

GRAPHITE

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GRAPHITE

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The importance of graphite is rapidly increasing as thermal environments become severe and the capabilities of other materials are exceeded. Graphite has interesting potential in this area as it is one of the few materials available with useful strength above 3000°F. When its light weight is considered, graphite becomes even more interesting as an aerospace material; on a strength-to-weight-ratio basis it stands alone above 3100°F. Although graphite has had a primary role in many industrial high temperature structural applications, several challenges to its extensive use and development for aerospace applications have been its unreliability (reproducibility and uniformity), low oxidation resistance, and "brittle fracture." These factors along with a general lack of understanding of the material, how to design for its strong features and around its undesirable features, and the necessity of using off-the-shelf grades of graphite have handicapped its use. This material should not be considered a shelf item in the more demanding aerospace applications. In the past this has been a necessity because this low volume market presented insufficient incentive for the graphite industry to tailor materials for these applications. This does not apply to pyrolytic graphite for the nature of the vapor deposition process makes it a custom made material. It is now apparent that the widely varying properties of polycrystalline graphites can be controlled, and that such properties can be tailored to meet specific materials applications.

For this reason graphite should be discussed in terms of specific or representative aerospace uses. In addition to so-called conventional bulk graphites, many new types of graphites have been developed in useful sizes during recent years and newer graphites are being developed at a rapid pace. The purpose of this paper is to review the state of the art as it applies to Air Force materials applications and attempt to establish the trends and potential of this material in meeting aerospace requirements.

Graphite and its Fabrication

To avoid any misunderstanding the word "graphite" should be explained. Strictly applied, "graphite" describes a particular form of crystalline carbon structure; but common usage more often refers to carbon materials that are characterized by a high content of graphitic carbon. This graphitic form of carbon is illustrated in figure 1. The carbon atoms are arranged in benzene rings bonded by strong covalent forces and in this direction (a-direction) the crystal is very strong. The layers formed by these rings are bound by much weaker van der Waal's forces and the crystal is very weak in the direction perpendicular to the layer planes. This anisotropy also has a similar affect on other properties. For example, thermal and electrical conductivity are high parallel to the benzene planes (a-direction) and low perpendicular to the planes (c-direction). Thermal expansion is low in the parallel direction and high in the perpendicular direction. Manufactured graphites are made up of crystallites of the structure described, but the preferred orientation of the crystallites within a piece may vary from near random orientation to a high degree of preferred orientation.

In a typical manufacturing process graphite is made by mixing calcined petroleum coke (the filler material) and coal tar pitch (the binder material). Shapes of this mixture are formed by extrusion or molding and the pieces are heat treated to 1400-1700°F in the baking cycle and then to 4500-5400°F in the graphitization cycle. This short description omits many of the process variables used to achieve the variety of properties available in the various bulk grades. In the carbon industry these process variables or tricks of the trade are closely guarded secrets. Nevertheless the process as generally described above is typical in the industry.

Raw Materials: Almost any organic material that leaves a high carbon residue when heated can be used to make graphite; however, petroleum cokes are the primary filler raw materials used in the industry. The selection of a particular coke might depend upon a number of considerations; however, in general the major reasons for their use are low cost, relatively low impurity content and ease of graphitization. These factors outweigh the disadvantages associated with a nonreproducible by-product raw material so far as the vast majority of the industrial market is concerned. Some of the things that effect the physical and chemical properties of the coke and also the final graphite piece are the source of the crude oil, refining operation, and coking conditions. It would be desirable to have more control over this raw material but this type of cooperation is seldom compatible with the objectives of the petroleum industry. Synthetic cokes prepared from aromatic hydrocarbons would overcome these problems but economic considerations are a big deterrent to their use. Particle size, shape and distribution also influence subsequent processing and the final product. Lampblack and various types of coke may be used when specific properties are desired. The cokes are calcined to remove volatile hydrocarbons and shrink the fillers material before incorporating them into a formed piece. The common binder material is coal tar pitch. Again this by-product material is conveniently cheap and leaves a high carbon residue. It is thermoplastic, solid at room temperature, and softens at approximately 200°F. This property permits the mixing and forming of shapes in steam heated equipment and allows handling of the formed piece at room temperature. This pitch also presents a problem by being thermoplastic as the piece must be carefully supported during subsequent baking to prevent slump of the piece prior to the curing of the binder. Thermosetting binders can be used but here again economic considerations are a major deterrent to their extensive use.

Forming: The prepared mix is formed into shapes by extrusion or molding. Both these forming methods have an effect on the anisotropy of the finished graphite. Particle size, shape and distribution of the calcined coke also have an influence on ordering that occurs during forming. Most cokes used by the industry have particles that have a long dimension; during extrusion forming the long dimension lines up parallel to the direction of extrusion and during molding the long dimension of the coke particles align normal to the molding pressure. The anisotropy induced by raw materials and forming carries through to the graphitized piece.

Baking and Graphitization: During the first heat treatment the formed piece must be carefully supported since the binder again liquifies and the piece becomes plastic. As the binder pyrolyzes large quantities of gases are evolved; therefore heating must be slow during the periods of high gas evolution to allow gases to escape without distorting or breaking the piece. Polymerization and cross linking in the binder and between the binder and the filler occurs as the temperature is raised to 1400-1700°F. After baking the piece may be impregnated with a pitch and baked again if a stronger, more impermeable graphite is desired. In the final heat treatment to 4500-5400°F the remaining volatiles are removed and the carbon is converted to graphite. By the time the temperature has reached approximately 2700°F most of the impurities have been removed and the carbon

piece is composed of small crystallites, of about 30\AA in size built of disorganized stacks of parallel planes of condensed benzene rings, in a matrix of a disorganized carbon phase. From 2700°F to final graphitization temperature the crystallites grow, first at the expense of the disorganized phase and then smaller crystallites. Around 3800°F the carbon crystallites have reached the size of about 150\AA in the a-direction and begin to change into crystallites of graphite by the rotation and relative shift of layer planes. Continued temperature increase results in a rapid growth of graphite crystallites. Mrozowski (1) suggests that perhaps the main driving force is due to the thermal stresses caused by the anisotropic expansion of the crystallites assisted by energy of the thermal motion. It is also believed that three-dimensional alignment proceeds by the movement of boundaries or arrays of dislocations (2).

Influence of Graphite Structure on Properties

Porosity: Without impregnations the process as described above produces a relatively porous, low density graphite. The porosity of graphite can be divided into two types; 1) pores that are left due to the loss of volatile constituents, and 2) those that are caused by differential contraction of the crystallites. The largest source of pores is between particle voids due to volatile constituents from the binder. This porosity may be decreased by successive impregnations and heat treatments but theoretically these pores cannot be processed out. The latter porosity is referred to by Mrozowski (3) as "unavoidable" porosity. Mrozowski states that even though the polycrystalline graphite should be perfectly dense at the highest heat treatment temperature, voids will be formed as it cools. These voids are caused by differences in contraction along the a- and c-directions of the randomly oriented crystallites. Unavoidable porosity would naturally decrease as the crystallites assumed a preferred orientation and would increase with more random orientation. A dense material (2.25 g/cc) has been obtained by applying very high pressure and temperature to a polycrystalline graphite with original density of 1.9 g/cc (4). The plastic flow produced at high temperature and pressure evidently allowed the crystallites almost to completely align with their c-axis parallel to the compressive force, therefore practically no unavoidable porosity was formed during cooling. Green (5) also suggested this technique as a means of increasing density and strength in graphite. A high density graphite (ZTA grade) developed by the National Carbon Company has been referred to as a "hot-worked recrystallized" graphite, and this description also implies the use of pressure and temperature to produce a high density graphite.

Thermal Properties

Thermal Expansion: Thermal expansion is a very interesting and not well understood property in polycrystalline graphite. The thermal expansion of graphites as temperature is increased shows the net influence of thermal vibrations of the lattice atoms, the elastic properties of the crystallites and the details of bonding and connection between the crystallites and particles consisting of these crystallites (6). The graphite crystallite is extremely anisotropic and as a result large differences in expansion are experienced in directions perpendicular and parallel to the layer planes. The most complete study of the thermal expansion of single crystal graphite was made by Nelson and Riley (7). Measurements were obtained over a range from 60 to 1470°F and extrapolated to higher and lower temperatures by a solid state theory development for the graphite lattice. Their results are shown in figures 2 and 3. These results show that in the c-direction graphite expands with increasing temperature at all temperatures above absolute zero. However, a shrinkage is experienced in the a-direction as the temperature is increased from absolute zero to approximately room temperature. As the temperature is increased further the crystal expands in the a-direction. Figures 2 and 3 also show the range of

expansion coefficients observed in bulk manufactured graphites. The relationship between bulk thermal expansion of manufactured graphites and the single crystal is not well understood. The extreme anisotropy of all properties of the graphite crystal complicates the situation. It is believed that a better understanding of the thermal expansion of polycrystalline graphites will also aid in understanding other properties. Mrozowski (8) has proposed a model for polycrystalline graphite and used it in an explanation of the relationship between single crystal and polycrystalline properties. According to the model, the anisotropic crystallites are joined by strong bonds at the peripheries of the larger planes. The model suggests that when polycrystalline graphite is cooled after heat treatment the strong cross linking of the bonds restrict the contractions of the body due to the low contraction of the crystallites in the direction parallel to the planes. The difference in contraction parallel and perpendicular to the planes causes unavoidable porosity and internal stress build up. Viscous creep relieves the stresses at temperature above 4100-4500°F, however, as the temperature is lowered the stresses are locked in.

Using the same model Collins (9) suggests that as the graphite is reheated the crystallites expand back into created voids thereby contributing little to the overall expansion of the system. This would help to explain some of the difference between the expansion of the crystallites and manufactured graphites.

From a process point of view, many variables affect thermal expansion of a graphite. Differences in coke have the strongest effects and these arise from many variables. Some of the variables are: raw material used in making the coke, various process parameters during coking and calcining, and particle size. These differences are further complicated by the effects of the binder on the coke and other process variables during forming and heat treatment of the graphite (10, 11).

The thermal expansion coefficient of all bulk graphite increases with increasing temperature and although the coefficients for various graphites vary over a wide range, the change in expansion coefficient with temperature is approximately the same for all graphites as shown in figures 2 and 3. As a result of this relationship the mean linear coefficient of the thermal expansion between room temperature and any final temperature can be obtained by adding a predetermined factor to the room temperature to 100°C coefficient.

Thermal Conductivity: In the a-direction the thermal conductivity of a graphite single crystal is probably higher than that of any other material. In the c-direction thermal conductivity is very low. Manufactured graphites are generally considered good thermal conductors; however, thermal conductivity can be varied over a wide range depending on the type of graphite and/or its crystallite orientation. Table 1 gives the thermal conductivity of a number of various graphites and illustrates this range. It is generally accepted that heat transfer in graphite is a lattice vibration mechanism; the decreasing thermal conductivity above room temperature is consistent with this assumption (12). In polycrystalline graphite thermal conductivity is greatly influenced by the size of the crystallites, intercrystallite bonding, orientation effects and porosity. Here again these are influenced by numerous interdependent variables from raw material processing to graphitization which in turn affect the final thermal properties. In manufactured graphites the thermal conductivity of the piece decreases as the temperature increases, as shown in figure 4.

Specific Heat: A review of the literature indicates that specific heat does not vary much from one grade of graphite to another. The specific heat curve of several graphites is summarized in figure 5.

Emissivity: Since the aerospace interest in graphite is primarily in the high temperature range where heat transfer by radiation is dominant, emissivity is an important property. Emissivity varies with different types of graphite and surface finish. Furthermore, even when starting with a polished surface, heating at high temperatures will alter the surface and increase its emissivity. A representative emissivity value for graphite is 0.77 (15). A value of 0.98 has been obtained based on reflectance measurements of the crater of an operating arc (16). It is noted that reflectance measurements yield higher emissivity values than are obtained with an optical pyrometer and the difference is not understood. Another reference stated that the spectral emissivity of graphite near 0.65 wave length is not structure dependent to a high degree and a value of 0.70 to 0.80 can be obtained with polished surfaces, while dull and oxidized surfaces can be as high as 0.98 (17).

From an aerospace standpoint one of the most interesting properties of graphite is its increased strength at high temperatures. For most graphites, strength reaches a maximum at approximately 4500°F and at this temperature, the strength may double the room temperature value. The strength of the majority of the bulk graphite grades drops off rapidly above 4500°F; however, creep data on a recently developed bulk graphite indicates it has a useful strength up to 5000-5500°F range. Mrozowski (18) explained graphite's strength-temperature dependence by attributing it to the relief of "frozen in" stresses which arise from the anisotropic contraction of the individual crystallites in the polycrystalline solid. Martens et al (19) suggested that increased plasticity of graphite at high temperature may permit local deformation around the stress-concentrations and therefore permit higher loads to be sustained before fracture. At temperatures above 4500°F the material is so plastic that changes in temperature do not materially affect flow around the stress concentration and strength decreases with increasing temperature in the manner exhibited by most other materials. Mrozowski (20) also suggested that the failure at high temperatures is of a plastic nature. He suggested that the surface of the fracture gave the appearance of a brittle fracture because failure occurs through the binder bridges or between the binder and the filler particles. Green (21) has offered an alternative interpretation based on the polymeric nature of the inter-crystalline valence bonding. The increase of strength with increasing temperature is shown in figure 6.

Flexural and compressive strengths also increase with increasing temperatures in the same manner as tensile strength. Flexural strengths are easier to measure than tensile strength and are commonly used for control purposes. It should be noted that it is important to state the method of measurement when giving flexural strength as "single point" loading gives a value approximately 20 to 25 percent higher than "third-point" loading (22).

The high temperature creep characteristics of an experimental high density graphite (ZT type) and a conventional grade are shown in figure 7. The low creep rate in its strong direction at 5500°F indicates that structural strength remains at this high temperature. The markedly higher creep with temperature across the grain as compared to along the grain of the ZT graphites indicates a different creep mechanism in the two directions as might be expected. (See figure 8 for sample grain orientation.)

The elastic moduli also increase with temperature up to about 3600°F and decrease after this peak. Hove (23) suggested that the increase is caused by the large c-direction expansion of the crystallites which tend to fill up the intercrystalline voids. This jamming would thus stiffen the structure.

Chemical Properties

Graphite is subject to three types of chemical attack: oxidation, formation of lamellar compounds, and reaction with and solution in carbide-forming metals in certain high temperature ranges. In many aerospace applications oxidation is a serious problem and graphite must be protected from oxidizing atmospheres at high temperatures. Janes (24) studied the effect of a number of raw material and process variables on oxidation resistance and concluded that particle size of the filler component, pore size, and total and type of porosity, type of forming, use of non-graphitizable components, and the use of binders other than coal tar pitch all have only a minor effect on oxidation rate. It was also noted that catalytic impurities have a decided effect on oxidation rate at relatively low temperatures. At high temperatures the oxidation reaction is reported to be diffusion controlled and catalytic impurities have little effect. Since the rate of oxidation is diffusion controlled it is quite responsive to the rate of flow of the oxidizing gas. Pyrolytic graphite is reported to have better oxidation resistance than bulk graphites; however this advantage disappears at high temperatures. At the present, the best high temperature protective coating for graphite is silicon carbide and this coating is limited to a temperature of approximately 3100°F. The protection afforded by this coating is time - temperature dependent so this temperature may be high or low depending upon the application. The major problem associated with present coatings is a mis-match of coefficients of thermal expansion between the substrate graphite and the coating which can cause spalling and cracking of a coating. Optimization of a coating system for graphite for higher temperatures will probably include tailoring the substrate graphite to more closely match the expansion of a coating and from the coating standpoint it appears that a composite coating will evolve which takes advantage of higher melting materials (e.g., oxides, borides, etc.). In this case a diffusion barrier would be necessary to protect the substrate from the higher melting coatings since carbon would react with many of these higher melting materials. Care must be taken not to compromise graphite's high emissivity by the application of a low emissivity coating thereby reducing the total capability of the graphite-coatings composite.

The second type of chemical reactivity is the formation of lamellar compounds. This type of reaction is characterized by the intrusion of various molecules or ions between the layer planes of the graphitic lattice. The formation of lamellar compounds can lead to the destruction of the piece. Graphite also reacts with carbide forming metals at high temperatures. This may be desirable or undesirable depending upon the combination of properties desired.

Thermal Shock Resistance: Since thermal shock resistance is not relatable to any single property but instead a combination of thermal and mechanical properties, it is convenient to treat this property as a separate item. By reducing thermal shock theories to the most significant factors as they effect graphite and most applications, it can be said that thermal shock resistance is directly proportional to tensile strength and conductivity and inversely proportional to Young's Modulus and coefficient of thermal expansion. The high conductivity, low thermal expansion and low modulus of most polycrystalline graphites primarily account for graphite's high thermal shock resistance as compared to other non-metals. It should be noted that the properties that affect thermal shock resistance can be varied in the various types of graphite, and thermal shock resistance can be affected. For an example, in rocket nozzle tests some of the higher density ZT graphites have cracked from thermal stresses.

Erosion: There are a number of factors that influence the erosion of graphite and as a result the exact mechanisms are not well understood. In its simplest terms erosion can be divided into chemical reactivity and mechanical abrasion. As with all chemical kinetics, other factors being equal, the rate of attack will increase with temperature. For use in the earth's atmosphere at high temperatures, oxidation is the major factor and as mentioned previously, graphite must be protected from oxidizing environments. In rocket nozzle applications, chemical and mechanical effects are magnified and complicated by the higher temperatures, pressures and velocity of the exhaust gases. In addition to the oxidizing effect (if present), other constituents in the exhaust gases may have a serious effect on the chemical reactivity of graphite. Impurities already present in the graphite are also believed to affect the mechanisms involved. A microscopic study of bulk graphites after exposure in a rocket motor reveals that attack occurs preferentially in the binder material. The particles thus weakened by the loss of the binder are then more susceptible to mechanical erosion. On a crystallite scale, attack is not on the basal planes, which are bonded by strong bonds but primarily on their edges. From this, one could conclude that the most beneficial structure at the exposed surface is a highly orientated structure with the basal planes exposed. Pyrolytic graphite rocket nozzle tests confirm this effect. On the other hand, nozzle inserts of a high density highly orientated bulk graphite (Grade ZTA) tested with the orientation so that more edges than basal surfaces are exposed, have also performed quite well. One can only conclude that the mechanism of erosion is quite complicated and not well understood. However it is apparent that microstructural detail, external environment, and the thermal, mechanical and chemical properties all affect erosion. A detailed understanding of the combined effects of these factors is in its infancy.

Requirements for Graphite in Aerospace Application

The full realization of drawing board capabilities is limited by the lack of suitable materials to cope with the severe environmental conditions of aerospace flight. Future progress in the aerospace realm largely depends upon improved materials that will endure these extreme environments. Of course the optimum aerospace material would have an extreme melting point, high strength, high thermal and mechanical shock resistance, and zero density. Unfortunately such a material does not exist. Materials that look good from the high melting point consideration have other detrimental properties, e.g. low strength, low thermal shock resistance. The aerospace materials problem represents a formidable challenge for both the designer and the materials developer. So that this challenge may be better understood where graphitic materials are concerned several of the more demanding materials applications will be discussed.

From a propulsion standpoint aerospace vehicles, at the present and in the foreseeable future, will depend upon some form of rocketry for the higher speeds and greater load carrying capabilities which are needed. The greater thrust required to achieve these capabilities can be obtained by simple scale up or more efficiently by higher energy fuel. These new fuels and greater thrust mean higher temperatures, higher pressures, greater total heat flux and in most cases a more corrosive environment.

From the vehicle structure standpoint, specific flight profiles must be considered as each profile presents different problems. For a ballistic type vehicle the nose cone experiences the most severe thermal environment. Its re-entry is characterized by extremely high temperatures for a short period of time. The optimization of the ballistic re-entry profile necessitates higher ground approach speeds to increase accuracy and lessen the possibility of interception. Nose cones incorporating graphite (pyrolytic graphite on a composite graphite system) offer interesting potential in this materials application.

Graphite's high emissivity and high temperature capability present some interesting advantages. Generally speaking, all graphites have these advantages but most are ruled out because of high conductivity. However, by controlling crystallite orientation and in some cases other properties, graphite can become a good high temperature insulator as in the case of pyrolytic graphite and some forms of bulk graphite. A glide re-entry is characterized by lower temperatures than ballistic re-entry and longer exposure to the earth's atmosphere. Whereas oxidation resistance is a minor factor in ballistic re-entry, it is a major concern for longer periods in oxidizing environments. Mechanical properties are somewhat more important in this type of application, but structures can be designed that will have the major load transmitted to stronger, thermally protected members of the structure. The addition of a man to these vehicles increases the reliability requirements and also of the materials. The materials applications mentioned above are probably the most challenging ones facing the materials developer and vehicle designer in this new era of aerospace vehicle development; however, the challenges are not insurmountable. Of the various materials possibilities, graphites in one form or another, or in combination with other materials, are outstanding candidates to meet the challenge.

The more exotic applications suggested above by no means constitute a limit of materials applications where graphites should be considered as candidates in aerospace designs. Graphites are a family of materials with the capability of being tailored to meet a large variety of high temperature applications. On a density scale this family extends from foams on the low side to high density bulk graphite and pyrolytic graphite approaching the theoretical density of 2.26 g/cc. It should be noted that even these high density graphites are in the same weight class as aluminum. As a result of its light weight and the importance of weight in aerospace vehicles, various forms of graphite also have the potential of being competitive in temperature ranges not normally associated with graphite. Table 2 illustrates the range of properties available in various forms of graphite. Graphite can be a thermal insulator or a conductor and the strength of various graphites vary over a wide range. It is also seen that there are limits to tailoring all the desirable properties of graphite into a single piece. The fibrous materials, yarn and felt, could be used in fibrous form or in composite materials such as the cloth laminate type. Single crystal and whisker properties are given only to indicate a property limit in the material and do not constitute a useful form.

The requirement for a more uniform and reproducible graphite product has long been a challenge to the graphite industry. New graphite technology has made significant progress in this area. Feasibility of reducing the variability of properties by at least one-third that of presently accepted missile grade graphite (in comparable sizes) has been proven. The processes involved also have the capability of scale-up so that higher quality graphites of the conventional bulk variety have the potential of being available in larger sizes. However, the day on which pieces fifty inches in diameter with properties equal to even present ATJ graphite is not in the foreseeable future.

Another major challenge and aerospace requirements is for oxidation resistant materials in the temperature range above 2900°F. A great deal of work has been done on developing coatings for graphite; but in useful shapes and sizes, most have had only limited success in the higher temperature range. As stated previously, failure is primarily due to the differences in thermal expansion of the coating and the substrate. Graphite substrates with higher expansion coefficients offer good potential in reducing this challenge. Coating materials with higher temperature capability than the best available siliconized coatings are available. Practical coating systems and experience with them in practical application has not yet been accomplished.

Summary

From a basic science standpoint it can be said that there are many areas where fundamental knowledge is inadequate. The classical approach to studying a material through single crystals is limited in the case of graphite by the difficulty of obtaining reasonably large crystals and the inability to account for the lack of correlation between single crystal and polycrystalline studies. The study of polycrystalline graphites has had an empirical approach for the most part and has been limited seriously by competitive considerations within the industry. It should also be mentioned that these competitive considerations have restricted the publication of the majority of the work done within the industry.

To obtain a better understanding of the industry and the graphite situation there are several things to be recognized: First, over the years the graphite industry cornered most of the graphite knowledge and skills, and proprietary secrecy hangs heavy over most of the industry's efforts, particularly work concerning fabrication technology. And second, this industry is a highly competitive one, with most of its resources directed to markets where commercial incentive was the greatest. Aerospace applications constitute only a very small fraction of the commercial market and demand much of graphite in terms of properties. Outside the industry very little work has been done on graphite until recent years, partly due to the need for specialized equipment.

When the time came to use graphite in aerospace designs, it was necessary to choose off the shelf items since there was no other choice; however, the need for greater reliability as an engineering material, and more severe environments, demanded improved materials. Therefore, various competitive factors, and a stimulated interest in graphite, required that major advances be made in graphite technology. New techniques that are in many ways revolutionary to graphite technology, are being developed and consequently the family of graphitic materials has been enlarged and improved. The variety of properties available in graphites is evidence that such a material can and should be tailored for specific aerospace materials applications. It is also clear that graphite is a material of great importance to high temperature aerospace technology and will find increased use in advanced systems.

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GRAPHITE CRYSTAL LATTICE

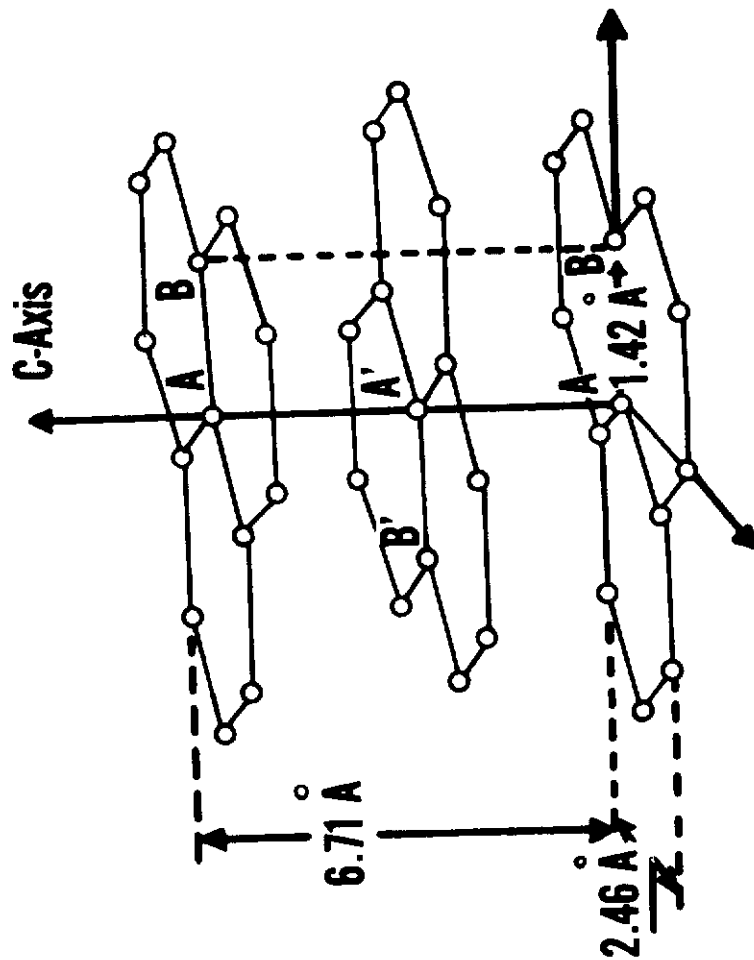


Figure 1. Structure of Graphite

THERMAL EXPANSION OF GRAPHITES

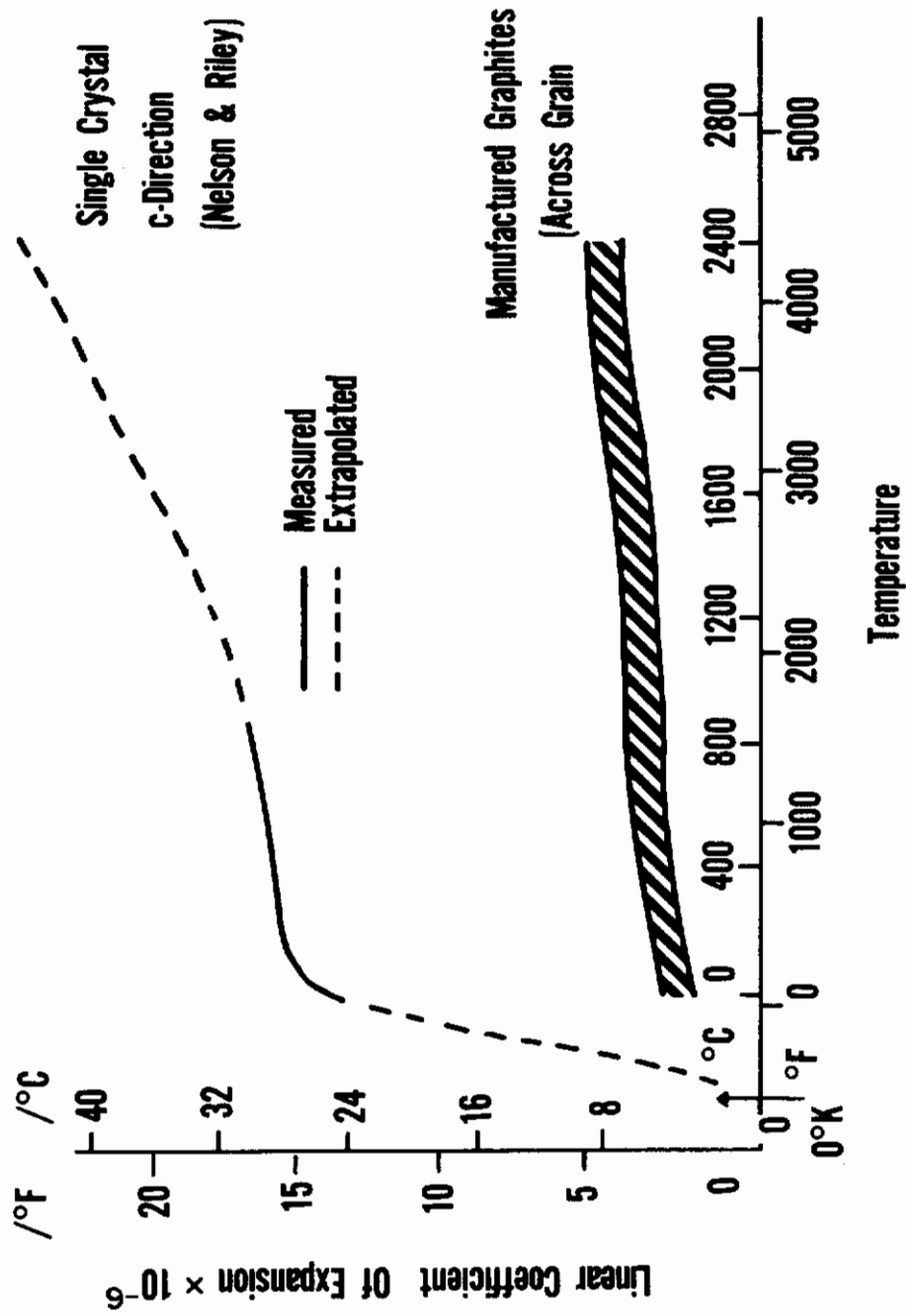


Figure 2. Thermal Expansion

THERMAL EXPANSION OF GRAPHITES

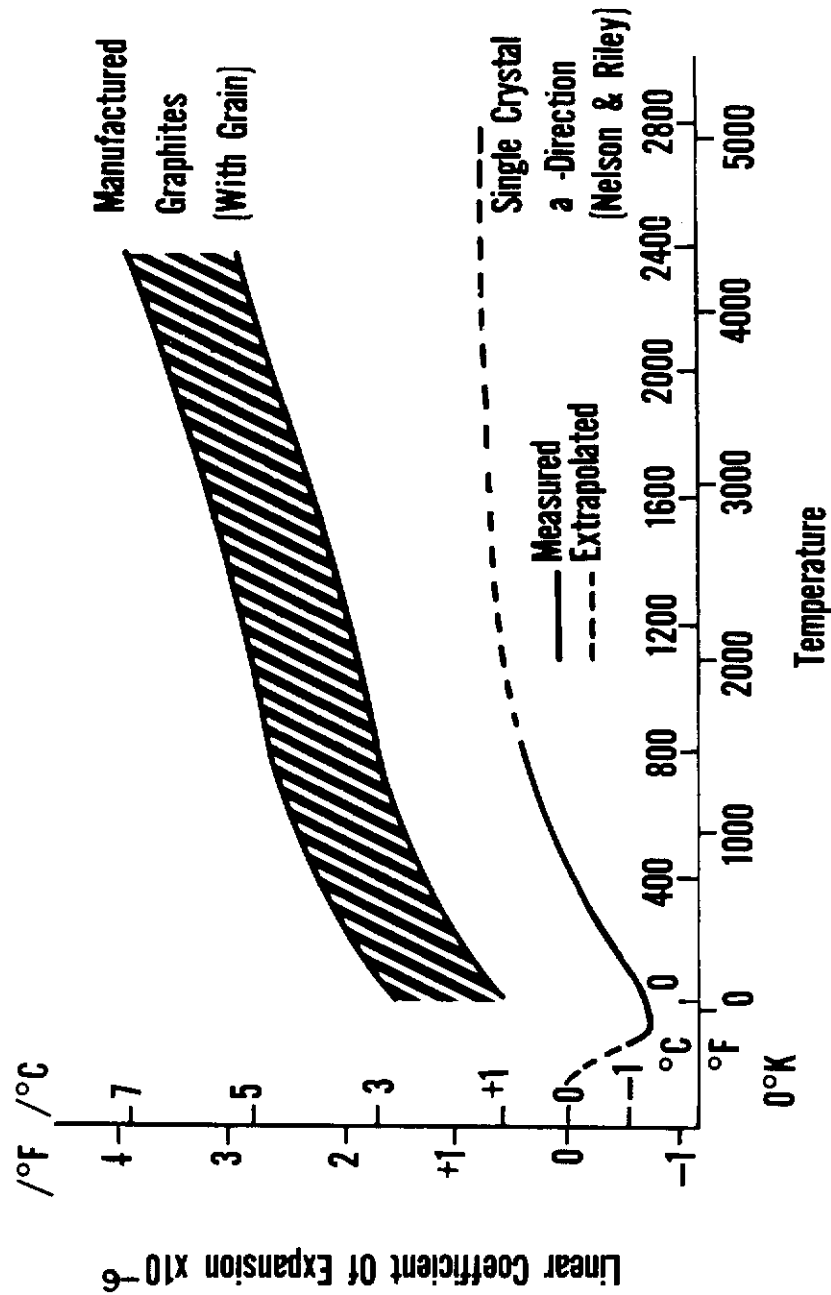


Figure 3. Thermal Expansion

THERMAL CONDUCTIVITY OF ATJ GRAPHITE

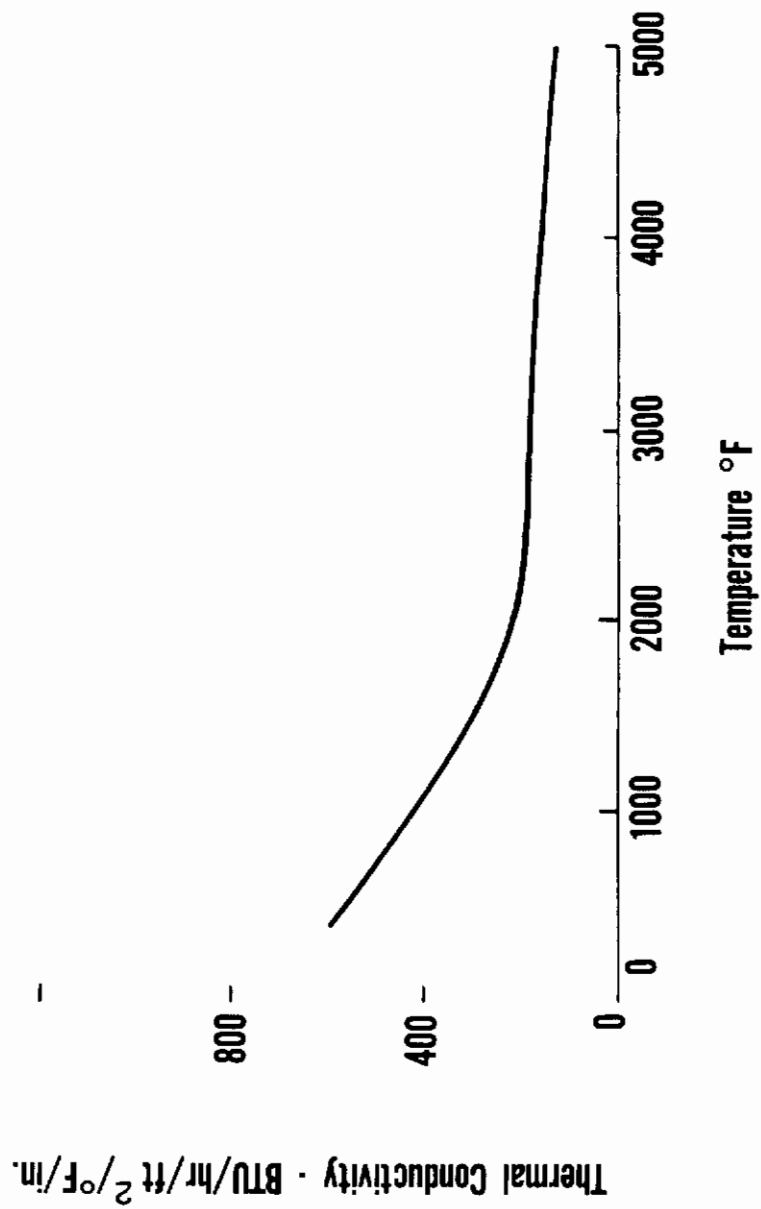


Figure 4. Thermal Conductivity vs ATJ Graphite

SPECIFIC HEAT OF FOUR GRAPHITES

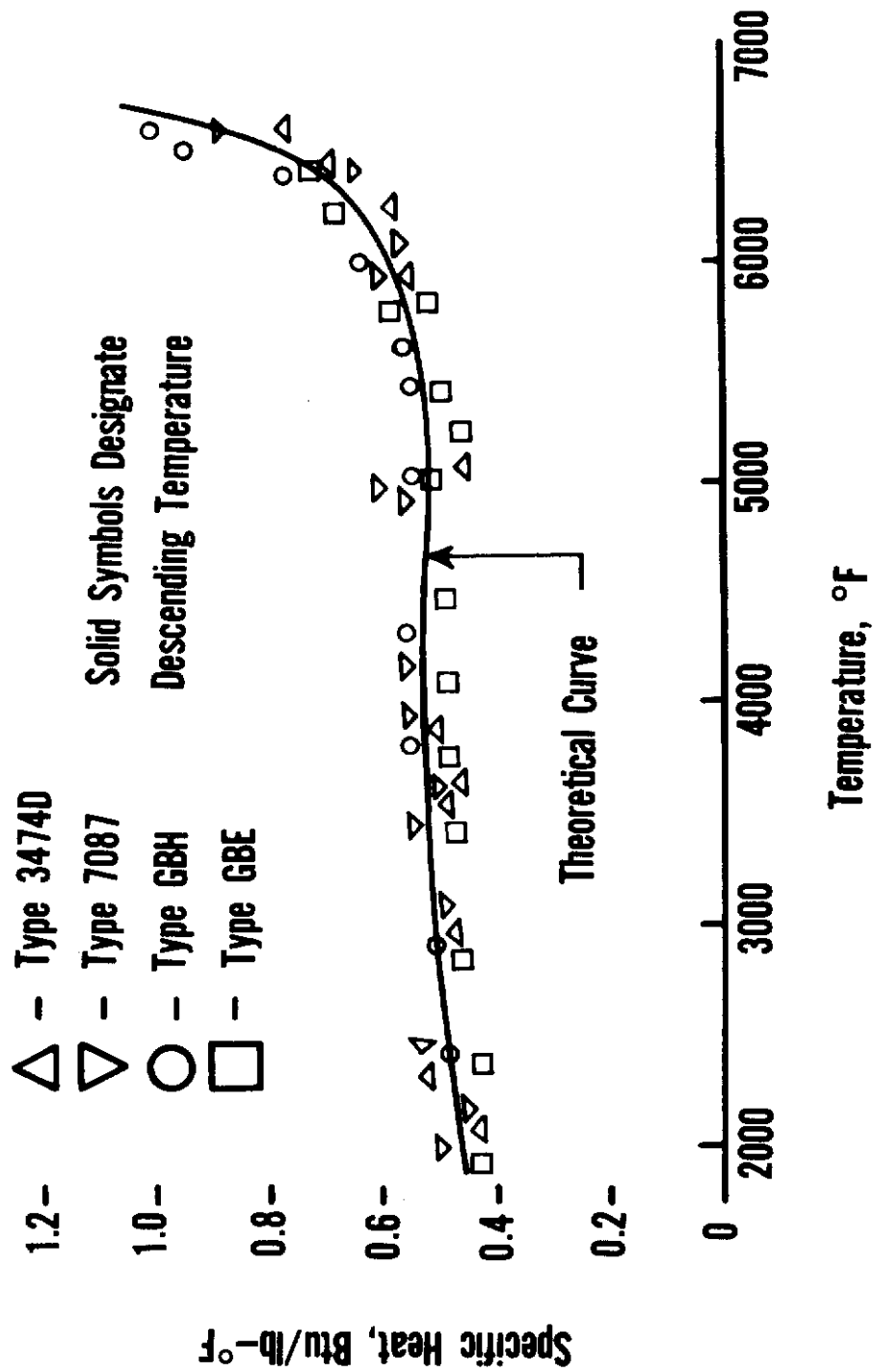


Figure 5. Specific Heat of Graphite

TENSILE STRENGTH vs. TEMPERATURE (Parallel To Grain)

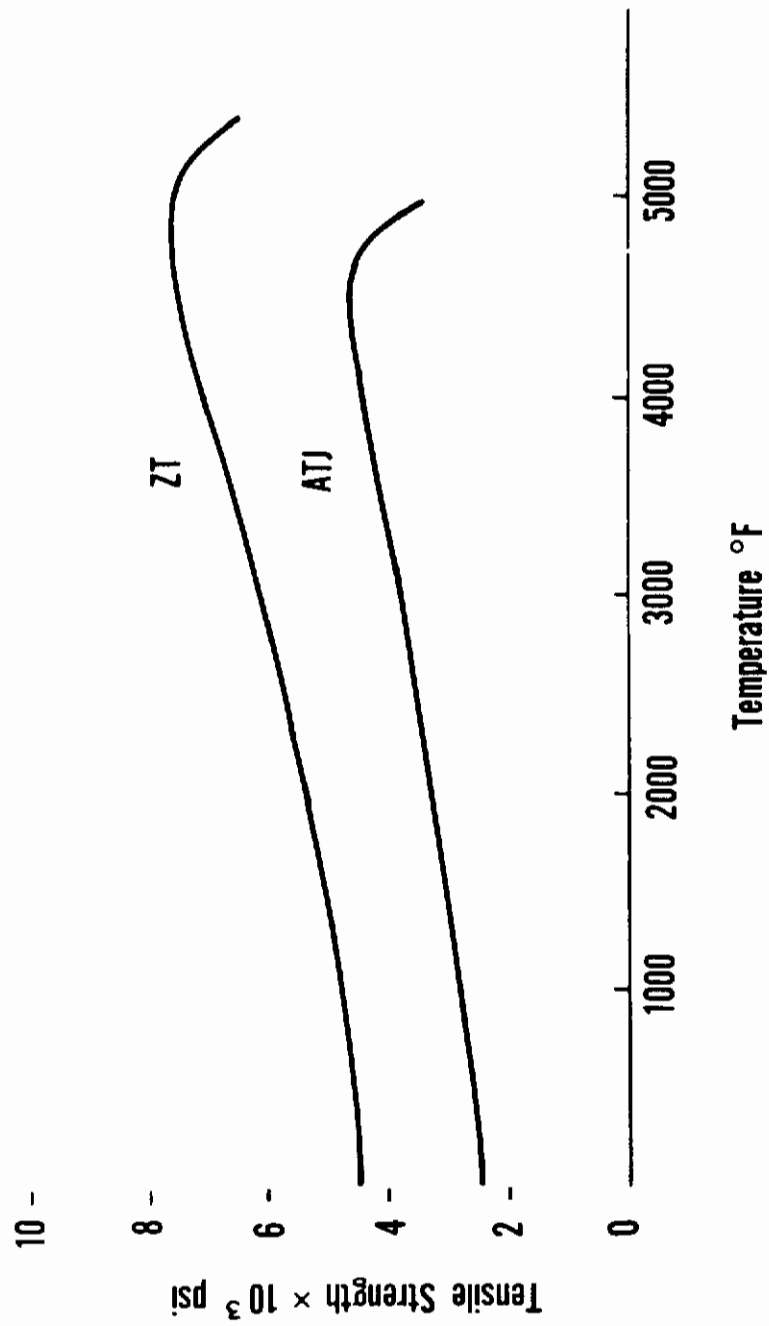


Figure 6. Strength vs Temperature

CREEP OF ZT AND ATJ GRAPHITES

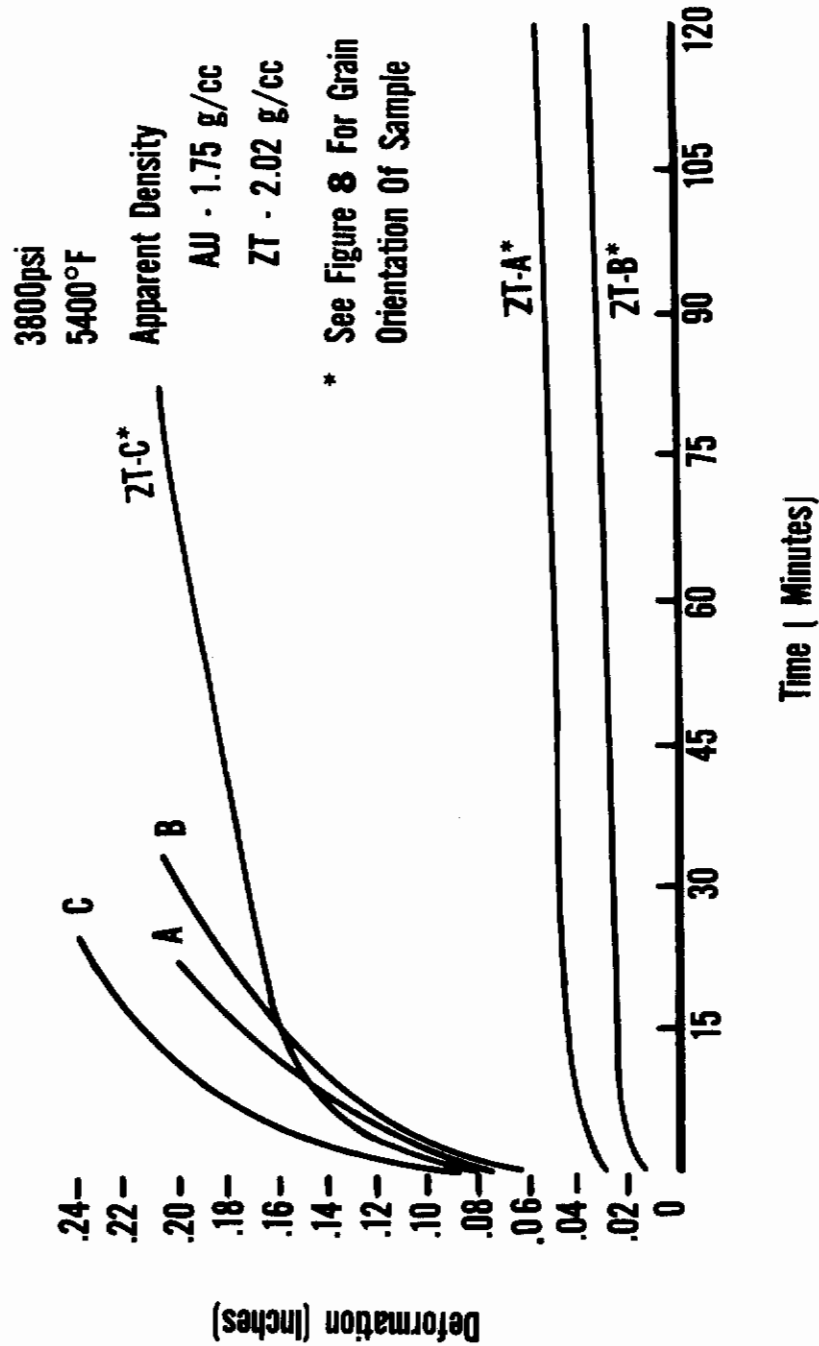


Figure 7. Creep of ZT and ATJ Graphite

GRAIN ORIENTATION FOR CREEP SAMPLES

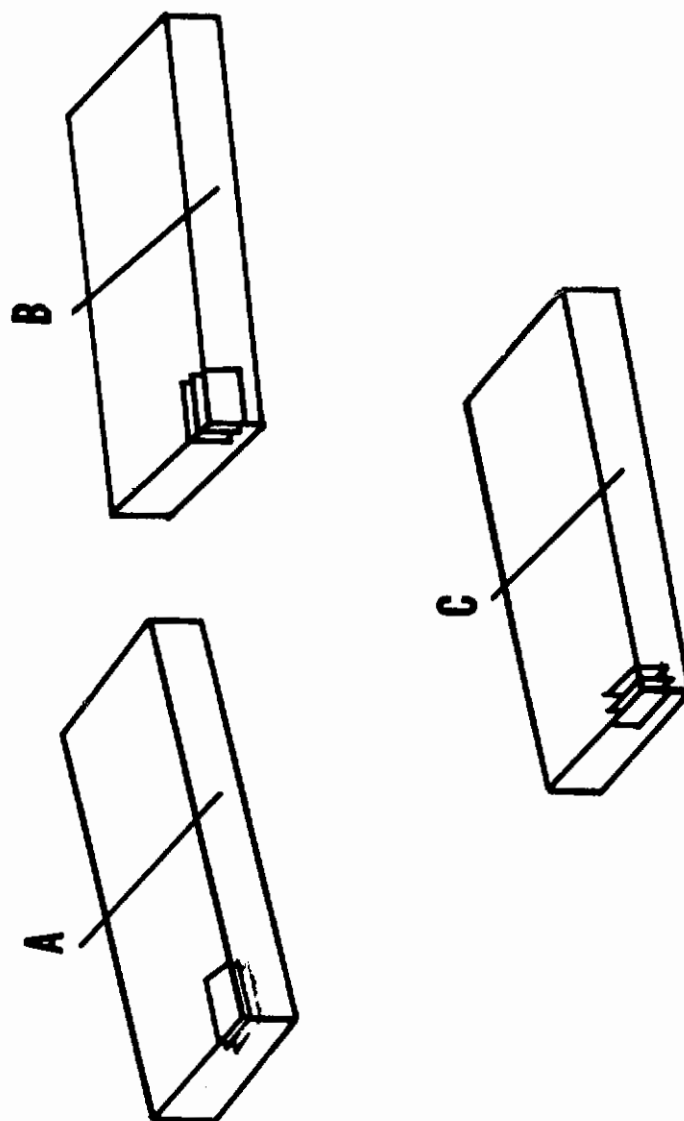


Figure 8. Grain Orientation of Creep Specimens

Table 1

THERMAL CONDUCTIVITY OF GRAPHITES

Room Temperature Conductivity
(BTU/ft. hr. °F)

	WITH GRAIN	ACROSS GRAIN
Graphite Crystal	800	
Pyrolytic Graphite	200	0.8
ZT Graphite	150	40
ATJ Graphite *	44	36
Graphite Cloth Laminare	1.2	.9
Graphite Foam	0.5	

* ATJ Graphite Is A Commercially Available High Quality Product Of The National Carbon Company

Which Has Become Widely Recognized As A Point Of Reference When Comparing Graphites.

For This Reason Extensive Use Of ATJ Characteristics Has Been Made

For The Convenience Of The Reader.

Table 2

PROPERTIES OF A NUMBER OF GRAPHITES

GRAPHITES	THERMAL PROPERTIES		MECHANICAL PROPERTIES	
	CONDUCTIVITY W ³ A ⁴	CTE W ³ A ⁴	TENSILE STR. W ³ A ⁴	MODULUS ⁶ W ³ A ⁴
Foam	0.5			
Yarn				
Felt	0.2			
Cloth Laminate	1.2			
ATJ	65	3.6	1700	1.40
ZTA	85	0.8	5000	2.4
Pyrolytic	200	-1.0		9.0
Single Crystal Whiskers	800		300,000,000	100

● BTU/Ft. Hr. °F/Ft.

● Coefficient Of Thermal Expansion x 10⁻⁶ /°C. (0 To 1000°C)

● With Grain

● Across Grain

● Tensile Strength psi (Room Temperature)

● Elastic Modulus x 10⁶psi