SMC-TR-03-09

AEROSPACE REPORT NO.
TR-2002(8565)-7

Thermomechanical Properties of Selected Space-Related Materials

30 September 2002

Prepared by

W. H. CHILDS
Space Materials Laboratory
Laboratory Operations
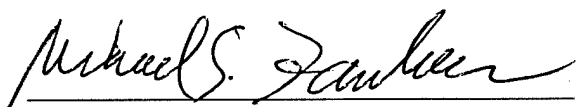
Edited by Tom Park and Sandra Gyetvay

Prepared for

SPACE AND MISSILE SYSTEMS CENTER
AIR FORCE SPACE COMMAND
2430 E. El Segundo Boulevard
Los Angeles Air Force Base, CA 90245

Engineering and Technology Group

THE AEROSPACE CORPORATION
El Segundo, California

APPROVED FOR PUBLIC RELEASE;
DISTRIBUTION UNLIMITED

20030312 132

This report was submitted by The Aerospace Corporation, El Segundo, CA 90245-4691, under Contract No. F04701-00-C-0009 with the Space and Missile Systems Center, 2430 E. El Segundo Blvd., Los Angeles Air Force Base, CA 90245. It was reviewed and approved for The Aerospace Corporation by P. D. Fleischauer, Principal Director, Space Materials Laboratory. Michael Zambrana was the project officer for the Mission-Oriented Investigation and Experimentation (MOIE) program.

This report has been reviewed by the Public Affairs Office (PAS) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nationals.

This technical report has been reviewed and is approved for publication. Publication of this report does not constitute Air Force approval of the report's findings or conclusions. It is published only for the exchange and stimulation of ideas.

Michael Zambrana
SMC/AXE

REPORT DOCUMENTATION PAGE	Form Approved OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing this collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number. **PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.**

1. REPORT DATE (DD-MM-YYYY) 30-09-2002	2. REPORT TYPE	3. DATES COVERED (From - To)

4. TITLE AND SUBTITLE	5a. CONTRACT NUMBER F04701-00-C-0009
Thermomechanical Properties of Selected Space-Related Materials	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)	5d. PROJECT NUMBER
W. H. Childs	5e. TASK NUMBER
Edited by Tom Park and Sandra Gyetvay	5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)	8. PERFORMING ORGANIZATION REPORT NUMBER
The Aerospace Corporation Laboratory Operations El Segundo, CA 90245-4691	TR-2002(8565)-7

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S) SMC
Space and Missile Systems Center Air Force Space Command 2450 E. El Segundo Blvd. Los Angeles Air Force Base, CA 90245	11. SPONSOR/MONITOR'S REPORT NUMBER(S) SMC-TR-03-09

12. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

Room-temperature values for nine thermomechanical material properties of 130 space-related materials have been tabulated in this report. These data are essential for analyses to determine material response to pulsed radiation that relate to survivability assessments of space systems based on above- and below-ground nuclear weapons effects experiments. The nine properties tabulated for each of the 130 materials include density, specific heat (constant pressure), specific heat (constant volume), Poisson's ratio, Grüneisen constant, adiabatic sound velocity, Young's modulus, isothermal bulk modulus, and volumetric coefficient of thermal expansion.

Various appropriate elements, oxides, carbides, halides, metallic alloys, semiconductors, optical materials, glasses, plastic and graphites are included in the tabulation. The majority of the materials are high density, low porosity, isotropic and polycrystalline in form.

15. SUBJECT TERMS

Thermomechanical properties, Grüneisen volumetric thermal expansion, Poisson's ratio, Heat capacity, Young's modulus, Sound velocity

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON Tom Park
a. REPORT UNCLASSIFIED	b. ABSTRACT UNCLASSIFIED	c. THIS PAGE UNCLASSIFIED		160	19b. TELEPHONE NUMBER (include area code) (310)336-5503

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. 239.18

Dedication

For Bill Childs; colleague and friend.

Foreword

The analysis of radiation interaction with, and damaging effects to, operational military systems requires a comprehensive database of thermophysical and other properties, covering the diversity of materials to be found in such systems, including spacecraft, launch and reentry vehicles, and their components. Computations of nuclear weapon or directed-energy weapon effects requires specialized knowledge and expertise, together with experience using the appropriate computer codes.

With the cessation of the cold war, efforts addressing the vulnerability, survivability, and hardening of military systems were severely scaled back. Consequently, the personnel who had maintained the associated analytical technologies were reassigned, retired, or discharged. Much knowledge and capability was lost in the process.

The Editors of this report have attempted to partially mitigate such losses by preserving this previously unpublished database of equation-of-state and related materials properties data, together with a tutorial on the derivation of equations for computing the Grüneisen constant. The data presented herein was collected and used by Mr. William H. "Bill" Childs in the analysis of thermal stress-related effects, and was found among his files at The Aerospace Corporation Space Materials Laboratory following his death in September, 1997.

During the period, 1965 through 1992, researchers in The Aerospace Corporation's Laboratory Operations conducted experiments on some 28 underground nuclear tests (UGTs) at Mercury, Nevada. Concurrently with these UGTs, and subsequent to the termination of underground testing in 1992, innumerable experiments were conducted using high-energy pulsed-power facilities at government and contractor laboratories in so-called "above ground tests" (AGTs). Bill Childs' career spanned the entire era of underground testing of space-related materials. His analytical efforts were critical to the support of virtually every nuclear weapon effects experiment conducted by Aerospace, whether underground or above ground, as well as the many "paper" studies related to vulnerability, survivability, and hardening done during that time.

In 1981, Childs published the first volume of his compendium of temperature-dependent thermophysical properties. Volume I[*] presented tables of data for 112 materials, together with curve fits suitable for computer code input. This was followed in 1986 by the publication of Volume II,[**] which presented data on an additional 107 materials. These volumes have become industry standards as data reference for radiation effects modeling and analysis. Childs was in the process of preparing a third volume, intended for the presentation of his collection of thermomechanical properties data, but

---

[*] Childs, W. H., "Thermophysical Properties of Selected Space-Related Materials", Vol. I, Aerospace Report No. TOR-0081(6435-02)-01, 20 February, 1981.

[**] Childs, W. H., "Thermophysical Properties of Selected Space-Related Materials", Vol. II, Aerospace Report No. TOR-0086(6435-02)-01, 15 February, 1986.

this was not completed during his lifetime. With its publication at this time, it is appropriate that this volume be dedicated to its original author.

The reader is cautioned that the information and data contained herein are presented as found among Childs' papers. These are known to be the data personally used by Childs, and informally provided by him to other workers in the field of radiation effects. Only minimal attempts have been made to compare the data in Childs' tables against data that might be found in the listed source materials. However, when comparisons were made, no inconsistencies could be found between Childs' data and those of other workers. In particular, Ho (ref. 88) presents a table of data calculated using a somewhat different method but that, nevertheless, agrees with Child's data to within about 10%.

The text has been edited and organized to comply with Corporation document standards. Corrections have been made where errors were found and some editorial changes have been made for clarity. However, the technical text remains essentially as written by Childs.

Data selection was made on the basis of Childs' judgement, in consultation with others. In particular, Dr. Robert Cooper is known to have given much advice and support to Childs' analytical activities. Cooper's editorial notes and comments on a draft copy of the text were found among Childs' papers and have been incorporated in this present document.

The list of data sources and references has been particularly a concern because Childs left multiple versions, including several pages of handwritten notes citing intended additions to the list of references. Explicit reference citations for the properties data selected by Childs and presented in his database could not be found. In an attempt to somewhat compensate for this lack, we have superficially reviewed the referenced documents to identify content related to the 130 materials in the database, without determining the actual source of data selected and tabulated by Childs. These observations of content have been appended to the materials list given in Section 7. However, the uncertainty of specific data origins remains a caveat to the reader.

Some of the referenced documents are quite obscure and will be difficult to locate using ordinary library services. Accordingly, the editors intend to preserve those reference documents found among Childs' holdings by transferring their possession to the Corporate Archivist of The Aerospace Corporation. Interested readers may obtain access to those reports by contacting the Corporate Archivist.

Symbols and Units

C_B	Bulk wave velocity	(cm/s)
C_L	Longitudinal wave velocity	(cm/s)
C_S	Shear wave velocity	(cm/s)
C_P	Heat capacity at constant pressure	(cal/g-°C)
C_V	Heat capacity at constant volume	(cal/g-°C)
E	Internal Energy	(cal/g)
G_R	Reuss averaged shear modulus	(dynes/cm^2)
G_V	Voigt averaged shear modulus	(dynes/cm^2)
B_H	Hashin averaged shear modulus	(dynes/cm^2)
G_S	Shtrikman averaged shear modulus	(dynes/cm^2)
K	Hashin and Shtrikman averaged bulk modulus	(dynes/cm^2)
K_R	Reuss averaged bulk modulus	(dynes/cm^2)
K_V	Voigt averaged bulk modulus	(dynes/cm^2)
K_A	Adiabatic bulk modulus	(dynes/cm^2)
K_I	Isothermal bulk modulus	(dynes/cm^2)
P	Pressure	(dynes/cm^2)
S	Entropy or degree of disorder	
T	Absolute Temperature	(°K)
V	Volume	(cm^3)
X_A	Adiabatic compressibility	(dynes/cm^2)$^{-1}$
X_I	Isothermal compressibility	(dynes/cm^2)$^{-1}$
Y	Young's modulus of elasticity	(dynes/cm^2)

β	Volumetric coefficient of thermal expansion	$(10^{-6}{}^{\circ}C^{-1})$
γ	Grüneisen constant	
λ	Lamè elastic constant	(dynes/cm^2)
μ	Shear modulus	(dynes/cm^2)
ν	Poisson's ratio	
ρ	Density	(g/cm^3)

Contents

1. Introduction

The thermomechanical material properties tabulated in this report are a consistent set of room-temperature data compiled for 130 space-related materials. These data are essential for analyses to determine material response to pulsed radiation, which relates to survivability assessments based on above and below ground weapons effects experiments. The need for such a compilation has been expressed by analysts on many occasions in connection with DoD, AFSD, AFRL, and DTRA-sponsored programs. The nine properties tabulated for each of the 130 materials include density, specific heat (constant pressure), specific heat (constant volume), Poisson's ratio, Grüneisen constant, adiabatic sound velocity, Young's modulus, isothermal bulk modulus, and volumetric coefficient of thermal expansion. Although the units are admittedly inconsistent, they have been selected for usage without conversion by the majority of users.

Among the 130 materials included in the tabulation are representative elements, oxides, carbides, halides, metallic alloys, semiconductors, optical materials, glasses, plastics, and graphites. The majority of the materials are high density, low porosity, isotropic and polycrystalline in form, unless otherwise stated. However, in a few cases, the materials are not completely characterized.

The tabulated values of material properties have been extracted from the literature without undertaking a complete or thorough search. The selected values represent the results of both experimental measurements and calculations. No attempt was made to validate the data. The bibliography, although not complete, provides the opportunity to consult the original references in most cases.

Whenever possible, experimentally measured isothermal properties were compared with values calculated from adiabatic measurements. The approach in this report was to calculate the Grüneisen constant, first based on an equation derived from thermodynamics relating to the adiabatic state, and second by means of an equation derived from thermodynamics relating to the isothermal state. These values are also compared with the Grüneisen constants that have been determined experimentally. This comparison was extended to provide a test of the consistency of the tabulated properties.

Sections 2, 3, and 4 of this report present the derivation of equations used for calculating the Grüneisen constants. Alternate methods of calculating elastic properties for isotropic materials from the anisotropic single-crystal elastic constants are presented in Section 5.

Section 6 provides the list of reference documents used by Childs as data sources for generating the compendium of material properties presented in Section 8. Section 7 presents an alphabetical list of the 130 space-related materials included in the database, together with citations to the specific data sources, to be found in the list of reference documents, for each material.

2. Methods of Analysis for the Grüneisen Constant

The format for the Compendium of Thermomechanical Properties presented in Section 8 provides for reporting values of the Grüneisen constant obtained using one or more of three distinct methods. For those materials for which no experimental data were available, values of the Grüneisen constant have been calculated using one of the two algorithms developed below.

Method 1 presents experimentally determined values of the Grüneisen constant for materials, when available in the literature.

The second method of calculating the Grüneisen constant uses the relation for isothermal conditions given in Eq. (3.15) of Section 3:

$$\gamma = \frac{\beta K_I}{C_V \rho}, \tag{2.1}$$

where β is the volumetric coefficient of thermal expansion, K_I is the isothermal bulk modulus, C_V is the heat capacity at constant volume, and ρ is the density.

To be consistent throughout this report, the values for the heat capacity at constant volume, C_V, will be calculated from the thermodynamic expression given in Eq. (2.3).

$$C_P - C_V = -T \left(\frac{\partial V}{\partial T}\right)_P^2 \bullet \left(\frac{\partial P}{\partial V}\right)_T \tag{2.2}$$

$$C_V = C_P - \left(\frac{\beta^2 T K_I}{\rho}\right), \tag{2.3}$$

where T is the absolute temperature. This equation applies equally to solids, liquids, and gases. There are many methods of calculating the heat capacity at constant volume, such as those given by Dulong and Petit, Einstein, Drude, Debye, and Born and Karman. It is felt that the above relationship should not introduce any appreciable errors in the calculations.

The isothermal bulk modulus, which is not always available for many materials, can be calculated by other expressions as given in Section 4. The table in Section 4 presents the relationships among five elastic constants: bulk modulus (K), Young's modulus (Y), Poisson's ratio (v), Lamè constants (λ and μ(shear)). The table is organized to facilitate computation of the remaining three of these parameters when any two of the five are known, for isotropic linear elastic materials.

3

It would be desirable to calculate the elastic properties for random, macroscopically isotropic aggregates of crystals from the single-crystal anisotropic elastic constants. This is not yet possible, but bounds have been obtained for the aggregate properties from the single-crystal constants (Section 4). These are called the "Voigt" and "Reuss" averages. Voigt averaged the elastic stiffnesses (C_{ij}) over all space, and Reuss averaged the elastic compliances (S_{ij}). [2] These values are considered the least upper bound and the greatest lower bound, respectively, for the aggregate.

The third method of calculating the Grüneisen constant uses the relation for adiabatic conditions given in Eq. (3.22) of Section 3.

$$\gamma = \frac{\beta K_A}{C_P \rho}, \tag{2.4}$$

where K_A is the adiabatic bulk modulus, C_P is the heat capacity at constant pressure, and

$$K_A = \rho C_B{}^2. \tag{2.5}$$

The adiabatic bulk wave speed (C_B) is calculated from shock wave measurements, where the longitudinal, C_L, and the shear, C_S, speeds have been determined. The shear wave is also referred to as the transverse wave. Then the bulk wave speed can be expressed as

$$C_B = \left(C_L{}^2 - \frac{4}{3} C_S{}^2 \right)^{\frac{1}{2}}. \tag{2.6}$$

The adiabatic bulk modulus can also be calculated from the isotropic elastic properties when shock wave measurements are not available. The longitudinal and shear wave speed can be expressed as follows:

$$C_L = \left(\frac{3K_A(1-\upsilon)}{\rho(1+\upsilon)} \right)^{\frac{1}{2}} \ ; \ \ C_S = \left(\frac{3K_A(1-2\upsilon)}{2\rho(1+\upsilon)} \right)^{\frac{1}{2}}. \tag{2.7}$$

The wave speeds can also be expressed in terms of the Lamè elastic constants.

$$C_L = \left(\frac{\lambda + 2\mu}{\rho} \right)^{\frac{1}{2}} \ ; \ \ C_S = \left(\frac{\mu}{\rho} \right)^{\frac{1}{2}}. \tag{2.8}$$

The same relationship exists as given in Section 5 by substituting values calculated from C_L and C_S.

$$\upsilon = \frac{C_L{}^2 - 2C_S{}^2}{2\left(C_L{}^2 - C_S{}^2\right)} \tag{2.9}$$

$$Y = \frac{\rho C_S{}^2\left(3C_L{}^2 - 4C_S{}^2\right)}{\left(C_L{}^2 - C_S{}^2\right)} \tag{2.10}$$

$$K_A = \rho\left(C_L{}^2 - \frac{4}{3}C_S{}^2\right) \tag{2.11}$$

3. Derivation of Equations to Calculate the Grüneisen Constant Using Various Experimental Parameters

For most solids, a simple relationship has been shown by Grüneisen to have experimental validity:

$$\gamma = \frac{\text{Volume Coefficient of Thermal Expansion} \times \text{Specific Volume}}{\text{Compressibility} \times \text{Specific Heat (Constant Volume)}}, \qquad (3.1)$$

and γ is called the Grüneisen constant.[5] Experimental values of γ for most solids lie between 1.5 and 2.5. A theoretical basis for the Grüneisen constant has been established by Slater in his derivation of the Mie-Grüneisen equation of state:

$$(P - P_0)V = \gamma(E - E_0), \qquad (3.2)$$

where the subscripted values of pressure (P) and internal energy (E) are the volume (V) dependent values at zero Kelvin. [6]

A number of expressions relating the Grüneisen constant to various thermoelastic and thermodynamic parameters can be derived from the Mie-Grüneisen equation of state. A simple and straightforward demonstration of their interrelationships, which follows, involves the use of Jacobians. By differentiating Eq. (3.2) while holding volume constant, we obtain:

$$\gamma = V \left(\frac{\partial P}{\partial E} \right)_V \qquad (3.3)$$

$$\left(\frac{\partial P}{\partial E} \right)_V = \frac{J(P,V)}{J(E,V)} = \frac{J(P,V)/J(T,V)}{J(E,V)/J(T,V)} = \frac{\left(\dfrac{\partial P}{\partial T} \right)_V}{\left(\dfrac{\partial E}{\partial T} \right)_V} . \qquad (3.4)$$

The specific heat (constant volume) is defined:

$$C_V = \left(\frac{\partial E}{\partial T} \right)_V = \left(\frac{\partial S}{\partial T} \right)_V . \qquad (3.5)$$

7

Substituting:

$$\gamma = \frac{V}{C_V}\left(\frac{\partial P}{\partial T}\right)_V, \tag{3.6}$$

and using Maxwell's relation:

$$\left(\frac{\partial S}{\partial V}\right)_T = \left(\frac{\partial P}{\partial T}\right)_V. \tag{3.7}$$

Eq. (3.6) can also be written:

$$\gamma = \frac{V}{C_V}\left(\frac{\partial S}{\partial V}\right)_T. \tag{3.8}$$

But

$$\left(\frac{\partial P}{\partial T}\right)_V = \frac{J(P,V)}{J(T,V)} = \frac{(-)J(V,P)/J(T,P)}{J(V,T)/J(P,T)} = \frac{(-)\left(\frac{\partial V}{\partial T}\right)_P}{\left(\frac{\partial V}{\partial P}\right)_T}, \tag{3.9}$$

so

$$\gamma = \frac{(-)V}{C_V} \bullet \frac{\left(\frac{\partial V}{\partial T}\right)_P}{\left(\frac{\partial V}{\partial P}\right)_T}. \tag{3.10}$$

The volume coefficient of thermal expansion is defined:

$$\beta = \frac{1}{V}\left(\frac{\partial V}{\partial T}\right)_P, \tag{3.11}$$

and the isothermal compressibility is defined:

$$X_I = \frac{(-)1}{V}\left(\frac{\partial V}{\partial P}\right)_T = \frac{1}{K_I}, \tag{3.12}$$

8

where K_I is the isothermal bulk modulus. Substituting in Eq. (3.10):

$$\gamma = \frac{\beta V}{C_V X_I} = \frac{\beta V K_I}{C_V}. \tag{3.13}$$

Usually the Mie-Grüneisen equation of state, Eq. (3.2), is expressed in terms of the specific volume which is related to the density:

$$V = \frac{1}{\rho}. \tag{3.14}$$

Therefore, Eq. (3.13) becomes

$$\gamma = \frac{\beta}{C_V X_I \rho} = \frac{\beta K_I}{C_V \rho}. \tag{3.15}$$

Using the alternate definition of C_V, Eq. (3.10) can be rewritten:

$$\gamma = \frac{(-)V}{T} \left(\frac{\partial V}{\partial T} \right)_P \bullet \frac{\left(\frac{\partial P}{\partial V} \right)_T}{\left(\frac{\partial S}{\partial T} \right)_V}. \tag{3.16}$$

But

$$\frac{\left(\frac{\partial P}{\partial V} \right)_T}{\left(\frac{\partial S}{\partial T} \right)_V} = \frac{J(P,T)/J(V,T)}{J(S,V)/J(T,V)} = \frac{J(P,S)/J(V,S)}{J(S,P)/J(T,P)} = \frac{\left(\frac{\partial P}{\partial V} \right)_S}{\left(\frac{\partial S}{\partial T} \right)_P}, \tag{3.17}$$

and the specific heat (constant pressure) is defined:

$$C_P = \left(\frac{\partial H}{\partial T} \right)_P = T \left(\frac{\partial S}{\partial T} \right)_P. \tag{3.18}$$

Substituting in the equation above:

$$\gamma = \frac{(-)V}{C_P} \left(\frac{\partial V}{\partial T} \right)_P \left(\frac{\partial P}{\partial V} \right)_S. \tag{3.19}$$

9

The adiabatic (isoentropic) compressibility and bulk modulus are defined:

$$X_A = (-)\frac{1}{V}\left(\frac{\partial V}{\partial P}\right)_S = \frac{1}{K_A}. \tag{3.20}$$

Substituting in Eq. (3.19):

$$\gamma = \frac{\beta V}{C_P X_A} = \frac{\beta V K_A}{C_P} \tag{3.21}$$

$$\gamma = \frac{\beta}{C_P X_A \, \rho} = \frac{\beta K_A}{C_P \, \rho}. \tag{3.22}$$

Equation (3.19) can be rewritten:

$$\gamma = \frac{(-)V^2 \beta}{C_P}\left(\frac{\partial P}{\partial V}\right)_S. \tag{3.23}$$

The adiabatic (isoentropic) sound speed is defined:

$$C_B = V\left[(-)\left(\frac{\partial P}{\partial V}\right)_S\right]^{\frac{1}{2}}. \tag{3.24}$$

Substituting in Eq. (3.23):

$$\gamma = \frac{\beta}{C_P} C_B{}^2. \tag{3.25}$$

Several facts are evident from the equations that have been derived. It is evident that Eq. (3.13) is identical to Eq. (3.1), which was the original definition of the Grüneisen constant, γ. It is possible to evaluate γ from several different sets of experimental data:

(1) Using Eq. (7), γ can be obtained from the specific heat (constant volume), density, volumetric thermal expansion, and isothermal compressibility (or bulk modulus).

(2) Using Eq. (10), γ can be obtained from the density, specific heat (constant pressure) volumetric thermal expansion, and adiabatic compressibility (or modulus).

(2) Using Eq. (12), γ can be obtained from the specific heat (constant pressure), volumetric thermal expansion, and adiabatic sound velocity.

10

4. Equations Linking Five Elastic Constants

	λ	μ	Y	ν	K
λ, μ			$\dfrac{\mu(3\lambda+2\mu)}{\lambda+\mu}$	$\dfrac{\lambda}{2(\lambda+\mu)}$	$\dfrac{3\lambda+2\mu}{3}$
λ, Y		$\dfrac{(Y-3\lambda)+\sqrt{(Y-3\lambda)^2+8\lambda Y}}{4}$		$\dfrac{-(Y+\lambda)+\sqrt{(Y+\lambda)^2+8\lambda^2}}{4\lambda}$	$\dfrac{(3\lambda+Y)+\sqrt{(3\lambda+Y)^2-4\lambda Y}}{6}$
λ, ν		$\dfrac{\lambda(1-2\nu)}{2\nu}$	$\dfrac{\lambda(1+\nu)(1-2\nu)}{\nu}$		$\dfrac{\lambda(1+\nu)}{3\nu}$
λ, K		$\dfrac{3(K-\lambda)}{2}$	$\dfrac{9K(K-\lambda)}{3K-\lambda}$	$\dfrac{\lambda}{3K-\lambda}$	
μ, Y	$\dfrac{(2\mu-Y)\mu}{Y-3\mu}$			$\dfrac{Y-2\mu}{2\mu}$	$\dfrac{\mu Y}{3(3\mu-Y)}$
μ, ν	$\dfrac{2\mu\nu}{(1-2\nu)}$		$2\mu(1+\nu)$		$\dfrac{2\mu(1+\nu)}{3(1-2\nu)}$
μ, K	$\dfrac{3K-2\mu}{3}$		$\dfrac{9K\mu}{3K+\mu}$	$\dfrac{1}{2}\left[\dfrac{3K-2\mu}{3K+\mu}\right]$	
Y, ν	$\dfrac{\nu Y}{(1+\nu)(1-2\nu)}$	$\dfrac{Y}{2(1+\nu)}$			$\dfrac{Y}{3(1-2\nu)}$
Y, K	$\dfrac{3K(3K-Y)}{9K-Y}$	$\dfrac{3YK}{9K-Y}$		$\dfrac{1}{2}\left[\dfrac{3K-Y}{3K}\right]$	
ν, K	$\dfrac{3K\nu}{1+\nu}$	$\dfrac{3K(1-2\nu)}{2(1+\nu)}$	$3K(1-2\nu)$		

13

5. Development of Equations to Calculate Aggregate Material Properties from Those of Single Crystals

Editor's Note: The text of this section presents the author's unabridged development and rationale for the calculation of aggregate properties from those of single crystals—it has been reproduced with only minor formatting changes from Childs' original draft. It is recognized that the uninitiated reader will likely have some difficulty in following this development because of the lack of rigor and other lapses. However, it is hoped that the inclusion of this section will provide useful insight into Childs' approach. The interested reader may find additional insights by referring to other treatments of this subject to be found in the literature. (cf. Ref. 88.)

The Voigt and Reuss bulk modulus averages are given by

$$K_V = (A + 2B)/3 \quad \text{and} \quad K_R = 1/(3a + 6b), \text{ respectively,} \tag{5.1}$$

and the shear moduli of rigidity averages are

$$G_V = (A - B + 3C)/5 \quad \text{and} \quad G_R = 5/(4a - 4b + 3c). \tag{5.2}$$

The constants A, B, C and a, b, c are related to the elastic stiffnesses and compliances by the relations

$$
\begin{aligned}
3A &= C_{11} + C_{22} + C_{33} & 3a &= S_{11} + S_{22} + S_{33} \\
3B &= C_{23} + C_{31} + C_{12} & 3b &= S_{23} + S_{31} + S_{12} \\
3C &= C_{44} + C_{55} + C_{66} & 3c &= S_{44} + S_{55} + S_{66}
\end{aligned}
\tag{5.3}
$$

Again, knowing any two of the elastic properties, the rest can be calculated from the isotropic elastic relations given in Section 4. No distinction is made between adiabatic and isothermal elastic properties, which should not differ by more than a few percent.

15

The constants, A, B, and C have been further reduced for six specific crystalline structures as follows [7]:

Crystalline Structure	Definition of Constants A, B, & C	
Cubic	$A = C_{11}$	
	$B = C_{12}$	(5.4)
	$C = C_{44}$	
Hexagonal and Trigonal	$A = 1/3 \, (2C_{11} + C_{33})$	
	$B = 1/3 \, (2C_{13} + C_{12})$	(5.5)
	$C = 1/3 \, (2C_{44} + C_{66})$	
	where $C_{66} = 1/2(C_{11} - C_{12})$	(5.6)
Tetragonal	$A = 1/3 \, (2C_{11} + C_{33})$	
	$B = 1/3 \, (2C_{13} + C_{12})$	(5.7)
	$C = 1/3 \, (2C_{44} + C_{66})$	
Orthorhombic and Monoclinic	$A = 1/3 \, (C_{11} + C_{22} + C_{33})$	
	$B = 1/3 \, (C_{13} + C_{23} + C_{12})$	(5.8)
	$C = 1/3 \, (C_{44} + C_{55} + C_{66})$	

Improvements have been made for the upper and lower bounds for cubic crystals and are known as the "Hashin" and "Shtrikman" averages. [2] For single-phase aggregate of a cubic material, the bulk modulus, K, is given unambiguously by

$$K = \frac{1}{3}(C_{11} + 2C_{12})$$

(5.9)

and the modulus of rigidity is bounded by

$$G_H = G_1 + 3\left(\frac{5}{G_2 - G_1} - 4\sigma_1\right)^{-1}$$

(5.10)

16

and

$$G_S = G_2 + 2\left(\frac{5}{G_1 - G_2} - 6\sigma_2\right)^{-1},$$

(5.11)

where

$$G_1 = \frac{1}{2}\left(C_{11} - C_{12}\right)$$

(5.12)

$$G_2 = C_{44}$$

(5.13)

$$\sigma_1 = -\frac{3\left(K + 2G_1\right)}{5G_1\left(3K + 4G_1\right)}$$

(5.14)

$$\sigma_2 = -\frac{3\left(K + 2G_2\right)}{5G_2\left(3K + 4G_2\right)}.$$

(5.15)

G_H is termed the Hashin rigidity, and G_S is the smaller Shtrikman rigidity.

In general, crystals are anisotropic with respect to their elastic properties. That is, the values of these moduli differ with direction in the crystal. A measure of the anisotropy of a cubic crystal is given by the anisotropy factor ($\tilde{A}$) and is defined as

$$\tilde{A} = \frac{2C_{44}}{\left(C_{11} - C_{12}\right)}$$

(5.16)

For those crystals with $\tilde{A} > 1$, such as germanium and silicon, Young's modulus has its maximum value along the <100> direction and the minimum value along the <111> direction. For crystals with $\tilde{A} < 1$, such as sodium chloride, Young's modulus has its maximum value along the <111> direction and its minimum along the <100> direction. The variation in elastic properties with direction may be as great as 30%.

17

6. References

1. Gray, D. E., Ed., <u>American Institute of Physics Handbook</u>, Third Edition, McGraw-Hill Book Co., New York, NY, (1972)**

2. Simmons, F.S., Wang, H., <u>Single Crystal Elastic Constants and Calculated Aggregate Properties Handbook</u>, MIT Press, MA, (1971)**

3. Marsh, S.P., <u>Los Alamos Scientific Laboratory Shock Hugoniot Data</u>, University of California Press, Berkeley and Los Angeles, CA (1980)

4. Urzendowski, R., Guenther,A.H., <u>The Grüneisen Parameter and Thermal Properties of Polymers</u>, Air Force Weapons Laboratory, AFWL-TR-71-6, Air Force Weapons Laboratory, Kirtland Air Force Base, NM, (May 1971)*

5. Grüneisen, E., "Zustand des festen Korpers," <u>HandBuch der Physik</u>, 10, 1-59, (1926)*

6. Slater, J.C., <u>Introduction to Chemical Physics</u>, McGraw-Hill 1939, Chapter XIII, Section 4, (1939)

7. Hearman, R.F.S., <u>An Introduction to Applied Anisotropic Elasticity</u>, Oxford University Press, (1961)

8. Wolfe, W.L., Zissis, G.J., <u>The Infrared Handbook</u>, Office of Naval Research, Department of the Navy, Washington, D.C., (1985)**

9. Childs, W.H., <u>Thermophysical Properties of Selected Space-Related Materials</u>, TOR-0081(6435-02)-1, Vol. I, The Aerospace Corporation, El Segundo, CA, (1981)*

10. Childs, W.H., <u>Thermophysical Properties of Selected Space-Related Materials</u>, TOR-0086(6435-02)-1, Vol. II, The Aerospace Corporation, El Segundo, CA, (1986)*

11. McQueen, R.G., Marsh, S.P., "Equation of State for Nineteen Metallic Elements from Shock-Wave Measurements to Two Megabars," <u>Journal of Applied Physics</u>, Vol. 31, No.7, (July 1960)*

12. Touloukian, Y.S., Buyco, E.H., <u>Thermophysical Properties of Matter</u>, The Thermophysical Properties Research Center Data Series, Purdue University, IFI/Plenum New York–Washington (1970)*

13. Kelley, K.K., <u>Contribution to the Data on Theoretical Metallurgy</u>, BOM Bulletin 476, U.S. Government Printing Office, Washington, D.C., (1949)

** Report available through The Aerospace Corporation Lauritsen Library.
* Report available through The Aerospace Corporation archivist

14. Corning Glass Works, <u>Properties of Selected Commercial Glasses</u>, B-83, New York, NY, (1965)

15. Moses, A.J., "Optical Materials Properties," <u>Handbook of Electronic Materials</u>, Vol 1, Hughes Aircraft Co. Electronic Properties Information Center, Plenum Press, New York, (1971)*

16. Taylor, R.E., Groot, H., <u>Thermophysical Properties of POCO Graphite</u>, Properties Research Laboratory, Report AFOSR-77-3280, Purdue University, West Lafayette, IN, (July 1978)*

17. <u>Modern Plastics Encyclopedia Annual Issue</u>, McGraw-Hill, New York, NY, (1964)**

18. Morey, G.W., <u>The Properties of Glass</u>, 2nd Edition, Reinhold Publishing Corp., New York, NY, (1960)*

19. Vier, D.T., <u>Thermal and Other Properties of Refractories</u>, Tech. Report No.. R056, U.S. Dept. of Commerce, VA, (1975)

20. Kingery, W.D., <u>Introduction to Ceramics</u>, John Wiley and Sons, Inc., New York, NY, (1960)*

21. Neuberger, M., <u>Group IV Semiconducting Materials, Handbook of Electronic Materials</u>, Vol. 5, Hughes Aircraft Co. Electronic Properties Information Center, IFI/Plenum, New York, (1971)*

22. Crotwell, G.P., Ward, H.P., <u>Hugoniot Data on Several Materials</u>, AFWL TR-68-82, Air Force Weapons Laboratory, Kirtland Air Force Base, NM, (Oct. 1968)*

23. Touloukian, Y.S., "Elements," <u>Thermophysical Properties of High Temperature Solid Materials</u>, Vol. 1, The Thermophysical Properties Research Center, Purdue University, Macmillan Company, New York (1967)**

24. Morris, C.E., et al, <u>Los Alamos Shock Wave Profile Data</u>, University of California Press, Berkeley, CA, (1982)**

25. Kohn, B.J., <u>Compilation of Hugonoit Equation of State</u>, AFWL-TR-69-38, Air Force Weapons Laboratory, Kirtland Air Force Base, NM, (1969)*

26. Cost, J.R., Janowski, K.R., Rossi, R.C., <u>Elastic Properties of Isotropic Graphite</u>, TR-0158(3250-10)-13, The Aerospace Corporation, El Segundo, CA, (Jan. 1968)*

27. Kolsky, H., <u>Stress Waves in Solids</u>, Oxford at the Clarendon Press, (1953)**

28. <u>Inconel 600</u>, Maxi, (1963)

29. E.I. DuPont DeNemours & Co. (Inc.), <u>Kapton® Polyimide Film</u>, DuPont Technical Bulletin H-1A, DuPont Co., Electronics Department, Wilmington, DE

30. Weast, R.C., Ed., <u>Handbook of Chemistry and Physics</u>, 53rd Edition, Chemical Rubber Company Press, Cleveland, OH, (1969)**

31. Hanlein, S.L., Hinckley, W.M., Stecher, F.P., <u>Comparison of Mechanical and Acoustic Properties for Selected Nonferrous, Ferrous, and Plastic Materials</u>, NOLTR 70-141, Naval Ordnance Laboratory, Report, White Oak, MD, (July 1970)*

32. Salama, M.A.,, et al, <u>Thermoelastic Analysis of Solar Cell Arrays and Their Material Properties</u>

33. General Electric, <u>Silicones,</u> Technical Data Bank S-35, Silicone Products Division, Waterford, NY.

34. Rinehart, J.S., <u>Compilation of Dynamic Equation of State Data for Solids and Liquids,</u> U.S. Naval Ordinance Test Station," NRS TP 3798, China Lake, CA, (May 1965)*

35. Brandrup, J., Immergut, E.H., <u>Polymer Handbook 2nd Edition</u>, Wiley-Interscience Publications, New York, (1975)*

36. Urzendowski,.R., Guenther, A.H., <u>Thermal Properties and Grüneisen Parameters for Several Polymers, Concretes, and Composite Materials,</u> , AFWL-TR-72-37, Air Force Weapons Laboratory. Kirtland Air Force Base, NM, (Sept. 1972)*

37. Weast, R.C., Astle, M.J., Beyer, W.H., <u>Handbook of Chemistry and Physics, 64th Edition</u>, CRC Press, Boca Raton, FL, (1984)

38. Samsonov, G.V., Ed, <u>The Oxide Handbook 2nd Edition</u>, IFI/Plenum, New York, NY, (1982)*

39. Ballard, S.S.,McCarthy, K.A., Wolfe, W.L., <u>Optical Materials for Infrared Instrumentation,</u> R.N. 2389-11-S, University of Michigan, Willow Run Laboratories, Ann Arbor, MI, (Jan. 1959)

40. Auld, B.A., <u>Acoustic fields and Waves in Solids Vol. I</u>, Wiley-Interscience, (1973)**

41. Darwin, G.E., Buddery, J.H., <u>Beryllium</u>, Academic Press, Inc., New York, (1960)**

42. Walsh, J.M., Rice, M.H, McQueen, R.G.,Yarger, F.L., "Shock-Wave Compressions of Twenty-Seven Metals, Equations of State of Metals;" <u>Physical Review</u>, Vol. 108, No. 2, pp 196-216; (October 1957)*

43. Spedding, F.H., Daane, A.H., <u>The Rare Earths</u>, John Wiley and Son, Inc., New York, (1961)

44. Filyand, M.A., Semenova, E.I., <u>Handbook of the Rare Elements, Trace Elements and Light Elements Vol I</u>, Boston Technical Publishers, Inc., Cambridge, MA, (1968)

45. Filyand, M.A., Semenova, E.I., <u>Handbook of the Rare Elements, Refractory Elements Vol II,</u> Boston Technical Publishers., Inc., Cambridge, MA, (1970)

46. Filyand, M.A., Semenova, E.I., <u>Handbook of the Rare Elements, Radioactive Elements and Rare Earth Elements Vol III</u>, Boston Technical Publishers., Inc., Cambridge, MA, (1970)

47. Krishnan, R.S, et al, <u>Thermal Expansion of Crystals</u>, Pergamon Press, New York, (1979)**

48. DeWitt, D.P., <u>Handbook of the Optical, Thermal, and Mechanical Properties of Six Polycrystalline Dielectric Materials</u>, TPRC Report No. 19, Thermophysical Properties Research Center, Purdue University, West Lafayette, IN, (Dec. 1972)*

49. McQuillan, A.D., McQuillan, M.K., <u>Titanium</u>, Butterworths Scientific Pub., London, (1956)**

50. Burke, J.J., Weiss, V. Ed., <u>Shock Waves and the Mechanical Properties of Solids</u>, Syracuse University Press, Syracuse, NY, (1971)*

51. Floyd, H.L., <u>Material Properties, Measured and Estimated</u>, Laboratory Report No, 68-6020, Sandia Corporation, Division 2635, (Sept. 1968)*

52. Corning Glass Works, <u>Low Expansion Materials</u>, Corning, NY, (1969)

53. Hodges, E.S., et al, <u>Tin and Its Alloys</u>, Edward Arnold LTD, London, (1960)

54. Bakken, L.H., Anderson, P.D., <u>An Equation-of-State Handbook (Conversion Relations Between the Wondy/Tody and the PUFF/KO/HEMP Classes of Shock Wave Propagation Computer Codes</u>, SCL-DR-68-123, Sandia Laboratories, Livermore, CA, (Jan. 1969)*

55. Neuberger, M., <u>IV–V Semiconducting Compounds Data Tables</u>, Hughes Aircraft Co. Electronic Properties Information Center, Report S-12, Culver City, CA, (Oct. 1969)*

56. Oswald, R.B., et al, <u>Grüneisen Data from the Free Surface Velocity of Thermoelastic Materials</u>, HDL-TR-1629, Harry Diamond Laboratories, Washington, DC, (May 1973)*

57. Oswald, R.B., McLean, F.B., <u>Grüneisen Data from the One-Dimensional Response of Solids</u>, HDL-TR-1502, Harry Diamond Laboratories, Washington, DC, (June 1970)*

58. Smithells, C.J., <u>Metals Reference Book, Vol. 3</u>, Plenum Press, New York, (1967)*

59. McLean, F.B., Oswald, R.B., Schalborn, D.R., Buxton, L,D., <u>Temperature Dependence of the Dynamic Response of Silicon, Germanium, and Indium Antimonide to a Pulse Electron Beam</u>, HDL-TR-1503; Harry Diamond Laboratories, Washington, D.C., (June 1970)

60. Barron, T.H.K., "Grüneisen Parameters for the Equation of State of Solids," <u>Annals of Physics</u>: 1, 77-90 (1957)*

61. Dugdale, J.S., MacDonald, D.K.C., "The Thermal Expansion of Solids," <u>Physical Review</u>, Vol. 89, No. 4 832-834; (Feb., 1953)*

62. Golian, S., Grandey, R., Bandaruk, W., <u>Methods of Calculating Thermal Shock Coefficients; Calculated Coefficients for Most Metals and Various Non-metals</u>, Philco, Corporation, Aeronautic Division, (July 1964)*

63. Touloukian, Y.S., et al, "Thermal Expansion, Metallic Elements and Alloys," <u>Thermophysical Properties of Matter</u>, Volume 12 , (1975)*

64. Brugger, K., Fritz, T.C., "Grüneisen Gamma from Elastic Data," <u>Physical Review</u>, Vol. 157, No. 3, pp 524-531, (May 1967)*

65. Ree, J.R., <u>Radiation Damage Study</u> (RADS Program), AFBSD and AVCO Missile Systems

66. Wimmer, J.M., <u>Mechanical and Physical Properties of Chemically Vapor-Deposited (CVD) Zinc Sulfide</u>, AFML-TR-70-4013, Air Force Materials Laboratory, Wright-Patterson Air Force Base, OH, (March 1979)*

67. Penning, J.R., et al, Negative Equation of State and Spall Criteria, RTD-TDR-63-3039, Boeing Co., Seattle, WA, (Sept. 1963)*

68. Morgan, D.T., Rockowitz, M., Atkinson, A.L., Measurement of the Grüneisen Parameter and the Internal Energy Dependence of the Solid Equation of State for Aluminum and Teflon, AFWL-TR-6 5-117, AVCO Corp., Wilmington, MA, (Oct. 1965)*

69. Anderson, G.D., Fahrenbruch, A.L., Equation of State of Solids II, Aluminum and Teflon, AFWL-TR-67-43, Stanford Research Institute, Poulter Laboratories, Menlo Park, CA, (Sept. 1967)*

70. Rauschenbach, H.S., Solar Cell Array Design Handbook: The Principles and Technology of Photovoltaic Energy Conversion, Van Nostrand Reinhold Publishers, (April 1980)*

71. Slater, J.C., Note on the Grüneisen Constant for the Incompressible Metals, Physical Review, Vol. 57, 744-746; (April 1940)*

72. Ballard, S.S., Browder, J.S., "Thermal Expansion and Other Physical Properties of the Newer Infrared–Transmitting Optical Material," Journal of Applied Optics, Vol.5, No. 12, (Dec. 1966)*

73. Materials Properties Data Handbook, LMSC F286269, Lockheed Missiles and Space Co., Inc., Sunnyvale, CA, Jan. 1991.**

74. Brian, J.K., Compilation of Hugonoit Equation of State, AFWL-TR-69-38, Air Force Weapons Laboratory, Kirtland Air Force Base, NM, (1969)

75. Yen, C.C.S., Dynamic Shear Stress Strain, Strain Rate Relations of Iron, TR-0158(3250-40)-3, The Aerospace Corporation, El Segundo, CA, (1967)

76. Rice, M.H., PUFF74 EOS Compilations, AFWL-TR-80-21, S-Cubed, La Jolla, CA, (1980)**

77. Durvasula, L.N., et al, Handbook of the Properties of Optical Materials, GACIAC HB 84-01, ITT Research Institute, Chicago, IL, (1984)*

78. Knupp,P., Stage III Materials Properties Handbook, PITR-1348-5-R4, Physics International, San Leandro, CA, (March 1983)

79. Adachi, S., "GaAs, AIAs, and $Al_xGa_{1-x}As$: Material Parameters for Use in Research and Device Applications," Journal of Applied Physics, Vol. 58, No. 3, 1, (August 1985)

80. Specification for Manufacture and Quality Assurance of CMX Solar Cell Covers, PS 292 (Issue 2), Pilkington Space Technology, United Kingdom, (1984)

81. Structural and Materials Engineering Bulletin, Aluminum-Lithium 8090, M&P 6867, Lockheed Missiles & Space, Co, Palo Alto, CA, (1991)

82. Urzendowski, R., et al, Ultrasonic and Thermal Studies of Selected Plastics, Laminated Materials,and Metals, AFWL-TR-67-91, Air Force Weapons Laboratory, Kirtland Air Force Base, NM, (1965)

23

83. E.I. DuPont DeNemours & C., <u>Delrin® Aceta 1 Resins</u>, Wilmington, DE

84. Pennsalt Chemicals Corp., <u>KYNAR</u>, Bulletin VFZR-62, 3 Penn Center, Philadelphia, PA,

85. <u>Metals Handbook, 1948 Edition</u>, The American Society for Metals, Materials Park, Cleveland, OH, (1948)**

86. Salama, M.A., et al, <u>Stress Analysis and Design of Silicon Solar Cell Arrays and Related Material Properties</u>, TR 32-1552, Jet Propulsion Laboratory, Pasadena, CA, (March 1972)**

87. Bogaard, et al, <u>Effects of Rapid Heating Rate on Materials Properties</u>, TEPIAC/CINDAS Report 87, (1986)

88. Ho, C.Y. (Ed.), Taylor, R.E., <u>Thermal Expansion of Solids</u>, CINDAS Data Series, Materials Park, OH, ASM International, (1998)**

89. Shea, Jr. et al., <u>Above ground Test/Underground Test (AGT/UGT) Validation Program</u> (U), DNA-TR-88-116, Physics International Co., San Leandro CA, 18 May 1988.

24

7. List of Materials with their Associated Data References

1	Aluminum	1, 2, 5, 8, 22, 25, 27, 31, 34, 42, 47, 51, 56, 57, 58, 62, 68, 69, 70, 85
2	Aluminum 2024	24, 25, 51, 54, 76
3	Aluminum Oxide (Poly)	2, 24, 38, 47, 48 51, 62, 88
4	Aluminum Oxide (S.C.)	2, 8, 24, 39, 47, 51, 72
5	Aluminum 6061-T6	24, 25, 31, 50, 51, 76
6	Antimony	7, 11, 25
7	ATJ Graphite	24, 25, 34, 36, 47, 62, 76
8	Barium	30
9	Beryllium	1, 2, 24, 25, 31, 34, 41, 42, 44, 47, 51, 54, 62, 76, 85
10	Beryllium Oxide	2, 24, 38, 41, 47, 51, 62
11	Bismuth	2, 8, 11, 25, 34, 42, 47
12	Boron	34, 45
13	Boron Carbide	24, 25
14	Brass 70/30	8, 22, 25, 31, 34, 42, 51, 54, 58, 62
15	Cadmium	1, 2, 5, 11, 25, 34, 42, 47, 51, 62
16	Cadmium Sulphide (S.C.)	2, 8, 39, 40, 47, 51, 77
17	Calcium	30
18	Calcium Carbonate (Calcite)	2, 8, 24, 39, 47, 77
19	Carbon Phenolic	22, 25, 36, 54
20	Cerium	46, 62
21	Chromium	2, 11, 25, 34, 42, 51, 54, 58, 62
22	Chromium Oxide	38
23	Cobalt	1, 2, 6, 11, 25, 31, 34, 42, 47, 51, 54, 62, 64
24	Cobalt Oxide	38, 51, 85
25	Copper	1, 2, 6, 8, 11, 22, 24, 25, 27, 31, 34, 42, 47, 50, 51, 54, 56, 57, 58, 62, 64, 70, 88
26	Corning 7740 (PYREX)	1, 8, 40, 51
27	Corning 7940 (Fused Silica)	1, 8, 14, 39, 40, 47, 48, 51, 62, 64, 72
28	Corning 7971 (ULE)	
29	Corning 9606 (PYROCERAM)	
30	Dysprosium	2, 46, 47, 62
31	Erbium	2, 46, 47, 62
32	Europium	46, 62
33	Gadolinium	2, 46, 47, 62, 77
34	Gallium Antimonide (S.C.)	2, 8, 39, 47, 77, 88
35	Gallium Arsenide	8, 21, 39, 40, 47, 51
36	Germanium (S.C.)	1, 2, 8, 9, 21, 24, 39, 40, 44, 47, 51, 56, 57, 64, 72, 88
37	Gold	1, 2, 5, 11, 25, 31, 34, 42, 47, 51, 54, 62, 64
38	Hafnium	2, 25, 31, 45, 47, 54

39	Hafnium Carbide	45, 47
40	Holmium	46, 47, 62
41	Indium	2, 34, 42, 44, 47, 51, 62
42	Indium Antimonide (S.C.)	2, 8, 39, 40, 47, 57, 77
43	INVAR 36/74	47, 58, 70
44	Iridium	2, 31, 47
45	Iron	1, 2, 5, 6, 8, 11, 24, 25, 34, 42, 47, 51, 54, 58, 62, 85
46	Iron (Ni 10)	51
47	Iron (Ni 18)	51
48	Iron (Ni 26)	51
49	Iron Oxide	34, 38
50	IRTRAN-1 (MgF2)	2, 38, 39, 48, 72, 73
51	IRTRAN-2 (ZnS)	2, 34, 66, 72, 77, 88
52	IRTRAN-3 (CaF2)	2, 5, 34, 39, 48, 72
53	IRTRAN-4 (ZnSe)	2, 34, 72, 77, 88
54	IRTRAN-5 (MgO)	2, 34, 39, 48, 62, 64, 72
55	IRTRAN-6 (CdTe)	2, 8, 39, 51, 72, 77, 88
56	Kapton	35, 70
57	KEL-F	7, 39, 51
58	Kovar	51, 70
59	Lanthanum	46, 62
60	Lead	1, 2, 5, 8, 11, 24, 25, 31, 34, 42, 47, 51, 54, 58, 62, 85
61	Lead Sulphide (S.C.)	2, 5, 8, 39, 47, 55, 77
62	Lithium Flouride (S.C.)	2, 8, 34, 39, 40, 47, 64, 77, 88
63	Lithium Niobate (S.C.)	2, 40, 47, 77
64	Lucite	1, 2, 25, 34, 35, 50, 67
65	Leutetium	40, 46, 47, 62
66	Magnesium	1, 2, 25, 31, 34, 42, 47, 51, 54, 58, 62, 85
67	Magnesium Oxide	2, 8, 38, 39, 40, 47, 48, 62, 64, 88
68	Molybdenum	2, 5, 11, 31, 34, 42, 45, 47, 51, 54, 58, 62, 70, 88
69	Mylar	25, 35, 51
70	Neodymium	46, 47, 62, 76
71	Nickel	1, 2, 5, 6, 11, 25, 31, 34, 42, 47, 51, 54, 58, 62
72	Nickel Oxide	38
73	Niobium	2, 6, 24, 25, 34, 42, 45, 47, 54, 58
74	Niobium Carbide	45, 47
75	Nylon 6	1, 4, 7, 17, 25, 35, 51, 67
76	OTWR (Quartz phenolic)	7, 22, 25, 54
77	Palladium	2, 5, 6, 25, 31, 34, 42, 47, 51, 54
78	Platinum	1, 2, 5, 6, 8, 25, 31, 34, 42, 47, 51, 54, 62, 88
79	Plutonium (alpha)	46
80	POCO Graphite (AXF)	16, 26
81	Polyethylene (high density)	1, 8, 17, 24, 25, 34, 35, 40, 54, 62
82	Polystyrene	1, 4, 17, 25, 31, 34, 35, 40, 51, 62
83	Polyvinylchloride	17, 35
84	Potassium Bromide (S.C.)	1, 2, 5, 8, 34, 39, 47, 77, 88

26

85	Potassium Chloride (S.C.)	1, 2, 5, 8, 34, 39, 47, 64, 77, 88
86	Potassium Iodide (S.C.)	2, 8, 34, 39, 47, 77, 88
87	Praseodymium	46, 47, 62
88	Pyrolytic Graphite	16, 26, 47
89	Quartz Phenolic	25, 50, 54
90	Quartz (S.C.)	2, 8, 34, 39, 40, 47, 48, 51, 54, 64, 76, 88
91	Rhenium	2, 44, 47
92	Rhodium	31, 34, 42, 47, 62
93	Scandium	46
94	Silicon	2, 8, 9, 21, 39, 40, 47, 51, 56, 57, 72, 77, 88
95	Silicon Carbide	9, 25, 62
96	Silver	1, 2, 5, 6, 8, 11, 25, 31, 34, 42, 47, 51, 54, 57, 58, 62, 64, 70
97	Silver Chloride (S.C.)	1, 2, 5, 8, 39, 47, 77
98	Sodium Chloride (S.C.)	2, 4, 5, 8, 24, 34, 47, 64, 72, 77, 88
99	Stainless Steel 304L	24, 25
100	Strontium	30
101	Tantalum	2, 5, 24, 25, 31, 34, 42, 45, 47, 51, 54, 58, 62
102	Tantalum Carbide	2, 24, 45, 47
103	Teflon	4, 8, 25, 35, 51, 68, 69, 70
104	Terbium	46, 47, 62, 76
105	Thallium Bromide (S.C.)	2, 34, 39
106	Thallium Bromide-Chloride	2, 34, 39
107	Thallium Bromide-Iodide	2, 39
108	Thallium Chloride (S.C.)	2, 39
109	Thorium	2, 11, 24, 25, 31, 34, 42, 46, 54
110	Thorium Dioxide	2, 38, 47
111	Thulium	46
112	Tin	1, 2, 8, 11, 24, 25, 31, 34, 42, 47, 51, 53, 58, 62, 85
113	Tin Oxide	38, 55
114	Titanium	1, 2, 11, 24, 25, 31, 34, 42, 45, 47, 49, 51, 54, 58, 62, 76, 85
115	Titanium Carbide	2, 24, 45, 47, 62
116	Titanium Dioxide	8, 38, 39, 47, 48, 49
117	Tungsten	1, 2, 5, 6, 11, 24, 31, 34, 45, 47, 51, 54, 58, 62, 88
118	Tungsten Carbide	24, 25, 45, 58
119	Uranium	2, 24, 25, 31, 46, 47, 54
120	Uranium Oxide	2, 38
121	Vanadium	2, 11, 25, 31, 34, 45, 54, 58, 62
122	VYCOR	
123	Ytterbium	46, 47, 62
124	Yttrium	2, 46, 47
125	Yttrium Aluminate (YAG, S.C.)	40, 47
126	Zinc	1, 2, 5, 8, 11, 25, 34, 42, 47, 51, 54, 58, 62, 85
127	Zinc Oxide	2, 38, 47, 50

128	Zirconium	2, 24, 25, 31, 34, 42, 45, 47, 51
129	Zirconium Carbide	2, 24, 45, 47
130	Zirconium Dioxide	38, 47, 62

8. Compendium of Thermomechanical Property Data for 130 Materials

ALUMINUM

DENSITY
(g/cm)

2.71

POISSON'S RATIO

0.345

SOUND VELOCITY
(cm/microsec)

0.5375

VOL. COEFF. THERMAL
EXPANSION, (10^{-6} °C^{-1})

69.6

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.2160	0.2064

YOUNGS MODULUS   BULK MODULUS
(Dynes/cm * 10^{12})

0.706	0.752

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
2.350	2.225	2.236

ALUMINUM 2024

DENSITY (g/cm)	POISSON'S RATIO
2.79	0.330

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} $°C^{-1}$)
0.5209	67.5

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.2200	0.2117

YOUNGS MODULUS   BULK MODULUS
(Dynes/cm * 10^{12})

0.724	0.710

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
2.000	1.990	1.939

32

ALUMINUM OXIDE (POLY)

DENSITY
(g/cm)

4.0

POISSON'S RATIO

0.232

SOUND VELOCITY

(cm/microsec)

0.7933

VOL. COEFF. THERMAL

EXPANSION, (10^{-6} °C^{-1})

16.5

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.1870	0.1858

YOUNGS MODULUS	**BULK MODULUS**
(Dynes/cm * 10^{12})	
4.060	2.500

GRÜNEISEN CONSTANT

METHOD 1	**METHOD 2**	**METHOD 3**
—	1.327	1.327

33

ALUMINUM OXIDE (S.C.)

DENSITY (g/cm)	POISSON'S RATIO
3.97	0.181

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, $(10^{-6}\ °C^{-1})$
0.7776	17.4

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.1850	0.1837

YOUNGS MODULUS	BULK MODULUS
(Dynes/cm * 10^{12})	
4.600	2.401

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	1.359	1.369

ALUMINUM 6061 —T6

DENSITY
(g/cm)

2.7

POISSON'S RATIO

0.331

SOUND VELOCITY

(cm/microsec)

0.5266

VOL. COEFF. THERMAL

EXPANSION, $(10^{-6} \, °C^{-1})$

68.1

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.2130	0.2041

YOUNGS MODULUS	**BULK MODULUS**
(Dynes/cm * 10^{12})	
0.738	0.728

GRÜNEISEN CONSTANT

METHOD 1	**METHOD 2**	**METHOD 3**
2.130	2.119	2.150

35

ANTIMONY

DENSITY (g/cm)	POISSON'S RATIO
6.7	0.088

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.2167	33.1

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.0483	0.0479

YOUNGS MODULUS   BULK MODULUS
(Dynes/cm * 10^{12})

0.778	0.315

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
0.801	0.769	0.775

ATJ GRAPHITE

DENSITY
(g/cm)

1.77

POISSON'S RATIO

0.270

SOUND VELOCITY

(cm/microsec)

0.1864

VOL. COEFF. THERMAL

EXPANSION, (10^{-6} °C^{-1})

5.7

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.1750	0.1750

YOUNGS MODULUS	BULK MODULUS
(Dynes/cm * 10^{12})	
0.079	0.057

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
0.027	0.027	0.025

BARIUM

DENSITY
(g/cm)

3.5

POISSON'S RATIO

0.229

SOUND VELOCITY

(cm/microsec)

0.1575

VOL. COEFF. THERMAL

EXPANSION, (10^{-6} °C^{-1})

62.0

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.0437	0.0430

YOUNGS MODULUS   **BULK MODULUS**
(Dynes/cm * 10^{12})

0.141	0.087

GRÜNEISEN CONSTANT

METHOD 1	**METHOD 2**	**METHOD 3**
—	0.841	0.854

38

BERYLLIUM

DENSITY
(g/cm)

1.85

POISSON'S RATIO

0.028

SOUND VELOCITY

(cm/microsec)

0.7931

VOL. COEFF. THERMAL

EXPANSION, (10^{-6} $°C^{-1}$)

33.5

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.4360	0.4310

YOUNGS MODULUS   **BULK MODULUS**

(Dynes/cm * 10^{12})

3.095	1.147

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
1.170	1.155	1.152

BERYLLIUM OXIDE

**DENSITY
(g/cm)**

3.03

POISSON'S RATIO

0.224

SOUND VELOCITY

(cm/microsec)

0.8437

VOL. COEFF. THERMAL

EXPANSION, (10^{-6} °C^{-1})

19.0

HEAT CAPACITY, (cal/ g –C)

(Cp) **(Cv)**

0.2460 0.2442

YOUNGS MODULUS **BULK MODULUS**

(Dynes/cm * 10^{12})

3.570 2.157

GRÜNEISEN CONSTANT

METHOD 1 **METHOD 2** **METHOD 3**

— 1.314 1.324

BISMUTH

DENSITY (g/cm)

9.8

POISSON'S RATIO

0.254

SOUND VELOCITY (cm/microsec)

0.1864

VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})

40.2

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.0293	0.0289

YOUNGS MODULUS   BULK MODULUS (Dynes/cm * 10^{12})

0.503	0.340

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	1.139	1.155

BORON

DENSITY
(g/cm)

2.5

POISSON'S RATIO

0.139

SOUND VELOCITY

(cm/microsec)

0.9231

VOL. COEFF. THERMAL

EXPANSION, (10^{-6} $°C^{-1}$)

14.1

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.2643	0.2631

YOUNGS MODULUS   **BULK MODULUS**
(Dynes/cm * 10^{12})

4.613	2.130

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	1.086	1.091

42

BORON CARBIDE

DENSITY (g/cm)	POISSON'S RATIO
2.45	0.172

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.9269	14.4

HEAT CAPACITY, (cal/ g –C)	
(Cp)	(Cv)
0.2500	0.2487

YOUNGS MODULUS	BULK MODULUS
(Dynes/cm * 10^{12})	
4.249	2.157

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	1.183	1.218

BRASS 70/30

DENSITY
(g/cm)

8.52

POISSON'S RATIO

0.350

SOUND VELOCITY

(cm/microsec)

0.3622

VOL. COEFF. THERMAL

EXPANSION, (10^{-6} °C^{-1})

59.7

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.0905	0.0872

YOUNGS MODULUS   **BULK MODULUS**

(Dynes/cm * 10^{12})

1.006	1.118

GRÜNEISEN CONSTANT

METHOD 1	**METHOD 2**	**METHOD 3**
—	2.069	2.148

44

CADMIUM

DENSITY (g/cm)	POISSON'S RATIO
8.65	0.319

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.2571	92.6

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.0553	0.0513

YOUNGS MODULUS   BULK MODULUS
(Dynes/cm * 10^{12})

0.621	0.572

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	2.645	2.854

45

CADMIUM SULPHIDE (S.C.)

DENSITY (g/cm)	POISSON'S RATIO
4.82	0.373

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.3566	15.0

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.0880	0.0878

YOUNGS MODULUS   BULK MODULUS
(Dynes/cm * 10^{12})

0.468	0.614

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	0.518	0.520

46

CALCIUM

DENSITY
(g/cm)

1.54

POISSON'S RATIO

0.263

SOUND VELOCITY

(cm/microsec)

0.3317

VOL. COEFF. THERMAL

EXPANSION, (10^{-6} $^\circ C^{-1}$)

67.0

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.1568	0.1533

YOUNGS MODULUS   **BULK MODULUS**
(Dynes/cm * 10^{12})

0.241	0.170

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	1.124	1.150

CALCIUM CARBONATE (CALCITE)

DENSITY
(g/cm)

2.71

POISSON'S RATIO

0.387

SOUND VELOCITY

(cm/microsec)

0.6918

VOL. COEFF. THERMAL

EXPANSION, (10^{-6} °C^{-1})

17.4

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.2030	0.2020

YOUNGS MODULUS   **BULK MODULUS**
(Dynes/cm * 10^{12})

0.883	1.297

GRÜNEISEN CONSTANT

METHOD 1	**METHOD 2**	**METHOD 3**
—	0.980	0.985

CARBON PHENOLIC

DENSITY (g/cm)	POISSON'S RATIO
1.43	0.342

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.3347	39.7

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.2085	0.2073

YOUNGS MODULUS	BULK MODULUS
(Dynes/cm * 10^{12})	
0.151	0.159

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
0.510	0.510	0.509

CERIUM

DENSITY
(g/cm)

6.67

POISSON'S RATIO

0.248

SOUND VELOCITY
(cm/microsec)

0.1742

VOL. COEFF. THERMAL
EXPANSION, $(10^{-6}\ {}^{\circ}C^{-1})$

15.7

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.0490	0.0489

YOUNGS MODULUS   BULK MODULUS
$(Dynes/cm * 10^{12})$

0.300	0.198

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	0.232	0.228

50

CHROMIUM

DENSITY (g/cm)	POISSON'S RATIO
7.16	0.210

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.4730	22.7

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.1075	0.1067

YOUNGS MODULUS   **BULK MODULUS**

(Dynes/cm * 10^{12})

2.790	1.602

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
1.080	1.129	1.138

CHROMIUM OXIDE

DENSITY
(g/cm)

5.25

POISSON'S RATIO

—

SOUND VELOCITY

(cm/microsec)

—

VOL. COEFF. THERMAL

EXPANSION, (10^{-6} °C^{-1})

26.4

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.1650	—

YOUNGS MODULUS   **BULK MODULUS**
(Dynes/cm * 10^{12})

—   —

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
1.400	—	—

52

COBALT

DENSITY (g/cm)	POISSON'S RATIO
8.67	0.320

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.4630	39.2

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.1010	0.0987

YOUNGS MODULUS	BULK MODULUS
(Dynes/cm * 10^{12})	
2.040	1.830

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
1.970	1.989	2.004

COBALT OXIDE

DENSITY
(g/cm)

5.7

POISSON'S RATIO

—

SOUND VELOCITY

(cm/microsec)

—

VOL. COEFF. THERMAL
EXPANSION, (10^{-6} °C^{-1})

36.6

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.1750	—

YOUNGS MODULUS   BULK MODULUS
(Dynes/cm * 10^{12})

—	—

GRÜNEISEN CONSTANT

METHOD 1	**METHOD 2**	**METHOD 3**
1.600	—	—

COPPER

DENSITY (g/cm)	POISSON'S RATIO
8.94	0.343

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.3927	49.6

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.0910	0.0883

YOUNGS MODULUS   **BULK MODULUS**

(Dynes/cm * 10^{12})

1.298	1.378

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
2.000	2.009	2.069

55

CORNING 7740 (PYREX®)

DENSITY (g/cm)	POISSON'S RATIO
2.23	0.200

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, $(10^{-6}\ {}^{\circ}C^{-1})$
0.3879	9.9

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.1840	0.1839

YOUNGS MODULUS	BULK MODULUS
(Dynes/cm * 10^{12})	
0.628	0.349

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	0.193	0.201

56

CORNING 7940 (FUSED SILICA)

DENSITY
(g/cm)

2.2

POISSON'S RATIO

0.160

SOUND VELOCITY

(cm/microsec)

0.4071

VOL. COEFF. THERMAL

EXPANSION, (10^{-6} °C^{-1})

1.7

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.1800	0.1800

YOUNGS MODULUS	**BULK MODULUS**
(Dynes/cm * 10^{12})	
0.725	0.366

GRÜNEISEN CONSTANT

METHOD 1	**METHOD 2**	**METHOD 3**
—	0.036	0.036

57

CORNING 7971 (ULE®)

DENSITY (g/cm)	POISSON'S RATIO
2.2	0.170

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, $(10^{-6}\ °C^{-1})$
0.3958	0.1

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.1780	0.1780

YOUNGS MODULUS   **BULK MODULUS**

$(Dynes/cm * 10^{12})$

0.676	0.345

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	0.002	0.002

CORNING 9606 (PYROCERAM®)

DENSITY (g/cm)	POISSON'S RATIO
2.6	0.240

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.5410	1.2

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.1720	0.1720

YOUNGS MODULUS   BULK MODULUS

(Dynes/cm * 10^{12})

1.187	0.761

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	0.049	0.049

DYSPROSIUM

DENSITY (g/cm)	POISSON'S RATIO
8.54	0.243

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, $(10^{-6} \, °C^{-1})$
0,2280	28.7

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.0414	0.0411

YOUNGS MODULUS	BULK MODULUS
(Dynes/cm * 10^{12})	
0.631	0.410

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	0.861	0.801`

ERBIUM

DENSITY (g/cm)	POISSON'S RATIO
9.05	0.238

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} $°C^{-1}$)
0.2298	28.3

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.0401	0.0398

YOUNGS MODULUS   **BULK MODULUS**
(Dynes/cm * 10^{12})

0.733	0.465

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	0.891	0.873

61

EUROPIUM

DENSITY
(g/cm)

5.25

POISSON'S RATIO

0.286

SOUND VELOCITY

(cm/microsec)

0.1581

VOL. COEFF. THERMAL

EXPANSION, (10^{-6} °C^{-1})

75.0

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.0421	0.411

YOUNGS MODULUS   **BULK MODULUS**
(Dynes/cm * 10^{12})

0.147	0.131

GRÜNEISEN CONSTANT

METHOD 1	**METHOD 2**	**METHOD 3**
—	1.064	1.090

62

GADOLINIUM

DENSITY
(g/cm)

7.9

POISSON'S RATIO

0.259

SOUND VELOCITY

(cm/microsec)

0.2212

VOL. COEFF. THERMAL

EXPANSION, $(10^{-6}\ {}^{\circ}C^{-1})$

6.0

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.0550	0.0550

YOUNGS MODULUS   **BULK MODULUS**

(Dynes/cm * 10^{12})

0.562	0.389

GRÜNEISEN CONSTANT

METHOD 1	**METHOD 2**	**METHOD 3**
—	0.128	0.128

63

GALLIUM ANTIMONIDE (S.C.)

DENSITY (g/cm)	POISSON'S RATIO
5.62	0.244

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, $(10^{-6}\ ^\circ C^{-1})$
0.3195	20.7

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.0602	0.599

YOUNGS MODULUS   BULK MODULUS
(Dynes/cm * 10^{12})

0.880	0.574

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	0.839	0.844

64

GALLIUM ARSENIDE

DENSITY
(g/cm)

5.31

POISSON'S RATIO

0.334

SOUND VELOCITY

(cm/microsec)

0.3873

VOL. COEFF. THERMAL

EXPANSION, (10^{-6} °C^{-1})

20.4

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.0803	0.0799

YOUNGS MODULUS **BULK MODULUS**
(Dynes/cm * 10^{12})

0.791	0.797

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	0.911	0.916

65

GERMANIUM (S.C.)

DENSITY (g/cm)	POISSON'S RATIO
5.32	0.279

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} $^\circ$C^{-1})
0.3824	17.2

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.0769	0.0766

YOUNGS MODULUS	BULK MODULUS
(Dynes/cm * 10^{12})	
1.025	0.778

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	0.782	0.785

66

GOLD

DENSITY
(g/cm)

19.24

POISSON'S RATIO

0.420

SOUND VELOCITY

(cm/microsec)

0.3056

VOL. COEFF. THERMAL

EXPANSION, (10^{-6} $^{\circ}C^{-1}$)

42.7

HEAT CAPACITY, (cal/ g –C)

(Cp)   **(Cv)**

0.0331   0.0320

YOUNGS MODULUS   **BULK MODULUS**

(Dynes/cm * 10^{12})

0.812   1.692

GRÜNEISEN CONSTANT

METHOD 1	**METHOD 2**	**METHOD 3**
2.970	2.879	2.808

HAFNIUM

DENSITY
(g/cm)

13.3

POISSON'S RATIO

0.284

SOUND VELOCITY

(cm/microsec)

0.2984

VOL. COEFF. THERMAL

EXPANSION, (10^{-6} °C^{-1})

18.0

HEAT CAPACITY, (cal/ g –C)	
(Cp)	**(Cv)**
0.0345	0.0343

YOUNGS MODULUS	BULK MODULUS
(Dynes/cm * 10^{12})	
1.535	1.184

GRÜNEISEN CONSTANT

METHOD 1	**METHOD 2**	**METHOD 3**
1.040	1.110	1.117

68

HAFNIUM CARBIDE

DENSITY (g/cm)	POISSON'S RATIO
12.6	0.200

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.3940	15.0

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.0460	0.0458

YOUNGS MODULUS   BULK MODULUS
(Dynes/cm * 10^{12})

3.521	1.956

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	1.210	1.217

HOLMIUM

DENSITY
(g/cm)

8.78

POISSON'S RATIO

0.255

SOUND VELOCITY

(cm/microsec)

0.2386

VOL. COEFF. THERMAL

EXPANSION, (10^{-6} °C^{-1})

29.4

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.0393	0.0390

YOUNGS MODULUS	**BULK MODULUS**
(Dynes/cm * 10^{12})	
0.667	0.458

GRÜNEISEN CONSTANT

METHOD 1	**METHOD 2**	**METHOD 3**
—	1.018	0.941

INDIUM

DENSITY (g/cm)	POISSON'S RATIO
7.3	0.452

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.2231	97.4

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.0550	0.0516

YOUNGS MODULUS   BULK MODULUS

(Dynes/cm * 10^{12})

0.105	0.363

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
2.240	2.106	2.243

71

INDIUM ANTIMONIDE (S.C.)

DENSITY (g/cm)	POISSON'S RATIO
5.78	0.259

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.2740	14.7

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.0497	0.0496

YOUNGS MODULUS   BULK MODULUS
(Dynes/cm * 10^{12})

YOUNGS MODULUS	BULK MODULUS
0.626	0.433

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	0.531	0.531

72

INVAR® 36/74

DENSITY (g/cm)	POISSON'S RATIO
8.05	0.259

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.3514	2.7

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.1230	0.1230

YOUNGS MODULUS   **BULK MODULUS**

(Dynes/cm * 10^{12})

1.440	0.994

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	0.065	0.065

73

IRIDIUM

DENSITY (g/cm)	POISSON'S RATIO
22.5	0.190

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.3724	19.3

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.0308	0.0304

YOUNGS MODULUS	BULK MODULUS
(Dynes/cm * 10^{12})	
5.798	3.117

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	2.077	2.100

IRON

DENSITY (g/cm)	POISSON'S RATIO
7.86	0.293

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.4595	35.4

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.1070	0.1051

YOUNGS MODULUS   BULK MODULUS
(Dynes/cm * 10^{12})

2.114	1.698

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
1.690	1.670	1.740

75

IRON (Ni 10)

DENSITY
(g/cm)

7.88

POISSON'S RATIO

0.285

SOUND VELOCITY

(cm/microsec)

0.4457

VOL. COEFF. THERMAL

EXPANSION, (10^{-6} °C^{-1})

28.2

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.1130	0.1119

YOUNGS MODULUS   **BULK MODULUS**

(Dynes/cm * 10^{12})

2.022	1.565

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	1.185	1.196

76

IRON (Ni 18)

DENSITY (g/cm)	POISSON'S RATIO
7.97	0.306

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} $°C^{-1}$)
0.4403	34.0

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.1150	0.1134

YOUNGS MODULUS	BULK MODULUS
(Dynes/cm * 10^{12})	
1.797	1.543

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	1.370	1.387

IRON (Ni 26)

DENSITY (g/cm)	POISSON'S RATIO
7.97	0.328

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.4368	39.7

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.1190	0.1169

YOUNGS MODULUS	BULK MODULUS
(Dynes/cm * 10^{12})	
1.566	1.521

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	1.521	1.550

IRON OXIDE

DENSITY
(g/cm)

4.98

POISSON'S RATIO

0.318

SOUND VELOCITY
(cm/microsec)

0.6243

VOL. COEFF. THERMAL
EXPANSION, (10^{-6} $^{\circ}C^{-1}$)

29.8

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.1560	0.1535

YOUNGS MODULUS   BULK MODULUS
(Dynes/cm * 10^{12})

2.121	1.941

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	1.779	1.808

IRTRAN® —1 (MgF2)

DENSITY
(g/cm)

3.18

POISSON'S RATIO

0.310

SOUND VELOCITY

(cm/microsec)

0.5620

VOL. COEFF. THERMAL

EXPANSION, (10^{-6} °C^{-1})

31.2

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.2440	0.2418

YOUNGS MODULUS   **BULK MODULUS**

(Dynes/cm * 10^{12})

| 1.145 | 1.004 |

GRÜNEISEN CONSTANT

METHOD 1	**METHOD 2**	**METHOD 3**
—	0.965	0.974

IRTRAN® —2 (ZnS)

DENSITY
(g/cm)

4.09

POISSON'S RATIO

0.310

SOUND VELOCITY

(cm/microsec)

0.4552

VOL. COEFF. THERMAL

EXPANSION, (10^{-6} $°C^{-1}$)

20.7

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.1130	0.1124

YOUNGS MODULUS   **BULK MODULUS**

(Dynes/cm * 10^{12})

0.966	0.847

GRÜNEISEN CONSTANT

METHOD 1	**METHOD 2**	**METHOD 3**
—	0.907	0.912

81

IRTRAN® —3 (CaF2)

DENSITY (g/cm)	POISSON'S RATIO
3.18	0.310

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.5218	57.6

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.2170	0.2106

YOUNGS MODULUS **BULK MODULUS**
(Dynes/cm * 10^{12})

0.987	0.866

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	1.727	1.780

IRTRAN® —4 (ZnSe)

DENSITY (g/cm)	POISSON'S RATIO
5.27	0.310

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.3440	22.2

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.0800	0.0796

YOUNGS MODULUS	BULK MODULUS
(Dynes/cm * 10^{12})	
0.711	0.624

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	0.785	0.789

IRTRAN® —5 (MgO)

DENSITY (g/cm)	POISSON'S RATIO
3.77	0.170

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.6675	31.7

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.2220	0.2188

YOUNGS MODULUS	BULK MODULUS
(Dynes/cm * 10^{12})	
3.326	1.680

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	1.521	1.543

IRTRAN® —6 (CdTe)

DENSITY (g/cm)	POISSON'S RATIO
5.85	0.250

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} $°C^{-1}$)
0.2042	15.9

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.0560	0.0559

YOUNGS MODULUS   **BULK MODULUS**

(Dynes/cm * 10^{12})

0.366	0.244

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	0.283	0.283

85

KAPTON®

DENSITY
(g/cm)

1.42

POISSON'S RATIO

0.433

SOUND VELOCITY

(cm/microsec)

0.2327

VOL. COEFF. THERMAL

EXPANSION, (10^{-6} °C^{-1})

85.2

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.2390	0.2362

YOUNGS MODULUS   **BULK MODULUS**

(Dynes/cm * 10^{12})

0.031	0.077

GRÜNEISEN CONSTANT

METHOD 1	**METHOD 2**	**METHOD 3**
—	0.461`	0.467

86

KEL —F®

DENSITY
(g/cm)

2.11

POISSON'S RATIO

0.378

SOUND VELOCITY

(cm/microsec)

0.1496

VOL. COEFF. THERMAL

EXPANSION, (10^{-6} °C^{-1})

228.0

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.2200	0.2117

YOUNGS MODULUS	**BULK MODULUS**
(Dynes/cm * 10^{12})	
0.035	0.047

GRÜNEISEN CONSTANT

METHOD 1	**METHOD 2**	**METHOD 3**
—	0.554	0.576

87

KOVAR®

DENSITY (g/cm)	POISSON'S RATIO
8.34	0.341

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.4038	18.0

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.1050	0.1046

YOUNGS MODULUS   **BULK MODULUS**

(Dynes/cm * 10^{12})

1.297	1.360

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	0.668	0.670

88

LANTHANUM

DENSITY (g/cm)	POISSON'S RATIO
6.17	0.288

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} $^{\circ}C^{-1}$)
0.2048	15.7

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.0470	0.0469

YOUNGS MODULUS **BULK MODULUS**

(Dynes/cm * 10^{12})

0.359	0.243

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	0.335	0.315

LEAD

DENSITY (g/cm)	POISSON'S RATIO
11.3	0.440

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.2002	86.9

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.0305	0.0283

YOUNGS MODULUS	BULK MODULUS
(Dynes/cm * 10^{12})	
0.161	0.458

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
2.780	2.729	2.972

90

LEAD SULPHIDE (S.C.)

DENSITY (g/cm)	POISSON'S RATIO
7.5	0.470

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, $(10^{-6} \; °C^{-1})$
0.2880	72.0

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.0390	0.0359

YOUNGS MODULUS	BULK MODULUS
(Dynes/cm * 10^{12})	
0.113	0.622

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	3.659	3.971

91

LITHIUM FLOURIDE (S.C.)

DENSITY
(g/cm)

2.64

POISSON'S RATIO

0.214

SOUND VELOCITY

(cm/microsec)

0.4870

VOL. COEFF. THERMAL

EXPANSION, (10^{-6} °C^{-1})

103.0

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.3860	0.3683

YOUNGS MODULUS   **BULK MODULUS**
(Dynes/cm * 10^{12})

1.059	0.617

GRÜNEISEN CONSTANT

METHOD 1	**METHOD 2**	**METHOD 3**
—	1.513	1.562

92

LITHIUM NIOBATE (S.C.)

DENSITY (g/cm)	POISSON'S RATIO
4.7	0.255

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} $°C^{-1}$)
0.4999	33.3

HEAT CAPACITY, (cal/ g –C)	
(Cp)	(Cv)
0.1515	0.1495

YOUNGS MODULUS	BULK MODULUS
(Dynes/cm * 10^{12})	
1.728	1.174

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	1.313	1.330

LUCITE®

DENSITY (g/cm)	POISSON'S RATIO
1.19	0.323

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.2177	223.0

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.3100	0.2932

YOUNGS MODULUS   **BULK MODULUS**
(Dynes/cm * 10^{12})

0.060	0.056

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	0.815	0.862

94

LEUTETIUM

DENSITY (g/cm)	POISSON'S RATIO
9.84	0.233

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.2313	24.9

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.0470	0.0468

YOUNGS MODULUS	BULK MODULUS
(Dynes/cm * 10^{12})	
0.843	0.526

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	0.677	0.681

95

MAGNESIUM

DENSITY (g/cm)	POISSON'S RATIO
1.74	0.291

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.4444	74.8

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.2444	0.2362

YOUNGS MODULUS	BULK MODULUS
(Dynes/cm * 10^{12})	
0.447	0.356

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
1.460	1.445	1.548

96

MAGNESIUM OXIDE

DENSITY (g/cm)	POISSON'S RATIO
3.77	0.182

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.6780	31.5

HEAT CAPACITY, (cal/ g –C)	
(Cp)	(Cv)
0.2220	0.2190

YOUNGS MODULUS	BULK MODULUS
(Dynes/cm * 10^{12})	
3.100	1.625

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	1.559	1.482

97

MOLYBDENUM

DENSITY (g/cm)
10.2

POISSON'S RATIO
0.293

SOUND VELOCITY (cm/microsec)
0.5033

VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
14.4

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.0592	0.0588

YOUNGS MODULUS	BULK MODULUS
(Dynes/cm * 10^{12})	
3.248	2.612

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
1.520	1.473	1.498

MYLAR®

DENSITY (g/cm)	POISSON'S RATIO
1.39	0.370

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.2200	171.0

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.2260	0.2166

YOUNGS MODULUS   **BULK MODULUS**

(Dynes/cm * 10^{12})

0.055	0.063

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	0.875	0.855

NEODYMIUM

DENSITY (g/cm)	POISSON'S RATIO
7.0	0.306

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, $(10^{-6}\ °C^{-1})$
0.2157	20.7

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.0490	0.0489

YOUNGS MODULUS	BULK MODULUS
(Dynes/cm * 10^{12})	
0.379	0.325

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	0.470	0.470

100

NICKEL

DENSITY (g/cm)	POISSON'S RATIO
8.9	0.306

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, $(10^{-6}\,°C^{-1})$
0.4523	40.3

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.1070	0.1046

YOUNGS MODULUS   **BULK MODULUS**
(Dynes/cm * 10^{12})

2.198	1.876

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
1.830	1.842	1.942

NICKEL OXIDE

DENSITY
(g/cm)

6.8

POISSON'S RATIO

—

SOUND VELOCITY

(cm/microsec)

—

VOL. COEFF. THERMAL

EXPANSION, (10^{-6} °C^{-1})

30.6

HEAT CAPACITY, (cal/ g –C)

(Cp)   **(Cv)**

0.1420   —

YOUNGS MODULUS   **BULK MODULUS**

(Dynes/cm * 10^{12})

—   —

GRÜNEISEN CONSTANT

METHOD 1   **METHOD 2**   **METHOD 3**

1.500   —   —

102

NIOBIUM

DENSITY
(g/cm)

8.57

POISSON'S RATIO

0.397

SOUND VELOCITY

(cm/microsec)

0.4460

VOL. COEFF. THERMAL

EXPANSION, $(10^{-6}\ {}^\circ C^{-1})$

21.9

HEAT CAPACITY, (cal/ g –C)

(Cp)

0.0633

(Cv)

0.0626

YOUNGS MODULUS   **BULK MODULUS**

(Dynes/cm * 10^{12})

1.049   1.703

GRÜNEISEN CONSTANT

METHOD 1   **METHOD 2**   **METHOD 3**

1.680   1.645   1.661

NIOBIUM CARBIDE

DENSITY
(g/cm)

7.63

POISSON'S RATIO

0.200

SOUND VELOCITY

(cm/microsec)

0.4981

VOL. COEFF. THERMAL

EXPANSION, $(10^{-6} \, °C^{-1})$

17.1

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.0880	0.0875

YOUNGS MODULUS   **BULK MODULUS**

(Dynes/cm * 10^{12})

3.407	1.893

GRÜNEISEN CONSTANT

METHOD 1	**METHOD 2**	**METHOD 3**
—	1.152	1.159

NYLON 6

DENSITY (g/cm)
1.11

POISSON'S RATIO
0.398

SOUND VELOCITY (cm/microsec)
0.2380

VOL. COEFF. THERMAL EXPANSION, (10^{-6} $°C^{-1}$)
257.0

HEAT CAPACITY, (cal/ g –C)	
(Cp)	(Cv)
0.3710	0.3437

YOUNGS MODULUS	BULK MODULUS
(Dynes/cm * 10^{12})	
0.039	0.064

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
1.020	0.938	1.036

105

OTWR (QUARTZ PHENOLIC)

DENSITY (g/cm)	POISSON'S RATIO
1.66	0.260

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, $(10^{-6} \ ^\circ C^{-1})$
0.3170	12.6

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.4160	0.4159

YOUNGS MODULUS   **BULK MODULUS**

(Dynes/cm * 10^{12})

0.240	0.167

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	0.073	0.073

106

PALLADIUM

DENSITY (g/cm)
11.4

POISSON'S RATIO
0.335

SOUND VELOCITY (cm/microsec)
0.3829

VOL. COEFF. THERMAL EXPANSION, $(10^{-6}\ °C^{-1})$
35.5

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.0580	0.0567

YOUNGS MODULUS	BULK MODULUS
(Dynes/cm * 10^{12})	
1.653	1.670

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
2.180	2.145	2.192

PLATINUM

DENSITY (g/cm)	POISSON'S RATIO
21.5	0.390

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.3538	26.5

HEAT CAPACITY, (cal/ g –C)	
(Cp)	(Cv)
0.0317	0.0311

YOUNGS MODULUS	BULK MODULUS
(Dynes/cm * 10^{12})	
1.670	2.530

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
2.400	2.501	2.396

108

PLUTONIUM (ALPHA)

DENSITY (g/cm)	POISSON'S RATIO
19.74	0.150

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.1611	141.0

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.0320	0.0287

YOUNGS MODULUS   BULK MODULUS

(Dynes/cm * 10^{12})

0.993	0.467

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	2.733	2.783

POCO GRAPHITE (AXF)

DENSITY (g/cm)	POISSON'S RATIO
1.84	0.280

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.2380	11.1

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.2110	0.2110

YOUNGS MODULUS   **BULK MODULUS**

(Dynes/cm * 10^{12})

0.138	0.104

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	0.071	0.071

POLYETHYLENE (HIGH DENSITY)

DENSITY (g/cm)	POISSON'S RATIO
0.95	0.385

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.2249	385.0

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.5300	0.4780

YOUNGS MODULUS   BULK MODULUS
(Dynes/cm * 10^{12})

0.032	0.047

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
0.950	0.878	0.949

111

POLYSTYRENE

DENSITY (g/cm)	POISSON'S RATIO
1.05	0.379

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.1976	220.0

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.3200	0.3063

YOUNGS MODULUS   BULK MODULUS

(Dynes/cm * 10^{12})

0.030	0.042

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
0.700	0.642	0.680

POLYVINYLCHLORIDE

DENSITY (g/cm)	POISSON'S RATIO
1.4	0.380

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.1933	207.0

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.2400	0.2286

YOUNGS MODULUS	BULK MODULUS
(Dynes/cm * 10^{12})	
0.038	0.052

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	0.770	0.808

113

POTASSIUM BROMIDE (S.C.)

DENSITY
(g/cm)

2.75

POISSON'S RATIO

0.245

SOUND VELOCITY

(cm/microsec)

0.2461

VOL. COEFF. THERMAL

EXPANSION, (10^{-6} °C^{-1})

116.0

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.1040	0.0982

YOUNGS MODULUS   **BULK MODULUS**

(Dynes/cm * 10^{12})

0.255	0.167

GRÜNEISEN CONSTANT

METHOD 1	**METHOD 2**	**METHOD 3**
—	1.615	1.715

114

POTASSIUM CHLORIDE (S.C.)

DENSITY (g/cm)	POISSON'S RATIO
1.98	0.216

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.2963	110.0

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.1636	0.1560

YOUNGS MODULUS   BULK MODULUS

(Dynes/cm * 10^{12})

0.297	0.174

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	1.411	1.479

POTASSIUM IODIDE (S.C.)

DENSITY (g/cm)	POISSON'S RATIO
3.13	0.251

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.1936	128.0

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.0790	0.0746

YOUNGS MODULUS **BULK MODULUS**
(Dynes/cm * 10^{12})

0.175	0.117

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	1.451	1.532

116

PRASEODYMIUM

DENSITY (g/cm)	POISSON'S RATIO
6.77	0.305

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.2114	16.2

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.0460	0.0459

YOUNGS MODULUS	BULK MODULUS
(Dynes/cm * 10^{12})	
0.352	0.299

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	0.376	0.372

117

PYROLYTIC GRAPHITE

DENSITY (g/cm)	POISSON'S RATIO
2.24	0.150

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.3319	1.7

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.1650	0.1650

YOUNGS MODULUS	BULK MODULUS
(Dynes/cm * 10^{12})	
0.518	0.247

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
0.023	0.026	0.026

118

QUARTZ PHENOLIC

DENSITY (g/cm)	POISSON'S RATIO
1.78	0.254

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.3156	25.0

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.2276	0.2272

YOUNGS MODULUS	BULK MODULUS
(Dynes/cm * 10^{12})	
0.262	0.177

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
0.289	0.261	0.262

119

QUARTZ (S.C.)

DENSITY (g/cm)	**POISSON'S RATIO**
2.65	0.140

SOUND VELOCITY (cm/microsec)	**VOL. COEFF. THERMAL EXPANSION**, (10^{-6} $^{\circ}C^{-1}$)
0.3770	40.8

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.1770	0.1753

YOUNGS MODULUS	**BULK MODULUS**
(Dynes/cm * 10^{12})	
0.700	0.370

GRÜNEISEN CONSTANT

METHOD 1	**METHOD 2**	**METHOD 3**
0.780	0.783	0.776

120

RHENIUM

DENSITY (g/cm)	POISSON'S RATIO
21.1	0.288

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.4118	18.6

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.0332	0.0328

YOUNGS MODULUS   **BULK MODULUS**

(Dynes/cm * 10^{12})

4.541	3.577

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	2.271	2.299

RHODIUM

DENSITY (g/cm)	POISSON'S RATIO
12.45	0.328

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.4778	24.7

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.0590	0.0580

YOUNGS MODULUS   **BULK MODULUS**

(Dynes/cm * 10^{12})

2.940	2.842

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
2.270	2.284	2.323

122

SCANDIUM

DENSITY (g/cm)	POISSON'S RATIO
2.99	0.269

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} $°C^{-1}$)
0.4296	30.1

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.1370	0.1358

YOUNGS MODULUS   **BULK MODULUS**
(Dynes/cm * 10^{12})

0.793	0.572

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	0.969	1.014

123

SILICON

DENSITY
(g/cm)

2.33

POISSON'S RATIO

0.212

SOUND VELOCITY

(cm/microsec)

0.6545

VOL. COEFF. THERMAL

EXPANSION, (10^{-6} $^{\circ}C^{-1}$)

7.9

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.1700	0.1698

YOUNGS MODULUS   **BULK MODULUS**

(Dynes/cm * 10^{12})

1.690	0.979

GRÜNEISEN CONSTANT

METHOD 1	**METHOD 2**	**METHOD 3**
—	0.475	0.466

124

SILICON CARBIDE

DENSITY (g/cm)	POISSON'S RATIO
3.12	0.165

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, $(10^{-6}\ °C^{-1})$
0.7999	10.2

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.1650	0.1645

YOUNGS MODULUS	BULK MODULUS
(Dynes/cm $* 10^{12}$)	
3.862	1.921

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	0.945	0.912

125

SILVER

DENSITY
(g/cm)

10.5

POISSON'S RATIO

0.367

SOUND VELOCITY

(cm/microsec)

0.3176

VOL. COEFF. THERMAL

EXPANSION, (10^{-6} $°C^{-1}$)

56.8

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.0564	0.0541

YOUNGS MODULUS   **BULK MODULUS**

(Dynes/cm * 10^{12})

0.827	1.036

GRÜNEISEN CONSTANT

METHOD 1	**METHOD 2**	**METHOD 3**
2.550	2.428	2.474

126

SILVER CHLORIDE (S.C.)

DENSITY (g/cm)	POISSON'S RATIO
5.56	0.409

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.2811	90.0

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.0850	0.0804

YOUNGS MODULUS   **BULK MODULUS**

(Dynes/cm * 10^{12})

0.240	0.442

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	2.000	2.127

SODIUM CHLORIDE (S.C.)

DENSITY (g/cm)	POISSON'S RATIO
2.14	0.252

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.3410	121.0

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.2040	0.1917

YOUNGS MODULUS **BULK MODULUS**

(Dynes/cm * 10^{12})

0.375	0.252

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	1.648	1.779

128

STAINLESS STEEL 304L

DENSITY (g/cm)	POISSON'S RATIO
7.9	0.280

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.4496	44.3

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.1160	0.1131

YOUNGS MODULUS	BULK MODULUS
(Dynes/cm * 10^{12})	
2.153	1.660

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	1.845	1.968

129

STRONTIUM

DENSITY (g/cm)	POISSON'S RATIO
2.6	0.297

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.2118	67.5

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.0686	0.0671

YOUNGS MODULUS   **BULK MODULUS**
(Dynes/cm * 10^{12})

0.142	0.117

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	1.055	1.078

130

TANTALUM

DENSITY (g/cm)	POISSON'S RATIO
16.6	0.342

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.3388	18.9

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.0330	0.0327

YOUNGS MODULUS   **BULK MODULUS**

(Dynes/cm * 10^{12})

1.857	1.963

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
1.690	1.571	1.634

TANTALUM CARBIDE

DENSITY (g/cm)	POISSON'S RATIO
14.4	0.200

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.3315	16.8

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.0455	0.0453

YOUNGS MODULUS   BULK MODULUS
(Dynes/cm * 10^{12})

2.848	1.582

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	0.970	0.974

132

TEFLON®

DENSITY (g/cm)	POISSON'S RATIO
2.18	0.433

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.1289	308.0

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.2410	0.2302

YOUNGS MODULUS   **BULK MODULUS**

(Dynes/cm * 10^{12})

0.014	0.035

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
0.480	0.508	0.509

TERBIUM

DENSITY (g/cm)

8.23

POISSON'S RATIO

0.261

SOUND VELOCITY (cm/microsec)

0.2199

VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})

28.3

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.0437	0.0434

YOUNGS MODULUS   BULK MODULUS (Dynes/cm * 10^{12})

0.575	0.400

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	0.748	0.758

134

THALLIUM BROMIDE (S.C.)

DENSITY (g/cm)	POISSON'S RATIO
7.56	0.321

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.1724	158.0

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.0450	0.0397

YOUNGS MODULUS   **BULK MODULUS**
(Dynes/cm * 10^{12})

0.241	0.225

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	2.494	2.830

THALLIUM BROMIDE —CHLORIDE

DENSITY (g/cm)	POISSON'S RATIO
7.19	0.333

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.1700	150.0

HEAT CAPACITY, (cal/ g –C)	
(Cp)	(Cv)
0.0480	0.0429

YOUNGS MODULUS	BULK MODULUS
(Dynes/cm * 10^{12})	
0.242	0.228

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	2.159	2.649

THALLIUM BROMIDE —IODIDE

DENSITY (g/cm)	POISSON'S RATIO
7.37	0.333

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.1635	174.0

HEAT CAPACITY, (cal/ g –C)	
(Cp)	(Cv)
0.0365	0.0307

YOUNGS MODULUS	BULK MODULUS
(Dynes/cm * 10^{12})	
0.199	0.198

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	3.046	3.638

137

THALLIUM CHLORIDE (S.C.)

DENSITY (g/cm)	POISSON'S RATIO
7.0	0.322

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.1835	159.0

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.0520	0.0459

YOUNGS MODULUS   BULK MODULUS
(Dynes/cm * 10^{12})

0.252	0.236

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	2.461	2.790

138

THORIUM

DENSITY (g/cm)	POISSON'S RATIO
11.7	0.302

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.2327	33.1

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.0283	0.0279

YOUNGS MODULUS   **BULK MODULUS**

(Dynes/cm * 10^{12})

0.751	0.632

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	1.514	1.534

139

THORIUM DIOXIDE

DENSITY
(g/cm)

9.87

POISSON'S RATIO

0.170

SOUND VELOCITY
(cm/microsec)

0.2651

VOL. COEFF. THERMAL
EXPANSION, (10^{-6} °C^{-1})

23.2

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.0560	0.0557

YOUNGS MODULUS   BULK MODULUS
(Dynes/cm * 10^{12})

1.373	0.693

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	0.696	0.699

140

THULIUM

DENSITY
(g/cm)

9.31

POISSON'S RATIO

0.235

SOUND VELOCITY
(cm/microsec)

0.2223

VOL. COEFF. THERMAL
EXPANSION, (10^{-6} $^{\circ}C^{-1}$)

36.0

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.0382	0.0377

YOUNGS MODULUS   BULK MODULUS
(Dynes/cm * 10^{12})

0.755	0.475

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	1.113	1.163

TIN

DENSITY (g/cm)	POISSON'S RATIO
7.29	0.340

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} $°C^{-1}$)
0.2703	66.4

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.0545	0.0525

YOUNGS MODULUS   BULK MODULUS
(Dynes/cm * 10^{12})

YOUNGS MODULUS	BULK MODULUS
0.450	0.469

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
2.110	2.128	1.944

TIN OXIDE

DENSITY (g/cm)	POISSON'S RATIO
6.95	—

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
—	11.4

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.0830	—

YOUNGS MODULUS	BULK MODULUS
(Dynes/cm * 10^{12})	
—	—

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
1.600	—	—

143

TITANIUM

DENSITY
(g/cm)

4.6

POISSON'S RATIO

0.340

SOUND VELOCITY
(cm/microsec)

0.4919

VOL. COEFF. THERMAL
EXPANSION, (10^{-6} °C^{-1})

25.3

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.1240	0.1229

YOUNGS MODULUS   BULK MODULUS
(Dynes/cm * 10^{12})

1.060	1.104

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
1.180	1.180	1.181

144

TITANIUM CARBIDE

DENSITY
(g/cm)

4.9

POISSON'S RATIO

0.200

SOUND VELOCITY

(cm/microsec)

0.5985

VOL. COEFF. THERMAL

EXPANSION, (10^{-6} °C^{-1})

19.2

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.1340	0.1331

YOUNGS MODULUS   **BULK MODULUS**
(Dynes/cm * 10^{12})

3.159	1.755

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	1.227	1.235

145

TITANIUM DIOXIDE

DENSITY (g/cm)	POISSON'S RATIO
4.0	0.271

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.6663	22.6

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.1690	0.1674

YOUNGS MODULUS   **BULK MODULUS**

(Dynes/cm * 10^{12})

2.440	1.776

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	1.419	1.433

TUNGSTEN

DENSITY (g/cm)	POISSON'S RATIO
19.3	0.280

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.4014	13.5

HEAT CAPACITY, (cal/ g –C)	
(Cp)	(Cv)
0.0318	0.0316

YOUNGS MODULUS	BULK MODULUS
(Dynes/cm * 10^{12})	
4.110	3.110

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
1.540	1.635	1.646

147

TUNGSTEN CARBIDE

DENSITY (g/cm)	POISSON'S RATIO
15.7	0.220

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} $^\circ C^{-1}$)
0.4508	11.1

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.0510	0.0508

YOUNGS MODULUS	BULK MODULUS
(Dynes/cm * 10^{12})	
5.344	3.190

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	1.057	1.061

URANIUM

DENSITY (g/cm)	POISSON'S RATIO
19.1	0.197

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.2431	41.9

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.0276	0.0269

YOUNGS MODULUS   **BULK MODULUS**

(Dynes/cm * 10^{12})

2.054	1.129

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
2.060	2.144	2.204

URANIUM OXIDE

DENSITY (g/cm)	POISSON'S RATIO
10.3	0.310

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.3985	28.2

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.0649	0.0640

YOUNGS MODULUS   **BULK MODULUS**

(Dynes/cm * 10^{12})

1.814	1.591

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	1.649	1.626

VANADIUM

DENSITY (g/cm)	POISSON'S RATIO
6.0	0.365

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.5072	23.4

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.1043	0.1033

YOUNGS MODULUS   **BULK MODULUS**

(Dynes/cm * 10^{12})

1.276	1.580

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
1.290	1.379	1.426

VYCOR®

DENSITY
(g/cm)

2.18

POISSON'S RATIO

0.190

SOUND VELOCITY

(cm/microsec)

0.4125

VOL. COEFF. THERMAL

EXPANSION, $(10^{-6}\ °C^{-1})$

2.4

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.2000	0.2000

YOUNGS MODULUS   **BULK MODULUS**
(Dynes/cm * 10^{12})

0.690	0.371

GRÜNEISEN CONSTANT

METHOD 1	**METHOD 2**	**METHOD 3**
—	0.049	0.049

152

YTTERBIUM

DENSITY
(g/cm)

6.97

POISSON'S RATIO

0.284

SOUND VELOCITY

(cm/microsec)

0.1446

VOL. COEFF. THERMAL
EXPANSION, (10^{-6} °C^{-1})

75.4

HEAT CAPACITY, (cal/ g –C)

(Cp)	**(Cv)**
0.0346	0.0338

YOUNGS MODULUS	**BULK MODULUS**
(Dynes/cm * 10^{12})	
0.178	0.138

GRÜNEISEN CONSTANT

METHOD 1	**METHOD 2**	**METHOD 3**
—	1.089	1.053

153

YTTRIUM

DENSITY
(g/cm)

4.46

POISSON'S RATIO

0.255

SOUND VELOCITY

(cm/microsec)

0.3274

VOL. COEFF. THERMAL

EXPANSION, (10^{-6} $°C^{-1}$)

33.9

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.0680	0.0671

YOUNGS MODULUS   **BULK MODULUS**
(Dynes/cm * 10^{12})

0.663	0.469

GRÜNEISEN CONSTANT

METHOD 1	**METHOD 2**	**METHOD 3**
—	1.277	1.270

154

YTTRIUM ALUMINATE (YAG®, S.C.)

DENSITY (g/cm)	POISSON'S RATIO
4.55	0.249

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.6374	26.7

HEAT CAPACITY, (cal/ g –C)	
(Cp)	(Cv)
0.1542	0.1521

YOUNGS MODULUS	BULK MODULUS
(Dynes/cm * 10^{12})	
2.780	1.849

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	1.681	1.705

155

ZINC

DENSITY (g/cm)	POISSON'S RATIO
6.92	0.249

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, $(10^{-6}\ °C^{-1})$
0.3128	90.9

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.0929	0.0870

YOUNGS MODULUS   **BULK MODULUS**
(Dynes/cm * 10^{12})

1.045	0.694

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
2.450	2.288	2.504

ZINC OXIDE

DENSITY (g/cm)	POISSON'S RATIO
5.6	0.354

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.5020	12.9

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.1180	0.1177

YOUNGS MODULUS	BULK MODULUS
(Dynes/cm * 10^{12})	
1.235	1.411

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	0.658	0.660

ZIRCONIUM

DENSITY
(g/cm)

6.5

POISSON'S RATIO

0.332

SOUND VELOCITY

(cm/microsec)

0.3747

VOL. COEFF. THERMAL

EXPANSION, $(10^{-6} \, ^\circ C^{-1})$

17.1

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.0652	0.0649

YOUNGS MODULUS   **BULK MODULUS**
(Dynes/cm * 10^{12})

0.951	0.892

GRÜNEISEN CONSTANT

METHOD 1	**METHOD 2**	**METHOD 3**
0.870	0.880	0.864

158

ZIRCONIUM CARBIDE

DENSITY
(g/cm)

6.4

POISSON'S RATIO

0.200

SOUND VELOCITY

(cm/microsec)

0.3460

VOL. COEFF. THERMAL

EXPANSION, $(10^{-6} \, °C^{-1})$

16.0

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.0900	0.0898

YOUNGS MODULUS	**BULK MODULUS**
(Dynes/cm * 10^{12})	
1.379	0.766

GRÜNEISEN CONSTANT

METHOD 1	**METHOD 2**	**METHOD 3**
—	0.509	0.510

159

ZIRCONIUM DIOXIDE

DENSITY
(g/cm)

5.7

POISSON'S RATIO

0.270

SOUND VELOCITY

(cm/microsec)

0.4428

VOL. COEFF. THERMAL

EXPANSION, (10^{-6} °C^{-1})

26.4

HEAT CAPACITY, (cal/ g –C)

(Cp)   **(Cv)**

0.1090   0.1079

YOUNGS MODULUS   **BULK MODULUS**

(Dynes/cm * 10^{12})

1.687   1.222

GRÜNEISEN CONSTANT

METHOD 1   **METHOD 2**   **METHOD 3**

—   1.135   1.254

160

LABORATORY OPERATIONS

The Aerospace Corporation functions as an "architect-engineer" for national security programs, specializing in advanced military space systems. The Corporation's Laboratory Operations supports the effective and timely development and operation of national security systems through scientific research and the application of advanced technology. Vital to the success of the Corporation is the technical staff's wide-ranging expertise and its ability to stay abreast of new technological developments and program support issues associated with rapidly evolving space systems. Contributing capabilities are provided by these individual organizations:

Electronics and Photonics Laboratory: Microelectronics, VLSI reliability, failure analysis, solid-state device physics, compound semiconductors, radiation effects, infrared and CCD detector devices, data storage and display technologies; lasers and electro-optics, solid state laser design, micro-optics, optical communications, and fiber optic sensors; atomic frequency standards, applied laser spectroscopy, laser chemistry, atmospheric propagation and beam control, LIDAR/LADAR remote sensing; solar cell and array testing and evaluation, battery electrochemistry, battery testing and evaluation.

Space Materials Laboratory: Evaluation and characterizations of new materials and processing techniques: metals, alloys, ceramics, polymers, thin films, and composites; development of advanced deposition processes; nondestructive evaluation, component failure analysis and reliability; structural mechanics, fracture mechanics, and stress corrosion; analysis and evaluation of materials at cryogenic and elevated temperatures; launch vehicle fluid mechanics, heat transfer and flight dynamics; aerothermodynamics; chemical and electric propulsion; environmental chemistry; combustion processes; space environment effects on materials, hardening and vulnerability assessment; contamination, thermal and structural control; lubrication and surface phenomena.

Space Science Applications Laboratory: Magnetospheric, auroral and cosmic ray physics, wave-particle interactions, magnetospheric plasma waves; atmospheric and ionospheric physics, density and composition of the upper atmosphere, remote sensing using atmospheric radiation; solar physics, infrared astronomy, infrared signature analysis; infrared surveillance, imaging, remote sensing, and hyperspectral imaging; effects of solar activity, magnetic storms and nuclear explosions on the Earth's atmosphere, ionosphere and magnetosphere; effects of electromagnetic and particulate radiations on space systems; space instrumentation, design fabrication and test; environmental chemistry, trace detection; atmospheric chemical reactions, atmospheric optics, light scattering, state-specific chemical reactions and radiative signatures of missile plumes.

Center for Microtechnology: Microelectromechanical systems (MEMS) for space applications; assessment of microtechnology space applications; laser micromachining; laser-surface physical and chemical interactions; micropropulsion; micro- and nanosatellite mission analysis; intelligent microinstruments for monitoring space and launch system environments.

Office of Spectral Applications: Multispectral and hyperspectral sensor development; data analysis and algorithm development; applications of multispectral and hyperspectral imagery to defense, civil space, commercial, and environmental missions.

**THE AEROSPACE
CORPORATION**

2350 E. El Segundo Boulevard
El Segundo, California 90245-4691
U.S.A.