1974

# Advanced Composites Status Review

Leslie M. Lackman
*Rockwell International*

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**Abstract**
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**Disciplines**
Materials Science and Engineering | Structures and Materials

# ADVANCED COMPOSITES STATUS REVIEW

Leslie M. Lackman
Los Angeles Aircraft Division
Rockwell International Science Center
Los Angeles, California

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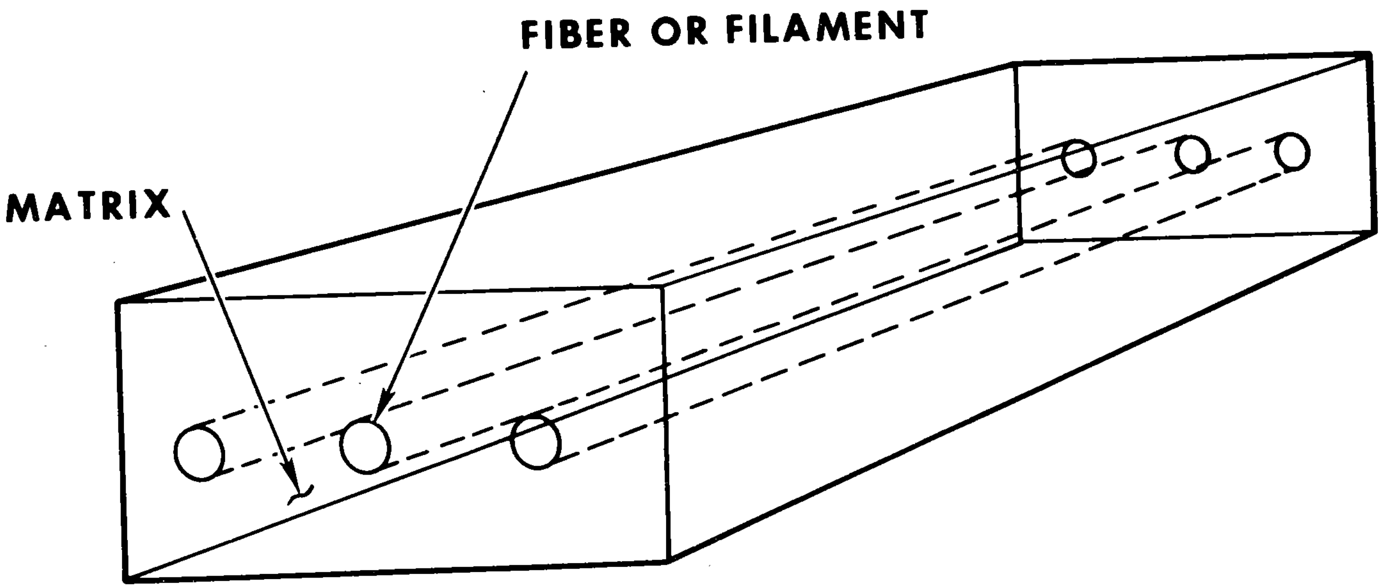
My talk will culminate with a brief film that was prepared by Rockwell for an AIAA talk in Washington. It will cover a few things I won't cover in my talk and also give you an overview summary of some of the ideas that I will discuss and bring to the forefront this morning.

I might start out with fundamentals and say, "What do I mean by filamentary composite materials?" For some of you who are not familiar with the field, what I am talking about is the embedment of unidirectional, collimated fibers in a low-stiffness matrix (Fig. 1). Normally, the fibers have high strength and high stiffness, and the matrix has good ductility, but low stiffness. We refer to this system as "advanced" composites, as opposed to composites like fiberglass, which has high strength but low stiffness. So, this is a more balanced material and, therefore, a very attractive material, which I will get into later. It has the stiffness and strength

# FILAMENTARY COMPOSITES

- THE EMBEDMENT OF UNIDIRECTIONAL COLLIMATED FIBERS IN A LOWER STIFFNESS MATRIX MATERIAL




- COMPOSITES USING HIGH STRENGTH AND HIGH STIFFNESS FIBERS ARE CLASSIFIED AS "ADVANCED COMPOSITES"

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Fig. 1

characteristics that one wants when considering its application to aerospace vehicles.

We might first take a look at the fiber reinforcement systems. The two principal ones we are utilizing today in the industry are boron and graphite (Fig. 2).

Boron comes in two sizes, a four-mil diameter fiber and a 5.6-mil diameter fiber. There are 70,000 feet of fiber to one pound. The center of the fiber is a half-mil tungsten substrate. In the cases where we utilize the boron for metal matrix applications, where we are talking today mainly about boron/aluminum, we want to consolidate the materials at a thousand degrees F. We do have degradation problems and interface problems between the matrix and the fiber at high temperature. To solve these problems, we coat the fiber with silicon carbide. The resulting fiber is normally referred to as the Borsic fiber, a Hamilton-Standard trade name. Today, most people are consolidating under a thousand degrees because the Borsic fiber has poorer qualities than the basic boron fiber.

On the right side of Fig. 2 is the graphite fiber. You notice it is only about a tenth of the diameter of boron. It comes in a different form, called a tow. It looks like rope. There are about 10,000 fibers per tow, and about 1,667 feet of tow in one pound of graphite.

Figure 3 summarizes the way in which we develop the material into a useful form and how we use it. We are talking about boron fibers. They are formed by a deposition process in which boron is deposited onto a tungsten substrate at 2,000 degrees F. We use tungsten because we have to use some type of material that is a conductor and has reasonable strength at 2,000 degrees temperature. After the deposition process, the fiber is rolled up on a spool. These spools are sent to a prepregnator who collimates the filaments from these spools, impregnates them with a resin, advances the resin or "B-stages" so it has some tack to it but is not too tacky, rolls it in a spool, and sends it to the user. The user performs incoming inspection of the material. After it has passed incoming inspection, the material is then crossplied to a given structural configuration and then cured in an autoclave under temperature and pressure for a specified time. The resin is thus hardened to its usable form.

# REINFORCEMENT FIBERS

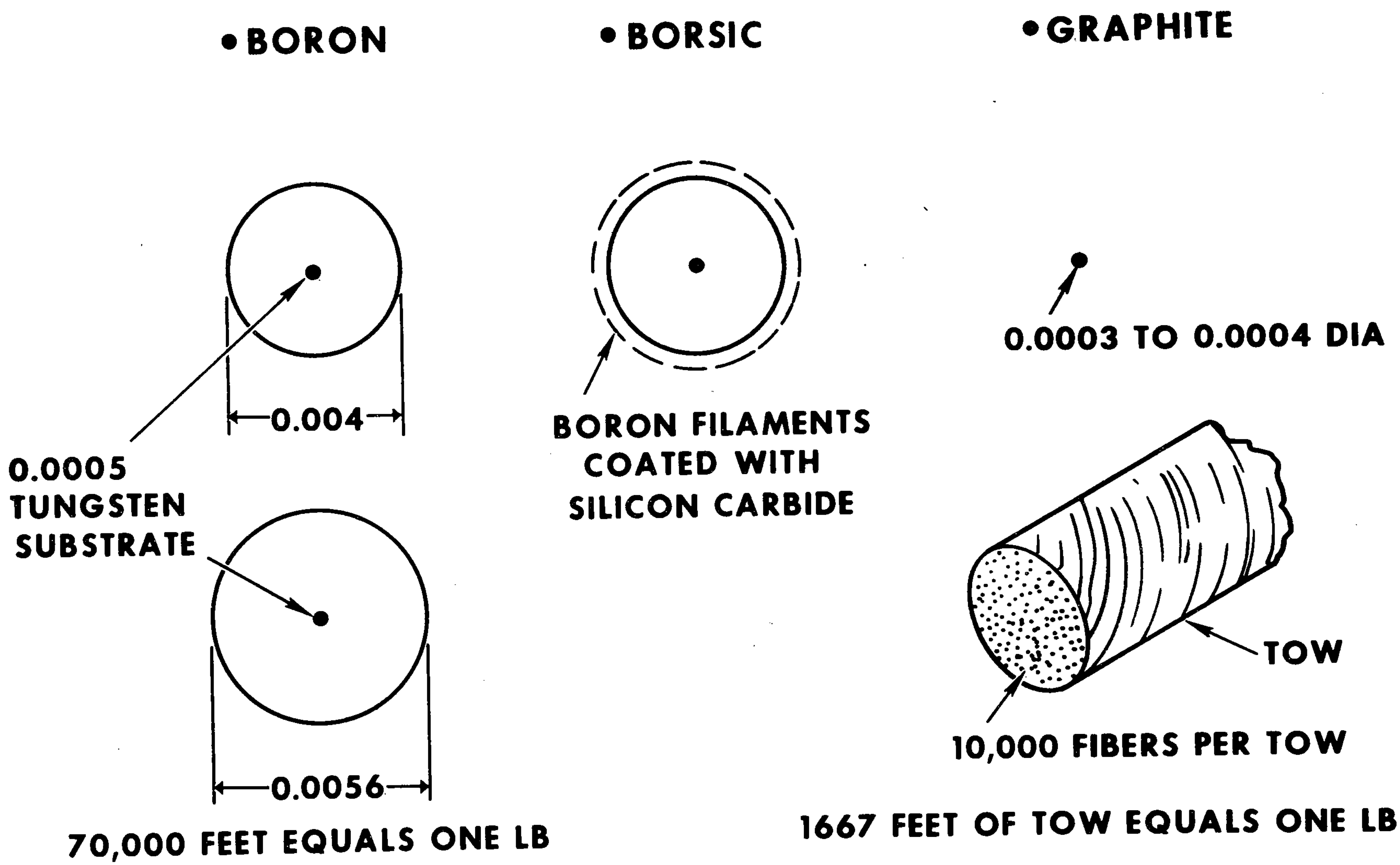


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Fig. 2

# BORON/EPOXY TAPE AND LAMINATE FABRICATION PROCESS

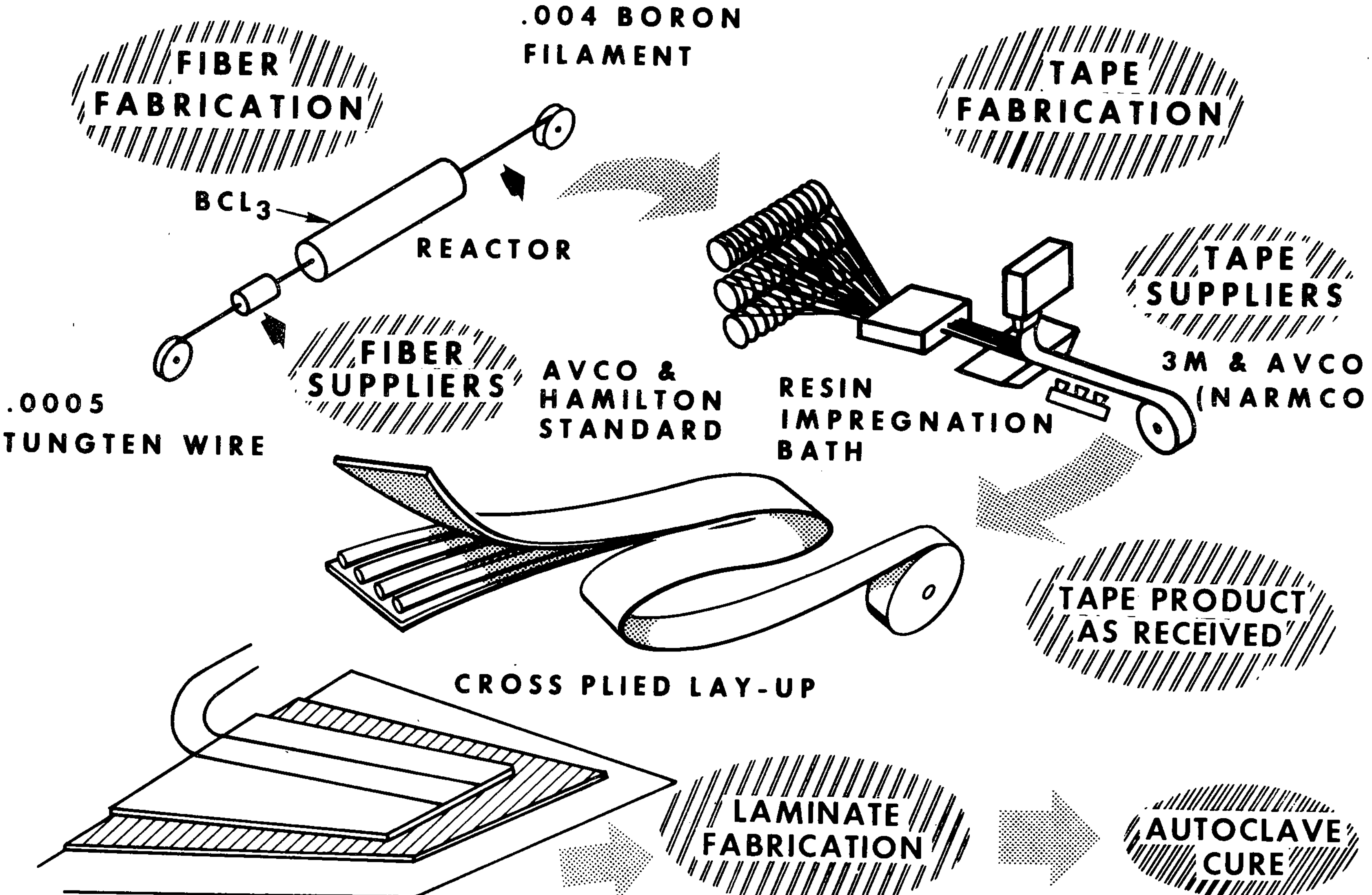


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Fig. 3

In contrast to the boron fiber, there is not one graphite fiber, but several. Figure 4 explains why. We start off with a precursor material. The predominant one utilized in the industry today is PAN (polyacrylonitrile). This PAN material is stretched in tension and is then put through a carbonization or graphitization cycle. The prestretching aligns all the crystals along the length of the fiber. In contrast to the boron fiber, which is basically isotropic, the graphite fiber is heavily orthotropic in nature. It has very good properties along the direction of the fiber, but its transverse properties are quite low, both in strength and stiffness. The first carbonization cycle results in a type A fiber or AF type fiber, which is a low-cost fiber. A second cycle of carbonization results in a high tensile strength fiber, which has strength properties equivalent to boron. A final graphitization cycle results in a high modulus type fiber which has modulus values similar to that of boron. Around 1800 or 1900 degrees centigrade is where we get the maximum tensile strength of the fiber; after that, the density of the fiber continues to increase with time and, very interestingly, the interlaminar or the bond shear capacity between the matrix and the fiber material decreases with increasing temperature. It is obvious that with every additional cycle, there is a cost delta. That is why the prices vary, depending on the type of graphite fiber purchased; however, recently industry has combined the first two cycles into one to get a system that falls somewhere between the two. This is the current low-cost fiber system that people are utilizing in general.

When we are talking about metal matrix, it is a different process entirely (Fig. 5). Basically, it is a diffusion bonding process, where one starts with two sheets of metal, either aluminum or titanium. The fibers are spaced between the two sheets of metal. We then put this system into a retort and we apply pressure and temperature. With time, the sheet metal flows between the fibers, filling the gaps, and we end up with consolidated hardware. Now, this type of material, for example, boron/aluminum, is readily available within industry; however, it is not cost-competitive to the epoxy systems and,

# GRAPHITE / EPOXY FIBER BROADGOODS AND LAMINATE FABRICATION PROCESS

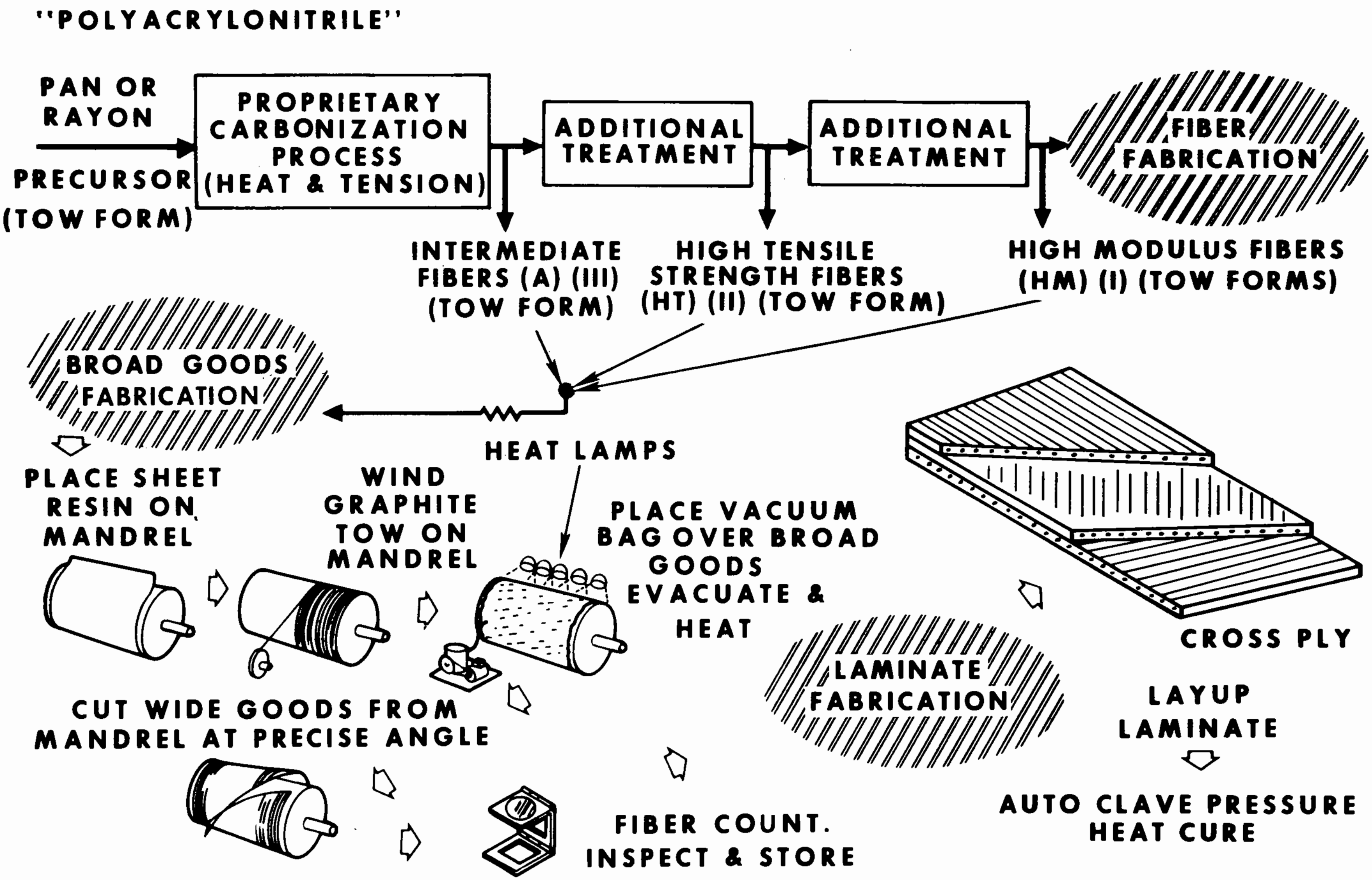


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Fig. 4

# METAL MATRIX FABRICATION PROCESS

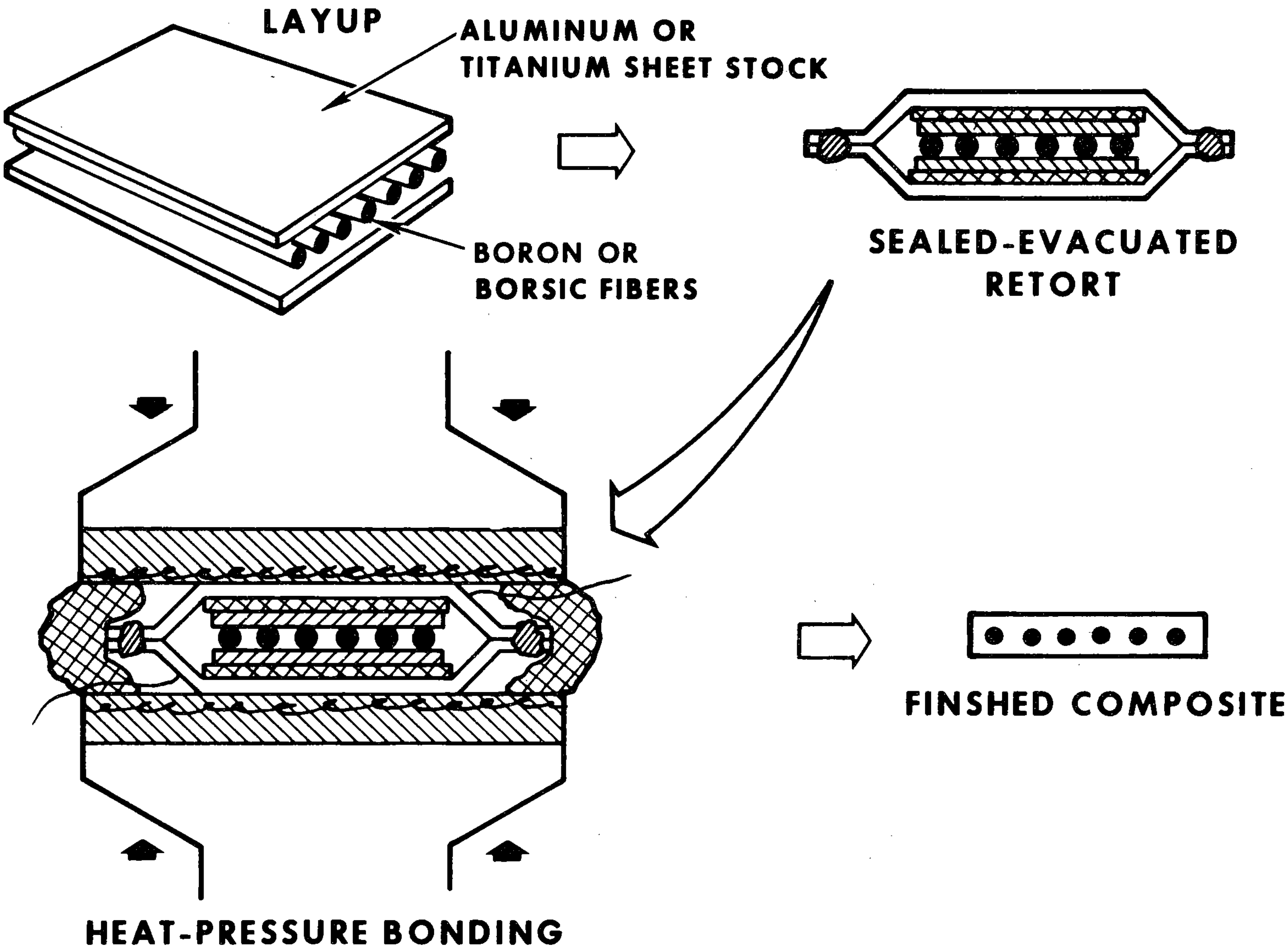


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Fig. 5

therefore, is mainly being utilized for the higher temperature systems where the epoxies will not suffice, or for certain types of environmental conditions where metal matrix systems are more suitable.

Here (Fig. 6) we see a summary of the boron and graphite systems. This is just fiber strength and stiffness. As I pointed out earlier, the graphite HT fiber compares very nicely with the boron fiber in tensile strength, but not modulus. It requires HM fiber to compete with the modulus of boron. When we talk about density, though, the density of graphite is about 70 percent that of boron.

The boron is usually 50 percent by volume. If we go to a graphite system, we are talking about 60 percent or greater. The graphite seems to be a little bit more optimum for the packing together of the filaments.

What is so great about composites? You probably have guessed already. First of all, composites have a very high strength-to-weight ratio (Fig. 7) but, in addition to that, they also have a high stiffness-to-weight ratio. Thus, they have both properties that are primary in the design of structures. In addition to that, they have a third feature which is very important. They have the ability to be tailored to meet design requirements. If strength is required in a certain direction, I can put the strength in that direction. I don't have to dilute it with strength in another direction that is not required. For example, in the case of a cylindrical pressure vessel, where the hoop stress is twice the longitudinal stress, the isotropic metal in a metal cylinder has the same strength in both directions. That isn't needed. I can go to a composite design and so design it that I have twice the hoop strength as longitudinal strength, so I can optimize my material and put it where I need it. This is a very important characteristic. The principal function in design is to find out what type of tailoring is needed to get a very efficient composite design.

We talk about temperature applications. What are the useful temperature ranges? Generally speaking (Fig. 8), the epoxy systems are useful up to about 400 degrees for short periods of time. That's about their limit. Above that, the strengths are very small. If it is desired to extend the range of this

# FIBER PROPERTIES

- BORON (4 OR 5.6 MIL)
- GRAPHITE WITH "PAN" PRECURSOR (TOW PROPERTIES)

HT=HIGH TENSILE STRENGTH
HM=HIGH MODULUS



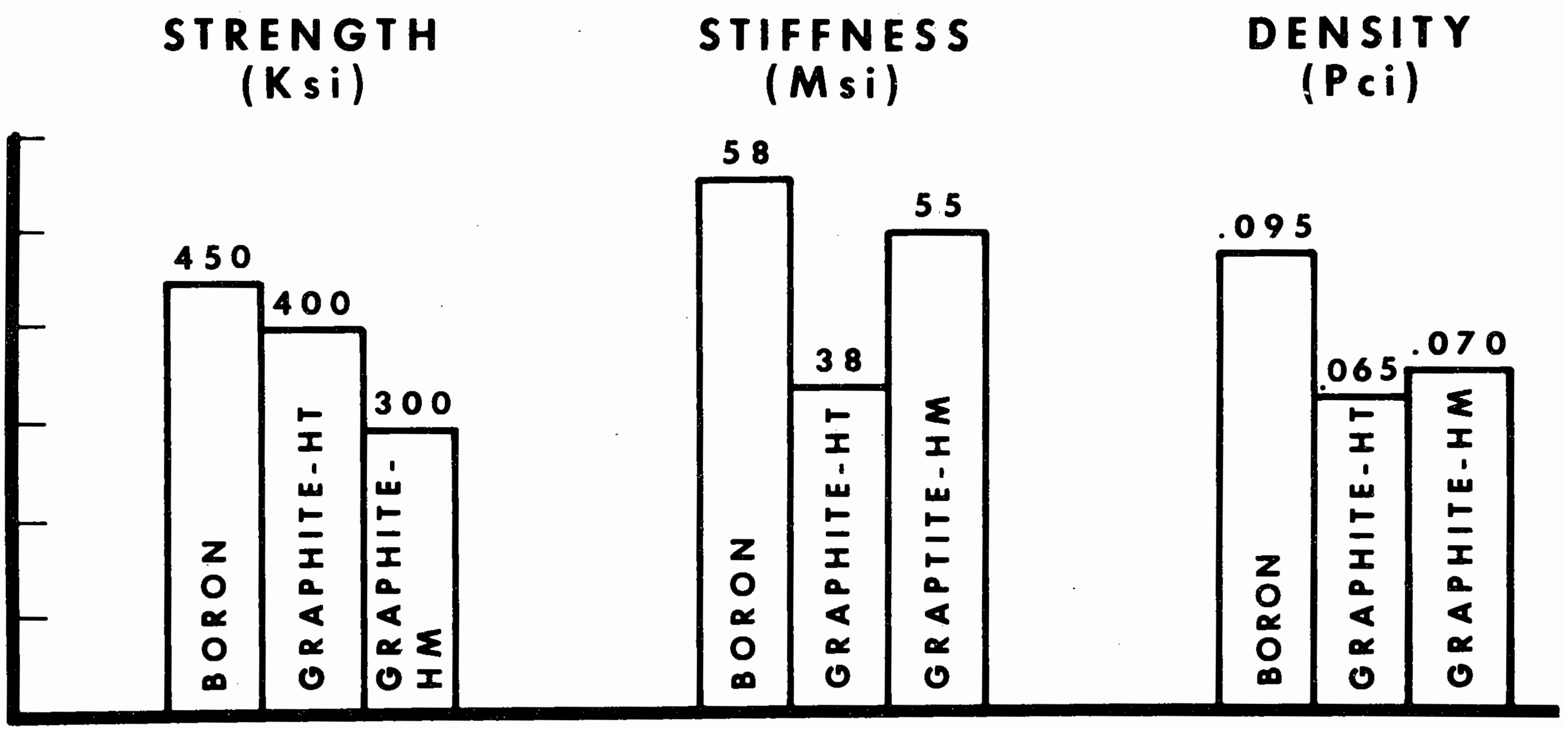


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Fig. 6

# ADVANTAGEOUS COMPOSITE CHARACTERISTICS



- HIGH STRENGTH/WEIGHT
- HIGH STIFFNESS/WEIGHT
- ABILITY TO BE TAILORED TO MEET DESIGN REQUIREMENTS

Fig. 7

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# AVAILABLE ADVANCED COMPOSITES USABLE TEMPERATURE RANGE

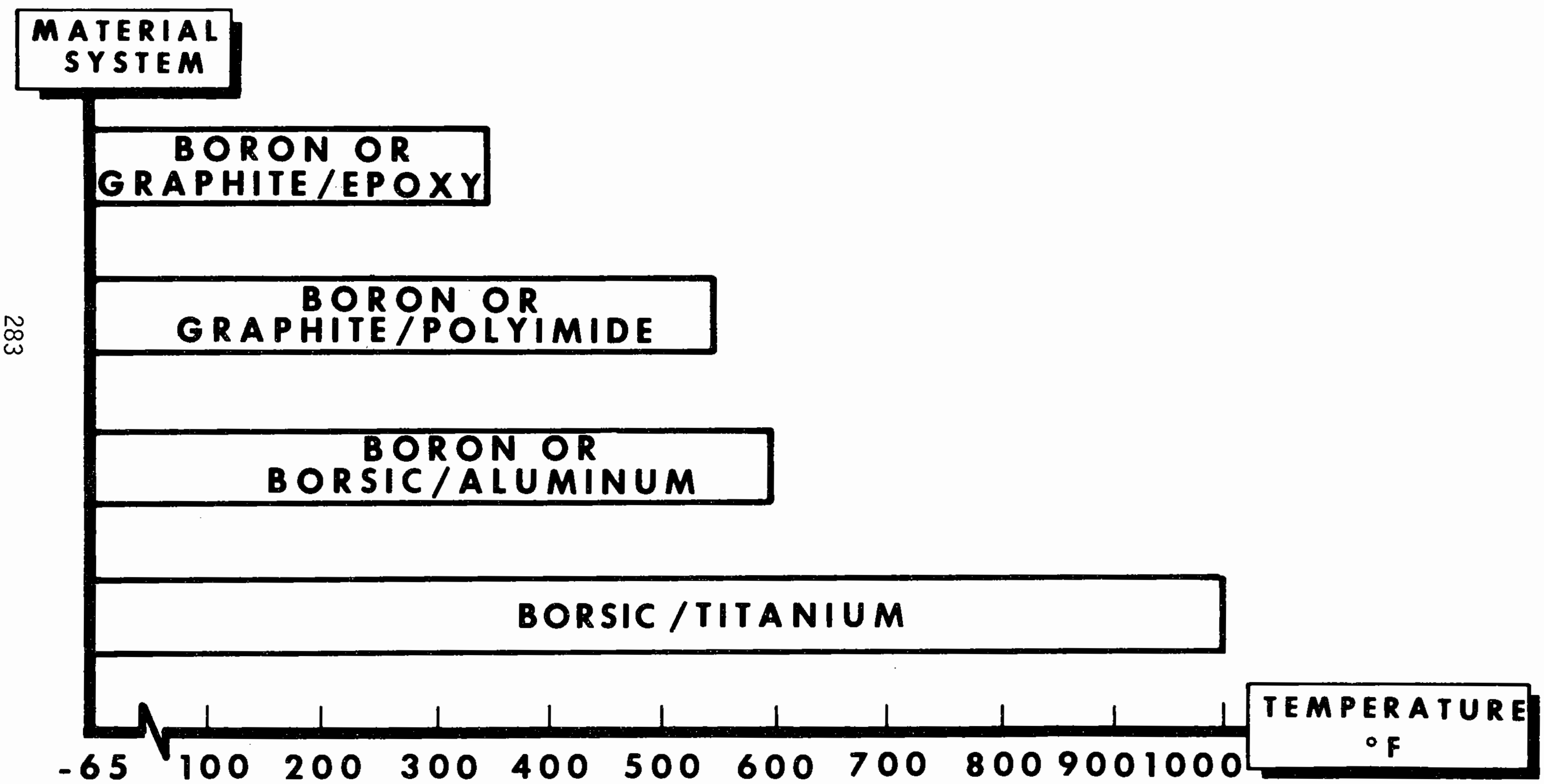


Fig. 8

TSP70-5913

type of system, a polyimide-resin type of system is needed. They have a maximum usefulness to about 550° F. If we want to go to 600° F, we can go to boron or borsic/titanium. There has been some work done in this area, but there have not been extensive applications of the titanium material system. It is available in the R & D phase today, however, and limited quantities could be purchased, if desired.

Everybody talks about the price of these materials, saying they are a hundred, two hundred, three hundred dollars a pound. That was true, but it is no longer. If we talk about the graphite/epoxy system, back in 1970, it was in the range of $100 to $200 a pound. Today, we can buy it between $40 and $50 a pound, and can buy all we want. We are predicting that by the end of this decade, the price of graphite fiber will be of the order of $10 to $20 a pound. Boron will be $50 a pound, but this will be a different fiber with a carbon substrate to replace the tungsten, which is getting very expensive. Some suppliers, especially Union Carbide, are looking into the use of pitch as a precursor for graphite fibers. We think, then, the price of these graphite fibers will be as low as one to two or maybe three dollars a pound. So we don't see this material being an expensive material by the end of this decade. We think it will be a very reasonably priced material. When you look at the escalating price of metals, the picture gets better all the time. With reasonable inflation factors of four or five percent per year for materials, this is realistic. Materials inflation factors are always much lower than labor inflation factors. So, with reasonable inflation, we think these predictions will hold.

Well, what is the payoff for airframe structures as far as composites are concerned? (Fig. 9). Well, obviously, we can reduce the weight of the airframe or we can trade this back in terms of several things. These include greater payload, greater performance (either speed or range) or a smaller size aircraft which may, indeed, be a cheaper aircraft. So, there are lots of options here. In any system one has to go through optimization trade studies to see what is the best configuration and try to trade that way for the particular system.

# POTENTIAL AIR VEHICLE PAY-OFFS WITH ADVANCED COMPOSITES

- REDUCED AIRFRAME WEIGHT

**GREATER PAY LOAD**

**GREATER PERFORMANCE** (SPEED OR RANGE)

**SMALLER AIRCRAFT SIZE**

TSP70-5931

Fig. 9

I would like to talk about the 1965 to 1970 or 1971 time span and what has been happening during that time. First of all, there were extensive efforts in developing a good design analysis technique for a laminated composite structure. As a result of that effort, today we can certainly predict with a great deal of confidence and reliability the overall stiffness and response behaviors of laminated plates, sheels, and beams. We can determine the internal load distribution of the interlaminar stresses and normal stresses that exist in laminated structures and, therefore, we feel we have a good handle from the standpoint of design in the area of bonded and mechanical joints. However, this area still remains more empirical in nature than analytical. Of course, the metal design of mechanical joints is also still somewhat empirical in nature.

During that same time period, we began to see some commitments of composites to production systems. Mainly, these were the types of commitments where the sandwich is in a membrane state of stress. We are talking about full-depth sandwich construction within facesheets. This construction minimizes interlaminar shear stresses, and minimizes normal stresses. These types of stresses are the Achilles' heel of the composite. This is a weak transition zone in which we are talking of stresses or strengths the order of 10 to 15 thousand psi. In the plane of the laminate we can have stresses as high as three or four hundred thousand psi. So, this type of construction is very efficient. It yields high payoffs and minimizes the loadings in the directions which are weak. Examples of full depth sandwich applications are the F-15 horizontal and vertical and the F-14 horizontal. There are some R & D programs looking at the F-111 horizontal tail. Some C-5A leading edge slats and some other surfaces were also fabricated; all these were full-depth sandwich varieties. This is really the first generation composite application to ongoing systems. McDonnell Douglas is just now committing themselves to a speed brake which will be composite. In addition to that, they have an ongoing program with the Air Force Materials Lab to design, test, and flight-test an all-composite wing that will be fully qualified for production. This work is a breakaway from the full-depth sandwich type of application. It is one of the earliest programs directed at going beyond the full-depth sandwich type of structure and selecting a built-up type of construction or a more conventional type of construction normally found in primary lifting surfaces. If we take a look at that design in a little more detail, we find that the skins are all boron. The stiffeners are graphite. It is kind of a minisandwich about two or three-tenths of an inch thick. The substructure is all graphite or metal; the front spar and the rear spar and several intermediate spars and ribs are metal. As you can see, this is getting away from the full-depth sandwich type of construction. It is built-up type of construction, and introduces new design problems and fabrication problems as well.

The other production application is the Grumman F-14 where the horizontals are full-depth sandwich with boron skins. If we take a look at the details, the surface area of the boron per side is 70 square feet. At the maximum thickness, it is 56 plies thick and has a weight saving of 19 percent over the metal baseline design.

Another approach which has been basically supported by NASA is what we call selective reinforcement. This is a kind of compromise where rather than saying, "Well, let's go all out and utilize composites", we say, "let's reinforce metal selectively with metallic or unidirectional laminated composite materials". Now, the payout from this is we do exploit our experience with metal structures. In other words, we have good design analysis procedures and fabrication procedures for metal structures, and we will only use reinforcement away from joints. Therefore, we don't have a joint problem, and by the same token, we certainly exploit the excellent properties of advanced composites. In other words, the highest properties are obtained when we use them in a unidirectional manner, when we don't cross-ply. When we begin to cross-ply, we begin to compromise the properties in one direction or another. When we use them in a unidirectional manner, we get the maximum strength and stiffness-to-weight payoffs. The disadvantages are: 1) you are never going to get as high a weight-saving as you would with all-composite application, and 2) it doesn't look like this type of construction can become cost-competitive with comparable metallic structure.

Figure 10 symbolizes what selective reinforcement concepts might look like applied to axial-load members such as longerons and skin stiffeners.

# TYPICAL REINFORCEMENT CONCEPTS

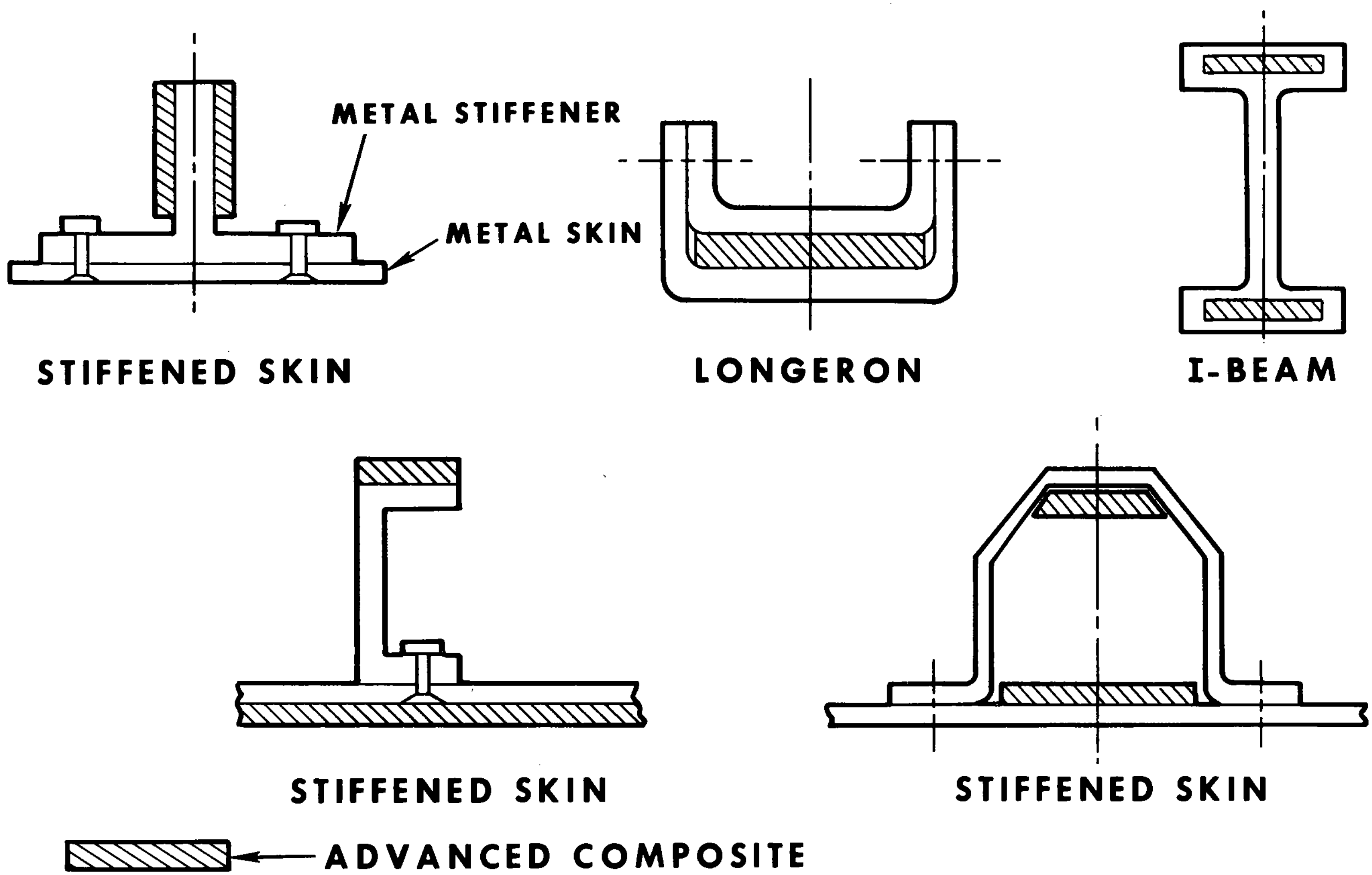


Fig. 10

There is a program with NASA that Lockheed-Georgia has looking at the C-131. They are utilizing this type of stiffening arrangement for that air vehicle. This figure shows several types of stiffening arrangement. You notice we try to keep, if possible, the reinforcement balanced about the neutral axis. If not, we will get warp as a result of the mismatch in coefficient of thermal expansion, resulting in thermal stresses from cool-down from the temperature at which the composite is bonded to the metal.

Also shown is another selective reinforcement concept in the I-beam. This is an embedment concept where the composite is embedded in the metal itself. AVCO is going to push for this type of concept, and will supply the user with materials in that configuration.

Probably the most successful application to date of selective reinforcement has been on the B-1 longeron, where composites were utilized in a secondary application. These longerons are basically stiffness-critical. There are five longerons: a dorsal longeron, two lower inboard longerons, and two lower outboard longerons. The design criterion currently being utilized is that the metal straps must be strong enough to carry limit load by themselves, whereas the metal plus the composite must satisfy the ultimate load conditions and the stiffness conditions for those longerons. Those longerons provide the overall EI which is required for the aft fuselage to support tail loads without undue flexibility. In this particular application, the boron is bonded to the straps. There are no fasteners through the composites. We all know that when we drill holes through composites, especially boron, which is next to diamond on the hardness scale, we have to use diamond tools. If we use a steel tool, we will dull it like a pencil on sandpaper and it won't last very long. Therefore, this is an all-bonded concept utilizing about 450 pounds of boron. We are saving almost 1200 pounds of weight or almost a three to one ratio; almost three pounds saved for every pound used, which is very attractive, indeed. We have a 44 percent weight saving for the lower longerons, which are compression-bucking critical, and since the metal is not as efficient in compression as tension, we need more for strength than we do for the dorsal. The amount of boron required for the dorsal is less, therefore; the payoffs are not as high.

I would like to go a little bit further in this design to point out some of the concerns when using composites. It is not without its problems. As someone said, composites are an analyst's dream and a designer's nightmare. In some degree that is probably true, because in general, one actually treats composites like a nondestructible durable material. They are very unforgiving if one misses a failure mode or a load path; it is not like a metal. For years, civil engineers have been very fortunate when they assumed the loads would go one way and in the structure they went another; the way they went yielded and they went back the way the engineers assumed they went in the first place, so civil engineers have not had too many failures. When we get to brittle materials, we don't get that second chance, so we have to be really sure that we have done a good job in analysis.

Now, let me point out here the role of a bonded joint; later on we will get to some of the inspection techniques that are required. In the case of the B-1 longerons, I have pointed out that the boron was totally bonded to a steel strap and we stepped the plies longitudinally. We had ply steps at every 3.5 inches. Consider a longeron which is two inches thick (the dorsal longeron) which we built up to about 300 plies. By stepping the plies every 3.5 inches, we were able to minimize the shear and peel stresses between each ply and also between the base ply and the metal strap to reasonable levels. Then we began to look at what happens in the transverse direction. The problem here is that we have all unidirectional boron, so that in the transverse direction we have basically only the resin thermally expanding. We have a transverse expansion coefficient of about 15 for the composite and about six for the steel with only a little adhesive bond line in between. We end up with a type of distribution of normal stresses and shearing stresses due to the thermal mismatch that results from curing the boron to the metal strap, which we believe occurs at about 320 degrees, compared to a minimum operating temperature of minus 65, which gives a delta of 385. As a result of this, we can get peel stresses in the rangeof 18 to 19 thousand psi in the corners. We were very much concerned about this relative to the fatigue strength of this design. We are talking about an airplane that is supposed to last 15 or 20 years. With those high peel stresses we were quite concerned.

As I pointed out earlier, one of the nice things of composites is the ability to tailor it to meet design requirements. In this case, we wanted a physical property such that the boron approximately matches the steel in coefficient of thermal expansion. So, we chose to put one 90° ply in this laminate for every nine plies of zero degrees. That reduced the coefficient of thermal expansion down to about 6.8 compared to 6.2 for the steel. We ended up with peel stresses in the neighborhood of a thousand to two thousand psi. We thought we had very nicely eliminated the problem. Then we started to look more closely and we found that we had pushed the problem into the laminate. In the laminate, where we have one 90° ply out of ten, the internal stresses resulting from just the cure of the laminate itself can amount to as much as 52 ksi at the free edge. Since the edge is free, we must have shear and normal stresses reacting at the edges to achieve equilibrium. What we chose to do in this case to minimize the peel and shear stress at the edges was to cut a sawtoothed pattern in the edges of the 90° plies such that when we cure the resin, the sawtooth pattern is filled with resin and, therefore, has basically the same properties as the ply above it at the free edge. This reduced these stresses by one to two thousand psi.

Since that time, Dr. Brown and I have done some analysis of this, and for those of you who are interested, there was a paper delivered at the AIAA-ASME materials conference in Las Vegas recently, where we discussed this serration problem and the effects of serration on blunting the normal stresses. Dr. Nick Pagano of the Air Force Materials Lab, along with Prof. Byron Pipes, of the University of Delaware, have done a lot of work in this area in the last few years. Those of you who have read the literature in the Composites Journal from AIAA and have followed Dr. Pagano's work know that he is beginning to characterize and develop design tools such that we can arrange stacking orders to minimize the normal stress, which is the Achilles' heel for composite materials.

Well, I have briefly covered where we have been. Let's talk about where we are today and let's end with where we are going.

The new thrust today is the development of cost-competitive composite hardware. Everyone thought that once we built some structure and showed we could save some weight, that was going to be good enough. Well now, that is not good enough anymore; we are in a very cost-conscious world, and designers are not going to utilize this construction unless it competes favorably on a direct cost basis. So, the new thrust of both the industry and the Air Force Materials Lab, who has been the leader from the beginning as far as composite technology goes, and who has the charter for the ADP from the Air Force, have been utilizing the B-1 as the demonstration article to show that for both primary and secondary structures, composites can be competitive on a production basis with comparable metal structures. Our goal is at least 20 percent weight savings and 10 percent cost reductions relative to metal parts.

In order to achieve this goal, we believe we have got to utilize low-cost manufacturing concepts. There are a lot of low-cost manufacturing concepts available today, such as co-curing, pultrusions, etc., which can be utilized to reduce the cost. We are also trying to automate. Considering where we are today in composites, we have come a long way in spite of the fact that we don't have a hundred thousand dollars' worth of machinery out in the shop such as the metals people have. We have very little in the way of automated equipment.

I think that there is a lot that can be done to improve this story. In the past, all composite designs have striven for the utmost in performance, aiming for 30 percent weight savings, if possible. This has driven up the cost. We have gone to very sophisticated, efficient types of constructions, but these have been very difficult to build in the shop. So we are saying, "Let's trade back some of that weight. Let's make it easier for the shop to build." We can drop the weight saving from 25 to 20 percent and the cost picture changes by almost 30 to 40 percent because we are going to simpler constructions that we rejected in the past because they did not give us great enough weight savings. We are going to constructions now that are easier to build, easier to inspect, and easier to service. At the Los Angeles Aircraft Division, as at a lot of other places, we have co-location of the engineering and manufacturing team. When the design is initiated, the manufacturing man is involved in that design. We can't wait until after the design is finished and say to the shop, "Build it cheaply." We have to get manufacturing involved from the beginning so they can get their inputs into the overall design loop. And, last but not least, is a thing called "optimum materials mixture of hybrids." If one goes through a design and attempts to minimize production costs, there is no such thing as an all-graphite design or all boron design. We will generally end up with all of the materials existing in our design, because we must look at each element of the overall concept and determine what is the best material for that element to minimize the overall costs of the structure. Therefore, there is generally a good percentage of metal in minimum-cost composite design in structures.

Now, the Advanced Composites Applications Office of AFML has initiated a major program using the B-1 as a demonstration base to show that both primary and secondary structures can be competitive on a production basis with metal construction. The program consists of four elements. The B-1 horizontal stabilizer program is currently underway with Grumman Aircraft Corporation as prime and Rockwell as subcontractor. That program has been underway since about June of 1973. The B-1 secondary structures program, which Rockwell has as prime, was initiated just recently; subcontractors in this program include Northrop, Lockheed-Georgia, and Rohr. The vertical stabilizer program is now in procurement for evaluation, and the wing program, which is a major effort, involves the development of a replaceable composite wing for the B-1 aircraft. The RFP is currently on the street. So, this is a viable program. I think it is going to go a long way toward documenting that on a production basis, whether it be primary structure or secondary structure, composites are viable competitors to metal structures.

Figure 11 attempts to summarize where we are going today, what we are trying to do. I am saying in the past we have gone from the point denoting the metal part over to the maximum efficiency composite part to optimize payouts.

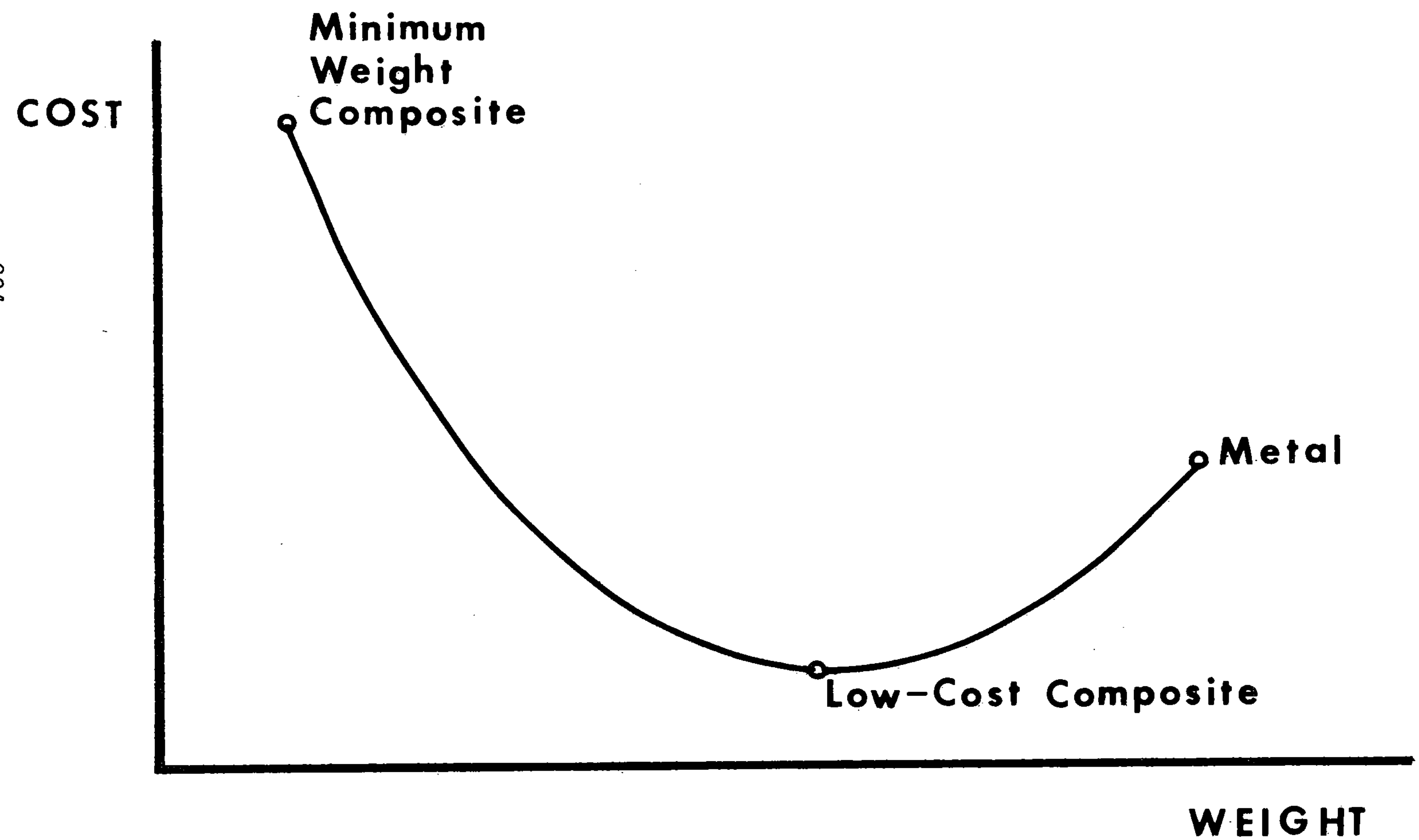
COST
Minimum
Weight
Composite
Metal
Low-Cost Composite
WEIGHT

Fig. 11

We have achieved 20 or 30 percent weight savings, but at a cost premium of 50 to 100 percent over the basic metallic cost. I am saying let's come down this curve. Let's trade back weight for improvement in cost. If we do that, we will still wind up with 10 to 20 percent weight saving but rather than being above the line on cost, we are going to be below the line on cost, we are going to be below the line, and that's what we are trying to do.

Well, let's take a look at the future now and see where we are going. We have already gone to substitution design where we replaced basic metallic structures with equivalent composite designs; the F-14 and F-15 are examples of that. The cost of the composite was of the order of $200 per pound. Today, we are looking at the B-1 applications and other advanced development applications which we can call first generation conceptual. We are talking of the order of a hundred dollars per pound for the structure. Second generation conceptual is where we want to go. Let's remove all the constraints, let's come up with air vehicles that can be prototyped and with new systems for military and commerical. And let's come up with configurations and solutions which are best for composites. We think that will yield structures in the order $50 per pound, which is equivalent to the cheapest aluminum structure today for commercial applications. So, that's our goal and we think we are going to get there, but, obviously, to get there, there are several major development areas. Obviously, one of them is the B-1 application because it is going to point out for all concerned that composites can be competitive on a production basis with metallic structures. The next development area is the second generation airframe design, where we are going to be looking at ways and means to further optimize composite structures once we have eliminated all practical constraints that now exist in the applications that we have considered to date. Another area is hot airframe applications. All our applications today use epoxy matrix materials. Later on, we want to look at metal matrix and polymides, not only for military application, but for the supersonic transport, even the shuttle application, or any type of application involving higher temperatures.

In the area of propulsion systems, there will be major efforts by the laboratories and industry involving the substitution type design for both static and rotational parts. They are somewhat lagging behind the airframe programs as far as utilization; therefore, material substitution would be the first stop in the broad utilization of composites for propulsion systems.

Last, but not least, is the area of life assurance and reliability. This is going to be a major requirement if we are going to see significant utilization of composites on future systems. The key areas are damage tolerance and durability requirements. As a result of the F-111 and the C-5A experiences, the industry and the Air Force both are well aware that we must have a safety factor in fatigue. We have a static factor for strength. That is not enough to insure adequate integrity of the structure during its design life. It is unfortunate, but it is a fact of life, that when a structure or an airframe or aircraft is delivered to the services from the builder, there are natural flaws that exist in that structure, defects that have been generated either during fabrication or during the basic fabrications of the materials utilized in the design of the airframe itself. These flaws, if undetected in certain sizes, can grow to proportions such that they can induce failure of the airplane prior to a critical inspection period or prior to the end of its design life. Therefore, the Air Force has initiated and developed two additional specifications. One is a structural integrity philosophy for fail-safe and safe-life, and the other is a damage tolerance specification. These are going to be fundamental requirements for all future Air Force systems.

Now, we in composites are going to have to satisfy these same types of specifications, although more in spirit than in the letter of the law because composite defects are not metal defects. Composite defects do not grow the same way as metal defects, but obviously we are going to have to show equivalence, that we have the same type of integrity and we can stand the same damage tolerance and durability requirements that the metal structures do.

One of the major areas is going to be NDI. This is going to be a major thrust area because without the support of reliable NDI techniques, we are not going to be able to get this job done. For example, in flaw detection, we are going to have to develop NDI techniques that can determine composite flaws. What are these flaws? For example, there are cracks in the resin. There are filaments that are broken as a result of fabrication. There are delaminations either at free edges or delaminations occurring from the drilling of holes through the composite laminates, for example. We are going to have to determine techniques that can find these flaws in both thin and thick laminates. Thin laminates are those with four or five plies; thick, a hundred or one hundred fifty plies. A major question concerns the relationship between a flaw that has been detected and the strength of the part. Obviously, we have to come up with some type of NDI structural correlation that currently is nonexistent. If I found a flaw today, I really couldn't tell you what it means.

There are a number of candidate NDI procedures as well as a number of needs with no candidate in sight. We think that NDI proof-testing is going to be one of the viable techniques we are going to use to detect and eliminate parts with critical flaws but how will such NDI be done and what will it mean? What about things like acoustic emission; can that play a role here? I don't know. I haven't seen it tried for composites. I don't know how viable it would be for proof-testing. That needs to be addressed. What about inspection techniques? We need inspection techniques, not only for production, but suitable for depot and in the field. Are they going to be practical means of finding these flaws? These things have to be addressed. Resin chemistry is most important. As most of you probably are aware, the resins that are supplied by the prepreggers are proprietary in nature. The suppliers will not tell the user what the chemistry consists of. How do I know that one day a supplier can't get constituent X, so he puts substitute Y in, and although it has affected the long-range durability of the composite part, I won't be aware of the substitution until five years downstream. We need some type of NDI technique that can scan these resins when they come in to assure there is consistency. That is a major problem today. Another problem is direct process control. I would like to see us monitor the cure of a resin and be able to change its time-temperature cure cycle to compensate for observed property variations indicated during the monitoring of the curing process to assure that required standards will be met. These are some of the areas where I think NDI must support us if we are going to reach our goal of extensive utilization of composites in future systems.

## DISCUSSION

DR. PAUL PACKMAN (Vanderbilt University): Les, I have a question concerning your comment that in the B-1 design, there are steel strips which have to take limit loads, and that the boron/steel epoxy combination has to take ultimate loads.

DR. LACKMAN: Right.

DR. PACKMAN: The difference between those things is about 20 to 30 percent. If the steel has to take limit loads, what kind of defects are going to reduce the overloads that the boron combination has to take? It seems to me you have to have a pretty major size defect before that 20 percent difference is made up.

DR. LACKMAN: No. There is a 50 percent difference because the difference between ultimate and limit is 50 percent. Ultimate load is 1.5 times limit load. What we are concerned about are defects in the bond line surface. It is true that the boron maximum stress level is about 100,000 psi, which is about 50 percent of its ultimate capability, but we do have a problem in that the boron is loaded up via shear loads which are transferred through the adhesive bond line. We have gone through extensive programs, first, to establish NDI standards for composites and second, to relate those standards quantitatively to degradation of strength so that we can assess, once the presence of a defect has been determined in the bond line, whether or not that defect must be repaired because of its potential degradation of strength in that particular area. We have also developed repair techniques. If there is an edge crack or edge debond, then we can obviously get into the side to repair it. If it is a buried defect, then what we have to do is drill a couple of holes through the metal strap and push the resin in from one side and out the other, and then plug the holes. So, we have developed repair techniques as well to fix those areas where we think the strengths are below tolerable levels.

DR. PACKMAN: That is only part of it. Let me explain what I mean. The two parts are bonded together at all times.

DR. LACKMAN: Correct.

DR. PACKMAN: In the sense that at all times the boron/steel interface is taking loads even though they are just at limit load design.

DR. LACKMAN: Right.

DR. PACKMAN: Now, the design requirement is such that the steel, the metallic component, has to take limit load and that the combination has to take ultimate load.

DR. LACKMAN: Correct.

DR. PACKMAN: But the point is that all times below limit load, at all loads, you are carrying load by the shear transfer across the interface at any one time.

DR. LACKMAN: Right.

DR. PACKMAN: But the point is that the defects that are present in the interface don't become important until you get above limit load design because of the fact that below that the steel could take everything. In other words, the composite need not be there at all.

DR. LACKMAN: I understand. I think what you really want to know is: What are the best criteria to utilize in the selective reinforcement application. I guess they are all somewhat arbitrary in nature. This is the one that was selected for the B-1, and that's all I can say. I am saying this is the one that we felt was somewhat conservative, but could give us significant payoffs. I think maybe one can go to a more aggressive philosophy, as you point out. It was chosen not to do so.

MR. ROBERT CRANE (Air Force Materials Laboratory, WPAFB): You indicated that acoustic emission could be used during proof-testing. I was going to ask you for your thoughts.

DR. LACKMAN: I don't know. I raised the question. I don't know what it will do for composites. I think that proof-testing is going to be a viable way to go. Basically, we have looked at composites as kind of an uninspectable material in which flaws are difficult to find. They don't really propagate with time and, therefore, proof-testing may be the best way to go to make sure we don't have critical flaw sizes within our virgin material as we deliver it for production. There are all types of proof-testing. Maybe acoustic emission might be part of that program. I don't know what role they will play. I don't know how you would relate this in total, but I think it is something that needs to be assessed by those who are supporters of acoustic emission.

DR. ROD PANOS (Air Force Materials Laboratory, WPAFB): Just at the end of your talk, you mentioned the importance of NDT or NDI with the problem of cracks under fasteners. I would think that, perhaps, you would want to elaborate on that a little more because it has been my understanding that this is really one of the major problems with composites. Yesterday we heard an awful lot about cracks under fasteners and the problem of fasteners and fastener holes in composites. As I understand it, it is very important.

DR. LACKMAN: Yes, fasteners are a problem; any type of hole in a composite is a problem. We have found that we get a significant degree of degradation in composites when we put holes in them, or where we have loaded holes becaused of the high concentrations that exist around those holes. However, we have gotten a lot smarter in the last few years. We have ways of attaching softening strips and other techniques to reduce these concentrations and improve the performance. However, the problem is that often when we are drilling a hole through a particular laminate, if the drill operator isn't careful, he tends to pry the laminate apart locally, producing delaminations. These delaminations are a problem. In addition, any free edge, be it a side of a laminate or be it a hole, is going to have normal stresses and interlaminar shear stresses existing because of the equilibrium. There is a stress field which must go to zero at that free edge, which means there must be some normal stresses to put those elements near the free surface in equilibrium. These stresses can be damaging in fatigue. So, there is an overall problem, certainly, in fastener holes or free edges, and, obviously, we need to come up with NDI techniques to inspect and determine that we don't have flaws there, or if we do, they are not of a critical nature or will not grow to a critical nature during a planned inspection interval for the aircraft.

DR. GEORGE ALERS (Science Center, Rockwell International): When we use composites, we are relying on the adhesive joint between the fiber and the matrix. Why don't we just admit that we are relying on an adhesive joint and just glue the composite on the side of the airplane and not go boring holes in it and putting screws in it and make it an adhesively bonded structure all the way through?

DR. LACKMAN: Because there is a lack of confidence in composites with bonded joints. In fact, in all these B-1 applications where we are talking about built-up construction in which the covers have to be fastened to the substructure, they all use mechanical fasteners simply because we don't believe that the reliability is present in general for bonded joints. There has been too much of a variability. There are too many factors involved. For example, if we are bonding to titanium, the strength is very much a function of how well that titanium is cleaned, how well it is primed. One day, we may get one type of tap water; the next day, another type. There are all kinds of problems involved. I, for one, don't believe that the reliability has been developed to the point for bonded joints that I would like to see them committed to primary structural applications. I think that is the general feeling in the industry regarding bonded joints, even for metals. You don't see bonded metal joints in primary structure. Why not? Because people say, "I don't know how well they are going to hold up. I don't know how to inspect them." There are great variables in their strength properties from day to day, from company to company, from shop to shop. I want to avoid that problem and, to me, that means mechanical fasteners.

DR. ALERS: Wouldn't it be a great weight saving if you could get rid of all those fasteners?

DR. LACKMAN: There is no question; the most efficient type of joint is a bonded joint. The most unreliable type of joint is also a bonded joint.

DR. ANTHONY EVANS (National Bureau of Standards): I would like to make a partial response to the question about acoustic emission in proof-testing. Acoustic emission has, of course, been monitored during proof testing and has been found to be a very good monitor of the number of fibers that are breaking. The question that hasn't been resolved yet is how one relates the number of broken fibers to the ultimate failure. One feels intuitively that there should be a correlation, but until we have the proper data criterion, I think we can't yet apply the concept.

DR. WILLIAM SCOTT (Naval Air Development Center): Having been called upon a couple of times to look at some composite structures, I find one of the main problems that I think people are going to have in inspecting them is that they are not particularly uniform products. There are lots of things like bond lines in them. The resins seem to vary in concentration somewhat around the material. The fibers seem to be clotted or stuck together in some places more than others. Is there anything being done to improve the uniformity of the material being fabricated?

DR. LACKMAN: You are probably referring to graphite composites. If you look at the fiber alignment and fiber properties for boron, you will see they are very standard. In fact, when one considers composites in the long run from the standpoint of consistency, I think that composites are going to be better than metals, because with metal structures we must contend with billets being received with flaws that are random in both size and location. In composites, we start with a very thin basic lamina and build up our structure, so we know what we have. There have been some fiber alignment problems and some growing pains with graphite, and it is still in a growing situation, but boron, no question about it, is like the Cadillac of the composite industry and it is very consistent. We hope graphite will soon be that way.

DR. PANOS: I think what you really want to emphasize to this audience about the lack of confidence in bonded composite structures is a lack of inspectability.

DR. LACKMAN: Exactly. Yes, I agree. It is a lack of inspectability. It is an inability to determine whether there is a bond and, if so, is it a good bonded joint or a poor bonded joint. Up to this time, in tests which have been run on scarf-type joints, which are very efficient structurally, the variability of the resulting data is very discouraging. This scatter forces us to set a low design allowable. We want to design to a degree of reliability, so, at present, we have to avoid that type of joint. There are so many factors involved; it isn't like a metal joint, where we buy a fastener from one supplier and everybody uses it. We drill a hole, install a fastener, and that's it. With bonded joints, it is a function of the tap water we use, the primer we use, the workman who cleans the metal, how long the metal stands after cleaning, what type of bonding element we use, what type of heater, what type of tear cycle; there are so many parameters involved that unless we have some good in-process control and NDI, we are just not going to convince people to accept bonded joints for primary structures.

DR. GIULANO D'ANDREA (Watervliet Arsenal): In your economic analysis, in order to make the composite materials competitive, you assigned a dollar value to the weight saved, a so-called weight penalty factor.

Can you tell me what the number was for the B-1?

DR. LACKMAN: No, sir.

DR. D'ANDREA: It is very important.

DR. LACKMAN: No, sir. What we are saying here is that on a direct cost basis, we are going to be competitive with metal structures on a production basis. We are not talking about a dollar value associated with pounds saved. That is an old game.

PROF. H. TIERSTEN (Rensseller Polytechnic Institute): I am not familiar with these bonded joints, but are they like the equivalent of two plates welded and you would be using this brittle material in that way? Isn't that highly unsafe as a joint? Shouldn't you have some ductility because of the concentrations at the end of it? That bothers me.

DR. LACKMAN: We use stepped thickness. We don't have a three-inch-thick layer of boron that starts or ends squarely cut off. We put down one ply, then a shorter one, then another. We build the thickness up very gradually. There are still concentrations, but if we build the thickness up slowly enough, we minimize the concentrations to a level that we can live with. Then the laminate joint has adequate strength and integrity during its design life.

PROF. TIERSTEN: Have careful tests been made so you know exactly what is happening in such a joint?

DR. LACKMAN: Extensively. In fact, for the B-1 design that we used, we took a major configuration of the dorsal longeron and went through 7.8 times design lifetime with no delaminations, then tested it at minus 65 degrees which gives us the maximum delta K, and then ran it over ultimate load, and there were still no disbonds.

PROF. TIERSTEN: Were strain gauges carefully put all around it to see how it was behaving at those critical points? It tends to get singular at those points.

DR. LACKMAN: We don't really measure a singular value, but rather an average value over a step of 3.5 inches. We measure average to average or peak to peak.

PROF. TIERSTEN: Don't you have to have some ductility in order for this thing not to break?

DR. LACKMAN: Oh, yes, but the resin does have ductility.

PROF. TIERSTEN: It does?

DR. LACKMAN: The adhesive has ductility.

PROF. TIERSTEN: You said it was brittle.

DR. LACKMAN: Not the adhesive; there is an adhesive bond line surface between the boron/epoxy and the metal strap.

PROF. TIERSTEN: And it has some ductility?

DR. LACKMAN: Yes.

LIEUTENANT MICHAEL BUCKLEY (Air Force Materials Laboratory, WPAFB): One of the classic problems here is what defects should people in NDE be looking for. We go through a lot of discussion as to who should decide what defects to look for. You have discussed the program you have under way. What progress are you making? Do you see those questions being answered? Could you comment on that problem?

DR. LACKMAN: The B-1 is the first airplane to have to be designed to some damage tolerance requirements, and not the damage tolerance requirements shown in HB-3444, which is the specification above and beyond the B-1. For this airplane, we are going through a damage tolerance reliability test program. We are building-in types of flaws that we think one could possibly induce unintentionally as a result of fabrication, and running through evaluation tests to see what the strength degradations are, and determining inspection techniques. However, this is not addressing the general problem of defect characterization. Also, the general thing I want to be able to do as a composites man is to design my structure efficiently to reduce the impact of flaws on my payoffs as I design my structure efficiently for strength and stiffness requirements. I want to be able to integrate my design for a pilot structure and have a reliable NDI technique to be sure that if I have flaws beyond the size that I say I design to, that I can detect them. So, the general problem has not yet been addressed. The Air Force Materials Lab and others are going to have this as a major thrust area in the next four to five years, but I can't see them getting very far unless NDI plays a significant role.