97	(1137.65)
75	(-324.7)	63.04	(437.40)	425	(305.3)	167.20	(1160.06)
100	(-279.7)	75.22	(521.91)	450	(350.3)	169.89	(1178.70)
125	(-234.7)	86.59	(600.80)	475	(395.3)	172.05	(1193.69)
150	(-189.7)	97.17	(674.19)	500	(440.3)	173.71	(1205.18)
175	(-144.7)	106.98	(742.25)	525	(485.3)	174.88	(1213.32)
200	(-99.7)	116.04	(805.10)	550	(530.3)	175.59	(1218.24)
225	(-54.7)	124.37	(862.89)	575	(575.3)	175.85	(1220.09)
250	(-9.7)	131.99	(915.76)	600	(620.3)	175.70	(1219.01)
275	(35.3)	138.92	(963.85)	625	(665.3)	175.14	(1215.13)
300	(80.3)	145.19	(1007.31)	650	(710.3)	174.20	(1208.61)
325	(125.3)	150.80	(1046.28)	675	(755.3)	172.90	(1199.59)
350	(170.3)	155.79	(1080.90)	702	(803.9)	171.11	(1187.19)

Application Notes: Data for thermal conductivity is collected from reference [1], and compared against data trend from reference [2]. Data is fitted with the equation below to approximate property trend with respect to temperature.

Fit Equation:

$$k(T) = A0 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2 + A3 \cdot \left(\frac{T}{1000}\right)^3$$

$k(T) = Thermal\ Conductivity\ [W/(m \cdot K)]$

$T = Temperature\ [K]$

Constants:

T Range [K]: $25 \leq T \leq 702$

A0 = 21.43

A1 = 607.2

A2 = -714.4

A3 = 218.2

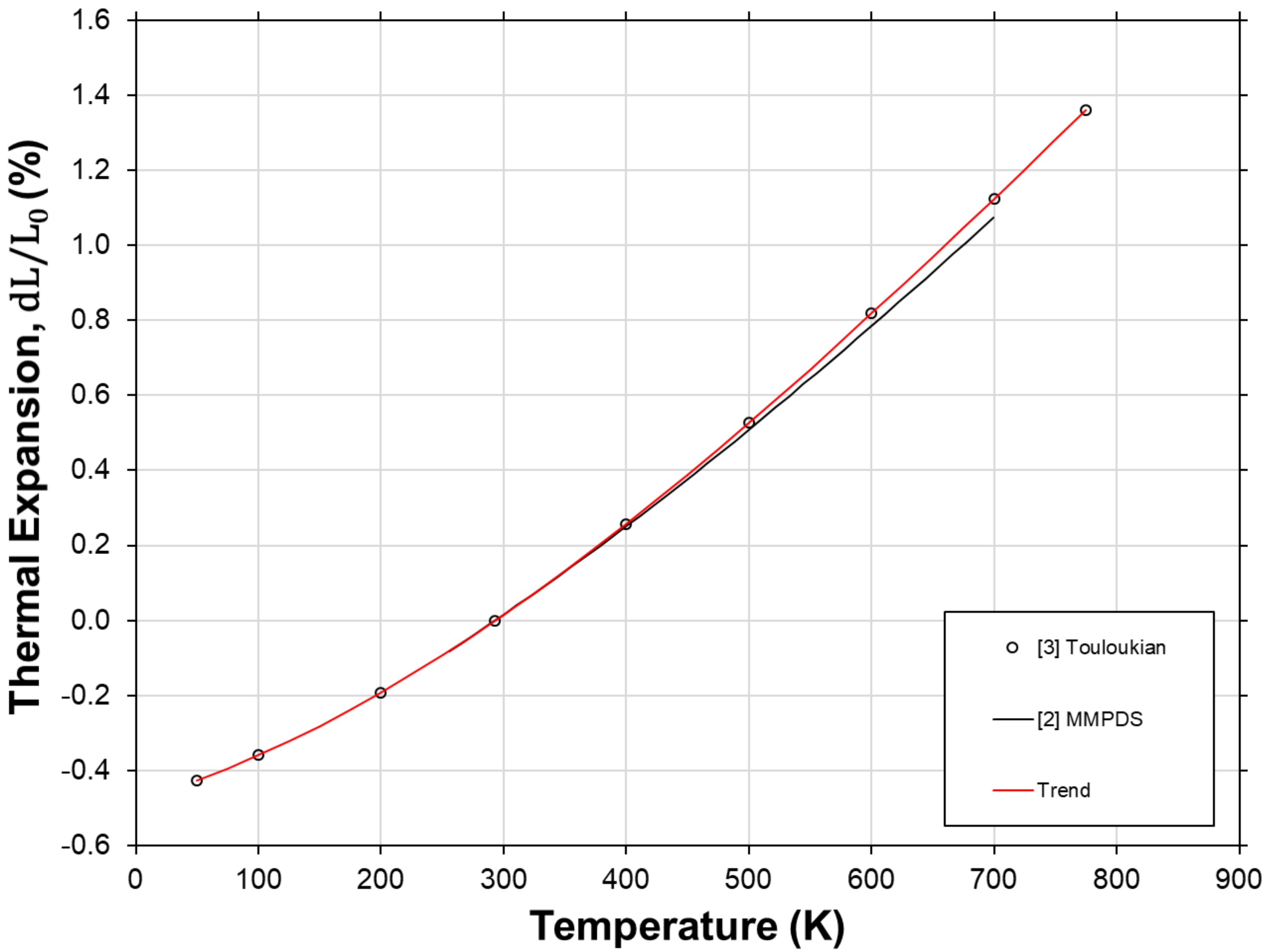

Figure 1.1.1-3: Thermal Expansion versus Temperature for Aluminum 7075, compared against trend from MMPDS -12, Al 7075, T-6, A Basis.

100% Theoretical Density

Temperature (T)		Thermal Expansion (dL/L_0)	Temperature (T)		Thermal Expansion (dL/L_0)
K	(°F)	%	K	(°F)	%
50	(-369.7)	-0.425	425	(305.3)	0.322
75	(-324.7)	-0.393	450	(350.3)	0.389
100	(-279.7)	-0.359	475	(395.3)	0.457
125	(-234.7)	-0.321	500	(440.3)	0.527
150	(-189.7)	-0.281	525	(485.3)	0.598
175	(-144.7)	-0.238	550	(530.3)	0.670
200	(-99.7)	-0.192	575	(575.3)	0.744
225	(-54.7)	-0.144	600	(620.3)	0.818
250	(-9.7)	-0.093	625	(665.3)	0.893
275	(35.3)	-0.040	650	(710.3)	0.970
300	(80.3)	0.016	675	(755.3)	1.046
325	(125.3)	0.073	700	(800.3)	1.124
350	(170.3)	0.133	725	(845.3)	1.202
375	(215.3)	0.194	750	(890.3)	1.280
400	(260.3)	0.257	775	(935.3)	1.359

Application Notes: Data for thermal expansion is collected from reference [3] and compared to data trend from reference [2]. Data is fitted with the equation below to approximate property trend with respect to temperature.

Fit Equation:

$$dL/L_0\,(T) = A0 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2 + A3 \cdot \left(\frac{T}{1000}\right)^3$$

$dL/L_0\,(T) = Thermal\ Expansion\ [\%]$

$T = Temperature\ [K]$

Constants:

T Range [K]: $50 \leq T \leq 775$

A0 =	-0.4785
A1 =	0.9386
A2 =	2.684
A3 =	-1.078

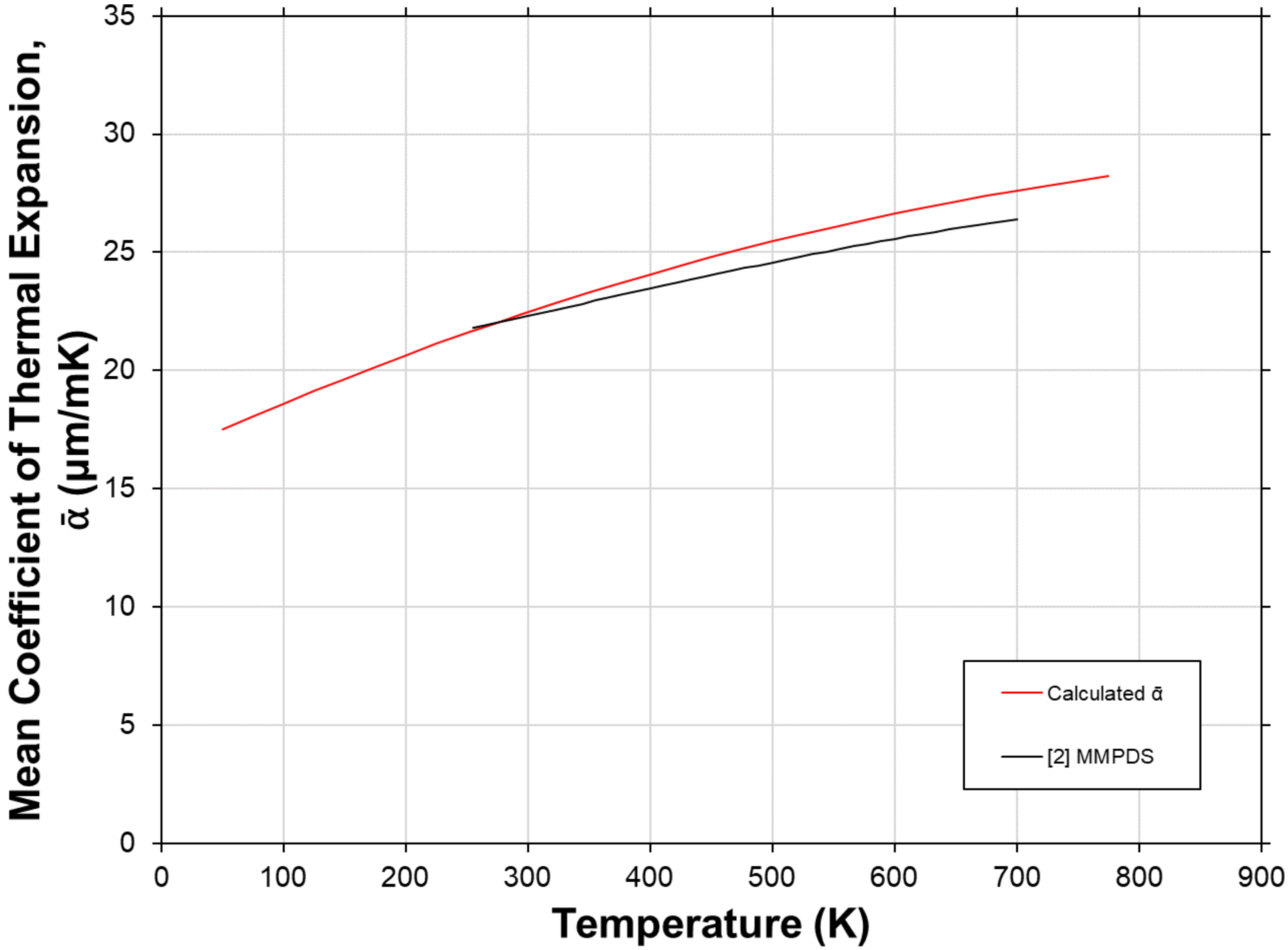

Figure 1.1.1-4: Mean Coefficient of Thermal Expansion verses Temperature for Aluminum 7075. Calculated from fitted trend of the Thermal Expansion data, and compared against trend from MMPDS -12, Al 7075, T-6, A Basis.

100% Theoretical Density

Temperature (T)		Mean CTE (ᾱ)		Temperature (T)		Mean CTE (ᾱ)	
K	(°F)	μm/(m-K)	(μin/(in-°F))	K	(°F)	μm/(m-K)	(μin/(in-°F))
50	(-369.7)	17.495	(9.720)	425	(305.3)	24.439	(13.577)
75	(-324.7)	18.057	(10.031)	450	(350.3)	24.793	(13.774)
100	(-279.7)	18.603	(10.335)	475	(395.3)	25.134	(13.963)
125	(-234.7)	19.136	(10.631)	500	(440.3)	25.461	(14.145)
150	(-189.7)	19.654	(10.919)	525	(485.3)	25.775	(14.320)
175	(-144.7)	20.158	(11.199)	550	(530.3)	26.076	(14.487)
200	(-99.7)	20.648	(11.471)	575	(575.3)	26.365	(14.647)
225	(-54.7)	21.124	(11.736)	600	(620.3)	26.640	(14.800)
250	(-9.7)	21.587	(11.993)	625	(665.3)	26.903	(14.946)
275	(35.3)	22.035	(12.242)	650	(710.3)	27.153	(15.085)
300	(80.3)	22.470	(12.483)	675	(755.3)	27.390	(15.217)
325	(125.3)	22.891	(12.717)	700	(800.3)	27.615	(15.341)
350	(170.3)	23.298	(12.943)	725	(845.3)	27.827	(15.459)
375	(215.3)	23.692	(13.162)	750	(890.3)	28.026	(15.570)
400	(260.3)	24.072	(13.374)	775	(935.3)	28.214	(15.674)

Application Notes: Data for mean coefficient of thermal expansion is calculated from the trend for thermal expansion. Calculated data is then fitted with the equation below to approximate property trend with respect to temperature and compared against data trend from reference [2].

Fit Equation:

$$\bar{\alpha}(T) = A0 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2 + A3 \cdot \left(\frac{T}{1000}\right)^3$$

$\bar{\alpha}(T) = Coefficient\ of\ Thermal\ Expansion\ [\mu m/(m \cdot K)]$

$T = Temperature\ [K]$

Constants:

T. Range [K]:	$50 \leq T \leq 775$
A0 =	16.33
A1 =	23.89
A2 =	-11.65
A3 =	0.7872

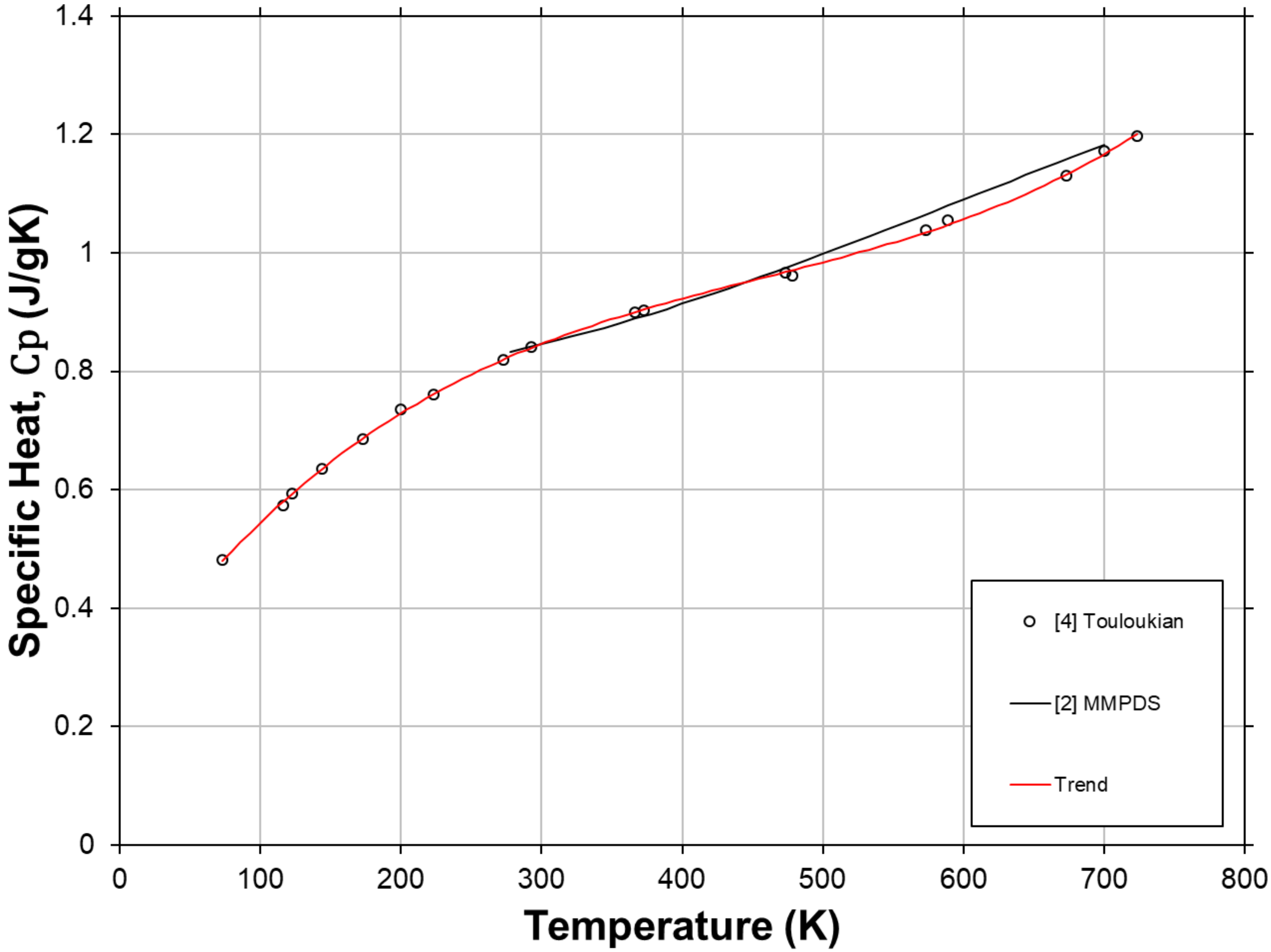

Figure 1.1.1-5: Specific Heat versus Temperature for Aluminum 7075, compared against data trend from MMPDS-12, Al 7075, T-6, A Basis.

100% Theoretical Density

Temperature (T)		Specific Heat (C_p)		Temperature (T)		Specific Heat (C_p)	
K	(°F)	J/(g-K)	(BTU/(lb-°F))	K	(°F)	J/(g-K)	(BTU/(lb-°F))
73	(-328.3)	0.479	(0.115)	425	(305.3)	0.938	(0.224)
100	(-279.7)	0.544	(0.130)	450	(350.3)	0.954	(0.228)
125	(-234.7)	0.598	(0.143)	475	(395.3)	0.969	(0.232)
150	(-189.7)	0.647	(0.155)	500	(440.3)	0.984	(0.235)
175	(-144.7)	0.690	(0.165)	525	(485.3)	1.000	(0.239)
200	(-99.7)	0.729	(0.174)	550	(530.3)	1.017	(0.243)
225	(-54.7)	0.764	(0.183)	575	(575.3)	1.036	(0.248)
250	(-9.7)	0.795	(0.190)	600	(620.3)	1.057	(0.253)
275	(35.3)	0.822	(0.196)	625	(665.3)	1.080	(0.258)
300	(80.3)	0.847	(0.202)	650	(710.3)	1.106	(0.264)
325	(125.3)	0.868	(0.208)	675	(755.3)	1.135	(0.271)
350	(170.3)	0.888	(0.212)	700	(800.3)	1.167	(0.279)
375	(215.3)	0.906	(0.217)	723	(841.7)	1.201	(0.287)
400	(260.3)	0.923	(0.221)				

Application Notes: Data for specific heat is collected from reference [4], and fitted with the equation below to approximate property trend with respect to temperature and compared against data trend from reference [2].

Fit Equation:

$$C_P(T) = A0 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2 + A3 \cdot \left(\frac{T}{1000}\right)^3$$

$C_P(T) = Specific\ Heat\ [J\ /\ (g \cdot K)]$

$T = Temperature\ [K]$

Constants:

T. Range [K]:	$73 \leq T \leq 723$
A0 =	0.2656
A1 =	3.343
A2 =	-6.003
A3 =	4.382

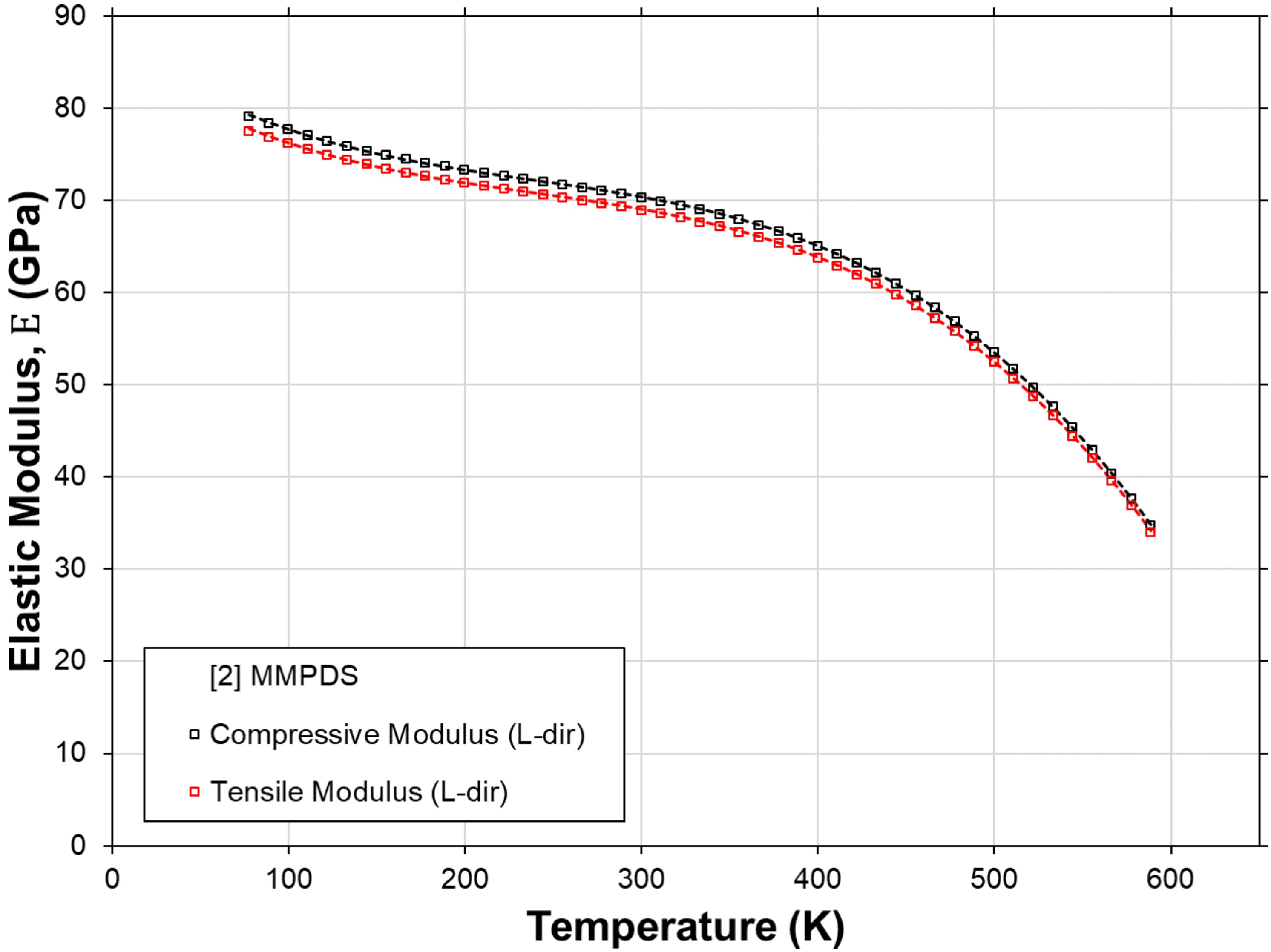

Figure 1.1.1-6: Compressive and Tensile Modulus versus Temperature for Aluminum 7075, T-6, A Basis.

100% Theoretical Density Tensile Modulus

Temperature (T) K	(°F)	Young's Modulus (E) GPa	(Msi)	Temperature (T) K	(°F)	Young's Modulus (E) GPa	(Msi)
75	(-324.7)	77.93	(11.31)	380	(224.3)	65.21	(9.46)
100	(-279.7)	76.18	(11.05)	400	(260.3)	63.80	(9.26)
120	(-243.7)	75.01	(10.88)	420	(296.3)	62.14	(9.02)
140	(-207.7)	74.03	(10.74)	440	(332.3)	60.20	(8.74)
160	(-171.7)	73.20	(10.62)	460	(368.3)	57.96	(8.41)
180	(-135.7)	72.49	(10.52)	480	(404.3)	55.37	(8.03)
200	(-99.7)	71.86	(10.43)	500	(440.3)	52.42	(7.61)
220	(-63.7)	71.30	(10.35)	520	(476.3)	49.07	(7.12)
240	(-27.7)	70.76	(10.27)	540	(512.3)	45.29	(6.57)
260	(8.3)	70.22	(10.19)	560	(548.3)	41.05	(5.96)
280	(44.3)	69.64	(10.11)	580	(584.3)	36.32	(5.27)
300	(80.3)	69.01	(10.01)	600	(620.3)	31.07	(4.51)
320	(116.3)	68.27	(9.91)				
340	(152.3)	67.42	(9.78)				
360	(188.3)	66.41	(9.64)				

Application Notes: The data for Young's Modulus (tensile and compressive) is collected from reference [2], and fitted with the equation below to approximate property trend with respect to temperature.

Fit Equations:

$$E(T) = A0 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2 + A3 \cdot \left(\frac{T}{1000}\right)^3$$

$E(T) = Young's\ Modulus\ [GPa]$

$T = Temperature\ [K]$

Constants:

T Range [K]: $75 \leq T \leq 600$

	Compressive	Tensile
A0 =	87.47	85.76
A1 =	-137.6	-134.9
A2 =	463.2	454.1
A3 =	-648	-635.3

Temp. (T) K	Physical and Electrical		Thermal				Elastic		
	Density (ρ) kg/m³	Electrical Resistivity (ρ_e) μΩ-m	Thermal Conductivity (k) W/(m-K)	Thermal Expansion (dL/L_0) %	Mean CTE ($\bar{\alpha}$) 10^{-6}/K	Specific Heat (C_p) J/(g-K)	Young's Modulus (E) GPa	Shear Modulus (G) GPa	Poisson's Ratio (ν)
100	2830		75.22	-0.359	18.60	0.544	76.18		
150	2824		97.17	-0.281	19.65	0.647	73.60		
200	2816		116.04	-0.192	20.65	0.729	71.86		
250	2808		131.99	-0.093	21.59	0.795	70.49		
293	2800		143.50	0.000	22.35	0.840	69.24		
300	2799		145.19	0.016	22.47	0.847	69.01		
325	2794		150.80	0.073	22.89	0.868	68.07		
350	2789		155.79	0.133	23.30	0.888	66.93		
375	2784		160.17	0.194	23.69	0.906	65.53		
400	2778		163.97	0.257	24.07	0.923	63.80		
425	2773		167.20	0.322	24.44	0.938	61.68		
450	2768		169.89	0.389	24.79	0.954	59.12		
475	2762		172.05	0.457	25.13	0.969	56.05		
500	2756		173.71	0.527	25.46	0.984	52.42		
525	2750		174.88	0.598	25.78	1.000	48.17		
550	2744		175.59	0.670	26.08	1.017	43.23		
575	2738		175.85	0.744	26.36	1.036	37.55		
600	2732		175.70	0.818	26.64	1.057	31.07		
625	2726		175.14	0.893	26.90	1.080	-		
650	2720		174.20	0.970	27.15	1.106	-		
675	2714		172.90	1.046	27.39	1.135	-		
700	2708		171.26	1.124	27.61	1.167	-		
725	2701		-	1.202	27.83	-	-		
750	2695		-	1.280	28.03	-	-		
775	2689		-	1.359	28.21	-	-		

References

[1] Y.S. Touloukian, R.W. Powell, C.Y. Ho, P.G. Klemens, Thermal Conductivity - Metallic Elements and Alloys, Thermophysical Properties of Matter - The TPRC Data Series, Vol. 1, Thermophysical and Electronic Properties Information Analysis Center, Lafayette, IN, 1970.

[2] MMPDS-12. (Accessed July 2019).

[3] Y.S. Touloukian, R.K. Kirby, R.E. Taylor, P.D. Desai, Thermal Expansion - Metallic Elements and Alloys, Thermophysical Properties of Matter - the TPRC Data Series, Vol. 12, Thermophysical and Electronic Properties Information Analysis Center, Lafayette, IN, web, 1975.

[4] Y.S. Touloukian, E.H. Buyco, Specific Heat - Nonmetallic Solids, Thermophysical Properties of Matter - the TPRC Data Series, Thermophysical and Electronic Properties Information Analysis Center, Lafayette, IN, 1970.

1 Light Metal Alloys

1.2 Titanium Alloys

Room Temperature Properties

Density, [kg/m^3]	4,430
Melting Point, [K]	1947
Specific Heat, [J/(g-K)]	0.538
Thermal Conductivity, [W/(m-K)]	7.3*
Linear expansion coefficient, [μm/(m-K)]	9.59
Electrical resistivity, [μΩ-m]	1.70
Young's Modulus, [GPa]	110.5
Shear Modulus, [GPa]	42.2
Poisson’s Ratio, [-]	0.310

*at 311 K

Composition

Table 1.2.1-1: Typical Composition ranges for grade 5 Ti-6Al-4V alloy (percent by weight) [1].

Grade		Ti	Al	V	Fe	O	C	N	H	Other
Ti-6Al-4V	Min.	87.6	5.5	3.5						
	Max.	91.0	6.75	4.5	0.40	0.20	0.08	0.05	0.015	0.40

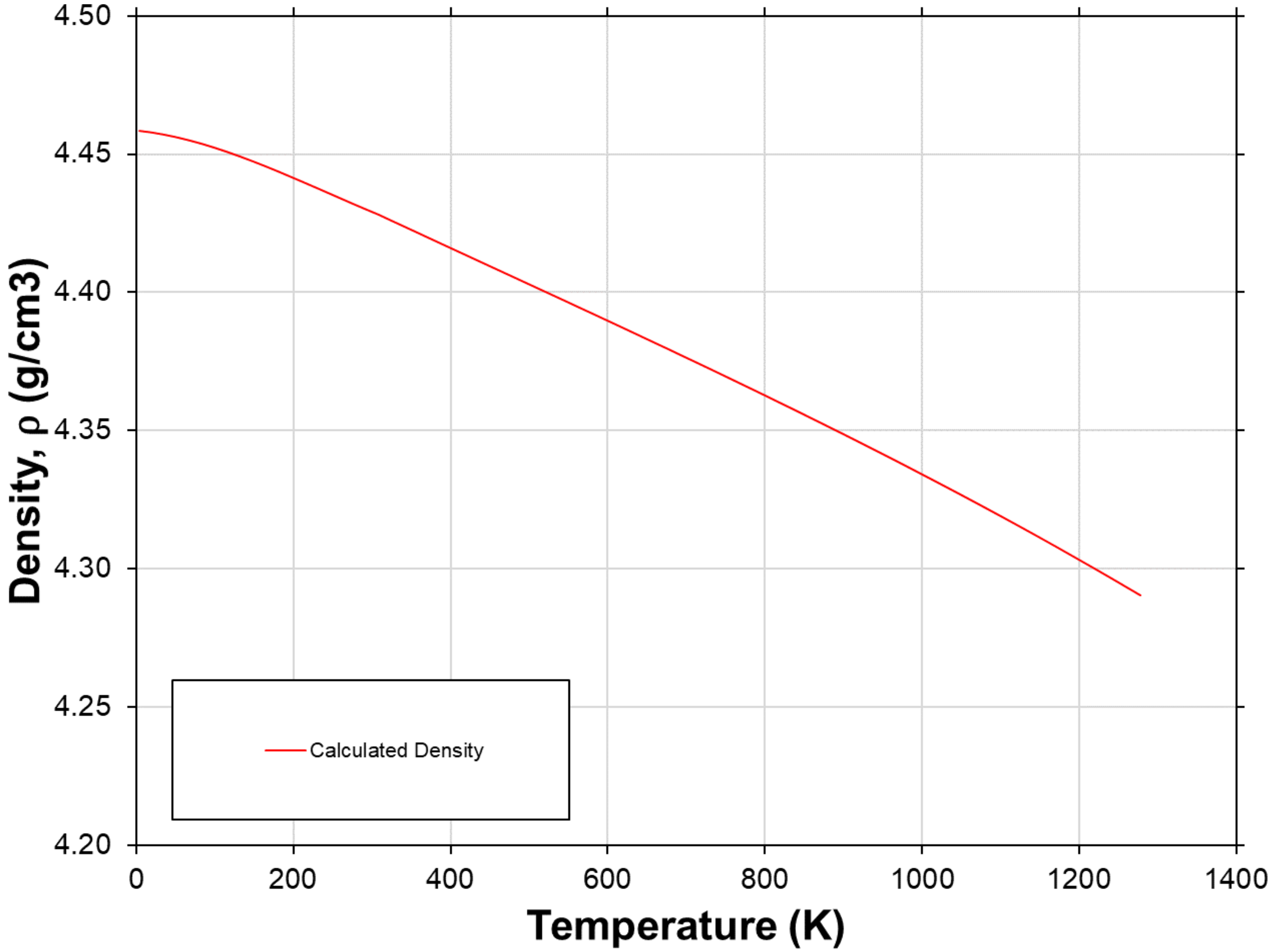

Figure 1.2.1-1: Density versus Temperature for Ti-6Al-4V. Calculated from fitted trend of the Thermal Expansion data.

Density with Temperature

100% Theoretical Density

Temperature (T)		Density (ρ)		Temperature (T)		Density (ρ)	
K	(°F)	kg/m³	(lb/ft³)	K	(°F)	kg/m³	(lb/ft³)
5	(-450.7)	4459	(278.3)	650	(710.3)	4383	(273.6)
25	(-414.7)	4458	(278.3)	700	(800.3)	4376	(273.2)
50	(-369.7)	4456	(278.2)	750	(890.3)	4370	(272.8)
75	(-324.7)	4455	(278.1)	800	(980.3)	4363	(272.4)
100	(-279.7)	4452	(278.0)	850	(1070.3)	4356	(271.9)
150	(-189.7)	4447	(277.6)	900	(1160.3)	4349	(271.5)
200	(-99.7)	4442	(277.3)	950	(1250.3)	4341	(271.0)
250	(-9.7)	4435	(276.9)	1000	(1340.3)	4334	(270.6)
300	(80.3)	4429	(276.5)	1050	(1430.3)	4327	(270.1)
350	(170.3)	4423	(276.1)	1100	(1520.3)	4319	(269.6)
400	(260.3)	4416	(275.7)	1150	(1610.3)	4311	(269.1)
450	(350.3)	4410	(275.3)	1200	(1700.3)	4303	(268.6)
500	(440.3)	4403	(274.9)	1250	(1790.3)	4295	(268.1)
550	(530.3)	4396	(274.5)	1278	(1840.7)	4290	(267.8)
600	(620.3)	4390	(274.1)				

Application Notes: Density is calculated as a function of Thermal Expansion as seen in the equation below to approximate property trend with respect to temperature.

Density Calculation:

$\rho(T) = \rho_{RT}/(1 + dL/L_0(T)/100)^3$

$\rho(T) = Density\ [kg/m^3]$

$Room\ Temperature\ Density\ (\rho_{RT}) = 4{,}430\ \ [kg/m^3]$

$T = Temperature\ [K]$

Temperature Range: $4 \le T \le 1278$

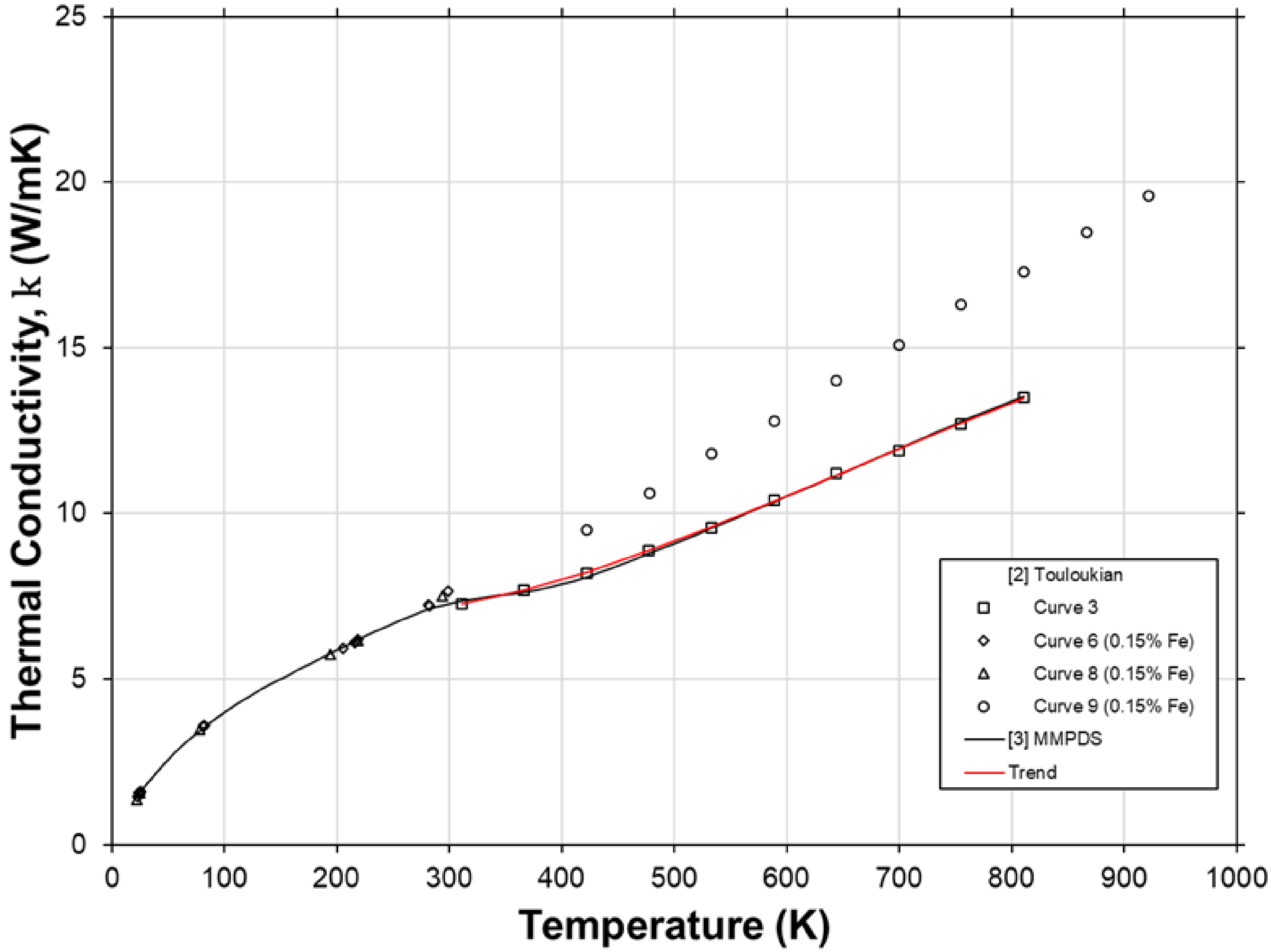

Figure 1.2.1-2: Thermal Conductivity versus Temperature for Ti-6Al-4V with comparison to MMPDS-12, solution treated and aged, S-Basis.

100% Theoretical Density

Temperature (T)		Thermal Conductivity (k)		Temperature (T)		Thermal Conductivity (k)	
K	(°F)	W/(m-K)	((Btu·in)/(ft²·hr·°F))	K	(°F)	W/(m-K)	((Btu·in)/(ft²·hr·°F))
311	(100.1)	7.27	(50.47)	580	(584.3)	10.24	(71.05)
320	(116.3)	7.33	(50.88)	600	(620.3)	10.52	(73.01)
340	(152.3)	7.48	(51.88)	620	(656.3)	10.81	(74.99)
360	(188.3)	7.64	(53.00)	640	(692.3)	11.10	(76.99)
380	(224.3)	7.82	(54.24)	660	(728.3)	11.39	(78.99)
400	(260.3)	8.01	(55.57)	680	(764.3)	11.67	(80.99)
420	(296.3)	8.22	(57.01)	700	(800.3)	11.96	(82.98)
440	(332.3)	8.44	(58.53)	720	(836.3)	12.25	(84.96)
460	(368.3)	8.67	(60.13)	740	(872.3)	12.53	(86.91)
480	(404.3)	8.91	(61.81)	760	(908.3)	12.80	(88.83)
500	(440.3)	9.16	(63.55)	780	(944.3)	13.07	(90.71)
520	(476.3)	9.42	(65.36)	800	(980.3)	13.34	(92.54)
540	(512.3)	9.69	(67.21)	811	(1000.1)	13.48	(93.52)
560	(548.3)	9.96	(69.11)				

Application Notes: Data for thermal conductivity is collected from reference [2] and fitted with the equation below to approximate the property trend with respect to temperature. Fitted trend is compared against reference [3].

Fit Equation:

$$k(T) = A0 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2 + A3 \cdot \left(\frac{T}{1000}\right)^3$$

$k(T) = Thermal\ Conductivity\ (W/m \cdot K)$

$T = Temperature\ [K]$

Constants:

T Range [K]	$311 \leq T \leq 811$
A0 =	8.254
A1 =	-14.85
A2 =	44.69
A3 =	-22.73

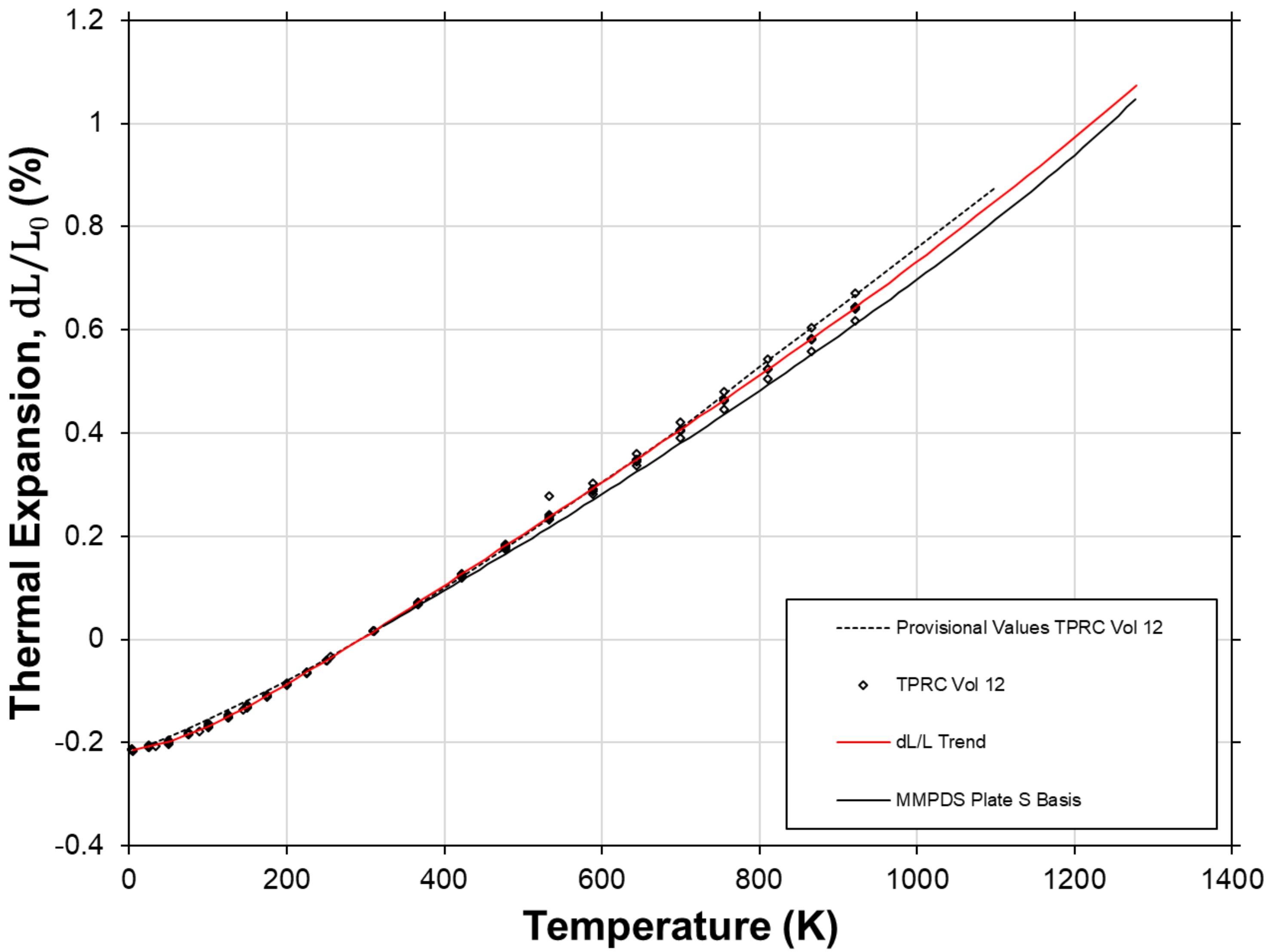

Figure 1.2.1-3: Thermal Expansion versus Temperature for Ti-6Al-4V. Calculated from fitted trend of Thermal Expansion with comparison against MMPDS-12, solution treated and aged, S-Basis.

100% Theoretical Density

Temperature (T) K	(°F)	Thermal Expansion (dL/L_0) %	Temperature (T) K	(°F)	Thermal Expansion (dL/L_0) %
5	(-450.7)	-0.214	650	(710.3)	0.355
25	(-414.7)	-0.208	700	(800.3)	0.407
50	(-369.7)	-0.198	750	(890.3)	0.459
75	(-324.7)	-0.184	800	(980.3)	0.511
100	(-279.7)	-0.168	850	(1070.3)	0.565
150	(-189.7)	-0.130	900	(1160.3)	0.619
200	(-99.7)	-0.087	950	(1250.3)	0.675
250	(-9.7)	-0.040	1000	(1340.3)	0.732
300	(80.3)	0.005	1050	(1430.3)	0.790
350	(170.3)	0.055	1100	(1520.3)	0.849
400	(260.3)	0.105	1150	(1610.3)	0.910
450	(350.3)	0.154	1200	(1700.3)	0.973
500	(440.3)	0.204	1250	(1790.3)	1.037
550	(530.3)	0.254	1278	(1840.7)	1.074
600	(620.3)	0.304			

Application Notes: Data for thermal expansion is collected from reference [4] and fitted with the equation below to approximate property trend with respect to temperature. Fitted trend is compared against trend from reference [3].

Fit Equation:

$$dL/L_0\,(T) = A0 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2 + A3 \cdot \left(\frac{T}{1000}\right)^3$$

$dL/L_0\,(T) = Thermal\ Expansion\ [\%]$

$T = Temperature\ [K]$

Constants:

T Range [K]:	$2 \le T < 293$	$293 \le T \le 1278$
A0 =	-0.2151	-0.3017
A1 =	0.2126	1.06
A2 =	2.949	-0.1675
A3 =	-4.007	0.1411

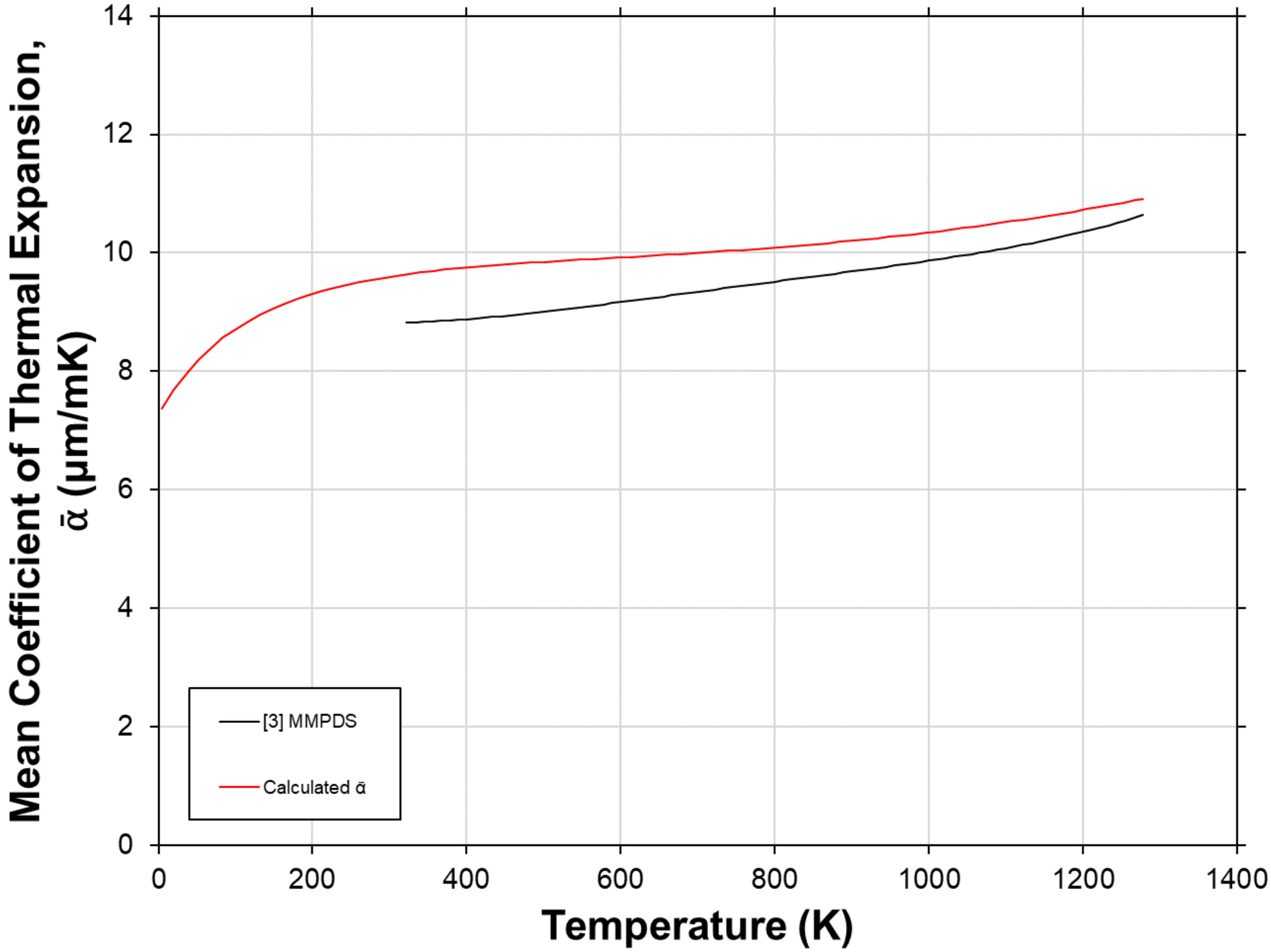

Figure 1.2.1-4: Mean Coefficient of Thermal Expansion versus Temperature for Ti-6Al-4V. Calculated from fitted trend of the Thermal Expansion data, with comparison to MMPDS-12, solution treated and aged, S-Basis.

100% Theoretical Density

Temperature (T)		Mean CTE (ᾱ)		Temperature (T)		Mean CTE (ᾱ)	
K	(°F)	μm/(m-K)	(μin/(in-°F))	K	(°F)	μm/(m-K)	(μin/(in-°F))
5	(-450.7)	7.394	(4.108)	650	(710.3)	9.959	(5.533)
25	(-414.7)	7.782	(4.324)	700	(800.3)	9.999	(5.555)
50	(-369.7)	8.168	(4.538)	750	(890.3)	10.042	(5.579)
75	(-324.7)	8.472	(4.707)	800	(980.3)	10.090	(5.606)
100	(-279.7)	8.714	(4.841)	850	(1070.3)	10.144	(5.636)
150	(-189.7)	9.070	(5.039)	900	(1160.3)	10.204	(5.669)
200	(-99.7)	9.311	(5.173)	950	(1250.3)	10.271	(5.706)
250	(-9.7)	9.479	(5.266)	1000	(1340.3)	10.346	(5.748)
300	(80.3)	9.598	(5.332)	1050	(1430.3)	10.428	(5.794)
350	(170.3)	9.685	(5.381)	1100	(1520.3)	10.519	(5.844)
400	(260.3)	9.751	(5.417)	1150	(1610.3)	10.618	(5.899)
450	(350.3)	9.803	(5.446)	1200	(1700.3)	10.727	(5.959)
500	(440.3)	9.847	(5.470)	1250	(1790.3)	10.844	(6.024)
550	(530.3)	9.885	(5.492)	1278	(1840.7)	10.914	(6.063)
600	(620.3)	9.922	(5.512)				

Application Notes: Data for mean coefficient of thermal expansion is calculated as a function of thermal expansion. Calculated data is fitted with the equation below to approximate property trend with respect to temperature. Fitted trend is compared against trend from reference [3].

Fit Equation:

$$\bar{\alpha}(T) = \left[A0 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2 + A3 \cdot \left(\frac{T}{1000}\right)^3\right] / \left[A\_0 + \left(\frac{T}{1000}\right)\right]$$

$\bar{\alpha}(T) = Coefficient\ of\ Thermal\ Expansion\ [\mu m/(m \cdot K)]$

$T = Temperature\ [K]$

Constants:

T. Range [K]:	$4 \le T \le 1278$
A0 =	1.477
A1 =	11.91
A2 =	-3.152
A3 =	2.209
A_0 =	0.2028

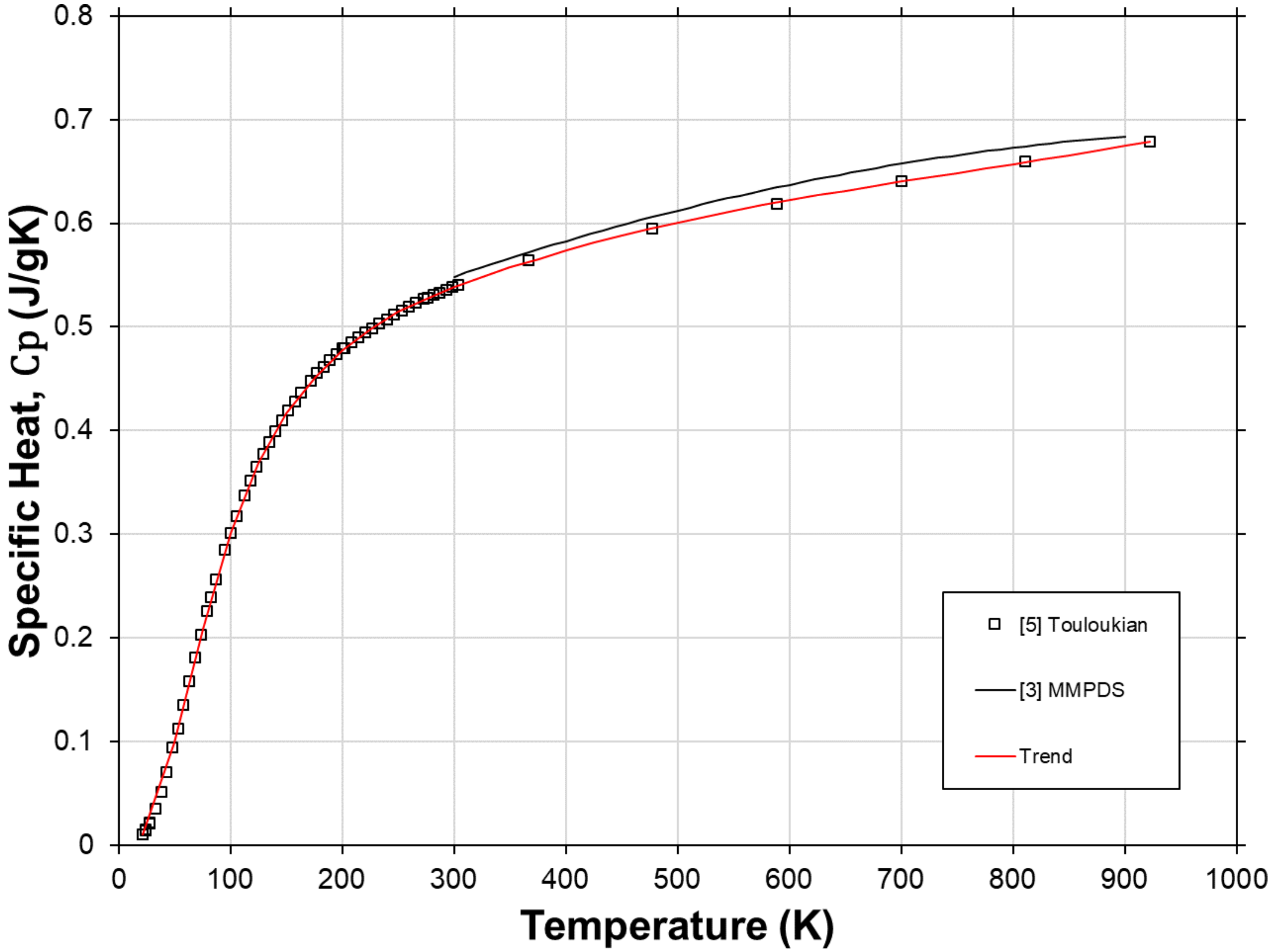

Figure 1.2.1-5: Specific Heat verses Temperature for Ti-6Al-4V with comparison to MMPDS-12, solution treated and aged, S-Basis.

100% Theoretical Density

Temperature (T)		Specific Heat (C_p)		Temperature (T)		Specific Heat (C_p)	
K	(°F)	J/(g-K)	(BTU/(lb-°F))	K	(°F)	J/(g-K)	(BTU/(lb-°F))
21	(-421.9)	0.011	(0.003)	350	(170.3)	0.557	(0.133)
50	(-369.7)	0.099	(0.024)	400	(260.3)	0.574	(0.137)
75	(-324.7)	0.209	(0.050)	450	(350.3)	0.588	(0.141)
100	(-279.7)	0.301	(0.072)	500	(440.3)	0.601	(0.144)
125	(-234.7)	0.368	(0.088)	550	(530.3)	0.612	(0.146)
150	(-189.7)	0.416	(0.100)	600	(620.3)	0.622	(0.149)
175	(-144.7)	0.451	(0.108)	650	(710.3)	0.631	(0.151)
200	(-99.7)	0.478	(0.114)	700	(800.3)	0.640	(0.153)
225	(-54.7)	0.498	(0.119)	750	(890.3)	0.648	(0.155)
250	(-9.7)	0.514	(0.123)	800	(980.3)	0.657	(0.157)
275	(35.3)	0.528	(0.126)	850	(1070.3)	0.666	(0.159)
300	(80.3)	0.538	(0.129)	900	(1160.3)	0.675	(0.161)
325	(125.3)	0.548	(0.131)	922	(1199.9)	0.679	(0.162)

Application Notes: Data for specific heat is collected from reference [5] and fitted with the equations below to approximate property trend with respect to temperature. Fitted trend is compared against trend from reference [3].

Fit Equation:

For temperature range: $21 \leq T < 293$

$$C_P(T) = \left[A0 \cdot \left(\frac{T}{1000}\right)^N\right] \Big/ \left[1 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2 + A3 \cdot \left(\frac{T}{1000}\right)^3\right]$$

For temperature range: $293 \leq T \leq 922$

$$C_P(T) = B0 + B1 \cdot \left(\frac{T}{1000}\right) + B2 \cdot \left(\frac{T}{1000}\right)^2 + B\_2 / \left(\frac{T}{1000}\right)^2$$

$C_P(T) = Specific\ Heat\ [J/(g \cdot K)]$

$T = Temperature\ [K]$

Constants:

T. Range [K]:	$21 \leq T \leq 293$		$293 < T \leq 922$
N =	2.982	B0 =	0.3615
A0 =	1126	B1 =	0.8142
A1 =	-0.415	B2 =	-0.8631
A2 =	124.9	B_2 =	0.3836
A3 =	1688		

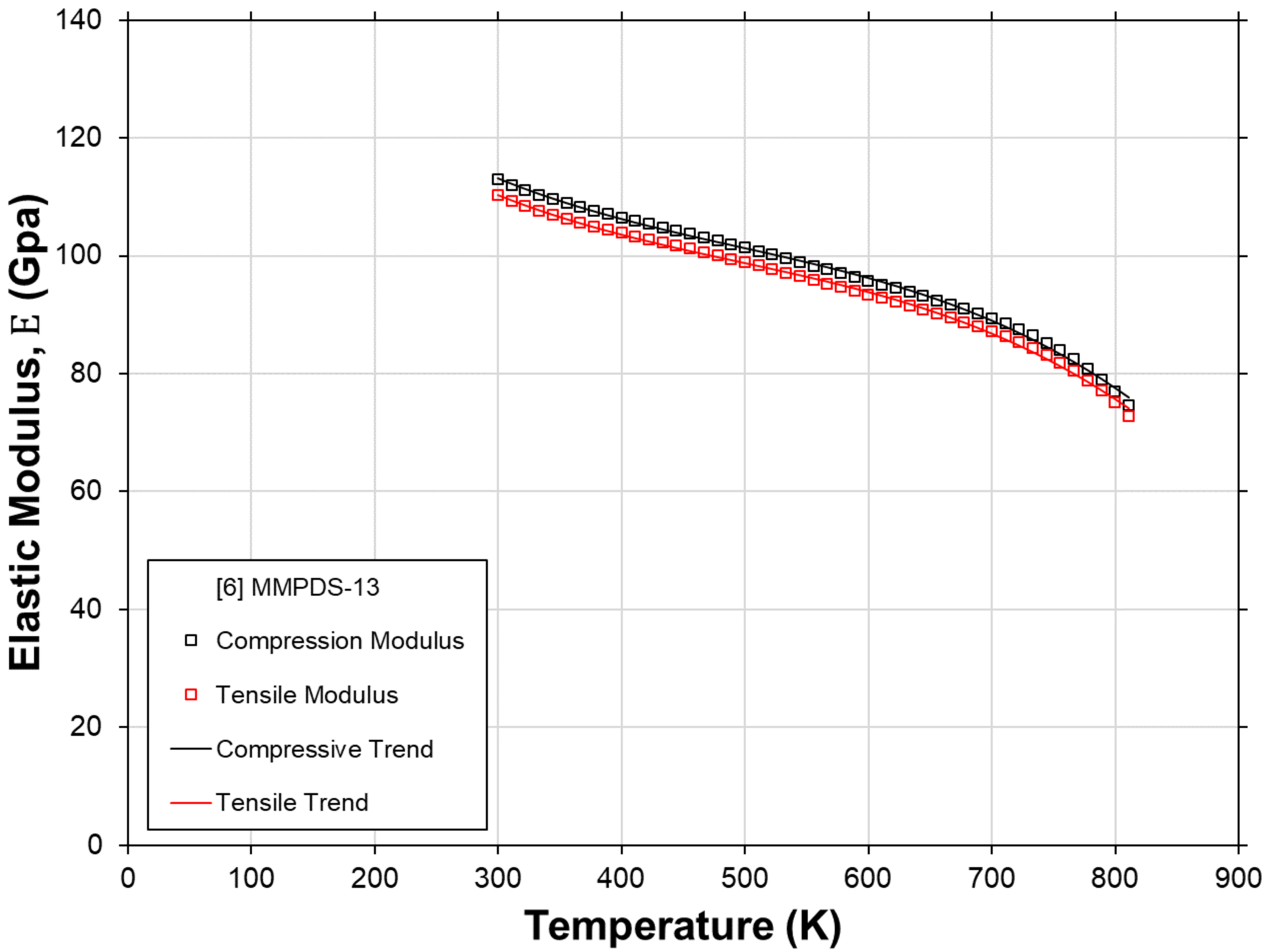

Figure 1.2.1-6: Tensile and Compressive Youngs Modulus vs Temperature, adapted from MMPDS-13, solution treated and aged, S-Basis.

100% Theoretical Density Tensile Modulus

Temperature (T)		Young's Modulus (E)		Temperature (T)		Young's Modulus (E)	
K	(°F)	GPa	(Msi)	K	(°F)	GPa	(Msi)
298	(76.7)	110.50	(16.03)	600	(620.3)	93.85	(13.62)
320	(116.3)	108.74	(15.78)	620	(656.3)	92.67	(13.45)
340	(152.3)	107.29	(15.57)	640	(692.3)	91.39	(13.26)
360	(188.3)	105.97	(15.38)	660	(728.3)	90.00	(13.06)
380	(224.3)	104.75	(15.20)	680	(764.3)	88.47	(12.84)
400	(260.3)	103.62	(15.03)	700	(800.3)	86.80	(12.59)
420	(296.3)	102.56	(14.88)	720	(836.3)	84.96	(12.33)
440	(332.3)	101.57	(14.74)	740	(872.3)	82.94	(12.03)
460	(368.3)	100.62	(14.60)	760	(908.3)	80.72	(11.71)
480	(404.3)	99.70	(14.47)	780	(944.3)	78.29	(11.36)
500	(440.3)	98.79	(14.33)	800	(980.3)	75.64	(10.97)
520	(476.3)	97.87	(14.20)	811	(1000.1)	74.07	(10.75)
540	(512.3)	96.94	(14.07)				
560	(548.3)	95.96	(13.92)				
580	(584.3)	94.94	(13.78)				

Application Notes: Data for Young's Modulus (tensile and compressive) is adapted from reference [6] and fitted with the equation below to approximate property trend with respect to temperature.

Fit Equations:

$$E(T) = A0 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2 + A3 \cdot \left(\frac{T}{1000}\right)^3$$

$E(T) = Elastic\ Modulus\ [GPa]$

$T = Temperature\ [K]$

Constants:

T Range [K]: $298 \leq T \leq 811$

	Tensile	Compressive
A0 =	161.8	165.9
A1 =	-289.8	-297.2
A2 =	494.1	506.8
A3 =	-333.1	-341.7

	Physical and Electrical		Thermal				Elastic		
Temp. (T) K	Density (ρ) kg/m³	Electrical Resistivity (ρ_e) μΩ-m	Thermal Conductivity (k) W/(m-K)	Thermal Expansion (dL/L_0) %	Mean CTE ($\bar{\alpha}$) 10^{-6}/K	Specific Heat (C_p) J/(g-K)	Young's Modulus (E) GPa	Shear Modulus (G) GPa	Poisson's Ratio (ν)
100	4452		-	-0.168	8.71	0.301	-		
150	4447		-	-0.130	9.07	0.416	-		
200	4442		-	-0.087	9.31	0.478	-		
250	4435		-	-0.040	9.48	0.514	-		
295	4430		-	0.000	9.59	0.536	-		
300	4429		-	0.005	9.60	0.538	110.34		
350	4423		7.56	0.055	9.69	0.557	106.62		
400	4416		8.01	0.105	9.75	0.574	103.62		
450	4410		8.55	0.154	9.80	0.588	101.09		
500	4403		9.16	0.204	9.85	0.601	98.79		
550	4396		9.82	0.254	9.89	0.612	96.46		
600	4390		10.52	0.304	9.92	0.622	93.85		
650	4383		11.24	0.355	9.96	0.631	90.71		
700	4376		11.96	0.407	10.00	0.640	86.80		
750	4370		12.67	0.459	10.04	0.648	81.85		
800	4363		13.34	0.511	10.09	0.657	75.64		
850	4356		-	0.565	10.14	0.666	-		
900	4349		-	0.619	10.20	0.675	-		
950	4341		-	0.675	10.27	-	-		
1000	4334		-	0.732	10.35	-	-		
1050	4327		-	0.790	10.43	-	-		
1100	4319		-	0.849	10.52	-	-		
1150	4311		-	0.910	10.62	-	-		
1200	4303		-	0.973	10.73	-	-		
1250	4295		-	1.037	10.84	-	-		

[1] Material Universe. (Accessed July 2019).

[2] Y.S. Touloukian, R.W. Powell, C.Y. Ho, P.G. Klemens, Thermal Conductivity - Metallic Elements and Alloys, Thermophysical Properties of Matter - The TPRC Data Series, Vol. 1, Thermophysical and Electronic Properties Information Analysis Center, Lafayette, IN, 1970.

[3] MMPDS-12. (Accessed July 2019).

[4] Y.S. Touloukian, R.K. Kirby, R.E. Taylor, P.D. Desai, Thermal Expansion - Metallic Elements and Alloys, Thermophysical Properties of Matter - the TPRC Data Series, Vol. 12, Thermophysical and Electronic Properties Information Analysis Center, Lafayette, IN, web, 1975.

[5] Y.S. Touloukian, R.K. Kirby, R.E. Taylor, P.D. Desai, Specific Heat - Metallic Elements and Alloys, Thermophysical Properties of Matter - The TPRC Data Series, Vol. 4, Thermophysical and Electronic Properties Information Analysis Center, Lafayette, IN, 1971.

[6] MMPDS-13. (Accessed 06/19/2020).

2 Nickel – Base Alloys

2.1 Precipitation Hardened Alloys

Room Temperature Properties

Theoretical Density, [kg/m^3]	8,220
Melting Point, [K]	1533
Specific Heat, [J/(g-K)]	0.420
Thermal Conductivity, [W/(m-K)]	11.0
Linear expansion coefficient, [µm/(m-K)]	12.09
Electrical resistivity, [µΩ-m]	1.17
Young's Modulus, [GPa]	202.3
Shear Modulus, [GPa]	78.4
Poisson’s Ratio, [-]	0.293

Composition

Table 2.1.1-1: Typical Composition ranges for Inconel 718 (percent by weight) [1].

Grade		C	Mn	P	S	Si	Cr	Ni	Mo	Nb
	Min.	-	-	-	-	-	17.0	50.0	2.80	2.40
	Max.	0.08	0.35	0.015	0.015	0.35	21.0	55.5	3.30	2.80
IN718		**Ta**	**Nb+Ta**	**Ti**	**Al**	**Co**	**B**	**Cu**	**Fe**	
	Min.	2.40	4.75	0.65	0.20	-	-	-	Balance	
	Max.	2.80	5.50	1.15	0.80	1.0	0.006	0.30		

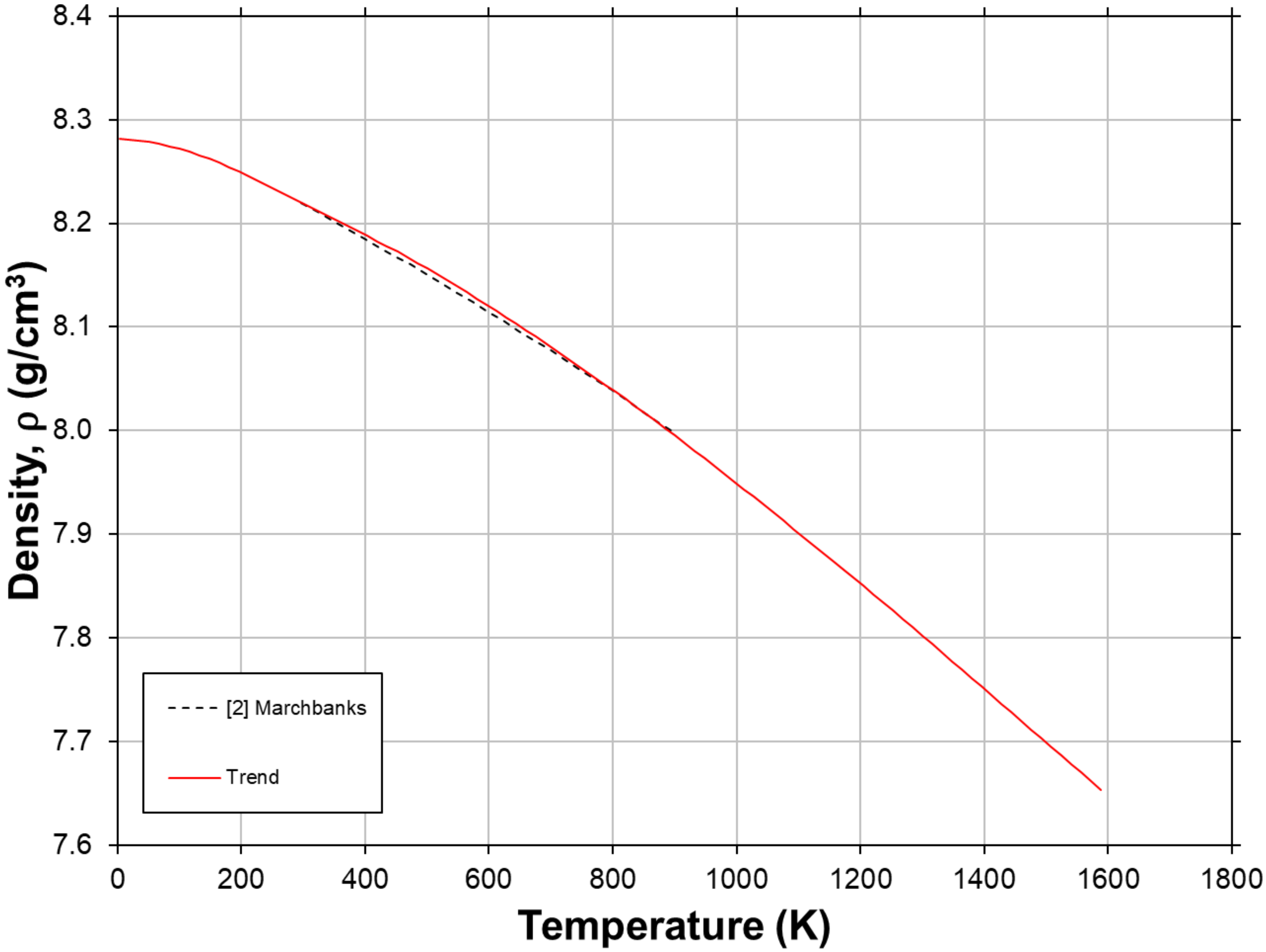

Figure 2.1.1-1: Density versus Temperature for Inconel 718. Calculated from fitted trend of the Thermal Expansion data with comparison to Marchbanks (1976).

100% Theoretical Density

Temperature (T)		Density (ρ)		Temperature (T)		Density (ρ)	
K	(°F)	kg/m³	(lb/ft³)	K	(°F)	kg/m³	(lb/ft³)
5	(-450.7)	8281	(517.0)	700	(800.3)	8081	(504.5)
25	(-414.7)	8281	(517.0)	750	(890.3)	8060	(503.2)
50	(-369.7)	8279	(516.8)	800	(980.3)	8039	(501.9)
100	(-279.7)	8272	(516.4)	850	(1070.3)	8017	(500.5)
150	(-189.7)	8262	(515.8)	900	(1160.3)	7995	(499.1)
200	(-99.7)	8249	(515.0)	950	(1250.3)	7972	(497.7)
250	(-9.7)	8234	(514.1)	1000	(1340.3)	7949	(496.3)
300	(80.3)	8219	(513.1)	1050	(1430.3)	7926	(494.8)
350	(170.3)	8204	(512.2)	1100	(1520.3)	7901	(493.3)
400	(260.3)	8189	(511.2)	1150	(1610.3)	7877	(491.8)
450	(350.3)	8173	(510.2)	1200	(1700.3)	7852	(490.2)
500	(440.3)	8156	(509.2)	1300	(1880.3)	7802	(487.1)
550	(530.3)	8138	(508.1)	1400	(2060.3)	7751	(483.9)
600	(620.3)	8120	(506.9)	1500	(2240.3)	7699	(480.7)
650	(710.3)	8101	(505.7)	1588	(2398.7)	7653	(477.8)

Application Notes: Density trend is calculated as a function of thermal expansion, shown in the equation below, and compared against trend from reference [2].

Density Calculation:

$\rho(T) = \rho_{RT}/(1 + dL/L_0(T)/100)^3$

$\rho(T) = Density\ [kg/m^3]$

$Room\ Temperature\ Density\ (\rho_{RT}) = 8{,}220\ [kg/m^3]$

$T = Temperature\ [K]$

Temperature Range: $4 \leq T \leq 1588$

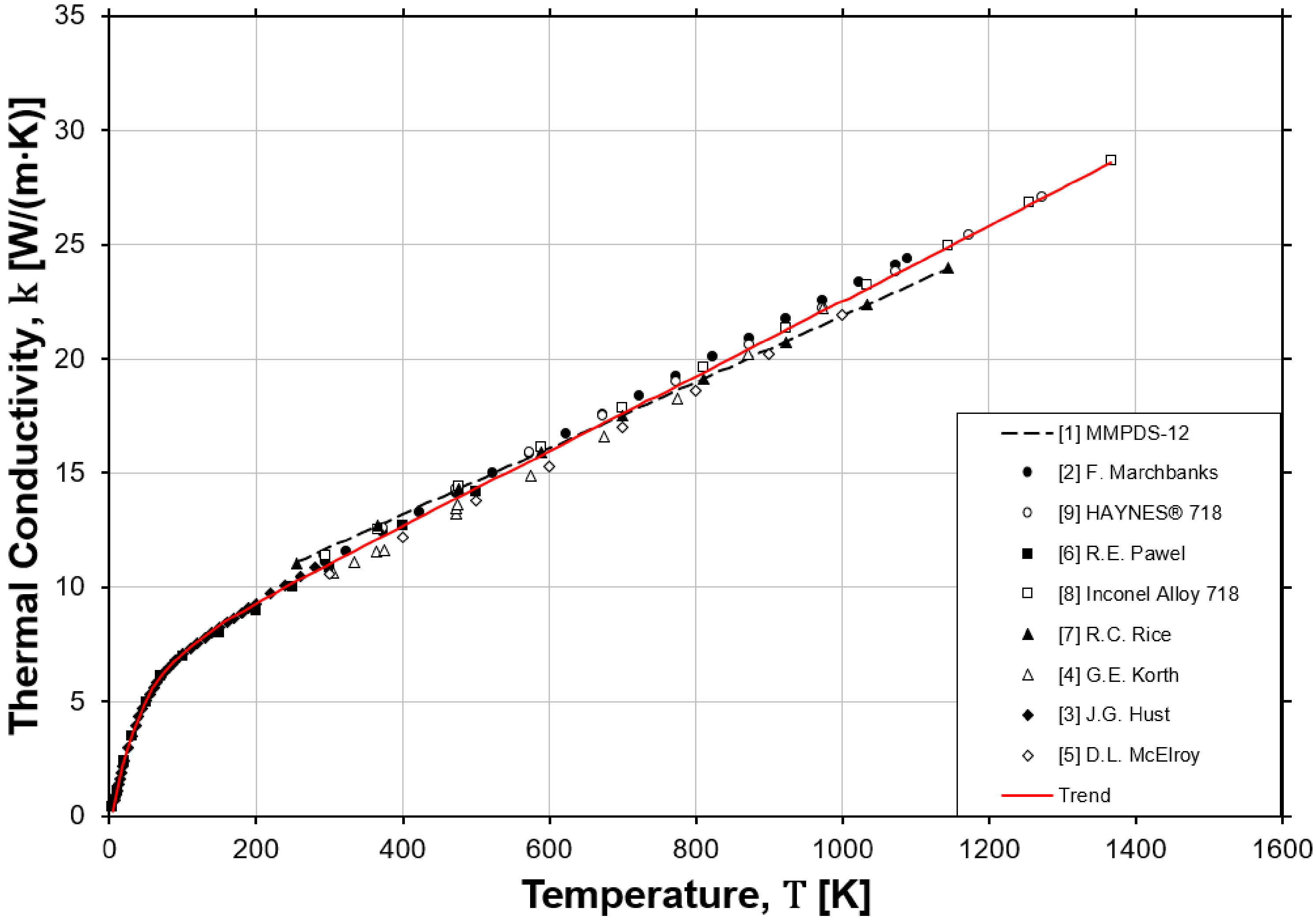

Figure 2.1.1-2: Thermal Conductivity versus Temperature of Inconel 718 with comparison to MMPDS-12.

100% Theoretical Density

Temperature (T)		Thermal Conductivity (k)		Temperature (T)		Thermal Conductivity (k)	
K	(°F)	W/(m-K)	((Btu·in)/(ft^2·hr·°F))	K	(°F)	W/(m-K)	((Btu·in)/(ft^2·hr·°F))
5	(-450.7)	0.38	(2.65)	700	(800.3)	17.60	(122.13)
25	(-414.7)	2.96	(20.55)	750	(890.3)	18.42	(127.81)
50	(-369.7)	5.04	(34.95)	800	(980.3)	19.24	(133.50)
100	(-279.7)	7.10	(49.23)	850	(1070.3)	20.06	(139.19)
150	(-189.7)	8.32	(57.72)	900	(1160.3)	20.88	(144.88)
200	(-99.7)	9.29	(64.47)	950	(1250.3)	21.70	(150.58)
250	(-9.7)	10.18	(70.61)	1000	(1340.3)	22.53	(156.29)
300	(80.3)	11.03	(76.51)	1050	(1430.3)	23.35	(162.00)
350	(170.3)	11.86	(82.29)	1100	(1520.3)	24.17	(167.72)
400	(260.3)	12.69	(88.03)	1150	(1610.3)	25.00	(173.44)
450	(350.3)	13.51	(93.73)	1200	(1700.3)	25.82	(179.17)
500	(440.3)	14.33	(99.42)	1250	(1790.3)	26.65	(184.91)
550	(530.3)	15.15	(105.10)	1300	(1880.3)	27.48	(190.65)
600	(620.3)	15.97	(110.77)	1350	(1970.3)	28.31	(196.40)
650	(710.3)	16.78	(116.45)	1367	(2000.9)	28.59	(198.35)

Application Notes: Data for thermal conductivity is collected from references [1-9] and fitted with the equation below to approximate the property trend with respect to temperature.

Fit Equation:

$$k(T) = A0 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2 + A3 \cdot \left(\frac{T}{1000}\right)^3 + A4 \cdot \left(\frac{T}{1000}\right)^4 + A\_2/\left(\frac{T}{1000}\right)^2$$

$k(T) = Thermal\ Conductivity\ [W\ /\ (m \cdot K)]$

$T = Temperature\ [K]$

Constants:

T Range [K]:	$4 \leq T < 115$	$115 \leq T \leq 1367$
A0 =	-4.293E-01	6.290E+00
A1 =	1.699E+02	1.605E+01
A2 =	-1.546E+03	1.944E-01
A3 =	7.385E+03	0
A4 =	-1.390E+04	0
A_2 =	0	-8.603E-03

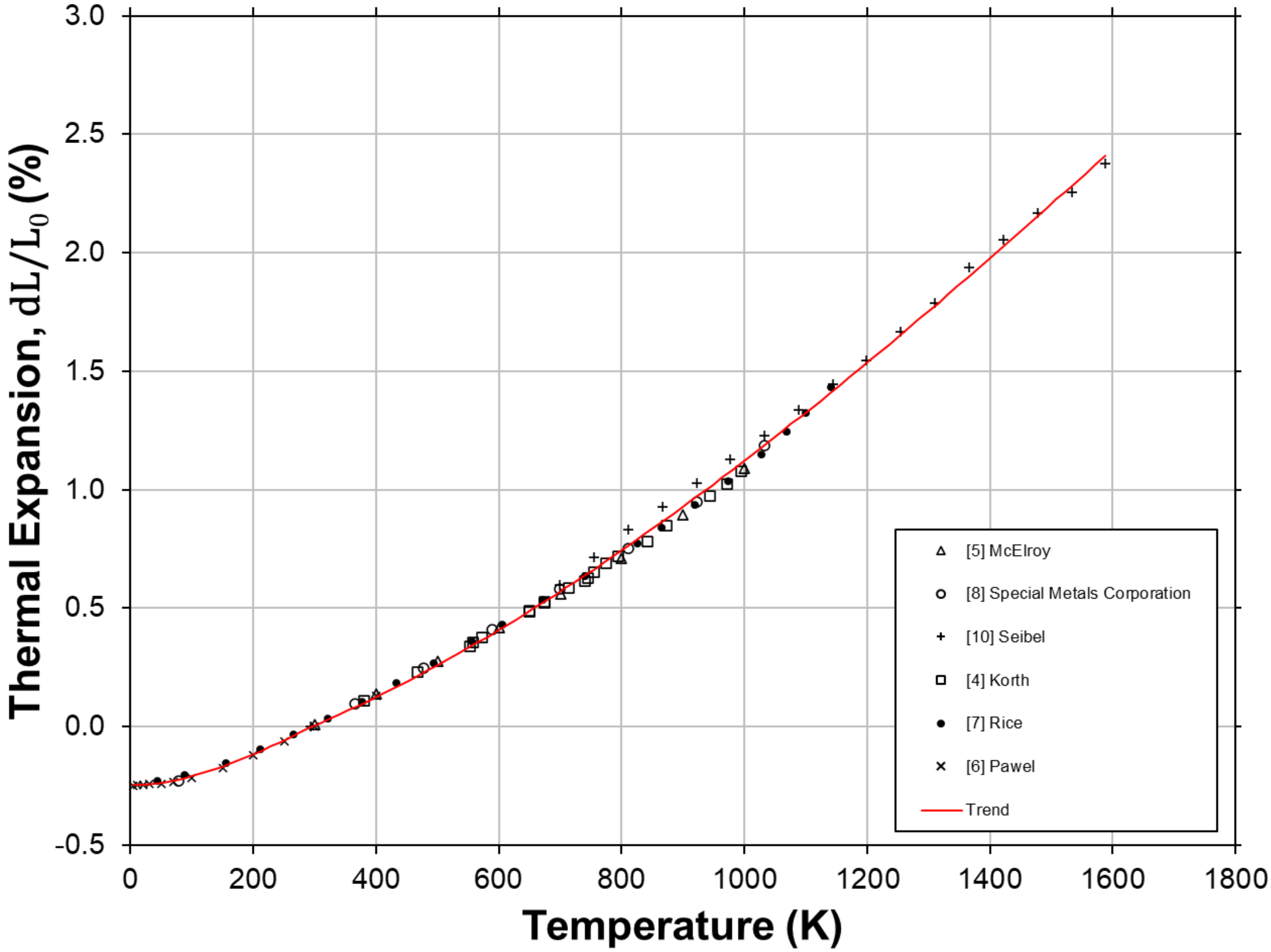

Figure 2.1.1-3: Thermal Expansion versus Temperature of Inconel 718.

100% Theoretical Density

Temperature (T)		Thermal Expansion (dL/L_0)	Temperature (T)		Thermal Expansion (dL/L_0)
K	(°F)	%	K	(°F)	%
5	(-450.7)	-0.247	700	(800.3)	0.571
25	(-414.7)	-0.244	750	(890.3)	0.656
50	(-369.7)	-0.237	800	(980.3)	0.744
100	(-279.7)	-0.209	850	(1070.3)	0.835
150	(-189.7)	-0.168	900	(1160.3)	0.929
200	(-99.7)	-0.116	950	(1250.3)	1.025
250	(-9.7)	-0.057	1000	(1340.3)	1.123
300	(80.3)	0.006	1050	(1430.3)	1.223
350	(170.3)	0.064	1100	(1520.3)	1.326
400	(260.3)	0.125	1150	(1610.3)	1.431
450	(350.3)	0.191	1200	(1700.3)	1.537
500	(440.3)	0.260	1300	(1880.3)	1.754
550	(530.3)	0.333	1400	(2060.3)	1.978
600	(620.3)	0.409	1500	(2240.3)	2.206
650	(710.3)	0.488	1588	(2398.7)	2.410

Application Notes: Data for thermal expansion is collected from [4-8, 10] and fitted with the equation below to approximate property trend with respect to temperature.

Fit Equation:

$$dL/L_0\,(T) = A0 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2 + A3 \cdot \left(\frac{T}{1000}\right)^3$$

$dL/L_0\,(T) = Thermal\ Expansion\ [\%]$

$T = Temperature\ [K]$

Constants:

T Range [K]:	$4 < T \leq 294$	$294 < T \leq 1588$
A0 =	-2.477E-01	-2.537E-01
A1 =	3.602E-02	5.934E-01
A2 =	3.907E+00	9.545E-01
A3 =	-4.015E+00	-1.713E-01

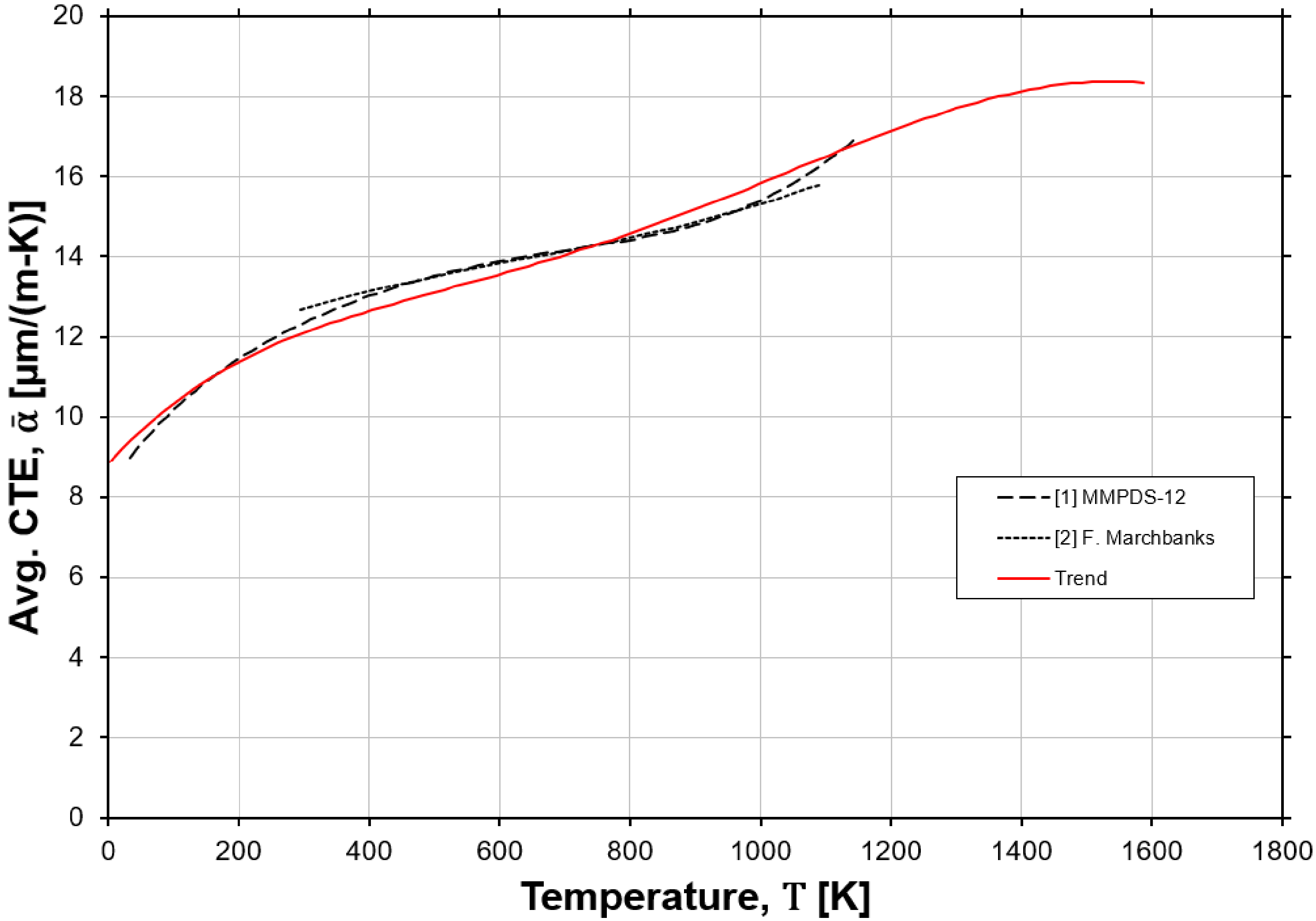

Figure 2.1.1-4: Mean Coefficient of Thermal Expansion versus Temperature of Inconel 718, with comparison to MMPDS-12 and Marchbanks (1976).

100% Theoretical Density

Temperature (T)		Mean CTE (ᾱ)		Temperature (T)		Mean CTE (ᾱ)	
K	(°F)	μm/(m-K)	(μin/(in-°F))	K	(°F)	μm/(m-K)	(μin/(in-°F))
5	(-450.7)	8.904	(4.946)	700	(800.3)	14.040	(7.800)
25	(-414.7)	9.249	(5.138)	750	(890.3)	14.302	(7.946)
50	(-369.7)	9.646	(5.359)	800	(980.3)	14.580	(8.100)
100	(-279.7)	10.336	(5.742)	850	(1070.3)	14.874	(8.264)
150	(-189.7)	10.906	(6.059)	900	(1160.3)	15.182	(8.435)
200	(-99.7)	11.379	(6.321)	950	(1250.3)	15.502	(8.612)
250	(-9.7)	11.773	(6.540)	1000	(1340.3)	15.831	(8.795)
300	(80.3)	12.106	(6.726)	1050	(1430.3)	16.164	(8.980)
350	(170.3)	12.394	(6.885)	1100	(1520.3)	16.496	(9.165)
400	(260.3)	12.649	(7.027)	1150	(1610.3)	16.822	(9.346)
450	(350.3)	12.884	(7.158)	1200	(1700.3)	17.136	(9.520)
500	(440.3)	13.109	(7.283)	1300	(1880.3)	17.699	(9.833)
550	(530.3)	13.331	(7.406)	1400	(2060.3)	18.125	(10.070)
600	(620.3)	13.557	(7.532)	1500	(2240.3)	18.352	(10.195)
650	(710.3)	13.792	(7.662)	1588	(2398.7)	18.334	(10.186)

Application Notes: Mean coefficient of thermal expansion is calculated as a function of thermal expansion. Calculated data has been fitted with the equation below to approximate property trend with respect to temperature, and compared to references [1, 2].

Fit Equation:

$$\bar{\alpha}(T) = A0 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2 + A3 \cdot \left(\frac{T}{1000}\right)^3 + A4 \cdot \left(\frac{T}{1000}\right)^4 + A5 \cdot \left(\frac{T}{1000}\right)^5$$

$\bar{\alpha}(T) = Coefficient\ of\ Thermal\ Expansion\ [\mu m/(m \cdot K)]$

$T = Temperature\ [K]$

Constants:

T. Range [K]:	$4 < T \leq 1588$
A0 =	8.813
A1 =	18.27
A2 =	-33.91
A3 =	36.66
A4 =	-16.21
A5 =	2.208

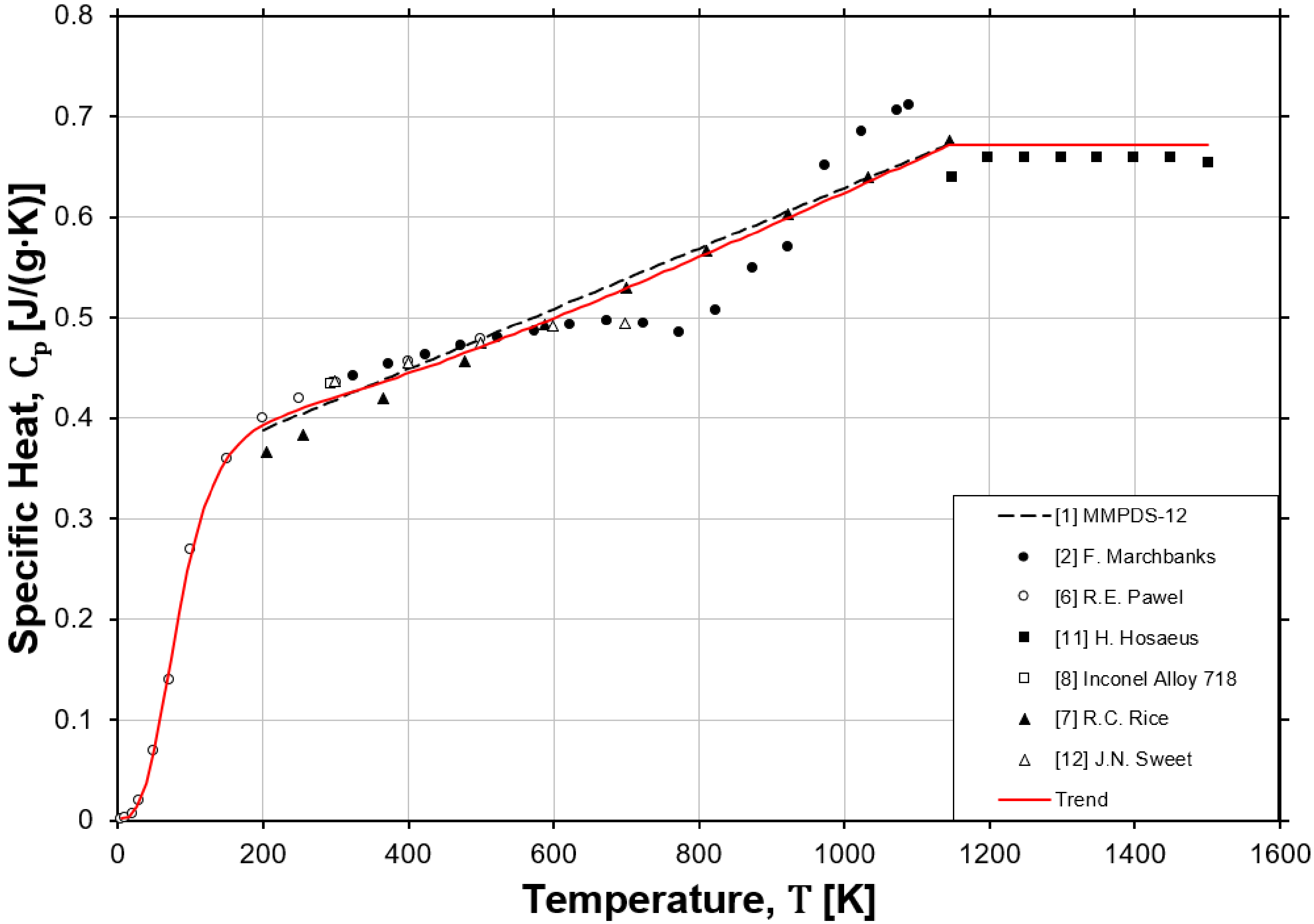

Figure 2.1.1-5: Specific Heat versus Temperature of Inconel 718 with comparison to MMPDS-12.

100% Theoretical Density

Temperature (T)		Specific Heat (C_p)		Temperature (T)		Specific Heat (C_p)	
K	(°F)	J/(g-K)	(BTU/(lb-°F))	K	(°F)	J/(g-K)	(BTU/(lb-°F))
5	(-450.7)	0.002	(0.001)	700	(800.3)	0.529	(0.127)
25	(-414.7)	0.011	(0.003)	750	(890.3)	0.545	(0.130)
50	(-369.7)	0.069	(0.017)	800	(980.3)	0.560	(0.134)
100	(-279.7)	0.261	(0.062)	850	(1070.3)	0.576	(0.138)
150	(-189.7)	0.360	(0.086)	900	(1160.3)	0.592	(0.142)
200	(-99.7)	0.393	(0.094)	950	(1250.3)	0.608	(0.145)
250	(-9.7)	0.409	(0.098)	1000	(1340.3)	0.624	(0.149)
300	(80.3)	0.421	(0.101)	1050	(1430.3)	0.641	(0.153)
350	(170.3)	0.432	(0.103)	1100	(1520.3)	0.657	(0.157)
400	(260.3)	0.445	(0.106)	1150	(1610.3)	0.671	(0.160)
450	(350.3)	0.458	(0.109)	1200	(1700.3)	0.671	(0.160)
500	(440.3)	0.471	(0.113)	1300	(1880.3)	0.671	(0.160)
550	(530.3)	0.485	(0.116)	1400	(2060.3)	0.671	(0.160)
600	(620.3)	0.500	(0.119)	1500	(2240.3)	0.671	(0.160)
650	(710.3)	0.514	(0.123)				

Application Notes: Data for specific heat is collected from references [2, 6-8, 11, 12] and fitted with the equation below to approximate the property trend with respect to temperature. Trend is compared to reference [1].

Fit Equation:

$$C_P(T) = \left[A0 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2 + A3 \cdot \left(\frac{T}{1000}\right)^3\right] \Big/ \left[B0 + B1 \cdot \left(\frac{T}{1000}\right) + \left(\frac{T}{1000}\right)^2\right]$$

$C_P(T) = Specific\ Heat\ [J/(g \cdot K)]$

$T = Temperature\ [K]$

Constants:

T. Range [K]:	$4 < T \leq 1150$		$1150 < T \leq 1500$
A0 =	3.356E-05	$C_P(T) =$	0.6715
A1 =	-3.836E-03		
A2 =	2.230E-01		
A3 =	3.441E-01		
B0 =	9.237E-03		
B1 =	-1.071E-01		

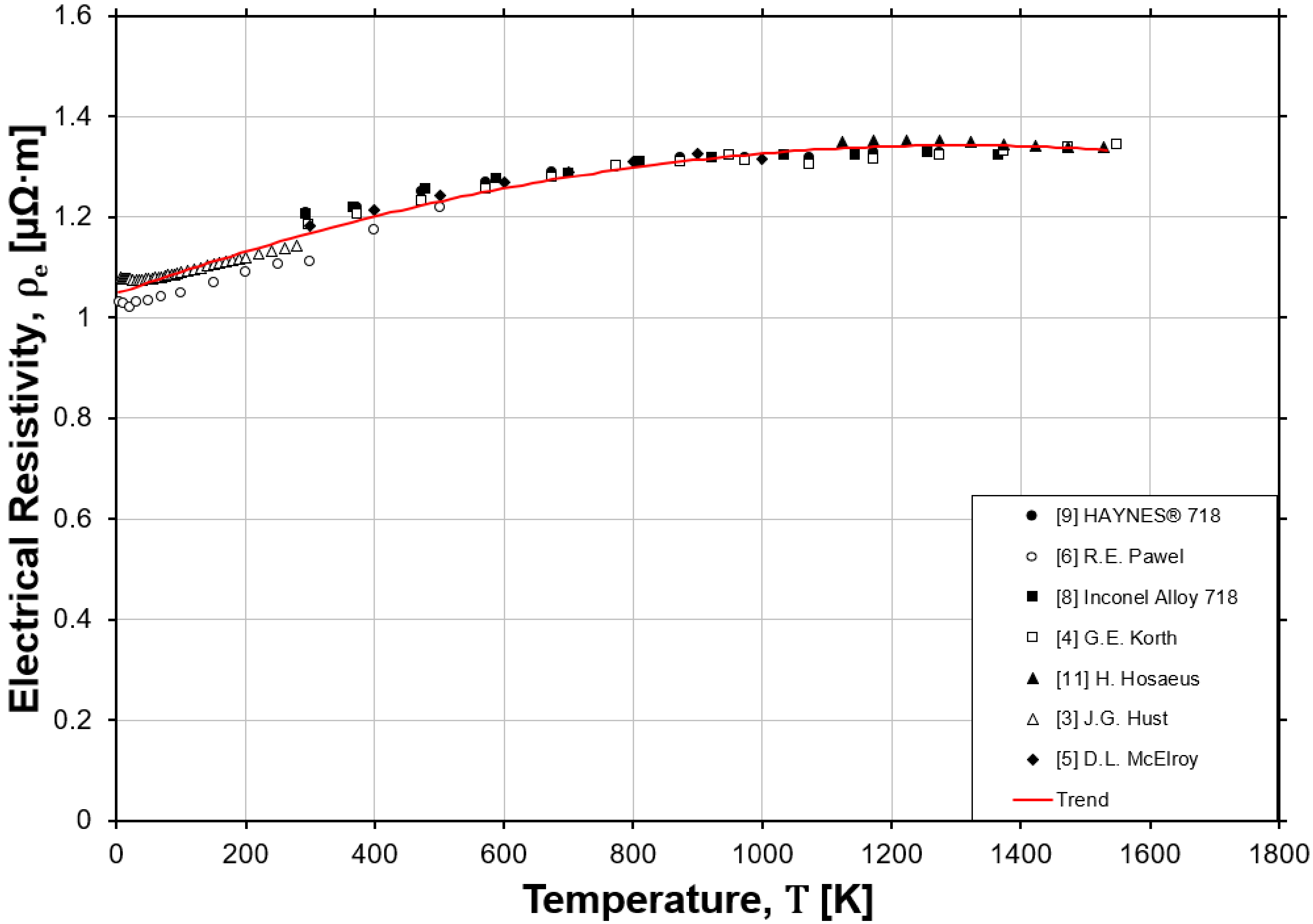

Figure 2.1.1-6: Electrical Resistivity versus Temperature of Inconel 718.

Electrical Resistivity with Temperature

100% Theoretical Density

Temperature (T)		Electrical Resistivity (ρ_e)		Temperature (T)		Electrical Resistivity (ρ_e)	
K	(°F)	μΩ-m	(μΩ-in)	K	(°F)	μΩ-m	(μΩ-in)
5	(-450.7)	1.050	(41.35)	700	(800.3)	1.280	(50.39)
25	(-414.7)	1.059	(41.70)	750	(890.3)	1.290	(50.78)
50	(-369.7)	1.070	(42.13)	800	(980.3)	1.299	(51.15)
100	(-279.7)	1.092	(42.97)	850	(1070.3)	1.307	(51.47)
150	(-189.7)	1.112	(43.78)	900	(1160.3)	1.315	(51.77)
200	(-99.7)	1.132	(44.55)	950	(1250.3)	1.321	(52.03)
250	(-9.7)	1.150	(45.29)	1000	(1340.3)	1.327	(52.25)
300	(80.3)	1.168	(45.99)	1050	(1430.3)	1.332	(52.44)
350	(170.3)	1.185	(46.66)	1100	(1520.3)	1.336	(52.60)
400	(260.3)	1.201	(47.30)	1150	(1610.3)	1.339	(52.72)
450	(350.3)	1.217	(47.90)	1200	(1700.3)	1.341	(52.81)
500	(440.3)	1.231	(48.46)	1300	(1880.3)	1.343	(52.89)
550	(530.3)	1.245	(49.00)	1400	(2060.3)	1.342	(52.82)
600	(620.3)	1.257	(49.49)	1500	(2240.3)	1.337	(52.63)
650	(710.3)	1.269	(49.96)	1548	(2326.7)	1.333	(52.48)

Application Notes: Data for electrical resistivity is collected from references [3-6, 8, 9, 11] and fitted with the equation below to approximate the property trend with respect to temperature.

Fit Equation:

$$\rho_e(T) = A0 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2$$

$\rho_e(T) = Electrical\ Resistivity\ (\mu\Omega \cdot m)$

$T = Temperature\ [K]$

Constants:

T. Range [K]: $4 \leq T \leq 1548$

A0 = 1.048

A1 = 0.4527

A2 = -0.1735

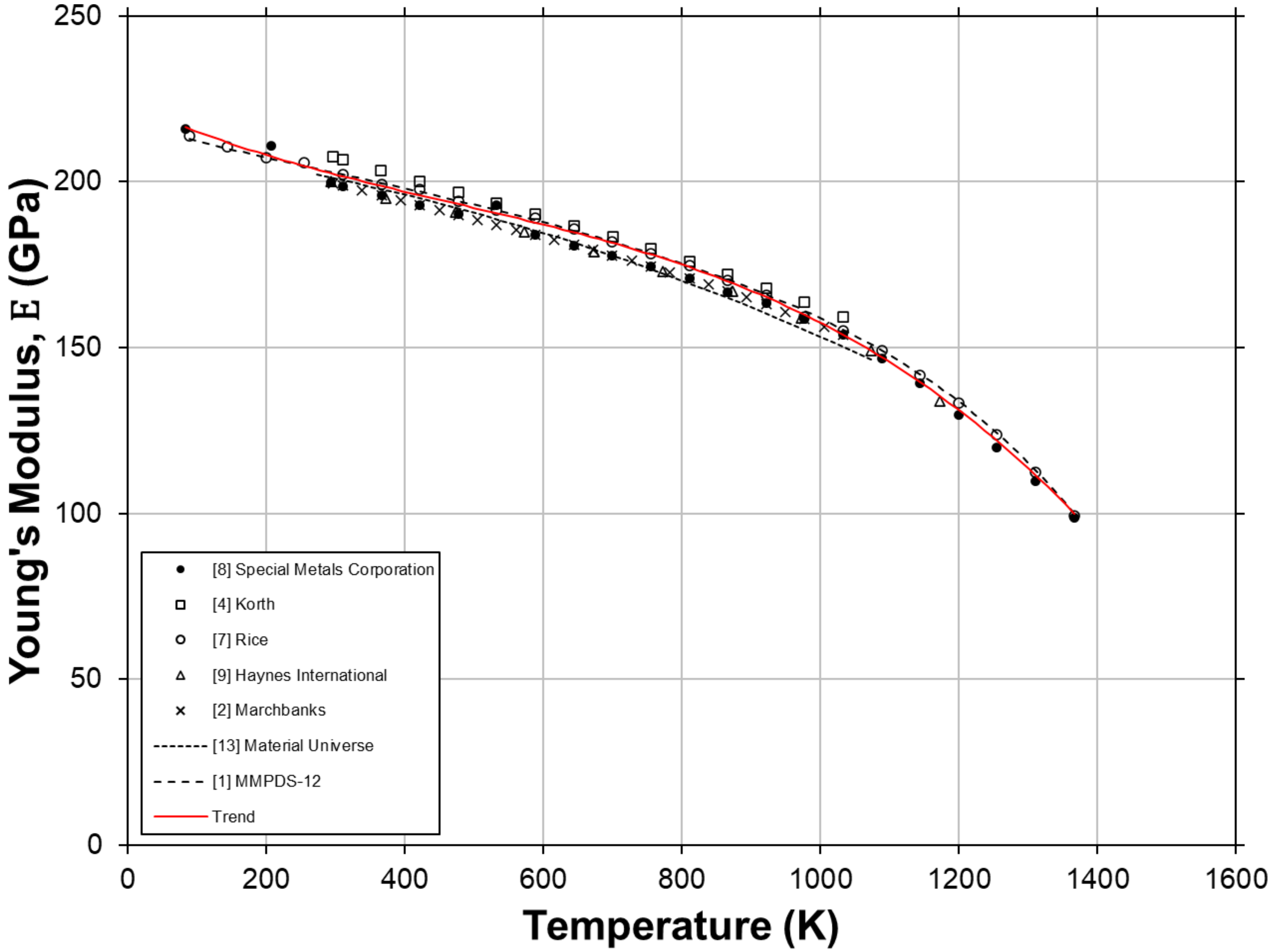

Figure 2.1.1-7: Young's Modulus versus Temperature of Inconel 718 with comparison to MMPDS-12, solution-treated and aged.

100% Theoretical Density

Temperature (T)		Young's Modulus (E)		Temperature (T)		Young's Modulus (E)	
K	(°F)	GPa	(Msi)	K	(°F)	GPa	(Msi)
84	(-308.5)	216.46	(31.41)	800	(980.3)	175.03	(25.40)
100	(-279.7)	215.19	(31.22)	850	(1070.3)	171.29	(24.85)
150	(-189.7)	211.50	(30.69)	900	(1160.3)	167.15	(24.25)
200	(-99.7)	208.14	(30.20)	950	(1250.3)	162.56	(23.59)
250	(-9.7)	205.06	(29.75)	1000	(1340.3)	157.48	(22.85)
300	(80.3)	202.22	(29.34)	1050	(1430.3)	151.85	(22.03)
350	(170.3)	199.55	(28.96)	1100	(1520.3)	145.61	(21.13)
400	(260.3)	197.02	(28.59)	1150	(1610.3)	138.71	(20.13)
450	(350.3)	194.55	(28.23)	1200	(1700.3)	131.11	(19.02)
500	(440.3)	192.11	(27.88)	1250	(1790.3)	122.75	(17.81)
550	(530.3)	189.64	(27.52)	1300	(1880.3)	113.57	(16.48)
600	(620.3)	187.09	(27.15)	1350	(1970.3)	103.53	(15.02)
650	(710.3)	184.41	(26.76)	1367	(2000.9)	99.91	(14.50)
700	(800.3)	181.54	(26.34)				
750	(890.3)	178.43	(25.89)				

Application Notes: Data for Young's Modulus is collected from references [1, 2, 4, 7-9, 13] and fitted with the equation below to approximate the property trend with respect to temperature.

Fit Equations:

$$E(T) = A0 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2 + A3 \cdot \left(\frac{T}{1000}\right)^3$$

$E(T) = Young's\ Modulus\ [GPa]$

$T = Temperature\ [K]$

Constants:

T Range [K]:	$84 \leq T \leq 1367$
A0 =	223.8
A1 =	-95.22
A2 =	98.49
A3 =	-69.59

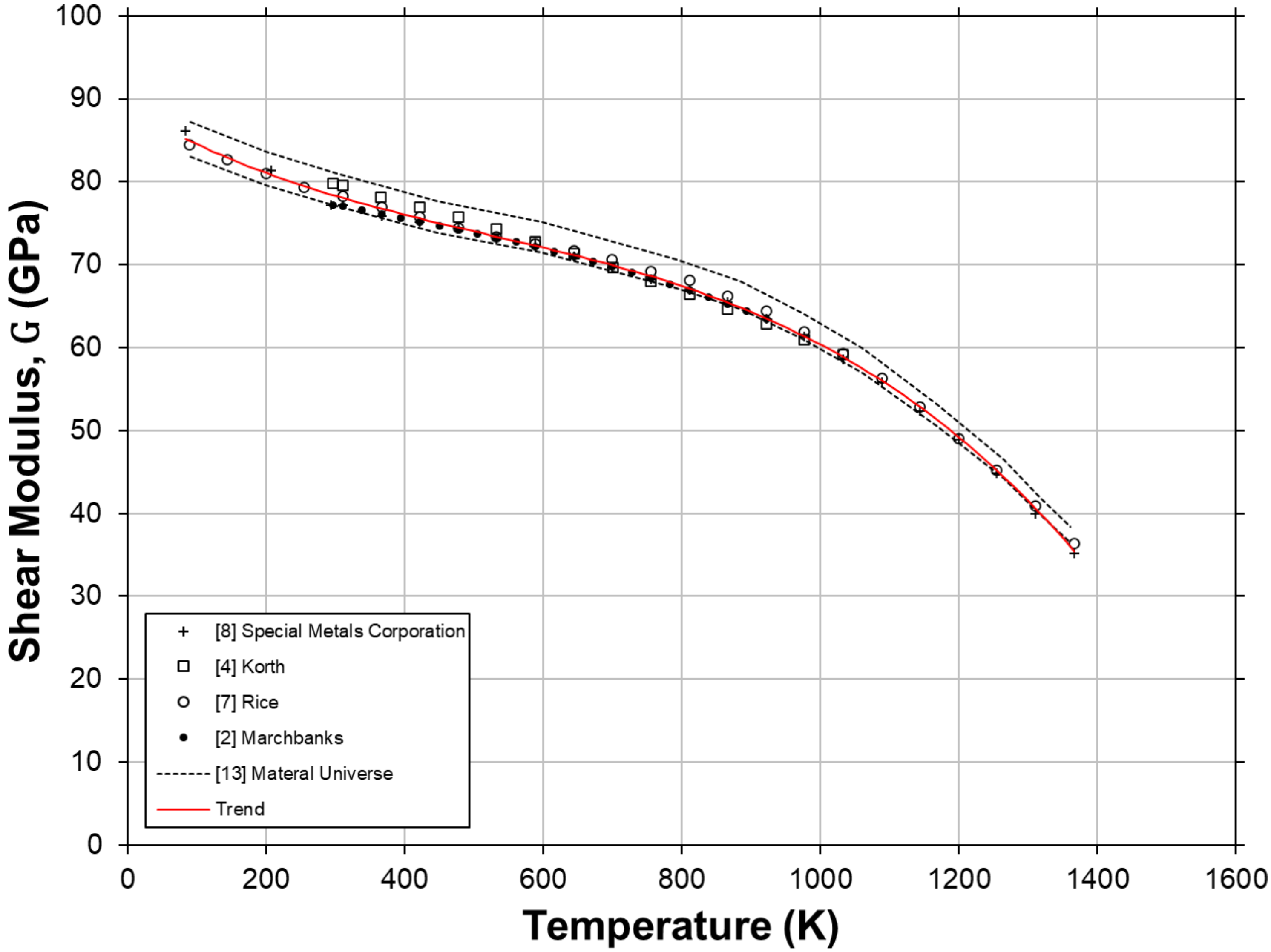

Figure 2.1.1-8: Shear Modulus versus Temperature of Inconel 718 with comparison to Material Universe High and Low trends for Inconel 718.

100% Theoretical Density

Temperature (T)		Shear Modulus (G)		Temperature (T)		Shear Modulus (G)	
K	(°F)	GPa	(Msi)	K	(°F)	GPa	(Msi)
84	(-308.5)	85.19	(12.36)	800	(980.3)	67.41	(9.78)
100	(-279.7)	84.55	(12.27)	850	(1070.3)	65.94	(9.57)
150	(-189.7)	82.72	(12.00)	900	(1160.3)	64.29	(9.33)
200	(-99.7)	81.08	(11.77)	950	(1250.3)	62.44	(9.06)
250	(-9.7)	79.63	(11.55)	1000	(1340.3)	60.36	(8.76)
300	(80.3)	78.32	(11.36)	1050	(1430.3)	58.02	(8.42)
350	(170.3)	77.13	(11.19)	1100	(1520.3)	55.39	(8.04)
400	(260.3)	76.03	(11.03)	1150	(1610.3)	52.45	(7.61)
450	(350.3)	75.01	(10.88)	1200	(1700.3)	49.17	(7.14)
500	(440.3)	74.02	(10.74)	1250	(1790.3)	45.53	(6.61)
550	(530.3)	73.04	(10.60)	1300	(1880.3)	41.49	(6.02)
600	(620.3)	72.05	(10.46)	1350	(1970.3)	37.02	(5.37)
650	(710.3)	71.02	(10.31)	1367	(2000.9)	35.41	(5.14)
700	(800.3)	69.92	(10.15)				
750	(890.3)	68.73	(9.97)				

Application Notes: Data for shear modulus is collected from references [2, 4, 7, 8, 13] and fitted with the equation below to approximate property trend with respect to temperature.

Fit Equations:

$$G(T) = A0 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2 + A3 \cdot \left(\frac{T}{1000}\right)^3$$

$G(T) = Shear\ Modulus\ [GPa]$

$T = Temperature\ [K]$

Constants:

T Range [K]:	$84 \le T \le 1367$
A0 =	88.94
A1 =	-49.19
A2 =	56.78
A3 =	-36.17

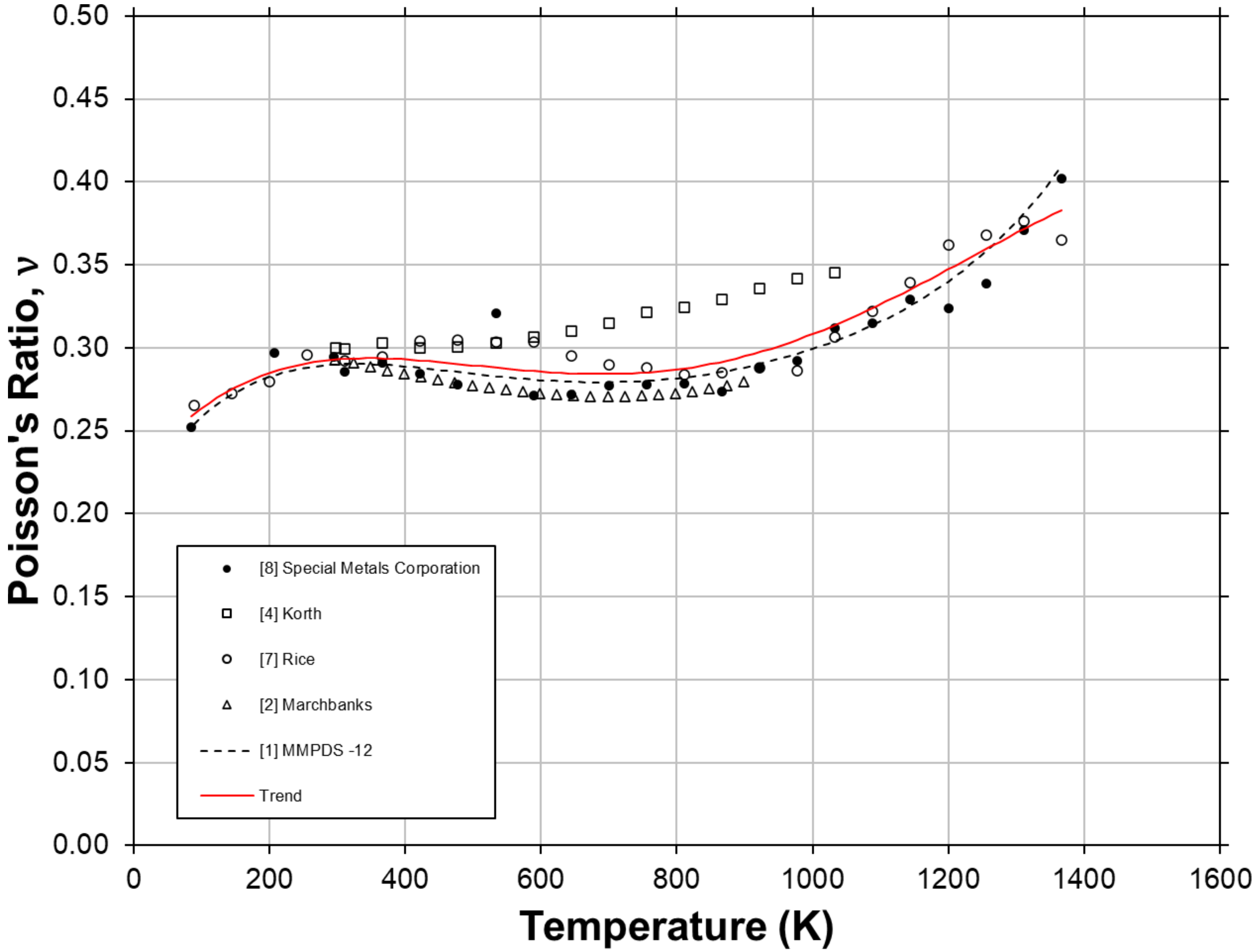

Figure 2.1.1-9: Poisson's Ratio versus Temperature of Inconel 718 with comparison to MMPDS-12, solution-treated and aged.

100% Theoretical Density

Temperature (T) K	(°F)	Poisson's Ratio (ν)	Temperature (T) K	(°F)	Poisson's Ratio (ν)
84	(-308.5)	0.259	800	(980.3)	0.287
100	(-279.7)	0.264	850	(1070.3)	0.290
150	(-189.7)	0.276	900	(1160.3)	0.295
200	(-99.7)	0.285	950	(1250.3)	0.301
250	(-9.7)	0.290	1000	(1340.3)	0.308
300	(80.3)	0.293	1050	(1430.3)	0.317
350	(170.3)	0.294	1100	(1520.3)	0.326
400	(260.3)	0.293	1150	(1610.3)	0.336
450	(350.3)	0.291	1200	(1700.3)	0.347
500	(440.3)	0.289	1250	(1790.3)	0.358
550	(530.3)	0.287	1300	(1880.3)	0.369
600	(620.3)	0.286	1350	(1970.3)	0.380
650	(710.3)	0.284	1367	(2000.9)	0.383
700	(800.3)	0.284			
750	(890.3)	0.285			

Application Notes: Data for Poisson's Ratio is collected from references [1, 2, 4, 7, 8] and fitted with the equation below to approximate the property trend with respect to temperature. Fitted trend is compared against trend from reference [1].

Fit Equations:

$$\nu(T) = A0 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2 + A3 \cdot \left(\frac{T}{1000}\right)^3 + A4 \cdot \left(\frac{T}{1000}\right)^4$$

$\nu(T) = Poisson's\ Ratio$

$T = Temperature\ [K]$

Constants:

T Range [K]:	$84 < T \leq 1367$
A0 =	0.2236
A1 =	0.5184
A2 =	-1.286
A3 =	1.197
A4 =	-0.3448

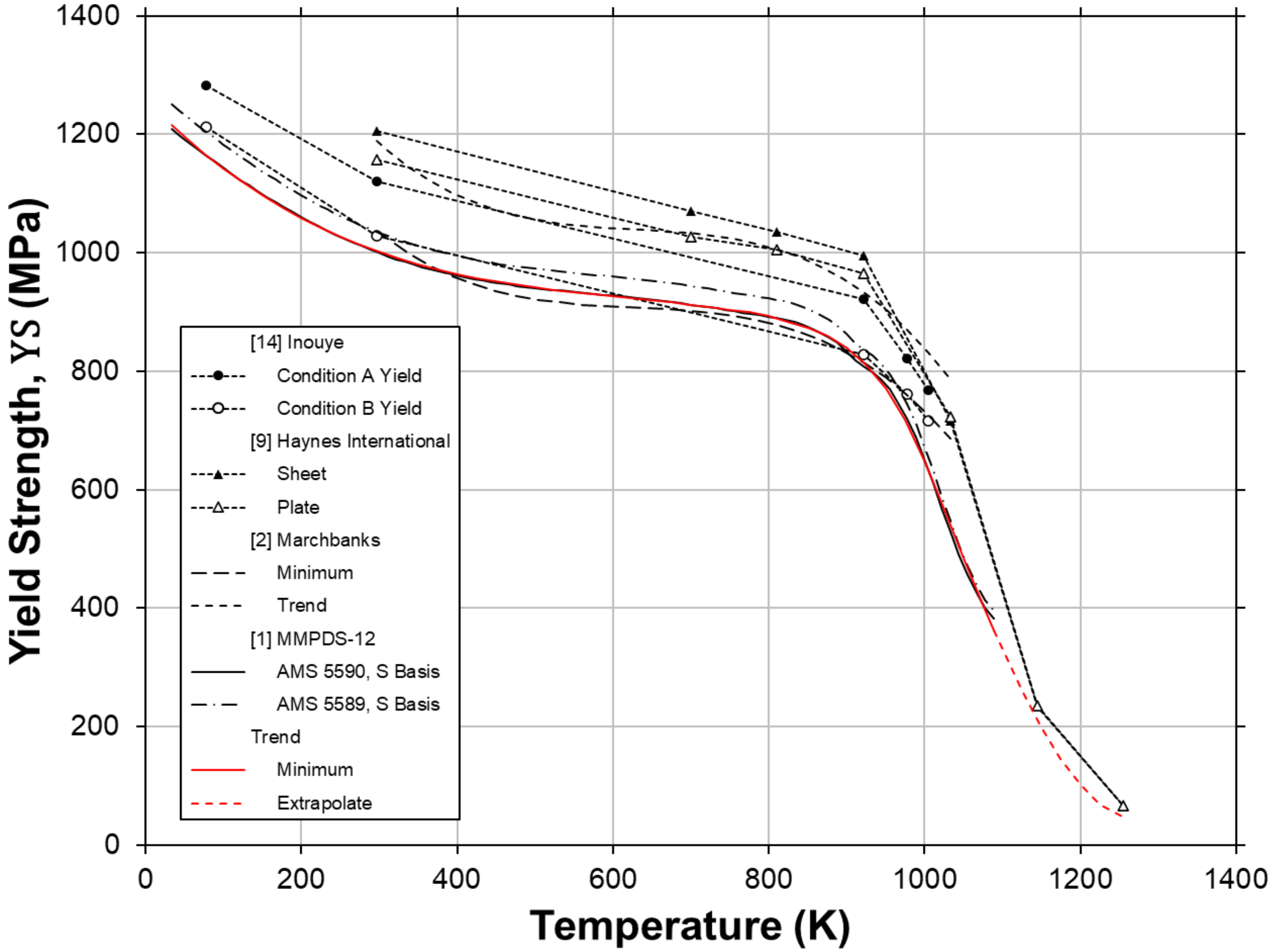

Figure 2.1.1-10: Yield Strength versus Temperature of Inconel 718, with comparison to MMPDS-12, solution-treated and aged wrought product.

Yield Strength with Temperature

100% Theoretical Density

Temperature (T)		Yield Strength (YS)		Temperature (T)		Yield Strength (YS)	
K	(°F)	MPa	(Ksi)	K	(°F)	MPa	(Ksi)
33	(-400.3)	1215.69	(176.40)	650	(710.3)	919.46	(133.41)
50	(-369.7)	1195.48	(173.46)	700	(800.3)	912.39	(132.39)
75	(-324.7)	1167.61	(169.42)	750	(890.3)	904.14	(131.19)
100	(-279.7)	1141.88	(165.69)	800	(980.3)	893.94	(129.71)
150	(-189.7)	1096.45	(159.09)	850	(1070.3)	873.87	(126.80)
200	(-99.7)	1058.38	(153.57)	900	(1160.3)	840.52	(121.96)
250	(-9.7)	1026.92	(149.01)	950	(1250.3)	772.05	(112.02)
300	(80.3)	1001.28	(145.29)	1000	(1340.3)	650.00	(94.32)
350	(170.3)	980.68	(142.30)	1050	(1430.3)	484.62	(70.32)
400	(260.3)	964.35	(139.93)	1100	(1520.3)	330.22	(47.91)
450	(350.3)	951.51	(138.06)	1150	(1610.3)	198.46	(28.80)
500	(440.3)	941.38	(136.59)	1200	(1700.3)	100.96	(14.65)
550	(530.3)	933.17	(135.40)	1256	(1801.1)	46.82	(6.79)
600	(620.3)	926.13	(134.38)				

Application Notes: Data for yield strength is collected from references [1, 2, 9, 14] and fitted with the equation below to approximate the property trend with respect to temperature.

Fit Equations:

$$YS(T) = A0 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2 + A3 \cdot \left(\frac{T}{1000}\right)^3$$

$YS(T) = Yield\ Strength\ [MPa]$

$T = Temperature\ [K]$

Valid Temperature Range: $33 \leq T \leq 1089$

Extended Temperature Range: $1089 < T < 1256$

Constants:

T Range [K]:	$33 < T \leq 800$	$800 < T \leq 1000$	$1000 < T \leq 1256$
A0 =	1.258E+3	1.396E+4	-1.166E+4
A1 =	-1.345E+3	-4.814E+4	4.348E+4
A2 =	1.942E+3	5.945E+4	-4.669E+4
A3 =	-1.037E+3	-2.462E+4	1.552E+4

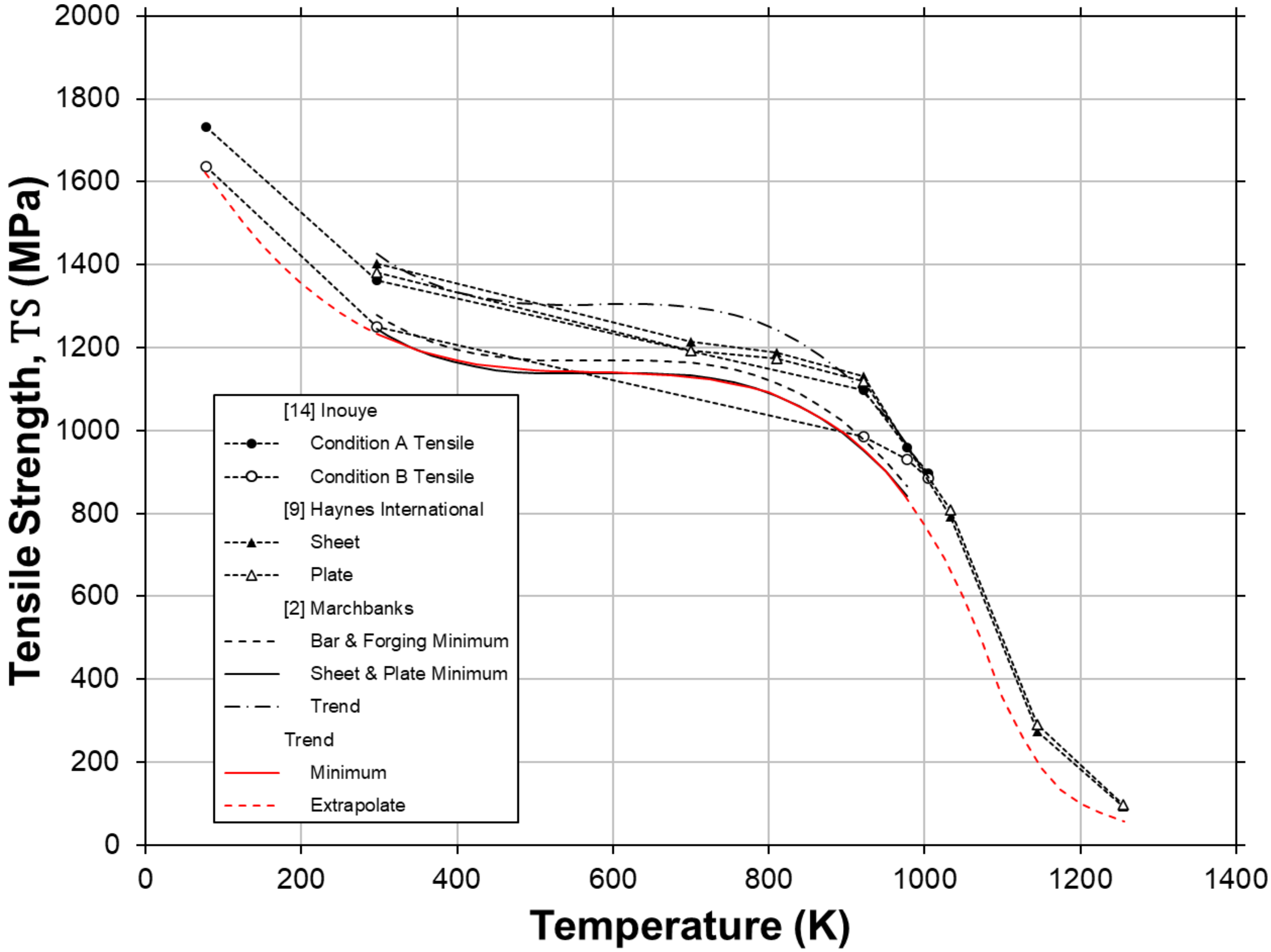

Figure 2.1.1-11: Tensile Strength versus Temperature of Inconel 718.

100% Theoretical Density

Temperature (T)		Tensile Strength (TS)		Temperature (T)		Tensile Strength (TS)	
K	(°F)	MPa	(Ksi)	K	(°F)	MPa	(Ksi)
77	(-321.1)	1622.12	(235.37)	700	(800.3)	1128.75	(163.78)
100	(-279.7)	1560.80	(226.47)	750	(890.3)	1115.00	(161.79)
150	(-189.7)	1446.16	(209.84)	800	(980.3)	1091.99	(158.45)
200	(-99.7)	1354.89	(196.59)	850	(1070.3)	1048.28	(152.11)
250	(-9.7)	1284.25	(186.34)	900	(1160.3)	989.09	(143.52)
300	(80.3)	1231.53	(178.70)	950	(1250.3)	901.24	(130.77)
350	(170.3)	1194.02	(173.25)	1000	(1340.3)	774.00	(112.31)
400	(260.3)	1168.98	(169.62)	1050	(1430.3)	596.66	(86.58)
450	(350.3)	1153.72	(167.40)	1100	(1520.3)	358.51	(52.02)
500	(440.3)	1145.50	(166.21)	1150	(1610.3)	185.90	(26.97)
550	(530.3)	1141.61	(165.65)	1200	(1700.3)	100.48	(14.58)
600	(620.3)	1139.34	(165.32)	1256	(1801.1)	56.70	(8.23)
650	(710.3)	1135.95	(164.83)				

Application Notes: Data for tensile strength is collected from references [2, 9, 14] and fitted with the equation below to approximate the property trend with respect to temperature.

Fit Equations:

$$TS(T) = A0 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2 + A3 \cdot \left(\frac{T}{1000}\right)^3$$

$TS(T) = Tensile\ Strength\ [MPa]$

$T = Temperature\ [K]$

Valid Temperature Range: $297 \leq T \leq 978$

Extended Temperature Range: $77 < T < 297$ and $978 < T < 1256$

Constants:

T Range [K]:	$77 < T \leq 800$	$800 < T \leq 1100$	$1100 < T \leq 1256$
A0 =	1.871E+3	8.054E+3	1.396E+5
A1 =	-3.696E+3	-2.584E+4	-3.356E+5
A2 =	6.302E+3	3.285E+4	2.696E+5
A3 =	-3.624E+3	-1.429E+4	-7.234E+4

Temp. (T) K	Physical and Electrical		Thermal				Elastic		
	Density (ρ) kg/m³	Electrical Resistivity (ρ_e) µΩ-m	Thermal Conductivity (k) W/(m-K)	Thermal Expansion (dL/L_0) %	Mean CTE ($\bar{\alpha}$) 10^{-6}/K	Specific Heat (C_p) J/(g-K)	Young's Modulus (E) GPa	Shear Modulus (G) GPa	Poisson's Ratio (ν)
100	8272	1.092	7.10	-0.209	10.34	0.261	215.19	84.55	0.264
150	8262	1.112	8.32	-0.168	10.91	0.360	211.50	82.72	0.276
200	8249	1.132	9.29	-0.116	11.38	0.393	208.14	81.08	0.285
250	8234	1.150	10.18	-0.057	11.77	0.409	205.06	79.63	0.290
295	8220	1.166	10.94	0.000	12.07	0.420	202.49	78.44	0.293
300	8219	1.168	11.03	0.006	12.11	0.421	202.22	78.32	0.293
350	8204	1.185	11.86	0.064	12.39	0.432	199.55	77.13	0.294
400	8189	1.201	12.69	0.125	12.65	0.445	197.02	76.03	0.293
450	8173	1.217	13.51	0.191	12.88	0.458	194.55	75.01	0.291
500	8156	1.231	14.33	0.260	13.11	0.471	192.11	74.02	0.289
550	8138	1.245	15.15	0.333	13.33	0.485	189.64	73.04	0.287
600	8120	1.257	15.97	0.409	13.56	0.500	187.09	72.05	0.286
650	8101	1.269	16.78	0.488	13.79	0.514	184.41	71.02	0.284
700	8081	1.280	17.60	0.571	14.04	0.529	181.54	69.92	0.284
750	8060	1.290	18.42	0.656	14.30	0.545	178.43	68.73	0.285
800	8039	1.299	19.24	0.744	14.58	0.560	175.03	67.41	0.287
850	8017	1.307	20.06	0.835	14.87	0.576	171.29	65.94	0.290
900	7995	1.315	20.88	0.929	15.18	0.592	167.15	64.29	0.295
1000	7949	1.327	22.53	1.123	15.83	0.624	157.48	60.36	0.308
1100	7901	1.336	24.17	1.326	16.50	0.657	145.61	55.39	0.326
1200	7852	1.341	25.82	1.537	17.14	0.671	131.11	49.17	0.347
1300	7802	1.343	27.48	1.754	17.70	0.671	113.57	41.49	0.369
1400	7751	1.342	-	1.978	18.13	0.671	-	-	-
1500	7699	1.337	-	2.206	18.35	0.671	-	-	-
1550	7673	-	-	2.321	18.37	-	-	-	-

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3 Refractory Metals and Alloys

3.1 Molybdenum and Molybdenum Alloys

Room Temperature Properties

Atomic Mass, [amu]	95.95
Theoretical Density, [kg/m^3]	10,280
Melting Point, [K]	2896
Boiling Point, [K]	4912
Specific Heat, [J/(g-K)]	0.249
Heat of Fusion, [kJ/mol]	36
Heat of Vaporization, [kJ/mol]	600
Thermal Conductivity, [W/(m-K)]	138.1
Linear expansion coefficient, [μm/(m-K)]	4.96
Electrical resistivity, [μΩ-m]	0.055
Young's Modulus, [GPa]	317.6
Shear Modulus, [GPa]	123.9
Poisson’s Ratio, [-]	0.356

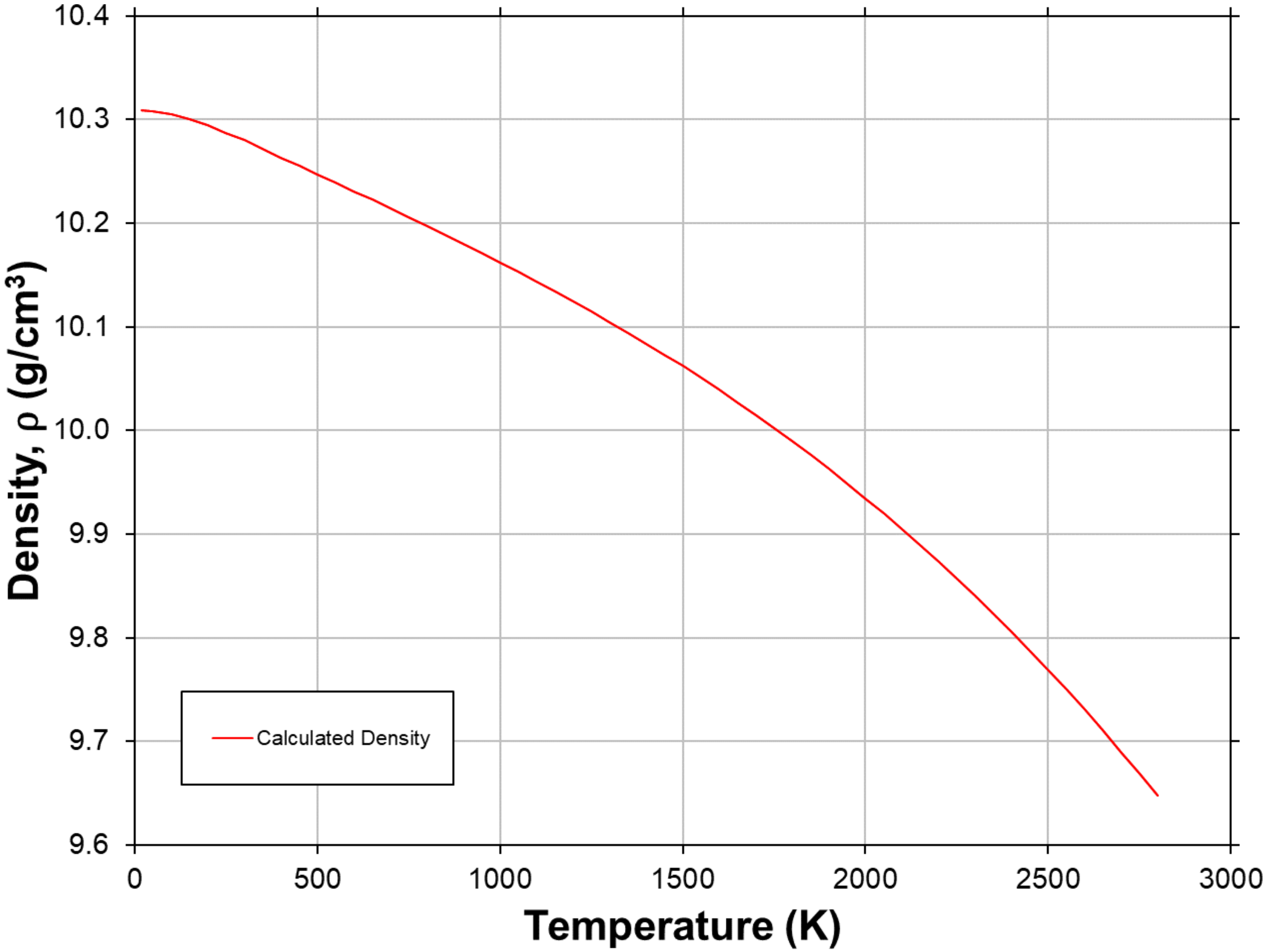

Figure 3.1.1-1: Density versus Temperature for Molybdenum. Calculated from fitted trend of the Thermal Expansion data.

100% Theoretical Density

Temperature (T)		Density (ρ)		Temperature (T)		Density (ρ)	
K	(°F)	kg/m³	(lb/ft³)	K	(°F)	kg/m³	(lb/ft³)
20	(-423.7)	10309	(643.6)	1400	(2060.3)	10084	(629.5)
60	(-351.7)	10308	(643.5)	1500	(2240.3)	10062	(628.2)
100	(-279.7)	10306	(643.4)	1600	(2420.3)	10039	(626.7)
200	(-99.7)	10294	(642.7)	1700	(2600.3)	10015	(625.2)
300	(80.3)	10280	(641.8)	1800	(2780.3)	9990	(623.7)
400	(260.3)	10264	(640.8)	1900	(2960.3)	9963	(622.0)
500	(440.3)	10247	(639.7)	2000	(3140.3)	9935	(620.2)
600	(620.3)	10231	(638.7)	2100	(3320.3)	9905	(618.4)
700	(800.3)	10214	(637.7)	2200	(3500.3)	9874	(616.4)
800	(980.3)	10197	(636.6)	2300	(3680.3)	9841	(614.4)
900	(1160.3)	10180	(635.5)	2400	(3860.3)	9806	(612.2)
1000	(1340.3)	10162	(634.4)	2500	(4040.3)	9769	(609.9)
1100	(1520.3)	10144	(633.3)	2600	(4220.3)	9731	(607.5)
1200	(1700.3)	10125	(632.1)	2700	(4400.3)	9690	(605.0)
1300	(1880.3)	10105	(630.8)	2800	(4580.3)	9648	(602.3)

Application Notes: Density trend is calculated as a function of thermal expansion, as seen in equation below.

Density Calculation:

$\rho(T) = \rho_{RT}/(1 + dL/L_0(T)/100)^3$

$\rho(T) = Density\ [kg/m^3]$

$Room\ Temperature\ Density\ (\rho_{RT}) = 10{,}280\ [kg/m^3]$

$T = Temperature\ [K]$

Temperature Range: $20 \leq T \leq 2800$

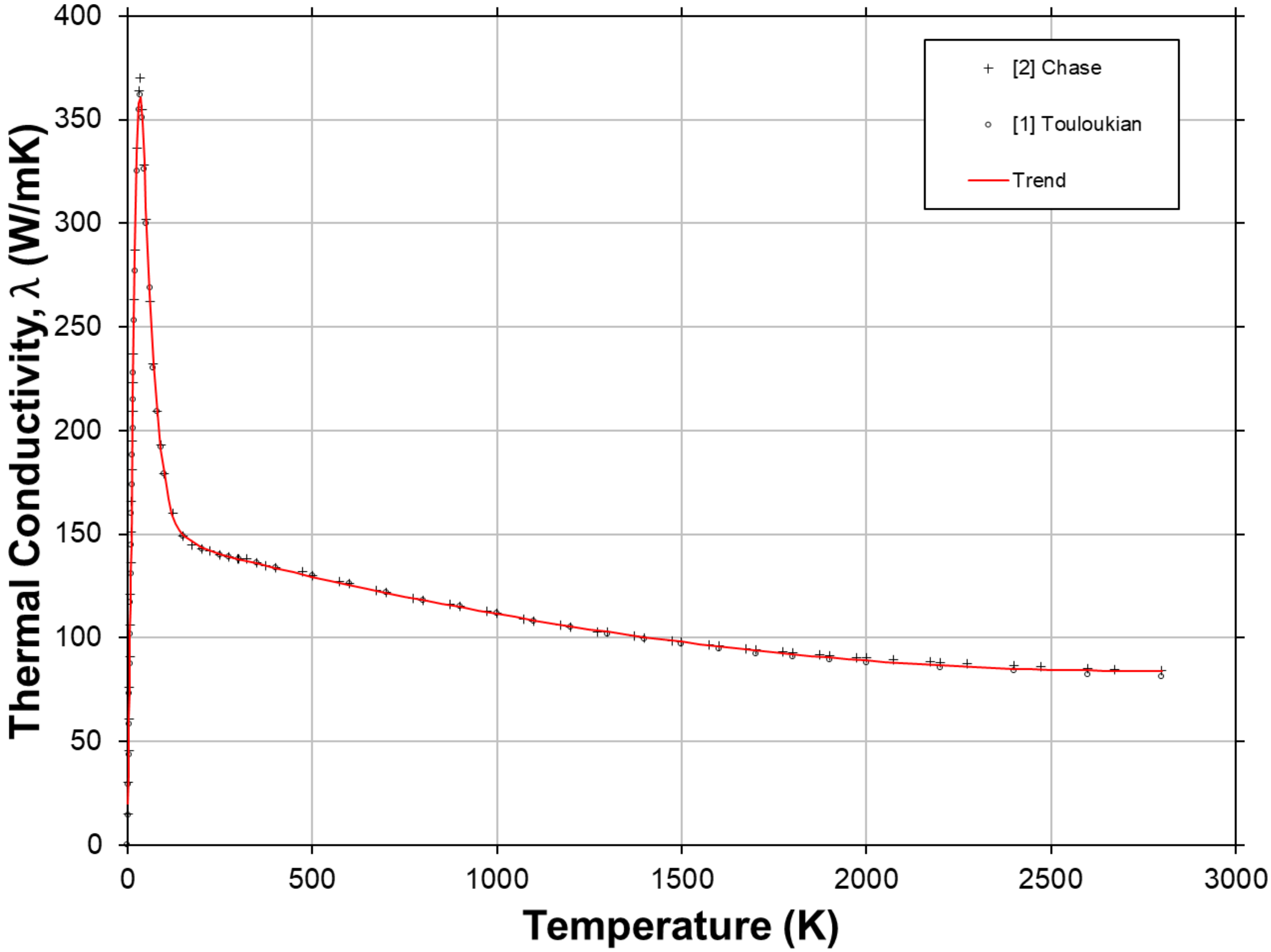

Figure 3.1.1-2: Thermal Conductivity versus Temperature of Molybdenum.

Thermal Conductivity with Temperature

100% Theoretical Density

Temperature (T)		Thermal Conductivity (k)		Temperature (T)		Thermal Conductivity (k)	
K	(°F)	W/(m-K)	((Btu·in)/(ft²·hr·°F))	K	(°F)	W/(m-K)	((Btu·in)/(ft²·hr·°F))
100	(-279.7)	179.19	(1243.26)	1500	(2240.3)	98.06	(680.38)
200	(-99.7)	143.58	(996.16)	1600	(2420.3)	95.91	(665.44)
300	(80.3)	138.03	(957.65)	1700	(2600.3)	93.94	(651.74)
400	(260.3)	133.59	(926.87)	1800	(2780.3)	92.14	(639.28)
500	(440.3)	129.44	(898.07)	1900	(2960.3)	90.52	(628.06)
600	(620.3)	125.49	(870.67)	2000	(3140.3)	89.08	(618.07)
700	(800.3)	121.73	(844.55)	2100	(3320.3)	87.82	(609.33)
800	(980.3)	118.14	(819.68)	2200	(3500.3)	86.74	(601.83)
900	(1160.3)	114.74	(796.06)	2300	(3680.3)	85.84	(595.56)
1000	(1340.3)	111.51	(773.68)	2400	(3860.3)	85.11	(590.53)
1100	(1520.3)	108.46	(752.54)	2500	(4040.3)	84.57	(586.75)
1200	(1700.3)	105.60	(732.64)	2600	(4220.3)	84.20	(584.20)
1300	(1880.3)	102.91	(713.98)	2700	(4400.3)	84.01	(582.89)
1400	(2060.3)	100.40	(696.56)	2800	(4580.3)	84.00	(582.82)

Application Notes: Data for thermal conductivity is collected from reference [1, 2] and fitted with the equations below to approximate the property trend with respect to temperature.

Fit Equation:

For temperature range: $1 \leq T < 100$

$$k(T) = \left(A0 \cdot \left(\frac{T}{1000}\right)^N\right) \Big/ \left(1 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2 + A3 \cdot \left(\frac{T}{1000}\right)^3\right)$$

For temperature range: $100 \leq T \leq 2801$

$$k(T) = B0 + B1 \cdot \left(\frac{T}{1000}\right) + B2 \cdot \left(\frac{T}{1000}\right)^2 + B3 \Big/ \left(\frac{T}{1000}\right)^N$$

$k(T) = Thermal\ Conductivity\ [W / (m \cdot K)]$

$T = Temperature\ [K]$

Constants:

T Range [K]:	$1 \leq T < 100$		$100 \leq T \leq 2801$
N =	7.361E-01	B0 =	1.518E+02
A0 =	3.075E+03	B1 =	-4.922E+01
A1 =	-3.869E+01	B2 =	8.931
A2 =	1.029E+03	B3 =	6.874E-04
A3 =	-4.274E+03	N =	4.671

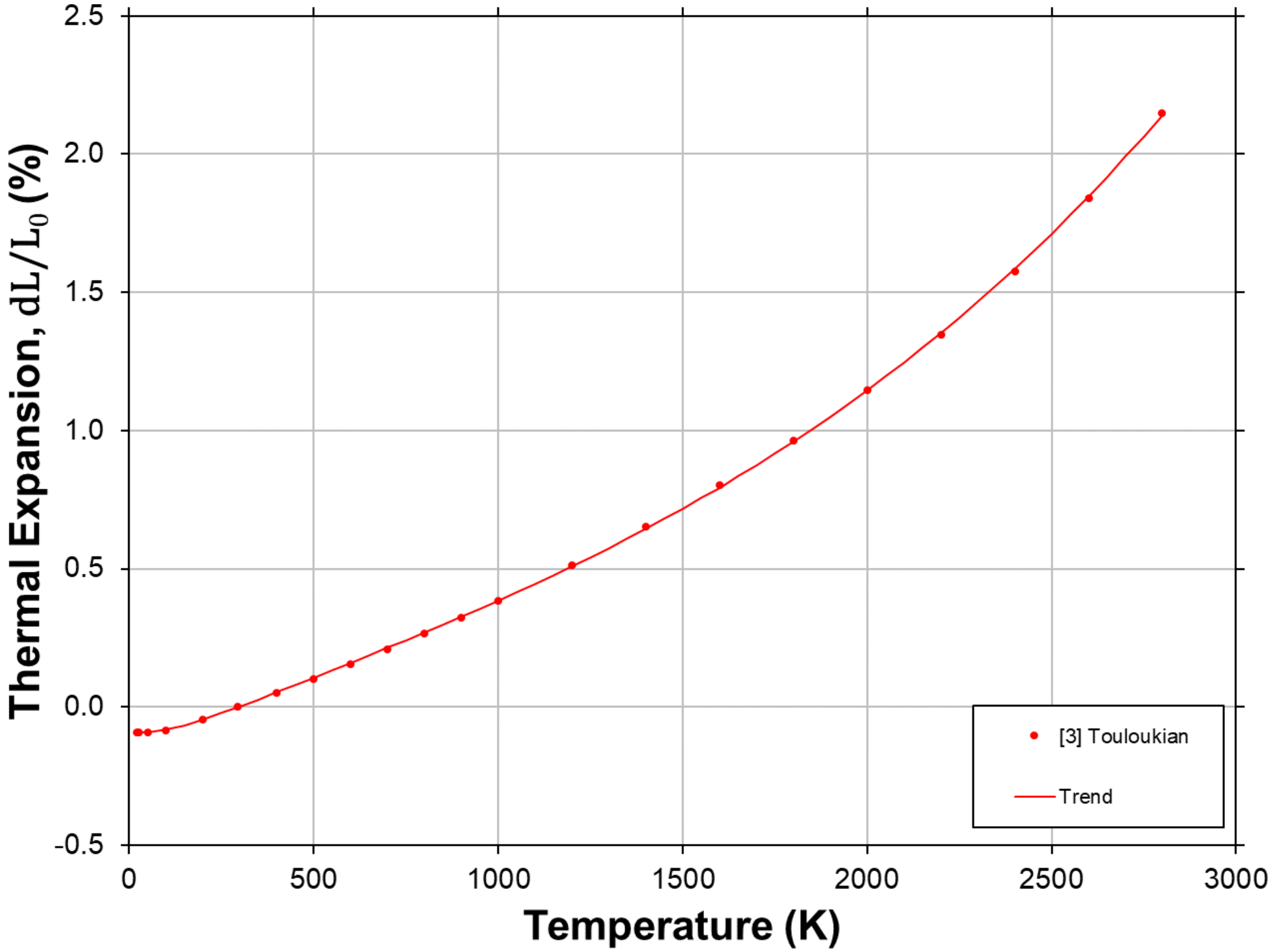

Figure 3.1.1-3: Thermal Expansion versus Temperature of Molybdenum.

100% Theoretical Density

Temperature (T)		Thermal Expansion (dL/L_0)	Temperature (T)		Thermal Expansion (dL/L_0)
K	(°F)	%	K	(°F)	%
20	(-423.7)	-0.092	1400	(2060.3)	0.644
60	(-351.7)	-0.090	1500	(2240.3)	0.717
100	(-279.7)	-0.083	1600	(2420.3)	0.793
200	(-99.7)	-0.046	1700	(2600.3)	0.874
300	(80.3)	0.000	1800	(2780.3)	0.959
400	(260.3)	0.053	1900	(2960.3)	1.050
500	(440.3)	0.106	2000	(3140.3)	1.145
600	(620.3)	0.160	2100	(3320.3)	1.246
700	(800.3)	0.214	2200	(3500.3)	1.353
800	(980.3)	0.269	2300	(3680.3)	1.466
900	(1160.3)	0.326	2400	(3860.3)	1.586
1000	(1340.3)	0.385	2500	(4040.3)	1.713
1100	(1520.3)	0.445	2600	(4220.3)	1.847
1200	(1700.3)	0.509	2700	(4400.3)	1.989
1300	(1880.3)	0.575	2800	(4580.3)	2.139

Application Notes: Data for thermal expansion is collected from reference [3] and fitted with the equation below to approximate the property trend with respect to temperature.

Fit Equation:

$$dL/L_0\,(T) = A0 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2 + A3 \cdot \left(\frac{T}{1000}\right)^3$$

$dL/L_0\,(T) = Thermal\ Expansion\ [\%]$

$T = Temperature\ [K]$

Constants:

T Range [K]:	$20 \leq T \leq 294$	$294 < T \leq 2800$
A0 =	-9.113E-02	-1.612E-01
A1 =	-1.096E-01	5.529E-01
A2 =	2.178E+00	-6.426E-02
A3 =	-2.532E+00	5.720E-02

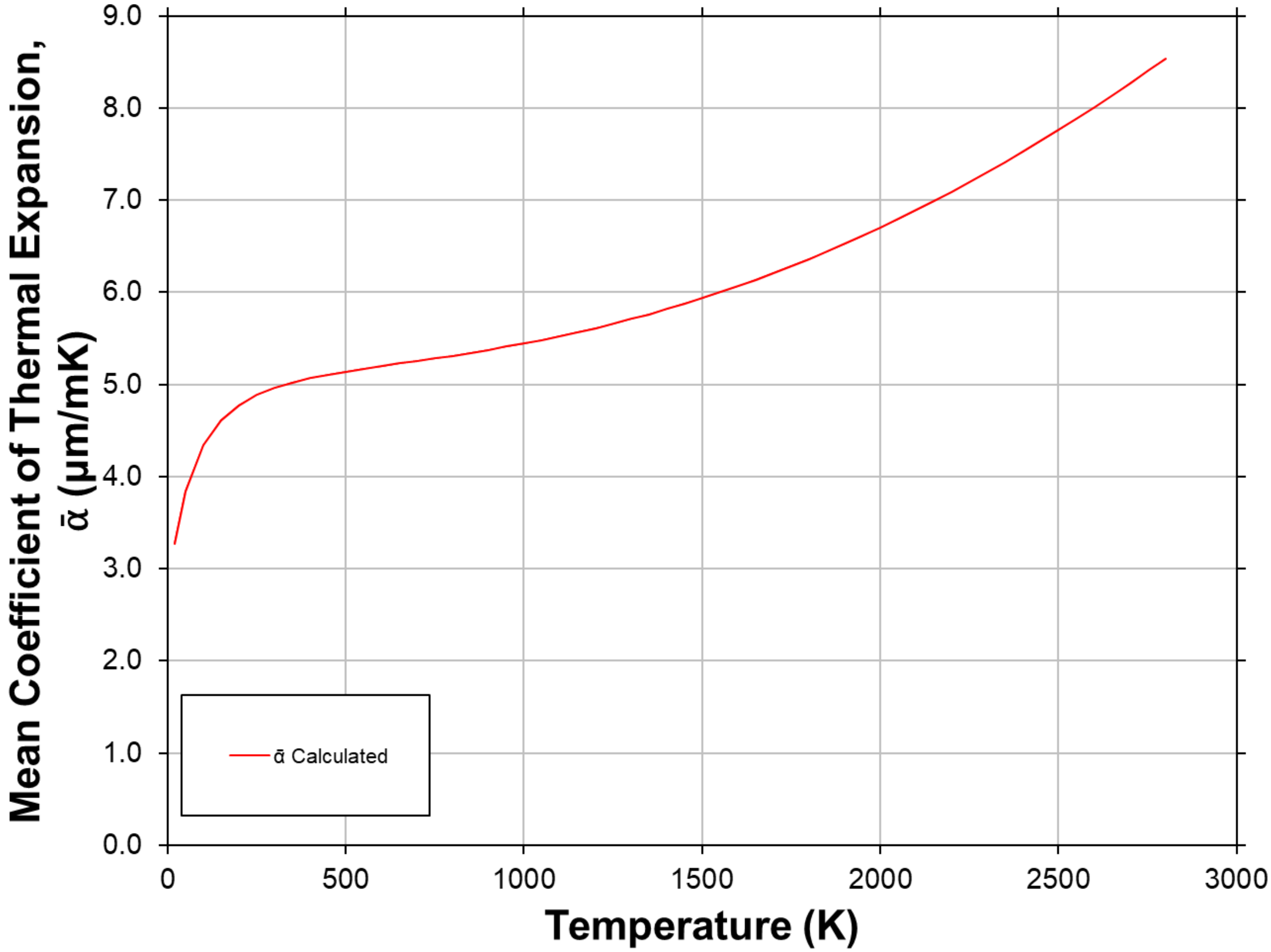

Figure 3.1.1-4: Mean Coefficient of Thermal Expansion versus Temperature of Molybdenum. Calculated from fitted trend of Thermal Expansion data.

Coefficient of Thermal Expansion with Temperature

100% Theoretical Density

Temperature (T)		Mean CTE (ᾱ)		Temperature (T)		Mean CTE (ᾱ)	
K	(°F)	µm/(m-K)	(µin/(in-°F))	K	(°F)	µm/(m-K)	(µin/(in-°F))
20	(-423.7)	3.270	(1.817)	1400	(2060.3)	5.819	(3.233)
60	(-351.7)	3.971	(2.206)	1500	(2240.3)	5.938	(3.299)
100	(-279.7)	4.342	(2.412)	1600	(2420.3)	6.068	(3.371)
200	(-99.7)	4.776	(2.653)	1700	(2600.3)	6.210	(3.450)
300	(80.3)	4.964	(2.758)	1800	(2780.3)	6.363	(3.535)
400	(260.3)	5.069	(2.816)	1900	(2960.3)	6.527	(3.626)
500	(440.3)	5.141	(2.856)	2000	(3140.3)	6.703	(3.724)
600	(620.3)	5.199	(2.889)	2100	(3320.3)	6.891	(3.829)
700	(800.3)	5.255	(2.919)	2200	(3500.3)	7.091	(3.940)
800	(980.3)	5.313	(2.952)	2300	(3680.3)	7.303	(4.057)
900	(1160.3)	5.376	(2.986)	2400	(3860.3)	7.527	(4.181)
1000	(1340.3)	5.446	(3.025)	2500	(4040.3)	7.762	(4.312)
1100	(1520.3)	5.524	(3.069)	2600	(4220.3)	8.010	(4.450)
1200	(1700.3)	5.612	(3.118)	2700	(4400.3)	8.269	(4.594)
1300	(1880.3)	5.710	(3.172)	2800	(4580.3)	8.541	(4.745)

Application Notes: Mean coefficient of thermal expansion is calculated as a function of the thermal expansion trend. The calculated data has been fitted with the equation below to approximate property trend with respect to temperature.

Fit Equation:

$$\bar{\alpha}(T) = \left(A0 + A1\cdot\left(\frac{T}{1000}\right) + A2\cdot\left(\frac{T}{1000}\right)^2 + A3\cdot\left(\frac{T}{1000}\right)^3\right)\Big/\left(A\_0 + \left(\frac{T}{1000}\right)\right)$$

$\bar{\alpha}(T) = Coefficient\ of\ Thermal\ Expansion\ [\mu m/(m\cdot K)]$

$T = Temperature\ [K]$

Constants:

T. Range [K]:	$20 \le T \le 2800$
A0 =	1.975E-01
A1 =	5.685E+00
A2 =	-6.415E-01
A3 =	6.136E-01
A_0 =	7.509E-02

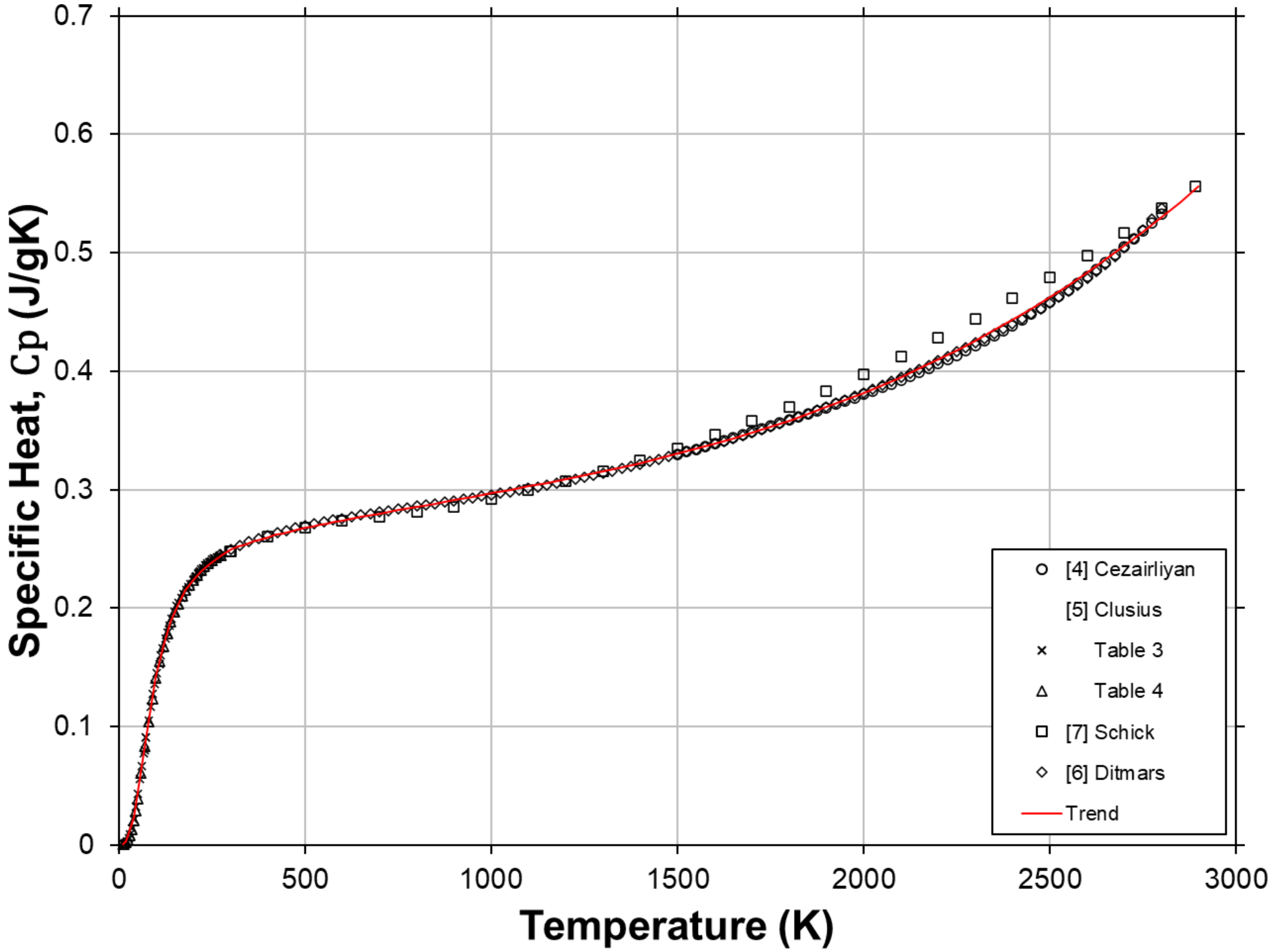

Figure 3.1.1-5: Specific Heat versus Temperature of Molybdenum.

100% Theoretical Density

Temperature (T)		Specific Heat (C_p)		Temperature (T)		Specific Heat (C_p)	
K	(°F)	J/(g-K)	(BTU/(lb-°F))	K	(°F)	J/(g-K)	(BTU/(lb-°F))
20	(-423.7)	0.003	(0.001)	1100	(1520.3)	0.303	(0.072)
60	(-351.7)	0.062	(0.015)	1200	(1700.3)	0.309	(0.074)
100	(-279.7)	0.142	(0.034)	1300	(1880.3)	0.315	(0.075)
200	(-99.7)	0.224	(0.053)	1400	(2060.3)	0.323	(0.077)
300	(80.3)	0.249	(0.060)	1500	(2240.3)	0.330	(0.079)
400	(260.3)	0.260	(0.062)	1600	(2420.3)	0.339	(0.081)
500	(440.3)	0.268	(0.064)	1800	(2780.3)	0.358	(0.086)
600	(620.3)	0.274	(0.066)	2000	(3140.3)	0.382	(0.091)
700	(800.3)	0.280	(0.067)	2200	(3500.3)	0.410	(0.098)
800	(980.3)	0.286	(0.068)	2400	(3860.3)	0.444	(0.106)
900	(1160.3)	0.291	(0.070)	2600	(4220.3)	0.483	(0.116)
1000	(1340.3)	0.297	(0.071)	2800	(4580.3)	0.530	(0.127)
1100	(1520.3)	0.303	(0.072)	2900	(4760.3)	0.556	(0.133)

Application Notes: Data for specific heat is collected from references [4-7] and fitted with the equations below to approximate property trend with respect to temperature.

Fit Equation:

For temperature range: $10 < T \leq 293$

$$C_P(T) = \left[A0 \cdot \left(\frac{T}{1000}\right)^N\right] \Big/ \left[1 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2 + A3 \cdot \left(\frac{T}{1000}\right)^3\right]$$

For temperature range: $293 < T \leq 2900$

$$C_P(T) = B0 + B1 \cdot \left(\frac{T}{1000}\right) + B2 \cdot \left(\frac{T}{1000}\right)^2 + B3 \cdot \left(\frac{T}{1000}\right)^3 + B\_2 \Big/ \left(\frac{T}{1000}\right)^2$$

$C_P(T) = Specific\ Heat\ [J/(g \cdot K)]$

$T = Temperature\ [K]$

Constants:

T. Range [K]:	$10 \leq T \leq 293$		$293 < T \leq 2900$
N =	2.964E+00	B0 =	2.422E-01
A0 =	3.230E+02	B1 =	7.138E-02
A1 =	-5.704E+00	B2 =	-3.057E-02
A2 =	1.002E+02	B3 =	1.493E-02
A3 =	1.046E+03	B_2 =	-1.082E-03

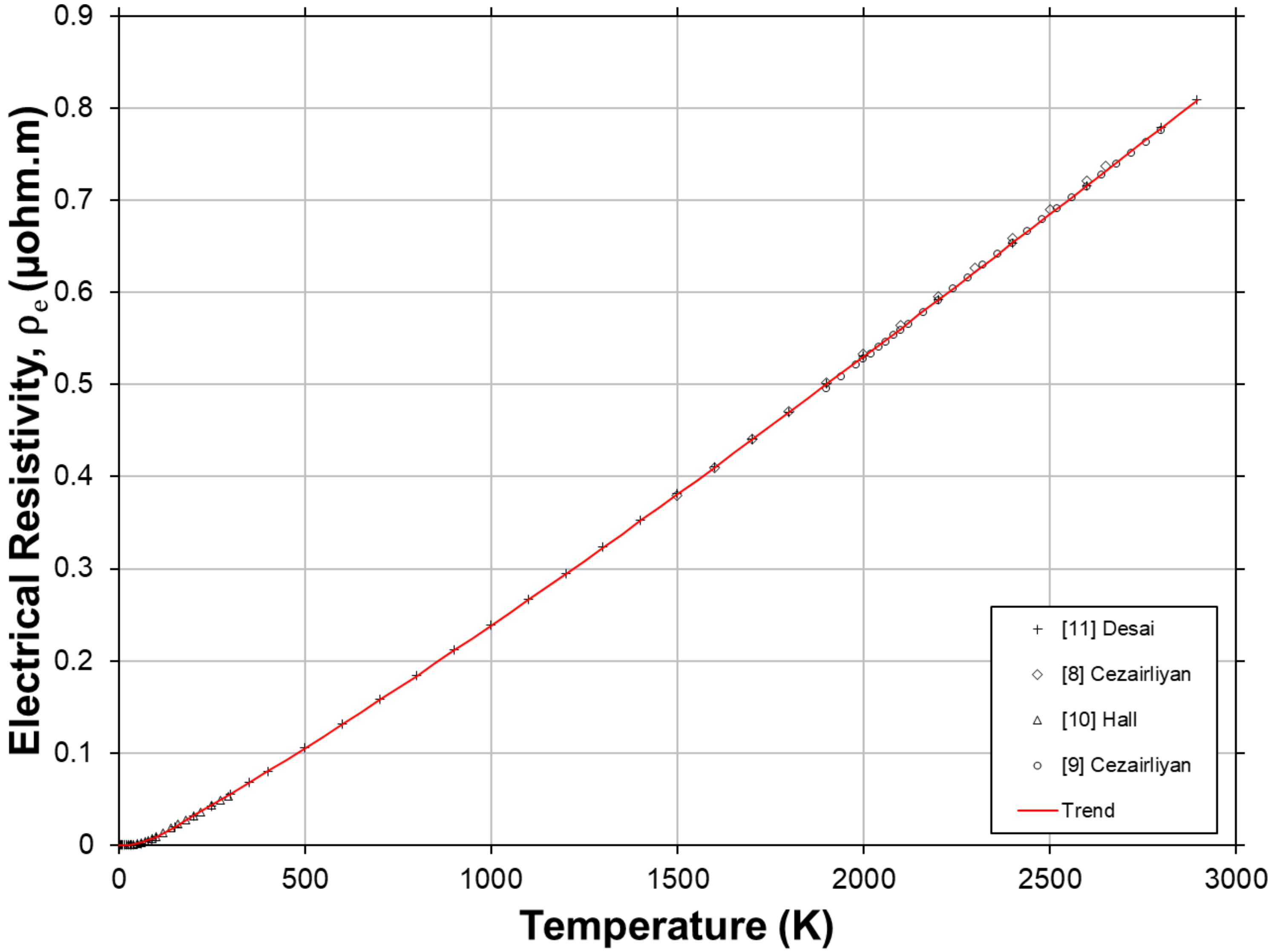

Figure 3.1.1-6: Electrical Resistivity versus Temperature for Molybdenum.

Electrical Resistivity with Temperature

100% Theoretical Density

Temperature (T)		Electrical Resistivity (ρ_e)		Temperature (T)		Electrical Resistivity (ρ_e)	
K	(°F)	μΩ-m	(μΩ-in)	K	(°F)	μΩ-m	(μΩ-in)
20	(-423.7)	0.000	(-0.01)	1500	(2240.3)	0.381	(14.99)
100	(-279.7)	0.009	(0.34)	1600	(2420.3)	0.410	(16.15)
200	(-99.7)	0.032	(1.25)	1700	(2600.3)	0.440	(17.32)
300	(80.3)	0.055	(2.18)	1800	(2780.3)	0.470	(18.49)
400	(260.3)	0.080	(3.15)	1900	(2960.3)	0.500	(19.68)
500	(440.3)	0.105	(4.15)	2000	(3140.3)	0.530	(20.88)
600	(620.3)	0.131	(5.16)	2100	(3320.3)	0.561	(22.08)
700	(800.3)	0.157	(6.19)	2200	(3500.3)	0.592	(23.29)
800	(980.3)	0.184	(7.24)	2300	(3680.3)	0.622	(24.51)
900	(1160.3)	0.211	(8.31)	2400	(3860.3)	0.654	(25.73)
1000	(1340.3)	0.238	(9.39)	2500	(4040.3)	0.685	(26.96)
1100	(1520.3)	0.266	(10.48)	2600	(4220.3)	0.716	(28.19)
1200	(1700.3)	0.294	(11.59)	2700	(4400.3)	0.747	(29.42)
1300	(1880.3)	0.323	(12.71)	2800	(4580.3)	0.779	(30.66)
1400	(2060.3)	0.352	(13.84)	2895	(4751.3)	0.809	(31.84)

Application Notes: Data for electrical resistivity is collected from references [8-11] and fitted with the equation below to approximate property trend with respect to temperature.

Fit Equation:

$$\rho_e(T) = A0 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2 + A3 \cdot \left(\frac{T}{1000}\right)^3$$

$\rho_e(T) = Electrical\ Resistivity\ [\mu\Omega \cdot m]$

$T = Temperature\ [K]$

Constants:

T. Range [K]:	$1 \leq T \leq 293$	$293 < T \leq 2895$
A0 =	-1.023E-04	-1.602E-02
A1 =	-3.404E-02	2.298E-01
A2 =	1.472E+00	2.758E-02
A3 =	-2.526E+00	-2.954E-03

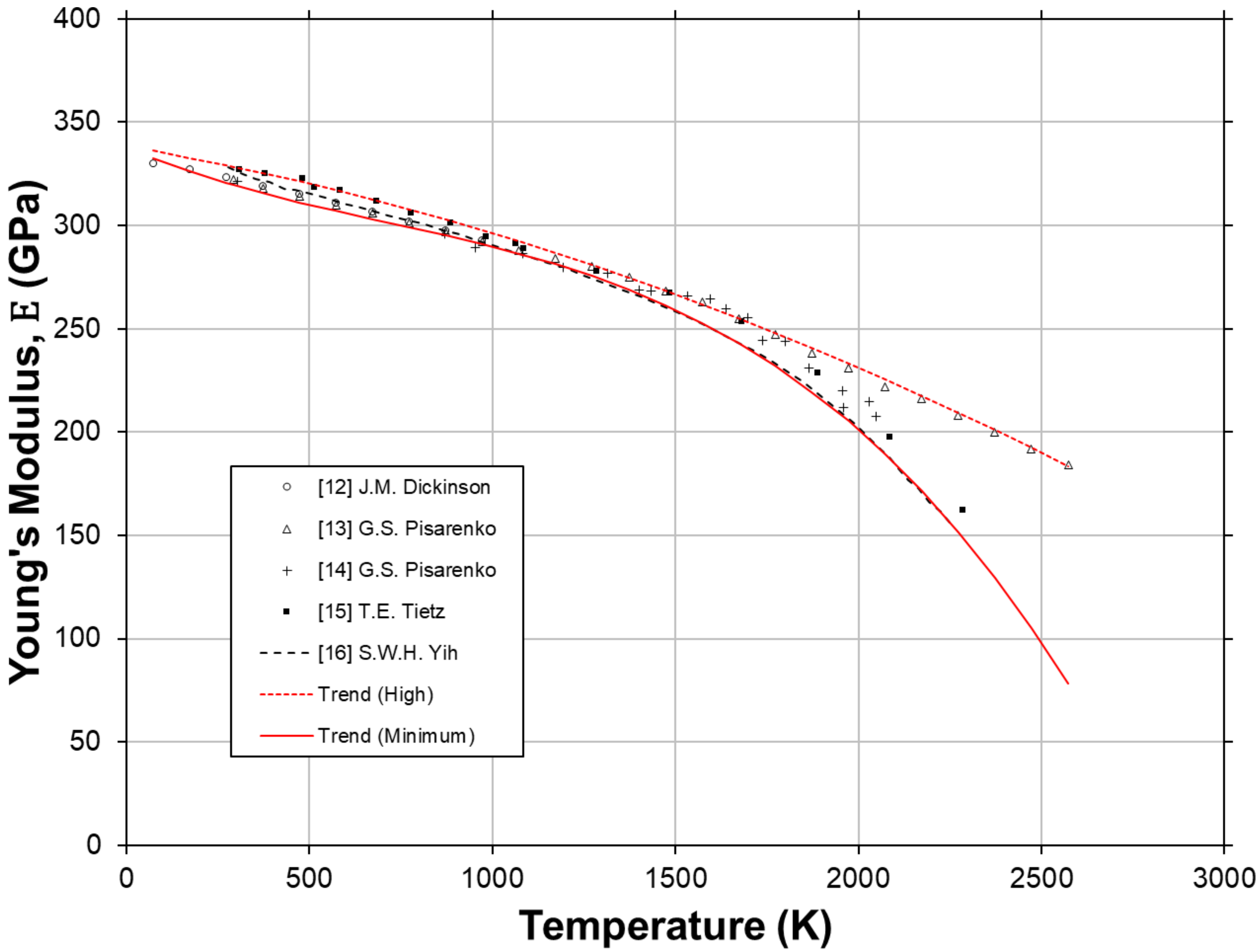

Figure 3.1.1-7: Young's modulus versus temperature for molybdenum.

Minimum Young's Modulus at 100% Theoretical Density

Temperature (T)		Young's Modulus (E)	
K	(°F)	GPa	(Msi)
73	(-328.3)	332.54	(48.25)
200	(-99.7)	324.65	(47.11)
293	(67.7)	319.61	(46.38)
500	(440.3)	310.05	(44.99)
700	(800.3)	302.01	(43.82)
900	(1160.3)	294.02	(42.66)
1100	(1520.3)	284.97	(41.35)
1300	(1880.3)	273.75	(39.72)
1500	(2240.3)	259.22	(37.61)
1700	(2600.3)	240.29	(34.87)
1900	(2960.3)	215.83	(31.32)
2100	(3320.3)	184.73	(26.80)
2300	(3680.3)	145.87	(21.17)
2500	(4040.3)	98.13	(14.24)
2573	(4171.7)	78.28	(11.36)

High Young's Modulus at 100% Theoretical Density

Temperature (T)		Young's Modulus (E)	
K	(°F)	GPa	(Msi)
73	(-328.3)	336.09	(48.77)
200	(-99.7)	331.79	(48.14)
293	(67.7)	328.40	(47.65)
500	(440.3)	320.15	(46.45)
700	(800.3)	311.25	(45.16)
900	(1160.3)	301.43	(43.74)
1100	(1520.3)	290.70	(42.18)
1300	(1880.3)	279.05	(40.49)
1500	(2240.3)	266.49	(38.67)
1700	(2600.3)	253.01	(36.71)
1900	(2960.3)	238.62	(34.62)
2100	(3320.3)	223.31	(32.40)
2300	(3680.3)	207.09	(30.05)
2500	(4040.3)	189.95	(27.56)
2573	(4171.7)	183.47	(26.62)

Application Notes: Data for Young's modulus is collected from references [12-16] and fitted with the equation below to approximate the property trend with respect to temperature. Since two distinct trends were observed, a minimum and a high equation were generated.

Fit Equations:

$$E(T) = A0 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2 + A3 \cdot \left(\frac{T}{1000}\right)^3$$

$E(T) = Young's\ Modulus\ [GPa]$

$T = Temperature\ [K]$

T Range [K]: $73 \leq T \leq 2573$

Constants:

Curve:	Minimum	High
A0 =	337.7	338.4
A1 =	-74.24	-30.78
A2 =	49.49	-11.44
A3 =	-23.25	0

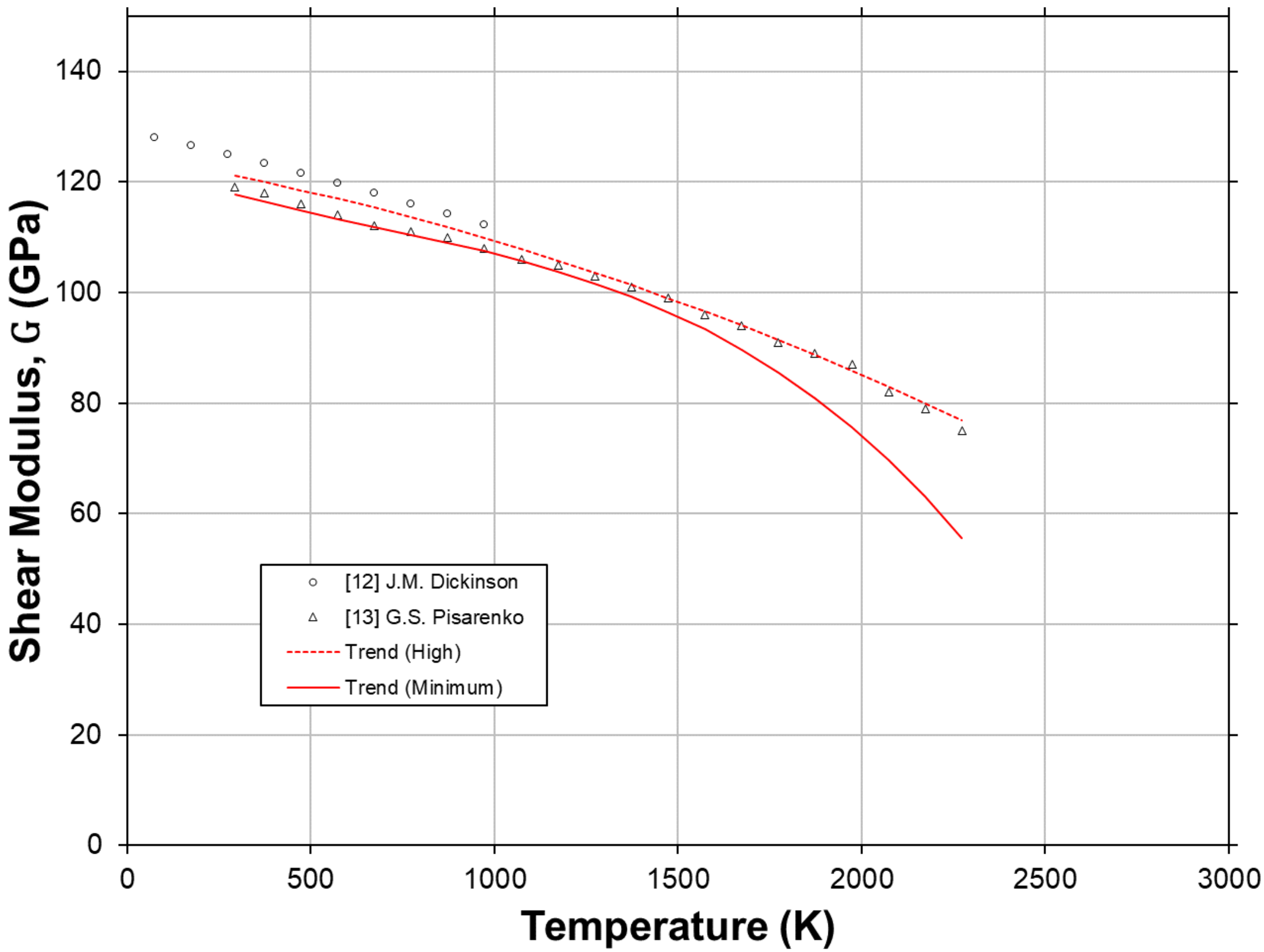

Figure 3.1.1-8: Shear modulus versus temperature for molybdenum. Trends were calculated from the fitted Young's modulus and Poisson's ratio trends.

Shear Modulus with Temperature

Minimum Young's Modulus at 100% Theoretical Density

Temperature (T)		Shear Modulus (G)	
K	(°F)	GPa	(Msi)
293	(67.7)	117.80	(17.09)
300	(80.3)	117.68	(17.07)
450	(350.3)	115.16	(16.71)
600	(620.3)	112.92	(16.39)
750	(890.3)	110.79	(16.08)
900	(1160.3)	108.58	(15.76)
1050	(1430.3)	106.13	(15.40)
1200	(1700.3)	103.28	(14.99)
1350	(1970.3)	99.84	(14.49)
1500	(2240.3)	95.65	(13.88)
1650	(2510.3)	90.54	(13.14)
1800	(2780.3)	84.33	(12.24)
1950	(3050.3)	76.86	(11.15)
2100	(3320.3)	67.95	(9.86)
2273	(3631.7)	55.67	(8.08)

High Young's Modulus at 100% Theoretical Density

Temperature (T)		Shear Modulus (G)	
K	(°F)	GPa	(Msi)
293	(67.7)	121.08	(17.57)
300	(80.3)	120.98	(17.55)
450	(350.3)	118.87	(17.25)
600	(620.3)	116.55	(16.91)
750	(890.3)	114.03	(16.55)
900	(1160.3)	111.30	(16.15)
1050	(1430.3)	108.37	(15.72)
1200	(1700.3)	105.23	(15.27)
1350	(1970.3)	101.89	(14.78)
1500	(2240.3)	98.35	(14.27)
1650	(2510.3)	94.60	(13.73)
1800	(2780.3)	90.65	(13.15)
1950	(3050.3)	86.49	(12.55)
2100	(3320.3)	82.13	(11.92)
2273	(3631.7)	76.84	(11.15)

Application Notes: Shear modulus is calculated as a function of Young's modulus and Poisson's ratio to approximate the property trend with respect to temperature. Since a minimum and a high trend were found for Young's modulus, this resulted in two shear modulus curves. Equivalent equations can be found below for readers' convenience. Trends are compared with [12, 13].

Fit Equations:

$$G(T) = A0 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2 + A3 \cdot \left(\frac{T}{1000}\right)^3$$

$G(T) = Shear\ Modulus\ [GPa]$

$T = Temperature\ [K]$

T Range [K]: $293 \leq T \leq 2273$

Constants:

Curve:	Minimum	High
A0 =	124.2	124.6
A1 =	-26.22	-10.69
A2 =	17.44	-4.541
A3 =	-8.433	0

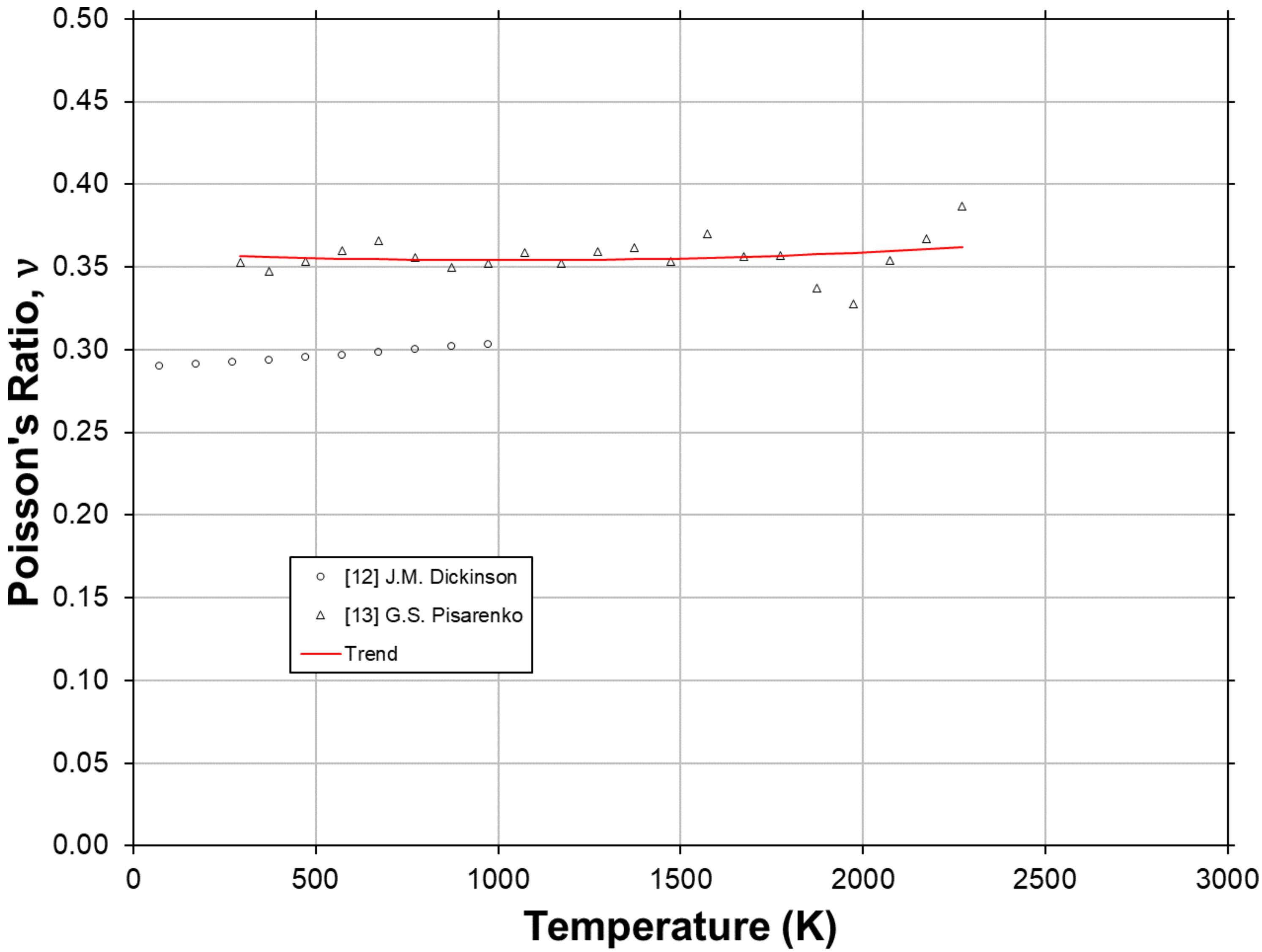

Figure 3.1.1-9: Poisson's ratio versus temperature for molybdenum.

100% Theoretical Density

Temperature (T) K	(°F)	Poisson's Ratio (ν)	Temperature (T) K	(°F)	Poisson's Ratio (ν)
293	(67.7)	0.357	1100	(1520.3)	0.354
300	(80.3)	0.356	1200	(1700.3)	0.354
350	(170.3)	0.356	1300	(1880.3)	0.354
400	(260.3)	0.356	1400	(2060.3)	0.355
450	(350.3)	0.356	1500	(2240.3)	0.355
500	(440.3)	0.355	1600	(2420.3)	0.356
550	(530.3)	0.355	1700	(2600.3)	0.356
600	(620.3)	0.355	1800	(2780.3)	0.357
650	(710.3)	0.355	1900	(2960.3)	0.358
700	(800.3)	0.354	2000	(3140.3)	0.359
800	(980.3)	0.354	2100	(3320.3)	0.360
900	(1160.3)	0.354	2200	(3500.3)	0.361
1000	(1340.3)	0.354	2273	(3631.7)	0.362

Application Notes: Data for Poisson's ratio was collected from [12, 13] and fitted with the equation below to approximate the property trend with respect to temperature.

Fit Equations:

$$\nu(T) = A0 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2$$

$\nu(T) = Poisson's\ Ratio$

$T = Temperature\ [K]$

Constants:

T Range [K]:	$293 \le T \le 2273$
A0 =	0.359
A1 =	-9.966E-3
A2 =	4.934E-3

Temp. (T) K	Physical and Electrical		Thermal				Elastic		
	Density (ρ) kg/m³	Electrical Resistivity (ρ_e) μΩ-m	Thermal Conductivity (k) W/(m-K)	Thermal Expansion (dL/L_0) %	Mean CTE ($\bar{\alpha}$) 10^{-6}/K	Specific Heat (C_p) J/(g-K)	Young's Modulus (E) GPa	Shear Modulus (G) GPa	Poisson's Ratio (ν)
100	10306	0.009	179.19	-0.083	4.34	0.142	325.62	127.61	0.358
200	10294	0.032	143.58	-0.046	4.78	0.224	321.55	125.72	0.357
300	10280	0.055	138.03	0.000	4.96	0.249	317.49	123.84	0.356
400	10264	0.080	133.59	0.053	5.07	0.260	313.41	121.95	0.356
500	10247	0.105	129.44	0.106	5.14	0.268	309.28	120.05	0.355
600	10231	0.131	125.49	0.160	5.20	0.274	305.08	118.13	0.355
700	10214	0.157	121.73	0.214	5.26	0.280	300.81	116.18	0.354
800	10197	0.184	118.14	0.269	5.31	0.286	296.42	114.19	0.354
900	10180	0.211	114.74	0.326	5.38	0.291	291.91	112.16	0.354
1000	10162	0.238	111.51	0.385	5.45	0.297	287.25	110.07	0.354
1100	10144	0.266	108.46	0.445	5.52	0.303	282.42	107.93	0.354
1200	10125	0.294	105.60	0.509	5.61	0.309	277.40	105.71	0.354
1300	10105	0.323	102.91	0.575	5.71	0.315	272.16	103.42	0.354
1400	10084	0.352	100.40	0.644	5.82	0.323	266.70	101.05	0.355
1500	10062	0.381	98.06	0.717	5.94	0.330	260.98	98.59	0.355
1600	10039	0.410	95.91	0.793	6.07	0.339	254.98	96.03	0.356
1700	10015	0.440	93.94	0.874	6.21	0.348	248.69	93.36	0.356
1800	9990	0.470	92.14	0.959	6.36	0.358	242.08	90.58	0.357
1900	9963	0.500	90.52	1.050	6.53	0.370	235.13	87.68	0.358
2000	9935	0.530	89.08	1.145	6.70	0.382	227.82	84.64	0.359
2100	9905	0.561	87.82	1.246	6.89	0.395	220.14	81.47	0.360
2200	9874	0.592	86.74	1.353	7.09	0.410	212.05	78.16	0.361
2400	9806	0.654	85.11	1.586	7.53	0.444	194.58	-	-
2600	9731	0.716	84.20	1.847	8.01	0.483	-	-	-
2800	9648	0.779	84.00	2.139	8.54	0.530	-	-	-

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3 Refractory Metals and Alloys

3.1 Molybdenum and Molybdenum Alloys

Room Temperature Properties

Density, [kg/m^3]	11,900
Melting Point, [K]	3,090
Specific Heat, [J/(g-K)]	0.214
Thermal Conductivity, [W/(m-K)]	92.2
Thermal Diffusivity [cm^2/s]	0.363
Linear expansion coefficient, [µm/(m-K)]	4.92
Electrical resistivity, [µΩ-m]	0.070
Young's Modulus, [GPa]	340.7
Shear Modulus, [GPa]	130.0
Poisson's Ratio, [-]	0.309

Molybdenum - Tungsten Phase Diagram

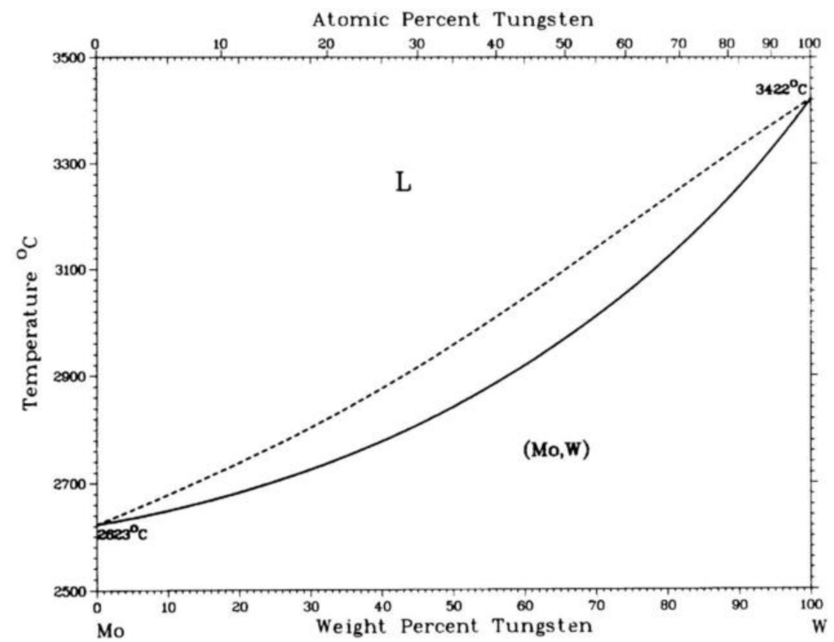

Figure 3.1.2-1: Molybdenum – Tungsten Phase Diagram [1].

Composition

Table 3.1.2-1: Typical Composition ranges for Mo-30W (percent by weight) [2].

Grade		Mo	W	C	Fe	Si	N	Ni
Mo-30W	Min.	66.9	27	-	-	-	-	-
	Max.	-	33	.03	.01	.01	.002	.002

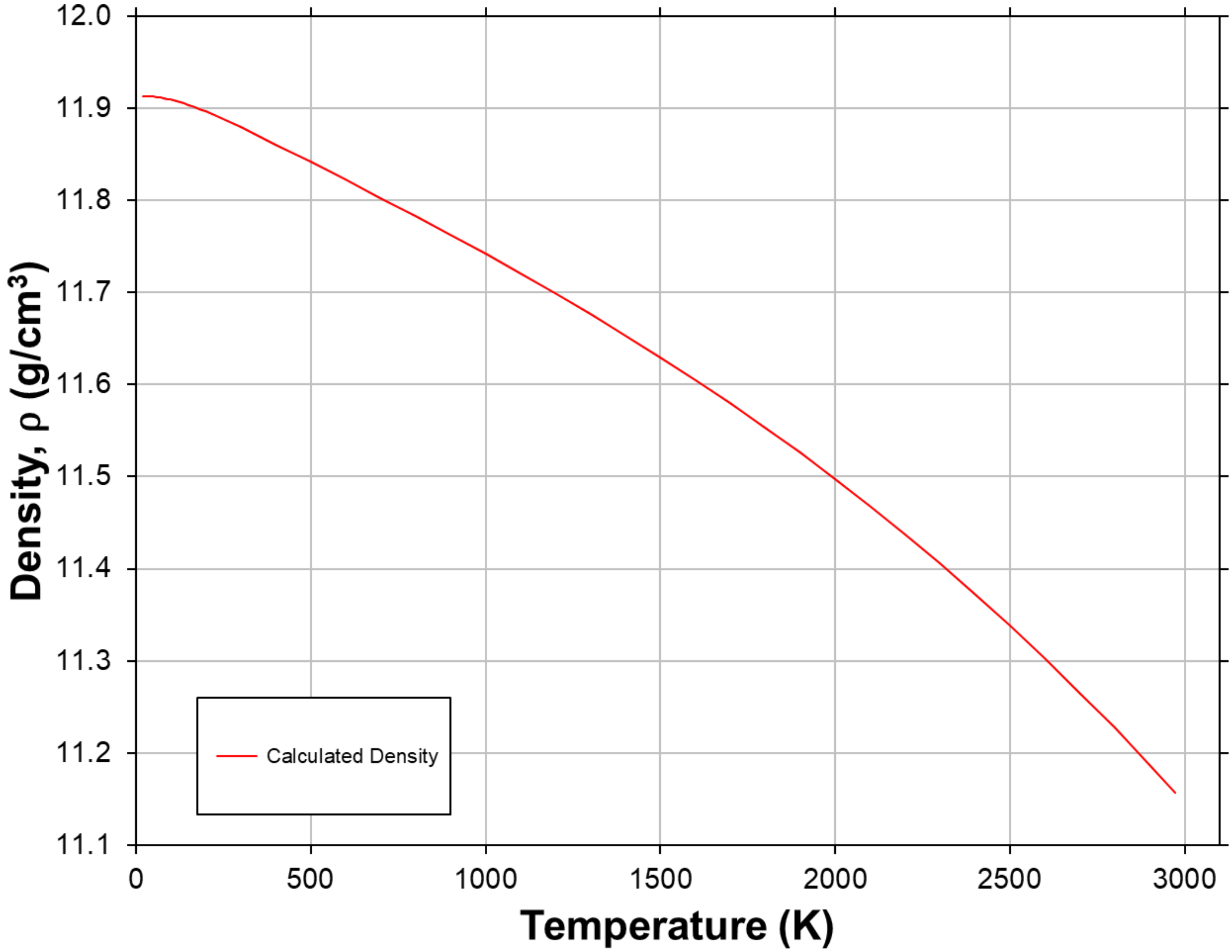

Figure 3.1.2-2: Density versus Temperature for Mo-30W. Calculated from Thermal Expansion trend.

100% Theoretical Density

Temperature (T)		Density (ρ)		Temperature (T)		Density (ρ)	
K	(°F)	kg/m^3	(lb/ft^3)	K	(°F)	kg/m^3	(lb/ft^3)
50	(-369.7)	11912	(743.7)	1500	(2240.3)	11630	(726.0)
100	(-279.7)	11909	(743.5)	1600	(2420.3)	11605	(724.5)
200	(-99.7)	11896	(742.7)	1700	(2600.3)	11580	(722.9)
300	(80.3)	11880	(741.6)	1800	(2780.3)	11553	(721.3)
400	(260.3)	11861	(740.5)	1900	(2960.3)	11526	(719.6)
500	(440.3)	11841	(739.3)	2000	(3140.3)	11498	(717.8)
600	(620.3)	11822	(738.0)	2100	(3320.3)	11468	(716.0)
700	(800.3)	11802	(736.8)	2200	(3500.3)	11438	(714.0)
800	(980.3)	11783	(735.6)	2300	(3680.3)	11406	(712.1)
900	(1160.3)	11762	(734.3)	2400	(3860.3)	11373	(710.0)
1000	(1340.3)	11742	(733.0)	2500	(4040.3)	11338	(707.9)
1100	(1520.3)	11720	(731.7)	2600	(4220.3)	11303	(705.6)
1200	(1700.3)	11699	(730.3)	2700	(4400.3)	11266	(703.3)
1300	(1880.3)	11676	(729.0)	2800	(4580.3)	11227	(700.9)
1400	(2060.3)	11653	(727.5)	2900	(4760.3)	11187	(698.4)

Application Notes: Density trend with respect to temperature is calculated as a function of thermal expansion as shown in the equation below.

Density Calculation:

$\rho(T) = \rho_{RT}/(1 + dL/L_0(T)/100)^3$

$\rho(T) = Density\ [kg/m^3]$

$\rho_{RT}\ (Room\ Temperature\ Density)\ = 11{,}900\ [kg/m^3]$

$T = Temperature\ [K]$

Temperature Range: $20 \leq T \leq 2974$

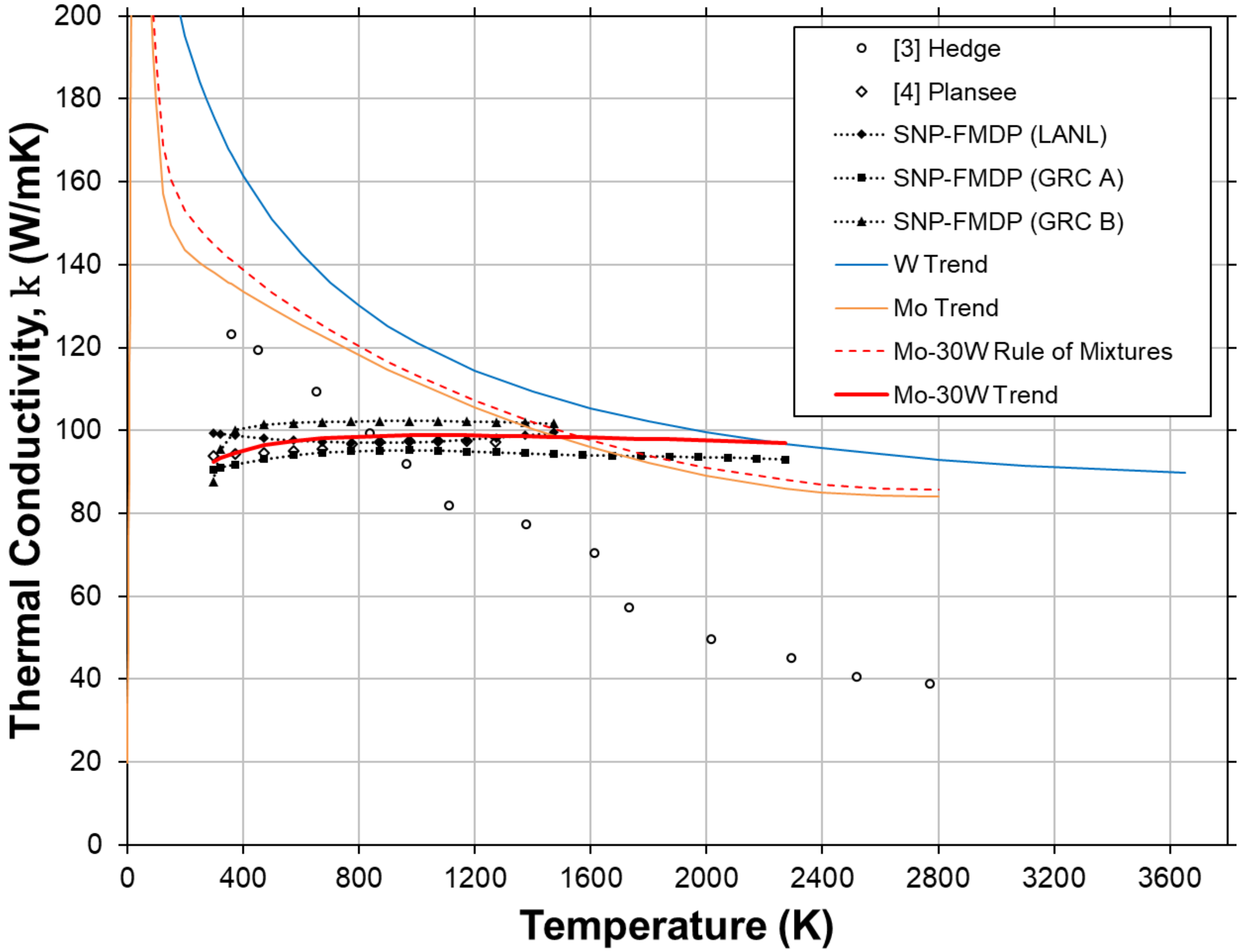

Figure 3.1.2-3: Thermal Conductivity versus Temperature of Mo-30W. Displaying fitted trend of the data with comparison to Molybdenum, Tungsten and Rule of Mixtures (70%Mo, 30%W).

100% Theoretical Density

Temperature (T)		Thermal Conductivity (k)		Temperature (T)		Thermal Conductivity (k)	
K	(°F)	W/(m-K)	((Btu·in)/(ft²·hr·°F))	K	(°F)	W/(m-K)	((Btu·in)/(ft²·hr·°F))
293	(67.7)	92.25	(640.01)	1300	(1880.3)	98.66	(684.50)
300	(80.3)	92.53	(641.98)	1400	(2060.3)	98.53	(683.60)
400	(260.3)	95.25	(660.84)	1500	(2240.3)	98.39	(682.61)
500	(440.3)	96.74	(671.21)	1600	(2420.3)	98.24	(681.59)
600	(620.3)	97.66	(677.56)	1700	(2600.3)	98.09	(680.55)
700	(800.3)	98.23	(681.55)	1800	(2780.3)	97.94	(679.49)
800	(980.3)	98.58	(683.97)	1900	(2960.3)	97.77	(678.36)
900	(1160.3)	98.77	(685.28)	2000	(3140.3)	97.59	(677.12)
1000	(1340.3)	98.84	(685.79)	2100	(3320.3)	97.38	(675.65)
1100	(1520.3)	98.83	(685.72)	2200	(3500.3)	97.12	(673.82)
1200	(1700.3)	98.77	(685.24)	2273	(3631.7)	96.88	(672.18)

Application Notes: Data from reference [3] was excluded from the Mo30W Trend Fit. All other internal data, and external data from reference [4], was used to generate the fit.

Calculated Equation:

$k(T) = \alpha(T) \cdot \rho(T) \cdot C_p(T)$

$k(T) = Thermal\ Conductivity\ [W\ /\ (m \cdot K)]$

$\alpha(T) = Thermal\ Diffusivity\ (m^2/s)$

$\rho(T) = Density\ (g/m^3)$

$C_p(T) = Specific\ Heat\ [J/(g \cdot K)]$

$T = Temperature\ [K]$

Fit Equation:

$$k(T) = A0 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2 + A\_1/\left(\frac{T}{1000}\right)$$

Fit Equation Constants:

T Range [K]:	$293 \leq T \leq 2273$
A0 =	106
A1 =	-3.693
A2 =	0.1844
A_1 =	-3.732

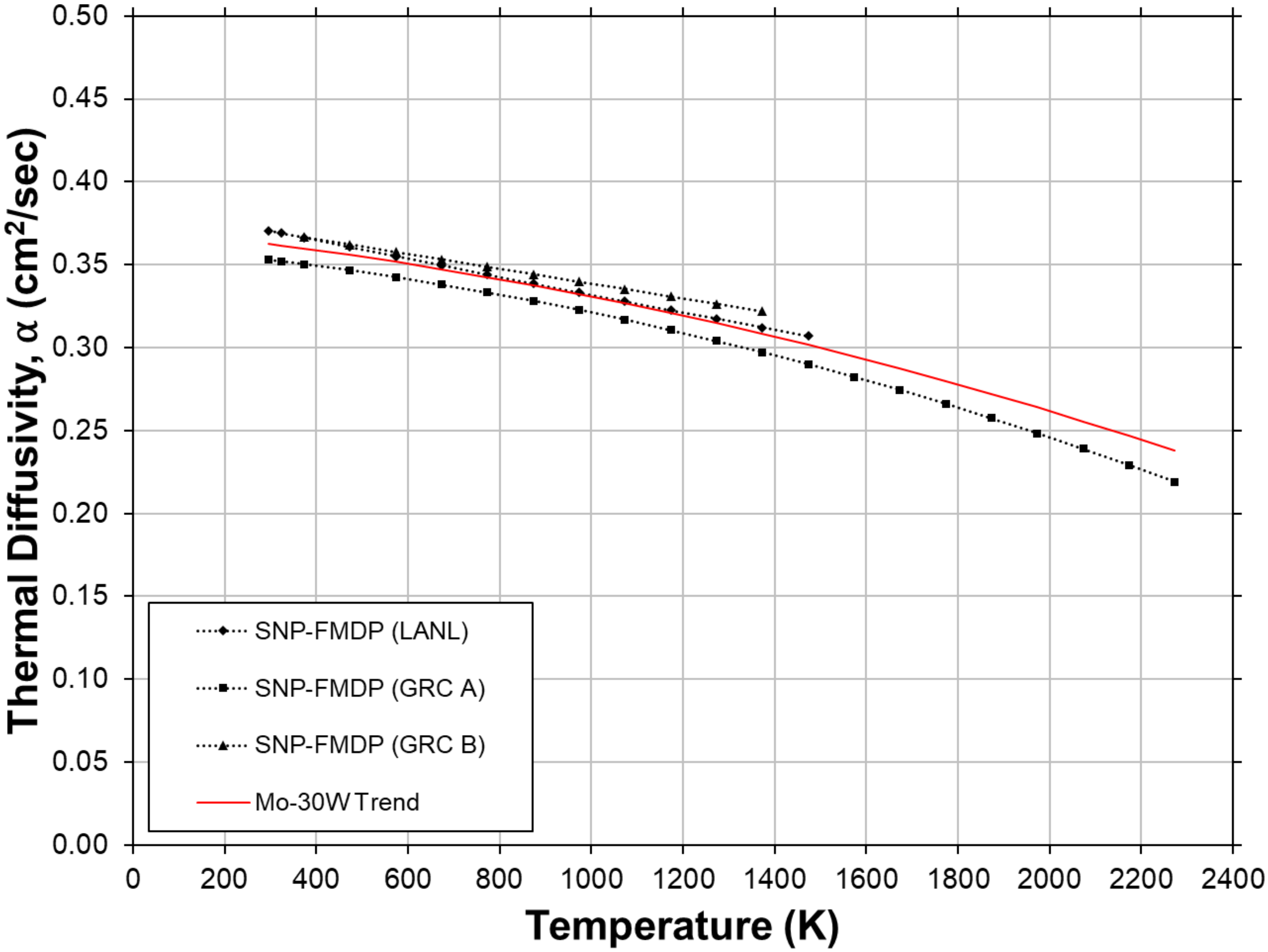

Figure 3.1.2-4: Thermal Diffusivity versus Temperature of Mo-30W.

100% Theoretical Density

Temperature (T)		Thermal Diffusivity (α)		Temperature (T)		Thermal Diffusivity (α)	
K	(°F)	cm^2/s	($in.^2/sec$)	K	(°F)	cm^2/s	($in.^2/sec$)
293	(67.7)	0.363	(0.056)	1300	(1880.3)	0.313	(0.049)
300	(80.3)	0.362	(0.056)	1400	(2060.3)	0.307	(0.048)
400	(260.3)	0.359	(0.056)	1500	(2240.3)	0.300	(0.046)
500	(440.3)	0.355	(0.055)	1600	(2420.3)	0.293	(0.045)
600	(620.3)	0.351	(0.054)	1700	(2600.3)	0.286	(0.044)
700	(800.3)	0.346	(0.054)	1800	(2780.3)	0.278	(0.043)
800	(980.3)	0.341	(0.053)	1900	(2960.3)	0.270	(0.042)
900	(1160.3)	0.336	(0.052)	2000	(3140.3)	0.262	(0.041)
1000	(1340.3)	0.331	(0.051)	2100	(3320.3)	0.253	(0.039)
1100	(1520.3)	0.325	(0.050)	2200	(3500.3)	0.244	(0.038)
1200	(1700.3)	0.319	(0.050)	2273	(3631.7)	0.238	(0.037)

Application Notes: Data for thermal diffusivity was fitted with the equation below to approximate property trend with respect to temperature.

Fit Equation:

$$\alpha(T) = A0 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2$$

$\alpha(T) = Thermal\ Diffusivity\ (cm^2/s)$

$T = Temperature\ [K]$

Constants:

T Range [K]: $293 \leq T \leq 2273$

A0 = 0.3714

A1 = -0.02609

A2 = -0.01437

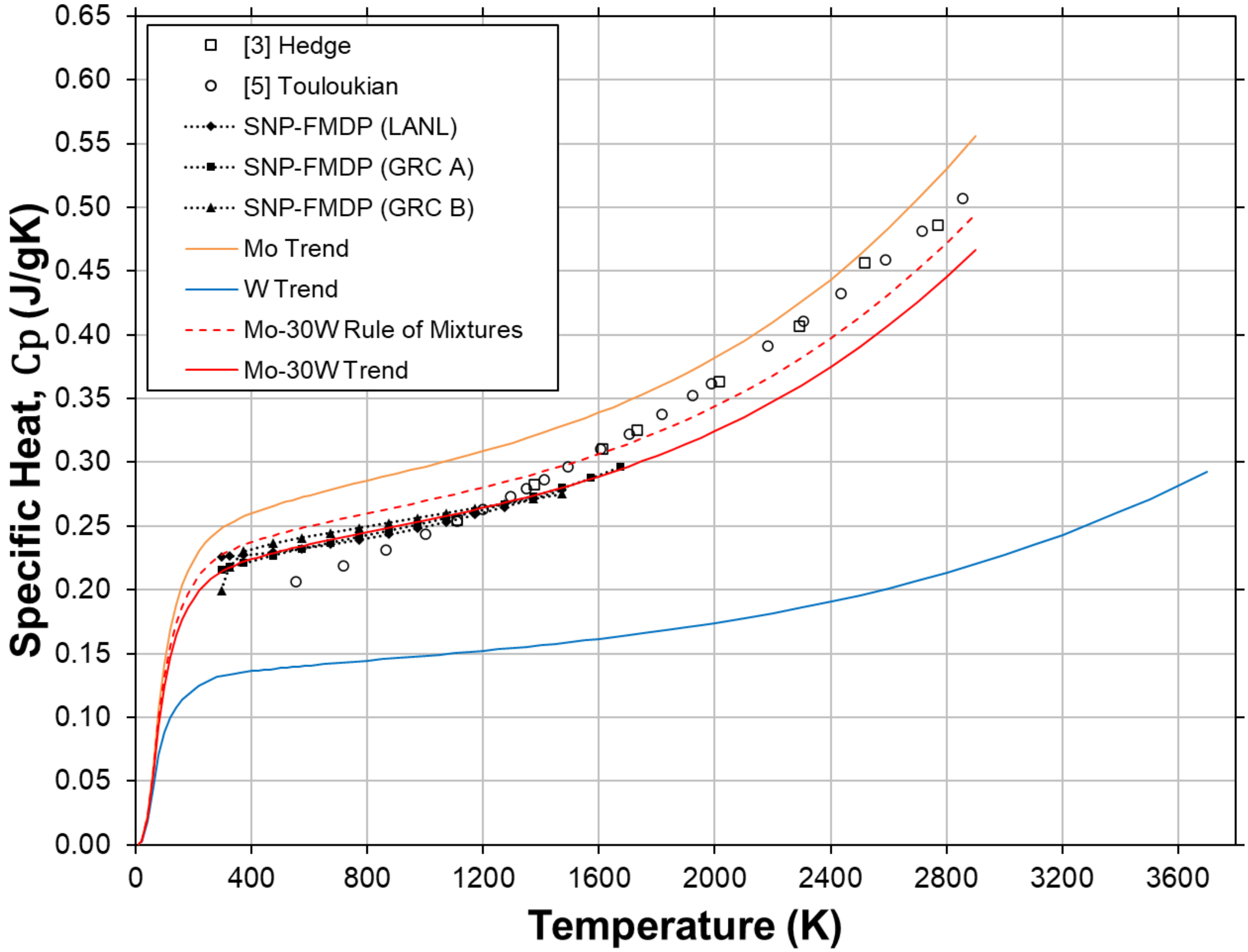

Figure 3.1.2-5: Specific Heat versus Temperature of Mo-30W. Displaying fitted trend of the data with comparison to Molybdenum, Tungsten and Rule of Mixtures (70%Mo, 30%W).

100% Theoretical Density

Temperature (T)		Specific Heat (C_p)		Temperature (T)		Specific Heat (C_p)	
K	(°F)	J/(g-K)	(BTU/(lb-°F))	K	(°F)	J/(g-K)	(BTU/(lb-°F))
40	(-387.7)	0.021	(0.005)	1100	(1520.3)	0.259	(0.062)
60	(-351.7)	0.056	(0.013)	1200	(1700.3)	0.264	(0.063)
80	(-315.7)	0.093	(0.022)	1300	(1880.3)	0.270	(0.064)
100	(-279.7)	0.124	(0.030)	1400	(2060.3)	0.276	(0.066)
200	(-99.7)	0.194	(0.046)	1500	(2240.3)	0.282	(0.067)
300	(80.3)	0.215	(0.051)	1600	(2420.3)	0.289	(0.069)
400	(260.3)	0.224	(0.054)	1800	(2780.3)	0.305	(0.073)
500	(440.3)	0.230	(0.055)	2000	(3140.3)	0.324	(0.078)
600	(620.3)	0.236	(0.056)	2200	(3500.3)	0.347	(0.083)
700	(800.3)	0.240	(0.057)	2400	(3860.3)	0.375	(0.090)
800	(980.3)	0.245	(0.059)	2600	(4220.3)	0.407	(0.097)
900	(1160.3)	0.250	(0.060)	2800	(4580.3)	0.445	(0.106)
1000	(1340.3)	0.254	(0.061)	2900	(4760.3)	0.467	(0.112)

Application Notes: Data from references [3, 5] was excluded from the Mo30W trend fit. Data was extrapolated based on rule-of-mixtures.

Fit Equation:

For temperature range: $10 < T \leq 293$

$$C_P(T) = \left[A0 \cdot \left(\frac{T}{1000}\right)^N\right] \Big/ \left[1 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2 + A3 \cdot \left(\frac{T}{1000}\right)^3\right]$$

For temperature range: $293 < T \leq 2900$

$$C_P(T) = B0 + B1 \cdot \left(\frac{T}{1000}\right) + B2 \cdot \left(\frac{T}{1000}\right)^2 + B3 \cdot \left(\frac{T}{1000}\right)^3 + B\_2 / \left(\frac{T}{1000}\right)^2$$

$C_P(T) = Specific\ Heat\ [J/(g \cdot K)]$

$T = Temperature\ [K]$

Constants:

T. Range [K]:	$10 \leq T \leq 293$		$293 < T \leq 2900$
N =	2.967E+00	B0 =	2.091E-01
A0 =	3.002E+02	B1 =	5.885E-02
A1 =	-5.805E+00	B2 =	-2.481E-02
A2 =	1.054E+02	B3 =	1.212E-02
A3 =	1.129E+03	B_2 =	-8.867E-04

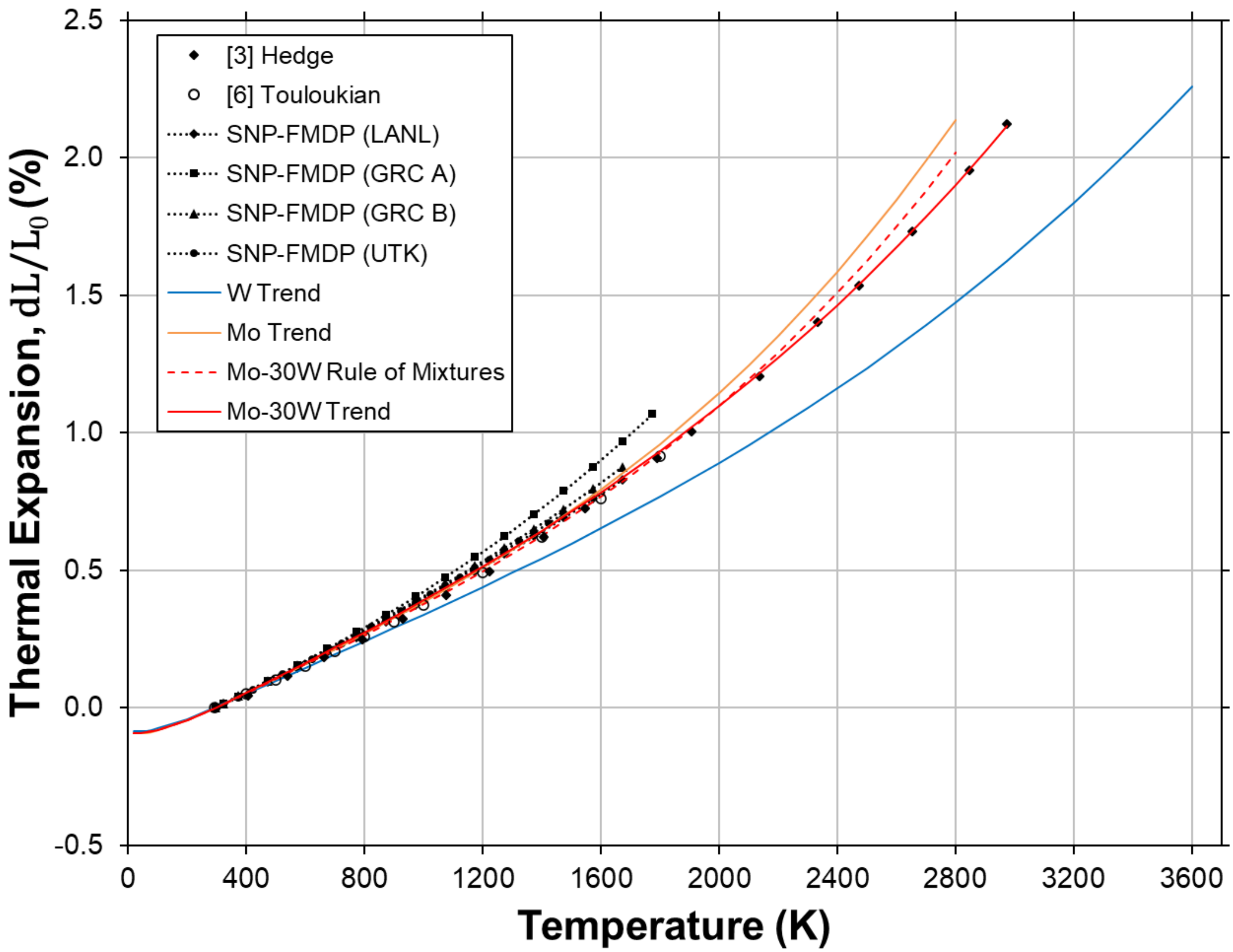

Figure 3.1.2-6: Thermal Expansion versus Temperature of Mo-30W. Displaying fitted trend of the data with comparison to Molybdenum, Tungsten and Rule of Mixtures (70%Mo, 30%W).

100% Theoretical Density

Temperature (T) K	(°F)	Thermal Expansion (dL/L_0) %	Temperature (T) K	(°F)	Thermal Expansion (dL/L_0) %
50	(-369.7)	-0.090	1500	(2240.3)	0.713
100	(-279.7)	-0.081	1600	(2420.3)	0.784
200	(-99.7)	-0.045	1700	(2600.3)	0.857
300	(80.3)	0.001	1800	(2780.3)	0.934
400	(260.3)	0.054	1900	(2960.3)	1.014
500	(440.3)	0.109	2000	(3140.3)	1.097
600	(620.3)	0.163	2100	(3320.3)	1.183
700	(800.3)	0.219	2200	(3500.3)	1.273
800	(980.3)	0.275	2300	(3680.3)	1.367
900	(1160.3)	0.332	2400	(3860.3)	1.465
1000	(1340.3)	0.391	2500	(4040.3)	1.567
1100	(1520.3)	0.452	2600	(4220.3)	1.674
1200	(1700.3)	0.514	2700	(4400.3)	1.785
1300	(1880.3)	0.578	2800	(4580.3)	1.901
1400	(2060.3)	0.644	2900	(4760.3)	2.023

Application Notes: Data from reference SNP-FMDP (GRC A) was excluded from the Mo30W trend fit. All other internal data, and external data from [3, 6], was used to generate the fit. Data below room temperature is based on rule-of-mixtures.

Fit Equation:

$$dL/L_0\,(T) = A0 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2 + A3 \cdot \left(\frac{T}{1000}\right)^3$$

$dL/L_0\,(T) = Thermal\ Expansion\ [\%]$

$T = Temperature\ [K]$

Constants:

T Range [K]:	$20 \leq T < 294$	$294 \leq T \leq 2974$
A0 =	-0.09111	-0.1599
A1 =	-0.07375	0.5386
A2 =	1.935	-0.01953
A3 =	-2.121	0.03218

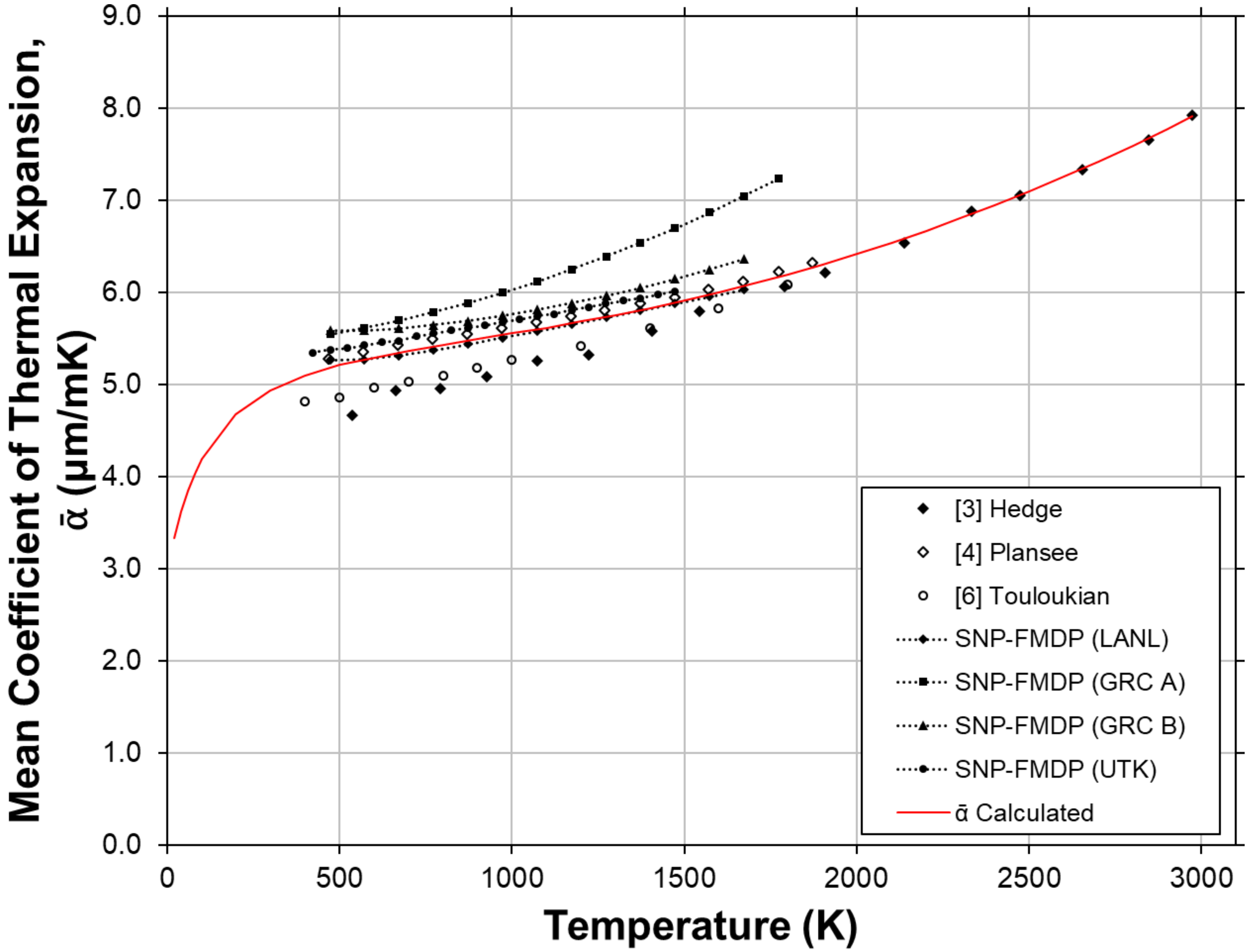

Figure 3.1.2-7: Mean Coefficient of Thermal Expansion versus Temperature of Mo-30W. Calculated from trend of the Thermal Expansion data.

Coefficient of Thermal Expansion with Temperature

100% Theoretical Density

Temperature (T)		Mean CTE (ᾱ)		Temperature (T)		Mean CTE (ᾱ)	
K	(°F)	μm/(m-K)	(μin/(in-°F))	K	(°F)	μm/(m-K)	(μin/(in-°F))
50	(-369.7)	3.741	(2.078)	1500	(2240.3)	5.912	(3.284)
100	(-279.7)	4.187	(2.326)	1600	(2420.3)	5.999	(3.333)
200	(-99.7)	4.676	(2.598)	1700	(2600.3)	6.093	(3.385)
300	(80.3)	4.936	(2.742)	1800	(2780.3)	6.194	(3.441)
400	(260.3)	5.096	(2.831)	1900	(2960.3)	6.301	(3.501)
500	(440.3)	5.208	(2.893)	2000	(3140.3)	6.415	(3.564)
600	(620.3)	5.293	(2.941)	2100	(3320.3)	6.536	(3.631)
700	(800.3)	5.364	(2.980)	2200	(3500.3)	6.665	(3.703)
800	(980.3)	5.429	(3.016)	2300	(3680.3)	6.800	(3.778)
900	(1160.3)	5.490	(3.050)	2400	(3860.3)	6.943	(3.857)
1000	(1340.3)	5.552	(3.084)	2500	(4040.3)	7.094	(3.941)
1100	(1520.3)	5.616	(3.120)	2600	(4220.3)	7.251	(4.029)
1200	(1700.3)	5.683	(3.157)	2700	(4400.3)	7.417	(4.120)
1300	(1880.3)	5.754	(3.197)	2800	(4580.3)	7.590	(4.217)
1400	(2060.3)	5.830	(3.239)	2900	(4760.3)	7.770	(4.317)

Application Notes: Data from reference SNP-FMDP (GRC A) was excluded from the Mo30W trend fit. Data below room temperature is based on rule-of-mixtures. The trend is compared against data from references [3, 4, 6].

Fit Equation:

$$\bar{\alpha}(T) = \left(A0 + A1\cdot\left(\frac{T}{1000}\right) + A2\cdot\left(\frac{T}{1000}\right)^2 + A3\cdot\left(\frac{T}{1000}\right)^3\right)\Big/\left(\left(\frac{T}{1000}\right) + B0\right)$$

$\bar{\alpha}(T) = Coefficient\ of\ Thermal\ Expansion\ [\mu m/(m\cdot K)]$

$T = Temperature\ [K]$

Constants:

T Range [K]: $20 \le T \le 2974$

A0 =	0.4278	A3 =	0.3975
A1 =	5.979	B0 =	0.144
A2 =	-0.4529		

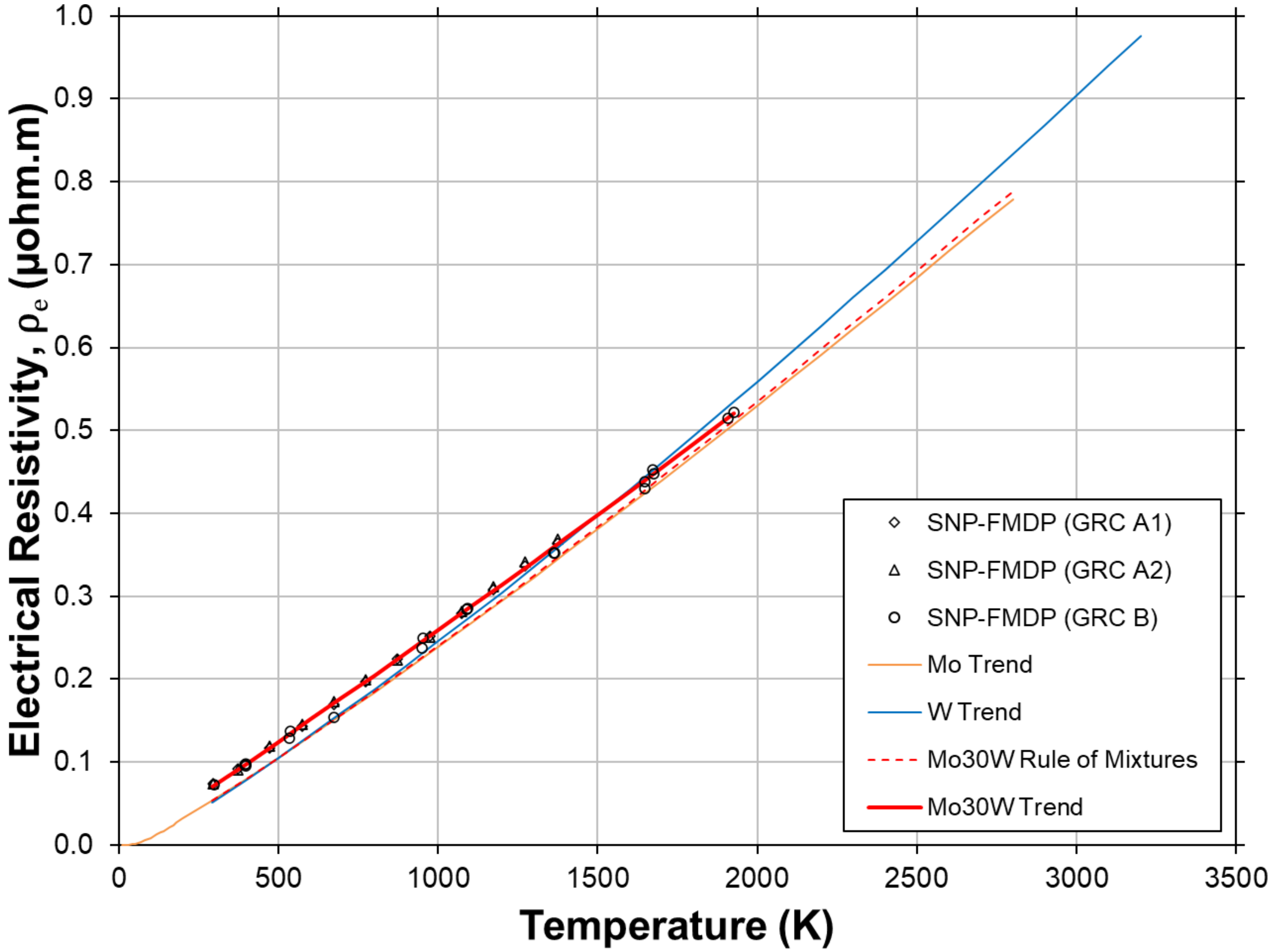

Figure 3.1.2-8: Electrical Resistivity versus Temperature for Mo-30W.

100% Theoretical Density

Temperature (T)		Electrical Resistivity (ρ_e)		Temperature (T)		Electrical Resistivity (ρ_e)	
K	(°F)	μΩ-m	(μΩ-in)	K	(°F)	μΩ-m	(μΩ-in)
293	(67.7)	0.0702	(0.004)	1200	(1700.3)	0.3139	(0.020)
400	(260.3)	0.0981	(0.006)	1300	(1880.3)	0.3418	(0.021)
500	(440.3)	0.1244	(0.008)	1400	(2060.3)	0.3698	(0.023)
600	(620.3)	0.1509	(0.009)	1500	(2240.3)	0.3980	(0.025)
700	(800.3)	0.1776	(0.011)	1600	(2420.3)	0.4264	(0.027)
800	(980.3)	0.2045	(0.013)	1700	(2600.3)	0.4550	(0.028)
900	(1160.3)	0.2316	(0.014)	1800	(2780.3)	0.4838	(0.030)
1000	(1340.3)	0.2588	(0.016)	1900	(2960.3)	0.5128	(0.032)
1100	(1520.3)	0.2863	(0.018)	1926	(3007.1)	0.5203	(0.032)

Application Notes: Data for electrical resistivity was fitted with the equation below to approximate property trend with respect to temperature.

Fit Equation:

$$\rho_e(T) = A0 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2$$

$\rho_e(T) = Electrical\ Resistivity\ [\mu\Omega \cdot m]$

$T = Temperature\ [K]$

Constants:

T. Range [K]: $293 \leq T \leq 1926$

A0 = -5.182E-03

A1 = 2.545E-01

A2 = 9.527E-03

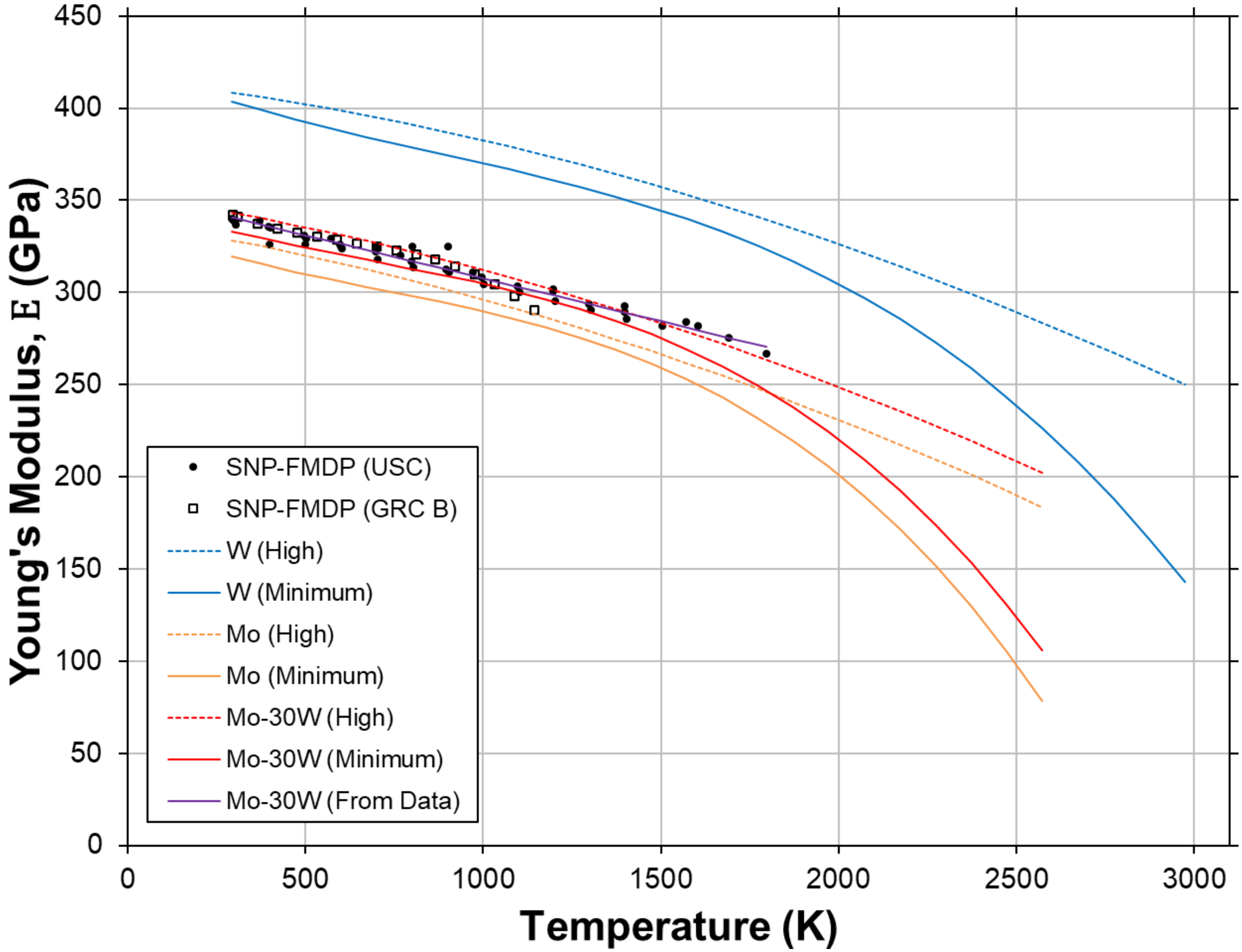

Figure 3.1.2-9: Young's modulus versus temperature for Mo-30W, with comparison to molybdenum and tungsten trends. Mo-30W high and minimum trends were calculated using the rule of mixtures, while the "from data" curve was fit using data alone.

Minimum Young's Modulus at 100% Theoretical Density

Temperature (T)		Young's Modulus (E)	
K	(°F)	GPa	(Msi)
293	(67.7)	333.26	(48.36)
300	(80.3)	332.93	(48.31)
400	(260.3)	328.47	(47.66)
500	(440.3)	324.35	(47.06)
700	(800.3)	316.69	(45.95)
900	(1160.3)	308.94	(44.83)
1100	(1520.3)	300.11	(43.55)
1300	(1880.3)	289.20	(41.96)
1500	(2240.3)	275.22	(39.93)
1700	(2600.3)	257.17	(37.32)
1900	(2960.3)	234.05	(33.96)
2100	(3320.3)	204.87	(29.73)
2300	(3680.3)	168.62	(24.47)
2500	(4040.3)	124.32	(18.04)
2573	(4171.7)	105.94	(15.37)

High Young's Modulus at 100% Theoretical Density

Temperature (T)		Young's Modulus (E)	
K	(°F)	GPa	(Msi)
293	(67.7)	343.29	(49.81)
300	(80.3)	343.04	(49.77)
400	(260.3)	339.32	(49.24)
500	(440.3)	335.38	(48.66)
700	(800.3)	326.81	(47.42)
900	(1160.3)	317.33	(46.04)
1100	(1520.3)	306.92	(44.53)
1300	(1880.3)	295.61	(42.89)
1500	(2240.3)	283.37	(41.12)
1700	(2600.3)	270.22	(39.21)
1900	(2960.3)	256.16	(37.17)
2100	(3320.3)	241.17	(34.99)
2300	(3680.3)	225.28	(32.69)
2500	(4040.3)	208.46	(30.25)
2573	(4171.7)	202.10	(29.32)

Application Notes: Young's modulus minimum and high curves for Mo-30W were calculated from corresponding molybdenum and tungsten curves using the rule of mixtures and a tungsten volume fraction of 0.186. Equivalent equations can be found below for readers' convenience.

Fit Equations:

$$E(T) = A0 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2 + A3 \cdot \left(\frac{T}{1000}\right)^3$$

$E(T) = Young's\ Modulus\ [GPa]$

$T = Temperature\ [K]$

T Range [K]: $293 \le T \le 2573$

Constants:

Curve:	Minimum	High
A0 =	349.7	352.8
A1 =	-66.79	-29.11
A2 =	42.58	-11.45
A3 =	-20.77	0

Data-Based Young's Modulus at 100% Theoretical Density

Temperature (T)		Young's Modulus (E)		Temperature (T)		Young's Modulus (E)	
K	(°F)	GPa	(Msi)	K	(°F)	GPa	(Msi)
293	(67.7)	340.72	(49.44)	1000	(1340.3)	307.72	(44.65)
300	(80.3)	340.40	(49.39)	1050	(1430.3)	305.39	(44.31)
350	(170.3)	338.06	(49.05)	1100	(1520.3)	303.05	(43.97)
400	(260.3)	335.73	(48.71)	1150	(1610.3)	300.72	(43.63)
450	(350.3)	333.39	(48.38)	1200	(1700.3)	298.38	(43.30)
500	(440.3)	331.06	(48.04)	1250	(1790.3)	296.05	(42.96)
550	(530.3)	328.73	(47.70)	1300	(1880.3)	293.72	(42.62)
600	(620.3)	326.39	(47.36)	1350	(1970.3)	291.38	(42.28)
650	(710.3)	324.06	(47.02)	1400	(2060.3)	289.05	(41.94)
700	(800.3)	321.72	(46.68)	1450	(2150.3)	286.71	(41.60)
750	(890.3)	319.39	(46.34)	1500	(2240.3)	284.38	(41.26)
800	(980.3)	317.06	(46.00)	1550	(2330.3)	282.05	(40.92)
850	(1070.3)	314.72	(45.67)	1600	(2420.3)	279.71	(40.59)
900	(1160.3)	312.39	(45.33)	1700	(2600.3)	275.04	(39.91)
950	(1250.3)	310.05	(44.99)	1797	(2774.9)	270.52	(39.25)

Application Notes: The "from data" equation for Young's modulus was fitted using SNP-FDP (USC) and SNP-FDP (SR) data, and it approximates the property trend with respect to temperature.

Fit Equations:

$$E(T) = A0 + A1 \cdot \left(\frac{T}{1000}\right)$$

$E(T) = Young's\ Modulus\ [GPa]$

$T = Temperature\ [K]$

T Range [K]: $293 \leq T \leq 1797$

Constants:

Curve:	From Data
A0 =	354.4
A1 =	-46.68

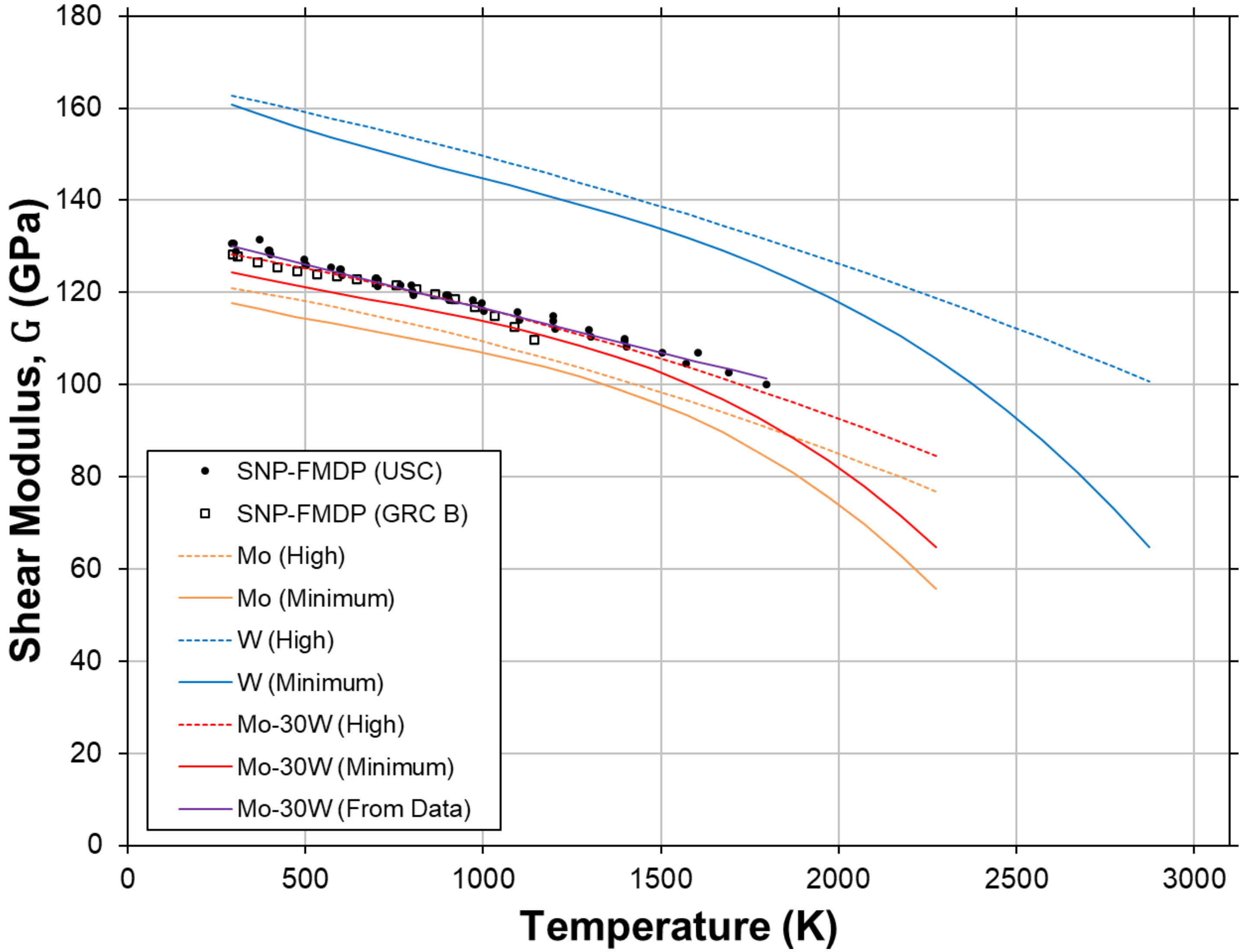

Figure 3.1.2-10: Shear modulus versus temperature for Mo-30W, with comparison to molybdenum and tungsten trends. Mo-30W high and minimum trends were calculated using the rule of mixtures, while the “from data” curve was fit using data alone.

Shear Modulus with Temperature

Minimum Shear Modulus at 100% Theoretical Density

Temperature (T)		Shear Modulus (E)	
K	(°F)	GPa	(Msi)
293	(67.7)	124.46	(18.06)
300	(80.3)	124.34	(18.04)
450	(350.3)	121.91	(17.69)
600	(620.3)	119.70	(17.37)
750	(890.3)	117.56	(17.06)
900	(1160.3)	115.35	(16.74)
1050	(1430.3)	112.90	(16.38)
1200	(1700.3)	110.07	(15.97)
1350	(1970.3)	106.69	(15.48)
1500	(2240.3)	102.62	(14.89)
1650	(2510.3)	97.70	(14.18)
1800	(2780.3)	91.78	(13.32)
1950	(3050.3)	84.71	(12.29)
2100	(3320.3)	76.32	(11.07)
2273	(3631.7)	64.83	(9.41)

High Shear Modulus at 100% Theoretical Density

Temperature (T)		Shear Modulus (E)	
K	(°F)	GPa	(Msi)
293	(67.7)	128.23	(18.61)
300	(80.3)	128.13	(18.59)
450	(350.3)	126.00	(18.28)
600	(620.3)	123.68	(17.95)
750	(890.3)	121.17	(17.58)
900	(1160.3)	118.45	(17.19)
1050	(1430.3)	115.55	(16.77)
1200	(1700.3)	112.45	(16.32)
1350	(1970.3)	109.15	(15.84)
1500	(2240.3)	105.66	(15.33)
1650	(2510.3)	101.97	(14.80)
1800	(2780.3)	98.09	(14.23)
1950	(3050.3)	94.01	(13.64)
2100	(3320.3)	89.74	(13.02)
2273	(3631.7)	84.57	(12.27)

Application Notes: Shear modulus minimum and high curves for Mo-30W were calculated from corresponding molybdenum and tungsten curves using the rule of mixtures and a tungsten volume fraction of 0.186. Equivalent equations can be found below for readers' convenience.

Fit Equations:

$$G(T) = A0 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2 + A3 \cdot \left(\frac{T}{1000}\right)^3$$

$G(T) = Shear\ Modulus\ [GPa]$

$T = Temperature\ [K]$

T Range [K]: $293 \leq T \leq 2273$

Constants:

Curve:	Minimum	High
A0 =	130.5	131.8
A1 =	-24.43	-10.93
A2 =	15.26	-4.332
A3 =	-7.577	0

Data-Based Shear Modulus at 100% Theoretical Density

Temperature (T)		Shear Modulus (G)		Temperature (T)		Shear Modulus (G)	
K	(°F)	GPa	(Msi)	K	(°F)	GPa	(Msi)
293	(67.7)	130.01	(18.86)	1000	(1340.3)	116.53	(16.91)
300	(80.3)	129.88	(18.85)	1050	(1430.3)	115.58	(16.77)
350	(170.3)	128.93	(18.71)	1100	(1520.3)	114.62	(16.63)
400	(260.3)	127.97	(18.57)	1150	(1610.3)	113.67	(16.49)
450	(350.3)	127.02	(18.43)	1200	(1700.3)	112.72	(16.36)
500	(440.3)	126.07	(18.29)	1250	(1790.3)	111.76	(16.22)
550	(530.3)	125.11	(18.15)	1300	(1880.3)	110.81	(16.08)
600	(620.3)	124.16	(18.02)	1350	(1970.3)	109.86	(15.94)
650	(710.3)	123.20	(17.88)	1400	(2060.3)	108.90	(15.80)
700	(800.3)	122.25	(17.74)	1450	(2150.3)	107.95	(15.66)
750	(890.3)	121.30	(17.60)	1500	(2240.3)	107.00	(15.52)
800	(980.3)	120.34	(17.46)	1550	(2330.3)	106.04	(15.39)
850	(1070.3)	119.39	(17.32)	1600	(2420.3)	105.09	(15.25)
900	(1160.3)	118.44	(17.19)	1700	(2600.3)	103.18	(14.97)
950	(1250.3)	117.48	(17.05)	1797	(2774.9)	101.33	(14.70)

Application Notes: The "from data" equation for shear modulus was fitted SNP-FDP (USC) and SNP-FDP (SR) data, and it approximates the property trend with respect to temperature.

Fit Equations:

$$G(T) = A0 + A1 \cdot \left(\frac{T}{1000}\right)$$

$G(T) = Shear\ Modulus\ [GPa]$

$T = Temperature\ [K]$

T Range [K]: $293 \leq T \leq 1797$

Constants:

Curve:	From Data
A0 =	135.6
A1 =	-19.07

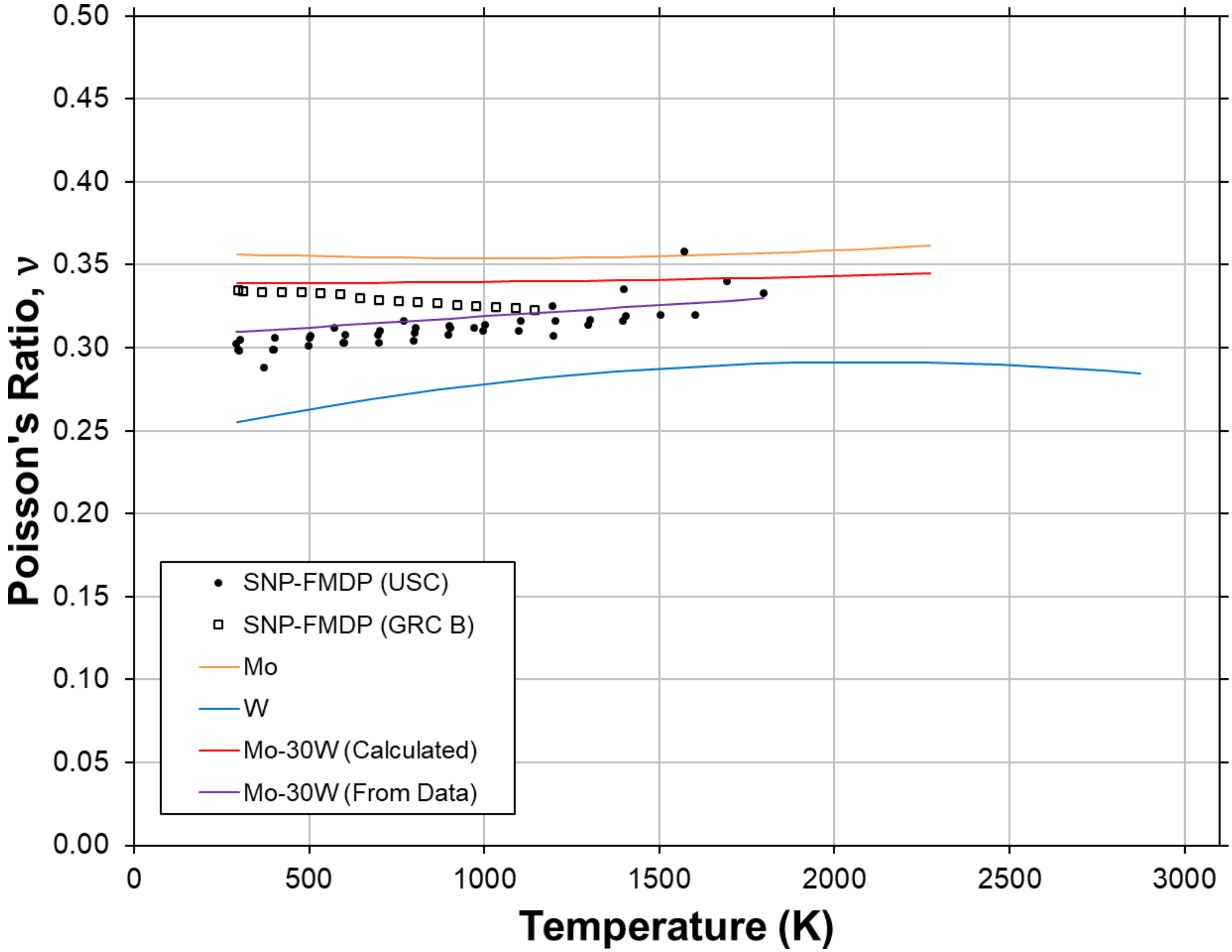

Figure 3.1.2-11: Poisson's ratio versus temperature for Mo-30W, with comparison to molybdenum and tungsten trends. The "calculated" curve was developed from the fitted Young's modulus (high) and shear modulus (high) curves, while the "from data" curve was fit using data alone.

Rule of Mixtures-Based Poisson's Ratio at 100% Theoretical Density

Temperature (T) K	(°F)	Poisson's Ratio (ν)	Temperature (T) K	(°F)	Poisson's Ratio (ν)
293	(67.7)	0.339	1000	(1340.3)	0.340
300	(80.3)	0.339	1050	(1430.3)	0.340
350	(170.3)	0.339	1100	(1520.3)	0.340
400	(260.3)	0.339	1200	(1700.3)	0.340
450	(350.3)	0.339	1300	(1880.3)	0.340
500	(440.3)	0.339	1400	(2060.3)	0.341
550	(530.3)	0.339	1500	(2240.3)	0.341
600	(620.3)	0.339	1600	(2420.3)	0.341
650	(710.3)	0.339	1700	(2600.3)	0.342
700	(800.3)	0.339	1800	(2780.3)	0.342
750	(890.3)	0.339	1900	(2960.3)	0.343
800	(980.3)	0.339	2000	(3140.3)	0.343
850	(1070.3)	0.339	2100	(3320.3)	0.344
900	(1160.3)	0.339	2200	(3500.3)	0.344
950	(1250.3)	0.340	2273	(3631.7)	0.345

Application Notes: The Poisson's ratio (calculated) curve for Mo-30W was calculated from corresponding molybdenum and tungsten curves using the rule of mixtures and a tungsten volume fraction of 0.186. An equivalent equation can be found below for readers' convenience.

Fit Equations:

$$\nu(T) = A0 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2 + A3 \cdot \left(\frac{T}{1000}\right)^3$$

$\nu(T) = Poisson's\ Ratio$

$T = Temperature\ [K]$

Constants:

T Range [K]:	$293 \leq T \leq 2273$
A0 =	0.3383
A1 =	1.164E-3
A2 =	-1.842E-4
A3 =	4.13E-4

Data-Based Poisson's Ratio at 100% Theoretical Density

Temperature (T) K	(°F)	Poisson's Ratio (ν)	Temperature (T) K	(°F)	Poisson's Ratio (ν)
293	(67.7)	0.309	1000	(1340.3)	0.319
300	(80.3)	0.310	1050	(1430.3)	0.320
350	(170.3)	0.310	1100	(1520.3)	0.320
400	(260.3)	0.311	1150	(1610.3)	0.321
450	(350.3)	0.312	1200	(1700.3)	0.322
500	(440.3)	0.312	1250	(1790.3)	0.322
550	(530.3)	0.313	1300	(1880.3)	0.323
600	(620.3)	0.314	1350	(1970.3)	0.324
650	(710.3)	0.314	1400	(2060.3)	0.324
700	(800.3)	0.315	1450	(2150.3)	0.325
750	(890.3)	0.316	1500	(2240.3)	0.326
800	(980.3)	0.316	1550	(2330.3)	0.326
850	(1070.3)	0.317	1600	(2420.3)	0.327
900	(1160.3)	0.318	1700	(2600.3)	0.328
950	(1250.3)	0.318	1797	(2774.9)	0.330

Application Notes: The "from data" equation for Poisson's ratio was fitted using SNP-FMDP (USC) and SNP-FMDP (GRC B) data, and it approximates the property trend with respect to temperature.

Fit Equations:

$$\nu(T) = A0 + A1 \cdot \left(\frac{T}{1000}\right)$$

$\nu(T) = Poisson's\ Ratio$

$T = Temperature\ [K]$

Constants:

T Range [K]:	$293 \leq T \leq 1797$
A0 =	0.3055
A1 =	0.01346

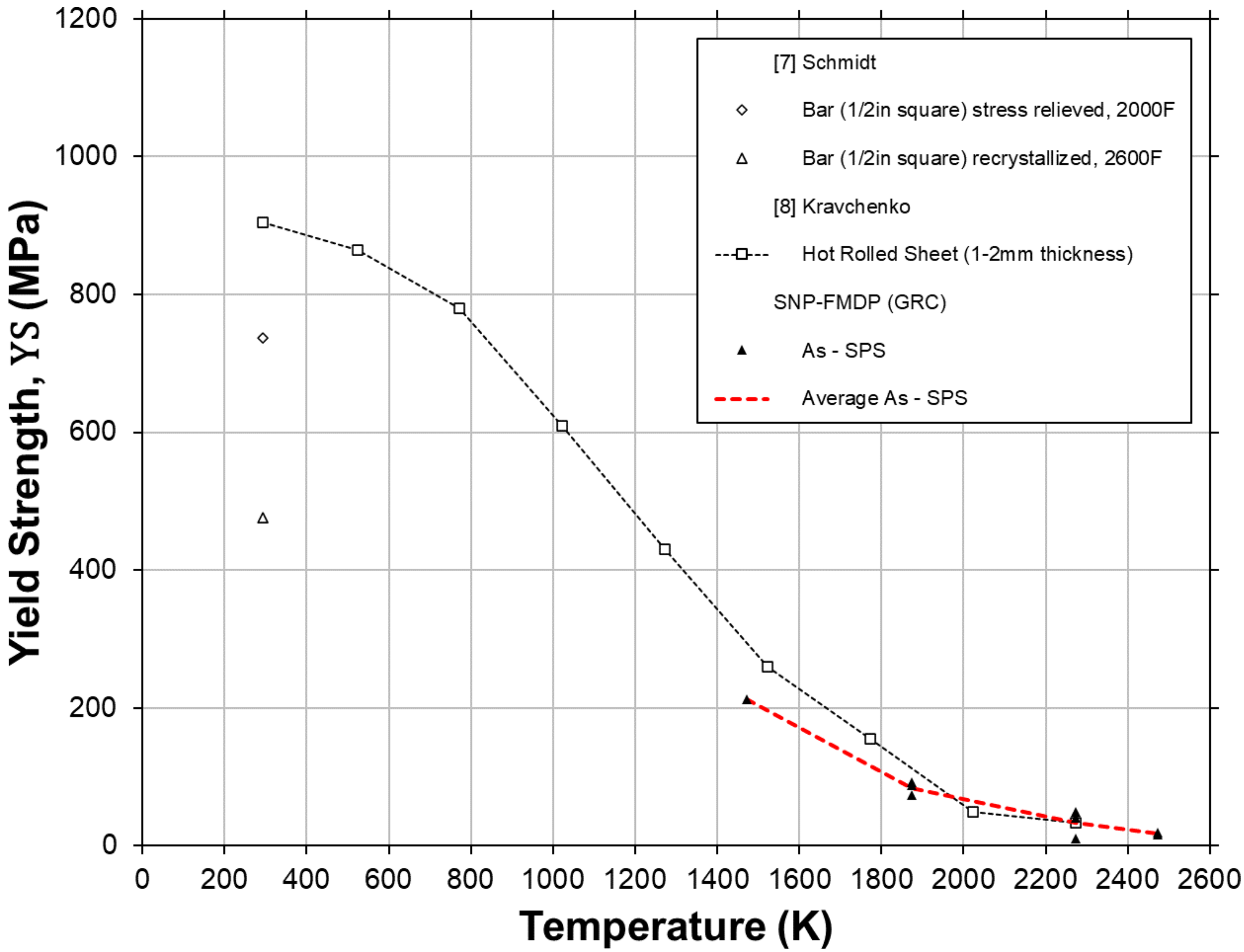

Figure 3.1.2-12: Yield Strength versus Temperature for Mo-30W. Displaying fitted trend for 1-2 mm thick hot rolled sheet.

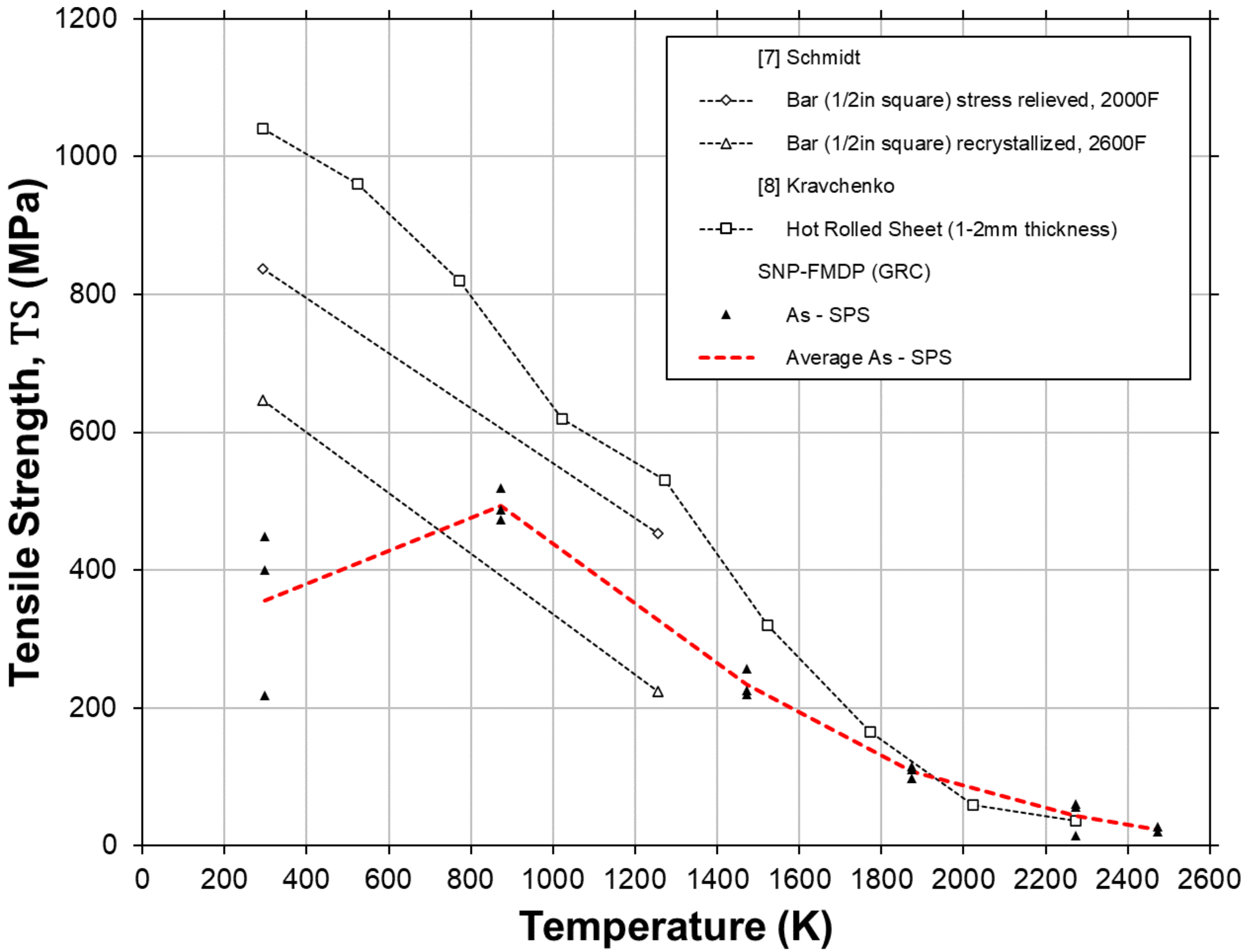

Figure 3.1.2-13: Tensile Strength versus Temperature for Mo-30W. Displaying fitted trend for 1-2 mm thick hot rolled sheet.

Temperature (T)		Yield Strength (YS)		Tensile Strength (TS)		Elongation	Reduction in Area (RA)
K	(F)	MPa	(ksi)	MPa	(ksi)	%	%
Bar (1/2in square) stress relieved, 1366 K							
293	(68)	737	(106.9)	838	(121.5)	26	40
1255	(1800)	-	-	453	(65.7)	25	77
Bar (1/2in square) recrystallized, 1700 K							
293	(68)	476	(69.1)	647	(93.8)	12	10
1255	(1800)	-	-	223	(32.4)	83	90
Hot Rolled Sheet (1-2mm thickness)							
293	(68)	905	(131.2)	1040	(150.8)	9	-
523	(482)	865	(125.4)	960	(139.2)	6.5	-
773	(932)	780	(113.1)	820	(118.9)	6	-
1023	(1382)	610	(88.5)	620	(89.9)	8.5	-
1273	(1832)	430	(62.4)	530	(76.9)	8.5	-
1523	(2282)	260	(37.7)	320	(46.4)	9	-
1773	(2732)	155	(22.5)	165	(23.9)	17	-
2023	(3182)	50	(7.3)	60	(8.7)	18	-
2273	(3632)	34	(4.9)	37	(5.4)	14	-
As – Spark Plasma Sintered (As – SPS) (SNP-FMDP)							
297	(75)	-	-	356	(51.6)	0.6	-
873	(1112)	-	-	494	(71.6)	9.1	-
1473	(2192)	212	(30.8)	234	(34.0)	0.8	-
1873	(2912)	84	(12.2)	108	(15.6)	2.6	-
2273	(3632)	33	(4.8)	44	(6.4)	4.5	-
2473	(3992)	18	(2.5)	24	(3.5)	6.9	-

Application Notes: Yield and tensile strength data was used from [7, 8] and SNP-FMDP (GRC) to develop the strength table and plots above.

Temp. (T) K	Physical and Electrical		Thermal				Elastic		
	Density (ρ) kg/m³	Electrical Resistivity (ρ_e) μΩ-m	Thermal Conductivity (k) W/(m-K)	Thermal Expansion (dL/L_0) %	Mean CTE ($\bar{\alpha}$) 10^{-6}/K	Specific Heat (C_p) J/(g-K)	Young's Modulus (E) GPa	Shear Modulus (G) GPa	Poisson's Ratio (ν)
100	11909	-	-	-0.081	4.19	0.124	-	-	-
200	11896	-	-	-0.045	4.68	0.194	-	-	-
300	11880	0.072	92.53	0.001	4.94	0.215	340.40	129.88	0.31
400	11861	0.098	95.25	0.054	5.10	0.224	335.73	127.97	0.31
500	11841	0.124	96.74	0.109	5.21	0.230	331.06	126.07	0.31
600	11822	0.151	97.66	0.163	5.29	0.236	326.39	124.16	0.31
700	11802	0.178	98.23	0.219	5.36	0.240	321.72	122.25	0.31
800	11783	0.205	98.58	0.275	5.43	0.245	317.06	120.34	0.32
900	11762	0.232	98.77	0.332	5.49	0.250	312.39	118.44	0.32
1000	11742	0.259	98.84	0.391	5.55	0.254	307.72	116.53	0.32
1100	11720	0.286	98.83	0.452	5.62	0.259	303.05	114.62	0.32
1200	11699	0.314	98.77	0.514	5.68	0.264	298.38	112.72	0.32
1300	11676	0.342	98.66	0.578	5.75	0.270	293.72	110.81	0.32
1400	11653	0.370	98.53	0.644	5.83	0.276	289.05	108.90	0.32
1500	11630	0.398	98.39	0.713	5.91	0.282	284.38	107.00	0.33
1600	11605	0.426	98.24	0.784	6.00	0.289	279.71	105.09	0.33
1700	11580	0.455	98.09	0.857	6.09	0.297	275.04	103.18	0.33
1800	11553	0.484	97.94	0.934	6.19	0.305	270.38	101.27	0.33
1900	11526	0.513	97.77	1.014	6.30	0.314	-	-	-
2000	11498	-	97.59	1.097	6.42	0.324	-	-	-
2200	11438	-	97.12	1.273	6.66	0.347	-	-	-
2400	11373	-	-	1.465	6.94	0.375	-	-	-
2600	11303	-	-	1.674	7.25	0.407	-	-	-
2800	11227	-	-	1.901	7.59	0.445	-	-	-
2900	11187	-	-	2.023	7.77	0.467	-	-	-

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[8] V.S. Kravchenko, V.K. Kharchenko, V.V. Bukhanovskii, et al., Soviet Powder Metallurgy and Metal Ceramics, Methods of Examination and Properties of Powder Materials 26(10) (1987).

3 Refractory Metals and Alloys

3.1 Molybdenum and Molybdenum Alloys

Room Temperature Properties

Density, [kg/m^3]	10,220
Melting Point, [K]	2,883 – 2,894 [1]
Specific Heat, [J/(g-K)]	0.269
Thermal Conductivity, [W/(m-K)]	123.2
Average linear expansion coefficient, [μm/(m-K)]	4.97
Electrical resistivity, [μΩ-m]	0.079
Young's Modulus, [GPa]	306.3
Shear Modulus, [GPa]	122.7 [1]
Poisson's Ratio, [-]	0.293 [1]

Composition

Table 3.1.3-1: Typical Composition ranges for molybdenum alloy 363, TZM (percent by weight) [1].

Grade		Mo	Ti	Zr	C	Si	Fe	O	Ni	N
TZM	Min.	99.3	0.4	0.06	0.010	-	-	-	-	-
	Max.	99.5	0.55	0.12	0.040	0.01	0.01	0.003	0.002	0.002

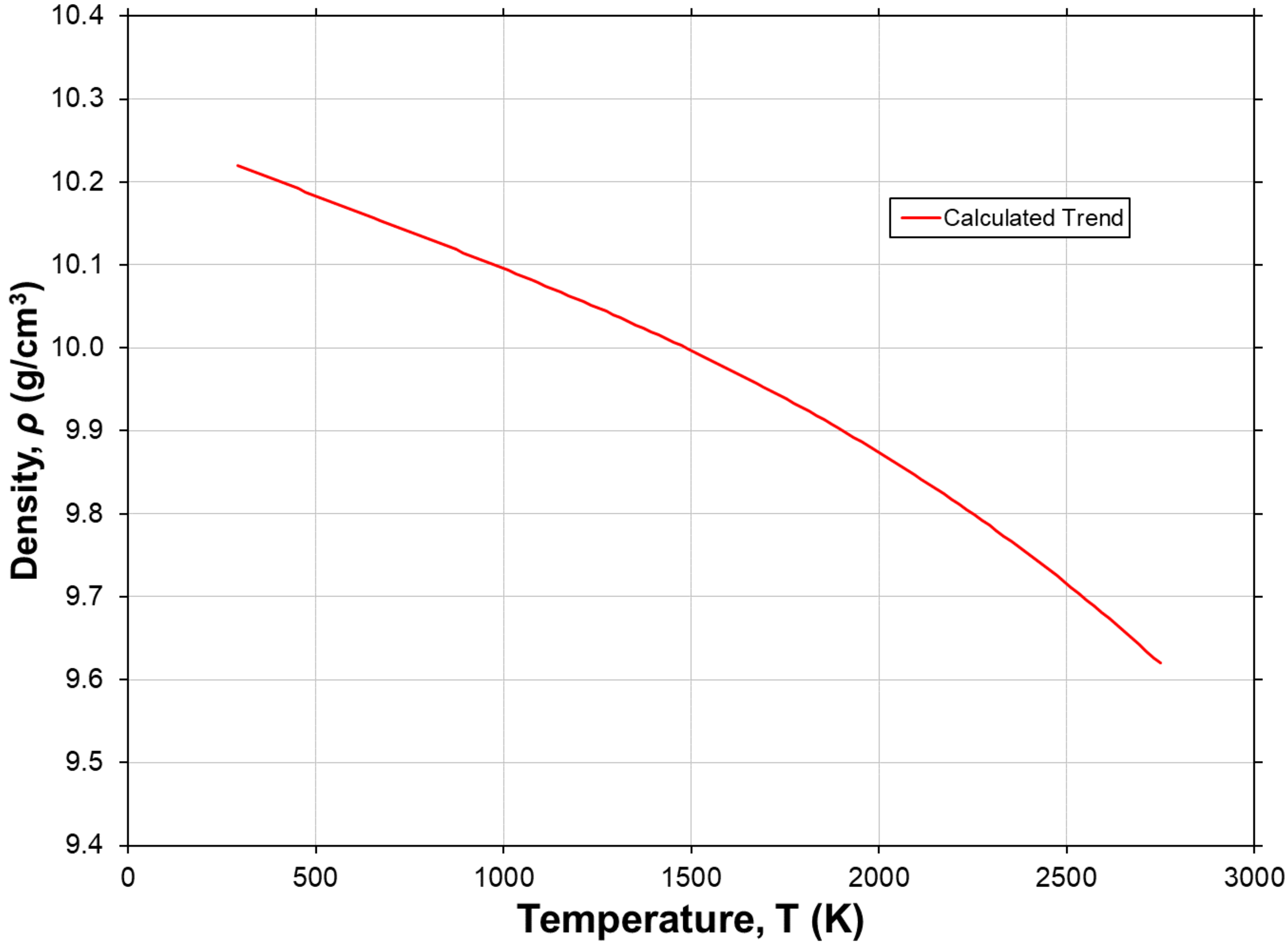

Figure 3.1.3-1: Density versus temperature for TZM. Calculated from fitted trend of the thermal expansion data.

100% Theoretical Density

Temperature (T)		Density (ρ)		Temperature (T)		Density (ρ)	
K	(°F)	kg/m^3	(lb/ft^3)	K	(°F)	kg/m^3	(lb/ft^3)
293	(67.7)	10220	(638.0)	1400	(2060.3)	10018	(625.4)
300	(80.3)	10219	(638.0)	1500	(2240.3)	9997	(624.1)
350	(170.3)	10210	(637.4)	1600	(2420.3)	9975	(622.7)
400	(260.3)	10201	(636.8)	1700	(2600.3)	9951	(621.3)
450	(350.3)	10192	(636.3)	1800	(2780.3)	9927	(619.7)
500	(440.3)	10184	(635.8)	1900	(2960.3)	9901	(618.1)
550	(530.3)	10175	(635.2)	2000	(3140.3)	9874	(616.4)
600	(620.3)	10166	(634.7)	2100	(3320.3)	9846	(614.7)
700	(800.3)	10149	(633.6)	2200	(3500.3)	9816	(612.8)
800	(980.3)	10131	(632.5)	2300	(3680.3)	9784	(610.8)
900	(1160.3)	10114	(631.4)	2400	(3860.3)	9751	(608.7)
1000	(1340.3)	10096	(630.3)	2500	(4040.3)	9716	(606.5)
1100	(1520.3)	10077	(629.1)	2600	(4220.3)	9679	(604.2)
1200	(1700.3)	10058	(627.9)	2700	(4400.3)	9640	(601.8)
1300	(1880.3)	10038	(626.7)	2749	(4488.5)	9620	(600.6)

Application Notes: Density is calculated as a function of thermal expansion, as seen in the equation below, to approximate property trend with respect to temperature.

Density Calculation:

$\rho(T) = \rho_{RT}/(1 + dL/L_0(T)/100)^3$

$\rho(T) = Density\ [kg/m^3]$

$Room\ Temperature\ Density\ (\rho_{RT}) = 10{,}220\ [kg/m^3]$

$T = Temperature\ [K]$

Temperature Range: $293 \leq T \leq 2749$

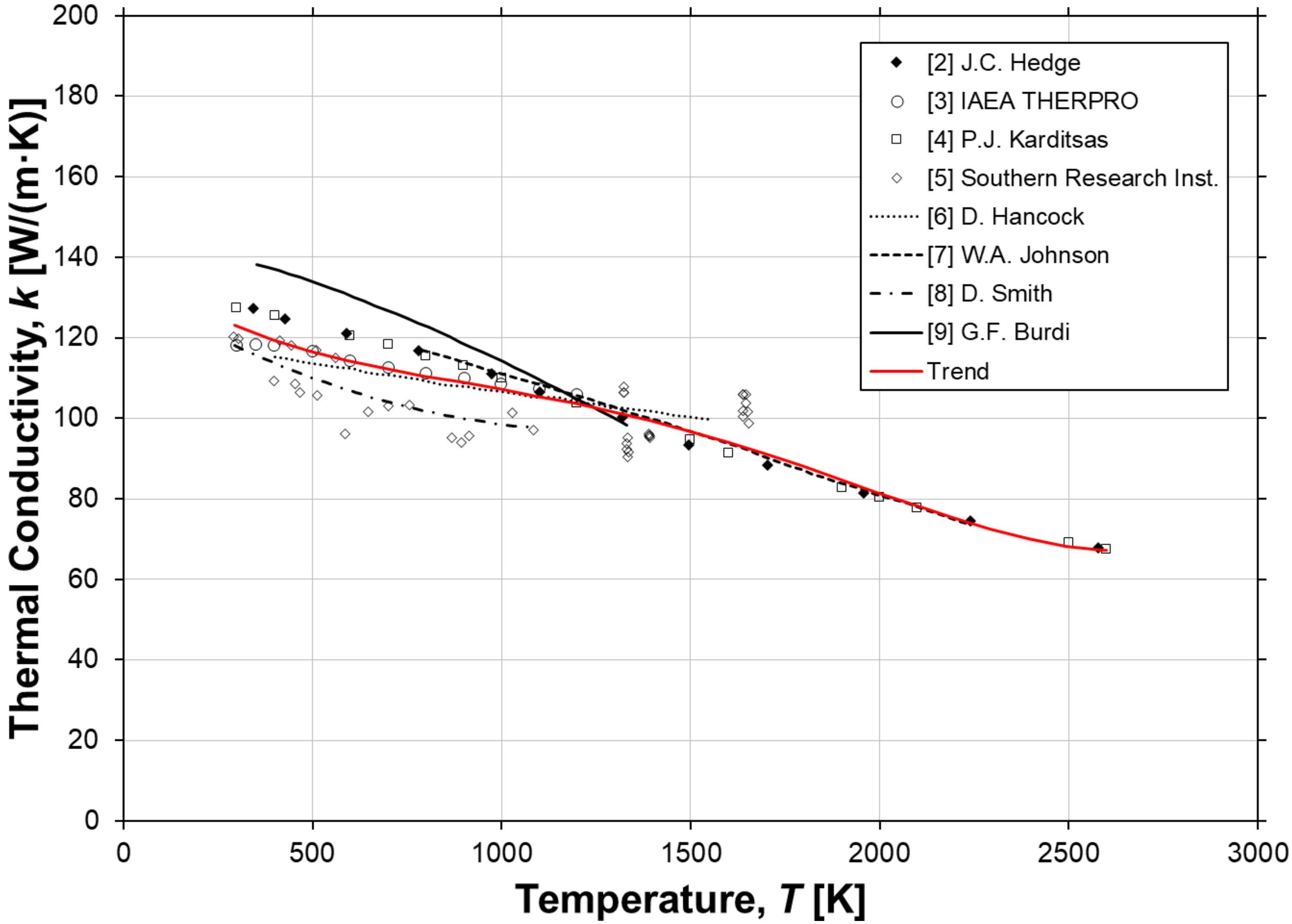

Figure 3.1.3-2: Thermal conductivity versus temperature for TZM.

100% Theoretical Density

Temperature (T)		Thermal Conductivity (k)		Temperature (T)		Thermal Conductivity (k)	
K	(°F)	W/(m-K)	(Btu-in/ft^2-hr-°F)	K	(°F)	W/(m-K)	(Btu-in/ft^2-hr-°F)
293	(67.7)	123.22	(854.91)	1200	(1700.3)	103.57	(718.60)
300	(80.3)	122.94	(852.98)	1300	(1880.3)	101.52	(704.36)
350	(170.3)	121.08	(840.04)	1400	(2060.3)	99.25	(688.59)
400	(260.3)	119.40	(828.43)	1500	(2240.3)	96.74	(671.20)
450	(350.3)	117.90	(818.01)	1600	(2420.3)	94.00	(652.21)
500	(440.3)	116.55	(808.61)	1700	(2600.3)	91.06	(631.77)
550	(530.3)	115.32	(800.10)	1800	(2780.3)	87.94	(610.14)
600	(620.3)	114.20	(792.34)	1900	(2960.3)	84.71	(587.71)
650	(710.3)	113.17	(785.20)	2000	(3140.3)	81.43	(564.98)
700	(800.3)	112.22	(778.57)	2100	(3320.3)	78.20	(542.59)
750	(890.3)	111.32	(772.32)	2200	(3500.3)	75.13	(521.28)
800	(980.3)	110.46	(766.35)	2300	(3680.3)	72.34	(501.92)
900	(1160.3)	108.80	(754.89)	2400	(3860.3)	69.97	(485.49)
1000	(1340.3)	107.16	(743.47)	2500	(4040.3)	68.19	(473.10)
1100	(1520.3)	105.44	(731.52)	2600	(4220.3)	67.16	(465.98)

Application Notes: Data for thermal conductivity is collected from references [2-9] and fitted with the equation below to approximate property trend with respect to temperature.

Fit Equation:

$$k(T) = A0 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2 + A3 \cdot \left(\frac{T}{1000}\right)^3 + A4 \cdot \left(\frac{T}{1000}\right)^4$$

$k(T) = Thermal\ Conductivity\ [W/(m \cdot K)]$

$T = Temperature\ [K]$

Constants:

T Range [K]: $293 \leq T < 2600$

A0 = 139.6

A1 = -74.98

A2 = 76.56

A3 = -41.24

A4 = 7.217

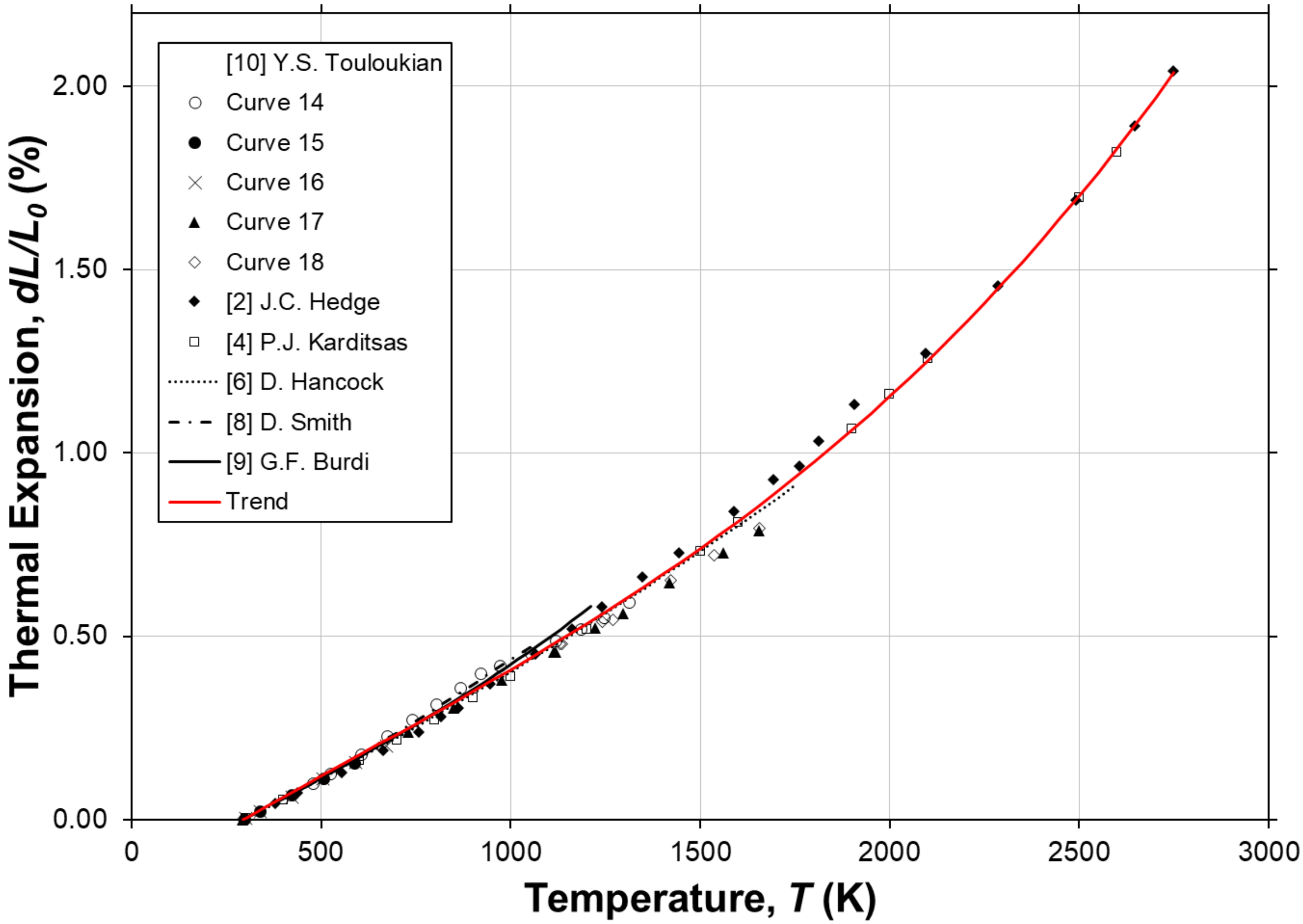

Figure 3.1.3-3: Thermal expansion versus temperature for TZM.

Thermal Expansion with Temperature

100% Theoretical Density

Temperature (T) K	(°F)	Thermal Expansion (dL/L_0) %	Temperature (T) K	(°F)	Thermal Expansion (dL/L_0) %
293	(67.7)	0.000	1400	(2060.3)	0.668
300	(80.3)	0.004	1500	(2240.3)	0.739
350	(170.3)	0.033	1600	(2420.3)	0.814
400	(260.3)	0.062	1700	(2600.3)	0.892
450	(350.3)	0.091	1800	(2780.3)	0.975
500	(440.3)	0.119	1900	(2960.3)	1.062
550	(530.3)	0.148	2000	(3140.3)	1.155
600	(620.3)	0.176	2100	(3320.3)	1.252
700	(800.3)	0.233	2200	(3500.3)	1.355
800	(980.3)	0.291	2300	(3680.3)	1.464
900	(1160.3)	0.349	2400	(3860.3)	1.579
1000	(1340.3)	0.409	2500	(4040.3)	1.702
1100	(1520.3)	0.470	2600	(4220.3)	1.831
1200	(1700.3)	0.534	2700	(4400.3)	1.968
1300	(1880.3)	0.599	2749	(4488.5)	2.037

Application Notes: Data for thermal expansion is collected from references [2, 4, 6, 8-10] and fitted with the equation below to approximate property trend with respect to temperature.

Fit Equation:

$$dL/L_0\,(T) = A0 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2 + A3 \cdot \left(\frac{T}{1000}\right)^3$$

$dL/L_0\,(T) = Thermal\ Expansion\ [\%]$

$T = Temperature\ [K]$

Constants:

T Range [K]: $293 \leq T \leq 2749$

A0 =	-0.1767
A1 =	0.6282
A2 =	-0.1035
A3 =	0.0611

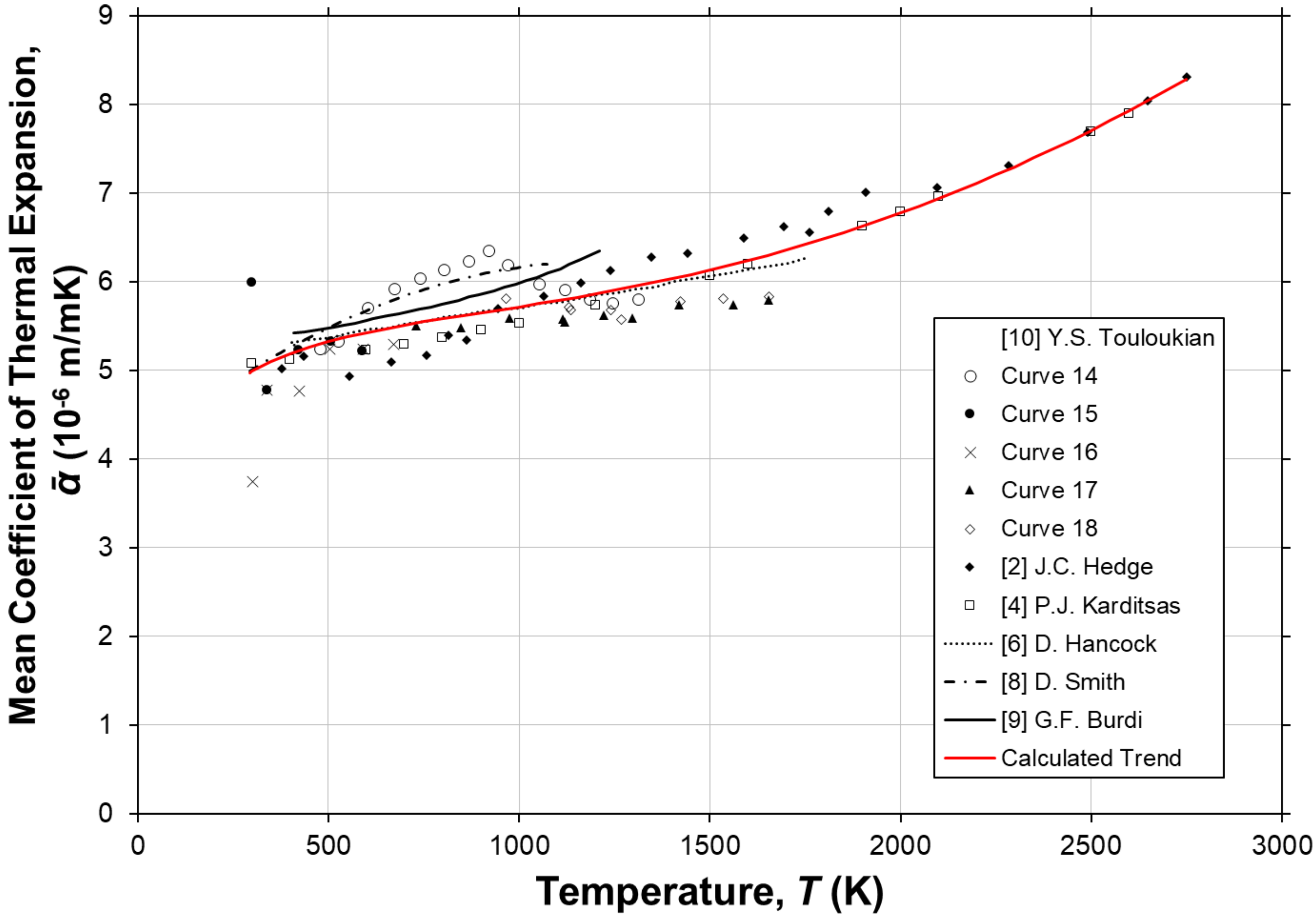

Figure 3.1.3-4: Mean coefficient of thermal expansion versus temperature for TZM, as calculated from fitted thermal expansion trend.

100% Theoretical Density

Temperature (T)		Mean CTE (ᾱ)		Temperature (T)		Mean CTE (ᾱ)	
K	(°F)	μm/(m-K)	(μin/(in-°F))	K	(°F)	μm/(m-K)	(μin/(in-°F))
293	(67.7)	4.971	(2.762)	1400	(2060.3)	6.035	(3.353)
300	(80.3)	4.988	(2.771)	1500	(2240.3)	6.133	(3.407)
350	(170.3)	5.096	(2.831)	1600	(2420.3)	6.241	(3.467)
400	(260.3)	5.185	(2.880)	1700	(2600.3)	6.358	(3.532)
450	(350.3)	5.259	(2.922)	1800	(2780.3)	6.487	(3.604)
500	(440.3)	5.322	(2.957)	1900	(2960.3)	6.626	(3.681)
550	(530.3)	5.377	(2.987)	2000	(3140.3)	6.776	(3.765)
600	(620.3)	5.426	(3.014)	2100	(3320.3)	6.938	(3.855)
700	(800.3)	5.509	(3.060)	2200	(3500.3)	7.112	(3.951)
800	(980.3)	5.582	(3.101)	2300	(3680.3)	7.298	(4.054)
900	(1160.3)	5.650	(3.139)	2400	(3860.3)	7.496	(4.164)
1000	(1340.3)	5.718	(3.176)	2500	(4040.3)	7.706	(4.281)
1100	(1520.3)	5.788	(3.216)	2600	(4220.3)	7.929	(4.405)
1200	(1700.3)	5.863	(3.257)	2700	(4400.3)	8.164	(4.535)
1300	(1880.3)	5.945	(3.303)	2749	(4488.5)	8.284	(4.602)

Application Notes: Trend for mean coefficient of thermal expansion is calculated from thermal expansion and shown in the equation below to approximate property trend with respect to temperature. The slope near room temperature was estimated using the trend for pure molybdenum.

Fit Equation:

$$\bar{\alpha}(T) = \left[A0 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2 + A3 \cdot \left(\frac{T}{1000}\right)^3\right] \Big/ \left[\left(\frac{T}{1000}\right) + A\_0\right]$$

$\bar{\alpha}(T) = Coefficient\ of\ Thermal\ Expansion\ [\mu m/(m \cdot K)]$

$T = Temperature\ [K]$

Constants:

T Range [K]:	$293 \leq T < 2749$
A0 =	0.9359
A1 =	6.897
A2 =	-1.158
A3 =	0.6734
A_0 =	0.2852

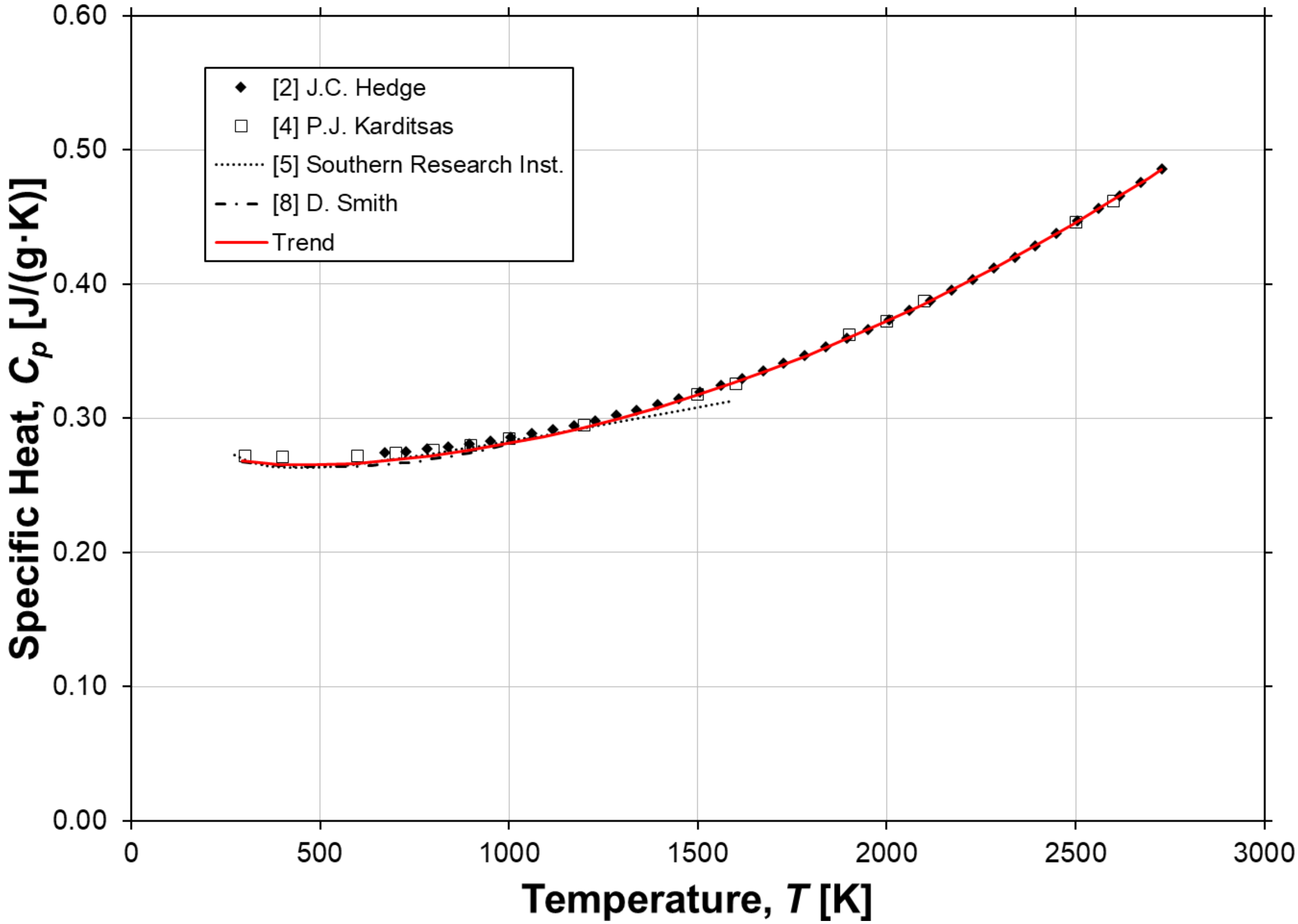

Figure 3.1.3-5: Specific heat versus temperature for TZM.

Specific Heat with Temperature

100% Theoretical Density

Temperature (T)		Specific Heat (C_p)		Temperature (T)		Specific Heat (C_p)	
K	(°F)	J/(g-K)	(BTU/(lb-°F))	K	(°F)	J/(g-K)	(BTU/(lb-°F))
293	(67.7)	0.269	(0.064)	1400	(2060.3)	0.309	(0.074)
300	(80.3)	0.268	(0.064)	1500	(2240.3)	0.317	(0.076)
350	(170.3)	0.266	(0.064)	1600	(2420.3)	0.327	(0.078)
400	(260.3)	0.265	(0.063)	1700	(2600.3)	0.337	(0.081)
450	(350.3)	0.265	(0.063)	1800	(2780.3)	0.348	(0.083)
500	(440.3)	0.265	(0.063)	1900	(2960.3)	0.360	(0.086)
550	(530.3)	0.266	(0.064)	2000	(3140.3)	0.372	(0.089)
600	(620.3)	0.267	(0.064)	2100	(3320.3)	0.386	(0.092)
700	(800.3)	0.269	(0.064)	2200	(3500.3)	0.399	(0.095)
800	(980.3)	0.272	(0.065)	2300	(3680.3)	0.414	(0.099)
900	(1160.3)	0.276	(0.066)	2400	(3860.3)	0.430	(0.103)
1000	(1340.3)	0.281	(0.067)	2500	(4040.3)	0.446	(0.107)
1100	(1520.3)	0.287	(0.069)	2600	(4220.3)	0.463	(0.111)
1200	(1700.3)	0.293	(0.070)	2700	(4400.3)	0.480	(0.115)
1300	(1880.3)	0.301	(0.072)	2728	(4450.7)	0.485	(0.116)

Application Notes: Data for specific heat is collected from references [2, 4, 5, 8] and fitted with the equation below to approximate property trend with respect to temperature.

Fit Equation:

$$C_P(T) = A0 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2 + A\_2/\left(\frac{T}{1000}\right)^2$$

$C_P(T) = Specific\ Heat\ [J/(g \cdot K)]$

$T = Temperature\ [K]$

Constants:

T Range [K]:	$293 \leq T < 2728$
A0 =	0.2631
A1 =	-0.01961
A2 =	0.03706
A_2 =	6.891E-4

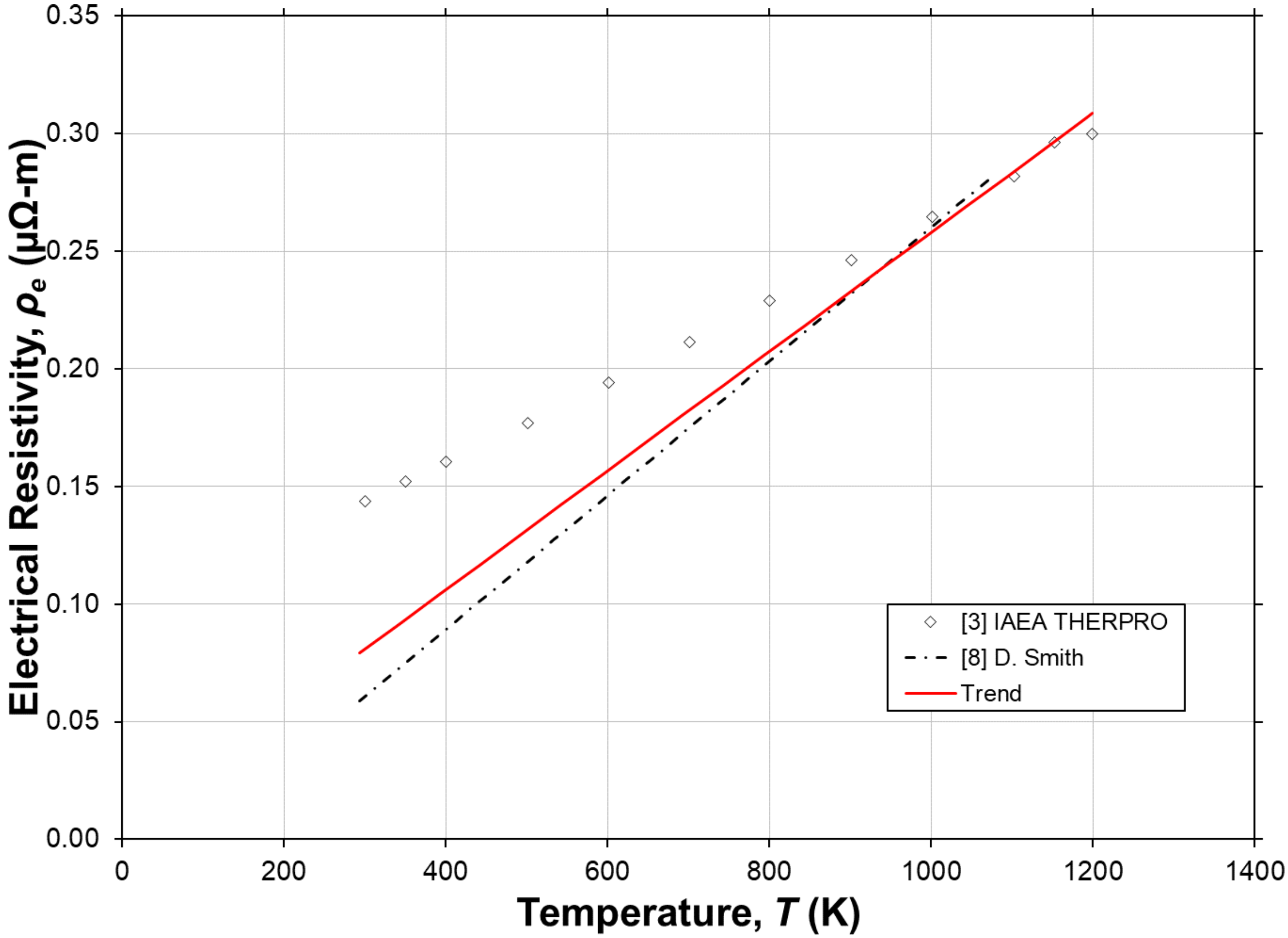

Figure 3.1.3-6: Electrical resistivity versus temperature for TZM.

100% Theoretical Density

Temperature (T)		Electrical Resistivity (ρ_e)		Temperature (T)		Electrical Resistivity (ρ_e)	
K	(°F)	μΩ-m	(μΩ-in)	K	(°F)	μΩ-m	(μΩ-in)
293	(67.7)	0.079	(0.0049)	580	(584.3)	0.152	(0.0095)
300	(80.3)	0.081	(0.0050)	600	(620.3)	0.157	(0.0098)
320	(116.3)	0.086	(0.0054)	620	(656.3)	0.162	(0.0101)
340	(152.3)	0.091	(0.0057)	650	(710.3)	0.169	(0.0106)
360	(188.3)	0.096	(0.0060)	700	(800.3)	0.182	(0.0114)
380	(224.3)	0.101	(0.0063)	750	(890.3)	0.195	(0.0122)
400	(260.3)	0.106	(0.0066)	800	(980.3)	0.207	(0.0130)
420	(296.3)	0.111	(0.0069)	850	(1070.3)	0.220	(0.0137)
440	(332.3)	0.116	(0.0073)	900	(1160.3)	0.233	(0.0145)
460	(368.3)	0.121	(0.0076)	950	(1250.3)	0.245	(0.0153)
480	(404.3)	0.126	(0.0079)	1000	(1340.3)	0.258	(0.0161)
500	(440.3)	0.132	(0.0082)	1050	(1430.3)	0.271	(0.0169)
520	(476.3)	0.137	(0.0085)	1100	(1520.3)	0.283	(0.0177)
540	(512.3)	0.142	(0.0088)	1150	(1610.3)	0.296	(0.0185)
560	(548.3)	0.147	(0.0092)	1199	(1698.5)	0.308	(0.0193)

Application Notes: Data for electrical resistivity is collected from references [3, 8] and fitted with the equation below to approximate property trend with respect to temperature.

Fit Equation:

$$\rho_e(T) = A0 + A1 \cdot \left(\frac{T}{1000}\right)$$

$\rho_e(T) = Electrical\ Resistivity\ [\mu\Omega \cdot m]$

$T = Temperature\ [K]$

Constants:

T Range [K]: $293 \leq T < 1199$

A0 = 4.904E-3

A1 = 0.2532

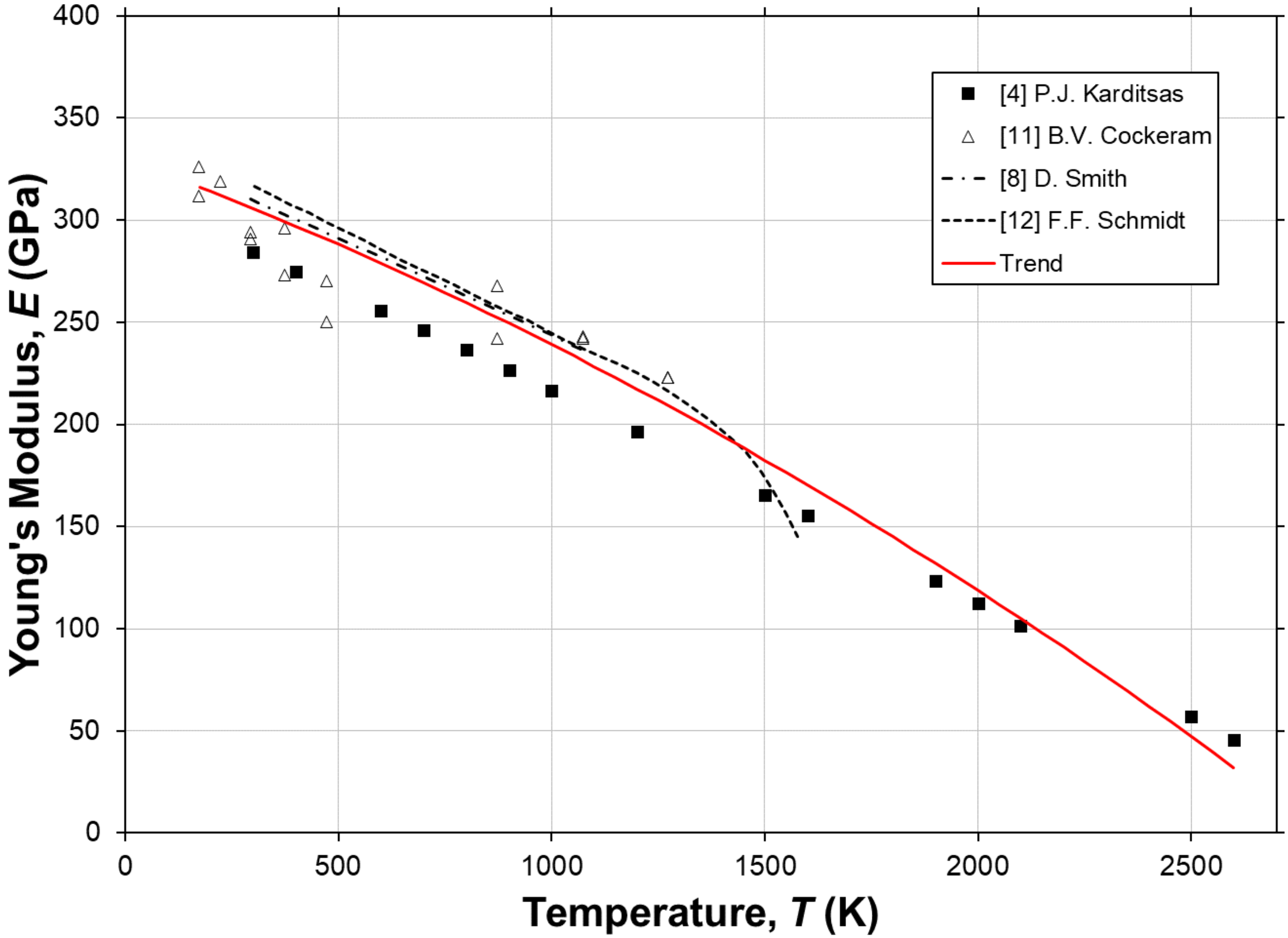

Figure 3.1.3-7: Young's modulus versus temperature for TZM.

100% Theoretical Density

Temperature (T)		Young's Modulus (E)		Temperature (T)		Young's Modulus (E)	
K	(°F)	GPa	(Msi)	K	(°F)	GPa	(Msi)
174	(-146.5)	316	(45.9)	1200	(1700.3)	217	(31.5)
200	(-99.7)	314	(45.6)	1300	(1880.3)	206	(29.9)
293	(67.7)	306	(44.4)	1400	(2060.3)	194	(28.2)
300	(80.3)	306	(44.4)	1500	(2240.3)	183	(26.5)
350	(170.3)	301	(43.7)	1600	(2420.3)	170	(24.7)
400	(260.3)	297	(43.1)	1700	(2600.3)	158	(22.9)
450	(350.3)	293	(42.5)	1800	(2780.3)	145	(21.1)
500	(440.3)	288	(41.8)	1900	(2960.3)	132	(19.2)
550	(530.3)	284	(41.1)	2000	(3140.3)	119	(17.2)
600	(620.3)	279	(40.5)	2100	(3320.3)	105	(15.2)
700	(800.3)	269	(39.1)	2200	(3500.3)	91	(13.2)
800	(980.3)	260	(37.7)	2300	(3680.3)	77	(11.1)
900	(1160.3)	250	(36.2)	2400	(3860.3)	62	(9.0)
1000	(1340.3)	239	(34.7)	2500	(4040.3)	47	(6.9)
1100	(1520.3)	228	(33.1)	2600	(4220.3)	32	(4.7)

Application Notes: Data for Young's modulus is collected from references [4, 8, 11, 12] and fitted with the equation below to approximate the property trend with respect to temperature.

Fit Equations:

$$E(T) = A0 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2$$

$E(T) = Young's\ Modulus\ [GPa]$

$T = Temperature\ [K]$

Constants:

T Range [K]: $174 \leq T \leq 2600$

A0 = 329.8

A1 = -75.83

A2 = -14.87

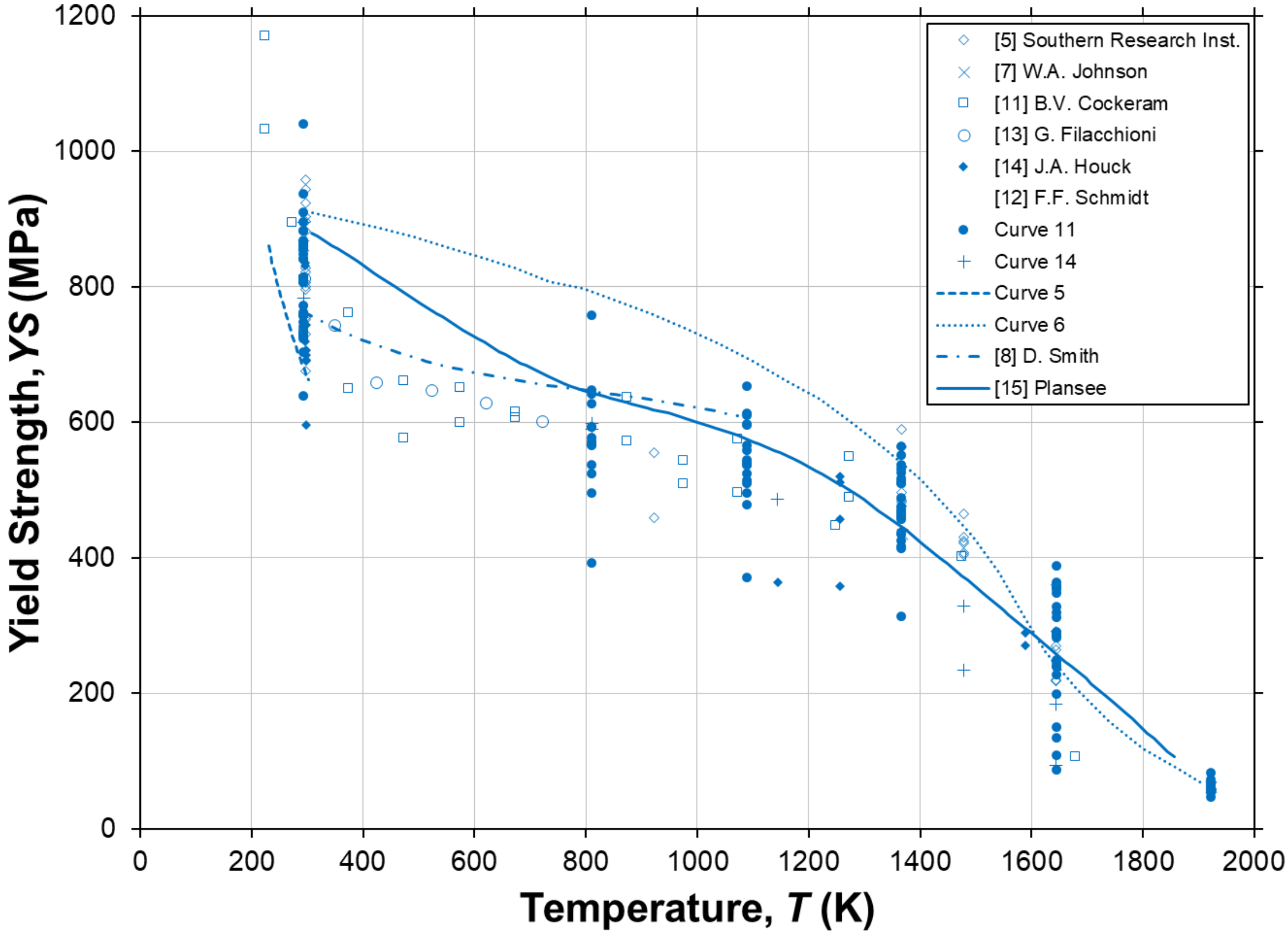

Figure 3.1.3-8: Yield strength versus temperature for stress relieved TZM. Due to the high variance in data, no trend is provided.

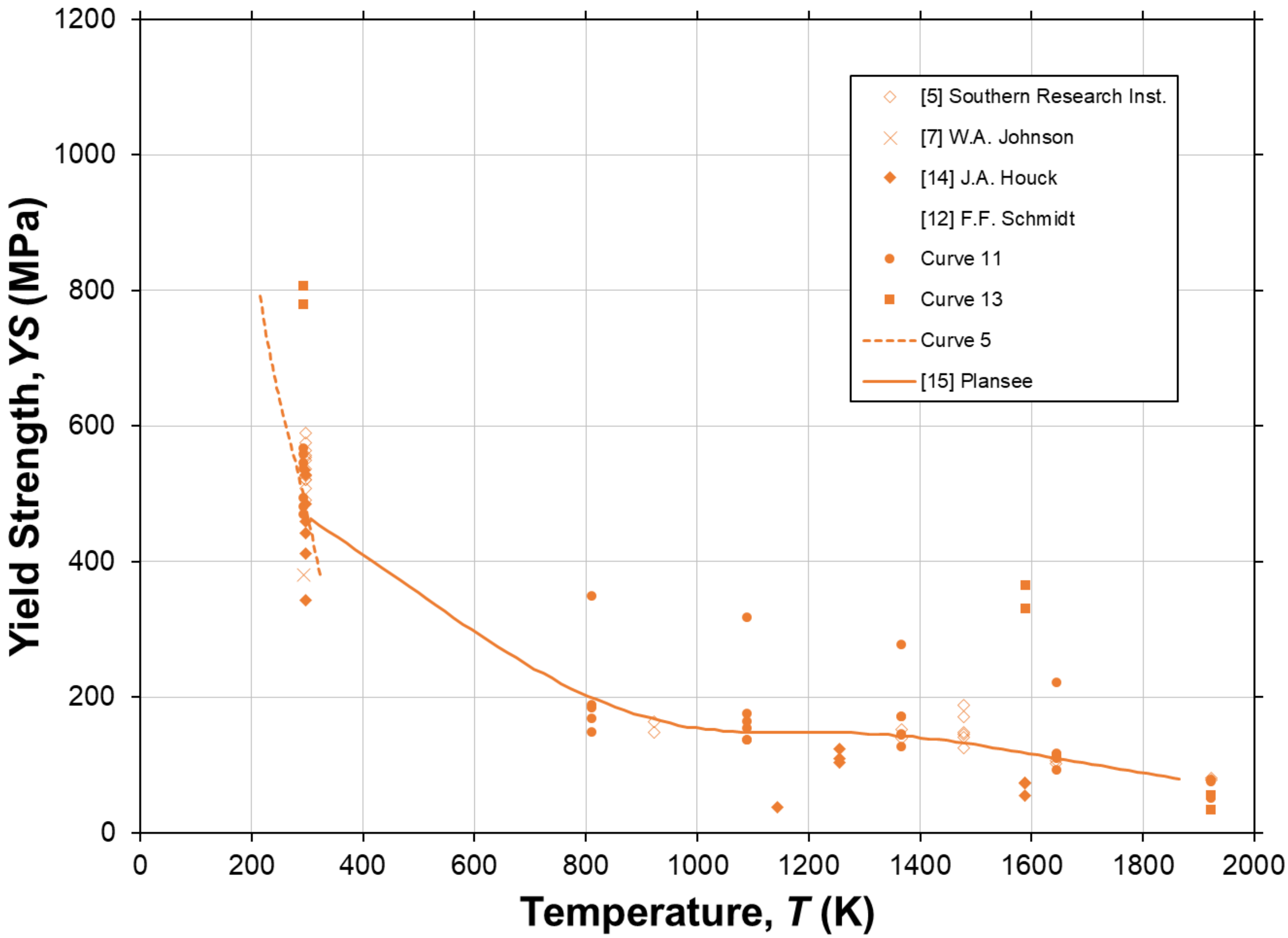

Figure 3.1.3-9: Yield strength versus temperature for recrystallized TZM. Due to the high variance in data, no trend is provided.

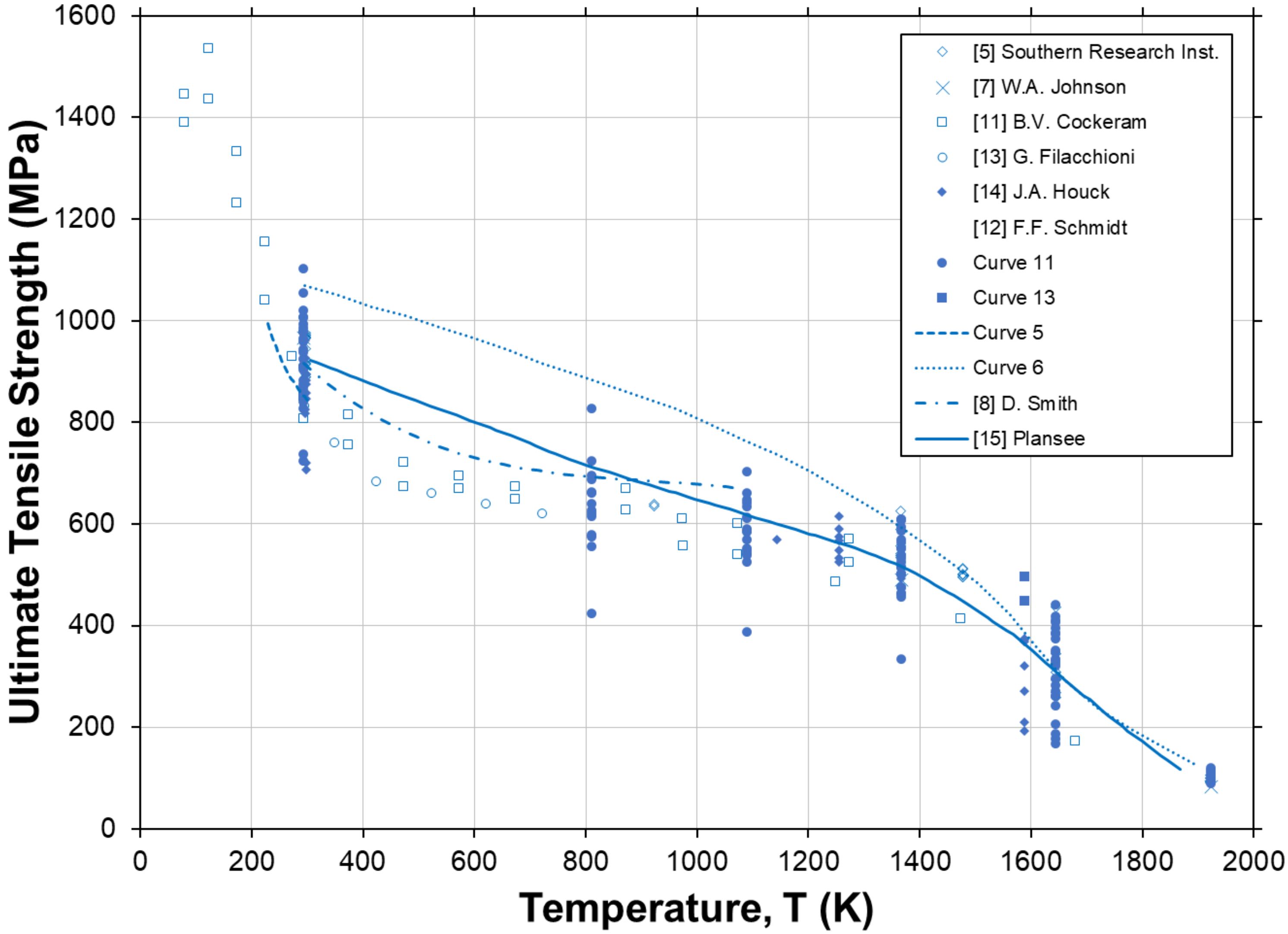

Figure 3.1.3-10: Tensile strength versus temperature for stress relieved TZM. Due to the high variance in data, no trend is provided.

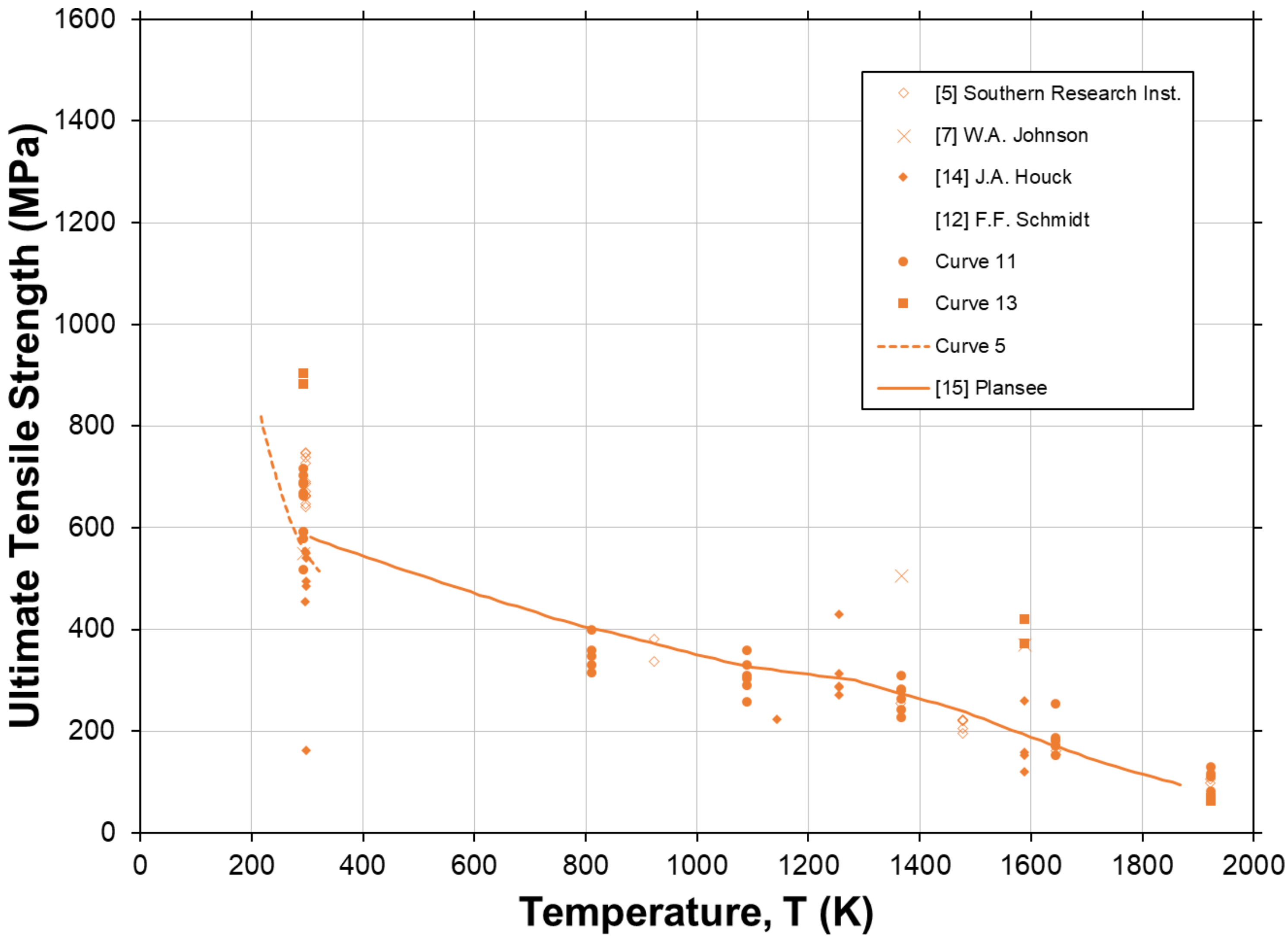

Figure 3.1.3-11: Tensile strength versus temperature for recrystallized TZM. Due to the high variance in data, no trend is provided.

Yield Strength Application Notes:

A material's yield strength is highly dependent on manufacturing procedures. A notable change in yield strength values occurs as a result of heat treatment. Stress relieved materials typically show higher yield strength at a given temperature than their otherwise-equivalent recrystallized forms. As a result, both stress relieved and recrystallized yield strength data have been included in this chapter. Stress relieved data is shown in blue, while recrystallized data is shown in orange. Data for stress relieved TZM is collected from references [5, 7, 8, 11-15]. Data for recrystallized TZM is collected from references [5, 7, 12, 14, 15]. No trends were generated for yield strength, due to the large fluctuations in yield strength at a given temperature.

Tensile Strength Application Notes:

As with yield strength, a material's ultimate tensile strength (or tensile strength) is highly dependent on manufacturing procedures. A notable change in tensile strength values occurs as a result of heat treatment. Stress relieved materials typically show higher tensile strength at a given temperature than their otherwise-equivalent recrystallized forms. As a result, both stress relieved and recrystallized tensile strength data have been included in this chapter. Stress relieved data is shown in blue, while recrystallized data is shown in orange. Data for stress relieved TZM is collected from references [5, 7, 8, 11-15]. Data for recrystallized TZM is collected from references [5, 7, 12, 14, 15]. No trends were generated for tensile strength, due to the large fluctuations in tensile strength at a given temperature.

A Note on *[12] F.F. Schmidt*:

Schmidt's report is a compilation of data from several other reports, none of which could be found before the creation of this TZM chapter. Schmidt typically separated data by references, so each reference was shown in its own separate table or plot. For simplicity, when translating Schmidt's data into this TZM chapter, all data is referred to as a "Curve," followed by the reference number it originated from in Schmidt's report. For those interested in verifying data, do not, for example, search for "Curve 11" in Schmidt's report. Instead look for a table or plot that cites "Reference 11." Also note that Schmidt repeats some data in their report.

Temp. (T) K	Physical and Electrical: Density (ρ) kg/m³	Physical and Electrical: Electrical Resistivity (ρ_e) µΩ-m	Thermal: Thermal Conductivity (k) W/(m-K)	Thermal: Thermal Expansion (dL/L_0) %	Thermal: Mean CTE ($\bar{\alpha}$) 10^{-6}/K	Thermal: Specific Heat (C_p) J/(g-K)	Elastic: Young's Modulus (E) GPa	Elastic: Shear Modulus (G) GPa	Elastic: Poisson's Ratio (ν)
200	-	-	-	-	-	-	314.04	-	-
293	10220	0.079	123.22	0.000	4.97	0.269	306.31	122.7	0.293
300	10219	0.081	122.94	0.004	4.99	0.268	305.71	-	-
400	10201	0.106	119.40	0.062	5.18	0.265	297.09	-	-
500	10184	0.132	116.55	0.119	5.32	0.265	288.17	-	-
600	10166	0.157	114.20	0.176	5.43	0.267	278.95	-	-
700	10149	0.182	112.22	0.233	5.51	0.269	269.43	-	-
800	10131	0.207	110.46	0.291	5.58	0.272	259.62	-	-
900	10114	0.233	108.80	0.349	5.65	0.276	249.51	-	-
1000	10096	0.258	107.16	0.409	5.72	0.281	239.10	-	-
1100	10077	0.283	105.44	0.470	5.79	0.287	228.39	-	-
1200	10058	-	103.57	0.534	5.86	0.293	217.39	-	-
1300	10038	-	101.52	0.599	5.95	0.301	206.09	-	-
1400	10018	-	99.25	0.668	6.03	0.309	194.49	-	-
1500	9997	-	96.74	0.739	6.13	0.317	182.60	-	-
1600	9975	-	94.00	0.814	6.24	0.327	170.40	-	-
1700	9951	-	91.06	0.892	6.36	0.337	157.91	-	-
1800	9927	-	87.94	0.975	6.49	0.348	145.13	-	-
1900	9901	-	84.71	1.062	6.63	0.360	132.04	-	-
2000	9874	-	81.43	1.155	6.78	0.372	118.66	-	-
2100	9846	-	78.20	1.252	6.94	0.386	104.98	-	-
2200	9816	-	75.13	1.355	7.11	0.399	91.00	-	-
2300	9784	-	72.34	1.464	7.30	0.414	76.73	-	-
2500	9716	-	68.19	1.702	7.71	0.446	47.29	-	-
2700	9640	-	-	1.968	8.16	0.480	-	-	-

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3 Refractory Metals and Alloys

3.2 Tungsten and Tungsten Alloys

Room Temperature Properties

Atomic Mass, [amu]	183.84
Theoretical Density, [kg/m^3]	19,250
Melting Point, [K]	3695
Boiling Point, [K]	5828
Specific Heat, [J/(g-K)]	0.133
Heat of Fusion, [kJ/mol]	35
Heat of Vaporization, [kJ/mol]	800
Thermal Conductivity, [W/(m-K)]	175.7
Linear expansion coefficient, [µm/(m-K)]	4.58
Electrical resistivity, [µΩ-m]	0.05
Young's Modulus, [GPa]	399.6
Shear Modulus, [GPa]	159.9
Poisson’s Ratio, [-]	0.249

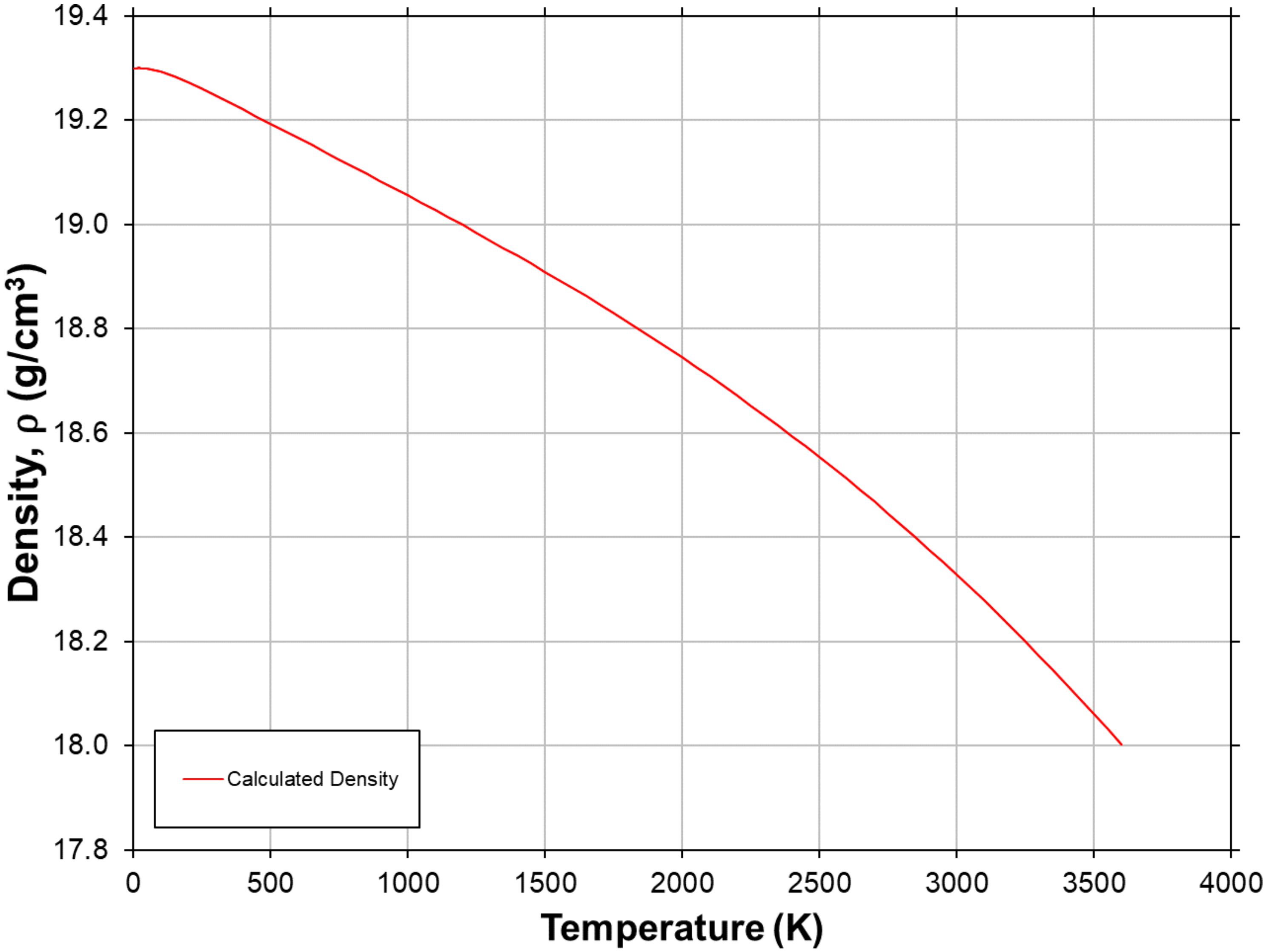

Figure 3.2.1-1: Density versus Temperature for Tungsten. Calculated from fitted trend of Thermal Expansion data.

100% Theoretical Density

Temperature (T)		Density (ρ)		Temperature (T)		Density (ρ)	
K	(°F)	kg/m³	(lb/ft³)	K	(°F)	kg/m³	(lb/ft³)
20	(-423.7)	19300	(1204.9)	1400	(2060.3)	18940	(1182.4)
100	(-279.7)	19294	(1204.5)	1500	(2240.3)	18909	(1180.5)
200	(-99.7)	19273	(1203.2)	1600	(2420.3)	18878	(1178.6)
300	(80.3)	19248	(1201.6)	1700	(2600.3)	18846	(1176.6)
400	(260.3)	19220	(1199.9)	1800	(2780.3)	18813	(1174.5)
500	(440.3)	19193	(1198.2)	1900	(2960.3)	18780	(1172.4)
600	(620.3)	19166	(1196.5)	2000	(3140.3)	18745	(1170.2)
700	(800.3)	19139	(1194.8)	2200	(3500.3)	18672	(1165.7)
800	(980.3)	19111	(1193.1)	2400	(3860.3)	18595	(1160.9)
900	(1160.3)	19084	(1191.4)	2600	(4220.3)	18512	(1155.7)
1000	(1340.3)	19056	(1189.6)	2800	(4580.3)	18423	(1150.2)
1100	(1520.3)	19027	(1187.9)	3000	(4940.3)	18328	(1144.2)
1200	(1700.3)	18999	(1186.1)	3200	(5300.3)	18227	(1137.9)
1300	(1880.3)	18970	(1184.3)	3400	(5660.3)	18118	(1131.1)
1400	(2060.3)	18940	(1182.4)	3600	(6020.3)	18002	(1123.9)

Application Notes: Density trend with respect to temperature is calculated as a function of the Thermal Expansion trend as seen the equation below to approximate property trend with respect to temperature.

Density Calculation:

$\rho(T) = \rho_{RT}/(1 + dL/L_0(T)/100)^3$

$\rho(T) = Density\ [kg/m^3]$

$Room\ Temperature\ Density\ (\rho_{RT}) = 19{,}250\ [kg/m^3]$

$T = Temperature\ [K]$

Temperature Range: $5 \leq T \leq 3600$

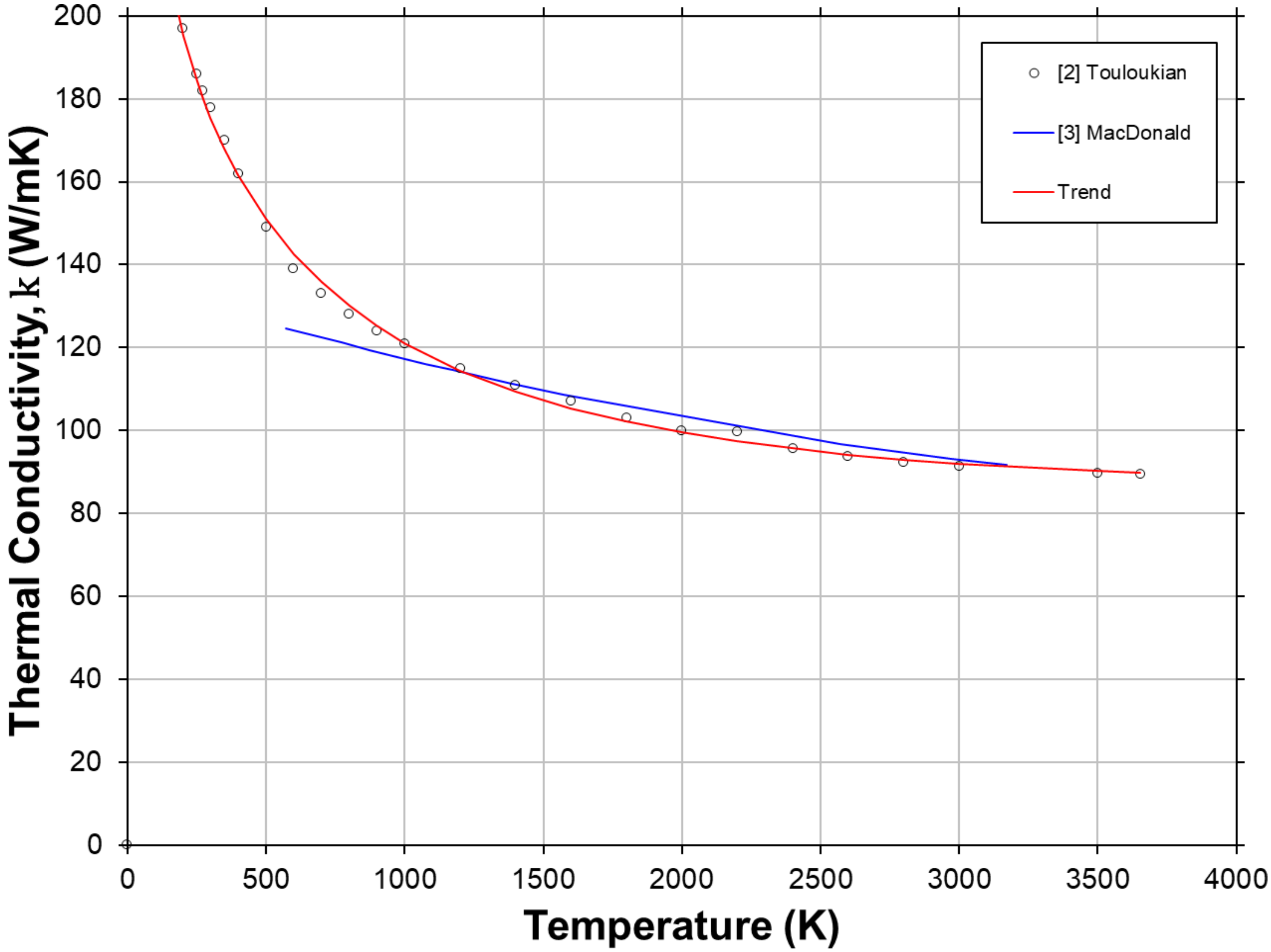

Figure 3.2.1-2: Thermal Conductivity versus Temperature of Tungsten with comparison to MacDonald (1976).

100% Theoretical Density

Temperature (T) K	(°F)	Thermal Conductivity (k) W/(m-K)	((Btu·in)/(ft²·hr·°F))	Temperature (T) K	(°F)	Thermal Conductivity (k) W/(m-K)	((Btu·in)/(ft²·hr·°F))
55	(-360.7)	349.03	(2421.58)	1300	(1880.3)	111.78	(775.53)
100	(-279.7)	236.43	(1640.35)	1400	(2060.3)	109.39	(758.93)
200	(-99.7)	195.24	(1354.57)	1600	(2420.3)	105.37	(731.09)
300	(80.3)	175.33	(1216.47)	1800	(2780.3)	102.16	(708.83)
400	(260.3)	161.49	(1120.46)	2000	(3140.3)	99.56	(690.78)
500	(440.3)	150.96	(1047.37)	2200	(3500.3)	97.43	(676.01)
600	(620.3)	142.59	(989.27)	2400	(3860.3)	95.68	(663.84)
700	(800.3)	135.75	(941.83)	2600	(4220.3)	94.23	(653.76)
800	(980.3)	130.06	(902.34)	2800	(4580.3)	93.02	(645.38)
900	(1160.3)	125.25	(868.97)	3000	(4940.3)	92.02	(638.42)
1000	(1340.3)	121.13	(840.44)	3200	(5300.3)	91.18	(632.65)
1100	(1520.3)	117.58	(815.80)	3400	(5660.3)	90.50	(627.88)
1200	(1700.3)	114.49	(794.35)	3600	(6020.3)	89.93	(623.96)
1300	(1880.3)	111.78	(775.53)	3653	(6115.7)	89.80	(623.05)

Application Notes: Data for thermal conductivity is collected from reference [2] and fitted with the equations below to approximate the property trend with respect to temperature. Fitted trend is compared to trend from reference [3].

Fit Equation:

For temperature range: $1 \leq T < 55$

$$k(T) = \left(A0 \cdot \left(\frac{T}{1000}\right)^N\right) \Big/ \left(1 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2 + A3 \cdot \left(\frac{T}{1000}\right)^3\right)$$

For temperature range: $55 \leq T \leq 3653$

$$k(T) = \left(B0 + B1 \cdot \left(\frac{T}{1000}\right) + B2 \cdot \left(\frac{T}{1000}\right)^2 + B3 \cdot \left(\frac{T}{1000}\right)^3\right) \Big/ \left(C0 + C1 \cdot \left(\frac{T}{1000}\right) + \left(\frac{T}{1000}\right)^2\right)$$

$k(T) = Thermal\ Conductivity\ [W\ /\ (m \cdot K)]$

$T = Temperature\ [K]$

Constants:

T Range [K]:	$1 \leq T < 55$		$55 \leq T \leq 3653$		
N =	8.740E-01	B0 =	-3.679E+00	B3 =	2.867E+00
A0 =	7.348E+05	B1 =	1.181E+02	C0 =	-2.052E-02
A1 =	2.544E+01	B2 =	5.879E+01	C1 =	4.741E-01
A2 =	-8.304E+03				
A3 =	1.180E+06				

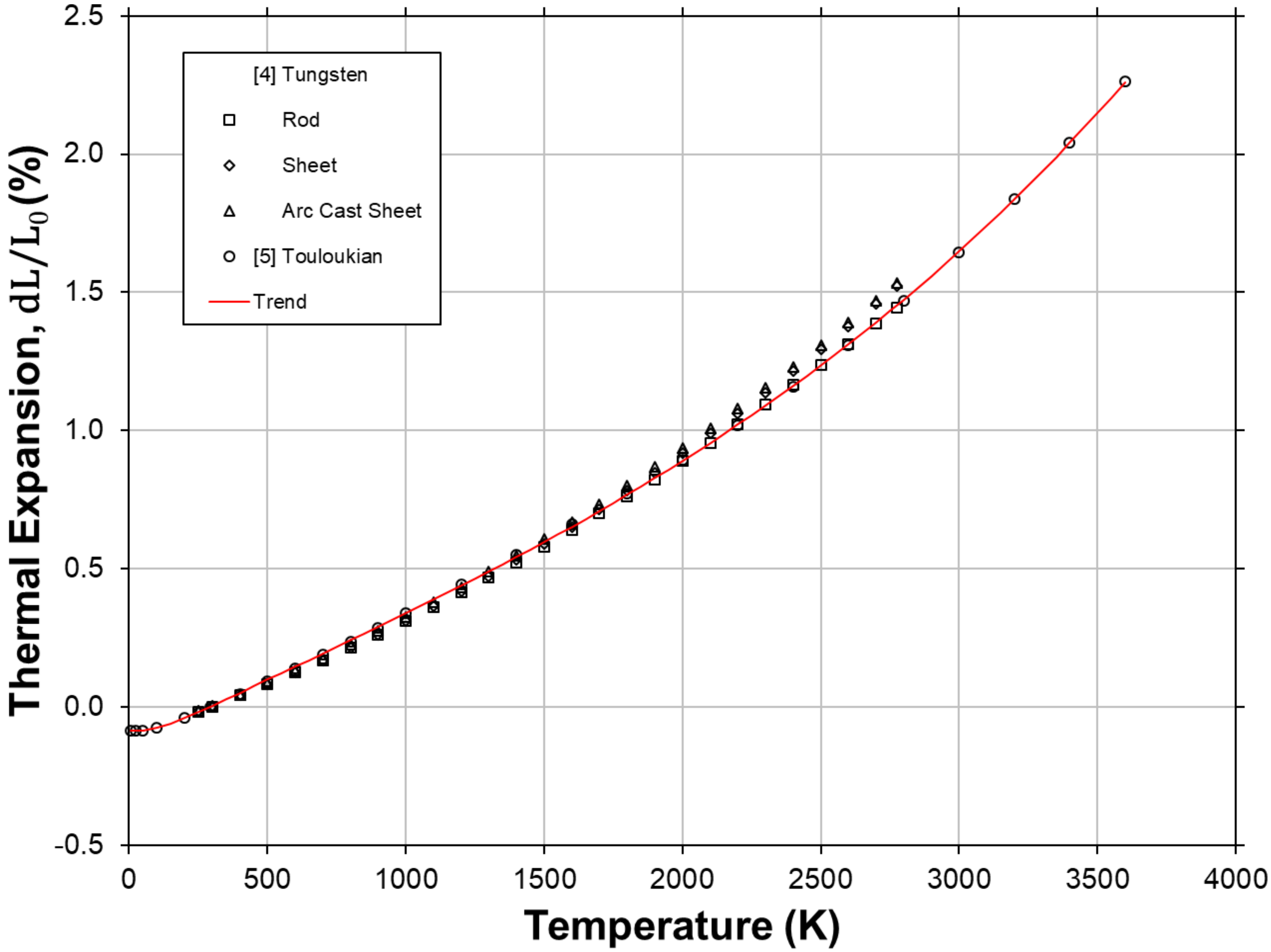

Figure 3.2.1-3: Thermal Expansion versus Temperature of Tungsten.

100% Theoretical Density

Temperature (T)		Thermal Expansion (dL/L_0)	Temperature (T)		Thermal Expansion (dL/L_0)
K	(°F)	%	K	(°F)	%
20	(-423.7)	-0.086	1400	(2060.3)	0.543
100	(-279.7)	-0.076	1500	(2240.3)	0.597
200	(-99.7)	-0.040	1600	(2420.3)	0.652
300	(80.3)	0.004	1700	(2600.3)	0.709
400	(260.3)	0.051	1800	(2780.3)	0.768
500	(440.3)	0.099	1900	(2960.3)	0.828
600	(620.3)	0.146	2000	(3140.3)	0.890
700	(800.3)	0.194	2200	(3500.3)	1.021
800	(980.3)	0.241	2400	(3860.3)	1.161
900	(1160.3)	0.290	2600	(4220.3)	1.312
1000	(1340.3)	0.339	2800	(4580.3)	1.474
1100	(1520.3)	0.388	3000	(4940.3)	1.649
1200	(1700.3)	0.439	3200	(5300.3)	1.837
1300	(1880.3)	0.490	3400	(5660.3)	2.040
1400	(2060.3)	0.543	3600	(6020.3)	2.259

Application Notes: Data for thermal expansion is collected from references [4, 5] and fitted with the equation below to approximate property trend with respect to temperature.

Fit Equation:

$$dL/L_0\,(T) = A0 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2 + A3 \cdot \left(\frac{T}{1000}\right)^3$$

$dL/L_0\,(T) = Thermal\ Expansion\ [\%]$

$T = Temperature\ [K]$

Constants:

T Range [K]:	$5 \leq T \leq 294$	$294 < T \leq 3600$
A0 =	-8.529E-02	-1.400E-01
A1 =	-9.915E-02	4.869E-01
A2 =	2.257E+00	-3.056E-02
A3 =	-3.157E+00	2.234E-02

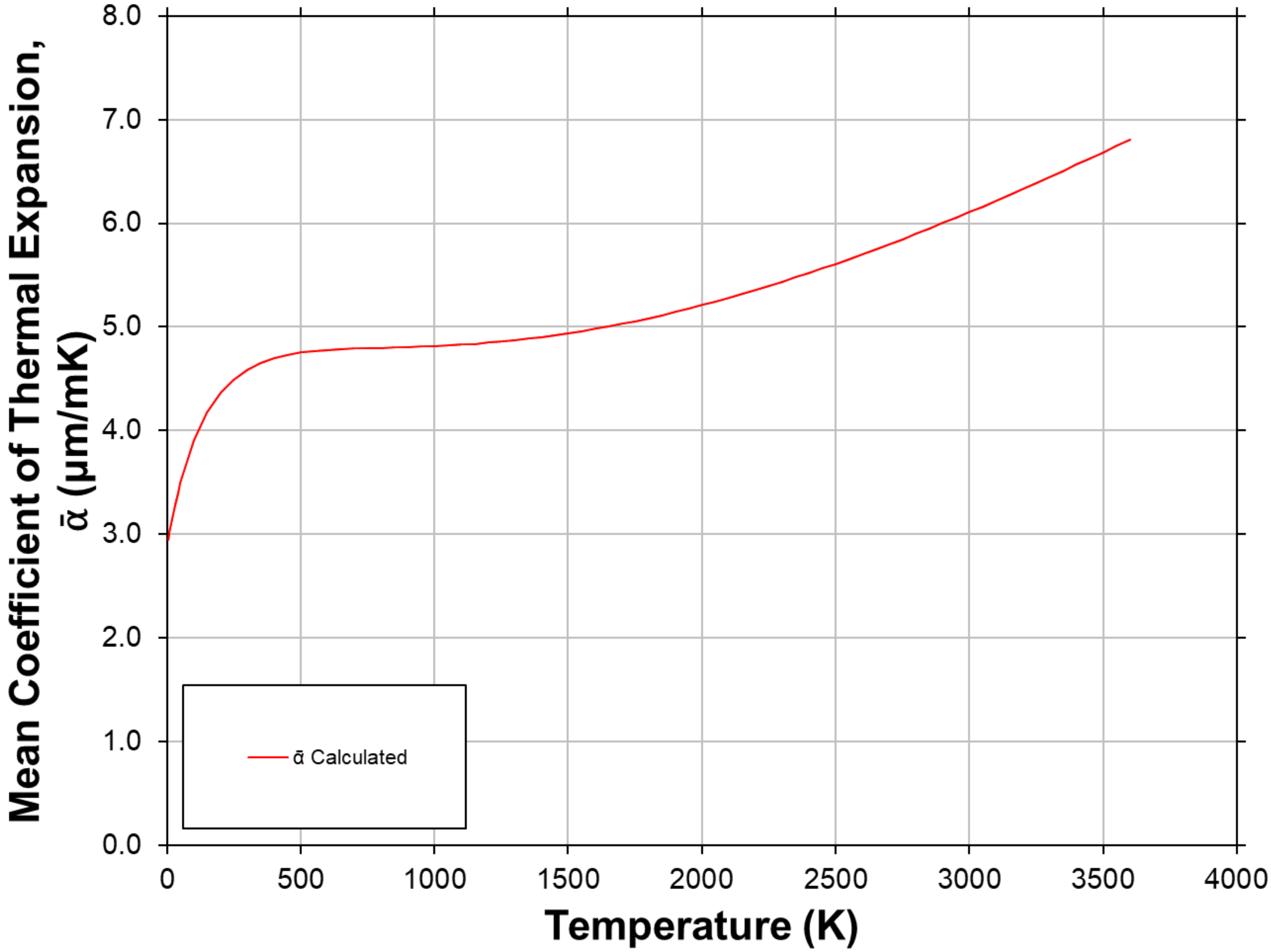

Figure 3.2.1-4: Mean Coefficient of Thermal Expansion versus Temperature of Tungsten. Calculated from fitted trend of Thermal Expansion data.

100% Theoretical Density

Temperature (T)		Mean CTE (ᾱ)		Temperature (T)		Mean CTE (ᾱ)	
K	(°F)	µm/(m-K)	(µin/(in-°F))	K	(°F)	µm/(m-K)	(µin/(in-°F))
20	(-423.7)	3.158	(1.755)	1400	(2060.3)	4.902	(2.723)
100	(-279.7)	3.904	(2.169)	1500	(2240.3)	4.938	(2.743)
200	(-99.7)	4.361	(2.423)	1600	(2420.3)	4.981	(2.767)
300	(80.3)	4.584	(2.547)	1700	(2600.3)	5.030	(2.794)
400	(260.3)	4.696	(2.609)	1800	(2780.3)	5.084	(2.825)
500	(440.3)	4.752	(2.640)	1900	(2960.3)	5.144	(2.858)
600	(620.3)	4.779	(2.655)	2000	(3140.3)	5.209	(2.894)
700	(800.3)	4.791	(2.662)	2200	(3500.3)	5.355	(2.975)
800	(980.3)	4.799	(2.666)	2400	(3860.3)	5.520	(3.066)
900	(1160.3)	4.806	(2.670)	2600	(4220.3)	5.701	(3.167)
1000	(1340.3)	4.815	(2.675)	2800	(4580.3)	5.897	(3.276)
1100	(1520.3)	4.828	(2.682)	3000	(4940.3)	6.107	(3.393)
1200	(1700.3)	4.847	(2.693)	3200	(5300.3)	6.330	(3.517)
1300	(1880.3)	4.871	(2.706)	3400	(5660.3)	6.564	(3.647)
1400	(2060.3)	4.902	(2.723)	3600	(6020.3)	6.808	(3.782)

Application Notes: Data for mean coefficient of thermal expansion is calculated as a function thermal expansion data, then fitted with the equation below to approximate property trend with respect to temperature.

Fit Equation:

$$\bar{\alpha}(T) = \left(A0 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2 + A3 \cdot \left(\frac{T}{1000}\right)^3\right) \Big/ \left(A\_0 + A\_1 \cdot \left(\frac{T}{1000}\right) + \left(\frac{T}{1000}\right)^2\right)$$

$\bar{\alpha}(T) = Coefficient\ of\ Thermal\ Expansion\ [\mu m/(m \cdot K)]$

$T = Temperature\ [K]$

Constants:

T. Range [K]: $5 \le T \le 3600$

A0 =	1.554E+00	A3 =	1.971E+00
A1 =	1.581E+01	A_0 =	5.412E-01
A2 =	2.714E-01	A_1 =	2.531E+00

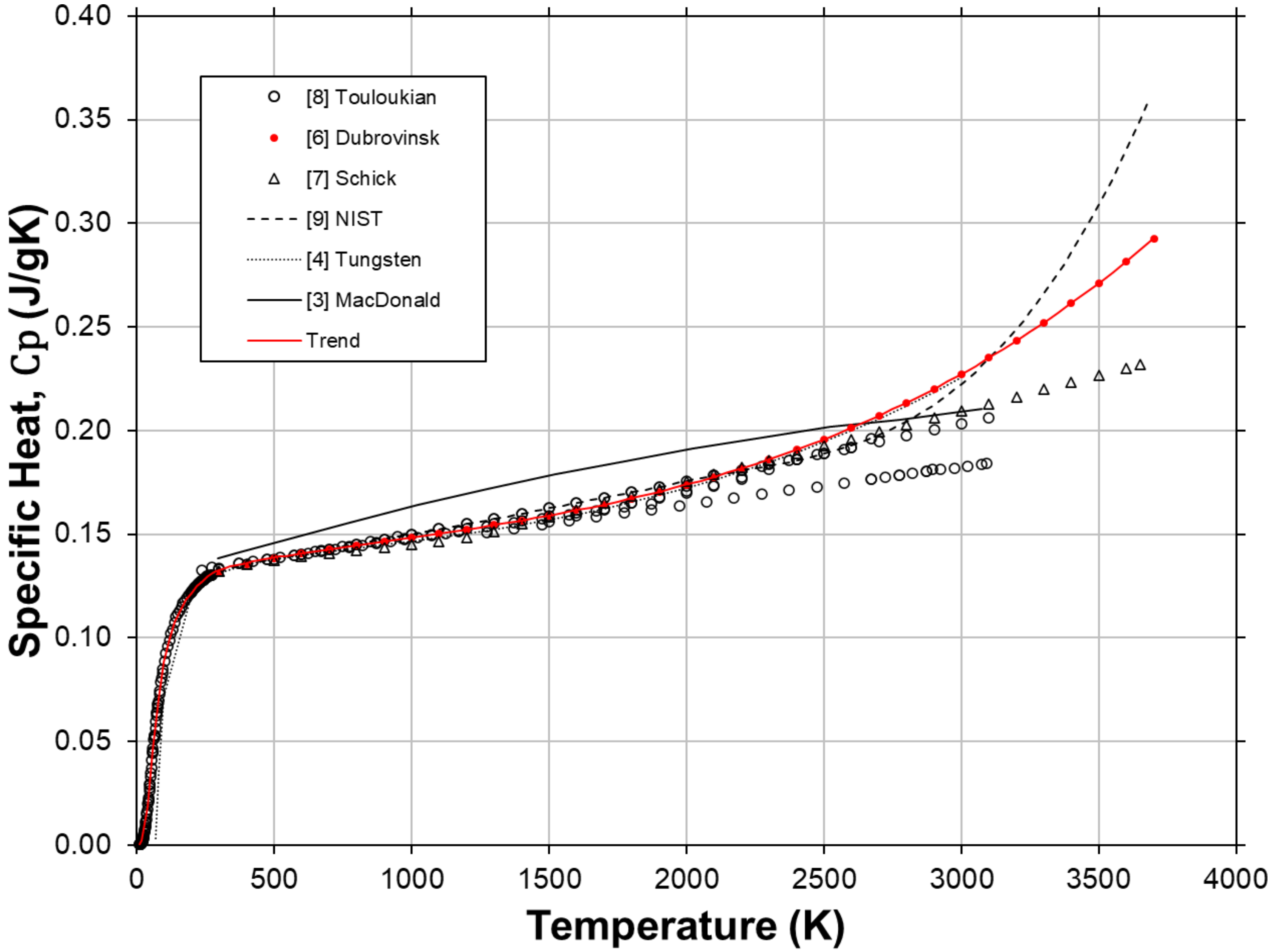

Figure 3.2.1-5: Specific Heat versus Temperature of Tungsten with comparison to reference.

100% Theoretical Density

Temperature (T)		Specific Heat (C_p)		Temperature (T)		Specific Heat (C_p)	
K	(°F)	J/(g-K)	(BTU/(lb-°F))	K	(°F)	J/(g-K)	(BTU/(lb-°F))
20	(-423.7)	0.002	(0.001)	1400	(2060.3)	0.157	(0.037)
100	(-279.7)	0.088	(0.021)	1600	(2420.3)	0.162	(0.039)
200	(-99.7)	0.122	(0.029)	1800	(2780.3)	0.167	(0.040)
300	(80.3)	0.133	(0.032)	2000	(3140.3)	0.174	(0.042)
400	(260.3)	0.136	(0.033)	2200	(3500.3)	0.182	(0.043)
500	(440.3)	0.139	(0.033)	2400	(3860.3)	0.191	(0.046)
600	(620.3)	0.141	(0.034)	2600	(4220.3)	0.201	(0.048)
700	(800.3)	0.143	(0.034)	2800	(4580.3)	0.213	(0.051)
800	(980.3)	0.145	(0.035)	3000	(4940.3)	0.227	(0.054)
900	(1160.3)	0.146	(0.035)	3200	(5300.3)	0.243	(0.058)
1000	(1340.3)	0.148	(0.035)	3400	(5660.3)	0.261	(0.062)
1100	(1520.3)	0.150	(0.036)	3600	(6020.3)	0.282	(0.067)
1200	(1700.3)	0.152	(0.036)	3700	(6200.3)	0.293	(0.070)

Application Notes: Data for specific heat is collected from references [6-8] and fitted with the equations below to approximate property trend with respect to temperature. Fitted trend is compared against trends from references [3, 4, 9].

Fit Equation:

For temperature range: $11 \leq T < 293$

$$C_P(T) = \left[A0 \cdot \left(\frac{T}{1000}\right)^N\right] \Big/ \left[1 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2 + A3 \cdot \left(\frac{T}{1000}\right)^3\right]$$

For temperature range: $293 \leq T \leq 3700$

$$C_P(T) = B0 + B1 \cdot \left(\frac{T}{1000}\right) + B2 \cdot \left(\frac{T}{1000}\right)^2 + B3 \cdot \left(\frac{T}{1000}\right)^3 + B\_2 \Big/ \left(\frac{T}{1000}\right)^2$$

$C_P(T) = Specific\ Heat\ [J/(g \cdot K)]$

$T = Temperature\ [K]$

Constants:

T. Range [K]:	$11 \leq T \leq 293$		$293 < T \leq 3700$
N =	3.030E+00	B0 =	1.301E-01
A0 =	3.103E+02	B1 =	2.225E-02
A1 =	-8.815E+00	B2 =	-7.224E-03
A2 =	1.295E+02	B3 =	3.539E-03
A3 =	1.874E+03	B_2 =	-3.061E-04

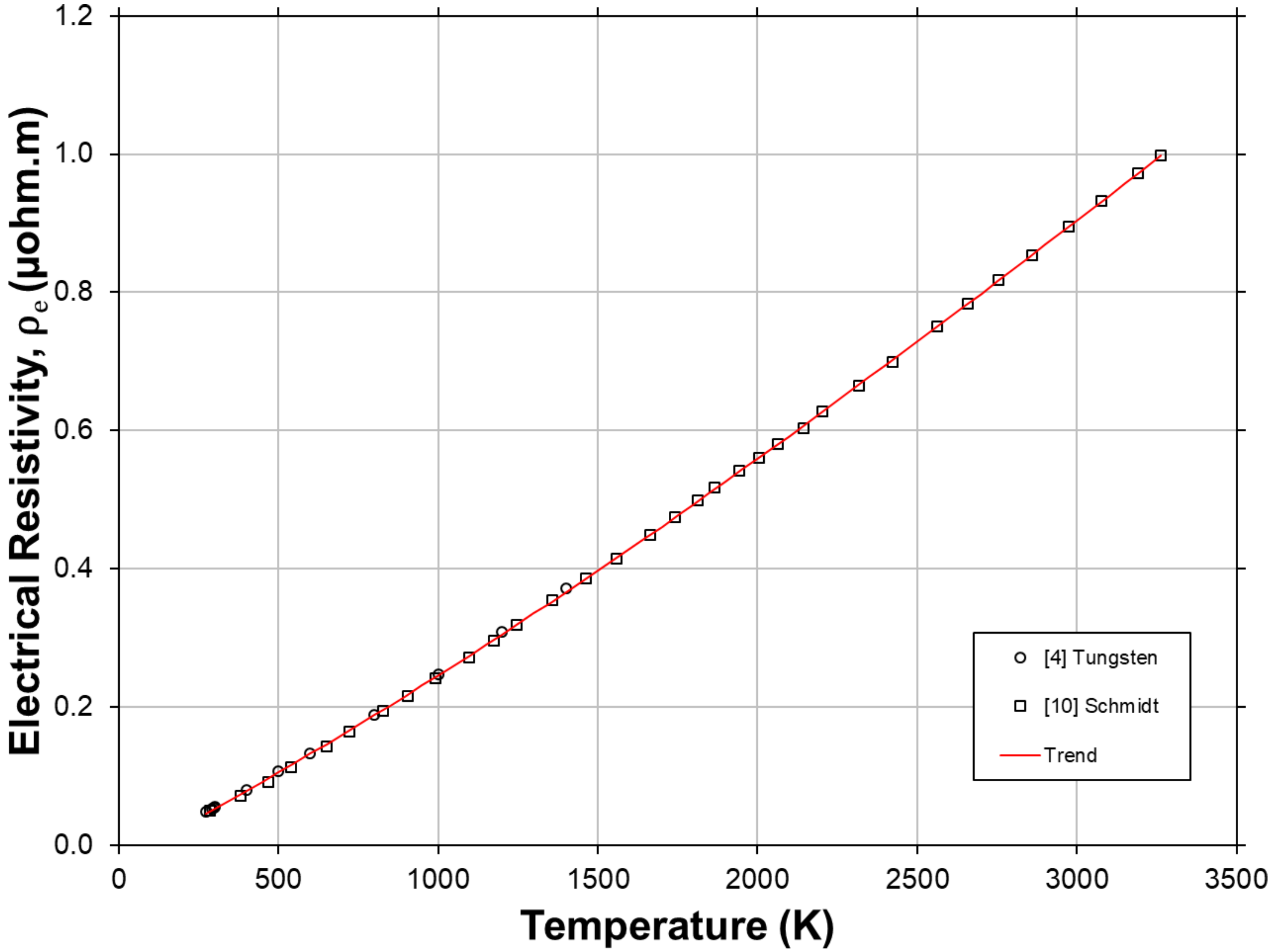

Figure 3.2.1-6: Electrical Resistivity versus Temperature for Tungsten.

100% Theoretical Density

Temperature (T)		Electrical Resistivity (ρ_e)		Temperature (T)		Electrical Resistivity (ρ_e)	
K	(°F)	μΩ-m	(μΩ-in)	K	(°F)	μΩ-m	(μΩ-in)
273	(31.7)	0.046	(1.81)	1700	(2600.3)	0.461	(18.15)
300	(80.3)	0.053	(2.08)	1800	(2780.3)	0.493	(19.42)
400	(260.3)	0.079	(3.10)	1900	(2960.3)	0.526	(20.71)
500	(440.3)	0.105	(4.15)	2000	(3140.3)	0.559	(22.01)
600	(620.3)	0.132	(5.21)	2100	(3320.3)	0.592	(23.32)
700	(800.3)	0.160	(6.29)	2200	(3500.3)	0.626	(24.65)
800	(980.3)	0.188	(7.40)	2300	(3680.3)	0.660	(25.99)
900	(1160.3)	0.216	(8.52)	2400	(3860.3)	0.694	(27.33)
1000	(1340.3)	0.245	(9.66)	2500	(4040.3)	0.729	(28.69)
1100	(1520.3)	0.275	(10.83)	2600	(4220.3)	0.763	(30.05)
1200	(1700.3)	0.305	(12.01)	2700	(4400.3)	0.798	(31.43)
1300	(1880.3)	0.335	(13.20)	2800	(4580.3)	0.833	(32.81)
1400	(2060.3)	0.366	(14.42)	3000	(4940.3)	0.904	(35.60)
1500	(2240.3)	0.397	(15.64)	3200	(5300.3)	0.976	(38.41)
1600	(2420.3)	0.429	(16.89)	3261	(5410.1)	0.998	(39.28)

Application Notes: Data for electrical resistivity is collected from references [4, 10] and fitted with the equation below to approximate property trend with respect to temperature.

Fit Equation:

$$\rho_e(T) = A0 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2 + A3 \cdot \left(\frac{T}{1000}\right)^3$$

$\rho_e(T) = Electrical\ Resistivity\ [\mu\Omega \cdot m]$

$T = Temperature\ [K]$

Constants:

T. Range [K]: $273 \leq T \leq 3261$

A0 = -2.122E-02

A1 = 2.381E-01

A2 = 3.116E-02

A3 = -2.566E-03

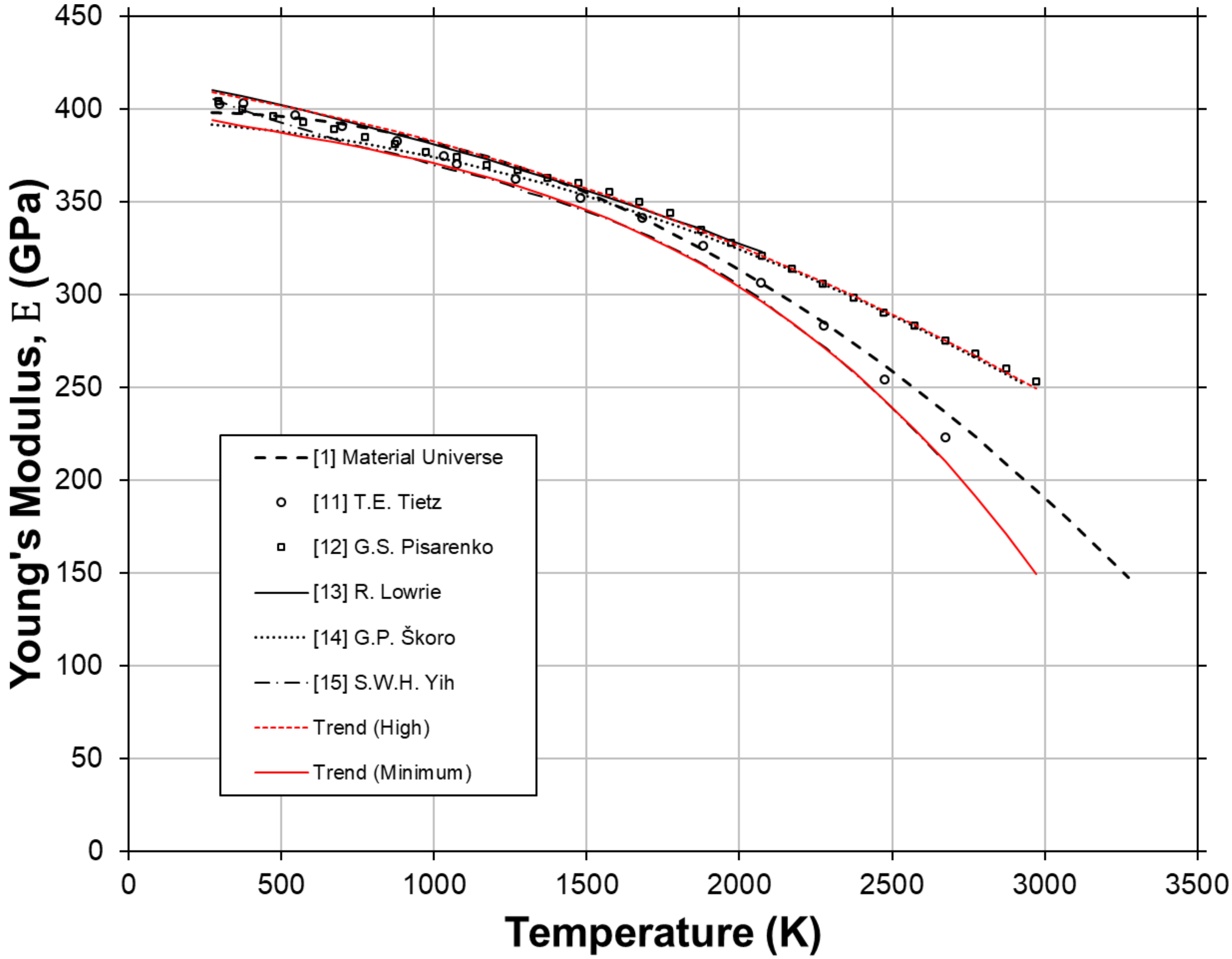

Figure 3.2.1-7: Young's modulus versus temperature for tungsten.

Young's Modulus with Temperature

Minimum Young's Modulus at 100% Theoretical Density

Temperature (T)		Young's Modulus (E)	
K	(°F)	GPa	(Msi)
273	(31.7)	393.79	(57.14)
300	(80.3)	392.99	(57.02)
500	(440.3)	387.16	(56.18)
700	(800.3)	381.12	(55.30)
900	(1160.3)	374.41	(54.33)
1100	(1520.3)	366.55	(53.19)
1300	(1880.3)	357.05	(51.81)
1500	(2240.3)	345.45	(50.12)
1700	(2600.3)	331.27	(48.07)
1900	(2960.3)	314.04	(45.57)
2100	(3320.3)	293.27	(42.55)
2300	(3680.3)	268.50	(38.96)
2500	(4040.3)	239.24	(34.71)
2700	(4400.3)	205.03	(29.75)
2973	(4891.7)	149.46	(21.69)

High Young's Modulus at 100% Theoretical Density

Temperature (T)		Young's Modulus (E)	
K	(°F)	GPa	(Msi)
273	(31.7)	408.89	(59.33)
300	(80.3)	408.13	(59.22)
500	(440.3)	401.93	(58.32)
700	(800.3)	394.81	(57.29)
900	(1160.3)	386.77	(56.12)
1100	(1520.3)	377.82	(54.82)
1300	(1880.3)	367.94	(53.39)
1500	(2240.3)	357.14	(51.82)
1700	(2600.3)	345.42	(50.12)
1900	(2960.3)	332.78	(48.29)
2100	(3320.3)	319.23	(46.32)
2300	(3680.3)	304.75	(44.22)
2500	(4040.3)	289.35	(41.98)
2700	(4400.3)	273.03	(39.62)
2973	(4891.7)	249.27	(36.17)

Application Notes: Data for Young's modulus is collected from references [1, 11-15] and fitted with the equation below to approximate the property trend with respect to temperature. Since two distinct trends were observed, a minimum and a high equation were generated.

Fit Equations:

$$E(T) = A0 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2 + A3 \cdot \left(\frac{T}{1000}\right)^3$$

$E(T) = Young's\ Modulus\ [GPa]$

$T = Temperature\ [K]$

T Range [K]: $273 \leq T \leq 2973$

Constants:

Curve:	Minimum	High
A0 =	402.4	415.7
A1 =	-34.17	-21.79
A2 =	12.33	-11.5
A3 =	-9.907	0

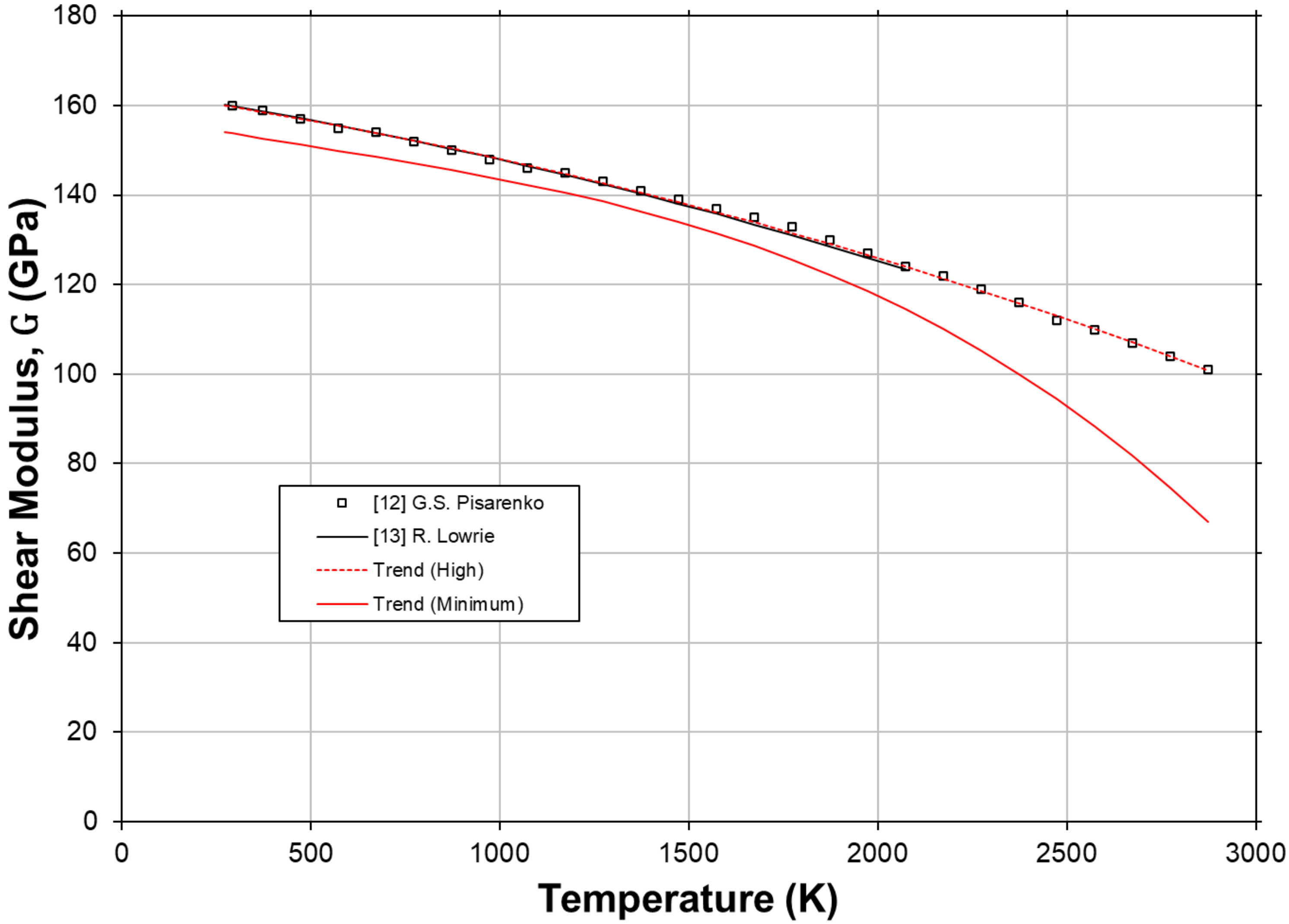

Figure 3.2.1-8: Shear modulus versus temperature for tungsten. The high trend was fitted using data, while the minimum trend was calculated from the Young's modulus (minimum) trend and the Poisson's ratio trend.

Minimum Shear Modulus at 100% Theoretical Density

Temperature (T) K	(°F)	Shear Modulus (E) GPa	(Msi)
273	(31.7)	154.14	(22.37)
300	(80.3)	153.75	(22.31)
500	(440.3)	150.94	(21.90)
700	(800.3)	148.15	(21.50)
900	(1160.3)	145.19	(21.07)
1100	(1520.3)	141.88	(20.59)
1300	(1880.3)	138.01	(20.03)
1500	(2240.3)	133.41	(19.36)
1700	(2600.3)	127.89	(18.56)
1900	(2960.3)	121.26	(17.59)
2100	(3320.3)	113.32	(16.44)
2300	(3680.3)	103.90	(15.08)
2500	(4040.3)	92.81	(13.47)
2700	(4400.3)	79.85	(11.59)
2873	(4711.7)	66.99	(9.72)

High Shear Modulus at 100% Theoretical Density

Temperature (T) K	(°F)	Shear Modulus (E) GPa	(Msi)
273	(31.7)	159.98	(23.21)
300	(80.3)	159.60	(23.16)
500	(440.3)	156.66	(22.73)
700	(800.3)	153.44	(22.26)
900	(1160.3)	149.95	(21.76)
1100	(1520.3)	146.19	(21.21)
1300	(1880.3)	142.16	(20.63)
1500	(2240.3)	137.85	(20.00)
1700	(2600.3)	133.27	(19.34)
1900	(2960.3)	128.41	(18.63)
2100	(3320.3)	123.29	(17.89)
2300	(3680.3)	117.89	(17.11)
2500	(4040.3)	112.21	(16.28)
2700	(4400.3)	106.27	(15.42)
2873	(4711.7)	100.90	(14.64)

Application Notes: Data for shear modulus is collected from references [12, 13] and fitted with the equation below to approximate a high property trend with respect to temperature. The minimum trend is calculated as a function of Young's modulus (minimum) and Poisson's ratio. Equivalent fit equations are provided below for readers' convenience.

Fit Equations:

$$G(T) = A0 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2 + A3 \cdot \left(\frac{T}{1000}\right)^3$$

$G(T) = Shear\ Modulus\ [GPa]$

$T = Temperature\ [K]$

T Range [K]: $273 \leq T \leq 2873$

Constants:

Curve:	Minimum	High
A0 =	158.4	163.5
A1 =	-16.99	-11.98
A2 =	6.101	-3.414
A3 =	-3.92	0

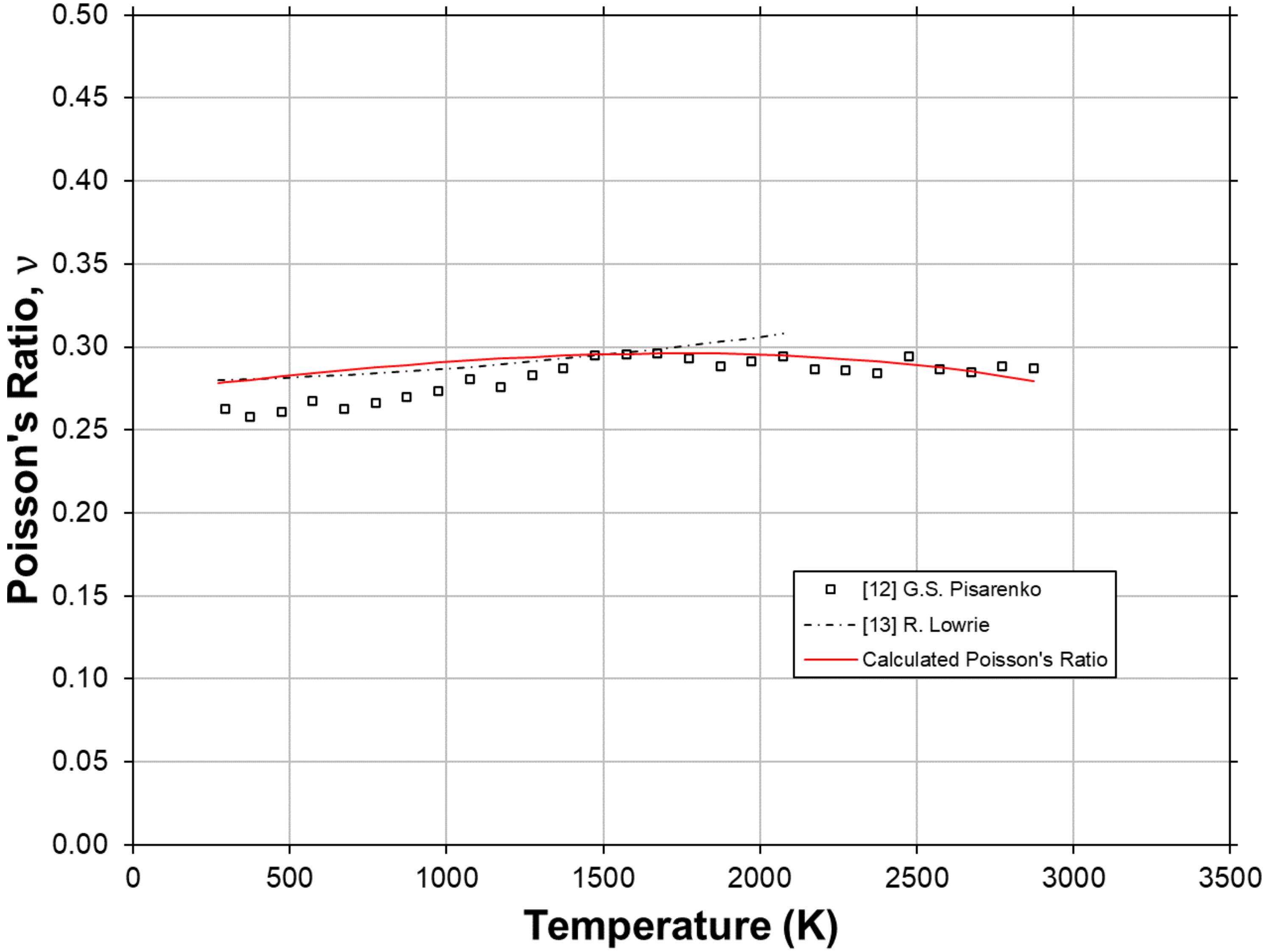

Figure 3.2.1-9: Poisson's ratio versus temperature for tungsten, calculated from fitted Young's modulus (high) and shear modulus (high) curves.

100% Theoretical Density

Temperature (T) K	(°F)	Poisson's Ratio (ν)	Temperature (T) K	(°F)	Poisson's Ratio (ν)
273	(31.7)	0.278	1000	(1340.3)	0.291
300	(80.3)	0.279	1100	(1520.3)	0.292
350	(170.3)	0.280	1200	(1700.3)	0.293
400	(260.3)	0.281	1300	(1880.3)	0.294
450	(350.3)	0.282	1400	(2060.3)	0.295
500	(440.3)	0.283	1500	(2240.3)	0.295
550	(530.3)	0.284	1600	(2420.3)	0.296
600	(620.3)	0.285	1700	(2600.3)	0.296
650	(710.3)	0.286	1800	(2780.3)	0.296
700	(800.3)	0.287	1900	(2960.3)	0.296
750	(890.3)	0.287	2000	(3140.3)	0.295
800	(980.3)	0.288	2200	(3500.3)	0.294
850	(1070.3)	0.289	2400	(3860.3)	0.291
900	(1160.3)	0.290	2600	(4220.3)	0.287
950	(1250.3)	0.290	2873	(4711.7)	0.279

Application Notes: Poisson's ratio is calculated as a function of Young's modulus (high) and shear modulus (high) to approximate the property trend with respect to temperature and is compared against references [12, 13]. The trend was then fitted with an equivalent equation below for readers' convenience.

Fit Equation:

$$\nu(T) = A0 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2 + A3 \cdot \left(\frac{T}{1000}\right)^3$$

$\nu(T) = Poisson's\ Ratio$

$T = Temperature\ [K]$

Constants:

T Range [K]:	$273 \leq T \leq 2873$
A0 =	0.2722
A1 =	0.02244
A2 =	-2.077E-3
A3 =	-1.682E-3

Temp.	Physical and Electrical		Thermal				Elastic		
	Density	Electrical Resistivity	Thermal Conductivity	Thermal Expansion	Mean CTE	Specific Heat	Young's Modulus	Shear Modulus	Poisson's Ratio
(T)	(ρ)	(ρ_e)	(k)	(dL/L_0)	($\bar{\alpha}$)	(C_p)	(E)	(G)	(ν)
K	kg/m³	μΩ-m	W/(m-K)	%	10^{-6}/K	J/(g-K)	GPa	GPa	
100	19294	-	236.43	-0.076	3.90	0.088	-	-	-
200	19273	-	195.24	-0.040	4.36	0.122	-	-	-
300	19248	0.053	175.33	0.004	4.58	0.133	399.54	159.87	0.250
400	19220	0.079	161.49	0.051	4.70	0.136	397.23	158.37	0.254
500	19193	0.105	150.96	0.099	4.75	0.139	394.66	156.80	0.259
600	19166	0.132	142.59	0.146	4.78	0.141	391.83	155.16	0.263
700	19139	0.160	135.75	0.194	4.79	0.143	388.75	153.45	0.267
800	19111	0.188	130.06	0.241	4.80	0.145	385.40	151.68	0.270
900	19084	0.216	125.25	0.290	4.81	0.146	381.79	149.85	0.274
1000	19056	0.245	121.13	0.339	4.81	0.148	377.92	147.95	0.277
1100	19027	0.275	117.58	0.388	4.83	0.150	373.79	145.98	0.280
1200	18999	0.305	114.49	0.439	4.85	0.152	369.40	143.95	0.283
1300	18970	0.335	111.78	0.490	4.87	0.154	364.75	141.86	0.286
1400	18940	0.366	109.39	0.543	4.90	0.157	359.84	139.69	0.288
1600	18878	0.429	105.37	0.652	4.98	0.162	349.24	135.17	0.292
1800	18813	0.493	102.16	0.768	5.08	0.167	337.60	130.39	0.295
2000	18745	0.559	99.56	0.890	5.21	0.174	324.92	125.34	0.296
2200	18672	0.626	97.43	1.021	5.36	0.182	311.20	120.03	0.296
2400	18595	0.694	95.68	1.161	5.52	0.191	296.43	114.46	0.295
2600	18512	0.763	94.23	1.312	5.70	0.201	280.63	108.63	0.292
2800	18423	0.833	93.02	1.474	5.90	0.213	263.79	102.53	0.286
3000	18328	0.904	92.02	1.649	6.11	0.227	245.90	-	-
3200	18227	0.976	91.18	1.837	6.33	0.243	226.97	-	-
3400	18118	-	90.50	2.040	6.56	0.261	207.01	-	-
3600	18002	-	89.93	2.259	6.81	0.282	186.00	-	-

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3 Refractory Metals and Alloys

3.3 Rhenium and Rhenium Alloys

Room Temperature Properties

Molar Mass, [g/mol]	186.2
Theoretical Density, [kg/m^3]	21,040
Melting Point, [K]	3,453
Specific Heat, [J/(g-K)]	0.138
Thermal Conductivity, [W/(m-K)]	46.3
Avg. Linear Expansion Coefficient, [μm/(m-K)]	5.93
Electrical resistivity, [μΩ-m]	0.209
Young's Modulus, [GPa]	460
Shear Modulus, [GPa]	177
Poisson’s Ratio, [-]	0.300

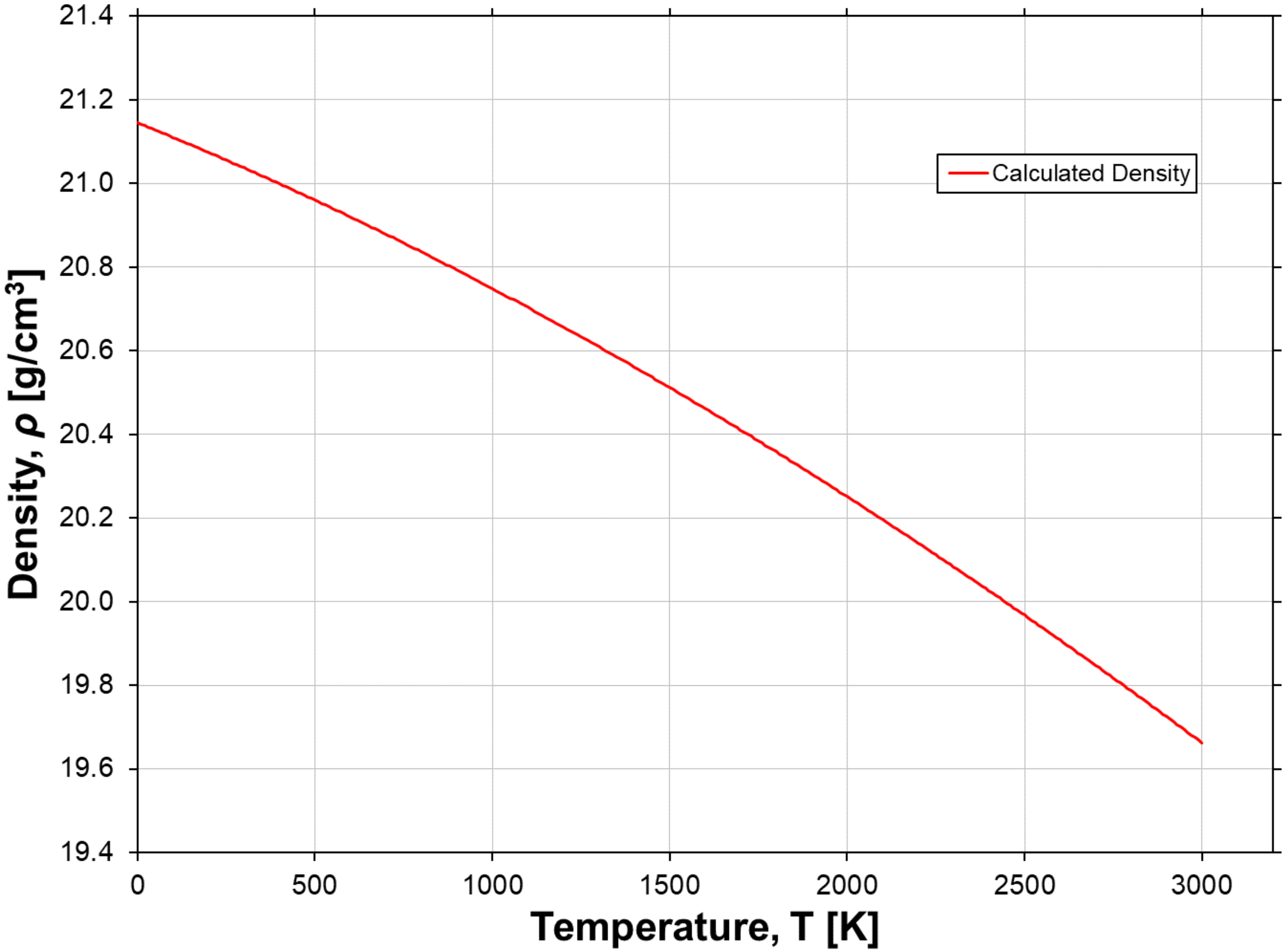

Figure 3.3.1-1: Density versus temperature for rhenium. Calculated from fitted trend of the thermal expansion data.

100% Theoretical Density

Temperature (T)		Density (ρ)		Temperature (T)		Density (ρ)	
K	(°F)	kg/m³	(lb/ft³)	K	(°F)	kg/m³	(lb/ft³)
100	(-279.7)	21110	(1317.9)	1600	(2420.3)	20462	(1277.4)
200	(-99.7)	21074	(1315.7)	1700	(2600.3)	20410	(1274.2)
300	(80.3)	21037	(1313.4)	1800	(2780.3)	20358	(1271.0)
400	(260.3)	20999	(1311.0)	1900	(2960.3)	20305	(1267.6)
500	(440.3)	20960	(1308.5)	2000	(3140.3)	20251	(1264.3)
600	(620.3)	20920	(1306.0)	2100	(3320.3)	20196	(1260.8)
700	(800.3)	20879	(1303.5)	2200	(3500.3)	20140	(1257.3)
800	(980.3)	20836	(1300.8)	2300	(3680.3)	20083	(1253.8)
900	(1160.3)	20793	(1298.1)	2400	(3860.3)	20026	(1250.2)
1000	(1340.3)	20749	(1295.3)	2500	(4040.3)	19967	(1246.6)
1100	(1520.3)	20703	(1292.5)	2600	(4220.3)	19908	(1242.8)
1200	(1700.3)	20657	(1289.6)	2700	(4400.3)	19848	(1239.1)
1300	(1880.3)	20610	(1286.7)	2800	(4580.3)	19787	(1235.3)
1400	(2060.3)	20561	(1283.6)	2900	(4760.3)	19725	(1231.4)
1500	(2240.3)	20512	(1280.6)	3000	(4940.3)	19662	(1227.5)

Application Notes: Density is calculated as a function of thermal expansion, as seen in the equation below, to approximate property trend with respect to temperature.

Density Calculation:

$\rho(T) = \rho_{RT}/(1 + dL/L_0(T)/100)^3$

$\rho(T) = Density\ [kg/m^3]$

$Room\ Temperature\ Density\ (\rho_{RT}) = 21{,}040\ [kg/m^3]$

$T = Temperature\ [K]$

Temperature Range: $0 \leq T \leq 3000$

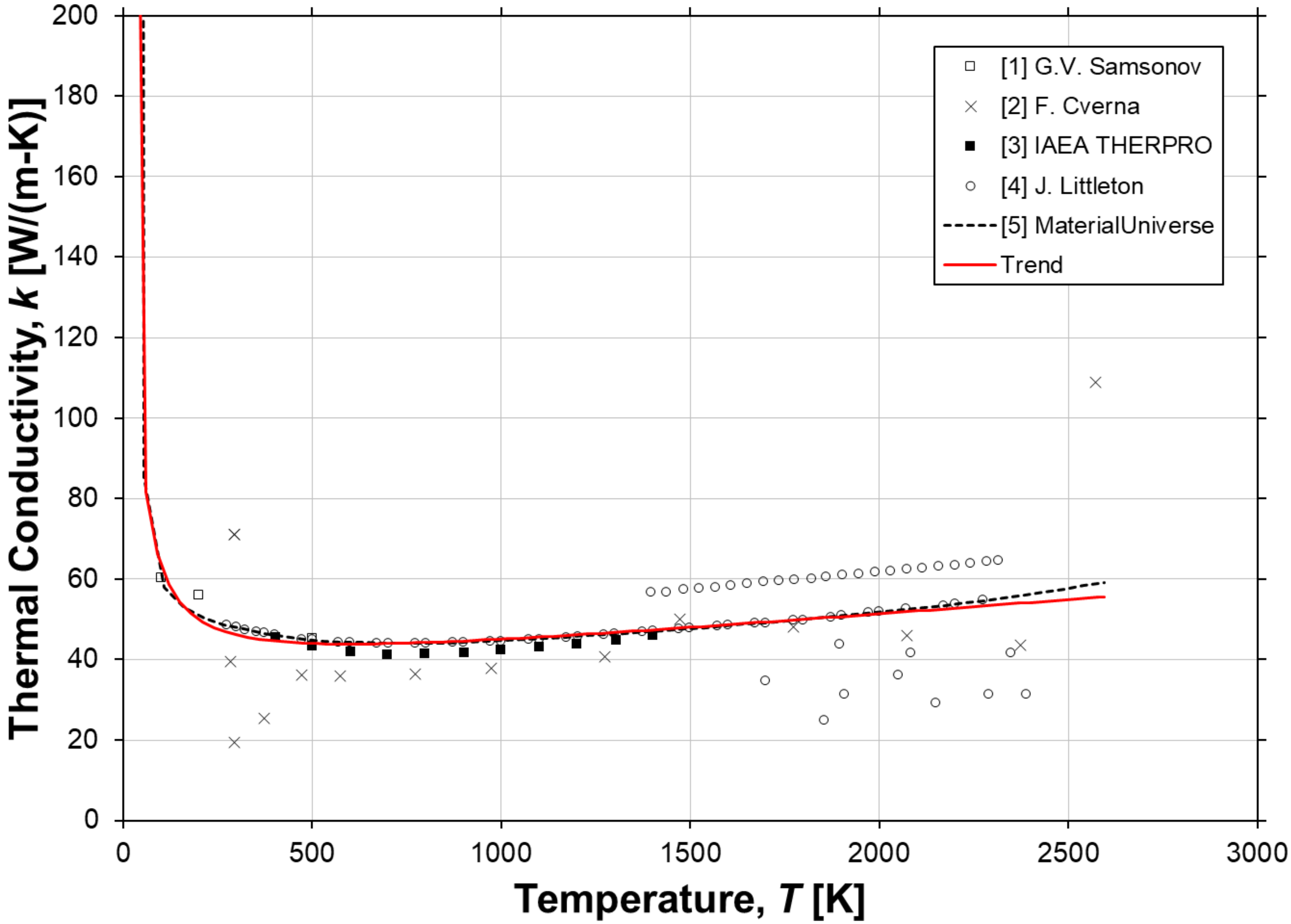

Figure 3.3.1-2: Thermal conductivity versus temperature for rhenium.

100% Theoretical Density

Temperature (T)		Thermal Conductivity (k)		Temperature (T)		Thermal Conductivity (k)	
K	(°F)	W/(m-K)	((Btu-in)/(ft^2-hr-°F))	K	(°F)	W/(m-K)	((Btu-in)/(ft^2-hr-°F))
3	(-454.3)	883.92	(6132.76)	1200	(1700.3)	46.18	(320.42)
100	(-279.7)	63.17	(438.27)	1300	(1880.3)	46.77	(324.50)
200	(-99.7)	49.99	(346.83)	1400	(2060.3)	47.38	(328.76)
300	(80.3)	46.15	(320.18)	1500	(2240.3)	48.02	(333.15)
400	(260.3)	44.62	(309.60)	1600	(2420.3)	48.67	(337.66)
500	(440.3)	44.02	(305.40)	1700	(2600.3)	49.33	(342.26)
600	(620.3)	43.87	(304.38)	1800	(2780.3)	50.00	(346.93)
700	(800.3)	43.99	(305.17)	1900	(2960.3)	50.69	(351.67)
800	(980.3)	44.26	(307.10)	2000	(3140.3)	51.38	(356.46)
900	(1160.3)	44.65	(309.77)	2200	(3500.3)	52.78	(366.18)
1000	(1340.3)	45.11	(312.97)	2400	(3860.3)	54.20	(376.04)
1100	(1520.3)	45.63	(316.55)	2594	(4209.5)	55.59	(385.71)

Application Notes: Data for thermal conductivity is collected from references [1-5] and fitted with the equation below to approximate property trend with respect to temperature.

Fit Equation:

For temperature range: $3 \leq T < 55$

$$k(T) = \left[A0 \cdot \left(\frac{T}{1000}\right)^{N\_A}\right] \Big/ \left[1 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2\right]$$

For temperature range: $55 \leq T \leq 2594$

$$k(T) = B0 + B1 \cdot \left(\frac{T}{1000}\right) + B\_2 \Big/ \left[\left(\frac{T}{1000}\right)^{N\_B}\right]$$

$k(T) = Thermal\ Conductivity\ [W/(m \cdot K)]$

$T = Temperature\ [K]$

Constants:

T Range [K]:	$3 \leq T < 55$		$55 \leq T \leq 2594$
A0 =	1323	B0 =	34.85
A1 =	-115.8	B1 =	7.609
A2 =	5548	B_2 =	2.65
N_A =	0.1302	N_B =	1.017

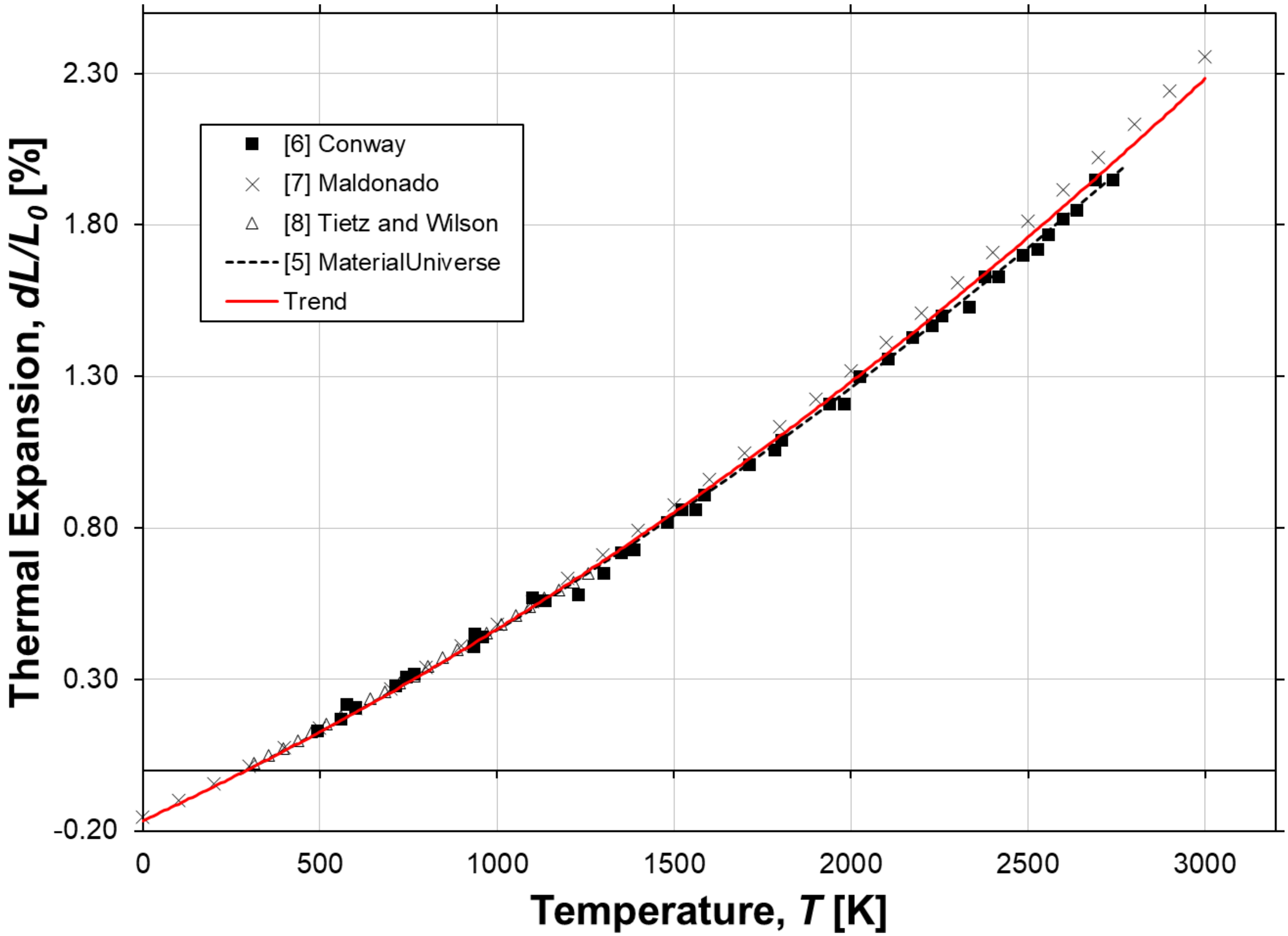

Figure 3.3.1-3: Thermal expansion versus temperature for rhenium.

100% Theoretical Density

Temperature (T) K	Temperature (T) (°F)	Thermal Expansion (dL/L_0) %	Temperature (T) K	Temperature (T) (°F)	Thermal Expansion (dL/L_0) %
100	(-279.7)	-0.111	1600	(2420.3)	0.933
200	(-99.7)	-0.054	1700	(2600.3)	1.018
300	(80.3)	0.004	1800	(2780.3)	1.104
400	(260.3)	0.065	1900	(2960.3)	1.192
500	(440.3)	0.127	2000	(3140.3)	1.282
600	(620.3)	0.191	2100	(3320.3)	1.374
700	(800.3)	0.257	2200	(3500.3)	1.468
800	(980.3)	0.325	2300	(3680.3)	1.563
900	(1160.3)	0.394	2400	(3860.3)	1.660
1000	(1340.3)	0.466	2500	(4040.3)	1.760
1100	(1520.3)	0.539	2600	(4220.3)	1.861
1200	(1700.3)	0.614	2700	(4400.3)	1.964
1300	(1880.3)	0.691	2800	(4580.3)	2.068
1400	(2060.3)	0.770	2900	(4760.3)	2.175
1500	(2240.3)	0.851	3000	(4940.3)	2.283

Application Notes: Data for thermal expansion is collected from references [5-8] and fitted with the equation below to approximate property trend with respect to temperature. Due to the limited data at low and extremely high temperatures, the trend provided is only recommended for use between 300 and 2700 K.

Fit Equation:

$$dL/L_0\,(T) = A0 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2$$

$dL/L_0\,(T) = Thermal\ Expansion\ [\%]$

$T = Temperature\ [K]$

Constants:

T Range [K]: $0 \leq T \leq 3000$ (recommended: $300 \leq T \leq 2700$)

A0 = -0.1659

A1 = 0.5392

A2 = 0.0924

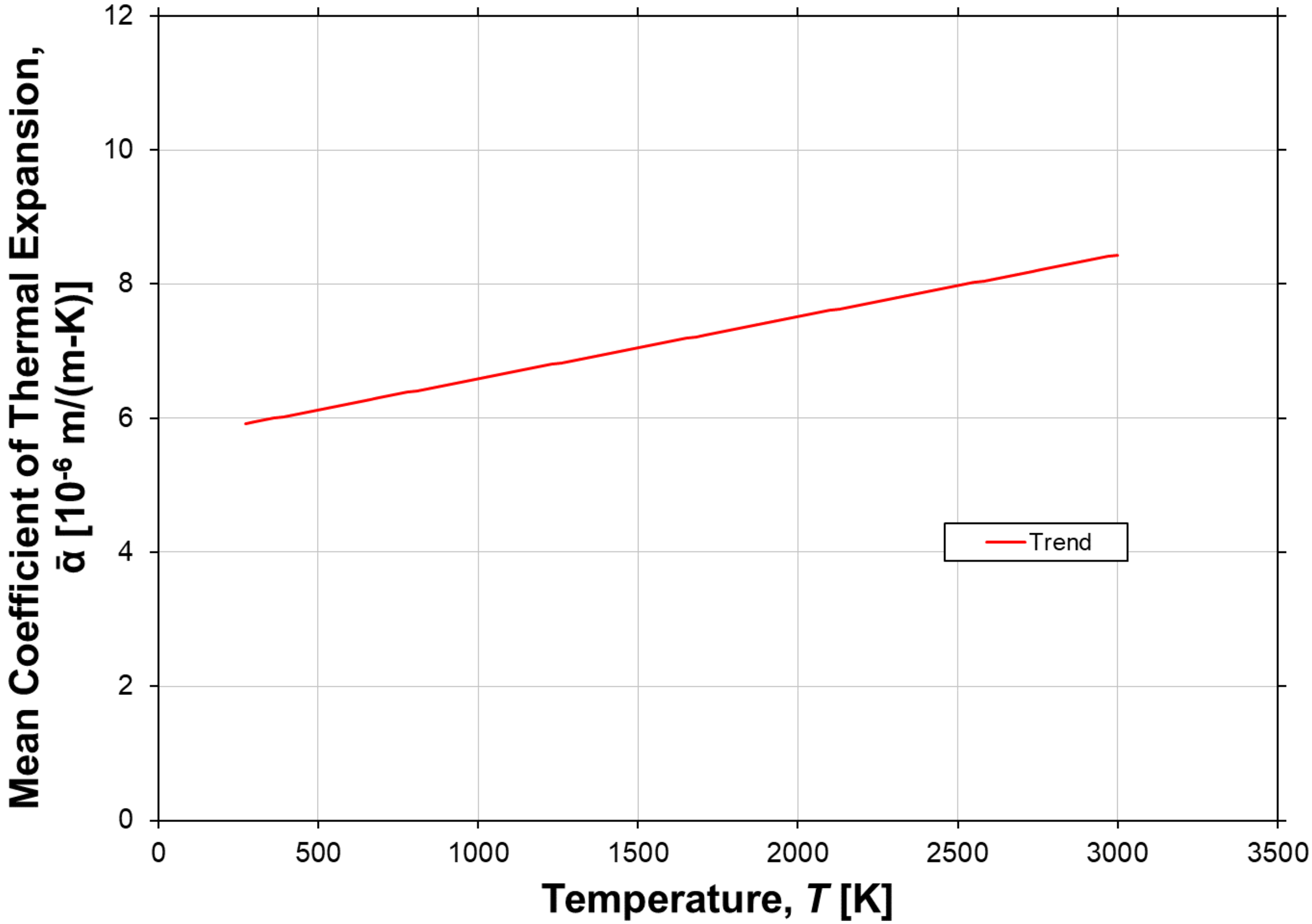

Figure 3.3.1-4: Mean coefficient of thermal expansion versus temperature for rhenium, as calculated from fitted thermal expansion trend.

100% Theoretical Density

Temperature (T)		Mean CTE (ᾱ)		Temperature (T)		Mean CTE (ᾱ)	
K	(°F)	μm/(m-K)	(μin/(in-°F))	K	(°F)	μm/(m-K)	(μin/(in-°F))
273	(31.7)	5.915	(3.286)	1600	(2420.3)	7.142	(3.968)
300	(80.3)	5.940	(3.300)	1700	(2600.3)	7.234	(4.019)
350	(170.3)	5.986	(3.326)	1800	(2780.3)	7.326	(4.070)
400	(260.3)	6.033	(3.351)	1900	(2960.3)	7.419	(4.122)
500	(440.3)	6.125	(3.403)	2000	(3140.3)	7.511	(4.173)
600	(620.3)	6.217	(3.454)	2100	(3320.3)	7.604	(4.224)
700	(800.3)	6.310	(3.505)	2200	(3500.3)	7.696	(4.276)
800	(980.3)	6.402	(3.557)	2300	(3680.3)	7.788	(4.327)
900	(1160.3)	6.495	(3.608)	2400	(3860.3)	7.881	(4.378)
1000	(1340.3)	6.587	(3.660)	2500	(4040.3)	7.973	(4.430)
1100	(1520.3)	6.680	(3.711)	2600	(4220.3)	8.066	(4.481)
1200	(1700.3)	6.772	(3.762)	2700	(4400.3)	8.158	(4.532)
1300	(1880.3)	6.864	(3.814)	2800	(4580.3)	8.250	(4.584)
1400	(2060.3)	6.957	(3.865)	2900	(4760.3)	8.343	(4.635)
1500	(2240.3)	7.049	(3.916)	3000	(4940.3)	8.435	(4.686)

Application Notes: Trend for mean coefficient of thermal expansion is calculated from thermal expansion and shown in the equation below to approximate property trend with respect to temperature. For reasons discussed in the thermal expansion section, the trend provided is only recommended for use between 300 and 2700 K.

Fit Equation:

$$\bar{\alpha}(T) = A0 + A1 \cdot \left(\frac{T}{1000}\right)$$

$\bar{\alpha}(T) = Coefficient\ of\ Thermal\ Expansion\ [\mu m/(m \cdot K)]$

$T = Temperature\ [K]$

Constants:

T Range [K]: $273 \leq T \leq 3000$ (recommended: $300 \leq T \leq 2700$)

A0 = 5.663

A1 = 0.9241

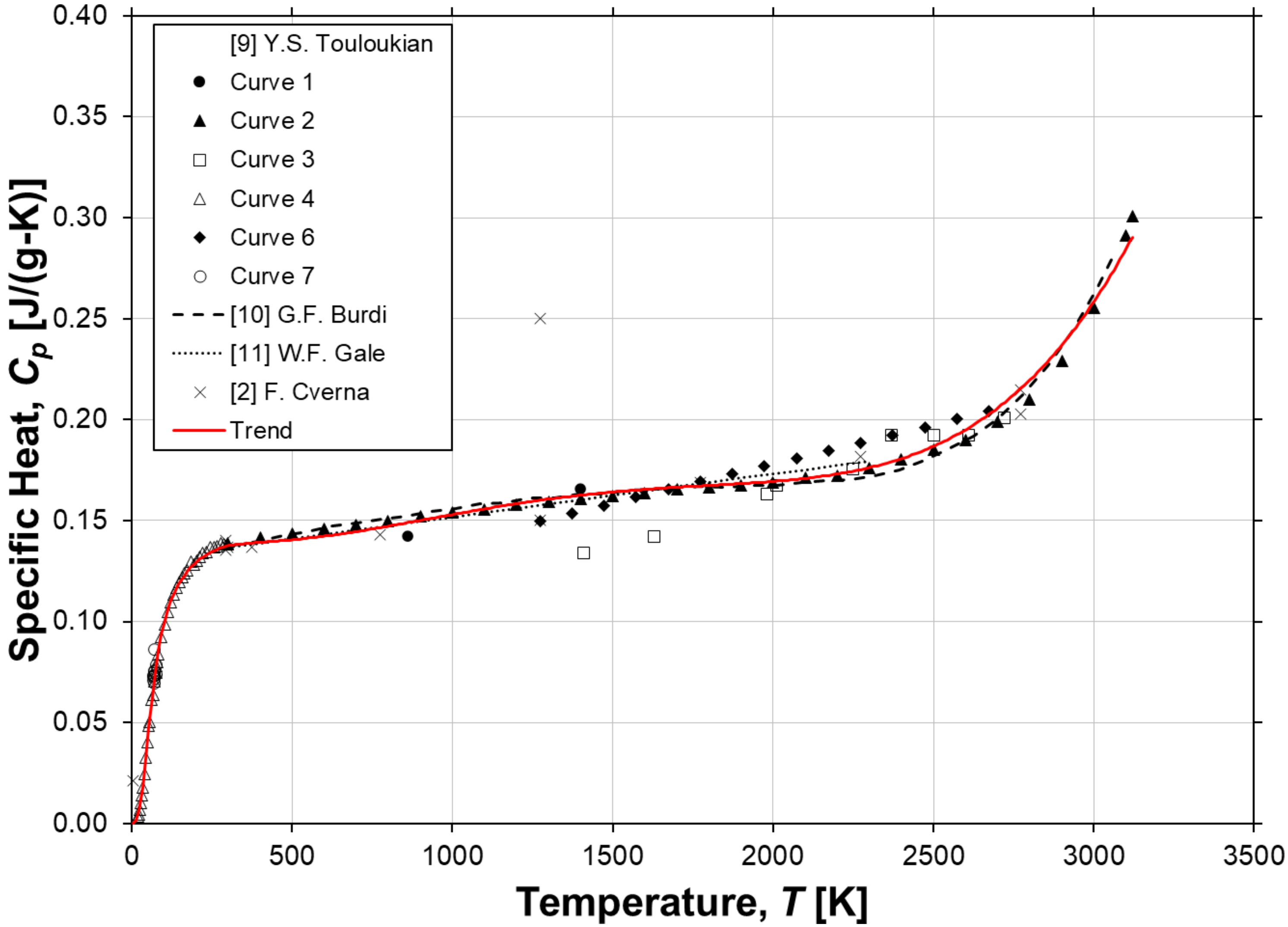

Figure 3.3.1-5: Specific heat versus temperature for rhenium.

100% Theoretical Density

Temperature (T)		Specific Heat (C_p)		Temperature (T)		Specific Heat (C_p)	
K	(°F)	J/(g-K)	(BTU/(lb-°F))	K	(°F)	J/(g-K)	(BTU/(lb-°F))
3	(-454.3)	0.000	(0.000)	1500	(2240.3)	0.164	(0.039)
100	(-279.7)	0.099	(0.024)	1600	(2420.3)	0.165	(0.040)
200	(-99.7)	0.129	(0.031)	1700	(2600.3)	0.166	(0.040)
300	(80.3)	0.138	(0.033)	1800	(2780.3)	0.167	(0.040)
400	(260.3)	0.139	(0.033)	1900	(2960.3)	0.168	(0.040)
500	(440.3)	0.141	(0.034)	2000	(3140.3)	0.169	(0.040)
600	(620.3)	0.142	(0.034)	2100	(3320.3)	0.171	(0.041)
700	(800.3)	0.145	(0.035)	2200	(3500.3)	0.173	(0.041)
800	(980.3)	0.147	(0.035)	2300	(3680.3)	0.176	(0.042)
900	(1160.3)	0.150	(0.036)	2400	(3860.3)	0.181	(0.043)
1000	(1340.3)	0.153	(0.037)	2500	(4040.3)	0.187	(0.045)
1100	(1520.3)	0.156	(0.037)	2600	(4220.3)	0.195	(0.047)
1200	(1700.3)	0.158	(0.038)	2800	(4580.3)	0.219	(0.052)

Application Notes: Data for specific heat is collected from references [2, 9-11] and fitted with the equation below to approximate property trend with respect to temperature.

Fit Equation:

For temperature range: $3 \leq T < 293$

$$C_P(T) = \left[A0 \cdot \left(\frac{T}{1000}\right)^N\right] \Big/ \left[1 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2 + A3 \cdot \left(\frac{T}{1000}\right)^3\right]$$

For temperature range: $293 \leq T \leq 3120$

$$C_P(T) = B0 + B1 \cdot \left(\frac{T}{1000}\right) + B2 \cdot \left(\frac{T}{1000}\right)^2 + B3 \cdot \left(\frac{T}{1000}\right)^3 + B4 \cdot \left(\frac{T}{1000}\right)^4 + B\_2 \Big/ \left(\frac{T}{1000}\right)^2$$

$C_P(T) = Specific\ Heat\ [J/(g \cdot K)]$

$T = Temperature\ [K]$

Constants:

T Range [K]:	$3 \leq T < 293$		$293 \leq T \leq 3120$
N =	2.816	B0 =	0.1626
A0 =	255.2	B1 =	-0.101
A1 =	-10.71	B2 =	0.1637
A2 =	244.5	B3 =	-0.08759
A3 =	1576	B4 =	0.01593
		B_2 =	-6.397E-4

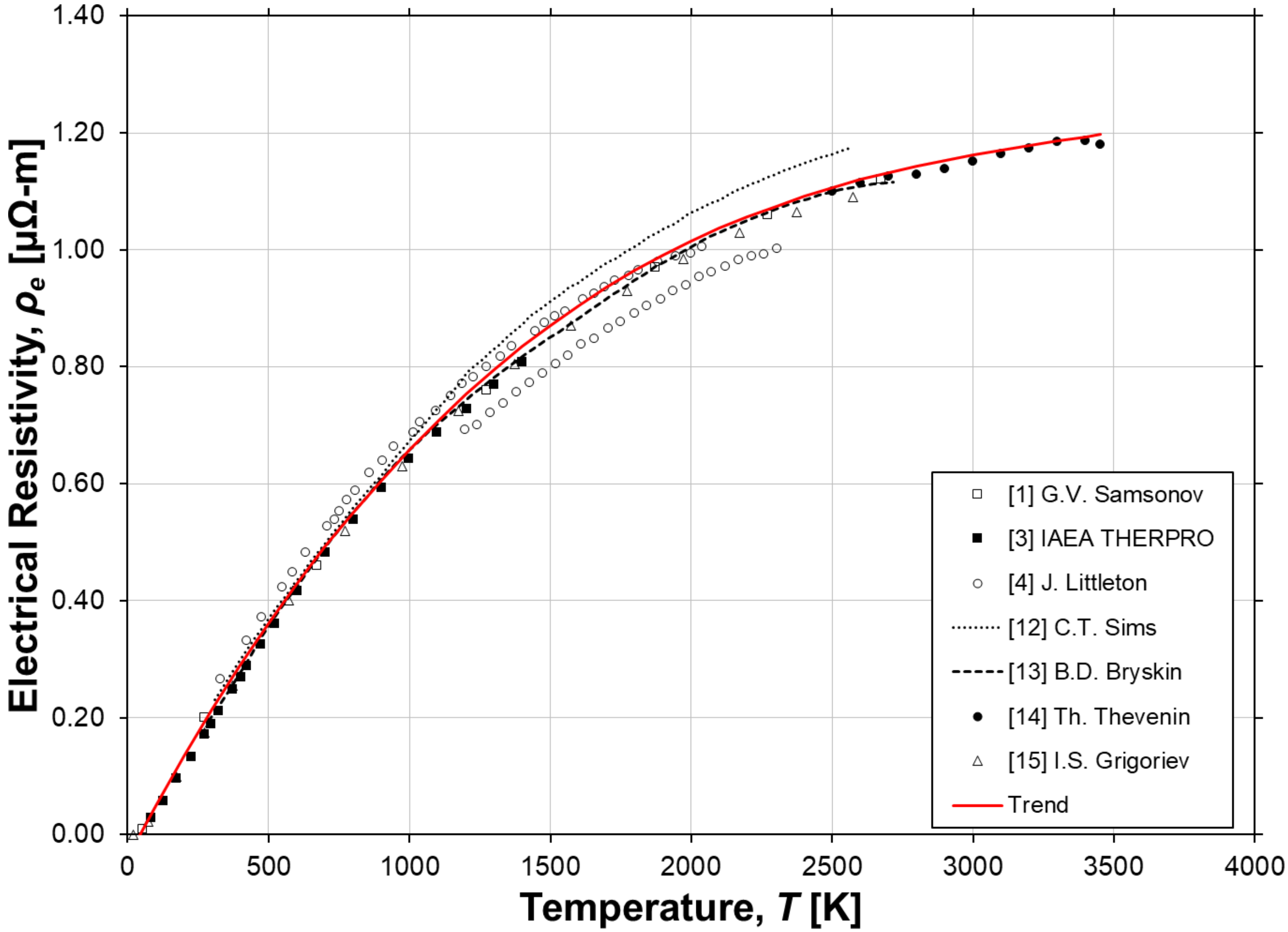

Figure 3.3.1-6: Electrical resistivity versus temperature for rhenium.

Electrical Resistivity with Temperature

100% Theoretical Density

Temperature (T) K	(°F)	Electrical Resistivity (ρ_e) µΩ-m	(µΩ-in)	Temperature (T) K	(°F)	Electrical Resistivity (ρ_e) µΩ-m	(µΩ-in)
100	(-279.7)	0.050	(1.966)	1600	(2420.3)	0.905	(35.630)
200	(-99.7)	0.134	(5.289)	1700	(2600.3)	0.936	(36.853)
300	(80.3)	0.214	(8.434)	1800	(2780.3)	0.965	(37.978)
400	(260.3)	0.290	(11.408)	1900	(2960.3)	0.991	(39.011)
500	(440.3)	0.361	(14.215)	2000	(3140.3)	1.015	(39.956)
600	(620.3)	0.428	(16.862)	2100	(3320.3)	1.037	(40.820)
700	(800.3)	0.492	(19.353)	2200	(3500.3)	1.057	(41.607)
800	(980.3)	0.551	(21.693)	2300	(3680.3)	1.075	(42.322)
900	(1160.3)	0.607	(23.888)	2400	(3860.3)	1.091	(42.972)
1000	(1340.3)	0.659	(25.943)	2600	(4220.3)	1.120	(44.093)
1100	(1520.3)	0.708	(27.863)	2800	(4580.3)	1.143	(45.013)
1200	(1700.3)	0.753	(29.654)	3000	(4940.3)	1.163	(45.774)
1300	(1880.3)	0.796	(31.321)	3200	(5300.3)	1.179	(46.418)
1400	(2060.3)	0.835	(32.869)	3400	(5660.3)	1.193	(46.988)
1500	(2240.3)	0.871	(34.303)	3453	(5755.7)	1.197	(47.132)

Application Notes: Data for electrical resistivity is collected from references [1, 3, 4, 12-15] and fitted with the equation below to approximate property trend with respect to temperature.

Fit Equation:

$$\rho_e(T) = A0 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2 + A3 \cdot \left(\frac{T}{1000}\right)^3$$

$\rho_e(T) = Electrical\ Resistivity\ [\mu\Omega \cdot m]$

$T = Temperature\ [K]$

Constants:

T Range [K]: $20 \leq T < 3453$

A0 =	-0.03907
A1 =	0.9137
A2 =	-0.238
A3 =	0.02232

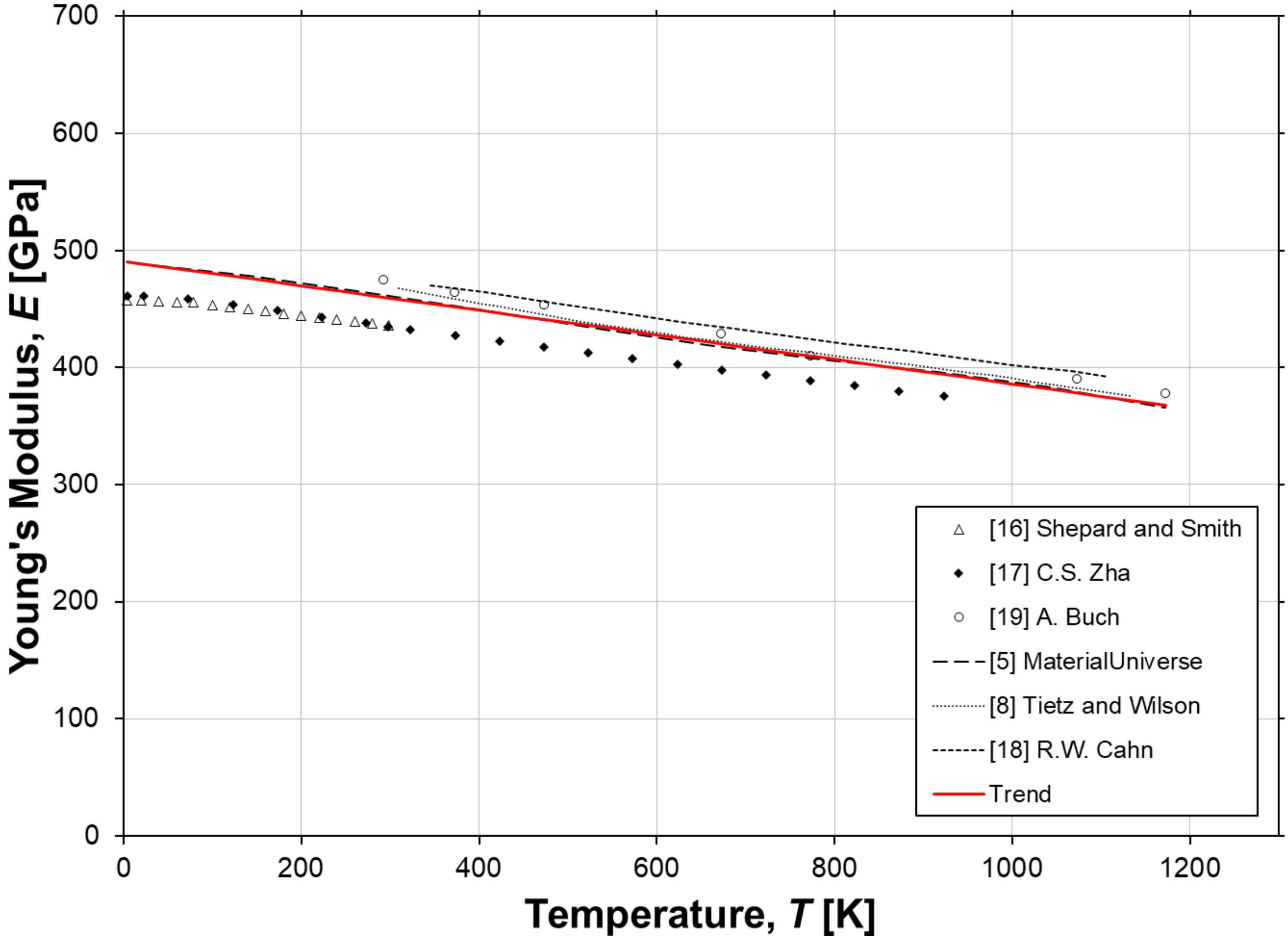

Figure 3.3.1-7: Young's modulus versus temperature for rhenium.

Young's Modulus with Temperature

100% Theoretical Density

Temperature (T)		Young's Modulus (E)		Temperature (T)		Young's Modulus (E)	
K	(°F)	GPa	(Msi)	K	(°F)	GPa	(Msi)
4	(-452.5)	490.48	(71.17)	700	(800.3)	417.47	(60.57)
50	(-369.7)	485.66	(70.47)	750	(890.3)	412.23	(59.81)
100	(-279.7)	480.41	(69.71)	800	(980.3)	406.98	(59.05)
150	(-189.7)	475.17	(68.95)	850	(1070.3)	401.74	(58.29)
200	(-99.7)	469.92	(68.19)	900	(1160.3)	396.49	(57.53)
250	(-9.7)	464.68	(67.42)	950	(1250.3)	391.25	(56.77)
293	(67.7)	460.16	(66.77)	1000	(1340.3)	386.00	(56.01)
300	(80.3)	459.43	(66.66)	1050	(1430.3)	380.76	(55.25)
350	(170.3)	454.19	(65.90)	1100	(1520.3)	375.51	(54.49)
400	(260.3)	448.94	(65.14)	1150	(1610.3)	370.27	(53.73)
450	(350.3)	443.70	(64.38)	1173	(1651.7)	367.85	(53.38)
500	(440.3)	438.45	(63.62)				
550	(530.3)	433.21	(62.86)				
600	(620.3)	427.96	(62.10)				
650	(710.3)	422.72	(61.34)				

Application Notes: Data for Young's modulus is collected from references [5, 8, 16-19] and fitted with the equation below to approximate the property trend with respect to temperature. Note that the polycrystalline values displayed in the figure above for [16] and [17] were calculated from single crystal data using an average of Voigt and Reuss methods.

Fit Equations:

$$E(T) = A0 + A1 \cdot \left(\frac{T}{1000}\right)$$

$E(T) = Young's\ Modulus\ [GPa]$

$T = Temperature\ [K]$

Constants:

T Range [K]: $4 \leq T \leq 1173$

A0 = 490.9

A1 = -104.9

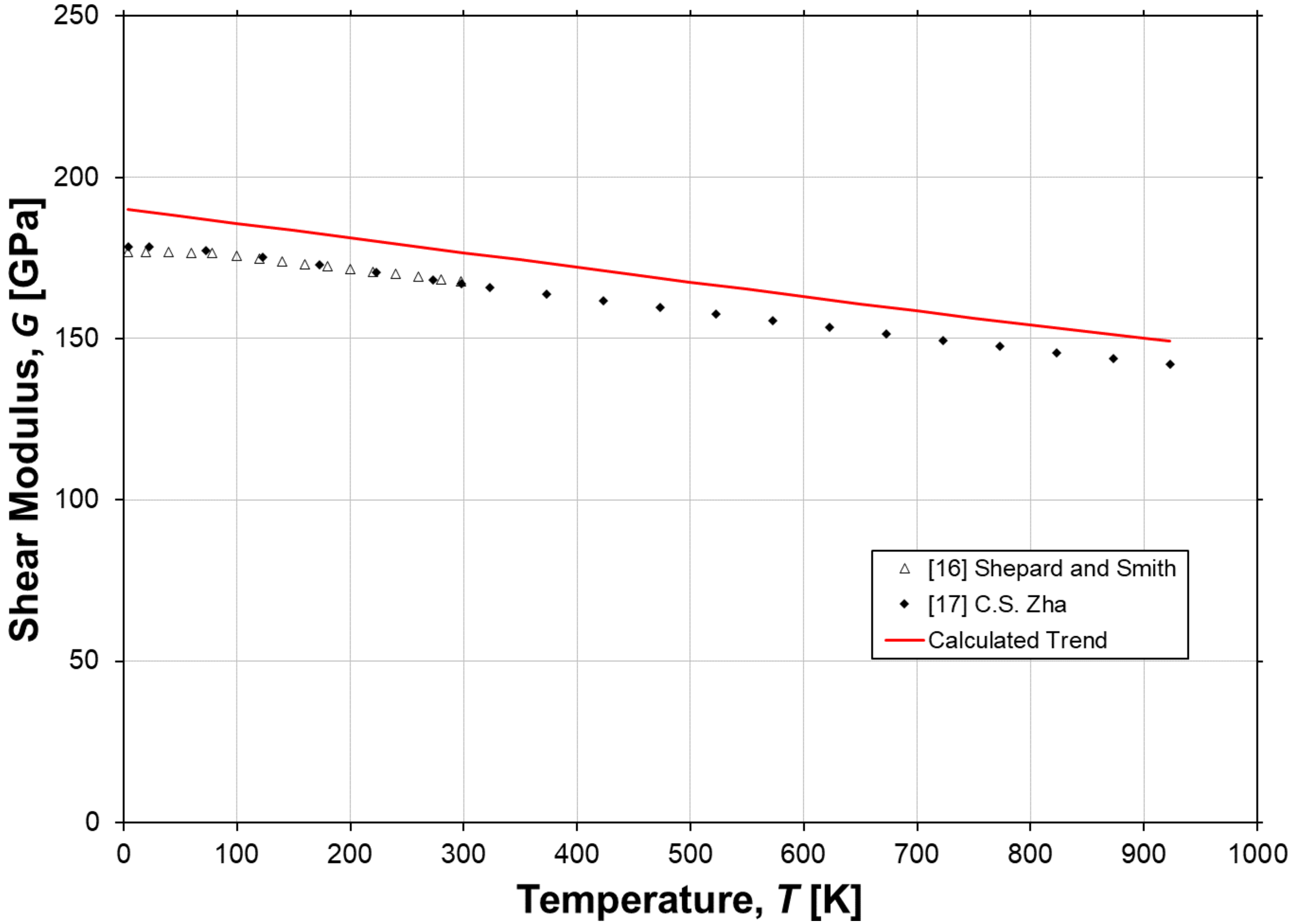

Figure 3.3.1-8: Shear modulus versus temperature for rhenium. Shear modulus is calculated from the Young’s modulus and Poisson’s ratio trends.

100% Theoretical Density

Temperature (T)		Shear Modulus (G)		Temperature (T)		Shear Modulus (G)	
K	(°F)	GPa	(Msi)	K	(°F)	GPa	(Msi)
4	(-452.5)	189.93	(27.56)	420	(296.3)	171.19	(24.84)
30	(-405.7)	188.79	(27.39)	450	(350.3)	169.82	(24.64)
60	(-351.7)	187.48	(27.20)	480	(404.3)	168.45	(24.44)
90	(-297.7)	186.15	(27.01)	510	(458.3)	167.09	(24.24)
120	(-243.7)	184.81	(26.82)	540	(512.3)	165.73	(24.05)
150	(-189.7)	183.47	(26.62)	570	(566.3)	164.38	(23.85)
180	(-135.7)	182.12	(26.43)	600	(620.3)	163.03	(23.66)
210	(-81.7)	180.77	(26.23)	630	(674.3)	161.69	(23.46)
240	(-27.7)	179.41	(26.03)	660	(728.3)	160.35	(23.27)
270	(26.3)	178.04	(25.83)	700	(800.3)	158.59	(23.01)
293	(67.7)	176.99	(25.68)	750	(890.3)	156.41	(22.70)
300	(80.3)	176.67	(25.64)	800	(980.3)	154.26	(22.38)
330	(134.3)	175.30	(25.44)	850	(1070.3)	152.15	(22.08)
360	(188.3)	173.93	(25.24)	900	(1160.3)	150.08	(21.78)
390	(242.3)	172.56	(25.04)	923	(1201.7)	149.14	(21.64)

Application Notes: Data for shear modulus with respect to temperature is collected from references [16, 17]. The shear modulus trend was first calculated from the Young's modulus and Poisson's ratio trends. An equivalent equation was developed and listed below for readers' convenience. Note that the polycrystalline values displayed in the figure above for [16] and [17] were calculated from single crystal data using an average of Voigt and Reuss methods.

Fit Equations:

$$G(T) = A0 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2 + A3 \cdot \left(\frac{T}{1000}\right)^3$$

$G(T) = Shear\ Modulus\ [GPa]$

$T = Temperature\ [K]$

Constants:

T Range [K]:	$4 \leq T \leq 923$
A0 =	190.1
A1 =	-43.38
A2 =	-6.272
A3 =	5.625

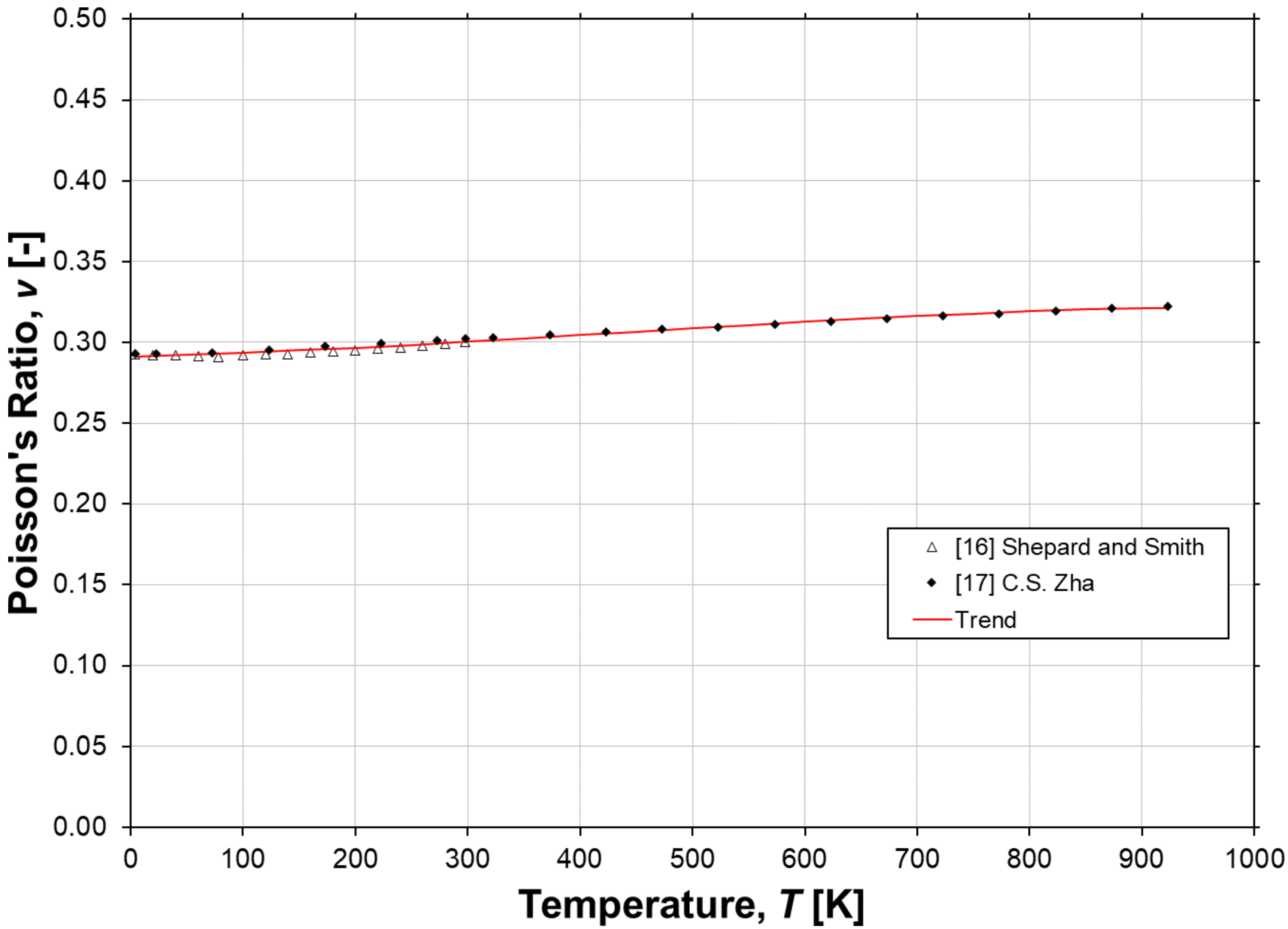

Figure 3.3.1-9: Poisson's ratio versus temperature for rhenium.

100% Theoretical Density

Temperature (T) K	(°F)	Poisson's Ratio (ν)	Temperature (T) K	(°F)	Poisson's Ratio (ν)
4	(-452.5)	0.291	420	(296.3)	0.305
30	(-405.7)	0.292	450	(350.3)	0.307
60	(-351.7)	0.293	480	(404.3)	0.308
90	(-297.7)	0.293	510	(458.3)	0.309
120	(-243.7)	0.294	540	(512.3)	0.310
150	(-189.7)	0.295	570	(566.3)	0.312
180	(-135.7)	0.296	600	(620.3)	0.313
210	(-81.7)	0.297	630	(674.3)	0.314
240	(-27.7)	0.298	660	(728.3)	0.315
270	(26.3)	0.299	700	(800.3)	0.316
293	(67.7)	0.300	750	(890.3)	0.318
300	(80.3)	0.300	800	(980.3)	0.319
330	(134.3)	0.302	850	(1070.3)	0.320
360	(188.3)	0.303	900	(1160.3)	0.321
390	(242.3)	0.304	923	(1201.7)	0.321

Application Notes: Data for Poisson's ratio is collected from references [16, 17] and fitted with the equation below to approximate the property trend with respect to temperature. Note that the polycrystalline values displayed in the figure above for [16] and [17] were calculated from single crystal data using an average of Voigt and Reuss methods.

Fit Equations:

$$\nu(T) = A0 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2 + A3 \cdot \left(\frac{T}{1000}\right)^3$$

$\nu(T) = Poisson's\ Ratio$

$T = Temperature\ [K]$

Constants:

T Range [K]:	$4 \leq T \leq 923$
A0 =	0.2914
A1 =	0.01628
A2 =	0.05884
A3 =	-0.04469

Temp. (T) K	Physical and Electrical		Thermal				Elastic		
	Density (ρ) kg/m³	Electrical Resistivity (ρ_e) μΩ-m	Thermal Conductivity (k) W/(m-K)	Thermal Expansion (dL/L_0) %	Mean CTE ($\bar{\alpha}$) 10^{-6}/K	Specific Heat (C_p) J/(g-K)	Young's Modulus (E) GPa	Shear Modulus (G) GPa	Poisson's Ratio (ν)
100	21110	0.050	63.17	-0.111	-	0.099	480	186	0.294
200	21074	0.134	49.99	-0.054	-	0.129	470	181	0.297
300	21037	0.214	46.15	0.004	5.94	0.138	459	177	0.300
400	20999	0.290	44.62	0.065	6.03	0.139	449	172	0.304
500	20960	0.361	44.02	0.127	6.13	0.141	438	168	0.309
600	20920	0.428	43.87	0.191	6.22	0.142	428	163	0.313
700	20879	0.492	43.99	0.257	6.31	0.145	417	159	0.316
800	20836	0.551	44.26	0.325	6.40	0.147	407	154	0.319
900	20793	0.607	44.65	0.394	6.49	0.150	396	150	0.321
1000	20749	0.659	45.11	0.466	6.59	0.153	386	-	-
1100	20703	0.708	45.63	0.539	6.68	0.156	376	-	-
1200	20657	0.753	46.18	0.614	6.77	0.158	-	-	-
1300	20610	0.796	46.77	0.691	6.86	0.161	-	-	-
1400	20561	0.835	47.38	0.770	6.96	0.163	-	-	-
1500	20512	0.871	48.02	0.851	7.05	0.164	-	-	-
1600	20462	0.905	48.67	0.933	7.14	0.165	-	-	-
1800	20358	0.965	50.00	1.104	7.33	0.167	-	-	-
2000	20251	1.015	51.38	1.282	7.51	0.169	-	-	-
2200	20140	1.057	52.78	1.468	7.70	0.173	-	-	-
2400	20026	1.091	54.20	1.660	7.88	0.181	-	-	-
2600	19908	1.120	-	1.861	8.07	0.195	-	-	-
2800	19787	1.143	-	2.068	8.25	0.219	-	-	-
3000	19662	1.163	-	2.283	8.44	0.258	-	-	-
3200	-	1.179	-	-	-	-	-	-	-
3400	-	1.193	-	-	-	-	-	-	-

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4 Other Nonferrous Metals and Alloys

4.1 Copper Alloys

Room Temperature Properties

Theoretical Density, [kg/m^3]	8,620
Specific Heat, [J/(g-K)]	0.382
Thermal Conductivity, [W/(m-K)]	284.6
Linear expansion coefficient, [µm/(m-K)]	14.72
Electrical resistivity, [µΩ-m]	0.025

Composition

Table 4.1.1-1: Typical Composition ranges for GRCop84 alloy (percent by weight).

Grade		Cr	Nb	O	Fe	Other	Cu
GRCop84	Min.	6.53	5.64				Balance
	Max.	6.72	5.82	600 ppm	20 ppm	50 ppm	

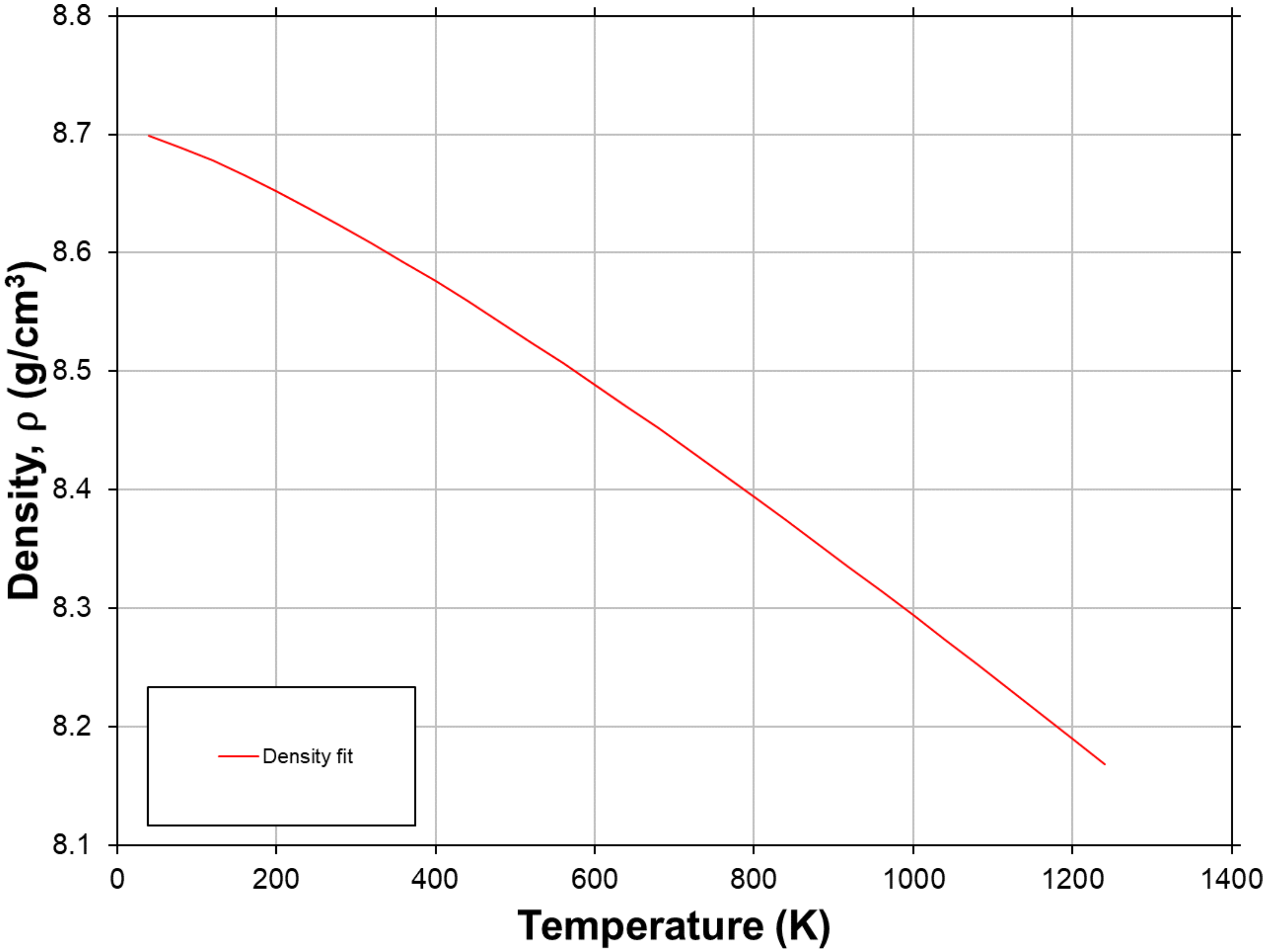

Figure 4.1.1-1: Density versus Temperature for GRCop84. Calculated from fitted trend of Thermal Expansion data.

100% Theoretical Density

Temperature (T)		Density (ρ)		Temperature (T)		Density (ρ)	
K	(°F)	kg/m^3	(lb/ft^3)	K	(°F)	kg/m^3	(lb/ft^3)
70	(-333.7)	8692	(542.6)	750	(890.3)	8418	(525.6)
100	(-279.7)	8684	(542.1)	800	(980.3)	8394	(524.0)
150	(-189.7)	8669	(541.2)	850	(1070.3)	8370	(522.5)
200	(-99.7)	8652	(540.1)	900	(1160.3)	8345	(521.0)
250	(-9.7)	8634	(539.0)	950	(1250.3)	8319	(519.4)
293	(67.7)	8618	(538.0)	1000	(1340.3)	8294	(517.8)
300	(80.3)	8616	(537.9)	1050	(1430.3)	8268	(516.2)
350	(170.3)	8596	(536.7)	1100	(1520.3)	8242	(514.6)
400	(260.3)	8576	(535.4)	1150	(1610.3)	8216	(512.9)
450	(350.3)	8555	(534.1)	1200	(1700.3)	8190	(511.3)
500	(440.3)	8533	(532.7)	1250	(1790.3)	8163	(509.6)
550	(530.3)	8511	(531.4)	1273	(1831.7)	8151	(508.9)
600	(620.3)	8489	(530.0)				
650	(710.3)	8466	(528.5)				
700	(800.3)	8442	(527.0)				

Application Notes: Density trend with respect to temperature is calculated as a function of thermal expansion as seen in the equation below.

Density Calculation:

$\rho(T) = \rho_{RT}/(1 + dL/L_0(T)/100)^3$

$\rho(T) = Density\ [kg/m^3]$

$Room\ Temperature\ Density\ (\rho_{RT}) = 8{,}620\ [kg/m^3]$

$T = Temperature\ [K]$

Temperature Range: $70 \leq T \leq 1273$

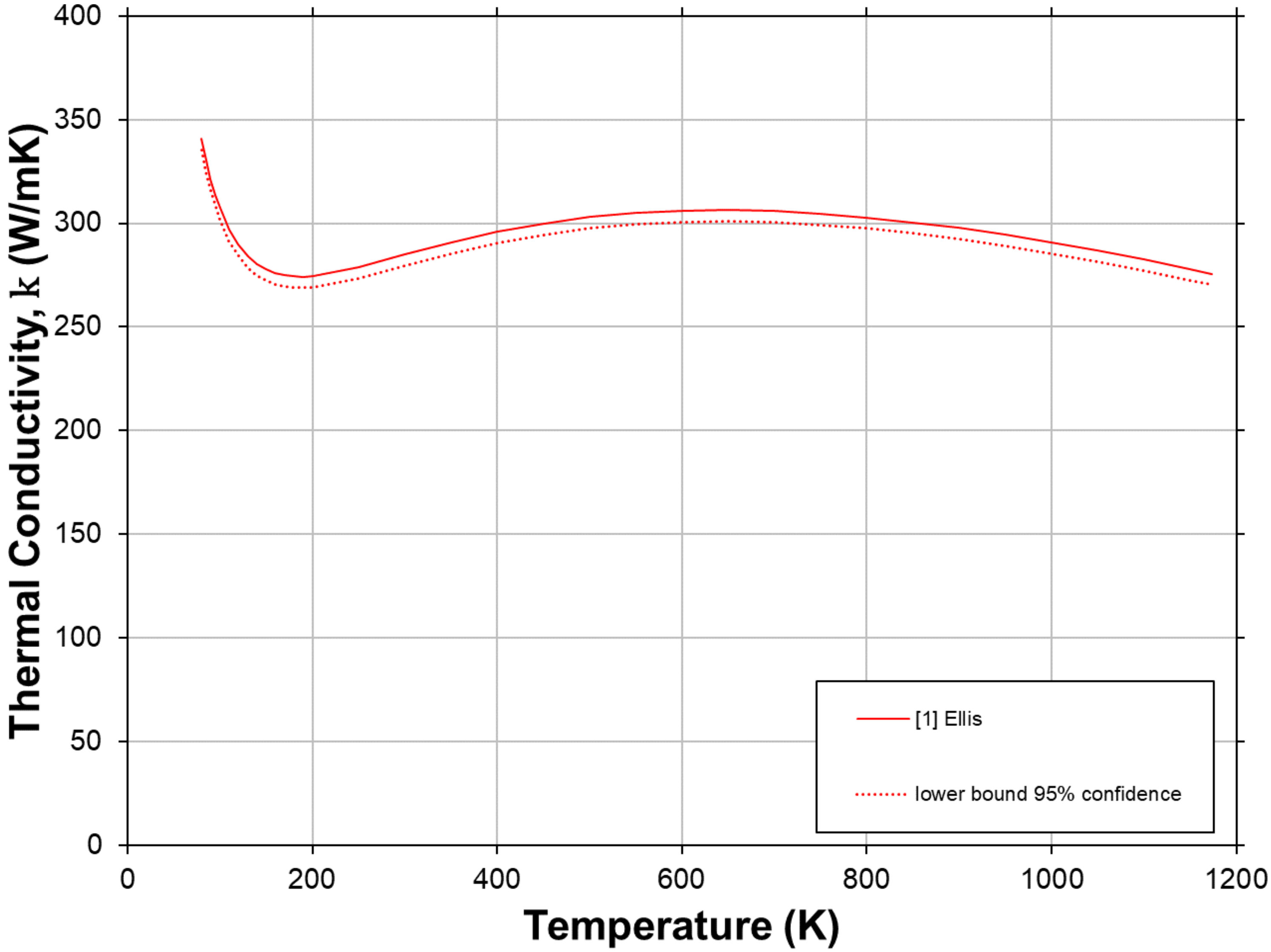

Figure 4.1.1-2: Thermal Conductivity versus Temperature of GRCop84 adapted from Ellis (2000).

100% Theoretical Density

Temperature (T)		Thermal Conductivity (k)		Temperature (T)		Thermal Conductivity (k)	
K	(°F)	W/(m-K)	((Btu·in)/(ft²·hr·°F))	K	(°F)	W/(m-K)	((Btu·in)/(ft²·hr·°F))
80	(-315.7)	340.53	(2362.67)	450	(350.3)	299.88	(2080.61)
100	(-279.7)	307.26	(2131.78)	475	(395.3)	301.52	(2091.99)
125	(-234.7)	286.65	(1988.84)	500	(440.3)	302.90	(2101.58)
150	(-189.7)	277.64	(1926.32)	525	(485.3)	304.03	(2109.42)
175	(-144.7)	274.52	(1904.64)	550	(530.3)	304.92	(2115.58)
200	(-99.7)	274.53	(1904.69)	575	(575.3)	305.58	(2120.14)
225	(-54.7)	276.21	(1916.38)	600	(620.3)	306.01	(2123.16)
250	(-9.7)	278.77	(1934.11)	625	(665.3)	306.24	(2124.73)
275	(35.3)	281.72	(1954.61)	650	(710.3)	306.27	(2124.92)
300	(80.3)	284.80	(1975.96)	675	(755.3)	306.11	(2123.80)
325	(125.3)	287.83	(1996.97)	700	(800.3)	305.77	(2121.45)
350	(170.3)	290.71	(2016.95)	800	(980.3)	302.80	(2100.89)
375	(215.3)	293.38	(2035.49)	900	(1160.3)	297.66	(2065.22)
400	(260.3)	295.81	(2052.34)	1000	(1340.3)	290.77	(2017.40)
425	(305.3)	297.98	(2067.40)	1173	(1651.7)	275.65	(1912.51)

Application Notes: Trend for thermal conductivity is collected from reference [1] presented in the equation below to approximate a fit of average property trend with respect to temperature.

Fit Equation:

$$k(T) = A0 + A1 \cdot \ln(T) + A2 \cdot [\ln(T)]^2 + A3 \cdot [\ln(T)]^3$$

$$k(T) = Thermal\ Conductivity\ [W\ /\ (m \cdot K)]$$

$$T = Temperature\ [K]$$

Constants:

T Range [K]:	$80 \leq T \leq 1173$
A0 =	6893
A1 =	-3466
A2 =	599.5
A3 =	-34.18

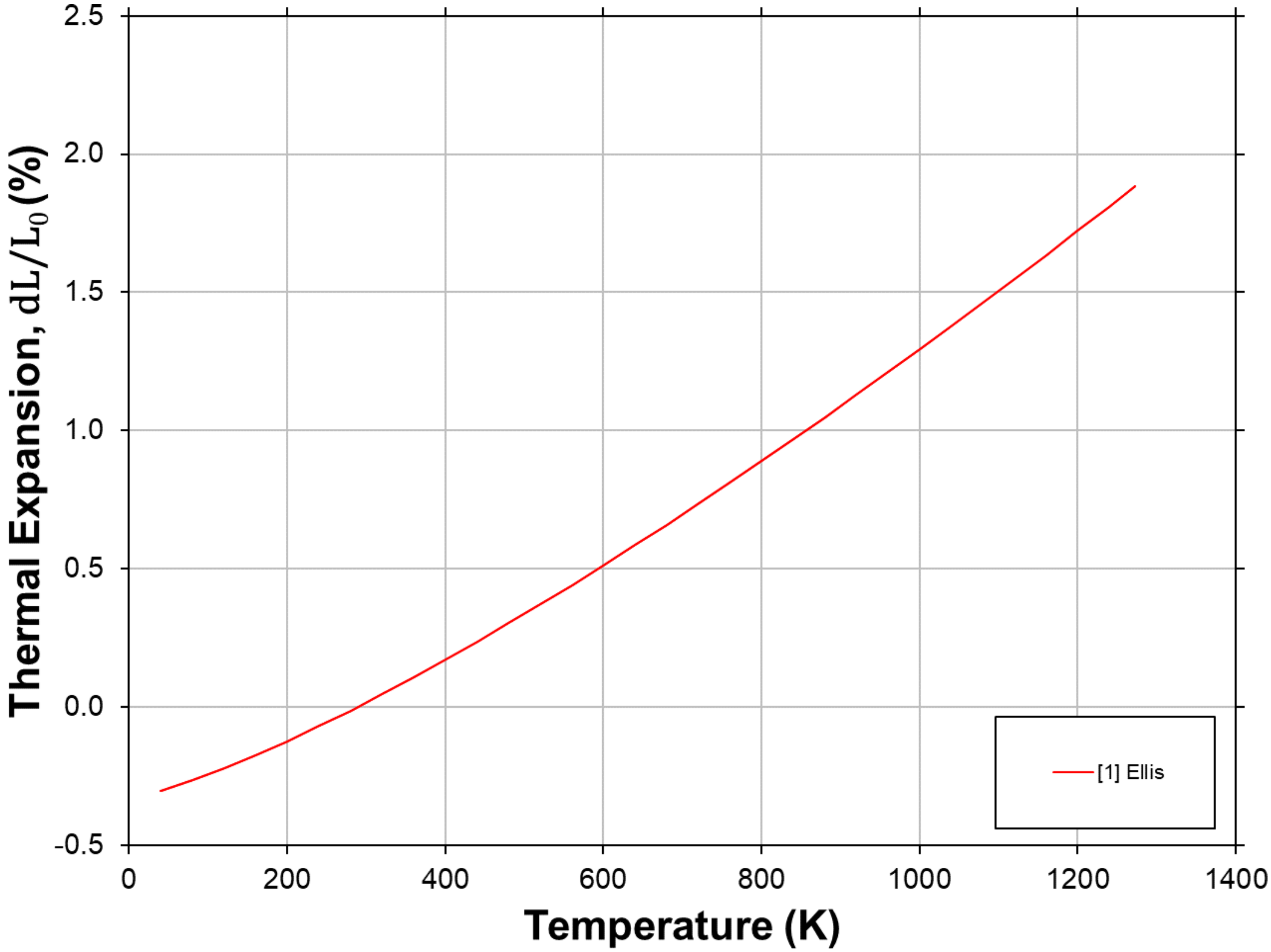

Figure 4.1.1-3: Thermal Expansion versus Temperature of GRCop84 adapted from Ellis (2000).

Thermal Expansion with Temperature

100% Theoretical Density

Temperature (T)		Thermal Expansion (dL/L_0)	Temperature (T)		Thermal Expansion (dL/L_0)
K	(°F)	%	K	(°F)	%
70	(-333.7)	-0.275	450	(350.3)	0.253
100	(-279.7)	-0.245	500	(440.3)	0.337
125	(-234.7)	-0.217	550	(530.3)	0.424
150	(-189.7)	-0.187	600	(620.3)	0.513
175	(-144.7)	-0.156	650	(710.3)	0.604
200	(-99.7)	-0.124	700	(800.3)	0.697
225	(-54.7)	-0.090	750	(890.3)	0.792
250	(-9.7)	-0.056	800	(980.3)	0.889
275	(35.3)	-0.020	850	(1070.3)	0.988
300	(80.3)	0.017	900	(1160.3)	1.088
325	(125.3)	0.054	950	(1250.3)	1.190
350	(170.3)	0.092	1000	(1340.3)	1.293
375	(215.3)	0.131	1100	(1520.3)	1.505
400	(260.3)	0.171	1200	(1700.3)	1.722
425	(305.3)	0.211	1273	(1831.7)	1.883

Application Notes: Trend for thermal expansion is collected from reference [1] and presented in the equation below to approximate property trend with respect to temperature.

Fit Equation:

$$dL/L_0\,(T) = A0 + A1 \cdot T^N$$

$$dL/L_0\,(T) = Thermal\ Expansion\ [\%]$$

$$T = Temperature\ [K]$$

Constants:

T Range [K]:	$70 \leq T \leq 1273$
A0 =	-0.3287
A1 =	2.265E-04
N =	1.285

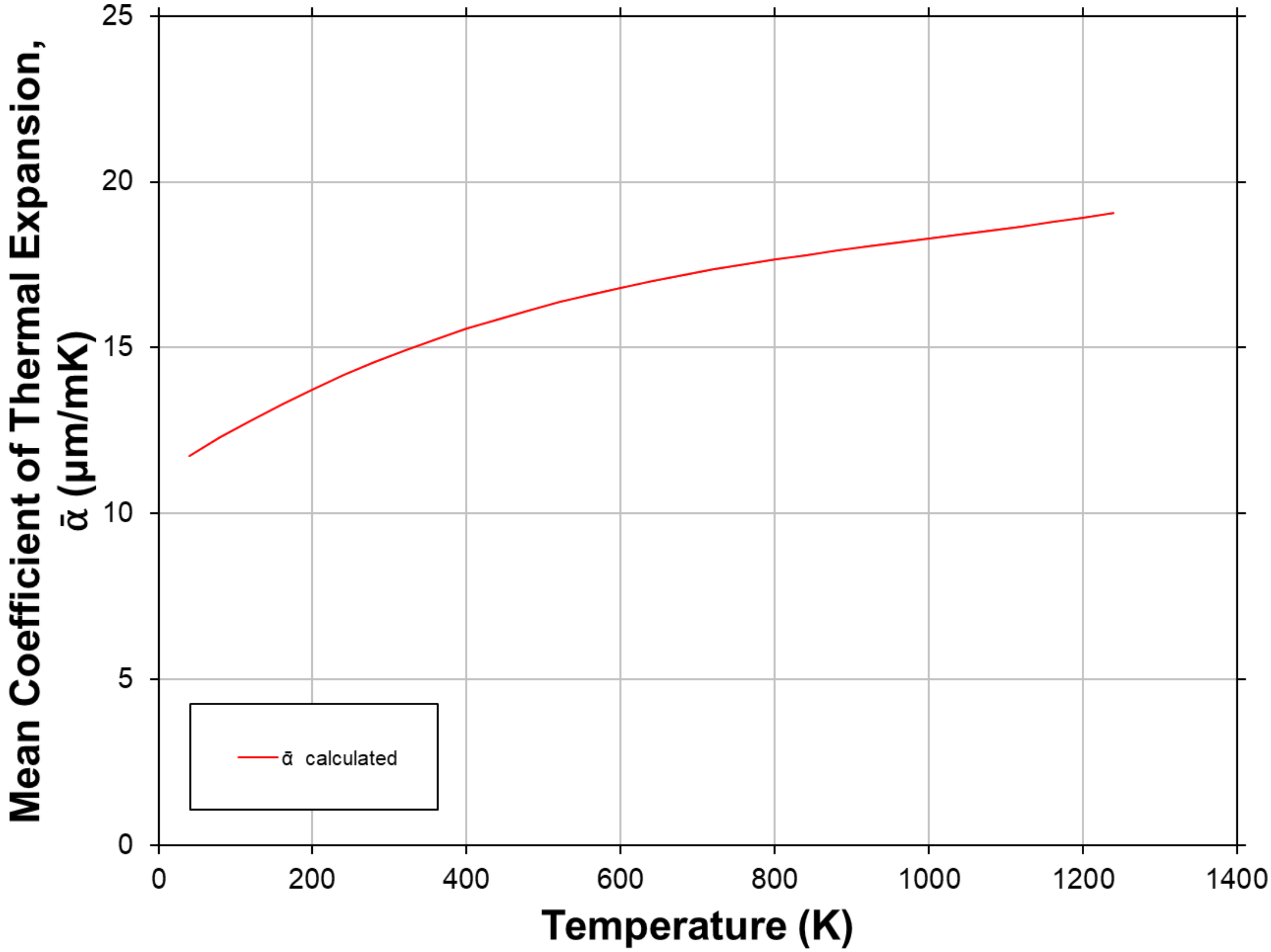

Figure 4.1.1-4: Mean Coefficient of Thermal Expansion versus Temperature of GRCop84. Calculated from fitted trend of the Thermal Expansion data.

100% Theoretical Density

Temperature (T)		Mean CTE (ᾱ)		Temperature (T)		Mean CTE (ᾱ)	
K	(°F)	μm/(m-K)	(μin/(in-°F))	K	(°F)	μm/(m-K)	(μin/(in-°F))
70	(-333.7)	12.151	(6.751)	450	(350.3)	15.928	(8.849)
100	(-279.7)	12.550	(6.972)	500	(440.3)	16.252	(9.029)
125	(-234.7)	12.868	(7.149)	550	(530.3)	16.546	(9.192)
150	(-189.7)	13.172	(7.318)	600	(620.3)	16.811	(9.340)
175	(-144.7)	13.464	(7.480)	650	(710.3)	17.052	(9.474)
200	(-99.7)	13.743	(7.635)	700	(800.3)	17.272	(9.595)
225	(-54.7)	14.010	(7.783)	750	(890.3)	17.472	(9.707)
250	(-9.7)	14.265	(7.925)	800	(980.3)	17.657	(9.809)
275	(35.3)	14.509	(8.060)	850	(1070.3)	17.828	(9.905)
300	(80.3)	14.742	(8.190)	900	(1160.3)	17.990	(9.995)
325	(125.3)	14.964	(8.313)	950	(1250.3)	18.145	(10.081)
350	(170.3)	15.176	(8.431)	1000	(1340.3)	18.296	(10.164)
375	(215.3)	15.378	(8.543)	1100	(1520.3)	18.598	(10.332)
400	(260.3)	15.570	(8.650)	1200	(1700.3)	18.919	(10.511)
425	(305.3)	15.753	(8.752)	1273	(1831.7)	19.180	(10.655)

Application Notes: Trend for mean coefficient of thermal expansion is calculated as a function of thermal expansion and shown in the equation below to approximate property trend with respect to temperature.

Fit Equation:

$$\bar{\alpha}(T) = A0 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2 + A3 \cdot \left(\frac{T}{1000}\right)^3$$

$\bar{\alpha}(T) = Coefficient\ of\ Thermal\ Expansion\ [\mu m/(m \cdot K)]$

$T = Temperature\ [K]$

Constants:

T. Range [K]:	$70 \leq T \leq 1273$
A0 =	11.14
A1 =	15.27
A2 =	-12.07
A3 =	3.956

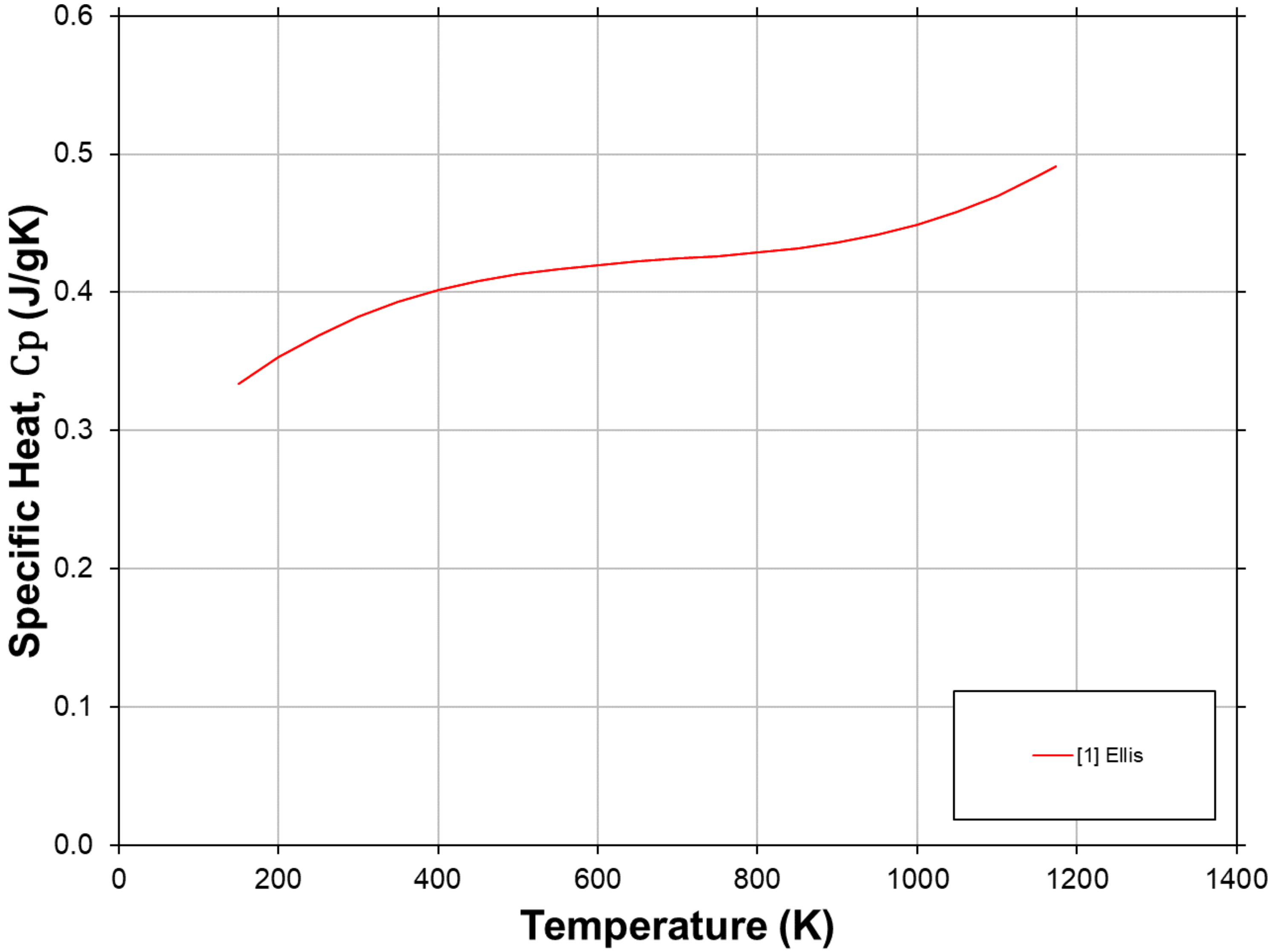

Figure 4.1.1-5: Specific Heat versus Temperature of GRCop84, adapted from Ellis (2000).

100% Theoretical Density

Temperature (T)		Specific Heat (C_p)		Temperature (T)		Specific Heat (C_p)	
K	(°F)	J/(g-K)	(BTU/(lb-°F))	K	(°F)	J/(g-K)	(BTU/(lb-°F))
293	(67.7)	0.381	(0.091)	700	(800.3)	0.424	(0.101)
325	(125.3)	0.388	(0.093)	725	(845.3)	0.425	(0.102)
350	(170.3)	0.393	(0.094)	750	(890.3)	0.426	(0.102)
375	(215.3)	0.397	(0.095)	775	(935.3)	0.428	(0.102)
400	(260.3)	0.401	(0.096)	800	(980.3)	0.429	(0.103)
425	(305.3)	0.405	(0.097)	825	(1025.3)	0.430	(0.103)
450	(350.3)	0.408	(0.098)	850	(1070.3)	0.432	(0.103)
475	(395.3)	0.411	(0.098)	875	(1115.3)	0.434	(0.104)
500	(440.3)	0.413	(0.099)	900	(1160.3)	0.436	(0.104)
525	(485.3)	0.415	(0.099)	925	(1205.3)	0.439	(0.105)
550	(530.3)	0.417	(0.100)	950	(1250.3)	0.442	(0.106)
575	(575.3)	0.419	(0.100)	975	(1295.3)	0.445	(0.106)
600	(620.3)	0.420	(0.100)	1000	(1340.3)	0.449	(0.107)
625	(665.3)	0.421	(0.101)	1100	(1520.3)	0.470	(0.112)
650	(710.3)	0.422	(0.101)	1173	(1651.7)	0.491	(0.117)

Application Notes: Trend for specific heat is collected from reference [1] and presented here in the equation below to approximate property trend with respect to temperature.

Fit Equation:

$$C_P(T) = A0 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2 + A3 \cdot \left(\frac{T}{1000}\right)^3$$

$C_P(T) = Specific\ Heat\ [J/(g \cdot K)]$

$T = Temperature\ [K]$

Constants:

T. Range [K]:	$293 \leq T \leq 1173$
A0 =	0.2539
A1 =	0.6563
A2 =	-0.8903
A3 =	0.4292

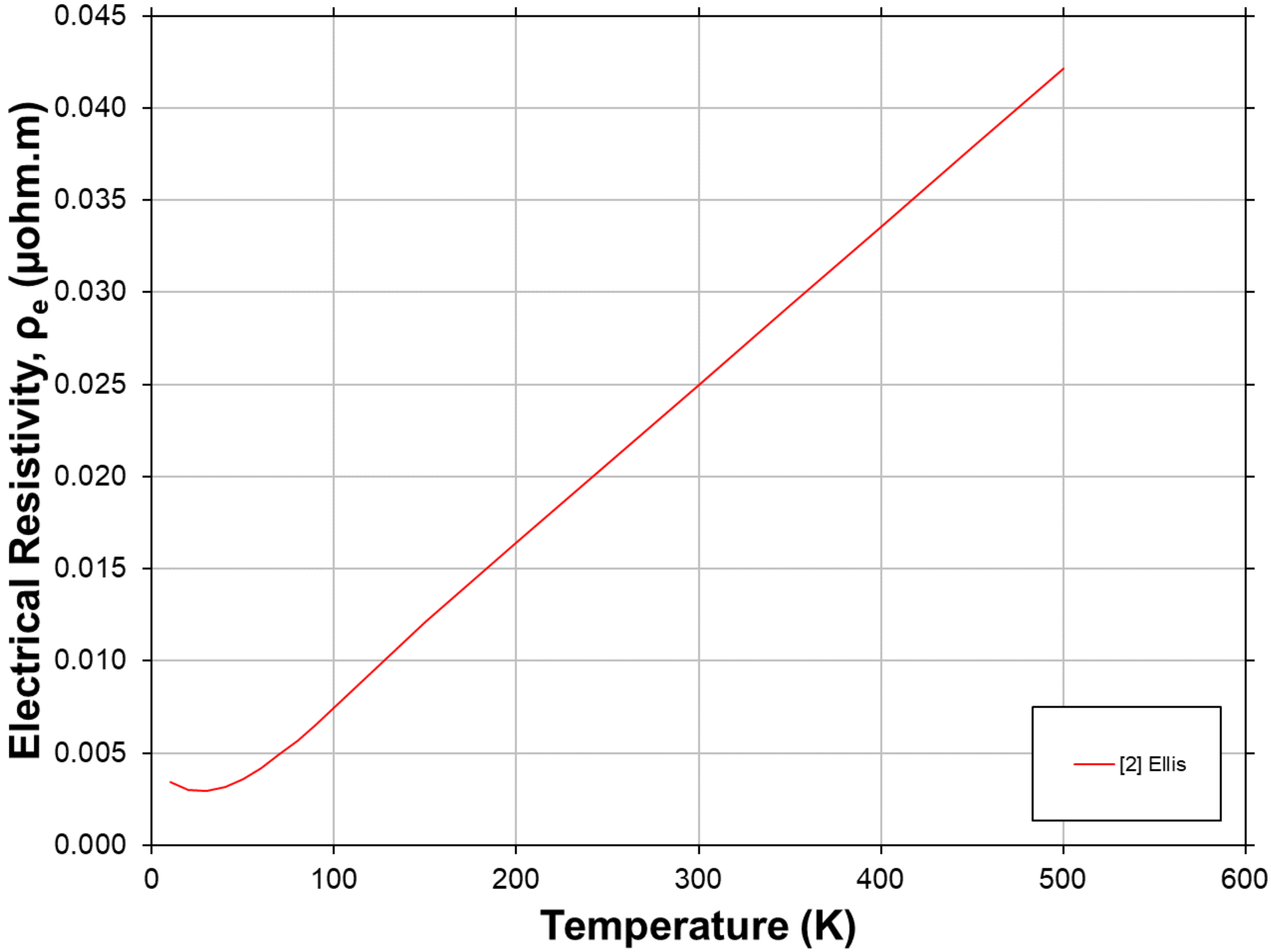

Figure 4.1.1-6: Electrical Resistivity versus Temperature of GRCop84, adapted from Ellis (2005).

100% Theoretical Density

Temperature (T)		Electrical Resistivity (ρe)		Temperature (T)		Electrical Resistivity (ρe)	
K	(°F)	μΩ-m	(μΩ-in)	K	(°F)	μΩ-m	(μΩ-in)
10	(-441.7)	0.003	(0.14)	260	(8.3)	0.022	(0.85)
20	(-423.7)	0.003	(0.12)	280	(44.3)	0.023	(0.92)
40	(-387.7)	0.003	(0.12)	300	(80.3)	0.025	(0.98)
60	(-351.7)	0.004	(0.17)	320	(116.3)	0.027	(1.05)
80	(-315.7)	0.006	(0.22)	340	(152.3)	0.028	(1.12)
100	(-279.7)	0.007	(0.29)	360	(188.3)	0.030	(1.19)
120	(-243.7)	0.009	(0.37)	380	(224.3)	0.032	(1.25)
140	(-207.7)	0.011	(0.44)	400	(260.3)	0.034	(1.32)
160	(-171.7)	0.013	(0.51)	420	(296.3)	0.035	(1.39)
180	(-135.7)	0.015	(0.58)	440	(332.3)	0.037	(1.46)
200	(-99.7)	0.016	(0.65)	460	(368.3)	0.039	(1.52)
220	(-63.7)	0.018	(0.71)	480	(404.3)	0.040	(1.59)
240	(-27.7)	0.020	(0.78)	500	(440.3)	0.042	(1.66)

Application Notes: Trend for electrical resistivity is collected from reference [2] and presented in the equations below to approximate property trend with respect to temperature.

Fit Equation:

For temperature range: $10 \leq T < 150$

$$\rho_e(T) = A0 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2 + A3 \cdot \left(\frac{T}{1000}\right)^3 + A4 \cdot \left(\frac{T}{1000}\right)^4 + A5 \cdot \left(\frac{T}{1000}\right)^5$$

For temperature range: $150 < T \leq 500$

$$\rho_e(T) = B0 + B1 \cdot \left(\frac{T}{1000}\right)$$

$\rho_e(T) = Electrical\ Resistivity\ [\mu\Omega \cdot cm]$

$T = Temperature\ [K]$

Constants:

T. Range [K]:	$10 \leq T < 150$		$150 \leq T \leq 500$
A0=	0.442	B0 =	-0.0717
A1=	-12.7	B1 =	8.57
A2=	326		
A3=	-2610		
A4=	11200		
A5=	-19800		

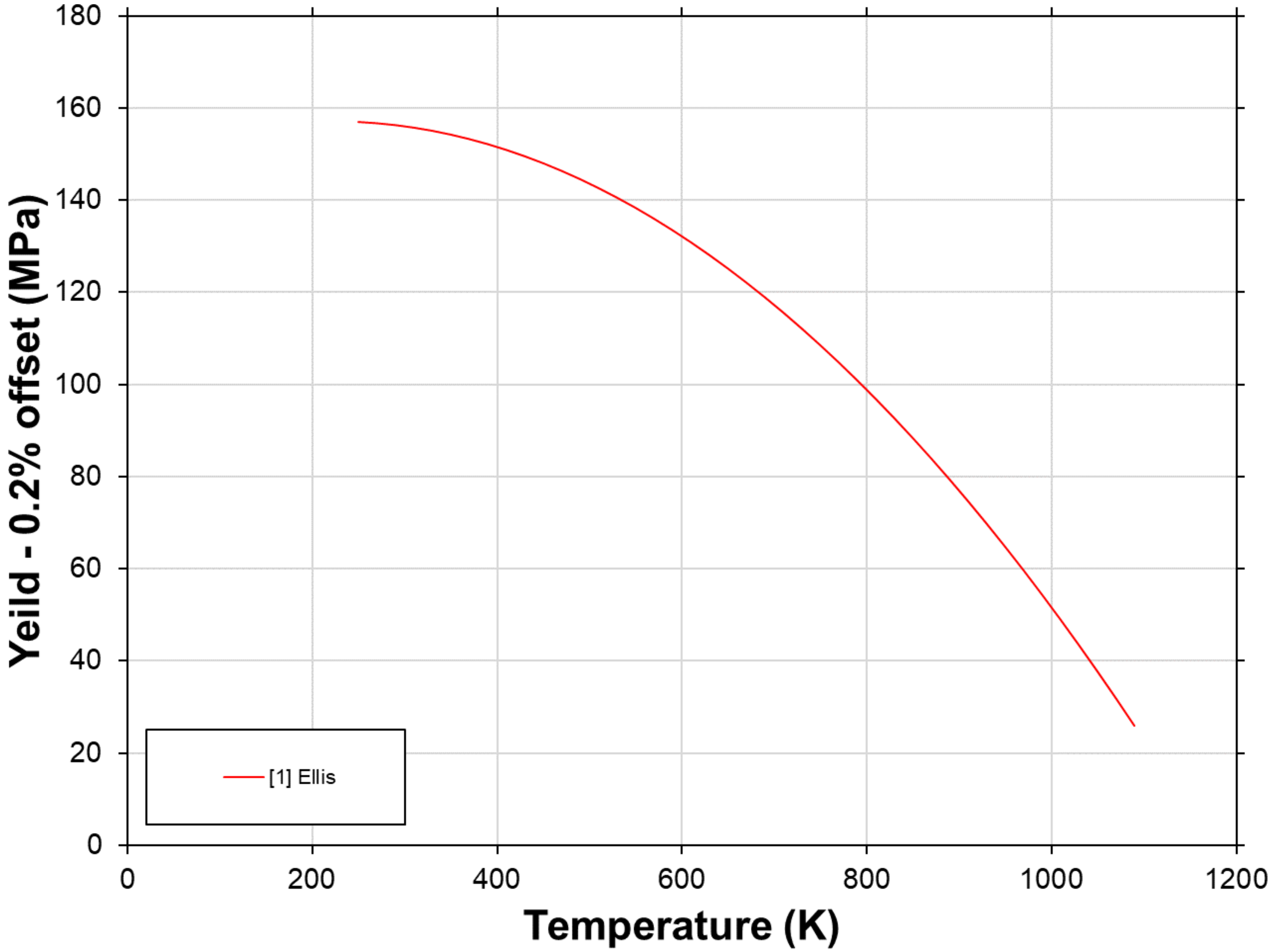

Figure 4.1.1-7: Yield versus Temperature of GRCop84, adapted from Ellis (2000).

100% Theoretical Density

Temperature (T)		Yield Strength (YS)		Temperature (T)		Yield Strength (YS)	
K	(°F)	MPa	(Ksi)	K	(°F)	MPa	(Ksi)
250	(-9.7)	157.08	(22.79)	625	(665.3)	128.86	(18.70)
275	(35.3)	156.72	(22.74)	650	(710.3)	125.24	(18.17)
300	(80.3)	156.14	(22.66)	675	(755.3)	121.40	(17.61)
325	(125.3)	155.35	(22.54)	700	(800.3)	117.34	(17.03)
350	(170.3)	154.34	(22.39)	725	(845.3)	113.07	(16.41)
375	(215.3)	153.11	(22.22)	750	(890.3)	108.58	(15.75)
400	(260.3)	151.66	(22.01)	775	(935.3)	103.87	(15.07)
425	(305.3)	150.00	(21.76)	800	(980.3)	98.94	(14.36)
450	(350.3)	148.12	(21.49)	825	(1025.3)	93.80	(13.61)
475	(395.3)	146.02	(21.19)	850	(1070.3)	88.44	(12.83)
500	(440.3)	143.70	(20.85)	900	(1160.3)	77.06	(11.18)
525	(485.3)	141.17	(20.48)	950	(1250.3)	64.82	(9.40)
550	(530.3)	138.42	(20.08)	1000	(1340.3)	51.70	(7.50)
575	(575.3)	135.45	(19.65)	1050	(1430.3)	37.72	(5.47)
600	(620.3)	132.26	(19.19)	1090	(1502.3)	25.90	(3.76)

Application Notes: Trend for yield strength is found in reference [1] and is presented here in the equation below to approximate property tend with respect to temperature.

Fit Equations:

$$YS(T) = A0 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2$$

$YS(T) = Yield\ Strength\ [MPa]$

$T = Temperature\ [K]$

Constants:

T Range [K]: $250 \leq T \leq 1090$

A0 = 148.7

A1 = 77.0

A2 = -174.0

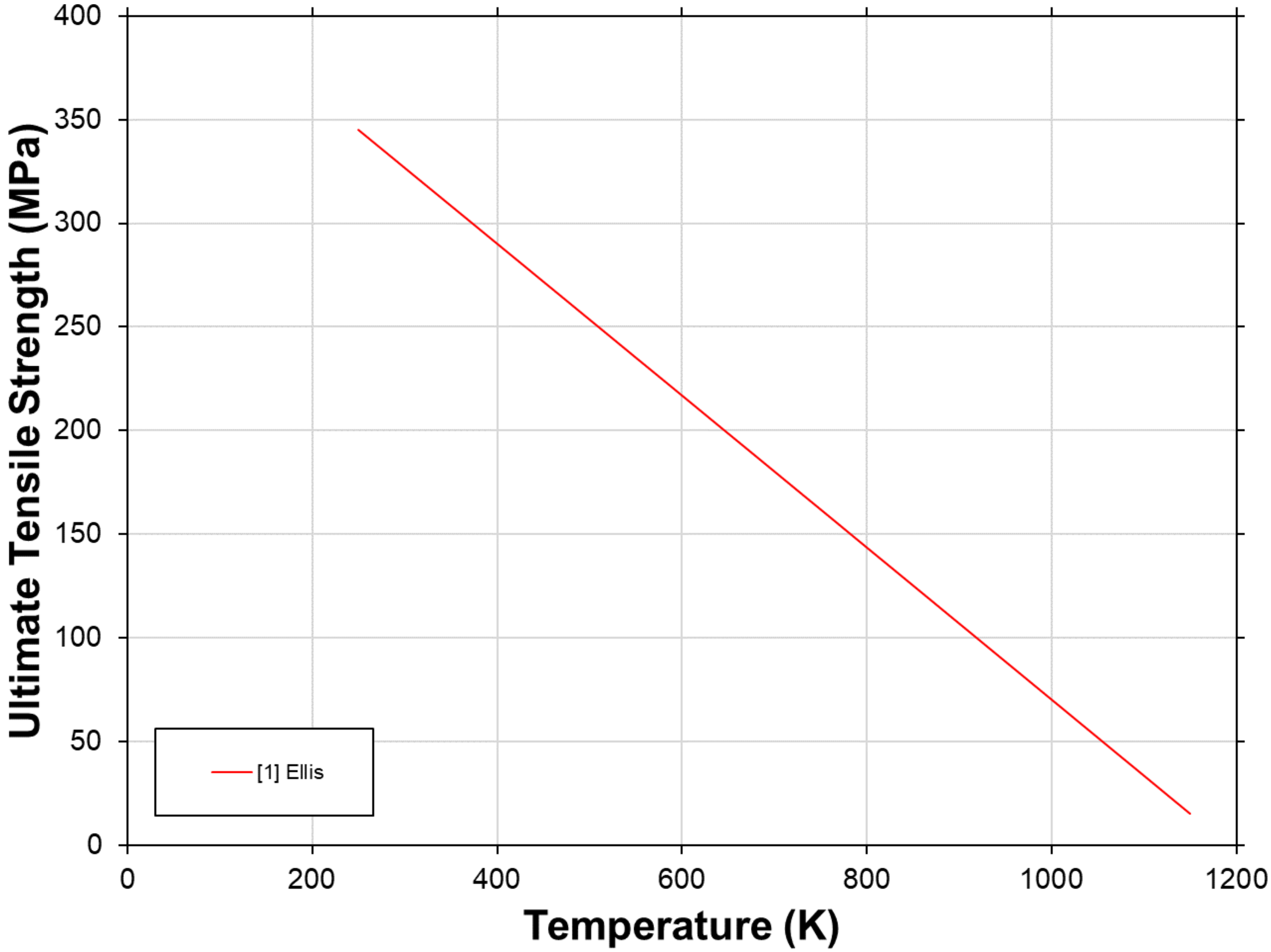

Figure 4.1.1-8: Tensile Strength versus Temperature of GRCop84, adapted from Ellis (2000).

100% Theoretical Density

Temperature (T)		Tensile Strength (TS)		Temperature (T)		Tensile Strength (TS)	
K	(°F)	MPa	(Ksi)	K	(°F)	MPa	(Ksi)
250	(-9.7)	344.98	(50.06)	625	(665.3)	207.75	(30.14)
275	(35.3)	335.84	(48.73)	650	(710.3)	198.59	(28.82)
300	(80.3)	326.70	(47.40)	675	(755.3)	189.43	(27.49)
325	(125.3)	317.56	(46.08)	700	(800.3)	180.27	(26.16)
350	(170.3)	308.42	(44.75)	725	(845.3)	171.10	(24.83)
375	(215.3)	299.27	(43.42)	750	(890.3)	161.94	(23.50)
400	(260.3)	290.13	(42.10)	775	(935.3)	152.77	(22.17)
425	(305.3)	280.98	(40.77)	800	(980.3)	143.60	(20.84)
450	(350.3)	271.83	(39.44)	850	(1070.3)	125.26	(18.18)
475	(395.3)	262.68	(38.11)	900	(1160.3)	106.92	(15.51)
500	(440.3)	253.53	(36.79)	950	(1250.3)	88.57	(12.85)
525	(485.3)	244.37	(35.46)	1000	(1340.3)	70.21	(10.19)
550	(530.3)	235.22	(34.13)	1050	(1430.3)	51.85	(7.52)
575	(575.3)	226.06	(32.80)	1100	(1520.3)	33.48	(4.86)
600	(620.3)	216.91	(31.47)	1150	(1610.3)	15.11	(2.19)

Application Notes: Trend for tensile strength is found in reference [1] and is presented in the equation below to approximate property tend with respect to temperature.

Fit Equations:

$$TS(T) = A0 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2$$

$TS(T) = Tensile\ Strength\ [MPa]$

$T = Temperature\ [K]$

Constants:

T Range [K]: $250 \leq T \leq 1150$

A0 = 436.3

A1 = -365.0

A2 = -1.09

Temp.	Physical and Electrical		Thermal				Elastic		
	Density	Electrical Resistivity	Thermal Conductivity	Thermal Expansion	Mean CTE	Specific Heat	Young's Modulus	Shear Modulus	Poisson's Ratio
(T)	(ρ)	(ρ_e)	(k)	(dL/L_0)	($\bar{\alpha}$)	(C_p)	(E)	(G)	(ν)
K	kg/m³	μΩ-cm	W/(m-K)	%	10^{-6}/K	J/(g-K)	GPa	GPa	
50	8697	0.360	462.30	-0.294	-	-	-	-	-
100	8684	0.744	307.26	-0.245	12.55	-	-	-	-
150	8669	1.214	277.64	-0.187	13.17	-	-	-	-
200	8652	1.642	274.53	-0.124	13.74	-	-	-	-
250	8634	2.071	278.77	-0.056	14.26	-	-	-	-
300	8616	2.499	284.80	0.017	14.74	0.382	-	-	-
350	8596	2.928	290.71	0.092	15.18	0.393	-	-	-
400	8576	3.356	295.81	0.171	15.57	0.401	-	-	-
450	8555	3.785	299.88	0.253	15.93	0.408	-	-	-
500	8533	4.213	302.90	0.337	16.25	0.413	-	-	-
550	8511	-	304.92	0.424	16.55	0.417	-	-	-
600	8489	-	306.01	0.513	16.81	0.420	-	-	-
650	8466	-	306.27	0.604	17.05	0.422	-	-	-
700	8442	-	305.77	0.697	17.27	0.424	-	-	-
750	8418	-	304.59	0.792	17.47	0.426	-	-	-
800	8394	-	302.80	0.889	17.66	0.429	-	-	-
850	8370	-	300.48	0.988	17.83	0.432	-	-	-
900	8345	-	297.66	1.088	17.99	0.436	-	-	-
950	8319	-	294.41	1.190	18.15	0.442	-	-	-
1000	8294	-	290.77	1.293	18.30	0.449	-	-	-
1050	8268	-	286.77	1.398	18.45	0.458	-	-	-
1100	8242	-	282.46	1.505	18.60	0.470	-	-	-
1150	8216	-	277.86	1.612	18.75	0.484	-	-	-
1200	8190	-	-	1.722	18.92	-	-	-	-
1250	8163	-	-	1.832	19.09	-	-	-	-

[1] D.L. Ellis, D.J. Keller, M. Nathal, Thermophysical properties of GRCop-84, Case Western Reserve Univ.; Cleveland, OH United States 2000.

[2] D.L. Ellis, GRCop-84: A high-temperature copper alloy for high-heat-flux applications, NASA Glenn Research Center; Cleveland, OH, United States 2005.

4 Other Nonferrous Metals and Alloys

4.2 Zirconium Alloys

Room Temperature Properties

Density, [kg/m^3]	6551
Melting Point, [K]	2150
Specific Heat, [J/(g-K)]	0.286
Thermal Conductivity, [W/(m-K)]	13.4
Linear expansion coefficient, [μm/(m-K)]	7.5
Electrical resistivity, [μΩ-m]	0.729
Young's Modulus, [GPa]	91
Shear Modulus, [GPa]	33.1
Poisson’s Ratio, [-]	0.37

Composition

Table 4.2.1-1: Typical Composition ranges for Zircaloy (percent by weight), adapted from [1].

Grade		Sn	Ni	Fe	Cr	Zr	Other
Zircaloy-2	High Zr Content	1.2	0.03	0.07	0.05	98.65	O-1118ppm
	Low Zr Content	1.7	0.08	0.2	0.15	97.87	C-113 ppm
Zircaloy-4	High Zr Content	1.2	-	0.18	0.07	98.55	O-1220 ppm
	Low Zr Content	1.7	-	0.24	0.13	97.93	C-113 ppm

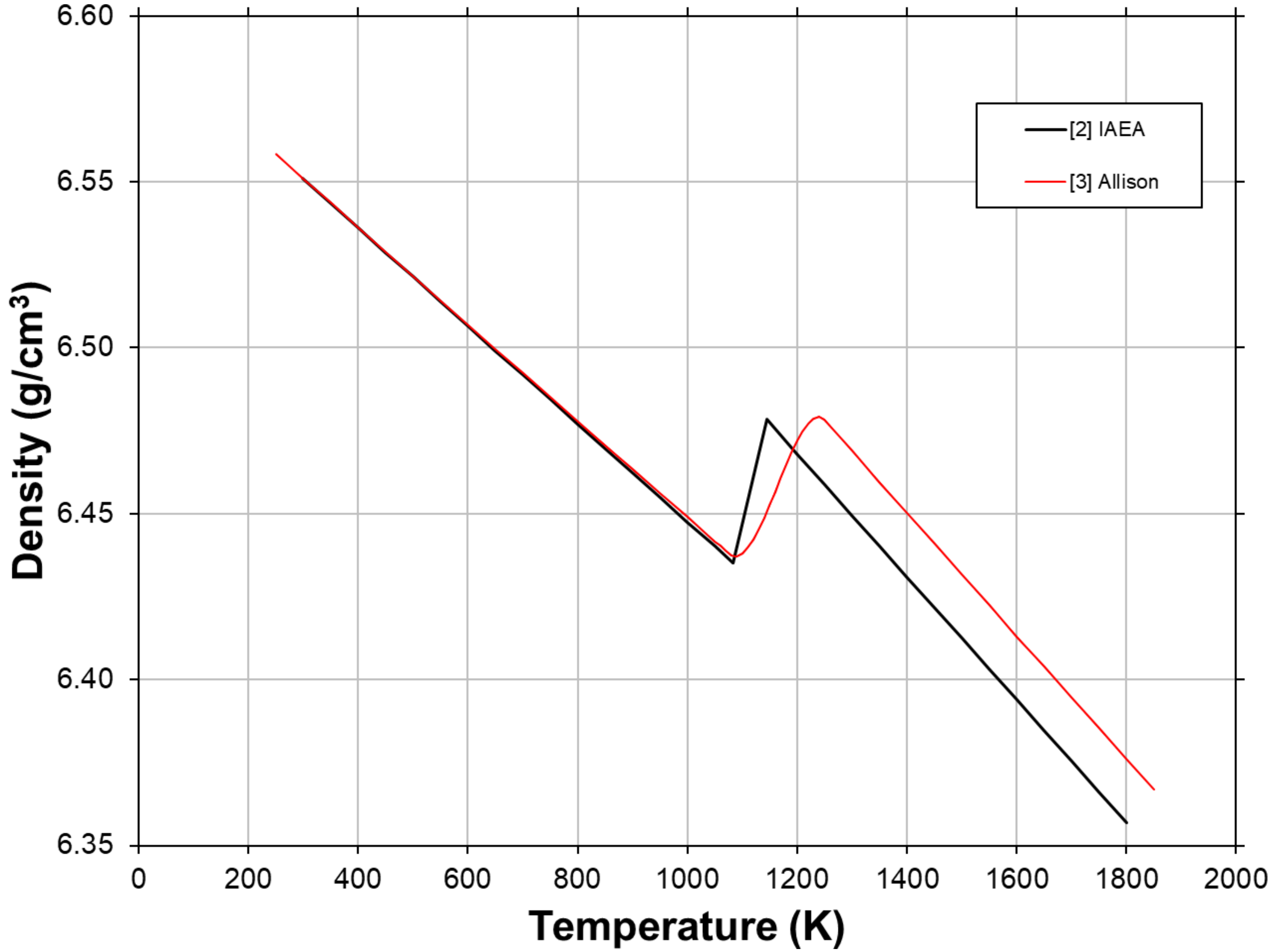

Figure 4.2.1-1: Density versus Temperature for Zircaloy.

100% Theoretical Density

Temperature (T)		Density (ρ)		Temperature (T)		Density (ρ)	
K	(°F)	kg/m^3	(lb/ft^3)	K	(°F)	kg/m^3	(lb/ft^3)
300	(80.3)	6551	(409.0)	1000	(1340.3)	6449	(402.6)
350	(170.3)	6544	(408.5)	1050	(1430.3)	6442	(402.2)
400	(260.3)	6536	(408.1)	1100	(1520.3)	6438	(401.9)
450	(350.3)	6529	(407.6)	1150	(1610.3)	6453	(402.8)
500	(440.3)	6522	(407.1)	1200	(1700.3)	6472	(404.0)
550	(530.3)	6514	(406.7)	1250	(1790.3)	6478	(404.4)
600	(620.3)	6507	(406.2)	1300	(1880.3)	6469	(403.9)
650	(710.3)	6500	(405.8)	1350	(1970.3)	6460	(403.3)
700	(800.3)	6492	(405.3)	1400	(2060.3)	6450	(402.7)
750	(890.3)	6485	(404.9)	1450	(2150.3)	6441	(402.1)
800	(980.3)	6478	(404.4)	1500	(2240.3)	6432	(401.5)
850	(1070.3)	6471	(404.0)	1600	(2420.3)	6413	(400.4)
900	(1160.3)	6463	(403.5)	1700	(2600.3)	6395	(399.2)
950	(1250.3)	6456	(403.1)	1800	(2780.3)	6376	(398.1)

Application Notes: Data for density is collected from reference [2]. The red curve is calculated from thermal expansion data collected from reference [3], utilizing the equation below to approximate density trend with respect to temperature.

Density Calculation:

$\rho(T) = \rho_{RT}/(1 + dL/L_0(T)/100)^3$

$\rho(T) = Density\ [kg/m^3]$

$Room\ Temperature\ Density\ (\rho_{RT}) = 6551\ [kg/m^3]$

$T = Temperature\ [K]$

Temperature Range: $0 \le T \le 1800$

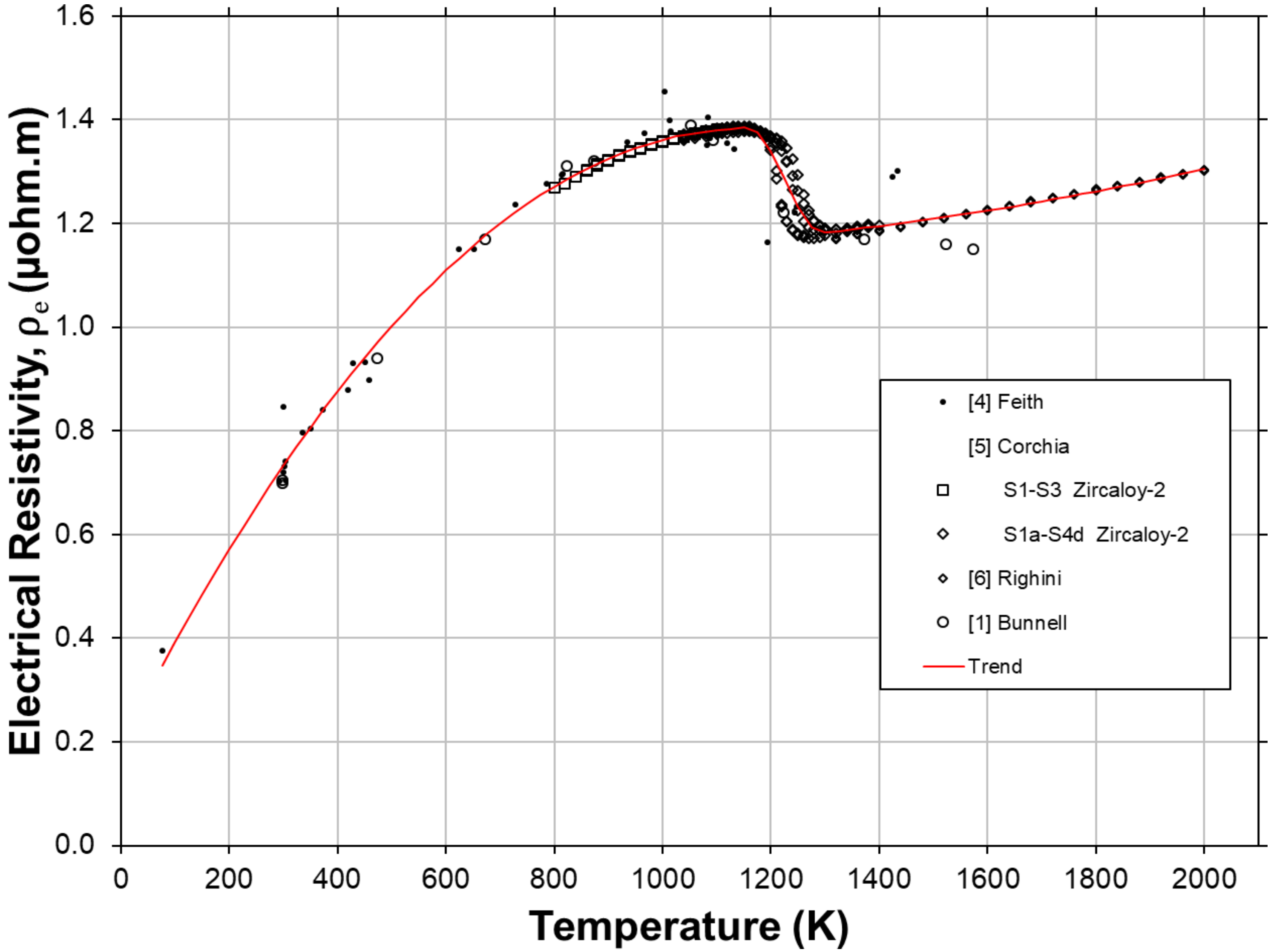

Figure 4.2.1-2: Electrical Resistivity versus Temperature of Zircaloy.

100% Theoretical Density

Temperature (T)		Electrical Resistivity (ρe)		Temperature (T)		Electrical Resistivity (ρe)	
K	(°F)	μΩ-m	(μΩ-in)	K	(°F)	μΩ-m	(μΩ-in)
77	(-321.1)	0.348	(13.70)	1100	(1520.3)	1.379	(54.30)
100	(-279.7)	0.392	(15.42)	1200	(1700.3)	1.339	(52.73)
200	(-99.7)	0.571	(22.48)	1300	(1880.3)	1.183	(46.56)
300	(80.3)	0.732	(28.84)	1400	(2060.3)	1.195	(47.04)
400	(260.3)	0.876	(34.49)	1500	(2240.3)	1.209	(47.59)
500	(440.3)	1.002	(39.43)	1600	(2420.3)	1.225	(48.21)
600	(620.3)	1.109	(43.67)	1700	(2600.3)	1.242	(48.90)
700	(800.3)	1.199	(47.21)	1800	(2780.3)	1.261	(49.66)
800	(980.3)	1.271	(50.04)	1900	(2960.3)	1.283	(50.49)
900	(1160.3)	1.325	(52.16)	2000	(3140.3)	1.305	(51.40)
1000	(1340.3)	1.361	(53.58)				

Application Notes: Data for electrical resistivity is collected from references [1, 4-6] and fitted with the equations below to approximate the property trend with respect to temperature. Trend equations are shown for 77 to 1150 K, and 1300 to 2000 K. There is a phase change in this material between 1150 and 1300 K. An equation for this section is not given, however there is tabulated data for this range at the end of the chapter.

Fit Equations:

For temperature range: $77 \leq T \leq 1150$

$$\rho_e(T) = A0 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2$$

For temperature range: $1300 \leq T \leq 2000$

$$\rho_e(T) = C0 + C1 \cdot \left(\frac{T}{1000}\right) + C2 \cdot \left(\frac{T}{1000}\right)^2$$

$\rho_e(T) = Electrical\ Resistivity\ [\mu\Omega \cdot m]$

$T = Temperature\ [K]$

Constants:

Temperature Range [K]:	$77 \leq T \leq 1150$		$1300 \leq T \leq 2000$
A0 =	0.1944	C0 =	1.187
A1 =	2.062	C1 =	-0.1196
A2 =	-0.8954	C2 =	0.08941

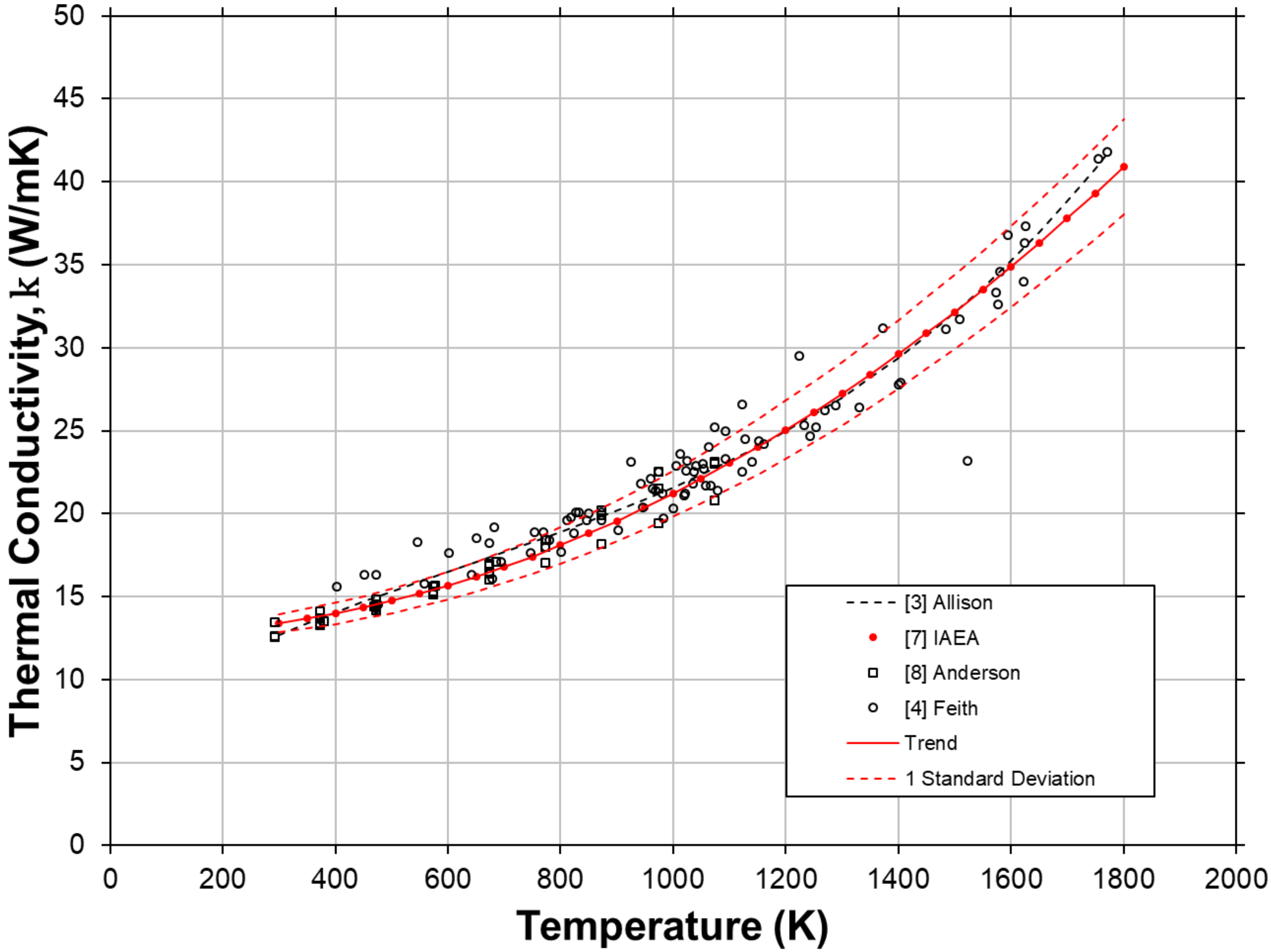

Figure 4.2.1-3: Thermal Conductivity versus Temperature of Zircaloy.

100% Theoretical Density

Temperature (T)		Thermal Conductivity (k)		Temperature (T)		Thermal Conductivity (k)	
K	(°F)	W/(m-K)	((Btu-in.)/(ft.²-hr-°F))	K	(°F)	W/(m-K)	((Btu-in.)/(ft.²-hr-°F))
300	(80.3)	13.41	(93.06)	1000	(1340.3)	21.21	(147.12)
350	(170.3)	13.68	(94.89)	1050	(1430.3)	22.10	(153.32)
400	(260.3)	13.99	(97.04)	1100	(1520.3)	23.04	(159.83)
450	(350.3)	14.34	(99.50)	1150	(1610.3)	24.02	(166.66)
500	(440.3)	14.74	(102.27)	1200	(1700.3)	25.05	(173.79)
550	(530.3)	15.19	(105.36)	1250	(1790.3)	26.12	(181.24)
600	(620.3)	15.67	(108.75)	1300	(1880.3)	27.24	(188.99)
650	(710.3)	16.21	(112.46)	1350	(1970.3)	28.40	(197.06)
700	(800.3)	16.79	(116.47)	1400	(2060.3)	29.61	(205.44)
750	(890.3)	17.41	(120.80)	1450	(2150.3)	30.86	(214.13)
800	(980.3)	18.08	(125.45)	1500	(2240.3)	32.16	(223.14)
850	(1070.3)	18.79	(130.40)	1600	(2420.3)	34.89	(242.08)
900	(1160.3)	19.55	(135.66)	1700	(2600.3)	37.80	(262.26)
950	(1250.3)	20.36	(141.24)	1800	(2780.3)	40.89	(283.70)

Application Notes: Data for thermal conductivity is collected from references [3, 4, 7, 8] and fitted with the equation below to approximate the property trend with respect to temperature.

Fit Equations:

$$k(T) = A0 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2$$

$k(T) = Thermal\ Conductivity\ [W\ /\ (m \cdot K)]$

$T = Temperature\ [K]$

Constants:

T Range [K]:	$298 \leq T < 1800$
A0 =	12.767
A1 =	-0.54348
A2 =	8.9818

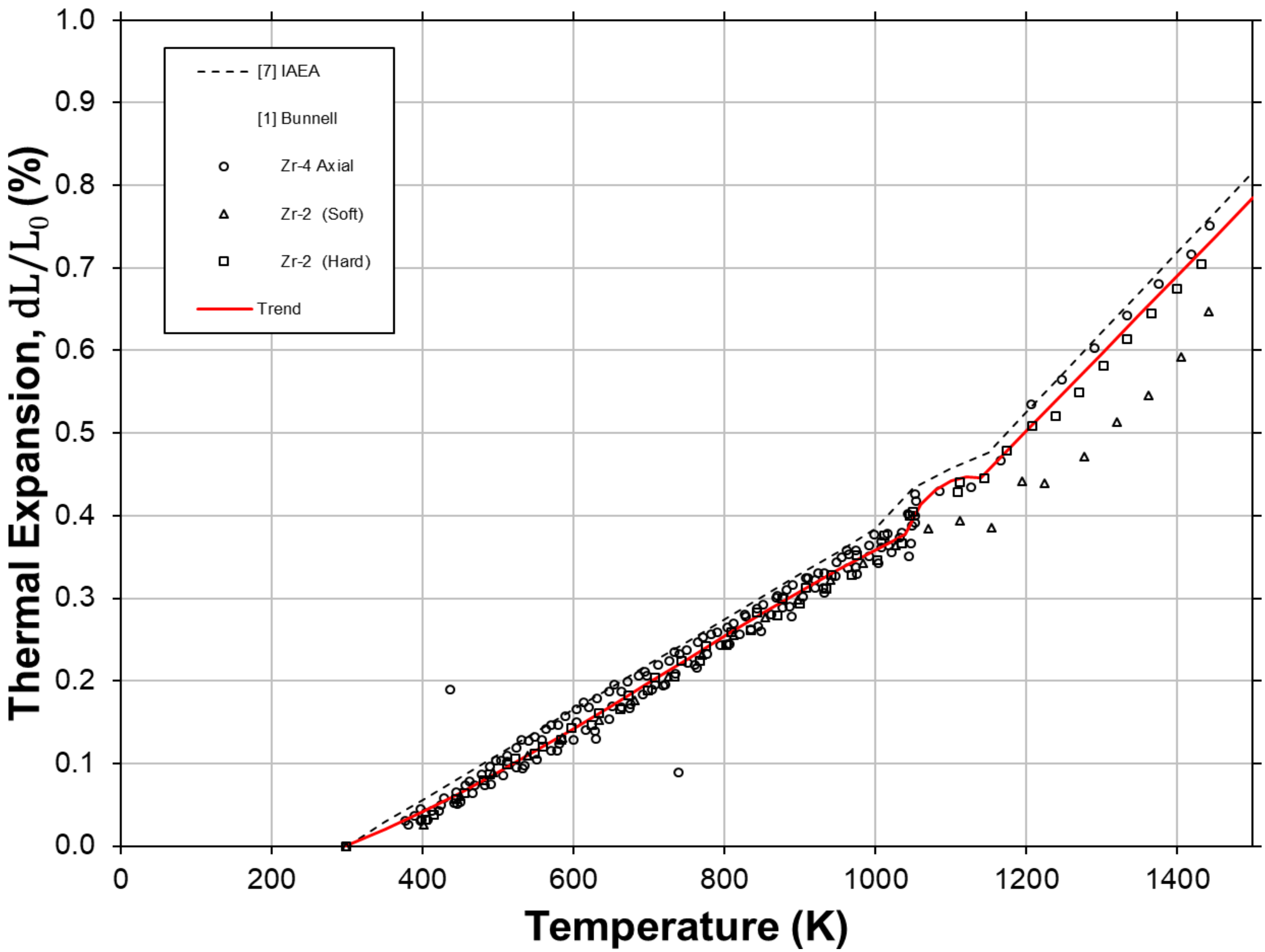

Figure 4.2.1-4: Axial Thermal Expansion versus Temperature of Zircaloy.

100% Theoretical Density

Temperature (T)		Axial Thermal Expansion (dL/L0)	Temperature (T)		Axial Thermal Expansion (dL/L0)
K	(°F)	%	K	(°F)	%
300	(80.3)	0.001	700	(800.3)	0.198
325	(125.3)	0.010	750	(890.3)	0.226
350	(170.3)	0.020	800	(980.3)	0.254
375	(215.3)	0.031	850	(1070.3)	0.282
400	(260.3)	0.042	900	(1160.3)	0.309
425	(305.3)	0.053	950	(1250.3)	0.334
450	(350.3)	0.065	1000	(1340.3)	0.359
475	(395.3)	0.077	1050	(1430.3)	0.382
500	(440.3)	0.090	1100	(1520.3)	0.442
525	(485.3)	0.103	1150	(1610.3)	0.456
550	(530.3)	0.116	1200	(1700.3)	0.503
575	(575.3)	0.129	1250	(1790.3)	0.550
600	(620.3)	0.143	1300	(1880.3)	0.597
625	(665.3)	0.157	1400	(2060.3)	0.691
650	(710.3)	0.170	1500	(2240.3)	0.785

Application Notes: Data for thermal expansion in axial direction was collected from references [1, 7] and fitted with the equation below to approximate the property trend with respect to temperature.

Fit Equation:

$$dL/L_0\,(T) = A0 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2 + A3 \cdot \left(\frac{T}{1000}\right)^3$$

$dL/L_0\,(T) = Thermal\ Expansion\ [\%]$

$T = Temperature\ [K]$

Constants:

T Range [K]:	$298 \leq T \leq 1050$	$1050 < T < 1140$	$1140 \leq T \leq 1500$
A0 =	-0.0596	-10.01	-0.625
A1 =	0.0005036	18.61	0.9398
A2 =	0.7761	-8.28	0
A3 =	-0.3579	0	0

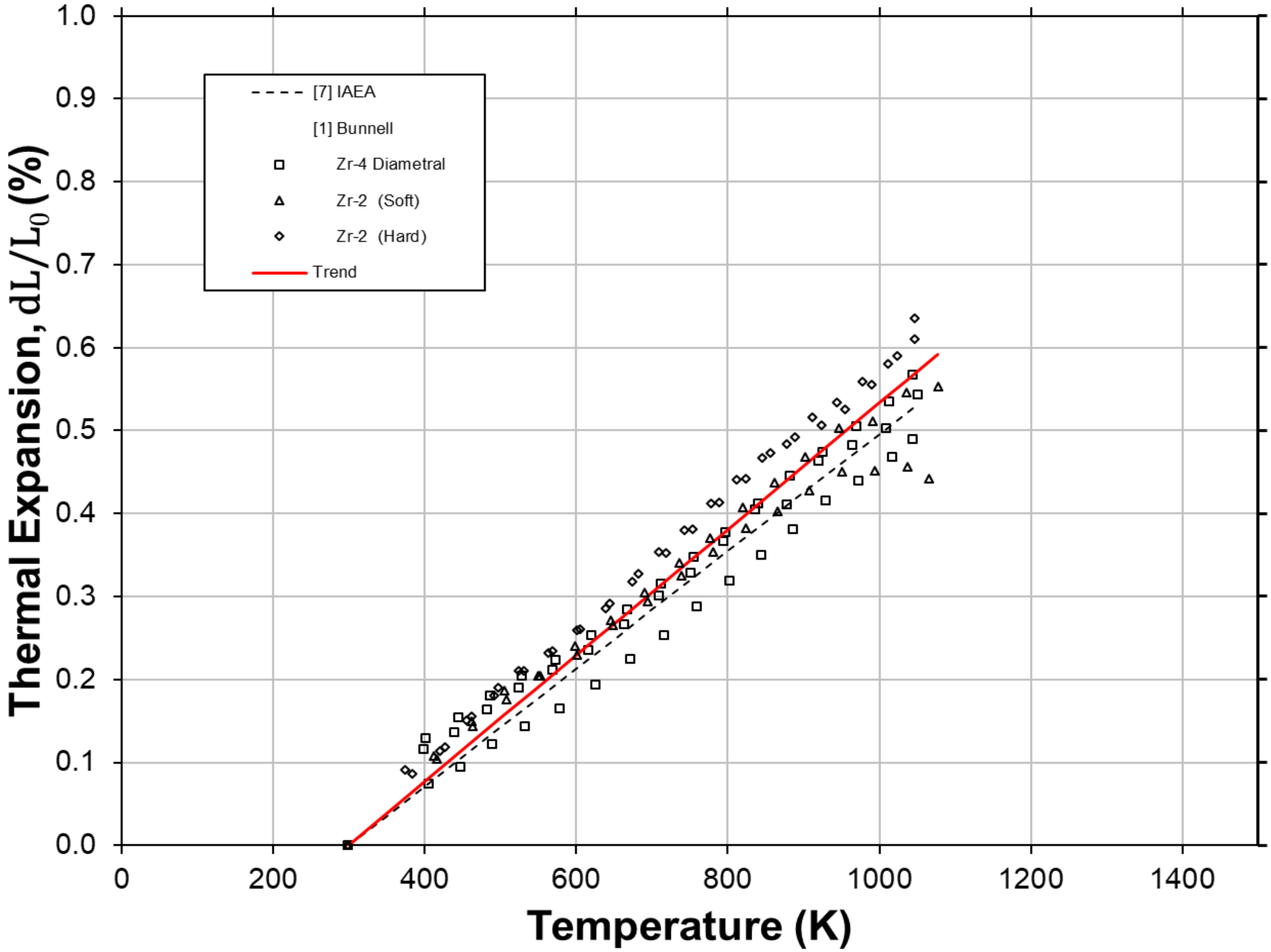

Figure 4.2.1-5: Diametral Thermal Expansion versus Temperature of Zircaloy.

100% Theoretical Density

Temperature (T) K	(°F)	Diametral Thermal Expansion (dL/L_0) %	Temperature (T) K	(°F)	Diametral Thermal Expansion (dL/L_0) %
300	(80.3)	0.002	675	(755.3)	0.286
325	(125.3)	0.021	700	(800.3)	0.305
350	(170.3)	0.039	725	(845.3)	0.324
375	(215.3)	0.058	750	(890.3)	0.343
400	(260.3)	0.077	775	(935.3)	0.362
425	(305.3)	0.096	800	(980.3)	0.381
450	(350.3)	0.115	825	(1025.3)	0.400
475	(395.3)	0.134	850	(1070.3)	0.419
500	(440.3)	0.153	875	(1115.3)	0.438
525	(485.3)	0.172	900	(1160.3)	0.457
550	(530.3)	0.191	925	(1205.3)	0.476
575	(575.3)	0.210	950	(1250.3)	0.495
600	(620.3)	0.229	975	(1295.3)	0.514
625	(665.3)	0.248	1000	(1340.3)	0.533
650	(710.3)	0.267	1077	(1478.9)	0.592

Application Notes: Data for thermal expansion in the diametral direction was collected from references [1, 7] and fitted with the equation below to approximate the property trend with respect to temperature.

Fit Equation:

$$dL/L_0\,(T) = A0 + A1 \cdot \left(\frac{T}{1000}\right)$$

$dL/L_0\,(T) = Thermal\ Expansion\ [\%]$

$T = Temperature\ [K]$

Constants:

T Range [K]: $298 < T \leq 1077$

A0 = -0.2264

A1 = 0.7597

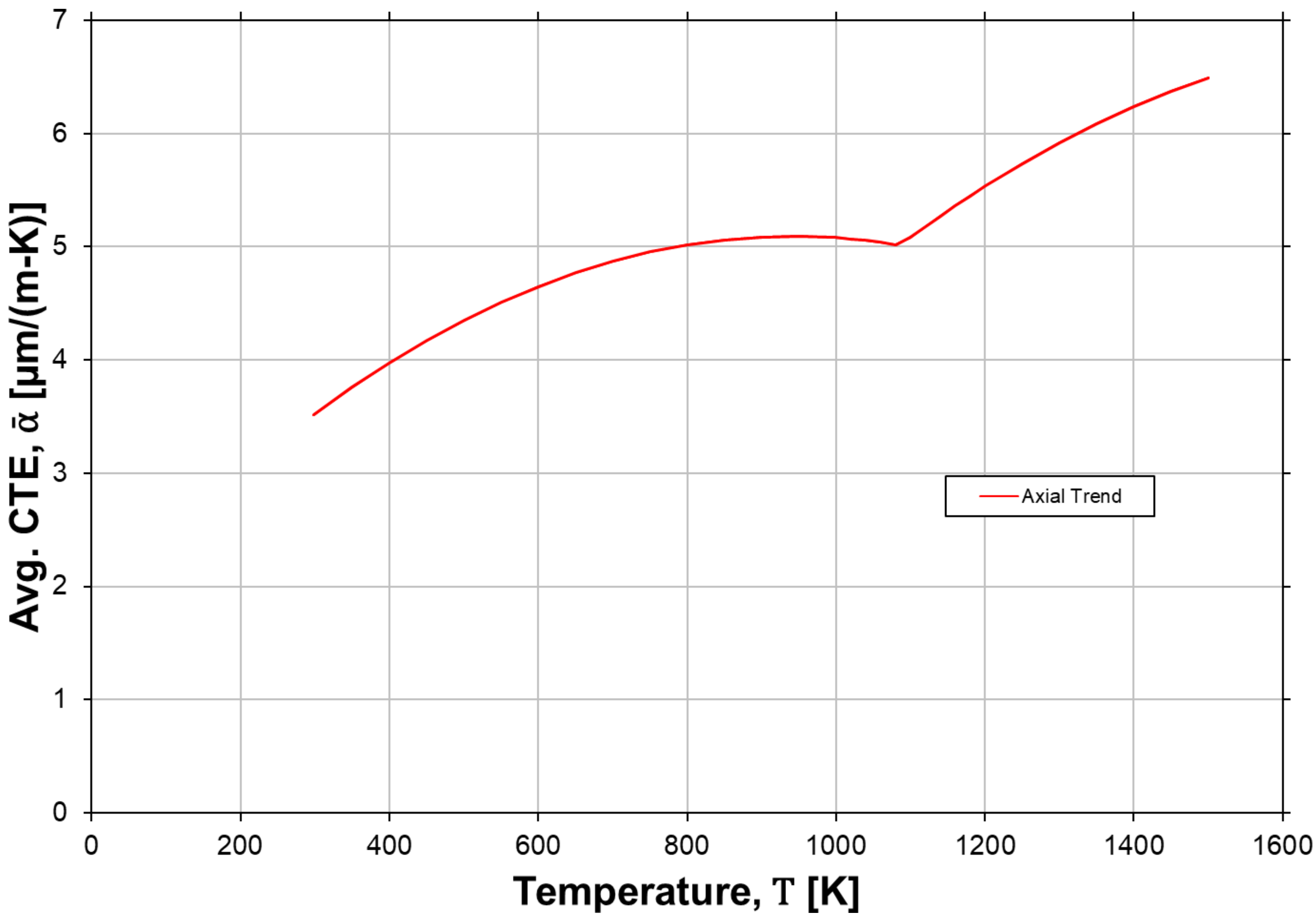

Figure 4.2.1-6: Axial Mean Coefficient of Thermal Expansion versus Temperature of Zircaloy. Calculated from fitted trend of the Thermal Expansion data.

100% Theoretical Density

Temperature (T)		Mean CTE (ᾱ)		Temperature (T)		Mean CTE (ᾱ)	
K	(°F)	μm/(m-K)	(μin/(in-°F))	K	(°F)	μm/(m-K)	(μin/(in-°F))
298	(76.7)	3.513	(1.952)	850	(1070.3)	5.061	(2.812)
300	(80.3)	3.523	(1.957)	900	(1160.3)	5.087	(2.826)
320	(116.3)	3.619	(2.011)	950	(1250.3)	5.093	(2.829)
340	(152.3)	3.713	(2.063)	1000	(1340.3)	5.080	(2.822)
360	(188.3)	3.803	(2.113)	1050	(1430.3)	5.048	(2.804)
380	(224.3)	3.890	(2.161)	1100	(1520.3)	5.083	(2.824)
400	(260.3)	3.975	(2.208)	1150	(1610.3)	5.317	(2.954)
450	(350.3)	4.172	(2.318)	1200	(1700.3)	5.535	(3.075)
500	(440.3)	4.350	(2.417)	1250	(1790.3)	5.736	(3.187)
550	(530.3)	4.509	(2.505)	1300	(1880.3)	5.921	(3.289)
600	(620.3)	4.649	(2.583)	1350	(1970.3)	6.088	(3.382)
650	(710.3)	4.769	(2.650)	1400	(2060.3)	6.239	(3.466)
700	(800.3)	4.871	(2.706)	1450	(2150.3)	6.374	(3.541)
750	(890.3)	4.954	(2.752)	1500	(2240.3)	6.492	(3.606)
800	(980.3)	5.017	(2.787)				

Application Notes: Trend for axial mean coefficient of thermal expansion is calculated based on the axial thermal expansion trend, and it is fitted with the equations below to approximate property trend with respect to temperature.

Fit Equation:

$$\bar{\alpha}(T) = A0 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2$$

$\bar{\alpha}(T) = Mean\ Coefficient\ of\ Themal\ Expansion\ [\mu m/(m \cdot K)]$

$T = Temperature\ [K]$

Constants:

Temperature Range [K]:	$298 \leq T \leq 1083$	$1083 < T \leq 1500$
A0 =	1.71	-4.292
A1 =	7.189	12.19
A2 =	-3.819	-3.334

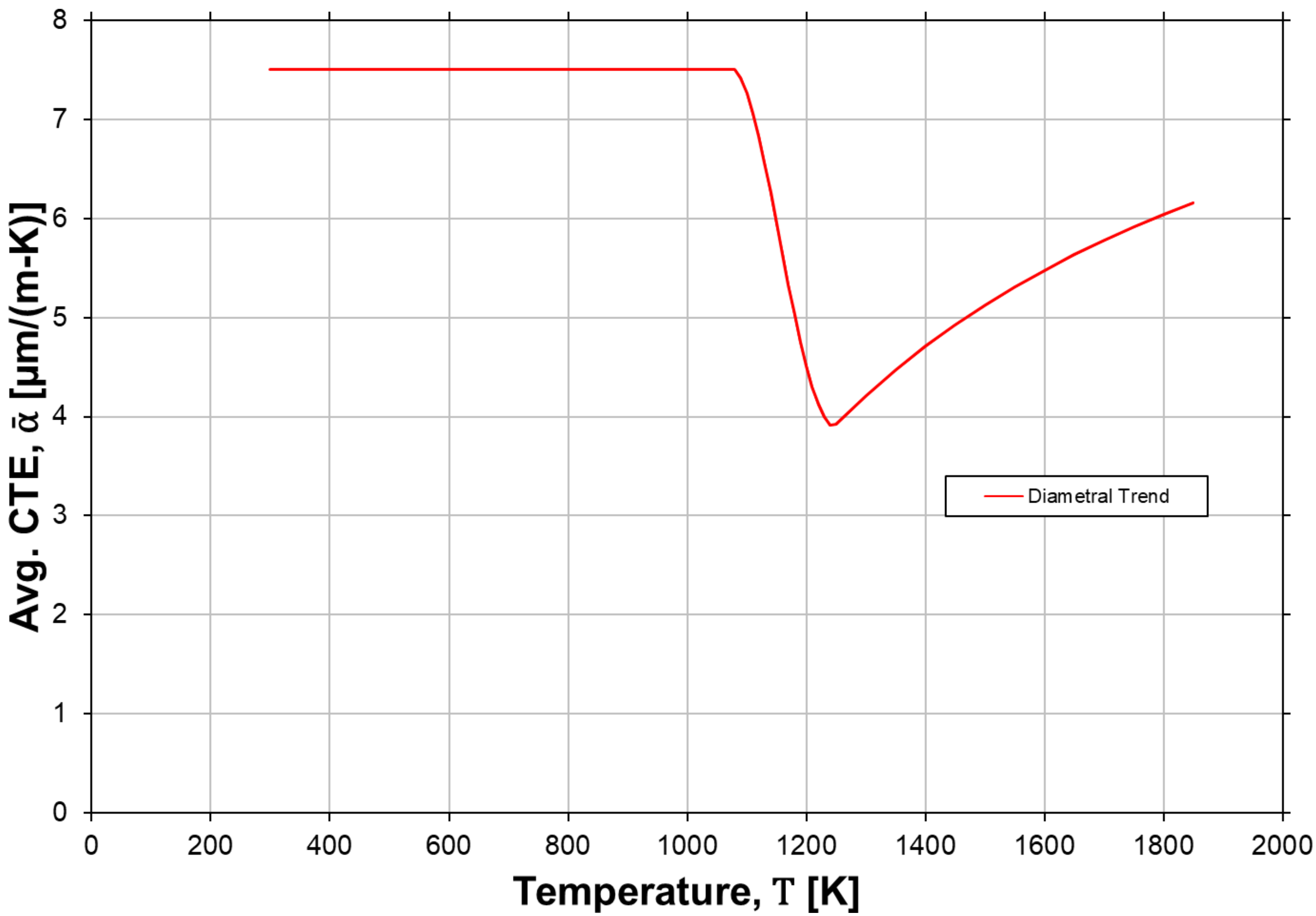

Figure 4.2.1-7: Diametral Mean Coefficient of Thermal Expansion versus Temperature of Zircaloy. Calculated from fitted trend of the Thermal Expansion data.

100% Theoretical Density

Temperature (T)		Mean CTE (ᾱ)		Temperature (T)		Mean CTE (ᾱ)	
K	(°F)	µm/(m-K)	(µin/(in-°F))	K	(°F)	µm/(m-K)	(µin/(in-°F))
300	(80.3)	7.500	(4.167)	1083	(1489.7)	7.500	(4.167)
350	(170.3)	7.500	(4.167)	1100	(1520.3)	7.266	(4.037)
400	(260.3)	7.500	(4.167)	1150	(1610.3)	5.953	(3.307)
450	(350.3)	7.500	(4.167)	1200	(1700.3)	4.507	(2.504)
500	(440.3)	7.500	(4.167)	1244	(1779.5)	3.894	(2.163)
550	(530.3)	7.500	(4.167)	1300	(1880.3)	4.210	(2.339)
600	(620.3)	7.500	(4.167)	1350	(1970.3)	4.471	(2.484)
650	(710.3)	7.500	(4.167)	1400	(2060.3)	4.709	(2.616)
700	(800.3)	7.500	(4.167)	1450	(2150.3)	4.926	(2.737)
750	(890.3)	7.500	(4.167)	1500	(2240.3)	5.125	(2.847)
800	(980.3)	7.500	(4.167)	1600	(2420.3)	5.477	(3.043)
850	(1070.3)	7.500	(4.167)	1700	(2600.3)	5.779	(3.210)
900	(1160.3)	7.500	(4.167)	1800	(2780.3)	6.040	(3.356)
1000	(1340.3)	7.500	(4.167)	1850	(2870.3)	6.158	(3.421)

Application Notes: Trend for diametral mean coefficient of thermal expansion is adapted from [3], and it is fitted with the equations below to approximate property trend with respect to temperature.

Fit Equation:

For temperature range: $300 \leq T \leq 1083$

$\bar{\alpha}(T) = A0$

For temperature range: $1083 \leq T \leq 1244$

$$\bar{\alpha}(T) = ((B0 + B1 * Cos(A * (\frac{T}{1000} + X0))))/(\frac{T}{1000} - T\_Ref)$$

For temperature range: $1244 \leq T \leq 1850$

$$\bar{\alpha}(T) = ((C0 + C1 * \frac{T}{1000}))/(\frac{T}{1000} - T\_Ref)$$

$\bar{\alpha}(T) = Mean\ Coefficient\ of\ Themal\ Expansion\ [\mu m/(m \cdot K)]$

$T = Temperature\ [K]$

Constants:

T Range [K]:	$300 \leq T \leq 1083$		$1083 \leq T \leq 1244$		$1244 \leq T \leq 1850$
A0 =	0.75	B0 =	0.477428	C0 =	-0.84
		B1 =	0.109822	C1 =	0.97
		T_{Ref} =	0.3	T_{Ref} =	0.3
		A =	19.513		
		X0 =	-1.083		

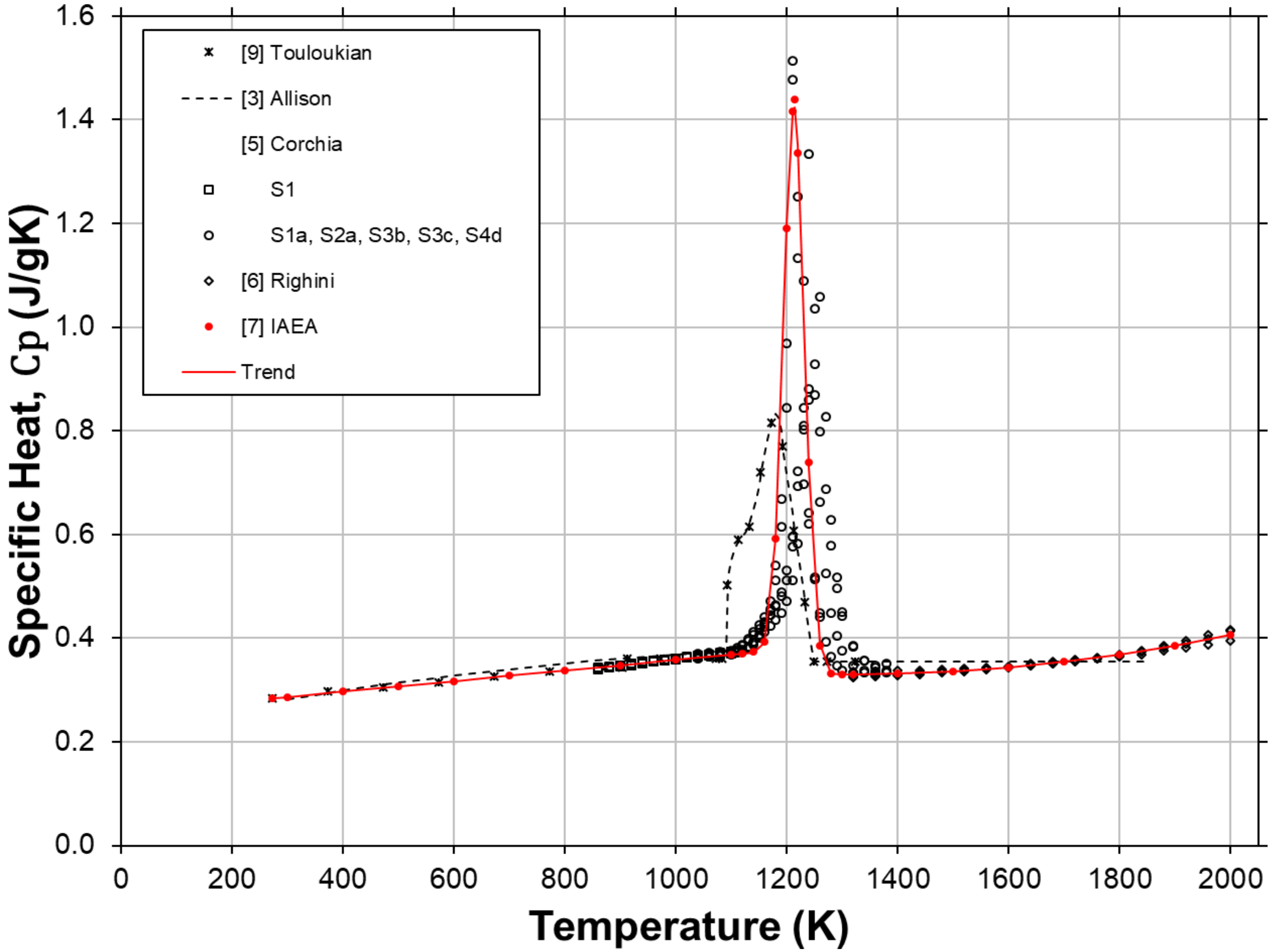

Figure 4.2.1-8: Specific Heat versus Temperature for Zircaloy.

100% Theoretical Density

Temperature (T)		Specific Heat (C_p)		Temperature (T)		Specific Heat (C_p)	
K	(°F)	J/(g-K)	(BTU/(lb-°F))	K	(°F)	J/(g-K)	(BTU/(lb-°F))
300	(80.3)	0.286	(0.068)	1050	(1430.3)	0.363	(0.087)
350	(170.3)	0.292	(0.070)	1100	(1520.3)	0.368	(0.088)
400	(260.3)	0.297	(0.071)	1150	(1610.3)	0.375	(0.090)
450	(350.3)	0.302	(0.072)	1200	(1700.3)	1.198	(0.286)
500	(440.3)	0.307	(0.073)	1250	(1790.3)	0.502	(0.120)
550	(530.3)	0.312	(0.075)	1300	(1880.3)	0.330	(0.079)
600	(620.3)	0.317	(0.076)	1350	(1970.3)	0.330	(0.079)
650	(710.3)	0.322	(0.077)	1400	(2060.3)	0.332	(0.079)
700	(800.3)	0.327	(0.078)	1450	(2150.3)	0.333	(0.080)
750	(890.3)	0.333	(0.079)	1500	(2240.3)	0.336	(0.080)
800	(980.3)	0.338	(0.081)	1600	(2420.3)	0.344	(0.082)
850	(1070.3)	0.343	(0.082)	1700	(2600.3)	0.354	(0.085)
900	(1160.3)	0.348	(0.083)	1800	(2780.3)	0.368	(0.088)
950	(1250.3)	0.353	(0.084)	1900	(2960.3)	0.385	(0.092)
1000	(1340.3)	0.358	(0.086)	2000	(3140.3)	0.406	(0.097)

Application Notes: Data for specific heat is collected from references [3, 5-7, 9] and fitted with the equations below to approximate the property trend with respect to temperature. Trend equations are shown for 273 to 1100 K, and 1320 to 2000 K. There is a phase change in this material between 1100 and 1320 K. An equation for this section is not given, however there is tabulated data for this range in the table.

Fit Equation:

$$C_P(T) = A0 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2$$

$C_P(T) = Specific\ Heat\ [J/(g \cdot K)]$

$T = Temperature\ [K]$

Constants:

T Range [K]:	$273 \leq T \leq 1100$	$1320 < T < 2000$
A0 =	0.2557	0.5971
A1 =	0.1024	-0.4088
A2 =	0	0.1565

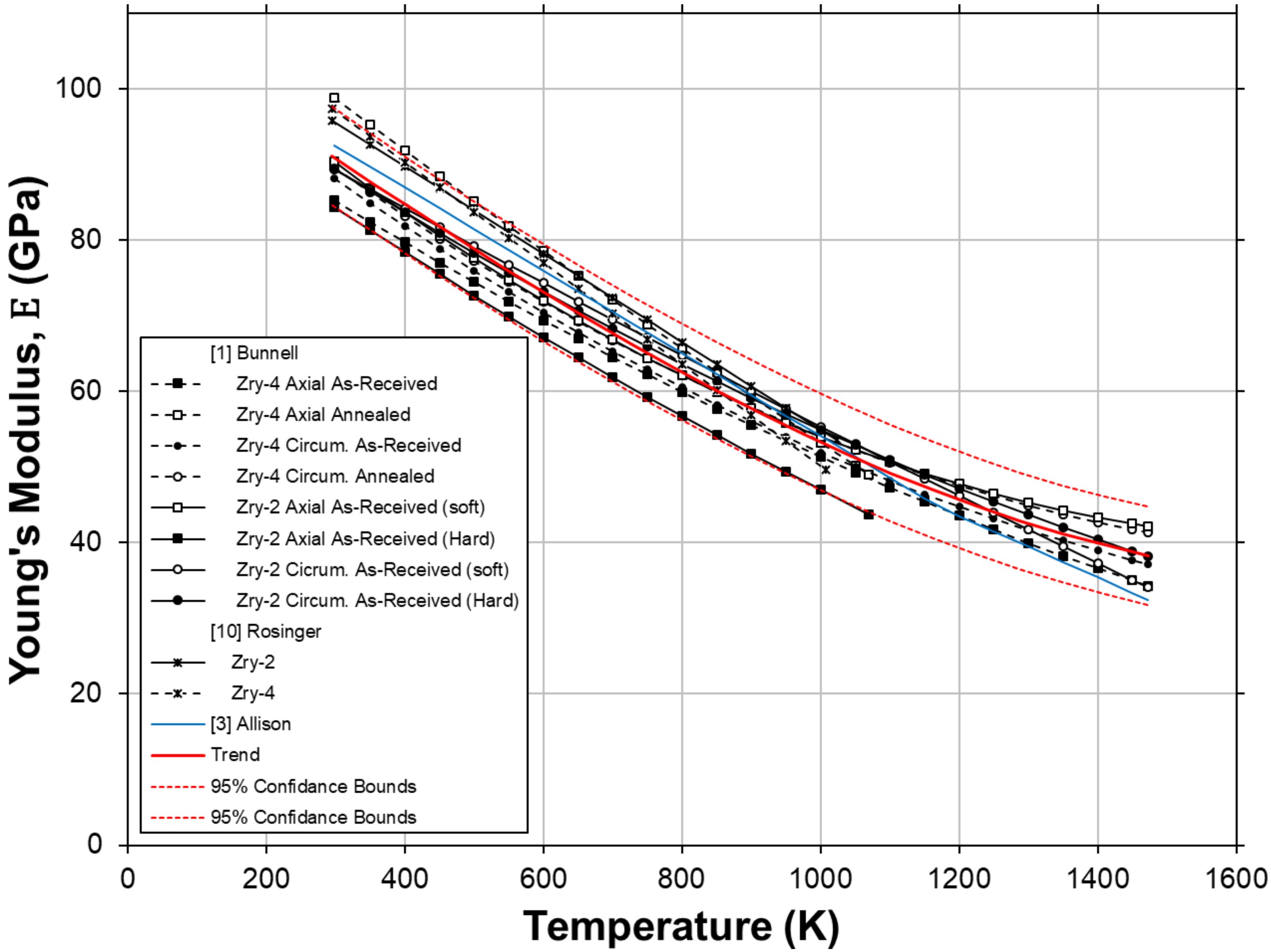

Figure 4.2.1-9: Young's Modulus versus Temperature of Zircaloy.

Young's Modulus with Temperature

100% Theoretical Density

Temperature (T)		Young's Modulus (E)		Temperature (T)		Young's Modulus (E)	
K	(°F)	GPa	(Msi)	K	(°F)	GPa	(Msi)
300	(80.3)	90.83	(13.18)	750	(890.3)	65.04	(9.44)
325	(125.3)	89.28	(12.95)	800	(980.3)	62.52	(9.07)
350	(170.3)	87.74	(12.73)	850	(1070.3)	60.08	(8.72)
375	(215.3)	86.22	(12.51)	900	(1160.3)	57.72	(8.38)
400	(260.3)	84.70	(12.29)	950	(1250.3)	55.46	(8.05)
425	(305.3)	83.20	(12.07)	1000	(1340.3)	53.29	(7.73)
450	(350.3)	81.71	(11.86)	1050	(1430.3)	51.22	(7.43)
475	(395.3)	80.23	(11.64)	1100	(1520.3)	49.26	(7.15)
500	(440.3)	78.77	(11.43)	1150	(1610.3)	47.41	(6.88)
525	(485.3)	77.32	(11.22)	1200	(1700.3)	45.66	(6.63)
550	(530.3)	75.89	(11.01)	1250	(1790.3)	44.04	(6.39)
575	(575.3)	74.48	(10.81)	1300	(1880.3)	42.53	(6.17)
600	(620.3)	73.08	(10.60)	1350	(1970.3)	41.15	(5.97)
650	(710.3)	70.33	(10.20)	1400	(2060.3)	39.89	(5.79)
700	(800.3)	67.65	(9.82)	1450	(2150.3)	38.78	(5.63)

Application Notes: Data for Young's Modulus is collected from references [1, 3, 10] and fitted with the equation below to approximate the property trend with respect to temperature.

Fit Equation:

$$E(T) = A0 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2 + A3 \cdot \left(\frac{T}{1000}\right)^3$$

$E(T) = Young's\ Modulus\ [GPa]$

$T = Temperature\ [K]$

Constants:

T Range [K]:	$295 \le T \le 1473$
A0 =	110.1
A1 =	-65.75
A2 =	3.43
A3 =	5.511

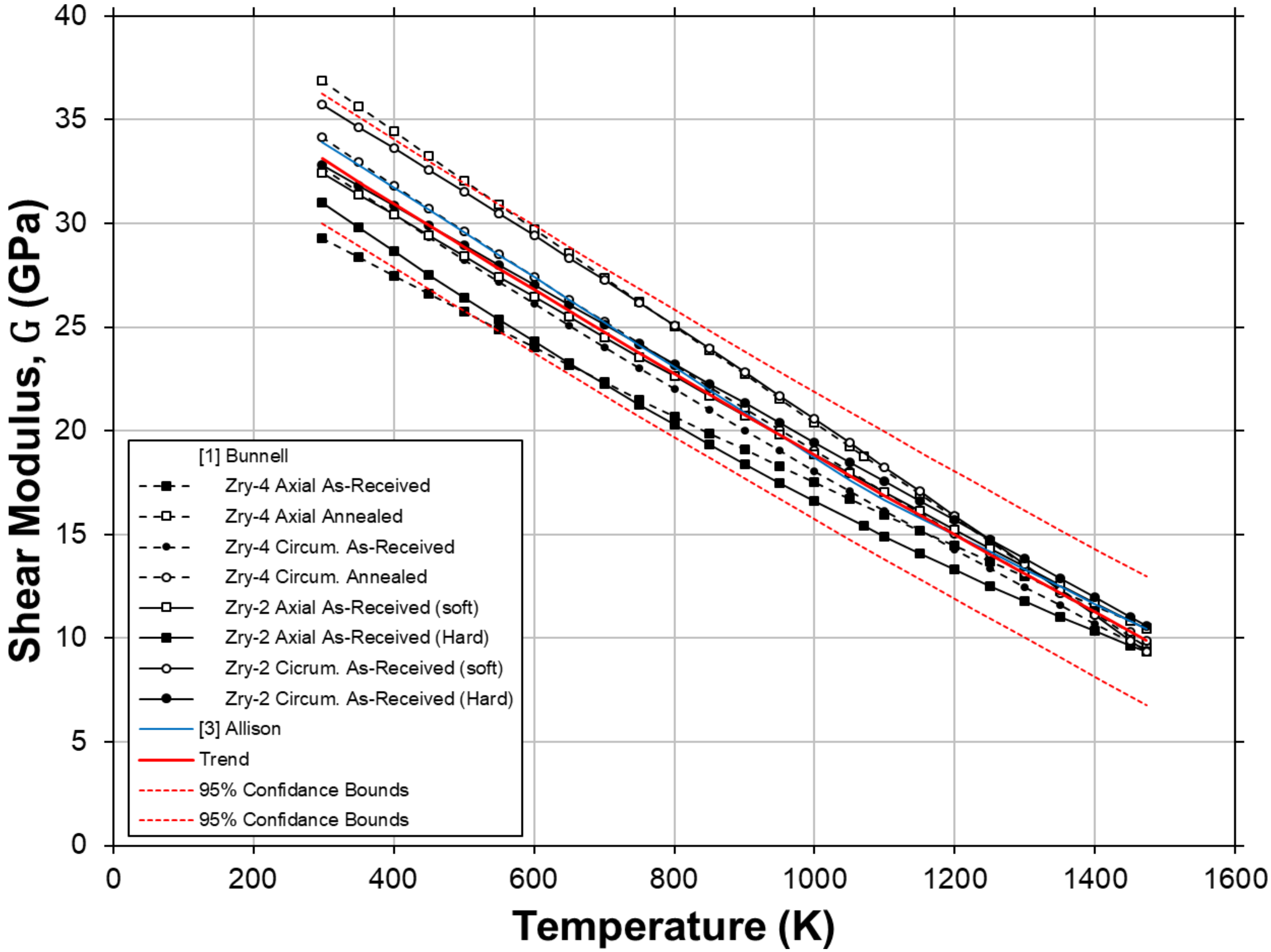

Figure 4.2.1-10: Shear Modulus versus Temperature of Zircaloy.

100% Theoretical Density

Temperature (T)		Shear Modulus (G)		Temperature (T)		Shear Modulus (G)	
K	(°F)	GPa	(Msi)	K	(°F)	GPa	(Msi)
300	(80.3)	33.08	(4.80)	750	(890.3)	23.77	(3.45)
325	(125.3)	32.55	(4.72)	800	(980.3)	22.77	(3.30)
350	(170.3)	32.02	(4.65)	850	(1070.3)	21.77	(3.16)
375	(215.3)	31.49	(4.57)	900	(1160.3)	20.78	(3.02)
400	(260.3)	30.97	(4.49)	950	(1250.3)	19.80	(2.87)
425	(305.3)	30.44	(4.42)	1000	(1340.3)	18.82	(2.73)
450	(350.3)	29.92	(4.34)	1050	(1430.3)	17.85	(2.59)
475	(395.3)	29.40	(4.27)	1100	(1520.3)	16.88	(2.45)
500	(440.3)	28.88	(4.19)	1150	(1610.3)	15.92	(2.31)
525	(485.3)	28.36	(4.12)	1200	(1700.3)	14.97	(2.17)
550	(530.3)	27.84	(4.04)	1250	(1790.3)	14.03	(2.04)
575	(575.3)	27.33	(3.97)	1300	(1880.3)	13.09	(1.90)
600	(620.3)	26.82	(3.89)	1350	(1970.3)	12.15	(1.76)
650	(710.3)	25.79	(3.74)	1400	(2060.3)	11.23	(1.63)
700	(800.3)	24.78	(3.60)	1450	(2150.3)	10.31	(1.50)

Application Notes: Data for shear modulus is collected from references [1, 3] and fitted with the equation below to approximate property trend with respect to temperature.

Fit Equations:

$$G(T) = A0 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2 + A3 \cdot \left(\frac{T}{1000}\right)^3$$

$G(T) = Shear\ Modulus\ [GPa]$

$T = Temperature\ [K]$

Constants:

T Range [K]:	$295 \le T \le 1473$
A0 =	39.57
A1 =	-22.01
A2 =	1.249
A3 =	0.008872

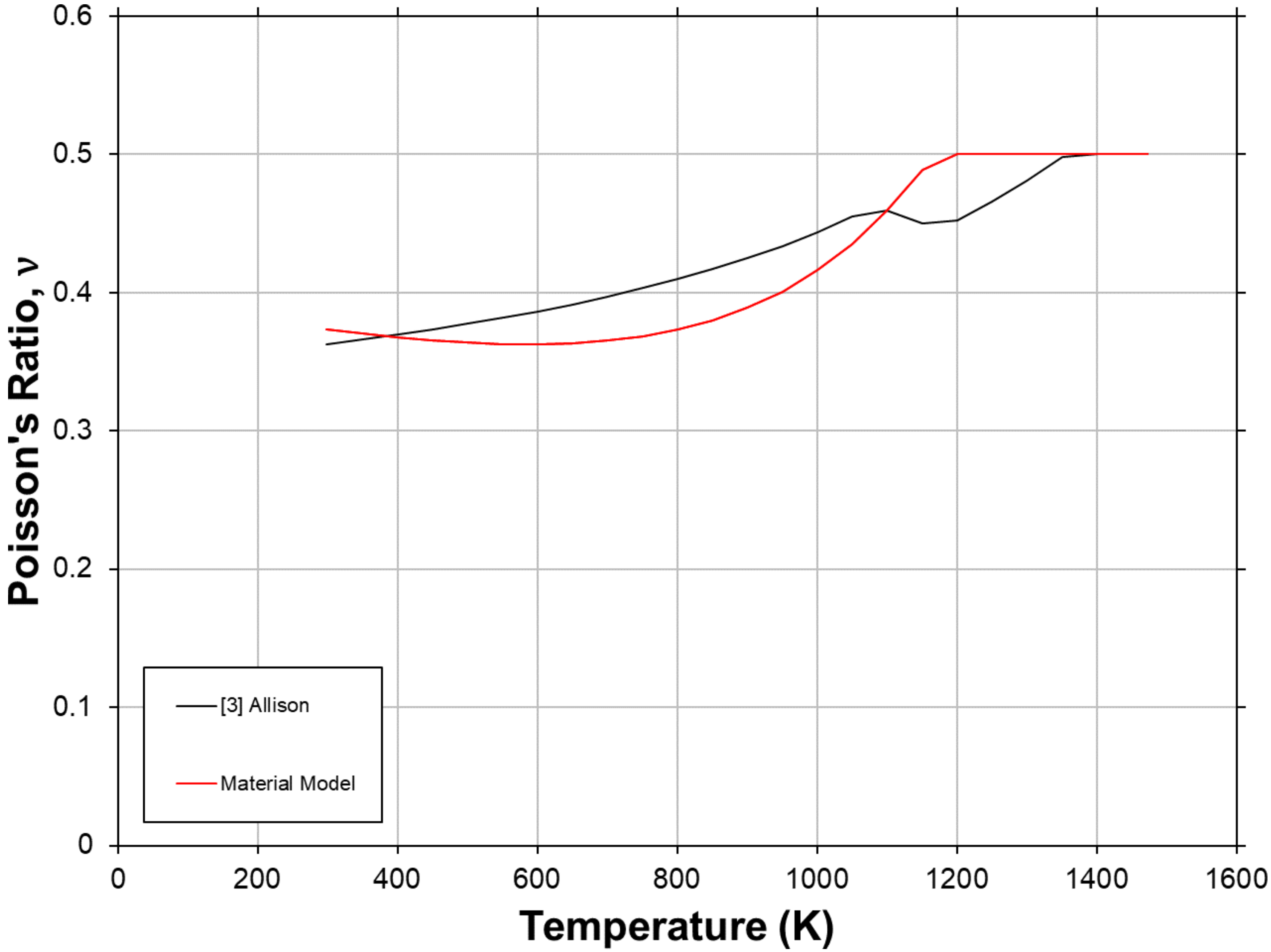

Figure 4.2.1-11: Poisson's Ratio versus Temperature of Zircaloy.

100% Theoretical Density

Temperature (T) K	(°F)	Poisson's Ratio (ν)	Temperature (T) K	(°F)	Poisson's Ratio (ν)
300	(80.3)	0.373	750	(890.3)	0.368
325	(125.3)	0.372	800	(980.3)	0.373
350	(170.3)	0.370	850	(1070.3)	0.380
375	(215.3)	0.369	900	(1160.3)	0.389
400	(260.3)	0.368	950	(1250.3)	0.401
425	(305.3)	0.367	1000	(1340.3)	0.416
450	(350.3)	0.365	1050	(1430.3)	0.435
475	(395.3)	0.365	1100	(1520.3)	0.459
500	(440.3)	0.364	1150	(1610.3)	0.489
525	(485.3)	0.363	1200	(1700.3)	0.500
550	(530.3)	0.363	1250	(1790.3)	0.500
575	(575.3)	0.363	1300	(1880.3)	0.500
600	(620.3)	0.363	1350	(1970.3)	0.500
650	(710.3)	0.363	1400	(2060.3)	0.500
700	(800.3)	0.365	1450	(2150.3)	0.500

Application Notes: Data for Poisson's Ratio is collected from reference [3]. Trend is calculated as a function of Young's and shear modulus as seen in the equation below to approximate the property trend with respect to temperature.

Fit Equation:

$\nu(T) = 0.5 \cdot (E(T)/\, G(T)) - 1$

$\nu(T) = Poisson's\ Ratio$

$T = Temperature\ [K]$

Constants:

T Range [K]: $295 < T \leq 1473$

	Physical and Electrical		Thermal						Elastic		
Temp.	Density	Electrical Resistivity	Thermal Conductivity	Thermal Expansion		Mean CTE		Specific Heat	Young's Modulus	Shear Modulus	Poisson's Ratio
				Axial	Diam.	Axial	Diam.				
(T)	(ρ)	(ρ_e)	(k)	(dL/L_0)	(dL/L_0)	($\bar{\alpha}$)	($\bar{\alpha}$)	(C_p)	(E)	(G)	(ν)
K	kg/m³	μΩ-m	W/(m-K)	%	%	10^{-6}/K	10^{-6}/K	J/(g-K)	GPa	GPa	
300	6551	0.732	13.41	0.00	0.00	3.52	7.50	0.286	90.8	33.1	0.37
350	6544	0.806	13.68	0.02	0.04	3.76	7.50	0.292	87.7	32.0	0.37
400	6536	0.876	13.99	0.04	0.08	3.97	7.50	0.297	84.7	31.0	0.37
450	6529	0.941	14.34	0.07	0.12	4.17	7.50	0.302	81.7	29.9	0.37
500	6522	1.002	14.74	0.09	0.15	4.35	7.50	0.307	78.8	28.9	0.36
550	6514	1.058	15.19	0.12	0.19	4.51	7.50	0.312	75.9	27.8	0.36
600	6507	1.109	15.67	0.14	0.23	4.65	7.50	0.317	73.1	26.8	0.36
650	6500	1.156	16.21	0.17	0.27	4.77	7.50	0.322	70.3	25.8	0.36
700	6492	1.199	16.79	0.20	0.31	4.87	7.50	0.327	67.6	24.8	0.37
750	6485	1.237	17.41	0.23	0.34	4.95	7.50	0.333	65.0	23.8	0.37
800	6478	1.271	18.08	0.25	0.38	5.02	7.50	0.338	62.5	22.8	0.37
850	6471	1.300	18.79	0.28	0.42	5.06	7.50	0.343	60.1	21.8	0.38
900	6463	1.325	19.55	0.31	0.46	5.09	7.50	0.348	57.7	20.8	0.39
950	6456	1.345	20.36	0.33	0.50	5.09	7.50	0.353	55.5	19.8	0.40
1000	6449	1.361	21.21	0.36	0.53	5.08	7.50	0.358	53.3	18.8	0.42
1050	6442	1.372	22.10	0.38	0.57	5.05	7.50	0.363	51.2	17.8	0.44
1100	6438	1.379	23.04	0.44		5.08	7.27	0.368	49.3	16.9	0.46
1150	6453	1.384	24.02	0.46		5.32	5.95	0.375	47.4	15.9	0.49
1200	6472	1.339	25.05	0.50		5.54	4.51	1.198	45.7	15.0	0.50
1250	6478	1.233	26.12	0.55		5.74	3.92	0.502	44.0	14.0	0.50
1300	6469	1.183	27.24	0.60		5.92	4.21	0.330	42.5	13.1	0.50
1350	6460	1.188	28.40	0.64		6.09	4.47	0.330	41.1	12.2	0.50
1400	6450	1.195	29.61	0.69		6.24	4.71	0.332	39.9	11.2	0.50
1450	6441	1.202	30.86	0.74		6.37	4.93	0.333	38.8	10.3	0.50
1500	6432	1.209	32.16	0.78		6.49	5.13	0.336			

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5 Ferrous Alloys

5.1 Austenitic Stainless Steels

Room Temperature Properties

Density, [kg/m^3]	8,018
Melting Point, [K]	1673
Specific Heat, [J/(g-K)]	0.476
Thermal Conductivity, [W/(m-K)]	14.9
Linear expansion coefficient, [μm/(m-K)]	14.83
Electrical resistivity, [μΩ-m]	0.72
Young's Modulus, [GPa]	197.0
Shear Modulus, [GPa]	77.8
Poisson's Ratio, [-]	0.265

Composition

Table 5.1.1-1: Typical Composition ranges for 304-grade stainless steel (percent by weight)

Grade		Fe	Cr	Ni	C	Mn	Si	P	S	N
304	Min.	Balance	18.0	8.0	-	-	-	-	-	-
	Max.		20.0	10.5	0.08	2.0	0.75	0.045	0.030	0.10
304L	Min.	Balance	18.0	8.0	-	-	-	-	-	-
	Max.		20.0	12	0.03	2.0	0.75	0.045	0.030	0.10
304H	Min.	Balance	18.0	8.0	0.04	-	-	-	-	-
	Max.		20.0	10.5	0.10	2.0	0.75	0.045	0.030	

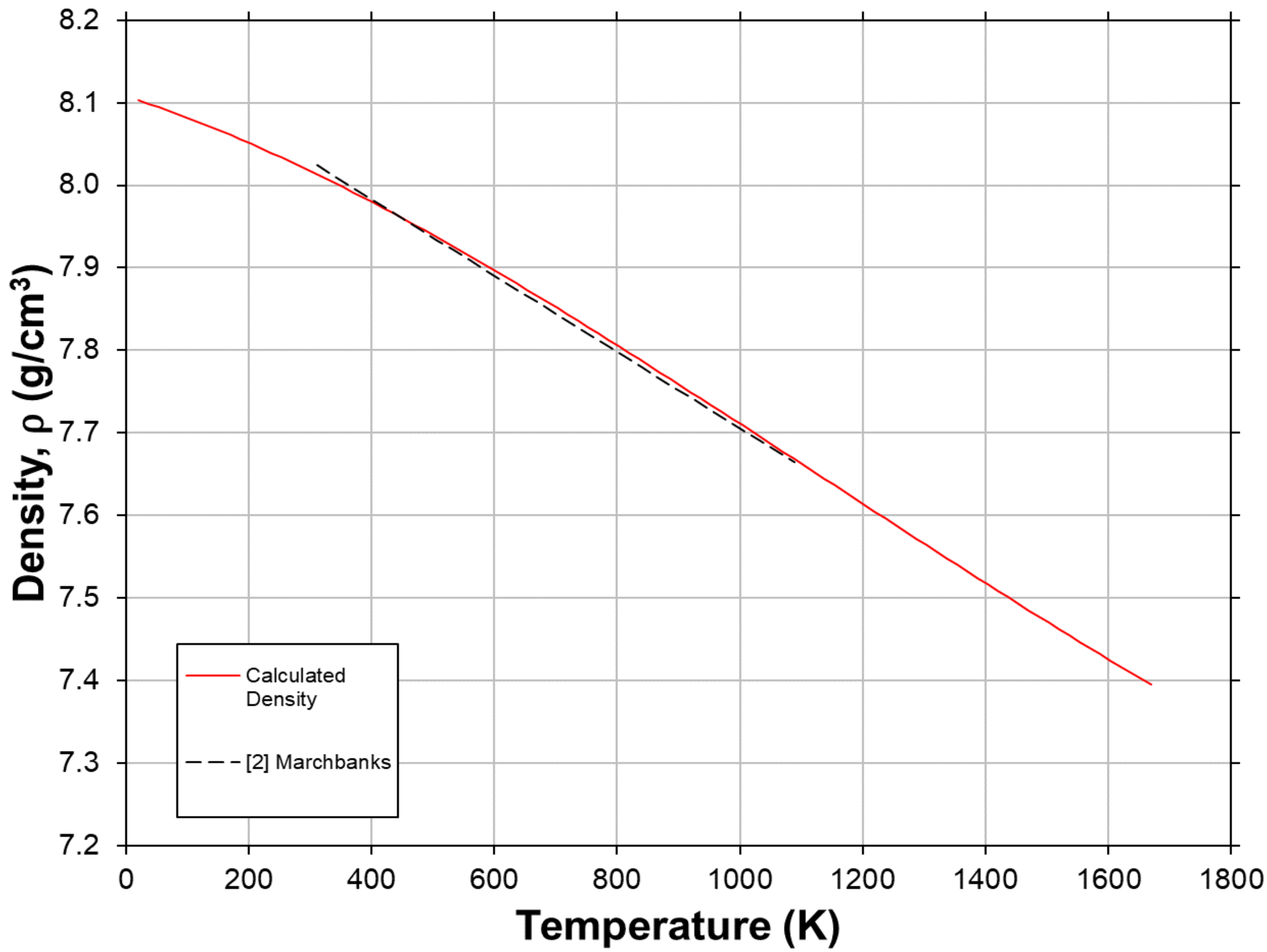

Figure 5.1.1-1: Density versus Temperature for SS304. Calculated from fitted trend of the Thermal Expansion data with comparison to Marchbanks (1976).

100% Theoretical Density

Temperature (T)		Density (ρ)		Temperature (T)		Density (ρ)	
K	(°F)	kg/m³	(lb/ft³)	K	(°F)	kg/m³	(lb/ft³)
20	(-423.7)	8103	(505.9)	700	(800.3)	7853	(490.2)
60	(-351.7)	8093	(505.2)	750	(890.3)	7830	(488.8)
80	(-315.7)	8087	(504.9)	800	(980.3)	7807	(487.4)
100	(-279.7)	8082	(504.5)	850	(1070.3)	7783	(485.9)
150	(-189.7)	8067	(503.6)	900	(1160.3)	7759	(484.4)
200	(-99.7)	8051	(502.6)	950	(1250.3)	7735	(482.9)
250	(-9.7)	8035	(501.6)	1000	(1340.3)	7711	(481.4)
300	(80.3)	8017	(500.5)	1050	(1430.3)	7687	(479.9)
350	(170.3)	7999	(499.4)	1100	(1520.3)	7663	(478.4)
400	(260.3)	7980	(498.2)	1200	(1700.3)	7614	(475.3)
450	(350.3)	7960	(497.0)	1300	(1880.3)	7566	(472.3)
500	(440.3)	7940	(495.7)	1400	(2060.3)	7518	(469.3)
550	(530.3)	7919	(494.4)	1500	(2240.3)	7471	(466.4)
600	(620.3)	7897	(493.0)	1600	(2420.3)	7426	(463.6)
650	(710.3)	7875	(491.6)	1670	(2546.3)	7395	(461.7)

Application Notes: Density is calculated here as a function of thermal expansion, as seen in the equation below to approximate the property trend with respect to temperature. The calculated trend is then compared against the density trend from reference [2].

Density Calculation:

$\rho(T) = \rho_{RT}/(1 + dL/L_0(T)/100)^3$

$\rho(T) = Density\ [kg/m^3]$

$Room\ Temperature\ Density\ (\rho_{RT}) = 8{,}020\ [kg/m^3]$

$T = Temperature\ [K]$

Temperature Range: $20 \leq T \leq 1670$

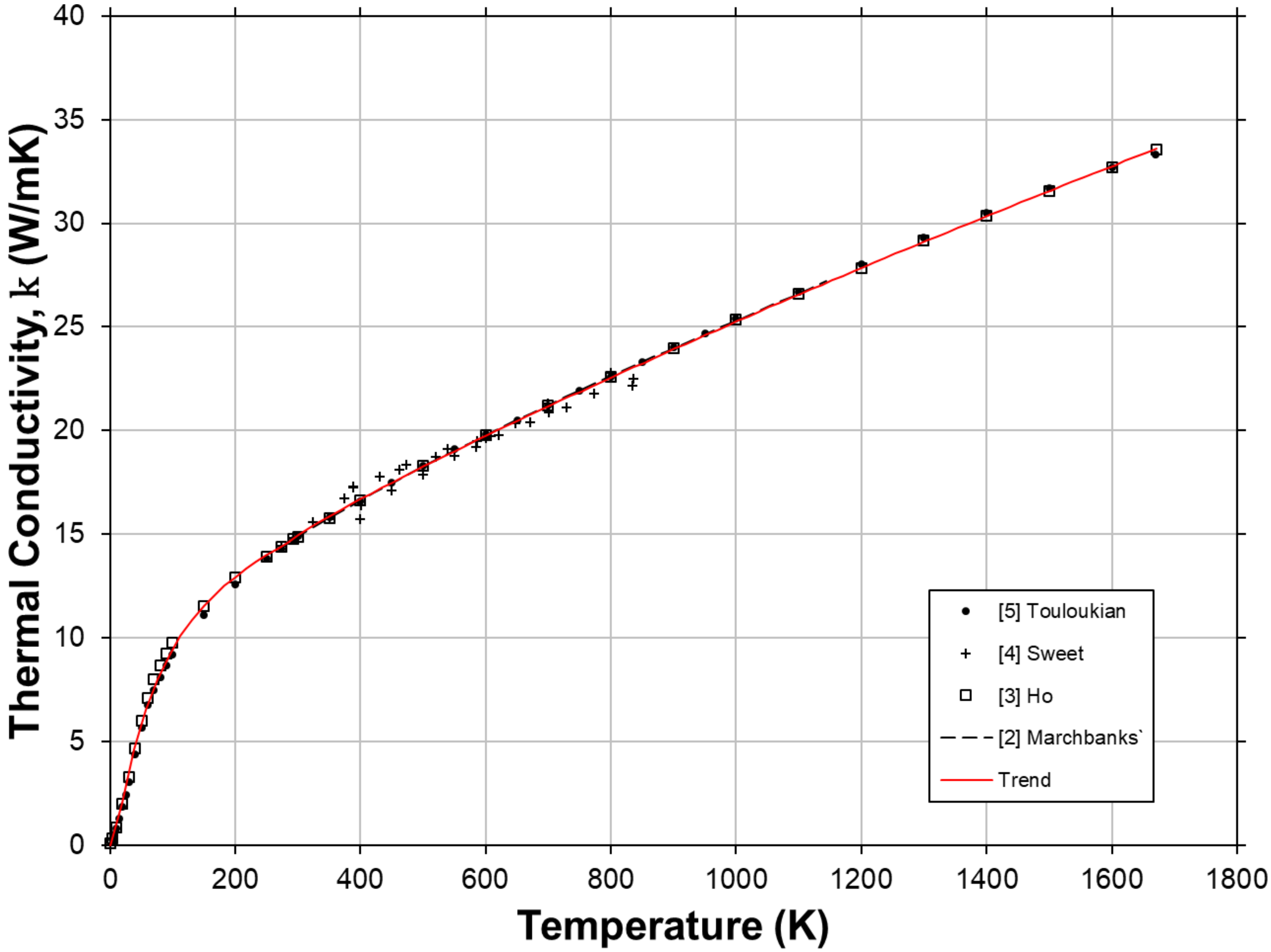

Figure 5.1.1-2: Thermal Conductivity versus Temperature of SS304 with comparison to Marchbanks (1976).

Thermal Conductivity with Temperature

100% Theoretical Density

Temperature (T)		Thermal Conductivity (k)		Temperature (T)		Thermal Conductivity (k)	
K	(°F)	W/(m-K)	((Btu·in)/(ft²·hr·°F))	K	(°F)	W/(m-K)	((Btu·in)/(ft²·hr·°F))
20	(-423.7)	2.10	(14.60)	650	(710.3)	20.46	(141.95)
60	(-351.7)	6.82	(47.31)	700	(800.3)	21.17	(146.86)
80	(-315.7)	8.32	(57.69)	750	(890.3)	21.87	(151.72)
100	(-279.7)	9.47	(65.73)	800	(980.3)	22.56	(156.51)
150	(-189.7)	11.53	(79.97)	850	(1070.3)	23.24	(161.25)
200	(-99.7)	12.93	(89.71)	900	(1160.3)	23.92	(165.95)
250	(-9.7)	13.99	(97.07)	1000	(1340.3)	25.25	(175.19)
300	(80.3)	14.95	(103.71)	1100	(1520.3)	26.56	(184.27)
350	(170.3)	15.86	(110.01)	1200	(1700.3)	27.84	(193.17)
400	(260.3)	16.70	(115.84)	1300	(1880.3)	29.10	(201.92)
450	(350.3)	17.49	(121.36)	1400	(2060.3)	30.34	(210.51)
500	(440.3)	18.26	(126.69)	1500	(2240.3)	31.56	(218.94)
550	(530.3)	19.01	(131.88)	1600	(2420.3)	32.75	(227.22)
600	(620.3)	19.74	(136.96)	1672	(2549.9)	33.60	(233.09)

Application Notes: The data for thermal conductivity is collected from references [2-5] and fitted with the equations below to approximate the property trend with respect to temperature.

Fit Equation:

For temperature range: $1 < T \leq 293$

$$k(T) = \left[A0 \cdot \left(\frac{T}{1000}\right)^N\right] \Big/ \left[1 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2\right]$$

For temperature range: $293 < T \leq 1672$

$$k(T) = B0 + B1 \cdot \left(\frac{T}{1000}\right) + B2 \cdot \left(\frac{T}{1000}\right)^2 + B\_2 / \left(\frac{T}{1000}\right)^2$$

$k(T) = Thermal\ Conductivity\ [W\ /\ (m \cdot K)]$

$T = Temperature\ [K]$

Constants:

T Range [K]	$1 < T \leq 293$		$293 < T \leq 1672$
N =	2.199	B0 =	11.17
A0 =	27080	B1 =	15.21
A1 =	42.47	B2 =	-1.067
A2 =	1283	B_2 =	-0.06204

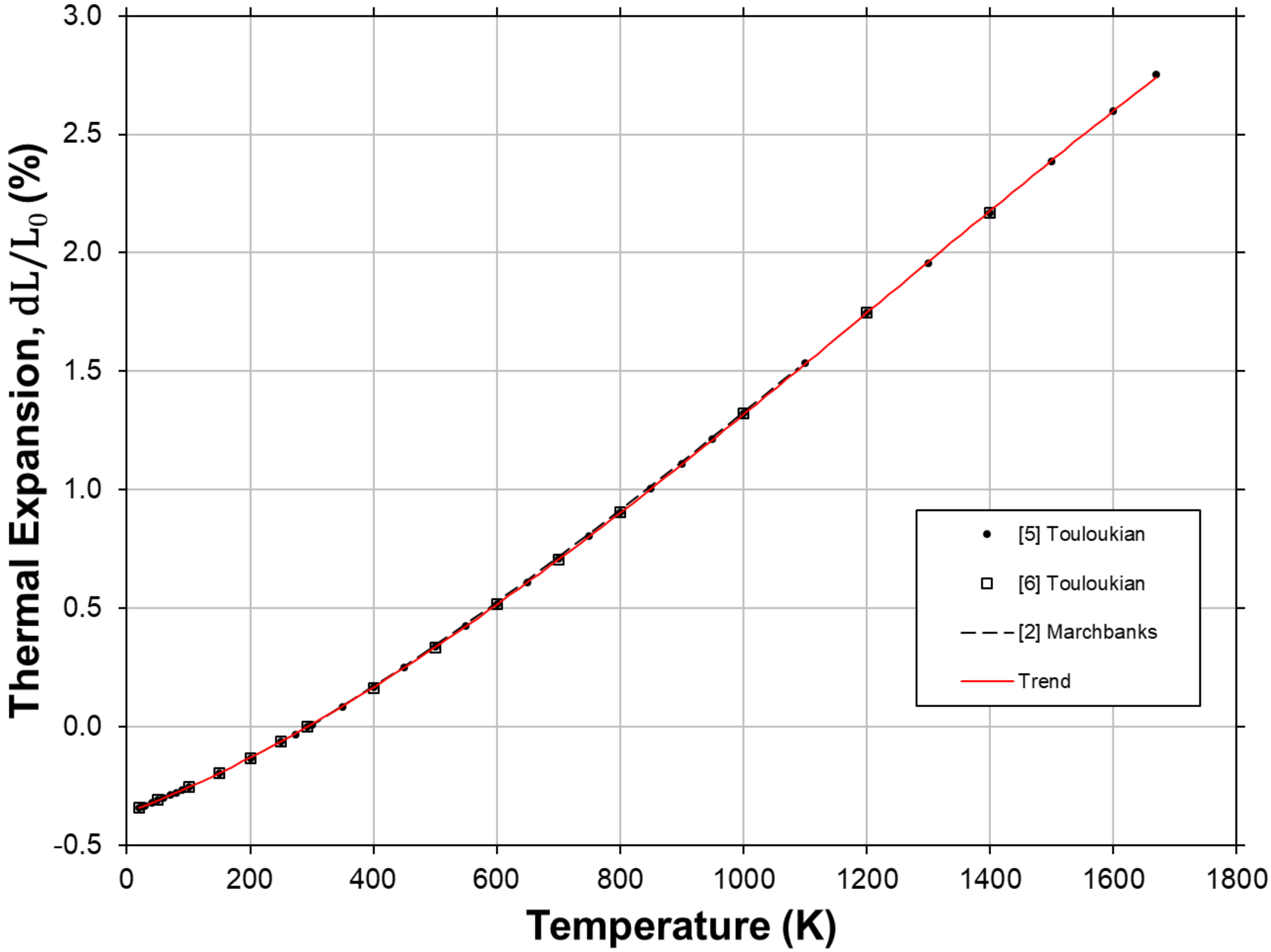

Figure 5.1.1-3: Thermal Expansion versus Temperature of SS304 with comparison to Marchbanks (1976).

100% Theoretical Density

Temperature (T) K	(°F)	Thermal Expansion (dL/L_0) %	Temperature (T) K	(°F)	Thermal Expansion (dL/L_0) %
20	(-423.7)	-0.343	700	(800.3)	0.705
60	(-351.7)	-0.301	750	(890.3)	0.804
80	(-315.7)	-0.278	800	(980.3)	0.903
100	(-279.7)	-0.255	850	(1070.3)	1.005
150	(-189.7)	-0.195	900	(1160.3)	1.108
200	(-99.7)	-0.130	950	(1250.3)	1.213
250	(-9.7)	-0.061	1000	(1340.3)	1.318
300	(80.3)	0.011	1050	(1430.3)	1.424
350	(170.3)	0.088	1100	(1520.3)	1.531
400	(260.3)	0.167	1200	(1700.3)	1.747
450	(350.3)	0.250	1300	(1880.3)	1.963
500	(440.3)	0.336	1400	(2060.3)	2.178
550	(530.3)	0.424	1500	(2240.3)	2.390
600	(620.3)	0.516	1600	(2420.3)	2.599
650	(710.3)	0.609	1670	(2546.3)	2.741

Application Notes: Data for thermal expansion was collected from references [2, 5, 6] and fitted with the equation below to approximate property trend with respect to temperature.

Fit Equation:

$$dL/L_0\,(T) = A0 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2 + A3 \cdot \left(\frac{T}{1000}\right)^3$$

$dL/L_0\,(T) = Thermal\ Expansion\ [\%]$

$T = Temperature\ [K]$

Constants:

T Range [K]: $20 \leq T \leq 1670$

A0 = -0.363

A1 = 0.9848

A2 = 0.9543

A3 = -0.2581

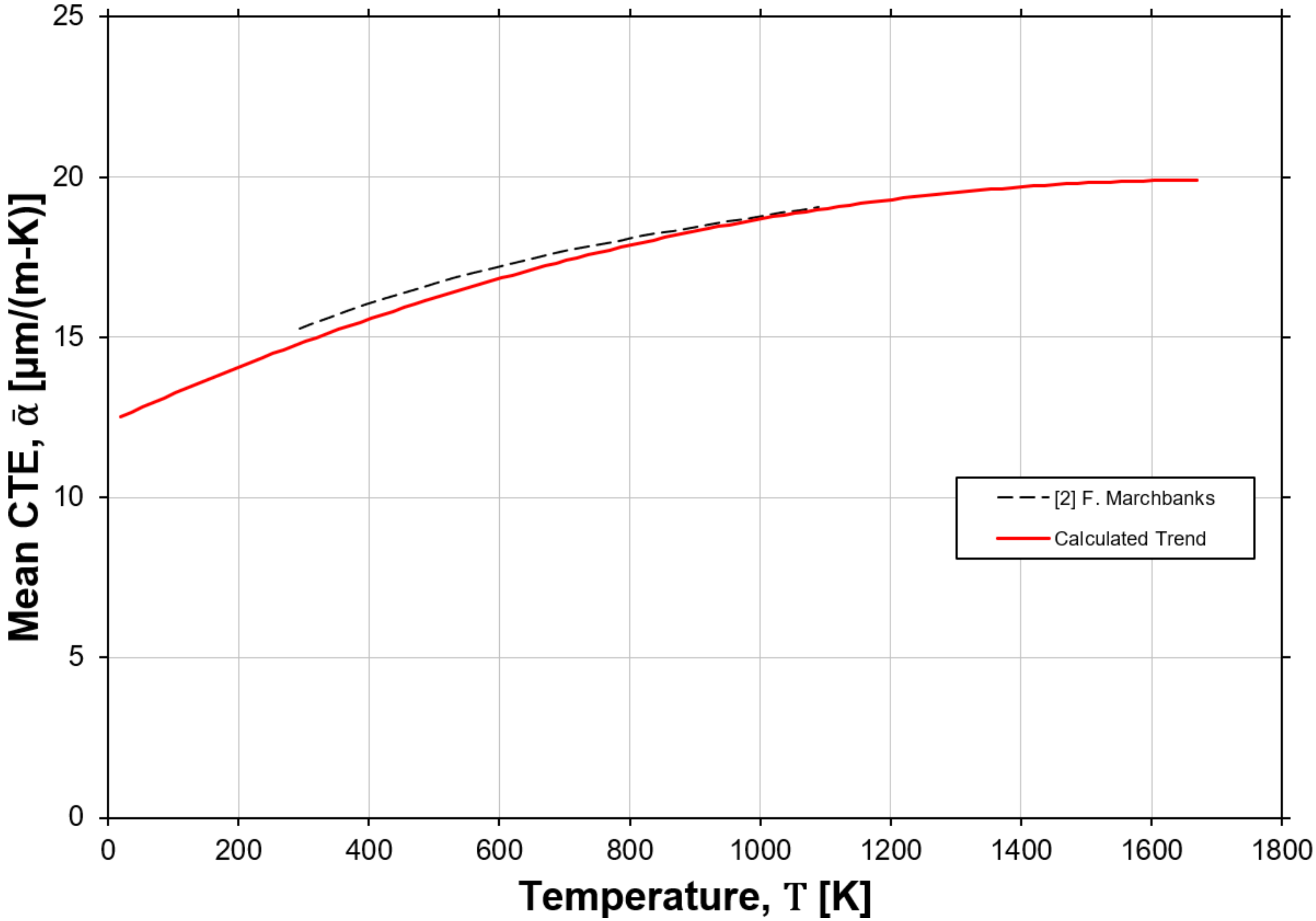

Figure 5.1.1-4: Mean Coefficient of Thermal Expansion versus Temperature of SS304. Calculated from fitted trend of the Thermal Expansion data for SS304 with comparison to Marchbanks (1976).

100% Theoretical Density

Temperature (T)		Mean CTE (ᾱ)		Temperature (T)		Mean CTE (ᾱ)	
K	(°F)	μm/(m-K)	(μin/(in-°F))	K	(°F)	μm/(m-K)	(μin/(in-°F))
20	(-423.7)	12.515	(6.953)	700	(800.3)	17.378	(9.654)
60	(-351.7)	12.877	(7.154)	750	(890.3)	17.630	(9.795)
80	(-315.7)	13.054	(7.252)	800	(980.3)	17.869	(9.927)
100	(-279.7)	13.229	(7.350)	850	(1070.3)	18.094	(10.052)
150	(-189.7)	13.656	(7.587)	900	(1160.3)	18.305	(10.170)
200	(-99.7)	14.068	(7.815)	950	(1250.3)	18.503	(10.280)
250	(-9.7)	14.464	(8.036)	1000	(1340.3)	18.688	(10.382)
300	(80.3)	14.846	(8.248)	1050	(1430.3)	18.859	(10.477)
350	(170.3)	15.213	(8.452)	1100	(1520.3)	19.017	(10.565)
400	(260.3)	15.566	(8.648)	1200	(1700.3)	19.293	(10.718)
450	(350.3)	15.903	(8.835)	1300	(1880.3)	19.518	(10.843)
500	(440.3)	16.227	(9.015)	1400	(2060.3)	19.691	(10.940)
550	(530.3)	16.536	(9.187)	1500	(2240.3)	19.815	(11.008)
600	(620.3)	16.831	(9.350)	1600	(2420.3)	19.890	(11.050)
650	(710.3)	17.111	(9.506)	1670	(2546.3)	19.913	(11.063)

Application Notes: Data for mean coefficient of thermal expansion is calculated as a function of thermal expansion. Calculated values are then fitted with the equation below to approximate property trend with respect to temperature. This trend is compared against the property trend from reference [2].

Fit Equation:

$$\bar{\alpha}(T) = A0 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2 + A3 \cdot \left(\frac{T}{1000}\right)^3$$

$\bar{\alpha}(T) = Coefficient\ of\ Thermal\ Expansion\ [\mu m/(m \cdot K)]$

$T = Temperature\ [K]$

Constants:

T. Range [K]: $20 \leq T \leq 1670$

A0 = 12.33

A1 = 9.298

A2 = -3.077

A3 = 0.1367

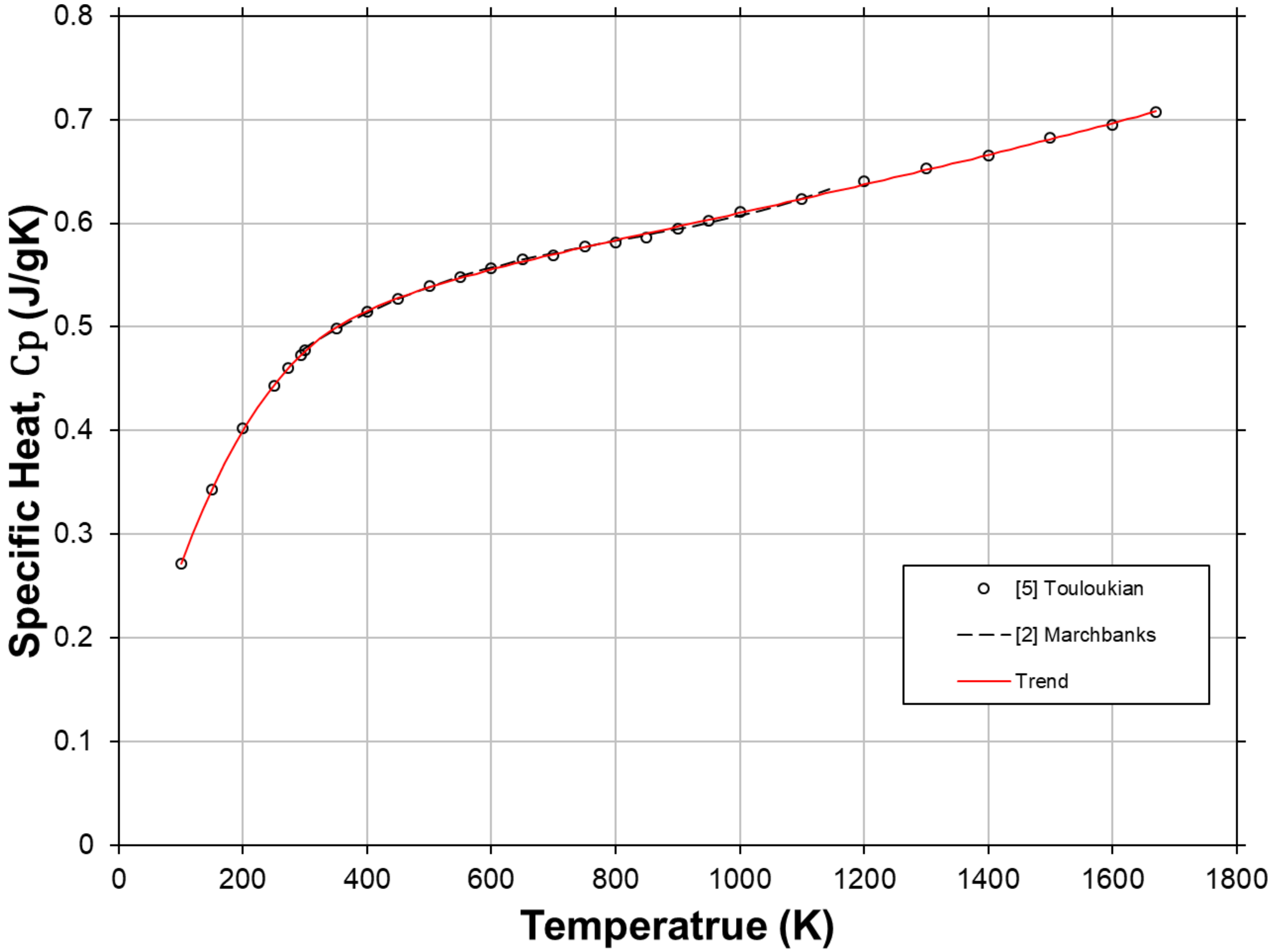

Figure 5.1.1-5: Specific Heat versus Temperature of SS304 with comparison to Marchbanks (1976).

100% Theoretical Density

Temperature (T)		Specific Heat (C_p)		Temperature (T)		Specific Heat (C_p)	
K	(°F)	J/(g-K)	(BTU/(lb-°F))	K	(°F)	J/(g-K)	(BTU/(lb-°F))
100	(-279.7)	0.272	(0.065)	850	(1070.3)	0.590	(0.141)
150	(-189.7)	0.344	(0.082)	900	(1160.3)	0.597	(0.143)
200	(-99.7)	0.401	(0.096)	950	(1250.3)	0.603	(0.144)
250	(-9.7)	0.444	(0.106)	1000	(1340.3)	0.610	(0.146)
300	(80.3)	0.477	(0.114)	1050	(1430.3)	0.617	(0.147)
350	(170.3)	0.499	(0.119)	1100	(1520.3)	0.623	(0.149)
400	(260.3)	0.515	(0.123)	1150	(1610.3)	0.630	(0.151)
450	(350.3)	0.528	(0.126)	1200	(1700.3)	0.637	(0.152)
500	(440.3)	0.538	(0.129)	1250	(1790.3)	0.644	(0.154)
550	(530.3)	0.547	(0.131)	1300	(1880.3)	0.651	(0.156)
600	(620.3)	0.555	(0.133)	1350	(1970.3)	0.659	(0.157)
650	(710.3)	0.563	(0.135)	1400	(2060.3)	0.666	(0.159)
700	(800.3)	0.570	(0.136)	1500	(2240.3)	0.681	(0.163)
750	(890.3)	0.577	(0.138)	1600	(2420.3)	0.697	(0.166)
800	(980.3)	0.584	(0.139)	1670	(2546.3)	0.708	(0.169)

Application Notes: Data for specific heat is collected from references [2, 5] and fitted with the equation below to approximate property trend with respect to temperature.

Fit Equation:

$$C_P(T) = A0 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2 + A3 \cdot \left(\frac{T}{1000}\right)^3 + A\_2/\left(\frac{T}{1000}\right)^2$$

$C_P(T) = Specific\ Heat\ [J/(g \cdot K)]$

$T = Temperature\ [K]$

Constants:

T. Range [K]:	$100 \leq T \leq 293$	$293 < T \leq 1670$
A0 =	0.07448	0.5244
A1 =	2.368	0.06317
A2 =	-4.202	0.02872
A3 =	2.584	0
A_2 =	0	-0.006221

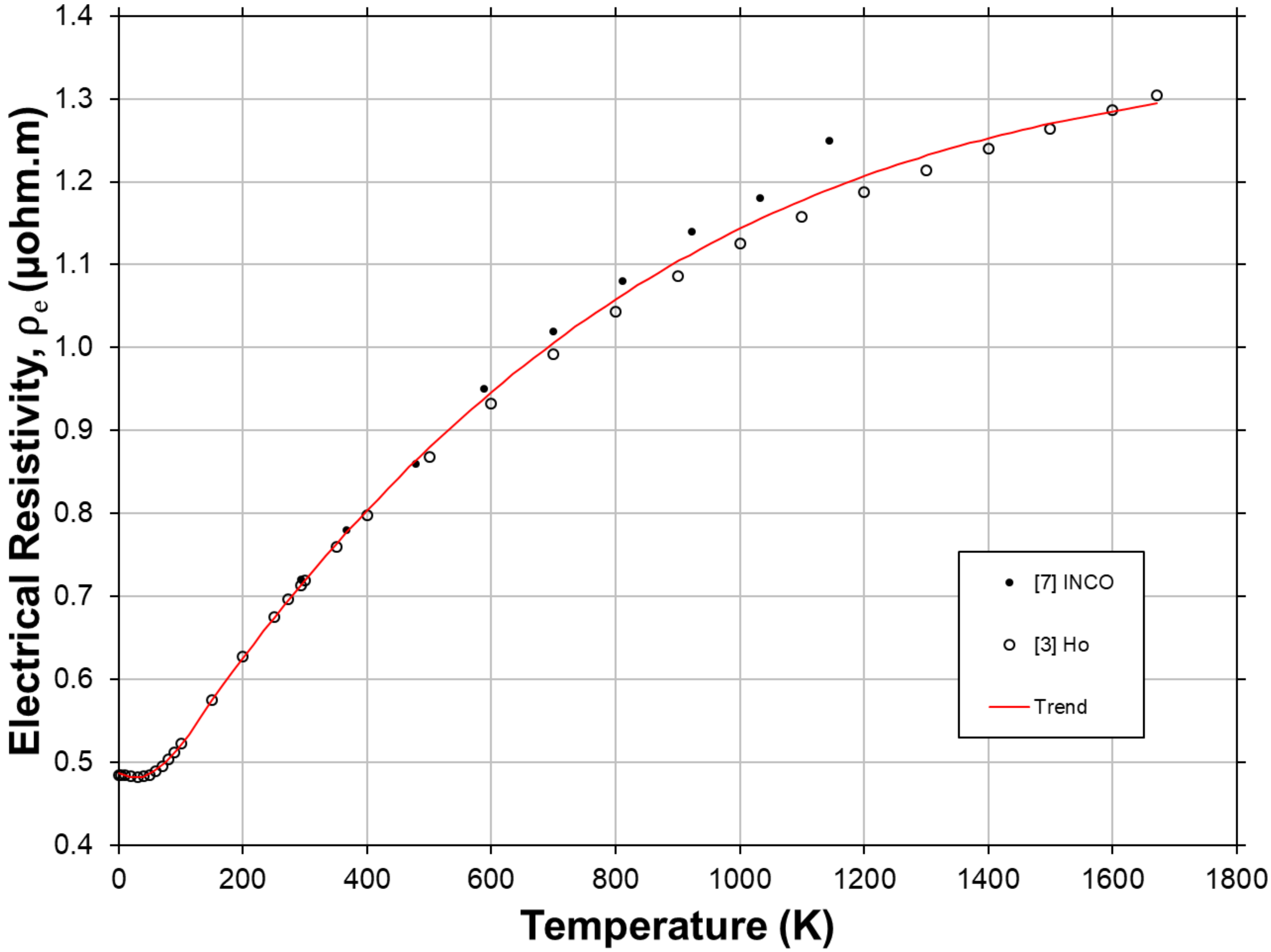

Figure 5.1.1-6: Electrical Resistivity versus Temperature of SS304.

Electrical Resistivity with Temperature

100% Theoretical Density

Temperature (T) K	(°F)	Electrical Resistivity (ρ_e) μΩ-m	(μΩ-in)	Temperature (T) K	(°F)	Electrical Resistivity (ρ_e) μΩ-m	(μΩ-in)
20	(-423.7)	0.481	(18.95)	700	(800.3)	1.006	(39.60)
60	(-351.7)	0.490	(19.31)	750	(890.3)	1.033	(40.66)
80	(-315.7)	0.503	(19.82)	800	(980.3)	1.058	(41.66)
100	(-279.7)	0.521	(20.49)	850	(1070.3)	1.082	(42.59)
150	(-189.7)	0.575	(22.63)	900	(1160.3)	1.104	(43.45)
200	(-99.7)	0.625	(24.63)	950	(1250.3)	1.124	(44.26)
250	(-9.7)	0.674	(26.52)	1000	(1340.3)	1.143	(45.01)
300	(80.3)	0.719	(28.32)	1050	(1430.3)	1.161	(45.71)
350	(170.3)	0.763	(30.02)	1100	(1520.3)	1.177	(46.36)
400	(260.3)	0.804	(31.64)	1200	(1700.3)	1.207	(47.51)
450	(350.3)	0.842	(33.17)	1300	(1880.3)	1.231	(48.48)
500	(440.3)	0.879	(34.61)	1400	(2060.3)	1.252	(49.31)
550	(530.3)	0.914	(35.97)	1500	(2240.3)	1.270	(50.00)
600	(620.3)	0.946	(37.26)	1600	(2420.3)	1.285	(50.59)
650	(710.3)	0.977	(38.46)	1672	(2549.9)	1.294	(50.96)

Application Notes: Data for electrical resistivity is collected from references [3, 7] and fitted with the equation below to approximate property trend with respect to temperature.

Fit Equation:

$$\rho_e(T) = A0 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2 + A3 \cdot \left(\frac{T}{1000}\right)^3$$

$\rho_e(T) = Electrical\ Resistivity\ [\mu\Omega \cdot m]$

$T = Temperature\ [K]$

Constants:

T. Range [K]:	$1 < T \leq 150$	$150 < T \leq 1672$
A0 =	0.4873	0.4075
A1 =	-0.4909	1.197
A2 =	10.31	-0.5541
A3 =	-20.8	0.09297

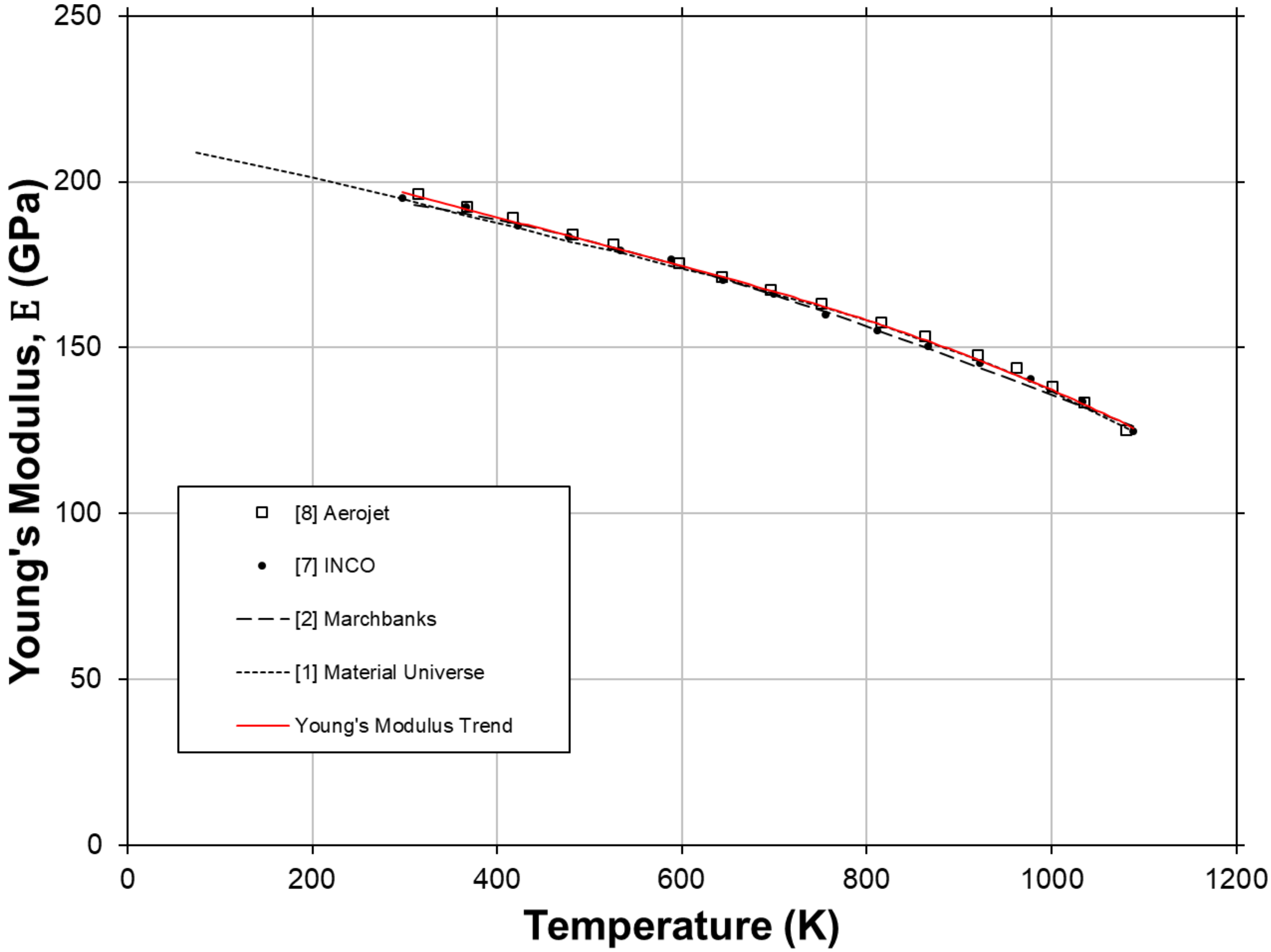

Figure 5.1.1-7: Young's Modulus versus Temperature of Inconel 718 with comparison to Marchbanks (1976) and Material Universe.

100% Theoretical Density

Temperature (T)		Young's Modulus (E)		Temperature (T)		Young's Modulus (E)	
K	(°F)	GPa	(Msi)	K	(°F)	GPa	(Msi)
297	(74.9)	197.06	(28.59)	675	(755.3)	168.94	(24.51)
325	(125.3)	194.92	(28.28)	700	(800.3)	166.93	(24.22)
350	(170.3)	193.04	(28.01)	725	(845.3)	164.86	(23.92)
375	(215.3)	191.19	(27.74)	750	(890.3)	162.74	(23.61)
400	(260.3)	189.35	(27.47)	775	(935.3)	160.56	(23.30)
425	(305.3)	187.53	(27.21)	800	(980.3)	158.32	(22.97)
450	(350.3)	185.72	(26.95)	825	(1025.3)	156.00	(22.64)
475	(395.3)	183.91	(26.69)	850	(1070.3)	153.61	(22.29)
500	(440.3)	182.10	(26.42)	875	(1115.3)	151.13	(21.93)
525	(485.3)	180.28	(26.16)	900	(1160.3)	148.57	(21.56)
550	(530.3)	178.46	(25.89)	925	(1205.3)	145.91	(21.17)
575	(575.3)	176.61	(25.63)	950	(1250.3)	143.16	(20.77)
600	(620.3)	174.74	(25.35)	1000	(1340.3)	137.34	(19.93)
625	(665.3)	172.84	(25.08)	1050	(1430.3)	131.06	(19.02)
650	(710.3)	170.91	(24.80)	1089	(1500.5)	125.82	(18.26)

Application Notes: Data for Young's Modulus is collected from references [1, 2, 7, 8] and fitted with the equation below to approximate property trend with respect to temperature.

Fit Equations:

$$E(T) = A0 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2 + A3 \cdot \left(\frac{T}{1000}\right)^3$$

$E(T) = Young's\ Modulus\ [GPa]$

$T = Temperature\ [K]$

Constants:

T Range [K]:	$297 \leq T \leq 1089$
A0 =	224.1
A1 =	-109.8
A2 =	80.16
A3 =	-57.12

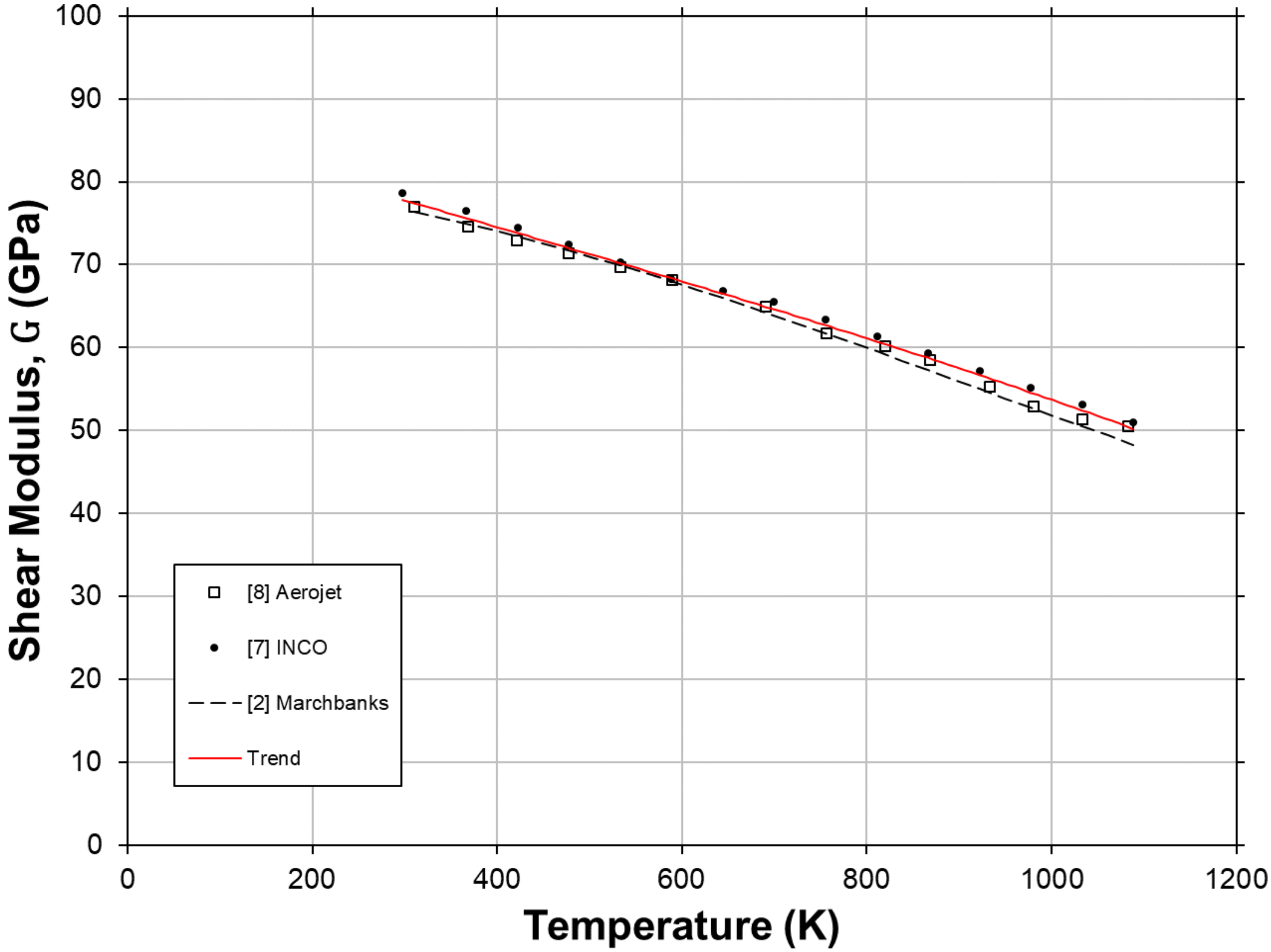

Figure 5.1.1-8: Shear Modulus versus Temperature of SS304 with comparison to Marchbanks (1976).

Shear Modulus with Temperature

100% Theoretical Density

Temperature (T)		Shear Modulus (G)		Temperature (T)		Shear Modulus (G)	
K	(°F)	GPa	(Msi)	K	(°F)	GPa	(Msi)
297	(74.9)	77.86	(11.30)	675	(755.3)	65.46	(9.50)
325	(125.3)	76.96	(11.17)	700	(800.3)	64.60	(9.37)
350	(170.3)	76.15	(11.05)	725	(845.3)	63.75	(9.25)
375	(215.3)	75.34	(10.93)	750	(890.3)	62.88	(9.12)
400	(260.3)	74.53	(10.81)	775	(935.3)	62.00	(9.00)
425	(305.3)	73.72	(10.70)	800	(980.3)	61.12	(8.87)
450	(350.3)	72.91	(10.58)	825	(1025.3)	60.23	(8.74)
475	(395.3)	72.10	(10.46)	850	(1070.3)	59.33	(8.61)
500	(440.3)	71.28	(10.34)	875	(1115.3)	58.42	(8.48)
525	(485.3)	70.46	(10.22)	900	(1160.3)	57.50	(8.34)
550	(530.3)	69.64	(10.10)	925	(1205.3)	56.58	(8.21)
575	(575.3)	68.81	(9.98)	950	(1250.3)	55.63	(8.07)
600	(620.3)	67.98	(9.86)	1000	(1340.3)	53.72	(7.79)
625	(665.3)	67.14	(9.74)	1050	(1430.3)	51.76	(7.51)
650	(710.3)	66.30	(9.62)	1089	(1500.5)	50.19	(7.28)

Application Notes: Data for shear modulus is collected from references [2, 7, 8] and fitted with the equation below to approximate property trend with respect to temperature.

Fit Equations:

$$G(T) = A0 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2 + A3 \cdot \left(\frac{T}{1000}\right)^3$$

$G(T) = Shear\ Modulus\ [GPa]$

$T = Temperature\ [K]$

Constants:

T Range [K]: $297 \leq T \leq 1089$

A0 =	87.66
A1 =	-34.06
A2 =	5.073
A3 =	-4.953

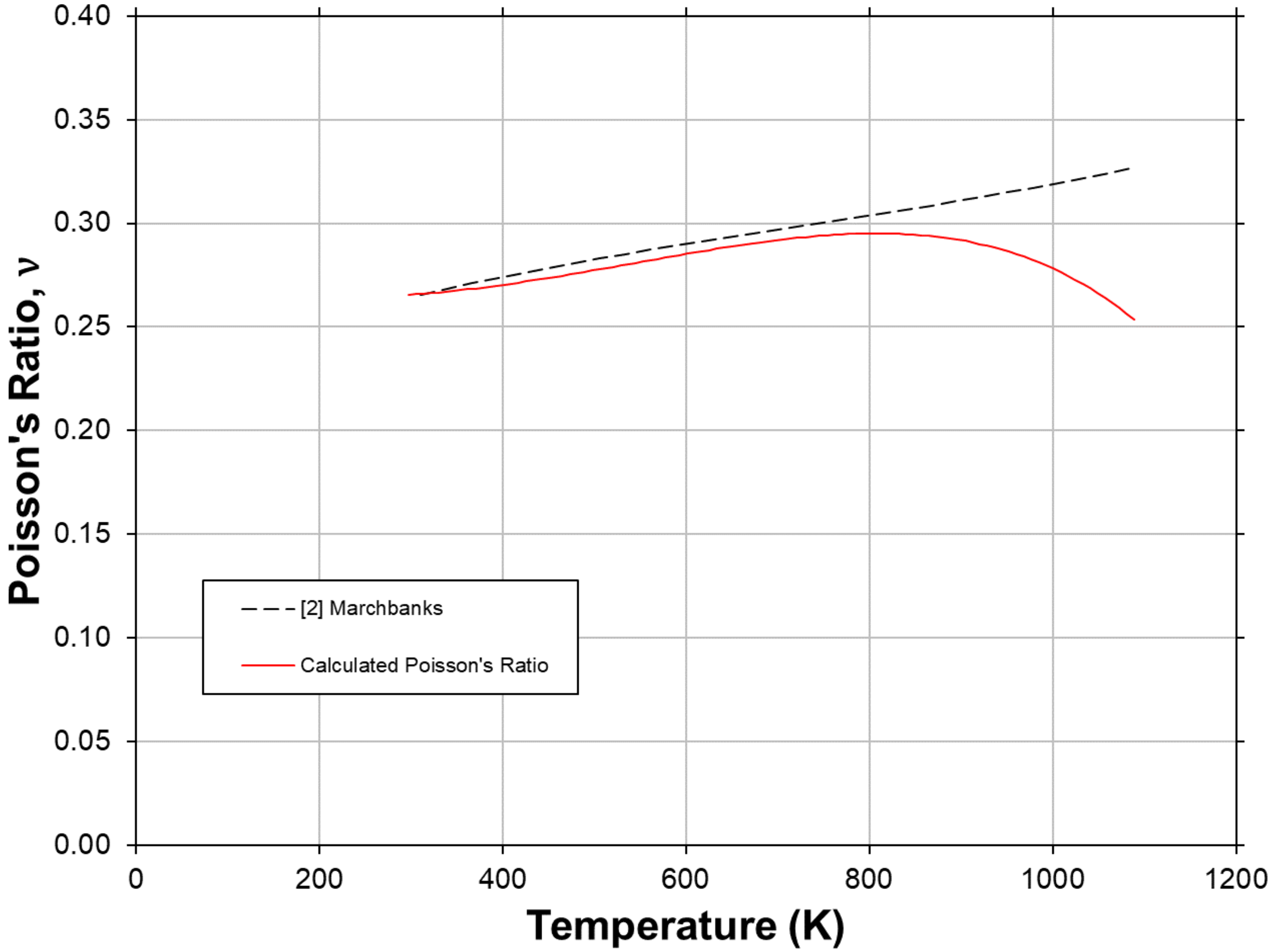

Figure 5.1.1-9: Poisson's Ratio versus Temperature of SS304. Calculated for the based Young's Modulus and Shear Modulus trends with comparison to Marchbanks (1976).

100% Theoretical Density

Temperature (T)		Poisson's Ratio (ν)	Temperature (T)		Poisson's Ratio (ν)
K	(°F)		K	(°F)	
297	(74.9)	0.265	675	(755.3)	0.290
325	(125.3)	0.266	700	(800.3)	0.292
350	(170.3)	0.268	725	(845.3)	0.293
375	(215.3)	0.269	750	(890.3)	0.294
400	(260.3)	0.270	775	(935.3)	0.295
425	(305.3)	0.272	800	(980.3)	0.295
450	(350.3)	0.274	825	(1025.3)	0.295
475	(395.3)	0.275	850	(1070.3)	0.294
500	(440.3)	0.277	875	(1115.3)	0.293
525	(485.3)	0.279	900	(1160.3)	0.292
550	(530.3)	0.281	925	(1205.3)	0.290
575	(575.3)	0.283	950	(1250.3)	0.287
600	(620.3)	0.285	1000	(1340.3)	0.278
625	(665.3)	0.287	1050	(1430.3)	0.266
650	(710.3)	0.289	1089	(1500.5)	0.254

Application Notes: Poisson's ratio is calculated as a function of Young's modulus and shear modulus, as seen in the equation below to approximate property trend with respect to temperature. This trend is then compared against property trend from reference [2].

Fit Equations:

$$\nu(T) = E(T)/(2 \cdot G(T)) - 1$$

$\nu(T) = Poisson's\ Ratio$

$T = Temperature\ [K]$

Temperature Range: $297 \leq T \leq 1089$

Temp. (T) K	Physical and Electrical: Density (ρ) kg/m³	Electrical Resistivity (ρ_e) μΩ-m	Thermal: Thermal Conductivity (k) W/(m-K)	Thermal Expansion (dL/L_0) %	Mean CTE ($\bar{\alpha}$) 10^{-6}/K	Specific Heat (C_p) J/(g-K)	Elastic: Young's Modulus (E) GPa	Shear Modulus (G) GPa	Poisson's Ratio (ν)
100	8082	0.521	9.47	-0.255	13.23	0.272	-	-	-
150	8067	0.575	11.53	-0.195	13.66	0.344	-	-	-
200	8051	0.625	12.93	-0.130	14.07	0.401	-	-	-
250	8035	0.674	13.99	-0.061	14.46	0.444	-	-	-
300	8017	0.719	14.95	0.011	14.85	0.477	196.83	77.76	0.27
350	7999	0.763	15.86	0.088	15.21	0.499	193.04	76.15	0.27
400	7980	0.804	16.70	0.167	15.57	0.515	189.35	74.53	0.27
450	7960	0.842	17.49	0.250	15.90	0.528	185.72	72.91	0.27
500	7940	0.879	18.26	0.336	16.23	0.538	182.10	71.28	0.28
550	7919	0.914	19.01	0.424	16.54	0.547	178.46	69.64	0.28
600	7897	0.946	19.74	0.516	16.83	0.555	174.74	67.98	0.29
650	7875	0.977	20.46	0.609	17.11	0.563	170.91	66.30	0.29
700	7853	1.006	21.17	0.705	17.38	0.570	166.93	64.60	0.29
750	7830	1.033	21.87	0.804	17.63	0.577	162.74	62.88	0.29
800	7807	1.058	22.56	0.903	17.87	0.584	158.32	61.12	0.30
850	7783	1.082	23.24	1.005	18.09	0.590	153.61	59.33	0.29
900	7759	1.104	23.92	1.108	18.31	0.597	148.57	57.50	0.29
950	7735	1.124	24.59	1.213	18.50	0.603	143.16	55.63	0.29
1000	7711	1.143	25.25	1.318	18.69	0.610	137.34	53.72	0.28
1100	7663	1.177	26.56	1.531	19.02	0.623	-	-	-
1200	7614	1.207	27.84	1.747	19.29	0.637	-	-	-
1300	7566	1.231	29.10	1.963	19.52	0.651	-	-	-
1400	7518	1.252	30.34	2.178	19.69	0.666	-	-	-
1500	7471	1.270	31.56	2.390	19.82	0.681	-	-	-
1600	7426	1.285	32.75	2.599	19.89	0.697	-	-	-

[1] Material Universe. (Accessed July 2019).

[2] F. Marchbanks, M.A. Moen, R.E. Irvin, Nuclear Systems Materials Handbook: Design Data, International Conference on the Mechanical Behavior of Materials, Oak Ridge National Laboratory, Boston, MA, USA, 1976.

[3] C.Y. Ho, T.K. Chu, Electrical Resistivity and Thermal Conductivity of Nine Selected AISI stainless Steels, Thermophysical and Electronic Properties Information Analysis Center, Lafayette, IN, 1977.

[4] J.N. Sweet, E.P. Roth, M. Moss, Thermal conductivity of Inconel 718 and 304 stainless steel, International Journal of Thermophysics 8(5) (1987) 593-606.

[5] Y.S. Touloukian, C.Y. Ho, Thermophysical Properties of Selected Aerospace Materials., Thermophysical Properties of Seven Materials, Thermophysical and Electronic Properties Information Analysis Center, Lafayette, IN, 1977.

[6] Y.S. Touloukian, R.K. Kirby, R.E. Taylor, P.D. Desai, Thermal Expansion - Metallic Elements and Alloys, Thermophysical Properties of Matter - the TPRC Data Series, 1975, pp. 1272-1284.

[7] Austenitic chromium-nickel stainless steels- Engineering properties at elevated temperatures, Engineering Properties at Elevated Temperatures, INCO databooks, 1968.

[8] Ferrous alloys, Materials properties data book Aerojet Nuclear Systems Co., Sacramento, Calif. (USA), 1970.

5 Ferrous Alloys

5.1 Austenitic Stainless Steels

Room Temperature Properties

Theoretical Density, [kg/m^3]	7,959
Melting Point, [K]	1650 to 1720
Specific Heat, [J/(g-K)]	0.455
Thermal Conductivity, [W/(m-K)]	14.5
Linear expansion coefficient, [μm/(m-K)]	15.69
Electrical resistivity, [μΩ-m]	0.74
Young's Modulus, [GPa]	198.3
Shear Modulus, [GPa]	78.7
Poisson's Ratio, [-]	0.260

Composition

Table 5.1.2-1: Typical Composition ranges for 347-grade stainless steel (percent by weight) [1].

Grade		Fe	Cr	Ni	C	Mn	Si	P	S	Nb+Ta
347	Min.	Balance	17.0	9.0	-	-	-	-	-	10xC
	Max.		19.0	13.0	0.08	2.0	0.75	0.045	0.030	1.0
347H	Min.	Balance	17.0	9.0	0.04	-	-	-	-	8xC
	Max.		19.0	13.0	0.10	2.0	0.75	0.045	0.030	1.0

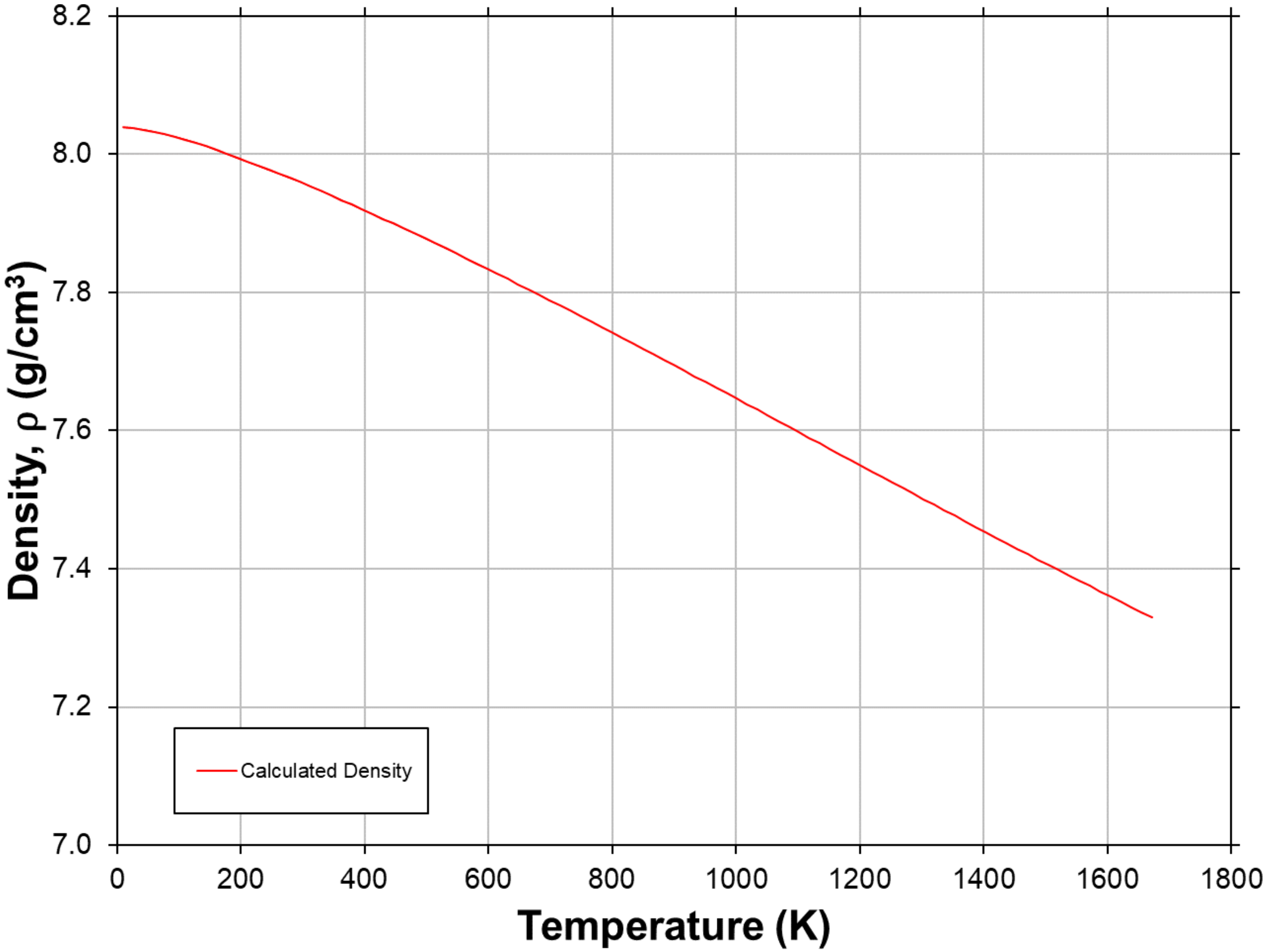

Figure 5.1.2-1: Density versus Temperature for SS347. Calculated from fitted trend of the Thermal Expansion data.

100% Theoretical Density

Temperature (T)		Density (ρ)		Temperature (T)		Density (ρ)	
K	(°F)	kg/m³	(lb/ft³)	K	(°F)	kg/m³	(lb/ft³)
20	(-423.7)	8038	(501.8)	700	(800.3)	7788	(486.2)
60	(-351.7)	8032	(501.5)	750	(890.3)	7765	(484.8)
80	(-315.7)	8028	(501.2)	800	(980.3)	7742	(483.3)
100	(-279.7)	8024	(500.9)	850	(1070.3)	7718	(481.8)
150	(-189.7)	8009	(500.0)	900	(1160.3)	7694	(480.4)
200	(-99.7)	7993	(499.0)	950	(1250.3)	7671	(478.9)
250	(-9.7)	7975	(497.9)	1000	(1340.3)	7647	(477.4)
300	(80.3)	7958	(496.8)	1050	(1430.3)	7622	(475.9)
350	(170.3)	7939	(495.6)	1100	(1520.3)	7598	(474.4)
400	(260.3)	7919	(494.4)	1200	(1700.3)	7550	(471.3)
450	(350.3)	7898	(493.1)	1300	(1880.3)	7502	(468.3)
500	(440.3)	7877	(491.8)	1400	(2060.3)	7454	(465.4)
550	(530.3)	7855	(490.4)	1500	(2240.3)	7408	(462.5)
600	(620.3)	7833	(489.0)	1600	(2420.3)	7362	(459.6)
650	(710.3)	7811	(487.6)	1672	(2549.9)	7330	(457.6)

Application Notes: Density trend is calculated as a function of thermal expansion as seen in the equation below to approximate property trend with respect to temperature.

Density Calculation:

$\rho(T) = \rho_{RT}/(1 + dL/L_0(T)/100)^3$

$\rho(T) = Density\ [kg/m^3]$

$Room\ Temperature\ Density\ (\rho_{RT}) = 7{,}960\ [kg/m^3]$

$T = Temperature\ [K]$

Temperature Range: $10 \leq T \leq 1672$

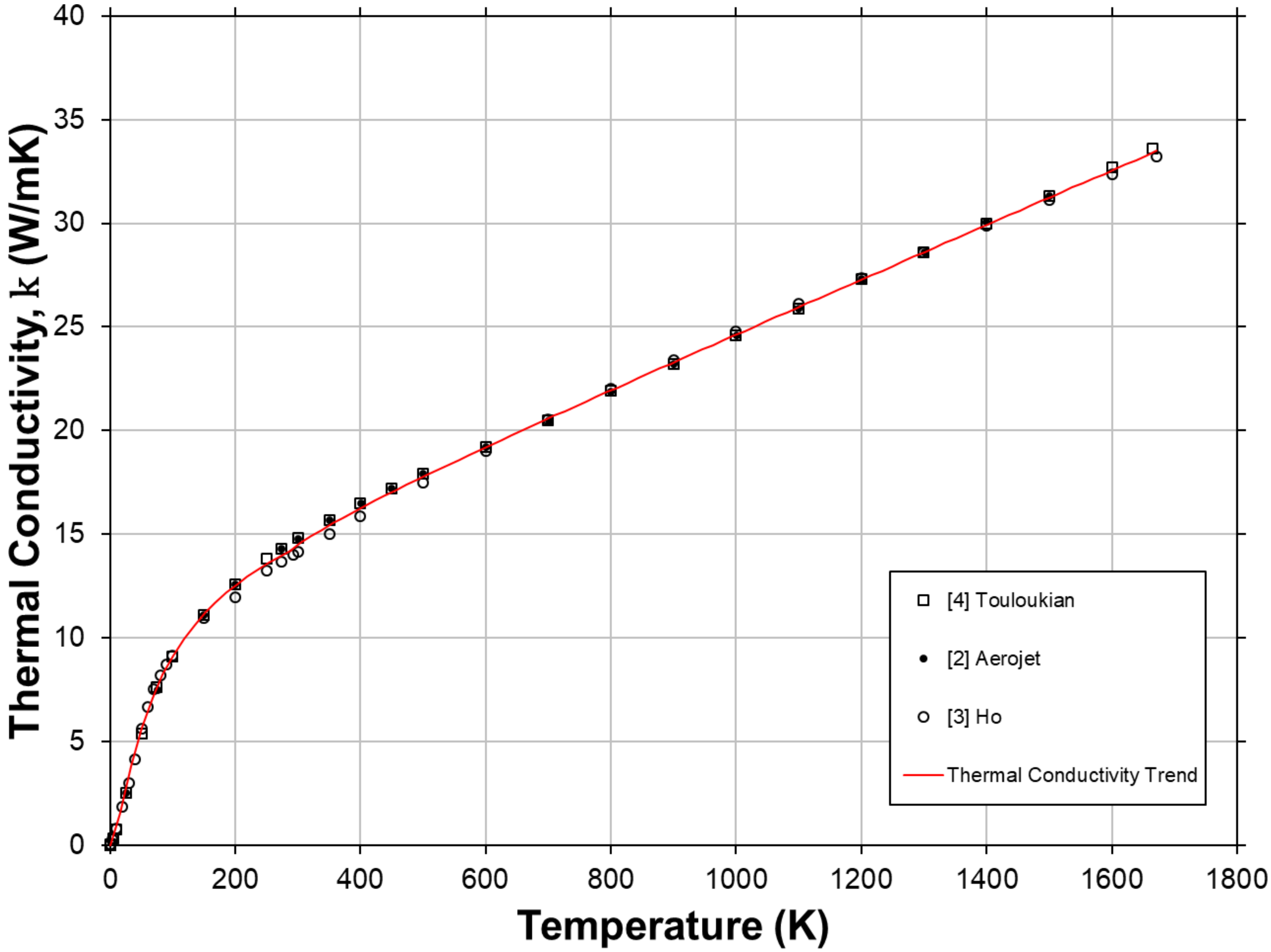

Figure 5.1.2-2: Thermal Conductivity versus Temperature of SS347. Displaying fitted trend of the data.

100% Theoretical Density

Temperature (T)		Thermal Conductivity (k)		Temperature (T)		Thermal Conductivity (k)	
K	(°F)	W/(m-K)	((Btu-in.)/(ft.^{2}-hr-°F))	K	(°F)	W/(m-K)	((Btu-in.)/(ft.^{2}-hr-°F))
20	(-423.7)	1.98	(13.72)	600	(620.3)	19.20	(133.23)
60	(-351.7)	6.48	(44.97)	700	(800.3)	20.58	(142.82)
80	(-315.7)	7.95	(55.16)	800	(980.3)	21.94	(152.25)
100	(-279.7)	9.10	(63.11)	900	(1160.3)	23.29	(161.58)
150	(-189.7)	11.14	(77.26)	1000	(1340.3)	24.62	(170.84)
200	(-99.7)	12.53	(86.91)	1100	(1520.3)	25.95	(180.07)
250	(-9.7)	13.57	(94.15)	1200	(1700.3)	27.28	(189.26)
300	(80.3)	14.51	(100.67)	1300	(1880.3)	28.60	(198.42)
350	(170.3)	15.43	(107.05)	1400	(2060.3)	29.92	(207.57)
400	(260.3)	16.26	(112.80)	1500	(2240.3)	31.23	(216.70)
450	(350.3)	17.03	(118.18)	1600	(2420.3)	32.55	(225.81)
500	(440.3)	17.78	(123.33)	1672	(2549.9)	33.49	(232.37)

Application Notes: Data for thermal conductivity is collected from references [2-4], and fitted with the equations below to approximate property trend with respect to temperature.

Fit Equation:

For temperature range: $1 < T \leq 293$

$$k(T) = \left[A0 \cdot \left(\frac{T}{1000}\right)^N\right] \Big/ \left[1 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2\right]$$

For temperature range: $293 < T \leq 1672$

$$k(T) = B0 + B1 \cdot \left(\frac{T}{1000}\right) + B2 \cdot \left(\frac{T}{1000}\right)^2 + B\_2/\left(\frac{T}{1000}\right)^2$$

$k(T) = Thermal\ Conductivity\ [W\ /\ (m \cdot K)]$

$T = Temperature\ [K]$

Constants:

Temperature Range [K]:	$1 < T \leq 293$		$293 < T \leq 1672$
N =	2.184	B0 =	11.52
A0 =	24520	B1 =	13.24
A1 =	46.76	B2 =	-0.04806
A2 =	1197	B_2 =	-0.08805

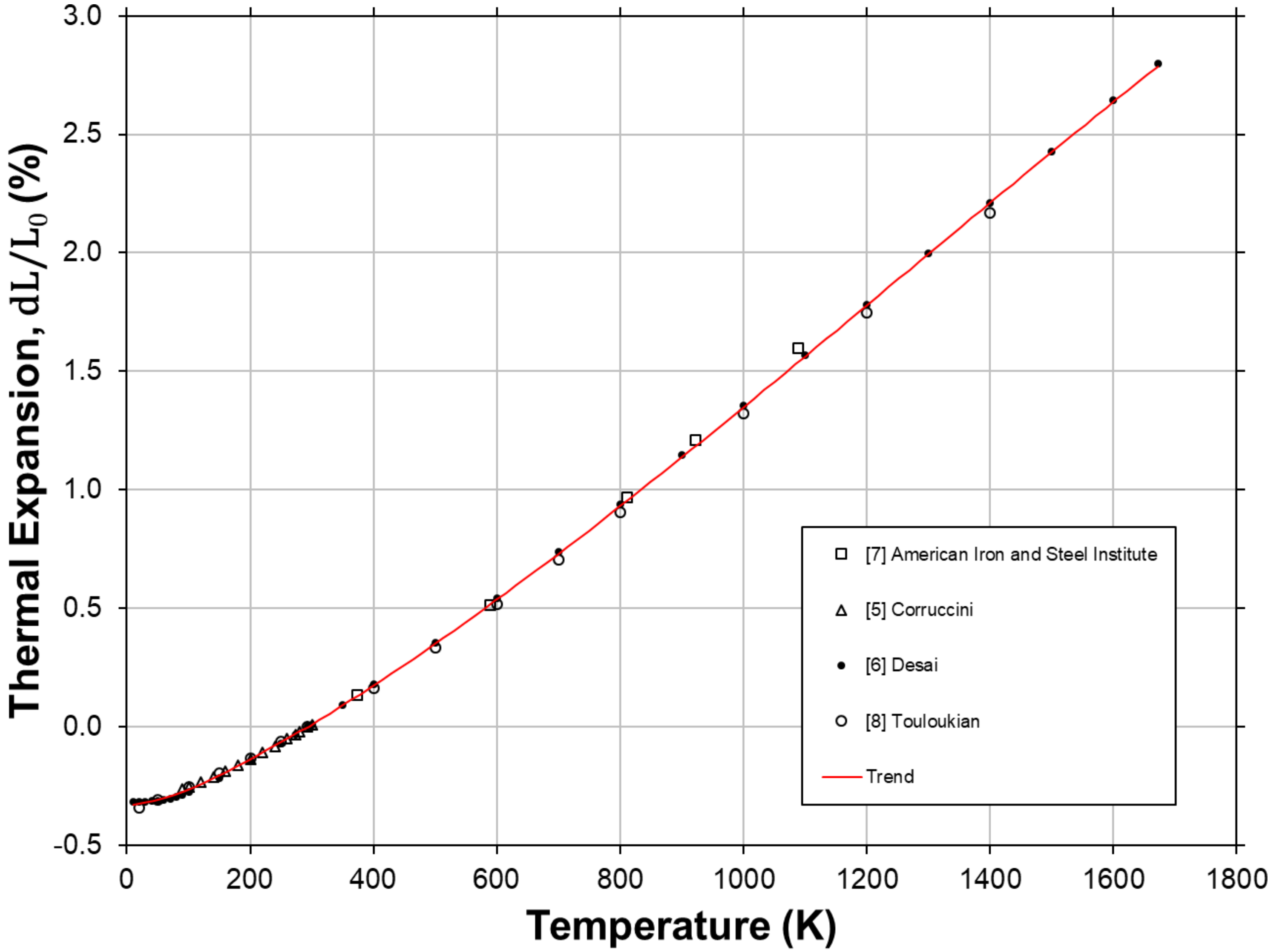

Figure 5.1.2-3: Thermal Expansion versus Temperature of SS347. Displaying fitted trend of the data.

100% Theoretical Density

Temperature (T) K	(°F)	Thermal Expansion (dL/L_0) %	Temperature (T) K	(°F)	Thermal Expansion (dL/L_0) %
20	(-423.7)	-0.325	700	(800.3)	0.730
60	(-351.7)	-0.302	750	(890.3)	0.830
80	(-315.7)	-0.285	800	(980.3)	0.931
100	(-279.7)	-0.265	850	(1070.3)	1.034
150	(-189.7)	-0.206	900	(1160.3)	1.137
200	(-99.7)	-0.137	950	(1250.3)	1.242
250	(-9.7)	-0.064	1000	(1340.3)	1.348
300	(80.3)	0.008	1050	(1430.3)	1.455
350	(170.3)	0.090	1100	(1520.3)	1.562
400	(260.3)	0.174	1200	(1700.3)	1.778
450	(350.3)	0.261	1300	(1880.3)	1.995
500	(440.3)	0.351	1400	(2060.3)	2.211
550	(530.3)	0.442	1500	(2240.3)	2.426
600	(620.3)	0.536	1600	(2420.3)	2.638
650	(710.3)	0.632	1672	(2549.9)	2.788

Application Notes: Thermal expansion is collected from references [5-8], and fitted with the equation below to approximate property trend with respect to temperature.

Fit Equation:

$$dL/L_0\,(T) = A0 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2 + A3 \cdot \left(\frac{T}{1000}\right)^3$$

$dL/L_0\,(T) = Thermal\ Expansion\ [\%]$

$T = Temperature\ [K]$

Constants:

Temperature Range [K]:	$10 < T \leq 293$	$293 < T \leq 1672$
A0 =	-0.3304	-0.4153
A1 =	0.1796	1.199
A2 =	5.497	0.7665
A3 =	-7.823	-0.202

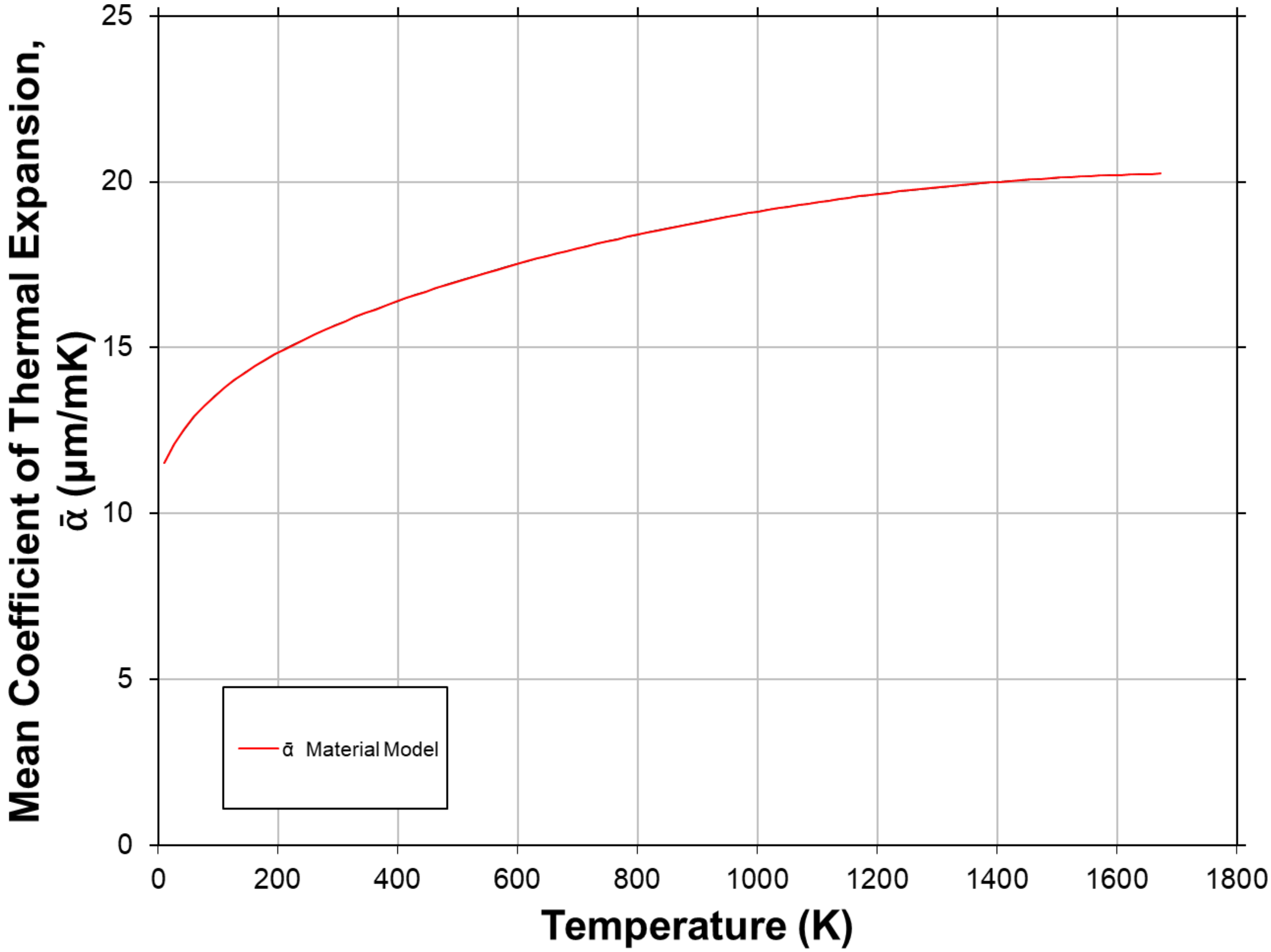

Figure 5.1.2-4: Mean Coefficient of Thermal Expansion versus Temperature of SS347. Calculated from Thermal Expansion data for SS347.

100% Theoretical Density

Temperature (T)		Mean CTE (ᾱ)		Temperature (T)		Mean CTE (ᾱ)	
K	(°F)	µm/(m-K)	(µin/(in-°F))	K	(°F)	µm/(m-K)	(µin/(in-°F))
20	(-423.7)	11.871	(6.595)	700	(800.3)	17.996	(9.998)
60	(-351.7)	12.912	(7.173)	750	(890.3)	18.209	(10.116)
80	(-315.7)	13.298	(7.388)	800	(980.3)	18.411	(10.228)
100	(-279.7)	13.630	(7.572)	850	(1070.3)	18.600	(10.334)
150	(-189.7)	14.307	(7.948)	900	(1160.3)	18.779	(10.433)
200	(-99.7)	14.846	(8.248)	950	(1250.3)	18.946	(10.526)
250	(-9.7)	15.304	(8.502)	1000	(1340.3)	19.103	(10.613)
300	(80.3)	15.708	(8.727)	1050	(1430.3)	19.250	(10.694)
350	(170.3)	16.072	(8.929)	1100	(1520.3)	19.386	(10.770)
400	(260.3)	16.406	(9.114)	1200	(1700.3)	19.628	(10.904)
450	(350.3)	16.715	(9.286)	1300	(1880.3)	19.830	(11.017)
500	(440.3)	17.004	(9.447)	1400	(2060.3)	19.993	(11.107)
550	(530.3)	17.275	(9.597)	1500	(2240.3)	20.118	(11.177)
600	(620.3)	17.529	(9.738)	1600	(2420.3)	20.205	(11.225)
650	(710.3)	17.769	(9.872)	1672	(2549.9)	20.244	(11.247)

Application Notes: Mean coefficient of thermal expansion is calculated as a function of thermal expansion. Calculated data is then fitted with the equation below to approximate property trend with respect to temperature.

Fit Equation:

$$\bar{\alpha}(T) = \left(A0 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2 + A3 \cdot \left(\frac{T}{1000}\right)^3\right) \Big/ \left(A\_0 + \left(\frac{T}{1000}\right)\right)$$

$\bar{\alpha}(T) = Coefficient\ of\ Thermal\ Expansion\ [\mu m/(m \cdot K)]$

$T = Temperature\ [K]$

Constants:

Temp. Range [K]: $10 < T \leq 1672$

A0 =	1.119
A1 =	15.57
A2 =	6.144
A3 =	-1.806
A_0 =	0.1007

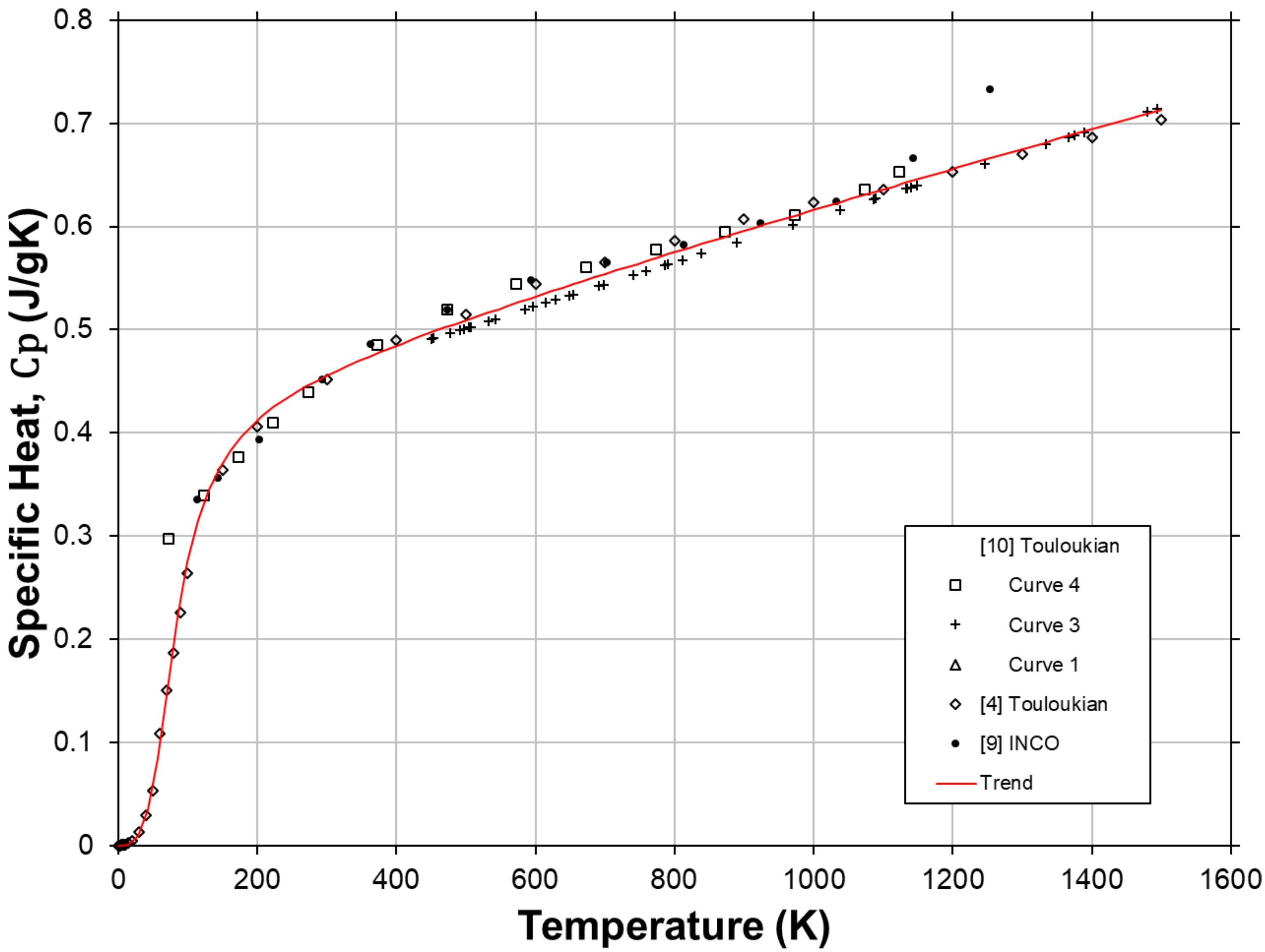

Figure 5.1.2-5: Specific Heat versus Temperature of SS347. Displaying fitted trend and data.

100% Theoretical Density

Temperature (T)		Specific Heat (C_p)		Temperature (T)		Specific Heat (C_p)	
K	(°F)	J/(g-K)	(BTU/(lb-°F))	K	(°F)	J/(g-K)	(BTU/(lb-°F))
100	(-279.7)	0.275	(0.066)	650	(710.3)	0.543	(0.130)
150	(-189.7)	0.371	(0.089)	700	(800.3)	0.554	(0.132)
200	(-99.7)	0.412	(0.099)	800	(980.3)	0.575	(0.137)
250	(-9.7)	0.437	(0.104)	900	(1160.3)	0.596	(0.142)
300	(80.3)	0.455	(0.109)	1000	(1340.3)	0.616	(0.147)
350	(170.3)	0.471	(0.113)	1100	(1520.3)	0.636	(0.152)
400	(260.3)	0.484	(0.116)	1200	(1700.3)	0.656	(0.157)
450	(350.3)	0.497	(0.119)	1300	(1880.3)	0.675	(0.161)
500	(440.3)	0.509	(0.122)	1400	(2060.3)	0.694	(0.166)
550	(530.3)	0.521	(0.124)	1500	(2240.3)	0.713	(0.170)
600	(620.3)	0.532	(0.127)				

Application Notes: Data for specific heat is collected from references [4, 9, 10] and fitted with the equations below to approximate property trend with respect to temperature.

Fit Equation:

For temperature range: $1 < T \leq 100$

$$C_P(T) = \left[A0 \cdot \left(\frac{T}{1000}\right)^N\right] / \left[1 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2\right]$$

For temperature range: $100 < T \leq 1500$

$$C_P(T) = B0 + B1 \cdot \left(\frac{T}{1000}\right) + B2 \cdot \left(\frac{T}{1000}\right)^2 + B\_2 / \left(\frac{T}{1000}\right)^2$$

$C_P(T) = Specific\ Heat\ [J/(g \cdot K)]$

$T = Temperature\ [K]$

Constants:

Temperature Range [K]:	$1 < T \leq 100$		$100 < T \leq 1500$
N =	2.755	B0 =	0.4071
A0 =	107.6	B1 =	0.2227
A1 =	-17.14	B2 =	-0.01218
A2 =	140.1	B_2 =	-0.001561

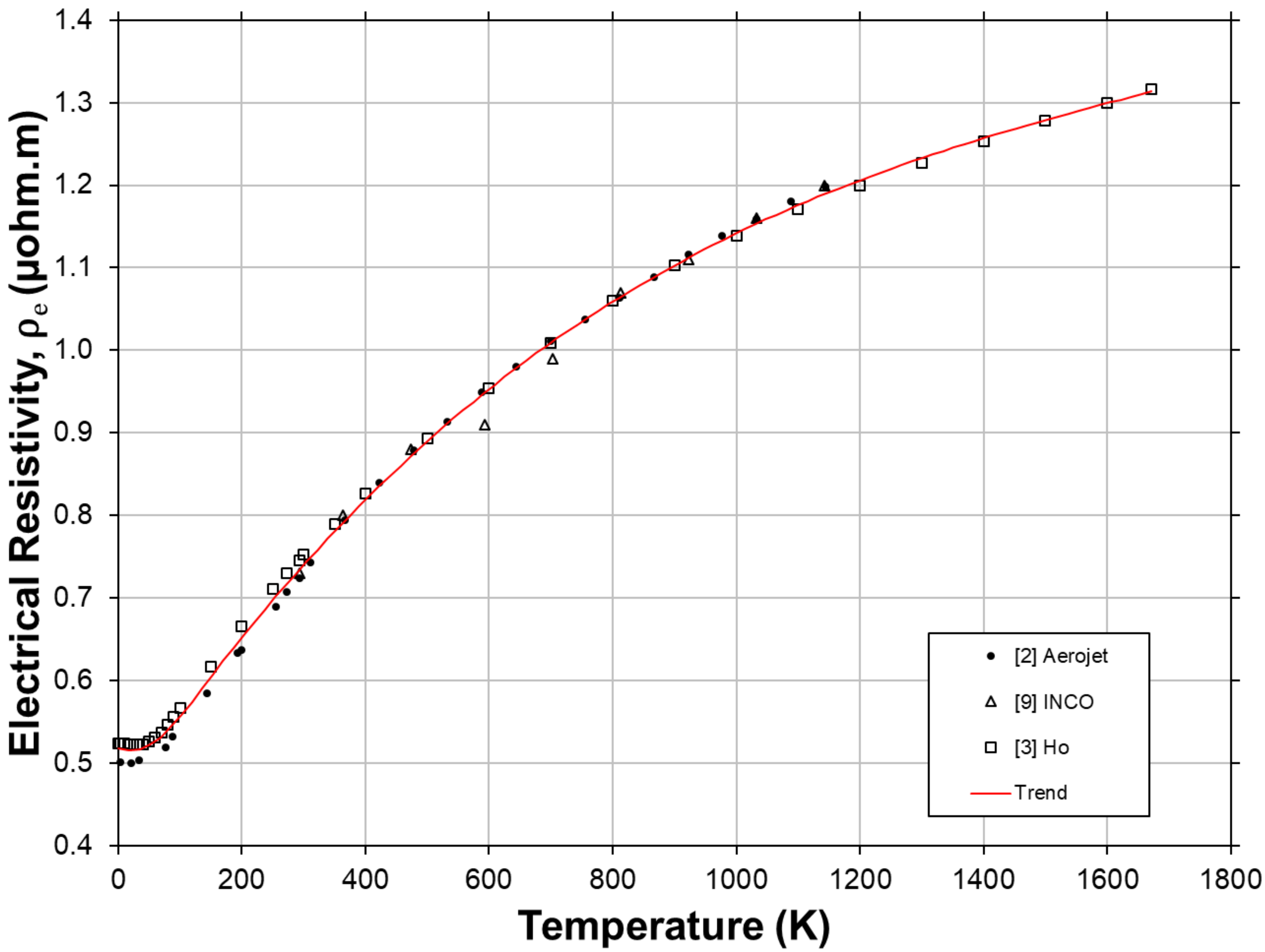

Figure 5.1.2-6: Electrical Resistivity versus Temperature of SS347.

100% Theoretical Density

Temperature (T)		Electrical Resistivity (ρe)		Temperature (T)		Electrical Resistivity (ρe)	
K	(°F)	μΩ-m	(μΩ-in)	K	(°F)	μΩ-m	(μΩ-in)
20	(-423.7)	0.515	(20.28)	700	(800.3)	1.009	(39.73)
60	(-351.7)	0.526	(20.73)	750	(890.3)	1.035	(40.74)
80	(-315.7)	0.539	(21.24)	800	(980.3)	1.059	(41.69)
100	(-279.7)	0.556	(21.88)	850	(1070.3)	1.082	(42.58)
150	(-189.7)	0.605	(23.81)	900	(1160.3)	1.103	(43.42)
200	(-99.7)	0.652	(25.68)	950	(1250.3)	1.123	(44.21)
250	(-9.7)	0.697	(27.45)	1000	(1340.3)	1.142	(44.95)
300	(80.3)	0.740	(29.14)	1050	(1430.3)	1.159	(45.64)
350	(170.3)	0.781	(30.73)	1100	(1520.3)	1.176	(46.30)
400	(260.3)	0.819	(32.25)	1200	(1700.3)	1.206	(47.49)
450	(350.3)	0.855	(33.68)	1300	(1880.3)	1.233	(48.54)
500	(440.3)	0.890	(35.03)	1400	(2060.3)	1.257	(49.49)
550	(530.3)	0.922	(36.31)	1500	(2240.3)	1.279	(50.36)
600	(620.3)	0.953	(37.52)	1600	(2420.3)	1.299	(51.16)
650	(710.3)	0.982	(38.66)	1672	(2549.9)	1.314	(51.71)

Application Notes: Data for electrical resistivity is collected from references [2, 3, 9], and fitted with the equation below to approximate property trend with respect to temperature.

Fit Equation:

$$\rho_e(T) = A0 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2 + A3 \cdot \left(\frac{T}{1000}\right)^3$$

$\rho_e(T) = Electrical\ Resistivity\ [\mu\Omega \cdot m]$

$T = Temperature\ [K]$

Constants:

T. Range [K]:	$1 < T \leq 150$	$150 < T \leq 1672$
A0 =	0.5185	0.4477
A1 =	-0.3548	1.125
A2 =	9.398	-0.532
A3 =	-21.16	0.101

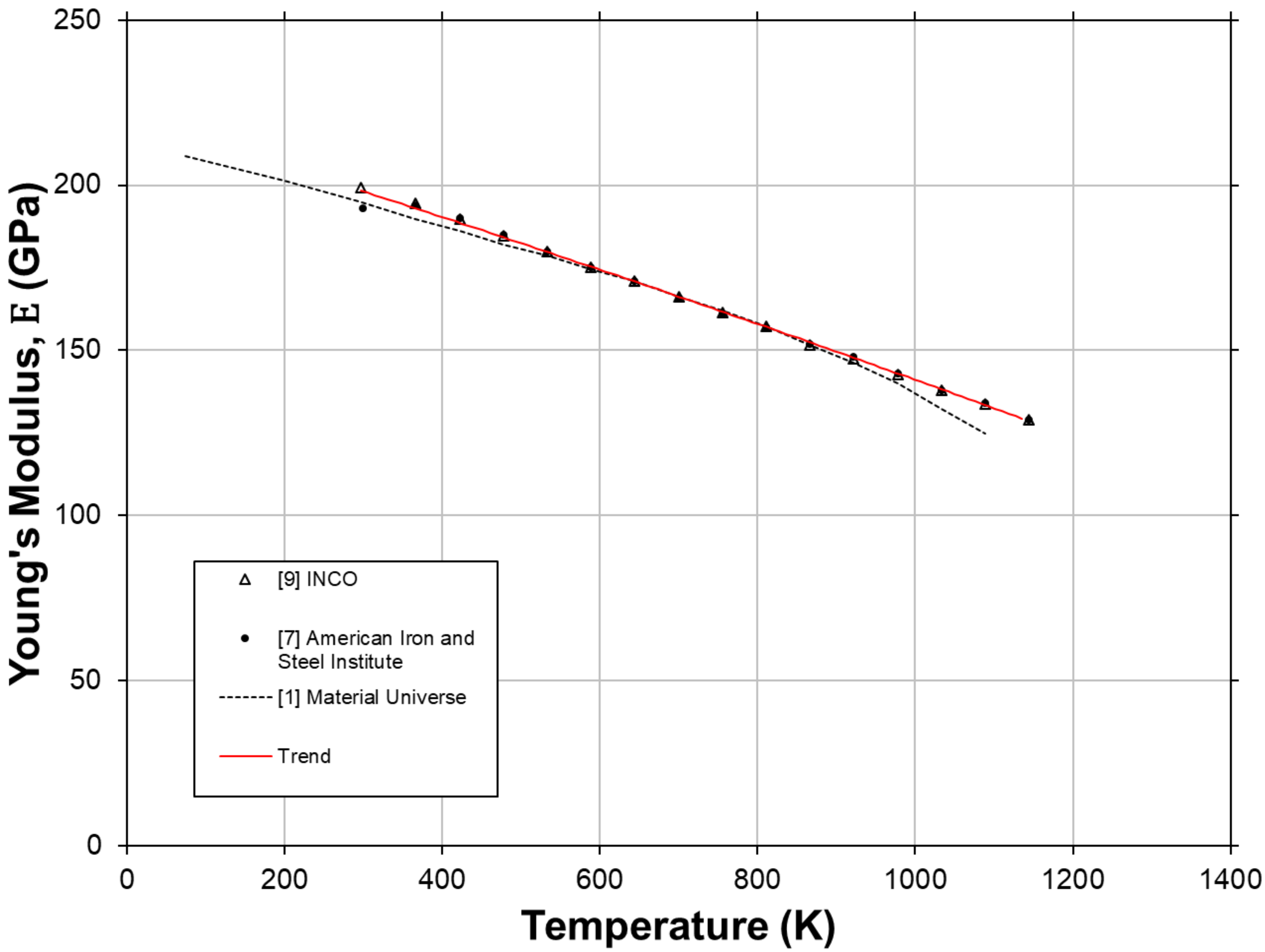

Figure 5.1.2-7: Young's Modulus versus Temperature of SS347. Displaying fitted trend and data with comparison to Materials Universe.

Young's Modulus with Temperature

100% Theoretical Density

Temperature (T)		Young's Modulus (E)		Temperature (T)		Young's Modulus (E)	
K	(°F)	GPa	(Msi)	K	(°F)	GPa	(Msi)
297	(74.9)	198.35	(28.78)	675	(755.3)	168.32	(24.42)
325	(125.3)	196.19	(28.47)	700	(800.3)	166.28	(24.13)
350	(170.3)	194.25	(28.19)	725	(845.3)	164.22	(23.83)
375	(215.3)	192.30	(27.90)	750	(890.3)	162.16	(23.53)
400	(260.3)	190.34	(27.62)	775	(935.3)	160.09	(23.23)
425	(305.3)	188.38	(27.33)	800	(980.3)	158.01	(22.93)
450	(350.3)	186.41	(27.05)	825	(1025.3)	155.92	(22.62)
475	(395.3)	184.43	(26.76)	850	(1070.3)	153.83	(22.32)
500	(440.3)	182.44	(26.47)	875	(1115.3)	151.72	(22.02)
525	(485.3)	180.45	(26.18)	900	(1160.3)	149.61	(21.71)
550	(530.3)	178.45	(25.89)	925	(1205.3)	147.50	(21.40)
575	(575.3)	176.44	(25.60)	950	(1250.3)	145.37	(21.09)
600	(620.3)	174.42	(25.31)	1000	(1340.3)	141.10	(20.47)
625	(665.3)	172.40	(25.01)	1100	(1520.3)	132.46	(19.22)
650	(710.3)	170.37	(24.72)	1144	(1599.5)	128.62	(18.66)

Application Notes: Data for Young's modulus is collected from references [1, 7, 9], and fitted with the equation below to approximate property trend with respect to temperature.

Fit Equations:

$$E(T) = A0 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2$$

$E(T) = Young's\ Modulus\ [GPa]$

$T = Temperature\ [K]$

Constants:

T Range [K]: $297 < T \leq 1144$

A0 = 220.7

A1 = -73.42

A2 = -6.182

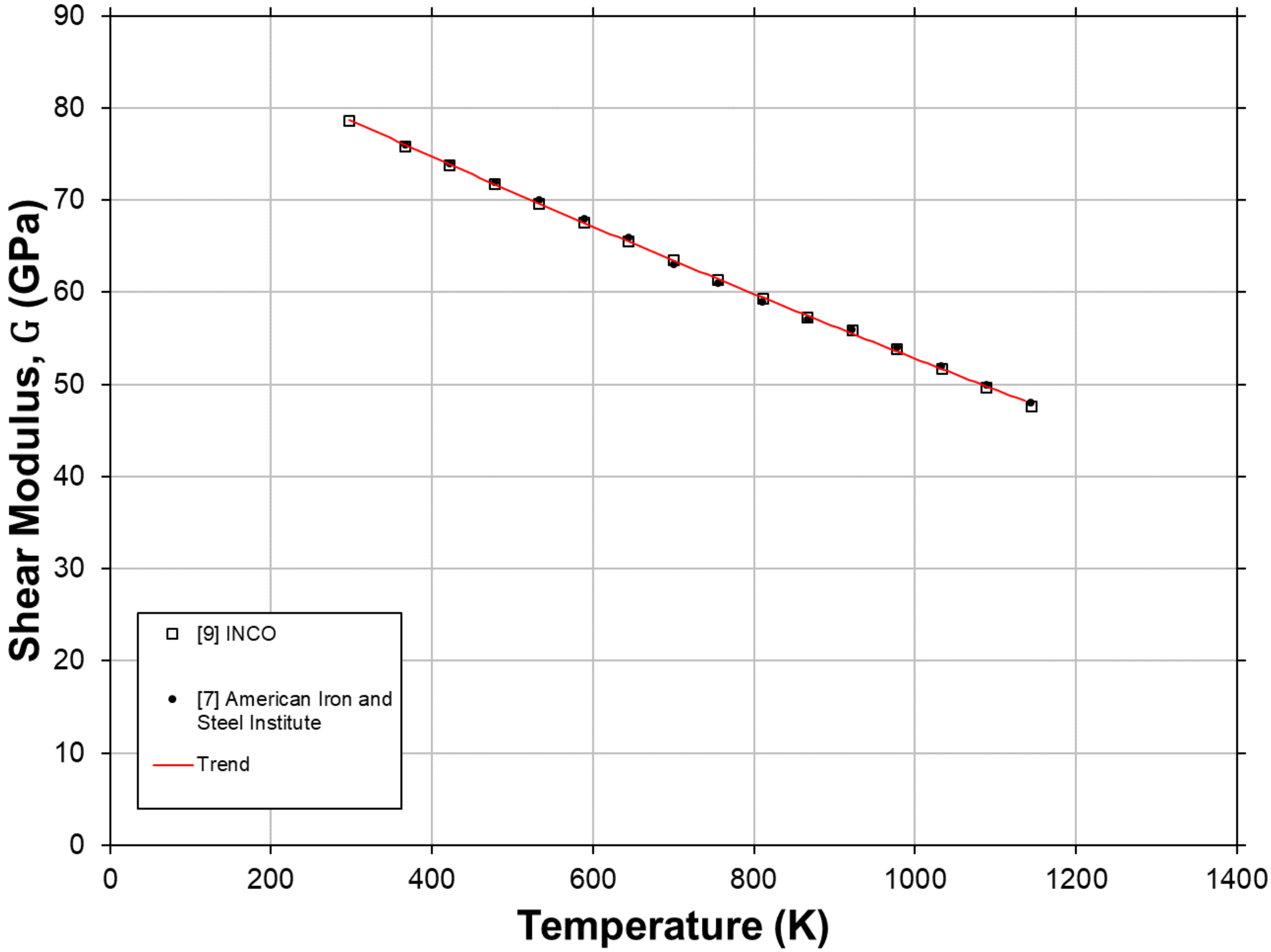

Figure 5.1.2-8: Shear Modulus versus Temperature of SS347. Displaying fitted trend and the data.

100% Theoretical Density

Temperature (T)		Shear Modulus (G)		Temperature (T)		Shear Modulus (G)	
K	(°F)	GPa	(Msi)	K	(°F)	GPa	(Msi)
297	(74.9)	78.74	(11.43)	675	(755.3)	64.37	(9.34)
325	(125.3)	77.64	(11.27)	700	(800.3)	63.46	(9.21)
350	(170.3)	76.66	(11.12)	725	(845.3)	62.55	(9.08)
375	(215.3)	75.69	(10.98)	750	(890.3)	61.65	(8.94)
400	(260.3)	74.72	(10.84)	775	(935.3)	60.74	(8.81)
425	(305.3)	73.76	(10.70)	800	(980.3)	59.85	(8.68)
450	(350.3)	72.80	(10.56)	825	(1025.3)	58.96	(8.55)
475	(395.3)	71.85	(10.43)	850	(1070.3)	58.07	(8.43)
500	(440.3)	70.90	(10.29)	875	(1115.3)	57.19	(8.30)
525	(485.3)	69.95	(10.15)	900	(1160.3)	56.31	(8.17)
550	(530.3)	69.01	(10.01)	925	(1205.3)	55.43	(8.04)
575	(575.3)	68.08	(9.88)	950	(1250.3)	54.56	(7.92)
600	(620.3)	67.14	(9.74)	1000	(1340.3)	52.84	(7.67)
625	(665.3)	66.22	(9.61)	1100	(1520.3)	49.44	(7.17)
650	(710.3)	65.29	(9.47)	1144	(1599.5)	47.96	(6.96)

Application Notes: Data for shear modulus is collected from references [7, 9], and fitted with the equation below to approximate property trend with respect to temperature.

Fit Equations:

$$G(T) = A0 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2$$

$G(T) = Shear\ Modulus\ [GPa]$

$T = Temperature\ [K]$

Constants:

T Range [K]: $297 \leq T \leq 1144$

A0 = 90.74

A1 = -41.46

A2 = 3.556

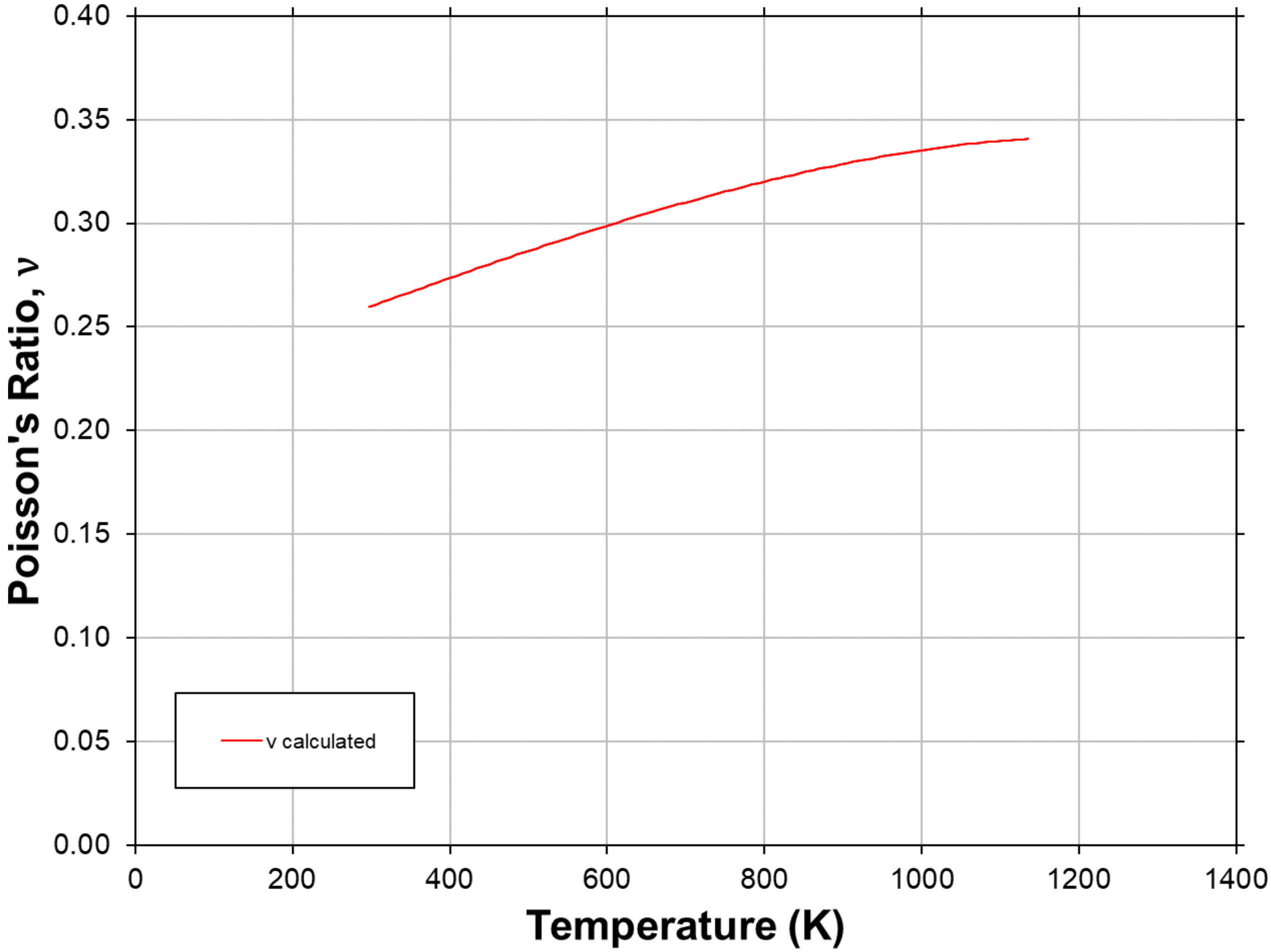

Figure 5.1.2-9: Poisson's Ratio versus Temperature of SS347. Calculated from the Young's Modulus and Shear Modulus fitted trends for SS347.

100% Theoretical Density

Temperature (T)		Poisson's Ratio (ν)	Temperature (T)		Poisson's Ratio (ν)
K	(°F)		K	(°F)	
297	(74.9)	0.260	675	(755.3)	0.307
325	(125.3)	0.263	700	(800.3)	0.310
350	(170.3)	0.267	725	(845.3)	0.313
375	(215.3)	0.270	750	(890.3)	0.315
400	(260.3)	0.274	775	(935.3)	0.318
425	(305.3)	0.277	800	(980.3)	0.320
450	(350.3)	0.280	825	(1025.3)	0.322
475	(395.3)	0.283	850	(1070.3)	0.325
500	(440.3)	0.287	875	(1115.3)	0.327
525	(485.3)	0.290	900	(1160.3)	0.329
550	(530.3)	0.293	925	(1205.3)	0.330
575	(575.3)	0.296	950	(1250.3)	0.332
600	(620.3)	0.299	1000	(1340.3)	0.335
625	(665.3)	0.302	1100	(1520.3)	0.340
650	(710.3)	0.305	1144	(1599.5)	0.341

Application Notes: Poisson's Ratio is calculated as a function of Young's modulus and shear modulus trends, as seen in the equation below to approximate property trend with respect to temperature.

Fit Equations:

$$\nu(T) = E(T)/(2 \cdot G(T)) - 1$$

$$\nu(T) = Poisson's\ Ratio$$

$$T = Temperature\ [K]$$

Temperature Range: $297 < T \leq 1144$

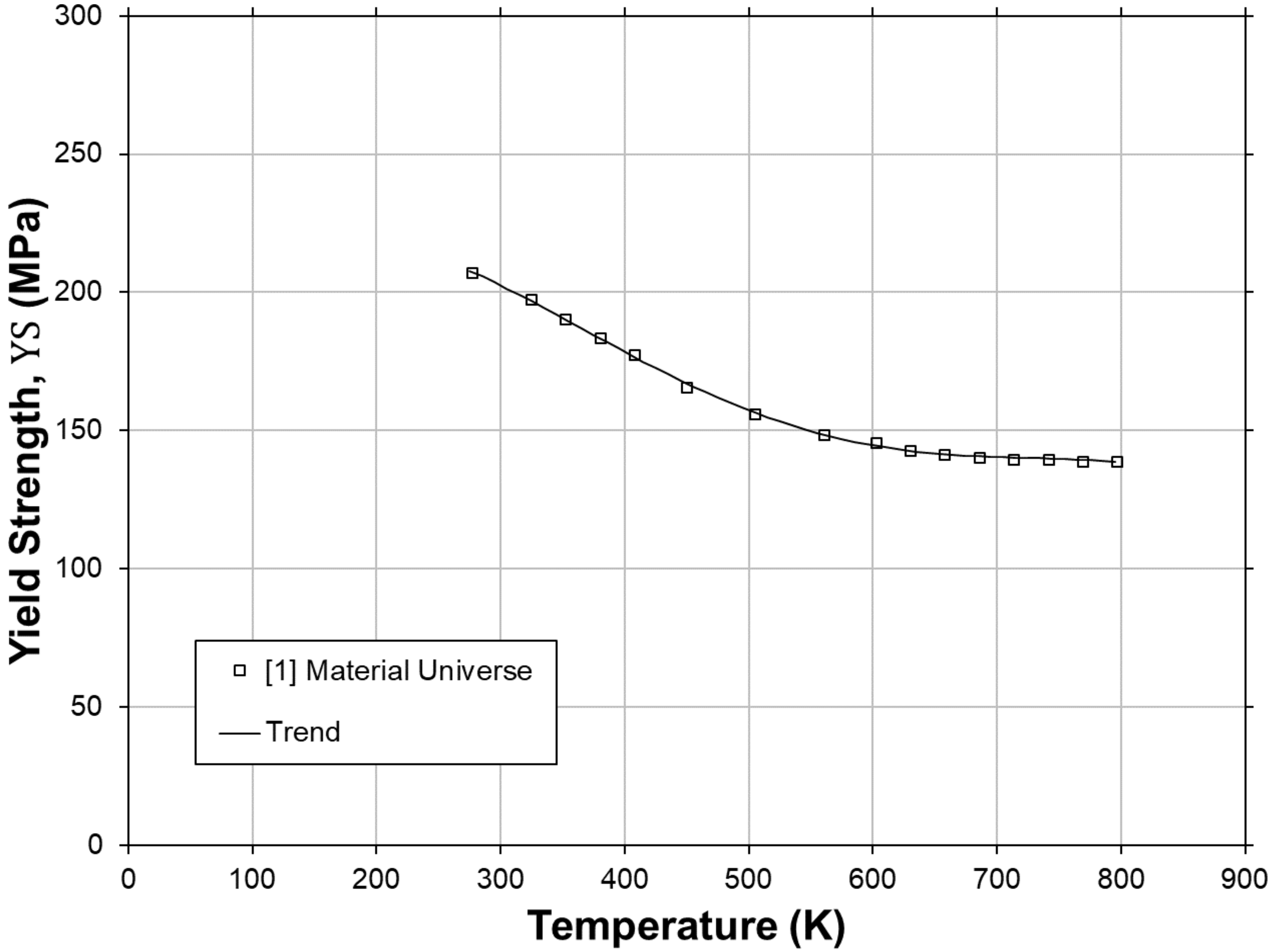

Figure 5.1.2-10: Yield Strength versus Temperature of SS347. Displaying fitted trend and data.

100% Theoretical Density

Temperature (T)		Yield Strength (YS)		Temperature (T)		Yield Strength (YS)	
K	(°F)	MPa	(Ksi)	K	(°F)	MPa	(Ksi)
270	(26.3)	208.70	(30.28)	520	(476.3)	154.05	(22.35)
290	(62.3)	204.68	(29.70)	540	(512.3)	151.13	(21.93)
310	(98.3)	200.27	(29.06)	560	(548.3)	148.61	(21.56)
330	(134.3)	195.59	(28.38)	580	(584.3)	146.46	(21.25)
350	(170.3)	190.74	(27.68)	600	(620.3)	144.69	(20.99)
370	(206.3)	185.83	(26.96)	620	(656.3)	143.27	(20.79)
390	(242.3)	180.93	(26.25)	640	(692.3)	142.18	(20.63)
410	(278.3)	176.12	(25.56)	660	(728.3)	141.37	(20.51)
430	(314.3)	171.49	(24.88)	680	(764.3)	140.79	(20.43)
450	(350.3)	167.08	(24.24)	700	(800.3)	140.40	(20.37)
470	(386.3)	162.94	(23.64)	720	(836.3)	140.12	(20.33)
490	(422.3)	159.12	(23.09)	750	(890.3)	139.74	(20.28)
510	(458.3)	155.65	(22.58)	800	(980.3)	138.45	(20.09)

Application Notes: Data for yield strength is collected from reference [1], and fitted with the equation below to approximate property trends with respect to temperature.

Fit Equation:

$$YS(T) = A0 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2 + A3 \cdot \left(\frac{T}{1000}\right)^3 + A4 \cdot \left(\frac{T}{1000}\right)^4$$

$YS(T) = Yield\ Strength\ [MPa]$

$T = Temperature\ (K)$

Constants:

T Range [K]: $270 < T \leq 800$

A0 =	147
A1 =	939.3
A2 =	-3895
A3 =	5334
A4 =	-2437

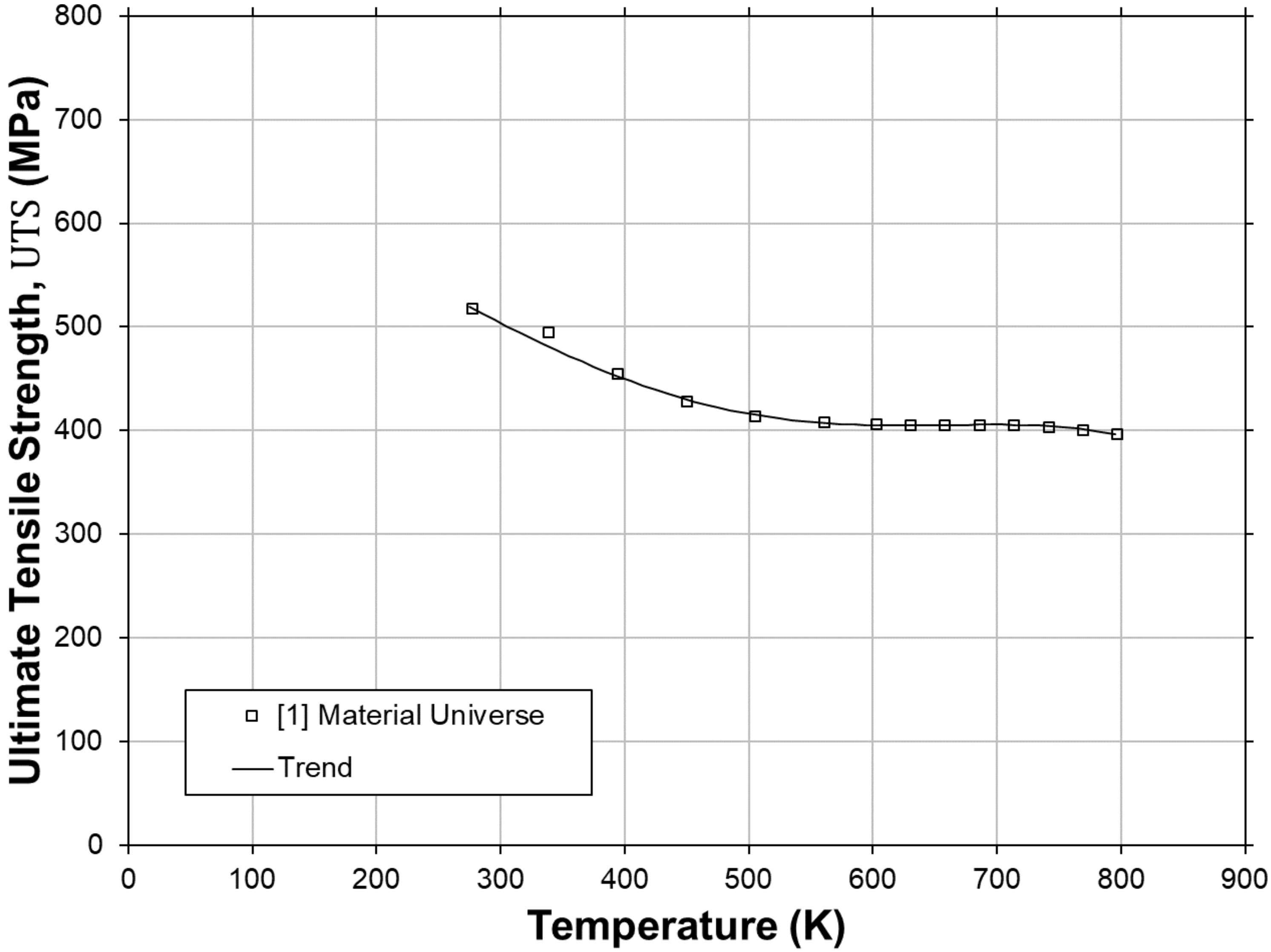

Figure 5.1.2-11: Ultimate Tensile Strength versus Temperature of SS347. Displaying fitted trend of the data.

100% Theoretical Density

Temperature (T)		Tensile Strength (TS)		Temperature (T)		Tensile Strength (TS)	
K	(°F)	MPa	(Ksi)	K	(°F)	MPa	(Ksi)
270	(26.3)	522.12	(75.76)	520	(476.3)	412.41	(59.84)
280	(44.3)	515.94	(74.86)	540	(512.3)	409.44	(59.41)
300	(80.3)	503.70	(73.09)	560	(548.3)	407.29	(59.10)
320	(116.3)	491.75	(71.35)	580	(584.3)	405.87	(58.89)
340	(152.3)	480.26	(69.69)	600	(620.3)	405.09	(58.78)
360	(188.3)	469.35	(68.10)	620	(656.3)	404.81	(58.74)
380	(224.3)	459.14	(66.62)	640	(692.3)	404.90	(58.75)
400	(260.3)	449.71	(65.25)	660	(728.3)	405.18	(58.79)
420	(296.3)	441.15	(64.01)	680	(764.3)	405.49	(58.84)
440	(332.3)	433.49	(62.90)	700	(800.3)	405.60	(58.85)
460	(368.3)	426.79	(61.93)	720	(836.3)	405.31	(58.81)
480	(404.3)	421.05	(61.09)	750	(890.3)	403.57	(58.56)
500	(440.3)	416.26	(60.40)	800	(980.3)	394.91	(57.30)

Application Notes: Data for ultimate tensile strength is collected from reference [1], and fitted with the equation below to approximate property trends with respect to temperature.

Fit Equation:

$$TS(T) = A0 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2 + A3 \cdot \left(\frac{T}{1000}\right)^3 + A4 \cdot \left(\frac{T}{1000}\right)^4$$

$TS(T) = Ultimate\ Tensile\ Strength\ (MPa)$

$T = Temperature\ (K)$

Constants:

Temperature Range [K]:	$270 < T \leq 800$
A0 =	586.7
A1 =	633
A2 =	-5429
A3 =	9529
A4 =	-5133

Temp. (T) K	Physical and Electrical		Thermal				Elastic		
	Density (ρ) kg/m³	Electrical Resistivity (ρ_e) μΩ-m	Thermal Conductivity (k) W/(m-K)	Thermal Expansion (dL/L_0) %	Mean CTE ($\bar{\alpha}$) 10^{-6}/K	Specific Heat (C_p) J/(g-K)	Young's Modulus (E) GPa	Shear Modulus (G) GPa	Poisson's Ratio (ν)
100	8024	0.556	9.10	-0.265	13.63	0.275	-	-	-
150	8009	0.605	11.14	-0.206	14.31	0.371	-	-	-
200	7993	0.652	12.53	-0.137	14.85	0.412	-	-	-
250	7975	0.697	13.57	-0.064	15.30	0.437	-	-	-
300	7958	0.740	14.51	0.008	15.71	0.455	198.12	78.62	0.26
350	7939	0.781	15.43	0.090	16.07	0.471	194.25	76.66	0.27
400	7919	0.819	16.26	0.174	16.41	0.484	190.34	74.72	0.27
450	7898	0.855	17.03	0.261	16.72	0.497	186.41	72.80	0.28
500	7877	0.890	17.78	0.351	17.00	0.509	182.44	70.90	0.29
550	7855	0.922	18.50	0.442	17.27	0.521	178.45	69.01	0.29
600	7833	0.953	19.20	0.536	17.53	0.532	174.42	67.14	0.30
650	7811	0.982	19.90	0.632	17.77	0.543	170.37	65.29	0.30
700	7788	1.009	20.58	0.730	18.00	0.554	166.28	63.46	0.31
750	7765	1.035	21.27	0.830	18.21	0.564	162.16	61.65	0.32
800	7742	1.059	21.94	0.931	18.41	0.575	158.01	59.85	0.32
850	7718	1.082	22.62	1.034	18.60	0.585	153.83	58.07	0.32
900	7694	1.103	23.29	1.137	18.78	0.596	149.61	56.31	0.33
950	7671	1.123	23.96	1.242	18.95	0.606	145.37	54.56	0.33
1000	7647	1.142	24.62	1.348	19.10	0.616	141.10	52.84	0.34
1100	7598	1.176	25.95	1.562	19.39	0.636	132.46	49.44	0.34
1200	7550	1.206	27.28	1.778	19.63	0.656	-	-	-
1300	7502	1.233	28.60	1.995	19.83	0.675	-	-	-
1400	7454	1.257	29.92	2.211	19.99	0.694	-	-	-
1500	7408	1.279	31.23	2.426	20.12	0.713	-	-	-
1600	7362	1.299	32.55	2.638	20.20	-	-	-	-

[1] Material Universe. (Accessed July 2019).

[2] Ferrous alloys, Materials properties data book Aerojet Nuclear Systems Co., Sacramento, Calif. (USA), 1970.

[3] C.Y. Ho, T.K. Chu, Electrical Resistivity and Thermal Conductivity of Nine Selected AISI stainless Steels, Thermophysical and Electronic Properties Information Analysis Center, Lafayette, IN, 1977.

[4] Y.S. Touloukian, C.Y. Ho, Recommended Values of the Thermophysical Properties of Eight Alloys, Major Constituents and Their Oxides, Thermophysical and Electronic Properties Information Analysis Center, Lafayette, IN, 1966.

[5] R.J. Corruccini, J.J. Gniewek, Thermal expansion of technical solids at low temperatures; a compilation from the literature, National Bureau of Standards, 1961.

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[8] Y.S. Touloukian, R.K. Kirby, R.E. Taylor, P.D. Desai, Thermal Expansion - Metallic Elements and Alloys, Thermophysical Properties of Matter - the TPRC Data Series, Vol. 12, Thermophysical and Electronic Properties Information Analysis Center, Lafayette, IN, web, 1975.

[9] Austenitic chromium-nickel stainless steels- Engineering properties at elevated temperatures, Engineering Properties at Elevated Temperatures, INCO databooks, 1968.

[10] Y.S. Touloukian, R.K. Kirby, R.E. Taylor, P.D. Desai, Specific Heat - Metallic Elements and Alloys, Thermophysical Properties of Matter - The TPRC Data Series, Vol. 4, Thermophysical and Electronic Properties Information Analysis Center, Lafayette, IN, 1971.

6 Nuclear Materials

6.1 Nuclear Fuel Materials

Room Temperature Properties

Molar Mass, [g/mol]	252.04
Theoretical Density, [kg/m^3]	14,330
Melting Point, [K]	3123 ± 30*
Specific Heat, [J/(g-K)]	0.189
Thermal Conductivity, [W/(m-K)]	14.2
Linear expansion coefficient, [µm/(m-K)]	7.25
Electrical resistivity, [µΩ-m]	1.48
Young's Modulus, [GPa]	263.6
Shear Modulus, [GPa]	104.0
Poisson's Ratio, [-]	0.268

* at nitrogen pressure ≥ 0.25 MPa (2.5 atm)

Uranium – Nitrogen Phase Diagram

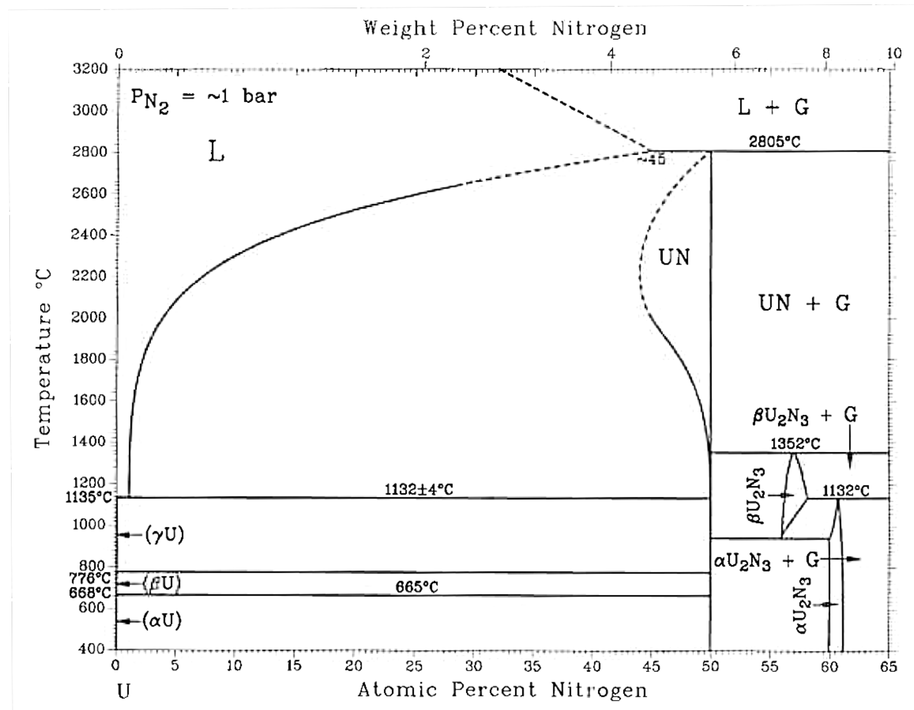

Figure 6.1.1-1: Uranium – Nitrogen Phase Diagram [1].
Stoichiometric UN = 5.56 wt% Nitrogen

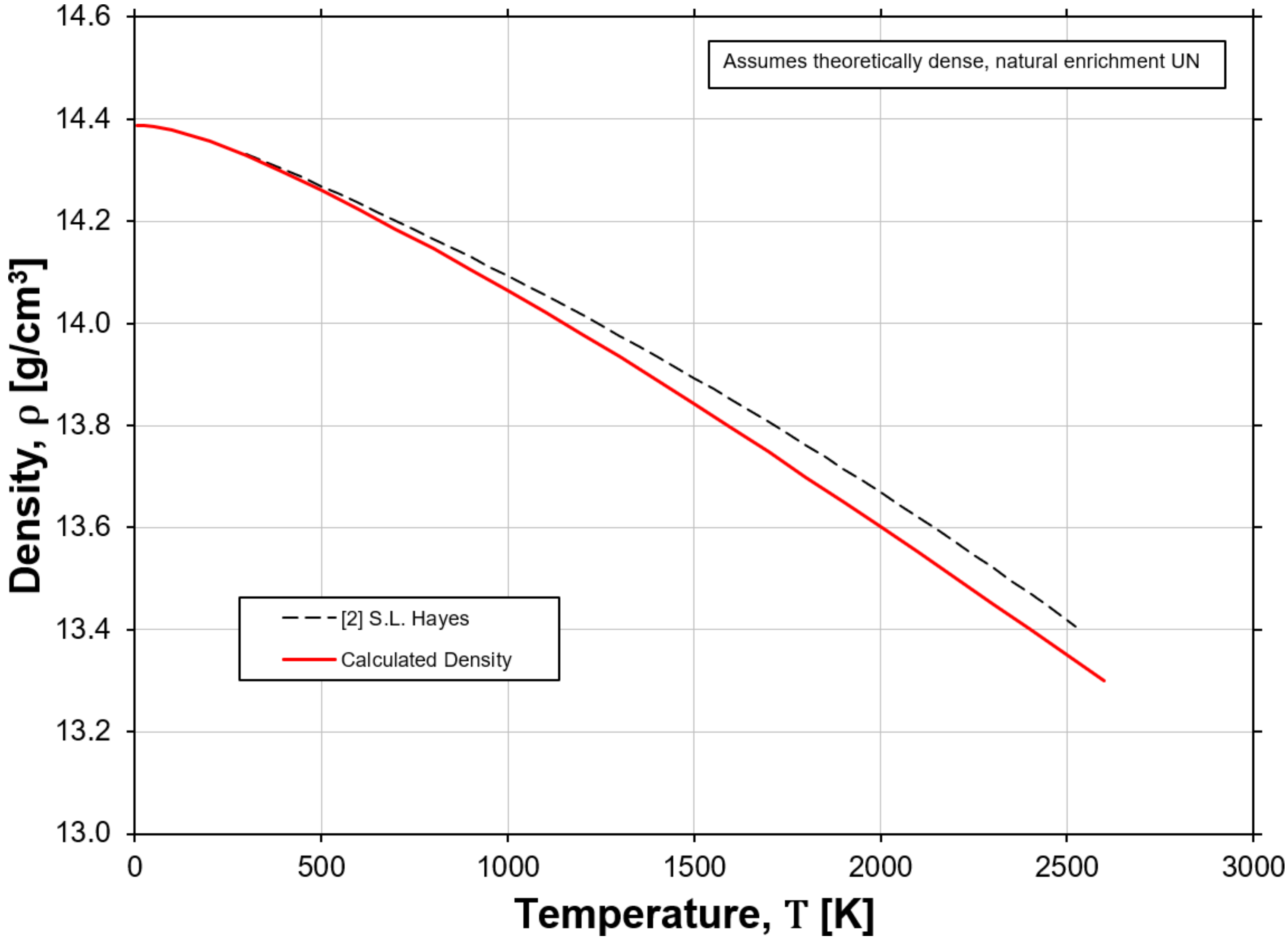

Figure 6.1.1-2: Density versus Temperature for UN. Calculated from fitted trend of the Thermal Expansion data with comparison to trend from Hayes (1990).

100% Theoretical Density

Temperature (T)		Density (ρ)		Temperature (T)		Density (ρ)	
K	(°F)	kg/m^3	(lb/ft^3)	K	(°F)	kg/m^3	(lb/ft^3)
5	(-450.7)	14387	(898.2)	1300	(1880.3)	13934	(869.9)
25	(-414.7)	14387	(898.1)	1400	(2060.3)	13888	(867.0)
50	(-369.7)	14385	(898.1)	1500	(2240.3)	13842	(864.2)
100	(-279.7)	14379	(897.7)	1600	(2420.3)	13795	(861.2)
200	(-99.7)	14357	(896.3)	1700	(2600.3)	13748	(858.3)
300	(80.3)	14329	(894.5)	1800	(2780.3)	13699	(855.3)
400	(260.3)	14295	(892.4)	1900	(2960.3)	13651	(852.2)
500	(440.3)	14260	(890.2)	2000	(3140.3)	13601	(849.1)
600	(620.3)	14223	(887.9)	2100	(3320.3)	13552	(846.0)
700	(800.3)	14185	(885.6)	2200	(3500.3)	13502	(842.9)
800	(980.3)	14146	(883.1)	2300	(3680.3)	13451	(839.8)
900	(1160.3)	14106	(880.6)	2400	(3860.3)	13401	(836.6)
1000	(1340.3)	14064	(878.0)	2500	(4040.3)	13350	(833.4)
1100	(1520.3)	14022	(875.4)	2600	(4220.3)	13299	(830.2)
1200	(1700.3)	13978	(872.6)				

Application Notes: Density is calculated here as a function of thermal expansion as seen in the equation below, to approximate property trend as a function of temperature. This trend is compared against trend from reference [2].

Density Calculation:

$\rho(T) = \rho_{RT}(1-P)/(1+dL/L_0(T)/100)^3$

$\rho(T) = Density\ [kg/m^3]$

$Room\ Temperature\ Density\ (\rho_{RT}) = 14{,}355\ [kg/m^3]$

$P = Fractional\ Porosity$

$T = Temperature\ [K]$

Temperature Range: $5 \le T \le 2600$

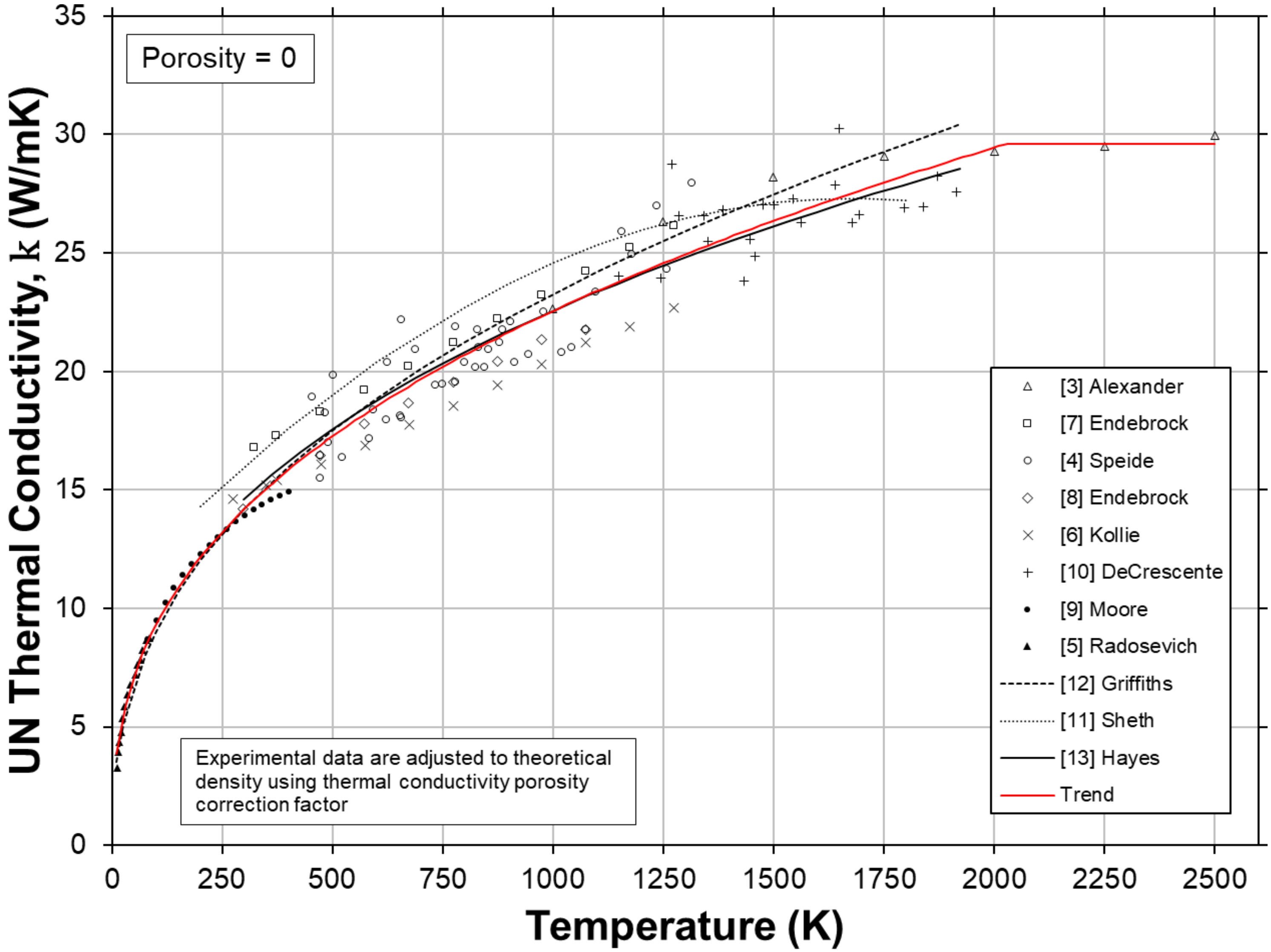

Figure 6.1.1-3: Thermal Conductivity versus Temperature of UN.

100% Theoretical Density

Temperature (T)		Thermal Conductivity (k)		Temperature (T)		Thermal Conductivity (k)	
K	(°F)	W/(m-K)	((Btu·in)/(ft²·hr·°F))	K	(°F)	W/(m-K)	((Btu·in)/(ft²·hr·°F))
10	(-441.7)	3.84	(26.63)	1200	(1700.3)	24.19	(167.82)
20	(-423.7)	5.01	(34.76)	1300	(1880.3)	24.94	(173.06)
50	(-369.7)	7.13	(49.45)	1400	(2060.3)	25.66	(178.06)
100	(-279.7)	9.30	(64.55)	1500	(2240.3)	26.35	(182.85)
200	(-99.7)	12.14	(84.26)	1600	(2420.3)	27.02	(187.44)
300	(80.3)	14.19	(98.48)	1700	(2600.3)	27.65	(191.86)
400	(260.3)	15.85	(110.00)	1800	(2780.3)	28.27	(196.13)
500	(440.3)	17.27	(119.85)	1900	(2960.3)	28.86	(200.25)
600	(620.3)	18.53	(128.55)	2000	(3140.3)	29.44	(204.24)
700	(800.3)	19.66	(136.40)	2100	(3320.3)	29.58	(205.23)
800	(980.3)	20.70	(143.59)	2200	(3500.3)	29.58	(205.23)
900	(1160.3)	21.65	(150.24)	2300	(3680.3)	29.58	(205.23)
1000	(1340.3)	22.55	(156.45)	2400	(3860.3)	29.58	(205.23)
1100	(1520.3)	23.39	(162.29)	2401	(3862.1)	29.58	(205.23)

Application Notes: Data for thermal conductivity is collected from references [3-13] and fitted with the equations below to approximate the property trend with respect to temperature and porosity.

Fit Equation:

$$k(T) = A0 \cdot \left(\frac{T}{1000}\right)^N$$

$k(T) = Thermal\ Conductivity\ [W\ /\ (m \cdot K)]$

$k_P = k \cdot (1 - P)/(1 + P)$

$P = Fractional\ Porosity\ (0 \leq P \leq 0.2)$

$T = Temperature\ [K]$

Constants:

T Range [K]:	$10 \leq T \leq 2025$	$2025 < T \leq 2500$
A0 =	22.55	29.58
N =	0.3845	0

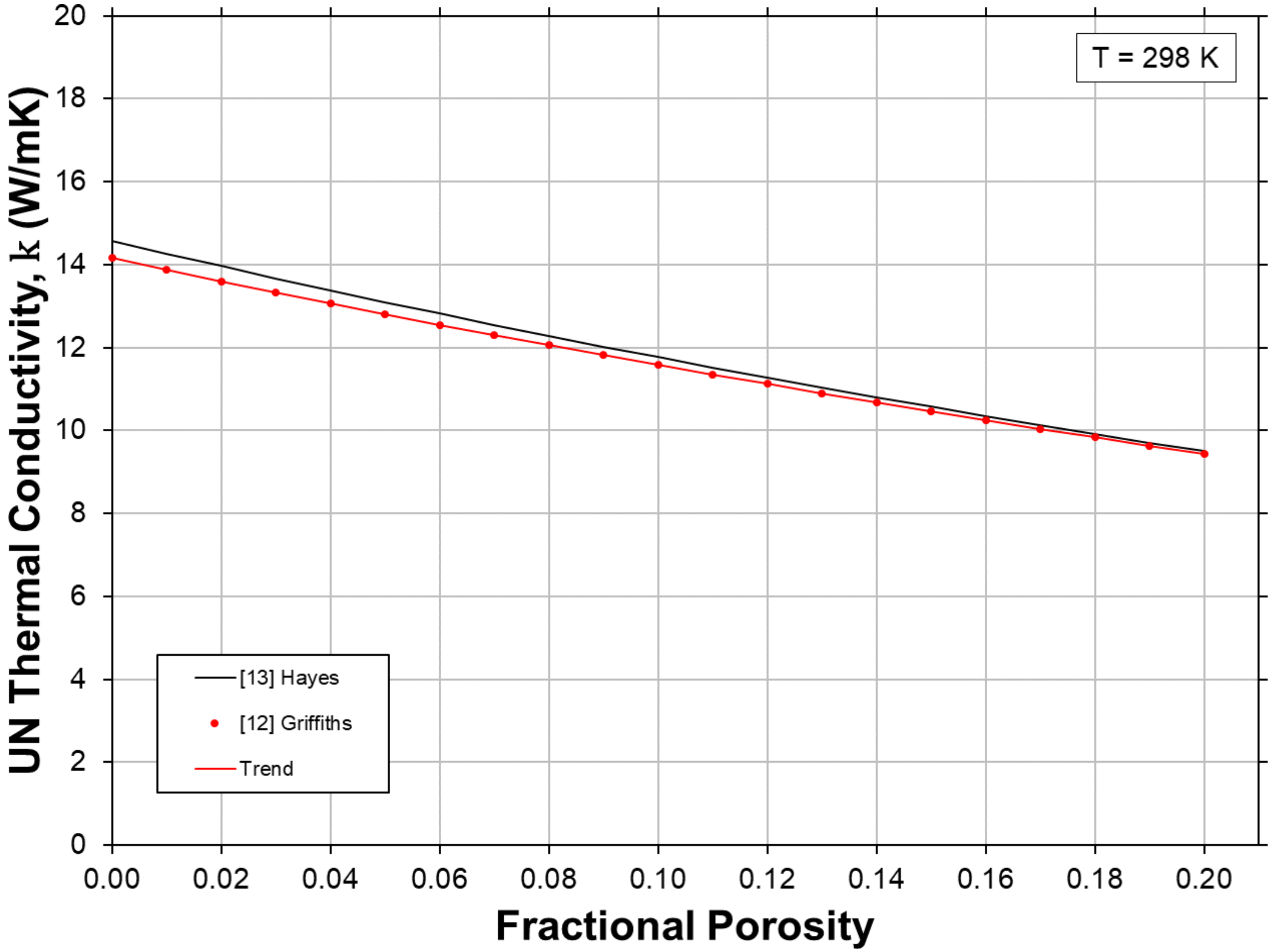

Figure 6.1.1-4: Thermal Conductivity versus Fractional Porosity of UN.

Room Temperature

Porosity (P)	Thermal Conductivity (k)	
	W/(m-K)	((Btu·in)/(ft²·hr·°F))
0.00	14.16	(98.23)
0.02	13.60	(94.37)
0.04	13.07	(90.67)
0.06	12.55	(87.11)
0.08	12.06	(83.67)
0.10	11.58	(80.37)
0.12	11.12	(77.18)
0.14	10.68	(74.10)
0.16	10.25	(71.13)
0.18	9.84	(68.26)
0.20	9.44	(65.48)

Application Notes: Data for thermal conductivity is collected from references [3-13], and fitted with the equations below to approximate the property trend with respect to temperature and porosity.

Fit Equation:

$k(T) = A0 \cdot \left(\frac{T}{1000}\right)^N$

$k(T) = Thermal\ Conductivity\ [W\ /\ (m \cdot K)]$

$k_P = k \cdot (1 - P)/(1 + P)$

$P = Fractional\ Porosity\ (0 \leq P \leq 0.2)$

$T = Temperature\ [K]$

Constants:

T Range [K]:	$10 \leq T \leq 2025$	$2025 < T \leq 2500$
A0 =	22.55	29.58
N =	0.3845	0

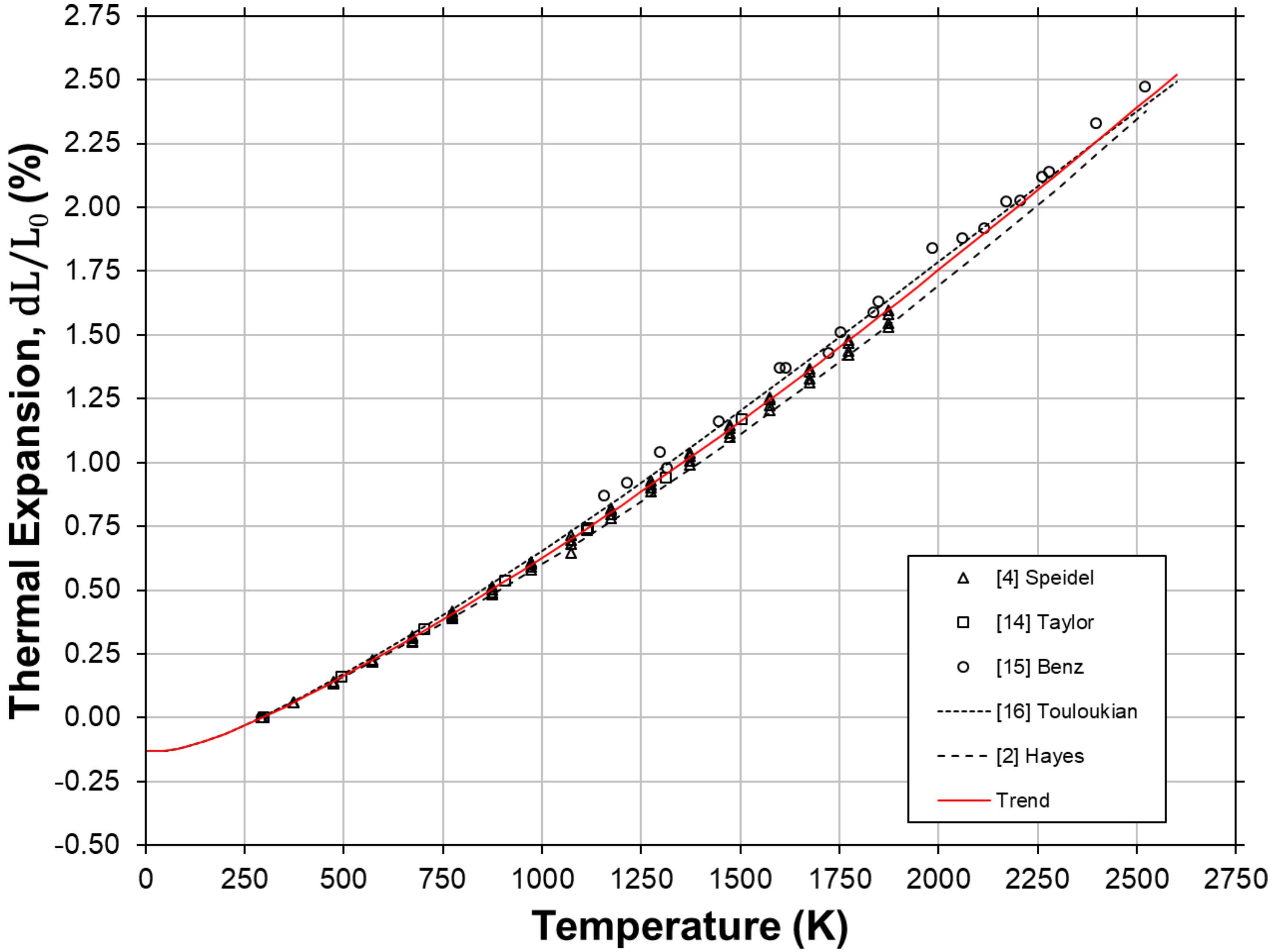

Figure 6.1.1-5: Thermal Expansion versus Temperature of UN.

100% Theoretical Density

Temperature (T)		Thermal Expansion (dL/L_0)	Temperature (T)		Thermal Expansion (dL/L_0)
K	(°F)	%	K	(°F)	%
5	(-450.7)	-0.132	1300	(1880.3)	0.940
25	(-414.7)	-0.131	1400	(2060.3)	1.049
50	(-369.7)	-0.128	1500	(2240.3)	1.161
100	(-279.7)	-0.115	1600	(2420.3)	1.276
200	(-99.7)	-0.064	1700	(2600.3)	1.393
300	(80.3)	0.003	1800	(2780.3)	1.511
400	(260.3)	0.081	1900	(2960.3)	1.632
500	(440.3)	0.164	2000	(3140.3)	1.755
600	(620.3)	0.250	2100	(3320.3)	1.879
700	(800.3)	0.339	2200	(3500.3)	2.005
800	(980.3)	0.432	2300	(3680.3)	2.132
900	(1160.3)	0.527	2400	(3860.3)	2.260
1000	(1340.3)	0.626	2500	(4040.3)	2.390
1100	(1520.3)	0.728	2600	(4220.3)	2.521
1200	(1700.3)	0.832			

Application Notes: Data for thermal expansion is collected from references [2, 4, 14-16] and fitted with the equation below to approximate property trend with respect to temperature.

Fit Equation:

$$dL/L_0\,(T) = A0 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2 + A3 \cdot \left(\frac{T}{1000}\right)^3$$

$dL/L_0\,(T) = Thermal\ Expansion$ [%]

$T = Temperature$ [K]

Constants:

T Range [K]:	$5 \leq T \leq 293$	$293 < T \leq 2600$
A0 =	-0.1313	-0.2103
A1 =	-0.05692	0.65
A2 =	2.515	0.2067
A3 =	-2.722	-0.02025

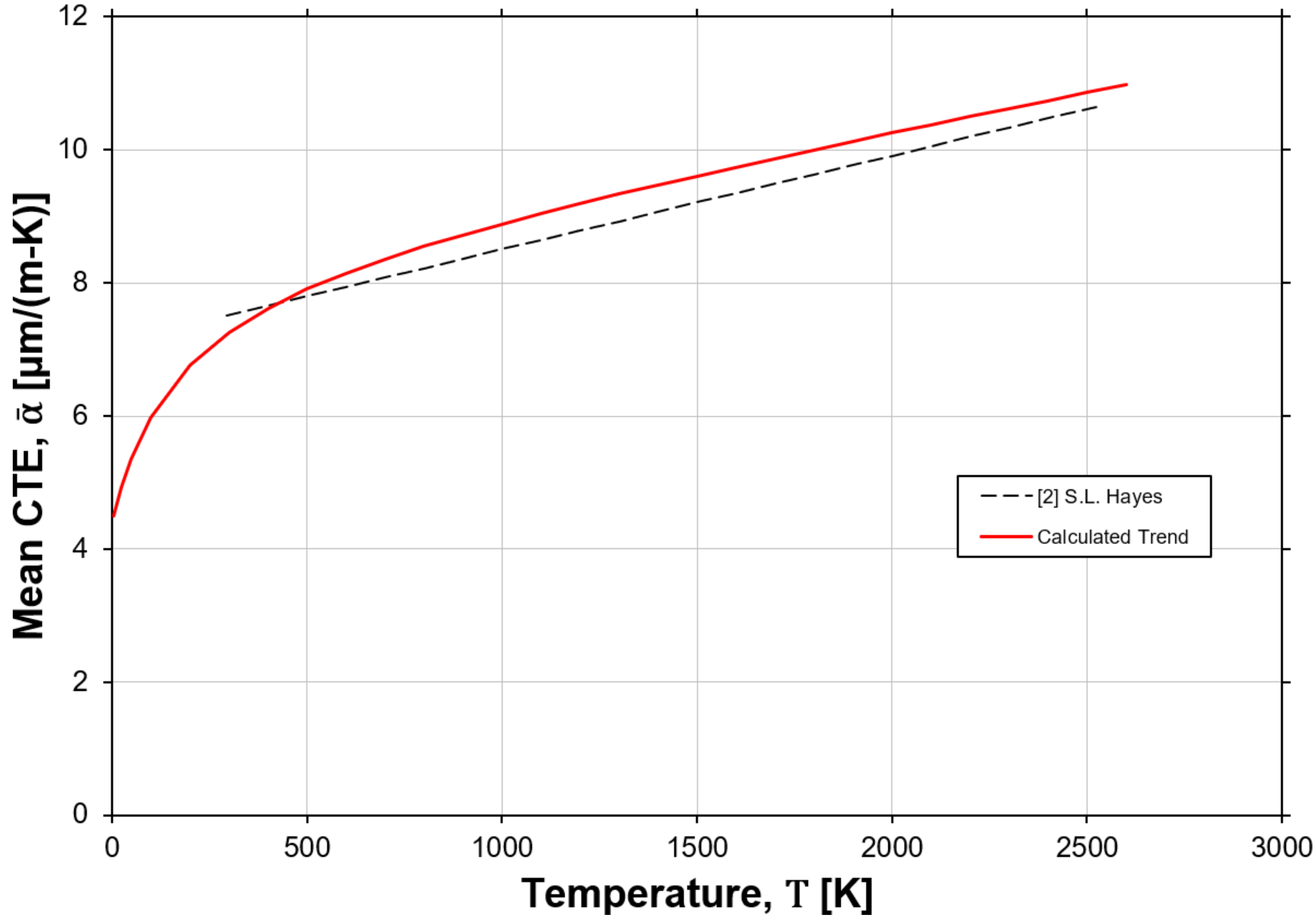

Figure 6.1.1-6: Mean Coefficient of Thermal Expansion versus Temperature of UN. Calculated from fitted trend of the Thermal Expansion data with comparison to trend from Hayes (1990).

100% Theoretical Density

Temperature (T)		Mean CTE (ᾱ)		Temperature (T)		Mean CTE (ᾱ)	
K	(°F)	µm/(m-K)	(µin/(in-°F))	K	(°F)	µm/(m-K)	(µin/(in-°F))
5	(-450.7)	4.503	(2.502)	1300	(1880.3)	9.333	(5.185)
25	(-414.7)	4.926	(2.736)	1400	(2060.3)	9.472	(5.262)
50	(-369.7)	5.350	(2.972)	1500	(2240.3)	9.608	(5.338)
100	(-279.7)	5.976	(3.320)	1600	(2420.3)	9.741	(5.412)
200	(-99.7)	6.763	(3.757)	1700	(2600.3)	9.872	(5.484)
300	(80.3)	7.260	(4.033)	1800	(2780.3)	10.000	(5.556)
400	(260.3)	7.621	(4.234)	1900	(2960.3)	10.127	(5.626)
500	(440.3)	7.907	(4.393)	2000	(3140.3)	10.252	(5.696)
600	(620.3)	8.147	(4.526)	2100	(3320.3)	10.376	(5.764)
700	(800.3)	8.357	(4.643)	2200	(3500.3)	10.499	(5.833)
800	(980.3)	8.547	(4.748)	2300	(3680.3)	10.620	(5.900)
900	(1160.3)	8.722	(4.845)	2400	(3860.3)	10.741	(5.967)
1000	(1340.3)	8.885	(4.936)	2500	(4040.3)	10.861	(6.034)
1100	(1520.3)	9.041	(5.023)	2600	(4220.3)	10.981	(6.100)
1200	(1700.3)	9.190	(5.105)				

Application Notes: Data for mean coefficient of thermal expansion is calculated as a function thermal expansion data, then fitted with the equation below to approximate property trend with respect to temperature. Fitted trend is compared against trend from reference [2].

Fit Equation:

$$\bar{\alpha}(T) = \left[A0 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2\right] / \left[1 + A\_0 \cdot \left(\frac{T}{1000}\right)\right]$$

$\bar{\alpha}(T) = Coefficient\ of\ Thermal\ Expansion\ [\mu m/(m \cdot K)]$

$T = Temperature\ [K]$

Constants:

T. Range [K]:	$5 \leq T \leq 2600$
A0 =	4.383
A1 =	50.92
A2 =	6.584
A_0 =	5.965

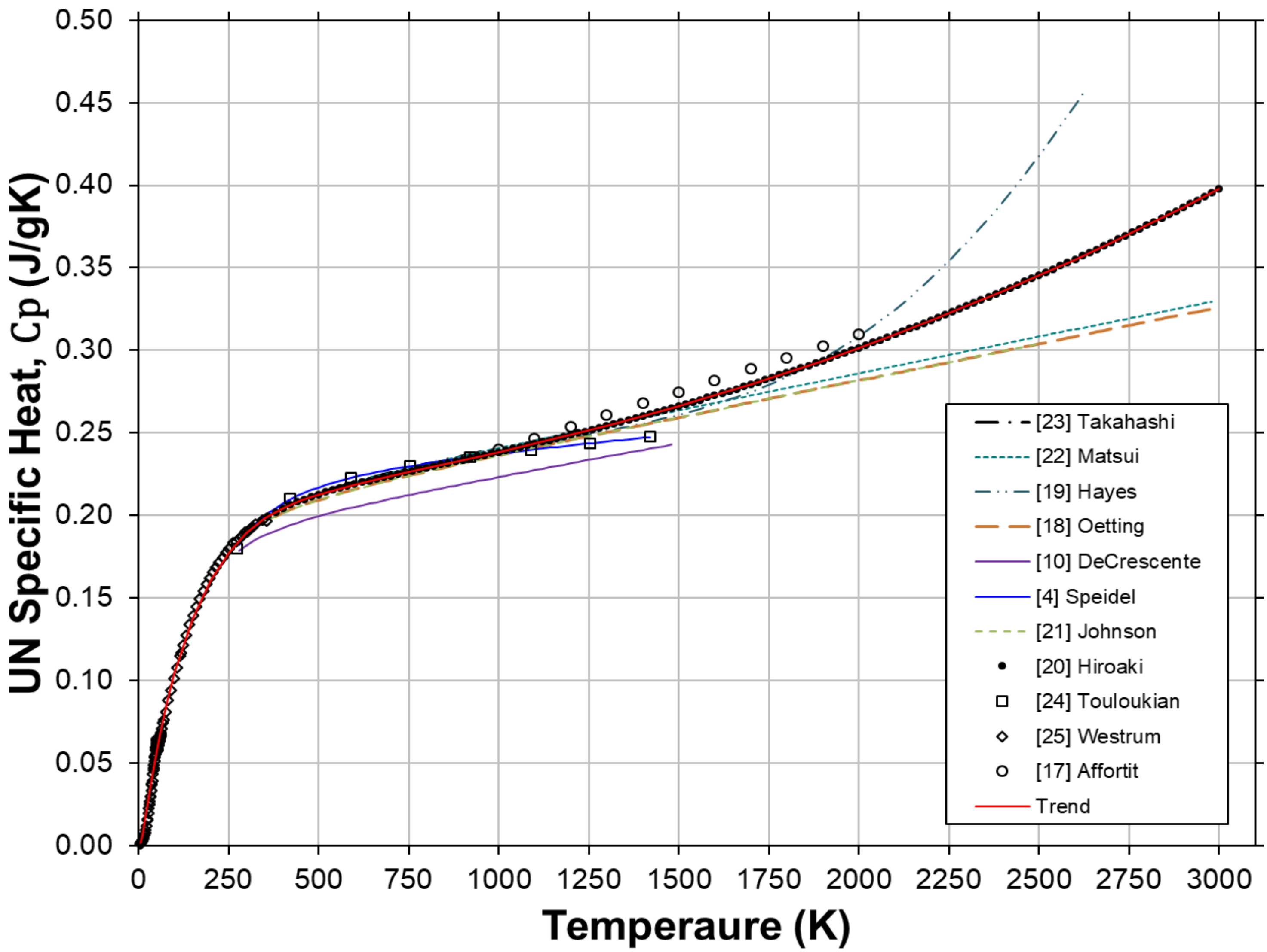

Figure 6.1.1-7: Specific Heat versus Temperature of UN. Displaying fitted trend and data.

100% Theoretical Density

Temperature (T)		Specific Heat (C_p)		Temperature (T)		Specific Heat (C_p)	
K	(°F)	J/(g-K)	(BTU/(lb-°F))	K	(°F)	J/(g-K)	(BTU/(lb-°F))
5	(-450.7)	0.002	(0.000)	1200	(1700.3)	0.249	(0.059)
50	(-369.7)	0.056	(0.013)	1300	(1880.3)	0.254	(0.061)
100	(-279.7)	0.104	(0.025)	1400	(2060.3)	0.260	(0.062)
200	(-99.7)	0.161	(0.038)	1500	(2240.3)	0.266	(0.064)
300	(80.3)	0.190	(0.045)	1600	(2420.3)	0.273	(0.065)
400	(260.3)	0.204	(0.049)	1700	(2600.3)	0.279	(0.067)
500	(440.3)	0.213	(0.051)	1800	(2780.3)	0.287	(0.068)
600	(620.3)	0.219	(0.052)	2000	(3140.3)	0.302	(0.072)
700	(800.3)	0.224	(0.054)	2200	(3500.3)	0.318	(0.076)
800	(980.3)	0.229	(0.055)	2400	(3860.3)	0.336	(0.080)
900	(1160.3)	0.234	(0.056)	2600	(4220.3)	0.355	(0.085)
1000	(1340.3)	0.238	(0.057)	2800	(4580.3)	0.376	(0.090)
1100	(1520.3)	0.243	(0.058)	3000	(4940.3)	0.398	(0.095)

Application Notes: Data for specific heat is collected from references [4, 10, 17-25] and fitted with the equations below to approximate property trend with respect to temperature.

Fit Equation:

For temperature range: $5 \leq T < 293$

$$C_P(T) = \left[A0 \cdot \left(\frac{T}{1000}\right)^N\right] \Big/ \left[1 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2 + A3 \cdot \left(\frac{T}{1000}\right)^3\right]$$

For temperature range: $293 \leq T \leq 3000$

$$C_P(T) = B0 + B1 \cdot \left(\frac{T}{1000}\right) + B2 \cdot \left(\frac{T}{1000}\right)^2 + B\_2 / \left(\frac{T}{1000}\right)^2$$

$C_P(T) = Specific\ Heat\ [J/(g \cdot K)]$

$T = Temperature\ [K]$

Constants:

T. Range [K]:	$5 \leq T \leq 293$		$293 < T \leq 3000$
N =	2.168	B0 =	2.141E-01
A0 =	2.784E+02	B1 =	9.746E-03
A1 =	9.191E+01	B2 =	1.718E-02
A2 =	7.568E+02	B_2 =	-2.607E-03
A3 =	4.086E+02		

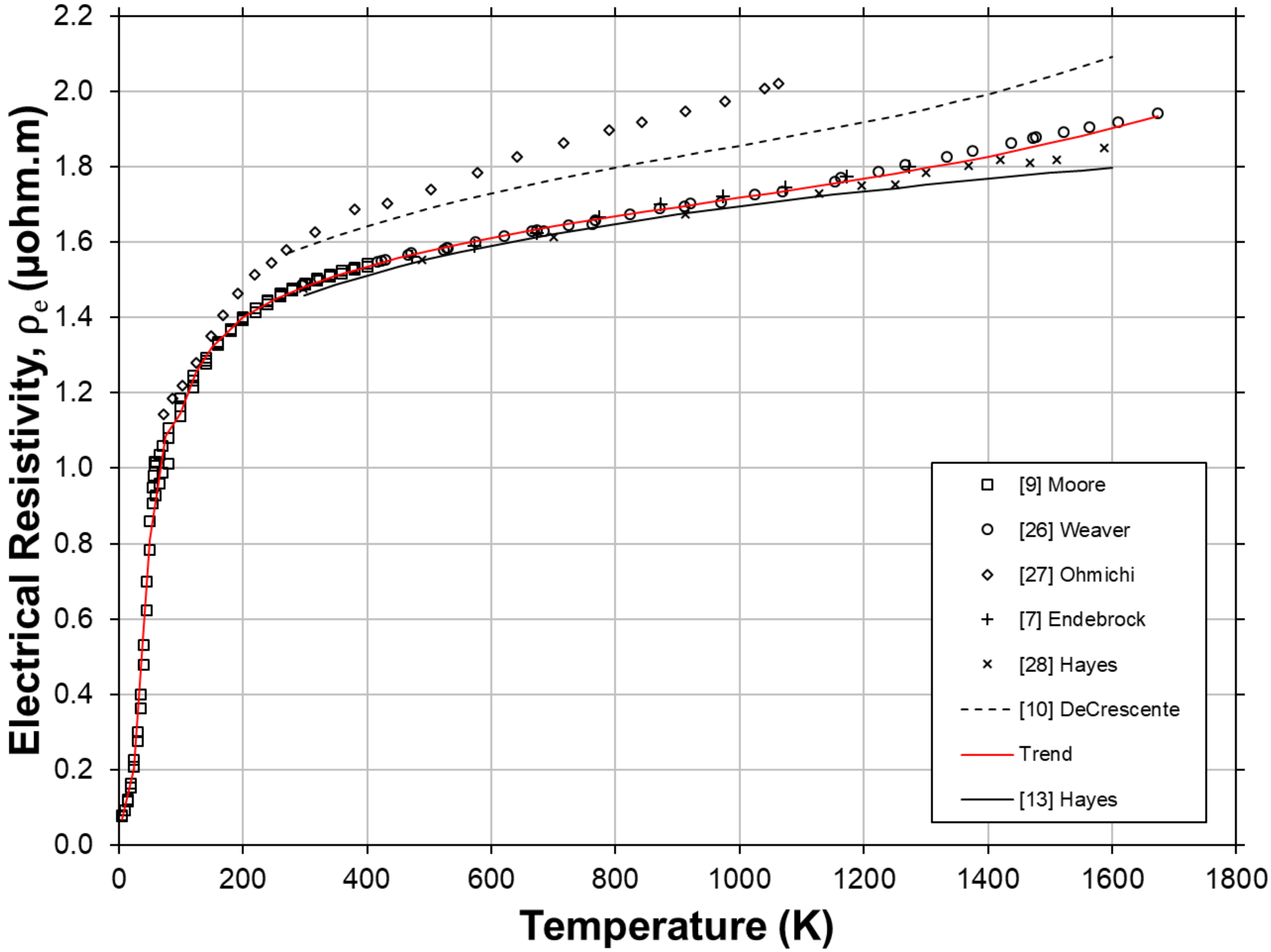

Figure 6.1.1-8: Electrical Resistivity versus Temperature of Uranium Nitride.

100% Theoretical Density

Temperature (T)		Electrical Resistivity (ρ_e)		Temperature (T)		Electrical Resistivity (ρ_e)	
K	(°F)	μΩ-m	(μΩ-in)	K	(°F)	μΩ-m	(μΩ-in)
5	(-450.7)	0.068	(2.66)	1100	(1520.3)	1.742	(68.59)
25	(-414.7)	0.203	(8.00)	1200	(1700.3)	1.768	(69.61)
50	(-369.7)	0.809	(31.87)	1300	(1880.3)	1.796	(70.71)
100	(-279.7)	1.147	(45.15)	1400	(2060.3)	1.827	(71.93)
200	(-99.7)	1.400	(55.10)	1500	(2240.3)	1.862	(73.31)
300	(80.3)	1.483	(58.38)	1600	(2420.3)	1.902	(74.89)
400	(260.3)	1.536	(60.47)	1673	(2551.7)	1.935	(76.18)
500	(440.3)	1.577	(62.09)				
600	(620.3)	1.611	(63.44)				
700	(800.3)	1.641	(64.61)				
800	(980.3)	1.668	(65.67)				
900	(1160.3)	1.693	(66.66)				
1000	(1340.3)	1.718	(67.62)				

Application Notes: Data for electrical resistivity is collected from references [7, 9, 10, 13, 26-28] and fitted with the equations below to best fit data and approximate property trend with respect to temperature.

Fit Equation:

For temperature range: $5 \le T < 100$

$$\rho_e(T) = \left[A \cdot \left(\frac{T}{1000}\right)^N + A0\right] \Big/ \left[1 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2\right]$$

For temperature range: $100 \le T \le 1673$

$$\rho_e(T) = B0 + B1 \cdot \left(\frac{T}{1000}\right) + B2 \cdot \left(\frac{T}{1000}\right)^2 + B3 \cdot \left(\frac{T}{1000}\right)^3 + B\_2 / \left(\frac{T}{1000}\right)^2$$

$\rho_e(T) = Electrical\ Resistivity\ [\mu\Omega \cdot m]$

$T = Temperature\ [K]$

Constants:

T. Range [K]:	$5 \le T < 100$		$100 \le T \le 1673$
N =	3	B0 =	1.353
A =	2.032E+03	B1 =	6.467E-01
A0 =	5.703E-02	B2 =	-4.299E-01
A1 =	-3.273E+01	B3 =	1.504E-01
A2 =	4.083E+02	B_2 =	-2.668E-03

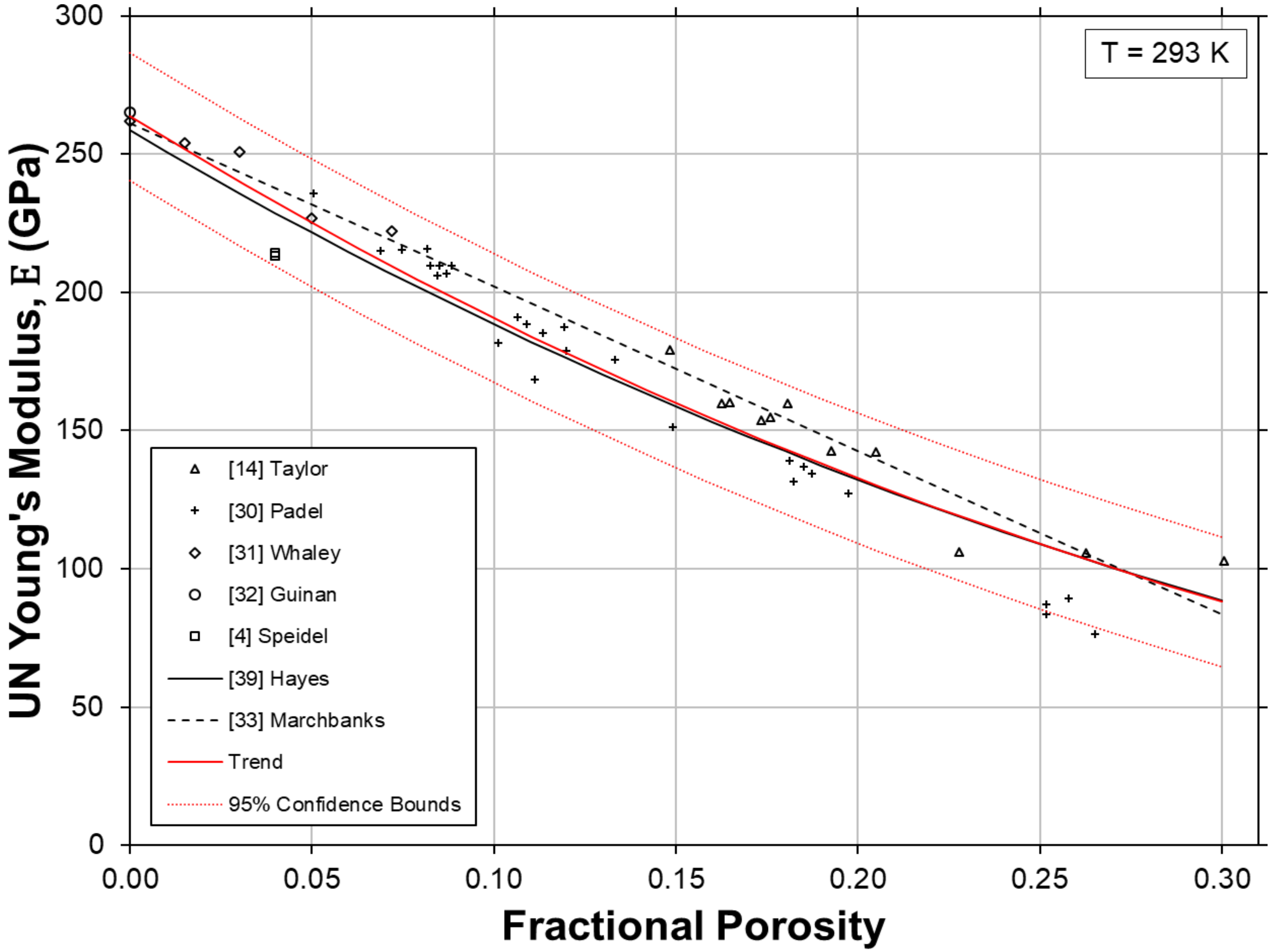

Figure 6.1.1-9: Young's Modulus versus Fractional Porosity of UN.

Room Temperature

Porosity (P)	Young's Modulus (E)	
	GPa	(Msi)
0.00	263.58	(38.25)
0.02	247.72	(35.94)
0.04	232.52	(33.74)
0.06	217.97	(31.63)
0.08	204.04	(29.61)
0.10	190.72	(27.67)
0.12	178.00	(25.83)
0.14	165.87	(24.07)
0.16	154.30	(22.39)
0.18	143.30	(20.79)
0.20	132.83	(19.27)
0.22	122.90	(17.83)
0.24	113.47	(16.46)
0.26	104.55	(15.17)
0.28	96.11	(13.95)
0.30	88.15	(12.79)

Application Notes: Data for Young's modulus is collected from references [4, 14, 29-34] and fitted with the equation below to approximate property trend with respect to temperature and porosity.

Fit Equations:

$E(T,P) = A \cdot (1-P)^N \, [A0 - A1 \cdot (T-273)]$

$E(T,P) = Young's\ Modulus\ [GPa]$

$T = Temperature\ [K]\ for\ 273 \leq T \leq 1700$

$P = Fractional\ Porosity\ for\ 0 \leq P \leq 0.3$

Constants:

A =	263.547
N =	3.071
A0 =	1.003
A1 =	1.148E-04

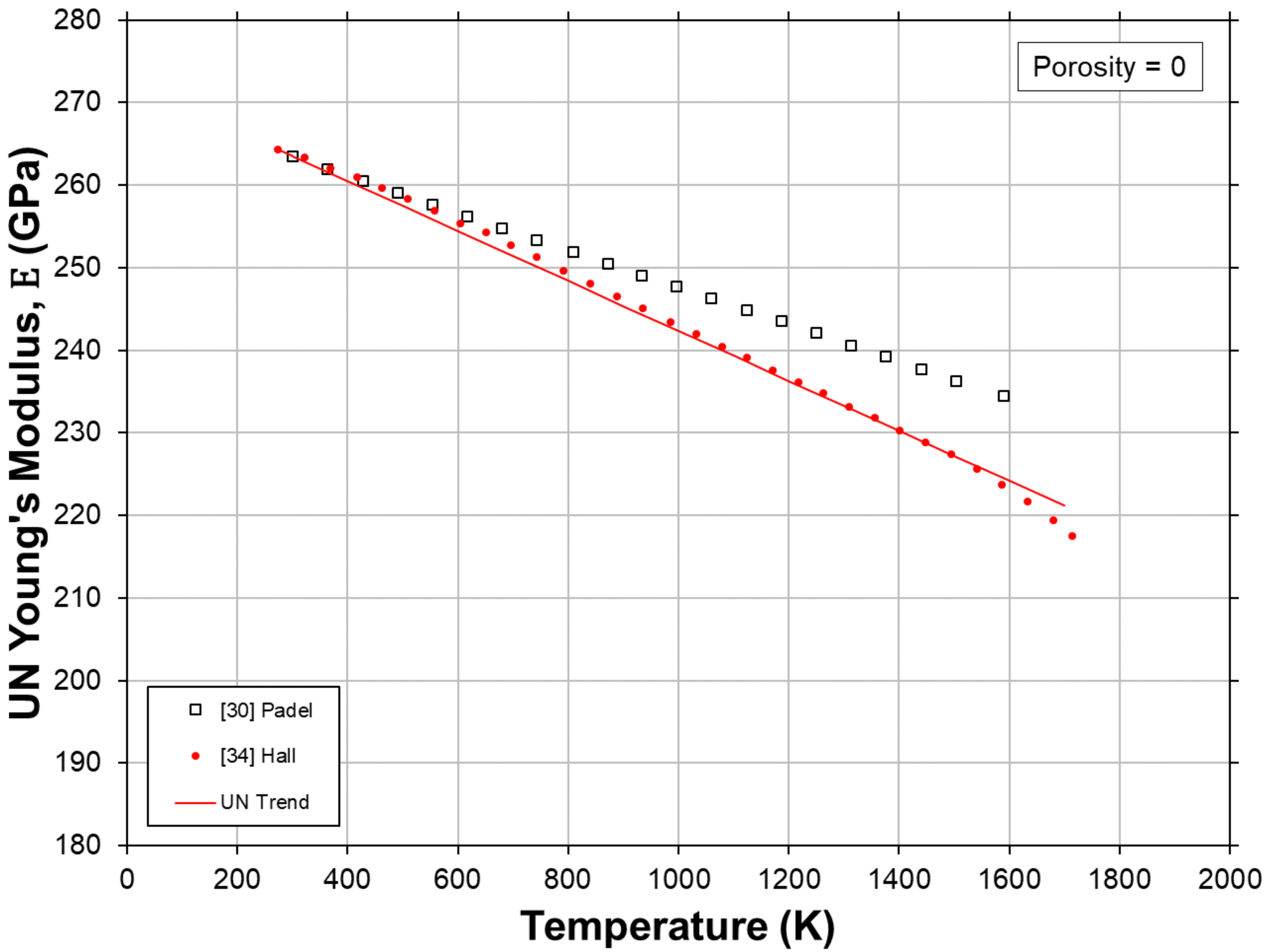

Figure 6.1.1-10: Young's Modulus versus Temperature of UN.

Young's Modulus with Temperature

100% Theoretical Density

Temperature (T)		Young's Modulus (E)		Temperature (T)		Young's Modulus (E)	
K	(°F)	GPa	(Msi)	K	(°F)	GPa	(Msi)
273	(31.7)	264.34	(38.36)	1000	(1340.3)	242.34	(35.16)
300	(80.3)	263.52	(38.24)	1050	(1430.3)	240.83	(34.94)
350	(170.3)	262.01	(38.02)	1100	(1520.3)	239.32	(34.72)
400	(260.3)	260.50	(37.80)	1150	(1610.3)	237.80	(34.51)
450	(350.3)	258.98	(37.58)	1200	(1700.3)	236.29	(34.29)
500	(440.3)	257.47	(37.36)	1250	(1790.3)	234.78	(34.07)
550	(530.3)	255.96	(37.14)	1300	(1880.3)	233.27	(33.85)
600	(620.3)	254.44	(36.92)	1350	(1970.3)	231.75	(33.63)
650	(710.3)	252.93	(36.70)	1400	(2060.3)	230.24	(33.41)
700	(800.3)	251.42	(36.48)	1450	(2150.3)	228.73	(33.19)
750	(890.3)	249.91	(36.26)	1500	(2240.3)	227.21	(32.97)
800	(980.3)	248.39	(36.04)	1550	(2330.3)	225.70	(32.75)
850	(1070.3)	246.88	(35.82)	1600	(2420.3)	224.19	(32.53)
900	(1160.3)	245.37	(35.60)	1650	(2510.3)	222.68	(32.31)
950	(1250.3)	243.85	(35.38)	1700	(2600.3)	221.16	(32.09)

Application Notes: Data for Young's modulus is collected from references [4, 14, 29-34] and fitted with the equations below to best fit data and approximate property trend with respect to temperature and porosity.

Fit Equations:

$E(T,P) = A \cdot (1-P)^N \, [A0 - A1 \cdot (T-273)]$

$E(T,P) = Young's\ Modulus\ [GPa]$

$T = Temperature\ [K]\ for\ 273 \leq T \leq 1700$

$P = Fractional\ Porosity\ for\ 0 \leq P \leq 0.3$

Constants:

T. Range [K]:	$273 \leq T \leq 1700$
A =	263.547
N =	3.071
A0 =	1.003
A1 =	1.148E-04

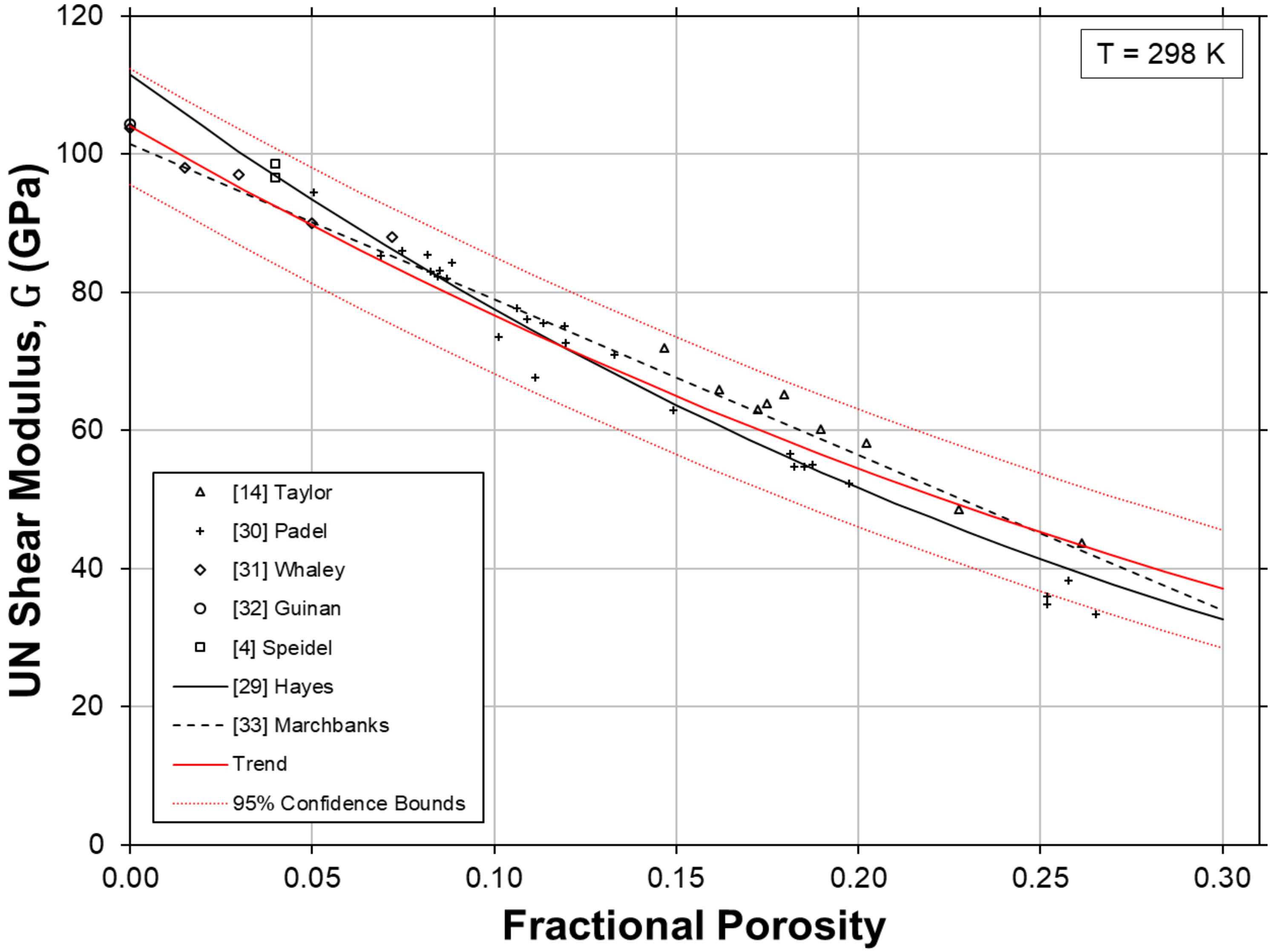

Figure 6.1.1-11: Shear Modulus versus Fractional Porosity of UN.

Shear Modulus with Porosity

Room Temperature

Porosity (P)	Shear Modulus (G)	
	GPa	(Msi)
0.00	104.01	(15.09)
0.02	98.11	(14.24)
0.04	92.43	(13.41)
0.06	86.96	(12.62)
0.08	81.72	(11.86)
0.10	76.68	(11.13)
0.12	71.86	(10.43)
0.14	67.23	(9.76)
0.16	62.81	(9.11)
0.18	58.58	(8.50)
0.20	54.54	(7.91)
0.22	50.69	(7.36)
0.24	47.02	(6.82)
0.26	43.53	(6.32)
0.28	40.21	(5.83)
0.30	37.06	(5.38)

Application Notes: Data for shear modulus is collected from references [4, 14, 29-33] and fitted with the equation below to approximate property trend with respect to temperature and porosity.

Fit Equations:

$G(T,P) = A \cdot (1-P)^N \, [A0 - A1 \cdot (T - 273)]$

$G(T,P) = Shear\ Modulus\ [GPa]$

$T = Temperature\ [K]$

$P = Fractional\ Porosity$

Constants:

Porosity (P):	$0 \leq P \leq 0.3$
A =	103.999
N =	2.893
A0 =	1.003
A1 =	1.148E-04

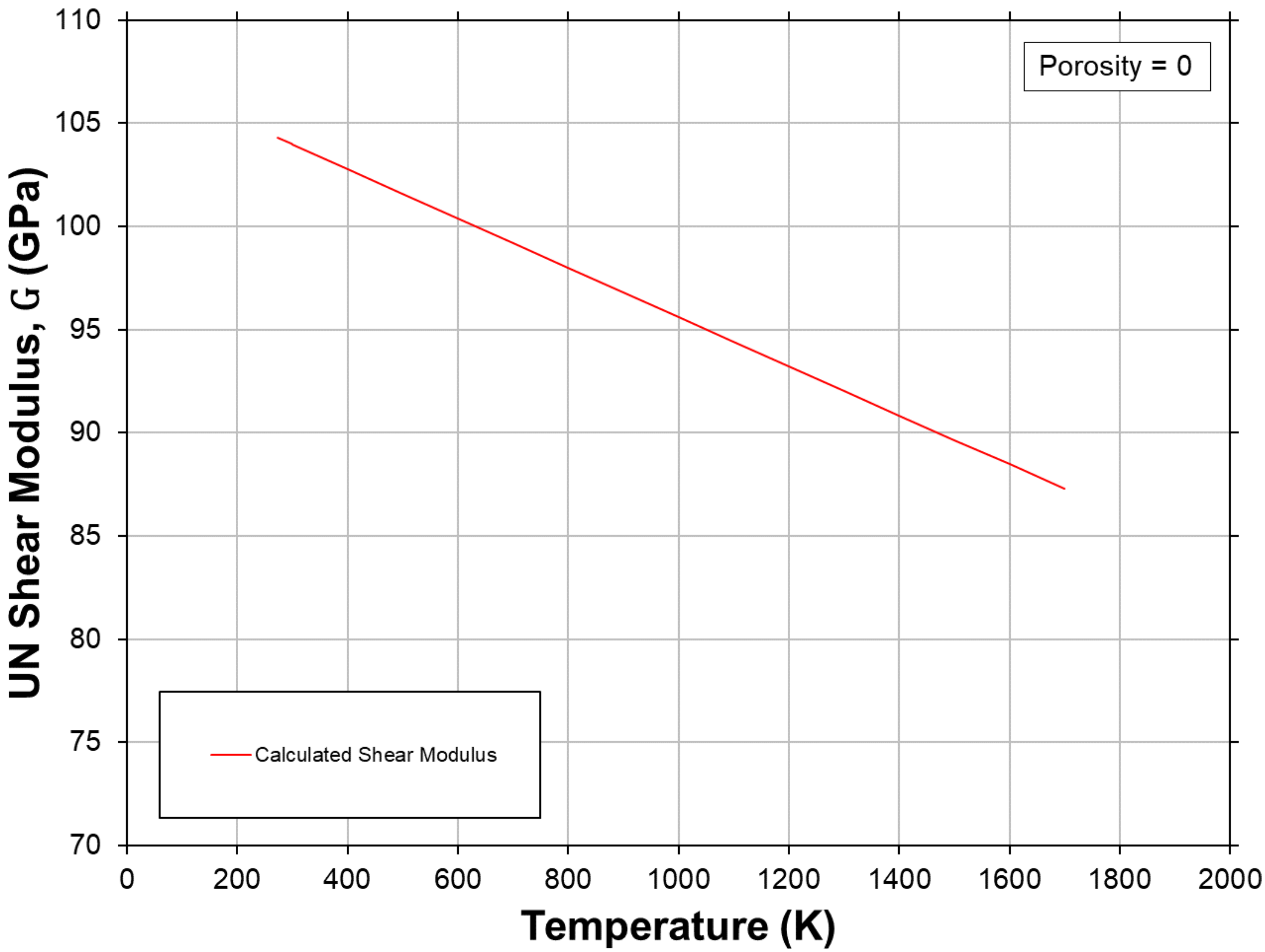

Figure 6.1.1-12: Shear Modulus versus Temperature of UN.

Shear Modulus with Temperature

100% Theoretical Density

Temperature (T)		Shear Modulus (G)		Temperature (T)		Shear Modulus (G)	
K	(°F)	GPa	(Msi)	K	(°F)	GPa	(Msi)
273	(31.7)	104.31	(15.14)	1000	(1340.3)	95.63	(13.88)
300	(80.3)	103.99	(15.09)	1050	(1430.3)	95.03	(13.79)
350	(170.3)	103.39	(15.00)	1100	(1520.3)	94.44	(13.70)
400	(260.3)	102.79	(14.92)	1150	(1610.3)	93.84	(13.62)
450	(350.3)	102.20	(14.83)	1200	(1700.3)	93.24	(13.53)
500	(440.3)	101.60	(14.74)	1250	(1790.3)	92.65	(13.44)
550	(530.3)	101.00	(14.66)	1300	(1880.3)	92.05	(13.36)
600	(620.3)	100.41	(14.57)	1350	(1970.3)	91.45	(13.27)
650	(710.3)	99.81	(14.48)	1400	(2060.3)	90.86	(13.18)
700	(800.3)	99.21	(14.40)	1450	(2150.3)	90.26	(13.10)
750	(890.3)	98.62	(14.31)	1500	(2240.3)	89.66	(13.01)
800	(980.3)	98.02	(14.22)	1550	(2330.3)	89.06	(12.92)
850	(1070.3)	97.42	(14.14)	1600	(2420.3)	88.47	(12.84)
900	(1160.3)	96.83	(14.05)	1650	(2510.3)	87.87	(12.75)
950	(1250.3)	96.23	(13.96)	1700	(2600.3)	87.27	(12.66)

Application Notes: Data for shear modulus is collected from references [4, 14, 29-33] and fitted with the equation below to approximate property trend with respect to temperature and porosity.

Fit Equations:

$$G(T,P) = A \cdot (1-P)^N \,[A0 - A1 \cdot (T-273)]$$

$G(T,P) = Shear\ Modulus\ [GPa]$

$T = Temperature\ [K]$

$P = Fractional\ Porosity$

Constants:

Temperature Range [K]: $273 \le T \le 1700$

A =	103.999
N =	2.893
A0 =	1.003
A1 =	1.148E-04

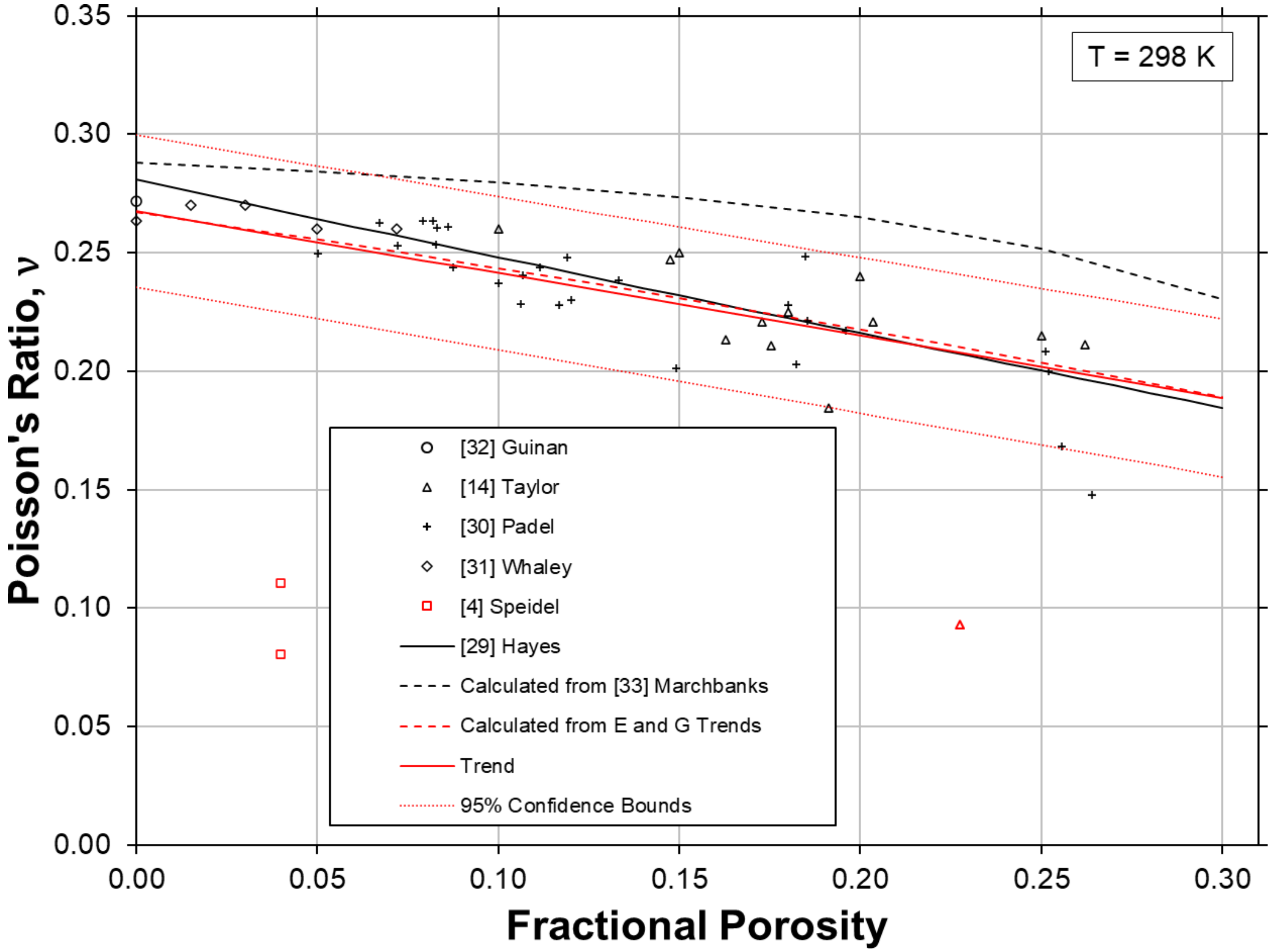

Figure 6.1.1-13: Poisson's Ratio versus Fractional Porosity of UN.

Room Temperature

Porosity (P)	Poisson's Ratio (ν)
0.00	0.268
0.02	0.262
0.04	0.257
0.06	0.252
0.08	0.247
0.10	0.241
0.12	0.236
0.14	0.231
0.16	0.226
0.18	0.220
0.20	0.215
0.22	0.210
0.24	0.205
0.26	0.199
0.28	0.194
0.30	0.189

Application Notes: Data for Poisson's Ratio is collected from references [4, 14, 29-33]. Property trend is calculated as a function of Young's modulus and shear modulus as seen in calculated equations below, and compared against the fitted trend equation below with respect to porosity. Only calculated trend is shown with respect to temperature.

Fit Equations:

$\nu(P) = A \cdot (1 - P)^N$

Calculated:

$\nu(P) = E(T,P)/(2 \cdot G(T,P)) - 1$

$\nu(P) = Poisson's\ Ratio$

$P = Fractional\ Porosity$

Constants:

Porosity (P):	$0 \leq P \leq 0.3$
A =	0.2676
N =	0.9772

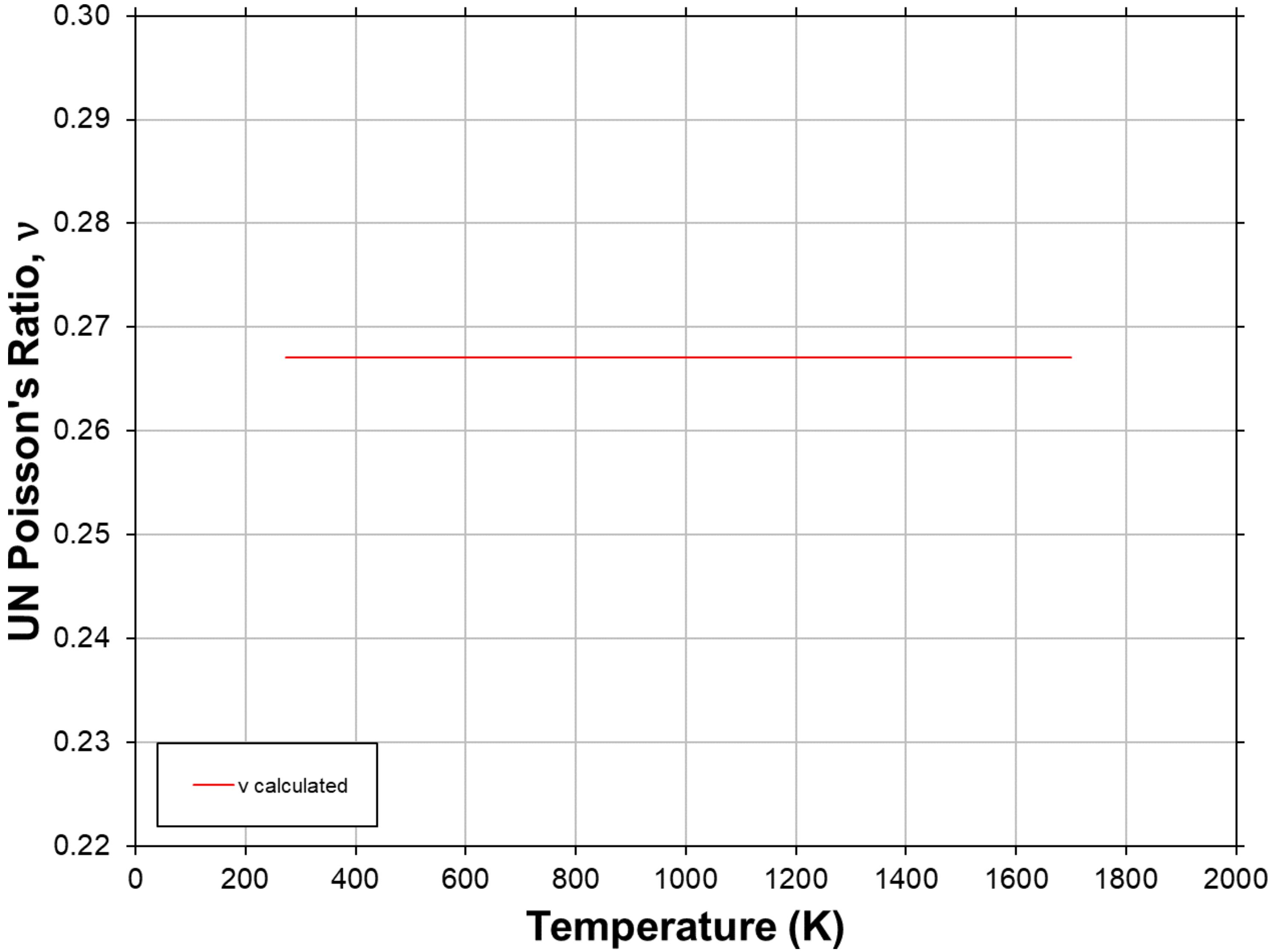

Figure 6.1.1-14: Poisson’s Ratio versus Temperature of UN.

100% Theoretical Density

Temperature (T) K	(°F)	Poisson's Ratio (ν)	Temperature (T) K	(°F)	Poisson's Ratio (ν)
273	(31.7)	0.268	1000	(1340.3)	0.268
300	(80.3)	0.268	1050	(1430.3)	0.268
350	(170.3)	0.268	1100	(1520.3)	0.268
400	(260.3)	0.268	1150	(1610.3)	0.268
450	(350.3)	0.268	1200	(1700.3)	0.268
500	(440.3)	0.268	1250	(1790.3)	0.268
550	(530.3)	0.268	1300	(1880.3)	0.268
600	(620.3)	0.268	1350	(1970.3)	0.268
650	(710.3)	0.268	1400	(2060.3)	0.268
700	(800.3)	0.268	1450	(2150.3)	0.268
750	(890.3)	0.268	1500	(2240.3)	0.268
800	(980.3)	0.268	1550	(2330.3)	0.268
850	(1070.3)	0.268	1600	(2420.3)	0.268
900	(1160.3)	0.268	1650	(2510.3)	0.268
950	(1250.3)	0.268	1700	(2600.3)	0.268

Application Notes: Data for Poisson's Ratio is collected from references [4, 14, 29-33]. Property trend is calculated as a function of Young's modulus and shear modulus as seen in calculated equations below.

Calculated:

$\nu(T,P) = E(T,P)/(2 \cdot G(T,P)) - 1$

$\nu(T,P) = Poisson's\ Ratio$

$G(T,P) = Shear\ Modulus\ [GPa]$

$E(T,P) = Young's\ Modulus\ [GPa]$

$P = Fractional\ Porosity$

$T = Temperature\ [K]$

Constants:

Temperature Range [K]: $273 \leq T \leq 1700$

Temp.	Physical and Electrical		Thermal				Elastic		
	Density	Electrical Resistivity	Thermal Conductivity	Thermal Expansion	Mean CTE	Specific Heat	Young's Modulus	Shear Modulus	Poisson's Ratio
(T)	(ρ)	(ρ_e)	(k)	(dL/L_0)	($\bar{\alpha}$)	(C_p)	(E)	(G)	(ν)
K	kg/m³	μΩ-m	W/(m-K)	%	10^{-6}/K	J/(g-K)	GPa	GPa	
100	14379	1.147	9.30	-0.115	5.98	0.104	-	-	-
200	14357	1.400	12.14	-0.064	6.76	0.161	-	-	-
300	14329	1.483	14.19	0.003	7.26	0.190	263.52	103.99	0.268
400	14295	1.536	15.85	0.081	7.62	0.204	260.50	102.79	0.268
500	14260	1.577	17.27	0.164	7.91	0.213	257.47	101.60	0.268
600	14223	1.611	18.53	0.250	8.15	0.219	254.44	100.41	0.268
700	14185	1.641	19.66	0.339	8.36	0.224	251.42	99.21	0.268
800	14146	1.668	20.70	0.432	8.55	0.229	248.39	98.02	0.268
900	14106	1.693	21.65	0.527	8.72	0.234	245.37	96.83	0.268
1000	14064	1.718	22.55	0.626	8.89	0.238	242.34	95.63	0.268
1100	14022	1.742	23.39	0.728	9.04	0.243	239.32	94.44	0.268
1200	13978	1.768	24.19	0.832	9.19	0.249	236.29	93.24	0.268
1300	13934	1.796	24.94	0.940	9.33	0.254	233.27	92.05	0.268
1400	13888	1.827	25.66	1.049	9.47	0.260	230.24	90.86	0.268
1500	13842	1.862	26.35	1.161	9.61	0.266	227.21	89.66	0.268
1600	13795	1.902	27.02	1.276	9.74	0.273	224.19	88.47	0.268
1700	13748	-	27.65	1.393	9.87	0.279	221.16	87.27	0.268
1800	13699	-	28.27	1.511	10.00	0.287	-	-	-
1900	13651	-	28.86	1.632	10.13	0.294	-	-	-
2000	13601	-	29.44	1.755	10.25	0.302	-	-	-
2100	13552	-	29.58	1.879	10.38	0.310	-	-	-
2200	13502	-	29.58	2.005	10.50	0.318	-	-	-
2300	13451	-	29.58	2.132	10.62	0.327	-	-	-
2400	13401	-	29.58	2.260	10.74	0.336	-	-	-
2600	13299	-	-	2.521	10.98	0.355	-	-	-

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6 Nuclear Materials

6.1 Nuclear Fuel Materials

Room Temperature Properties

Molar Mass, [g/mol]	250.04
Theoretical Density, [kg/m^3]	13,630
Melting Point, [K]	2773±30
Boiling Point, [K]	4691-4866
Specific Heat, [J/(g-K)]	0.202
Heat of Fusion, [kJ/kg]	195.6
Heat of Vapourization, [kJ/kg]	2120
Thermal Conductivity, [W/(m-K)]	20.8
Linear expansion coefficient, [µm/(m-K)]	10.1
Electrical resistivity, [µΩ-m]	0.727
Young's Modulus, [GPa]	224.9
Shear Modulus, [GPa]	87.3
Poisson's Ratio, [-]	0.288

Uranium – Carbon Phase Diagram

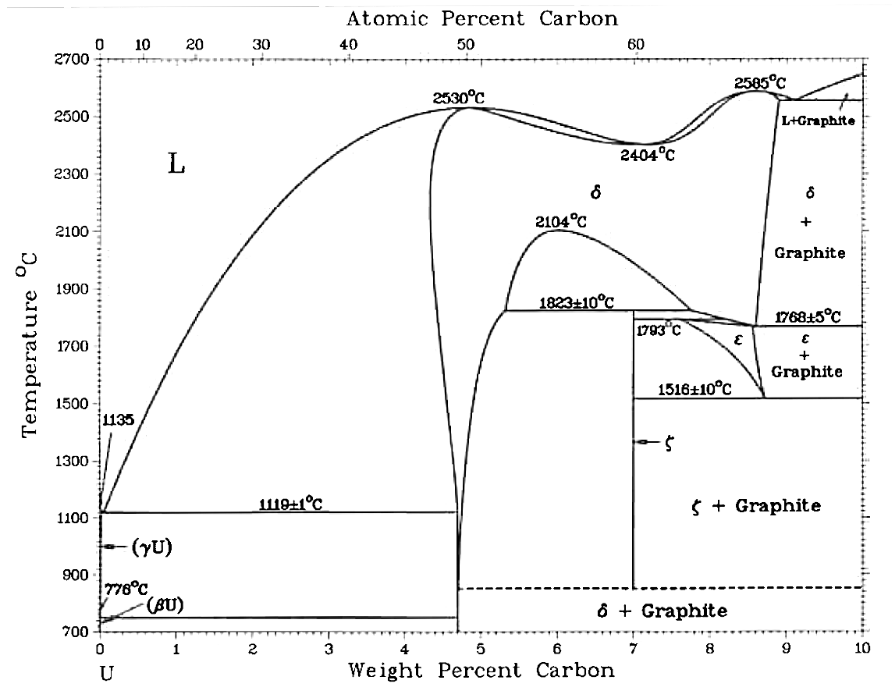

Figure 6.1.2-1: Uranium – Carbon Phase Diagram [1].
Stoichiometric UC = 4.80 wt% Carbon.

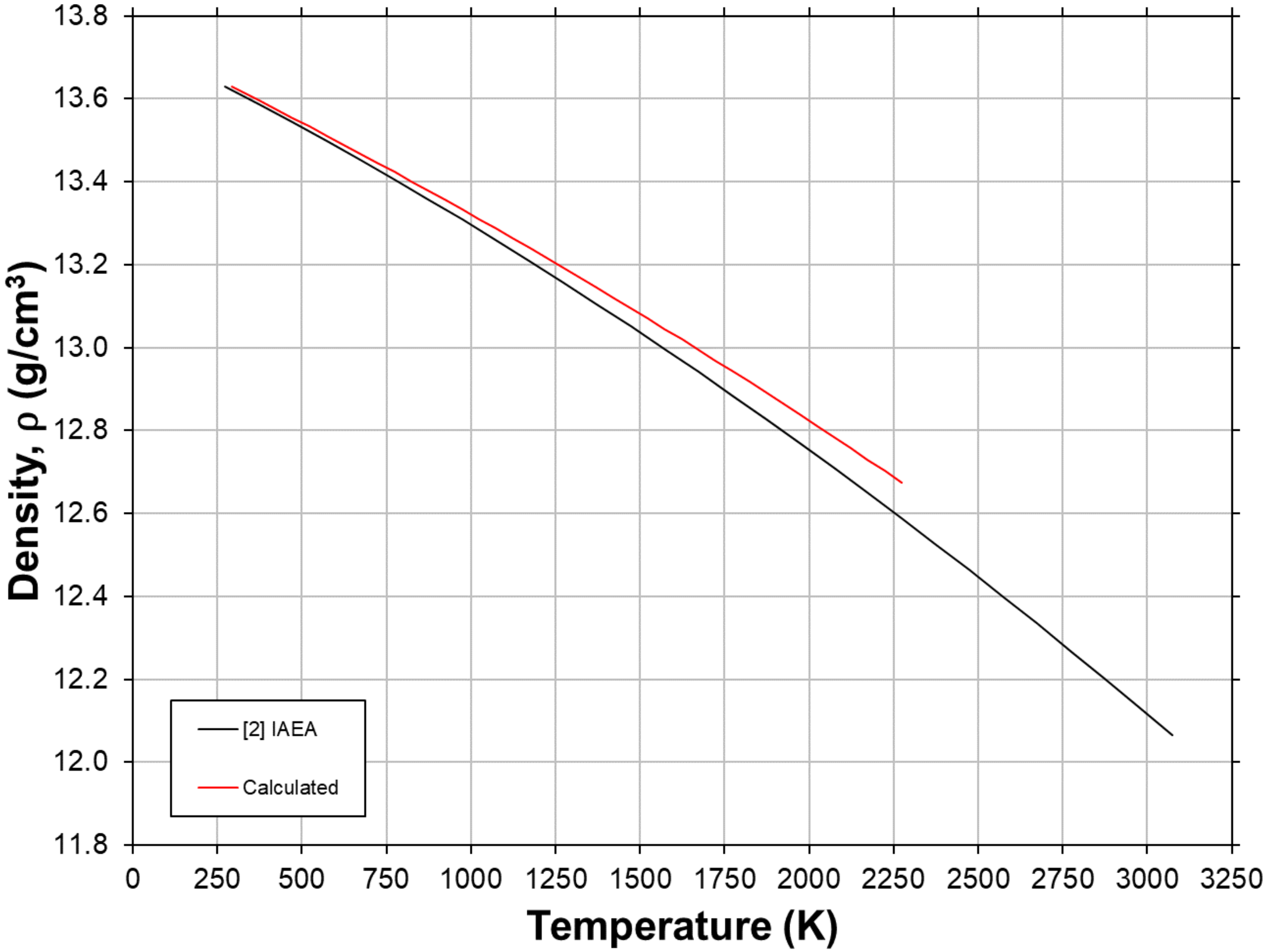

Figure 6.1.2-2: Density versus Temperature for UC. Calculated from fitted trend of the Thermal Expansion data with comparison to trend from the IAEA (2008).

100% Theoretical Density

Temperature (T)		Density (ρ)		Temperature (T)		Density (ρ)	
K	(°F)	kg/m³	(lb/ft³)	K	(°F)	kg/m³	(lb/ft³)
293	(67.7)	13630	(850.9)	1050	(1430.3)	13298	(830.2)
350	(170.3)	13606	(849.4)	1100	(1520.3)	13275	(828.7)
400	(260.3)	13585	(848.1)	1150	(1610.3)	13251	(827.3)
450	(350.3)	13564	(846.8)	1200	(1700.3)	13228	(825.8)
500	(440.3)	13543	(845.5)	1300	(1880.3)	13180	(822.8)
550	(530.3)	13522	(844.1)	1400	(2060.3)	13131	(819.8)
600	(620.3)	13500	(842.8)	1500	(2240.3)	13082	(816.7)
650	(710.3)	13478	(841.4)	1600	(2420.3)	13032	(813.6)
700	(800.3)	13456	(840.1)	1700	(2600.3)	12981	(810.4)
750	(890.3)	13434	(838.7)	1800	(2780.3)	12929	(807.2)
800	(980.3)	13412	(837.3)	1900	(2960.3)	12877	(803.9)
850	(1070.3)	13390	(835.9)	2000	(3140.3)	12824	(800.6)
900	(1160.3)	13367	(834.5)	2100	(3320.3)	12770	(797.2)
950	(1250.3)	13344	(833.1)	2200	(3500.3)	12715	(793.8)
1000	(1340.3)	13321	(831.6)	2273	(3631.7)	12675	(791.3)

Application Notes: Density is calculated here as a function of thermal expansion as seen in the equation below to approximate property trend as a function of temperature. This trend is compared against trend from reference [2].

Density Calculation:

$\rho(T) = \rho_{RT}/(1 + dL/L_0(T)/100)^3$

$\rho(T) = Density\ [kg/m^3]$

$Room\ Temperature\ Density\ (\rho_{RT}) = 13{,}630\ [kg/m^3]$

$P = Fractional\ Porosity$

$T = Temperature\ [K]$

Temperature Range: $293 \leq T \leq 2273$

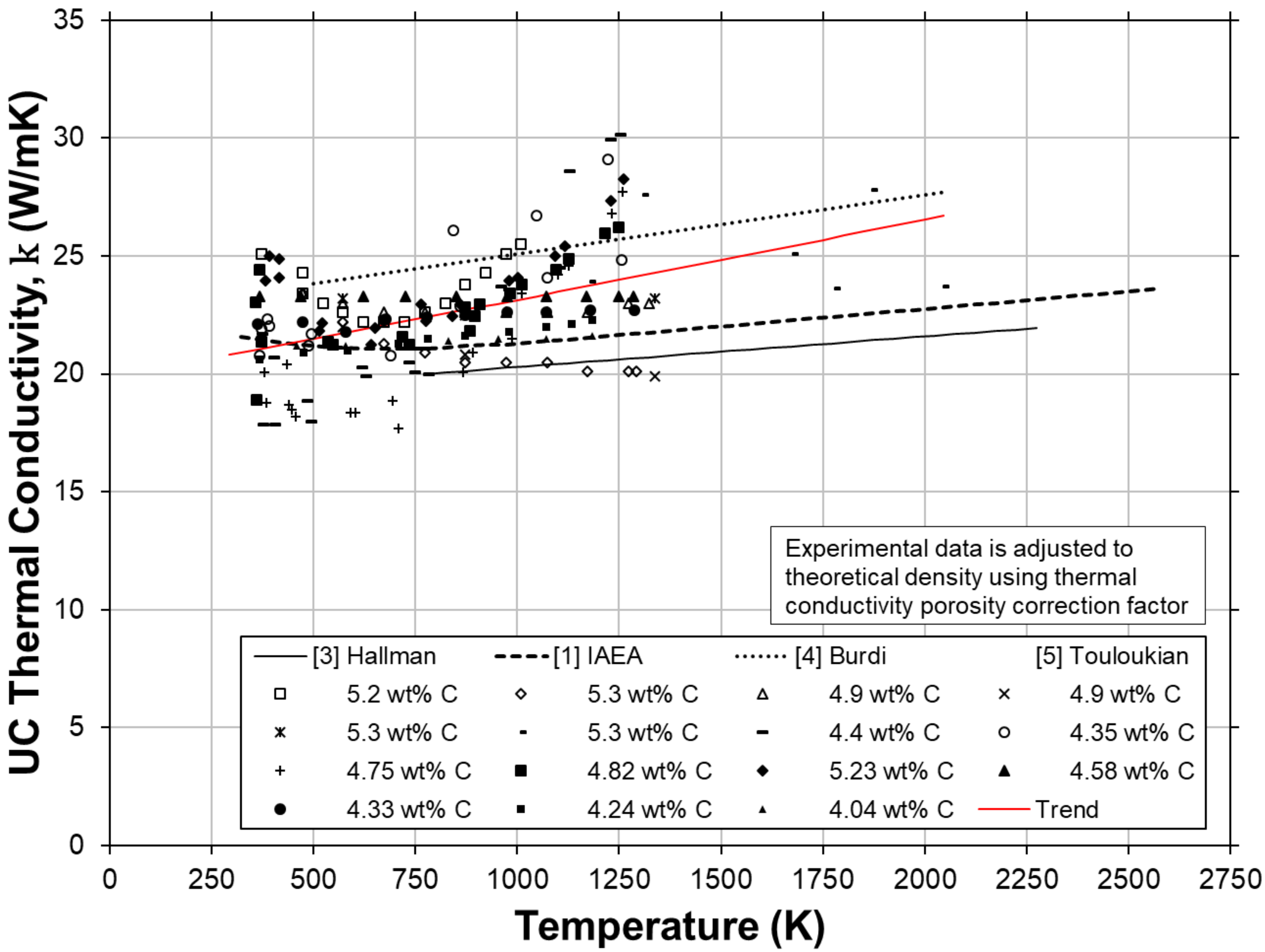

Figure 6.1.2-3: Thermal Conductivity versus Temperature of UC.

100% Theoretical Density

Temperature (T)		Thermal Conductivity (k)		Temperature (T)		Thermal Conductivity (k)	
K	(°F)	W/(m-K)	((Btu·in)/(ft²·hr·°F))	K	(°F)	W/(m-K)	((Btu·in)/(ft²·hr·°F))
293	(67.7)	20.81	(144.40)	1050	(1430.3)	23.31	(161.70)
350	(170.3)	21.00	(145.68)	1100	(1520.3)	23.47	(162.86)
400	(260.3)	21.16	(146.81)	1150	(1610.3)	23.64	(164.03)
450	(350.3)	21.32	(147.94)	1200	(1700.3)	23.81	(165.20)
500	(440.3)	21.49	(149.07)	1250	(1790.3)	23.98	(166.37)
550	(530.3)	21.65	(150.21)	1300	(1880.3)	24.15	(167.55)
600	(620.3)	21.81	(151.34)	1350	(1970.3)	24.32	(168.72)
650	(710.3)	21.98	(152.48)	1400	(2060.3)	24.49	(169.90)
700	(800.3)	22.14	(153.63)	1500	(2240.3)	24.83	(172.27)
750	(890.3)	22.31	(154.77)	1600	(2420.3)	25.17	(174.64)
800	(980.3)	22.47	(155.92)	1700	(2600.3)	25.52	(177.03)
850	(1070.3)	22.64	(157.07)	1800	(2780.3)	25.86	(179.43)
900	(1160.3)	22.81	(158.22)	1900	(2960.3)	26.21	(181.84)
950	(1250.3)	22.97	(159.38)	2000	(3140.3)	26.56	(184.26)
1000	(1340.3)	23.14	(160.54)	2045	(3221.3)	26.71	(185.35)

Application Notes: Data for thermal conductivity is collected from references [2-5] and fitted with the equation below to approximate the property trend with respect to temperature and porosity.

Fit Equation:

$$k(T) = A0 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2$$

$k(T) = Thermal\ Conductivity\ [W\ /\ (m \cdot K)]$

$k_P = k \cdot (1 - P)/(1 + P)$

$P = Fractional\ Porosity\ (0 \le P \le 0.2)$

$T = Temperature\ [K]$

Constants:

T Range [K]:	$293 \le T \le 2045$
A0 =	19.87
A1 =	3.194
A2 =	0.07475

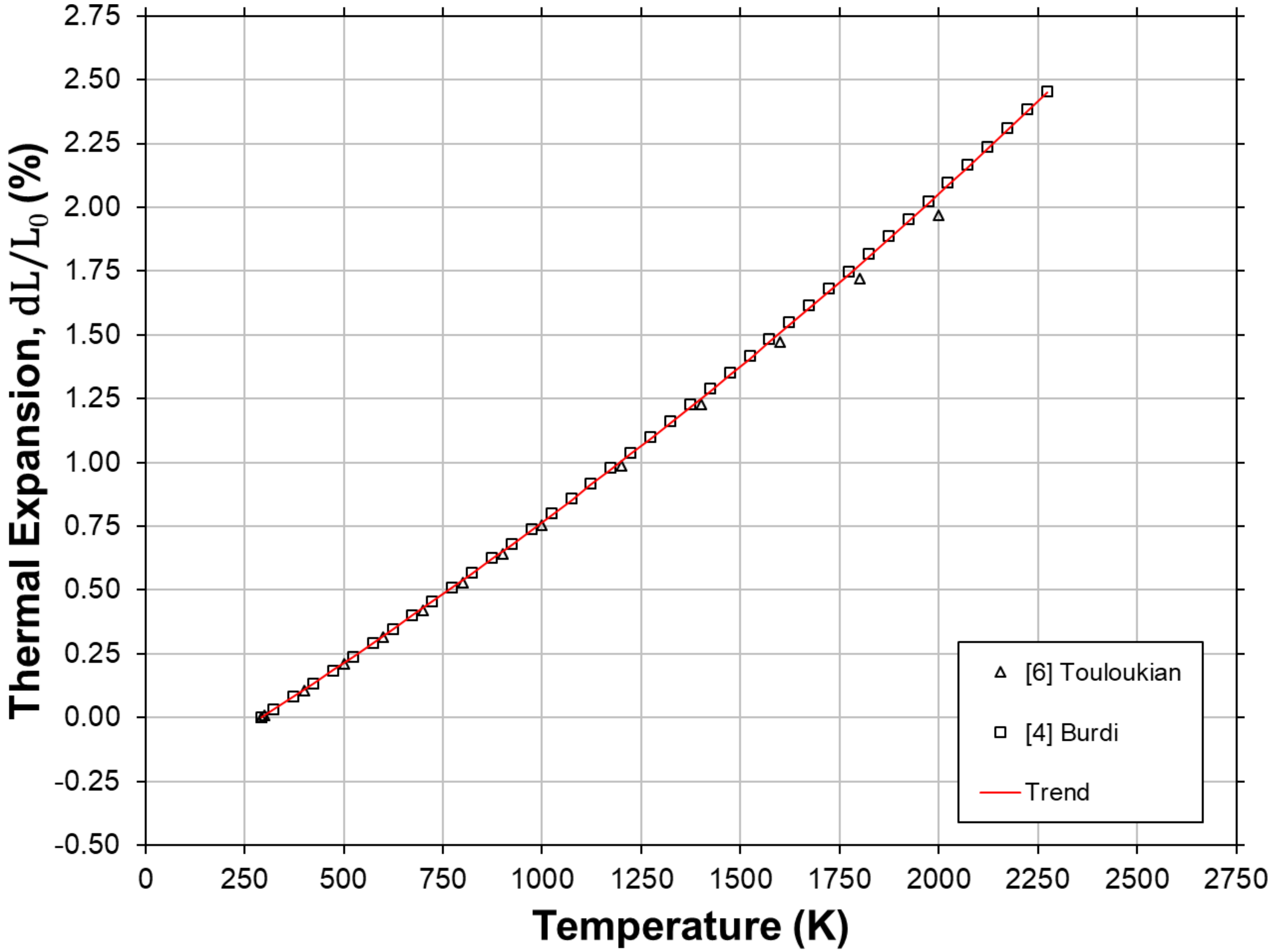

Figure 6.1.2-4: Thermal Expansion versus Temperature of UC.

100% Theoretical Density

Temperature (T)		Thermal Expansion (dL/L_0)	Temperature (T)		Thermal Expansion (dL/L_0)
K	(°F)	%	K	(°F)	%
293	(67.7)	0.000	1050	(1430.3)	0.825
350	(170.3)	0.058	1100	(1520.3)	0.884
400	(260.3)	0.109	1150	(1610.3)	0.944
450	(350.3)	0.161	1200	(1700.3)	1.004
500	(440.3)	0.214	1300	(1880.3)	1.126
550	(530.3)	0.267	1400	(2060.3)	1.250
600	(620.3)	0.320	1500	(2240.3)	1.377
650	(710.3)	0.374	1600	(2420.3)	1.507
700	(800.3)	0.429	1700	(2600.3)	1.639
750	(890.3)	0.484	1800	(2780.3)	1.774
800	(980.3)	0.539	1900	(2960.3)	1.912
850	(1070.3)	0.595	2000	(3140.3)	2.052
900	(1160.3)	0.652	2100	(3320.3)	2.196
950	(1250.3)	0.709	2200	(3500.3)	2.342
1000	(1340.3)	0.767	2273	(3631.7)	2.451

Application Notes: Data for thermal expansion is collected from references [4, 6] and fitted with the equation below to approximate property trend with respect to temperature.

Fit Equation:

$$dL/L_0\,(T) = A0 + A1\cdot\left(\frac{T}{1000}\right) + A2\cdot\left(\frac{T}{1000}\right)^2 + A3\cdot\left(\frac{T}{1000}\right)^3$$

$dL/L_0\,(T) = Thermal\ Expansion$ [%]

$T = Temperature\ [K]$

Constants:

T Range [K]:	$293 < T \leq 2273$
A0 =	-0.2887
A1 =	0.9588
A2 =	0.08756
A3 =	0.009167

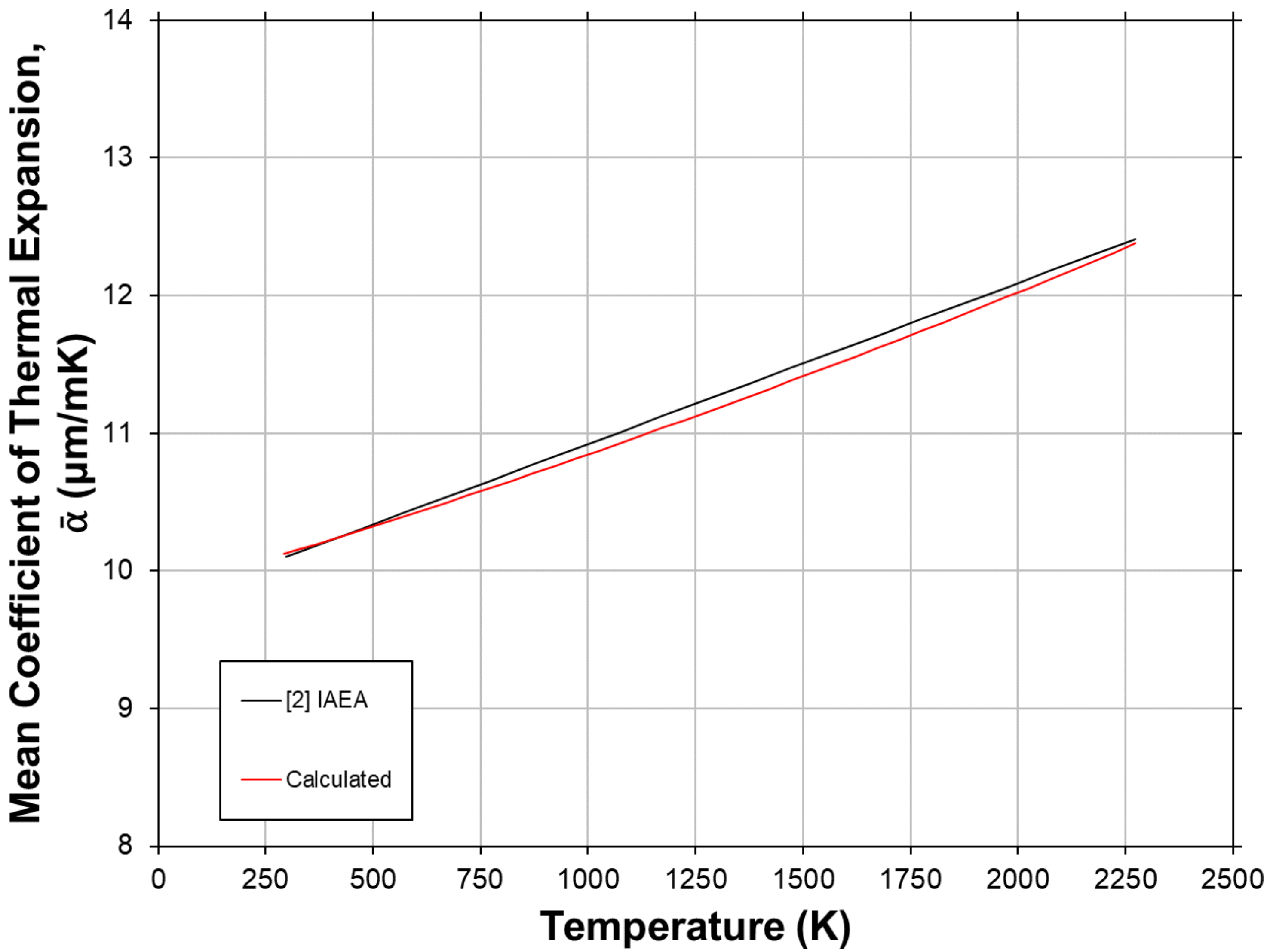

Figure 6.1.2-5: Mean Coefficient of Thermal Expansion versus Temperature of UC. Calculated from fitted trend of the Thermal Expansion data with comparison to IAEA (2008).

100% Theoretical Density

Temperature (T)		Mean CTE (ᾱ)		Temperature (T)		Mean CTE (ᾱ)	
K	(°F)	μm/(m-K)	(μin/(in-°F))	K	(°F)	μm/(m-K)	(μin/(in-°F))
293	(67.7)	10.121	(5.623)	1050	(1430.3)	10.900	(6.056)
350	(170.3)	10.176	(5.653)	1100	(1520.3)	10.955	(6.086)
400	(260.3)	10.225	(5.681)	1150	(1610.3)	11.011	(6.117)
450	(350.3)	10.274	(5.708)	1200	(1700.3)	11.067	(6.148)
500	(440.3)	10.324	(5.736)	1300	(1880.3)	11.180	(6.211)
550	(530.3)	10.374	(5.763)	1400	(2060.3)	11.295	(6.275)
600	(620.3)	10.425	(5.791)	1500	(2240.3)	11.412	(6.340)
650	(710.3)	10.476	(5.820)	1600	(2420.3)	11.531	(6.406)
700	(800.3)	10.527	(5.848)	1700	(2600.3)	11.651	(6.473)
750	(890.3)	10.579	(5.877)	1800	(2780.3)	11.774	(6.541)
800	(980.3)	10.632	(5.906)	1900	(2960.3)	11.898	(6.610)
850	(1070.3)	10.684	(5.936)	2000	(3140.3)	12.023	(6.680)
900	(1160.3)	10.738	(5.965)	2100	(3320.3)	12.151	(6.751)
950	(1250.3)	10.791	(5.995)	2200	(3500.3)	12.280	(6.822)
1000	(1340.3)	10.846	(6.025)	2273	(3631.7)	12.376	(6.876)

Application Notes: Data for mean coefficient of thermal expansion is calculated as a function thermal expansion data, then fitted with the equation below to approximate property trend with respect to temperature. Fitted trend is compared against trend from reference [2].

Fit Equation:

$$\bar{\alpha}(T) = A0 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2$$

$\bar{\alpha}(T) = Coefficient\ of\ Thermal\ Expansion\ [\mu m/(m \cdot K)]$

$T = Temperature\ [K]$

Constants:

T. Range [K]: $293 \leq T \leq 2273$

A0 = 9.847

A1 = 0.909

A2 = 0.0896

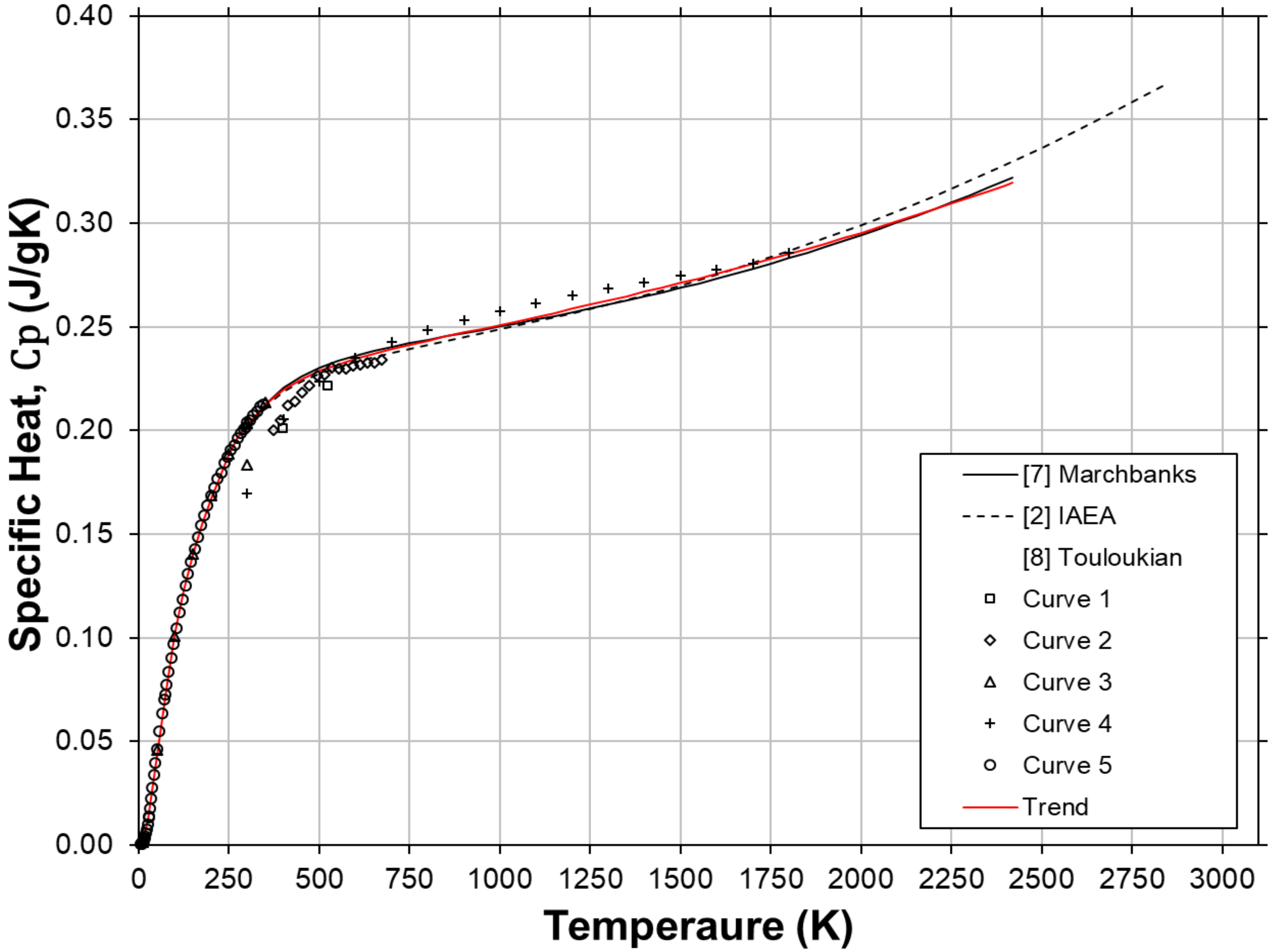

Figure 6.1.2-6: Specific Heat versus Temperature of UC. Displaying fitted trend and data.

100% Theoretical Density

Temperature (T)		Specific Heat (C_p)		Temperature (T)		Specific Heat (C_p)	
K	(°F)	J/(g-K)	(BTU/(lb-°F))	K	(°F)	J/(g-K)	(BTU/(lb-°F))
25	(-414.7)	0.012	(0.003)	1200	(1700.3)	0.259	(0.062)
50	(-369.7)	0.043	(0.010)	1300	(1880.3)	0.263	(0.063)
100	(-279.7)	0.101	(0.024)	1400	(2060.3)	0.267	(0.064)
200	(-99.7)	0.167	(0.040)	1500	(2240.3)	0.271	(0.065)
300	(80.3)	0.203	(0.048)	1600	(2420.3)	0.276	(0.066)
400	(260.3)	0.220	(0.053)	1700	(2600.3)	0.280	(0.067)
500	(440.3)	0.229	(0.055)	1800	(2780.3)	0.285	(0.068)
600	(620.3)	0.235	(0.056)	1900	(2960.3)	0.290	(0.069)
700	(800.3)	0.239	(0.057)	2000	(3140.3)	0.295	(0.071)
800	(980.3)	0.243	(0.058)	2100	(3320.3)	0.301	(0.072)
900	(1160.3)	0.247	(0.059)	2200	(3500.3)	0.306	(0.073)
1000	(1340.3)	0.251	(0.060)	2300	(3680.3)	0.312	(0.075)
1100	(1520.3)	0.255	(0.061)	2400	(3860.3)	0.318	(0.076)

Application Notes: Data for specific heat is collected from references [2, 7, 8] and fitted with the equations below to approximate property trend with respect to temperature.

Fit Equation:

For temperature range: $10 \leq T < 293$

$$C_P(T) = \left[A0 \cdot \left(\frac{T}{1000}\right)^N\right] \Big/ \left[1 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2\right]$$

For temperature range: $293 \leq T \leq 2418$

$$C_P(T) = B0 + B1 \cdot \left(\frac{T}{1000}\right) + B2 \cdot \left(\frac{T}{1000}\right)^2 + B\_2 / \left(\frac{T}{1000}\right)^2$$

$C_P(T) = Specific\ Heat\ [J/(g \cdot K)]$

$T = Temperature\ [K]$

Constants:

T. Range [K]:	$10 \leq T < 293$		$293 \leq T \leq 2418$
N =	2.352	B0 =	2.331E-01
A0 =	90.53	B1 =	1.053E-02
A1 =	2.954	B2 =	1.051E-02
A2 =	267.2	B_2 =	-3.091E-03

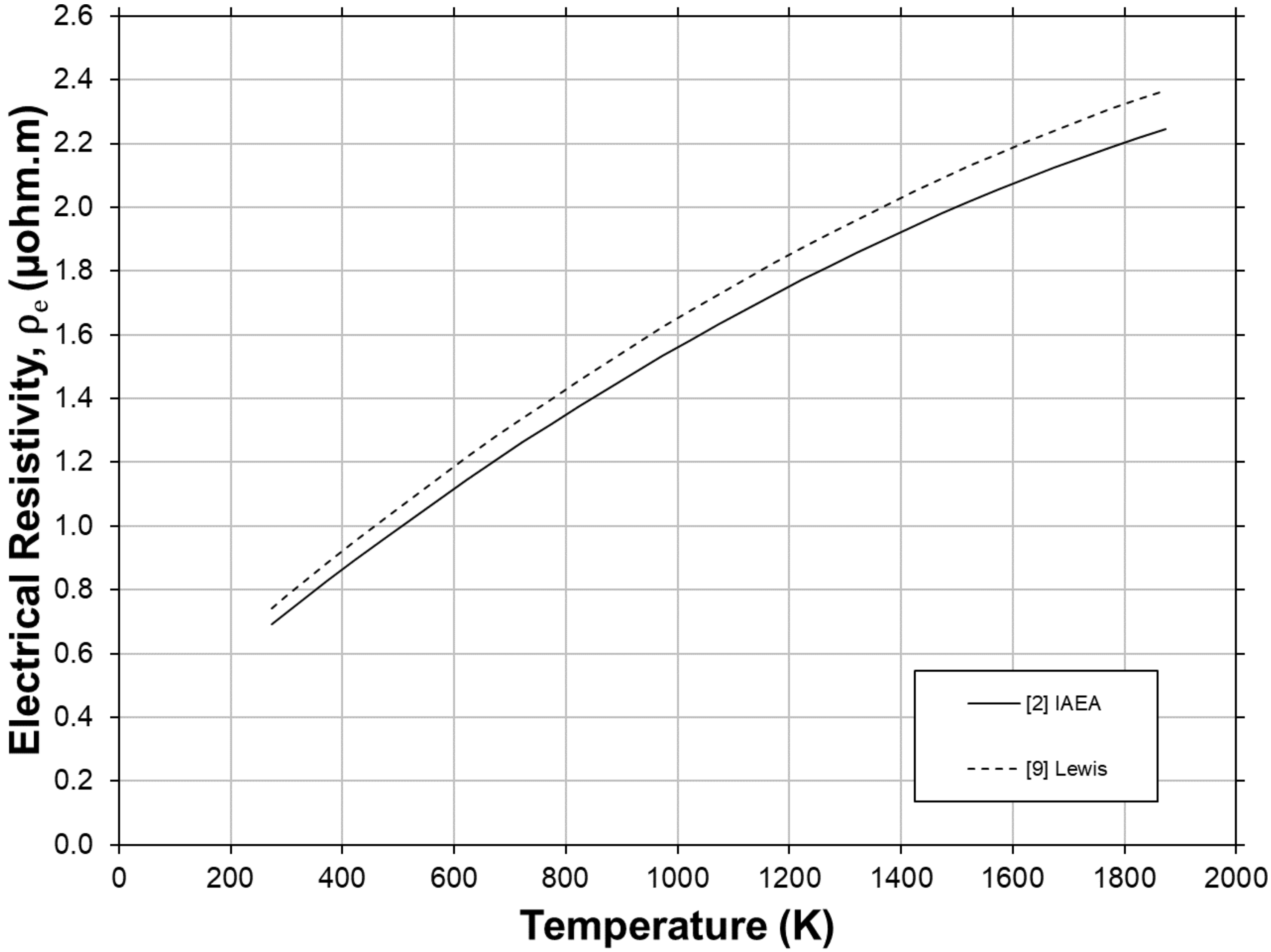

Figure 6.1.2-7: Electrical Resistivity versus Temperature of UC from IAEA (2008) and Lewis (1975).

100% Theoretical Density High Purity

Temperature (T)		Electrical Resistivity (ρ_e)		Temperature (T)		Electrical Resistivity (ρ_e)	
K	(°F)	μΩ-m	(μΩ-in)	K	(°F)	μΩ-m	(μΩ-in)
273	(31.7)	0.743	(29.26)	1000	(1340.3)	1.651	(65.00)
300	(80.3)	0.782	(30.78)	1050	(1430.3)	1.703	(67.05)
350	(170.3)	0.853	(33.57)	1100	(1520.3)	1.754	(69.04)
400	(260.3)	0.922	(36.30)	1150	(1610.3)	1.803	(70.99)
450	(350.3)	0.990	(38.99)	1200	(1700.3)	1.851	(72.88)
500	(440.3)	1.057	(41.61)	1250	(1790.3)	1.898	(74.71)
550	(530.3)	1.122	(44.19)	1300	(1880.3)	1.943	(76.50)
600	(620.3)	1.187	(46.71)	1350	(1970.3)	1.987	(78.23)
650	(710.3)	1.249	(49.18)	1400	(2060.3)	2.030	(79.91)
700	(800.3)	1.311	(51.60)	1450	(2150.3)	2.071	(81.54)
750	(890.3)	1.371	(53.97)	1500	(2240.3)	2.111	(83.11)
800	(980.3)	1.429	(56.28)	1600	(2420.3)	2.187	(86.10)
850	(1070.3)	1.487	(58.54)	1700	(2600.3)	2.257	(88.88)
900	(1160.3)	1.543	(60.74)	1800	(2780.3)	2.323	(91.44)
950	(1250.3)	1.598	(62.90)	1873	(2911.7)	2.367	(93.18)

Application Notes: Data for electrical resistivity is collected from reference [9] and is fitted with the equation below to approximate property trend with respect to temperature for high purity UC. The trend is compared against data from reference [2].

Fit Equation:

$$\rho_e(T) = A0 + A1 \cdot T + A2 \cdot T^2$$

$$\rho_e(T) = Electrical\ Resistivity\ [\mu\Omega \cdot m]$$

$$T = Temperature\ [K]$$

Constants:

T. Range [K]: $273 \leq T \leq 1873$

A0 = 0.329

A1 = 1.59E-03

A2 = -2.68E-07

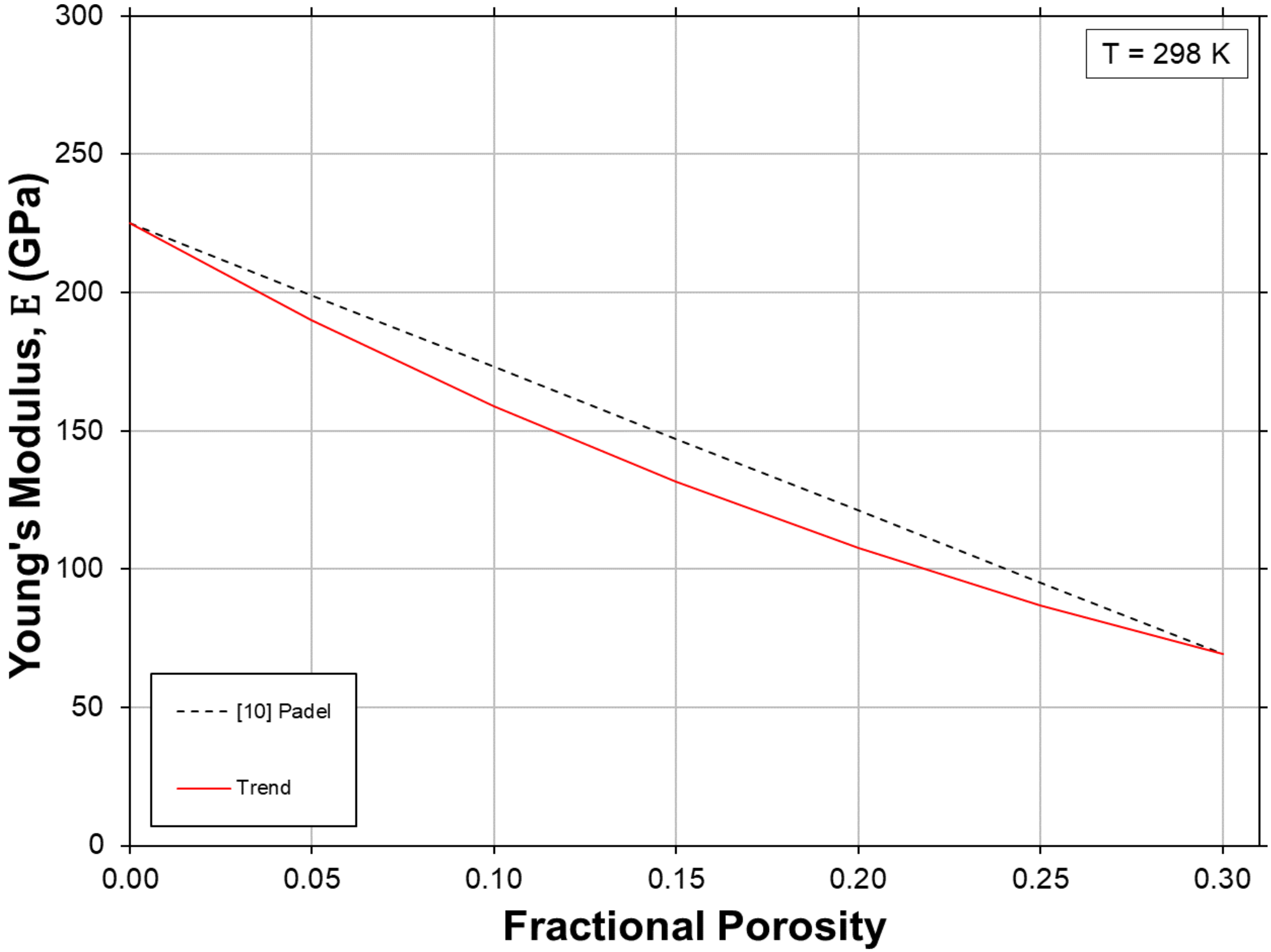

Figure 6.1.2-8: Young's Modulus versus Fractional Porosity of UC with comparison to Padel (1969).

Room Temperature

Porosity (P)	Young's Modulus (E)	
	GPa	(Msi)
0.00	224.90	(32.63)
0.02	210.39	(30.53)
0.04	196.54	(28.52)
0.06	183.34	(26.60)
0.08	170.77	(24.78)
0.10	158.82	(23.04)
0.12	147.46	(21.40)
0.14	136.68	(19.83)
0.16	126.46	(18.35)
0.18	116.79	(16.95)
0.20	107.64	(15.62)
0.22	99.01	(14.37)
0.24	90.87	(13.19)
0.26	83.21	(12.07)
0.28	76.02	(11.03)
0.30	69.26	(10.05)

Application Notes: Data for Young's modulus is collected from references [7, 10] and compared against the equation below to approximate property trend with respect to porosity at T=298K.

Fit Equations:

$$E(T,P) = A \cdot (1-P)^N \, [1 - A0 \cdot (T - 298)]$$

$E(T,P) = Young's\ Modulus\ [GPa]$

$T = Temperature\ [K]\ for\ 298 \leq T \leq 1600$

$P = Fractional\ Porosity\ for\ 0 \leq P \leq 0.3$

Constants:

A =	224.9
N =	3.302
A0 =	1.00E-04

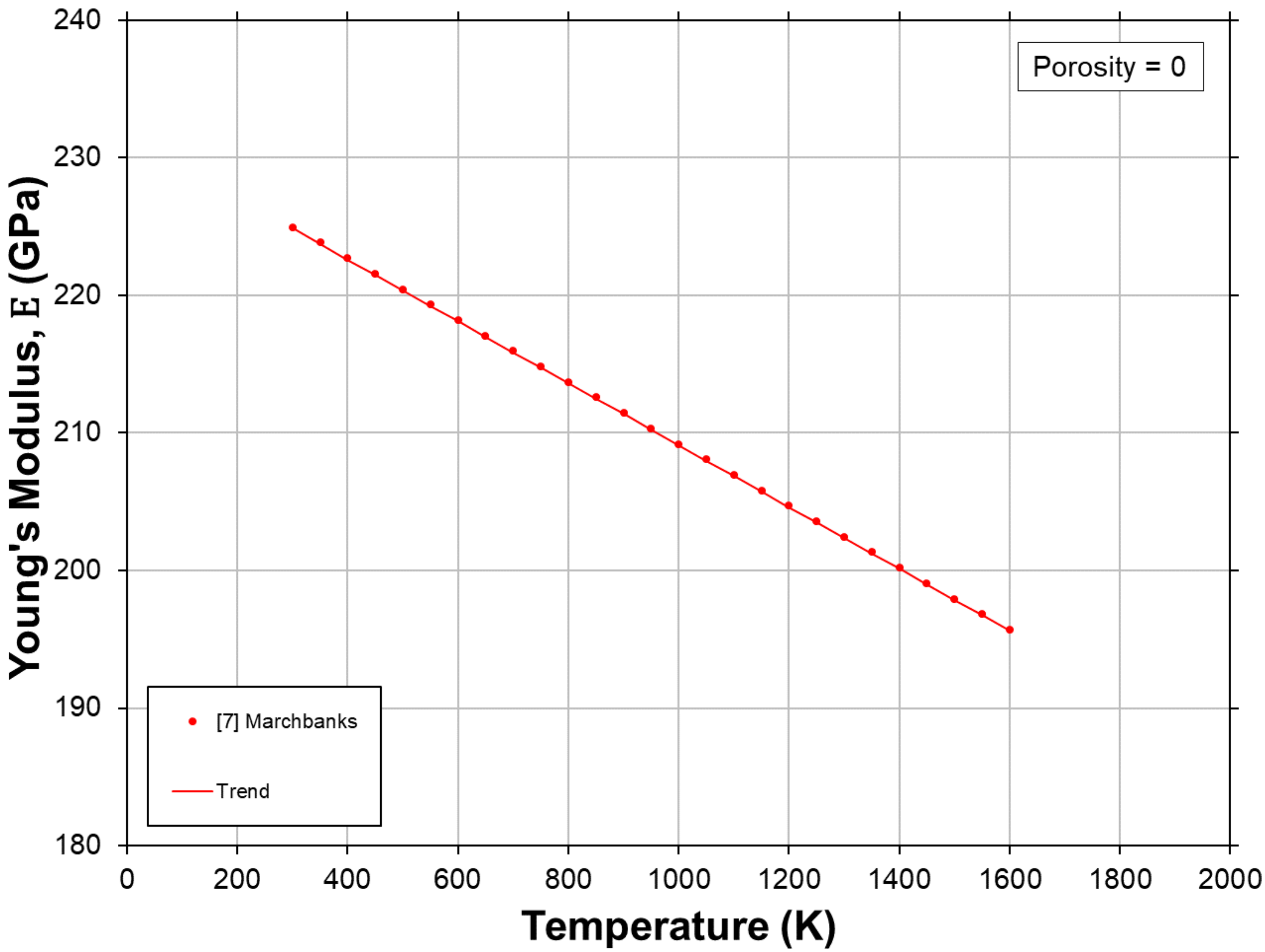

Figure 6.1.2-9: Young's Modulus versus Temperature of UC.

100% Theoretical Density

Temperature (T)		Young's Modulus (E)		Temperature (T)		Young's Modulus (E)	
K	(°F)	GPa	(Msi)	K	(°F)	GPa	(Msi)
298	(76.7)	224.90	(32.63)	1000	(1340.3)	209.11	(30.34)
300	(80.3)	224.86	(32.63)	1050	(1430.3)	207.99	(30.18)
350	(170.3)	223.73	(32.46)	1100	(1520.3)	206.86	(30.02)
400	(260.3)	222.61	(32.30)	1150	(1610.3)	205.74	(29.85)
450	(350.3)	221.48	(32.14)	1200	(1700.3)	204.61	(29.69)
500	(440.3)	220.36	(31.97)	1250	(1790.3)	203.49	(29.53)
550	(530.3)	219.23	(31.81)	1300	(1880.3)	202.37	(29.36)
600	(620.3)	218.11	(31.65)	1350	(1970.3)	201.24	(29.20)
650	(710.3)	216.98	(31.48)	1400	(2060.3)	200.12	(29.04)
700	(800.3)	215.86	(31.32)	1450	(2150.3)	198.99	(28.87)
750	(890.3)	214.73	(31.16)	1500	(2240.3)	197.87	(28.71)
800	(980.3)	213.61	(30.99)	1550	(2330.3)	196.74	(28.55)
850	(1070.3)	212.49	(30.83)	1600	(2420.3)	195.62	(28.38)
900	(1160.3)	211.36	(30.67)				
950	(1250.3)	210.24	(30.51)				

Application Notes: Data for Young's modulus is collected from references [7, 10] and compared against the equation below to approximate property trend with respect to temperature and porosity.

Fit Equations:

$E(T,P) = A \cdot (1-P)^N \, [1 - A0 \cdot (T - 298)]$

$E(T,P) = Young's\ Modulus\ [GPa]$

$T = Temperature\ [K]\ for\ 298 \leq T \leq 1600$

$P = Fractional\ Porosity\ for\ 0 \leq P \leq 0.3$

Constants:

A =	224.9
N =	3.302
A0 =	1.00E-04

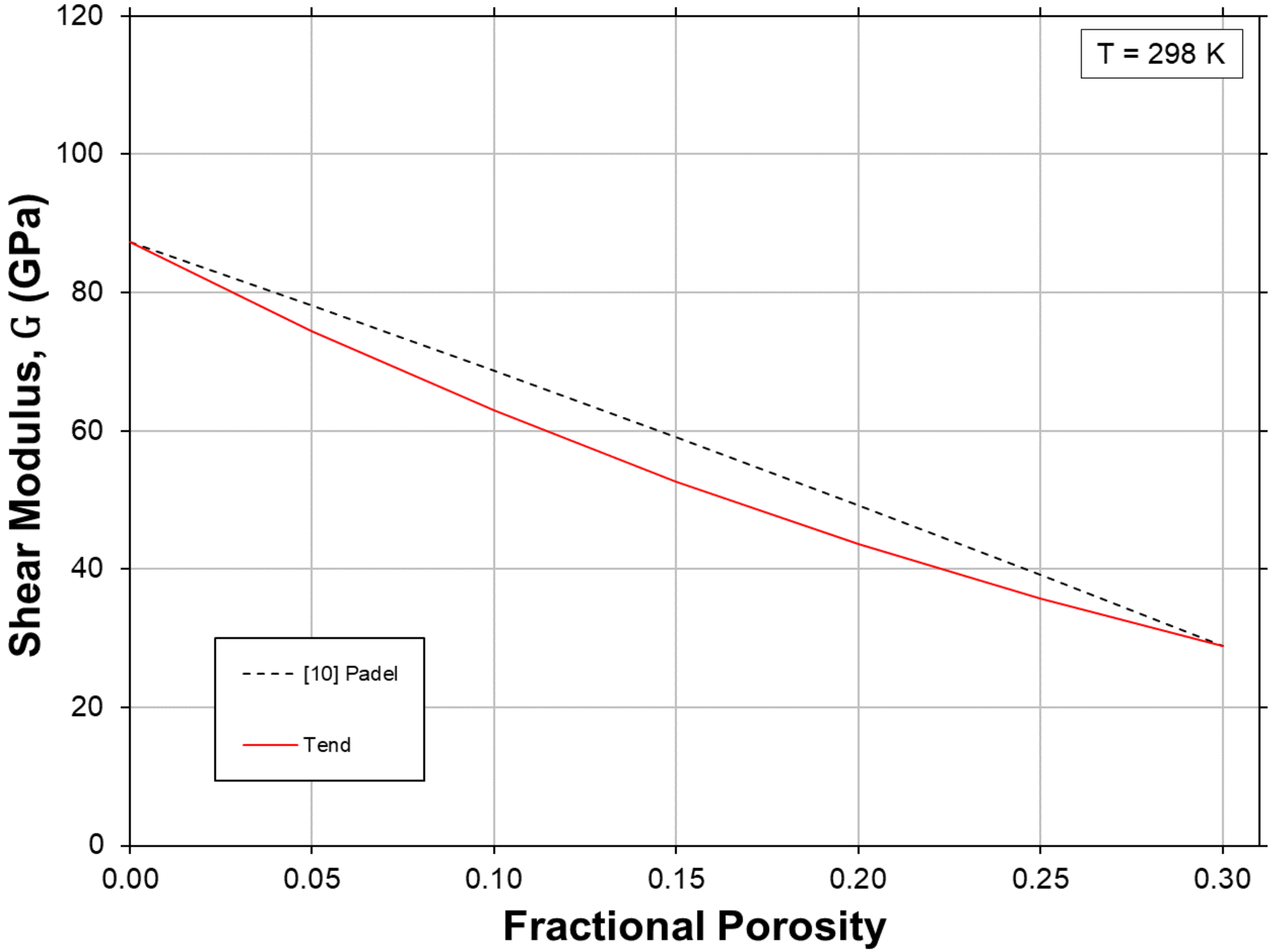

Figure 6.1.2-10: Shear Modulus versus Fractional Porosity of UC.

Room Temperature

Porosity (P)	Shear Modulus (G)	
	GPa	(Msi)
0.00	87.30	(12.67)
0.02	81.99	(11.90)
0.04	76.89	(11.16)
0.06	72.02	(10.45)
0.08	67.36	(9.77)
0.10	62.92	(9.13)
0.12	58.67	(8.51)
0.14	54.62	(7.93)
0.16	50.77	(7.37)
0.18	47.10	(6.83)
0.20	43.62	(6.33)
0.22	40.32	(5.85)
0.24	37.19	(5.40)
0.26	34.23	(4.97)
0.28	31.44	(4.56)
0.30	28.80	(4.18)

Application Notes: Data for shear modulus is collected from reference [7, 10] and fitted with the equation below to approximate property trend with respect to temperature and porosity.

Fit Equations:

$G(T,P) = A \cdot (1 - P)^N \cdot [1 - A0 \cdot (T - 298)]/[1 - A1 \cdot (T - 298)]$

$G(T,P) = Shear\ Modulus\ [GPa]$

$T = Temperature\ [K]$

$P = Fractional\ Porosity$

Constants:

A =	87.3
N =	3.109
A0 =	1.00E-04
A1 =	4.40E-05

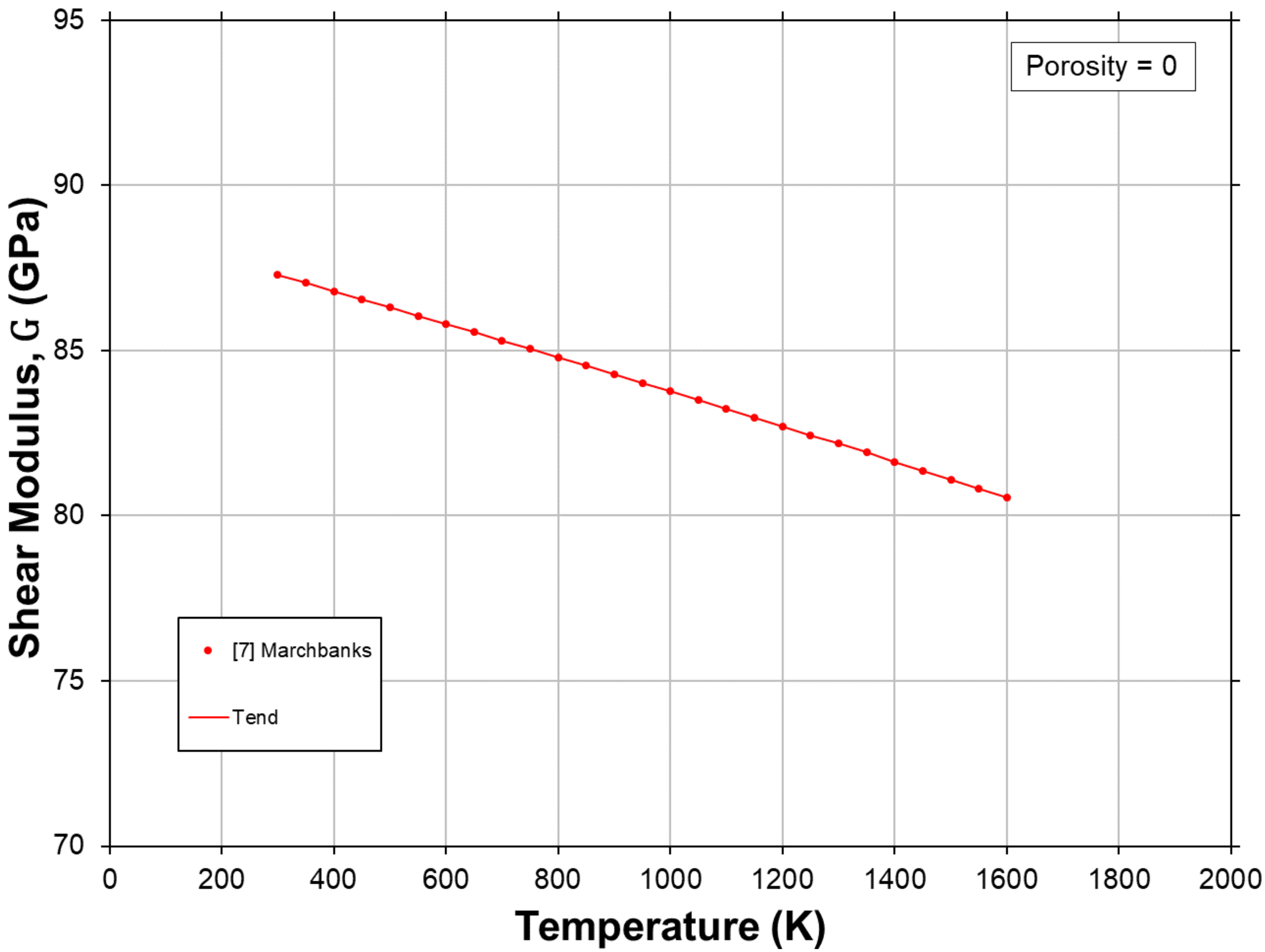

Figure 6.1.2-11: Shear Modulus versus Temperature of UC.

100% Theoretical Density

Temperature (T)		Shear Modulus (G)		Temperature (T)		Shear Modulus (G)	
K	(°F)	GPa	(Msi)	K	(°F)	GPa	(Msi)
298	(76.7)	87.30	(12.67)	1000	(1340.3)	83.76	(12.15)
300	(80.3)	87.29	(12.67)	1050	(1430.3)	83.50	(12.12)
350	(170.3)	87.05	(12.63)	1100	(1520.3)	83.24	(12.08)
400	(260.3)	86.80	(12.59)	1150	(1610.3)	82.97	(12.04)
450	(350.3)	86.55	(12.56)	1200	(1700.3)	82.71	(12.00)
500	(440.3)	86.30	(12.52)	1250	(1790.3)	82.44	(11.96)
550	(530.3)	86.05	(12.49)	1300	(1880.3)	82.18	(11.92)
600	(620.3)	85.80	(12.45)	1350	(1970.3)	81.91	(11.88)
650	(710.3)	85.55	(12.41)	1400	(2060.3)	81.64	(11.85)
700	(800.3)	85.30	(12.38)	1450	(2150.3)	81.37	(11.81)
750	(890.3)	85.05	(12.34)	1500	(2240.3)	81.10	(11.77)
800	(980.3)	84.79	(12.30)	1550	(2330.3)	80.82	(11.73)
850	(1070.3)	84.53	(12.27)	1600	(2420.3)	80.55	(11.69)
900	(1160.3)	84.28	(12.23)				
950	(1250.3)	84.02	(12.19)				

Application Notes: Data for Young's modulus is collected from references [7, 10] and compared against the equation below to approximate property trend with respect to temperature and porosity.

Fit Equations:

$G(T,P) = A \cdot (1-P)^N \cdot [1 - A0 \cdot (T-298)]/[1 - A1 \cdot (T-298)]$

$G(T,P) = Shear\ Modulus\ [GPa]$

$T = Temperature\ [K]$

$P = Fractional\ Porosity$

Constants:

A =	87.3
N =	3.109
A0 =	1.00E-04
A1 =	4.40E-05

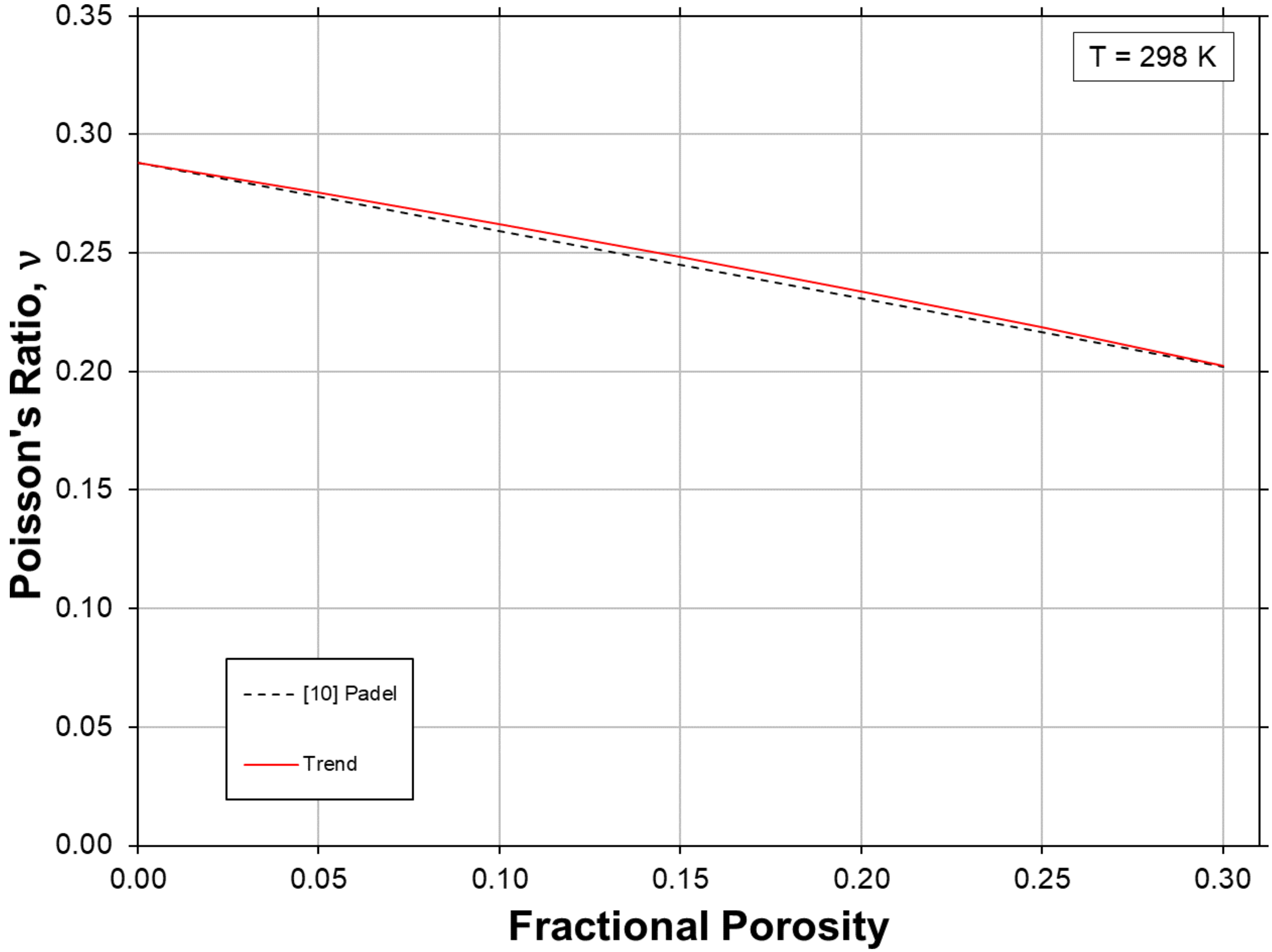

Figure 6.1.2-12: Poisson's Ratio versus Fractional Porosity of UC.

Room Temperature

Porosity (P)	Poisson's Ratio (ν)
0.00	0.288
0.02	0.283
0.04	0.278
0.06	0.273
0.08	0.268
0.10	0.262
0.12	0.257
0.14	0.251
0.16	0.245
0.18	0.240
0.20	0.234
0.22	0.228
0.24	0.222
0.26	0.215
0.28	0.209
0.30	0.202

Application Notes: Data for Poisson's Ratio is calculated from Young's modulus and Shear modulus data collected from references [7, 10] using the equation below to approximate property trend with respect to temperature and porosity.

Fit Equations:

$\nu(T,P) = E(T,P)/(2 \cdot G(T,P)) - 1$

$\nu(T,P) = Poisson's\ Ratio$

$E(T,P) = Young's\ modulus$

$G(T,P) = Shear\ modulus$

$T = Temperature\ [K], P = Fractional\ Porosity$

Constants:

Temperature [K] = 298

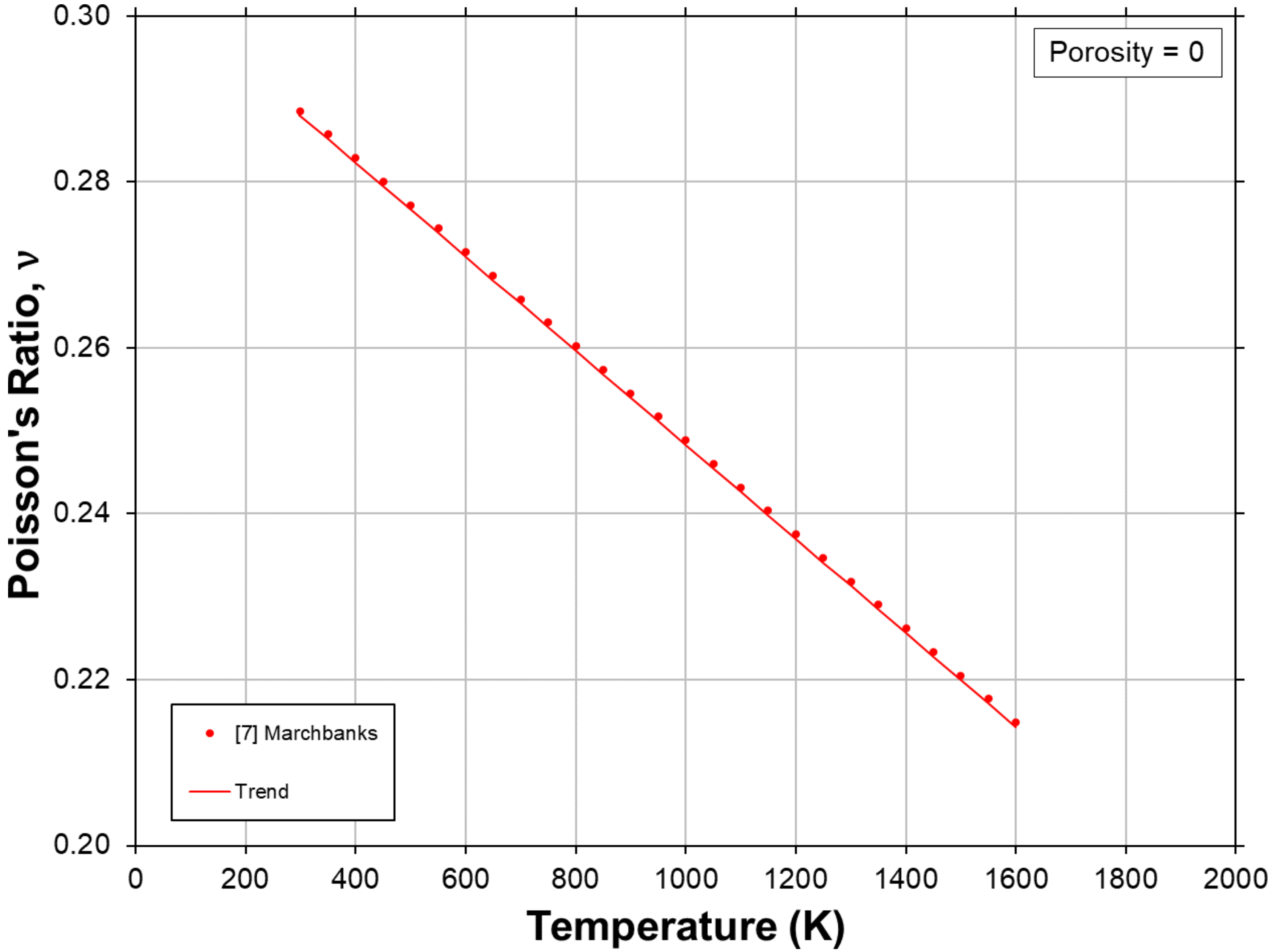

Figure 6.1.2-13: Poisson's Ratio versus Temperature of UC.

100% Theoretical Density

Temperature (T) K	(°F)	Poisson's Ratio (ν)	Temperature (T) K	(°F)	Poisson's Ratio (ν)
298	(76.7)	0.288	1000	(1340.3)	0.248
300	(80.3)	0.288	1050	(1430.3)	0.245
350	(170.3)	0.285	1100	(1520.3)	0.243
400	(260.3)	0.282	1150	(1610.3)	0.240
450	(350.3)	0.279	1200	(1700.3)	0.237
500	(440.3)	0.277	1250	(1790.3)	0.234
550	(530.3)	0.274	1300	(1880.3)	0.231
600	(620.3)	0.271	1350	(1970.3)	0.228
650	(710.3)	0.268	1400	(2060.3)	0.226
700	(800.3)	0.265	1450	(2150.3)	0.223
750	(890.3)	0.262	1500	(2240.3)	0.220
800	(980.3)	0.260	1550	(2330.3)	0.217
850	(1070.3)	0.257	1600	(2420.3)	0.214
900	(1160.3)	0.254			
950	(1250.3)	0.251			

Application Notes: Data for Poisson's Ratio is calculated from fitted Young's modulus and Shear modulus data collected from references [7, 10], using the equation below to approximate property trend with respect to temperature and porosity.

Fit Equations:

$\nu(T,P) = E(T,P)/(2 \cdot G(T,P)) - 1$

$\nu(T,P) = Poisson's\ Ratio$

$E(T,P) = Young's\ modulus$

$G(T,P) = Shear\ modulus$

$T = Temperature\ [K], P = Fractional\ Porosity$

Constants:

Fractional Porosity (P) = 0

Temp.	Physical and Electrical		Thermal				Elastic		
	Density	Electrical Resistivity	Thermal Conductivity	Thermal Expansion	Mean CTE	Specific Heat	Young's Modulus	Shear Modulus	Poisson's Ratio
(T)	(ρ)	(ρ_e)	(k)	(dL/L_0)	($\bar{\alpha}$)	(C_p)	(E)	(G)	(ν)
K	kg/m³	μΩ-m	W/(m-K)	%	10^{-6}/K	J/(g-K)	GPa	GPa	
300	13627	0.782	20.83	0.007	10.13	0.203	224.86	87.29	0.288
350	13606	0.853	21.00	0.058	10.18	0.213	223.73	87.05	0.285
400	13585	0.922	21.16	0.109	10.22	0.220	222.61	86.80	0.282
450	13564	0.990	21.32	0.161	10.27	0.225	221.48	86.55	0.279
500	13543	1.057	21.49	0.214	10.32	0.229	220.36	86.30	0.277
550	13522	1.122	21.65	0.267	10.37	0.232	219.23	86.05	0.274
600	13500	1.187	21.81	0.320	10.42	0.235	218.11	85.80	0.271
650	13478	1.249	21.98	0.374	10.48	0.237	216.98	85.55	0.268
700	13456	1.311	22.14	0.429	10.53	0.239	215.86	85.30	0.265
750	13434	1.371	22.31	0.484	10.58	0.241	214.73	85.05	0.262
800	13412	1.429	22.47	0.539	10.63	0.243	213.61	84.79	0.260
850	13390	1.487	22.64	0.595	10.68	0.245	212.49	84.53	0.257
900	13367	1.543	22.81	0.652	10.74	0.247	211.36	84.28	0.254
1000	13321	1.651	23.14	0.767	10.85	0.251	209.11	83.76	0.248
1100	13275	1.754	23.47	0.884	10.96	0.255	206.86	83.24	0.243
1200	13228	1.851	23.81	1.004	11.07	0.259	204.61	82.71	0.237
1300	13180	1.943	24.15	1.126	11.18	0.263	202.37	82.18	0.231
1400	13131	2.030	24.49	1.250	11.30	0.267	200.12	81.64	0.226
1500	13082	2.111	24.83	1.377	11.41	0.271	197.87	81.10	0.220
1600	13032	2.187	25.17	1.507	11.53	0.276	195.62	80.55	0.214
1700	12981	2.257	25.52	1.639	11.65	0.280	-	-	-
1800	12929	2.323	25.86	1.774	11.77	0.285	-	-	-
1900	12877	-	26.21	1.912	11.90	0.290	-	-	-
2000	12824	-	26.56	2.052	12.02	0.295	-	-	-
2200	12715	-	-	2.342	12.28	0.306	-	-	-

[1] T.B. Massalski, H. Okamoto, Binary Alloy Phase Diagrams, Volume 1, ASM International, Metals Park, Ohio, 1990, p. 893.

[2] Thermophysical Properties of Materials For Nuclear Engineering: A Tutorial and Collection of Data IAEA-THPH International Atomic Energy Agency, Austria, 2008.

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6 Nuclear Materials

6.1 Nuclear Fuel Materials

Data for this material can be found in the SNP-HDBK-0008 Annex.

6 Nuclear Materials

6.2 Neutron Control Materials

ZrH_2 Room Temperature Properties

Molar Mass, [g/mol]	93.24
Theoretical Density, [kg/m^3]	5,586
Melting Point, [K]	*
Heat Capacity, [J/(g-K)]	0.331
Thermal Conductivity, [W/(m-K)]	67.7
Linear expansion coefficient, [μm/(m-K)]	8.34
Electrical resistivity, [μΩ-m]	0.158[a]
Young's Modulus, [GPa]	77.4[b]
Shear Modulus, [GPa]	27.5[b]
Poisson’s Ratio, [-]	0.41[b]

* Thermal decomposition is dependent on temperature, pressure and atmosphere

[a] Extrapolated from fitted curve

[b] Based on average density functional theory (DFT) by P.F. Weck [1]

Zirconium – Hydrogen Phase Diagram

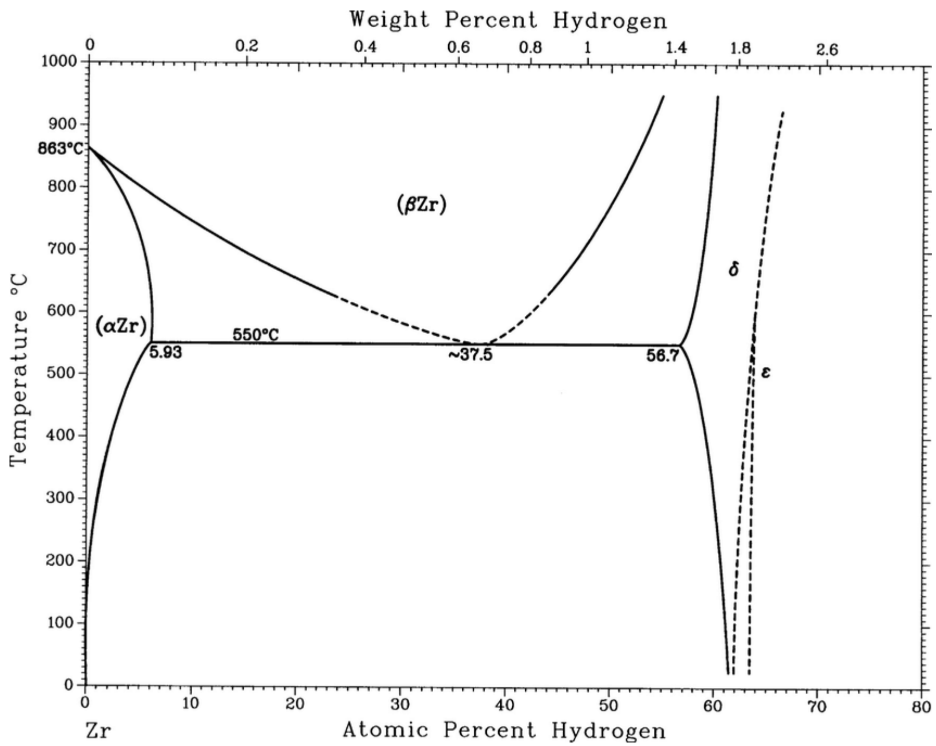

Figure 6.2.1-1: Zirconium – Hydrogen Phase Diagram [2].

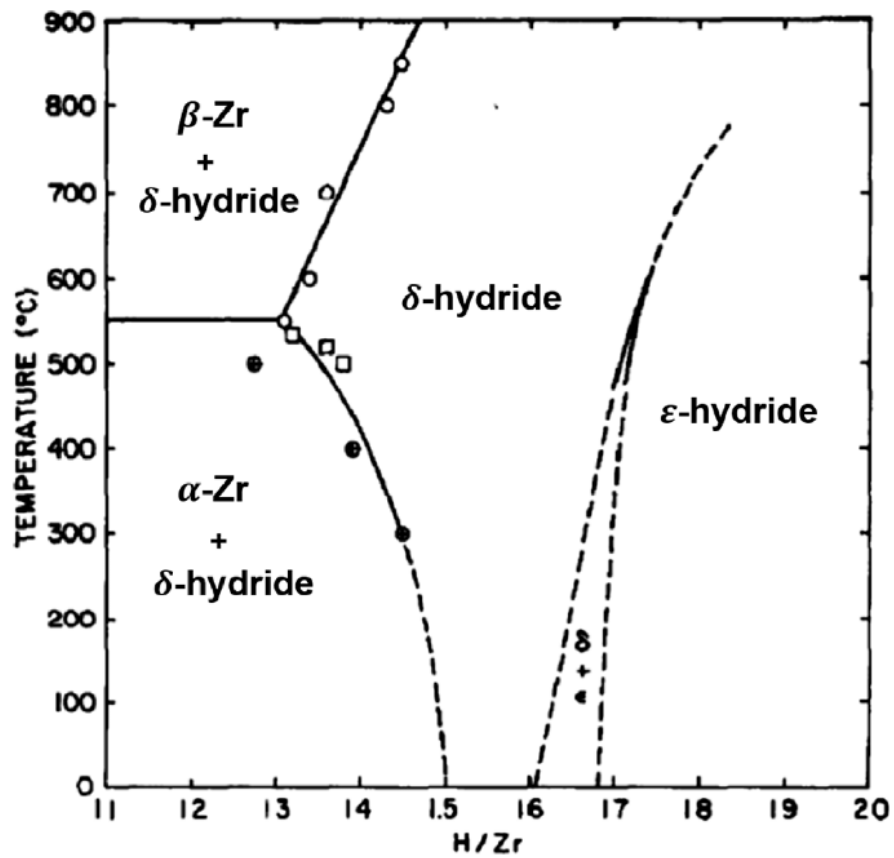

Figure 6.2.1-2: Zirconium – Hydrogen Phase Diagram [3].

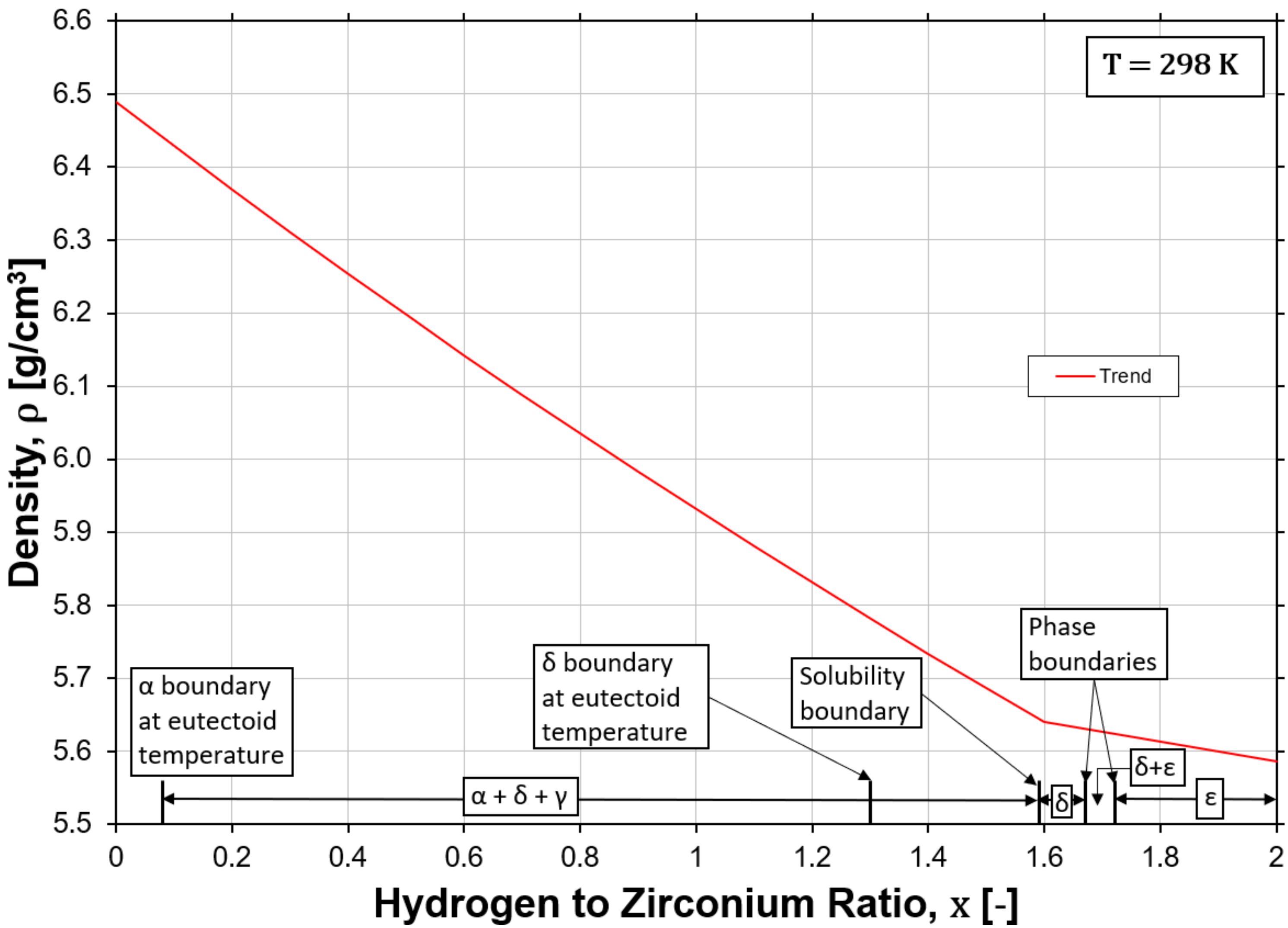

Figure 6.2.1-3: Density versus Hydrogen to Zirconium ratio (x), adapted from M.T. Simnad [4]. Different phases of ZrH_x are also identified.

100% Theoretical Density

H/Zr Ratio(x)	Room Temperature Density (ρ_{RT})		H/Zr Ratio(x)	Room Temperature Density (ρ_{RT})	
	kg/m³	(lb/ft³)		kg/m³	(lb/ft³)
0.00	6489	(405.1)	1.10	5881	(367.1)
0.10	6429	(401.3)	1.20	5831	(364.0)
0.20	6369	(397.6)	1.30	5782	(361.0)
0.30	6311	(394.0)	1.40	5734	(358.0)
0.40	6254	(390.4)	1.50	5687	(355.0)
0.50	6198	(386.9)	1.60	5640	(352.1)
0.60	6143	(383.5)	1.70	5626	(351.2)
0.70	6088	(380.1)	1.80	5613	(350.4)
0.80	6035	(376.8)	1.90	5600	(349.6)
0.90	5983	(373.5)	2.00	5587	(348.8)
1.00	5931	(370.3)			

Application Notes: Density as a function of H/Zr ratio is calculated using the equations below to approximate property trend with H/Zr ratio. The equation for room temperature density is taken from [4]. Density with respect to temperature is calculated as a function of thermal expansion, as shown below, for (H/Zr) from 1.6 to 2.0. Data in the table is for T = 298 K.

Density Calculation:

$\rho_{RT}(x) = 1000/(A0 + A1 \cdot x)$

$\rho(T) = \rho_{RT}(x)/(1 + dL/L_0(T)/100)^3$

$\rho_{RT}(x) = Room\ Temperature\ Density\ [kg/m^3]$

$\rho(T) = Density\ [kg/m^3]$

$x = Hydrogen/Zirconium\ ratio$

$T = Temperature\ [K]$

Constants:

T Range:	$293 \le T \le 977$	
H/Zr Ratio:	$0 \le x \le 1.6$	$1.6 \le x \le 2.0$
A0 =	0.1541	0.1706
A1 =	0.0145	0.0042

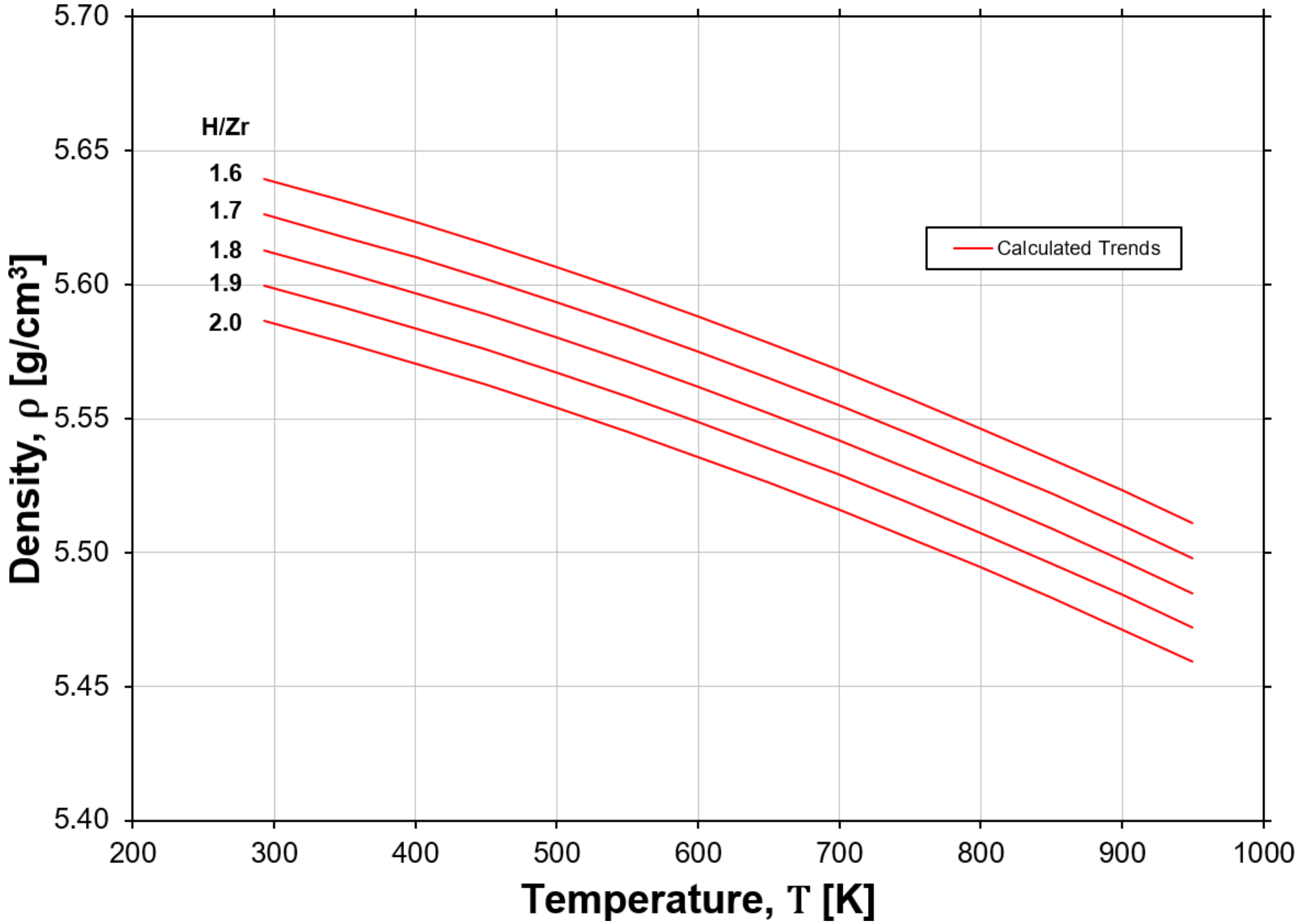

Figure 6.2.1-4: Density versus Temperature for Zirconium Hydrides at various H/Zr ratios. Calculated from fitted trend of the Thermal Expansion data.

100% Theoretical Density

Temperature (T)		Density (ρ)		Temperature (T)		Density (ρ)	
K	(°F)	kg/m³	(lb/ft³)	K	(°F)	kg/m³	(lb/ft³)
300	(80.3)	5586	(348.7)	650	(710.3)	5526	(345.0)
325	(125.3)	5582	(348.5)	675	(755.3)	5521	(344.7)
350	(170.3)	5578	(348.3)	700	(800.3)	5516	(344.4)
375	(215.3)	5575	(348.0)	725	(845.3)	5511	(344.0)
400	(260.3)	5571	(347.8)	750	(890.3)	5505	(343.7)
425	(305.3)	5567	(347.5)	775	(935.3)	5500	(343.4)
450	(350.3)	5563	(347.3)	800	(980.3)	5494	(343.0)
475	(395.3)	5558	(347.0)	825	(1025.3)	5489	(342.7)
500	(440.3)	5554	(346.7)	850	(1070.3)	5483	(342.3)
525	(485.3)	5550	(346.5)	875	(1115.3)	5477	(341.9)
550	(530.3)	5545	(346.2)	900	(1160.3)	5471	(341.6)
575	(575.3)	5541	(345.9)	925	(1205.3)	5465	(341.2)
600	(620.3)	5536	(345.6)	950	(1250.3)	5459	(340.8)
625	(665.3)	5531	(345.3)	975	(1295.3)	5453	(340.4)

Application Notes: Density as a function of H/Zr ratio is calculated using the equations below to approximate property trend with H/Zr ratio. The equation for room temperature density is taken from [4]. Density with respect to temperature is calculated as a function of thermal expansion, as shown below, for (H/Zr) from 1.6 to 2.0. Data in the table is for x = 2.0.

Density Calculation:

$\rho_{RT}(x) = 1000/(A0 + A1 \cdot x)$

$\rho(T) = \rho_{RT}(x)/(1 + dL/L_0(T)/100)^3$

$\rho_{RT}(x) = Room\ Temperature\ Density\ [kg/m^3]$

$\rho(T) = Density\ \ [kg/m^3]$

$x = Hydrogen/Zirconium\ ratio$

$T = Temperature\ [K]$

Constants:

T Range:	$293 \le T \le 977$	
H/Zr Ratio:	$0 \le x \le 1.6$	$1.6 \le x \le 2.0$
A0 =	0.1541	0.1706
A1 =	0.0145	0.0042

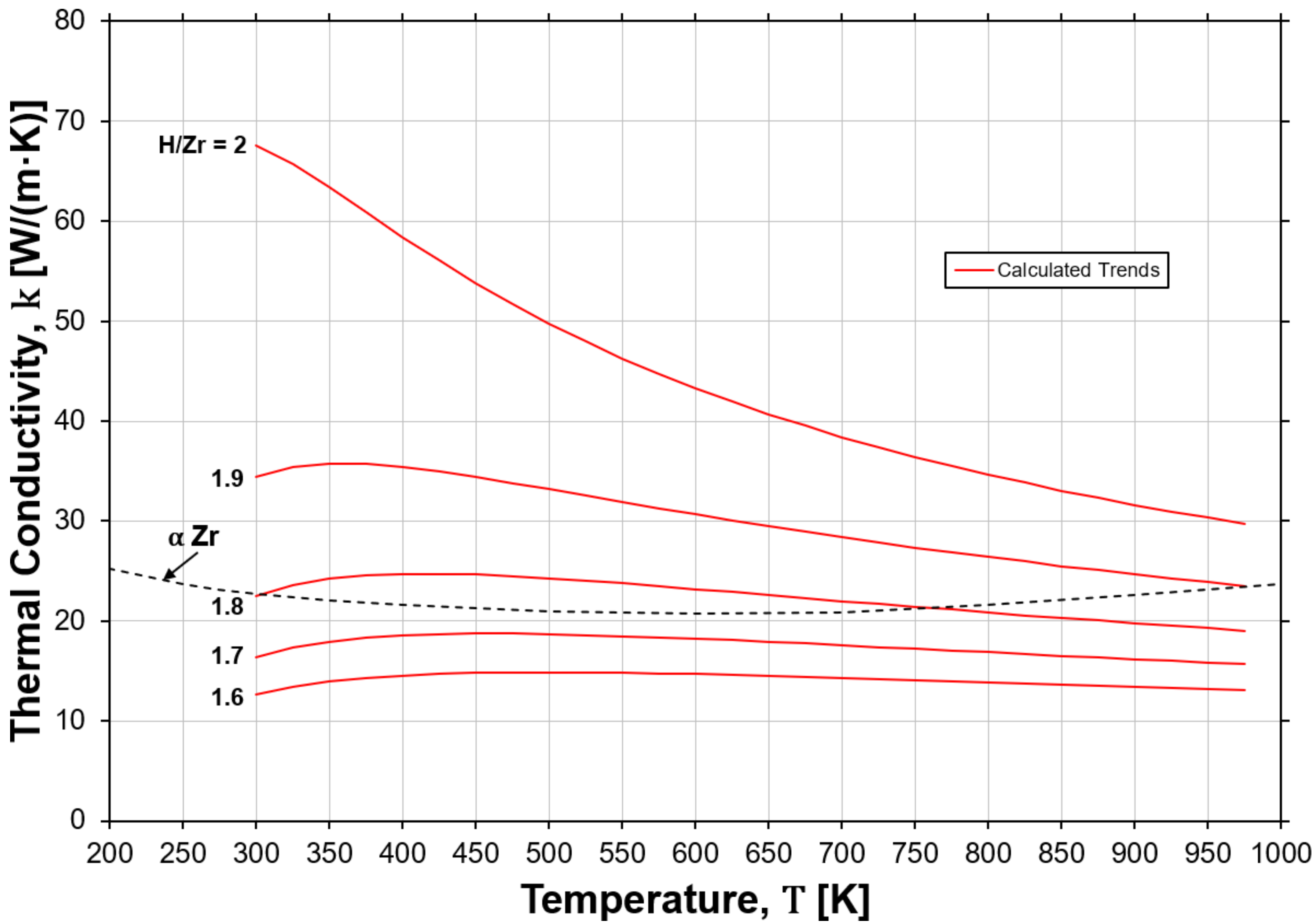

Figure 6.2.1-5: Thermal Conductivity versus Temperature of Zirconium Hydrides.

100% Theoretical Density

Temperature (T)		Thermal Conductivity (k)		Temperature (T)		Thermal Conductivity (k)	
K	(°F)	W/(m-K)	((Btu-in.)/(ft.^{2}-hr-°F))	K	(°F)	W/(m-K)	((Btu-in.)/(ft.^{2}-hr-°F))
300	(80.3)	67.57	(468.80)	575	(575.3)	44.73	(310.34)
325	(125.3)	65.72	(455.99)	600	(620.3)	43.29	(300.32)
350	(170.3)	63.38	(439.71)	650	(710.3)	40.69	(282.28)
375	(215.3)	60.88	(422.39)	700	(800.3)	38.41	(266.53)
400	(260.3)	58.41	(405.23)	750	(890.3)	36.42	(252.65)
425	(305.3)	56.03	(388.76)	800	(980.3)	34.64	(240.34)
450	(350.3)	53.80	(373.24)	850	(1070.3)	33.05	(229.33)
475	(395.3)	51.71	(358.74)	900	(1160.3)	31.62	(219.41)
500	(440.3)	49.76	(345.26)	950	(1250.3)	30.33	(210.42)
525	(485.3)	47.96	(332.74)	975	(1295.3)	29.72	(206.23)
550	(530.3)	46.28	(321.13)				

Application Notes: The thermal conductivity trend is calculated from the thermal diffusivity, specific heat, and density trends, as shown in the equation below, to approximate property trend with respect to hydrogen-zirconium ratio and temperature. Data in the table is for H/Zr = 2.0.

Fit Equation:

$k(x,T) = \alpha \cdot C_p \cdot \rho$

$k(x,T) = Thermal\ Conductivity\ \ [W/m \cdot K]$

$\alpha(x,T) = Thermal\ Diffusivity\ \ [m^2/s]$

$C_P(x,T) = Specific\ Heat\ [J/kg \cdot K]$

$\rho(x,T) = Density\ \ [kg/m^3]$

$T = Temperature\ [K]$

$x = Hydrongen/Zirconium\ ratio$

Temperature Range: $293 \leq T \leq 977$

H/Zr Ratio: $1.6 \leq x \leq 2.0$

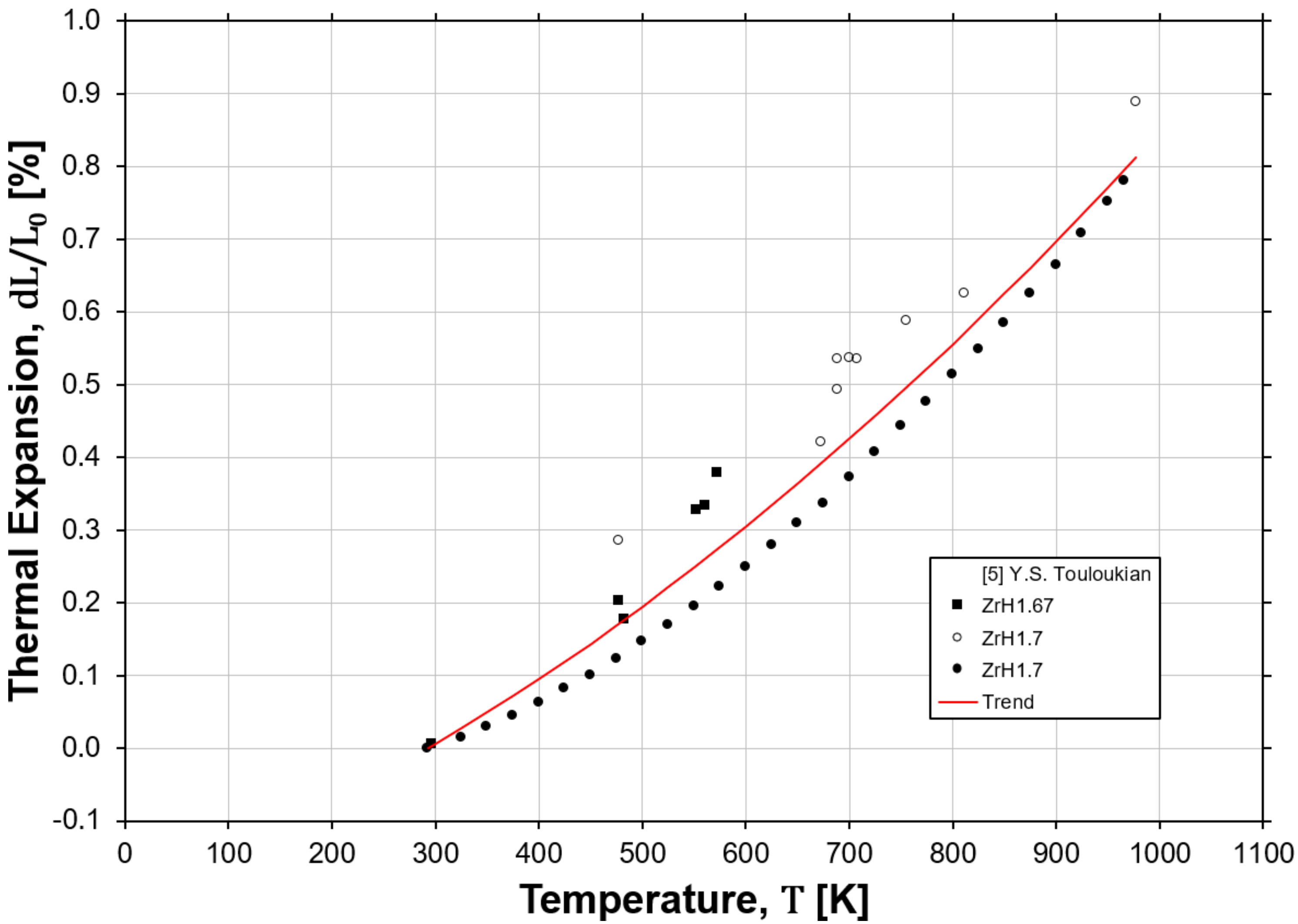

Figure 6.2.1-6: Thermal Expansion versus temperature of Zirconium Hydride.

100% Theoretical Density

Temperature (T) K	(°F)	Thermal Expansion (dL/L_0) %	Temperature (T) K	(°F)	Thermal Expansion (dL/L_0) %
300	(80.3)	0.006	650	(710.3)	0.364
325	(125.3)	0.027	675	(755.3)	0.394
350	(170.3)	0.049	700	(800.3)	0.425
375	(215.3)	0.072	725	(845.3)	0.457
400	(260.3)	0.095	750	(890.3)	0.489
425	(305.3)	0.119	775	(935.3)	0.522
450	(350.3)	0.144	800	(980.3)	0.556
475	(395.3)	0.169	825	(1025.3)	0.590
500	(440.3)	0.195	850	(1070.3)	0.625
525	(485.3)	0.221	875	(1115.3)	0.661
550	(530.3)	0.248	900	(1160.3)	0.697
575	(575.3)	0.276	925	(1205.3)	0.734
600	(620.3)	0.305	950	(1250.3)	0.772
625	(665.3)	0.334	975	(1295.3)	0.810

Application Notes: Data for thermal expansion is collected from reference [5], and it is fitted with the equation below to approximate property trend with respect to temperature. While the trend applies for a hydrogen/zirconium ratio of 1.67 to 1.7, the trend is used for ratios of 1.6 to 2.0 for use in density calculations; density, in turn, is used in thermal conductivity calculations.

Fit Equation:

$$dL/L_0\,(T) = A0 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2$$

$dL/L_0\,(T) = Thermal\ Expansion\ [\%]$

$T = Temperature\ [K]$

Constants:

T Range:	$293 \leq T \leq 977$
A0 =	-0.1997
A1 =	0.5292
A2 =	0.5194

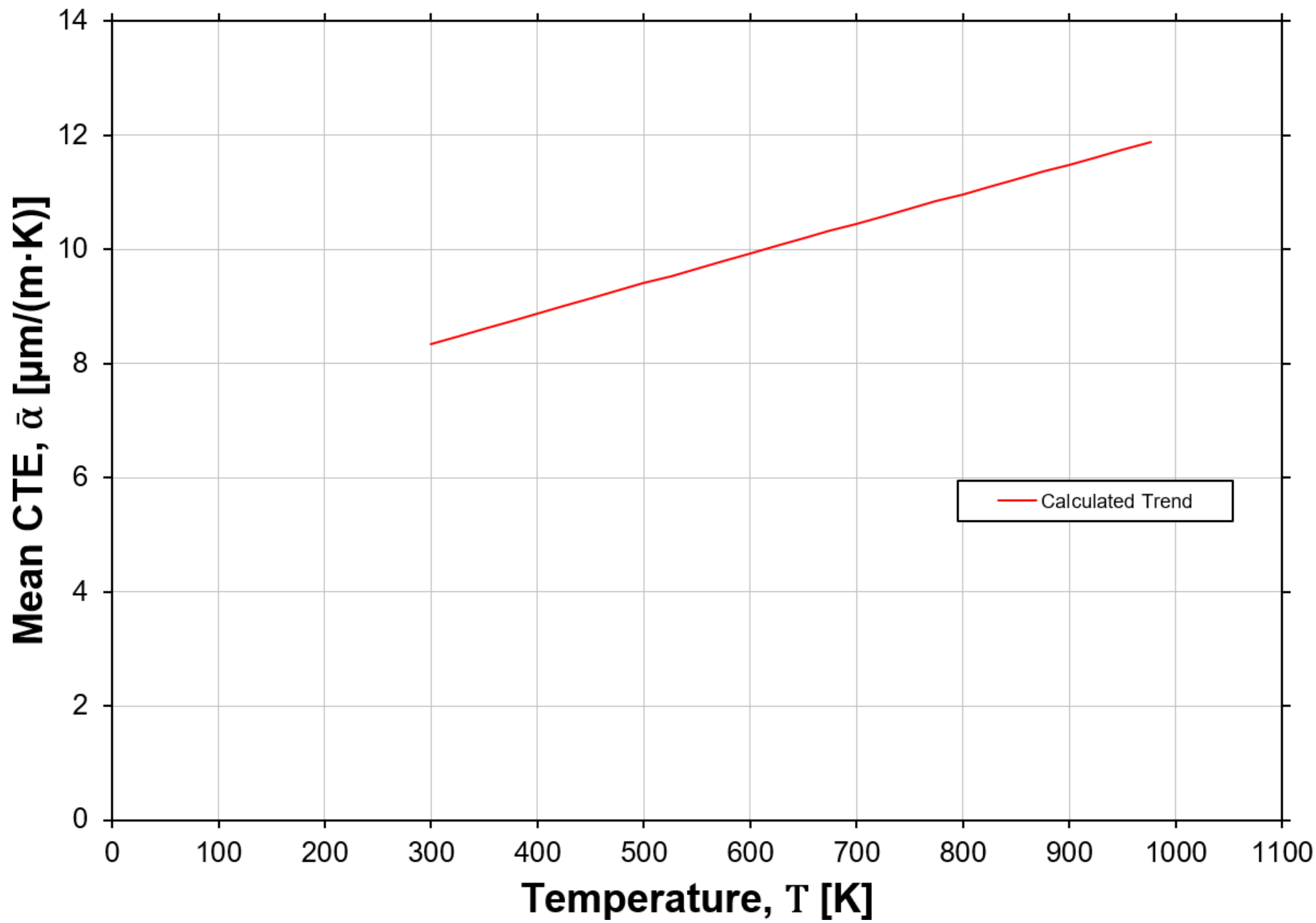

Figure 6.2.1-7: Mean Coefficient of Thermal Expansion versus Temperature of Zirconium Hydride. Calculated from fitted trend of the Thermal Expansion data.

100% Theoretical Density

Temperature (T)		Mean CTE (ᾱ)		Temperature (T)		Mean CTE (ᾱ)	
K	(°F)	µm/(m-K)	(µin/(in-°F))	K	(°F)	µm/(m-K)	(µin/(in-°F))
300	(80.3)	8.342	(4.635)	650	(710.3)	10.193	(5.663)
325	(125.3)	8.476	(4.709)	675	(755.3)	10.323	(5.735)
350	(170.3)	8.609	(4.783)	700	(800.3)	10.453	(5.807)
375	(215.3)	8.743	(4.857)	725	(845.3)	10.583	(5.880)
400	(260.3)	8.876	(4.931)	750	(890.3)	10.713	(5.952)
425	(305.3)	9.008	(5.005)	775	(935.3)	10.843	(6.024)
450	(350.3)	9.141	(5.078)	800	(980.3)	10.972	(6.095)
475	(395.3)	9.273	(5.152)	825	(1025.3)	11.101	(6.167)
500	(440.3)	9.405	(5.225)	850	(1070.3)	11.230	(6.239)
525	(485.3)	9.537	(5.298)	875	(1115.3)	11.358	(6.310)
550	(530.3)	9.668	(5.371)	900	(1160.3)	11.487	(6.382)
575	(575.3)	9.800	(5.444)	925	(1205.3)	11.615	(6.453)
600	(620.3)	9.931	(5.517)	950	(1250.3)	11.743	(6.524)
625	(665.3)	10.062	(5.590)	975	(1295.3)	11.871	(6.595)

Application Notes: Data for mean coefficient of thermal expansion is calculated from thermal expansion and fitted with the equation below to approximate property trend with respect to temperature.

Fit Equation:

$$\bar{\alpha}(T) = A0 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2$$

$\bar{\alpha}(T) = Coefficient\ of\ Thermal\ Expansion\ [\mu m/(m \cdot K)]$

$T = Temperature\ [K]$

Constants:

T. Range: $293 \leq T \leq 977$

A0 = 6.721

A1 = 5.459

A2 = -0.1818

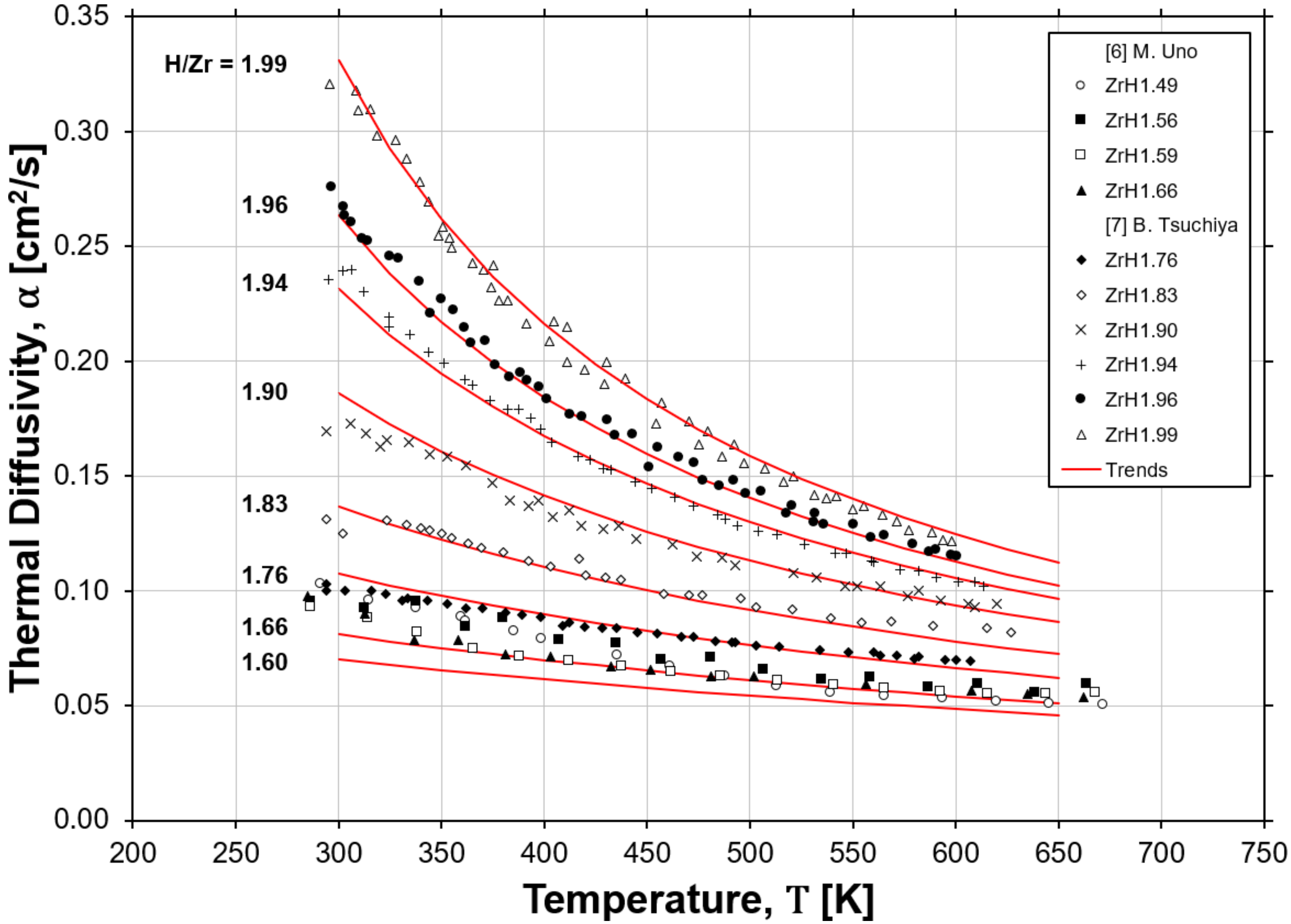

Figure 6.2.1-8: Thermal Diffusivity versus Temperature of Zirconium Hydrides.

Thermal Diffusivity with Temperature

100% Theoretical Density

Temperature (T)		Thermal Diffusivity (α)		Temperature (T)		Thermal Diffusivity (α)	
K	(°F)	cm^2/s	(in^2/s)	K	(°F)	μm/(m-K)	(μin/(in-°F))
300	(80.3)	0.361	(0.0560)	650	(710.3)	0.116	(0.0180)
325	(125.3)	0.316	(0.0490)	675	(755.3)	0.110	(0.0171)
350	(170.3)	0.281	(0.0436)	700	(800.3)	0.105	(0.0163)
375	(215.3)	0.253	(0.0392)	725	(845.3)	0.100	(0.0155)
400	(260.3)	0.229	(0.0355)	750	(890.3)	0.096	(0.0149)
425	(305.3)	0.210	(0.0325)	775	(935.3)	0.092	(0.0142)
450	(350.3)	0.193	(0.0299)	800	(980.3)	0.088	(0.0136)
475	(395.3)	0.179	(0.0277)	825	(1025.3)	0.084	(0.0131)
500	(440.3)	0.166	(0.0258)	850	(1070.3)	0.081	(0.0126)
525	(485.3)	0.155	(0.0241)	875	(1115.3)	0.078	(0.0121)
550	(530.3)	0.146	(0.0226)	900	(1160.3)	0.075	(0.0117)
575	(575.3)	0.137	(0.0212)	925	(1205.3)	0.073	(0.0112)
600	(620.3)	0.129	(0.0200)	950	(1250.3)	0.070	(0.0109)
625	(665.3)	0.122	(0.0190)	975	(1295.3)	0.068	(0.0105)

Application Notes: Data for thermal diffusivity is collected from references [6, 7] and fitted with the equation below to approximate the property trend with respect to temperature and H/Zr ratio. Data in table is for H/Zr = 2.0.

Fit Equation:

$\alpha(x,T) = A0/\{T + A1(A2 - x) + A3\} + A4$

$\alpha(x,T) = Thermal\ Diffusivity\ (cm^2/s)$

$x = Hydrogen/Zirconium\ ratio$

$T = Temperature\ [K]$

Constants:

T. Range:	$300 \le T \le 977$
H/Zr ratio (x):	$1.6 \le X \le 2.0$
A0 =	67.9
A1 =	1620
A2 =	2.0
A3 =	-118
A4 =	-0.0116

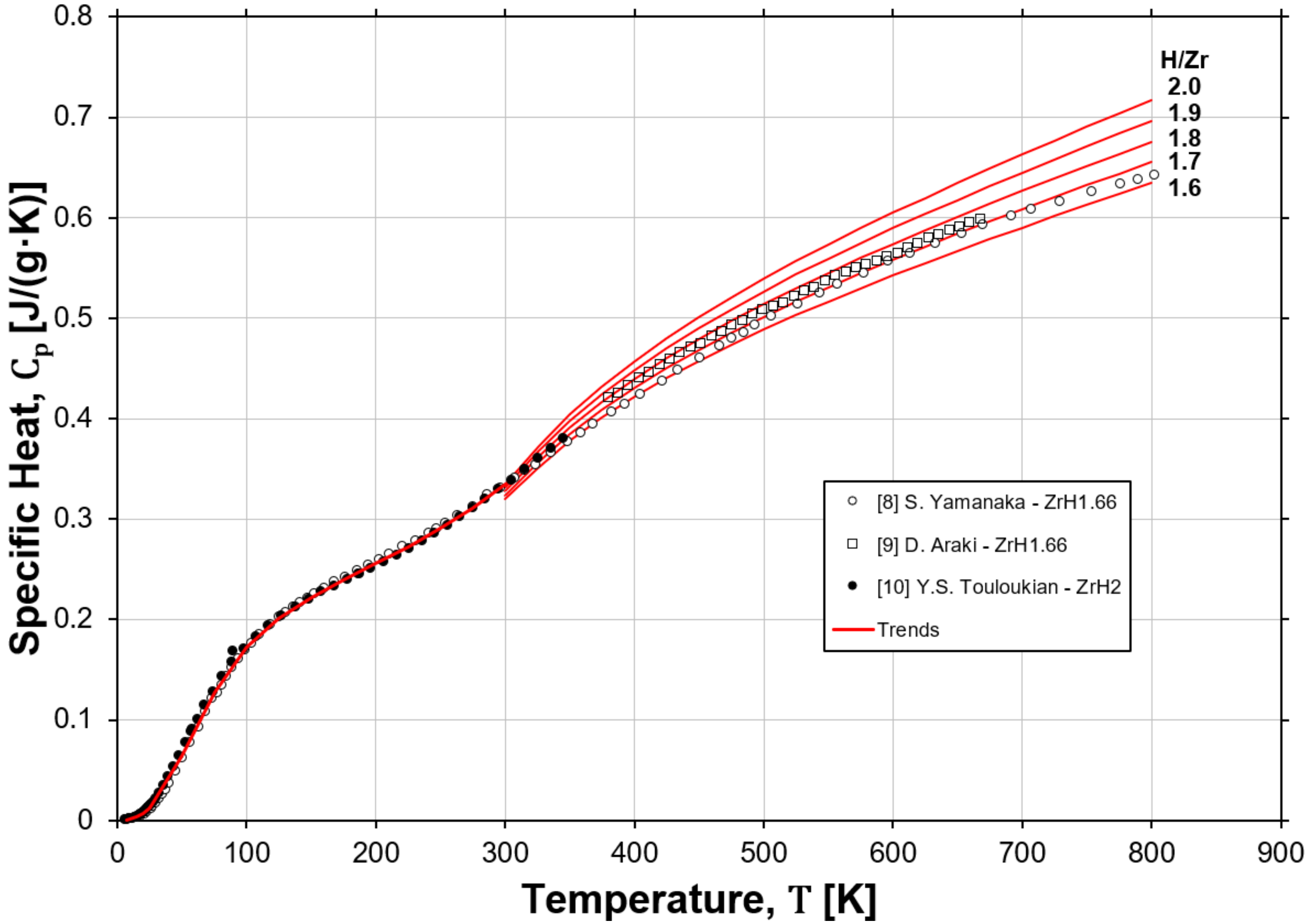

Figure 6.2.1-9: Specific Heat versus Temperature of Zirconium Hydrides. Trends above 300 K are from M. Uno [6].

100% Theoretical Density

Temperature (T) K	(°F)	Specific Heat (C_p) J/(g-K)	(BTU/(lb-°F))	Temperature (T) K	(°F)	Specific Heat (C_p) J/(g-K)	(BTU/(lb-°F))
7	(-447.1)	0.001	(0.000)	350	(170.3)	0.404	(0.097)
25	(-414.7)	0.012	(0.003)	400	(260.3)	0.457	(0.109)
50	(-369.7)	0.064	(0.015)	450	(350.3)	0.501	(0.120)
75	(-324.7)	0.127	(0.030)	500	(440.3)	0.539	(0.129)
100	(-279.7)	0.172	(0.041)	550	(530.3)	0.573	(0.137)
125	(-234.7)	0.201	(0.048)	600	(620.3)	0.605	(0.145)
150	(-189.7)	0.221	(0.053)	650	(710.3)	0.635	(0.152)
175	(-144.7)	0.239	(0.057)	700	(800.3)	0.663	(0.158)
200	(-99.7)	0.256	(0.061)	750	(890.3)	0.690	(0.165)
225	(-54.7)	0.273	(0.065)	800	(980.3)	0.717	(0.171)
250	(-9.7)	0.291	(0.070)	850	(1070.3)	0.743	(0.178)
275	(35.3)	0.311	(0.074)	900	(1160.3)	0.768	(0.184)
293	(67.7)	0.326	(0.078)	950	(1250.3)	0.794	(0.190)
300	(80.3)	0.335	(0.080)	977	(1298.9)	0.807	(0.193)

Application Notes: Data for specific heat is collected from references [8-10]. Trends above 300 K are from [6], while the trend below 300 K was generated using data from [8, 10]. The equations below approximate the trend with respect to temp. and H/Zr ratio. Data in table is for H/Zr = 2.0.

Fit Equation:

For temperature range: $7 \leq T < 300$

$$C_P(T) = \left(D0 \cdot \left(\frac{T}{1000}\right)^N\right) \Big/ \left(1 + D1 \cdot \left(\frac{T}{1000}\right) + D2 \cdot \left(\frac{T}{1000}\right)^2 + D3 \cdot \left(\frac{T}{1000}\right)^3\right)$$

For temperature range: $300 \leq T \leq 977$

$$C_P[J/(mol \cdot K)] = A0 + A1 \cdot x + (B0 + B1 \cdot x)T - (C0 + C1 \cdot x)/T^2$$

$$C_P(T) = Specific\ Heat\ [J/(g \cdot K)] = C_P[J/(mol \cdot K)]/MW$$

$$x = Hydrogen/Zirconium\ ratio; \quad T = Temperature\ [K]$$

$$MW = Molecular\ Weight = 91.224 + 1.008 \cdot x$$

Constants:

T. Range:	$7 \leq T < 300$		$300 \leq T \leq 977$
H/Zr ratio (x):	$1.66 \leq x \leq 2.0$		$1.6 \leq x \leq 2.0$
N =	2.325	A0 =	25.02
D0 =	47.25	A1 =	4.746
D1 =	-16.25	B0 =	.003103
D2 =	219	B1 =	.02008
D3 =	-266	C0 =	1.943 E05
		C1 =	6.358 E05

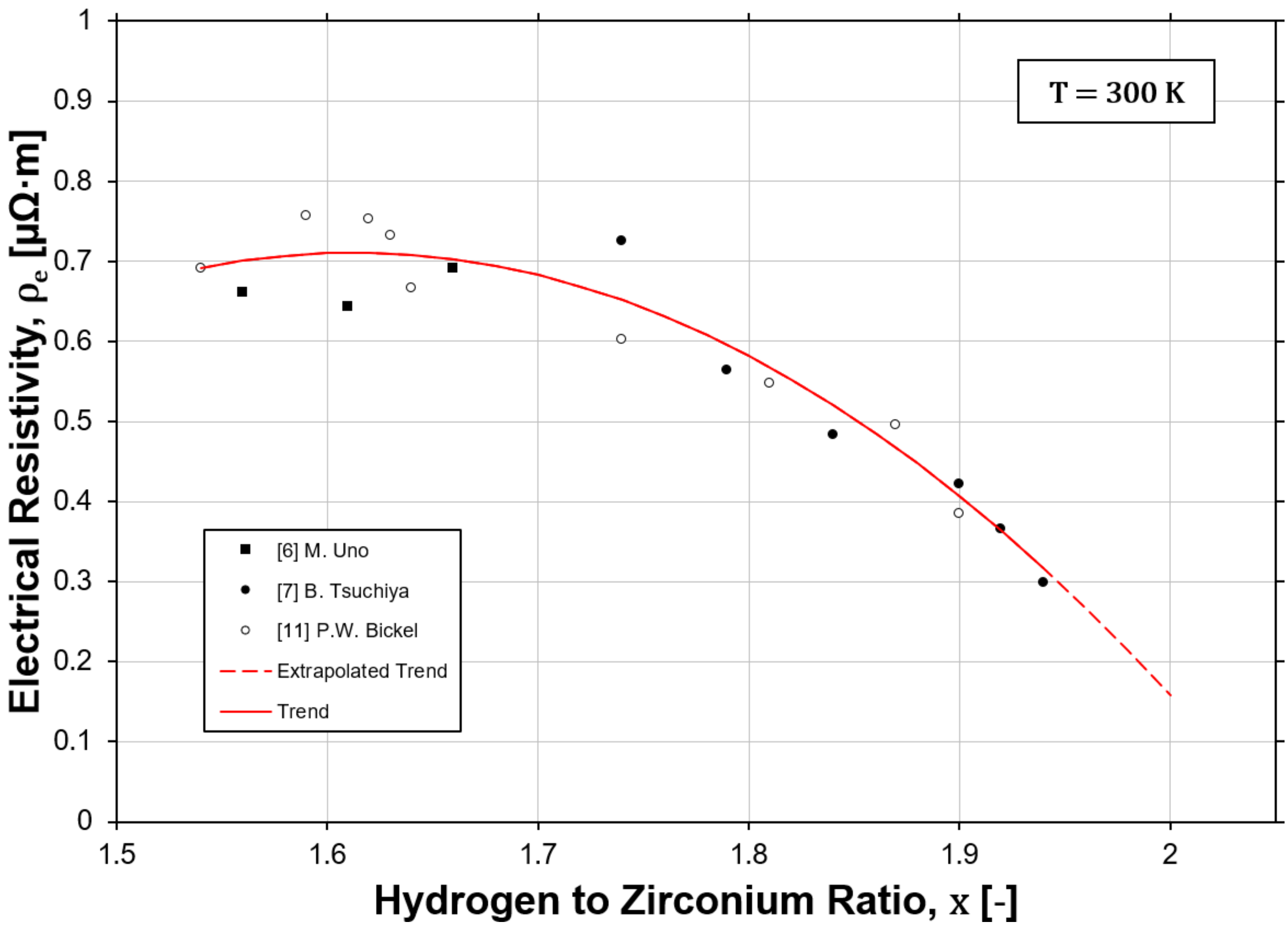

Figure 6.2.1-10: Electrical Resistivity versus Hydrogen to Zirconium ratio (x).

100% Theoretical Density

H/Zr Ratio (x)	Electrical Resistivity (ρe)		H/Zr Ratio (x)	Electrical Resistivity (ρe)	
	μΩ-m	(μΩ-in)		μΩ-m	(μΩ-in)
1.54	0.691	(27.21)	1.76	0.631	(24.84)
1.56	0.700	(27.58)	1.78	0.608	(23.93)
1.58	0.707	(27.83)	1.80	0.582	(22.90)
1.60	0.710	(27.96)	1.82	0.553	(21.75)
1.62	0.711	(27.98)	1.84	0.521	(20.49)
1.64	0.708	(27.88)	1.86	0.486	(19.12)
1.66	0.703	(27.66)	1.88	0.448	(17.62)
1.68	0.694	(27.33)	1.90	0.407	(16.01)
1.70	0.683	(26.88)	1.92	0.363	(14.29)
1.72	0.668	(26.32)	1.94	0.316	(12.44)
1.74	0.651	(25.64)			

Application Notes: Data for electrical resistivity is collected from references [6, 7, 11] and fitted with the equation below to approximate the property trend with respect to atomic ratio.

Fit Equation:

$\rho_e(x) = A0 + A1 \cdot x + A2 \cdot x^2$

$\rho_e(T) = Electrical\ Resistivity\ [\mu\Omega \cdot m]$

$x = Hydrogen/Zirconium\ ratio$

Constants:

H/Zr Ratio Range (x): $1.54 \leq x \leq 1.94$

A0 = -8.886

A1 = 11.9

A2 = -3.689

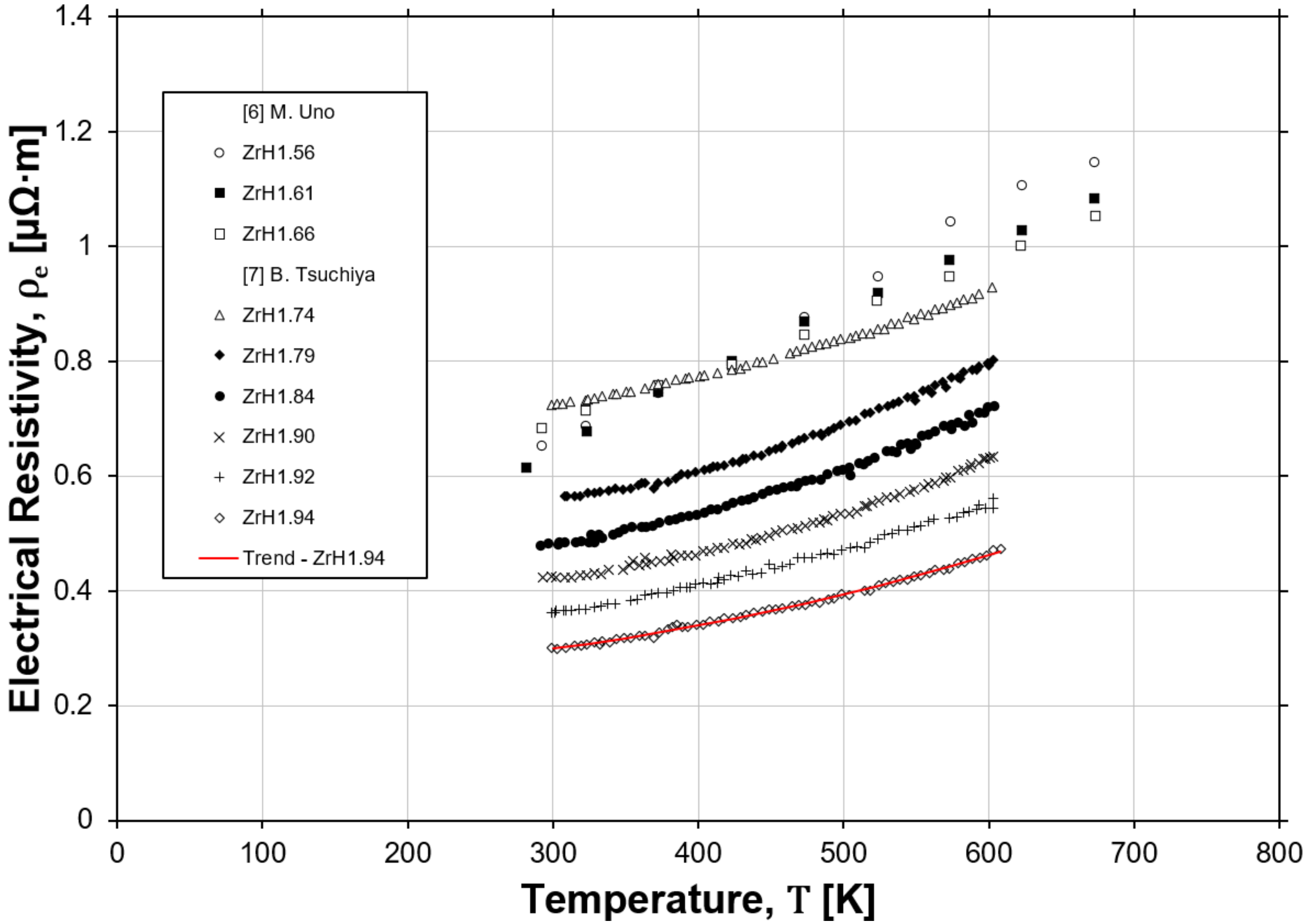

Figure 6.2.1-11: Electrical Resistivity versus Temperature of Zirconium Hydrides.

100% Theoretical Density

Temperature (T)		Electrical Resistivity (ρe)		Temperature (T)		Electrical Resistivity (ρe)	
K	(°F)	μΩ-m	(μΩ-in)	K	(°F)	μΩ-m	(μΩ-in)
300	(80.3)	0.299	(11.77)	480	(404.3)	0.382	(15.04)
320	(116.3)	0.306	(12.05)	500	(440.3)	0.394	(15.51)
340	(152.3)	0.314	(12.35)	520	(476.3)	0.407	(16.01)
360	(188.3)	0.322	(12.66)	540	(512.3)	0.420	(16.53)
380	(224.3)	0.330	(13.01)	560	(548.3)	0.433	(17.07)
400	(260.3)	0.340	(13.37)	580	(584.3)	0.448	(17.63)
420	(296.3)	0.349	(13.75)	600	(620.3)	0.463	(18.21)
440	(332.3)	0.360	(14.16)	608	(634.7)	0.469	(18.45)
460	(368.3)	0.371	(14.59)				

Application Notes: Data for electrical resistivity is collected from references [6, 7]. Data from [7] is fitted with the equation below to approximate the property trend with respect to temperature for H/Zr = 1.94.

Fit Equation:

$x = Hydrogen/Zirconium\ ratio\ = 1.94$

$$\rho_e(T) = A0 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2$$

$\rho_e(T) = Electrical\ Resistivity\ [\mu\Omega \cdot m]$

$T = Temperature\ [K]$

Constants:

T. Range:	$298 \leq T < 608$
A0 =	0.2613
A1 =	-0.08387
A2 =	0.6988

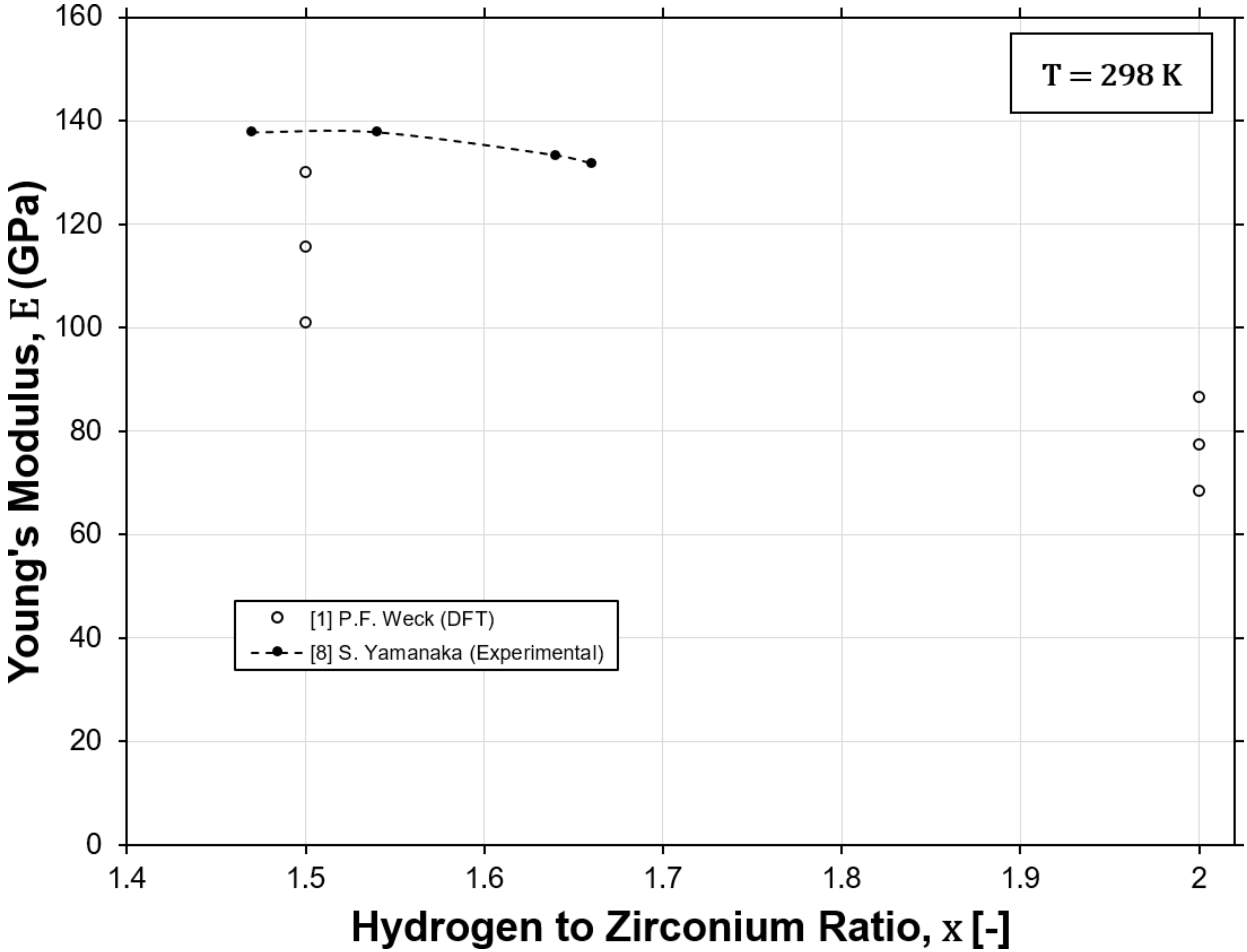

Figure 6.2.1-12: Young's Modulus versus Hydrogen to Zirconium ratio (x).

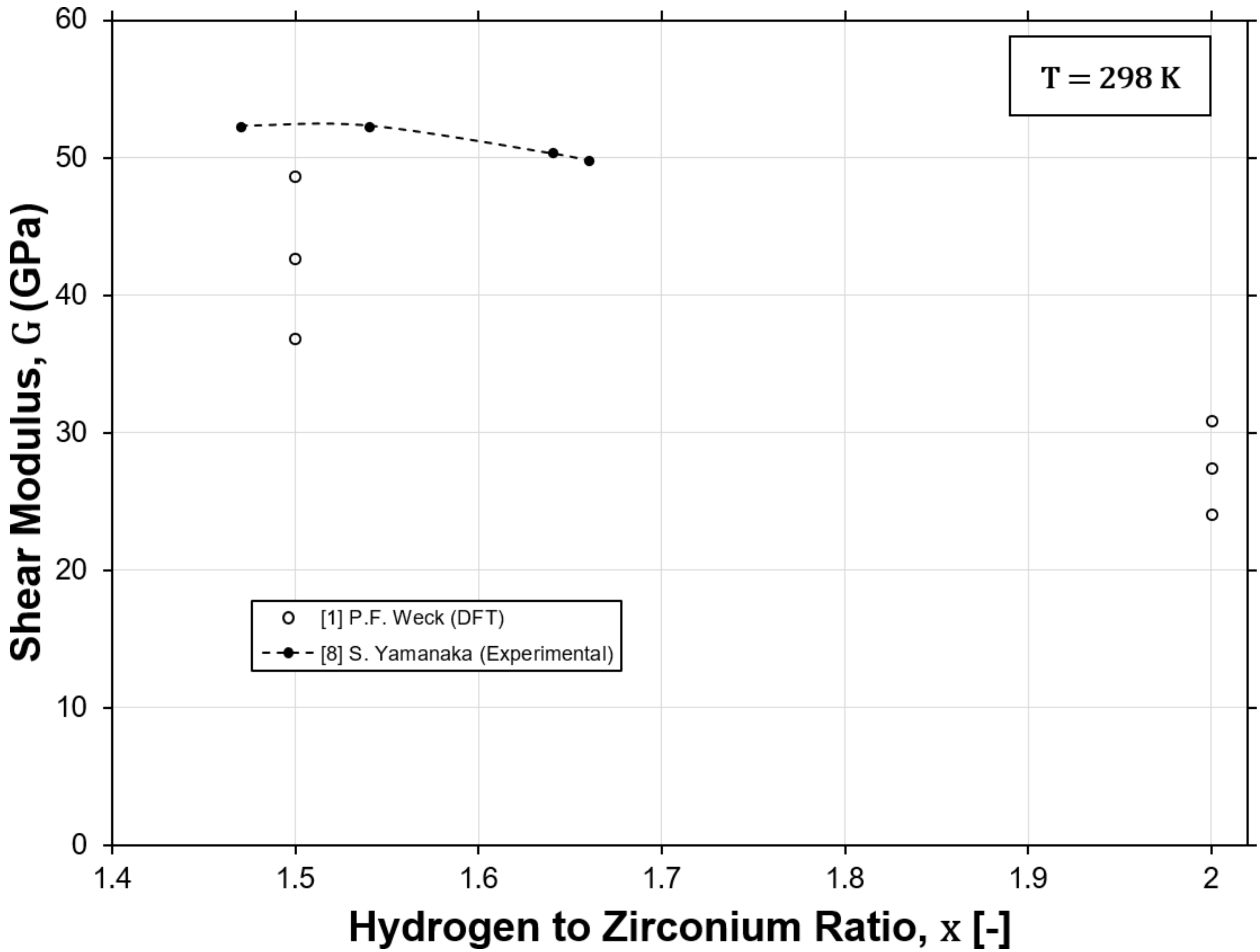

Figure 6.2.1-13: Shear Modulus for Hydrogen to Zirconium ratio (x).

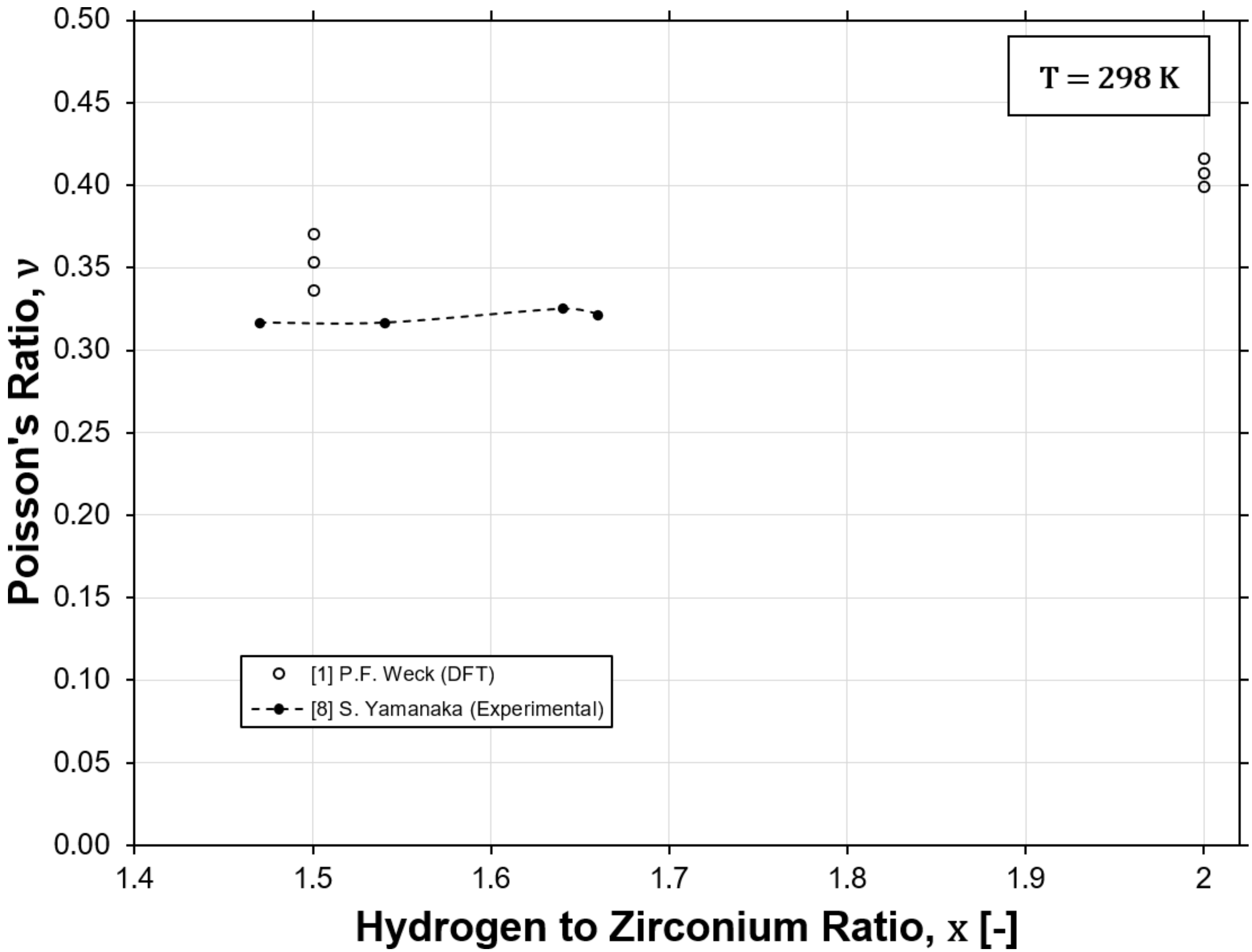

Figure 6.2.1-14: Poisson's Ratio for Hydrogen to Zirconium ratio (x).

Temp. (T) K	Physical and Electrical: Density (ρ) kg/m³	Physical and Electrical: Electrical Resistivity (ρ_e) μΩ-m	Thermal: Thermal Conductivity (k) W/(m-K)	Thermal: Thermal Expansion (dL/L_0) %	Thermal: Mean CTE ($\bar{\alpha}$) 10^{-6}/K	Thermal: Specific Heat (C_p) J/(g-K)	Elastic: Young's Modulus (E) GPa	Elastic: Shear Modulus (G) GPa	Elastic: Poisson's Ratio (ν)
293	5587	-	67.91	0.00	-	0.326	-	-	-
300	5586	0.299	67.57	0.01	8.34	0.335	77.40	27.50	0.41
320	5583	0.306	66.15	0.02	8.45	0.365	-	-	-
340	5580	0.314	64.35	0.04	8.56	0.392	-	-	-
360	5577	0.322	62.38	0.06	8.66	0.416	-	-	-
380	5574	0.330	60.38	0.08	8.77	0.438	-	-	-
400	5571	0.340	58.41	0.10	8.88	0.457	-	-	-
420	5567	0.349	56.50	0.11	8.98	0.476	-	-	-
440	5564	0.360	54.67	0.13	9.09	0.493	-	-	-
460	5561	0.371	52.94	0.15	9.19	0.509	-	-	-
480	5558	0.382	51.31	0.17	9.30	0.525	-	-	-
500	5554	0.394	49.76	0.19	9.41	0.539	-	-	-
520	5551	0.407	48.31	0.22	9.51	0.553	-	-	-
540	5547	0.420	46.94	0.24	9.62	0.567	-	-	-
560	5543	0.433	45.65	0.26	9.72	0.580	-	-	-
580	5540	0.448	44.43	0.28	9.83	0.593	-	-	-
600	5536	0.463	43.29	0.30	9.93	0.605	-	-	-
650	5526	-	40.69	0.36	10.19	0.635	-	-	-
700	5516	-	38.41	0.43	10.45	0.663	-	-	-
750	5505	-	36.42	0.49	10.71	0.690	-	-	-
800	5494	-	34.64	0.56	10.97	0.717	-	-	-
850	5483	-	33.05	0.63	11.23	0.743	-	-	-
900	5471	-	31.62	0.70	11.49	0.768	-	-	-
950	5459	-	30.33	0.77	11.74	0.794	-	-	-
977	5453	-	29.68	0.81	11.88	0.807	-	-	-

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[6] M. Uno, K. Yamada, T. Maruyama, et al., Thermophysical properties of zirconium hydride and deuteride, Journal of Alloys and Compounds 366(1-2) (2004) 101-106.

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6 Nuclear Materials

6.2 Neutron Control Materials

Room Temperature Properties

Atomic Mass, [amu]	9.012
Theoretical Density, [kg/m^3]	1,848
Melting Point, [K]	1560
Boiling Point, [K]	2743
Specific Heat, [J/(g-K)]	1.807
Heat of Fusion, [kJ/mol]	7.95
Heat of Vaporization, [kJ/mol]	297
Thermal Conductivity, [W/(m-K)]	185.4
Linear expansion coefficient, [µm/(m-K)]	11.1
Electrical resistivity, [µΩ-m]	0.0458
Young's Modulus, [GPa]	288.5
Shear Modulus, [GPa]	136.6
Poisson’s Ratio, [-]	0.056

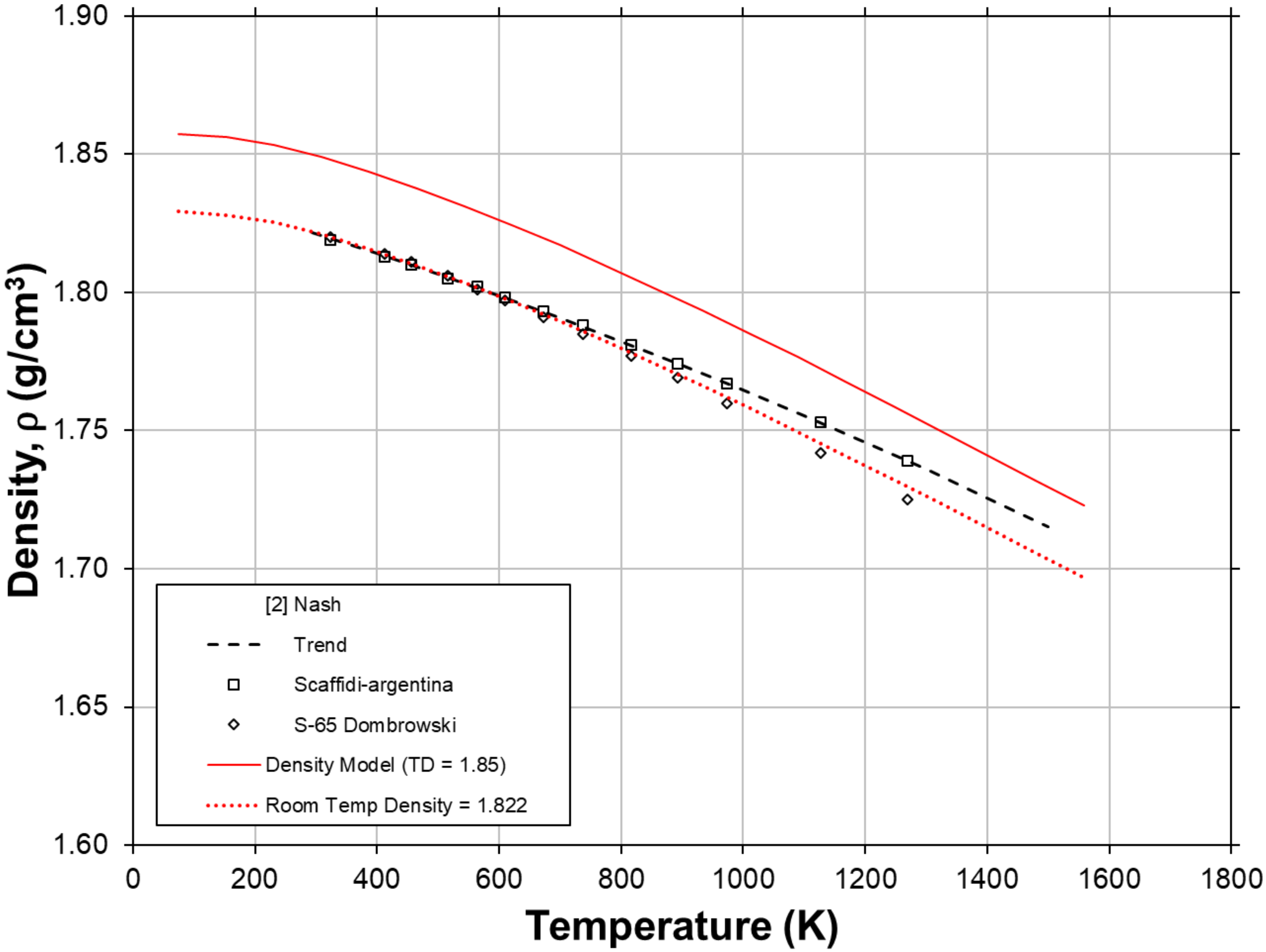

Figure 6.2.2-1: Density versus Temperature for Be. Trend calculated from fitted Thermal Expansion data and compared to trend from Nash (2005).

100% Theoretical Density

Temperature (T)		Density (ρ)		Temperature (T)		Density (ρ)	
K	(°F)	kg/m^3	(lb/ft^3)	K	(°F)	kg/m^3	(lb/ft^3)
75	(-324.7)	1857	(116.0)	800	(980.3)	1807	(112.8)
100	(-279.7)	1857	(115.9)	850	(1070.3)	1802	(112.5)
150	(-189.7)	1856	(115.9)	900	(1160.3)	1797	(112.2)
200	(-99.7)	1855	(115.8)	950	(1250.3)	1792	(111.9)
250	(-9.7)	1853	(115.7)	1000	(1340.3)	1786	(111.5)
300	(80.3)	1850	(115.5)	1050	(1430.3)	1781	(111.2)
350	(170.3)	1846	(115.3)	1100	(1520.3)	1775	(110.8)
400	(260.3)	1843	(115.0)	1150	(1610.3)	1770	(110.5)
450	(350.3)	1839	(114.8)	1200	(1700.3)	1764	(110.1)
500	(440.3)	1835	(114.5)	1250	(1790.3)	1758	(109.8)
550	(530.3)	1830	(114.3)	1300	(1880.3)	1753	(109.4)
600	(620.3)	1826	(114.0)	1350	(1970.3)	1747	(109.1)
650	(710.3)	1822	(113.7)	1400	(2060.3)	1741	(108.7)
700	(800.3)	1817	(113.4)	1500	(2240.3)	1730	(108.0)
750	(890.3)	1812	(113.1)	1558	(2344.7)	1723	(107.6)

Application Notes: Density Model and Room Temp Density are calculated as functions of thermal expansion utilizing theoretical density of beryllium, and measured room temperature density of beryllium, respectively. The equation below is used to generate these trends. Experimental data for density is collected from references [2-4].

Density Calculation:

$$\rho(T) = \rho_{RT}(1-P)/(1+dL/L_0(T)/100)^3$$

$\rho(T) = Density\ [kg/m^3]$

$Room\ Temperature\ Density\ (\rho_{RT}) = 1{,}848\ [kg/m^3]$

$P = Fractional\ Porosity$

$T = Temperature\ [K]$

Temperature Range: $75 \leq T \leq 1558$

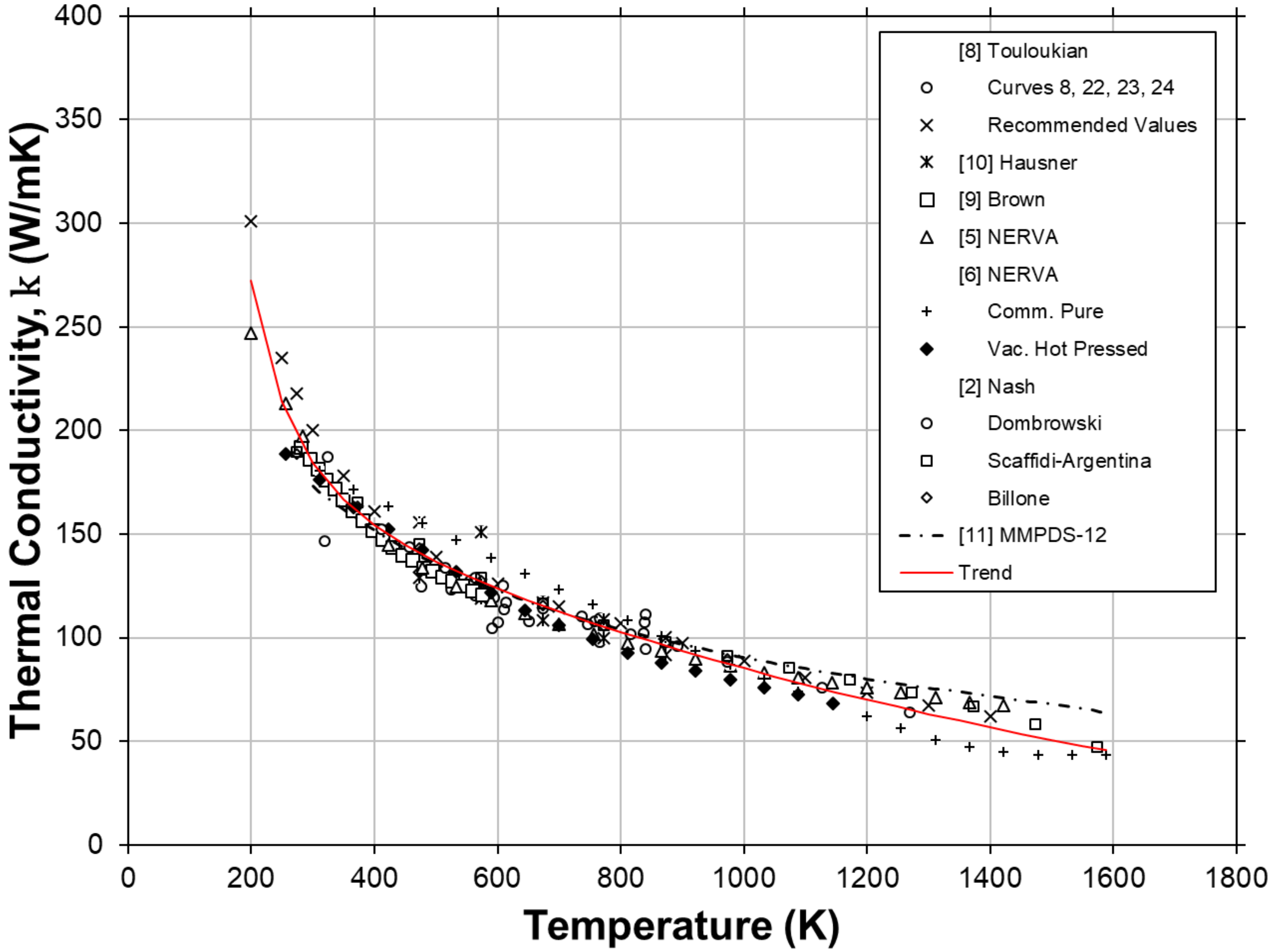

Figure 6.2.2-2: Thermal Conductivity versus Temperature of Beryllium. Displaying fitted trend of the data with comparison to MMPDS-12, S-Basis trend.

100% Theoretical Density

Temperature (T)		Thermal Conductivity (k)		Temperature (T)		Thermal Conductivity (k)	
K	(°F)	W/(m-K)	((Btu·in)/(ft²·hr·°F))	K	(°F)	W/(m-K)	((Btu·in)/(ft²·hr·°F))
200	(-99.7)	272.06	(1887.62)	900	(1160.3)	93.78	(650.63)
225	(-54.7)	237.49	(1647.72)	950	(1250.3)	89.50	(620.94)
250	(-9.7)	214.01	(1484.82)	1000	(1340.3)	85.36	(592.25)
300	(80.3)	184.53	(1280.31)	1050	(1430.3)	81.36	(564.50)
350	(170.3)	166.63	(1156.09)	1100	(1520.3)	77.49	(537.63)
400	(260.3)	154.18	(1069.72)	1150	(1610.3)	73.74	(511.61)
450	(350.3)	144.62	(1003.36)	1200	(1700.3)	70.11	(486.42)
500	(440.3)	136.71	(948.54)	1250	(1790.3)	66.59	(462.04)
550	(530.3)	129.85	(900.91)	1300	(1880.3)	63.19	(438.44)
600	(620.3)	123.68	(858.08)	1350	(1970.3)	59.90	(415.61)
650	(710.3)	117.99	(818.62)	1400	(2060.3)	56.72	(393.54)
700	(800.3)	112.67	(781.68)	1450	(2150.3)	53.65	(372.23)
750	(890.3)	107.63	(746.72)	1500	(2240.3)	50.69	(351.67)
800	(980.3)	102.82	(713.38)	1550	(2330.3)	47.83	(331.85)
850	(1070.3)	98.21	(681.40)	1589	(2400.5)	45.68	(316.90)

Application Notes: Data for thermal conductivity is collected from references [2, 5-10] and fitted with the equation below to approximate property trend with respect to temperature. Fitted trend is compared to trend from reference [11].

Fit Equation:

$$k(T) = A0 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2 + AN \cdot \left(\frac{T}{1000}\right)^N$$

$k(T) = Thermal\ Conductivity\ [W\ /\ (m \cdot K)]$

$T = Temperature\ [K]$

Constants:

T Range [K]: $200 \leq T \leq 1589$

A0 = 182.6

A1 = -118.9

A2 = 20.47

AN = 1.192

N = -2.825

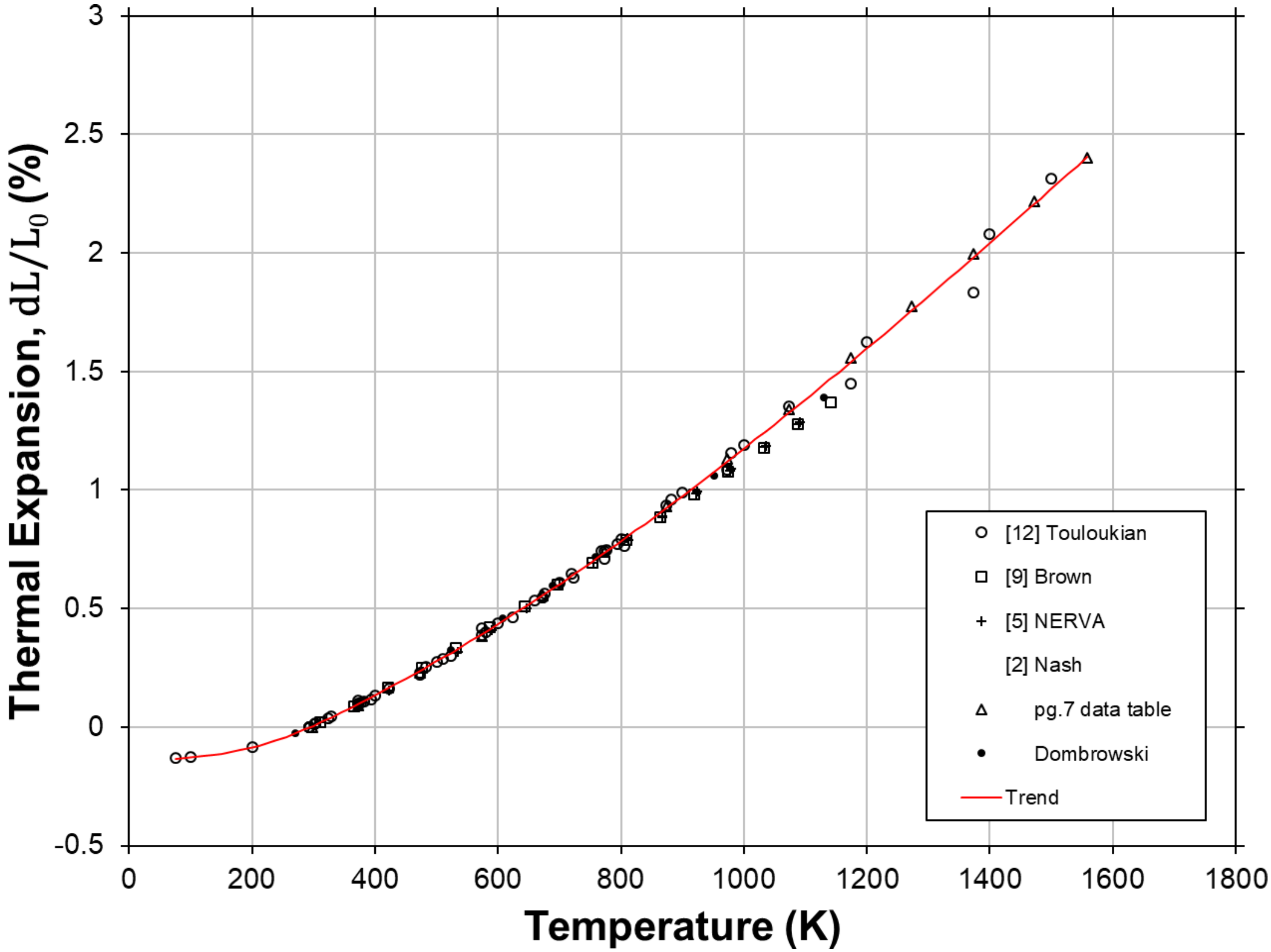

Figure 6.2.2-3: Thermal Expansion versus Temperature of Beryllium, displaying fitted trend and collected data.

100% Theoretical Density

Temperature (T)		Thermal Expansion (dL/L_0)	Temperature (T)		Thermal Expansion (dL/L_0)
K	(°F)	%	K	(°F)	%
75	(-324.7)	-0.132	800	(980.3)	0.784
100	(-279.7)	-0.127	850	(1070.3)	0.878
150	(-189.7)	-0.112	900	(1160.3)	0.975
200	(-99.7)	-0.085	950	(1250.3)	1.074
250	(-9.7)	-0.046	1000	(1340.3)	1.175
300	(80.3)	0.006	1050	(1430.3)	1.278
350	(170.3)	0.068	1100	(1520.3)	1.382
400	(260.3)	0.134	1150	(1610.3)	1.489
450	(350.3)	0.204	1200	(1700.3)	1.597
500	(440.3)	0.277	1250	(1790.3)	1.707
550	(530.3)	0.354	1300	(1880.3)	1.817
600	(620.3)	0.434	1350	(1970.3)	1.929
650	(710.3)	0.517	1400	(2060.3)	2.042
700	(800.3)	0.603	1500	(2240.3)	2.270
750	(890.3)	0.692	1558	(2344.7)	2.404

Application Notes: Data for thermal expansion is collected from references [2, 5, 9, 12] and fitted with the equation below to approximate property trend with respect to temperature.

Fit Equation:

$$dL/L_0\,(T) = A0 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2 + A3 \cdot \left(\frac{T}{1000}\right)^3$$

$dL/L_0\,(T) = Thermal\ Expansion\ [\%]$

$T = Temperature\ [K]$

Constants:

T Range [K]:	$75 \le T \le 293$	$293 < T \le 1558$
A0 =	-0.1385	-0.2791
A1 =	0.02396	0.6761
A2 =	0.5172	0.9682
A3 =	3.451	-0.1906

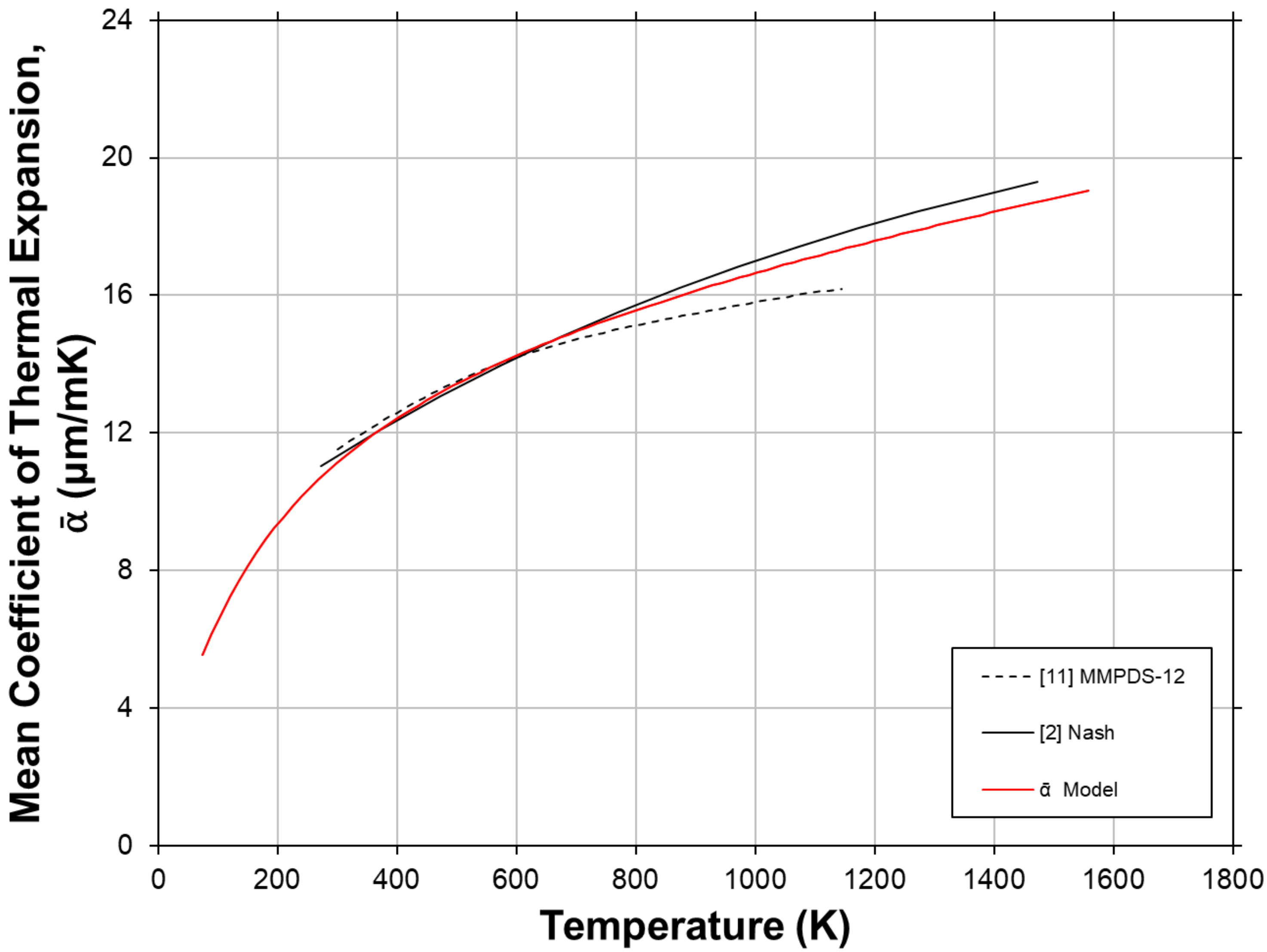

Figure 6.2.2-4: Mean Coefficient of Thermal Expansion versus Temperature of Beryllium. Calculated from fitted trend of the Thermal Expansion data and compared against trends from MMPDS-12 and Nash (2005).

100% Theoretical Density

Temperature (T)		Mean CTE (ᾱ)		Temperature (T)		Mean CTE (ᾱ)	
K	(°F)	μm/(m-K)	(μin/(in-°F))	K	(°F)	μm/(m-K)	(μin/(in-°F))
75	(-324.7)	5.535	(3.075)	800	(980.3)	15.572	(8.651)
100	(-279.7)	6.530	(3.628)	850	(1070.3)	15.859	(8.810)
150	(-189.7)	8.119	(4.510)	900	(1160.3)	16.133	(8.963)
200	(-99.7)	9.342	(5.190)	950	(1250.3)	16.396	(9.109)
250	(-9.7)	10.323	(5.735)	1000	(1340.3)	16.649	(9.249)
300	(80.3)	11.135	(6.186)	1050	(1430.3)	16.893	(9.385)
350	(170.3)	11.824	(6.569)	1100	(1520.3)	17.130	(9.517)
400	(260.3)	12.423	(6.902)	1150	(1610.3)	17.360	(9.644)
450	(350.3)	12.951	(7.195)	1200	(1700.3)	17.584	(9.769)
500	(440.3)	13.424	(7.458)	1250	(1790.3)	17.803	(9.890)
550	(530.3)	13.853	(7.696)	1300	(1880.3)	18.017	(10.009)
600	(620.3)	14.247	(7.915)	1350	(1970.3)	18.226	(10.126)
650	(710.3)	14.611	(8.117)	1400	(2060.3)	18.431	(10.240)
700	(800.3)	14.951	(8.306)	1500	(2240.3)	18.832	(10.462)
750	(890.3)	15.270	(8.483)	1558	(2344.7)	19.058	(10.588)

Application Notes: Data for mean coefficient of thermal expansion is calculated as a function of thermal expansion and fitted with the equation below to approximate property trend with respect to temperature. Calculated trend is compared against references [2, 11].

Fit Equation:

$$\bar{\alpha}(T) = \left[A0 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2\right] / \left[A\_0 + \left(\frac{T}{1000}\right)\right]$$

$\bar{\alpha}(T) = Coefficient\ of\ Thermal\ Expansion\ [\mu m/(m \cdot K)]$

$T = Temperature\ [K]$

Constants:

T. Range [K]:	$75 \le T \le 1558$
A0 =	0.2195
A1 =	16.75
A2 =	2.919
A_0 =	0.1946

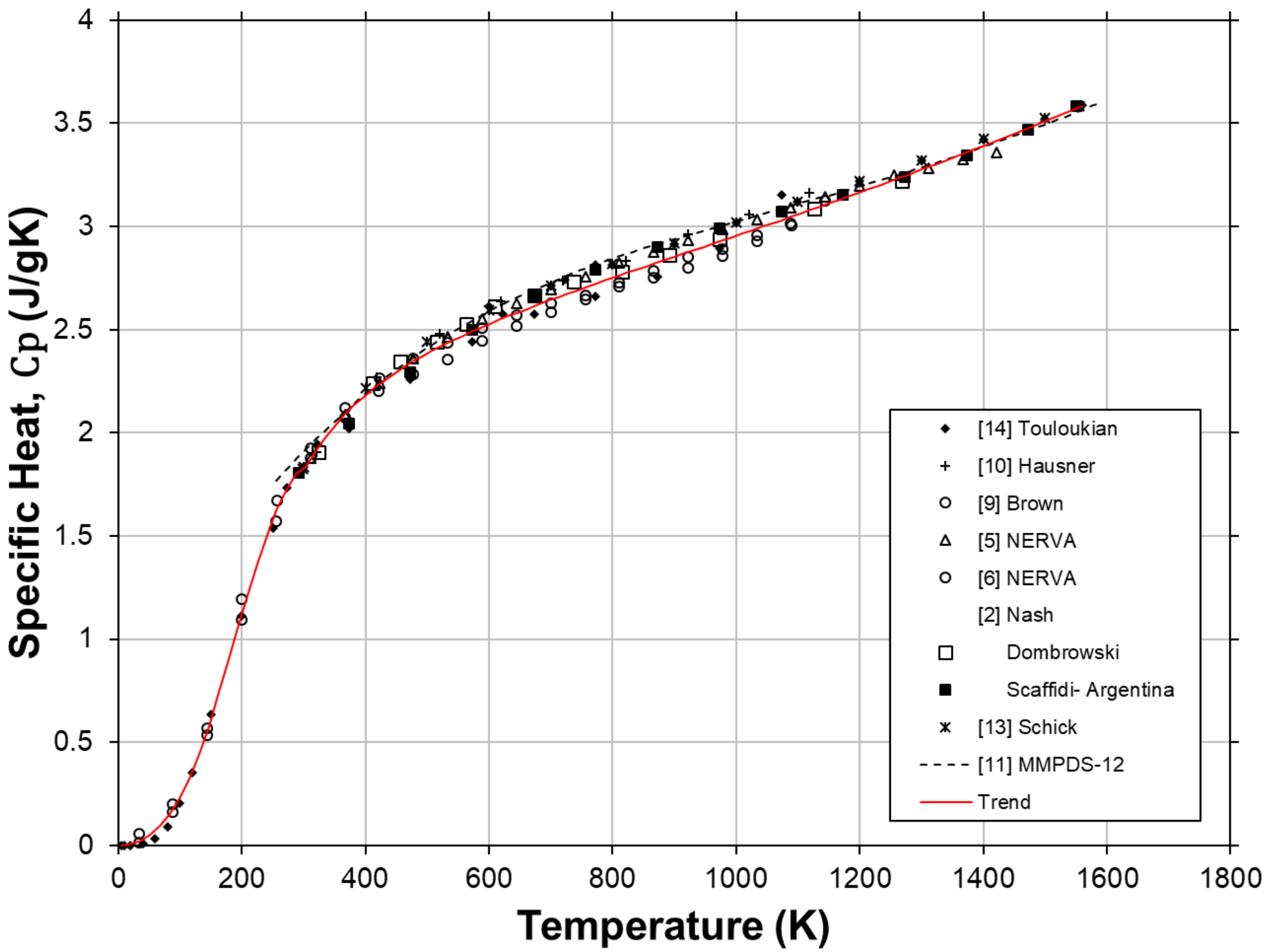

Figure 6.2.2-5: Specific Heat versus Temperature of Be fitted trend and data with comparison to MMPDS-12.

100% Theoretical Density

Temperature (T)		Specific Heat (C_p)		Temperature (T)		Specific Heat (C_p)	
K	(°F)	J/(g-K)	(BTU/(lb-°F))	K	(°F)	J/(g-K)	(BTU/(lb-°F))
25	(-414.7)	0.010	(0.002)	650	(710.3)	2.588	(0.618)
50	(-369.7)	0.046	(0.011)	700	(800.3)	2.644	(0.632)
100	(-279.7)	0.233	(0.056)	750	(890.3)	2.698	(0.645)
150	(-189.7)	0.613	(0.146)	800	(980.3)	2.751	(0.657)
200	(-99.7)	1.122	(0.268)	850	(1070.3)	2.802	(0.670)
250	(-9.7)	1.577	(0.377)	900	(1160.3)	2.853	(0.682)
300	(80.3)	1.818	(0.434)	1000	(1340.3)	2.955	(0.706)
350	(170.3)	2.032	(0.486)	1100	(1520.3)	3.059	(0.731)
400	(260.3)	2.182	(0.521)	1200	(1700.3)	3.165	(0.757)
450	(350.3)	2.294	(0.548)	1300	(1880.3)	3.276	(0.783)
500	(440.3)	2.384	(0.570)	1400	(2060.3)	3.390	(0.810)
550	(530.3)	2.460	(0.588)	1500	(2240.3)	3.510	(0.839)
600	(620.3)	2.527	(0.604)	1560	(2348.3)	3.584	(0.857)

Application Notes: Data for specific heat is collected from references [2, 5, 6, 13, 14] and fitted with the equations below to approximate property trend with respect to temperature. Fitted trend is compared against trend from [11].

Fit Equation:

For temperature range: $5 \leq T < 293$

$$C_P(T) = \left[A0 \cdot \left(\frac{T}{1000}\right)^2\right] \Big/ \left[1 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2\right]$$

For temperature range: $293 \leq T \leq 1560$

$$C_P(T) = B0 + B1 \cdot \left(\frac{T}{1000}\right) + B2 \cdot \left(\frac{T}{1000}\right)^2 + B\_2 \Big/ \left(\frac{T}{1000}\right)^2$$

$C_P(T) = Specific\ Heat\ [J/(g \cdot K)]$

$T = Temperature\ [K]$

Constants:

T. Range [K]:	$5 \leq T < 293$		$293 \leq T \leq 1560$
A0 =	14.23	B0 =	2.401
A1 =	-5.341	B1 =	0.3375
A2 =	14.39	B2 =	0.2804
		B_2 =	-0.06388

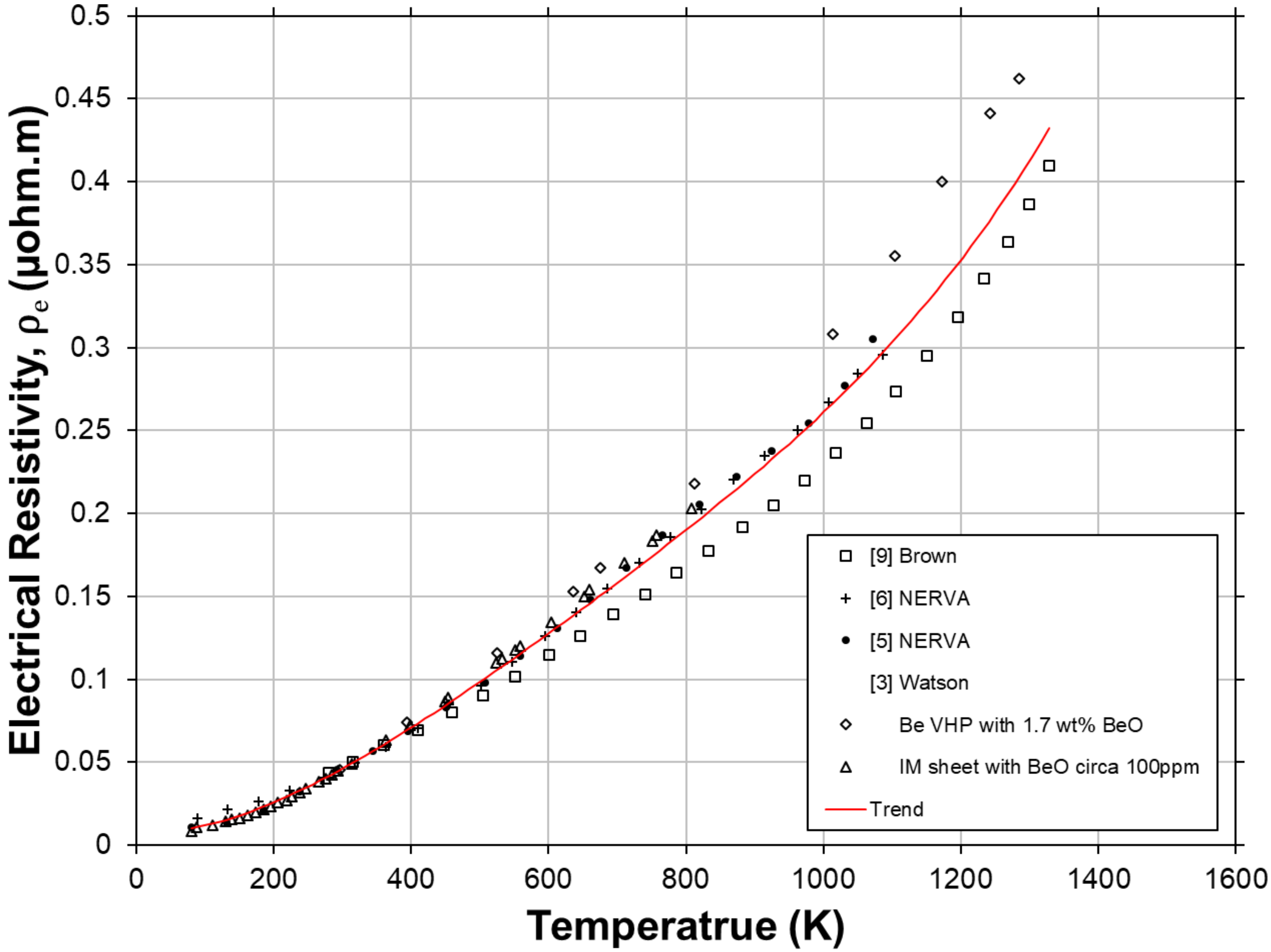

Figure 6.2.2-6: Electrical Resistivity versus Temperature of Beryllium.

100% Theoretical Density

Temperature (T)		Electrical Resistivity (ρ_e)		Temperature (T)		Electrical Resistivity (ρ_e)	
K	(°F)	μΩ-m	(μΩ-in)	K	(°F)	μΩ-m	(μΩ-in)
79	(-317.5)	0.010	(0.39)	800	(980.3)	0.190	(7.48)
100	(-279.7)	0.012	(0.47)	850	(1070.3)	0.207	(8.14)
150	(-189.7)	0.018	(0.70)	900	(1160.3)	0.224	(8.82)
200	(-99.7)	0.026	(1.02)	950	(1250.3)	0.242	(9.53)
250	(-9.7)	0.035	(1.39)	1000	(1340.3)	0.261	(10.28)
300	(80.3)	0.046	(1.82)	1050	(1430.3)	0.281	(11.08)
350	(170.3)	0.058	(2.29)	1100	(1520.3)	0.303	(11.94)
400	(260.3)	0.071	(2.79)	1150	(1610.3)	0.327	(12.87)
450	(350.3)	0.084	(3.32)	1200	(1700.3)	0.353	(13.89)
500	(440.3)	0.098	(3.88)	1250	(1790.3)	0.381	(15.01)
550	(530.3)	0.113	(4.44)	1300	(1880.3)	0.413	(16.25)
600	(620.3)	0.128	(5.03)	1329	(1932.5)	0.433	(17.03)
650	(710.3)	0.143	(5.62)				
700	(800.3)	0.158	(6.23)				
750	(890.3)	0.174	(6.85)				

Application Notes: Data for electrical resistivity is collected from references [3, 5, 6, 9] and fitted with the equation below to approximate property trend with respect to temperature.

Fit Equation:

$$\rho_e(T) = A0 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2 + A3 \cdot \left(\frac{T}{1000}\right)^3 + A4 \cdot \left(\frac{T}{1000}\right)^4$$

$\rho_e(T) = Electrical\ Resistivity\ [\mu\Omega \cdot m]$

$T = Temperature\ [K]$

Constants:

T. Range [K]:	$79 \leq T < 1329$
A0 =	7.141E-03
A1 =	-9.177E-03
A2 =	6.214E-01
A3 =	-5.928E-01
A4 =	2.345E-01

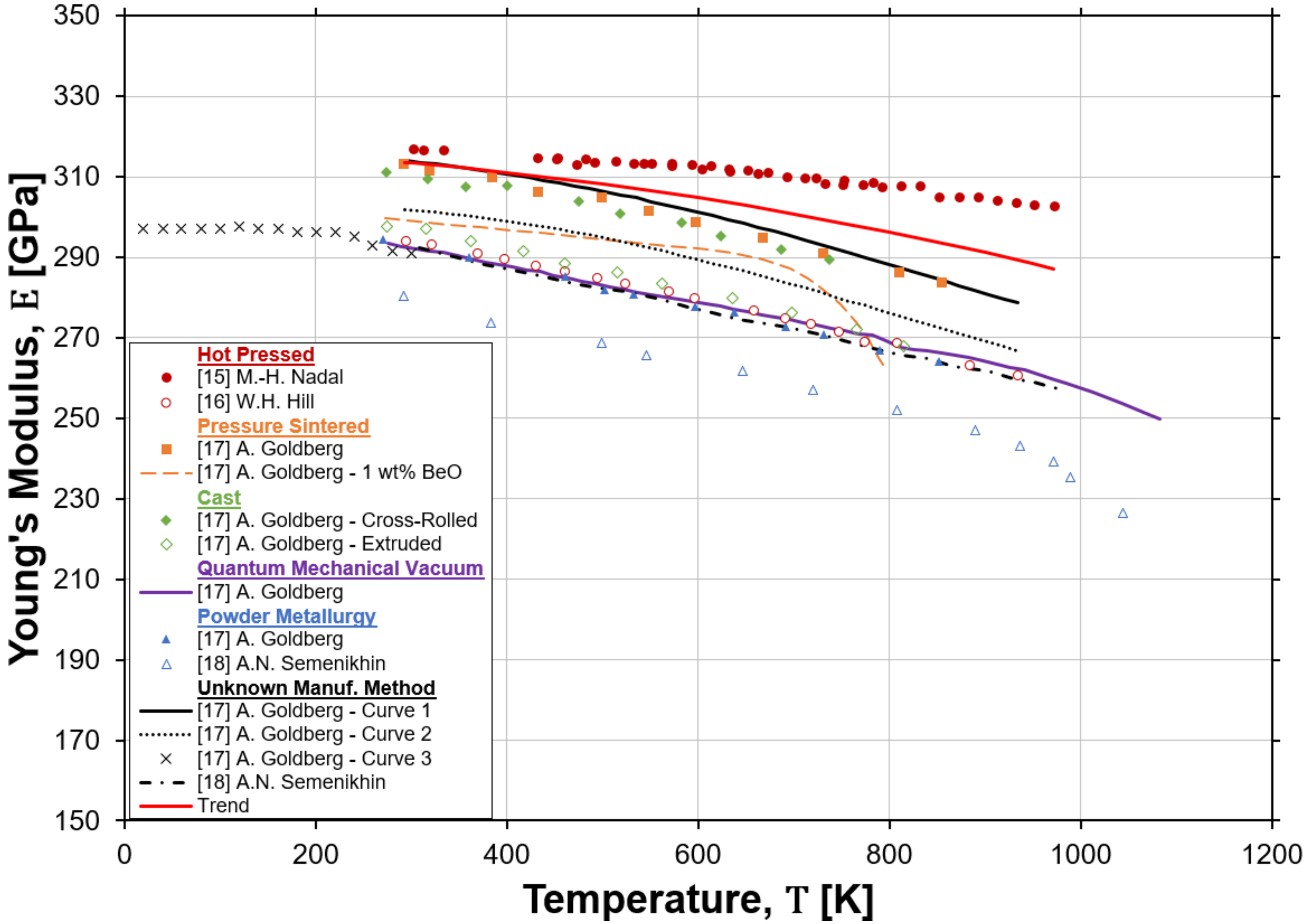

Figure 6.2.2-7: Young's Modulus versus Temperature for Beryllium. Data is sorted by manufacturing method, but the trend is solely based on datasets which contained both Young's modulus and shear modulus data: hot pressed data from Nadal and cast, cross-rolled data from Goldberg.

Young's Modulus with Temperature

100% Theoretical Density

Temperature (T)		Young's Modulus (E)		Temperature (T)		Young's Modulus (E)	
K	(°F)	GPa	(Msi)	K	(°F)	GPa	(Msi)
293	(67.7)	313.63	(45.51)	580	(584.3)	305.52	(44.33)
300	(80.3)	313.49	(45.49)	600	(620.3)	304.78	(44.22)
320	(116.3)	313.06	(45.42)	620	(656.3)	304.03	(44.11)
340	(152.3)	312.61	(45.36)	640	(692.3)	303.25	(44.00)
360	(188.3)	312.14	(45.29)	660	(728.3)	302.46	(43.89)
380	(224.3)	311.65	(45.22)	680	(764.3)	301.64	(43.77)
400	(260.3)	311.13	(45.14)	700	(800.3)	300.79	(43.65)
420	(296.3)	310.59	(45.07)	720	(836.3)	299.93	(43.52)
440	(332.3)	310.03	(44.99)	740	(872.3)	299.05	(43.39)
460	(368.3)	309.45	(44.90)	750	(890.3)	298.60	(43.33)
480	(404.3)	308.85	(44.81)	800	(980.3)	296.26	(42.99)
500	(440.3)	308.23	(44.72)	850	(1070.3)	293.79	(42.63)
520	(476.3)	307.58	(44.63)	900	(1160.3)	291.19	(42.25)
540	(512.3)	306.92	(44.53)	950	(1250.3)	288.44	(41.85)
560	(548.3)	306.23	(44.43)	972	(1289.9)	287.20	(41.67)

Application Notes: Data for Young's modulus is collected from references [15-18]. However, only datasets which contained both Young's modulus and shear modulus data were used to make the trend below. The fit equation is an approximation of Young's modulus with respect to temperature. For more information, please see the Additional Application Notes section at the end of this chapter.

Fit Equation:

$$E(T) = A0 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2$$

$E(T) = Young's\ Modulus\ [GPa]$

$T = Temperature\ [K]$

Constants:

T. Range [K]: $293 \leq T \leq 972$

A0 = 317.3

A1 = -4.553

A2 = -27.18

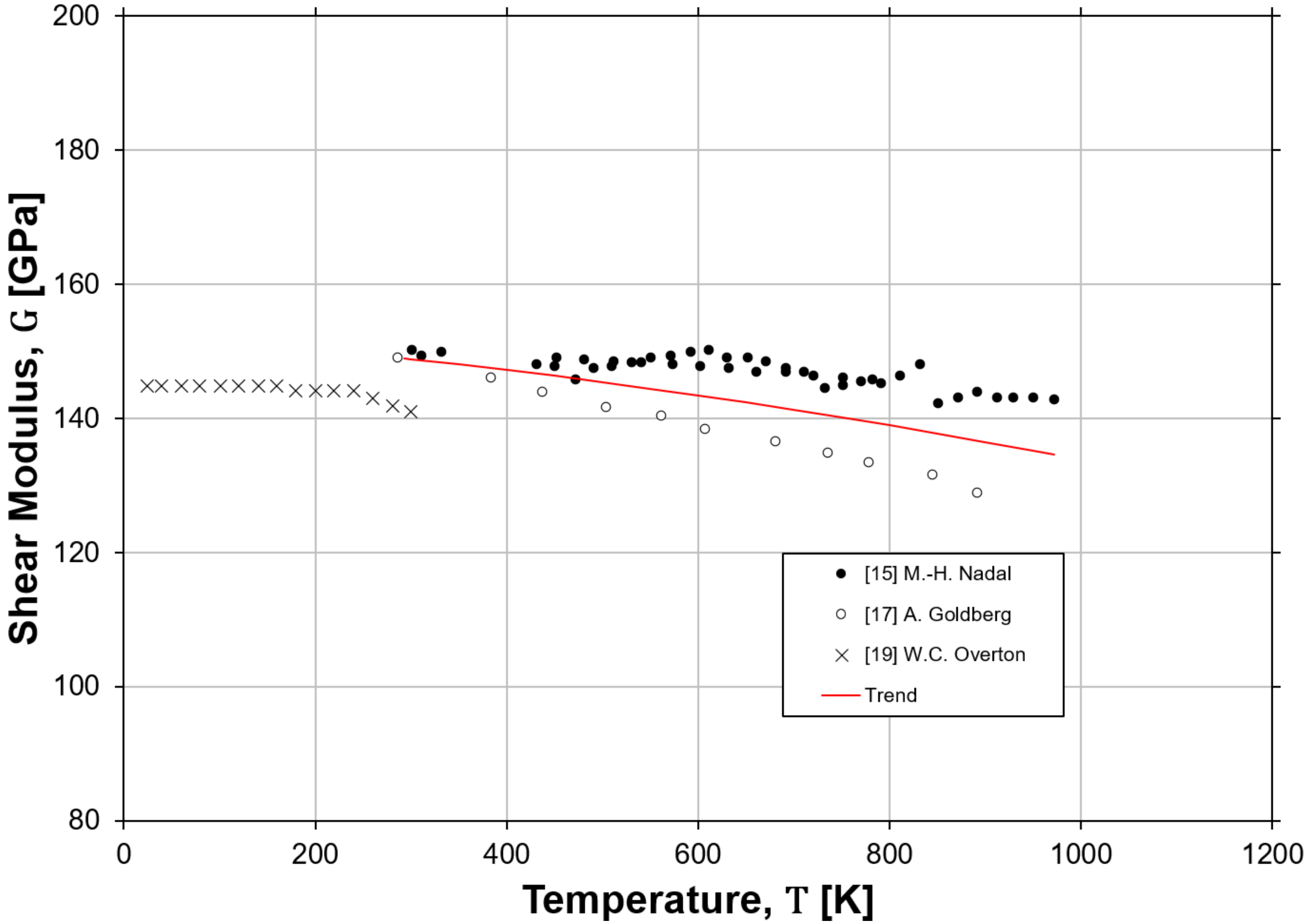

Figure 6.2.2-8: Shear Modulus versus Temperature for Beryllium.

Shear Modulus with Temperature

100% Theoretical Density

Temperature (T)		Shear Modulus (G)		Temperature (T)		Shear Modulus (G)	
K	(°F)	GPa	(Msi)	K	(°F)	GPa	(Msi)
293	(67.7)	148.92	(21.61)	580	(584.3)	143.86	(20.87)
300	(80.3)	148.81	(21.59)	600	(620.3)	143.45	(20.81)
320	(116.3)	148.51	(21.55)	620	(656.3)	143.04	(20.75)
340	(152.3)	148.19	(21.50)	640	(692.3)	142.62	(20.69)
360	(188.3)	147.87	(21.46)	660	(728.3)	142.19	(20.63)
380	(224.3)	147.54	(21.41)	680	(764.3)	141.75	(20.57)
400	(260.3)	147.20	(21.36)	700	(800.3)	141.31	(20.50)
420	(296.3)	146.86	(21.31)	720	(836.3)	140.86	(20.44)
440	(332.3)	146.51	(21.26)	740	(872.3)	140.41	(20.37)
460	(368.3)	146.15	(21.21)	750	(890.3)	140.18	(20.34)
480	(404.3)	145.79	(21.15)	800	(980.3)	139.00	(20.17)
500	(440.3)	145.41	(21.10)	850	(1070.3)	137.77	(19.99)
520	(476.3)	145.04	(21.04)	900	(1160.3)	136.51	(19.81)
540	(512.3)	144.65	(20.99)	950	(1250.3)	135.20	(19.62)
560	(548.3)	144.26	(20.93)	972	(1289.9)	134.61	(19.53)

Application Notes: Data for shear modulus is collected from references [15, 17, 19]. Datasets from [15, 17] were fitted with the equation below to approximate property trend with respect to temperature. For more information, please see the Additional Application Notes section at the end of this chapter.

Fit Equation:

$$G(T) = A0 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2$$

$G(T) = Shear\ Modulus\ [GPa]$

$T = Temperature\ [K]$

Constants:

T Range [K]:	$293 \leq T \leq 972$
A0 =	152.6
A1 =	-9.985
A2 =	-8.773

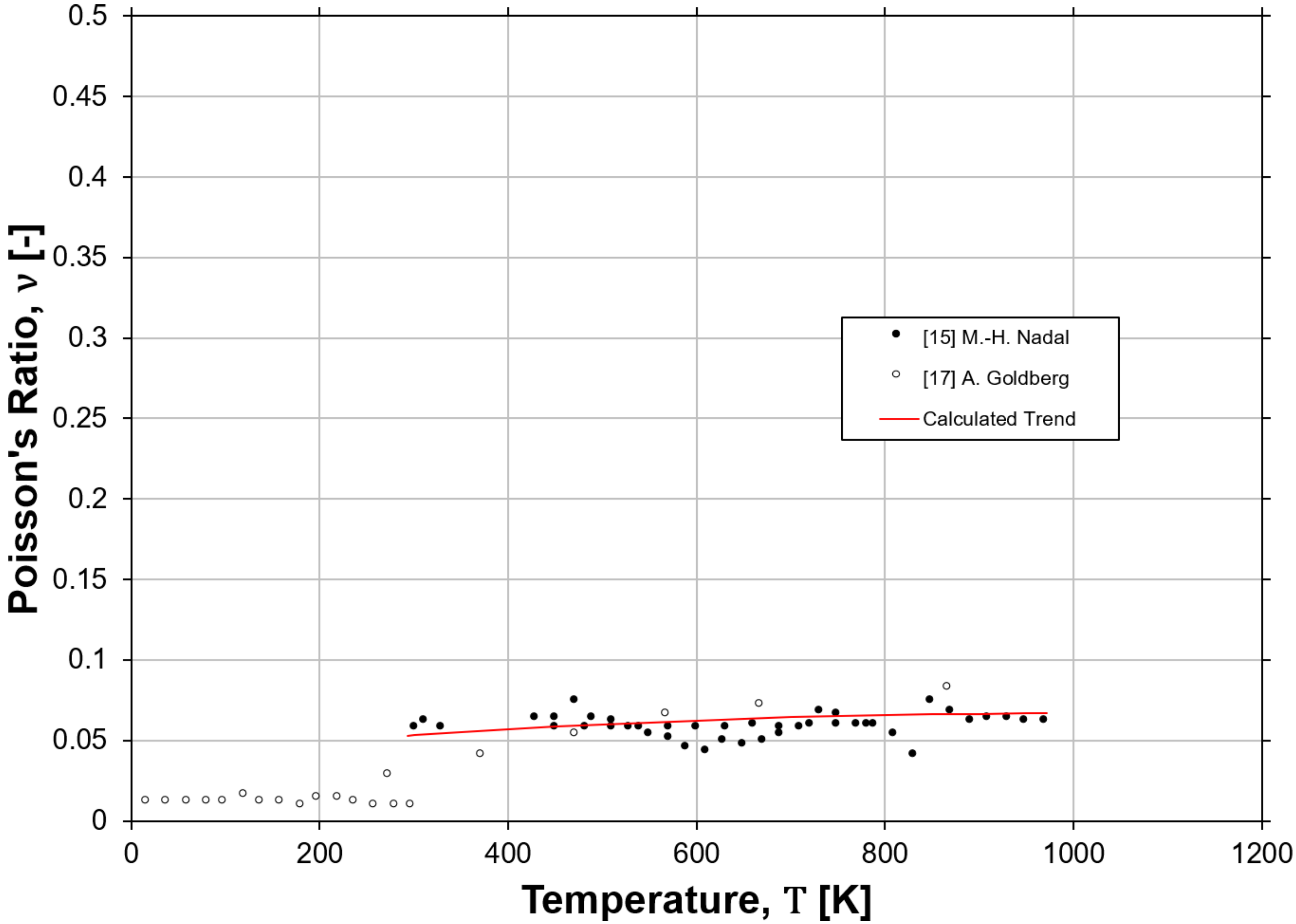

Figure 6.2.2-9: Poisson's Ratio versus Temperature for Beryllium. Calculated from trends for Young's modulus and shear modulus.

100% Theoretical Density

Temperature (T) K	(°F)	Poisson's Ratio (ν)	Temperature (T) K	(°F)	Poisson's Ratio (ν)
293	(67.7)	0.053	580	(584.3)	0.062
300	(80.3)	0.053	600	(620.3)	0.062
320	(116.3)	0.054	620	(656.3)	0.063
340	(152.3)	0.055	640	(692.3)	0.063
360	(188.3)	0.055	660	(728.3)	0.064
380	(224.3)	0.056	680	(764.3)	0.064
400	(260.3)	0.057	700	(800.3)	0.064
420	(296.3)	0.057	720	(836.3)	0.065
440	(332.3)	0.058	740	(872.3)	0.065
460	(368.3)	0.059	750	(890.3)	0.065
480	(404.3)	0.059	800	(980.3)	0.066
500	(440.3)	0.060	850	(1070.3)	0.066
520	(476.3)	0.060	900	(1160.3)	0.067
540	(512.3)	0.061	950	(1250.3)	0.067
560	(548.3)	0.061	972	(1289.9)	0.067

Application Notes: Data for Poisson's Ratio is collected from references [15, 17]. Property trend is calculated as a function of Young's modulus and shear modulus, then converted to an equivalent equation for readers' convenience. For more information, please see the Additional Application Notes section at the end of this chapter.

Fit Equation:

$$\nu(T) = A0 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2 + A3 \cdot \left(\frac{T}{1000}\right)^3$$

$\nu(T) = Poisson's\ Ratio\ [-]$

$T = Temperature\ [K]$

Constants:

T Range [K]:	$293 \leq T \leq 972$
A0 =	0.03986
A1 =	0.05156
A2 =	-0.02185
A3 =	-0.002744

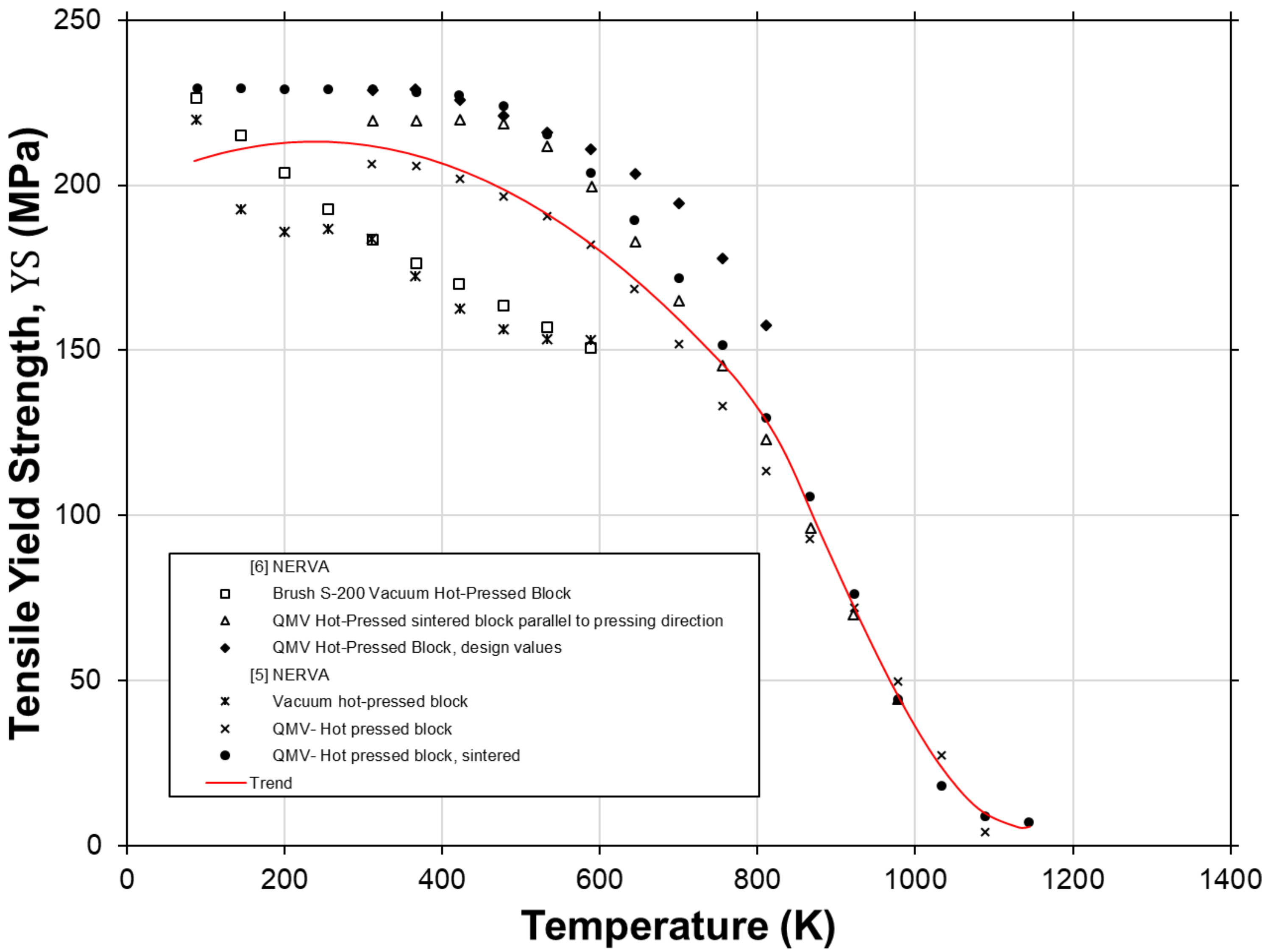

Figure 6.2.2-10: Yield Strength versus Temperature of Beryllium.

100% Theoretical Density

Temperature (T)		Yield Strength (YS)		Temperature (T)		Yield Strength (YS)	
K	(°F)	MPa	(Ksi)	K	(°F)	MPa	(Ksi)
85	(-306.7)	223.99	(32.50)	450	(350.3)	199.72	(28.98)
100	(-279.7)	221.40	(32.12)	475	(395.3)	198.54	(28.81)
125	(-234.7)	217.61	(31.58)	500	(440.3)	197.08	(28.60)
150	(-189.7)	214.42	(31.11)	525	(485.3)	195.26	(28.33)
175	(-144.7)	211.76	(30.73)	550	(530.3)	193.03	(28.01)
200	(-99.7)	209.58	(30.41)	575	(575.3)	190.32	(27.61)
225	(-54.7)	207.80	(30.15)	600	(620.3)	187.06	(27.14)
250	(-9.7)	206.37	(29.94)	625	(665.3)	183.21	(26.58)
275	(35.3)	205.21	(29.78)	650	(710.3)	178.68	(25.93)
300	(80.3)	204.28	(29.64)	700	(800.3)	167.38	(24.29)
325	(125.3)	203.50	(29.53)	800	(980.3)	133.98	(19.44)
350	(170.3)	202.82	(29.43)	900	(1160.3)	83.79	(12.16)
375	(215.3)	202.16	(29.33)	1000	(1340.3)	36.00	(5.22)
400	(260.3)	201.46	(29.23)	1100	(1520.3)	8.01	(1.16)
425	(305.3)	200.67	(29.12)	1150	(1610.3)	6.16	(0.89)

Application Notes: Data for yield strength is collected from references [5, 6] and fitted with the equations below to approximate property trends with respect to temperature. For more information, please see the Additional Application Notes section at the end of this chapter.

Fit Equations:

$$YS(T) = A0 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2 + A3 \cdot \left(\frac{T}{1000}\right)^3$$

$YS(T) = Yield\ Strength\ [MPa]$

$T = Temperature\ [K]$

Constants:

T Range [K]:	$85 \leq T \leq 810$	$810 < T \leq 1150$
A0 =	243.8	-1084
A1 =	-290.4	5158
A2 =	731.4	-6552
A3 =	-675	2514

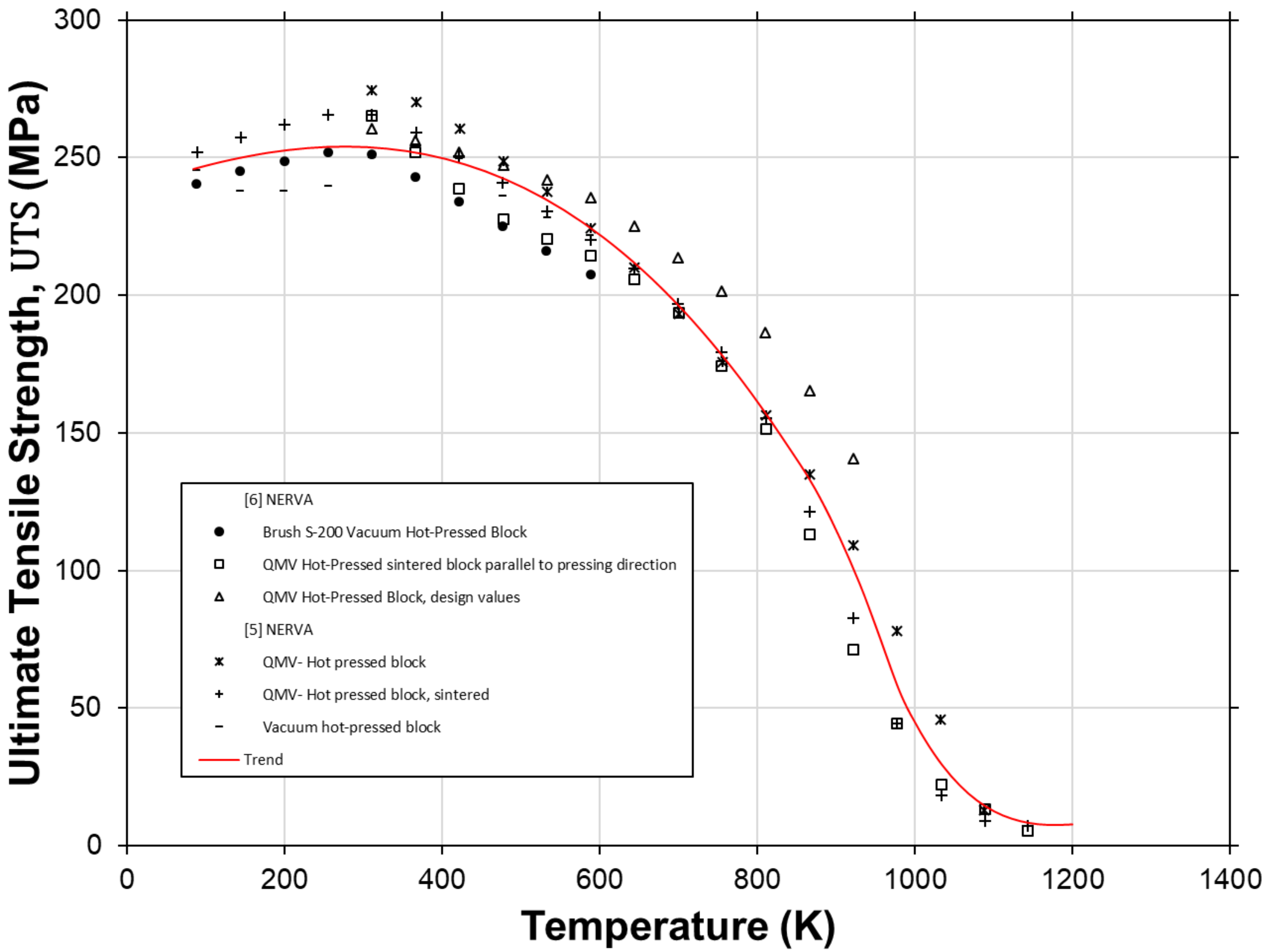

Figure 6.2.2-11: Ultimate Tensile Strength versus Temperature of Beryllium.

100% Theoretical Density

Temperature (T)		Tensile Strength (TS)		Temperature (T)		Tensile Strength (TS)	
K	(°F)	MPa	(Ksi)	K	(°F)	MPa	(Ksi)
85	(-306.7)	245.78	(35.66)	450	(350.3)	245.51	(35.62)
100	(-279.7)	246.93	(35.83)	475	(395.3)	242.74	(35.22)
125	(-234.7)	248.68	(36.08)	500	(440.3)	239.54	(34.76)
150	(-189.7)	250.21	(36.31)	525	(485.3)	235.88	(34.23)
175	(-144.7)	251.50	(36.49)	550	(530.3)	231.75	(33.63)
200	(-99.7)	252.53	(36.64)	575	(575.3)	227.14	(32.96)
225	(-54.7)	253.29	(36.75)	600	(620.3)	222.04	(32.22)
250	(-9.7)	253.77	(36.82)	625	(665.3)	216.42	(31.40)
275	(35.3)	253.95	(36.85)	650	(710.3)	210.27	(30.51)
300	(80.3)	253.81	(36.83)	700	(800.3)	196.32	(28.49)
325	(125.3)	253.34	(36.76)	800	(980.3)	161.43	(23.42)
350	(170.3)	252.53	(36.64)	900	(1160.3)	116.38	(16.89)
375	(215.3)	251.36	(36.47)	1000	(1340.3)	45.00	(6.53)
400	(260.3)	249.80	(36.25)	1100	(1520.3)	12.61	(1.83)
425	(305.3)	247.86	(35.96)	1200	(1700.3)	7.74	(1.12)

Application Notes: Data for ultimate tensile strength is collected from references [5, 6] and fitted with the equations below to approximate property trends with respect to temperature. For more information, please see the Additional Application Notes section at the end of this chapter.

Fit Equations:

$$TS(T) = A0 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2 + A3 \cdot \left(\frac{T}{1000}\right)^3$$

$TS(T) = Tensile\ Strength\ [MPa]$

$T = Temperature\ [K]$

Constants:

T Range [K]:	$85 \leq T \leq 921$	$921 \leq T \leq 1200$
A0 =	238	6472
A1 =	102.8	-15800
A2 =	-118.3	12850
A3 =	-162.3	-3477

Young's Modulus, Shear Modulus, and Poisson's Ratio Application Notes:

Starting with revision 2 of this handbook, the beryllium Young's modulus and shear modulus datasets have been updated to increase the accuracy of trends. In previous versions, static modulus data was displayed in each plot. Static modulus testing methods are known for the broad uncertainty intervals of their results, particularly at elevated temperatures. As a result, moduli values are often greatly underestimated by static testing. Luckily, more recent testing has been performed [15, 17], contributing toward a more realistic trend. All datasets shown in the Young's modulus, shear modulus, and Poisson's ratio plots for beryllium were gathered using dynamic modulus testing instead of static modulus testing. However, since a wide spread was still observed in Young's modulus data, only sources that measured Young's modulus and shear modulus in a single experiment were used to generate the Young's modulus trend. Over time, and where dynamic modulus data is available, improvements can be implemented for other materials' moduli trends as well.

While dynamic modulus testing generally provides more consistent values than static modulus testing, note that the dynamic modulus and static modulus represent two different scenarios. Dynamic modulus values are more appropriate for modeling a system experiencing vibration, while static modulus values become more useful for structures experiencing static loading. Other industries, such as the construction industry, employ equations to relate static and dynamic moduli values [20].

Poisson's ratio is calculated from Young's modulus and shear modulus as usual. Note that both the data and trend shown in the Poisson's ratio plot are approximately constant, and they are very close to zero. A Poisson's ratio of zero indicates that stretching or compressing one dimension (i.e. the length) of a body has no impact on the other dimensions (i.e. the width and height). Versions 0 and 1 of this handbook suggested that the Poisson's ratio for beryllium could be negative at high temperatures, but this is no longer expected.

General Application Notes:

For all materials, properties will vary slightly by lot due to material composition and other factors. Beryllium, however, is more sensitive to these variables. Others have reported significant differences between beryllium pieces. BeO content, grain size, and manufacturing methods contribute to these differences [5, 6]. For mechanical properties in particular, additional testing with consistent material variables should be performed to determine the accuracy of this handbook's trends.

Temp. (T) K	Physical and Electrical		Thermal				Elastic		
	Density (ρ) kg/m³	Electrical Resistivity (ρ_e) μΩ-m	Thermal Conductivity (k) W/(m-K)	Thermal Expansion (dL/L_0) %	Mean CTE ($\bar{\alpha}$) 10^{-6}/K	Specific Heat (C_p) J/(g-K)	Young's Modulus (E) GPa	Shear Modulus (G) GPa	Poisson's Ratio (ν)
100	1857	0.012	-	-0.127	6.53	0.233	-	-	-
200	1855	0.026	272.06	-0.085	9.34	1.122	-	-	-
300	1850	0.046	184.53	0.006	11.13	1.818	313.49	148.81	0.053
350	1846	0.058	166.63	0.068	11.82	2.032	312.38	148.03	0.055
400	1843	0.071	154.18	0.134	12.42	2.182	311.13	147.20	0.057
450	1839	0.084	144.62	0.204	12.95	2.294	309.75	146.33	0.058
500	1835	0.098	136.71	0.277	13.42	2.384	308.23	145.41	0.060
550	1830	0.113	129.85	0.354	13.85	2.460	306.57	144.45	0.061
600	1826	0.128	123.68	0.434	14.25	2.527	304.78	143.45	0.062
650	1822	0.143	117.99	0.517	14.61	2.588	302.86	142.40	0.063
700	1817	0.158	112.67	0.603	14.95	2.644	300.79	141.31	0.064
750	1812	0.174	107.63	0.692	15.27	2.698	298.60	140.18	0.065
800	1807	0.190	102.82	0.784	15.57	2.751	296.26	139.00	0.066
850	1802	0.207	98.21	0.878	15.86	2.802	293.79	137.77	0.066
900	1797	0.224	93.78	0.975	16.13	2.853	291.19	136.51	0.067
950	1792	0.242	89.50	1.074	16.40	2.904	288.44	135.20	0.067
1000	1786	0.261	85.36	1.175	16.65	2.955	-	-	-
1050	1781	0.281	81.36	1.278	16.89	3.007	-	-	-
1100	1775	0.303	77.49	1.382	17.13	3.059	-	-	-
1150	1770	0.327	73.74	1.489	17.36	3.112	-	-	-
1200	1764	0.353	70.11	1.597	17.58	3.165	-	-	-
1300	1753	0.413	63.19	1.817	18.02	3.276	-	-	-
1400	1741	-	56.72	2.042	18.43	3.390	-	-	-
1500	1730	-	50.69	2.270	18.83	3.510	-	-	-
1550	1724	-	47.83	2.385	19.03	3.571	-	-	-

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7 Refractory Ceramics

7.1 Oxides

Room Temperature Properties

Molar Mass, [g/mol]	25.01
Theoretical Density, [kg/m^3]	3,010
Melting Point, [K]	2823 ± 25
Boiling Point, [K]	4533
α - β phase transition [K]	2322
Specific Heat, [J/(g-K)]	1.00
Thermal Conductivity, [W/(m-K)]	275.33
Linear expansion coefficient, [μm/(m-K)]	4.87
Young's Modulus, [GPa]	344.7

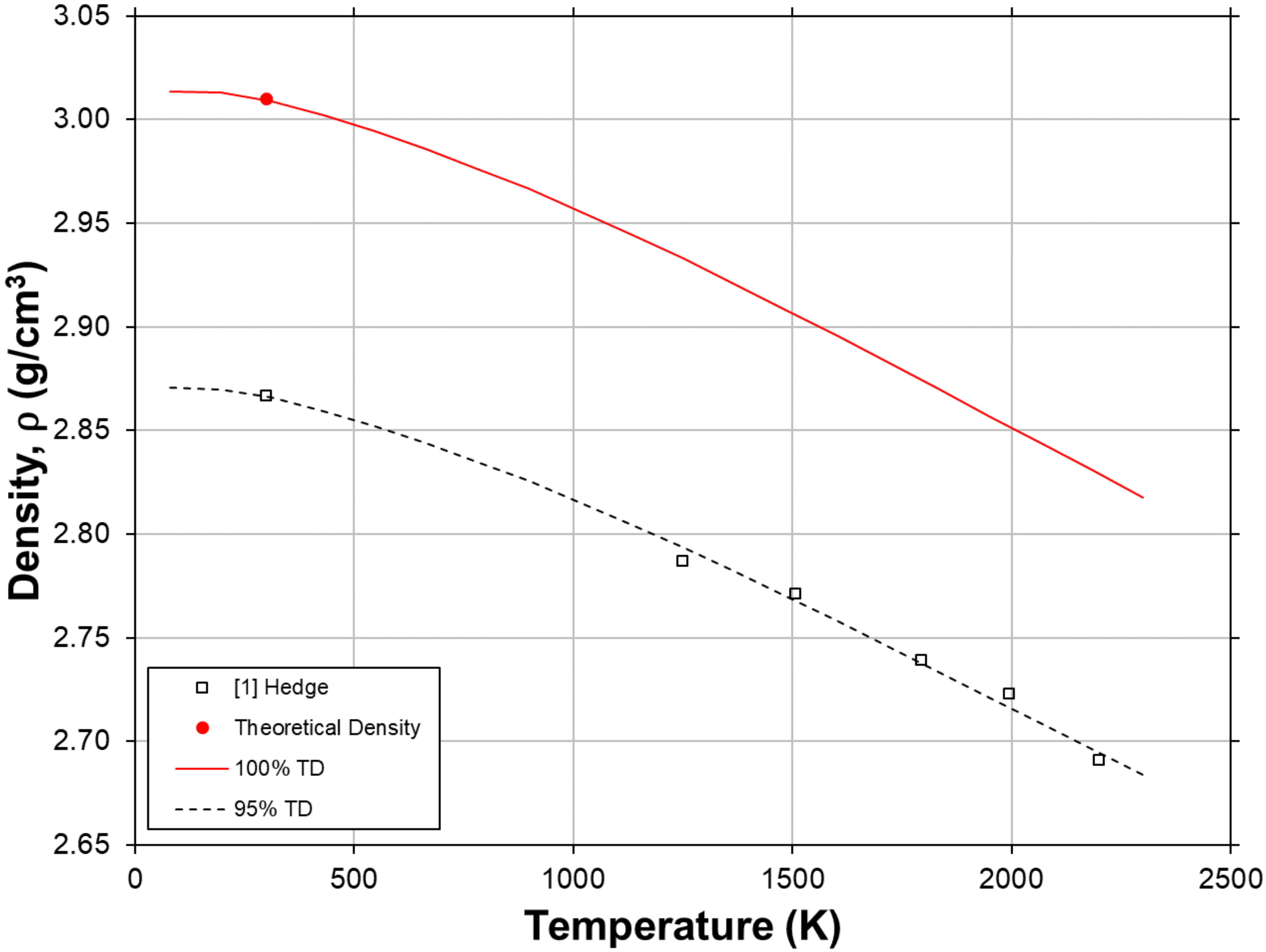

Figure 7.1.1-1: Density versus Temperature for Beryllia. Calculated from fitted trend of the Thermal Expansion data based on 100% TD (red) and 95% TD (dotted black). Compared against data from Hedge (1963).

100% Theoretical Density

Temperature (T)		Density (ρ)		Temperature (T)		Density (ρ)	
K	(°F)	kg/m³	(lb/ft³)	K	(°F)	kg/m³	(lb/ft³)
79	(-317.5)	3014	(188.1)	900	(1160.3)	2966	(185.2)
100	(-279.7)	3014	(188.1)	1000	(1340.3)	2957	(184.6)
150	(-189.7)	3014	(188.1)	1100	(1520.3)	2948	(184.0)
200	(-99.7)	3013	(188.1)	1200	(1700.3)	2938	(183.4)
250	(-9.7)	3012	(188.0)	1300	(1880.3)	2928	(182.8)
300	(80.3)	3009	(187.9)	1400	(2060.3)	2917	(182.1)
350	(170.3)	3007	(187.7)	1500	(2240.3)	2907	(181.5)
400	(260.3)	3004	(187.5)	1600	(2420.3)	2896	(180.8)
450	(350.3)	3001	(187.3)	1700	(2600.3)	2885	(180.1)
500	(440.3)	2997	(187.1)	1800	(2780.3)	2874	(179.4)
550	(530.3)	2994	(186.9)	1900	(2960.3)	2863	(178.7)
600	(620.3)	2991	(186.7)	2000	(3140.3)	2851	(178.0)
650	(710.3)	2987	(186.5)	2100	(3320.3)	2840	(177.3)
700	(800.3)	2983	(186.2)	2200	(3500.3)	2829	(176.6)
800	(980.3)	2975	(185.7)	2300	(3680.3)	2818	(175.9)

Application Notes: Density trends are calculated as a function of thermal expansion data, as seen in the equation below for 100% theoretical density. Trend for 95% TD is compared against data from reference [1].

Density Calculation:

$\rho(T) = \rho_{RT}(1-P)/(1+dL/L_0(T)/100)^3$

$\rho(T) = Density\ [kg/m^3]$

$Room\ Temperature\ Density\ (\rho_{RT}) = 3{,}010\ [kg/m^3]$

$P = Fractional\ Porosity$

$T = Temperature\ [K]$

Temperature Range: $79 \leq T \leq 2301$

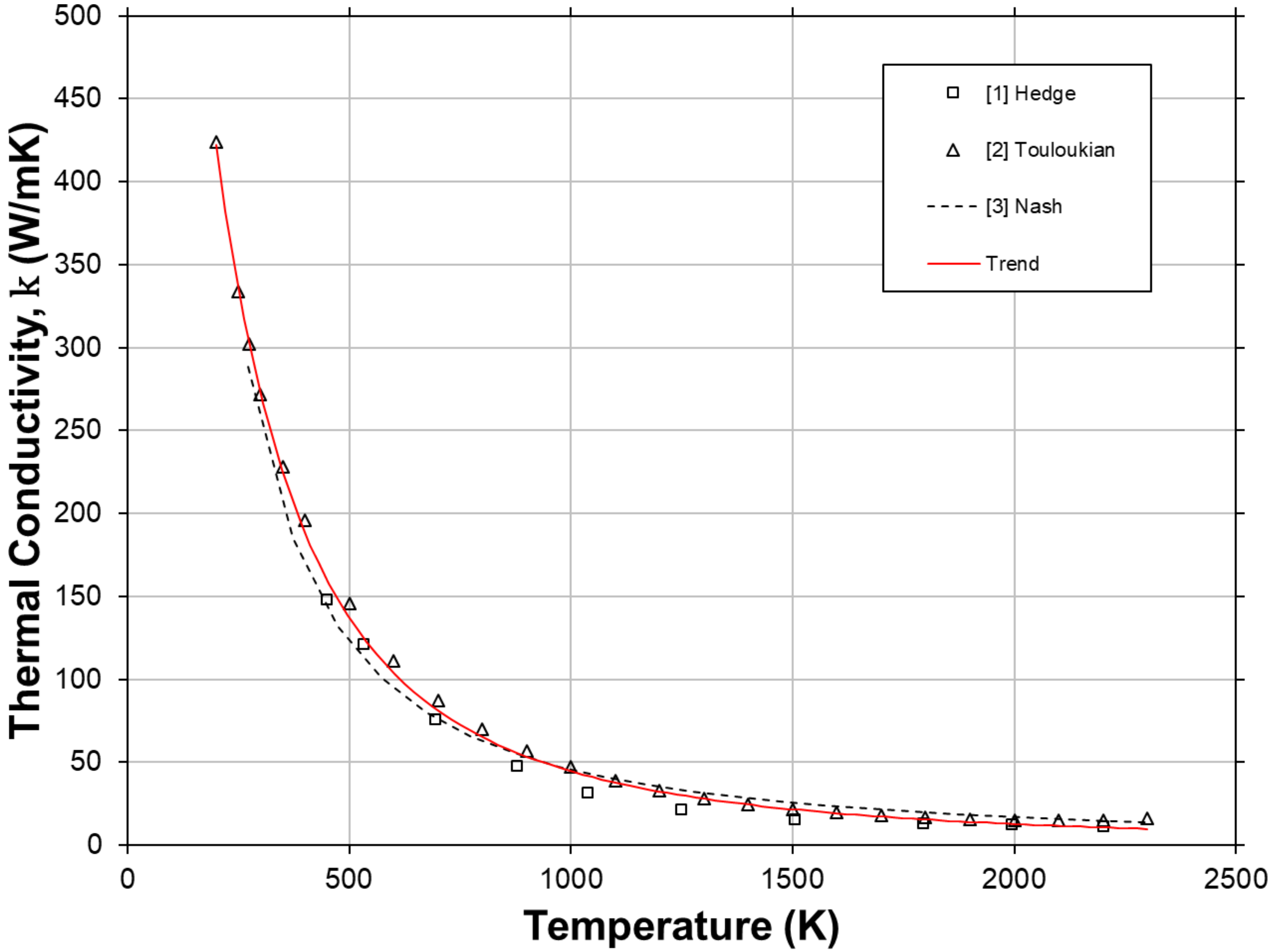

Figure 7.1.1-2: Thermal Conductivity versus Temperature of Beryllia. Displaying fitted trend of the data with comparison to trend from Nash (2005).

100% Theoretical Density

Temperature (T)		Thermal Conductivity (k)		Temperature (T)		Thermal Conductivity (k)	
K	(°F)	W/(m-K)	((Btu·in)/(ft^2·hr·°F))	K	(°F)	W/(m-K)	((Btu·in)/(ft^2·hr·°F))
200	(-99.7)	421.93	(2927.41)	950	(1250.3)	48.78	(338.42)
250	(-9.7)	336.46	(2334.39)	1000	(1340.3)	44.64	(309.73)
300	(80.3)	273.13	(1895.02)	1100	(1520.3)	37.80	(262.25)
350	(170.3)	225.36	(1563.60)	1200	(1700.3)	32.41	(224.87)
400	(260.3)	188.67	(1309.03)	1300	(1880.3)	28.10	(194.93)
450	(350.3)	160.00	(1110.12)	1400	(2060.3)	24.59	(170.58)
500	(440.3)	137.24	(952.22)	1500	(2240.3)	21.69	(150.52)
550	(530.3)	118.92	(825.06)	1600	(2420.3)	19.28	(133.79)
600	(620.3)	103.96	(721.31)	1700	(2600.3)	17.25	(119.71)
650	(710.3)	91.62	(635.66)	1800	(2780.3)	15.53	(107.74)
700	(800.3)	81.32	(564.21)	1900	(2960.3)	14.05	(97.48)
750	(890.3)	72.64	(504.01)	2000	(3140.3)	12.77	(88.62)
800	(980.3)	65.27	(452.86)	2100	(3320.3)	11.66	(80.92)
850	(1070.3)	58.96	(409.05)	2200	(3500.3)	10.69	(74.18)
900	(1160.3)	53.51	(371.25)	2300	(3680.3)	9.84	(68.25)

Application Notes: Data for thermal conductivity is collected from references [1, 2] and fitted with the equation below to approximate the property trend with respect to temperature. This trend is compared against trend from reference [3].

Fit Equation:

$$k(T) = \left[A0 + A1\cdot\left(\frac{T}{1000}\right)\right] / \left[A\_0 + A\_1\cdot\left(\frac{T}{1000}\right) + \left(\frac{T}{1000}\right)^2\right]$$

$k(T) = Thermal\ Conductivity\ [W\ /\ (m\cdot K)]$

$T = Temperature\ [K]$

Constants:

T Range [K]:	$200 \leq T \leq 2301$
A0 =	57.1
A1 =	0.3584
A_0 =	0.0476
A_1 =	0.2395

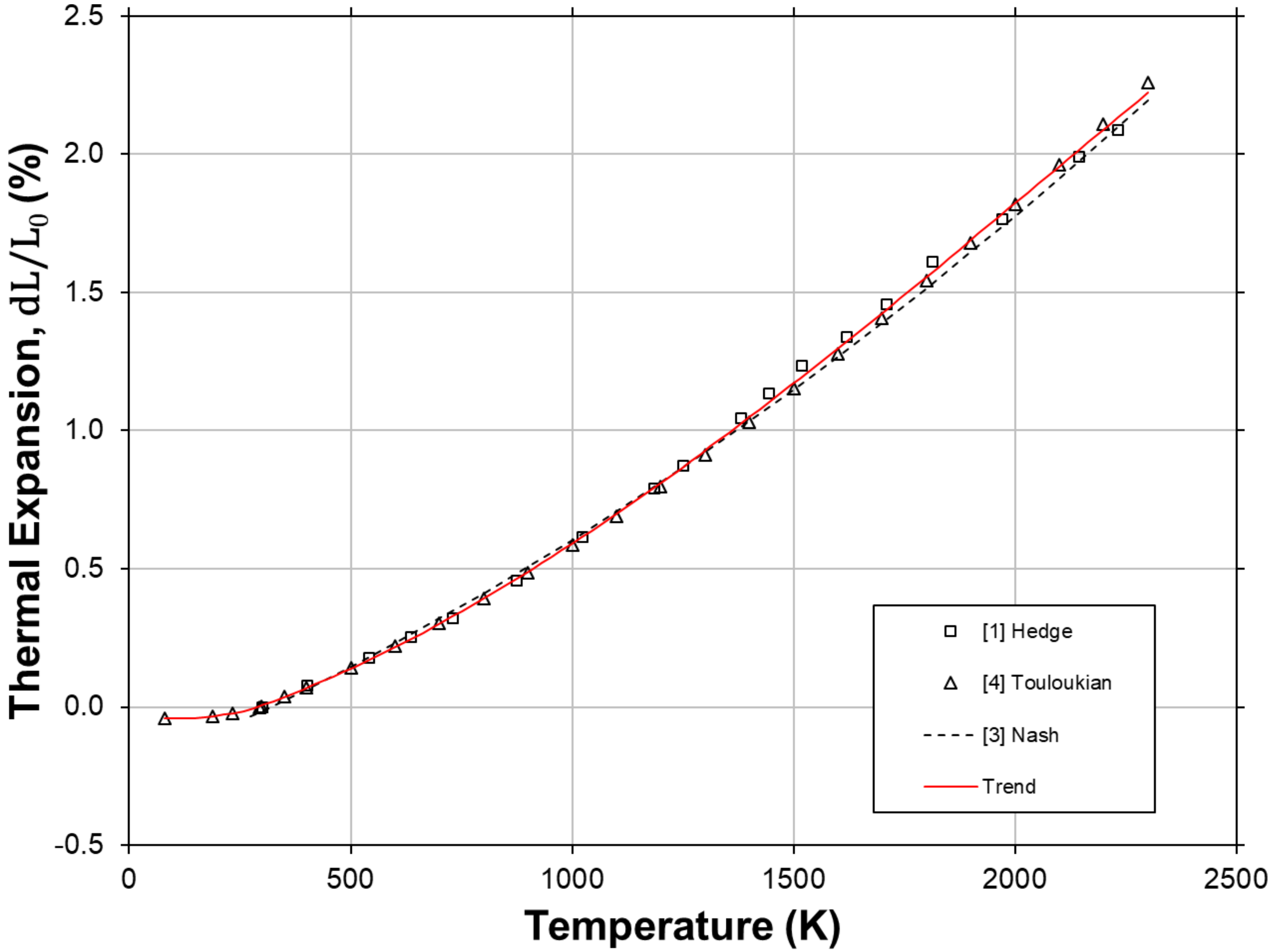

Figure 7.1.1-3: Thermal Expansion versus Temperature of Beryllia. Displaying fitted trend of the data with comparison to Nash (2005).

100% Theoretical Density

Temperature (T)		Thermal Expansion (dL/L_0)	Temperature (T)		Thermal Expansion (dL/L_0)
K	(°F)	%	K	(°F)	%
79	(-317.5)	-0.041	900	(1160.3)	0.489
100	(-279.7)	-0.042	1000	(1340.3)	0.591
150	(-189.7)	-0.039	1100	(1520.3)	0.699
200	(-99.7)	-0.031	1200	(1700.3)	0.811
250	(-9.7)	-0.018	1300	(1880.3)	0.927
300	(80.3)	0.006	1400	(2060.3)	1.047
350	(170.3)	0.036	1500	(2240.3)	1.171
400	(260.3)	0.069	1600	(2420.3)	1.297
450	(350.3)	0.103	1700	(2600.3)	1.426
500	(440.3)	0.139	1800	(2780.3)	1.556
550	(530.3)	0.177	1900	(2960.3)	1.688
600	(620.3)	0.216	2000	(3140.3)	1.821
650	(710.3)	0.258	2100	(3320.3)	1.955
700	(800.3)	0.301	2200	(3500.3)	2.089
800	(980.3)	0.392	2300	(3680.3)	2.222

Application Notes: Data for thermal expansion is collected from references [1, 4] and fitted with the equation below to approximate property trend with respect to temperature. This trend is compared against trend from reference [3].

Fit Equation:

$$dL/L_0\,(T) = A0 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2 + A3 \cdot \left(\frac{T}{1000}\right)^3$$

$dL/L_0\,(T) = Thermal\ Expansion\ [\%]$

$T = Temperature\ [K]$

Constants:

T Range [K]:	$79 \leq T \leq 293$	$293 < T \leq 2301$
A0 =	-0.03153	-0.1294
A1 =	-0.1969	0.3148
A2 =	0.9181	0.481
A3 =	0.3533	-0.07535

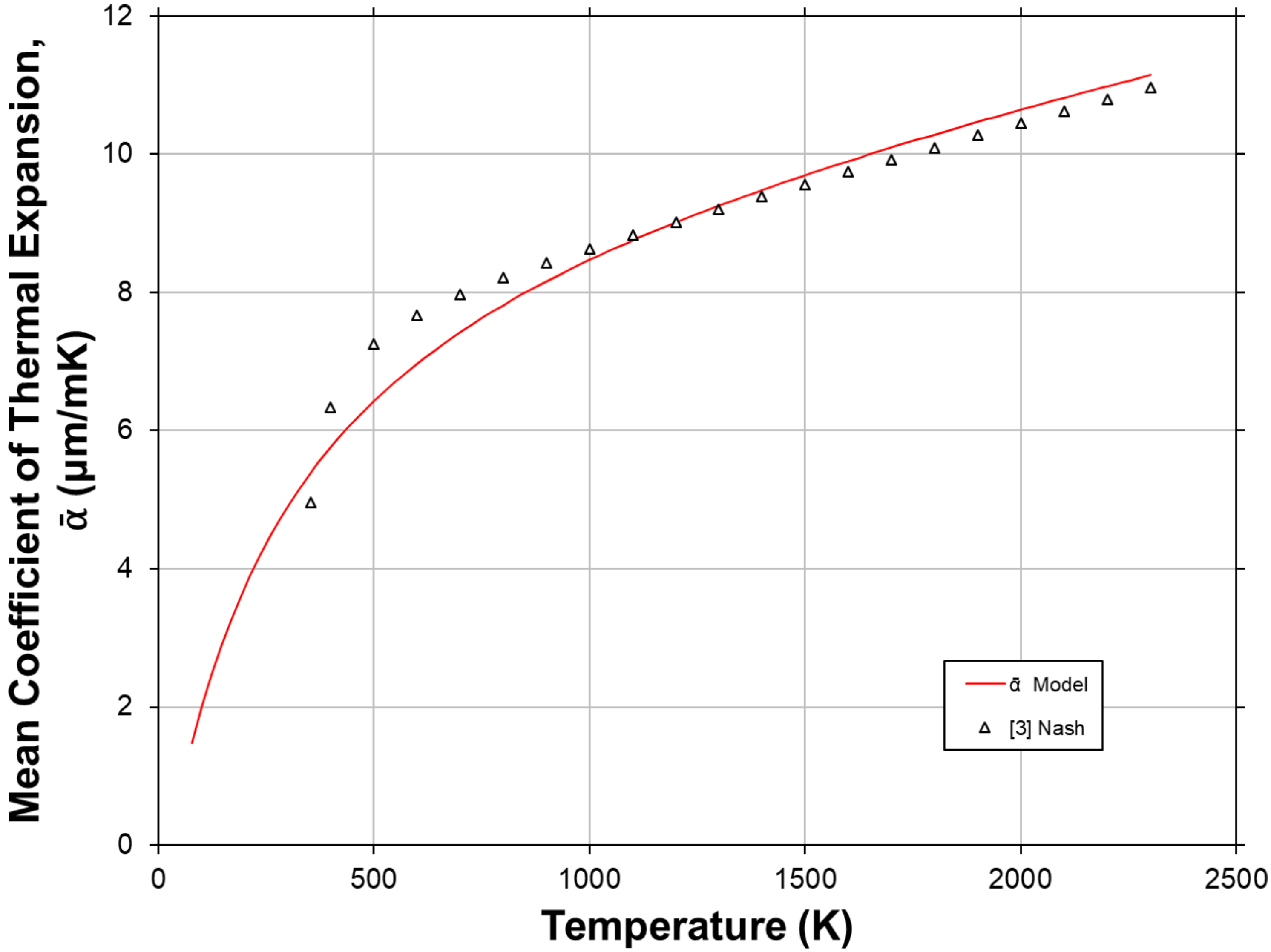

Figure 7.1.1-4: Mean Coefficient of Thermal Expansion versus Temperature of Beryllia calculated trend with comparison to Nash (2005).

100% Theoretical Density

Temperature (T)		Mean CTE (ᾱ)		Temperature (T)		Mean CTE (ᾱ)	
K	(°F)	μm/(m-K)	(μin/(in-°F))	K	(°F)	μm/(m-K)	(μin/(in-°F))
79	(-317.5)	1.484	(0.825)	900	(1160.3)	8.161	(4.534)
100	(-279.7)	1.970	(1.094)	1000	(1340.3)	8.471	(4.706)
150	(-189.7)	2.940	(1.634)	1100	(1520.3)	8.752	(4.862)
200	(-99.7)	3.718	(2.065)	1200	(1700.3)	9.012	(5.007)
250	(-9.7)	4.357	(2.421)	1300	(1880.3)	9.254	(5.141)
300	(80.3)	4.895	(2.719)	1400	(2060.3)	9.481	(5.267)
350	(170.3)	5.356	(2.975)	1500	(2240.3)	9.696	(5.387)
400	(260.3)	5.756	(3.198)	1600	(2420.3)	9.900	(5.500)
450	(350.3)	6.110	(3.394)	1700	(2600.3)	10.096	(5.609)
500	(440.3)	6.425	(3.570)	1800	(2780.3)	10.284	(5.714)
550	(530.3)	6.709	(3.727)	1900	(2960.3)	10.466	(5.815)
600	(620.3)	6.968	(3.871)	2000	(3140.3)	10.643	(5.913)
650	(710.3)	7.204	(4.002)	2100	(3320.3)	10.814	(6.008)
700	(800.3)	7.423	(4.124)	2200	(3500.3)	10.981	(6.101)
800	(980.3)	7.815	(4.342)	2300	(3680.3)	11.145	(6.191)

Application Notes: Data for mean coefficient of thermal expansion is calculated from thermal expansion trend. Calculated data is fitted with the equation below to approximate property trend with respect to temperature. Trend is compared against data collected from reference [3].

Fit Equation:

$$\bar{\alpha}(T) = \left[A0 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2\right] / \left[A\_0 + \left(\frac{T}{1000}\right)\right]$$

$\bar{\alpha}(T) = Coefficient\ of\ Thermal\ Expansion\ [\mu m/(m \cdot K)]$

$T = Temperature\ [K]$

Constants:

T. Range [K]:	$79 \leq T \leq 2301$
A0 =	-0.2658
A1 =	9.845
A2 =	1.186
A_0 =	0.2709

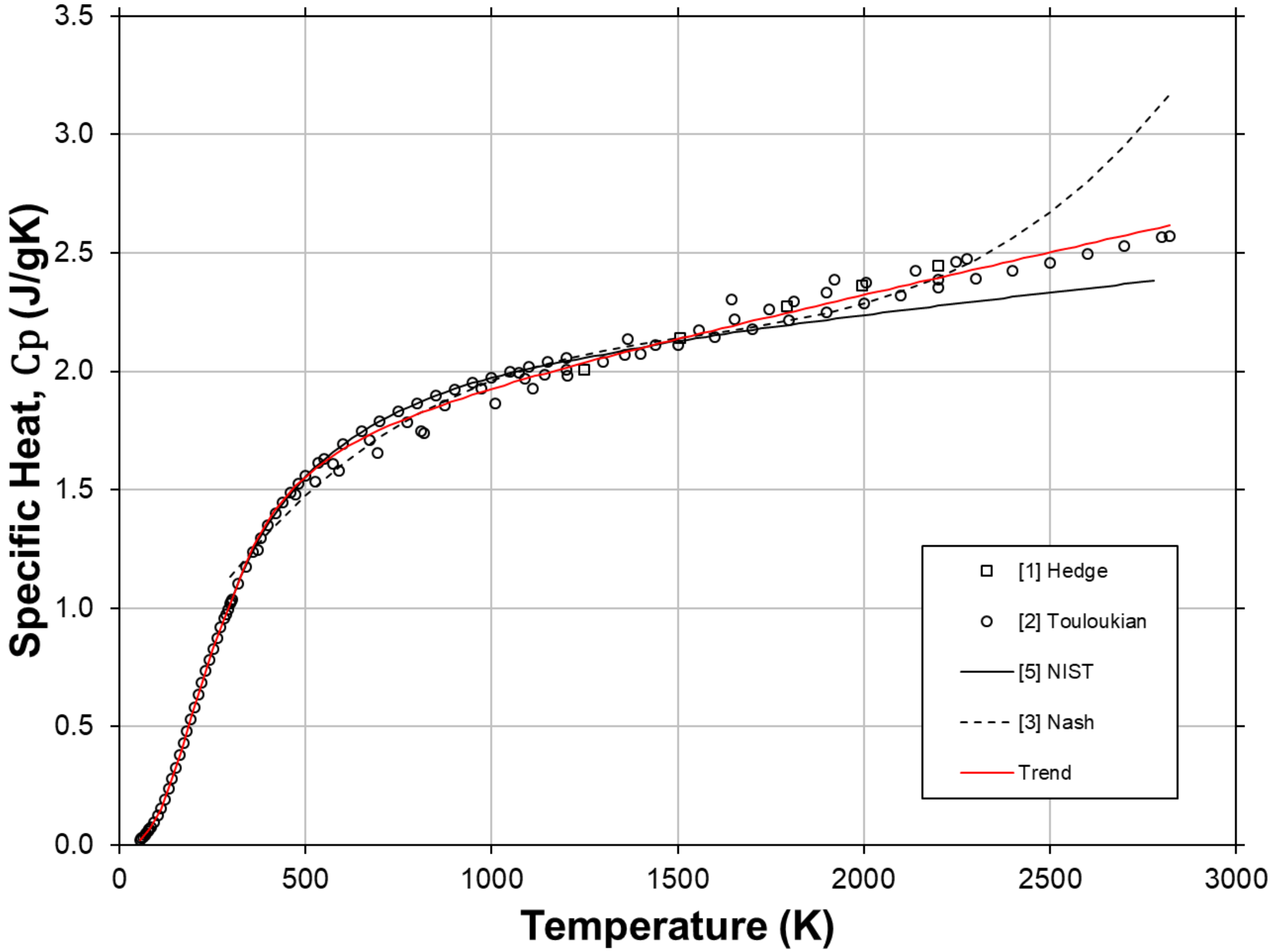

Figure 7.1.1-5: Specific Heat versus Temperature of Beryllia. Displaying fitted trend of the data with comparison to Nash (2005) and the NIST Webbook.

100% Theoretical Density

Temperature (T)		Specific Heat (C_p)		Temperature (T)		Specific Heat (C_p)	
K	(°F)	J/(g-K)	(BTU/(lb-°F))	K	(°F)	J/(g-K)	(BTU/(lb-°F))
55	(-360.7)	0.022	(0.005)	1100	(1520.3)	1.972	(0.471)
100	(-279.7)	0.115	(0.027)	1200	(1700.3)	2.016	(0.482)
150	(-189.7)	0.318	(0.076)	1300	(1880.3)	2.057	(0.492)
200	(-99.7)	0.573	(0.137)	1400	(2060.3)	2.097	(0.501)
250	(-9.7)	0.818	(0.195)	1500	(2240.3)	2.137	(0.511)
300	(80.3)	1.014	(0.242)	1600	(2420.3)	2.175	(0.520)
400	(260.3)	1.371	(0.328)	1700	(2600.3)	2.213	(0.529)
500	(440.3)	1.554	(0.371)	1800	(2780.3)	2.250	(0.538)
600	(620.3)	1.670	(0.399)	2000	(3140.3)	2.323	(0.555)
700	(800.3)	1.753	(0.419)	2200	(3500.3)	2.395	(0.573)
800	(980.3)	1.820	(0.435)	2400	(3860.3)	2.467	(0.590)
900	(1160.3)	1.876	(0.448)	2600	(4220.3)	2.538	(0.607)
1000	(1340.3)	1.926	(0.460)	2820	(4616.3)	2.616	(0.625)

Application Notes: Data for specific heat is collected from references [1, 2] and fitted with the equations below to approximate property trend with respect to temperature. This trend is compared against trends from references [3, 5]

Fit Equation:

For temperature range: $55 \leq T < 293$

$$C_P(T) = \left[A0 \cdot \left(\frac{T}{1000}\right)^N\right] \Big/ \left[1 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2\right]$$

For temperature range: $293 \leq T \leq 2820$

$$C_P(T) = B0 + B1 \cdot \left(\frac{T}{1000}\right) + B\_2 \Big/ \left(\frac{T}{1000}\right)^2$$

$C_P(T) = Specific\ Heat\ [J/(g \cdot K)]$

$T = Temperature\ [K]$

Constants:

T. Range [K]:	$55 \leq T \leq 293$		$293 < T \leq 2820$
N =	2.715	B0 =	1.645
A0 =	47.44	B1 =	0.3473
A1 =	-4.321	B_2 =	-0.06613
A2 =	22.82		

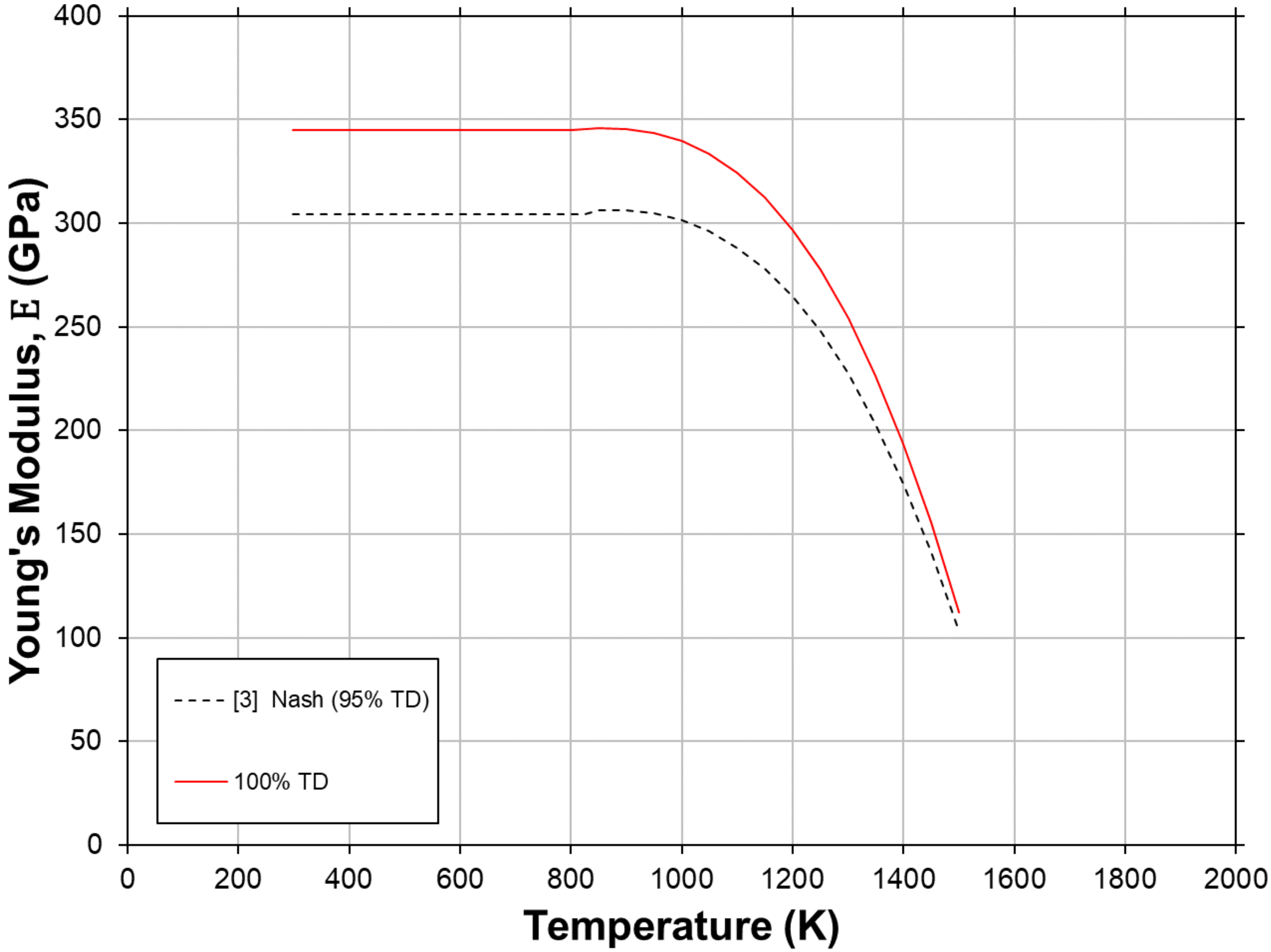

Figure 7.1.1-6: Young's Modulus versus Temperature of Beryllia for 100% from 95% TD as adapted from Nash (2005).

100% Theoretical Density

Temperature (T)		Young's Modulus (E)		Temperature (T)		Young's Modulus (E)	
K	(°F)	GPa	(Msi)	K	(°F)	GPa	(Msi)
298	(76.7)	344.70	(50.02)	800	(980.3)	344.70	(50.02)
300	(80.3)	344.70	(50.02)	850	(1070.3)	345.72	(50.16)
325	(125.3)	344.70	(50.02)	900	(1160.3)	345.40	(50.12)
350	(170.3)	344.70	(50.02)	950	(1250.3)	343.45	(49.83)
375	(215.3)	344.70	(50.02)	1000	(1340.3)	339.53	(49.27)
400	(260.3)	344.70	(50.02)	1050	(1430.3)	333.27	(48.36)
425	(305.3)	344.70	(50.02)	1100	(1520.3)	324.31	(47.06)
450	(350.3)	344.70	(50.02)	1150	(1610.3)	312.29	(45.31)
475	(395.3)	344.70	(50.02)	1200	(1700.3)	296.85	(43.07)
500	(440.3)	344.70	(50.02)	1250	(1790.3)	277.63	(40.28)
550	(530.3)	344.70	(50.02)	1300	(1880.3)	254.27	(36.89)
600	(620.3)	344.70	(50.02)	1350	(1970.3)	226.41	(32.85)
650	(710.3)	344.70	(50.02)	1400	(2060.3)	193.70	(28.11)
700	(800.3)	344.70	(50.02)	1450	(2150.3)	155.76	(22.60)
750	(890.3)	344.70	(50.02)	1500	(2240.3)	112.24	(16.29)

Application Notes: Equations for Young's modulus are taken from reference [3], and shown below to approximate property trend as a function of both temperature and porosity.

Fit Equations:

For temperature range: $298 \leq T \leq 800$

$E(T) = A0 + A1 \cdot P$

For temperature range: $800 < T \leq 1500$

$$E(T) = (A0 + A1 \cdot P) \cdot \left(B0 + B1 \cdot \left(\frac{T}{1000}\right) + B2 \cdot \left(\frac{T}{1000}\right)^2 + B3 \cdot \left(\frac{T}{1000}\right)^3\right)$$

$E(T) = Young's\ Modulus\ [GPa]$

$T = Temperature\ [K]$

$P = Frantional\ Porosity, 0 < P < 0.30$

Constants:

T. Range [K]:	$298 \leq T \leq 800$		$800 < T \leq 1500$
A0 =	344.7	B0 =	1.313
A1 =	-805.7	B1 =	-1.757
		B2 =	2.822
		B3 =	-1.393

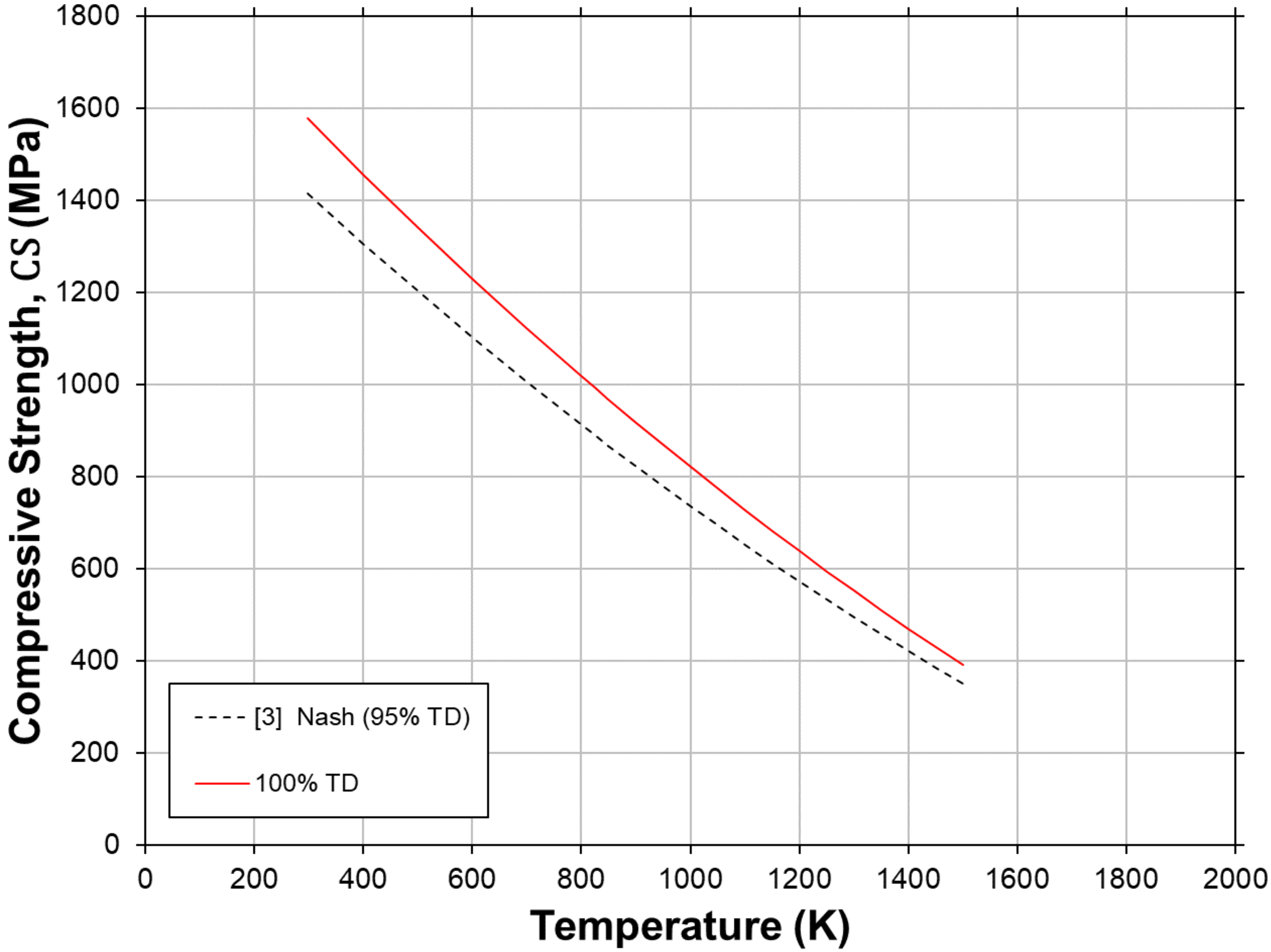

Figure 7.1.1-7: Compressive Strength versus Temperature of Beryllia, 100% TD and 95% TD as adapted from Nash (2005).

100% Theoretical Density

Temperature (T)		Compressive Strength (CS)		Temperature (T)		Compressive Strength (CS)	
K	(°F)	MPa	(Ksi)	K	(°F)	MPa	(Ksi)
298	(76.7)	1577.52	(228.90)	800	(980.3)	1018.15	(147.73)
300	(80.3)	1575.11	(228.55)	850	(1070.3)	967.44	(140.37)
325	(125.3)	1545.11	(224.20)	900	(1160.3)	917.62	(133.15)
350	(170.3)	1515.34	(219.88)	950	(1250.3)	868.72	(126.05)
375	(215.3)	1485.79	(215.59)	1000	(1340.3)	820.71	(119.09)
400	(260.3)	1456.48	(211.33)	1050	(1430.3)	773.62	(112.25)
425	(305.3)	1427.38	(207.11)	1100	(1520.3)	727.42	(105.55)
450	(350.3)	1398.52	(202.92)	1150	(1610.3)	682.14	(98.98)
475	(395.3)	1369.88	(198.77)	1200	(1700.3)	637.75	(92.54)
500	(440.3)	1341.46	(194.65)	1250	(1790.3)	594.28	(86.23)
550	(530.3)	1285.32	(186.50)	1300	(1880.3)	551.70	(80.05)
600	(620.3)	1230.07	(178.48)	1350	(1970.3)	510.04	(74.01)
650	(710.3)	1175.74	(170.60)	1400	(2060.3)	469.27	(68.09)
700	(800.3)	1122.30	(162.85)	1450	(2150.3)	429.42	(62.31)
750	(890.3)	1069.78	(155.22)	1500	(2240.3)	390.46	(56.66)

Application Notes: Equations for compressive strength are taken from reference [3], and shown below to approximate property trend as a function of both temperature and porosity.

Fit Equations:

$$CS(T) = (A0 + A1 \cdot P) \cdot \left(B0 + B1 \cdot \left(\frac{T}{1000}\right) + B2 \cdot \left(\frac{T}{1000}\right)^2\right)$$

$CS(T) = Compressive\ Strength\ [MPa]$

$T = Temperature\ [K]$

$P = Frantional\ Porosity, 0 < P < 0.30$

Constants:

T Range [K]: $298 \leq T \leq 1500$

A0 =	1585	B0 =	1.232
A1 =	-3273	B1 =	-0.8284
		B2 =	0.1142

Temp. (T) K	Physical and Electrical		Thermal				Elastic		
	Density (ρ) kg/m³	Electrical Resistivity (ρ_e) μΩ-m	Thermal Conductivity (k) W/(m-K)	Thermal Expansion (dL/L_0) %	Mean CTE ($\bar{\alpha}$) 10^{-6}/K	Specific Heat (C_p) J/(g-K)	Young's Modulus (E) GPa	Shear Modulus (G) GPa	Poisson's Ratio (ν)
100	3014		-	-0.042	1.97	0.115	-		
200	3013		421.93	-0.031	3.72	0.573	-		
250	3012		336.46	-0.018	4.36	0.818	-		
300	3009		273.13	0.006	4.89	1.014	344.70		
350	3007		225.36	0.036	5.36	1.227	344.70		
400	3004		188.67	0.069	5.76	1.371	344.70		
500	2997		137.24	0.139	6.43	1.554	344.70		
600	2991		103.96	0.216	6.97	1.670	344.70		
700	2983		81.32	0.301	7.42	1.753	344.70		
800	2975		65.27	0.392	7.82	1.820	344.70		
900	2966		53.51	0.489	8.16	1.876	345.40		
1000	2957		44.64	0.591	8.47	1.926	339.53		
1100	2948		37.80	0.699	8.75	1.972	324.31		
1200	2938		32.41	0.811	9.01	2.016	296.85		
1300	2928		28.10	0.927	9.25	2.057	254.27		
1400	2917		24.59	1.047	9.48	2.097	193.70		
1500	2907		21.69	1.171	9.70	2.137	112.24		
1600	2896		19.28	1.297	9.90	2.175	-		
1700	2885		17.25	1.426	10.10	2.213	-		
1800	2874		15.53	1.556	10.28	2.250	-		
1900	2863		14.05	1.688	10.47	2.287	-		
2000	2851		12.77	1.821	10.64	2.323	-		
2100	2840		11.66	1.955	10.81	2.359	-		
2200	2829		10.69	2.089	10.98	2.395	-		
2300	2818		9.84	2.222	11.14	2.431	-		

[1] J.C. Hedge, C. Kostenko, J.I. Lang, Thermal Properties of Refractory Alloys, IIT Research Institute, Chicago, IL, 1963.

[2] Y.S. Touloukian, E.H. Buyco, Specific Heat - Nonmetallic Solids, Thermophysical Properties of Matter - the TPRC Data Series, Thermophysical and Electronic Properties Information Analysis Center, Lafayette, IN, 1970.

[3] J. Nash, Reflector and Shield Material Properties for Project Prometheus, Knolls Atomic Power Laboratory (KAPL), Niskayuna, NY, 2005.

[4] Y.S. Touloukian, R.K. Kirby, E.R. Taylor, T.Y.R. Lee, Thermal Expansion - Nonmetallic Solids, Thermophysical Properties of Matter - the TPRC Data Series, Volume 13, Thermophysical and Electronic Properties Information Analysis Center, Lafayette, IN, 1977.

[5] NIST Webbook. https://webbook.nist.gov (Accessed July 2019).

7 Refractory Ceramics

7.1 Oxides

Room Temperature Properties

Theoretical Density, [kg/m^3]	6014
Melting Point, [K]	2823 to 2973
Specific Heat, [J/(g-K)]	0.465
Thermal Conductivity, [W/(m-K)]	1.9
Linear expansion coefficient, [µm/(m-K)]	6.85
Young's Modulus, [GPa]	226.1
Shear Modulus, [GPa]	86.4
Poisson's Ratio, [-]	0.308

Zirconia - Yttria Phase Diagram

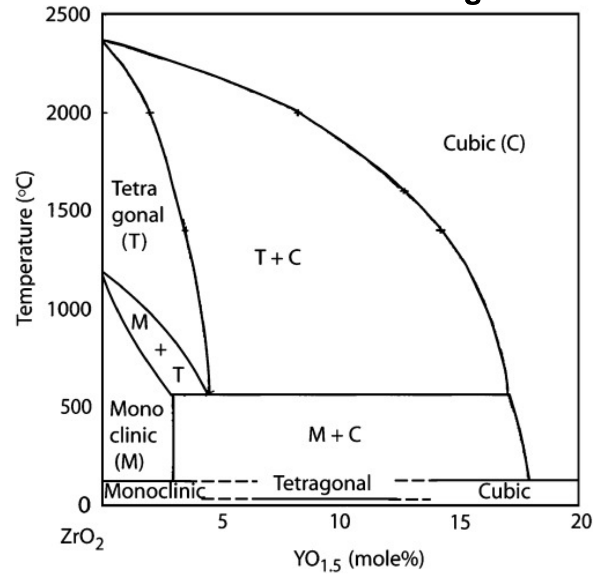

Figure 7.1.2-1: Zicronia - Yttria Phase Diagram [1]

Composition

Table 7.1.2-1: Typical Composition ranges for yttria stabilized zirconia (percent by weight).

Grade		ZrO2	Y2O3	Other
YSZ	Low Yttria Content	97	3	-
	High Yttria Content	90	10	1

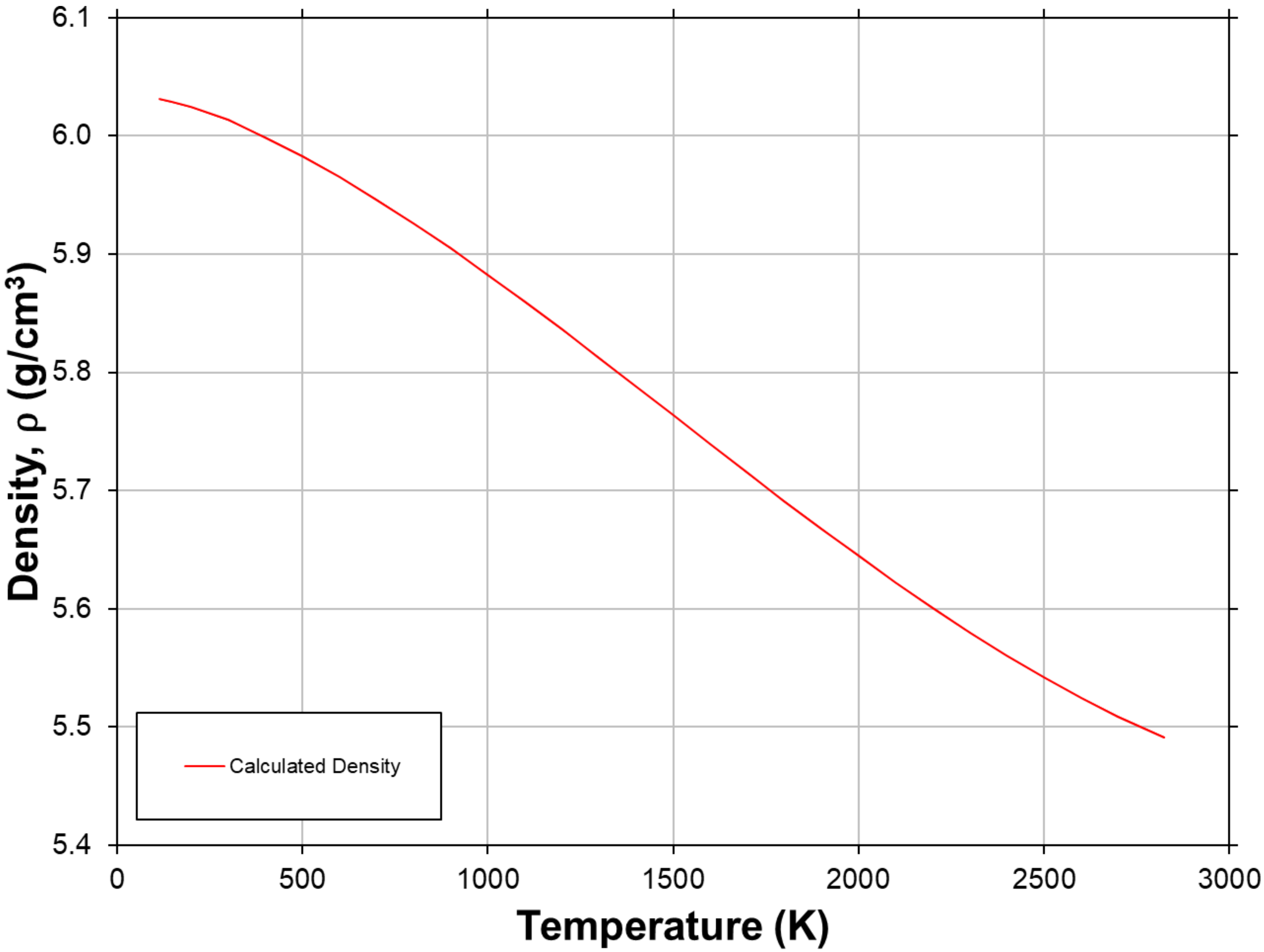

Figure 7.1.2-2: Density versus Temperature for YSZ. Calculated from fitted trend of the Thermal Expansion data.

100% Theoretical Density

Temperature (T)		Density (ρ)		Temperature (T)		Density (ρ)	
K	(°F)	kg/m³	(lb/ft³)	K	(°F)	kg/m³	(lb/ft³)
115	(-252.7)	6031	(376.5)	1600	(2420.3)	5739	(358.3)
200	(-99.7)	6024	(376.1)	1700	(2600.3)	5715	(356.8)
300	(80.3)	6013	(375.4)	1800	(2780.3)	5691	(355.3)
400	(260.3)	5999	(374.5)	1900	(2960.3)	5668	(353.8)
500	(440.3)	5983	(373.5)	2000	(3140.3)	5645	(352.4)
600	(620.3)	5965	(372.4)	2100	(3320.3)	5622	(351.0)
700	(800.3)	5946	(371.2)	2200	(3500.3)	5601	(349.7)
800	(980.3)	5926	(370.0)	2300	(3680.3)	5580	(348.4)
900	(1160.3)	5905	(368.6)	2400	(3860.3)	5560	(347.1)
1000	(1340.3)	5883	(367.3)	2500	(4040.3)	5542	(346.0)
1100	(1520.3)	5860	(365.8)	2600	(4220.3)	5525	(344.9)
1200	(1700.3)	5836	(364.4)	2700	(4400.3)	5509	(343.9)
1300	(1880.3)	5812	(362.9)	2800	(4580.3)	5495	(343.0)
1400	(2060.3)	5788	(361.4)	2824	(4623.5)	5491	(342.8)
1500	(2240.3)	5764	(359.8)				

Application Notes: Density trend is calculated as a function of thermal expansion as seen in the equation below to approximate property trend with respect to temperature.

Density Calculation:

$\rho(T) = \rho_{RT}/(1 + dL/L_0(T)/100)^3$

$\rho(T) = Density\ [kg/m^3]$

$Room\ Temperature\ Density\ (\rho_{RT}) = 6014\ [kg/m^3]$

$T = Temperature\ [K]$

Temperature Range: $115 \leq T \leq 2824$

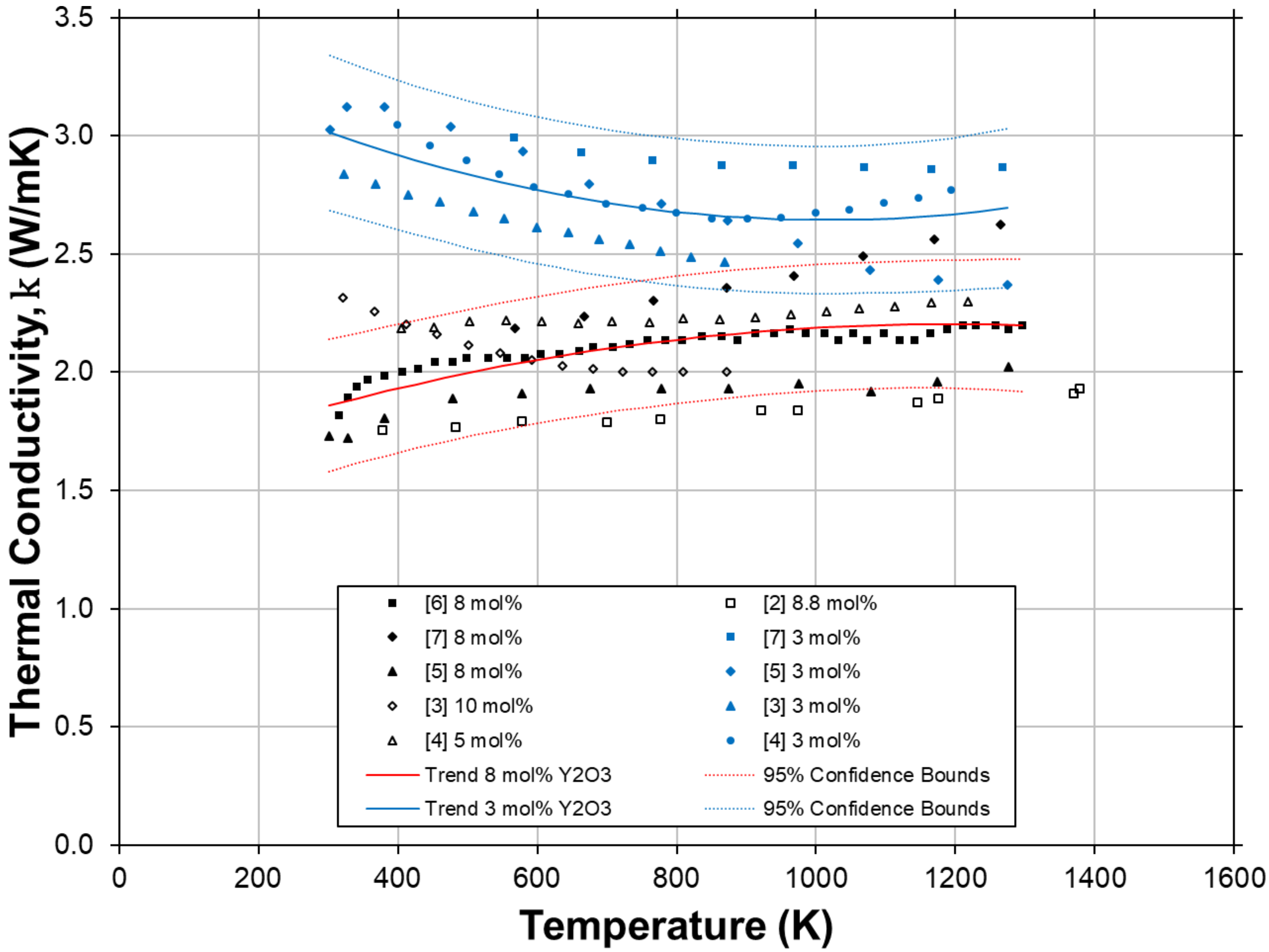

Figure 7.1.2-3: Thermal Conductivity versus Temperature of YSZ. Fitted trends of the data with 95% confidence bounds for 8 mol% and 3 mol% of Y_2O_3.

100% Theoretical Density

Temperature (T)		Thermal Conductivity (k)		Temperature (T)		Thermal Conductivity (k)	
K	(°F)	W/(m-K)	((Btu-in.)/(ft.^{2}-hr-°F))	K	(°F)	W/(m-K)	((Btu-in.)/(ft.^{2}-hr-°F))
300	(80.3)	1.86	(12.89)	650	(710.3)	2.08	(14.41)
325	(125.3)	1.88	(13.03)	700	(800.3)	2.10	(14.56)
350	(170.3)	1.90	(13.16)	750	(890.3)	2.12	(14.71)
375	(215.3)	1.91	(13.28)	800	(980.3)	2.14	(14.83)
400	(260.3)	1.93	(13.40)	850	(1070.3)	2.15	(14.94)
425	(305.3)	1.95	(13.52)	900	(1160.3)	2.17	(15.04)
450	(350.3)	1.97	(13.63)	950	(1250.3)	2.18	(15.12)
475	(395.3)	1.98	(13.74)	1000	(1340.3)	2.19	(15.18)
500	(440.3)	2.00	(13.85)	1050	(1430.3)	2.20	(15.23)
525	(485.3)	2.01	(13.95)	1100	(1520.3)	2.20	(15.27)
550	(530.3)	2.03	(14.05)	1150	(1610.3)	2.20	(15.29)
575	(575.3)	2.04	(14.15)	1200	(1700.3)	2.20	(15.29)
600	(620.3)	2.05	(14.24)	1250	(1790.3)	2.20	(15.28)
625	(665.3)	2.06	(14.33)	1297	(1874.9)	2.20	(15.26)

Application Notes: Data for thermal conductivity was collected from references [2-7] and fitted with equation (7.1.2-2) to approximate the property trend with respect to temperature for 3 mol% and 8 mol% Y_2O_3 added to Zirconia. Data in table is trend for 8 mol% Y_2O_3.

Fit Equation:

$$k(T) = A0 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2$$

$k(T) = Thermal\ Conductivity\ [W / (m \cdot K)]$

$T = Temperature\ [K]$

Constants:

Y_2O_3 mol%:	3 mol%	8 mol%
Temperature Range [K]:	$300 \leq T \leq 1297$	$300 \leq T \leq 1297$
A0 =	3.395	1.586
A1 =	-1.481	1.039
A2 =	0.7307	-0.4368

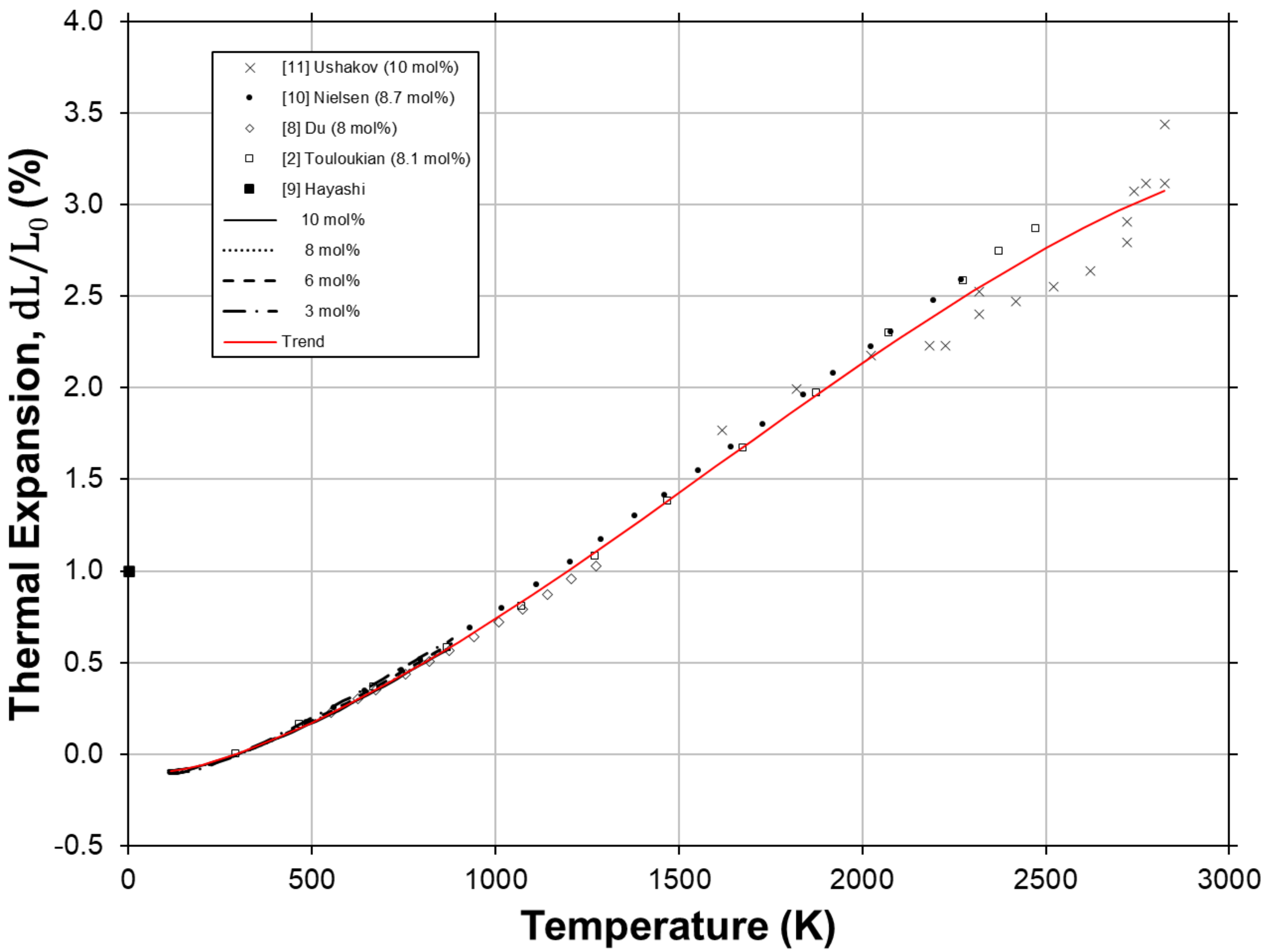

Figure 7.1.2-4: Thermal Expansion versus Temperature of YSZ.

100% Theoretical Density

Temperature (T) K	(°F)	Thermal Expansion (dL/L_0) %	Temperature (T) K	(°F)	Thermal Expansion (dL/L_0) %
115	(-252.7)	-0.093	1600	(2420.3)	1.570
200	(-99.7)	-0.058	1700	(2600.3)	1.713
300	(80.3)	0.004	1800	(2780.3)	1.856
400	(260.3)	0.083	1900	(2960.3)	1.997
500	(440.3)	0.173	2000	(3140.3)	2.135
600	(620.3)	0.271	2100	(3320.3)	2.270
700	(800.3)	0.378	2200	(3500.3)	2.401
800	(980.3)	0.492	2300	(3680.3)	2.528
900	(1160.3)	0.613	2400	(3860.3)	2.648
1000	(1340.3)	0.739	2500	(4040.3)	2.762
1100	(1520.3)	0.870	2600	(4220.3)	2.869
1200	(1700.3)	1.005	2700	(4400.3)	2.967
1300	(1880.3)	1.143	2800	(4580.3)	3.057
1400	(2060.3)	1.284	2824	(4623.5)	3.077
1500	(2240.3)	1.427			

Application Notes: Data for thermal expansion is collected from references [2, 8-11] and fitted with the equation below to approximate property trend with respect to temperature. The thermal expansion fit is valid between 8 and 10 mol% yttria.

Fit Equation:

$$dL/L_0\,(T) = A0 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2 + A3 \cdot \left(\frac{T}{1000}\right)^3$$

$dL/L_0\,(T) = Thermal\ Expansion, Percent$ [%]

$T = Temperature$ [K]

Constants:

Temperature Range [K]:	$115 \leq T \leq 293$	$293 < T \leq 2824$
A0 =	-0.1168	-0.1689
A1 =	0.08241	0.392
A2 =	1.056	0.6514
A3 =	0	-0.1357

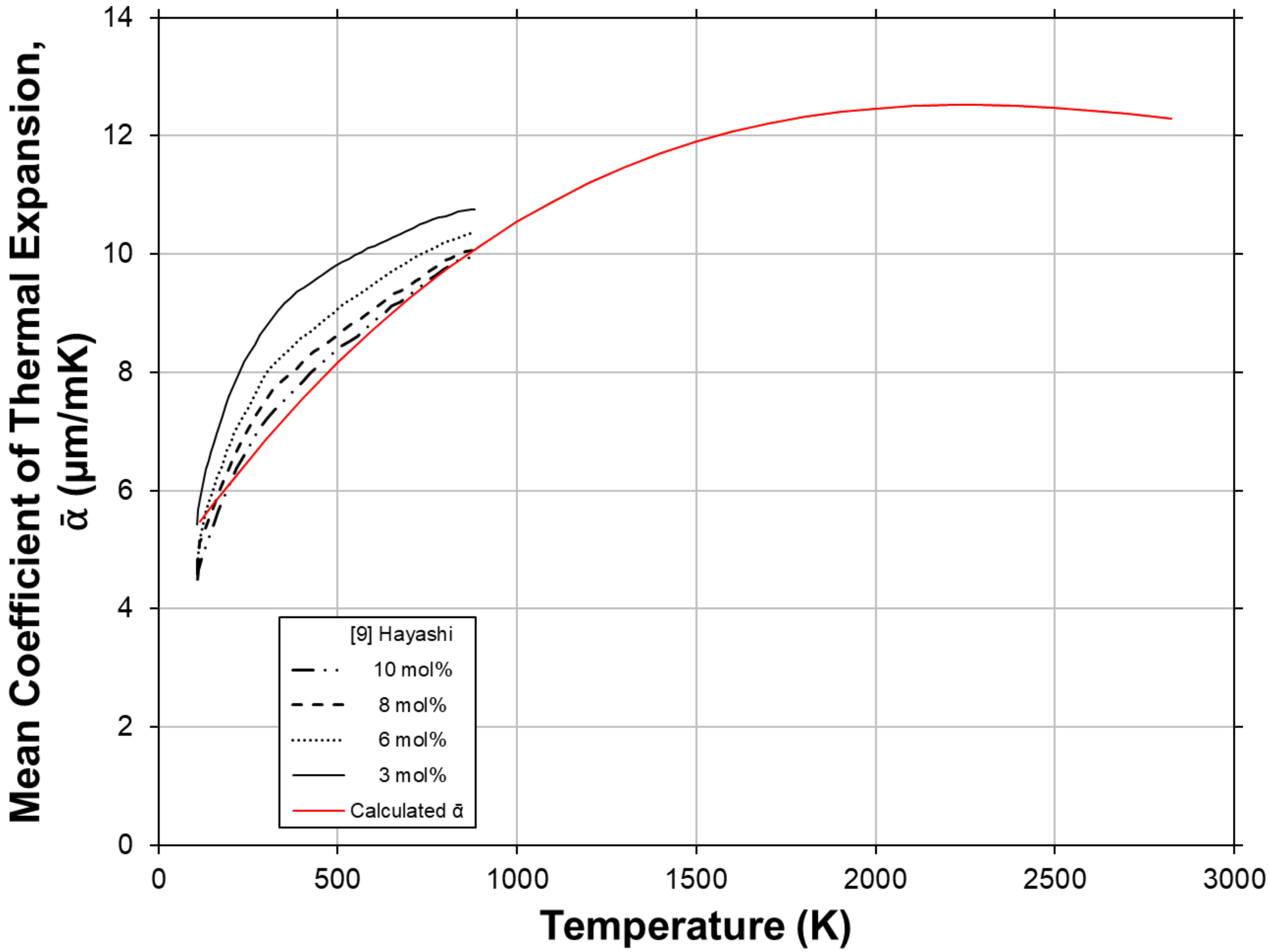

Figure 7.1.2-5: Mean Coefficient of Thermal Expansion verse Temperature of YSZ. Calculated from fitted trend of the Thermal Expansion data with comparison to Hayashi (2005).

100% Theoretical Density

Temperature (T)		Mean CTE (ᾱ)		Temperature (T)		Mean CTE (ᾱ)	
K	(°F)	μm/(m-K)	(μin/(in-°F))	K	(°F)	μm/(m-K)	(μin/(in-°F))
115	(-252.7)	5.470	(3.039)	1600	(2420.3)	12.071	(6.706)
200	(-99.7)	6.135	(3.408)	1700	(2600.3)	12.209	(6.783)
300	(80.3)	6.865	(3.814)	1800	(2780.3)	12.320	(6.844)
400	(260.3)	7.540	(4.189)	1900	(2960.3)	12.404	(6.891)
500	(440.3)	8.163	(4.535)	2000	(3140.3)	12.465	(6.925)
600	(620.3)	8.734	(4.852)	2100	(3320.3)	12.503	(6.946)
700	(800.3)	9.256	(5.142)	2200	(3500.3)	12.521	(6.956)
800	(980.3)	9.732	(5.407)	2300	(3680.3)	12.521	(6.956)
900	(1160.3)	10.162	(5.646)	2400	(3860.3)	12.504	(6.947)
1000	(1340.3)	10.549	(5.861)	2500	(4040.3)	12.474	(6.930)
1100	(1520.3)	10.895	(6.053)	2600	(4220.3)	12.430	(6.906)
1200	(1700.3)	11.201	(6.223)	2700	(4400.3)	12.376	(6.876)
1300	(1880.3)	11.470	(6.372)	2800	(4580.3)	12.314	(6.841)
1400	(2060.3)	11.703	(6.502)	2824	(4623.5)	12.298	(6.832)
1500	(2240.3)	11.903	(6.613)				

Application Notes: Data for mean coefficient of thermal expansion is calculated as a function of thermal expansion. This calculated data is then fitted with the equation below to approximate property trend with respect to temperature and compared to data from reference [9]. The coefficient of thermal expansion fit is valid between 8 and 10 mol% yttria.

Fit Equation:

$$\bar{\alpha}(T) = A0 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2 + A3 \cdot \left(\frac{T}{1000}\right)^3$$

$\bar{\alpha}(T) = Coefficient\ of\ Thermal\ Expansion\ [\mu m/(m \cdot K)]$

$T = Temperature\ [K]$

Constants:

Temp. Range [K]: $115 \leq T \leq 2824$

A0 = 4.503
A1 = 8.752
A2 = -3.026
A3 = 0.3202

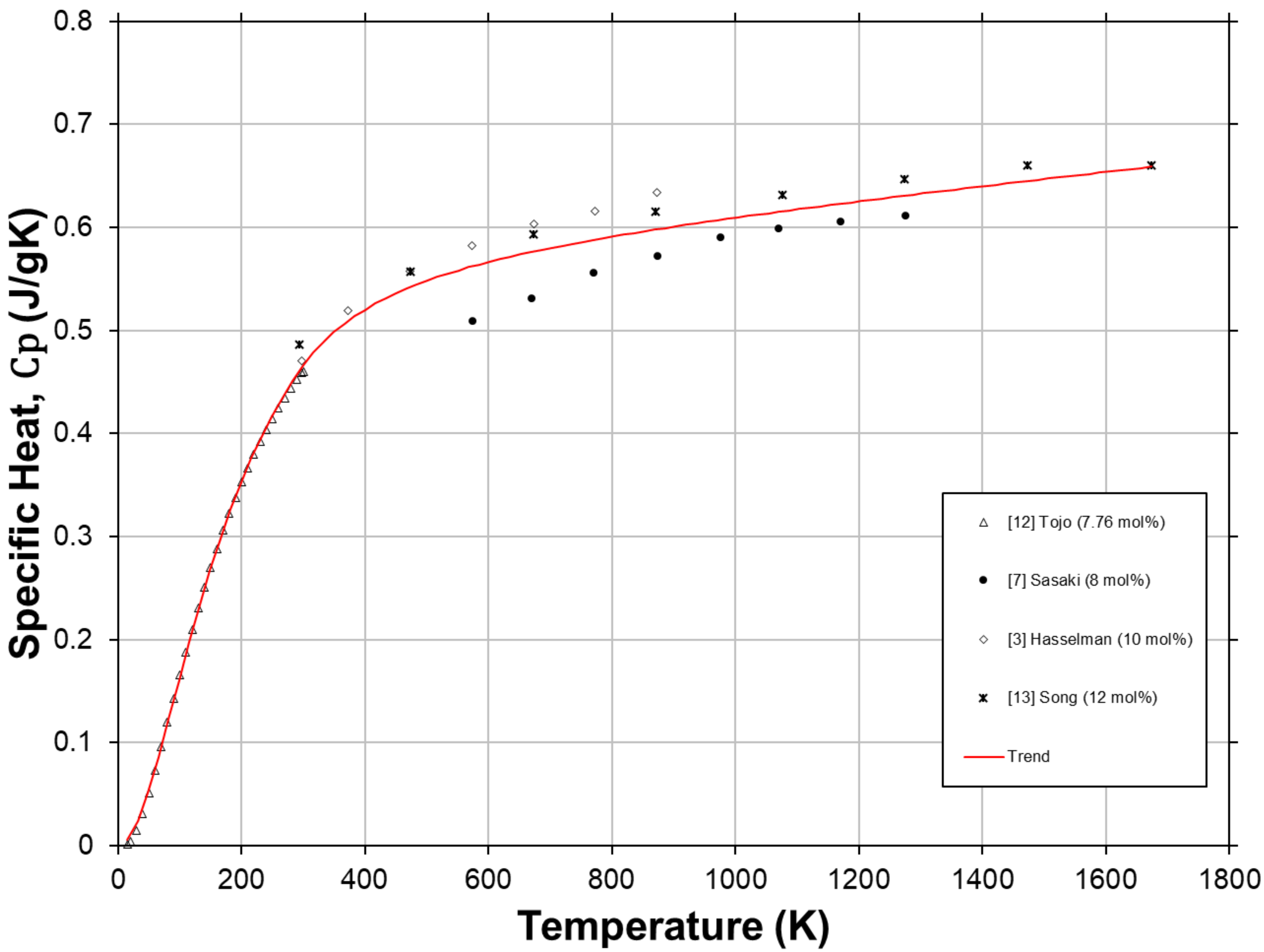

Figure 7.1.2-6: Specific Heat versus Temperature of YSZ.

100% Theoretical Density

Temperature (T)		Specific Heat (C_p)		Temperature (T)		Specific Heat (C_p)	
K	(°F)	J/(g-K)	(BTU/(lb-°F))	K	(°F)	J/(g-K)	(BTU/(lb-°F))
50	(-369.7)	0.055	(0.013)	750	(890.3)	0.586	(0.140)
100	(-279.7)	0.164	(0.039)	800	(980.3)	0.591	(0.141)
150	(-189.7)	0.269	(0.064)	850	(1070.3)	0.596	(0.142)
200	(-99.7)	0.354	(0.085)	900	(1160.3)	0.601	(0.144)
250	(-9.7)	0.418	(0.100)	950	(1250.3)	0.605	(0.145)
300	(80.3)	0.467	(0.112)	1000	(1340.3)	0.609	(0.146)
350	(170.3)	0.498	(0.119)	1050	(1430.3)	0.614	(0.147)
400	(260.3)	0.520	(0.124)	1100	(1520.3)	0.618	(0.148)
450	(350.3)	0.536	(0.128)	1200	(1700.3)	0.625	(0.149)
500	(440.3)	0.548	(0.131)	1300	(1880.3)	0.633	(0.151)
550	(530.3)	0.558	(0.133)	1400	(2060.3)	0.640	(0.153)
600	(620.3)	0.567	(0.135)	1500	(2240.3)	0.647	(0.155)
650	(710.3)	0.574	(0.137)	1600	(2420.3)	0.654	(0.156)
700	(800.3)	0.580	(0.139)	1674	(2553.5)	0.659	(0.158)

Application Notes: Data for specific heat is collected from references [3, 7, 12, 13] and fitted with the equations below to approximate property trend with respect to temperature. The specific heat fit is valid between 8 and 12 mol% yttria.

Fit Equation:

For temperature range: $15 \leq T < 293$

$$C_P(T) = \left[A0 \cdot \left(\frac{T}{1000}\right)^2\right] \Big/ \left[1 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2\right]$$

For temperature range: $293 \leq T \leq 1674$

$$C_P(T) = B0 + B1 \cdot \left(\frac{T}{1000}\right) + B\_2 / \left(\frac{T}{1000}\right)^2$$

$C_P(T) = Specific\ Heat\ [J/(g \cdot K)]$

$T = Temperature\ [K]$

Constants:

T. Range [K]:	$55 \leq T \leq 293$		$293 < T \leq 1674$
A0 =	27.02	B0 =	0.5549
A1 =	2.726	B1 =	0.06425
A2 =	37.79	B_2 =	-0.009664

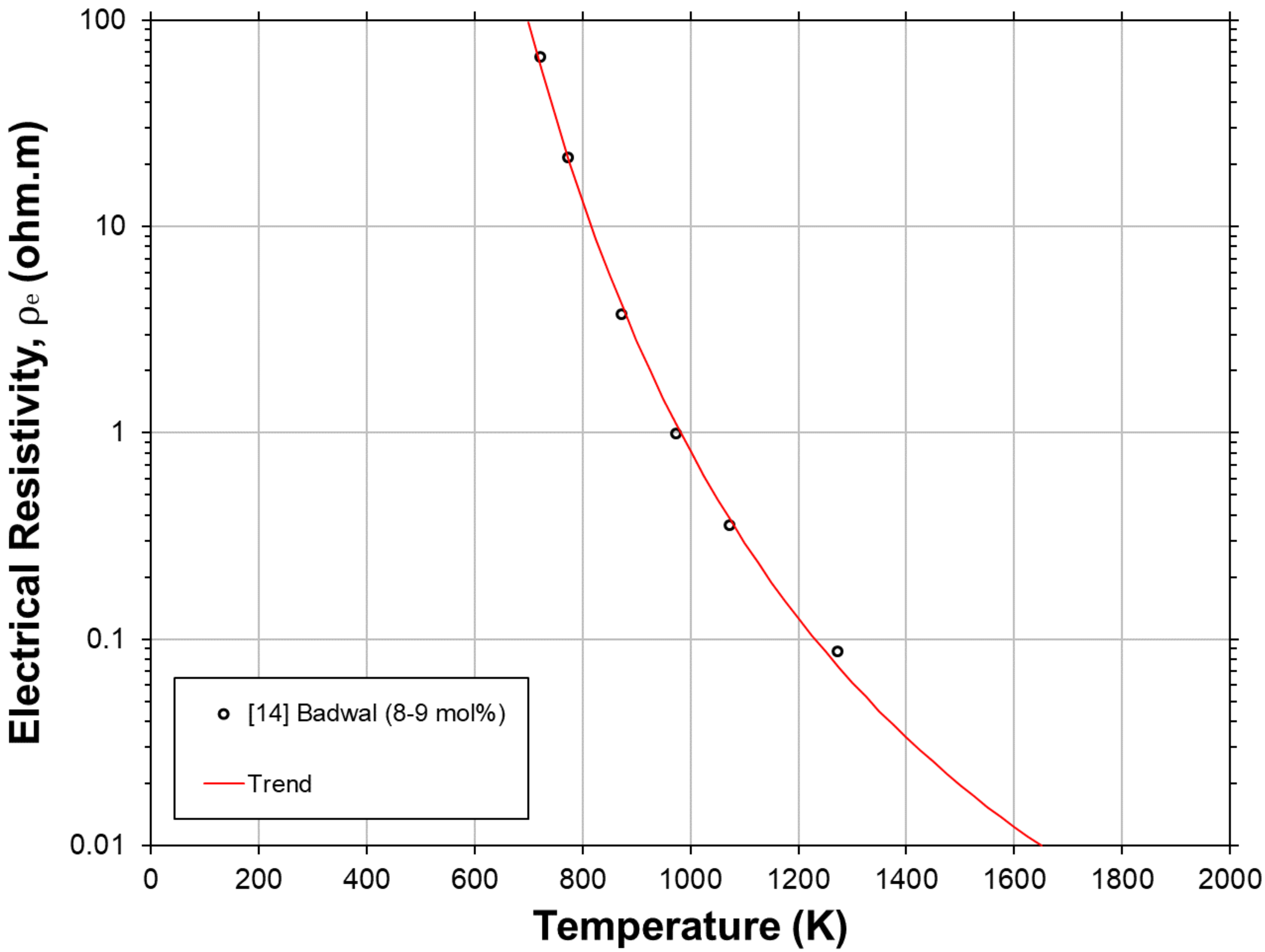

Figure 7.1.2-7: Electrical Resistivity versus Temperature of YSZ.

100% Theoretical Density

Temperature (T)		Electrical Resistivity (ρe)		Temperature (T)		Electrical Resistivity (ρe)	
K	(°F)	Ω-m	(Ω-in)	K	(°F)	Ω-m	(Ω-in)
700	(800.3)	97.258	(3829.04)	1025	(1385.3)	0.619	(24.35)
725	(845.3)	56.110	(2209.06)	1050	(1430.3)	0.477	(18.79)
750	(890.3)	33.580	(1322.06)	1075	(1475.3)	0.373	(14.67)
775	(935.3)	20.774	(817.86)	1100	(1520.3)	0.294	(11.59)
800	(980.3)	13.243	(521.36)	1125	(1565.3)	0.235	(9.25)
825	(1025.3)	8.675	(341.55)	1150	(1610.3)	0.189	(7.45)
850	(1070.3)	5.827	(229.39)	1175	(1655.3)	0.154	(6.06)
875	(1115.3)	4.003	(157.61)	1200	(1700.3)	0.126	(4.97)
900	(1160.3)	2.808	(110.57)	1225	(1745.3)	0.104	(4.11)
925	(1205.3)	2.008	(79.07)	1250	(1790.3)	0.087	(3.43)
950	(1250.3)	1.462	(57.55)	1273	(1831.7)	0.074	(2.92)
975	(1295.3)	1.081	(42.58)				
1000	(1340.3)	0.812	(31.98)				

Application Notes: Data for electrical resistivity is collected from reference [14] and fitted with the equation below to approximate property trend with respect to temperature.

Fit Equations:

$$\boldsymbol{\rho_e}(T) = \exp\left(A0 + \frac{1000}{T} * A1\right)$$

$\boldsymbol{\rho_e}(T) = Electrical\ Resistivity\ [\Omega \cdot m]$

$T = Temperature\ [K]$

Constants:

Temperature Range [K]:	$700 \leq T \leq 1273$
A0 =	-11.37399
A1 =	11.16595

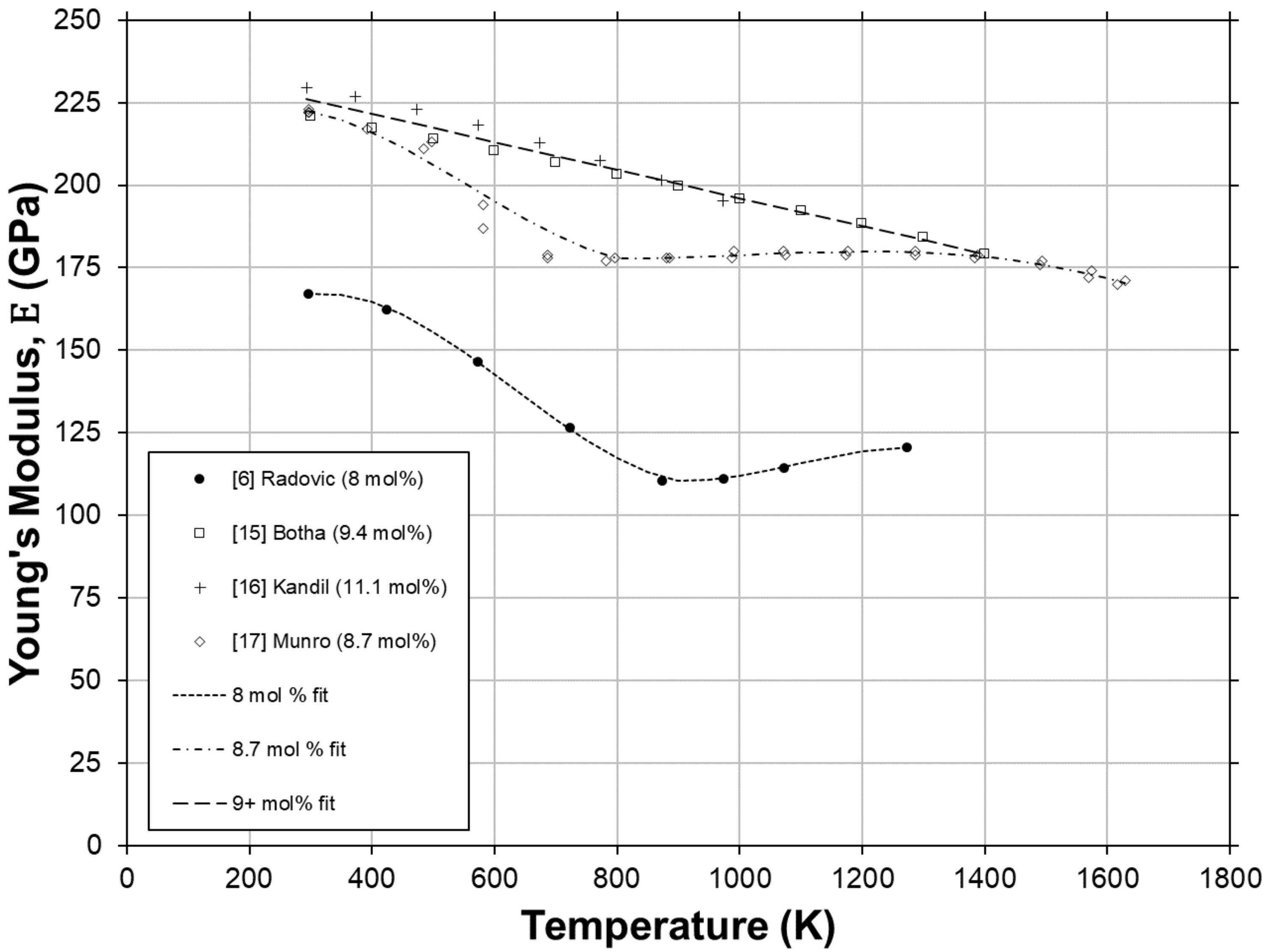

Figure 7.1.2-8: Young's Modulus versus Temperature of YSZ.

100% Theoretical Density

Temperature (T)		Young's Modulus (E)		Temperature (T)		Young's Modulus (E)	
K	(°F)	GPa	(Msi)	K	(°F)	GPa	(Msi)
300	(80.3)	222.30	(32.26)	850	(1070.3)	177.96	(25.82)
350	(170.3)	219.75	(31.89)	900	(1160.3)	178.17	(25.85)
400	(260.3)	216.04	(31.35)	950	(1250.3)	178.47	(25.90)
450	(350.3)	211.44	(30.68)	1000	(1340.3)	178.81	(25.95)
500	(440.3)	206.23	(29.92)	1050	(1430.3)	179.16	(26.00)
550	(530.3)	200.69	(29.12)	1100	(1520.3)	179.47	(26.04)
600	(620.3)	195.11	(28.31)	1150	(1610.3)	179.71	(26.08)
650	(710.3)	189.76	(27.53)	1200	(1700.3)	179.83	(26.09)
700	(800.3)	184.92	(26.83)	1250	(1790.3)	179.79	(26.09)
750	(890.3)	180.88	(26.25)	1300	(1880.3)	179.56	(26.05)
800	(980.3)	177.88	(25.81)				

Application Notes:. Data for Young's modulus is collected from references [6, 15-17] and fitted with the equations below to approximate property trend with respect to temperature. Fitted curves follow the data trends from 8 mol%, 8.7 mol%, and 9-11.1 mol% (noted as 9+ in the figure) yttria in zirconia. Table data represents modulus values for 8.7 mol% Y_2O_3.

Fit Equation:

$$E(T) = A0 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2 + A3 \cdot \left(\frac{T}{1000}\right)^3$$

$E(T) = Young's\ Modulus\ [GPa]$

$T = Temperature\ [K]$

Constants:

Y_2O_3 mol%:	8 mol%	8.7 mol%	9-11.1 mol%
T. Range [K]:	$295 \leq T < 911$	$295 \leq T < 790$	$295 \leq T < 1410$
A0 =	104.5	197.4	238.6
A1 =	441	237.1	-42.5
A2 =	-922.2	-625.7	0
A3 =	488.6	373.6	0
	$911 \leq T < 1300$	$790 \leq T < 1630$	
A0 =	561.4	226.7	-
A1 =	-1299	-156.7	-
A2 =	1220	162.7	-
A3 =	-370.4	-53.89	-

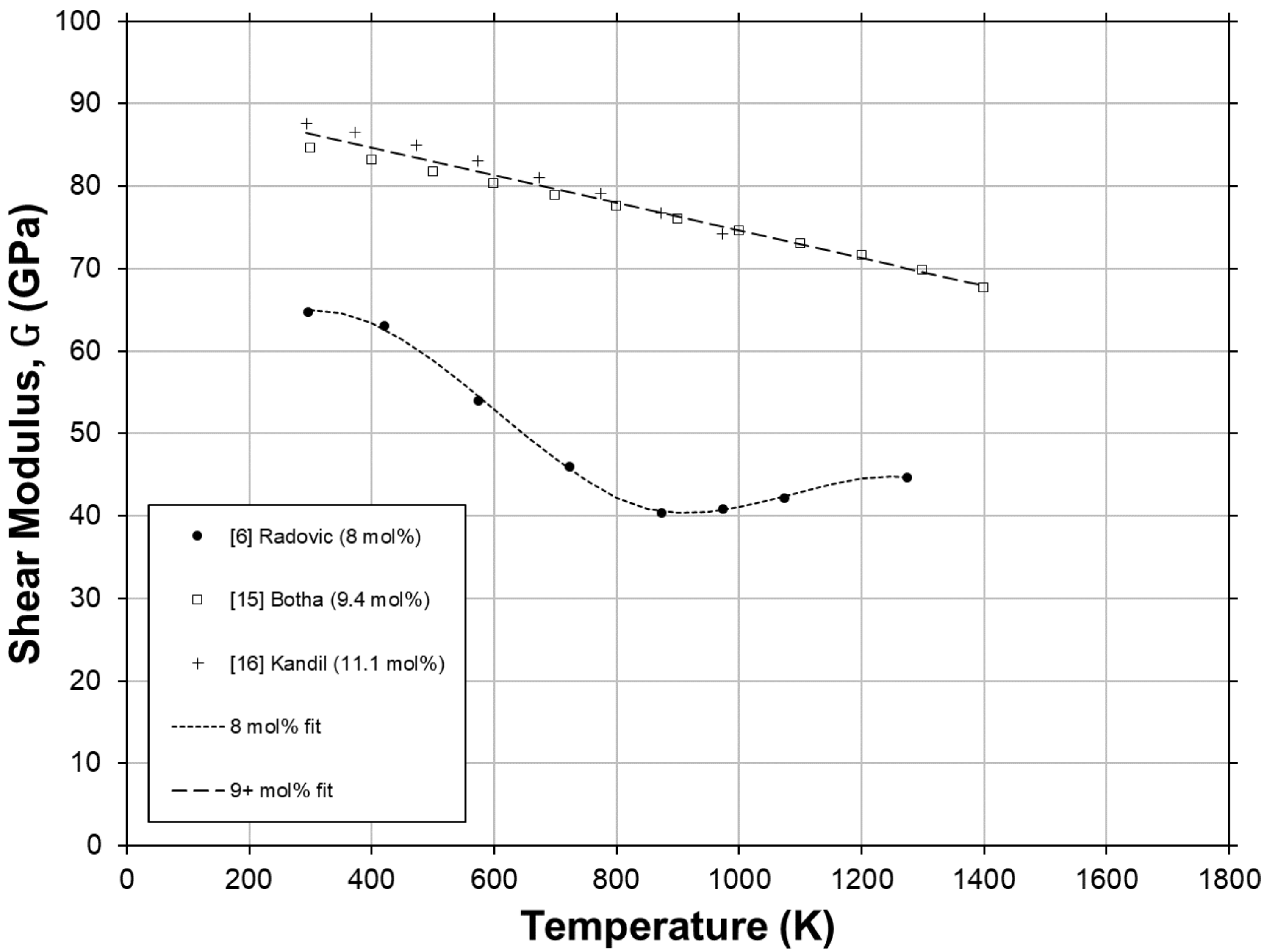

Figure 7.1.2-9: Shear Modulus versus Temperature of YSZ

100% Theoretical Density

Temperature (T)		Shear Modulus (G)		Temperature (T)		Shear Modulus (G)	
K	(°F)	GPa	(Msi)	K	(°F)	GPa	(Msi)
300	(80.3)	64.93	(9.42)	850	(1070.3)	40.80	(5.92)
350	(170.3)	64.61	(9.38)	900	(1160.3)	40.38	(5.86)
400	(260.3)	63.39	(9.20)	950	(1250.3)	40.51	(5.88)
450	(350.3)	61.43	(8.91)	1000	(1340.3)	41.10	(5.96)
500	(440.3)	58.92	(8.55)	1050	(1430.3)	41.97	(6.09)
550	(530.3)	56.03	(8.13)	1100	(1520.3)	42.94	(6.23)
600	(620.3)	52.95	(7.68)	1150	(1610.3)	43.85	(6.36)
650	(710.3)	49.84	(7.23)	1200	(1700.3)	44.53	(6.46)
700	(800.3)	46.90	(6.80)	1250	(1790.3)	44.80	(6.50)
750	(890.3)	44.29	(6.43)	1273	(1831.7)	44.73	(6.49)
800	(980.3)	42.20	(6.12)				

Application Notes: Data for shear modulus is collected from references [6, 15, 16] and fitted with the equations below to approximate property trend with respect to temperature. Fitted curves follow the data trends from 8 mol% and 9-11.1 mol% (noted as 9+ in the figure) yttria in zirconia. Table data represents shear modulus for 8.0 mol% Y_2O_3.

Fit Equations:

$$G(T) = A0 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2 + A3 \cdot \left(\frac{T}{1000}\right)^3$$

$G(T) = Shear\ Modulus\ [GPa]$

$T = Temperature\ [K]$

Constants:

Y_2O_3 mol%:	8 mol%	9-11.1 mol%
T. Range [K]:	$275 \leq T < 870$	$293 \leq T < 1400$
A0 =	37.67	91.43
A1 =	199.1	-16.9
A2 =	-432.2	0.07455
A3 =	238	0
	$870 \leq T < 1273$	
A0 =	311.1	-
A1 =	-784.2	-
A2 =	743.3	-
A3 =	-229.1	-

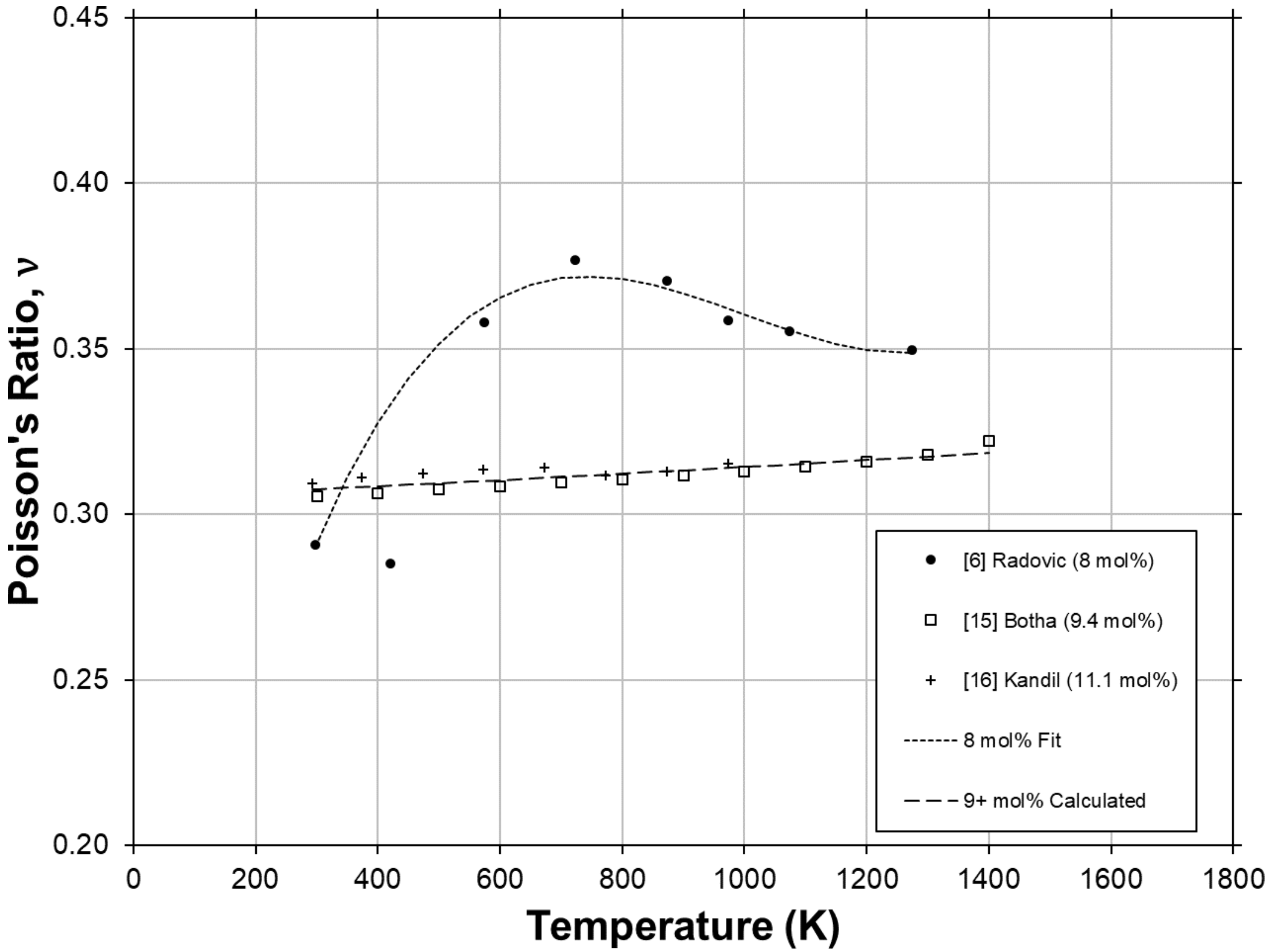

Figure 7.1.2-10: Poisson's Ratio versus Temperature of YSZ.

100% Theoretical Density

Temperature (T) K	(°F)	Poisson's Ratio (ν)	Temperature (T) K	(°F)	Poisson's Ratio (ν)
300	(80.3)	0.291	700	(800.3)	0.371
325	(125.3)	0.302	750	(890.3)	0.372
350	(170.3)	0.311	800	(980.3)	0.371
375	(215.3)	0.320	850	(1070.3)	0.369
400	(260.3)	0.328	900	(1160.3)	0.367
425	(305.3)	0.335	950	(1250.3)	0.364
450	(350.3)	0.341	1000	(1340.3)	0.360
475	(395.3)	0.347	1050	(1430.3)	0.357
500	(440.3)	0.352	1100	(1520.3)	0.354
525	(485.3)	0.356	1150	(1610.3)	0.351
550	(530.3)	0.360	1200	(1700.3)	0.349
575	(575.3)	0.363	1250	(1790.3)	0.349
600	(620.3)	0.365	1273	(1831.7)	0.349
625	(665.3)	0.368			
650	(710.3)	0.369			

Application Notes:. Poisson's Ratio is calculated as a function of Young's modulus and shear modulus – as seen in the equation below – to approximate property trend with respect to temperature. The two curves displayed are calculated from the trends for Young's and Shear moduli at 8 mol% and 9-11.1 mol% (noted as 9+ in the figure) of yttria added to zirconia. Table data represents shear modulus for 8.0 mol% Y_2O_3.

Fit Equations:

$$\nu(T) = E(T)/(2 \cdot G(T)) - 1$$

$\nu(T) = Poisson's\ Ratio$

$T = Temperature\ [K]$

Constants:

T Range [K]: $300 \leq T \leq 1273$

Temp. (T) K	Physical and Electrical: Density (ρ) kg/m^3	Physical and Electrical: Electrical Resistivity (ρ_e) Ω-m	Thermal: Thermal Conductivity 8 mol% (k) W/(m-K)	Thermal: Thermal Expansion (dL/L_0) %	Thermal: Mean CTE ($\bar{\alpha}$) 10^{-6}/K	Thermal: Specific Heat (C_p) J/(g-K)	Elastic: Young's Modulus 9+ mol% (E) GPa	Elastic: Shear Modulus 9+ mol% (G) GPa	Elastic: Poisson's Ratio 9+ mol% (ν)
200	6024	-	-	-0.06	6.13	0.354	-	-	-
300	6013	-	1.86	0.00	6.86	0.467	225.9	86.4	0.308
400	5999	-	1.93	0.08	7.54	0.520	221.6	84.7	0.308
500	5983	-	2.00	0.17	8.16	0.548	217.4	83.0	0.309
600	5965	-	2.05	0.27	8.73	0.567	213.1	81.3	0.310
700	5946	97.3	2.10	0.38	9.26	0.580	208.9	79.6	0.311
800	5926	13.2	2.14	0.49	9.73	0.591	204.6	78.0	0.312
900	5905	2.8	2.17	0.61	10.16	0.601	200.4	76.3	0.313
1000	5883	0.8	2.19	0.74	10.55	0.609	196.1	74.6	0.314
1100	5860	0.3	2.20	0.87	10.89	0.618	191.9	72.9	0.315
1200	5836	0.1	2.20	1.01	11.20	0.625	187.6	71.3	0.316
1300	5812	-	-	1.14	11.47	0.633	183.4	69.6	0.317
1400	5788	-	-	1.28	11.70	0.640	179.1	67.9	0.319
1500	5764	-	-	1.43	11.90	0.647	-	-	-
1600	5739	-	-	1.57	12.07	0.654	-	-	-
1700	5715	-	-	1.71	12.21	-	-	-	-
1800	5691	-	-	1.86	12.32	-	-	-	-
1900	5668	-	-	2.00	12.40	-	-	-	-
2000	5645	-	-	2.14	12.46	-	-	-	-
2100	5622	-	-	2.27	12.50	-	-	-	-
2200	5601	-	-	2.40	12.52	-	-	-	-
2300	5580	-	-	2.53	12.52	-	-	-	-
2400	5560	-	-	2.65	12.50	-	-	-	-
2600	5525	-	-	2.87	12.43	-	-	-	-
2800	5495	-	-	3.06	12.31	-	-	-	-

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7 Refractory Ceramics

7.2 Carbides

Room Temperature Properties

Molar Mass, [g/mol]	55.25
Theoretical Density, [kg/m^3]	2,500
Melting Point, [K]	2723
Boiling Point, [K]	3773
Specific Heat, [J/(g-K)]	0.93
Thermal Conductivity, [W/(m-K)]	28.57
Linear expansion coefficient, [μm/(m-K)]	3.98
Young's Modulus, [GPa]	450.0
Shear Modulus, [GPa]	189.1
Poisson's Ratio, [-]	0.190

Boron – Carbon Phase Diagram

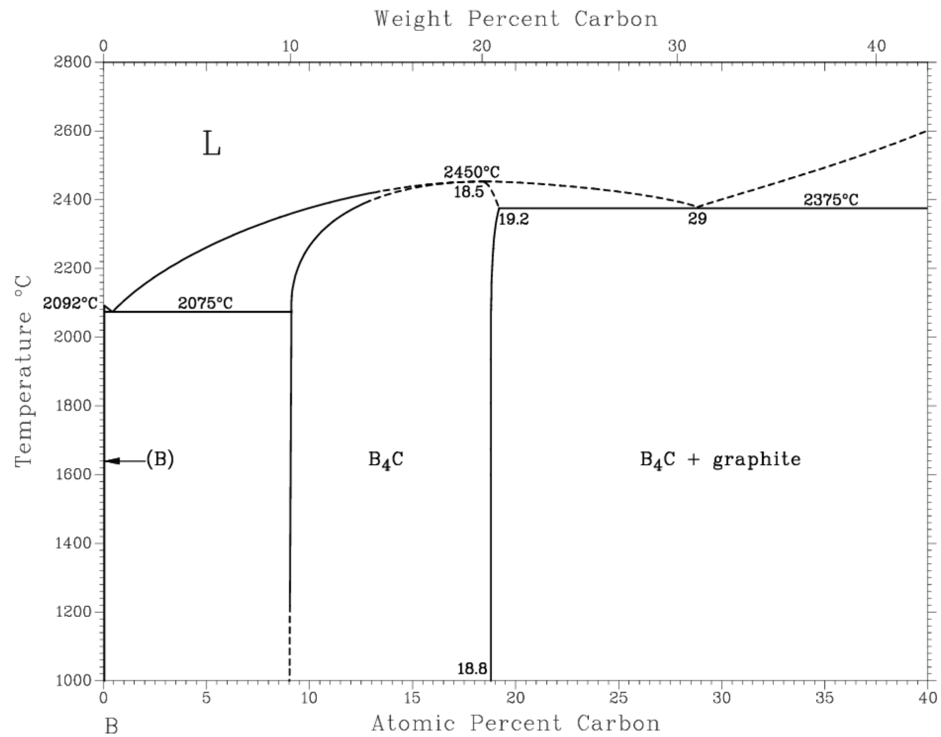

Figure 7.2.1-1: Boron – Carbon Phase Diagram

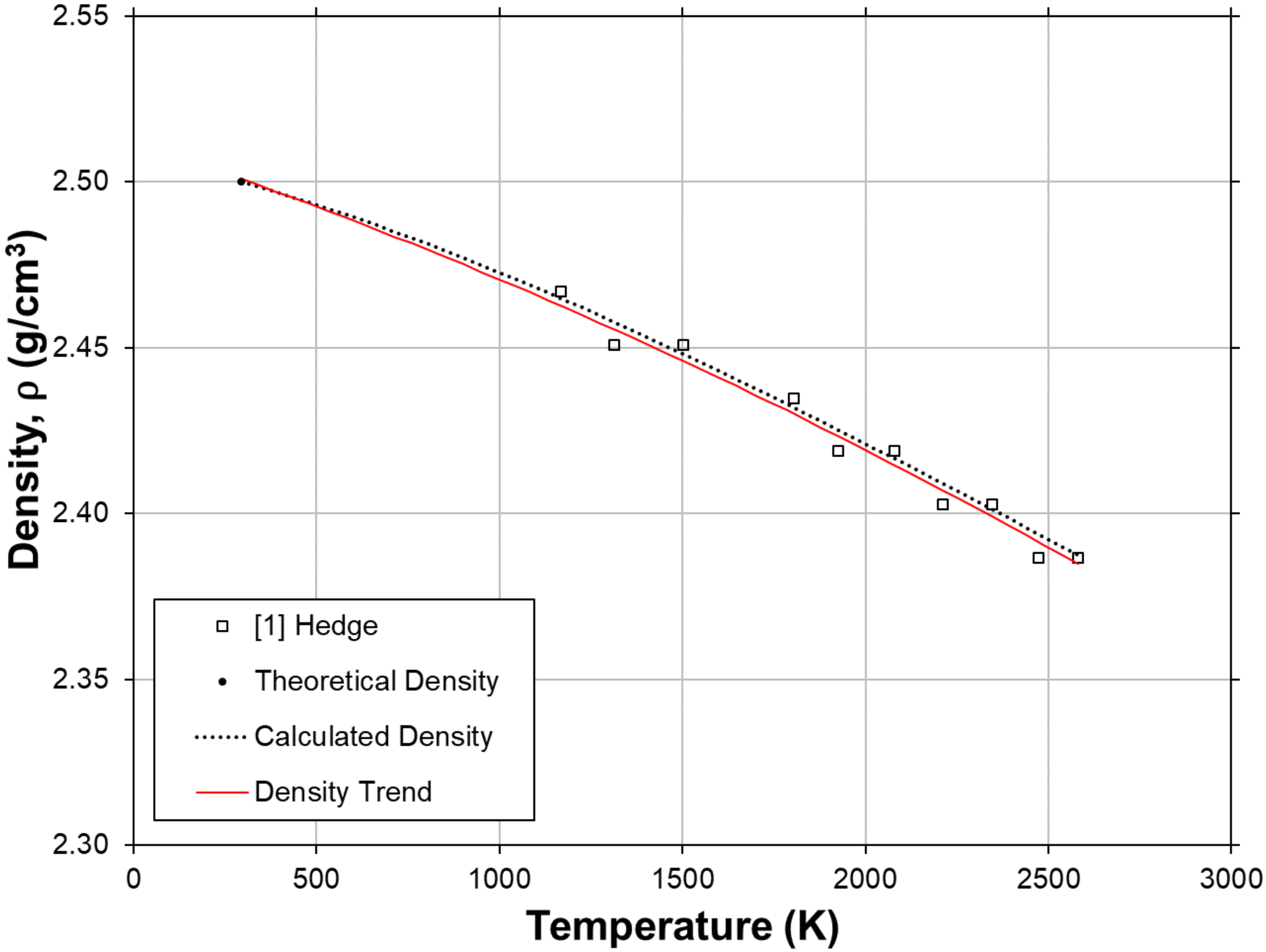

Figure 7.2.1-2: Density versus Temperature for B4C. Displaying fitted trend of data with comparison to the density calculated from the fitted trend of the Thermal Expansion data.

100% Theoretical Density

Temperature (T)		Density (ρ)		Temperature (T)		Density (ρ)	
K	(°F)	kg/m³	(lb/ft³)	K	(°F)	kg/m³	(lb/ft³)
293	(67.7)	2500	(156.1)	1200	(1700.3)	2463	(153.8)
300	(80.3)	2500	(156.1)	1300	(1880.3)	2458	(153.5)
350	(170.3)	2498	(156.0)	1400	(2060.3)	2453	(153.2)
400	(260.3)	2497	(155.9)	1500	(2240.3)	2448	(152.8)
450	(350.3)	2495	(155.8)	1600	(2420.3)	2443	(152.5)
500	(440.3)	2493	(155.6)	1700	(2600.3)	2438	(152.2)
550	(530.3)	2491	(155.5)	1800	(2780.3)	2432	(151.8)
600	(620.3)	2489	(155.4)	1900	(2960.3)	2427	(151.5)
650	(710.3)	2487	(155.3)	2000	(3140.3)	2421	(151.1)
700	(800.3)	2486	(155.2)	2100	(3320.3)	2415	(150.8)
750	(890.3)	2483	(155.0)	2200	(3500.3)	2410	(150.4)
800	(980.3)	2481	(154.9)	2300	(3680.3)	2404	(150.1)
900	(1160.3)	2477	(154.6)	2400	(3860.3)	2398	(149.7)
1000	(1340.3)	2473	(154.4)	2500	(4040.3)	2392	(149.3)
1100	(1520.3)	2468	(154.1)	2581	(4186.1)	2388	(149.1)

Application Notes: Data for density is collected from reference [1] and fitted with density fit equation below to approximate property trend with respect to temperature. Density is also calculated as a function of thermal expansion as seen in density calculation equation and compared against data trend.

Density Calculation Equation:

$$\rho(T) = \rho_{RT}(1 - P)/(1 + dL/L_0(T)/100)^3$$

$\rho(T) = Density\ [kg/m^3]$

$Room\ Temperature\ Density\ (\rho_{RT}) = 2{,}500\ [kg/m^3]$

$P = Fractional\ Porosity$

$T = Temperature\ [K]$

Density Fit:

$$\rho(T) = A0 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2$$

Constants:

T Range [K]:	$293 \leq T \leq 2581$
A0 =	2512
A1 =	-36.44
A2 =	-4.987

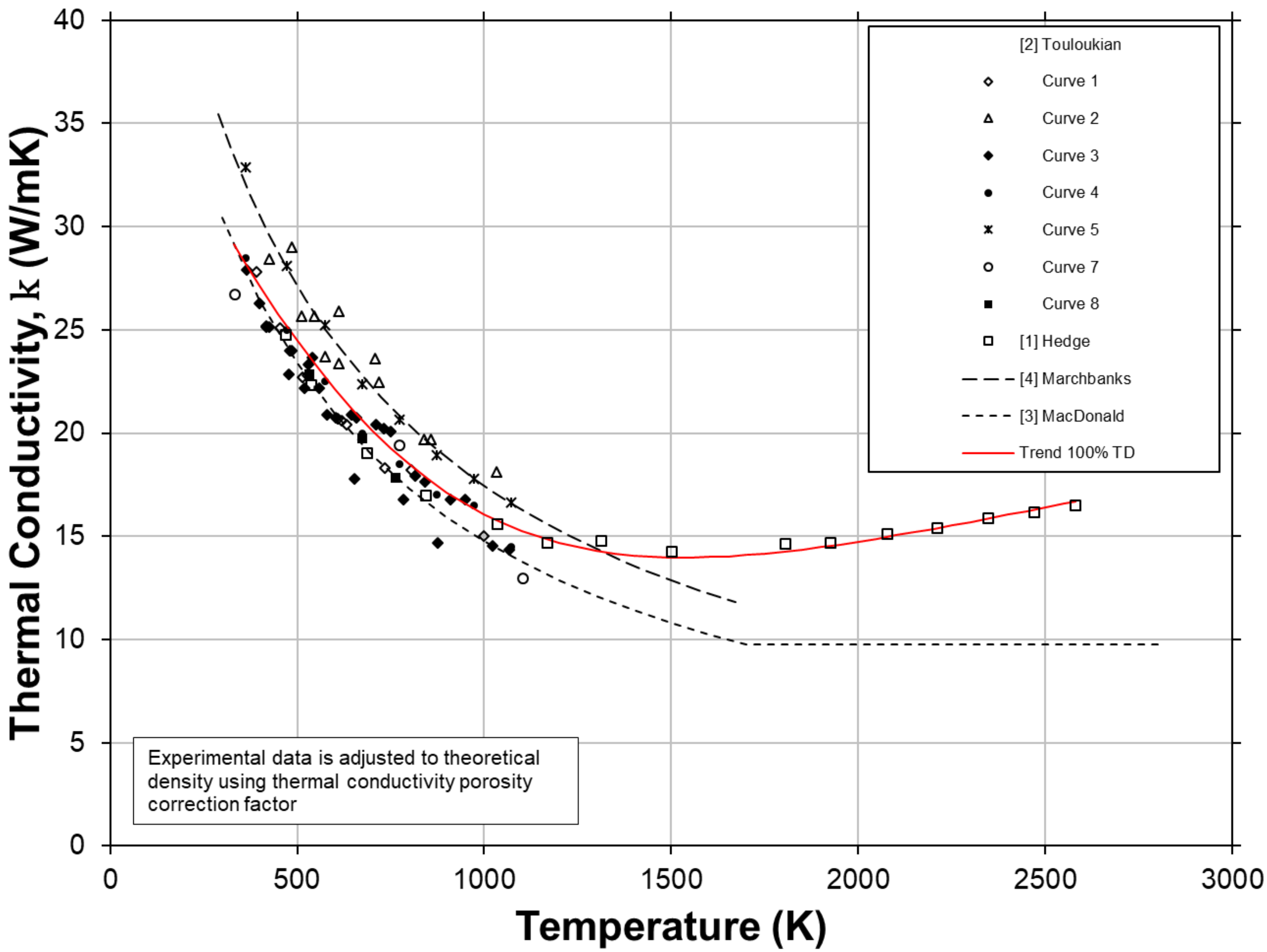

Figure 7.2.1-3: Thermal Conductivity versus Temperature of B4C. Displaying fitted trend of the data with comparison to Marchbanks (1976) and MacDonald (1976) for 100% Theoretical density.

100% Theoretical Density

Temperature (T) K	(°F)	Thermal Conductivity (k) W/(m-K)	((Btu·in)/(ft²·hr·°F))	Temperature (T) K	(°F)	Thermal Conductivity (k) W/(m-K)	((Btu·in)/(ft²·hr·°F))
330	(134.3)	29.16	(202.31)	1200	(1700.3)	14.69	(101.95)
350	(170.3)	28.57	(198.19)	1300	(1880.3)	14.31	(99.25)
400	(260.3)	27.13	(188.20)	1400	(2060.3)	14.08	(97.66)
450	(350.3)	25.76	(178.72)	1500	(2240.3)	13.98	(96.99)
500	(440.3)	24.47	(169.78)	1600	(2420.3)	13.99	(97.07)
550	(530.3)	23.26	(161.40)	1700	(2600.3)	14.09	(97.75)
600	(620.3)	22.14	(153.60)	1800	(2780.3)	14.26	(98.92)
650	(710.3)	21.10	(146.39)	1900	(2960.3)	14.48	(100.46)
700	(800.3)	20.14	(139.76)	2000	(3140.3)	14.74	(102.30)
750	(890.3)	19.27	(133.71)	2100	(3320.3)	15.04	(104.36)
800	(980.3)	18.48	(128.23)	2200	(3500.3)	15.36	(106.58)
850	(1070.3)	17.77	(123.30)	2300	(3680.3)	15.70	(108.92)
900	(1160.3)	17.14	(118.89)	2400	(3860.3)	16.05	(111.34)
1000	(1340.3)	16.08	(111.54)	2500	(4040.3)	16.40	(113.81)
1100	(1520.3)	15.27	(105.98)	2581	(4186.1)	16.69	(115.82)

Application Notes: Data for thermal conductivity is collected from references [1, 2] and fitted with the equation below to approximate property trend with respect to temperature and porosity. Trend for 100% TD is compared against references [3, 4].

Fit Equation:

$$k(T) = \left(A0 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2\right) \Big/ \left(1 + A\_2 \cdot \left(\frac{T}{1000}\right)^2\right)$$

$k(T) = Thermal\ Conductivity\ [W\ /\ (m \cdot K)]$

$k_P = k \cdot (1 - P)/(1 + P)$

$P = Fractional\ Porosity\ (0 \leq P \leq 0.24)$

$T = Temperature\ [K]$

Constants:

T Range [K]:	$330 \leq T \leq 2581$
A0 =	39.96
A1 =	-33.8
A2 =	18.11
A_2 =	0.5096

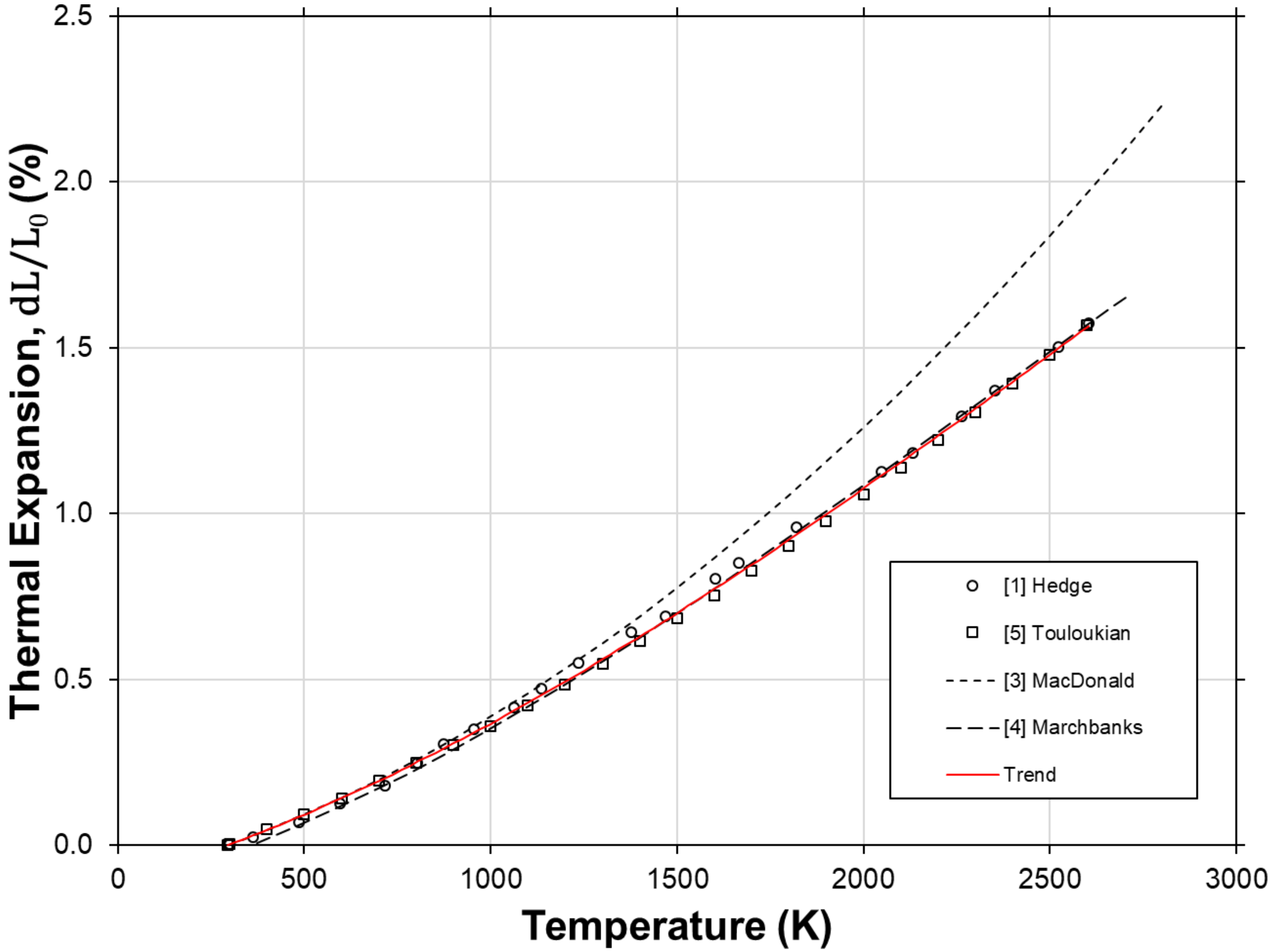

Figure 7.2.1-4: Thermal Expansion versus Temperature of B4C. Displaying fitted trend of the data with comparison to Marchbanks (1976) and MacDonald (1976).

100% Theoretical Density

Temperature (T)		Thermal Expansion (dL/L_0)	Temperature (T)		Thermal Expansion (dL/L_0)
K	(°F)	%	K	(°F)	%
293	(67.7)	0.000	1200	(1700.3)	0.494
300	(80.3)	0.003	1300	(1880.3)	0.560
350	(170.3)	0.024	1400	(2060.3)	0.629
400	(260.3)	0.046	1500	(2240.3)	0.700
450	(350.3)	0.069	1600	(2420.3)	0.772
500	(440.3)	0.092	1700	(2600.3)	0.846
550	(530.3)	0.117	1800	(2780.3)	0.921
600	(620.3)	0.142	1900	(2960.3)	0.998
650	(710.3)	0.168	2000	(3140.3)	1.076
700	(800.3)	0.194	2100	(3320.3)	1.155
750	(890.3)	0.221	2200	(3500.3)	1.235
800	(980.3)	0.249	2300	(3680.3)	1.316
900	(1160.3)	0.306	2400	(3860.3)	1.397
1000	(1340.3)	0.367	2500	(4040.3)	1.479
1100	(1520.3)	0.429	2600	(4220.3)	1.562

Application Notes: Data for thermal expansion is collected from references [1, 5] and fitted with the equation below to approximate property trend with respect to temperature. Trend is compared against trends from references [3, 4].

Fit Equation:

$$dL/L_0\,(T) = A0 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2 + A3 \cdot \left(\frac{T}{1000}\right)^3$$

$dL/L_0\,(T) = Thermal\ Expansion\ [\%]$

$T = Temperature\ [K]$

Constants:

T Range [K]:	$293 \leq T \leq 2605$
A0 =	-0.1068
A1 =	0.3132
A2 =	0.1812
A3 =	-0.02107

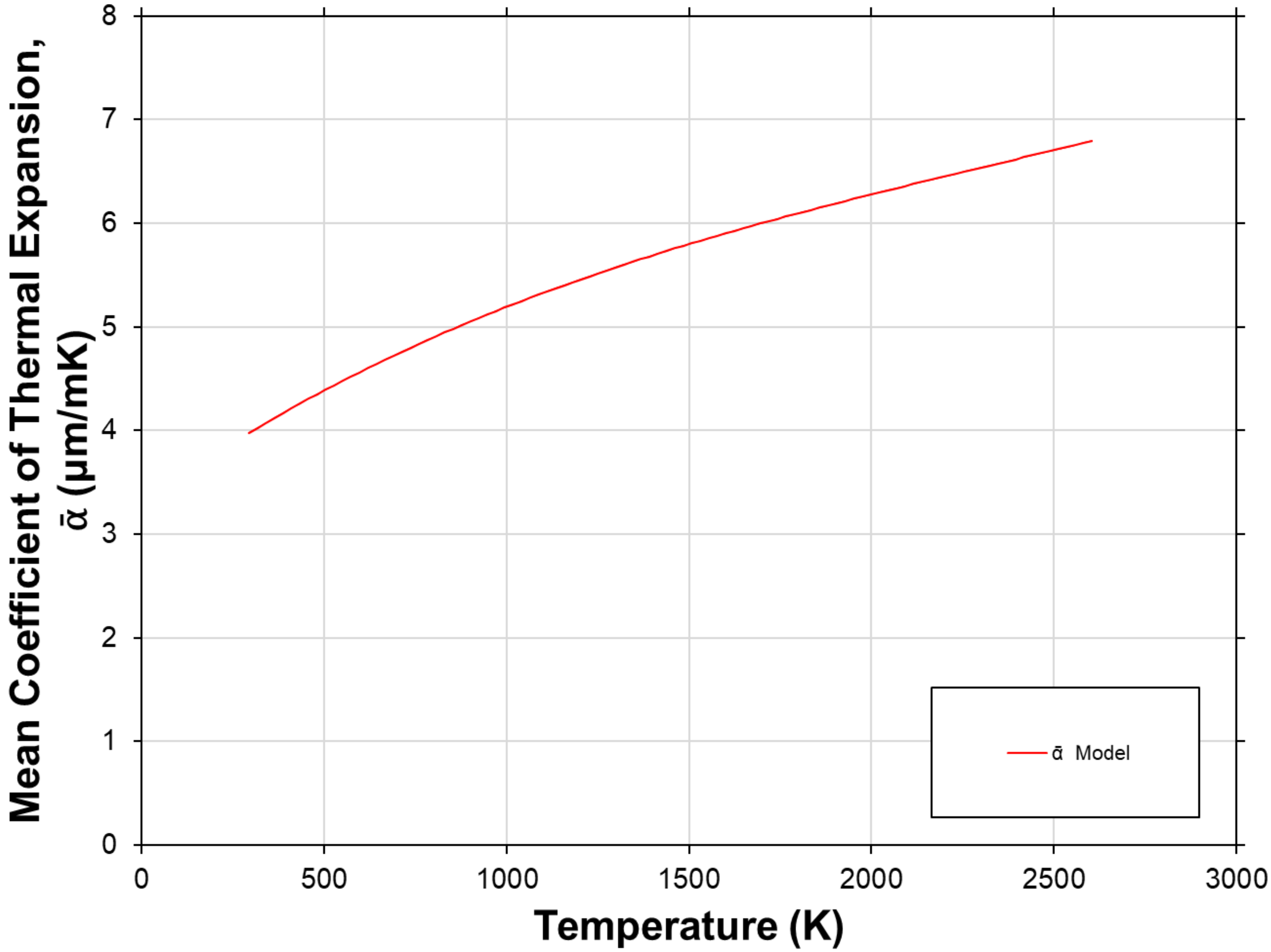

Figure 7.2.1-5: Mean Coefficient of Thermal Expansion versus Temperature of B4C. Calculated from fitted trend of the Thermal Expansion data for B4C.

100% Theoretical Density

Temperature (T)		Mean CTE (ᾱ)		Temperature (T)		Mean CTE (ᾱ)	
K	(°F)	µm/(m-K)	(µin/(in-°F))	K	(°F)	µm/(m-K)	(µin/(in-°F))
293	(67.7)	3.978	(2.210)	1200	(1700.3)	5.456	(3.031)
300	(80.3)	3.993	(2.218)	1300	(1880.3)	5.577	(3.098)
350	(170.3)	4.096	(2.275)	1400	(2060.3)	5.691	(3.162)
400	(260.3)	4.196	(2.331)	1500	(2240.3)	5.800	(3.222)
450	(350.3)	4.293	(2.385)	1600	(2420.3)	5.904	(3.280)
500	(440.3)	4.388	(2.438)	1700	(2600.3)	6.003	(3.335)
550	(530.3)	4.480	(2.489)	1800	(2780.3)	6.098	(3.388)
600	(620.3)	4.569	(2.538)	1900	(2960.3)	6.190	(3.439)
650	(710.3)	4.655	(2.586)	2000	(3140.3)	6.279	(3.488)
700	(800.3)	4.739	(2.633)	2100	(3320.3)	6.366	(3.537)
750	(890.3)	4.821	(2.678)	2200	(3500.3)	6.452	(3.584)
800	(980.3)	4.900	(2.722)	2300	(3680.3)	6.537	(3.632)
900	(1160.3)	5.051	(2.806)	2400	(3860.3)	6.621	(3.679)
1000	(1340.3)	5.194	(2.886)	2500	(4040.3)	6.706	(3.726)
1100	(1520.3)	5.329	(2.961)	2600	(4220.3)	6.792	(3.773)

Application Notes: Trend for mean coefficient of thermal expansion is calculated as a function of thermal expansion as seen in the equation below to approximate property trend with respect to temperature.

Fit Equation:

$$\bar{\alpha}(T) = A0 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2 + A3 \cdot \left(\frac{T}{1000}\right)^3$$

$\bar{\alpha}(T) = Coefficient\ of\ Thermal\ Expansion\ [\mu m/(m \cdot K)]$

$T = Temperature\ [K]$

Constants:

T. Range [K]: $293 \le T \le 2605$

A0 = 3.307

A1 = 2.486

A2 = -0.6976

A3 = 0.09882

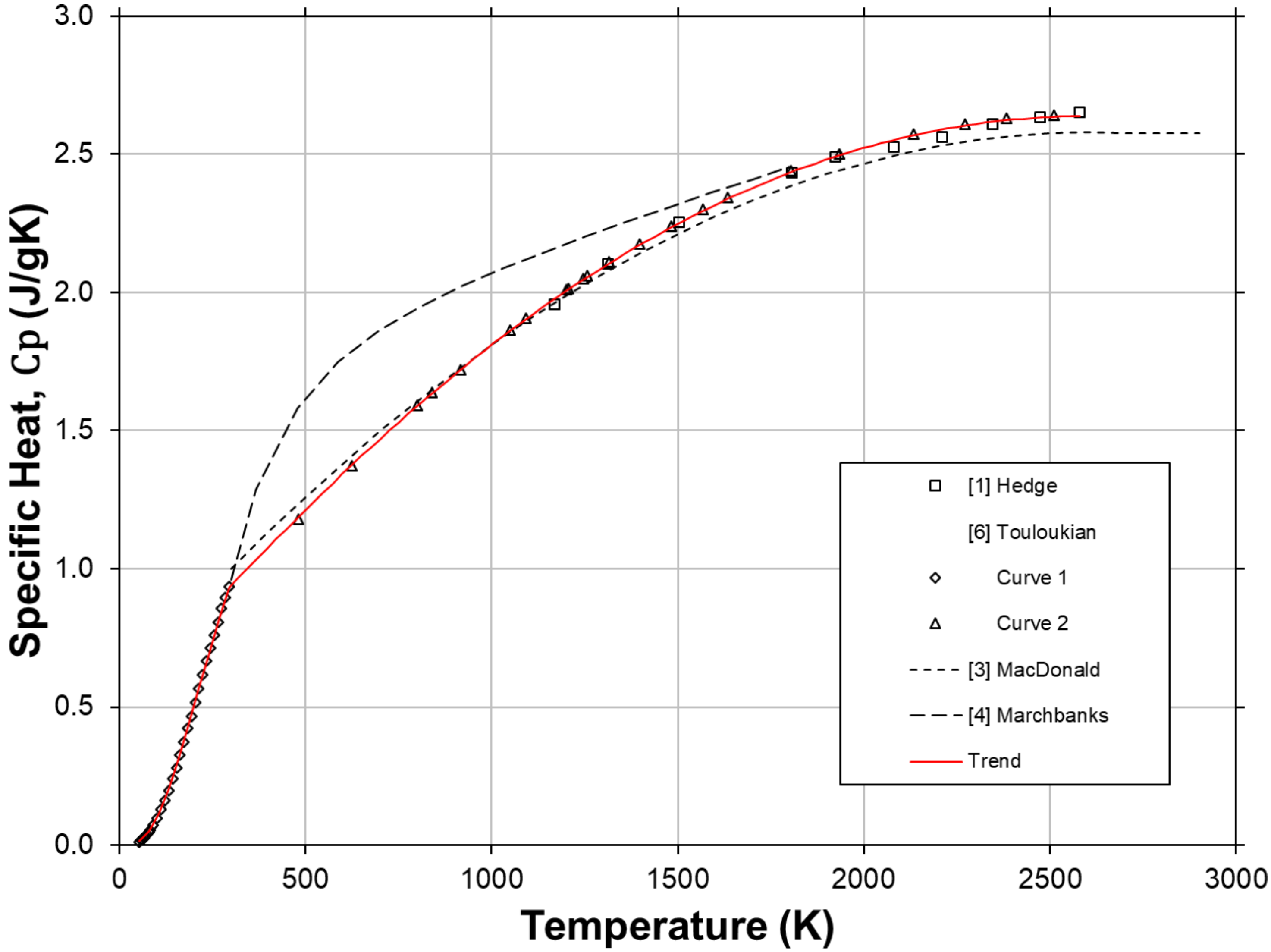

Figure 7.2.1-6: Specific Heat versus Temperature of B4C. Displaying fitted trend of the data with 95% confidence bounds with comparison to Marchbanks (1976) and MacDonald (1976).

100% Theoretical Density

Temperature (T)		Specific Heat (C_p)		Temperature (T)		Specific Heat (C_p)	
K	(°F)	J/(g-K)	(BTU/(lb-°F))	K	(°F)	J/(g-K)	(BTU/(lb-°F))
54	(-362.5)	0.014	(0.003)	1200	(1700.3)	2.004	(0.479)
100	(-279.7)	0.093	(0.022)	1300	(1880.3)	2.092	(0.500)
150	(-189.7)	0.267	(0.064)	1400	(2060.3)	2.173	(0.519)
200	(-99.7)	0.496	(0.119)	1500	(2240.3)	2.248	(0.537)
250	(-9.7)	0.740	(0.177)	1600	(2420.3)	2.316	(0.554)
300	(80.3)	0.941	(0.225)	1700	(2600.3)	2.378	(0.568)
350	(170.3)	1.009	(0.241)	1800	(2780.3)	2.433	(0.581)
400	(260.3)	1.077	(0.257)	1900	(2960.3)	2.481	(0.593)
500	(440.3)	1.212	(0.290)	2000	(3140.3)	2.523	(0.603)
600	(620.3)	1.344	(0.321)	2100	(3320.3)	2.558	(0.611)
700	(800.3)	1.469	(0.351)	2200	(3500.3)	2.587	(0.618)
800	(980.3)	1.589	(0.380)	2300	(3680.3)	2.609	(0.624)
900	(1160.3)	1.702	(0.407)	2400	(3860.3)	2.625	(0.627)
1000	(1340.3)	1.810	(0.432)	2500	(4040.3)	2.634	(0.630)
1100	(1520.3)	1.910	(0.457)	2581	(4186.1)	2.637	(0.630)

Application Notes: Data for specific heat is collected from references [1, 6], and fitted with the equation below to approximate property trend with respect to temperature. Fitted trend is compared against trends from references [3, 4].

Fit Equation:

$$C_P(T) = A0 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2 + A3 \cdot \left(\frac{T}{1000}\right)^3 + A\_2/\left(\frac{T}{1000}\right)^2$$

$C_P(T) = Specific\ Heat\ [J/(g \cdot K)]$

$T = Temperature\ [K]$

Constants:

T. Range [K]:	$54 \leq T < 293$	$293 \leq T \leq 2581$
A0 =	0.0647	0.4356
A1 =	-2.65	1.7
A2 =	34.56	-0.3283
A3 =	-52.65	0
A_2 =	0	0.00223

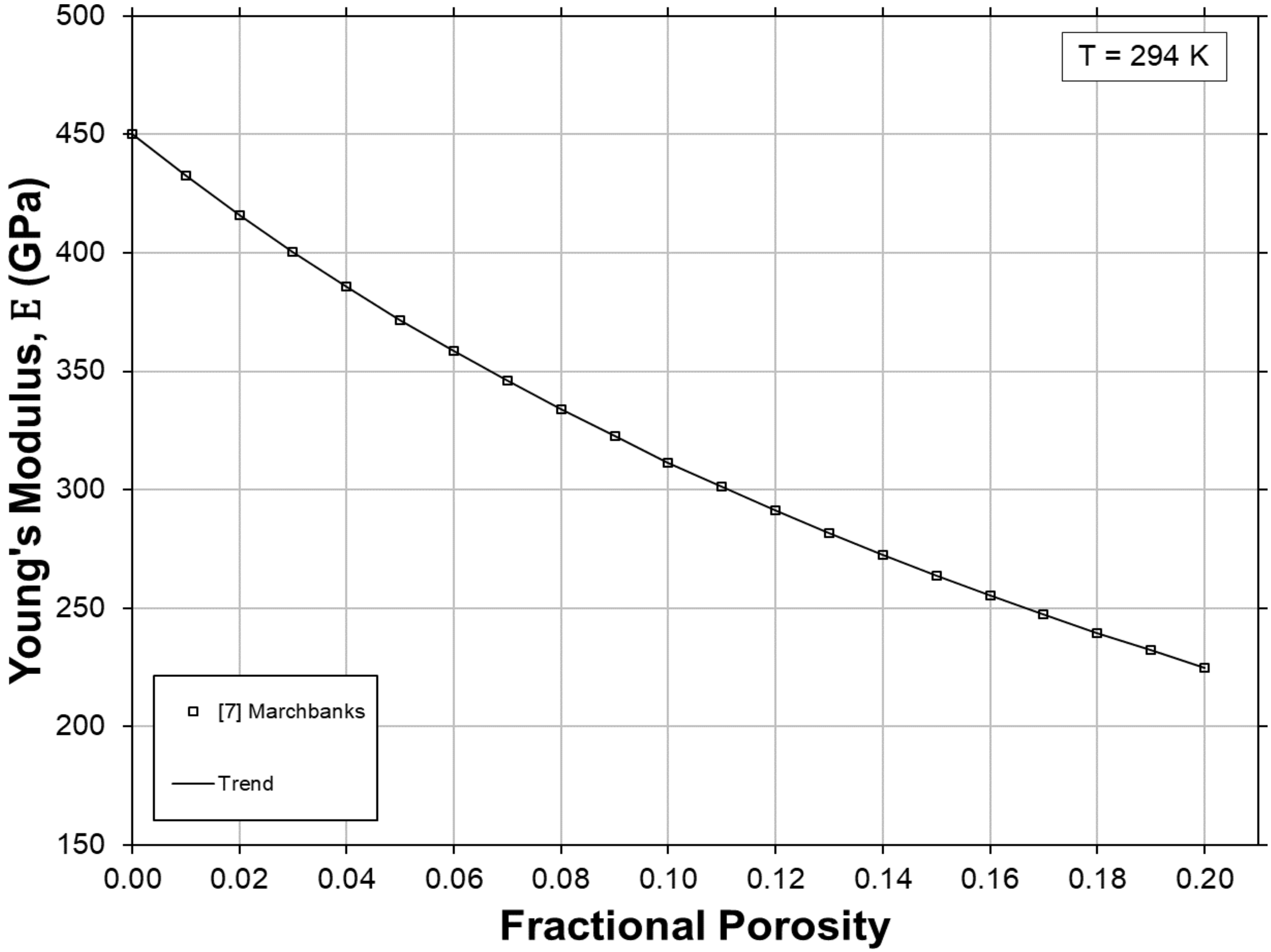

Figure 7.2.1-7: Young's Modulus versus Fractional Porosity of B4C adapted from Marchbanks (1976).

Room Temperature

Porosity (P)	Young's Modulus (E)	
	GPa	(Msi)
0.00	450.00	(65.29)
0.02	416.04	(60.37)
0.04	385.73	(55.97)
0.06	358.49	(52.02)
0.08	333.89	(48.45)
0.10	311.56	(45.21)
0.12	291.20	(42.25)
0.14	272.56	(39.55)
0.16	255.43	(37.06)
0.18	239.64	(34.77)
0.20	225.03	(32.65)

Application Notes: Data for Young's modulus is collected from reference [7] and fitted with the equation below to approximate property trend with respect to both temperature and fractional porosity. Data in the table is for T = 294 K.

Fit Equations:

$$E(T) = \left(\frac{1-P}{1+A\cdot P}\right)\cdot\left(A0 + A1\cdot\left(\frac{T}{1000}\right) + A2\cdot\left(\frac{T}{1000}\right)^2\right)$$

$E(T) = Young's\ Modulus\ [GPa]$

$P = Fractional\ Porosity\ for\ 0 \leq P < 0.2$

$T = Temperature\ [K]$

Constants:

Porosity Range:	$0 \leq P < 0.2$
Temperature [K]	294
A =	2.999
A0 =	452.1
A1 =	-7.101
A2 =	-1.540E-08

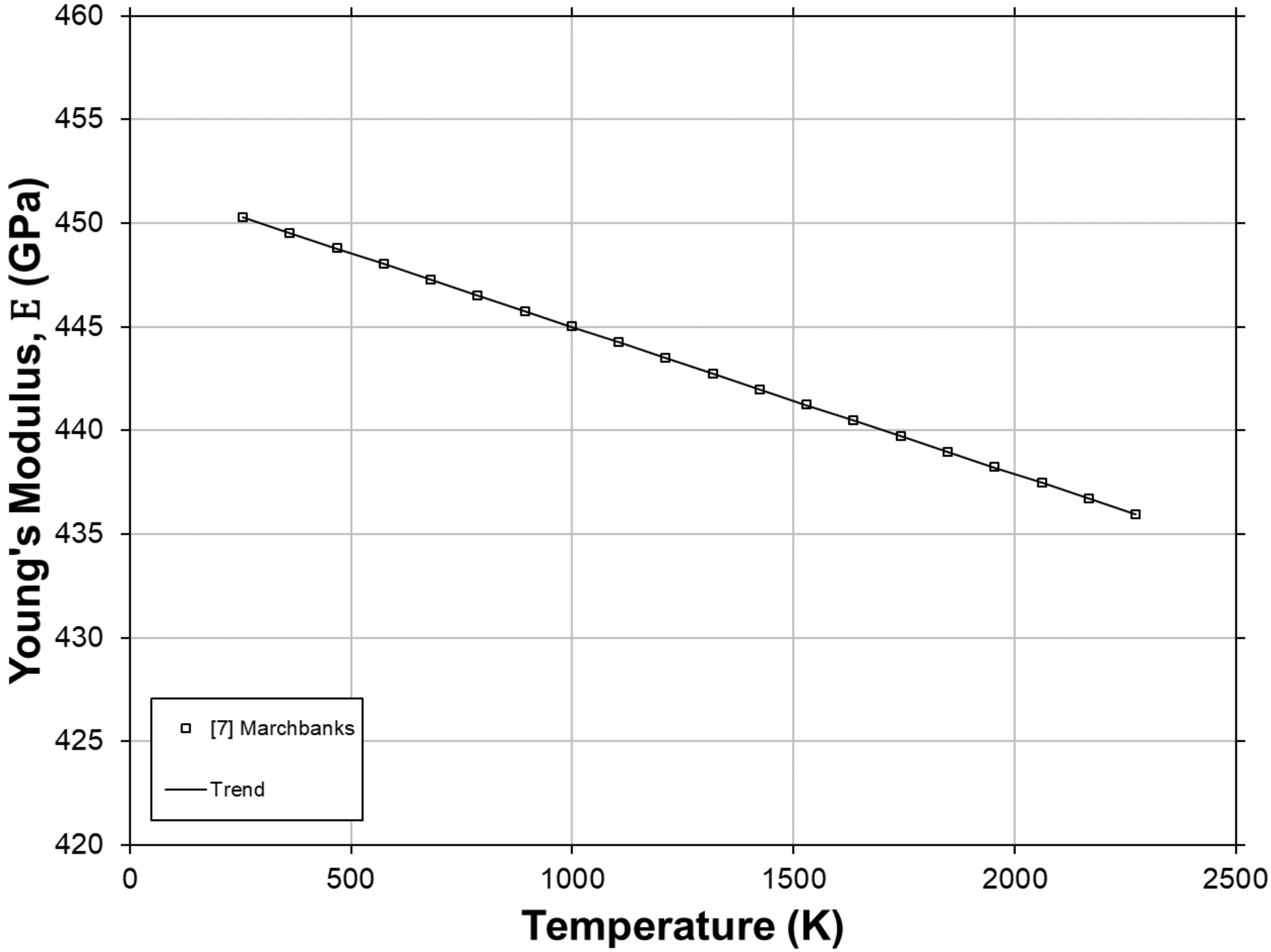

Figure 7.2.1-8: Young's Modulus versus Temperature of B4C adapted from Marchbanks (1976)

100% Theoretical Density

Temperature (T)		Young's Modulus (E)		Temperature (T)		Young's Modulus (E)	
K	(°F)	GPa	(Msi)	K	(°F)	GPa	(Msi)
255	(-0.7)	450.29	(65.34)	1000	(1340.3)	445.00	(64.57)
300	(80.3)	449.97	(65.29)	1050	(1430.3)	444.64	(64.52)
350	(170.3)	449.61	(65.24)	1100	(1520.3)	444.29	(64.47)
400	(260.3)	449.26	(65.19)	1200	(1700.3)	443.58	(64.36)
450	(350.3)	448.90	(65.14)	1300	(1880.3)	442.87	(64.26)
500	(440.3)	448.55	(65.08)	1400	(2060.3)	442.16	(64.16)
550	(530.3)	448.19	(65.03)	1500	(2240.3)	441.45	(64.05)
600	(620.3)	447.84	(64.98)	1600	(2420.3)	440.74	(63.95)
650	(710.3)	447.48	(64.93)	1700	(2600.3)	440.03	(63.85)
700	(800.3)	447.13	(64.88)	1800	(2780.3)	439.32	(63.75)
750	(890.3)	446.77	(64.83)	1900	(2960.3)	438.61	(63.64)
800	(980.3)	446.42	(64.78)	2000	(3140.3)	437.90	(63.54)
850	(1070.3)	446.06	(64.72)	2100	(3320.3)	437.19	(63.44)
900	(1160.3)	445.71	(64.67)	2200	(3500.3)	436.48	(63.33)
950	(1250.3)	445.35	(64.62)	2274	(3633.5)	435.95	(63.26)

Application Notes: Data for Young's modulus is collected from reference [7] and fitted with the equation below to approximate property trend with respect to both temperature and fractional porosity. Data shown in table is for fractional porosity P=0.

Fit Equations:

$$E(T) = \left(\frac{1-P}{1+A\cdot P}\right)\cdot\left(A0 + A1\cdot\left(\frac{T}{1000}\right) + A2\cdot\left(\frac{T}{1000}\right)^2\right)$$

$E(T) = Young's\ Modulus\ [GPa]$

$P = Fractional\ Porosity\ for\ 0 < P < 0.2$

$T = Temperature\ [K]$

Constants:

T. Range [K]:	$255 \leq T < 2274$
Fractional Porosity (P)	0
A =	2.999
A0 =	452.1
A1 =	-7.101
A2 =	-1.540E-08

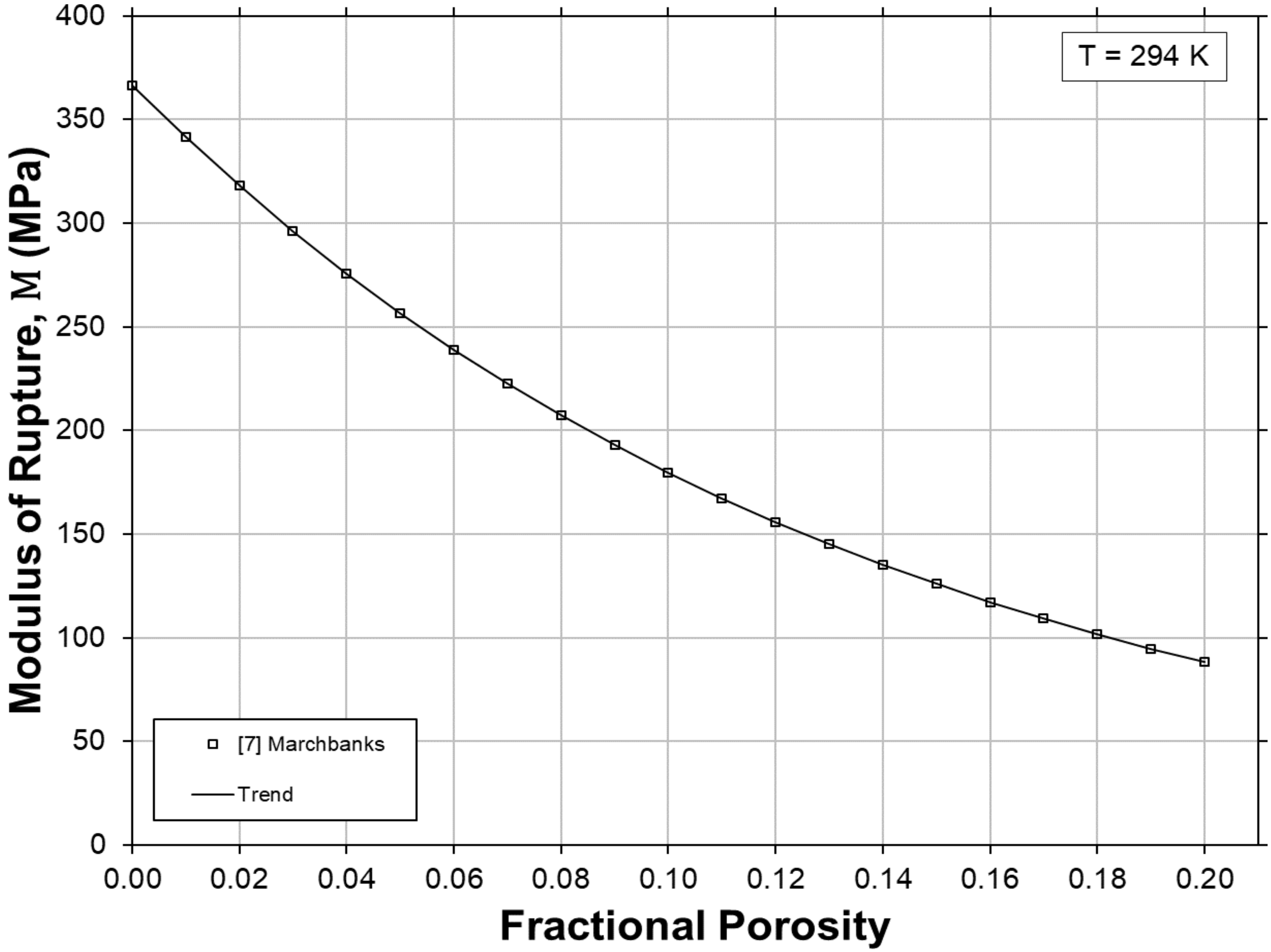

Figure 7.2.1-9: Modulus of Rupture verse Fractional Porosity of B4C adapted from Marchbanks (1976).

Room Temperature

Porosity (P)	Modulus of Rupture (M)	
	MPa	(Ksi)
0.00	366.67	(53.20)
0.02	317.98	(46.14)
0.04	275.76	(40.01)
0.06	239.15	(34.70)
0.08	207.39	(30.09)
0.10	179.86	(26.10)
0.12	155.97	(22.63)
0.14	135.26	(19.63)
0.16	117.30	(17.02)
0.18	101.73	(14.76)
0.20	88.22	(12.80)

Application Notes: Data for modulus of rupture has been collected from reference [7] and fitted with the equation below to approximate property trend with respect to both temperature and fractional porosity. Data shown in the table is for T = 294 K.

Fit Equations:

$$M(T) = e^{(A \cdot P)} \cdot \left(A0 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2 \right)$$

$M(T) = Modulus\ of\ Rupture$

$P = Fractional\ Porosity\ for\ 0 \leq P < 0.2$

$T = Temperature\ [K]$

Constants:

Porosity Range:	$0 \leq P < 0.2$
Temperature [K]	294
A =	-7.123
A0 =	358.9
A1 =	41.76
A2 =	-52.43

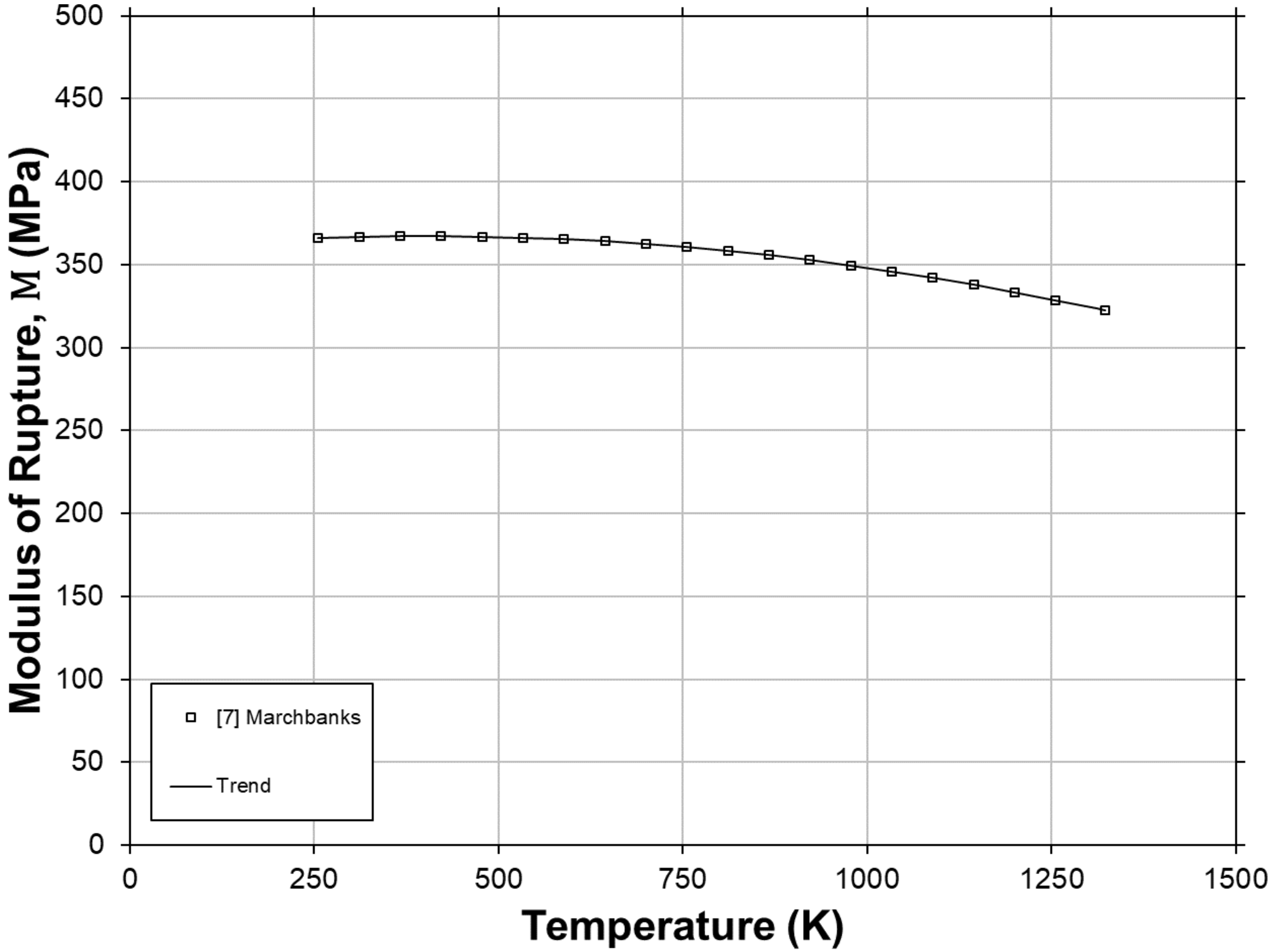

Figure 7.2.1-10: Modulus of Rupture versus Temperature of B4C adapted from Marchbanks (1976).

100% Theoretical Density

Temperature (T)		Modulus of Rupture (M)		Temperature (T)		Modulus of Rupture (M)	
K	(°F)	MPa	(Ksi)	K	(°F)	MPa	(Ksi)
296	(73.1)	366.67	(53.20)	650	(710.3)	363.89	(52.80)
300	(80.3)	366.71	(53.21)	675	(755.3)	363.20	(52.70)
325	(125.3)	366.93	(53.24)	700	(800.3)	362.44	(52.59)
350	(170.3)	367.09	(53.27)	725	(845.3)	361.62	(52.47)
375	(215.3)	367.19	(53.28)	750	(890.3)	360.73	(52.34)
400	(260.3)	367.22	(53.28)	775	(935.3)	359.77	(52.20)
425	(305.3)	367.18	(53.28)	800	(980.3)	358.75	(52.06)
450	(350.3)	367.07	(53.26)	825	(1025.3)	357.67	(51.90)
475	(395.3)	366.91	(53.24)	850	(1070.3)	356.52	(51.73)
500	(440.3)	366.67	(53.20)	900	(1160.3)	354.02	(51.37)
525	(485.3)	366.37	(53.16)	1000	(1340.3)	348.23	(50.53)
550	(530.3)	366.01	(53.11)	1100	(1520.3)	341.40	(49.54)
575	(575.3)	365.58	(53.05)	1200	(1700.3)	333.51	(48.39)
600	(620.3)	365.08	(52.97)	1300	(1880.3)	324.58	(47.10)
625	(665.3)	364.52	(52.89)	1324	(1923.5)	322.28	(46.76)

Application Notes: : Data for modulus of rupture has been collected from reference [7] and fitted with the equation below to approximate property trend with respect to both temperature and fractional porosity. Data shown in table is for fractional porosity P=0.

Fit Equations:

$$M(T) = e^{(A\cdot P)} \cdot \left(A0 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2\right)$$

$M(T) = Modulus\ of\ Rupture$

$P = Fractional\ Porosity\ for\ 0 \leq P < 0.2$

$T = Temperature\ [K]$

Constants:

T. Range [K]:	$255 \leq T < 1324$
Fractional Porosity (P)	0
A =	-7.123
A0 =	358.9
A1 =	41.76
A2 =	-52.43

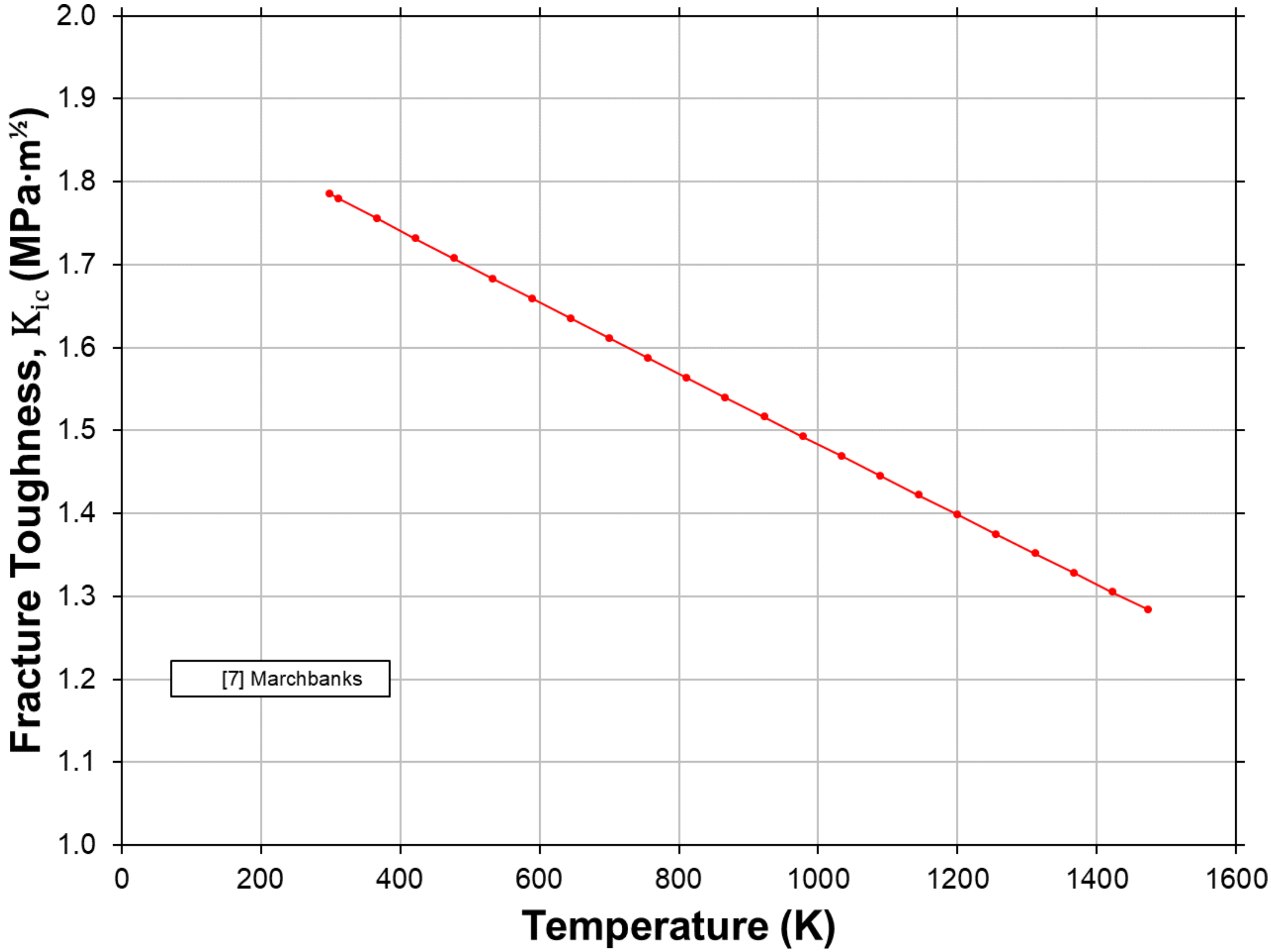

Figure 7.2.1-11: Fracture Toughness versus Temperature of B4C adapted from Marchbanks (1976).

100% Theoretical Density

Temperature (T)		Fracture Toughness (K_{IC})		Temperature (T)		Fracture Toughness (K_{IC})	
K	(°F)	MPa $m^{1/2}$	(Ksi $in^{1/2}$)	K	(°F)	MPa $m^{1/2}$	(Ksi $in^{1/2}$)
296	(73.1)	1.79	(1.63)	650	(710.3)	1.63	(1.49)
300	(80.3)	1.78	(1.62)	675	(755.3)	1.62	(1.48)
325	(125.3)	1.77	(1.61)	700	(800.3)	1.61	(1.47)
350	(170.3)	1.76	(1.60)	725	(845.3)	1.60	(1.46)
375	(215.3)	1.75	(1.59)	750	(890.3)	1.59	(1.45)
400	(260.3)	1.74	(1.58)	775	(935.3)	1.58	(1.44)
425	(305.3)	1.73	(1.57)	800	(980.3)	1.57	(1.43)
450	(350.3)	1.72	(1.56)	850	(1070.3)	1.55	(1.41)
475	(395.3)	1.71	(1.55)	900	(1160.3)	1.53	(1.39)
500	(440.3)	1.70	(1.54)	1000	(1340.3)	1.48	(1.35)
525	(485.3)	1.69	(1.54)	1100	(1520.3)	1.44	(1.31)
550	(530.3)	1.68	(1.53)	1200	(1700.3)	1.40	(1.27)
575	(575.3)	1.67	(1.52)	1300	(1880.3)	1.36	(1.23)
600	(620.3)	1.65	(1.51)	1400	(2060.3)	1.31	(1.20)
625	(665.3)	1.64	(1.50)	1474	(2193.5)	1.28	(1.17)

Application Notes: Data and trend for fracture toughness is from reference [7]. The equation from this reference is shown below and approximates property trend with respect to temperature.

Fit Equations:

$$K_{ic}(T) = A0 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2$$

$$K_{ic}(T) = Fracture\ Toughness\ \left[MPa \cdot \sqrt{m}\right]$$

$$T = Temperature\ [K]$$

Constants:

T. Range [K]: $296 \leq T < 1474$

A0 = 1.916E+00

A1 = -4.408E-01

A2 = 7.926E-03

Temp. (T) K	Physical and Electrical		Thermal				Elastic		
	Density (ρ) kg/m³	Electrical Resistivity (ρ_e) μΩ-m	Thermal Conductivity (k) W/(m-K)	Thermal Expansion (dL/L_0) %	Mean CTE ($\bar{\alpha}$) 10^{-6}/K	Specific Heat (C_p) J/(g-K)	Young's Modulus (E) GPa	Shear Modulus (G) GPa	Poisson's Ratio (ν)
300	2500		-	0.003	3.99	0.941	450.0		
350	2498		28.57	0.024	4.10	1.009	449.6		
400	2497		27.13	0.046	4.20	1.077	449.3		
450	2495		25.76	0.069	4.29	1.145	448.9		
500	2493		24.47	0.092	4.39	1.212	448.5		
550	2491		23.26	0.117	4.48	1.279	448.2		
600	2489		22.14	0.142	4.57	1.344	447.8		
700	2486		20.14	0.194	4.74	1.469	447.1		
800	2481		18.48	0.249	4.90	1.589	446.4		
1000	2473		16.08	0.367	5.19	1.810	445.0		
1100	2468		15.27	0.429	5.33	1.910	444.3		
1200	2463		14.69	0.494	5.46	2.004	443.6		
1300	2458		14.31	0.560	5.58	2.092	442.9		
1400	2453		14.08	0.629	5.69	2.173	442.2		
1500	2448		13.98	0.700	5.80	2.248	441.4		
1600	2443		13.99	0.772	5.90	2.316	440.7		
1700	2438		14.09	0.846	6.00	2.378	440.0		
1800	2432		14.26	0.921	6.10	2.433	439.3		
1900	2427		14.48	0.998	6.19	2.481	438.6		
2000	2421		14.74	1.076	6.28	2.523	437.9		
2100	2415		15.04	1.155	6.37	2.558	437.2		
2200	2410		15.36	1.235	6.45	2.587	436.5		
2300	2404		15.70	1.316	6.54	2.609	-		
2400	2398		16.05	1.397	6.62	2.625	-		
2500	2392		16.40	1.479	6.71	2.634	-		

[1] J.C. Hedge, C. Kostenko, J.I. Lang, Thermal Properties of Refractory Alloys, IIT Research Institute, Chicago, IL, 1963.

[2] Y.S. Touloukian, R.W. Powell, C.Y. Ho, P.G. Klemens, Thermal conductivity - Nonmetallic Solids, Thermophysical Properties of Matter - The TPRC Data Series, Volume 2, Thermophysical and Electronic Properties Information Analysis Center, Lafayette, IN, 1971.

[3] P.E. MacDonald, L.B. Thompson, MATPRO: a handbook of materials properties for use in the analysis of light water reactor fuel rod behavior, SEE CODE- 9502158 Aerojet Nuclear Co., Idaho Falls, Idaho (USA). Idaho National Engineering Lab., 1976.

[4] F. Marchbanks, M.A. Moen, R.E. Irvin, Nuclear Systems Materials Handbook: Design Data, International Conference on the Mechanical Behavior of Materials, Oak Ridge National Laboratory, Boston, MA, USA, 1976.

[5] Y.S. Touloukian, R.K. Kirby, E.R. Taylor, T.Y.R. Lee, Thermal Expansion - Nonmetallic Solids, Thermophysical Properties of Matter - the TPRC Data Series, Volume 13, Thermophysical and Electronic Properties Information Analysis Center, Lafayette, IN, 1977.

[6] Y.S. Touloukian, E.H. Buyco, Specific Heat - Nonmetallic Solids, Thermophysical Properties of Matter - the TPRC Data Series, Thermophysical and Electronic Properties Information Analysis Center, Lafayette, IN, 1970.

[7] F. Marchbanks, M.A. Moen, R.E. Irvin, Nuclear Systems Materials Handbook: Supporting Documentation for Design Data, International Conference on the Mechanical Behavior of Materials, Oak Ridge National Laboratory, Boston, MA, USA, 1976.

7 Refractory Ceramics

7.2 Carbides

Room Temperature Properties

Molar Mass, [g/mol]	103.23
Theoretical Density, [kg/m^3]	6,730
Melting Point, [K]	3693±30
Specific Heat, [J/(g-K)]	0.363
Thermal Conductivity, [W/(m-K)]	26.3
Linear expansion coefficient, [μm/(m-K)]	5.10
Electrical resistivity, [μΩ-m]	0.61
Young's Modulus, [GPa]	397.9
Shear Modulus, [GPa]	161.8
Poisson's Ratio, [-]	0.229

Zirconium – Carbon Phase Diagram

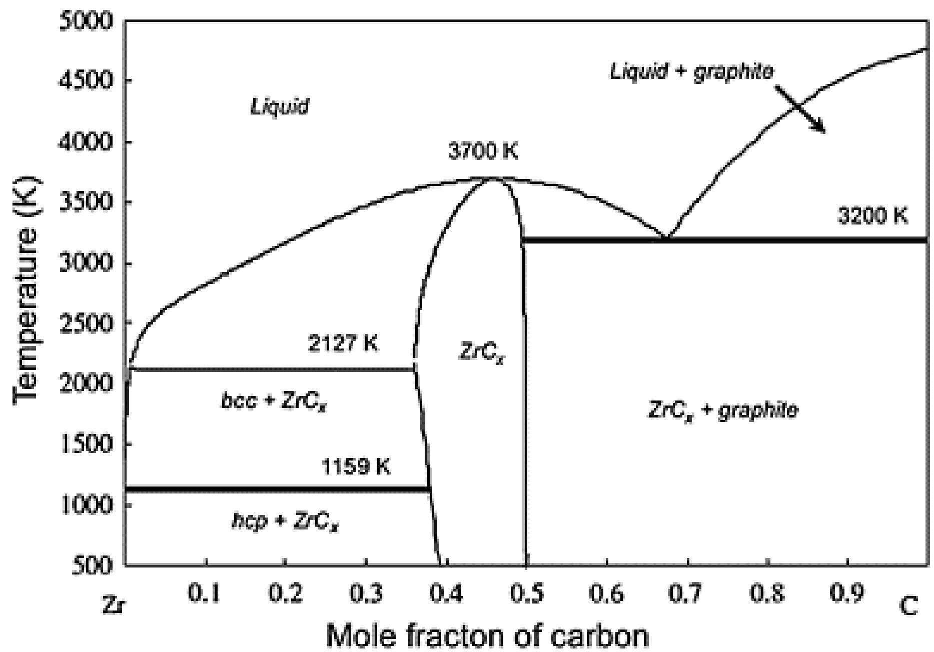

Figure 7.2.2-1: Zirconium – Carbon Phase Diagram [1].

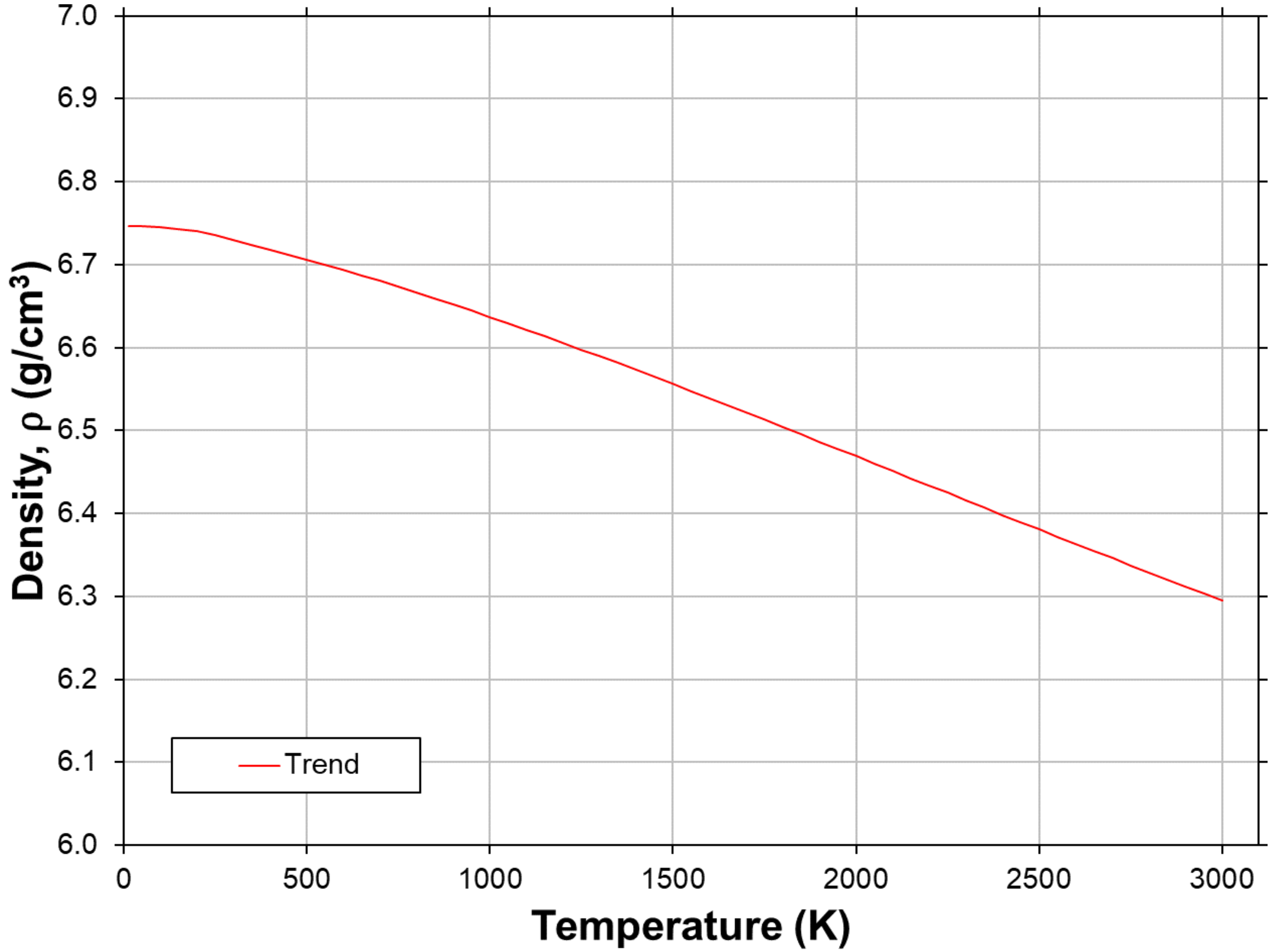

Figure 7.2.2-2: Density versus Temperature for ZrC. Calculated from fitted trend of the Thermal Expansion data.

100% Theoretical Density

Temperature (T)		Density (ρ)		Temperature (T)		Density (ρ)	
K	(°F)	kg/m^3	(lb/ft^3)	K	(°F)	kg/m^3	(lb/ft^3)
100	(-279.7)	6745	(421.1)	1600	(2420.3)	6539	(408.2)
200	(-99.7)	6740	(420.8)	1700	(2600.3)	6522	(407.2)
300	(80.3)	6729	(420.1)	1800	(2780.3)	6504	(406.1)
400	(260.3)	6718	(419.4)	1900	(2960.3)	6487	(405.0)
500	(440.3)	6706	(418.7)	2000	(3140.3)	6469	(403.9)
600	(620.3)	6694	(417.9)	2100	(3320.3)	6451	(402.8)
700	(800.3)	6680	(417.0)	2200	(3500.3)	6434	(401.6)
800	(980.3)	6666	(416.2)	2300	(3680.3)	6416	(400.5)
900	(1160.3)	6652	(415.3)	2400	(3860.3)	6398	(399.4)
1000	(1340.3)	6637	(414.3)	2500	(4040.3)	6381	(398.3)
1100	(1520.3)	6622	(413.4)	2600	(4220.3)	6363	(397.3)
1200	(1700.3)	6606	(412.4)	2700	(4400.3)	6346	(396.2)
1300	(1880.3)	6590	(411.4)	2800	(4580.3)	6329	(395.1)
1400	(2060.3)	6573	(410.4)	2900	(4760.3)	6312	(394.1)
1500	(2240.3)	6556	(409.3)	3000	(4940.3)	6296	(393.0)

Application Notes: Density is calculated as a function of Thermal Expansion, as seen in the equation below to approximate the property trend with respect to temperature.

Density Calculation:

$\rho(T) = \rho_{RT}/(1 + dL/L_0(T)/100)^3$

$\rho(T) = Density\ [kg/m^3]$

$Room\ Temperature\ Density\ (\rho_{RT}) = 6{,}730\ [kg/m^3]$

$T = Temperature\ [K]$

Temperature Range: $12 \leq T \leq 3000$

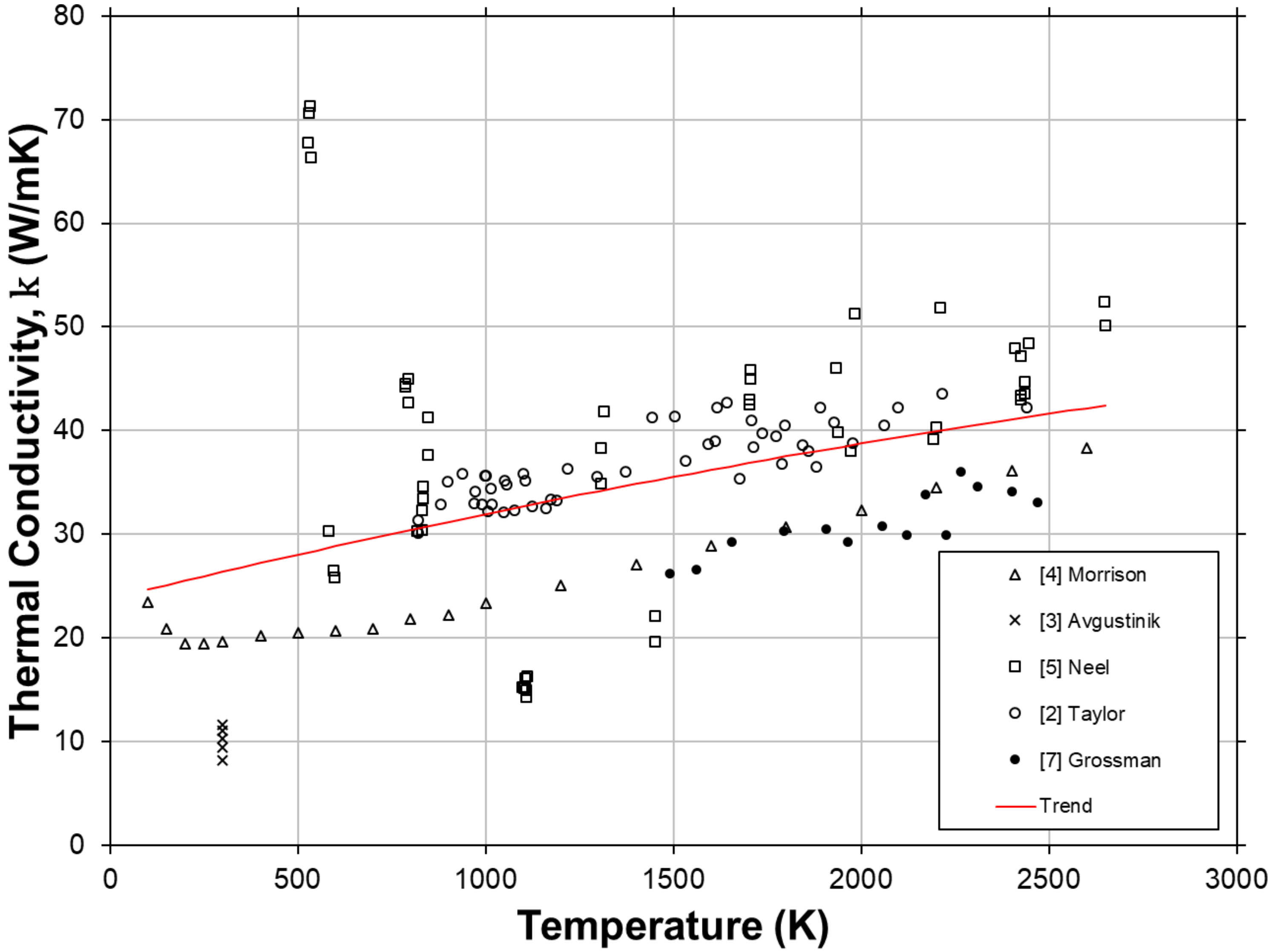

Figure 7.2.2-3: Thermal Conductivity versus Temperature for ZrC.

100% Theoretical Density

Temperature (T)		Thermal Conductivity (k)		Temperature (T)		Thermal Conductivity (k)	
K	(°F)	W/(m-K)	((Btu·in)/(ft^2·hr·°F))	K	(°F)	W/(m-K)	((Btu·in)/(ft^2·hr·°F))
100	(-279.7)	24.64	(170.98)	1400	(2060.3)	34.85	(241.76)
150	(-189.7)	25.08	(174.00)	1500	(2240.3)	35.53	(246.52)
200	(-99.7)	25.51	(177.00)	1600	(2420.3)	36.20	(251.19)
300	(80.3)	26.37	(182.94)	1700	(2600.3)	36.86	(255.76)
400	(260.3)	27.21	(188.77)	1800	(2780.3)	37.51	(260.23)
500	(440.3)	28.03	(194.51)	1900	(2960.3)	38.14	(264.61)
600	(620.3)	28.85	(200.15)	2000	(3140.3)	38.75	(268.88)
700	(800.3)	29.65	(205.69)	2100	(3320.3)	39.36	(273.06)
800	(980.3)	30.43	(211.13)	2200	(3500.3)	39.95	(277.14)
900	(1160.3)	31.20	(216.48)	2300	(3680.3)	40.52	(281.13)
1000	(1340.3)	31.96	(221.73)	2400	(3860.3)	41.08	(285.02)
1100	(1520.3)	32.70	(226.89)	2500	(4040.3)	41.63	(288.81)
1200	(1700.3)	33.43	(231.94)	2600	(4220.3)	42.16	(292.50)
1300	(1880.3)	34.14	(236.90)	2650	(4310.3)	42.42	(294.31)

Application Notes: Data for thermal conductivity is collected from references [2-7] and fitted with the equation below to approximate the property trend with respect to temperature. There is a large scatter in this data, which is primarily experimental. Due to this scatter, the trend attempts to capture the behavior of lower points.

Fit Equation:

$$k(T) = A0 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2$$

$k(T) = Thermal\ Conductivity\ [W\ /\ (m \cdot K)]$

$T = Temperature\ [K]$

Constants:

T Range [K]:	$100 \leq T \leq 2650$
A0 =	23.76
A1 =	8.900
A2 =	-0.7014

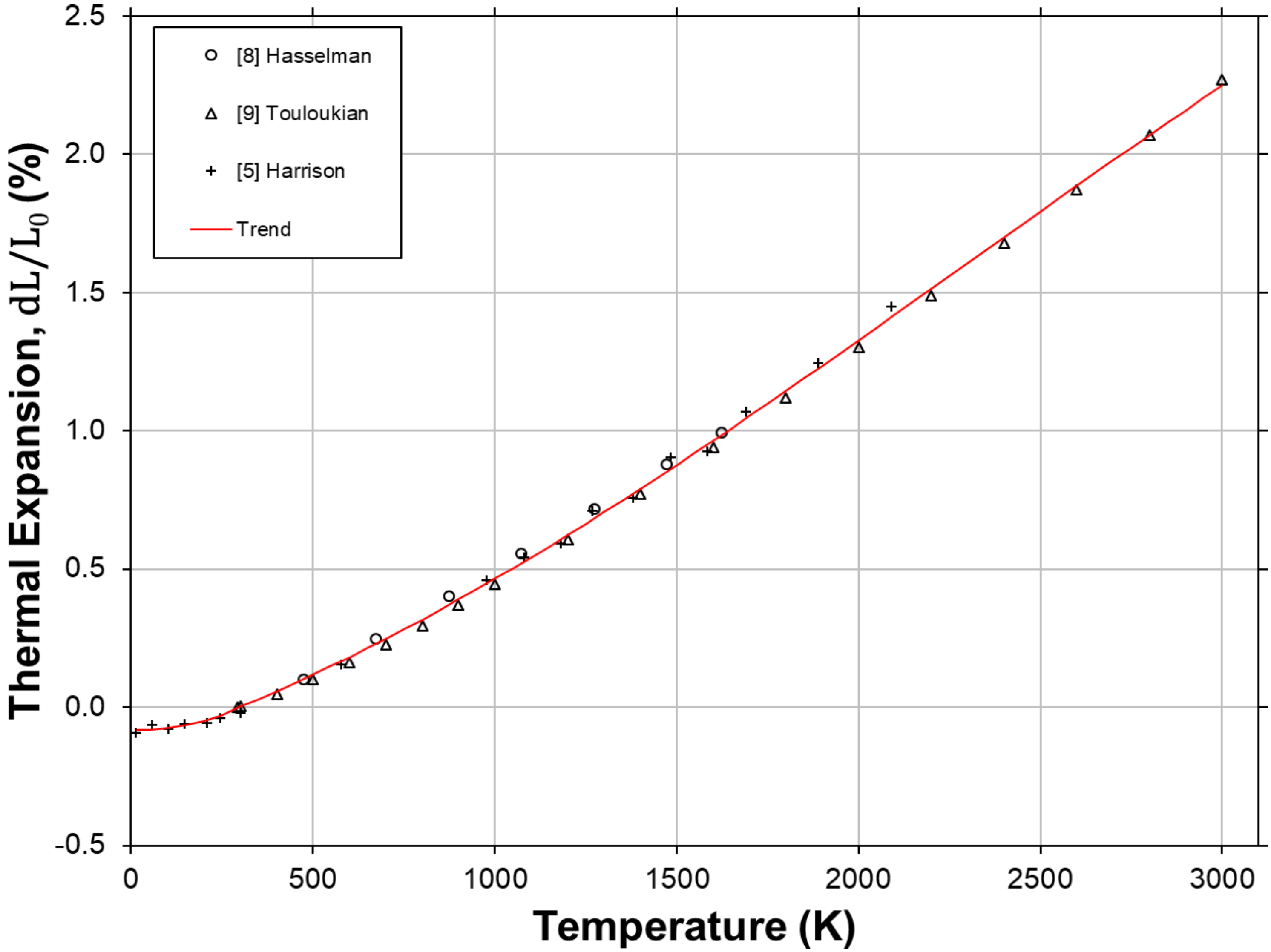

Figure 7.2.2-4: Thermal Expansion versus Temperature for ZrC.

100% Theoretical Density

Temperature (T)		Thermal Expansion (dL/L_0)	Temperature (T)		Thermal Expansion (dL/L_0)
K	(°F)	%	K	(°F)	%
100	(-279.7)	-0.076	1600	(2420.3)	0.964
200	(-99.7)	-0.050	1700	(2600.3)	1.053
300	(80.3)	0.003	1800	(2780.3)	1.143
400	(260.3)	0.058	1900	(2960.3)	1.235
500	(440.3)	0.118	2000	(3140.3)	1.327
600	(620.3)	0.181	2100	(3320.3)	1.420
700	(800.3)	0.247	2200	(3500.3)	1.513
800	(980.3)	0.317	2300	(3680.3)	1.606
900	(1160.3)	0.390	2400	(3860.3)	1.700
1000	(1340.3)	0.465	2500	(4040.3)	1.793
1100	(1520.3)	0.543	2600	(4220.3)	1.886
1200	(1700.3)	0.623	2700	(4400.3)	1.978
1300	(1880.3)	0.705	2800	(4580.3)	2.069
1400	(2060.3)	0.790	2900	(4760.3)	2.160
1500	(2240.3)	0.876	3000	(4940.3)	2.249

Application Notes: Data for thermal expansion is collected from references [6, 8, 9] and fitted with the equation below to approximate the property trend with respect to temperature.

Fit Equation:

$$dL/L_0\,(T) = A0 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2 + A3 \cdot \left(\frac{T}{1000}\right)^3$$

$dL/L_0\,(T) = Thermal\ Expansion\ [\%]$

$T = Temperature\ [K]$

Constants:

T Range [K]:	$12 \le T \le 293$	$293 < T \le 3000$
A0 =	-0.07982	-0.1399
A1 =	-0.07271	0.4103
A2 =	1.118	0.2274
A3 =	0	-0.03291

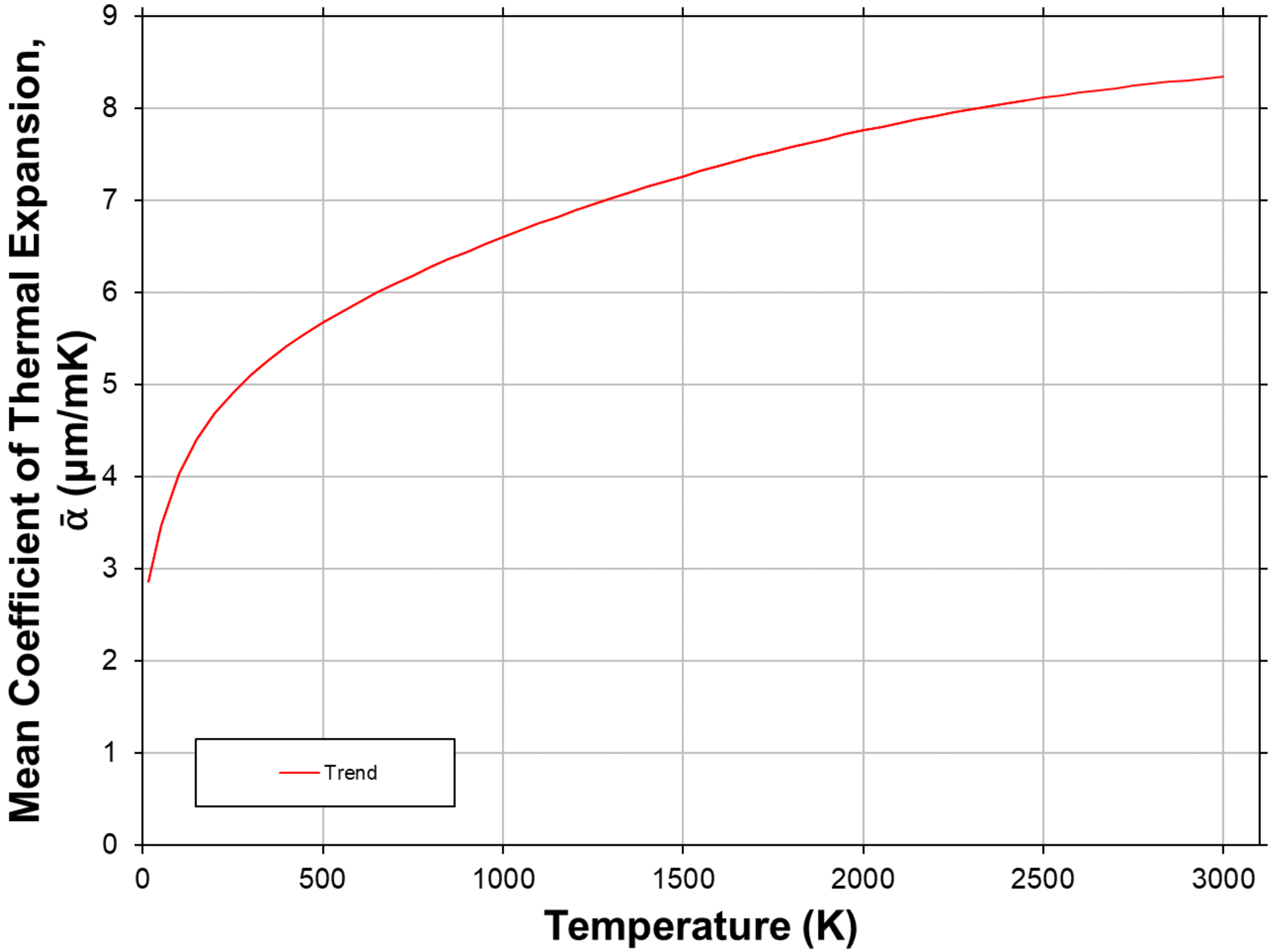

Figure 7.2.2-5: Mean Coefficient of Thermal Expansion versus Temperature for ZrC.

100% Theoretical Density

Temperature (T)		Mean CTE (ᾱ)		Temperature (T)		Mean CTE (ᾱ)	
K	(°F)	μm/(m-K)	(μin/(in-°F))	K	(°F)	μm/(m-K)	(μin/(in-°F))
100	(-279.7)	4.028	(2.238)	1600	(2420.3)	7.372	(4.096)
200	(-99.7)	4.687	(2.604)	1700	(2600.3)	7.477	(4.154)
300	(80.3)	5.103	(2.835)	1800	(2780.3)	7.576	(4.209)
400	(260.3)	5.415	(3.008)	1900	(2960.3)	7.669	(4.261)
500	(440.3)	5.672	(3.151)	2000	(3140.3)	7.757	(4.309)
600	(620.3)	5.894	(3.275)	2100	(3320.3)	7.838	(4.355)
700	(800.3)	6.093	(3.385)	2200	(3500.3)	7.915	(4.397)
800	(980.3)	6.276	(3.486)	2300	(3680.3)	7.986	(4.437)
900	(1160.3)	6.444	(3.580)	2400	(3860.3)	8.052	(4.473)
1000	(1340.3)	6.601	(3.667)	2500	(4040.3)	8.112	(4.507)
1100	(1520.3)	6.749	(3.750)	2600	(4220.3)	8.167	(4.537)
1200	(1700.3)	6.888	(3.827)	2700	(4400.3)	8.217	(4.565)
1300	(1880.3)	7.020	(3.900)	2800	(4580.3)	8.262	(4.590)
1400	(2060.3)	7.144	(3.969)	2900	(4760.3)	8.302	(4.612)
1500	(2240.3)	7.261	(4.034)	3000	(4940.3)	8.337	(4.631)

Application Notes: Data for mean coefficient of thermal expansion is calculated as a function of thermal expansion. Calculated data was fitted with the equation below to approximate property trend with respect to temperature.

Fit Equation:

$$\bar{\alpha}(T) = \left[A0 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2 + A3 \cdot \left(\frac{T}{1000}\right)^3\right] / \left[1 + A\_0 \cdot \left(\frac{T}{1000}\right)\right]$$

$\bar{\alpha}(T) = Coefficient\ of\ Thermal\ Expansion\ [\mu m/(m \cdot K)]$

$T = Temperature\ [K]$

Constants:

T. Range [K]: $12 \leq T \leq 3000$

A0 = 2.49

A1 = 49.67

A2 = 15.26

A3 = -2.158

A_0 = 8.886

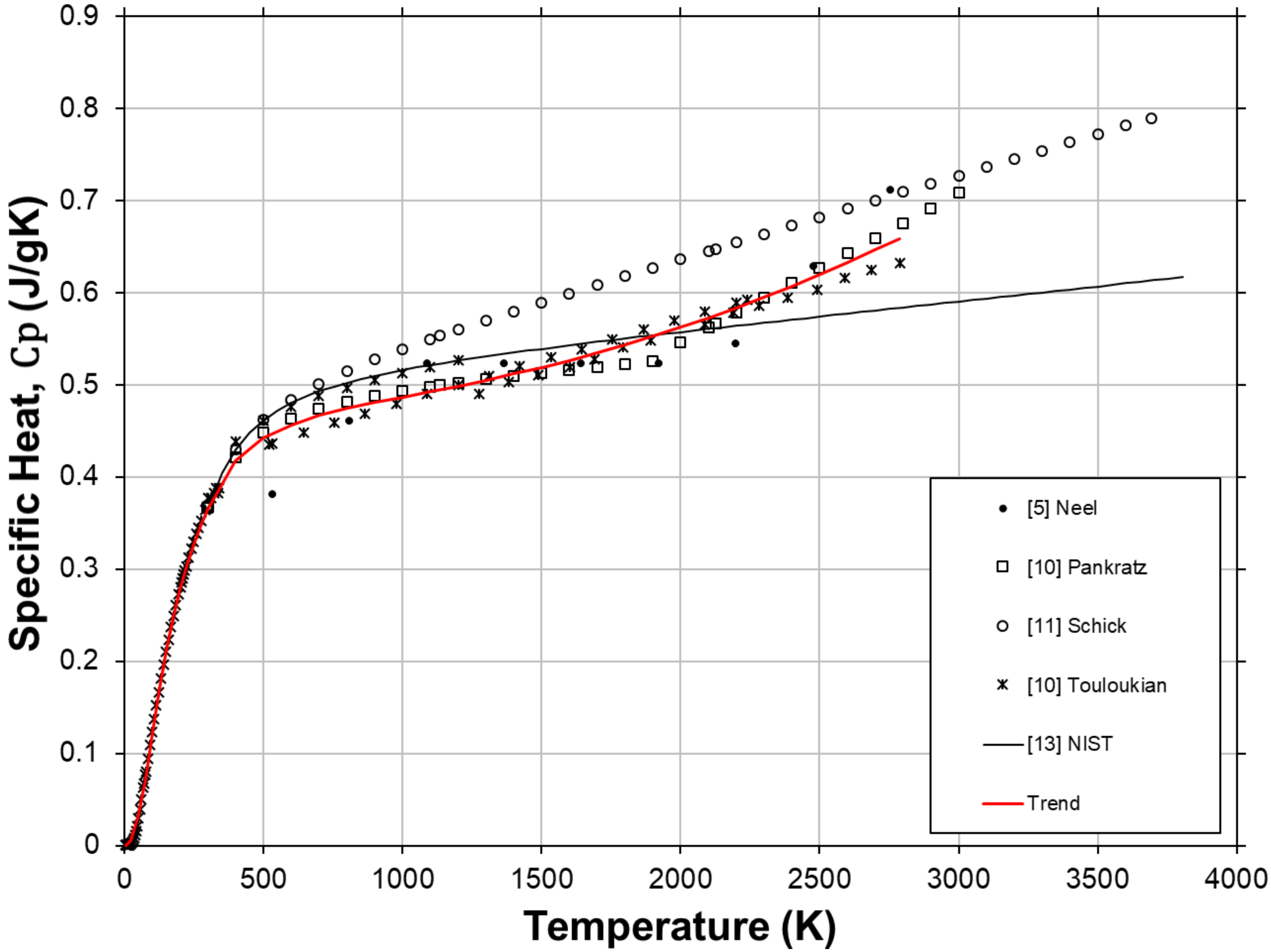

Figure 7.2.2-6: Specific Heat verses Temperature for ZrC. Displaying fit and data with comparison to NIST Webbook, and The Atomic Energy Review.

100% Theoretical Density

Temperature (T)		Specific Heat (C_p)		Temperature (T)		Specific Heat (C_p)	
K	(°F)	J/(g-K)	(BTU/(lb-°F))	K	(°F)	J/(g-K)	(BTU/(lb-°F))
100	(-279.7)	0.122	(0.029)	1400	(2060.3)	0.512	(0.122)
200	(-99.7)	0.278	(0.066)	1500	(2240.3)	0.519	(0.124)
300	(80.3)	0.364	(0.087)	1600	(2420.3)	0.526	(0.126)
400	(260.3)	0.417	(0.100)	1700	(2600.3)	0.535	(0.128)
500	(440.3)	0.442	(0.106)	1800	(2780.3)	0.543	(0.130)
600	(620.3)	0.457	(0.109)	1900	(2960.3)	0.552	(0.132)
700	(800.3)	0.466	(0.111)	2000	(3140.3)	0.562	(0.134)
800	(980.3)	0.474	(0.113)	2100	(3320.3)	0.572	(0.137)
900	(1160.3)	0.480	(0.115)	2200	(3500.3)	0.583	(0.139)
1000	(1340.3)	0.486	(0.116)	2300	(3680.3)	0.595	(0.142)
1100	(1520.3)	0.492	(0.118)	2400	(3860.3)	0.607	(0.145)
1200	(1700.3)	0.498	(0.119)	2600	(4220.3)	0.632	(0.151)
1300	(1880.3)	0.505	(0.121)	2788	(4558.7)	0.658	(0.157)

Application Notes: Data for specific heat is collected from references [5, 6, 10-12] and fitted with the equations below to approximate the property trend with respect to temperature. Fitted trend is compared to trends from references[13, 14].

Fit Equation:

For temperature range: $4 < T \leq 294$

$$C_P(T) = \left[A0 \cdot \left(\frac{T}{1000}\right)^N\right] \Big/ \left[1 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2\right]$$

For temperature range: $294 < T \leq 2788$

$$C_P(T) = B0 + B1 \cdot \left(\frac{T}{1000}\right) + B2 \cdot \left(\frac{T}{1000}\right)^2 + B\_2 / \left(\frac{T}{1000}\right)^2$$

$C_P(T) = Specific\ Heat\ [J/(g \cdot K)]$

$T = Temperature\ [K]$

Constants:

T. Range [K]:	$5 \leq T < 293$		$293 \leq T \leq 2788$
N =	2.509	B0 =	0.4889
A0 =	52.73	B1 =	-0.02133
A1 =	-4.986	B2 =	0.02964
A2 =	83.5	B_2 =	-0.01088

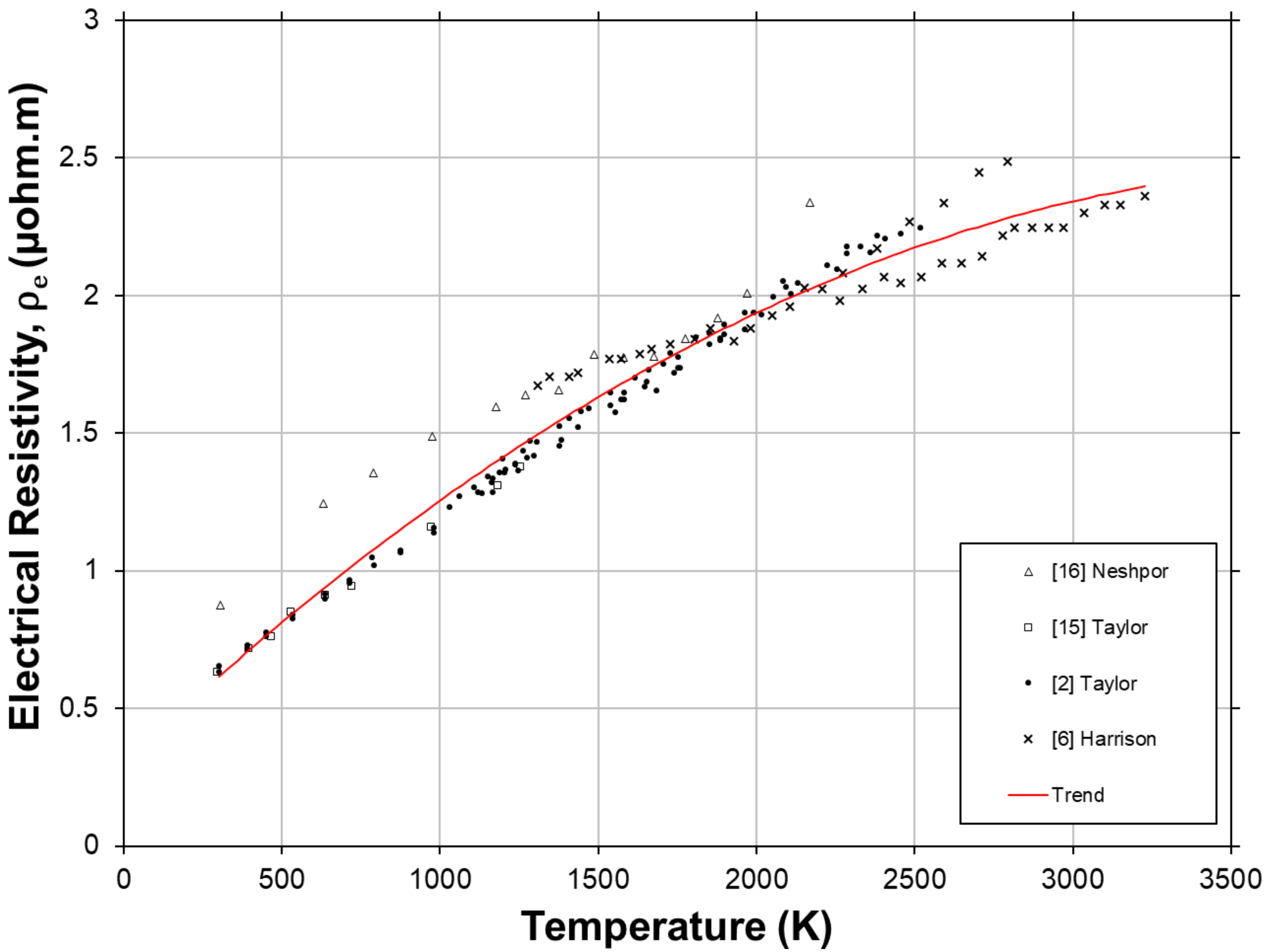

Figure 7.2.2-7: Electrical Resistivity versus Temperature for ZrC.

100% Theoretical Density

Temperature (T)		Electrical Resistivity (ρ_e)		Temperature (T)		Electrical Resistivity (ρ_e)	
K	(°F)	μΩ-m	(μΩ-in)	K	(°F)	μΩ-m	(μΩ-in)
290	(62.3)	0.605	(23.81)	1800	(2780.3)	1.822	(71.74)
400	(260.3)	0.715	(28.14)	1900	(2960.3)	1.881	(74.04)
500	(440.3)	0.812	(31.96)	2000	(3140.3)	1.936	(76.23)
600	(620.3)	0.906	(35.67)	2100	(3320.3)	1.989	(78.32)
700	(800.3)	0.997	(39.27)	2200	(3500.3)	2.039	(80.29)
800	(980.3)	1.086	(42.76)	2300	(3680.3)	2.087	(82.16)
900	(1160.3)	1.172	(46.15)	2400	(3860.3)	2.132	(83.92)
1000	(1340.3)	1.255	(49.43)	2500	(4040.3)	2.173	(85.57)
1100	(1520.3)	1.336	(52.59)	2600	(4220.3)	2.213	(87.11)
1200	(1700.3)	1.414	(55.65)	2700	(4400.3)	2.249	(88.55)
1300	(1880.3)	1.489	(58.61)	2800	(4580.3)	2.283	(89.87)
1400	(2060.3)	1.561	(61.45)	2900	(4760.3)	2.314	(91.09)
1500	(2240.3)	1.630	(64.18)	3000	(4940.3)	2.342	(92.20)
1600	(2420.3)	1.697	(66.81)	3150	(5210.3)	2.379	(93.66)
1700	(2600.3)	1.761	(69.33)	3300	(5480.3)	2.410	(94.87)

Application Notes: Data for electrical resistivity is collected from references [2, 6, 15, 16] and fitted with the equation below to approximate the property trend with respect to temperature.

Fit Equation:

$$\rho_e(T) = A0 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2$$

$\rho_e(T) = Electrical\ Resistivity\ [\mu\Omega \cdot m]$

$T = Temperature\ [K]$

Constants:

T. Range [K]: $290 \leq T < 3300$

A0 = 0.2991

A1 = 1.094

A2 = -0.1377

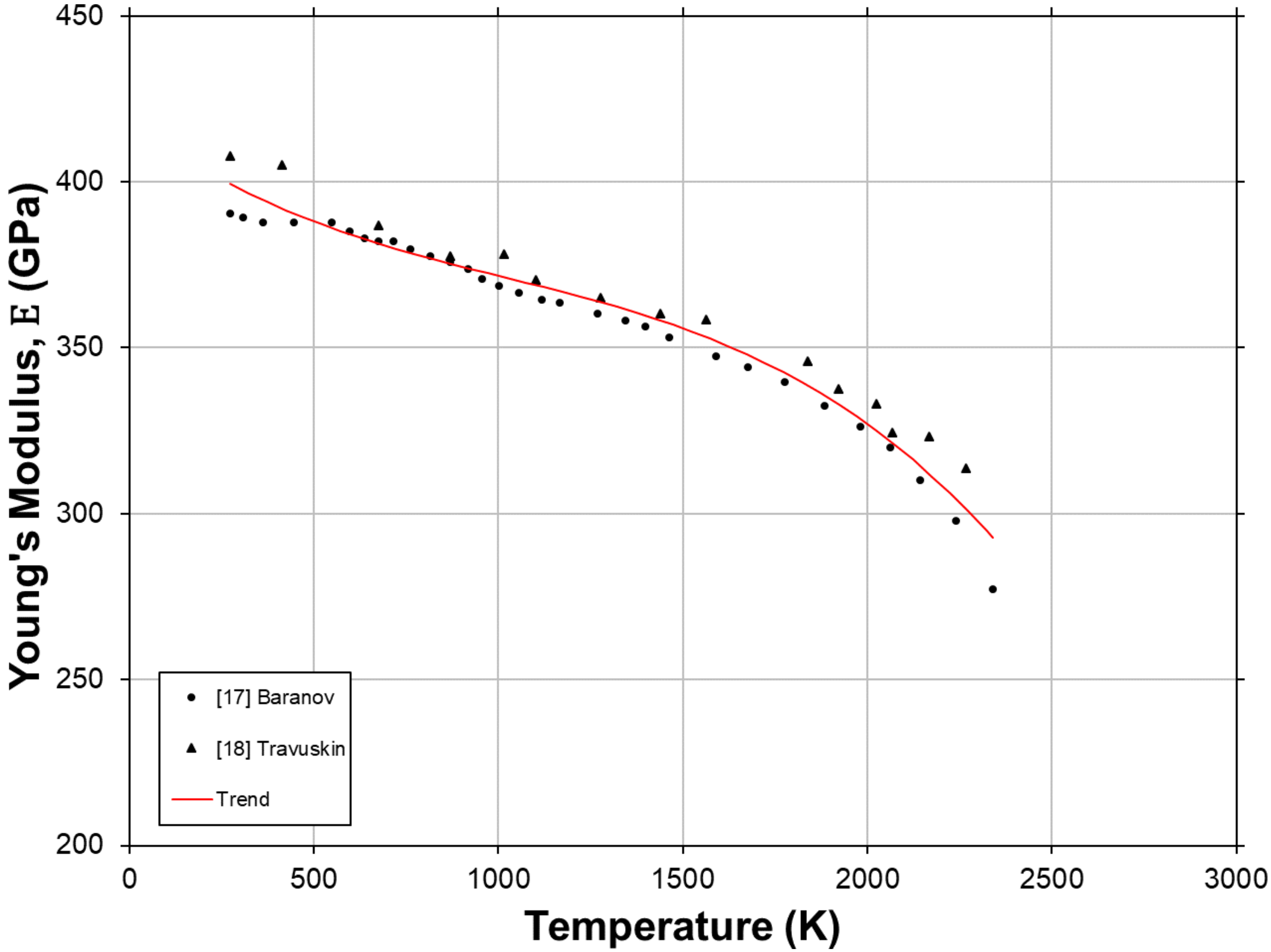

Figure 7.2.2-8: Young's Modulus versus Temperature for ZrC.

100% Theoretical Density

Temperature (T)		Young's Modulus (E)		Temperature (T)		Young's Modulus (E)	
K	(°F)	GPa	(Msi)	K	(°F)	GPa	(Msi)
273	(31.7)	399.37	(57.95)	1000	(1340.3)	371.66	(53.93)
300	(80.3)	397.83	(57.72)	1100	(1520.3)	368.90	(53.53)
350	(170.3)	395.11	(57.33)	1200	(1700.3)	366.06	(53.12)
400	(260.3)	392.58	(56.96)	1300	(1880.3)	363.03	(52.68)
450	(350.3)	390.22	(56.62)	1400	(2060.3)	359.68	(52.19)
500	(440.3)	388.02	(56.30)	1500	(2240.3)	355.92	(51.64)
550	(530.3)	385.96	(56.00)	1600	(2420.3)	351.64	(51.02)
600	(620.3)	384.03	(55.72)	1700	(2600.3)	346.71	(50.31)
650	(710.3)	382.22	(55.46)	1800	(2780.3)	341.04	(49.48)
700	(800.3)	380.52	(55.21)	1900	(2960.3)	334.50	(48.54)
750	(890.3)	378.90	(54.98)	2000	(3140.3)	327.00	(47.45)
800	(980.3)	377.35	(54.75)	2100	(3320.3)	318.42	(46.20)
850	(1070.3)	375.87	(54.54)	2200	(3500.3)	308.65	(44.78)
900	(1160.3)	374.44	(54.33)	2300	(3680.3)	297.57	(43.18)
950	(1250.3)	373.04	(54.13)	2340	(3752.3)	292.75	(42.48)

Application Notes: Data for Young's modulus is collected from references [17, 18] and fitted with the equation below to approximate the property trend with respect to temperature.

Fit Equations:

$$E(T) = A0 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2 + A3 \cdot \left(\frac{T}{1000}\right)^3$$

$E(T) = Young's\ Modulus\ [GPa]$

$T = Temperature\ [K]$

Constants:

T. Range [K]: $273 \leq T < 2340$

A0 =	418.8
A1 =	-85.2
A2 =	56.47
A3 =	-18.41

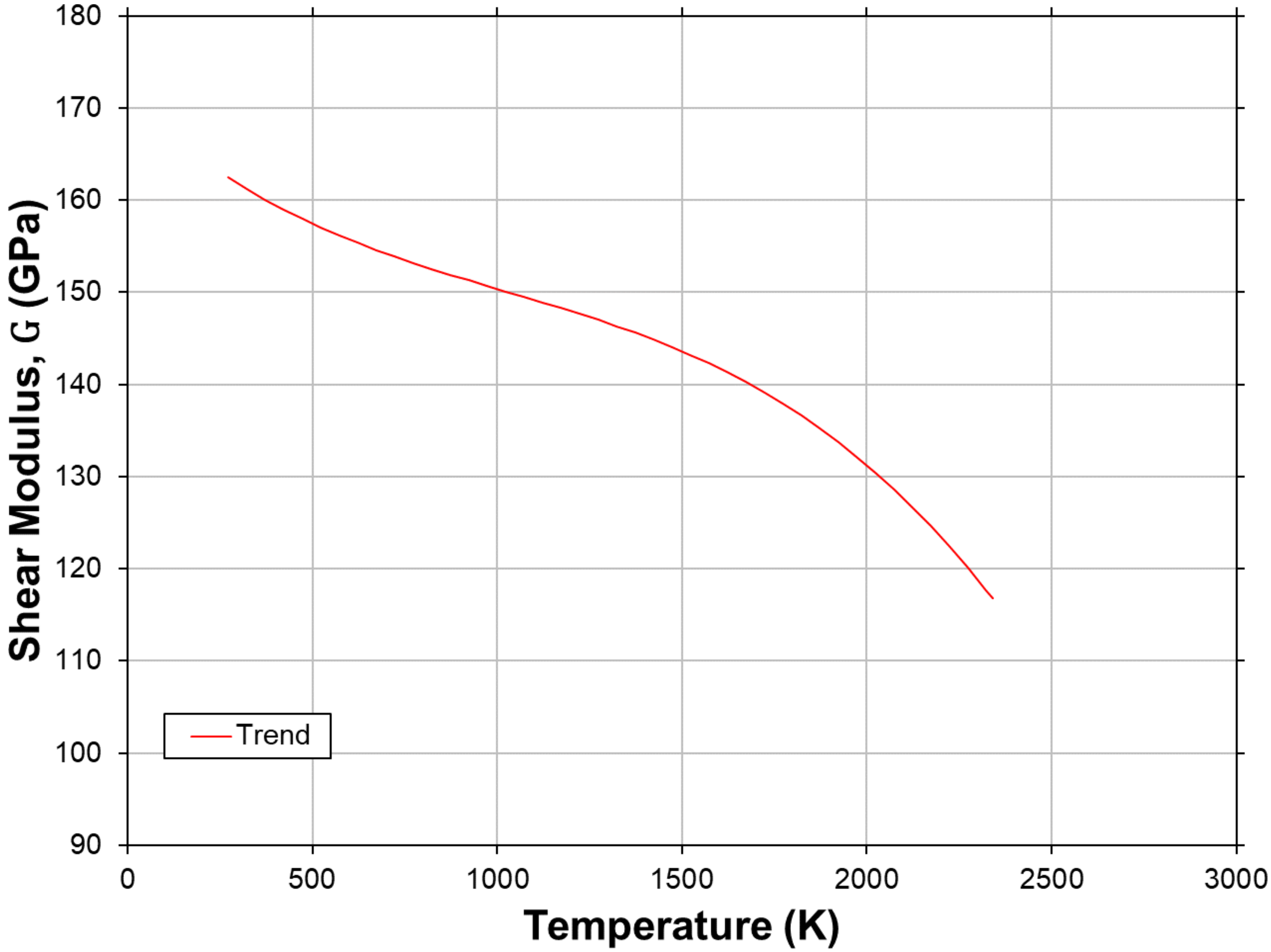

Figure 7.2.2-9: Shear Modulus versus Temperature for ZrC.

100% Theoretical Density

Temperature (T)		Shear Modulus (G)		Temperature (T)		Shear Modulus (G)	
K	(°F)	GPa	(Msi)	K	(°F)	GPa	(Msi)
273	(31.7)	162.47	(23.57)	1000	(1340.3)	150.36	(21.82)
300	(80.3)	161.78	(23.47)	1100	(1520.3)	149.17	(21.65)
350	(170.3)	160.59	(23.30)	1200	(1700.3)	147.95	(21.47)
400	(260.3)	159.47	(23.14)	1300	(1880.3)	146.65	(21.28)
450	(350.3)	158.44	(22.99)	1400	(2060.3)	145.22	(21.07)
500	(440.3)	157.47	(22.85)	1500	(2240.3)	143.60	(20.84)
550	(530.3)	156.57	(22.72)	1600	(2420.3)	141.77	(20.57)
600	(620.3)	155.73	(22.60)	1700	(2600.3)	139.66	(20.26)
650	(710.3)	154.94	(22.48)	1800	(2780.3)	137.24	(19.91)
700	(800.3)	154.20	(22.37)	1900	(2960.3)	134.45	(19.51)
750	(890.3)	153.49	(22.27)	2000	(3140.3)	131.26	(19.05)
800	(980.3)	152.82	(22.17)	2100	(3320.3)	127.61	(18.52)
850	(1070.3)	152.18	(22.08)	2200	(3500.3)	123.47	(17.92)
900	(1160.3)	151.56	(21.99)	2300	(3680.3)	118.80	(17.24)
950	(1250.3)	150.96	(21.90)	2340	(3752.3)	116.77	(16.94)

Application Notes: Shear modulus is calculated as a function of Young's modulus and Poisson's Ratio using the equation below to approximate property trend with respect to temperature.

Fit Equations:

$G(T) = 0.5 \cdot E(T)/(1 + \nu(T))$

$G(T) = Shear\ Modulus\ [GPa]$

$T = Temperature\ [K]$

Temperature Range: $273 \leq T \leq 2340$

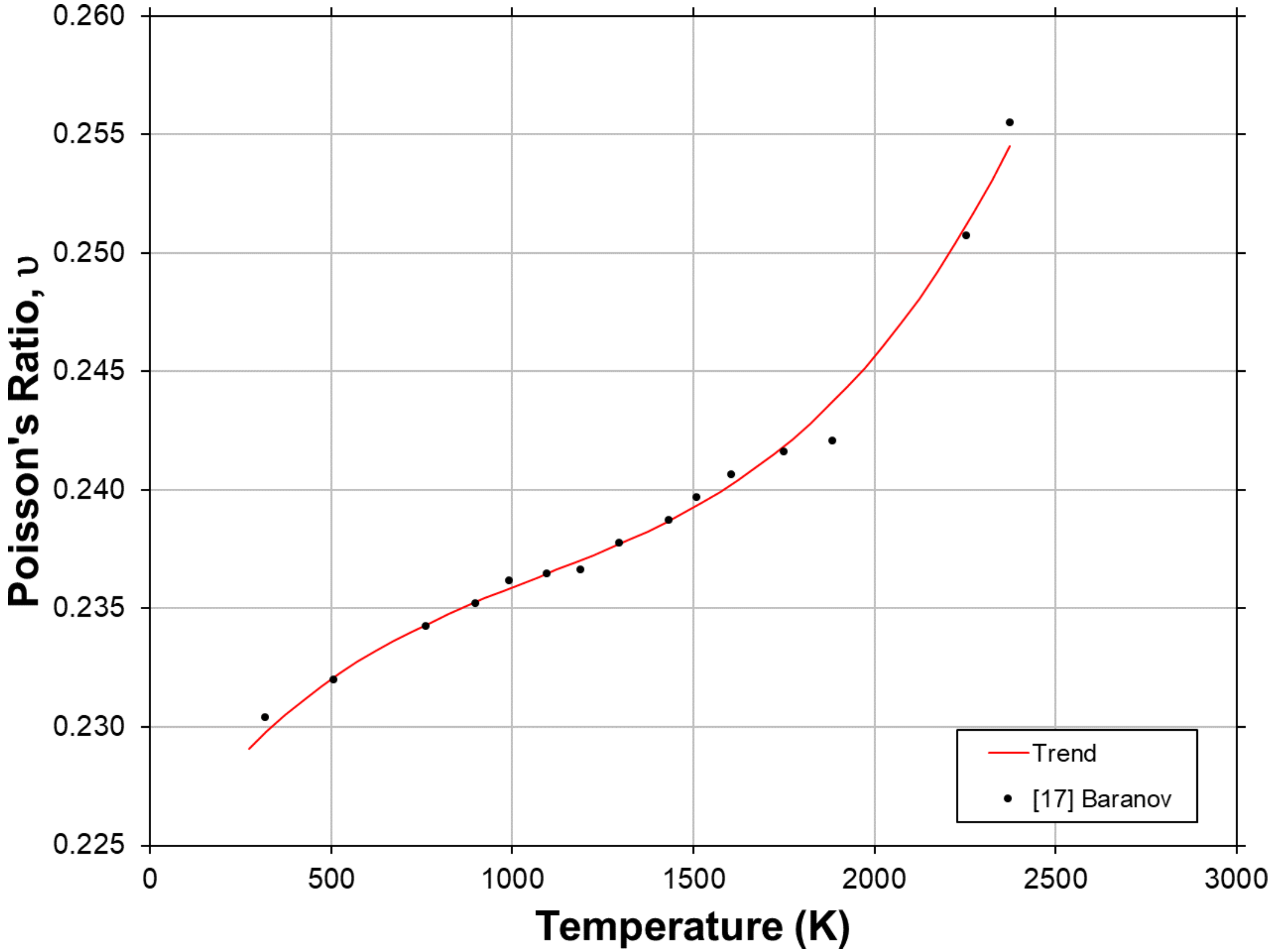

Figure 7.2.2-10: Poisson's Ratio versus Temperature for ZrC.

100% Theoretical Density

Temperature (T)		Poisson's Ratio (ν)	Temperature (T)		Poisson's Ratio (ν)
K	(°F)		K	(°F)	
273	(31.7)	0.229	1000	(1340.3)	0.236
300	(80.3)	0.229	1100	(1520.3)	0.236
350	(170.3)	0.230	1200	(1700.3)	0.237
400	(260.3)	0.231	1300	(1880.3)	0.238
450	(350.3)	0.231	1400	(2060.3)	0.238
500	(440.3)	0.232	1500	(2240.3)	0.239
550	(530.3)	0.233	1600	(2420.3)	0.240
600	(620.3)	0.233	1700	(2600.3)	0.241
650	(710.3)	0.233	1800	(2780.3)	0.242
700	(800.3)	0.234	1900	(2960.3)	0.244
750	(890.3)	0.234	2000	(3140.3)	0.246
800	(980.3)	0.235	2100	(3320.3)	0.248
850	(1070.3)	0.235	2200	(3500.3)	0.250
900	(1160.3)	0.235	2300	(3680.3)	0.252
950	(1250.3)	0.236	2375	(3815.3)	0.255

Application Notes: Data for Poisson's Ratio is collected from reference [17] and fitted with the equation below to approximate property trend with respect to temperature.

Fit Equations:

$$\boldsymbol{\nu}(T) = A0 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2 + A3 \cdot \left(\frac{T}{1000}\right)^3$$

$\boldsymbol{\nu}(T) = \textit{Poisson's Ratio}$ [-]

$T = Temperature\ [K]$

Constants:

T. Range [K]: $273 \leq T < 2375$

A0 = 0.224

A1 = 0.02248

A2 = -0.01534

A3 = 0.004755

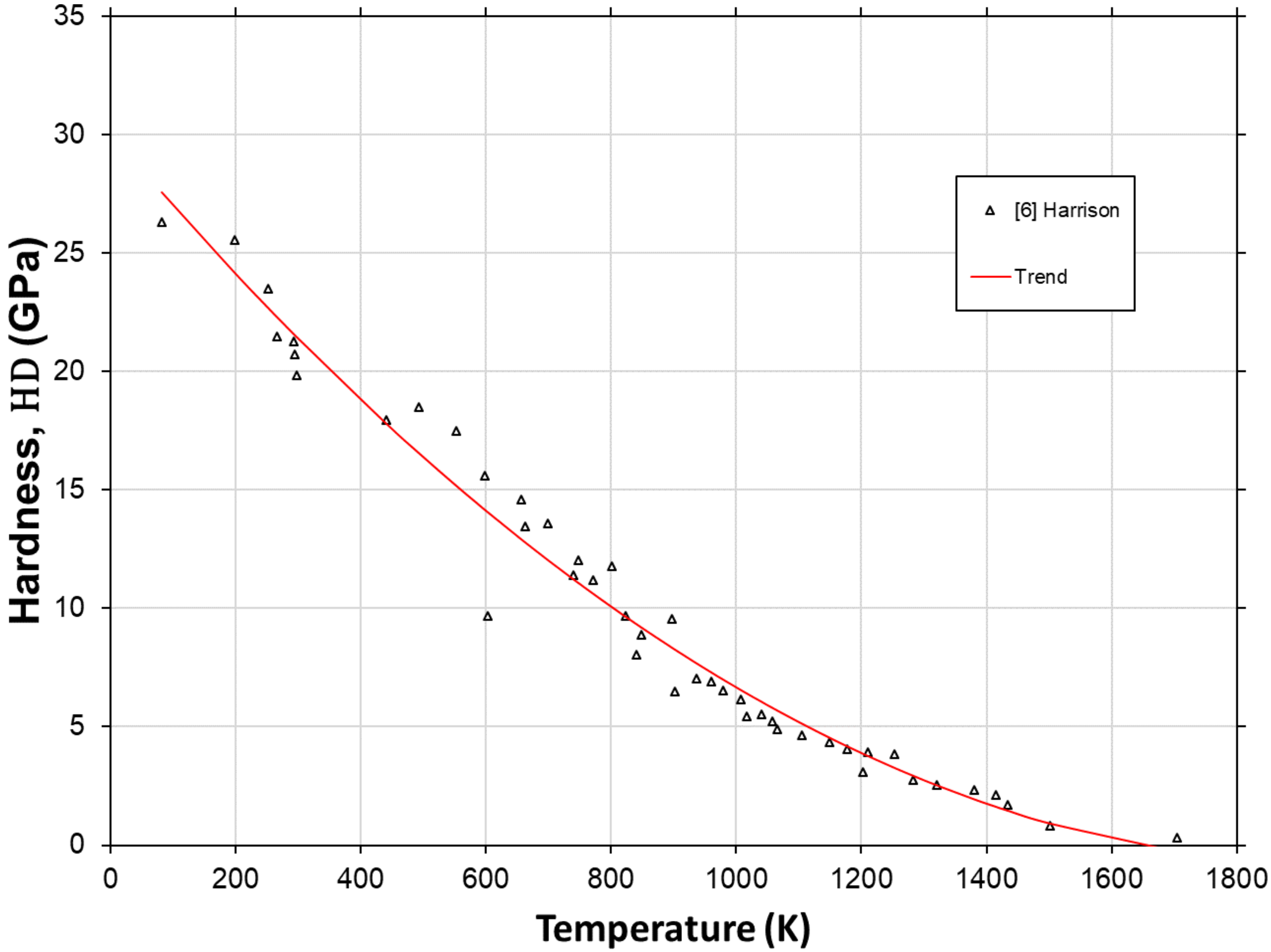

Figure 7.2.2-11: Hardness versus Temperature for ZrC.

100% Theoretical Density

Temperature (T) K	(°F)	Hardness (GPa)	Temperature (T) K	(°F)	Hardness (GPa)
80	(-315.7)	27.639	800	(980.3)	10.078
100	(-279.7)	27.040	850	(1070.3)	9.165
150	(-189.7)	25.569	900	(1160.3)	8.292
200	(-99.7)	24.139	950	(1250.3)	7.458
250	(-9.7)	22.748	1000	(1340.3)	6.665
300	(80.3)	21.397	1050	(1430.3)	5.911
350	(170.3)	20.086	1100	(1520.3)	5.198
400	(260.3)	18.814	1150	(1610.3)	4.524
450	(350.3)	17.583	1200	(1700.3)	3.890
500	(440.3)	16.391	1250	(1790.3)	3.295
550	(530.3)	15.239	1300	(1880.3)	2.741
600	(620.3)	14.127	1400	(2060.3)	1.751
650	(710.3)	13.055	1500	(2240.3)	0.921
700	(800.3)	12.023	1600	(2420.3)	0.250
750	(890.3)	11.030			

Application Notes: Data for hardness is collected from reference [6] and fitted with the equation below to approximate the property trend with respect to temperature.

Fit Equations:

$$HD(T) = A0 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2$$

$HD(T) = Hardness\ [GPa]$

$T = Temperature\ [K]$

Constants:

T. Range [K]: $80 \le T < 1600$

A0 = 30.1

A1 = -31.4

A2 = 7.965

Temp.	Physical and Electrical		Thermal				Elastic		
	Density	Electrical Resistivity	Thermal Conductivity	Thermal Expansion	Mean CTE	Specific Heat	Young's Modulus	Shear Modulus	Poisson's Ratio
(T) K	(ρ) kg/m³	(ρ_e) μΩ-m	(k) W/(m-K)	(dL/L_0) %	($\bar{\alpha}$) 10^{-6}/K	(C_p) J/(g-K)	(E) GPa	(G) GPa	(ν)
100	6745	-	24.64	-0.08	4.03	0.122	-	-	-
200	6740	-	25.51	-0.05	4.69	0.278	-	-	-
300	6729	0.615	26.37	0.00	5.10	0.364	397.8	161.8	0.229
400	6718	0.715	27.21	0.06	5.41	0.417	392.6	159.5	0.231
500	6706	0.812	28.03	0.12	5.67	0.442	388.0	157.5	0.232
600	6694	0.906	28.85	0.18	5.89	0.457	384.0	155.7	0.233
700	6680	0.997	29.65	0.25	6.09	0.466	380.5	154.2	0.234
800	6666	1.086	30.43	0.32	6.28	0.474	377.4	152.8	0.235
900	6652	1.172	31.20	0.39	6.44	0.480	374.4	151.6	0.235
1000	6637	1.255	31.96	0.46	6.60	0.486	371.7	150.4	0.236
1100	6622	1.336	32.70	0.54	6.75	0.492	368.9	149.2	0.236
1200	6606	1.414	33.43	0.62	6.89	0.498	366.1	148.0	0.237
1300	6590	1.489	34.14	0.71	7.02	0.505	363.0	146.6	0.238
1400	6573	1.561	34.85	0.79	7.14	0.512	359.7	145.2	0.238
1500	6556	1.630	35.53	0.88	7.26	0.519	355.9	143.6	0.239
1600	6539	1.697	36.20	0.96	7.37	0.526	351.6	141.8	0.240
1700	6522	1.761	36.86	1.05	7.48	0.535	346.7	139.7	0.241
1800	6504	1.822	37.51	1.14	7.58	0.543	341.0	137.2	0.242
1900	6487	1.881	38.14	1.23	7.67	0.552	334.5	134.5	0.244
2000	6469	1.936	38.75	1.33	7.76	0.562	327.0	131.3	0.246
2200	6434	2.039	39.95	1.51	7.91	0.583	308.6	123.5	0.250
2400	6398	2.132	41.08	1.70	8.05	0.607	-	-	-
2600	6363	2.213	42.16	1.89	8.17	0.632	-	-	-
2800	6329	2.283	-	2.07	8.26	-	-	-	-
3000	6296	2.342	-	2.25	8.34	-	-	-	-

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7 Refractory Ceramics

7.3 Nitrides

Room Temperature Properties

Molar Mass, [g/mol]	105.23
Theoretical Density, [kg/m^3]	7,350
Melting Point, [K]	3253
Specific Heat, [J/(g-K)]	0.388
Thermal Conductivity, [W/(m-K)]	6.2
Linear expansion coefficient, [μm/(m-K)]	6.62
Electrical resistivity, [μΩ-m]	0.22
Young's Modulus, [GPa]	366.8
Shear Modulus, [GPa]	149.9
Poisson's Ratio, [-]	0.223

Zirconium – Nitrogen Phase Diagram

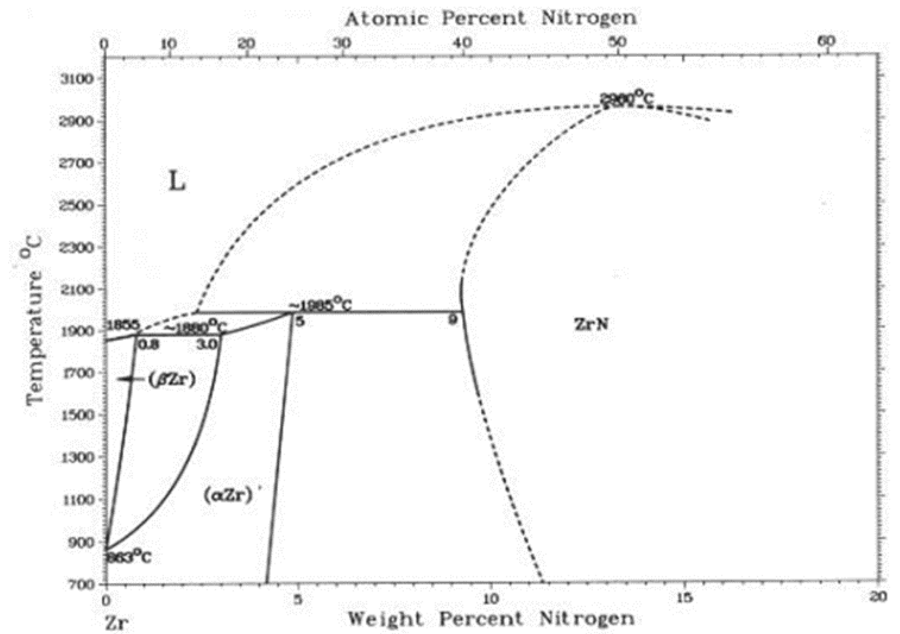

Figure 7.3.1-1: Zirconium – Nitrogen Phase Diagram [1].

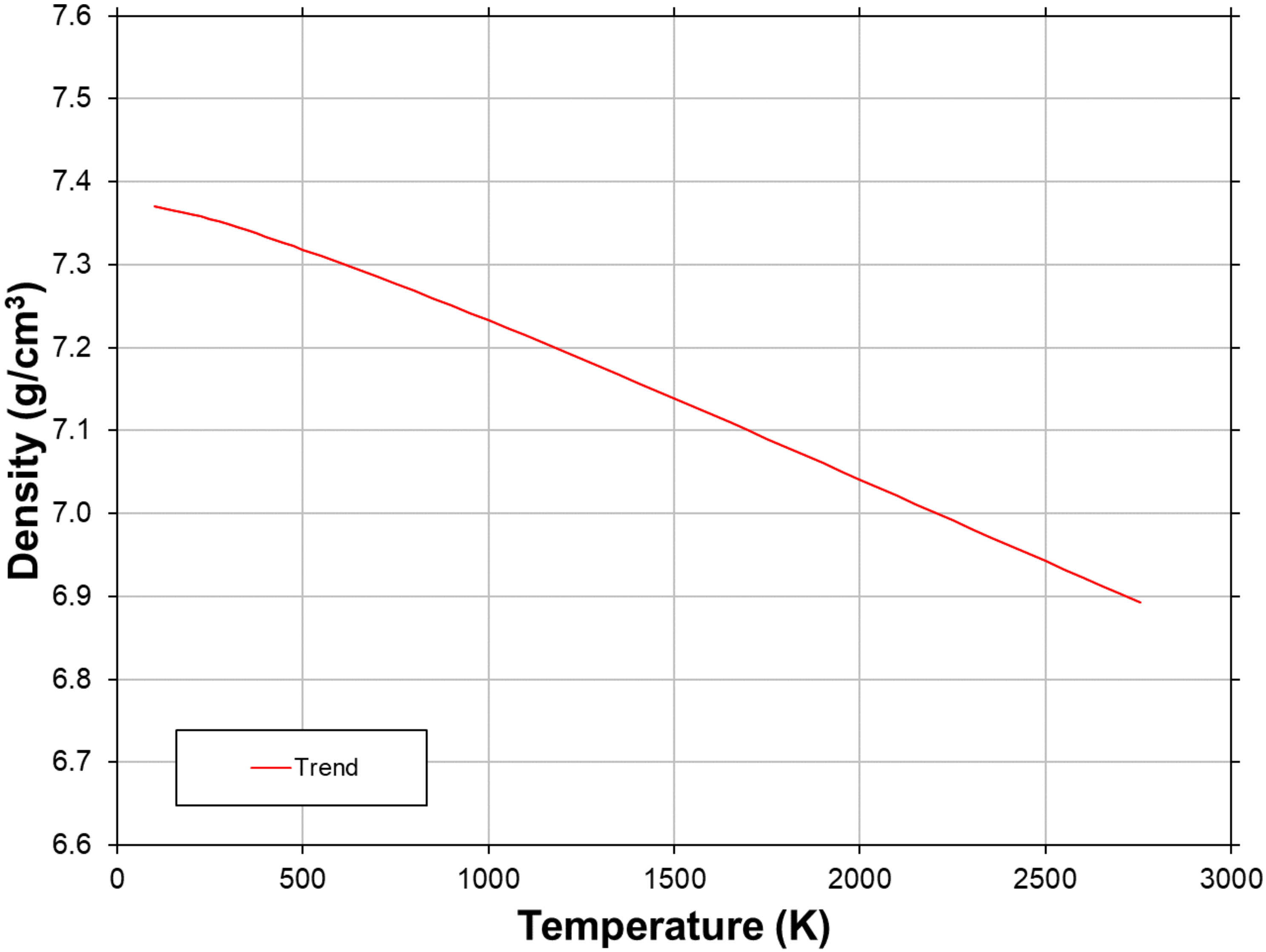

Figure 7.3.1-2: Density versus Temperature for ZrN. Calculated from fitted trend of the Thermal Expansion data.

100% Theoretical Density

Temperature (T)		Density (ρ)		Temperature (T)		Density (ρ)	
K	(°F)	kg/m^3	(lb/ft^3)	K	(°F)	kg/m^3	(lb/ft^3)
100	(-279.7)	7370	(460.1)	1400	(2060.3)	7158	(446.9)
150	(-189.7)	7366	(459.9)	1500	(2240.3)	7139	(445.7)
200	(-99.7)	7361	(459.5)	1600	(2420.3)	7120	(444.5)
250	(-9.7)	7355	(459.2)	1700	(2600.3)	7100	(443.3)
300	(80.3)	7349	(458.8)	1800	(2780.3)	7080	(442.0)
400	(260.3)	7334	(457.9)	1900	(2960.3)	7061	(440.8)
500	(440.3)	7318	(456.9)	2000	(3140.3)	7041	(439.6)
600	(620.3)	7302	(455.9)	2100	(3320.3)	7021	(438.3)
700	(800.3)	7285	(454.8)	2200	(3500.3)	7001	(437.1)
800	(980.3)	7268	(453.8)	2300	(3680.3)	6982	(435.9)
900	(1160.3)	7251	(452.7)	2400	(3860.3)	6962	(434.6)
1000	(1340.3)	7233	(451.5)	2500	(4040.3)	6942	(433.4)
1100	(1520.3)	7215	(450.4)	2600	(4220.3)	6923	(432.2)
1200	(1700.3)	7196	(449.3)	2700	(4400.3)	6904	(431.0)
1300	(1880.3)	7177	(448.1)	2755	(4499.3)	6893	(430.3)

Application Notes: Density is calculated as a function of thermal expansion as seen in the equation below to approximate property trend with respect to temperature.

Density Calculation:

$\rho(T) = \rho_{RT}/(1 + dL/L_0(T)/100)^3$

$\rho(T) = Density\ [kg/m^3]$

$Room\ Temperature\ Density\ (\rho_{RT}) = 7{,}350\ [kg/m^3]$

$T = Temperature\ [K]$

Temperature Range: $100 \leq T \leq 2755$

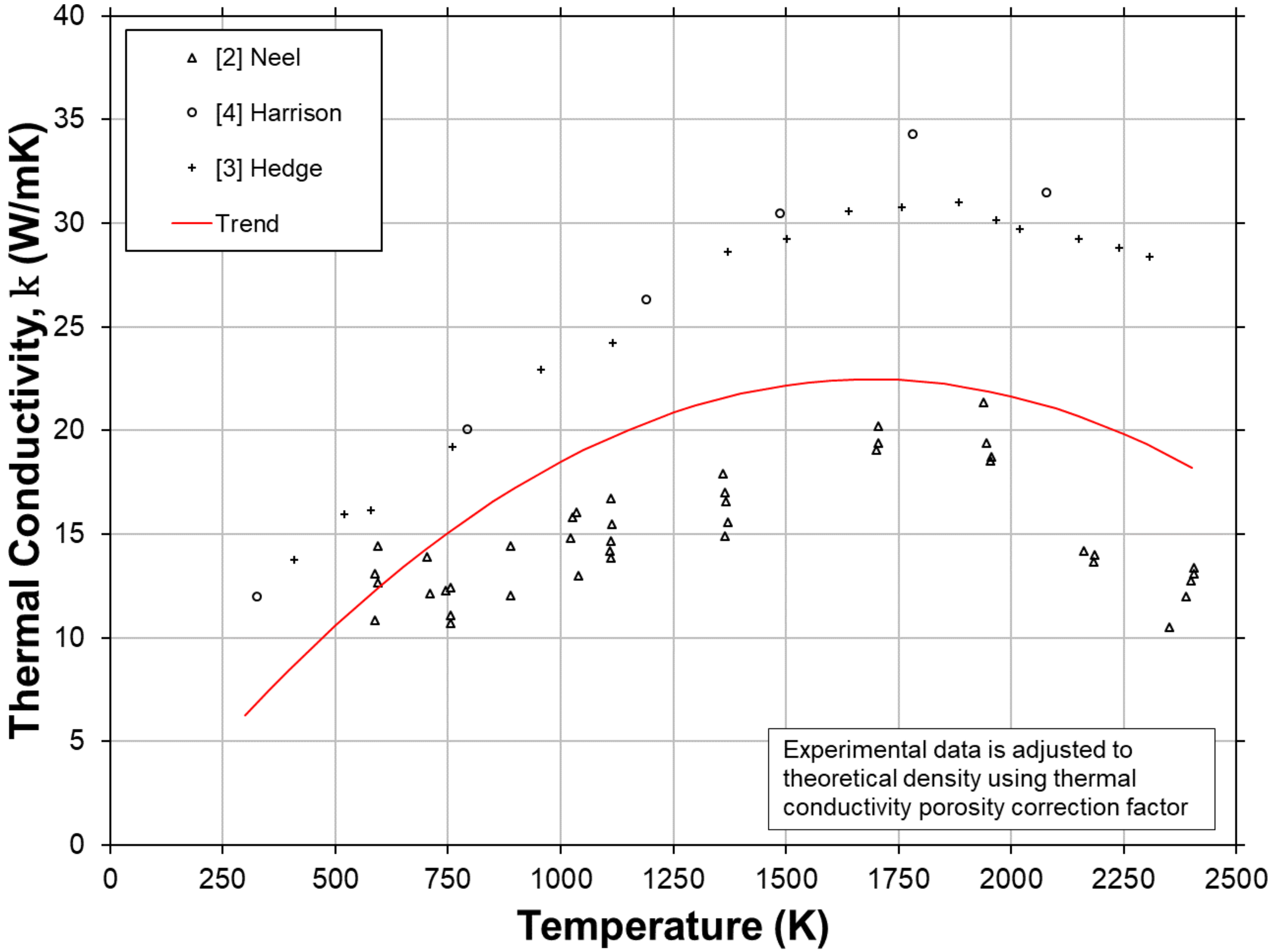

Figure 7.3.1-3: Thermal Conductivity versus Temperature of ZrN.

100% Theoretical Density

Temperature (T)		Thermal Conductivity (k)		Temperature (T)		Thermal Conductivity (k)	
K	(°F)	W/(m-K)	((Btu·in)/(ft²·hr·°F))	K	(°F)	W/(m-K)	((Btu·in)/(ft²·hr·°F))
293	(67.7)	6.10	(42.34)	1000	(1340.3)	18.49	(128.28)
300	(80.3)	6.27	(43.48)	1100	(1520.3)	19.56	(135.73)
350	(170.3)	7.41	(51.43)	1200	(1700.3)	20.47	(142.01)
400	(260.3)	8.52	(59.09)	1300	(1880.3)	21.21	(147.12)
450	(350.3)	9.58	(66.46)	1400	(2060.3)	21.77	(151.07)
500	(440.3)	10.60	(73.54)	1500	(2240.3)	22.18	(153.85)
550	(530.3)	11.58	(80.33)	1600	(2420.3)	22.41	(155.47)
600	(620.3)	12.51	(86.82)	1700	(2600.3)	22.47	(155.92)
650	(710.3)	13.41	(93.02)	1800	(2780.3)	22.37	(155.20)
700	(800.3)	14.26	(98.93)	1900	(2960.3)	22.10	(153.32)
750	(890.3)	15.07	(104.55)	2000	(3140.3)	21.66	(150.27)
800	(980.3)	15.84	(109.88)	2100	(3320.3)	21.05	(146.05)
850	(1070.3)	16.56	(114.92)	2200	(3500.3)	20.27	(140.66)
900	(1160.3)	17.25	(119.66)	2300	(3680.3)	19.33	(134.11)
950	(1250.3)	17.89	(124.12)	2400	(3860.3)	18.22	(126.40)

Application Notes: Data for thermal conductivity is collected from references [2-4] and fitted with the equation below to approximate property trend with respect to temperature.

Fit Equation:

$$k(T) = A0 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2$$

$k(T) = Thermal\ Conductivity\ [W\ /\ (m \cdot K)]$

$T = Temperature\ [K]$

Constants:

T Range [K]:	$293 \leq T \leq 2400$
A0 =	-1.494
A1 =	28.39
A2 =	-8.407

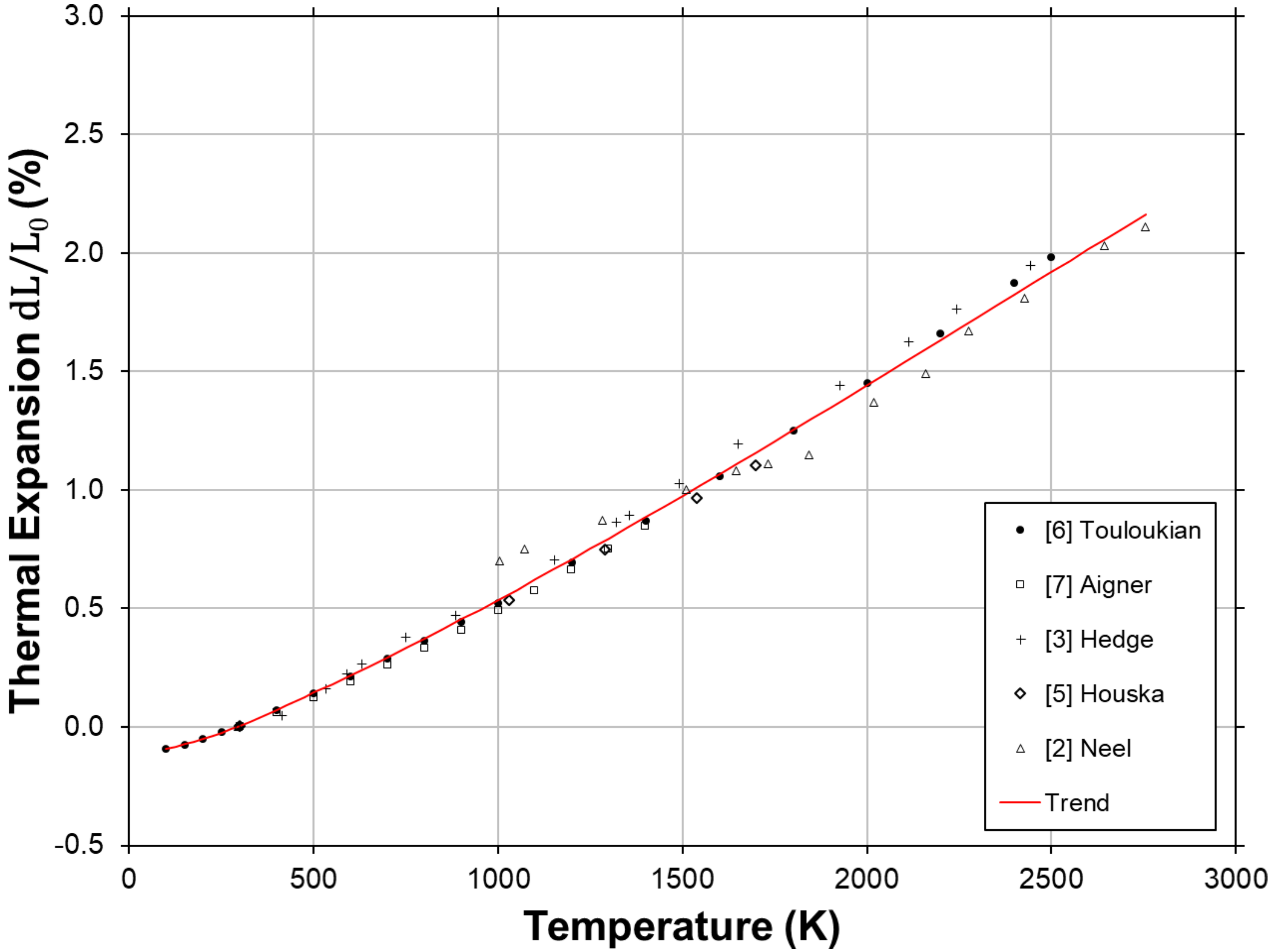

Figure 7.3.1-4: Thermal Expansion versus Temperature of ZrN.

100% Theoretical Density

Temperature (T)		Thermal Expansion (dL/L_0)	Temperature (T)		Thermal Expansion (dL/L_0)
K	(°F)	%	K	(°F)	%
100	(-279.7)	-0.093	1400	(2060.3)	0.885
150	(-189.7)	-0.072	1500	(2240.3)	0.975
200	(-99.7)	-0.049	1600	(2420.3)	1.067
250	(-9.7)	-0.024	1700	(2600.3)	1.160
300	(80.3)	0.004	1800	(2780.3)	1.253
400	(260.3)	0.073	1900	(2960.3)	1.347
500	(440.3)	0.144	2000	(3140.3)	1.442
600	(620.3)	0.218	2100	(3320.3)	1.537
700	(800.3)	0.295	2200	(3500.3)	1.633
800	(980.3)	0.373	2300	(3680.3)	1.729
900	(1160.3)	0.454	2400	(3860.3)	1.824
1000	(1340.3)	0.537	2500	(4040.3)	1.920
1100	(1520.3)	0.621	2600	(4220.3)	2.015
1200	(1700.3)	0.708	2700	(4400.3)	2.110
1300	(1880.3)	0.796	2755	(4499.3)	2.162

Application Notes: Data for thermal expansion is collected from references [2, 3, 5-7] and fitted with the equation below to approximate property trend with respect to temperature.

Fit Equation:

$$dL/L_0\,(T) = A0 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2 + A3 \cdot \left(\frac{T}{1000}\right)^3$$

$dL/L_0\,(T) = Thermal\ Expansion\ [\%]$

$T = Temperature\ [K]$

Constants:

T Range [K]:	$100 \leq T < 293$	$293 \leq T \leq 2755$
A0 =	-0.1259	-0.1847
A1 =	0.2824	0.5826
A2 =	0.4987	0.1624
A3 =	0	-0.02349

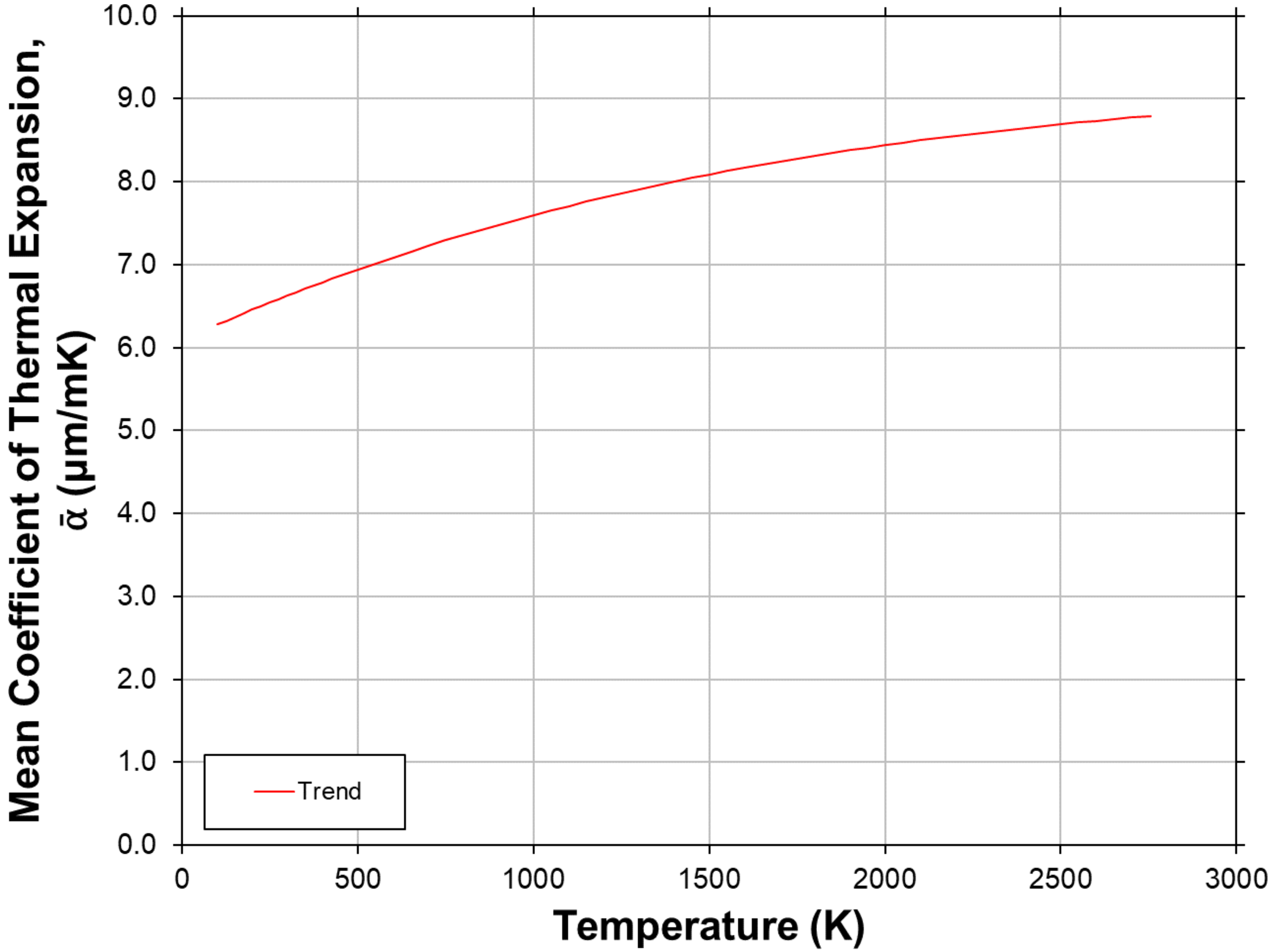

Figure 7.3.1-5: Mean Coefficient of Thermal Expansion versus Temperature of ZrN. Calculated from fitted trend of the Thermal Expansion data.

100% Theoretical Density

Temperature (T)		Mean CTE (ᾱ)		Temperature (T)		Mean CTE (ᾱ)	
K	(°F)	μm/(m-K)	(μin/(in-°F))	K	(°F)	μm/(m-K)	(μin/(in-°F))
100	(-279.7)	6.277	(3.487)	1400	(2060.3)	8.001	(4.445)
150	(-189.7)	6.368	(3.538)	1500	(2240.3)	8.087	(4.493)
200	(-99.7)	6.456	(3.587)	1600	(2420.3)	8.168	(4.538)
250	(-9.7)	6.542	(3.635)	1700	(2600.3)	8.243	(4.580)
300	(80.3)	6.627	(3.681)	1800	(2780.3)	8.314	(4.619)
400	(260.3)	6.789	(3.771)	1900	(2960.3)	8.380	(4.656)
500	(440.3)	6.942	(3.857)	2000	(3140.3)	8.442	(4.690)
600	(620.3)	7.088	(3.938)	2100	(3320.3)	8.500	(4.722)
700	(800.3)	7.227	(4.015)	2200	(3500.3)	8.553	(4.752)
800	(980.3)	7.357	(4.087)	2300	(3680.3)	8.603	(4.780)
900	(1160.3)	7.481	(4.156)	2400	(3860.3)	8.650	(4.806)
1000	(1340.3)	7.598	(4.221)	2500	(4040.3)	8.694	(4.830)
1100	(1520.3)	7.708	(4.282)	2600	(4220.3)	8.735	(4.853)
1200	(1700.3)	7.812	(4.340)	2700	(4400.3)	8.773	(4.874)
1300	(1880.3)	7.909	(4.394)	2755	(4499.3)	8.793	(4.885)

Application Notes: Data for mean coefficient of thermal expansion is calculated as a function of thermal expansion. Calculated data is then fitted with the equation below to approximate property trend with respect to temperature.

Fit Equation:

$$\bar{\alpha}(T) = A0 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2 + A3 \cdot \left(\frac{T}{1000}\right)^3$$

$\bar{\alpha}(T) = Coefficient\ of\ Thermal\ Expansion\ [\mu m/(m \cdot K)]$

$T = Temperature\ [K]$

Constants:

T. Range [K]: $100 \leq T \leq 2755$

A0 =	6.089
A1 =	1.926
A2 =	-0.4595
A3 =	0.04236

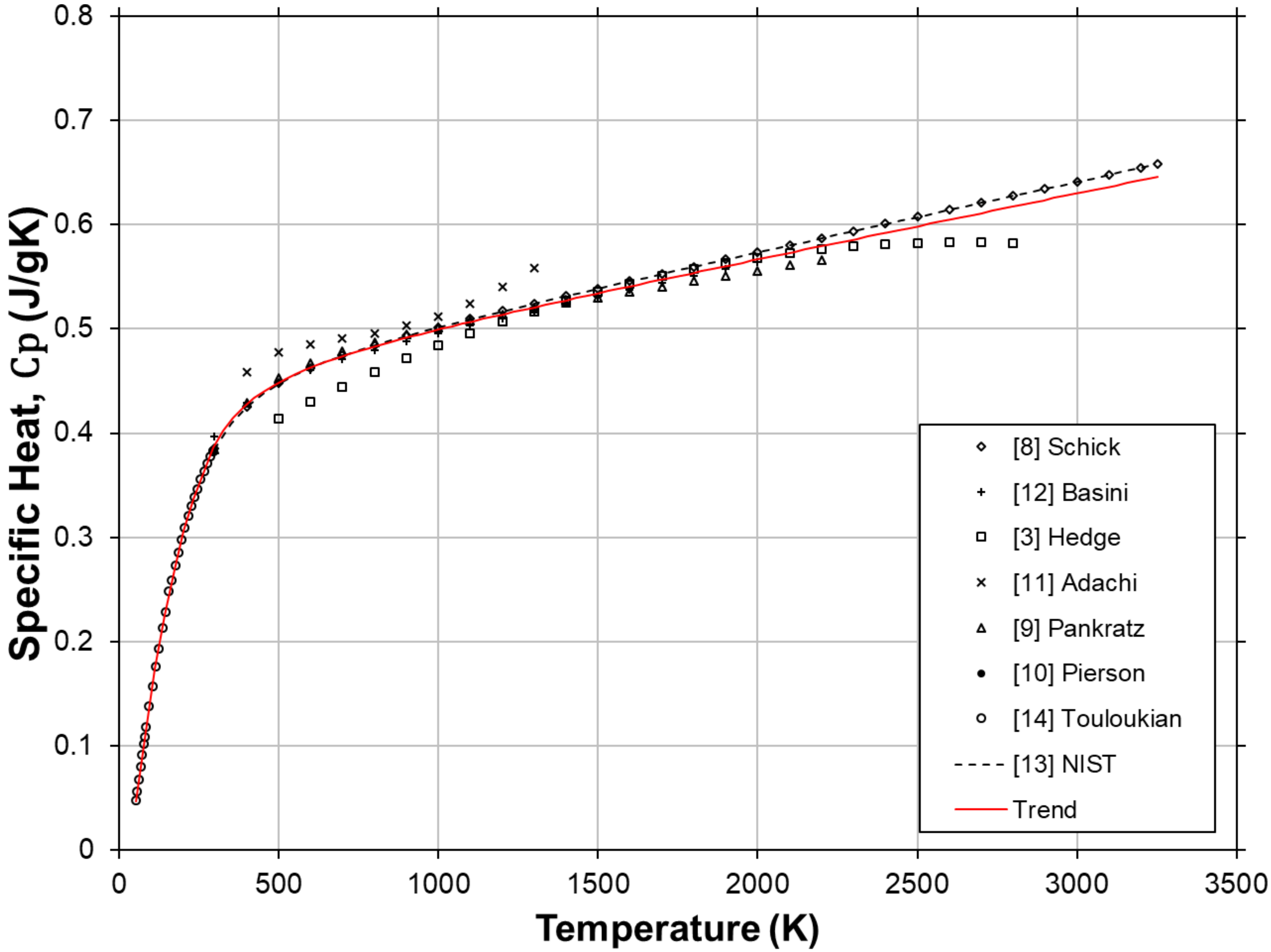

Figure 7.3.1-6: Specific Heat versus Temperature of ZrN.

100% Theoretical Density

Temperature (T)		Specific Heat (C_p)		Temperature (T)		Specific Heat (C_p)	
K	(°F)	J/(g-K)	(BTU/(lb-°F))	K	(°F)	J/(g-K)	(BTU/(lb-°F))
53	(-364.3)	0.047	(0.011)	1300	(1880.3)	0.521	(0.124)
100	(-279.7)	0.149	(0.036)	1400	(2060.3)	0.527	(0.126)
200	(-99.7)	0.302	(0.072)	1500	(2240.3)	0.534	(0.128)
300	(80.3)	0.390	(0.093)	1600	(2420.3)	0.541	(0.129)
400	(260.3)	0.427	(0.102)	1800	(2780.3)	0.554	(0.132)
500	(440.3)	0.448	(0.107)	2000	(3140.3)	0.567	(0.135)
600	(620.3)	0.463	(0.111)	2200	(3500.3)	0.579	(0.138)
700	(800.3)	0.474	(0.113)	2400	(3860.3)	0.592	(0.141)
800	(980.3)	0.483	(0.115)	2600	(4220.3)	0.605	(0.145)
900	(1160.3)	0.491	(0.117)	2800	(4580.3)	0.617	(0.148)
1000	(1340.3)	0.499	(0.119)	3000	(4940.3)	0.630	(0.151)
1100	(1520.3)	0.507	(0.121)	3200	(5300.3)	0.642	(0.154)
1200	(1700.3)	0.514	(0.123)	3253	(5395.7)	0.646	(0.154)

Application Notes: Data for specific heat is collected from references [3, 8-14] and fitted with the equations below to approximate property trend with respect to temperature.

Fit Equation:

For temperature range: 53 ≤T≤ 294

$$C_P(T) = A0 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2 + A3 \cdot \left(\frac{T}{1000}\right)^3$$

For temperature range: 294 ≤T≤ 3253

$$C_P(T) = B0 + B1 \cdot \left(\frac{T}{1000}\right) + B\_2/\left(\frac{T}{1000}\right)^2$$

$C_P(T) = Specific\ Heat\ [J/(g \cdot K)]$

$T = Temperature\ [K]$

Constants:

T. Range [K]:	$53 \leq T < 293$		$293 \leq T \leq 3253$
A0 =	-0.09452	B0 =	0.4432
A1 =	2.94	B1 =	0.06247
A2 =	-5.398	B_2 =	-0.006519
A3 =	3.077		

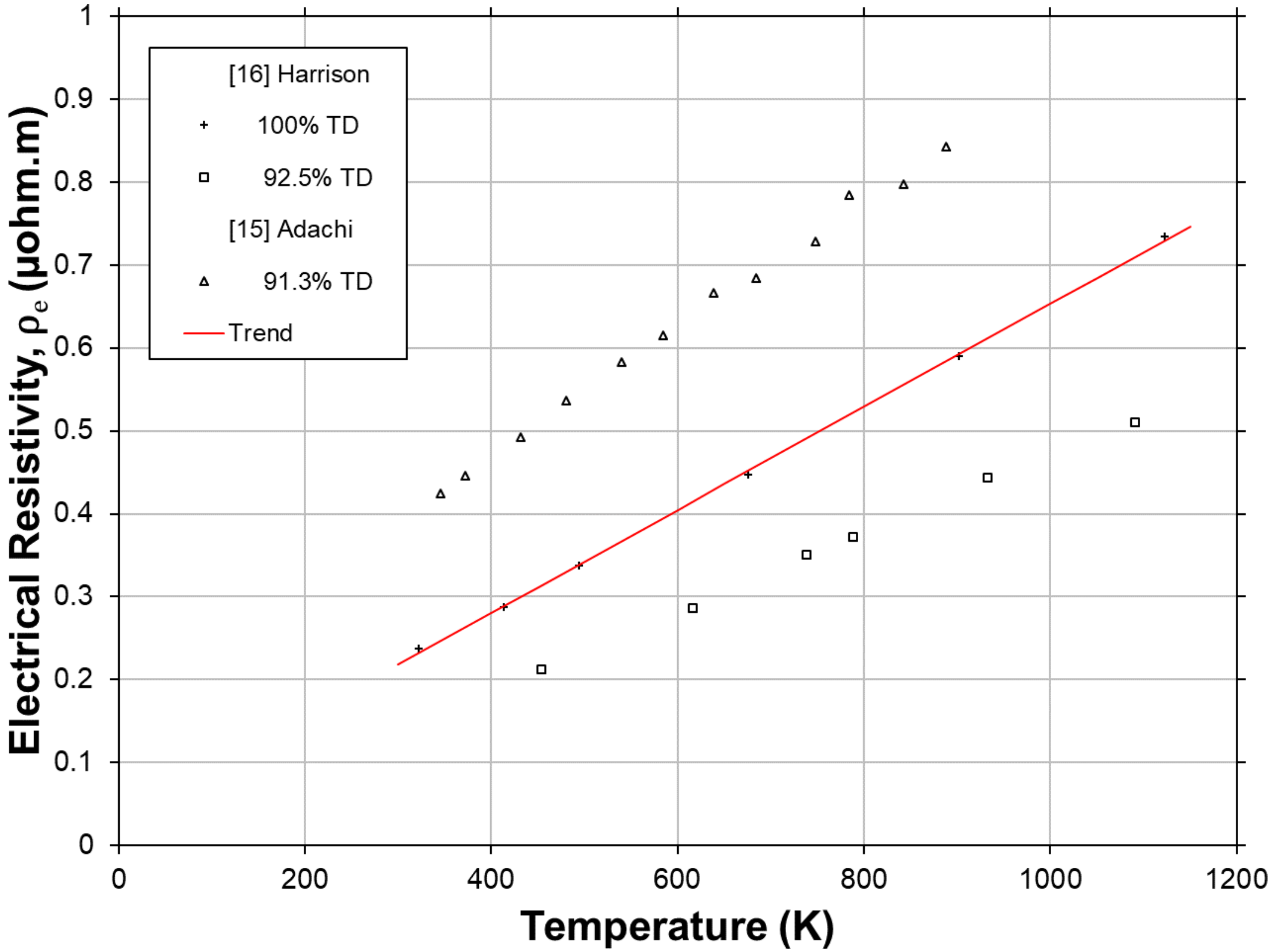

Figure 7.3.1-7: Reference data for Electrical Resistivity versus Temperature of ZrN.

100% Theoretical Density

Temperature (T)		Electrical Resistivity (ρ_e)		Temperature (T)		Electrical Resistivity (ρ_e)	
K	(°F)	μΩ-m	(μΩ-in)	K	(°F)	μΩ-m	(μΩ-in)
293	(67.7)	0.214	(8.42)	650	(710.3)	0.436	(17.16)
300	(80.3)	0.218	(8.59)	675	(755.3)	0.451	(17.77)
325	(125.3)	0.234	(9.21)	700	(800.3)	0.467	(18.38)
350	(170.3)	0.249	(9.82)	725	(845.3)	0.482	(18.99)
375	(215.3)	0.265	(10.43)	750	(890.3)	0.498	(19.61)
400	(260.3)	0.280	(11.04)	775	(935.3)	0.514	(20.22)
425	(305.3)	0.296	(11.65)	800	(980.3)	0.529	(20.83)
450	(350.3)	0.312	(12.26)	825	(1025.3)	0.545	(21.44)
475	(395.3)	0.327	(12.88)	850	(1070.3)	0.560	(22.05)
500	(440.3)	0.343	(13.49)	900	(1160.3)	0.591	(23.28)
525	(485.3)	0.358	(14.10)	950	(1250.3)	0.622	(24.50)
550	(530.3)	0.374	(14.71)	1000	(1340.3)	0.653	(25.72)
575	(575.3)	0.389	(15.32)	1050	(1430.3)	0.684	(26.95)
600	(620.3)	0.405	(15.94)	1100	(1520.3)	0.716	(28.17)
625	(665.3)	0.420	(16.55)	1175	(1655.3)	0.762	(30.00)

Application Notes: Data for electrical resistivity is collected from references [15, 16] and fitted with the equation below for 100% theoretical density to approximate property trend with respect to temperature.

Fit Equation:

$$\rho_e(T) = A0 + A1 \cdot \left(\frac{T}{1000}\right)$$

$\rho_e(T) = Electrical\ Resistivity\ [\mu\Omega \cdot m]$

$T = Temperature\ [K]$

Constants:

T. Range [K]: $293 \leq T < 1175$

A0 = 0.03185

A1 = 0.6215

Temp. (T) K	Physical and Electrical: Density (ρ) kg/m³	Physical and Electrical: Electrical Resistivity (ρ_e) μΩ-m	Thermal: Thermal Conductivity (k) W/(m-K)	Thermal: Thermal Expansion (dL/L_0) %	Thermal: Mean CTE ($\bar{\alpha}$) 10^{-6}/K	Thermal: Specific Heat (C_p) J/(g-K)	Elastic: Young's Modulus (E) GPa	Elastic: Shear Modulus (G) GPa	Elastic: Poisson's Ratio (ν)
100	7370	-	-	-0.093	6.277	0.149			
200	7361	-	-	-0.049	6.456	0.302			
300	7349	0.218	6.27	0.004	6.627	0.390	366.8	149.9	0.223
400	7334	0.280	8.52	0.073	6.789	0.427			
500	7318	0.343	10.60	0.144	6.942	0.448			
600	7302	0.405	12.51	0.218	7.088	0.463			
700	7285	0.467	14.26	0.295	7.227	0.474			
800	7268	0.529	15.84	0.373	7.357	0.483			
900	7251	0.591	17.25	0.454	7.481	0.491			
1000	7233	0.653	18.49	0.537	7.598	0.499			
1100	7215	0.716	19.56	0.621	7.708	0.507			
1200	7196	-	20.47	0.708	7.812	0.514			
1300	7177	-	21.21	0.796	7.909	0.521			
1400	7158	-	21.77	0.885	8.001	0.527			
1500	7139	-	22.18	0.975	8.087	0.534			
1600	7120	-	22.41	1.067	8.168	0.541			
1700	7100	-	22.47	1.160	8.243	0.547			
1800	7080	-	22.37	1.253	8.314	0.554			
2000	7041	-	21.66	1.442	8.442	0.567			
2200	7001	-	20.27	1.633	8.553	0.579			
2400	6962	-	18.22	1.824	8.650	0.592			
2600	6923	-	-	2.015	8.735	0.605			
2800	-	-	-	-	-	0.617			
3000	-	-	-	-	-	0.630			
3200	-	-	-	-	-	0.642			

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7 Refractory Ceramics

7.3 Nitrides

Room Temperature Properties

Molar Mass, [g/mol]	192.50
Theoretical Density, [kg/m^3]	13,940
Melting Point, [K]	3660
Specific Heat, [J/(g-K)]	0.210
Thermal Conductivity, [W/(m-K)]	9.0
Linear expansion coefficient, [μm/(m-K)]	5.73
Electrical resistivity, [μΩ-m]	0.30
Young's Modulus, [GPa]	404.1
Shear Modulus, [GPa]	172.4
Poisson’s Ratio, [-]	0.172

Hafnium – Nitrogen Phase Diagram

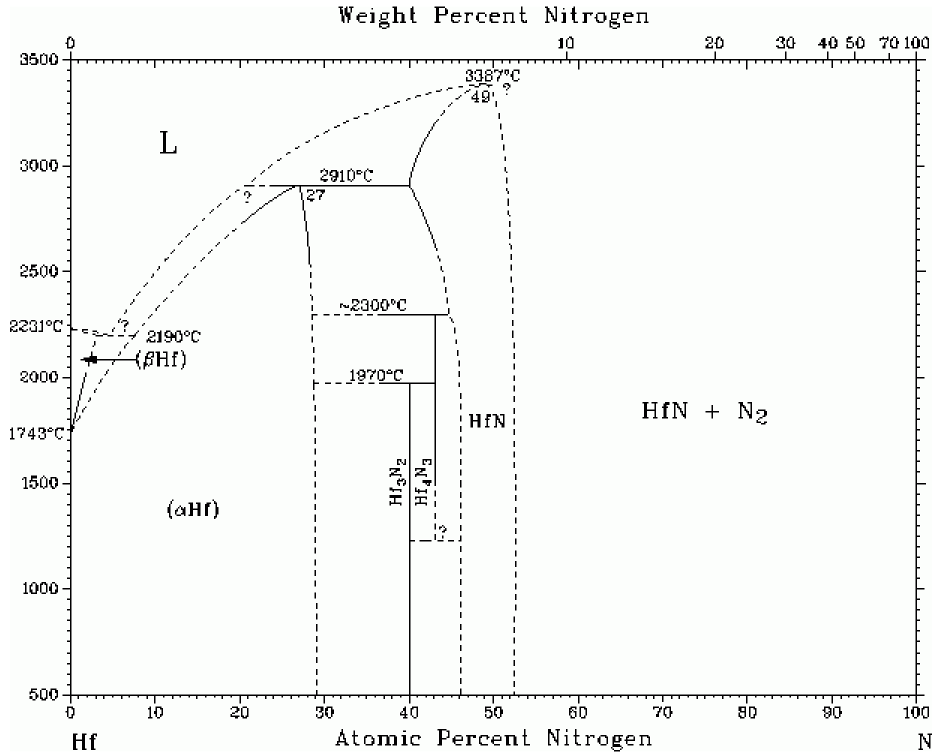

Figure 7.3.2-1: Hafnium – Nitrogen Phase Diagram.

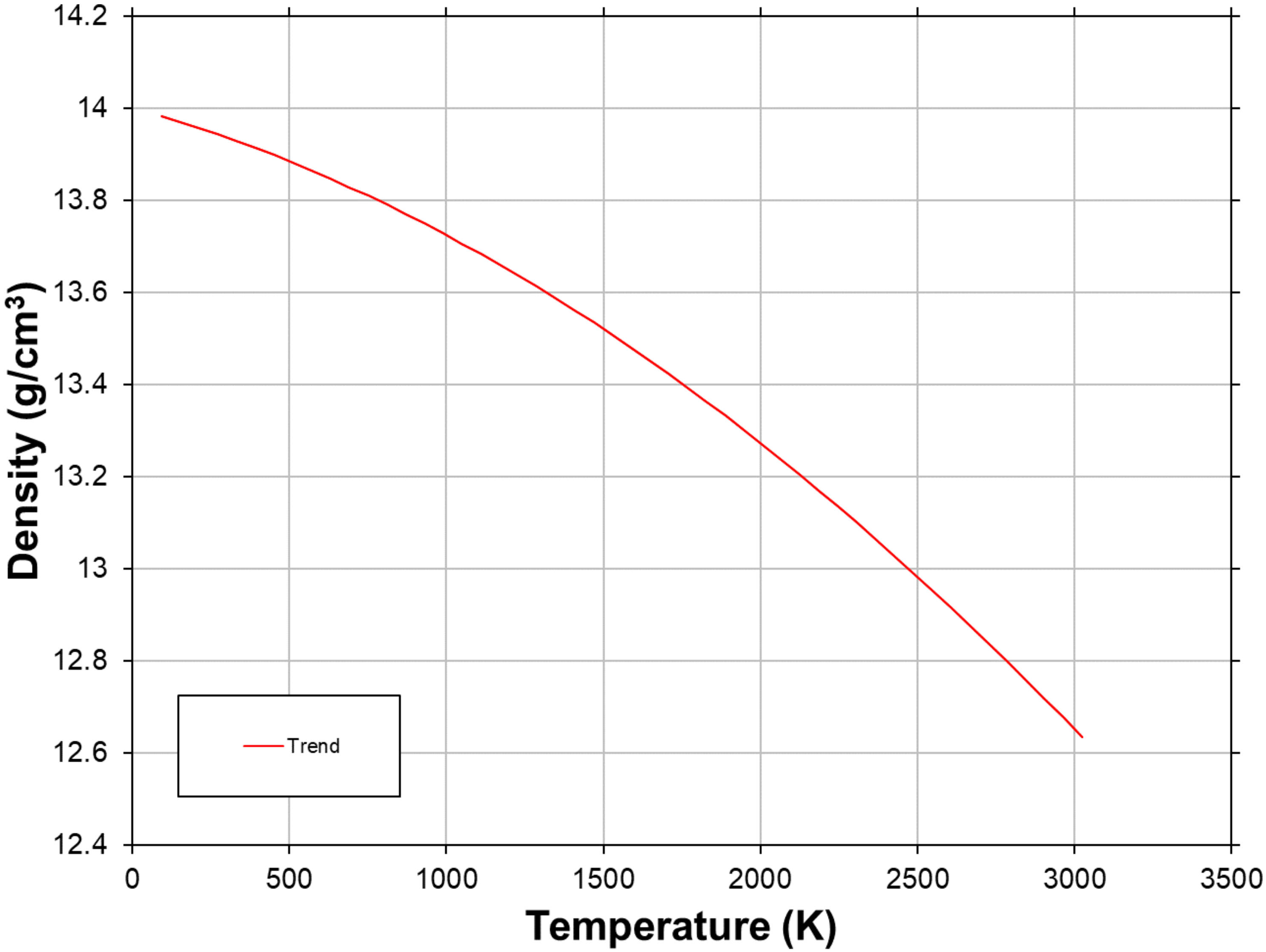

Figure 7.3.2-2: Density versus Temperature for HfN. Calculated from fitted trend of the Thermal Expansion data.

100% Theoretical Density

Temperature (T)		Density (ρ)		Temperature (T)		Density (ρ)	
K	(°F)	kg/m³	(lb/ft³)	K	(°F)	kg/m³	(lb/ft³)
93	(-292.3)	13983	(872.9)	1500	(2240.3)	13520	(844.1)
100	(-279.7)	13981	(872.9)	1600	(2420.3)	13474	(841.2)
200	(-99.7)	13960	(871.5)	1700	(2600.3)	13426	(838.2)
300	(80.3)	13936	(870.1)	1800	(2780.3)	13377	(835.1)
400	(260.3)	13911	(868.5)	1900	(2960.3)	13326	(831.9)
500	(440.3)	13885	(866.8)	2000	(3140.3)	13273	(828.6)
600	(620.3)	13856	(865.0)	2100	(3320.3)	13218	(825.2)
700	(800.3)	13826	(863.1)	2200	(3500.3)	13162	(821.7)
800	(980.3)	13794	(861.1)	2300	(3680.3)	13104	(818.1)
900	(1160.3)	13760	(859.0)	2400	(3860.3)	13044	(814.3)
1000	(1340.3)	13724	(856.8)	2500	(4040.3)	12983	(810.5)
1100	(1520.3)	13687	(854.5)	2600	(4220.3)	12920	(806.6)
1200	(1700.3)	13648	(852.0)	2700	(4400.3)	12855	(802.5)
1300	(1880.3)	13607	(849.5)	2850	(4670.3)	12755	(796.3)
1400	(2060.3)	13565	(846.8)	3025	(4985.3)	12634	(788.8)

Application Notes: Density is calculated as a function of thermal expansion, as seen in the equation below to approximate property trend with respect to temperature.

Density Calculation:

$\rho(T) = \rho_{RT}/(1 + dL/L_0(T)/100)^3$

$\rho(T) = Density\ [kg/m^3]$

$Room\ Temperature\ Density\ (\rho_{RT}) = 13{,}940\ [kg/m^3]$

$T = Temperature\ [K]$

Temperature Range: $93 \leq T \leq 3025$

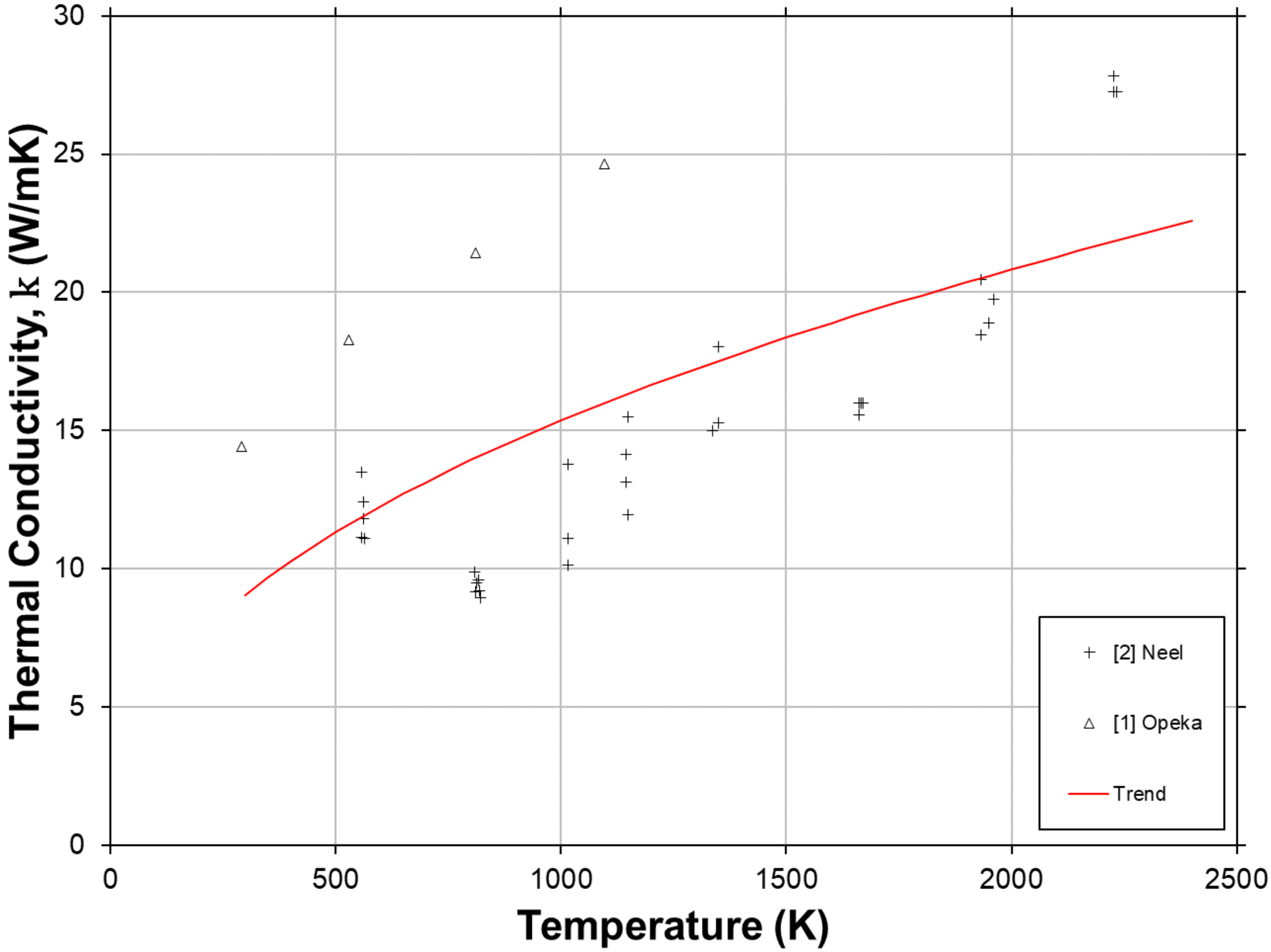

Figure 7.3.2-3: Thermal Conductivity versus Temperature of HfN.

100% Theoretical Density

Temperature (T)		Thermal Conductivity (k)		Temperature (T)		Thermal Conductivity (k)	
K	(°F)	W/(m-K)	((Btu·in)/(ft^2·hr·°F))	K	(°F)	W/(m-K)	((Btu·in)/(ft^2·hr·°F))
298	(76.7)	9.02	(62.56)	1050	(1430.3)	15.69	(108.87)
350	(170.3)	9.68	(67.15)	1100	(1520.3)	16.02	(111.12)
400	(260.3)	10.26	(71.21)	1200	(1700.3)	16.64	(115.45)
450	(350.3)	10.81	(75.00)	1300	(1880.3)	17.24	(119.59)
500	(440.3)	11.32	(78.55)	1400	(2060.3)	17.81	(123.55)
550	(530.3)	11.81	(81.92)	1500	(2240.3)	18.36	(127.36)
600	(620.3)	12.27	(85.11)	1600	(2420.3)	18.89	(131.03)
650	(710.3)	12.71	(88.16)	1700	(2600.3)	19.40	(134.57)
700	(800.3)	13.13	(91.08)	1800	(2780.3)	19.89	(137.99)
750	(890.3)	13.53	(93.89)	1900	(2960.3)	20.37	(141.32)
800	(980.3)	13.92	(96.59)	2000	(3140.3)	20.83	(144.54)
850	(1070.3)	14.30	(99.20)	2100	(3320.3)	21.28	(147.68)
900	(1160.3)	14.66	(101.73)	2200	(3500.3)	21.72	(150.73)
950	(1250.3)	15.02	(104.18)	2300	(3680.3)	22.15	(153.70)
1000	(1340.3)	15.36	(106.56)	2400	(3860.3)	22.57	(156.61)

Application Notes: Data for thermal conductivity is collected from references [1, 2] and fitted with the equation below to approximate property trend with respect to temperature.

Fit Equation:

$$k(T) = A0 \cdot \left(\frac{T}{1000}\right)^{N}$$

$k(T) = Thermal\ Conductivity\ [W\ /\ (m \cdot K)]$

$T = Temperature\ [K]$

Constants:

T Range [K]: $298 \leq T \leq 2400$

A0 = 15.358

N = 0.4399

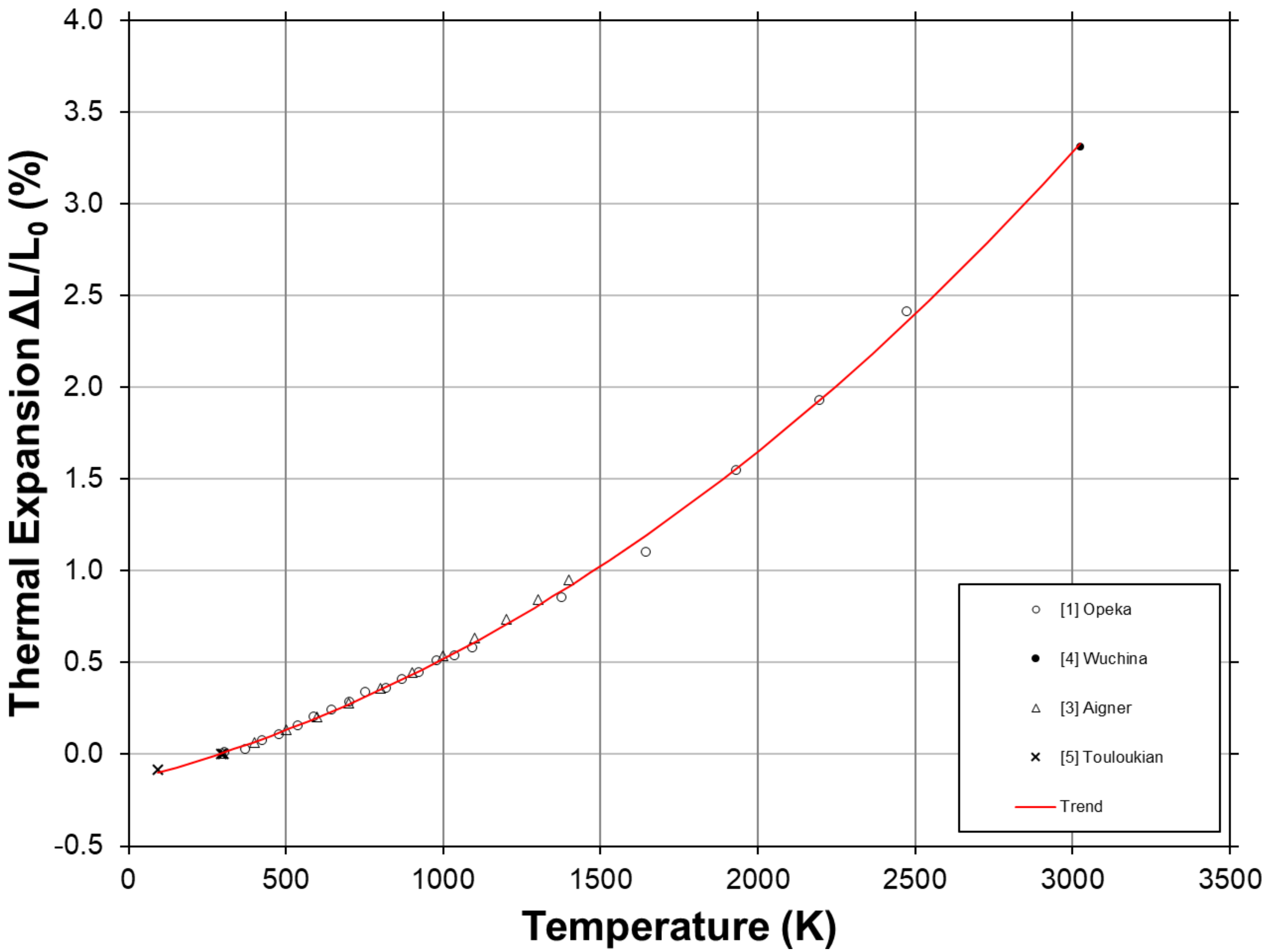

Figure 7.3.2-4: Thermal Expansion versus Temperature of HfN.

100% Theoretical Density

Temperature (T) K	(°F)	Thermal Expansion (dL/L_0) %	Temperature (T) K	(°F)	Thermal Expansion (dL/L_0) %
93	(-292.3)	-0.102	1500	(2240.3)	1.024
100	(-279.7)	-0.099	1600	(2420.3)	1.139
200	(-99.7)	-0.047	1700	(2600.3)	1.259
300	(80.3)	0.008	1800	(2780.3)	1.384
400	(260.3)	0.068	1900	(2960.3)	1.514
500	(440.3)	0.133	2000	(3140.3)	1.649
600	(620.3)	0.201	2100	(3320.3)	1.789
700	(800.3)	0.275	2200	(3500.3)	1.934
800	(980.3)	0.352	2300	(3680.3)	2.084
900	(1160.3)	0.434	2400	(3860.3)	2.239
1000	(1340.3)	0.521	2500	(4040.3)	2.400
1100	(1520.3)	0.612	2600	(4220.3)	2.566
1200	(1700.3)	0.708	2700	(4400.3)	2.738
1300	(1880.3)	0.809	2850	(4670.3)	3.005
1400	(2060.3)	0.914	3025	(4985.3)	3.333

Application Notes: Data for thermal expansion is collected from references [1, 3-5] and fitted with the equation below to approximate property trend with respect to temperature.

Fit Equation:

$$dL/L_0\,(T) = A0 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2 + A3 \cdot \left(\frac{T}{1000}\right)^3$$

$dL/L_0\,(T) = Thermal\ Expansion\ [\%]$

$T = Temperature\ [K]$

Constants:

T Range [K]:	$93 \leq T \leq 3025$
A0 =	-0.1461
A1 =	0.4525
A2 =	0.2065
A3 =	0.007964

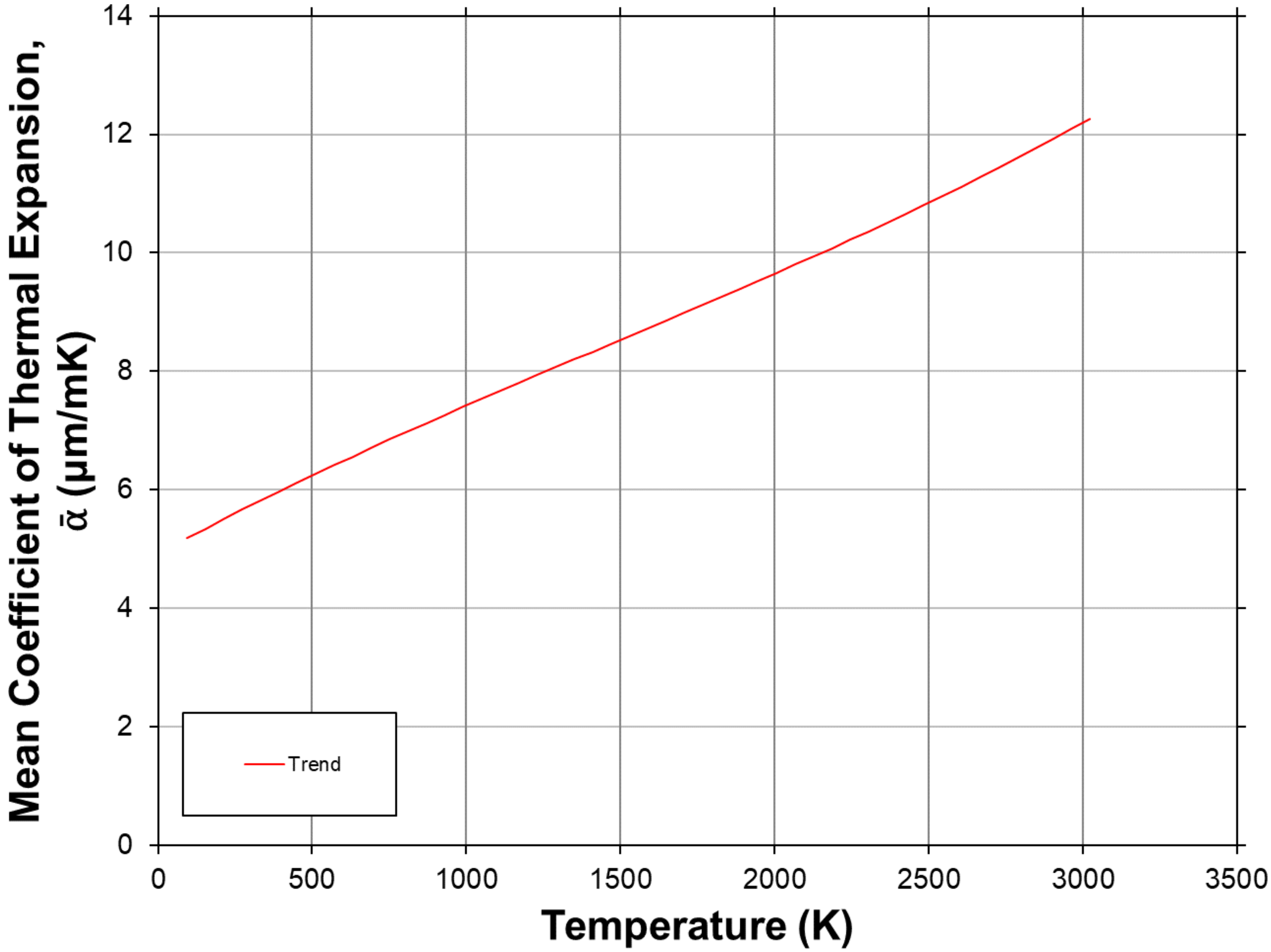

Figure 7.3.2-5: Mean Coefficient of Thermal Expansion versus Temperature of HfN as calculated from fitted trend of the Thermal Expansion.

100% Theoretical Density

Temperature (T)		Mean CTE (ᾱ)		Temperature (T)		Mean CTE (ᾱ)	
K	(°F)	µm/(m-K)	(µin/(in-°F))	K	(°F)	µm/(m-K)	(µin/(in-°F))
93	(-292.3)	5.179	(2.877)	1500	(2240.3)	8.532	(4.740)
100	(-279.7)	5.199	(2.888)	1600	(2420.3)	8.753	(4.863)
200	(-99.7)	5.470	(3.039)	1700	(2600.3)	8.974	(4.985)
300	(80.3)	5.734	(3.186)	1800	(2780.3)	9.197	(5.109)
400	(260.3)	5.991	(3.328)	1900	(2960.3)	9.421	(5.234)
500	(440.3)	6.242	(3.468)	2000	(3140.3)	9.648	(5.360)
600	(620.3)	6.487	(3.604)	2100	(3320.3)	9.879	(5.488)
700	(800.3)	6.727	(3.737)	2200	(3500.3)	10.113	(5.618)
800	(980.3)	6.962	(3.868)	2300	(3680.3)	10.352	(5.751)
900	(1160.3)	7.194	(3.996)	2400	(3860.3)	10.595	(5.886)
1000	(1340.3)	7.422	(4.123)	2500	(4040.3)	10.845	(6.025)
1100	(1520.3)	7.647	(4.248)	2600	(4220.3)	11.100	(6.167)
1200	(1700.3)	7.870	(4.372)	2700	(4400.3)	11.362	(6.312)
1300	(1880.3)	8.091	(4.495)	2850	(4670.3)	11.769	(6.539)
1400	(2060.3)	8.312	(4.618)	3025	(4985.3)	12.268	(6.816)

Application Notes: Trend for mean coefficient of thermal expansion is calculated from thermal expansion and shown in the equation below to approximate property trend with respect to temperature.

Fit Equation:

$$\bar{\alpha}(T) = A0 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2 + A3 \cdot \left(\frac{T}{1000}\right)^3$$

$\bar{\alpha}(T) = Coefficient\ of\ Thermal\ Expansion\ [\mu m/(m \cdot K)]$

$T = Temperature\ [K]$

Constants:

T. Range [K]: $93 \leq T \leq 3025$

A0 = 4.919

A1 = 2.839

A2 = -0.4357

A3 = 0.09928

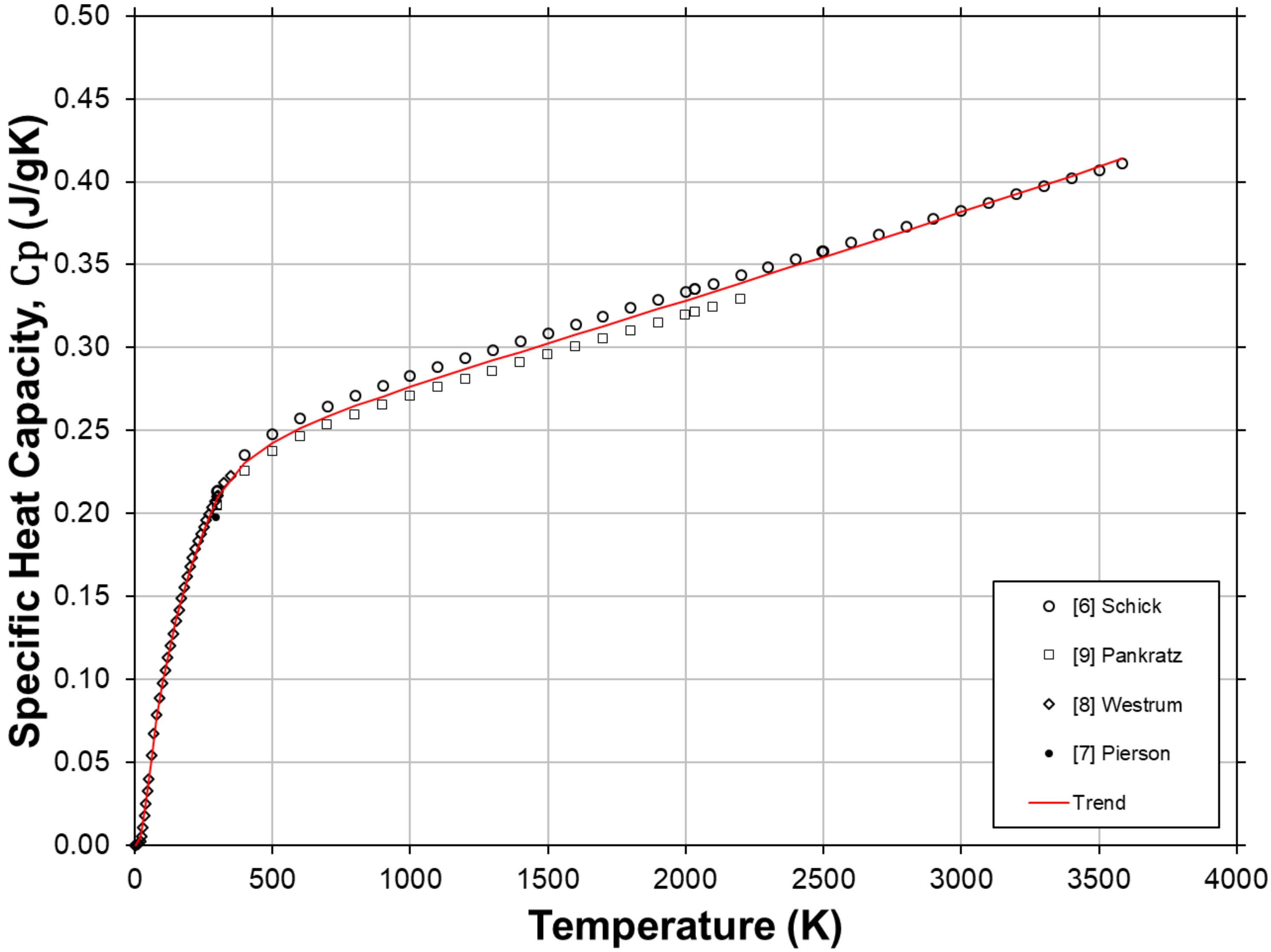

Figure 7.3.2-6: Specific Heat versus Temperature of HfN.

100% Theoretical Density

Temperature (T) K	(°F)	Specific Heat (C_p) J/(g-K)	(BTU/(lb-°F))	Temperature (T) K	(°F)	Specific Heat (C_p) J/(g-K)	(BTU/(lb-°F))
293	(67.7)	0.208	(0.050)	1600	(2420.3)	0.308	(0.074)
400	(260.3)	0.231	(0.055)	1700	(2600.3)	0.313	(0.075)
500	(440.3)	0.243	(0.058)	1800	(2780.3)	0.318	(0.076)
600	(620.3)	0.251	(0.060)	1900	(2960.3)	0.323	(0.077)
700	(800.3)	0.259	(0.062)	2000	(3140.3)	0.328	(0.079)
800	(980.3)	0.265	(0.063)	2200	(3500.3)	0.339	(0.081)
900	(1160.3)	0.271	(0.065)	2400	(3860.3)	0.349	(0.084)
1000	(1340.3)	0.276	(0.066)	2600	(4220.3)	0.360	(0.086)
1100	(1520.3)	0.282	(0.067)	2800	(4580.3)	0.371	(0.089)
1200	(1700.3)	0.287	(0.069)	3000	(4940.3)	0.382	(0.091)
1300	(1880.3)	0.292	(0.070)	3200	(5300.3)	0.393	(0.094)
1400	(2060.3)	0.297	(0.071)	3400	(5660.3)	0.404	(0.096)
1500	(2240.3)	0.303	(0.072)	3583	(5989.7)	0.414	(0.099)

Application Notes: Data for specific heat is collected from references [6-9] and fitted with the equation below to approximate property trend with respect to temperature.

Fit Equation:

For temperature range: $5 \leq T < 293$

$$C_P(T) = \left[A0 \cdot \left(\frac{T}{1000}\right)^N\right] \Big/ \left[1 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2\right]$$

For temperature range: $293 \leq T \leq 3583$

$$C_P(T) = B0 + B1 \cdot \left(\frac{T}{1000}\right) + B2 \cdot \left(\frac{T}{1000}\right)^2 + B\_2 / \left(\frac{T}{1000}\right)^2$$

$C_P(T) = Specific\ Heat\ [J/(g \cdot K)]$

$T = Temperature\ [K]$

Constants:

T. Range [K]:	$5 \leq T < 293$		$293 \leq T \leq 3583$
N =	2.586	B0 =	0.2326
A0 =	120.7	B1 =	0.04545
A1 =	-7.663	B2 =	0.001445
A2 =	296.5	B_2 =	-0.003245

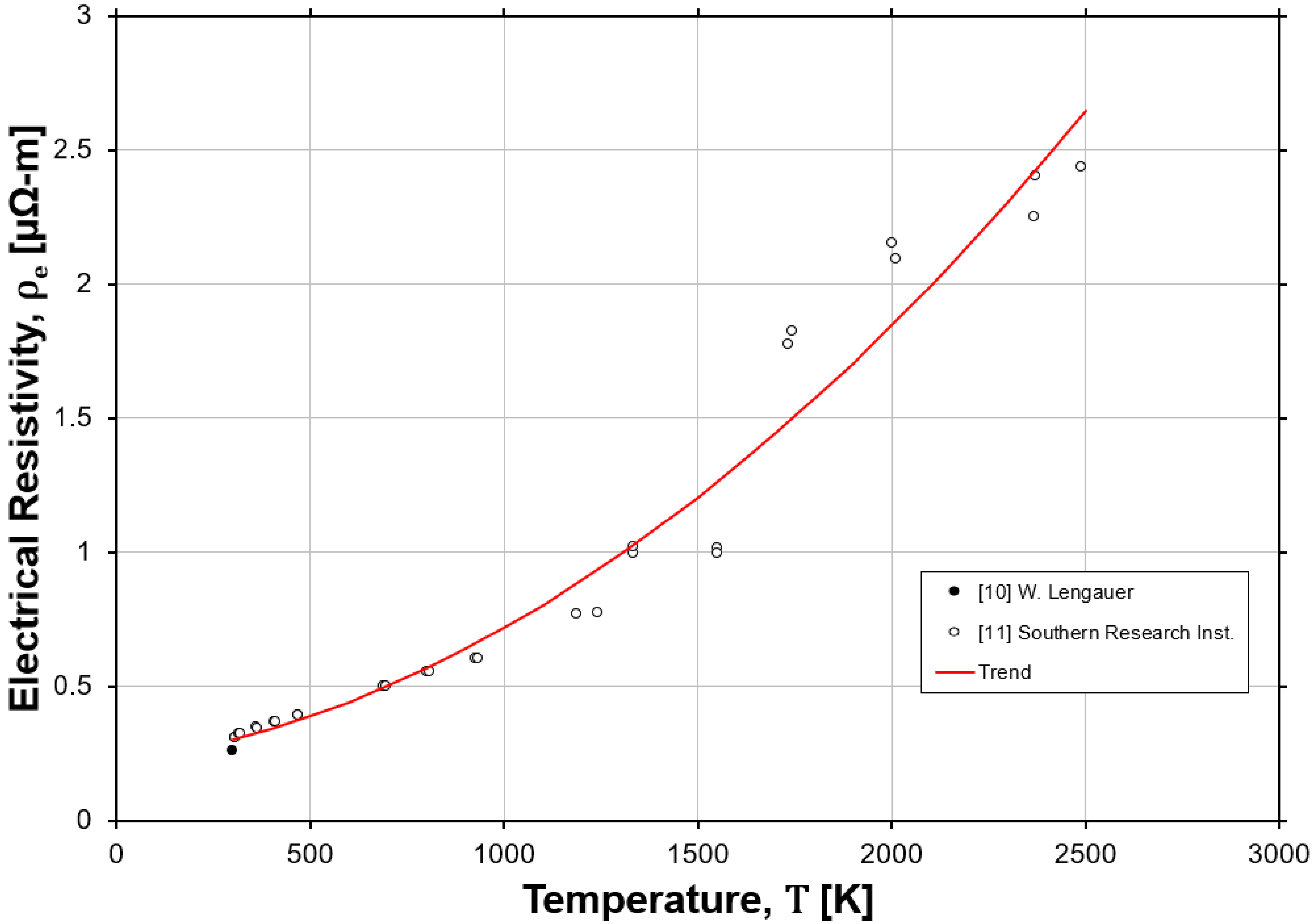

Figure 7.3.2-7: Electrical Resistivity versus Temperature of HfN.

Electrical Resistivity with Temperature

100% Theoretical Density

Temperature (T)		Electrical Resistivity (ρ_e)		Temperature (T)		Electrical Resistivity (ρ_e)	
K	(°F)	μΩ-m	(μΩ-in)	K	(°F)	μΩ-m	(μΩ-in)
290	(62.3)	0.296	(11.66)	1100	(1520.3)	0.803	(31.61)
300	(80.3)	0.300	(11.81)	1200	(1700.3)	0.894	(35.19)
350	(170.3)	0.320	(12.58)	1300	(1880.3)	0.991	(39.02)
400	(260.3)	0.341	(13.42)	1400	(2060.3)	1.095	(43.10)
450	(350.3)	0.364	(14.32)	1500	(2240.3)	1.205	(47.43)
500	(440.3)	0.388	(15.28)	1600	(2420.3)	1.321	(52.00)
550	(530.3)	0.414	(16.30)	1700	(2600.3)	1.443	(56.82)
600	(620.3)	0.442	(17.38)	1800	(2780.3)	1.572	(61.88)
650	(710.3)	0.471	(18.53)	1900	(2960.3)	1.707	(67.19)
700	(800.3)	0.501	(19.73)	2000	(3140.3)	1.848	(72.75)
750	(890.3)	0.533	(21.00)	2100	(3320.3)	1.995	(78.55)
800	(980.3)	0.567	(22.33)	2200	(3500.3)	2.149	(84.61)
850	(1070.3)	0.603	(23.72)	2300	(3680.3)	2.309	(90.90)
900	(1160.3)	0.640	(25.18)	2400	(3860.3)	2.475	(97.45)
1000	(1340.3)	0.718	(28.27)	2500	(4040.3)	2.648	(104.24)

Application Notes: Data for electrical resistivity is collected from references [10, 11] and fitted with the equation below to approximate property trend with respect to temperature.

Fit Equation:

$$\rho_e(T) = A0 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2$$

$\rho_e(T) = Electrical\ Resistivity\ [\mu\Omega \cdot m]$

$T = Temperature\ [K]$

Constants:

T. Range [K]: $290 \leq T < 2500$

A0 = 0.2147

A1 = 0.1901

A2 = 0.3132

Temp. (T) K	Physical and Electrical		Thermal				Elastic		
	Density (ρ) kg/m³	Electrical Resistivity (ρ_e) μΩ-m	Thermal Conductivity (k) W/(m-K)	Thermal Expansion (dL/L_0) %	Mean CTE ($\bar{\alpha}$) 10^{-6}/K	Specific Heat (C_p) J/(g-K)	Young's Modulus (E) GPa	Shear Modulus (G) GPa	Poisson's Ratio (ν)
100	13981	-	-	-0.10	5.20	0.098			
200	13960	-	-	-0.05	5.47	0.166	404.1	172.4	0.172
300	13936	0.300	9.04	0.01	5.73	0.210			
400	13911	0.341	10.26	0.07	5.99	0.231			
500	13885	0.388	11.32	0.13	6.24	0.243			
600	13856	0.442	12.27	0.20	6.49	0.251			
700	13826	0.501	13.13	0.27	6.73	0.259			
800	13794	0.567	13.92	0.35	6.96	0.265			
900	13760	0.640	14.66	0.43	7.19	0.271			
1000	13724	0.718	15.36	0.52	7.42	0.276			
1100	13687	0.803	16.02	0.61	7.65	0.282			
1200	13648	0.894	16.64	0.71	7.87	0.287			
1300	13607	0.991	17.24	0.81	8.09	0.292			
1400	13565	1.095	17.81	0.91	8.31	0.297			
1500	13520	1.205	18.36	1.02	8.53	0.303			
1600	13474	1.321	18.89	1.14	8.75	0.308			
1800	13377	1.572	19.89	1.38	9.20	0.318			
2000	13273	1.848	20.83	1.65	9.65	0.328			
2200	13162	2.149	21.72	1.93	10.11	0.339			
2400	13044	2.475	22.57	2.24	10.60	0.349			
2600	12920	-	-	2.57	11.10	0.360			
2800	12789	-	-	2.91	11.63	0.371			
3000	12652	-	-	3.28	12.20	0.382			
3200	-	-	-	-	-	0.393			
3400	-	-	-	-	-	0.404			

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8 Composites and Structures

8.1 Carbide Based

Room Temperature Properties

Theoretical Density, [kg/m^3]	2,300-2,800	
Specific Heat, [J/(g-K)]	0.670	
Thermal Conductivity, [W/(m-K)]	10.0-16.0	
Linear expansion coefficient, [μm/(m-K)]	2.47	
Electrical Conductivity, [MS/m]	365.00	
Young's Modulus, [GPa]	200-280	
Shear Modulus, [GPa]	80-120	
Poisson's Ratio	0.13-0.25	
Proportional Limit Stress [MPa]	90-120	Flat Specimen
	80-110	Tube Axial
	100-160	Tube Hoop
Ultimate Tensile Strength [MPa]	250-350	Flat Specimen
	230-270	Tube Axial
	200-340	Tube Hoop

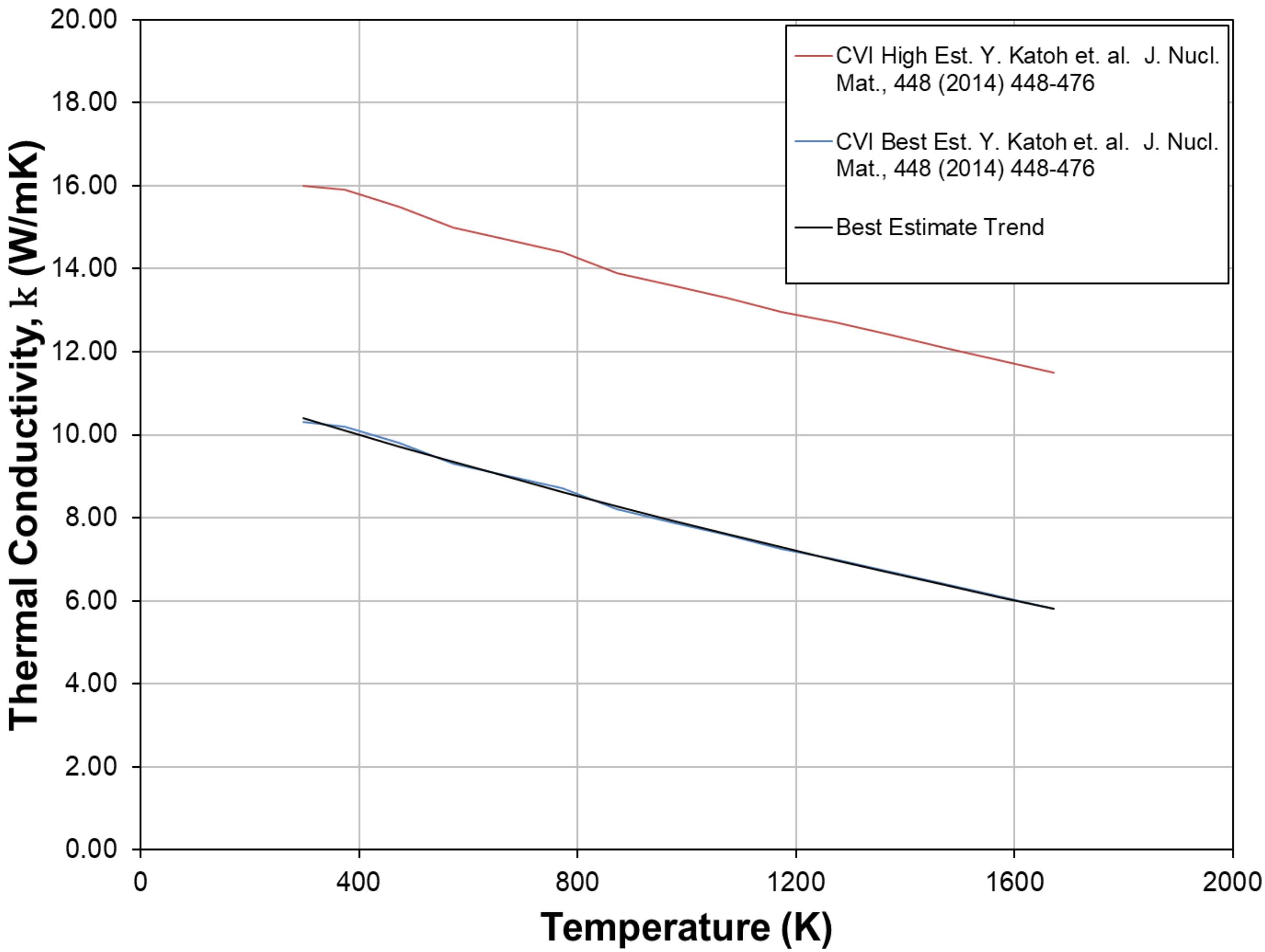

Figure 8.1.1-1: Thermal Conductivity vs. Temperature. Displaying fitted trend of data for best estimate values from Katoh (2104).

Thermal Conductivity with Temperature

100% Theoretical Density

Temperature (T)		Thermal Conductivity (k)		Temperature (T)		Thermal Conductivity (k)	
K	(°F)	W/(m-K)	((Btu-in.)/(ft.^{2}-hr-°F))	K	(°F)	W/(m-K)	((Btu-in.)/(ft.^{2}-hr-°F))
330	(134.3)	10.28	(71.33)	1000	(1430.3)	7.85	(54.45)
300	(80.3)	10.40	(72.15)	1050	(1520.3)	7.68	(53.30)
350	(170.3)	10.20	(70.78)	1100	(1610.3)	7.52	(52.17)
400	(260.3)	10.01	(69.43)	1150	(1700.3)	7.36	(51.06)
450	(350.3)	9.81	(68.09)	1200	(1790.3)	7.20	(49.97)
500	(440.3)	9.62	(66.77)	1250	(1880.3)	7.05	(48.88)
550	(530.3)	9.44	(65.47)	1300	(1970.3)	6.89	(47.82)
600	(620.3)	9.25	(64.18)	1350	(2060.3)	6.74	(46.77)
650	(710.3)	9.07	(62.91)	1400	(2150.3)	6.59	(45.74)
700	(800.3)	8.89	(61.65)	1450	(2240.3)	6.45	(44.72)
750	(890.3)	8.71	(60.41)	1500	(2330.3)	6.30	(43.72)
800	(980.3)	8.53	(59.19)	1550	(2420.3)	6.16	(42.74)
850	(1070.3)	8.36	(57.98)	1600	(2420.3)	6.02	(41.77)
900	(1160.3)	8.18	(56.78)	1650	(2510.3)	5.88	(40.82)
950	(1250.3)	8.01	(55.61)	1673	(2551.7)	5.82	(40.38)

Application Notes: Data for thermal conductivity is collected from reference [1] and fitted with the equation below to approximate property trend with respect to temperature. Best estimate data is for Hi-Nicalon Type S (HNLS) fiber / chemical vapor-infiltrated (CVI) SiC composite with either pyrolytic carbon (PyC) or multi-layer PyC/SiC interface.

Fit Equation:

$$k(T) = A0 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2$$

$k(T) = Thermal\ Conductivity\ [W\ /\ (m \cdot K)]$

$T = Temperature\ [K]$

Constants:

T Range [K]: $298 \leq T \leq 1673$

A0 = 11.631

A1 = -4.244

A2 = 0.46103

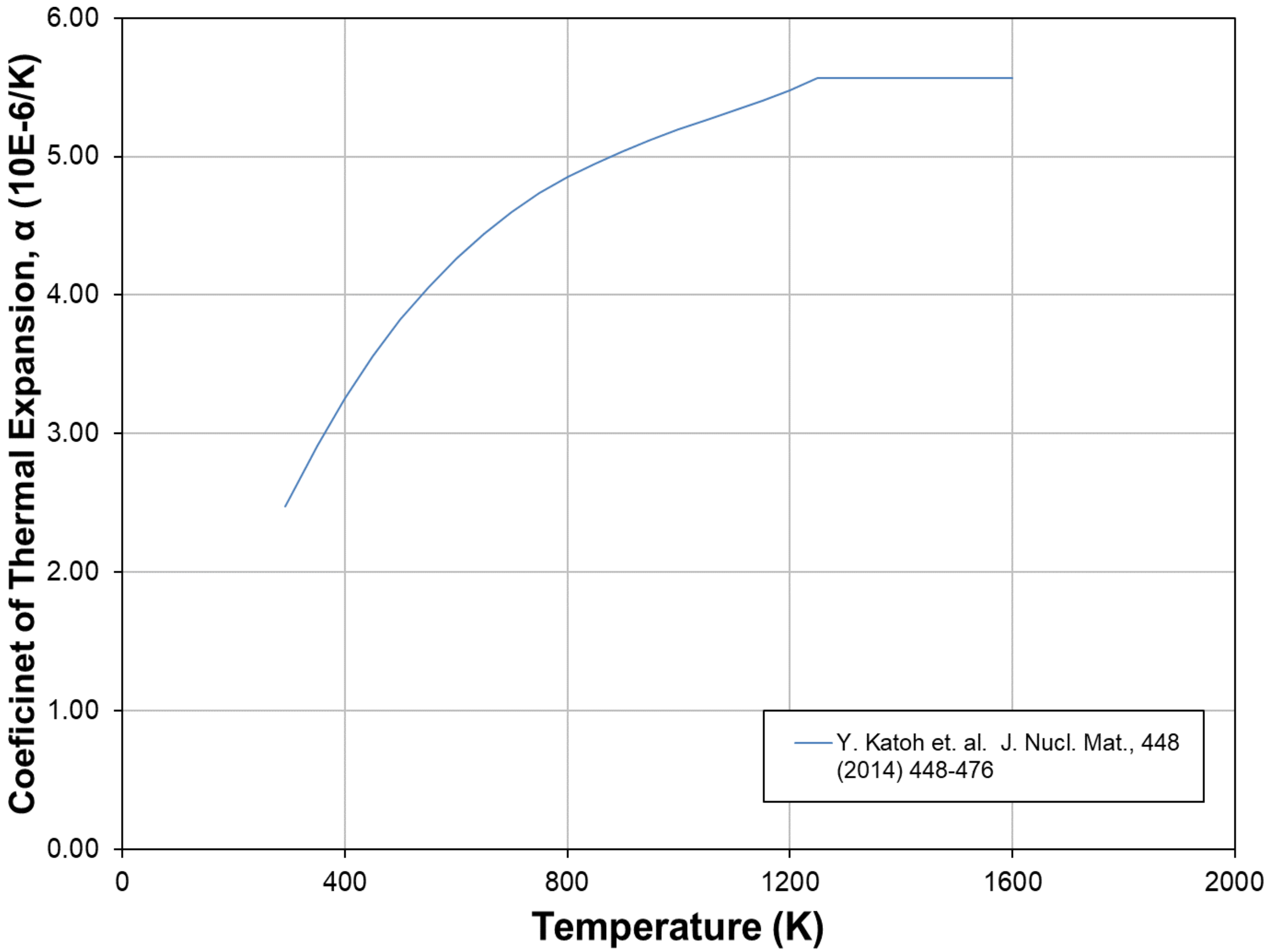

Figure 8.1.1-2: Thermal Expansion versus Temperature of SiC/SiC Composite.

Coefficient of Thermal Expansion with Temperature

100% Theoretical Density

Temperature (T) K	(°F)	CTE µm/(m-K)	(µin/(in-°F))	Temperature (T) K	(°F)	CTE µm/(m-K)	(µin/(in-°F))
293	(67.7)	2.476	(1.376)	1150	(1610.3)	5.403	(3.002)
300	(80.3)	2.533	(1.407)	1200	(1700.3)	5.479	(3.044)
350	(170.3)	2.915	(1.619)	1250	(1790.3)	5.563	(3.090)
400	(260.3)	3.255	(1.808)	1300	(1880.3)	5.563	(3.090)
450	(350.3)	3.558	(1.976)	1350	(1970.3)	5.563	(3.090)
500	(440.3)	3.825	(2.125)	1400	(2060.3)	5.563	(3.090)
550	(530.3)	4.060	(2.255)	1450	(2150.3)	5.563	(3.090)
600	(620.3)	4.265	(2.370)	1500	(2240.3)	5.563	(3.090)
650	(710.3)	4.444	(2.469)	1550	(2330.3)	5.563	(3.090)
700	(800.3)	4.599	(2.555)	1600	(2420.3)	5.563	(3.090)
750	(890.3)	4.734	(2.630)	1650	(2510.3)	5.563	(3.090)
800	(980.3)	4.850	(2.695)	1700	(2600.3)	5.563	(3.090)
900	(1160.3)	5.040	(2.800)	1750	(2690.3)	5.563	(3.090)
1000	(1340.3)	5.193	(2.885)	1800	(2780.3)	5.563	(3.090)
1100	(1520.3)	5.332	(2.962)				

Application Notes: Data for thermal expansion is collected from reference [1] and fitted using the equation below to approximate property trend with respect to temperature. CTE is assumed to be constant for T>1273K based on Snead et al. [2]. For this range, α(1250K) is used.

Fit Equation:

$$\boldsymbol{\alpha}(T) = A0 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2 + A3 \cdot \left(\frac{T}{1000}\right)^3$$

$\alpha(T) = Thermal\ Expansion\ Coefficient\ [\mu m/(m \cdot K)]$

$T = Temperature\ [K]$

Constants:

T Range [K]:	$293 \leq T < 1273$	$1273 \leq T \leq 1800$
A0 =	−0.7765	$\alpha(T) = \alpha(1250) = 5.563$
A1 =	14.35	
A2 =	−12.209	
A3 =	3.8289	

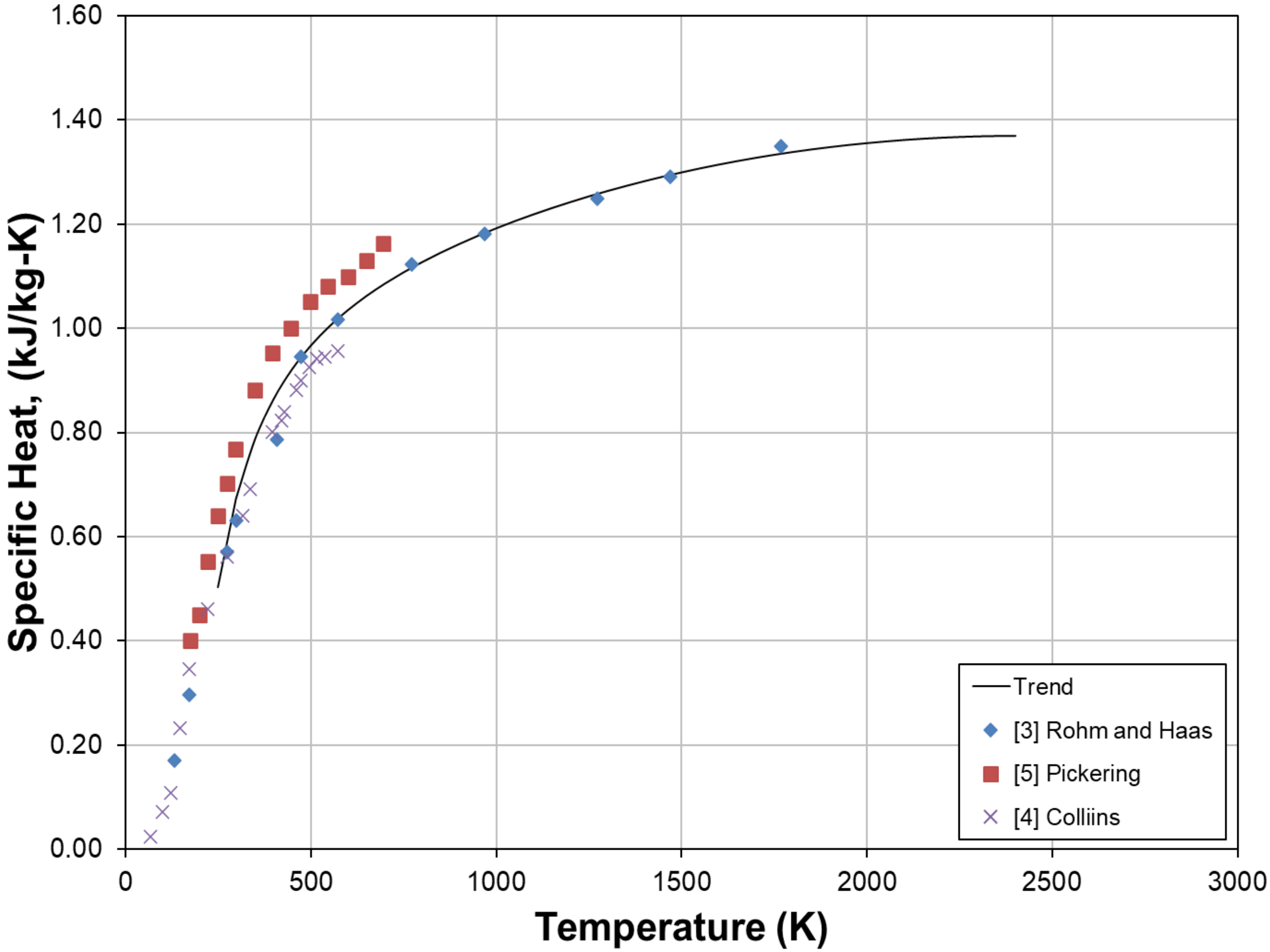

Figure 8.1.1-3: Specific Heat versus Temperature of SiC/SiC composite assuming behavior is the same as monolithic SiC. Trend line calculated from various test data [1]

100% Theoretical Density

Temperature (T)		Specific Heat (C_p)		Temperature (T)		Specific Heat (C_p)	
K	(°F)	J/(g-K)	(BTU/(lb-°F))	K	(°F)	J/(g-K)	(BTU/(lb-°F))
250	(-9.7)	0.504	(0.120)	1000	(1340.3)	1.192	(0.285)
300	(80.3)	0.677	(0.162)	1100	(1520.3)	1.218	(0.291)
350	(170.3)	0.787	(0.188)	1200	(1700.3)	1.242	(0.297)
400	(260.3)	0.864	(0.207)	1300	(1880.3)	1.263	(0.302)
450	(350.3)	0.922	(0.220)	1400	(2060.3)	1.282	(0.306)
500	(440.3)	0.967	(0.231)	1500	(2240.3)	1.299	(0.310)
550	(530.3)	1.004	(0.240)	1600	(2420.3)	1.314	(0.314)
600	(620.3)	1.035	(0.247)	1700	(2600.3)	1.327	(0.317)
650	(710.3)	1.062	(0.254)	1800	(2780.3)	1.338	(0.320)
700	(800.3)	1.086	(0.259)	1900	(2960.3)	1.347	(0.322)
750	(890.3)	1.107	(0.265)	2000	(3140.3)	1.355	(0.324)
800	(980.3)	1.127	(0.269)	2100	(3320.3)	1.361	(0.325)
850	(1070.3)	1.145	(0.274)	2200	(3500.3)	1.365	(0.326)
900	(1160.3)	1.161	(0.278)	2300	(3680.3)	1.368	(0.327)
950	(1250.3)	1.177	(0.281)	2400	(3860.3)	1.369	(0.327)

Application Notes: Specific heat values for monolithic SiC were compiled and summarized in reference [3-5] and fit using the equation below to approximate property trend as a function of temperature. Based on findings from reference [2], SiC/SiC composite specific heat trend with temperature is assumed to closely follow monolithic SiC.

Fit Equation:

$$C_P(T) = A0 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2 + A\_2/\left(\frac{T}{1000}\right)^2$$

$C_P(T) = Specific\ Heat\ [J/(g \cdot K)]$

$T = Temperature\ [K]$

Constants:

T. Range [K]:	$250 \leq T < 2400$
A0 =	0.92565
A1 =	0.3772
A2 =	-0.079259
A_2 =	-0.031946

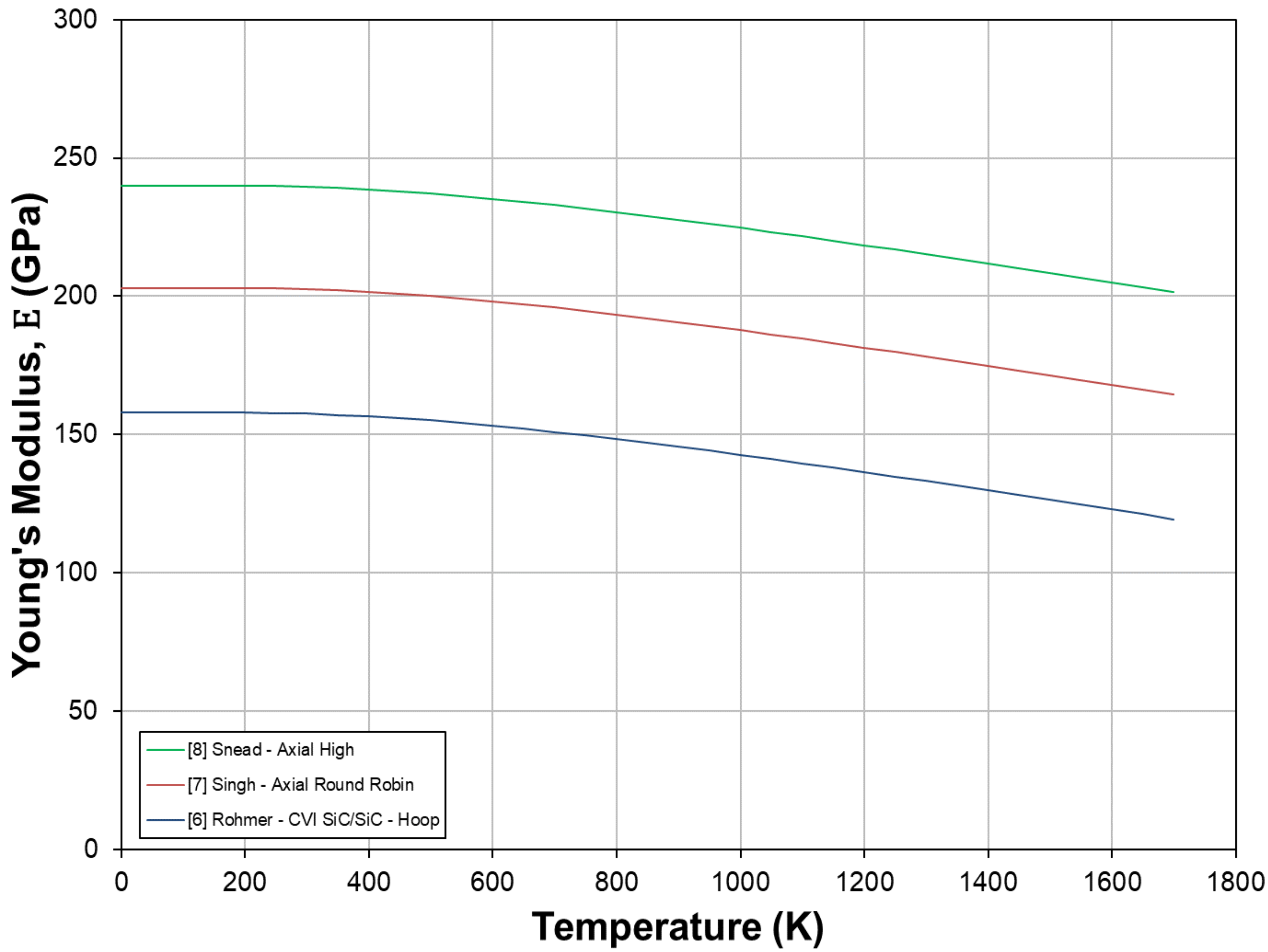

Figure 8.1.1-4: Elastic Modulus versus Temperature for SiC/SiC composite.

100% Theoretical Density

Temperature (T)		Young's Modulus (E)		Temperature (T)		Young's Modulus (E)	
K	(°F)	GPa	(Msi)	K	(°F)	GPa	(Msi)
300	(80.3)	203.51	(29.53)	1100	(1520.3)	185.65	(26.94)
350	(170.3)	203.10	(29.47)	1150	(1610.3)	184.07	(26.71)
400	(260.3)	202.56	(29.39)	1200	(1700.3)	182.47	(26.48)
450	(350.3)	201.88	(29.29)	1250	(1790.3)	180.84	(26.24)
500	(440.3)	201.08	(29.18)	1300	(1880.3)	179.19	(26.00)
550	(530.3)	200.17	(29.05)	1350	(1970.3)	177.52	(25.76)
600	(620.3)	199.17	(28.90)	1400	(2060.3)	175.83	(25.51)
650	(710.3)	198.08	(28.74)	1450	(2150.3)	174.13	(25.27)
700	(800.3)	196.92	(28.57)	1500	(2240.3)	172.40	(25.02)
750	(890.3)	195.68	(28.39)	1550	(2330.3)	170.67	(24.76)
800	(980.3)	194.39	(28.21)	1600	(2420.3)	168.92	(24.51)
850	(1070.3)	193.04	(28.01)	1650	(2510.3)	167.16	(24.25)
900	(1160.3)	191.64	(27.81)	1700	(2600.3)	165.39	(24.00)
950	(1250.3)	190.20	(27.60)	1750	(2690.3)	163.60	(23.74)
1000	(1340.3)	188.71	(27.38)	1800	(2780.3)	161.81	(23.48)
1050	(1430.3)	187.20	(27.16)				

Application Notes: Temperature dependence of SiC/SiC composite is assumed to follow the same trend as monolithic SiC [1] and shown in the equation below. Trend data generated using room temperature composite modulus values from [6-8].

Fit Equation:

$$E(T) = E_0 - B \cdot T \exp\left(-\frac{T_0}{T}\right)$$

$\boldsymbol{E}(T) = Modulus\ of\ Elasticity\ [GPa]$

$E_0 = Room\ Temperature\ Modulus$

$T = Temperature\ [K]$

Constants:

T. Range [K]:	$0 \leq T \leq 1800$
$E_0 =$	204 GPa
$T_0 =$	962K
$B =$	0.04 GPa/K

Thermal Conductivity Application Notes:

Through-thickness thermal conductivity for SiC/SiC composites can vary greatly and is dependent on fiber, interface and matrix. Room temperature ranges are:

- 8.5-18.1 W/m K for Hi Nicalon S / CVI-SiC composties with PyC or multi-layer PyC/SiC interfaces.
- 15.2-23.7 W/m K for Tyranno SA3 / CVI-SiC composties with PyC or multi-layer PyC/SiC interfaces.

- Even for composties with similar fiber, matrix and architecure, through-thickness thermal conductivity values can vary by as much as 40%. It is likely that the interface porosity, not total porosity is the main influence.
- For amorhous SiC/SiC composties, very little data exists regarding thermal conductivity as a function of temperature. Values ranging from 1.26-1.64 W/m K for polymer impregnation and pyrolysis (PIP) SiC/SiC with a PyC or multi-layer PyC/SiC interface have been reported by Zhao [9].

Specific Heat Application Notes:

According to Snead et al. [7], heat capacity for crystalline SiC/SiC composites is expected to be essentially the same as that for high-purity monolithic SiC. Data used is collected from various sources for monolithic SiC.

Very little data exists for temperature dependent specific heat for SiC/SiC composites.

Thermal Expansion Application Notes:

Experimental results from Katoh [1] indicates that CTE for SA3 and HNLS composites exhibit the same linear thermal expansion behavior with no detectable differences between the CVI composites and high-purity CVD SiC.

Elastic Modulus Application Notes:

Elastic Modulus data shown assumes the composite behavior follows the same trend as monolithic SiC. The formula uses room temperature values for Elastic Modulus as the starting point. Very little experimental data exists to support this assumption.

Proportional and Ultimate Stress Application Notes:

Substantial room temperature tensile testing of specimens cut from plate plates has been performed, while limited axial and hoop strength testing has been performed for tubes [7]. The fiber type, the fiber architecture, the fiber interface coating and the matrix microstructure (including porosity) all influence the strength characteristics for SiC/SiC composites, including the proportional limit stress (PLS) and strain, the ultimate tensile strength (UTS) and the strain at the UTS. Consequently, mechanical properties used for analyses must be obtain for specimens prepared from composite components fabricated using the same materials and process steps as those intended for the final components. Until such data are available, strength data provided should be considered as reference values only.

Although some limited data for temperature dependent proportional limit stress are available [10], values are greatly influenced by fiber architecture as well as interface type and thickness, Therefore, the same comments apply regarding the need for application specific material testing. Additionally, elevated temperature testing data available in the literature in most cases are from tests performed in air where oxidation drives the the resulting reduction in strength.

[1] Y. Katoh, K. Ozawa, C. Shih, et al., Continuous SiC fiber, CVI SiC matrix composites for nuclear applications: Properties and irradiation effects, Journal of Nuclear Materials 448(1-3) (2014) 448-476.

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[4] A.K. Collins, M.A. Pickering, R.L. Taylor, Grain size dependence of the thermal conductivity of polycrystalline chemical vapor deposited β-SiC at low temperatures, Journal of Applied Physics 68(12) (1990) 6510-6512.

[5] M.A. Pickering, R.L. Taylor, J.T. Keeley, G.A. Graves, Chemically vapor deposited silicon carbide (SiC) for optical applications, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 291(1) (1990) 95-100.

[6] E. Rohmer, E. Martin, C. Lorrette, Mechanical properties of SiC/SiC braided tubes for fuel cladding, Journal of Nuclear Materials 453(1) (2014) 16-21.

[7] M.A. Snead, Y. Katoh, T. Koyanagi, G.P. Singh, SiC/SiC Cladding Materials Properties Handbook, Oak Ridge National Lab. (ORNL), Oak Ridge, TN (United States), 2017.

[8] G. Singh, S.T. Gonczy, E. Lara-Curzio, Y. Katoh, Interlaboratory Round Robin Study on Axial Tensile Properties of Tubular SiC/SiC Specimens, Oak Ridge National Lab. (ORNL), Oak Ridge, TN (United States), 2018.

[9] S. Zhao, Z. Yang, X.-G. Zhou, et al., Design, Fabrication, Characterization and Simulation of PIP-SiC/SiC Composites, Computers, Materials \& Continua 42(2) (2014) 103-124.

[10] L. Li, Temperature-dependent proportional limit stress of SiC/SiC fiber-reinforced ceramic-matrix composites, High Temperature Materials and Processes 39(1) (2020) 209-218.

8 Composites and Structures

8.1 Carbide Based

Room Temperature Properties

Theoretical Density, [kg/m^3]	6,700	
Specific Heat, [J/(g-K]	0.350	
Thermal Conductivity, [W/(m-K)]	40-60	
Linear expansion coefficient, [µm/(m-K)]	4.50	
Electrical resistivity, [µΩ-m]	0.61	
Young's Modulus, [GPa]	200-360	Dependent on Carbon content and Porosity
Shear Modulus, [GPa]	80-140	
Modulus of Rupture [MPa]	100-130	
Ultimate Tensile Strength [MPa]	77-120	
Poisson’s Ratio, [-]	0.165-0.21	

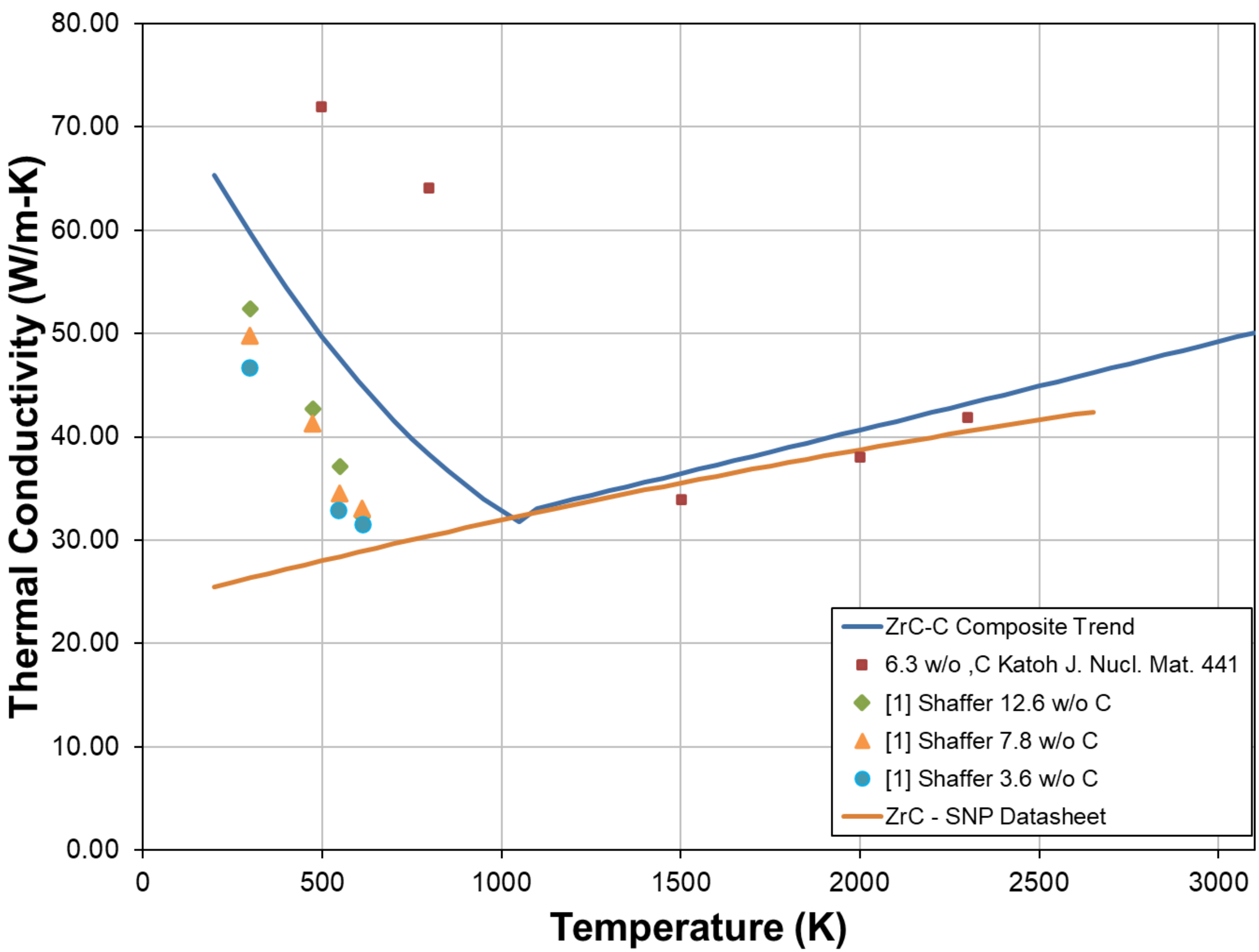

Figure 8.1.2-1: Thermal Conductivity vs. Temperature. Displaying fitted trend of data for best estimate values from Schaffer.

Temperature (T)		Thermal Conductivity (k)		Temperature (T)		Thermal Conductivity (k)	
K	(°F)	W/(m-K)	((Btu-in.)/(ft.^{2}-hr-°F))	K	(°F)	W/(m-K)	((Btu-in.)/(ft.^{2}-hr-°F))
300	(80.3)	59.65	(413.84)	1100	(1700.3)	33.10	(229.62)
350	(170.3)	56.99	(395.42)	1200	(1880.3)	33.93	(235.41)
400	(260.3)	54.45	(377.79)	1300	(2060.3)	34.77	(241.22)
450	(350.3)	52.02	(360.95)	1400	(2240.3)	35.60	(247.03)
500	(440.3)	49.71	(344.91)	1500	(2420.3)	36.44	(252.85)
550	(530.3)	47.51	(329.65)	1600	(2600.3)	37.29	(258.69)
600	(620.3)	45.43	(315.18)	1700	(2780.3)	38.13	(264.53)
650	(710.3)	43.46	(301.50)	1800	(2960.3)	38.97	(270.39)
700	(800.3)	41.60	(288.62)	1900	(3140.3)	39.82	(276.25)
750	(890.3)	39.86	(276.52)	2000	(3320.3)	40.66	(282.13)
800	(980.3)	38.23	(265.22)	2100	(3500.3)	41.51	(288.02)
850	(1070.3)	36.71	(254.70)	2200	(3680.3)	42.36	(293.91)
900	(1160.3)	35.31	(244.98)	2300	(3680.3)	43.21	(299.82)
950	(1250.3)	34.02	(236.04)	2400	(3860.3)	44.07	(305.74)
1000	(1340.3)	32.85	(227.90)	2500	(4040.3)	44.92	(311.67)

Application Notes: Data for thermal conductivity is collected from reference [1] and fitted with the equation below to approximate property trend with respect to temperature.

Fit Equation:

$$k(T) = A0 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2$$

$k(T) = Thermal\ Conductivity\ [W\ /\ (m \cdot K)]$

$T = Temperature\ [K]$

Constants:

T Range [K]:	$200 \le T \le 1100$	T Range [K]:	$1100 \le T \le 3100$
A0 =	77.967	A0 =	24.012
A1 =	-67.901	A1 =	8.175
A2 =	22.781	A2 =	0.07545

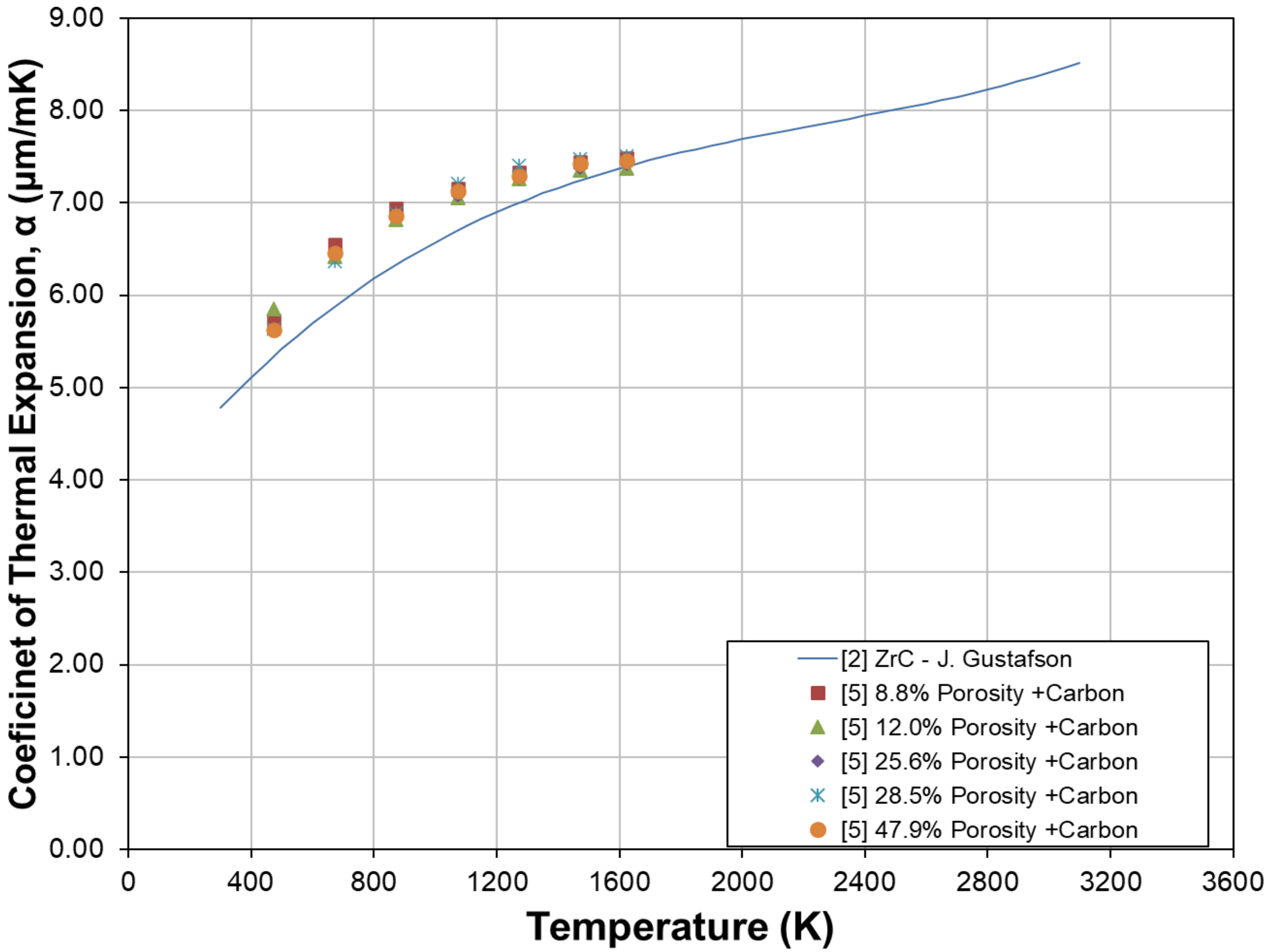

Figure 8.1.2-2: Thermal Expansion versus Temperature for ZrC-C composite based on dense ZrC data from Gustafson.

Temperature (T)		CTE		Temperature (T)		CTE	
K	(°F)	µm/(m-K)	(µin/(in-°F))	K	(°F)	µm/(m-K)	(µin/(in-°F))
300	(80.3)	4.781	(2.656)	1800	(2780.3)	7.545	(4.192)
400	(260.3)	5.112	(2.840)	1900	(2960.3)	7.620	(4.234)
500	(440.3)	5.415	(3.008)	2000	(3140.3)	7.690	(4.272)
600	(620.3)	5.692	(3.162)	2100	(3320.3)	7.756	(4.309)
700	(800.3)	5.946	(3.303)	2200	(3500.3)	7.819	(4.344)
800	(980.3)	6.176	(3.431)	2300	(3680.3)	7.882	(4.379)
900	(1160.3)	6.385	(3.547)	2400	(3860.3)	7.944	(4.414)
1000	(1340.3)	6.574	(3.652)	2500	(4040.3)	8.009	(4.449)
1100	(1520.3)	6.745	(3.747)	2600	(4220.3)	8.077	(4.487)
1200	(1700.3)	6.899	(3.833)	2700	(4400.3)	8.149	(4.527)
1300	(1880.3)	7.037	(3.909)	2800	(4580.3)	8.228	(4.571)
1400	(2060.3)	7.161	(3.978)	2900	(4760.3)	8.314	(4.619)
1500	(2240.3)	7.272	(4.040)	3000	(4940.3)	8.410	(4.672)
1600	(2420.3)	7.373	(4.096)	3100	(5120.3)	8.516	(4.731)
1700	(2600.3)	7.463	(4.146)	3200	(5300.3)	8.634	(4.796)

Application Notes: Since CTE is not significantly affected by porosity or additional carbon, data presented for thermal expansion is based on the fit equation below for dense, near stoichiometric ZrC [2].

Fit Equation:

$$\boldsymbol{\alpha}(T) = A0 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2 + A3 \cdot \left(\frac{T}{1000}\right)^3$$

$\alpha(T) = Thermal\ Expansion\ Coefficient\ [\mu m/(m \cdot K)]$

$T = Temperature\ [K]$

Constants:

T Range [K]: $0 \le T \le 3300$

A0 =	3.6129
A1 =	4.3674
A2 =	-1.6475
A3 =	0.2416

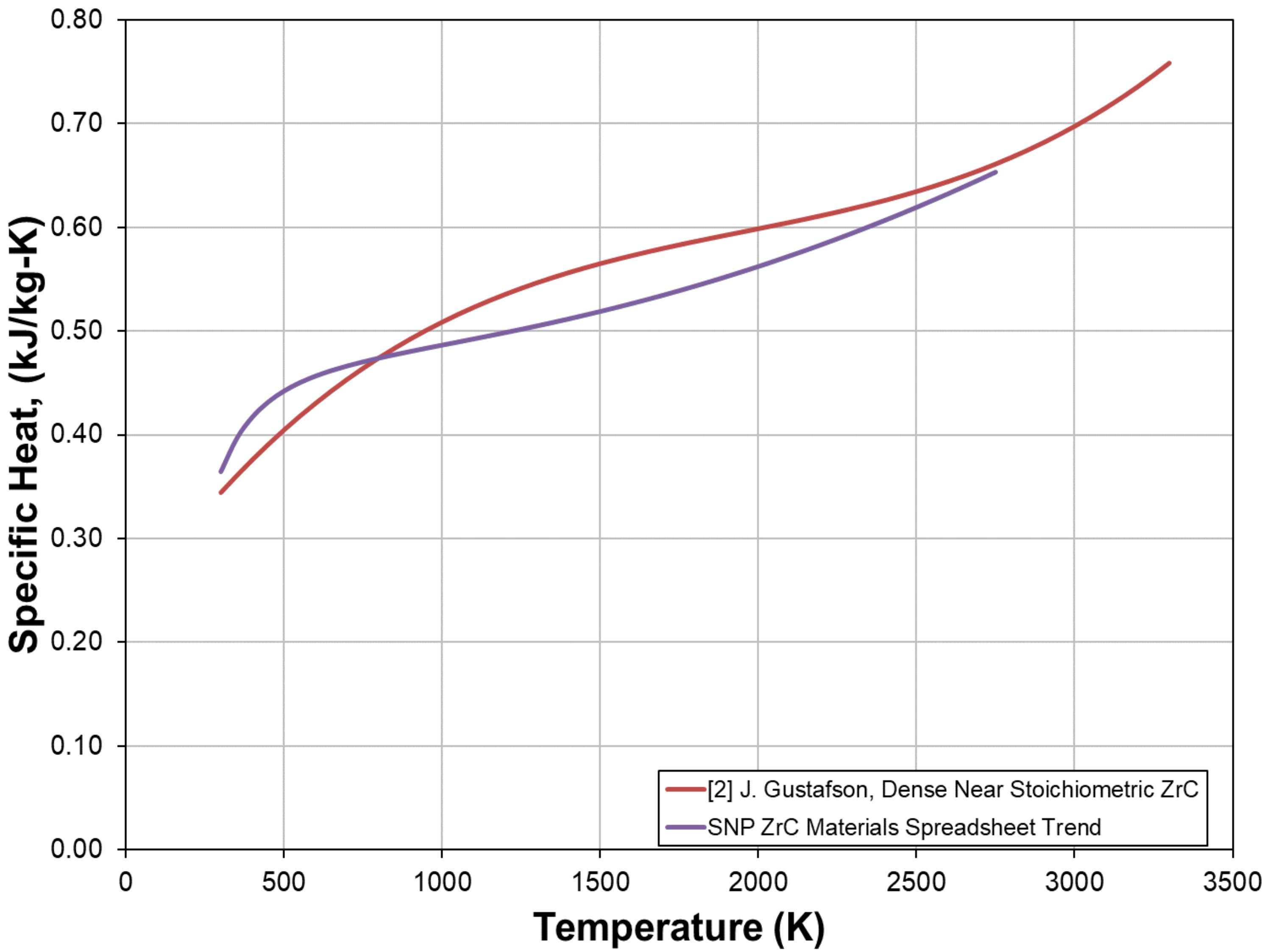

Figure 8.1.2-3: Estimated Specific Heat versus Temperature for ZrC-C composite based on dense, near stoichiometric ZrC.

Temperature (T)		Specific Heat (C_p)		Temperature (T)		Specific Heat (C_p)	
K	(°F)	J/(g-K)	(BTU/(lb-°F))	K	(°F)	J/(g-K)	(BTU/(lb-°F))
300	(80.3)	0.344	(0.082)	1800	(2780.3)	0.586	(0.140)
400	(260.3)	0.376	(0.090)	1900	(2960.3)	0.593	(0.142)
500	(440.3)	0.405	(0.097)	2000	(3140.3)	0.599	(0.143)
600	(620.3)	0.430	(0.103)	2100	(3320.3)	0.605	(0.145)
700	(800.3)	0.453	(0.108)	2200	(3500.3)	0.611	(0.146)
800	(980.3)	0.474	(0.113)	2300	(3680.3)	0.618	(0.148)
900	(1160.3)	0.492	(0.118)	2400	(3860.3)	0.626	(0.150)
1000	(1340.3)	0.509	(0.122)	2500	(4040.3)	0.635	(0.152)
1100	(1520.3)	0.523	(0.125)	2600	(4220.3)	0.644	(0.154)
1200	(1700.3)	0.536	(0.128)	2700	(4400.3)	0.655	(0.157)
1300	(1880.3)	0.547	(0.131)	2800	(4580.3)	0.667	(0.160)
1400	(2060.3)	0.556	(0.133)	2900	(4760.3)	0.682	(0.163)
1500	(2240.3)	0.565	(0.135)	3000	(4940.3)	0.697	(0.167)
1600	(2420.3)	0.573	(0.137)	3100	(5120.3)	0.716	(0.171)
1700	(2600.3)	0.580	(0.139)	3200	(5300.3)	0.736	(0.176)

Application Notes: Data for thermal conductivity is collected from reference [2] and fitted with the equation below for dense, near stoichiometric ZrC. Based on data from reference [3], specific heat is not significantly affected by additional carbon or porosity.

Fit Equation:

$$C_P(T) = A0 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2 + A3 \cdot \left(\frac{T}{1000}\right)^3$$

$C_P(T) = Specific\ Heat\ [J/(g \cdot K)]$

$T = Temperature\ [K]$

Constants:

T Range [K]: $0 \leq T \leq 3300$

A0 = .22803

A1 = 0.4422

A2 = - 0.1948

A3 = 0.03318

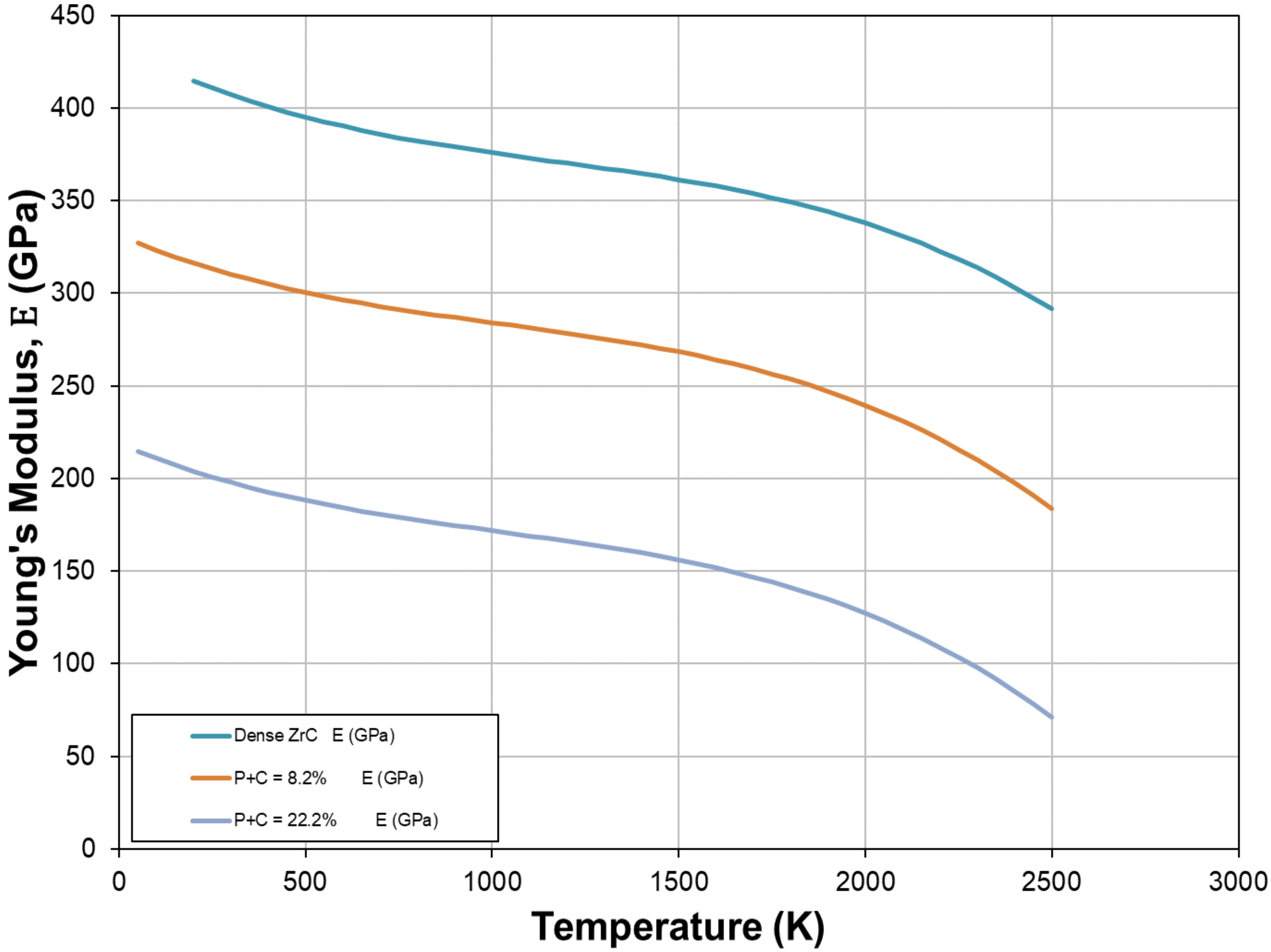

Figure 8.1.2-4:: : Estimated Elastic Modulus versus Temperature for ZrC-C Composite with ZrC shown for comparison.

Young's Modulus with Temperature and Carbon + Porosity

Temperature (T)		Young's Modulus (E) [GPa]		
K	(°F)	Dense ZrC	P+C = 8.2% E [GPa]	P+C = 22% E [GPa]
300	(80.3)	397.83	365.52	247.58
500	(440.3)	388.02	356.50	241.48
700	(800.3)	380.52	349.61	236.81
900	(1160.3)	374.44	344.03	233.03
1100	(1520.3)	368.90	338.95	229.58
1300	(1880.3)	363.03	333.55	225.93
1500	(2240.3)	355.92	327.02	221.51
1700	(2600.3)	346.71	318.55	215.77
1900	(2960.3)	334.50	307.34	208.17
2100	(3320.3)	318.42	292.56	198.16
2300	(3680.3)	297.57	273.41	185.19
2500	(4040.3)	271.08	249.07	168.70
2700	(4400.3)	238.06	218.73	148.16
2900	(4760.3)	197.63	181.58	122.99
3100	(5120.3)	148.90	136.81	92.67
3300	(5480.3)	91.00	83.61	56.63

Application Notes: Trend data based on empirical modulus relationship shown in the equation below from reference [4] and using temperature dependent modulus data for dense ZrC from reference [2]. Scaled values used for temperature dependent modulus with the addition of porosity and carbon.

Fit Equation:

$$E(T) = A0 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2 + A3 \cdot \left(\frac{T}{1000}\right)^3$$

$E(T) = Modulus\ of\ Elasticity\ [GPa]$

$T = Temperature\ [K]$

T Range [K]: $273 \leq T \leq 3300$

A0 =	418.8
A1 =	-85.2
A2 =	56.47
A3 =	-18.41

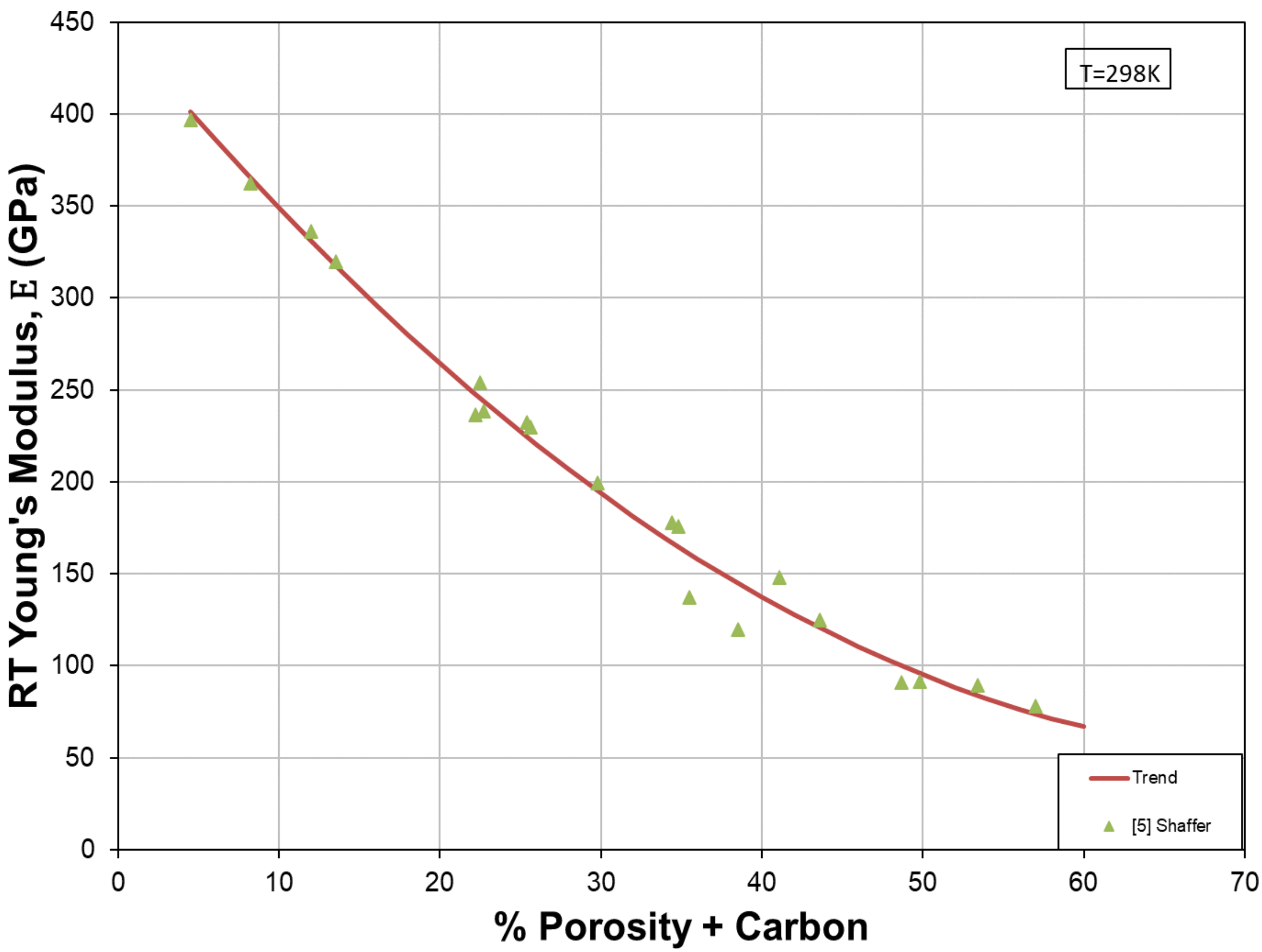

Figure 8.1.2-5: Estimated RT Elastic Modulus versus %Carbon and %Porosity for ZrC-C Composite.

%Porosity + %Carbon	RT Modulus [GPa]	%Porosity + %Carbon	RT Modulus [GPa]
4.500	401.29	26	220.33
6.000	386.55	28	206.80
8.000	367.40	30	193.83
10.000	348.81	32	181.43
12.000	330.78	34	169.58
14.000	313.31	36	158.30
16.000	296.41	38	147.59
18.000	280.07	40	137.43
20.000	264.29	42	127.84
22.000	249.07	44	118.81
24.000	234.42	46	110.34

Application Notes: Data for Young's modulus is collected from [1, 5] and fitted using the equation below based on the assumption that porosity and excess carbon have similar effects on modulus based on findings from reference [4].

Fit Equation:

$$E_P = A0 + A1 \cdot P + A2 \cdot P^2$$

E_P = Porosity + Carbon Scaled Modulus of Elasticity [GPa]

P = %Porosity + %Carbon

Constants:

Porosity + Carbon Range: $4.5\% \le P \le 60\%$

A0 = 447.39

A1 = -10.561

A2 = 0.0703

[1] P. Schaffer, D. Hasselman, A. Chaerski, Factors Affecting Thermal Shock Resistance of Polyphase Ceramic Bodies - Part 2, The Carborundum Company, R&DD, 1962.

[2] J. Gustafson, NASA GCD Feasibility NTP Material Property Handbook Development Status, 2019.

[3] Y. Katoh, G. Vasudevamurthy, T. Nozawa, L.L. Snead, Properties of zirconium carbide for nuclear fuel applications, Journal of Nuclear Materials 441(1) (2013) 718-742.

[4] V.M. Baranov, V.I. Knyazev, O.S. Korostin, The temperature dependence of the elastic constants of nonstoichiometric zirconium carbides, Strength of Materials 5(9) (1973) 1074-1077.

[5] P. Schaffer, D. Hasselman, A. Chaerski, Factors Affecting Thermal Shock Resistance of Polyphase Ceramic Bodies - Part 1, The Carborundum Company, R&DD, 1961.

8 Composites and Structures

8.1 Carbide Based

Room Temperature Properties

Theoretical Density, [kg/m^3]	1,300	80% porosity
Specific Heat, [J/(g-K)]	0.340	
Thermal Conductivity, [W/(m-K)]	0.4-1.0	
Linear expansion coefficient, [μm/(m-K)]	4.5-5.0	
Young's Modulus, [GPa]	55.0	
Compressive Yield Stress [MPa]	17	72% porosity

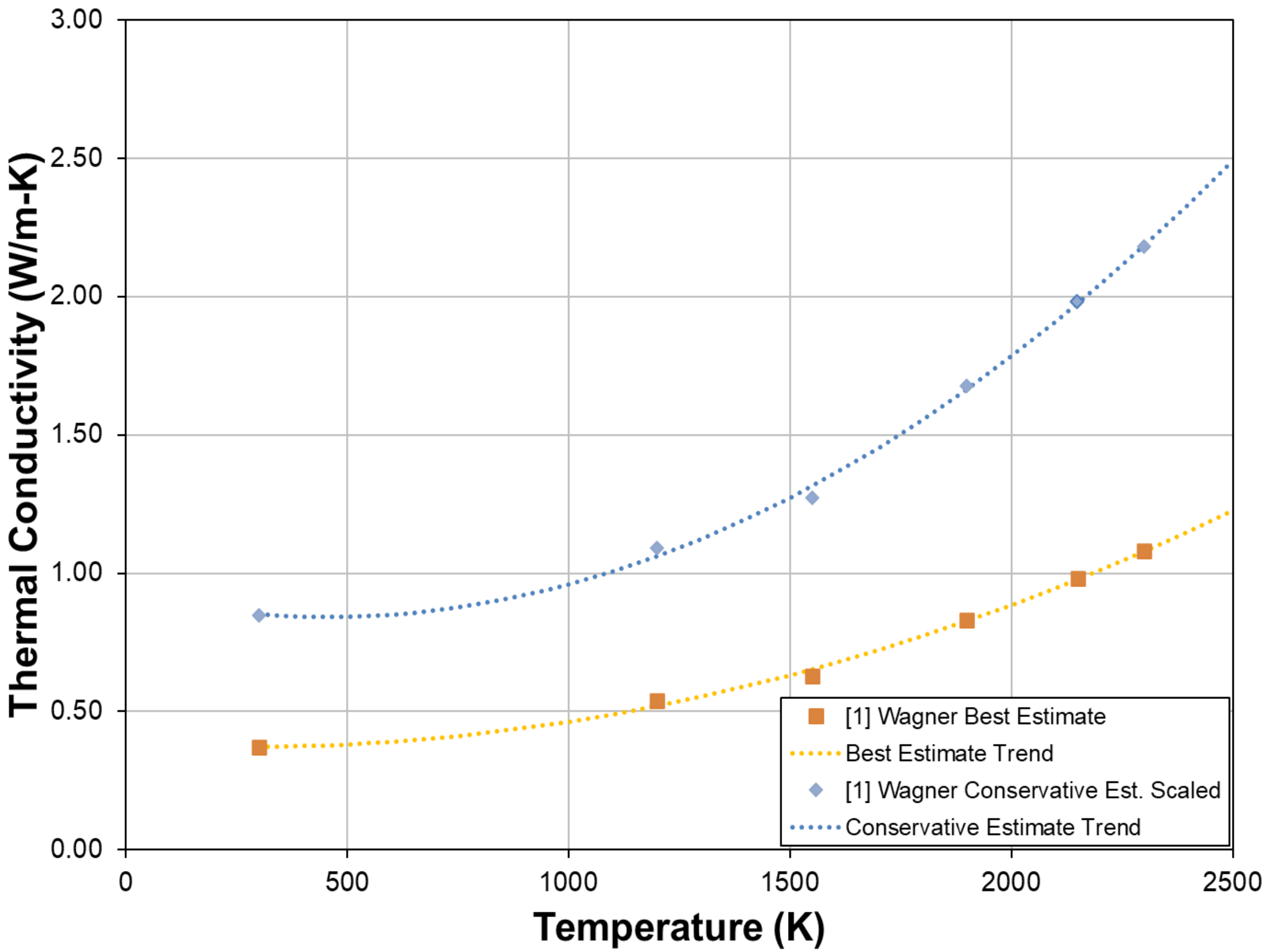

Figure 8.1.3-1: Thermal Conductivity vs. Temperature for high porosity ZrC.

Temperature (T)		Thermal Conductivity (k)		Temperature (T)		Thermal Conductivity (k)	
K	(°F)	W/(m-K)	((Btu-in.)/(ft.^{2}-hr-°F))	K	(°F)	W/(m-K)	((Btu-in.)/(ft.^{2}-hr-°F))
300	(80.3)	0.37	(2.59)	1100	(1700.3)	0.49	(3.40)
350	(170.3)	0.37	(2.59)	1200	(1880.3)	0.52	(3.61)
400	(260.3)	0.38	(2.61)	1300	(2060.3)	0.55	(3.84)
450	(350.3)	0.38	(2.62)	1400	(2240.3)	0.59	(4.10)
500	(440.3)	0.38	(2.65)	1500	(2420.3)	0.63	(4.38)
550	(530.3)	0.39	(2.68)	1600	(2600.3)	0.68	(4.69)
600	(620.3)	0.39	(2.71)	1700	(2780.3)	0.72	(5.01)
650	(710.3)	0.40	(2.76)	1800	(2960.3)	0.77	(5.37)
700	(800.3)	0.40	(2.80)	1900	(3140.3)	0.83	(5.74)
750	(890.3)	0.41	(2.86)	2000	(3320.3)	0.89	(6.14)
800	(980.3)	0.42	(2.92)	2100	(3500.3)	0.95	(6.56)
850	(1070.3)	0.43	(2.98)	2200	(3680.3)	1.01	(7.01)
900	(1160.3)	0.44	(3.06)	2300	(3680.3)	1.08	(7.48)
950	(1250.3)	0.45	(3.13)	2400	(3860.3)	1.15	(7.98)
1000	(1340.3)	0.46	(3.22)	2500	(4040.3)	1.22	(8.50)

Application Notes: Data for thermal conductivity is collected from reference [1] and fitted with the equation below to approximate property trend with respect to temperature. Table data represents best estimate data for ZrC with a porosity of 72% and C/Zr ratio of 0.94.

Fit Equation:

$$k(T) = A0 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2$$

$k(T) = Thermal\ Conductivity\ [W / (m \cdot K)]$

$T = Temperature\ [K]$

Constants:

T Range [K]:	$300 \leq T \leq 2500$
A0 =	0.38532
A1 =	-0.093246
A2 =	0.017156

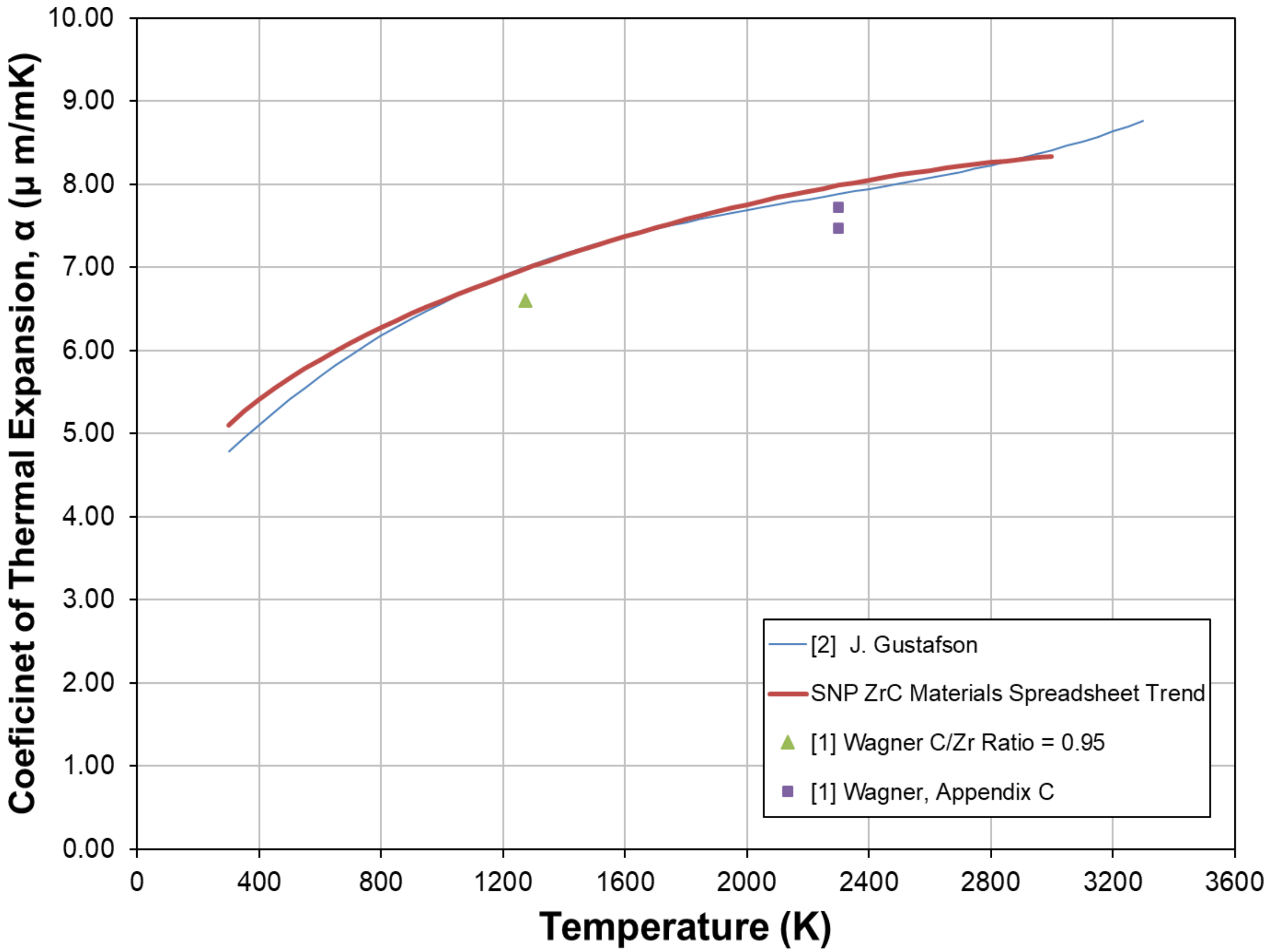

Figure 8.1.3-2: Thermal Expansion versus Temperature for porous ZrC.

Temperature (T)		CTE		Temperature (T)		CTE	
K	(°F)	µm/(m-K)	(µin/(in-°F))	K	(°F)	µm/(m-K)	(µin/(in-°F))
300	(80.3)	4.781	(2.656)	1800	(2780.3)	7.545	(4.192)
400	(260.3)	5.112	(2.840)	1900	(2960.3)	7.620	(4.234)
500	(440.3)	5.415	(3.008)	2000	(3140.3)	7.690	(4.272)
600	(620.3)	5.692	(3.162)	2100	(3320.3)	7.756	(4.309)
700	(800.3)	5.946	(3.303)	2200	(3500.3)	7.819	(4.344)
800	(980.3)	6.176	(3.431)	2300	(3680.3)	7.882	(4.379)
900	(1160.3)	6.385	(3.547)	2400	(3860.3)	7.944	(4.414)
1000	(1340.3)	6.574	(3.652)	2500	(4040.3)	8.009	(4.449)
1100	(1520.3)	6.745	(3.747)	2600	(4220.3)	8.077	(4.487)
1200	(1700.3)	6.899	(3.833)	2700	(4400.3)	8.149	(4.527)
1300	(1880.3)	7.037	(3.909)	2800	(4580.3)	8.228	(4.571)
1400	(2060.3)	7.161	(3.978)	2900	(4760.3)	8.314	(4.619)
1500	(2240.3)	7.272	(4.040)	3000	(4940.3)	8.410	(4.672)
1600	(2420.3)	7.373	(4.096)	3100	(5120.3)	8.516	(4.731)
1700	(2600.3)	7.463	(4.146)	3200	(5300.3)	8.634	(4.796)

Application Notes: Since CTE is not significantly affected by porosity, data presented for thermal expansion is based on the fit equation below for dense, near stoichiometric ZrC [2]. CTE is also assumed to be weakly influenced by C/Zr ratio from reference [3].

Fit Equation:

$$\boldsymbol{\alpha}(T) = A0 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2 + A3 \cdot \left(\frac{T}{1000}\right)^3$$

$\alpha(T) = Thermal\ Expansion\ Coefficient\ [\mu m/(m \cdot K)]$

$T = Temperature\ [K]$

Constants:

T Range [K]:	$0 \leq T \leq 3300$
A0 =	3.6129
A1 =	4.3674
A2 =	- 1.6475
A3 =	0.2416

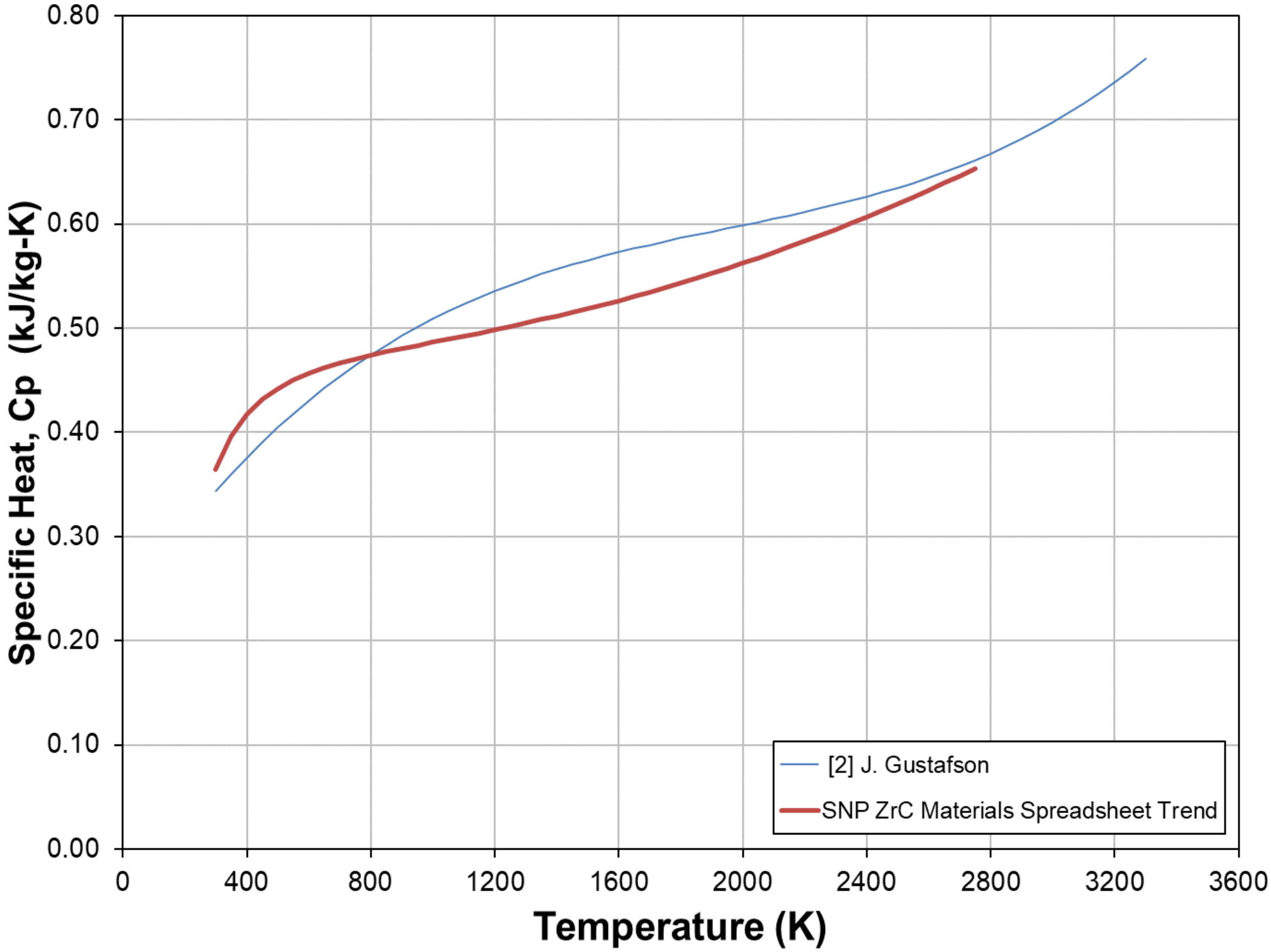

Figure 8.1.3-3: Estimated Specific Heat versus Temperature of porous ZrC.

Temperature (T)		Specific Heat (C_p)		Temperature (T)		Specific Heat (C_p)	
K	(°F)	J/(g-K)	(BTU/(lb-°F))	K	(°F)	J/(g-K)	(BTU/(lb-°F))
300	(80.3)	0.344	(0.082)	1800	(2780.3)	0.586	(0.140)
400	(260.3)	0.376	(0.090)	1900	(2960.3)	0.593	(0.142)
500	(440.3)	0.405	(0.097)	2000	(3140.3)	0.599	(0.143)
600	(620.3)	0.430	(0.103)	2100	(3320.3)	0.605	(0.145)
700	(800.3)	0.453	(0.108)	2200	(3500.3)	0.611	(0.146)
800	(980.3)	0.474	(0.113)	2300	(3680.3)	0.618	(0.148)
900	(1160.3)	0.492	(0.118)	2400	(3860.3)	0.626	(0.150)
1000	(1340.3)	0.509	(0.122)	2500	(4040.3)	0.635	(0.152)
1100	(1520.3)	0.523	(0.125)	2600	(4220.3)	0.644	(0.154)
1200	(1700.3)	0.536	(0.128)	2700	(4400.3)	0.655	(0.157)
1300	(1880.3)	0.547	(0.131)	2800	(4580.3)	0.667	(0.160)
1400	(2060.3)	0.556	(0.133)	2900	(4760.3)	0.682	(0.163)
1500	(2240.3)	0.565	(0.135)	3000	(4940.3)	0.697	(0.167)
1600	(2420.3)	0.573	(0.137)	3100	(5120.3)	0.716	(0.171)
1700	(2600.3)	0.580	(0.139)	3200	(5300.3)	0.736	(0.176)

Application Notes: The table data is a fit of equation below for dense, near stoichiometric ZrC from reference [2]. Based on data from reference [3], specific heat decreases as C/Zr ratio decreases, however, the reduction is small for materials at near stoichiometric ratios.

Fit Equation:

$$C_P(T) = A0 + A1 \cdot \left(\frac{T}{1000}\right) + A2 \cdot \left(\frac{T}{1000}\right)^2 + A3 \cdot \left(\frac{T}{1000}\right)^3$$

$C_P(T) = Specific\ Heat\ [J/(g \cdot K)]$

$T = Temperature\ [K]$

Constants:

T Range [K]: $0 \leq T \leq 3300$

A0 = .22803

A1 = 0.4422

A2 = - 0.1948

A3 = 0.03318

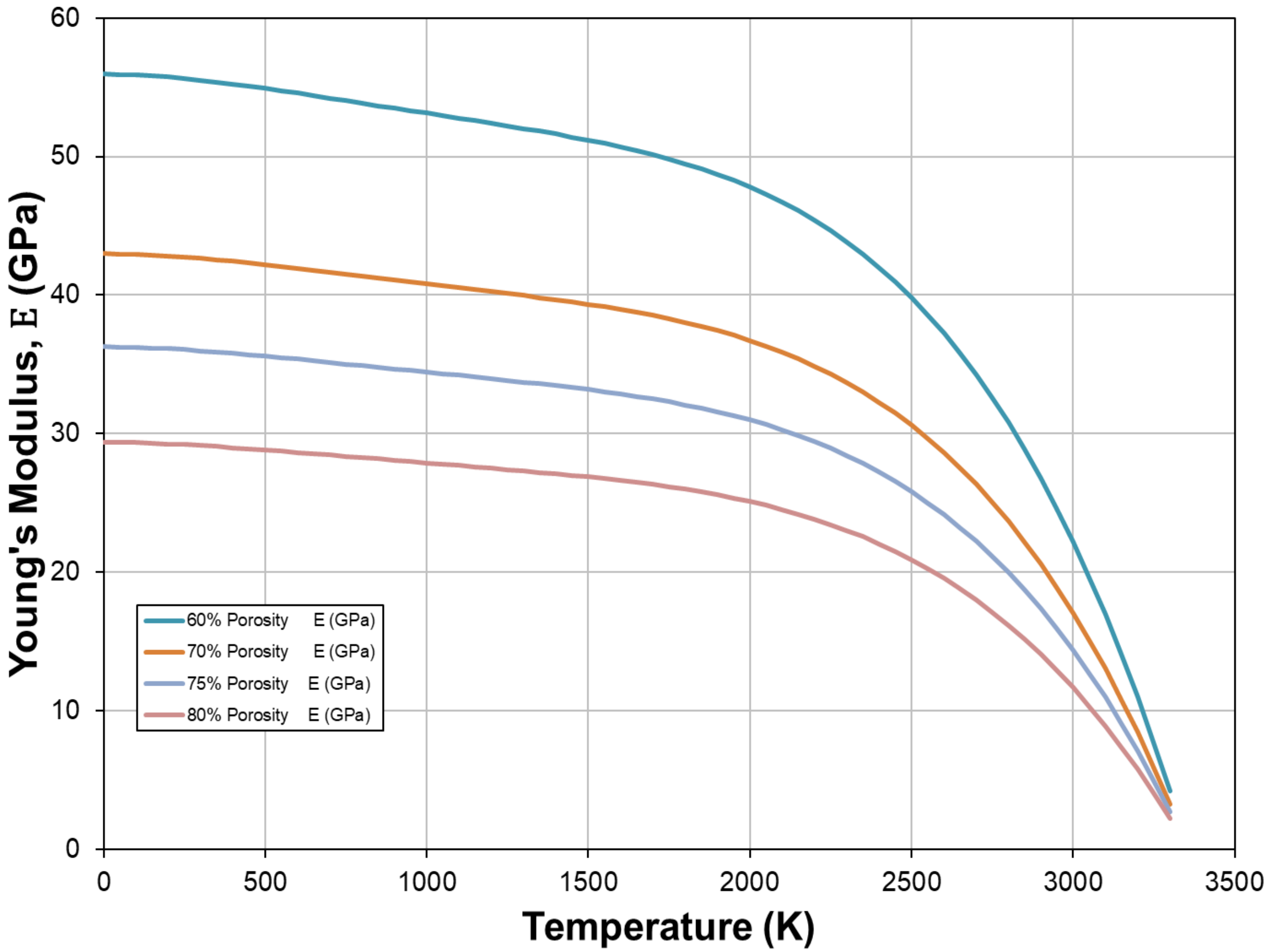

Figure 8.1.3-4: Estimated Elastic Modulus versus Temperature for Porous ZrC.

Temperature (T)		Young's Modulus (E) [GPa]				
K	(°F)	Dense ZrC	60% Porosity	70% Porosity	75% Porosity	80% Porosity
100	(-279.7)	308.31	55.89	42.95	36.23	29.34
200	(-99.7)	307.47	55.73	42.83	36.13	29.26
400	(260.3)	304.67	55.23	42.44	35.80	28.99
600	(620.3)	301.02	54.57	41.93	35.37	28.65
800	(980.3)	297.07	53.85	41.38	34.91	28.27
1000	(1340.3)	293.08	53.13	40.82	34.44	27.89
1200	(1700.3)	289.07	52.40	40.27	33.97	27.51
1400	(2060.3)	284.78	51.62	39.67	33.46	27.10
1600	(2420.3)	279.68	50.70	38.96	32.86	26.62
1800	(2780.3)	273.00	49.49	38.03	32.08	25.98
2000	(3140.3)	263.69	47.80	36.73	30.98	25.09
2200	(3500.3)	250.43	45.39	34.88	29.43	23.83
2400	(3860.3)	231.65	41.99	32.27	27.22	22.04
2600	(4220.3)	205.50	37.25	28.63	24.15	19.56
2800	(4580.3)	169.90	30.80	23.67	19.96	16.17
3000	(4940.3)	122.46	22.20	17.06	14.39	11.65
3200	(5300.3)	60.55	10.98	8.43	7.11	5.76
3300	(5480.3)	23.27	4.22	3.24	2.73	2.21

Application Notes: Table data generated by using temperature dependent modulus data from [2] as the input to the equation below from reference [4]. Due to the lack of experimental data, the model-based relationship in this equation should only serve as a guide.

Fit Equation:

$$E_P = E_0[(1 - \exp(-r(1-P)))]$$

$E_P = Porosity\ Scaled\ Modulus\ of\ Elasticity\ [GPa]$

$E_0 = Modulus\ for\ dense\ ZrC$

$P = Porosity$

$r = constant = 0.5$

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[3] Y. Katoh, G. Vasudevamurthy, T. Nozawa, L.L. Snead, Properties of zirconium carbide for nuclear fuel applications, Journal of Nuclear Materials 441(1) (2013) 718-742.

[4] J.A. Choren, S.M. Heinrich, M.B. Silver-Thorn, Young's modulus and volume porosity relationships for additive manufacturing applications, Journal of Materials Science 48(15) (2013) 5103-5112.