STRUCTURAL APPLICATIONS

FOR ADVANCED COMPOSITE MATERIALS

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Structural requirements for space vehicles place emphasis on the use of light-weight, high-strength materials. The combination of two or more different materials into composites has produced superior characteristics over single phase arrangements. The greatest advantage will result from the provision of a method for predicting the properties of composites based on the properties of their constituents. When this is accomplished, composites can be developed to render optimum performance for their specific applications. A nine-step program is envisioned to meet the goal of prediction and optimization. It would involve both analytical and experimental development. Several steps must be taken simultaneously in order to provide feedback and demonstrate potential for various forms and types of materials.

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Introduction

The structural requirements for spacecraft place great emphasis on the proper selection and use of materials. While strength and stiffness are prime factors in structural design, there are environmental factors which operate simultaneously and must not be neglected. These environmental factors result from the total mission requirement for structural performance, and missions for manned and unmanned vehicles are analyzed to yield the requirements for structural and materials performance. The final selection of structural geometry and type of material involves a number of trade-offs usually with material density or structural weight as the basis for comparison.

It has been convenient and practical to develop materials that are broadly applicable rather than specific. The primary reason for this approach is the large cost and complex development associated with the attainment of a basically new material. It is a tribute to both the chemical and metal industries that large numbers of materials are available as standard alloys, compounds, polymers, ceramics, etc.

Plastics alone have been utilized many times in space applications for solutions to structural problems, and promise to continue to be. However, for many specific structural design and fabrication needs, it has been found that combinations of essentially different classes of materials in various forms and proportions can produce characteristics which are not available from single phase systems, and which are often more suited to the specific application. Such combinations are classed as composite materials. For example, the composite concept combines the light weight and flexible characteristics of plastics with the higher strength but inflexible characteristics of metals or ceramics. Composites are not solely materials since they can be formed directly as structures, such as in a filament-wound rocket case, where glass and resin are combined as the case is formed. Thus the material is intimately identified with its use, and the applications define specific material characteristics. It is in the area of composites then, that the majority of applications can be envisioned for plastics in space.

However, a number of fundamental problems exist in the development and application of composites. A general approach to their solution is possible. Such approach will be discussed in its relationship to the solution steps involved.

The Nature of Composites

Historically, it has been shown that composites have been utilized by man almost as long as single phase materials (Reference 1) and, of course, nature has utilized them infinitely longer. In the case of man-made composites, the uses and forms have been largely the result of an intuitive approach. This approach has lacked the equivalent of the solid-state physics, basic metallurgical, or the organic chemistry science. In fact, true fundamental research stands out as the great void in an otherwise commendable network of progress in this field.

The nature of composites has been partly responsible for this situation. Since composites can be structures as well as materials, a knowledge of both materials science and structural engineering is required for the accomplishment of significant research. The materials specialist disciplined in metallurgy, or polymer chemistry, or ceramics alone cannot cope with the entire problem, nor can the structural specialist adequately handle the materials aspect. Another, not insignificant, aspect is that the almost immediate rewards of developing new composites for particular applications are so promising that the effort towards the fundamental research is diluted.

Reference 2 lists five major classes of composites as follows:

Laminar - Example: inflated satellite skin
Particulate - Example: rocket nozzle
Fiber - Example: filament-wound shells
Flake - Example: leak-proof plastic shells
Filled - Example: honeycomb heat shield

Figures 1 through 5 show examples of the use of these classes of composites in space vehicles. Figure 1 shows the Echo II passive communications satellite during a static inflation test. This spacecraft is constructed with a three-ply laminate skin of aluminum foil and Mylar. Figure 2 illustrates a particulate composite employed in a rocket nozzle. This is a composite of 30 per cent graphite particles in silicon-carbide.

Figure 3 is an example of a filamentary composite applied to an experimental cryogenic fuel tank. This structure utilized an E glass filament with an epoxy-resin matrix.

Figure 4 represents an approach to solving the problem of containing a cryogenic liquid in a composite shell by application of glass flakes in a resin matrix.

Figure 5 illustrates a filled composite. This is a section of the heat shield structure for the Gemini space vehicle. It is composed of a phenolic-fibreglass honeycomb filled with a silicone-elastomer charring ablative.

From a research viewpoint, it is essential that emphasis should be placed on the fundamentals of composites. Such emphasis will provide a more substantial basis for the applied programs of the future and should result in materials which possess properties optimized by design for particular future vehicle structures.

The need for such research has been recognized by the military and space agencies in the Government and some of the primary problems are now under study by Government laboratories and through contracts with industry and universities. Where applicable, some of the NASA investigations will be mentioned in relationship to the discussion of particular problem areas.

The Research Objective

The broad research objective is to derive the maximum performance from a structure in terms of its weight by means of the optimum selection of materials used in composite form. More specific objectives are to comprehend the basic nature of composites sufficiently, and to specifically design materials with predicted and optimized properties.

It is obvious that the prediction and optimization of composite material properties is a complex problem and one which may never be solved completely. However, there are elements of the problem which are favorable. One is that the development of new materials is not necessarily required. Another is that simple composites may be studied with discrete experimental verification of analysis, prior to studies of more complex systems. A third favorable element is that many techniques in structural mechanics are available as solution tools. These, coupled with an approach from the materials science viewpoint, permit an interdisciplinary attack to be made.

The problem area then may be approached from several directions. However, these must be related and guided by an over-all plan involving the following essential steps:

1. Predict composite properties based on the characteristics of component materials.

2. Define guidelines for development of improved composites.

3. Develop required material forms.

4. Demonstrate (by experiment) the improvement.

5. Examine system applications to determine advantages.

6. Define guidelines for development of improved materials for specific application.

7. Develop design concepts.

8. Demonstrate (by experiment) the improvement.

9. Evaluate needs (assessment of desirability for improvement).

Because the above program is of large magnitude in terms of time, several steps would be initiated simultaneously. In the initial phases each step would include general considerations which apply to the development of methods and are later specifically related to the over-all process.

The Problem of Prediction

There are two general approaches to the prediction of composite properties. One is the materials science approach involving related studies of chemistry, metallurgy, and the fundamental nature of materials, and the other is the mechanical or engineering approach. Both are important and indications are that neither will be sufficient alone as a basis for prediction.

Prediction requires first the development of methods of analysis which produce solutions which match experimental results. But more than this should be expected, namely the definition of important factors which affect structural properties. In view of the abundance of composites available or attainable, separate analytical methods may be needed for each general type.

The materials in each class of composite are in various sizes, shapes, and quantities. Although sizes may vary from macroscopic to microscopic, it is probable that analytical procedures common to both sizes may be applied.

Several noteworthy comparisons of material properties of interest to the structures specialist have been made. One example is shown in Figure 6 (Reference 3) which compares various elements and compounds on the basis of specific stiffness (E/ρ), where E is Young's modulus and ρ is the material density. It was from such comparisons that research was initiated on less commonly used materials such as boron and boron compounds in composites.

Physical characteristics of each component material of importance in structures are:

Strength
Stiffness (elasticity)
Density
Ductility
Thermal Characteristics
Oxidation Characteristics
Abrasion Characteristics and Hardness

The first two items enter directly into analytical treatment of material behavior in structures, whereas the others are those which must be controlled or selected. It is possible, therefore, to concentrate on methods of prediction which regard the behavior of the composite from the mechanical standpoint. Problems of phase material compatibility and other chemical-metallurgical aspects of the composite can be studied separately, and later related to the mechanical investigations.

Studies (Reference 4) have shown that analytical methods which utilize a continuum mechanics approach have been fruitful in allowing reasonable predictions to be made for the elastic characteristics of the composite. Expressions are derived which represent the contribution of each material to the material coefficients of a composite in terms of geometry and elastic characteristics. Figure 7 is an illustration of the method showing the effect of Young's modulus of the reinforcing filament on the composite modulus for various proportions of matrix resin. It can be seen that the contribution is significant in the filament axial direction, but less important for the transverse direction, and considerably less for shear. Similar analysis was applied to predicting the effects of matrix stiffness, and of Poisson's ratio of matrix and filament to the composite characteristics. These predictions were later verified by cylindrical pressure vessel tests as shown in Figure 8. In this example, hoop strain and longitudinal strain are plotted for various values of cross ply ratios. It will be noted that the commonly accepted netting analysis is not acceptable for predicting strain.

Similar improved techniques can be applied to the prediction of strength. However, not all composites consist of continuous filaments or continuous matrix. Nor are reinforcing materials necessarily circular in cross section. It is expected that the factors of particle or filament geometry which include size and shape may strongly influence some of the properties of composites (although not necessarily all). Possible forms include:

1. Crystals (whiskers)
2. Grains
3. Spheres (hollow or solid)
4. Flakes
5. Fibers
6. Filaments (hollow or solid)
7. Films and Foils
8. Sheets
9. Bars
10. Foams

Figure 9 is a comparison of size for some common or promising reinforcing filamentary materials. It can be noted that the one mil (25 micron) fine wire is large in comparison to materials now being used or considered. It can also be noted that these materials cover a wide range within themselves such as wire ranging from 4 to 30 microns (Reference 5). The picture shows the ranges of greatest interest for composites. As a contrast to some of these recent fine filament developments, it is of interest to note that nature has produced its own version of small-dimensioned, high-strength filaments in the form of asbestos fibrils. As shown in Figure 10, these range from 200 to 400 Angstroms in diameter (Reference 6).

Shape factors for filaments and particles and their influence on composite properties are under investigation (Reference 7). Figure 11 shows experimental data on the effect of various volumes of glass particles (shape unknown) on Young's modulus, tensile strength, and total strain at failure. As yet there is no analytical basis for predicting these results and it can be noted that the results shown in Figure 11 are somewhat contrary to expectations.

An advantage of the analytical approach in predicting characteristics is that it provides for the determination of optimum characteristics as well as those resulting from given constituents. Thus one may determine the bounds of performance for various proportions of constituent materials and also establish a measure of efficiency for the composite. One expected indication will be the need for improvement of the interface between reinforcement and matrix to achieve increased efficiency. It may be necessary to attack this problem from the chemical-metallurgical level rather than the mechanical aspect. An example of interfacial effect is shown in Figure 12 which is a plot of strength of tungsten filaments in a matrix of various alloys of copper (Reference 8). The decrease in strength caused by an alloying effect between the copper alloy matrix and the tungsten is evident. It can be noted that the curve for pure copper matrix follows the results predicted by the law of mixtures. It is expected, therefore, that a sound program will include an equitable share of effort in chemical-metallurgical theoretical and experimental research.

<u>Guidelines for and Development of Required Materials and Forms</u>

Once the important factors which control the major characteristics of composites are determined theoretically, specific requirements for further research in kinds and forms of materials can be delineated. Only those materials in the forms of offering the greatest hypothetical improvement need be investigated.

As previously noted, it is expected that there will be two groups of requirements. A mechanical group will establish requirements for geometry of cross section, strength and sizes of constituents and elastic characteristics. A chemical group will require certain surface chemistry, bonding or alloying characteristics, etc. There could also be requirements for new materials developments, although at this point such requirements could be premature and not inclusive enough to warrant research cost and effort.

In anticipation of guidelines specifying particular forms of materials, it is necessary to provide the technology which allows such forms to be produced. The various configurations previously listed are not necessarily available in all materials or in the cross sectional geometry needed.

Initial efforts (Reference 9) have shown, for example, that it is possible to produce glass in a variety of filaments of various cross sections. It is anticipated that these techniques can be applied to other filament materials as well, including plastics. Figure 13 shows examples of glass filaments which were attenuated using a technique described in Reference 9.

Until recently, materials such as boron were difficult to utilize in structures despite their high potential specific strength and modulus. It has been found (Reference 10) that a technique of vapor deposition on a suitable substrate may be used to form boron compounds and elemental boron in continuous filaments. Initial tests of boron-epoxy composites in the form of filament-wound rings and as boron-aluminum in rod form indicate that substantial strength-weight ratios are probable (Reference 11). Figure 14 lists recently obtained values for properties of boron-magnesium composites. The most significant aspect of this research is the indication that acceptable forms of materials which possess desired structural properties may be developed. In other words, composites will not necessarily be limited to a relatively few elements now utilized extensively for structures but will be able to be formed in their optimum combinations for particular applications.

Demonstration of Improvement

Certain carefully controlled experiments must be devised to demonstrate the validity of prediction analysis and the trend toward improvement. In some cases, unique fabrication methods may be required. This is true, for example, in dealing with angstrom-dimensioned particles or fibres. It is also true that scaled-up experiments may be needed which require material forms larger than those readily available. For example, in one set of experiments, it was found convenient and reliable to make composites using epoxy resins and large diameter (3 mil) E glass fibers, rather than the usual 0.3 mil filaments. Some anticipatory effort to develop fabrication techniques is considered essential. Concurrent with the development of complex geometry glass filaments was a development of improved winding techniques which allowed precise placement of filaments on a mandrel form. Figure 15 is a micro-photo of a section through a glass-resin composite. Note that the filament form is rectangular.

Steps 1 through 4 would constitute a first phase section of an optimum composite development program. Step 4 provides information which realigns and guides the rest of the phase. With such information, a re-cycling can be performed with modified orientation. It is anticipated that empirical and semi-empirical methods may predominate the first attempts at completing the first phase, but each cycle would provide a shift towards more exact methods.

Examination of System Applications and Definition of Guidelines

Through step 4 in the program, the methods used can be generally applied to most composites (of a particular major type). Beyond this, however, the peculiar requirements of mission application must be considered in order to provide the next step in optimization. This can be viewed as the second phase in the program.

The functional requirements for a structure encompass the following factors:

Load	Meteoroids
Temperature	Radiation
Gravity	Bio-medical
Vacuum	Duration

Each factor may contain a number of associated factors. For example, bio-medical requirements for structures include:

Temperature	Psychological
Vibration	Gravity
Radiation	Color
Atmospheric	Odor
Acceleration	Chemical
Noise	

The functional factors related to future missions can be analyzed to define the prime parameters and ranges of values, functional and environmental factors. It is necessary to recognize that a feedback can occur here which provides requirements and guidance for the structural material investigations of the first phase (steps 2 and 3). These functional environmental factors begin to define the regimes in which strength and elasticity must be provided at particular levels. Thus as the program progresses, the steps in the first phase will be related more closely with particular application requirements. Initially, the effects of each factor can be considered by analysis of representative classes of structures. As studies progress, the cumulative or simultaneous effects of other factors would be considered. As an example, analyses were made concerning the requirement of a structure to carry load (Reference 12). The use of filament reinforced composites for compression load-carrying shells representing launch vehicle primary structure was compared to metal sandwich systems for present and planned launch vehicles. Filament-wound glass-resin structures were heavier than isotropic faced metal sandwich structures. The utilization of high modulus glass with denser winding showed some improvement at higher unit stresses. However, boron-filament epoxy systems indicate an advantage over either glass or metal systems (Figure 16).

Development of Design Concepts and Demonstration

None of the preceding developmental steps for composites would continue to be significant without the development of design concepts, followed by experimental demonstration. It is only by studying hypothetical mission requirements involving vehicle performance and environmental factors that both new structural geometry and new material requirements can be produced. These studies are related to those described in steps 5 and 6 (examination of system applications) except that the approach is from the opposite direction, namely, starting with the mission, evolving a concept, and lastly defining both geometry and material requirements. The development of concepts is probably the most severe requirement in the process because it makes demands on the talents of individuals of limited numbers and availability. Indeed, it produces a severe requirement on the program managers to seek out these unusual people who by nature and background can relate the mission to an advanced concept, and who can see possibilities for applications from new material and structural developments. An example of such studies is shown in Figure 17, which illustrates a study made for an advanced 150 KW space power system which would be deployed and stabilized by rotation. It would be used as part of a large spacecraft power supply system for long space missions. It represents a unique use for flexible high temperature materials such as some of the new polybenzimidizols and polyimides, in composites with other materials.

Studies like these must be able to express structural and material performance requirements in parametric terms of significance to the specialists in these disciplinary fields. Such parametric requirements restrict the talent search even further.

Following analytical and conceptual development is the necessary experimental evidence that feasibility is at least achievable. Since fabricated specimens are required, special fabrication techniques may need to be developed. Accordingly, a developmental program could be required if none exists. Such experimentation produces feedback to steps 5 and 6 where a reexamination of system applications and a redefinition of guidelines is in order.

Evaluation of Needs

The remaining step, evaluation of needs, relates the factors of cost, availability, personnel factors, etc., to the merits of the optimized composites and the structural concepts. Two alternatives will result. Desirable areas of improvement will become evident, or perhaps existing methods will be shown in their true perspective with little need for improvement indicated. The former result will produce a re-cycling of the system to provide the needed improvement.

Conclusions

A composite materials program for optimizing applications to structures is of complex nature and expected to be of lengthy duration. The greatest obstacle to progress in such a program is the tendency to diversion and specialization. One approach which has indicated promise is that of the "team" concept. This concept involves the free flow of information among the various investigators in the separate organizations and research centers. On approximately a semi-annual basis, meetings can be held where the printed reporting is supplemented by an oral review of work accomplished and planned. Included also is a statement of problem areas remaining for which solutions are needed but not necessarily indicated. Such reports are followed by liberal discussions of the solution approaches and the problems in relationship to the broad objectives. This method provides for a periodic reorienting of the program and for direct application of the research talent to guidance. The role of the technical administrator is broadened by the diverse talent available without the usual recourse to all data and its significance being judged solely by one man or office.

Summary

Structural requirements for space vehicles place great emphasis on light-weight, high-strength, high-stiffness materials. Although many single materials in metals, plastics, and ceramics have been utilized in vehicle design, composites of these materials offer greater promise in achieving higher efficiencies by means of optimum design. However, fundamental research in composite design is necessary to understand the basic nature of these materials and optimize them for future applications.

A program has been outlined which describes the essential steps in improving the application of composites to space vehicle structures. The primary problem of predicting composite properties based on the characteristics of component materials requires both a mechanical approach and a chemical approach. The various major classes of composites are laminar, particulate, fiber, flake, and filled. A different predictive analysis may be required for each type. There are many characteristics materials possess which are of interest to the structural designer, but the primary ones are strength and stiffness, provided the others can be controlled or selected.

Research in filament or particle materials of various sizes and shapes should be performed in anticipation of actual needs in order to develop necessary technology. Examples of this include glass filaments of various cross sectional geometries.

After the basic relationships for composites are established, the fundamental requirements for a structure must be considered. An example of a study of load intensity versus material selection shows that glass filament-wound structures are not competitive for compresssively loaded shells unless improvements are made.

A team approach is required to achieve the basic objectives in optimized composite materials programs.

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ECHO A-12 STATIC INFLATION TEST

NASA RV63 - 1727

ROCKET NOZZLE

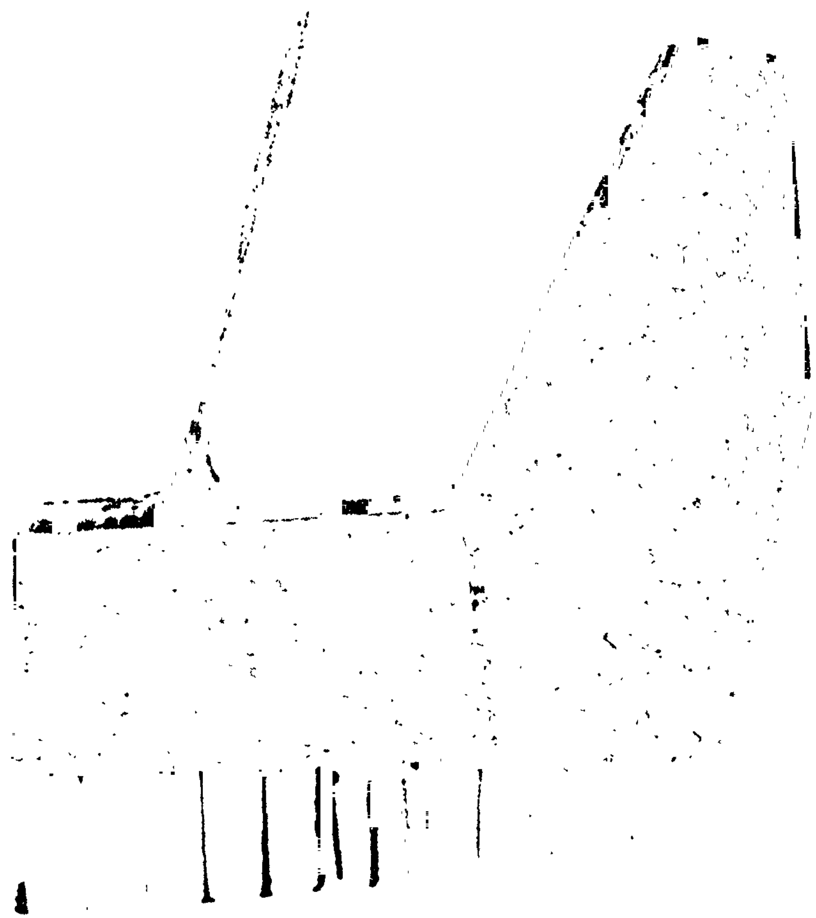
NASA RV64-1833

EXPERIMENTAL LIQUID PROPELLANT TANK

NASA RV64-1834

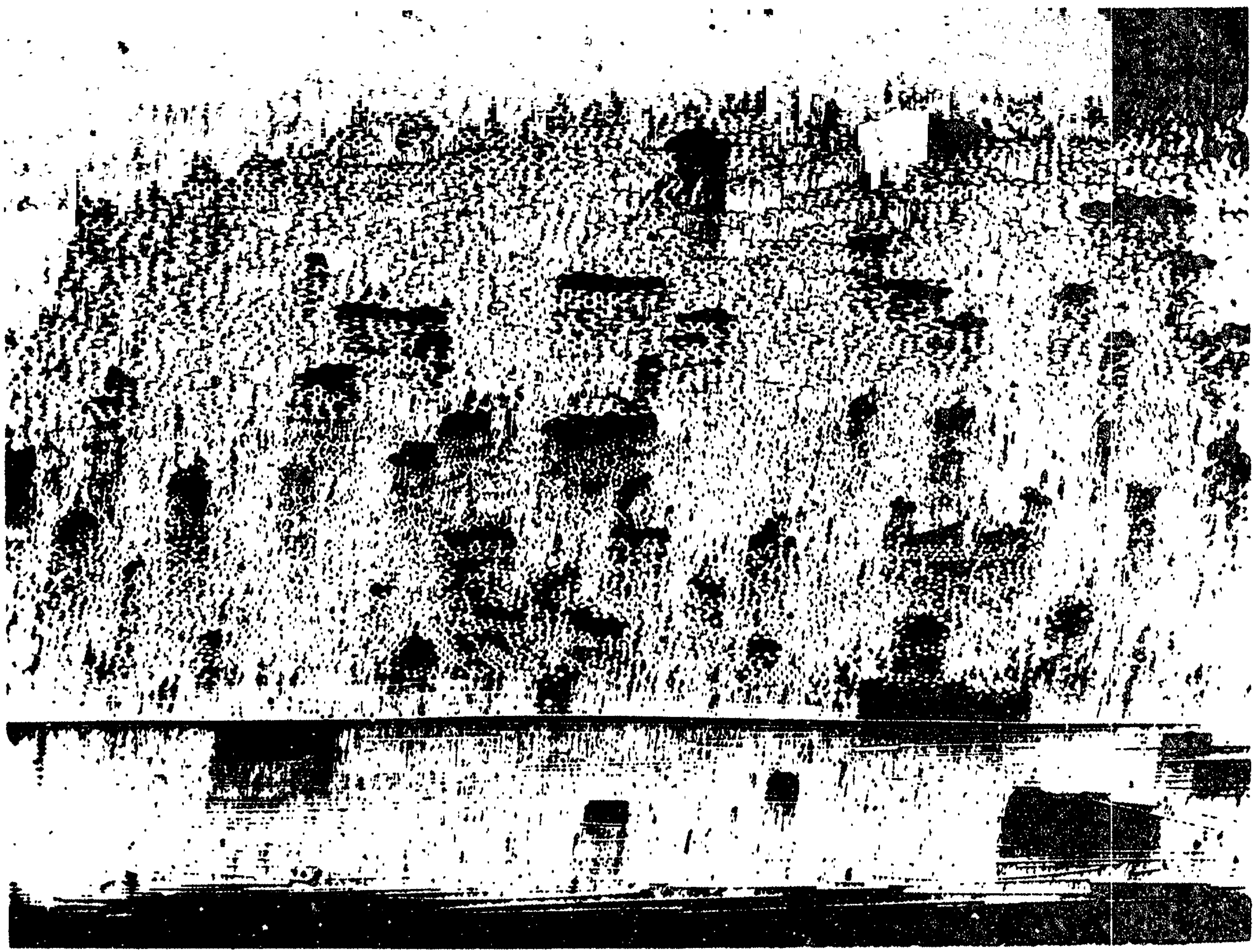
Figure 3

GEMINI HEAT SHIELD STRUCTURE



NASA RV64-1839

FILAMENT FLAKE COMPOSITE



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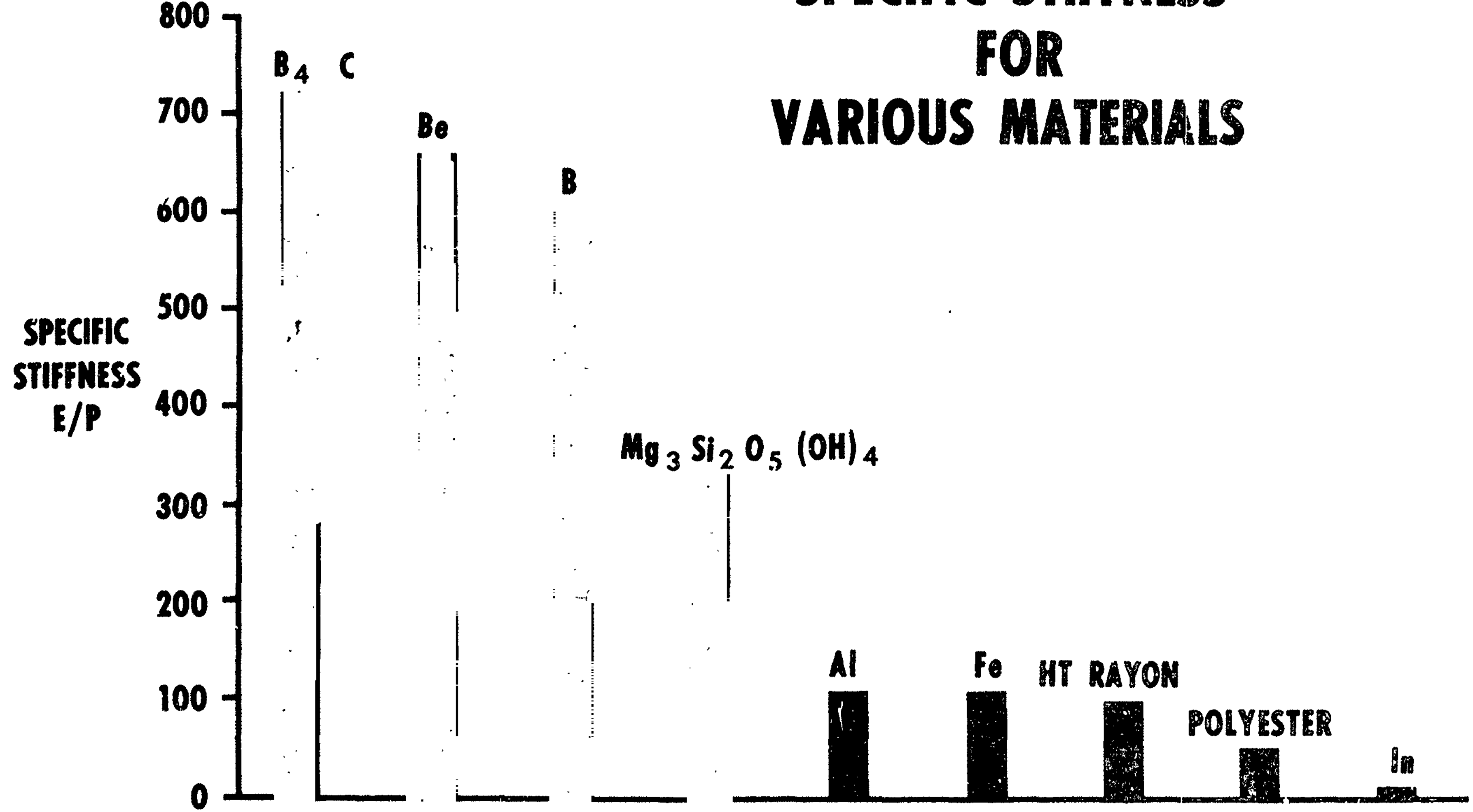
COMPARISONS OF SPECIFIC STIFFNESS FOR VARIOUS MATERIALS



NASA RV64-1838

CONTRIBUTION OF E_f to E_{11}, E_{22} and G

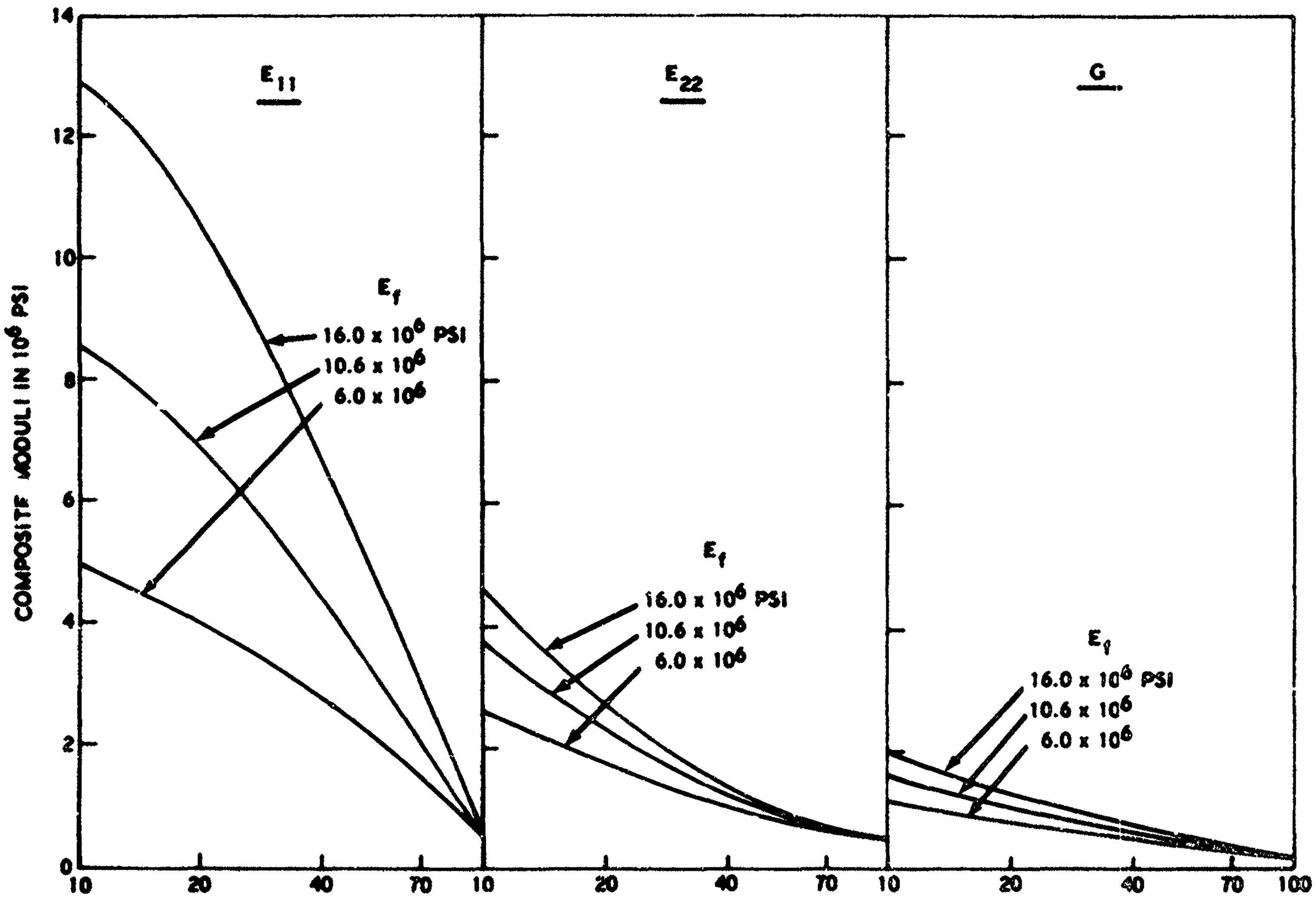


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Figure 7

CROSS-PLY CYLINDER

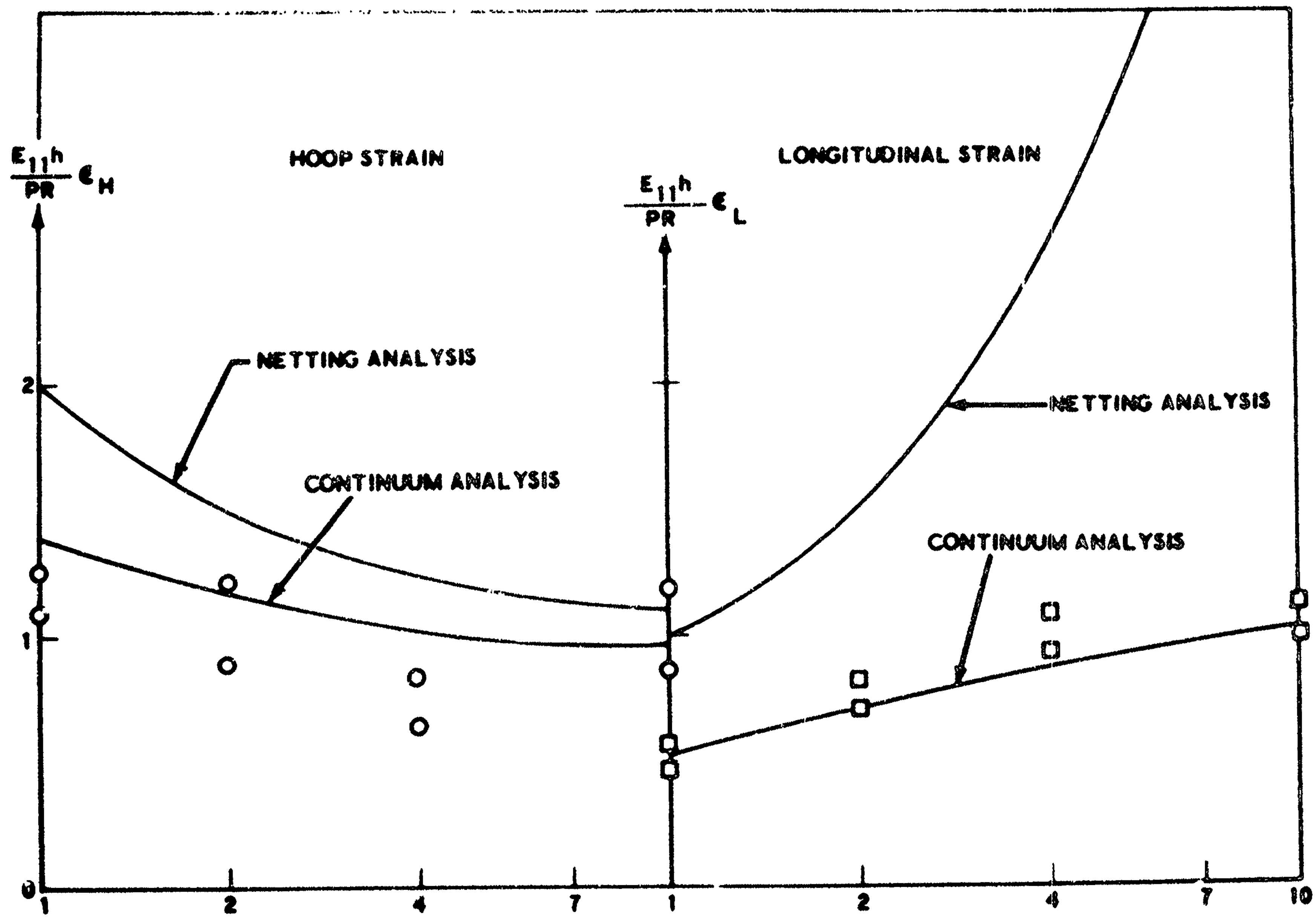

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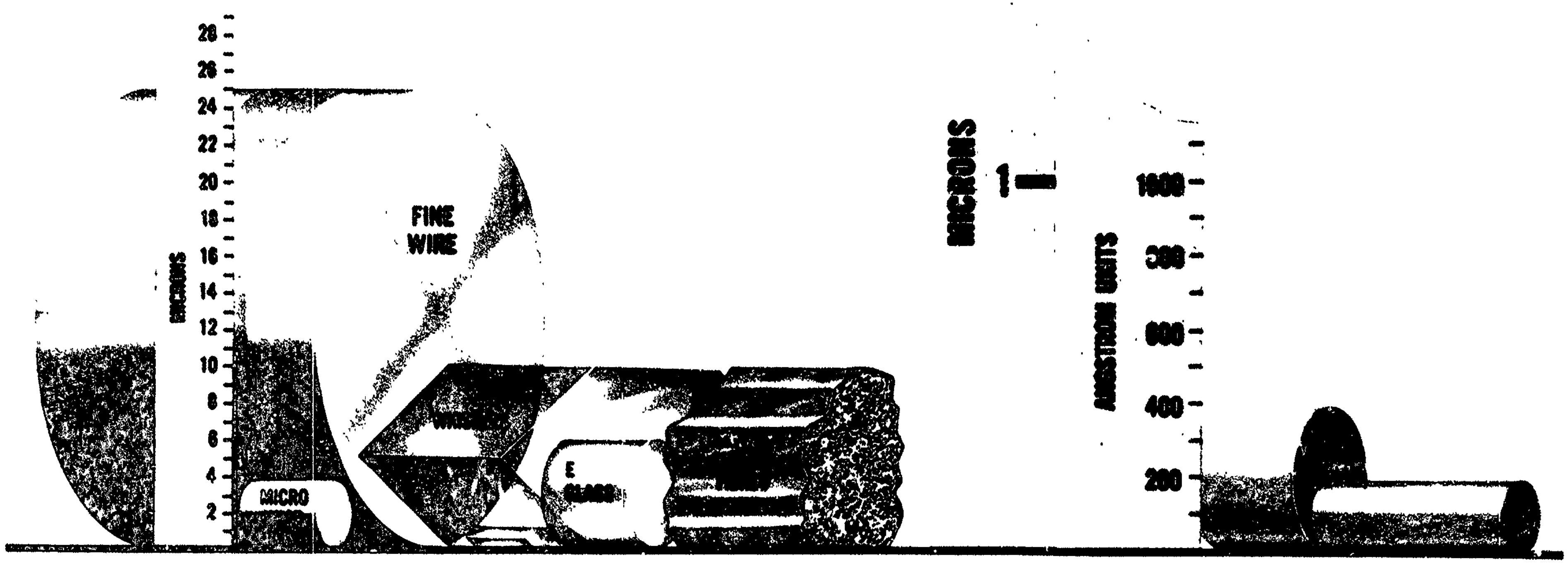
Figure 8

SIZES OF FILAMENTS

SIZES OF ASBESTOS FIBRILS



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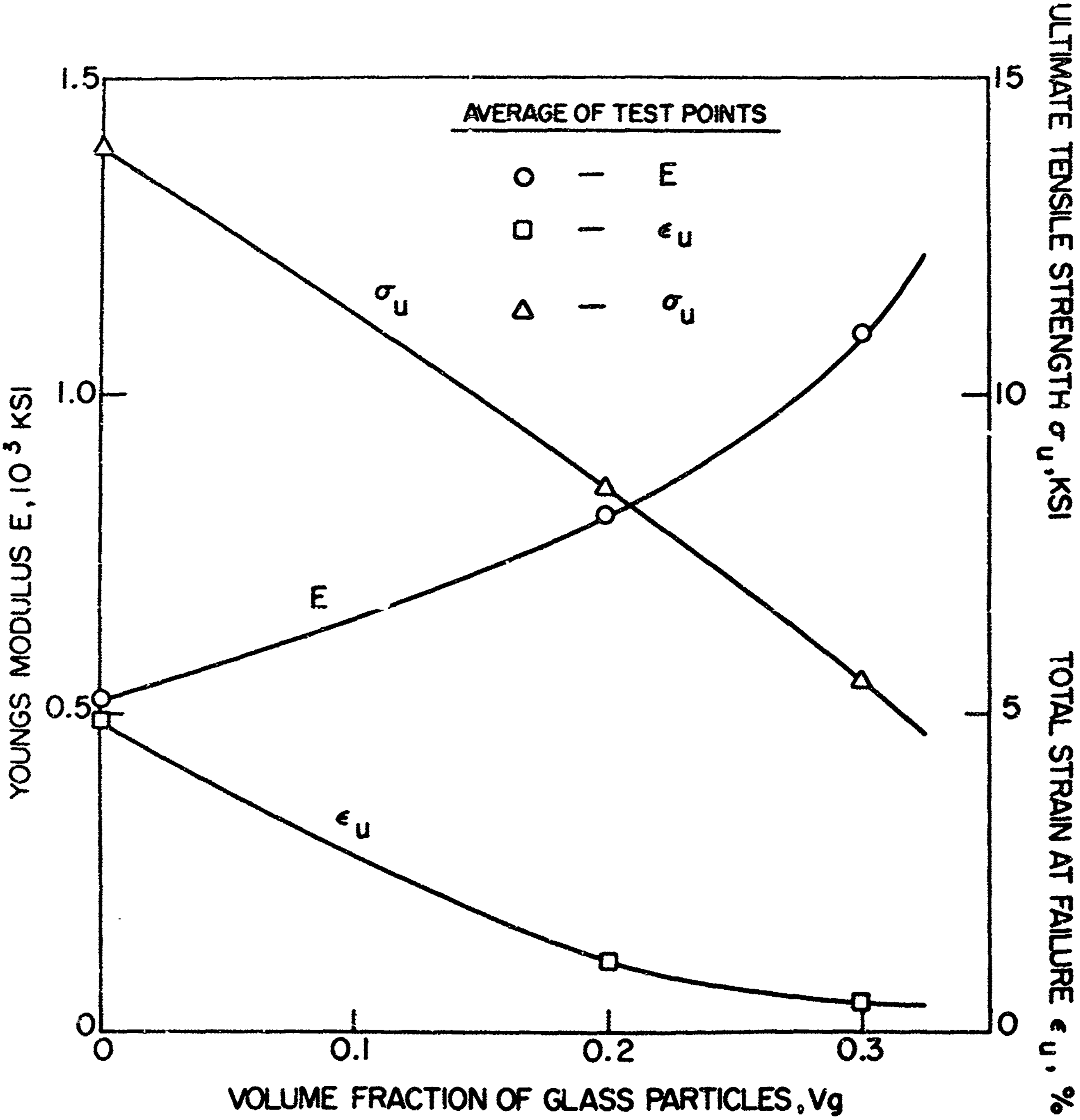
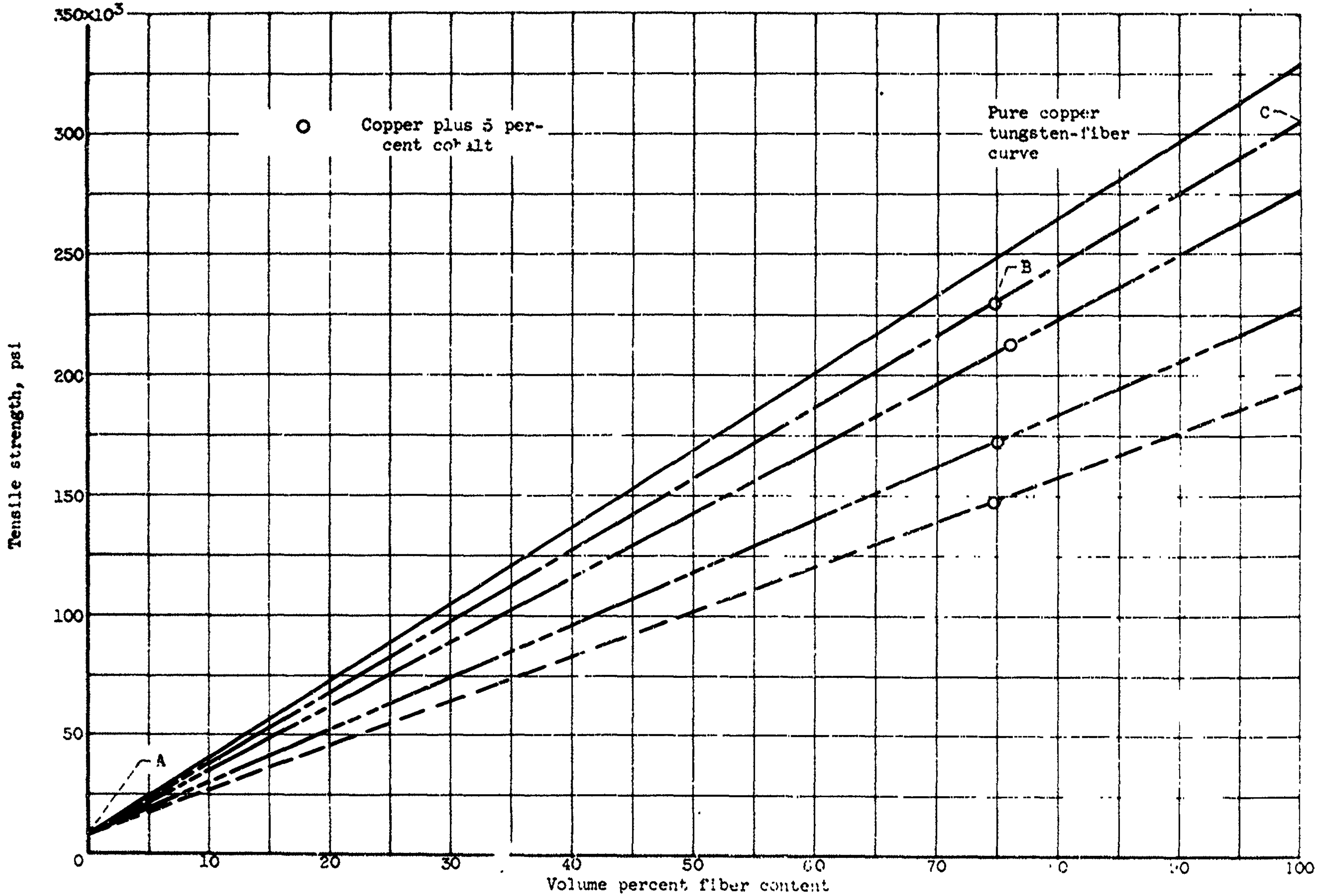
TENSILE PROPERTIES OF GLASS PARTICLE REINFORCED PLASTIC COMPOSITES



NASA RV64-1832

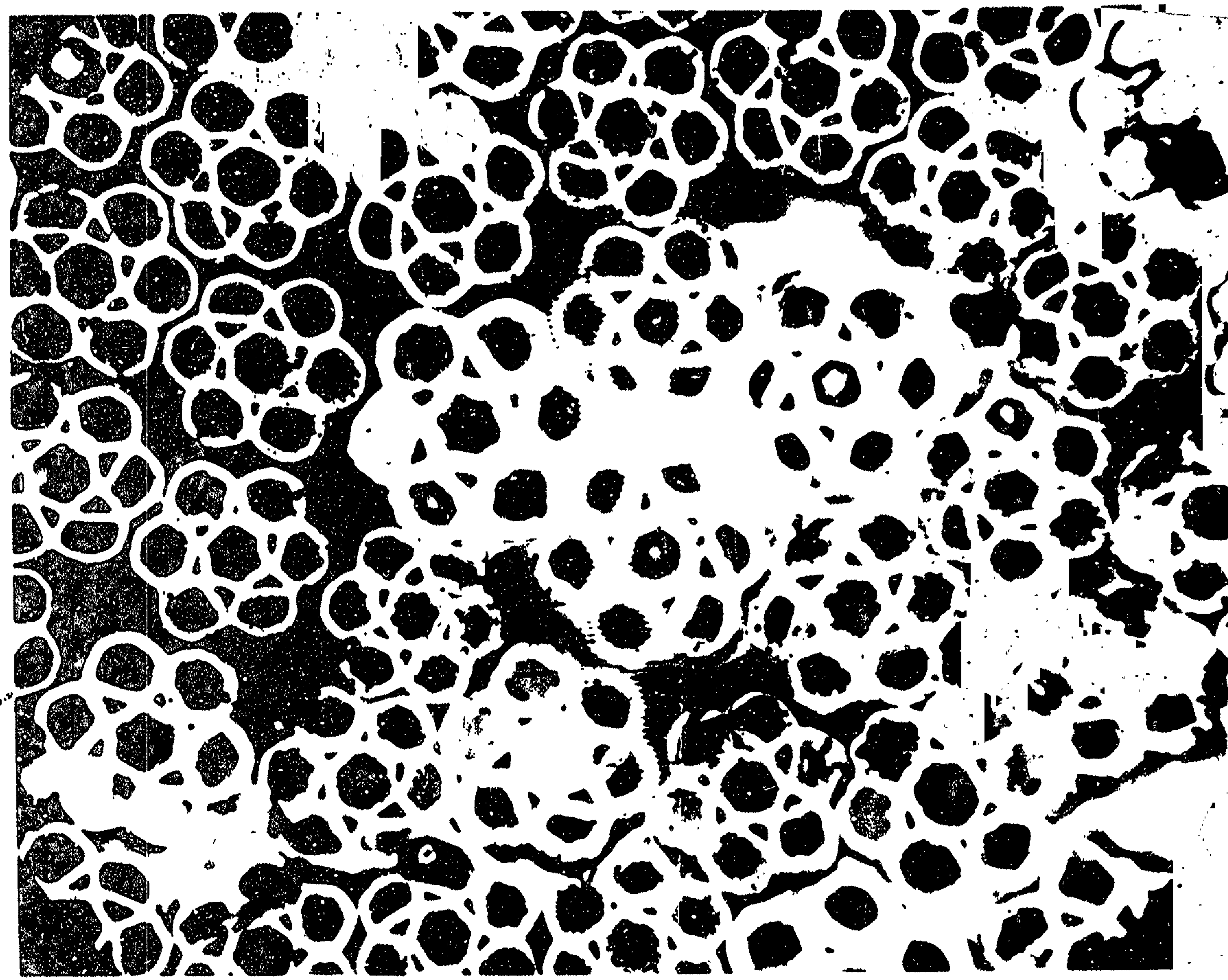
STRENGTH-COMPOSITION CURVE FOR TUNGSTEN-FIBER-REINFORCED COPPER PLUS 5 PERCENT COBALT COMPOSITES



NASA RV64-1829

HONEYCOMB 7 HEX TUBES

SCALE = .010"



NASA RV64- 1841

BORON FIBER COMPOSITE PRELIMINARY TEST DATA

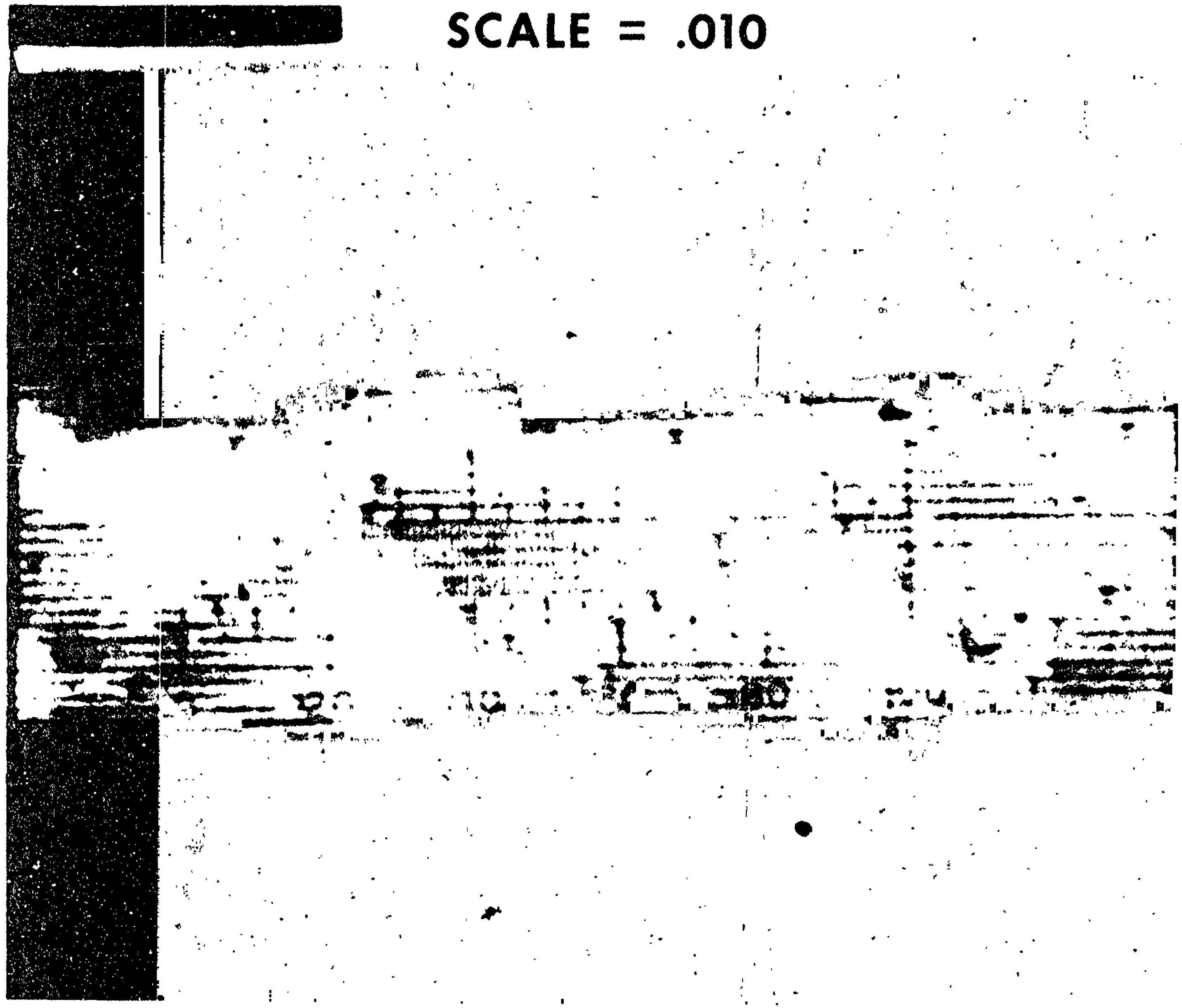
MATRIX	TEST	FIBER DENSITY	ULTIMATE STRESS, PSI	
			COMPOSITE	FIBER
MAGNESIUM	BENDING	52%	199,000	382,000
	COMPRESSION	52%	188,000	362,000
	COMPRESSION	71%	349,000	495,000
COPPER	BENDING	49%	31,800*	65,000 *
	COMPRESSION	49%	199,000	406,000

* PREMATURE FAILURE

NASA RV64-1842

WELL PLACED MICROTAPE

SCALE = .010



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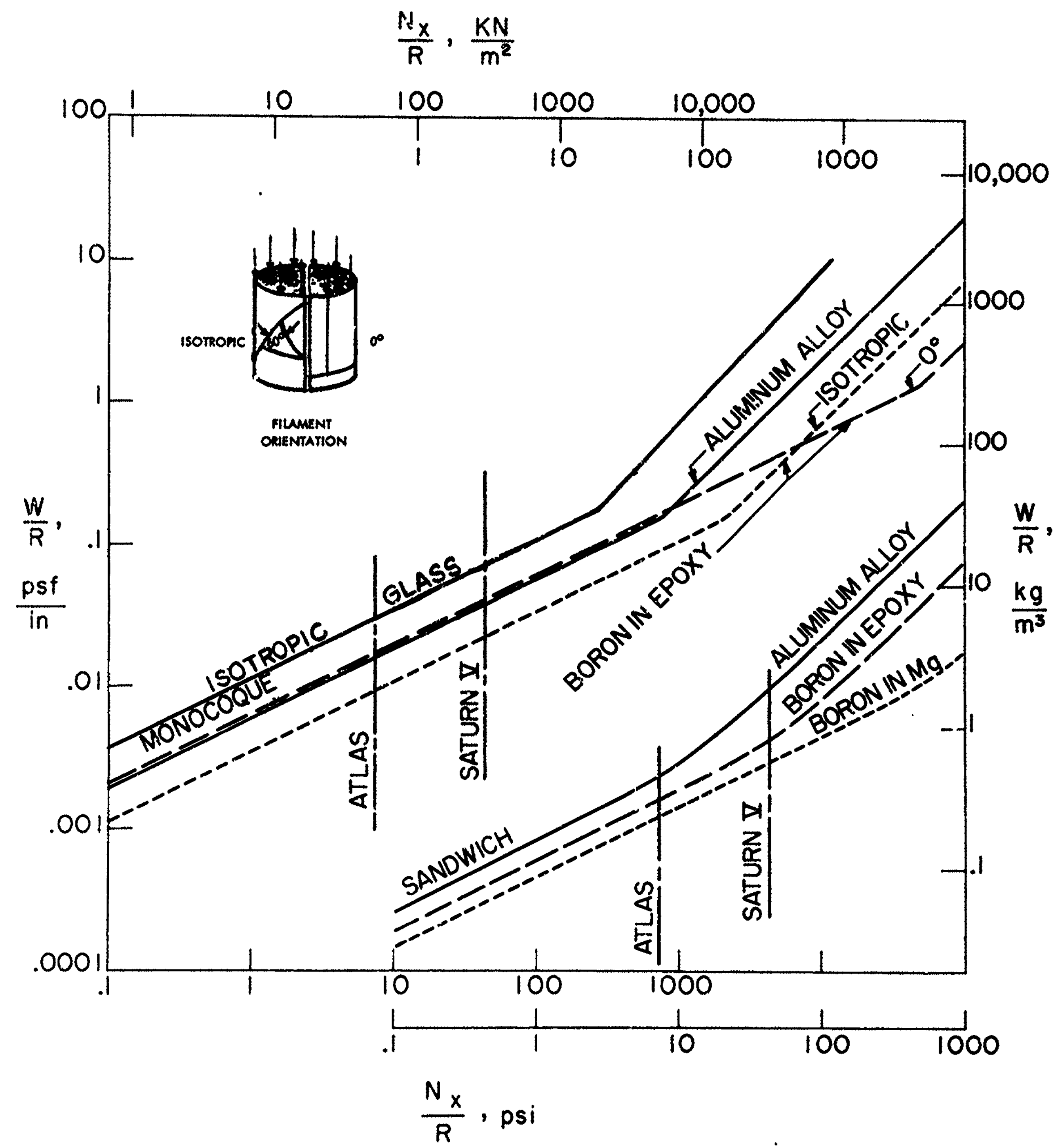

Nx/R, KN/m²
100
10
1000
10,000
1
10
100
1000
10,000
W/R, psf/in
.1
.01
.001
.0001
W/R, kg/m³
ISOTROPIC
0°
FILAMENT ORIENTATION
ALUMINUM ALLOY
ISOTROPIC
BORON IN EPOXY
GLASS
MONOCOQUE
ATLAS
SATURN V
SANDWICH
BORON IN Mg
Nx/R, psi