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[redacted]

FROM: S. Kiersarsky
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The attached Vu-graphs and associated text covering the development status of advanced composite materials and their structural applications to advanced manned space vehicles, particularly the space shuttle, were prepared by A. S. Kiersarsky and C. C. Ong and presented by J. A. Schelke to a group of OMSF and OART personnel at NASA Headquarters on April 23, 1970. Contents of the presentation are summarized as follows.

Advanced composites are attractive materials for primary structures of aerospace vehicles because of their properties of high specific tensile strength, high specific modulus and excellent fatigue strength which in turn can lead to potential weight savings and cost effectiveness. Among all the advanced composites developed, boron/epoxy, graphite/epoxy, and boron/aluminum are generally considered to be candidates for near term applications.

Boron/epoxy is the earliest and most widely used advanced composite. Its material properties are well-characterized and a significant amount of engineering experience has been accumulated. The main concern with this material is the large diameter and the extreme hardness of boron filaments which make boron composites difficult to fabricate. Graphite/epoxy is a newer material which has become increasingly important in aerospace applications. A family of graphite filaments and composites have been developed. Both Great Britain and the United States are actively engaging in the development, manufacture and structural application of these materials. Graphite composites are easy to fabricate and have potential for further improvement of their mechanical properties. Of present concern is primarily their relatively poor compressive and shear strengths. Boron/aluminum is behind the epoxy matrix composites in terms of application experience, design data and fabrication techniques.

Air Force and NASA R & D programs for application of advanced composites to primary structures of aerospace vehicle were reviewed. While Air Force efforts have been largely centered on all-composite structures, NASA's current emphasis is placed on composite reinforced metal structures.

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Experience and progress made to date indicates that advanced composites can be applied to the space shuttle. There are, however, several basic technologies in which improvements would enhance the confidence level and, therefore facilitate early application of advanced composites to operational vehicles. These include standardization of test methods, development of mass production fabrication technique, and techniques for quality assurance.

It is concluded that (1) boron/epoxy is technologically ready for selective application; (2) graphite/resin-matrix composites are potentially superior to boron composites in almost all the major considerations, including material properties, fabrications and cost; (3) all-composite structures present several design and fabrication problems such as low strength at joints and around cutouts, lack of established fabrication and production technology, and high material cost. (These difficulties, however, may be avoided or alleviated by applying the composite reinforced structure concept.); and (4) based on a selective application of advanced composites to 40% of the space shuttle structure, it is estimated that a 4% saving on the inert weight of the vehicle is possible which results in a major payload increase.

In view of the potential weight saving capability and the rapid progress being made on advanced composites, it is recommended that (1) these materials be seriously considered in the Phase B study of the space shuttle; (2) NASA R & D programs on application of advanced composites to primary aerospace vehicle structures be expanded with emphasis placed on the selective reinforcement concept; and (3) to fully capitalize on the experience gained by the Air Force and to avoid duplication of future effort, close coordination and cooperation be maintained between NASA and Air Force personnel at all levels.

A. S. Kiersarsky

1013-ASK/CCO-baw

C. C. Ong

Attachments

ADVANCED COMPOSITES

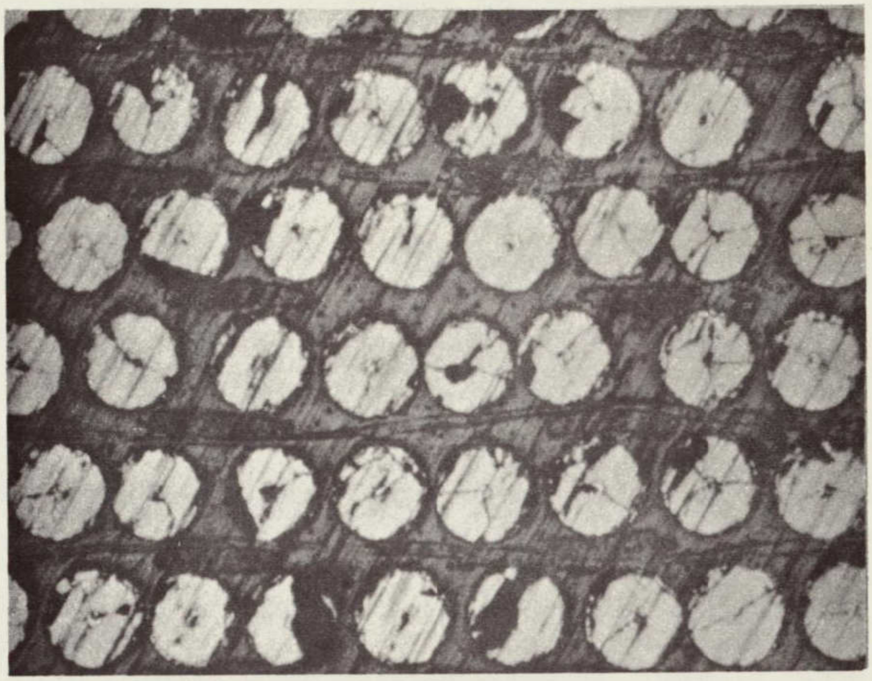
APRIL 23, 1970

ADVANCED COMPOSITES

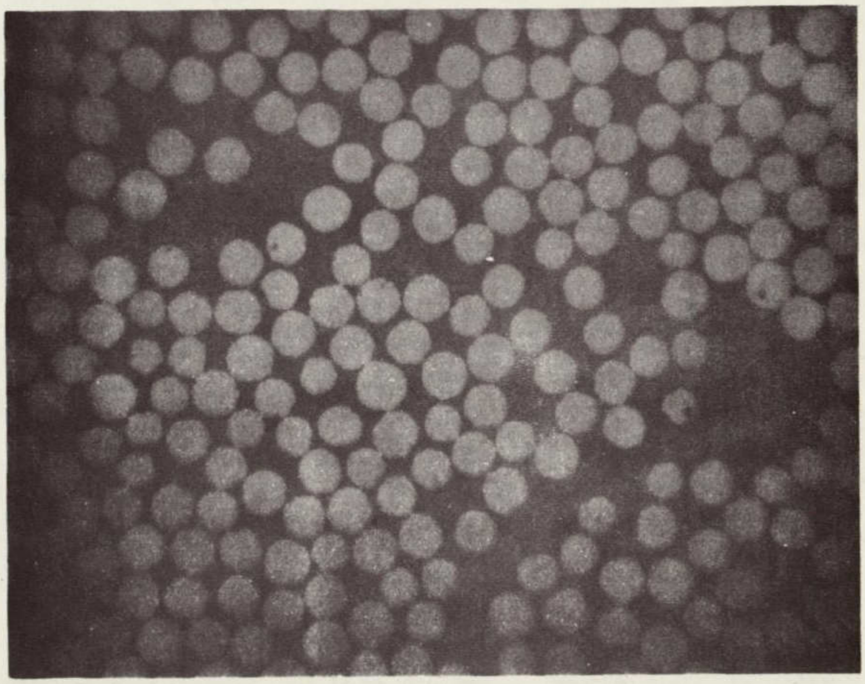
Advanced composites are defined for our purpose of discussion as fiber-reinforced composites with specific strength and specific modulus higher than those of conventional structural metals, and in particular, with a specific modulus higher than those of fiberglass-reinforced composites. Therefore, fiberglass composites are explicitely excluded from the family of advanced composites.

Two examples of unidirectional composite are shown in this graph. The top one is a cross-section of boron filaments embeded in a polymer matrix system called epoxy; the bottom one shows graphite filaments bound by the same matrix material. The cross-sections shown are of different scales; boron filaments have a nominal diameter of 4 mils and graphite filaments, 0.3 mil. These two systems are the most widely utilized advanced composites to date for structural applications.

UNIDIRECTIONAL COMPOSITE CROSS-SECTIONS



BORON/EPOXY



GRAPHITE/EPOXY (ENGLISH)

ADVANCED COMPOSITES OF CURRENT INTEREST

Boron/epoxy is the earliest developed and most widely used advanced composite. Material properties are well-characterized and reproducible. Sufficient engineering experience has been accumulated to make it the most likely candidate for large scale production programs.

Graphite/epoxy is a newer material which has become increasingly important in structural application. A family of graphite filaments and composites have been developed. Several countries, notably Great Britain and the United States, are actively engaging in the development, manufacturing, and structural application of these materials. The improvement in material properties of graphite filament has been progressing so rapidly that it is extremely difficult to keep abreast with the new development.

Boron/aluminum is the only metal matrix composite of which significant engineering data on structural application are available. The aluminum matrix composites are far behind the epoxy matrix composites in terms of application experience and data generation; material forms and fabrication techniques have not been firmly established. Nevertheless, this material, along with boron/epoxy and graphite/epoxy, is generally considered to be a potential candidate for near term applications.

ADVANCED COMPOSITES OF FUTURE INTEREST

Some of the advanced composites which are in a relatively early stage of development and which have a potential for higher temperature applications are boron/polyimide, graphite/polyimide, boron/titanium, graphite/graphite and silicon carbide composites. Polyimide matrix is a high temperature resistant resin which might be ready for structural application in the near future. 60.

Commercially available graphite fiber-reinforced graphite composites can withstand temperatures in excess of 6000°F. Their unique properties of thermal stability and resistance to thermal shock make these materials promising candidates for certain very high temperature applications such as engine structures and the the thermal protection system of a reentry vehicle.

Our study will be confined to near term application of advanced composites for the primary structures of aerospace vehicles, particularly the space shuttle. Emphasis will be placed on boron/epoxy, graphite/epoxy and boron/aluminum; high temperature composites listed in this chart will not be discussed in any detail.

ADVANCED COMPOSITES OF FUTURE INTEREST

- BORON/POLYIMIDE
- GRAPHITE/POLYIMIDE
- BORON/TITANIUM
- GRAPHITE/GRAPHITE
- SILICON CARBIDE COMPOSITES

WHY ADVANCED COMPOSITES?

Advanced composites are attractive materials for primary structures of aerospace vehicles owing to their unique properties, weight saving potential, and cost effectiveness.

Due to their high strength, high modulus, low weight, excellent fatigue strength and, for some composites, high temperature capability, advanced composites can be utilized for structural elements resulting in a weight saving up to 60% as compared to an equivalent aluminum or titanium structure. For a two stage fully reusable space shuttle, one pound of inert weight saved for the booster would result in a 0.15 lb payload increase, and the inert weight saved in the orbiter would go directly to the payload increase, pound for pound.

It is estimated that each pound of inert weight saved in a shuttle orbiter would be worth as much as $14,000. This estimate is based on a vehicle with a payload capability of 50 K lbs, a reusability of 100 flights, a vehicle cost of $200 M̄, and an operational and refurbishment cost of $5 M̄ for each flight.

WHY ADVANCED COMPOSITES?

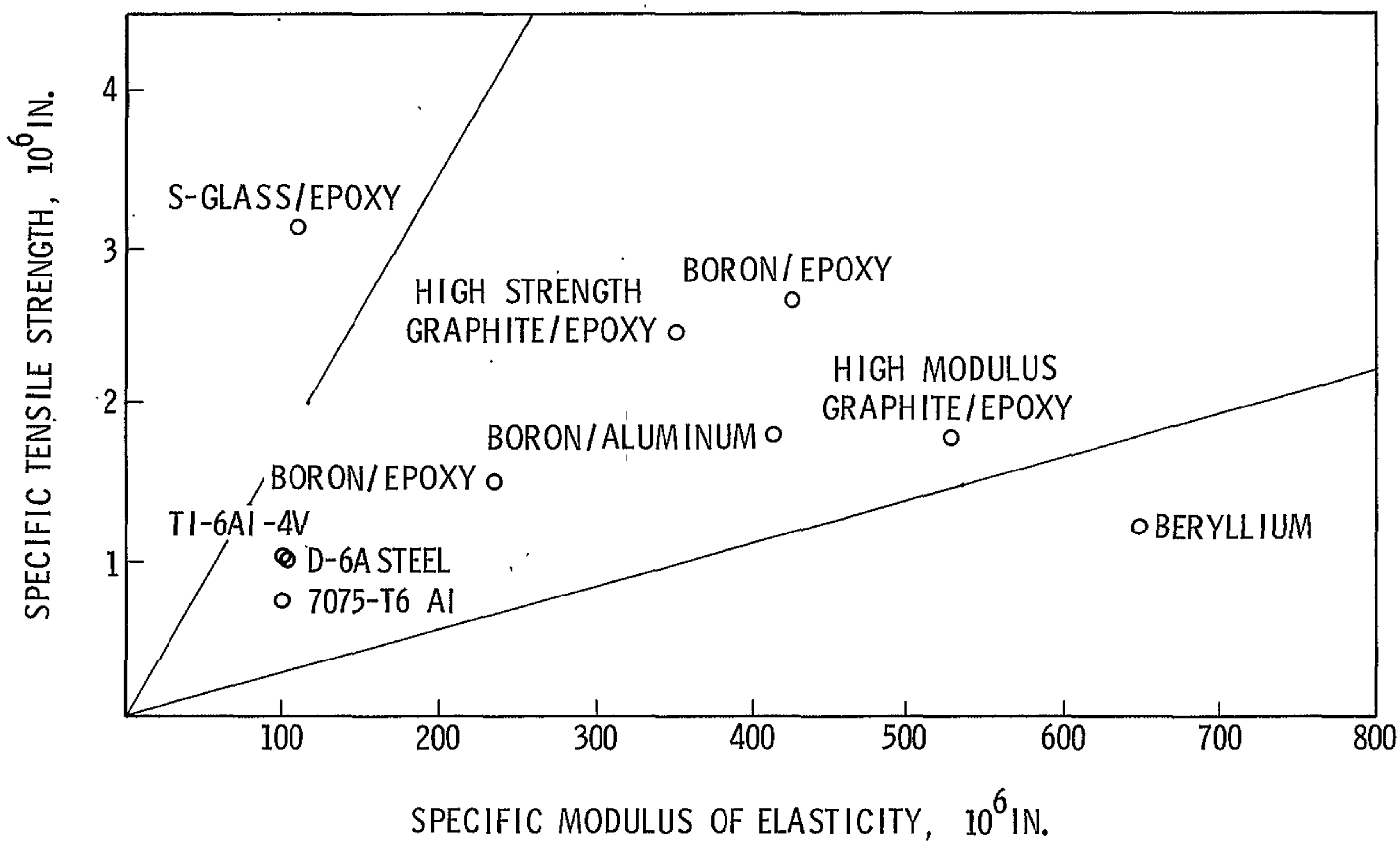
- ATTRACTIVE MATERIALS PROPERTIES
  - HIGH STRENGTH
  - HIGH MODULUS
  - LOW WEIGHT
  - EXCELLENT FATIGUE STRENGTH
  - POTENTIAL HIGH TEMPERATURE CAPABILITY
- POTENTIAL WEIGHT SAVINGS
  - UP TO 60% FOR STRUCTURAL ELEMENTS
  - SHUTTLE BOOSTERS: 0.15 LB P/L INCREASE FOR 1 LB INERT WEIGHT SAVED
  - SHUTTLE ORBITER: 1 LB P/L INCREASE FOR 1 LB INERT WEIGHT SAVED
- POTENTIAL COST EFFECTIVENESS
  - 1 LB SAVED ON SHUTTLE ORBITER WORTH $14,000 (BASED ON 100 FLIGHTS)

SPECIFIC PROPERTIES OF STRUCTURAL MATERIALS

The specific properties of several structural materials are compared in this graph. The specific tensile strength and specific modulus of elasticity are a measure of the strength to weight ratio and are defined, respectively, as tensile strength and modulus divided by the density.

Fiberglass composites have very high specific tensile strength and low specific modulus while beryllium has outstanding specific modulus but low specific strength. Several unidirectional advanced composite materials shown exhibit a balanced feature of both high specific strength and high specific modulus. However, if angle-ply construction is necessary in structural application, both the strength and the modulus of the composites would be reduced substantially as indicated in the figure for $0_2° \pm 45°$ boron/epoxy. Therefore, greatest advantage of advanced composites can be taken if these materials are used for structural elements subjected to a unidirectional force.

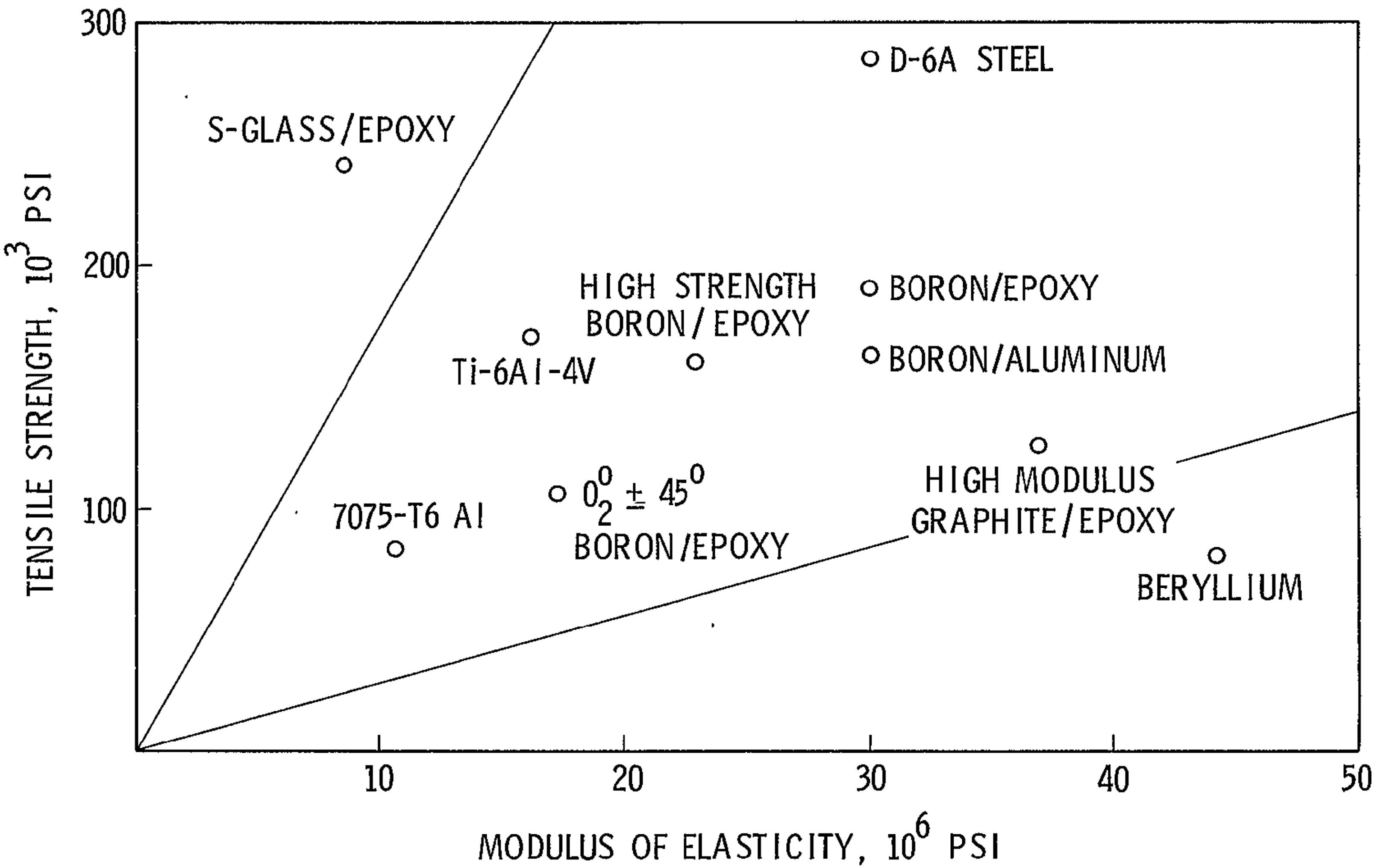
SPECIFIC PROPERTIES OF STRUCTURAL MATERIALS



PROPERTIES OF STRUCTURAL MATERIALS

This figure compares the tensile strength and the modulus of the same materials shown in the previous graph. It is seen that unidirectional advanced composites in general have higher modulus than aluminum and titanium; it is also of higher strength than aluminum.

PROPERTIES OF STRUCTURAL MATERIALS

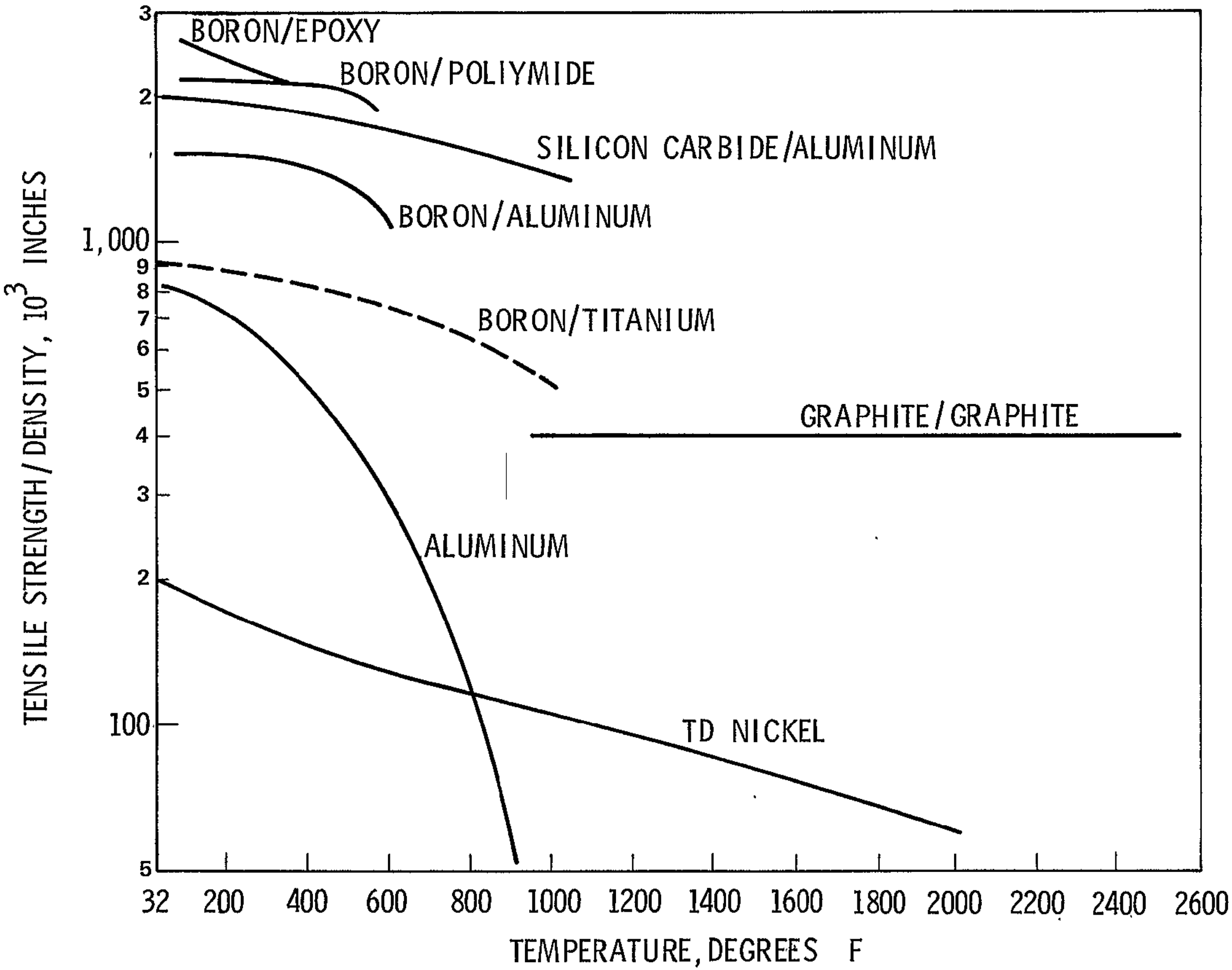


SPECIFIC TENSILE STRENGTH VERSUS TEMPERATURE OF STRUCTURAL MATERIALS

Most advanced composites exhibit superior specific strength at high temperatures compared to metal alloys. Some of the curves shown are abruptly terminated at certain temperature level, indicating the weakening of the matrix system at this temperature. The maximum utilization temperature of composites is usually governed by the temperature capability of the matrix system.

Boron/epoxy and graphite/epoxy have a maximum utilization temperature of 350°F; boron/polyimide, 500°F, borSic/aluminum, 600°F; and Bor Sic/titanium, 1000°F. Within the temperature range shown, the tensile strength of graphite/graphite is almost invarient to temperature changes. This tensile strength is largely retained until a temperature in excess of 6000°F.

SPECIFIC TENSILE STRENGTH VERSUS TEMPERATURE
OF STRUCTURAL MATERIALS



FILAMENT PROPERTIES

Boron filaments are produced by vapor deposition of elemental boron onto a heated 0.5 mil tungsten wire through hydrogen reduction of boron trichroride (BC_3). The final filament has a diameter of 4 mil compare to 0.3 mil for a graphite filament. The main concern of boron filaments are their extreme hardness (9.5 on the MOH scale), large diameter and low ducility which make boron composites very difficult to fabricate.

Graphite filaments are made of graphitization of carbon which is formed by heat conversion of a rayon or polyacrylonitrile (PAN) precursor. The filament is soft and easy to fabricate. Some of the current products have a specific modulus higher than that of boron filament, and graphite filaments have a great potential for further improvement both in strength and in modulus. Present concerns are primarily the poor compressive and shear strengths of graphite composites, largely a result of the unsatisfactory bond between the fiber and the resin matrix.

FILAMENT PROPERTIES

BORON

- EXTREME HARDNESS
- LARGE FILAMENT
- LOW DUCTILITY
- GOOD BOND WITH MATRIX
- LOW THERMAL CONDUCTIVITY

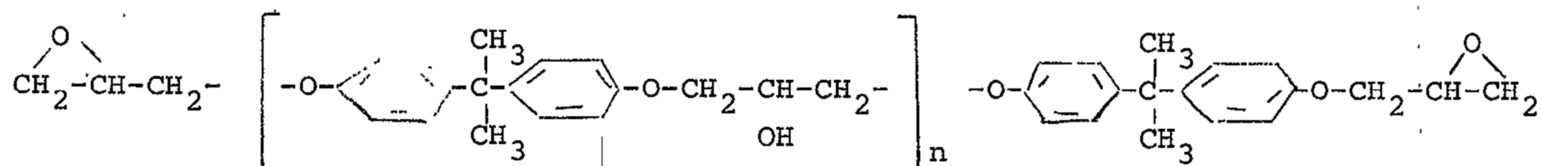
GRAPHITE

- SOFT FIBERS
- HIGH MODULUS
- LOW THERMAL COEFFICIENT OF EXPANSION
- POOR OXIDATION RESISTANCE
- POOR IN COMPRESSION AND SHEAR STRENGTHS

MATRIX PROPERTIES

Although the properties of resin and metal matrices given in this chart are primarily for epoxy and aluminum, which are of intense current interest, they are generally applicable to other resins or metals used in composites.

Epoxy resins commonly supplied are the linear intermediate polymers made by reaction of a bisphenal A with epichlorohydrin. These intermediate resins must be cross-linked with a curing agent for their application in end products. A typical example of an epoxy resin has the following chemical structure



Epoxy resins have been used in fiberglass composites for a long time and are in an advanced stage of development. They have a density of 0.04 lbs/in^3 and a low thermal conductivity. The prepreg tapes of epoxy matrix composite can be bonded to an existing structural element easily to accommodate a design change. The main concern for these resin systems are their low strength, limited temperature capability and being an organic material.

Metal matrix composites are potentially stronger, particularly in shear strength and in tensile strength at transverse direction of unidirectionally reinforced composite. Metals such as titanium and nickel alloys exhibit a much higher temperature capability than polymers. Joining of metal matrix composites to the same composite or other metals is much easier than resin matrix composites because of the metal-metal contact and the high bearing strength of the metal.

MATRIX PROPERTIES

RESIN MATRIX

- LOW DENSITY
- ADVANCED STAGE OF DEVELOPMENT
- LOW COST
- ADAPTABILITY TO DESIGN CHANGES
- AN INSULATOR
- HIGH POROSITY

METAL MATRIX

- POTENTIALLY HIGH STRENGTH
- HARD SURFACE
- HIGH TEMPERATURE CAPABILITY
- NON-ORGANIC MATERIAL
- METAL-TO-METAL JOINING

MATERIAL AVAILABILITY

There are, currently, two suppliers of boron filament: the AVCO Corporation and the Hamilton Standard Division of United Aircraft Corporation. Hamilton Standard produced approximately 5000 lbs of boron filament in 1969, and is expected to have a production capability of 1,500 lbs/month by the end of 1970. AVCO produced boron filament at a rate of 800 lbs/year in 1969 and is also expanding its production facilities. Of graphite filament, there are many suppliers both in the United Stages and in Great Britain; Union Carbide is the leading U.S. manufacturer, and products of British Morganite Research and Development have been widely used in this country.

One-eighth inch and 3 inch resin pre-inpregnated tapes have been produced with both collimated boron filaments and collimated graphite filaments. Nominal thickness of these tapes is around 5 mils, although graphite/epoxy prepreg tapes as thin as 1 mil have been manufactured. The term "wide goods" is applied to pre-inpregnated filaments collimated to a width greater than 3 inches. Wide goods of boron/epoxy and graphite/epoxy up to 48 inch wide have been produced which, in contrast to continuous tape, have specified lengths.

The production of boron/aluminum has not been standardized but rather has been produced according to users requirements. BorSic/Al tape, collimated boron filaments coated with silicon carbide and bonded between 6061 aluminum foil, have been produced in 6 inch widths and lengths up to 10 feet. Sheet forms up to 48 inches square have also been manufactured. These products can have various thickness with each layer consisting of collimated borSic filaments held between 1 mil thick aluminum foils by diffusion bonding.

MATERIAL AVAILABILITY

- FILAMENTS
  - BORON : 0.004" DIAMETER
  - GRAPHITE : 0.0003" DIAMETER
- BORON/EPOXY
  - PREPREG TAPE : 1/8" AND 3" WIDE
  - WIDE GOODS : UP TO 48" WIDE
- GRAPHITE/EPOXY
  - PREPREG TAPE :
  - WIDE GOODS :
- BORON/ALUMINUM
  - BORSIC/A1 6061 TAPE : 6" WIDE; UP TO 10' LONG
  - BORSIC/A1 6061 SHEET : UP TO 48" x 48" IN SIZE

FABRICATION QUALITIES

Graphite filaments are soft and small in diameter so graphite/epoxy can be formed and machined easily. The tooling and fabrication technology used for fiberglass composite are generally applicable to graphite/epoxy. While fiber abrasion does not present as serious a problem, unprotected graphite yarns have a tendency to "fuzz" during mechanical handling; some sort of protective finish is required which may not be desirable for the enhancement of fiber-matrix bonding.

Due to the large diameter and the hardness of the boron filament, diamond grit coated tools are required for machining, cutting, and drilling. Forming is radius limited to a minimum of 4 inches. Boron/aluminum elements have been successfully joined by resistance spot and seam welding, diffusion bonding, non impact riveting, and mechanical fastening. For resin matrix composites, adhesive bonding is the most commonly used method of joining but joint efficiency is generally low. Boron/aluminum is susceptible to peeling and edge delamination which requires special attention during fabrication.

FABRICATION QUALITIES

GRAPHITE/EPOXY

- MACHINING, CUTTING, DRILLING, FORMING, AND JOINING - GLASS FIBER TOOLING AND TECHNOLOGY APPLICABLE
- HANDLING - PROBLEM CAUSED BY POOR ABRASION RESISTANCE

BORON/EPOXY AND BORON/ALUMINUM

- MACHINING, CUTTING AND DRILLING - DIAMOND GRIT COATED TOOLS REQUIRED
- FORMING - RADIUS LIMITED
- JOINING - MATRIX DEPENDENT
- DELAMINATING - SPECIAL ATTENTION REQUIRED FOR B/Al

ADVANCED COMPOSITE UTILIZATION

The various composite application methods in use or under study are described below.

Substitution - This method retains the basic structural configuration and replaces metal structural elements with composite members. Typical examples of this method are honeycomb panel face sheets and wing cover panels. It is generally applied to simply or lightly loaded parts. Weight reduction is achieved principally because of lower material weight.

Composite Reinforced Metal Structures - This method reinforces or replaces highly loaded (unidirectionally) metal structure with composite materials to increase strength for the same or a smaller structural element weight. The advanced composite members are attached by either bonding or mechanically fastening the composite part to the metal structural element. An alternative method of reinforcing metal structures is done by integrating the filaments directly into metal to form a composite.

Typical uses of this method are stringer reinforcements, beam caps, and panel stiffeners. This method is currently receiving the major study emphasis by NASA.

All Composite Structures - Here, maximum use of composites is made for structural elements under complex loading conditions. The composite structural element is optimally designed for the particular loading condition. Experience with this approach (in fabrication and analysis) is being generated by the Air Force on a large fuselage structural element.

ADVANCED COMPOSITE UTILIZATION

- SUBSTITUTION

  Retaining Basic Configuration and Substituting Composite Materials for Metal Elements

  - Honeycomb Panel Face Sheets
  - Wing Covers

- COMPOSITE REINFORCED METAL STRUCTURE

  Selective Placement of Composite Materials in Metal Structures to Increase Structural Effectiveness

  - Stringer Reinforcement
  - Beam Caps
  - Panel Stiffeners

- ALL COMPOSITE STRUCTURE

  Maximum Composite Utilization for Structural Assemblies

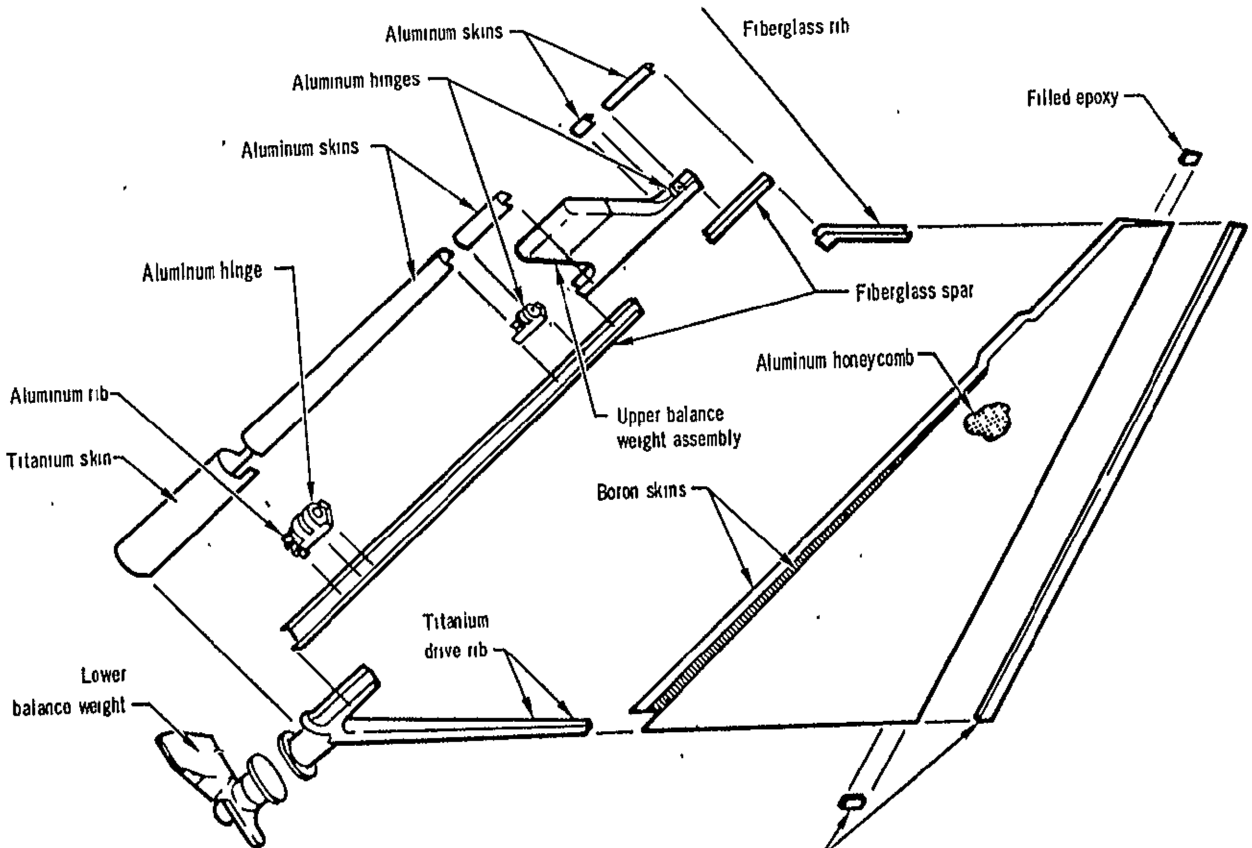
  - Major Fuselage Assembly

HONEYCOMB PANEL FACE SHEETS

One of the initial applications of advanced composites as a structural material was the F4 aircraft rudder with boron epoxy skin replacing the existing aluminum skin. This rudder, designed as a honeycomb panel, provided the ideal base on which the composite material could be applied.

HONEYCOMB PANEL FACE SHEETS

(Substitution)



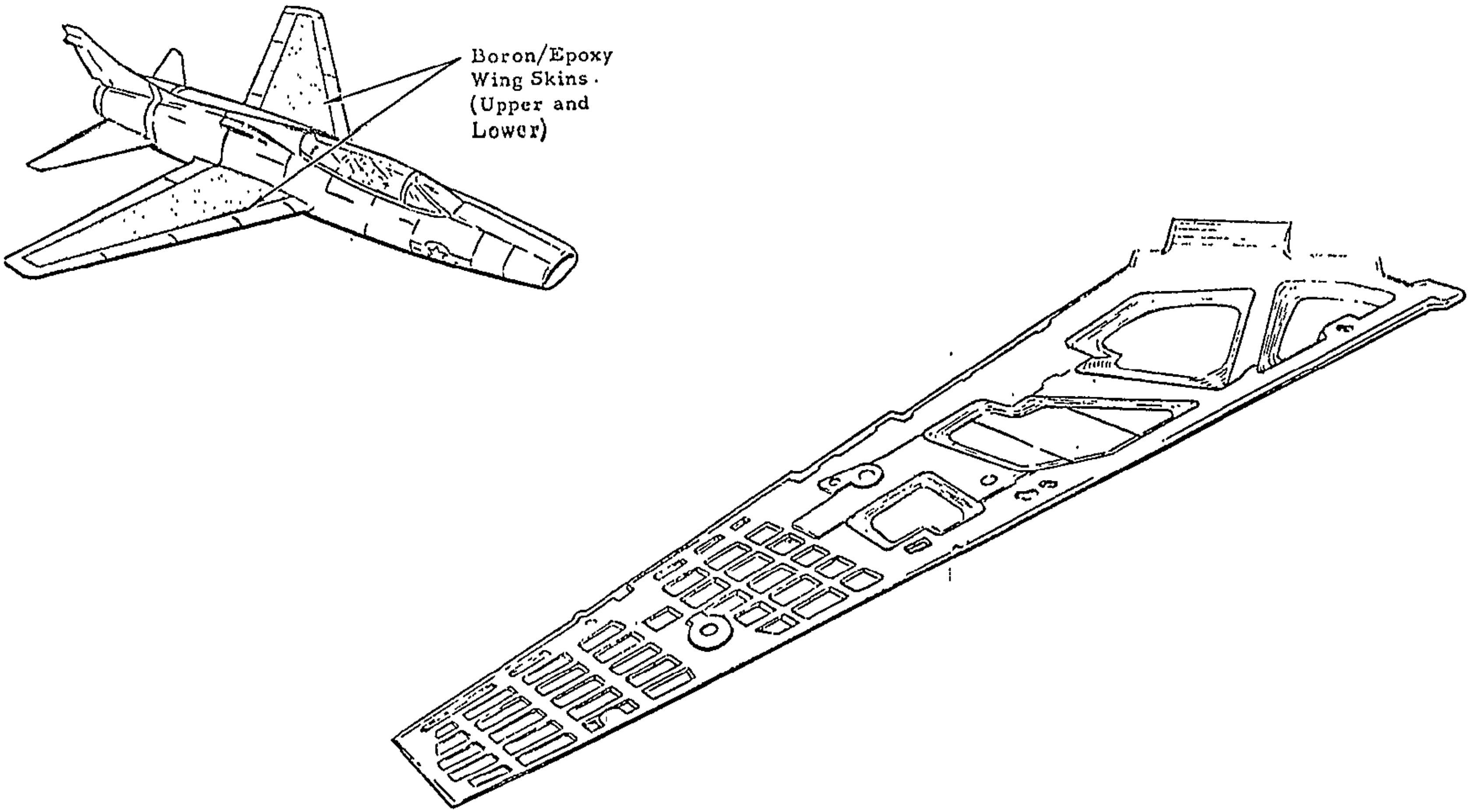
F-4 RUDDER

INTEGRALLY MACHINED WING COVERS

This illustration of substitution is one of the more advanced uses of advanced composites. Here, the present wing cover for the F100 aircraft, which is fabricated from aluminum, is being replaced entirely by composite material. The basic raw material is fabricated by laminating successive layers of boron epoxy sheets to provide the basic material thickness. As shown, the inside surface of the wing cover will be extensively machined similar to the present part. Development of this particular part is being conducted by North American Rockwell under contract from the Air Force Materials Laboratory (AFML). This contract covers design, fabrication, and a flight testing program.

INTEGRALLY MACHINED WING COVERS

(Substitution)



F100 AIRCRAFT

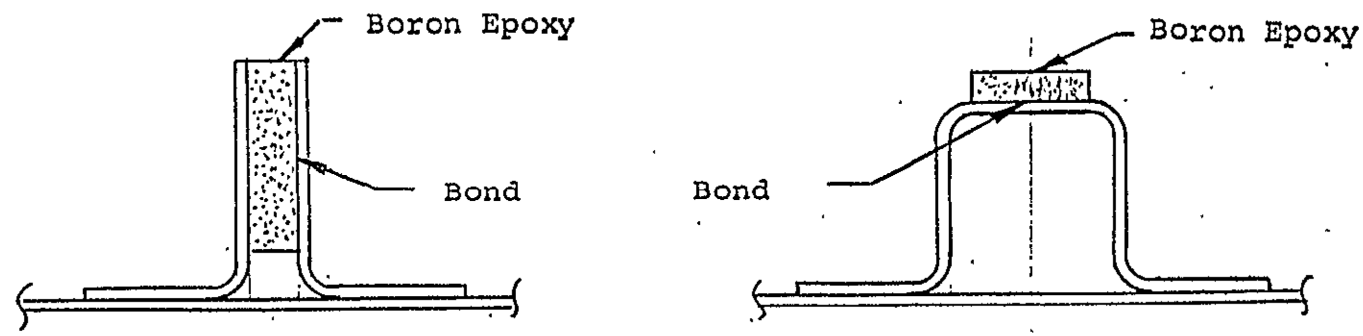
STRINGER REINFORCEMENT

Here are several examples of stringer reinforcement using composites as external members bonded to metal stringers or as reinforcing filaments in a metal matrix.

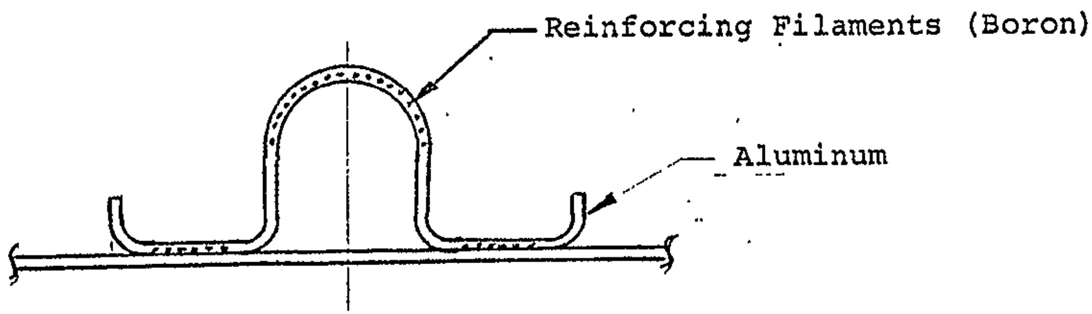
Epoxy Matrix Composites - The Boeing Company under contract to NASA Langley is presently conducting a research program using this application of advanced composites. As shown, the composite members are attached by bonding to the metal structure. This approach has also been studied for application on the SST by Boeing for a portion of the aft fuselage and showed a weight saving potential of 21%.

Metal Matrix Composites - Selective placement of filaments in a metal matrix provides an alternate method of increasing the structural strength. This type of composite structure was used by General Dynamics on a missile payload adapter structure.

STRINGER REINFORCEMENT



EPOXY MATRIX COMPOSITES



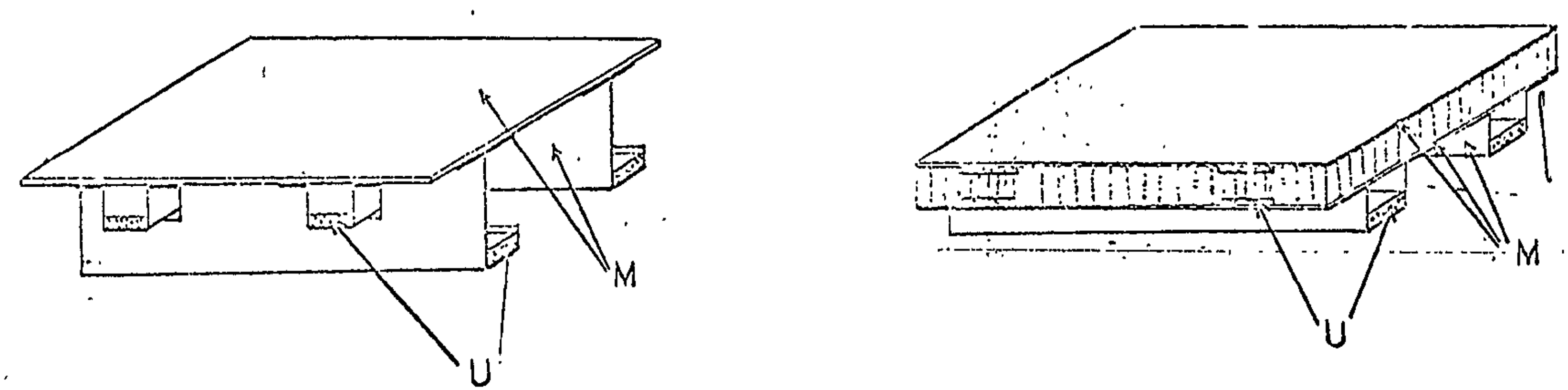
METAL MATRIX COMPOSITE

PANEL STIFFENERS

(Reinforcement)

Two examples of panel assemblies further illustrate the use of composites in the structural reinforcement mode. The panel shown on the left incorporates advanced composites in the manner shown previously for stringer reinforcement. The panel assembly on the right, a combination of a honeycomb panel and frames, integrates the composite into the honeycomb panel as well as on the frames. Samples using each of these methods have been fabricated and tested by the Boeing Company.

PANEL STIFFENERS
(Reinforcement)



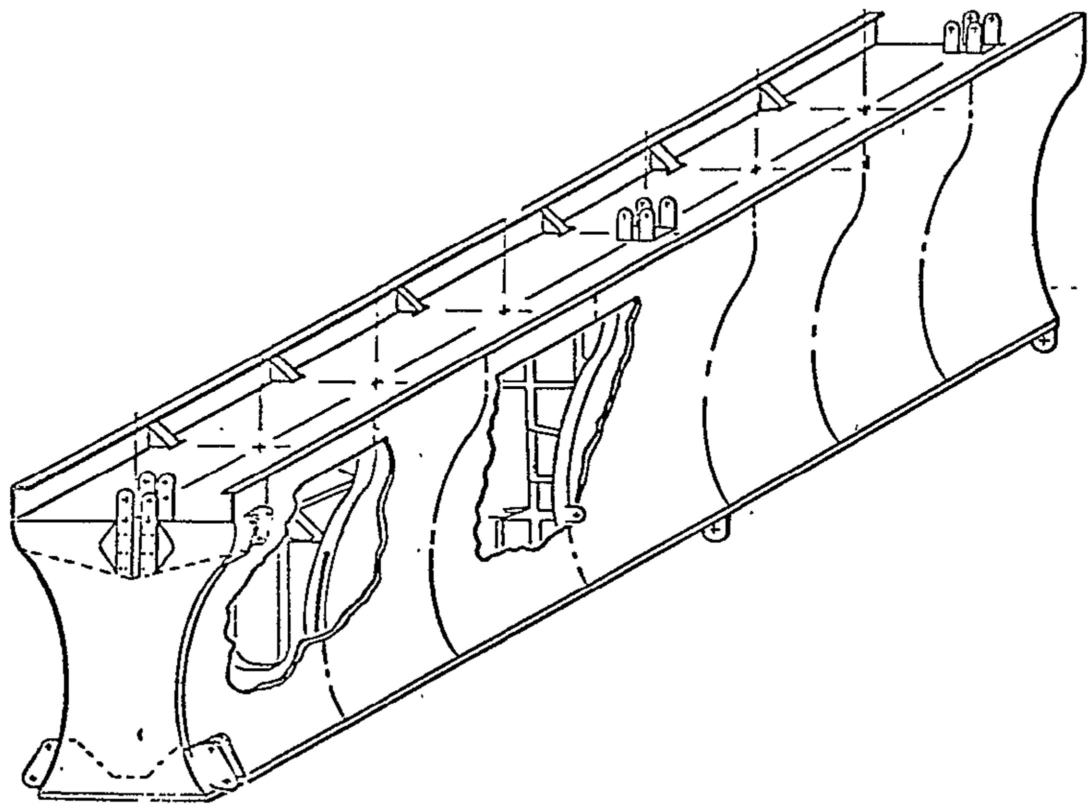
M – METAL
U – UNIDIRECTIONAL
COMPOSITE

MAJOR FUSELAGE ASSEMBLY

(All Composite)

As previously shown, the uses of composites have been simple applications of either a substitution or local reinforcement nature. The ultimate goal is an all composite structure where complex shaped parts, attachments and joints are produced from advanced composites. To accomplish this goal, General Dynamics under contract to the AFML, is presently conducting a design development program for maximum application of composites to a major structural aircraft assembly. This structure, as shown, forms a part of the aft fuselage for the F111 aircraft and is approximately 13 feet long. Several of many candidate composite materials will be used for this part. These include laminates of boron-epoxy, graphite epoxy, glass epoxy, boron aluminum, and composite reinforced molded components.

MAJOR FUSELAGE ASSEMBLY
(All Composite)



AFT FUSELAGE STRUCTURE (F-111)

WEIGHT REDUCTION POTENTIAL

To illustrate the weight saving potential using advanced composites, this chart of various types of structures with varying degrees of composite utilization was prepared as part of a study by the Martin Marietta Corp. As shown in this figure, weight savings ranged from 15% for a minimum application of composites to 60% for a maximum application of composites.

WEIGHT REDUCTION POTENTIAL

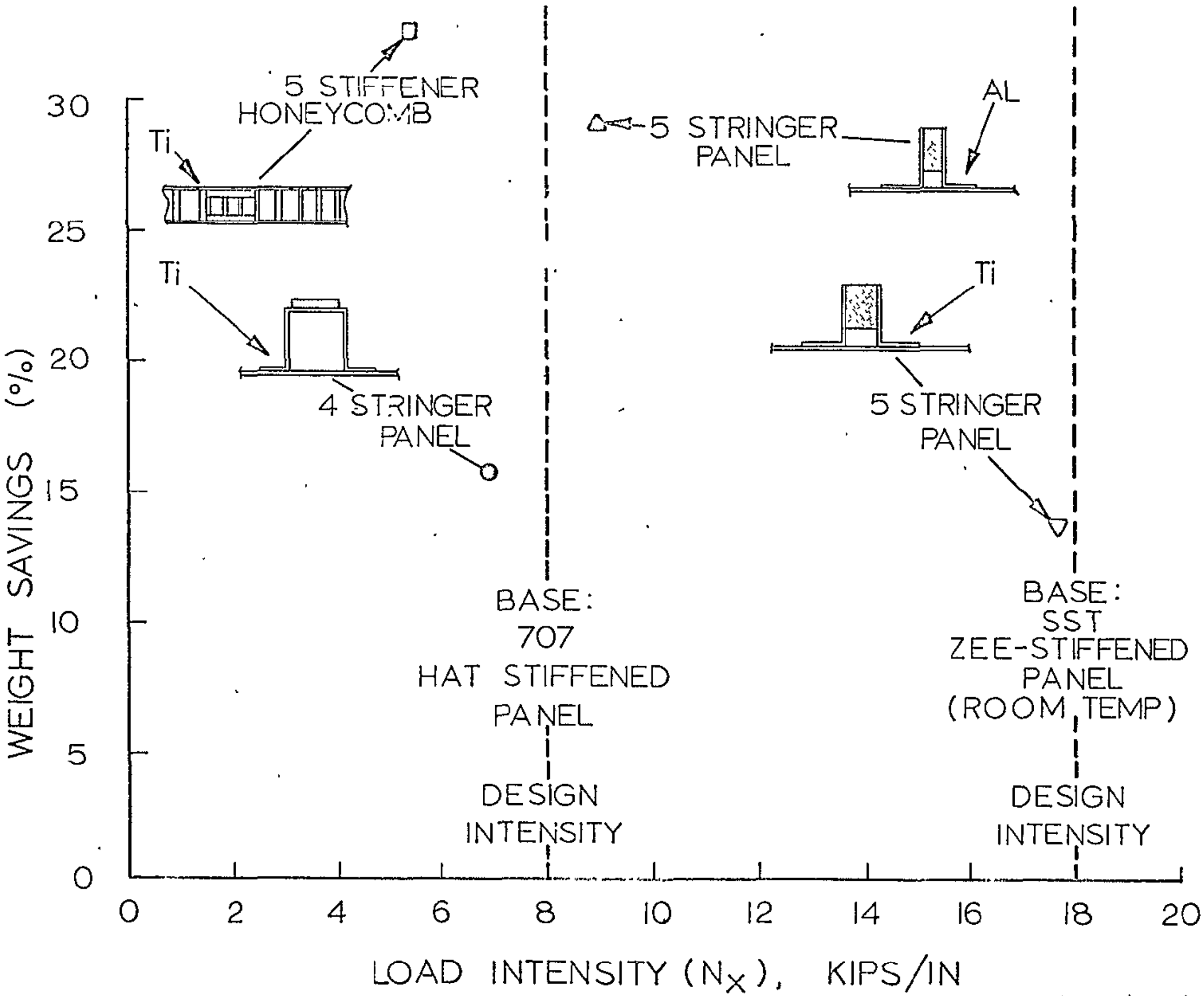
	Expected Practical Percent Reduction
COLUMN All Composite Barrel with Tapered Metal End Attachments (Ends 10% of Total Length)	60%
COLUMN Composite and Metal Barrel with Tapered Metal End Attachments (Ends 10% of Total Length)	55%
BEAM All Composite Flanges and Webs with Metal Flange to Web Angles and Metal Web Core Material	45%
BEAM Composite and Metal Flanges with Metal Sandwich Web	40%
SKIN PANEL All Composite Honeycomb Sandwich with Metal Shimmed Edge Attachment (Edge Area 30% of Total Panel Area)	30%
SKIN/STRINGER/FRAME PANEL Composite Skin with HAT Composite Reinforced Metal Stringers and Z Composite Reinforced Metal Frames	25%
SANDWICH/FRAME PANEL Metal Sandwich with all Composite Stringer Built-In and Composite Reinforced Metal HAT Section Frames	15%

Martin Marietta Co.

TYPICAL WEIGHT REDUCTION

This figure illustrates several different panel designs using the composite reinforcement technique previously discussed. Each of the different panel designs were fabricated and tested and results were compared with conventional metal structures data to determine typical weight savings. For different load intensities, depending on the type of panel design, weight savings of from 15% to 35% or an average of 25% was achieved. As a baseline for comparison, both the 707 and SST design load intensity are illustrated on the chart. These results form part of the Boeing study of composites being conducted for the Langley Research Center.

TYPICAL WEIGHT REDUCTION



LaRc/Boeing

ADVANCED COMPOSITE APPLICATION

A survey of some of the past, present, and future programs illustrates the emphasis which has been placed on developing these materials for structural applications. Boron, the forerunner of advanced composites and receiving most of the funding is furthest along but graphite is quickly closing the gap. Specimens of each material have been and are being fabricated and tested.

Flight testing of structural elements using advanced composite materials has been minimal, with only the F-4 rudder and flap and some panel specimens being tested. Other structural elements are planned for flight testing in the future. Also, to gain in service data, the F-4 rudder and C-5A in board slats are programmed for limited production.

ADVANCED COMPOSITE APPLICATION

	SPECIMEN BUILT & TESTED	COMPONENT FLIGHT TESTED	PRODUCTION ITEM
• BORON EPOXY			
– F-111 STABILIZER	YES	NO	---
– F-4 FLAP	YES	YES	---
– F-4 RUDDER	YES	YES	(50)
– F-5 LANDING GEAR DOOR	YES	NO	---
– F-100 WING COVERS	IN PROGRESS	PLANNED	---
– C-5A L.E. SLAT	IN PROGRESS	PLANNED	(10)
– 737 SPOILER	IN PROGRESS	PLANNED	---
– SPECIMENS			
• WING BOX	YES	NO	---
• AFT FUSELAGE	IN PROGRESS	NO	---
• FORWARD FUSELAGE	PLANNED	NO	---
• WING TO FUSELAGE	PLANNED	NO	---
• GRAPHITE EPOXY			
– F-4 FLAP	YES	YES	---
– F-4 RUDDER	YES	YES	---
– F-5 L.E. SLAT	IN PROGRESS	NO	---
• LANDING GEAR DOOR	IN PROGRESS	NO	---
• SPEED BRAKE	IN PROGRESS	NO	---
• HORIZONTAL STABILIZER	IN PROGRESS	NO	---
• VERTICAL FIN	IN PROGRESS	NO	---
• BORON ALUMINUM			
– ATLAS PAYLOAD ADAPTER	YES	NO	---

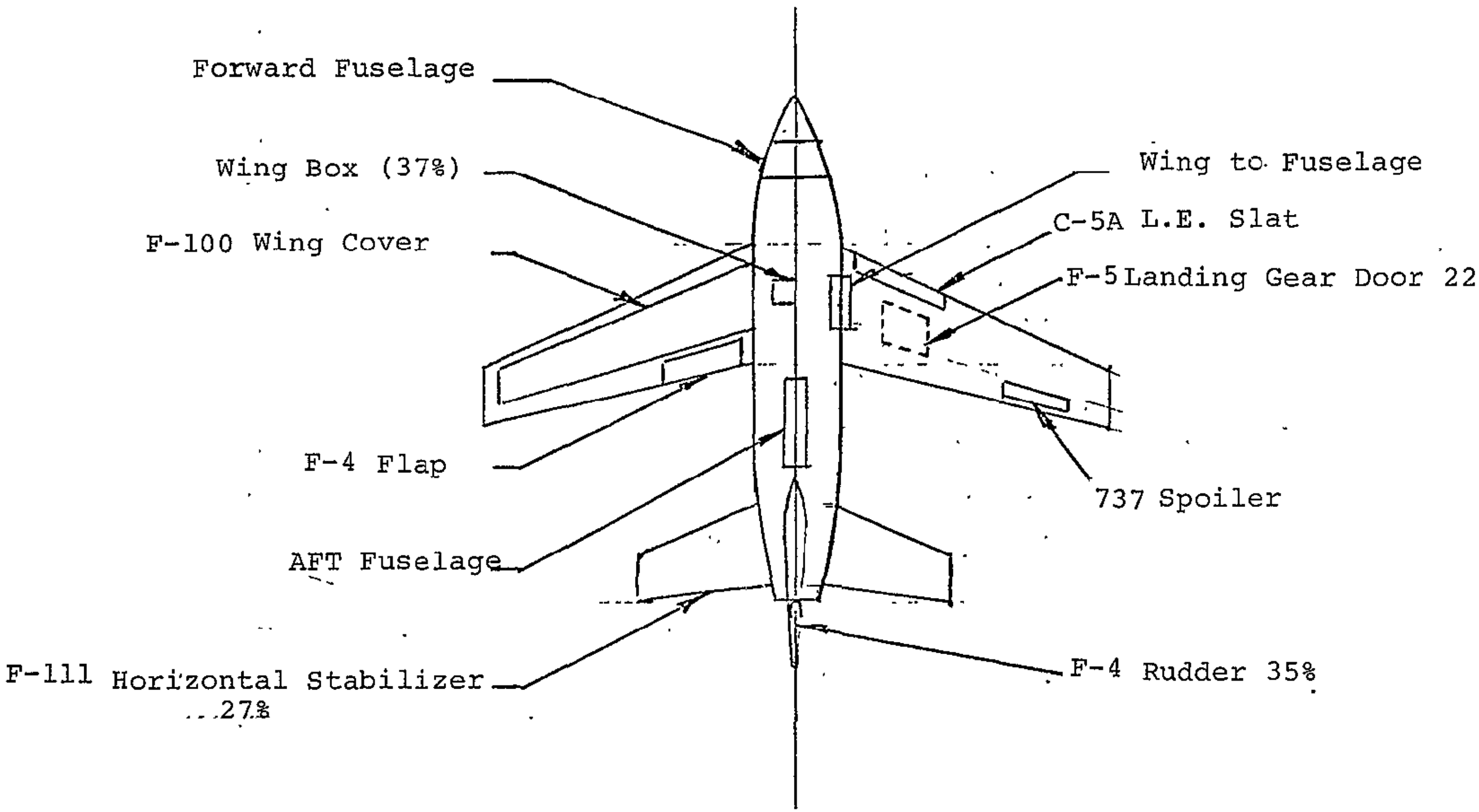
BORON-EPOXY

Illustrated here are the various aircraft components which have been studied using Boron-epoxy. A significant feature is the diversity of application. It is readily apparent that not only secondary structure, but also primary structural applications are being researched.

Weight savings, one of the major objectives for use of composites, are shown below for several components.

F-111 Horizontal Stabilizer	27%
F-4 Rudder	35%
F-5 Landing Gear Door	22%

BORON EPOXY



Forward Fuselage
Wing Box (37%)
F-100 Wing Cover
F-4 Flap
AFT Fuselage
F-111 Horizontal Stabilizer 27%
Wing to Fuselage
C-5A L.E. Slat
F-5 Landing Gear Door 22%
737 Spoiler
F-4 Rudder 35%

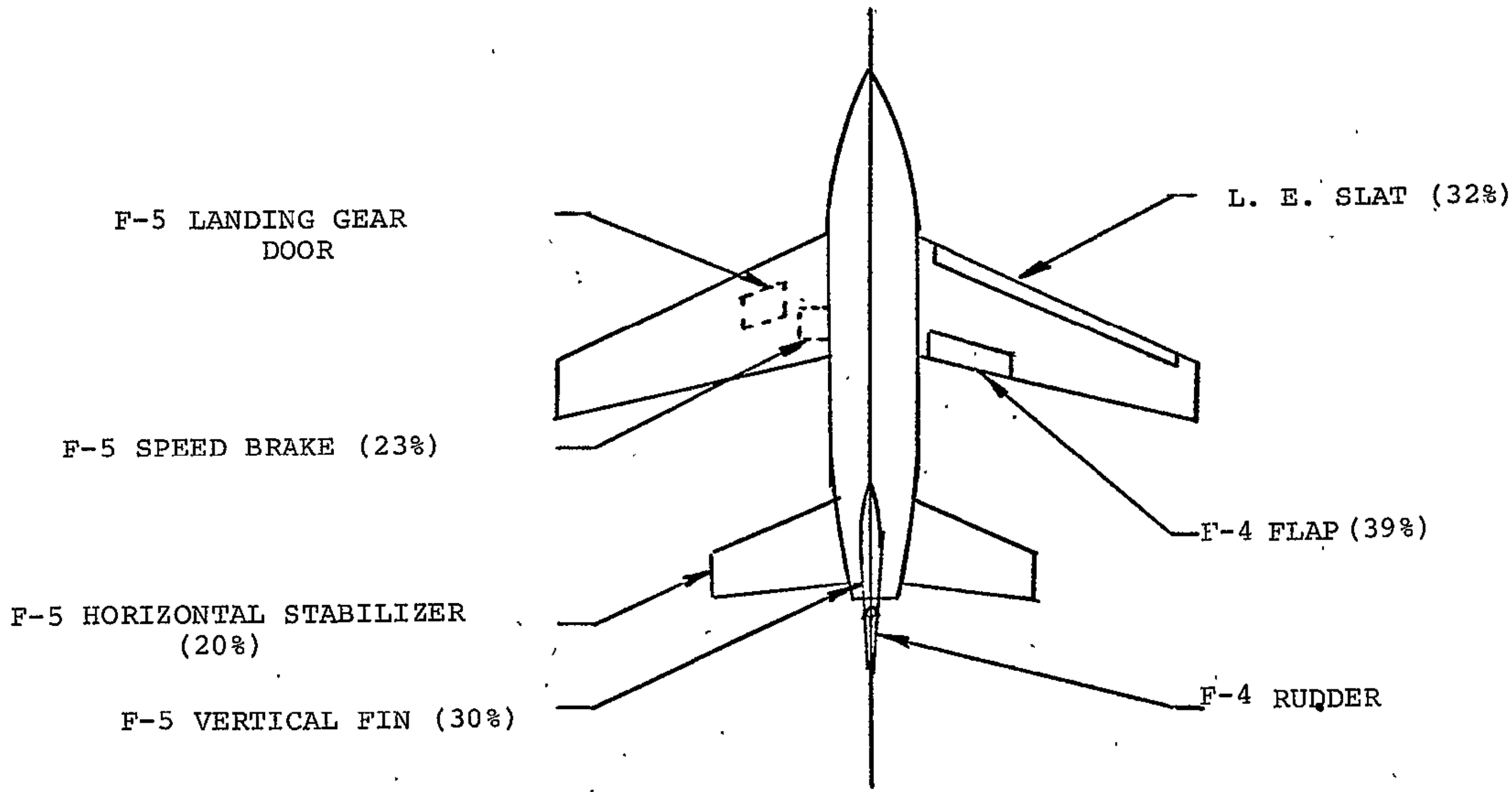
GRAPHITE EPOXY

In this figure are shown some of the typical aircraft components presently being studied for application of graphite-epoxy. Although structural application of this material is relatively new, the extent is significant.

Here again, some of the typical weight savings are listed.

F-5 Horizontal Stabilizer	20%
F-5 Leading Edge Slat	32%
F-4 Flap	39%

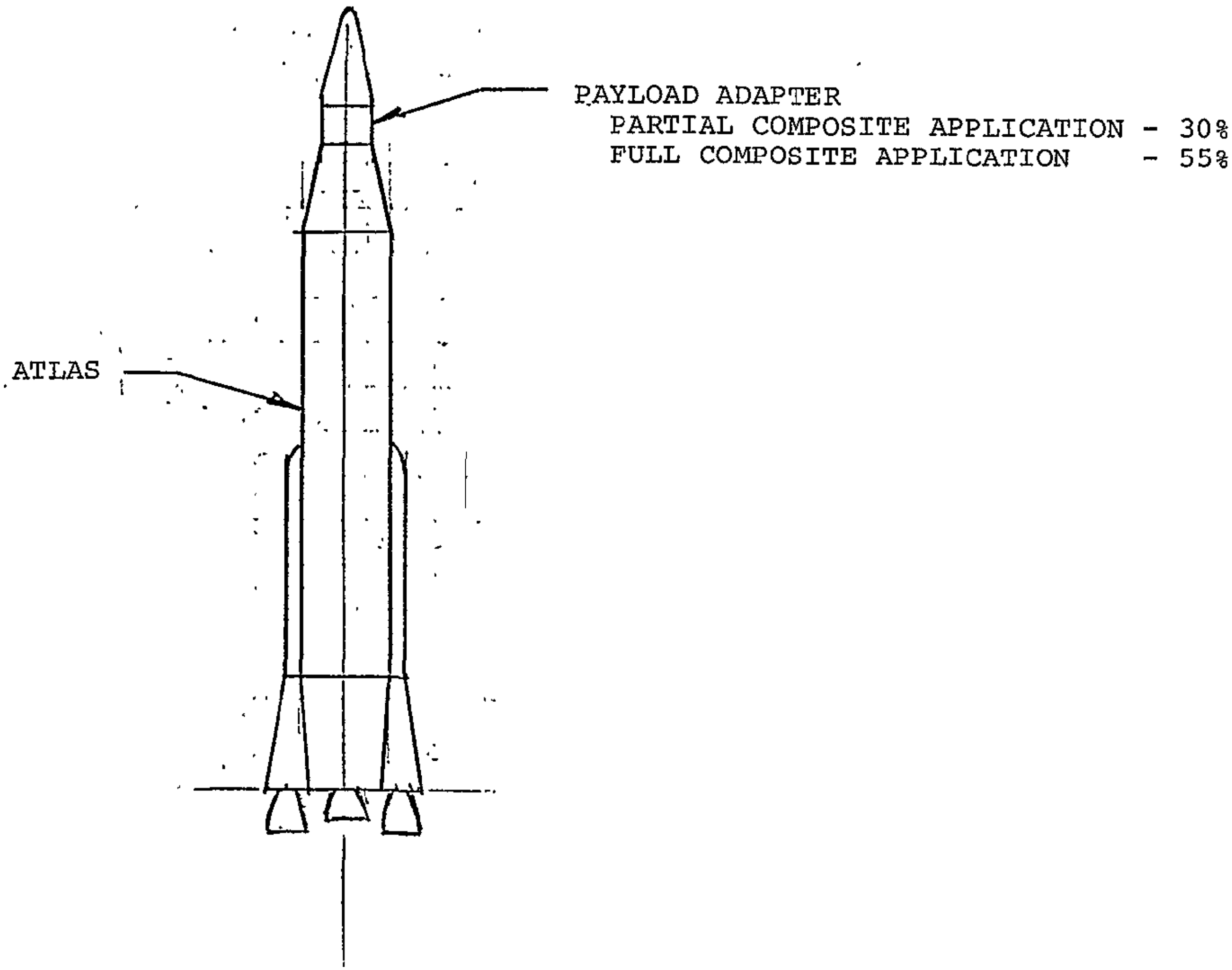
GRAPHITE EPOXY



BORON-ALUMINUM

This figure illustrates one application of boron-aluminum, which has received much less emphasis than either boron-epoxy or graphite-epoxy. The application shown is a payload adapter structure designed and fabricated by General Dynamics under contract to the AFML. For economy reasons only the exterior skin and stringers were fabricated from boron-aluminum. Even with only partial application of boron-aluminum, the weight saved over a conventional metal structure was 35%. Studies show that for a full composite application, the weight saved would have been 55%.

BORON ALUMINUM



SPACE SHUTTLE APPLICATIONS

On the space shuttle there are both suitable and unsuitable structural elements for application of composite material. The suitable elements consist of the engine thrust structure; interior fuselage structure including substructure panels, frames and stringers; and primary structure where high concentrated loads are applied such as landing gear support frame. Unsuitable elements are the propellant tankage, due to the porosity of filamentary composites, and the in orbit docking mechanism, since it is a relatively low-loaded structure.

North American Rockwell has conducted an in-house study for composite application to the space shuttle structure. The elements, identified and studied, are shown with their estimated weight savings.

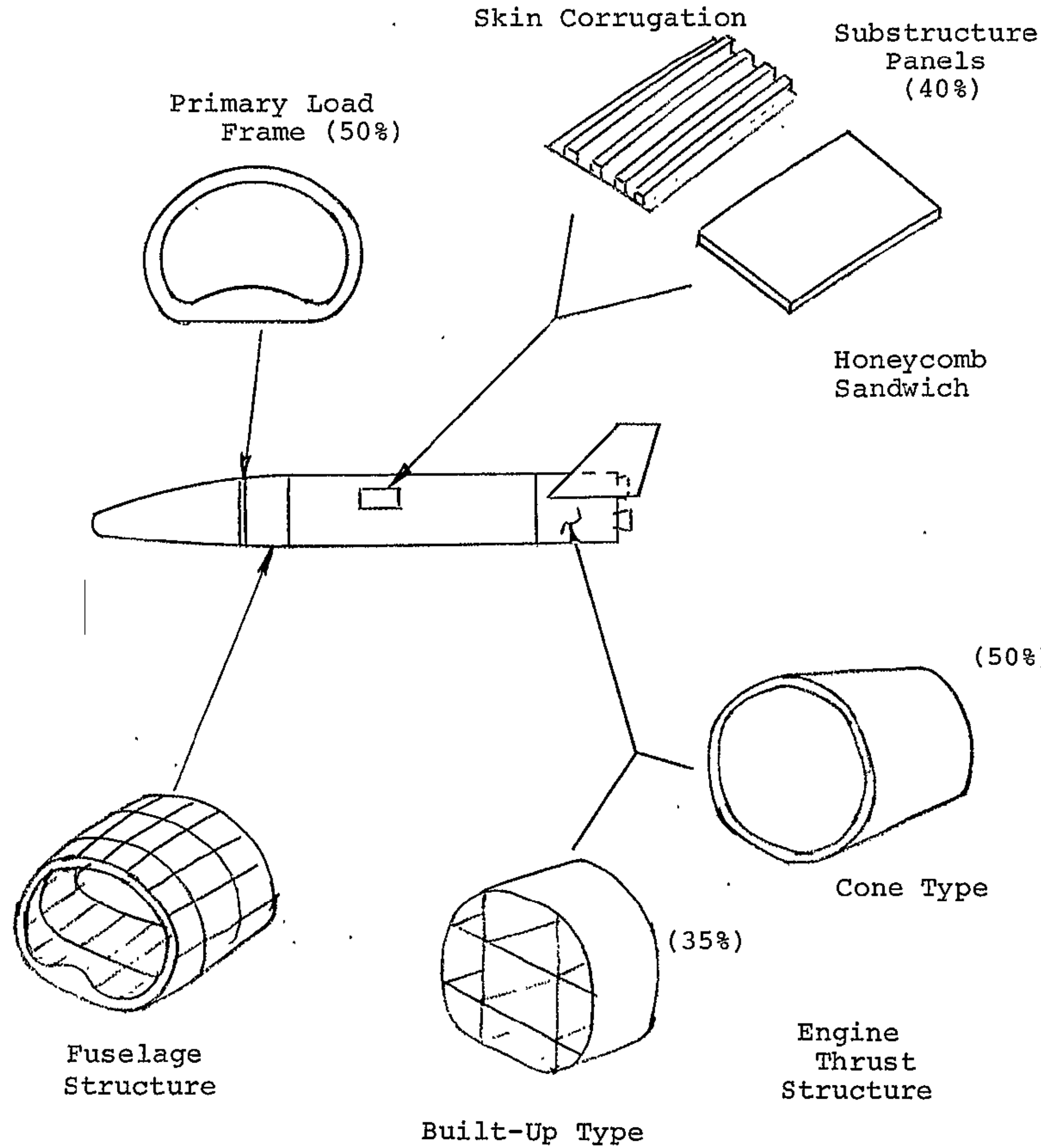
SPACE SHUTTLE APPLICATIONS

SUITABLE ELEMENTS

- ENGINE THRUST STRUCTURE
- FUSELAGE STRUCTURE
- SUBSTRUCTURE PANELS
- PRIMARY LOAD FRAMES
- INTERSTAGE STRUCTURE
- WING TO FUSELAGE STRUCTURE

UNSUITABLE AND POOR

- PROPELLANT TANKAGE
- IN-ORBIT DOCKING STRUCTURE

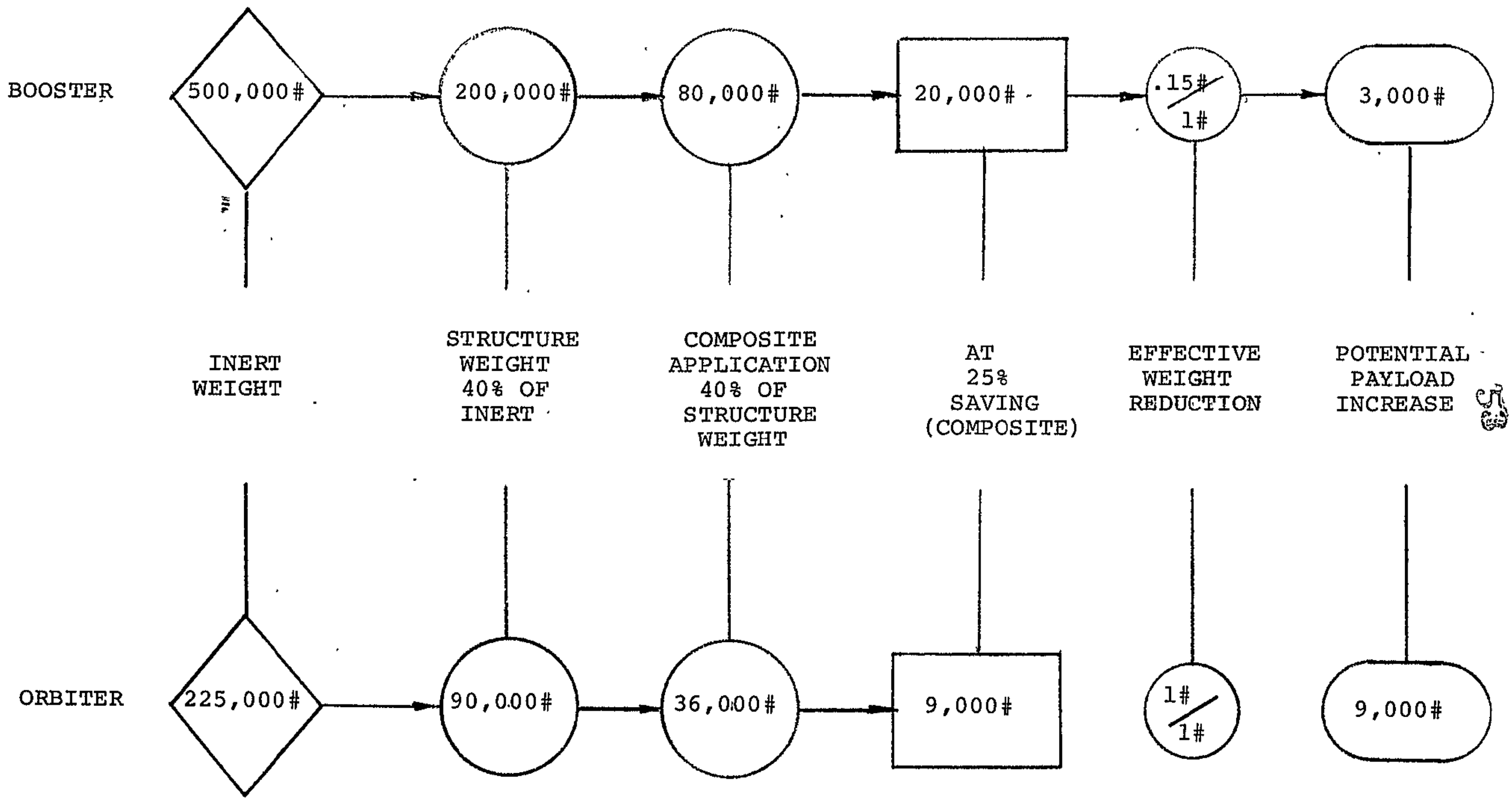


POTENTIAL SAVINGS: 3,500,000 LB GLOW VEHICLE

Since the payload capability of the shuttle is quite sensitive to inert weight, the structure part of this inert weight was examined to determine how and to what degree the payload would be affected. Orbiter total inert weight is approximately 225,000 lb of which 40% or 90,000 lb is structure. As previously stated, weight saving for the selective reinforcement method is about 25%. Of the 36,000 lb selected for composite application, this reduction represented a saving of 9000 lb. Since the ratio of weight decrease to payload increase is one to one, the full 9000 lb is realized as a payload increase. For the booster this same reasoning shows a weight reduction of 20,000 lb. But here the weight reduction to payload increase ratio results in a payload increase of 3000 lb.

If the application of composites actually saved 40% instead of 25% the payload increase would be approximately 19000 lb. Such savings would be expected with maximum utilization of composites.

POTENTIAL SAVINGS 3,500,000 LB GLOW VEHICLE



OTHER SPACE ORIENTED STRUCTURES

Although the present study has emphasized the structural aspects of the Space Shuttle, other future space vehicles and space structures may use advanced composites to advantage.

OTHER SPACE ORIENTED STRUCTURES

- NUCLEAR STAGE
  - INTERSTAGE
  - STRUCTURAL SHROUD
  - CRYOGENIC TANK SUPPORTS
- SPACE TUG
  - INTERSTAGE
  - LANDING GEAR STRUTS
  - TANK SUPPORTS
- UNMANNED SATELLITES
  - DEPLOYABLE ANTENNAE
  - INTRA SATELLITE STRUCTURE
- EXTENDABLE STRUCTURE
  - ARTIFICIAL "G" CONFIGURATION

AIR FORCE ADVANCED COMPOSITE PROGRAMS

The Air Force effort on advanced composites has been directed largely to the aircraft system applications which have been summarized in the previous charts. In addition to primary aircraft structures, advanced composites have also been applied to such structures as helicopter rotor blades and fan and compressor blades of gas turbine engines.

On missile and space applications, the Air Force has sponsored limited studies on reentry vheicle shells and interstage structures of an ICBM in addition to the ATLAS vehicle payload adapter discussed earlier. Further development studies in the missile and space area have been planned for FY'70.

Publication of a design guide was the first step toward the generation and industry wide presentation of basic engineering data and methodology necessary to perform high confidence level design of primary aerospace structures utilizing advanced composites. The data given in the first edition of the Structural Design Guide for Advanced Composite Applications are largely limited to an in depth generation of basic material and structural allowables for boron/epoxy material systems. In preparing the second edition, efforts are being directed toward expanding technical data, standardizing test methods and broadening the spectrum of applications based on a format established in the first edition.

In addition to the flight tests of advanced composite structural components and the limited quantity of production items planned for the various aircraft systems, design and construction of a horizontal stabilizer with a boron/epoxy cover skin for the Navy fighter F-14A is currently underway. Incorporation of this structure into the operational vehicles has been considered; the success of this program may lead to additional utilization of advanced composites in the advanced version of the aircraft, F-14B.

It is noted that the USAF plans for operational use of composites (and other advancements) are based upon economical rather than technological criteria. Improvements are incorporated only after their manufacturing cost per pound of weight saved is less than $100 for transports or less than $200 per fighters. A low production rate NASA vehicle, such as the space shuttle, might benefit from weight savings at a higher cost.

AIR FORCE ADVANCED COMPOSITE PROGRAMS

- EXTENSIVE R & D CONTINUING
  - AIRCRAFT SYSTEM APPLICATIONS
  - MISSILE AND SPACE APPLICATIONS
- EVOLVING DESIGN GUIDE
  - FIRST EDITION PUBLISHED IN AUGUST, 1969
  - SECOND EDITION TO BE PUBLISHED IN OCTOBER, 1970
- INCORPORATION OF ADVANCED COMPOSITES INTO FLIGHT SYSTEMS

NASA ADVANCED COMPOSITE PROGRAMS

NASA research effort on advanced composites has emphasized basic study, development of constituent materials, and fabrication of representative structural components rather than direct application to flight articles. In most of the study programs application aspects have been considered as a broad guideline rather than specific requirements. A large portion of the studies have been conducted through Langley and Lewis Research Centers.

For primary aircraft and spacecraft structure applications, emphasis is being placed on the selective reinforcement concept at Langley. In this concept, composites are used as reinforcement to a basically metallic structure. Use can be made of the design flexibility and structural efficiency which composites possess. Should this concept prove to be generally applicable, problems such as joints, cutout and high cost could be alleviated. The feasibility of various design configurations using selective composite reinforcement is being studied through the research programs listed in this chart.

In association with space shuttle development, Marshall Space Flight Center is planning to build a 1/4 scale shuttle thrust structure. Candidate materials are boron/epoxy, graphite/epoxy and boron/aluminum.

NASA ADVANCED COMPOSITE PROGRAM

RESEARCH & TECHNOLOGY EVALUATIONS

- CONSTITUENT MATERIALS
- TEST SPECIMENS
- FABRICATION OF REPRESENTATIVE STRUCTURAL COMPONENTS

CURRENT EMPHASIS IS ON SELECTIVE REINFORCEMENT CONCEPT

- COMPOSITE REINFORCED AIRCRAFT STRUCTURES: BOEING
- STRENGTHENING C130 CENTER WING BOX: LOCKHEED
- POLYIMIDE ADHESIVE: TRW
- COMPOSITE INFILTRATED HOLLOW METAL ELEMENTS: AVCO
- BORON/EPOXY REINFORCED WING STRUCTURE: LaRC

1/4 SCALE SHUTTLE THRUST STRUCTURE: MSFC

COMPOSITE COSTS

Raw material costs for manufacturing boron filaments presently run about $105/lb which includes about $57/lb for the 0.5 mil tungsten wire used as substrate. A substantial price reduction of tungsten wire cannot be expected as a result of expanded production of boron filament. It is generally believed that the price of boron filament will not go down much below $125/lb by 1980 from the current price of $291/lb (for large quantities over 600 lbs) and probably will level off at about $100/lb eventually unless the tungsten substrate can be replaced by a low cost material such as carbon fiber.

High quality graphite filaments are presently a little more expensive than the boron filaments. They are considered, however, to have much greater potential for rapid price reduction. Northrup Corporation estimated that the price of graphite filaments will drop to under $100/lb by 1975 and to $20-30/lb by 1980. British manufacturers estimated that with large-scale production, they can produce graphite fibers for $12/lb.

Boron/epoxy and graphite/epoxy tapes are currently selling at approximately the same price as the filaments.

In structural application of advanced composites, increased engineering and fabrication time are necessary because of the unisotropic nature of material properties, new fabrication process required, and the hand layup procedure for composite tapes still in use in many programs. All these factors contribute to the present high cost of structures utilizing advanced composites.

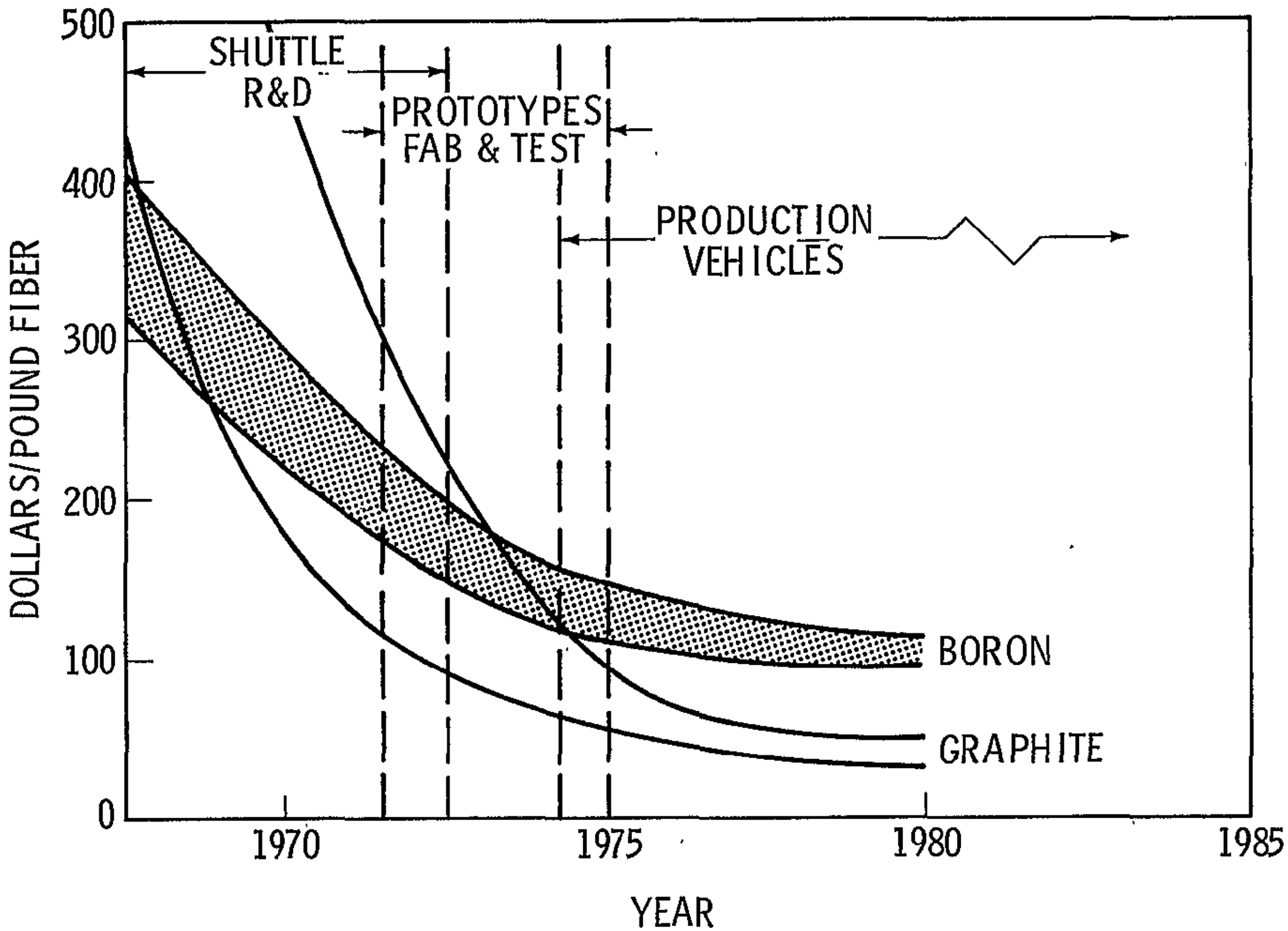
COMPOSITE COSTS

- MATERIALS
  - GRAPHITE FIBER : \$300 - 400/LB NOW TO \$25/LB FUTURE
  - BORON FIBER : \$300 - 400/LB NOW TO \$125/LB FUTURE
  - BORON/ALUMINUM : \$750/LB NOW
- ENGINEERING
  - INCREASED ENGINEERING TIME
- FABRICATION
  - PROCESS CHANGE REQUIREMENT
  - NO MASS PRODUCTION TECHNIQUE
  - INCREASED FABRICATION TIME

PROJECTED COST OF COMPOSITE FIBERS

Projected costs of boron and graphite filaments discussed in the previous chart are shown here in association of the time span of space shuttle development. It is seen that by the time when the production of shuttle vehicles is initiated, graphite filaments would most probably be priced much lower than the boron filaments.

PROJECTED COST OF COMPOSITE FIBERS



AREAS WHERE R&D EFFORTS NEEDED

Listed here are some of the important areas where R&D efforts are needed. While many items in this chart may very well be valid 10 or 20 years from now, the basic technological improvements which are most urgently needed at present to facilitate early application of advanced composites to operational vehicles are standardization of test methods, generation of new design concepts, and improvement of techniques for quality assurance.

Many users of advanced composites have developed their own test techniques for basic material properties which vary to a great extent from one another. Correlation of test results from different sources in order to generate reliable material data is very difficult. It is generally agreed among the users that both the test method and the size of the specimen should be standardized.

New design concepts are needed, particularly in the area of selective composite reinforced structures, to best utilize the unique properties of composite materials and, at the same time, to circumvent the most difficult problems such as joints, cutouts, attachments and high material and manufacturing costs.

As of today, there is no satisfactory nondestructive testing technique (NDT) for the quality assurance of advanced composites, particularly for thick laminates (more than 20 plies) and at a joint of structural elements. The feasibility of applying advanced composite to complex structural configurations is, to a great extent, dependent upon the progress to be made on the NDT techniques, without which high confidence on the reliability of the product cannot be established.

Very little information on material characteristics of advanced composites under the effect of long term space environment, i.e., radiation, vacuum, thermal cycles, and meteoroid are available. Such information is needed for the space shuttle application although no serious problems are expected at this time.

AREAS WHERE R & D EFFORTS NEEDED

- MATERIAL
  - PROPERTY DATA
  - EFFECTS OF SPACE ENVIRONMENTS
  - STANDARDIZATION OF TEST METHODS
- ANALYSIS AND DESIGN
  - FAILURE MECHANISMS
  - JOINTS, CUTOUTS AND ATTACHMENTS
  - DESIGN CONCEPTS
  - CORRELATION BETWEEN TEST RESULTS AND THEORIES
- FABRICATION
  - EFFECTS OF FABRICATION PROCESS TO THE QUALITY OF PRODUCTS
  - MASS PRODUCTION TECHNIQUES
  - COMPLEX SHAPED STRUCTURES
  - TECHNIQUES FOR QUALITY ASSURANCE

CONCLUSIONS

Boron/epoxy is technologically ready for selective application. Although some uncertainties and difficulties exist, sufficient experience in producing and testing boron/epoxy structural parts has been accumulated. Even more encouraging is that a series of flight tests on primary structural components made of boron/epoxy have been scheduled in the next two years; the results would certainly enhance the confidence on using this material in production vehicles.

All-composite structures present several design and fabrication problems such as low joint efficiency and reliability, strength around cutout, lack of established fabrication and production technology, the extreme sensitivity of product quality to process variation and the high cost of materials. These problems must be solved before realizing wide-scale application. Composite reinforced structural concept, on the other hand, has the potential to avoid or alleviate these difficulties. Selective reinforcement, therefore, may turn out to be a practical approach for near term applications of advanced composites.

Based on the selective application of advanced composites to the space shuttle primary structures it is estimated that a 5% saving on the inert weight of the vehicle is possible.

Finally, it should be pointed out that graphite/resin-matrix composites are potentially superior to boron composites in almost all the major considerations including material properties, fabrication and cost.

CONCLUSIONS

- BORON/EPOXY IS TECHNOLOGICALLY READY FOR SELECTIVE APPLICATION
- REINFORCED STRUCTURAL CONCEPT FACILITATES USE OF ADVANCED COMPOSITES
- UTILIZATION OF ADVANCED COMPOSITES COULD SAVE 5% INERT WEIGHT OF SPACE SHUTTLE
- GRAPHITE COMPOSITES ARE POTENTIALLY SUPERIOR TO BORON COMPOSITES IN MATERIAL PROPESTIES, FABRICATION, AND COST

RECOMMENDATIONS

The technical status and the potential weight saving capability of advanced composites warrant serious consideration of these materials in Phase B study of the space shuttle. Structural components of the space shuttle for which advanced composites can best be utilized should be defined; the true weight saving potential of different design concepts and different degree of utilization of advanced composite should be assessed; and the technical difficulties on design and fabrication of each type of structural elements as well as structure assembly should be pinpointed.

NASA research and technology programs on advanced composites should be expanded. Near term emphasis should be placed on structural application of existing materials, particularly on the selective reinforcement concept being pursued at Langley Research Center. This is an area in which Air Force has not sponsored much effort, and it is also an area where lies the potential of promoting an early, wide-scale structural application of advanced composites.

To fully capitalize on the experience gained by the Air Force and to avoid duplication of future effort, close coordination and cooperation between NASA and Air Force technical personnel at all levels are desirable.

RECOMMENDATIONS

- CONSIDER ADVANCED COMPOSITES IN SPACE SHUTTLE PHASE B
- EXPAND NASA TECHNOLOGY PROGRAM NOW
- INSTITUTE COOPERATIVE PROGRAM WITH AIR FORCE

BELLCOMM, INC.

Subject: Advanced Composites for Aerospace Structures - Case 105-6

From: A. S. Kiersarsky
C. C. Ong

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