ME 463 Design, Analysis, and Manufacturing Project
Fall Semester, 2009

Douglas S. Cairns, Ph.D.
Lysle A. Wood Distinguished Professor
Mechanical and Industrial Engineering
Montana State University
Bozeman, MT 59715

Background
This paper is a study of various materials which could be used to replace the current Sitka spruce laminate in various aircraft structures. Surprisingly, it is a difficult task to replace Sitka spruce which has been the "gold standard" for modern aircraft structures. Nature spent a long time to self-optimize the properties of this material, and modern artificial composites can be considered as being "bio-inspired" by materials such as wood, bone, tendons, etc. Sitka spruce has an excellent stiffness to weight ratio, and an excellent strength to weight ratio [e.g. 1]. Indeed, anyone examining the beautiful construction of the Hughes Hercules (aka Spruce Goose) is immediately struck by the elegance and craftsmanship of this structure. A photograph of the wing construction is shown in Figure 1 below.

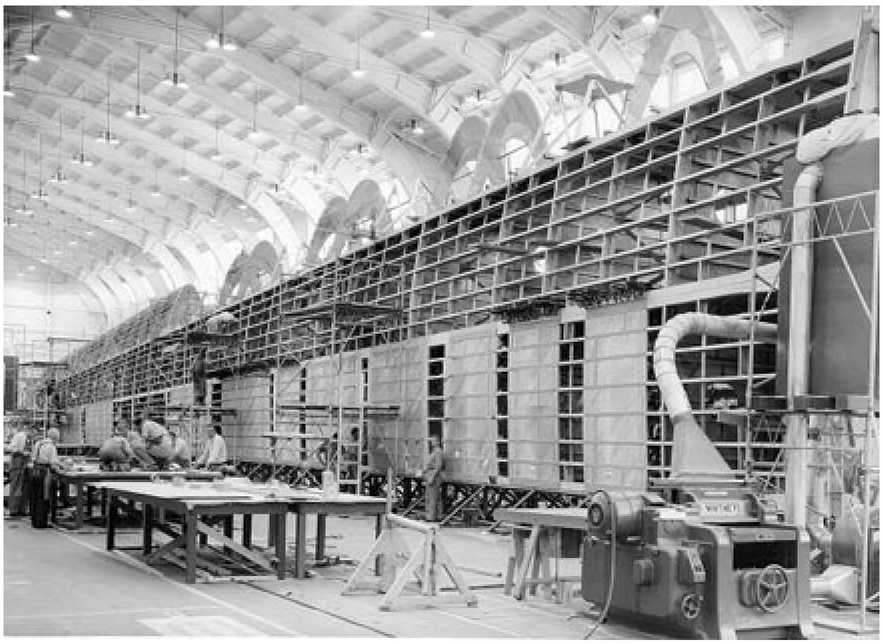

Figure 1. Construction of the Hughes Hercules ("Spruce Goose") Wing [2]

Unfortunately, Sitka spruce is not what it used to be, and others are struggling with alternative materials. The following excerpt on Aircraft Wood, written by Ron Alexander, is from "Sport Aviation" in 1998 [3]:

> "From the very beginning of aviation wood has been used in aircraft construction. Early aircraft designers and builders often used ash or hickory. They were looking for a type of wood that would be relatively lightweight in addition to being very strong. Just prior to World War I, Sitka Spruce was discovered by aircraft builders and found to be very well suited to their needs. The strength to weight ratio was discovered to be very favorable for aircraft use. Several other types of wood had similar strength to weight ratios but were not as easily harvested or as plentiful. At the time, spruce proved to be the best choice, not only because of the physical characteristics, but of equal importance was the fact that spruce was readily available and easy to use as a building material. With the advantages noted, spruce became very widely accepted as the primary material to be used in building an airplane.

With the advent of World War II, spruce became even more popular. Manufacturers used the material in the construction of a large number of aircraft. Wooden spars were fabricated from spruce in many airplanes along with ribs and other structural parts. Because of the high demand for both aircraft production and for spruce to be used as a major material in manufacturing parts, forests of this popular wood were rapidly depleted. The use of Sitka Spruce was carried into post-war construction in many aircraft. The maintenance and restoration process of existing aircraft required a large supply of wood. Wood was a popular choice for aircraft construction because of its advantageous strength to weight ratio, workability, abundance, and low cost. The largest plane ever constructed—the Spruce Goose—is largely comprised of spruce. During this time in aviation history spruce was cheaper than aluminum or steel.

SITKA SPRUCE

Spruce has long been recognized as the best type of wood to use in the construction of aircraft. It is the standard against which all other woods are judged. It has several characteristics that make it the best type of wood for an airplane. It is light in weight with a corresponding greater strength and toughness than is found in other woods. It is easily worked, uniform in texture, resistant to rotting, and has no odor. It can also be obtained in clear, straight-grained pieces having very few defects. This is possible because of the size of a mature spruce tree. Sitka Spruce is the preferred type of wood for aircraft construction. The name Sitka was derived from a town located not far from Juneau, Alaska. Sitka Spruce is found mainly along the Pacific Northwest, particularly along the Alaskan coast. (Most of the spruce forests have been depleted along the coast of the United States and Canada.) The trees grow best in a wet, moderate climate. They will rarely be found more than 50 miles from a coastline. Spruce trees typically grow close together and in so doing they must grow very tall and fast in order to obtain necessary sunlight. Because of this type of growth they usually have few, if any, branches except near the top of the tree. This facilitates the type of growth necessary to yield knot free lumber suitable for aircraft use. A spruce tree will grow to heights of 200 feet and higher with a diameter of 8 feet or more. A tree of this size will have taken 400 years or more to reach this dimension. A spruce tree will not yield usable aircraft lumber until it is at least 5 feet in diameter. Even with this size tree only 5% or less of the resulting lumber will be of the quality necessary for aircraft construction. With this in mind it is easy to understand why we often have a deficit in aircraft grade lumber. As I mentioned earlier, use of Sitka Spruce prior to and during World War II depleted large forests of the wood.

The sale of spruce is a nightmare for a supply company. The price they pay for shipments of spruce is very high. In addition, they have high costs in preparing the wood for shipment. The wood is very easily damaged when working with it or storing it. And finally, at least 40% of the wood they receive cannot be used for spar material. That means they must either cut the wood into smaller pieces to be sold as capstrips and longerons or burn them in their fireplace. Cutting the wood into smaller pieces is labor intensive. Even with the high price you will pay for a spruce spar the aircraft company is not making money. I was in that business for over 17 years and can personally attest to that fact.

Alternative woods have emerged to replace Sitka spruce as a primary structure material, most notably fir, but these still have some of the construction problems associated with Sitka spruce. For reference and comparison to spruce, these are listed in Figure 2 below, taken from FAA Advisory Circular AC 43.13-1B.

TABLE 1-1. Selection and Properties of Aircraft Wood. (See notes following table.)

Species of Wood	Strength properties as compared to spruce	Maximum permissible grain deviation (slope of grain)	Remarks
1.	2.	3.	4.
Spruce(Picea) Sitka (P. Sitchensis) Red (P. Rubra) White (P. Glauca).	100%	1:15	Excellent for all uses. Considered as standard for this table.
Douglas Fir (Pseudotsuga Taxifolia).	Exceeds spruce.	1:15	May be used as substitute for spruce in same sizes or in slightly reduced sizes providing reductions are substantiated. Difficult to work with handtools. Some tendency to split and splinter during fabrication and considerable more care in manufacture is necessary. Large solid pieces should be avoided due to inspection difficulties. Gluing satisfactory.
Noble Fir (Abies Nobiles).	Slightly exceeds spruce except 8% deficient in shear.	1:15	Satisfactory characteristics with respect to workability, warping, and splitting. May be used as direct substitute for spruce in same sizes providing shear does not become critical. Hardness somewhat less than spruce. Gluing satisfactory.
Western Hemlock (Tsuga Heterpphylla).	Slightly exceeds spruce.	1:15	Less uniform in texture than spruce. May be used as direct substitute for spruce. Upland growth superior to lowland growth. Gluing satisfactory.
Pine, Northern White (Pinus Strobus).	Properties between 85 % and 96 % those of spruce.	1:15	Excellent working qualities and uniform in properties, but somewhat low in hardness and shock-resisting capacity. Cannot be used as substitute for spruce without increase in sizes to compensate for lesser strength. Gluing satisfactory.
White Cedar, Port Orford (Charaecyparis Lawsoniana).	Exceeds spruce.	1:15	May be used as substitute for spruce in same sizes or in slightly reduced sizes providing reductions are substantiated. Easy to work with handtools. Gluing difficult, but satisfactory joints can be obtained if suitable precautions are taken.
Poplar, Yellow (Liriodendrow Tulipifera).	Slightly less than spruce except in compression (crushing) and shear.	1:15	Excellent working qualities. Should not be used as a direct substitute for spruce without carefully accounting for slightly reduced strength properties. Somewhat low in shock-resisting capacity. Gluing satisfactory.

Notes for Table 1-1

1. Defects Permitted.

a. Cross grain. Spiral grain, diagonal grain, or a combination of the two is acceptable providing the grain does not diverge from the longitudinal axis of the material more than specified in column 3. A check of all four faces of the board is necessary to determine the amount of divergence. The direction of free-flowing ink will frequently assist in determining grain direction.

b. Wavy, curly, and interlocked grain. Acceptable, if local irregularities do not exceed limitations specified for spiral and diagonal grain.

c. Hard knots. Sound, hard knots up to 3/8 inch in maximum diameter are acceptable providing: (1) they are not projecting portions of I-beams, along the edges of rectangular or beveled unrouted beams, or along the edges of flanges of box beams (except in lowly stressed portions); (2) they do not cause grain divergence **at the edges of** the board or in the flanges of a beam more than specified in column 3; and (3) they are in the center third of the beam and are not closer than 20 inches to another knot or other defect (pertains to 3/8 inch knots—smaller knots may be proportionately closer). Knots greater than 1/4 inch must be used with caution.

d. Pin knot clusters. Small clusters are acceptable providing they produce only a small effect on grain direction.

e. Pitch pockets. Acceptable in center portion of a beam providing they are at least 14 inches apart when they lie in the same growth ring and do not exceed 1-1/2 inches length by 1/8 inch width by 1/8 inch depth, and providing they are not along the projecting portions of I-beams, along the edges of rectangular or beveled unrouted beams, or along the edges of the flanges of box beams.

f. Mineral streaks. Acceptable, providing careful inspection fails to reveal any decay.

Figure 2. Alternative Wood Materials for Spruce

The material specifications in Reference [1] are quite detailed, and even more stringent than in FAA Advisory Circular AC 43.13-1B [4]. Hence, it is worthwhile looking at non-woods as a replacement for aircraft structures.

Basic Mechanical Property Specification for Sitka Spruce Replacement

The basic mechanical properties for Sitka spruce used in aerospace structures are shown in Table 1.

TABLE 1 PROPERTIES OF SITKA SPRUCE LAMINA
10% MOISTURE CONTENT
DESIGN STRENGTH, AVERAGE MODULUS
PROPERTY VALUE

Property	Value
Ft 1	11.0 KSI
Ft 2	0.4 KSI
Ft 3	
Fc 1	6.2 KSI
Fc 2	0.77 KSI
Fc 3	
Fs12	1.20 KSI
E1	1.600 MSI
E2	0.130 MSI
E3	0.069 MSI
G12	0.102 MSI
G13	0.098 MSI
G23	0.048 MSI
ν12	0.370
ν13	0.470
ν23	0.440
ν21	0.029
ν31	0.020
ν32	0.24

F are strength values; E,G are elastic moduli, ν are Poisson ratios
DIRECTION 1 Is PARALLEL TO THE GRAIN
DIRECTION 2 IS ACROSS THE GRAIN
DIRECTION 3 IS TANGENT TO THE GRAIN (THROUGH THICKNESS)

The nominal specific gravity for the Sitka spruce is stated as 0.36 (approx. 0.013lbm/in^3) in [1].

The author has checked these values for consistency to a generally-orthotropic, homogeneous material. They are close, but not exact. For example, ν21 is not exactly equal to ν12x(E2/E1) as it should be for the elastic material symmetry of a generally orthotropic material. However, the differences are small and acceptable for a typical structural analysis.

The author has also compared the values in Table 1 against those published in the open literature. Reported recent values for Sitka spruce from Alaska have lower strength and modulus of elasticity values, but are similar to those in Table 1 above [5]. In any event, it is the author's opinion that maintaining the nominal properties listed in Table 1 may be difficult.

Constraints for Selecting Alternative Materials

The constraints for this project are: "Performance to requirements - must remain equal or better than current."

"Better" is defined as lower mass, stiffer, and stronger, where applicable.

Candidates for Alternative Materials

Four types of fibers have been considered. Of these the most viable ones are glass, Kevlar, and carbon fibers. Each is already in use to some extent in aircraft structures. Also, four types of polymeric matrix resin systems have been considered for floor structure. These are vinyl-esters, epoxies, and polyimides, and engineering thermoplastics. Epoxies and polyimides are common matrix materials for primary aerospace structure.

Pros and Cons of Alternative Fibers

A qualitative comparison for alternative fibers is shown in Table 2. below. These comparisons are based on information provided in [6].

Table 2. Qualitative Comparison of Fibers for Alternative Materials

Fiber Type	Pros	Cons
Glass	Moderate cost, higher stiffness than current design, much stronger than Sitka spruce, good hygrothermal properties (environmental resistance)	High density, approx 7x Sitka spruce; comparable stiffness/density ratio in a typical composite
Intermediate modulus carbon fiber	Very stiff, greater than 3X stiffness to weight compared to Sitka spruce, very good hygrothermal properties, already extensively used for aerospace structures	Design with equivalent membrane stiffness, much thinner than current design, potential RF transmittance problems.
Kevlar 49	Lowest density of all fibers considered; very high stiffness to density ratio, excellent tensile strength,	Questionable hygrothermal (environmental) properties, very low compression strength, difficult to

	already used for aerospace structures	machine
Ceramic Fibers	Very expensive, limited data for use in primary aerospace structure. Various types; SiC, alumina, ceramic oxides, etc.	Use only if the non-mechanical requirements are not met with one of the above fibers

Pros and Cons of Alternative Polymeric Matrix Systems
The matrix system candidates were chosen based on previous applications to primary structure, and for the utilization of the various manufacturing techniques to be discussed later. Table 3 is a qualitative comparison.

Table 3. Qualitative Comparison of Matrix Materials for Alternative Materials

Resin Type	Pros	Cons
Vinyl-Ester	Modest cost, can be toughened, low viscosity phase for various manufacturing processes, good compatibility with epoxies and the sizings of the fiber candidates	Lower glass transition temperature (T_g), environmental issues while manufacturing, e.g. styrene monomer "stinks",
Epoxies	Higher cost, used extensively for aerospace and other high performance structures	High viscosities makes infusion type processing with some variants difficult, must be cured at elevated temperatures to get acceptable T_g. Tough variants have lower compressive strengths and hygrothermal properties
Polyimides	Highest temperature material of proposed candidates, low viscosity of some variants for good infusion type processing	Brittle (low strain to failure), requires highest processing temperature, not as extensively used as previous two.
Engineering Thermoplastics; e.g. PEEK, PEK, PES	Good damage resistance compared to toughened thermosetting matrices; composite damage tolerance can be poorer than good thermosetting resins. Difficult processing, expensive tooling, Limited database compared to thermosetting matrices.	As with ceramic fibers, consider only if there is some compelling non-mechanical reason.

Alternative Material Mechanical Properties
A preliminary estimate of the mechanical properties for the polymer-reinforced composites was constructed for comparison purposes. Micro-mechanics was used where

there was no experimental data. It was assumed that the matrix stiffness properties are of the same order, so while some variation will be evident from changing the stiffness properties of the resins, a complete study for the breadth of stiffness within each candidate was not conducted. This is not necessary for relative comparisons, but would be necessary for a design validation and allowables database. Preliminary design values are provided in Table 4.

TABLE 4 PROPERTIES OF ALTERNATIVE MATERIAL CANDIDATES
DESIGN STRENGTH, AVERAGE MODULUS
PROPERTY VALUE

Property	Sitka Spruce	Glass/Polymer (S-glass type)	Carbon Fiber/Polymer	Kevlar 49/Polymer
Ft 1	11.0 KSI	350 KSI	300 KSI	226 KSI
Ft 2	0.4 KSI	6.0 KSI	8.5 KSI	5.1 KSI
Ft 3				
Fc 1	6.2 KSI	120 KSI	225 KSI	133 KSI
Fc 2	0.77 KSI	21.0 KSI	30.0 KSI	18.2 KSI
Fc 3				
Fs12	1.20 KSI	10.0 KSI	12.5 KSI	7.7 KSI
E1	1.600 MSI	8.20 MSI	25 MSI	11.2 MSI
E2	0.130 MSI	2.0 MSI	1.6 MSI	0.83 MSI
E3	0.069 MSI	2.0 MSI	1.6 MSI	0.83 MSI
G12	0.102 MSI	1.0 MSI	0.87 MSI	0.3 MSI
G13	0.098 MSI	1.0 MSI	0.87 MSI	0.3 MSI
G23	0.048 MSI	0.8 MSI	0.6 MSI	0.3 MSI
ν12	0.370	0.28	0.29	0.34
ν13	0.470	0.28	0.29	0.34
ν23	0.440	0.3	0.34	0.34
ν21	0.029	0.07	0.02	0.025
ν31	0.020	0.07	0.02	0.025
ν32	0.24	0.3	0.34	0.34
Specific Gravity	0.36	2.0	1.58	1.38

F are strength values; E,G are elastic moduli, ν are Poisson ratios
DIRECTION 1 Is PARALLEL TO THE FIBER
DIRECTION 2 IS TRANSVERSE TO THE FIBER
DIRECTION 3 IS TANGENT TO THE FIBER (THROUGH THICKNESS)

A cursory comparison to these materials to Sitka spruce has some stark contrasts. The most obvious are the much higher absolute stiffnesses (e.g., 5x to 15x for E1) and the much higher strengths (e.g., 19x to 36x for F1c). However, the densities are also much higher. The specific gravity of Sitka spruce is reported at 0.36 above, while the specific gravity of the composites considered range from 1.38 to 2.0.

Table 5 is a list of potential core materials with a discussion of Pros and Cons.

Table 5. Candidate Sandwich Core Materials

Core Material	Pros	Cons	Good Source for Applicable Products
End grain balsa wood	Excellent core material, minimizes facesheet buckling at a low weight, low cost	Not as readily accepted in aerospace structures, supply chains can have the same challenges for the current Sitka spruce materials	BALTEK core materials http://www.baltek.com/alcan/acsites.nsf/pages_accm3_en/index.htm
End grain or laminated Sitka spruce	Strong material, accepted for current laminate, could more closely match mass/area of current shell	Heavier than other materials	http://www.aircraftspruce.com/ or other current suppliers for Sitka spruce.
Aramid paper honeycomb	Good stiffness to weight, widely used in aerospace structures, used in aerospace structures with RF or RADAR equipment	Some problems with long term environmental exposure, manufacturing challenges in shell structures	HEXCEL, Inc. http://www.hexcel.com/NR/rdonlyres/7F70671B-ED6E-4562-9659-ABA426A7453F/0/RevisedHexWebSelectorGuide.pdf
Aluminum honeycomb	Excellent stiffness to weight, widely used in aerospace, better temperature capability compared to aramid papers	Expensive, some problems with long term environmental exposure, manufacturing challenges in shell structures	HEXCEL, Inc. http://www.hexcel.com/NR/rdonlyres/7F70671B-ED6E-4562-9659-ABA426A7453F/0/RevisedHexWebSelectorGuide.pdf
High temperature, thermosetting foams	Good temperature capability, can be made in very thin sheets, good handling characteristics, density tailorable to match mass properties	May need to be dense (heavy) to handle facesheet buckling and transverse shear.	Rohacell http://www.rohacell.com/en/performanceplastics8344.html

Table 6 is a list of Specific Candidate Materials and Suppliers.

Table 6. Specific Candidate Materials

Specific Candidate Material	Impetus for Selection	Supplier	Comments
IM7/8552	Workhorse system, large database for aerospace applications including allowable and hygrothermal performance, robust processing characteristics	http://www.hexcel.com/NR/rdonlyres/9229D78D-51BC-4460-9248-CC256BC6B6A4/0/HexPly_8552_2_22_US.pdf	This material has very robust processing. It is a 350 ^{0}F curing system, but the author has experience in curing it at 250 ^{0}F wherein it developed nearly 350 ^{0}F cure T_g
AS4/3501-6	Another workhorse system, developed for the Navy F-18, very large database	http://www.hexcel.com/Products/Downloads/ http://www.cytec.com/engineered-materials/prepreg.htm	This system may have the largest database of any advanced composite material; sometimes called the Navy Material. It is dated compared to IM7/8552 or IM7/977-x, but the extensive use has value for lower risk
IM7/977-x	The 977-x family is another highly characterized system. It is used on many DOD applications (F18EF, V22, F22, JSF, etc.)	http://www.cytec.com/engineered-materials/products/Cycom977-2.htm http://www.cytec.com/engineered-materials/products/Cycom977-3.htm	The 977-x family has a variety of cure schedules depending on material requirements
Kevlar 49/epoxy	Well characterized for the aircraft structures, including accelerated ageing studies	http://www.hexcel.com/Products/Downloads/ http://www.cytec.com/engineered-materials/prepreg.htm	Accelerated ageing of Kevlar fibers and poor environmental performance in commercial and general aviation aircraft raises concerns, should consider a higher strain to failure resin system than typically used with carbon fibers.
Quartz Glass/Epoxy	Excellent transmittance properties	http://www.cytec.com/engineered-materials/prepreg.htm http://www.hexcel.com/Products/Downloads/	Relatively poor mechanical properties, but the best of the candidates for transmittance
S-Glass /8552 or 977-X	Strong glass fiber with a robust, high	Would need to be specially prepregged by	Not a lot of specific data on the combinations of fiber and matrix, but

	strain to failure matrix	http://www.hexcel.com/Products/Downloads/ or http://www.cytec.com/engineered-materials/prepreg.htm	each of the constituents is well-characterized, better weight matching and RF transmittance compared to other candidates in Table 8.
IM7/5250	Bismaleimide, highest temperature capabilities of all resins suggested	http://www.cytec.com/engineered-materials/products/Cycom5250-4.htm	Use only if absolutely necessary for temperature capability. It is expensive, difficult to process, and has poorer mechanical properties compared to epoxies at lower temperatures. Given that the 250 ^{0}F cure Sitka spruce-fiberglass laminate has been adequate, the high temperature capability is probably not necessary

All of the material systems listed in Table 6 are readily available. No materials development is necessary for the proposed alternative materials. Some specific fill-in data may be needed, but Table 6 has been carefully constructed to build on the large databases discussed above.

From a purely mechanical performance perspective, the author would favor one of the carbon fiber/epoxy candidates because of the superior mechanical properties over a wide variety of requirements, and for the potential weight reduction. The minimal change in weight compared to the current Sitka spruce flooring is represented by the glass/polymer candidates.

Testing
If this product were to go into production, material candidates should be evaluated for their basic mechanical properties. The first tests to be conducted should be on the facesheets. These are the major load carrying elements of the floor structure. These tests include basic tensile, compression, and shear. The motivation for conducting these tests is not to develop an allowables database, but to determine the basic properties and compare them to the Sitka spruce laminate baseline. These facesheets would be probably be hand laid, autoclave cured prepregs from candidate materials in Table 6. Any competent composites manufacturing or test lab could make these laminates, but it might be good to have them made by potential subcontractors who would make the actual parts. This would incorporate the manufacturing process into the evaluation as well. Basic facesheet tests are recommended in Table 7.

Table 7. Basic Mechanical Test Properties of Facesheets

Test Type	Basic Description and Specifications for the Test
Tension	http://www.astm.org/Standards/D3039.htm
Compression	http://www.astm.org/Standards/D695.htm
Shear	http://www.fpl.fs.fed.us/documnts/pdf2000/liu00b.pdf

Some preliminary tests would also be conducted on the proposed sandwich construction for screening prior to going into production. Facesheet/core bonding is necessary. A good way to do this is with film adhesives [e.g., 7]

Two tests which will determine how the facesheet and core act as a combined structure are facesheet tensile testing and sandwich beam flex testing as identified in Table 8.

Table 8. Basic Sandwich Construction Tests

Test Type	Basic Description and Specifications for the Test
Sandwich Facesheet tensile testing	http://www.ptli.com/testlopedia/tests/Flatwise-Tensile-ASTM-C297.asp
Sandwich Beam Flex Testing	http://www.astm.org/Standards/D7250.htm ; http://www.astm.org/DATABASE.CART/HISTORICAL/C393-00.htm

These are good, basic mechanical property tests, but a more in-depth screening matrix could be developed. A good overview has been provided by Dr. Don Adams in 2006. [8,9]. (On a side note, Dr. Adams was the author's MSME thesis advisor and co-author for the work published in References [10,11].)

Manufacturing (For Background Only)

With respect to manufacturing the structure, four methods emerged as viable candidates. These are hand layup (with autoclave curing), filament winding, automated fiber placement and Infusion type processing. These are described and illustrated below.

<u>Hand Layup</u>

Hand layup is still a composites industry standard for small volume, high quality laminates. Typically, prepregs are used for aerospace structures. Prepregs are materials which are a combination of the uncured resin and the reinforcing fibers. In this method, plies of the composite prepreg are hand laid into a mold, much like the current construction with Sitka spruce.

An example of hand layup is shown in Figure 3 [12].

Figure 3. Example of Hand Lay-up Construction [12]

After the plies are laid into the mold, a vacuum bag is applied to debulk and remove voids. This is then cured in an autoclave. There are many companies in the US and abroad skilled in this type of manufacturing. Hence, having multiple suppliers has advantages. It is probably the fastest avenue for doing some manufacturing studies with candidate materials, assuming that molds exist and are compatible with modern prepregs. New tooling is moderate cost. Disadvantages include that it is slow and the quality is dependent on individual skills.

Filament winding

Filament winding is an efficient and low cost method for making axisymmetric structures. An illustration of the filament winding technique is shown in Figure 4 [13].

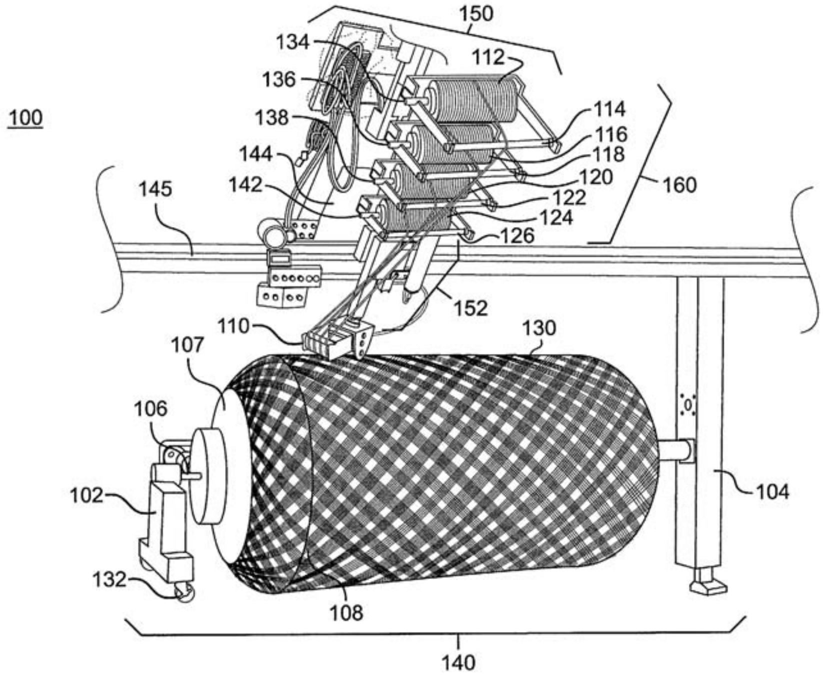

Figure 4. Illustration of Filament Winding [13]

While filament winding is most appropriate for rocket motor cases (or other pressure vessels), there are several disadvantages for manufacturing a wide variety of structures. First, a winding path can only follow geodesic or near-geodesic paths (along principal curvatures). This means that there is less flexibility to tailor the laminate stiffness properties governed by Classical Laminated Plate Theory (CLPT). It also means that it will be difficult or impossible to have axial plies. This may not be necessary to match stiffnesses of the current design. Filament winding holds very good inside dimensional tolerances, but since there is not an outer mold, the outer surface is not controlled. An additional mold could be placed on the as-wound, uncured structure or a sacrificial layer to be machined could be wound, but these are cumbersome and relatively unconventional. Internal mandrel tooling is moderate cost, but external molds could be expensive, depending on the dimensional tolerances required.

Fiber Placement

A newer manufacturing technique, an evolution of filament winding, is known as fiber placement. A tool is used, and a robotic head places the fiber in any direction as desired. The “tackiness” of the uncured material holds the plies in place. Concave surfaces are possible. This is shown in Figure 5.

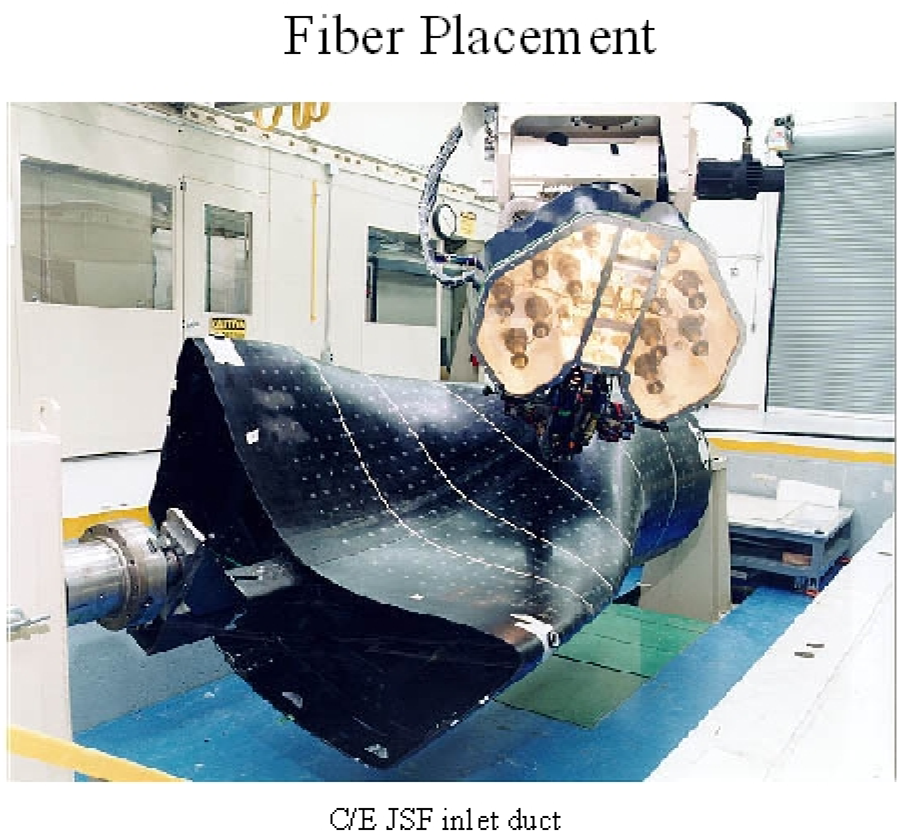

Figure 5. Fiber Placement, Robotic Head Placing Fibers on a Tool;
Possible to Make Convex and Concave Surfaces [14].

With fiber placement, the outer surface can be maintained with precision compared to filament winding. Tooling is usually expensive, especially if it is made from materials such as Invar.

<u>Infusion Type Processing</u>

With infusion type processing, dry fibers are placed into a mold. Then, heated resin is injected via various configurations to make a laminate. Common variants include Resin Transfer Molding (RTM), Vacuum Assisted Resin Transfer Molding (VARTM), Infusion processing, etc. There are differences in complexity and speed, but they all rely on providing a pressure gradient, and flowing the resin into the dry fibers with this gradient. One sided and closed mold variants are possible. Infusion type processing has the advantage that it is near net shape, with minimal post machining. The basic process for a one-sided infusion is shown in Figure 6 below. A closed mold process includes another mold to control the dimensions of outer and inner surfaces.

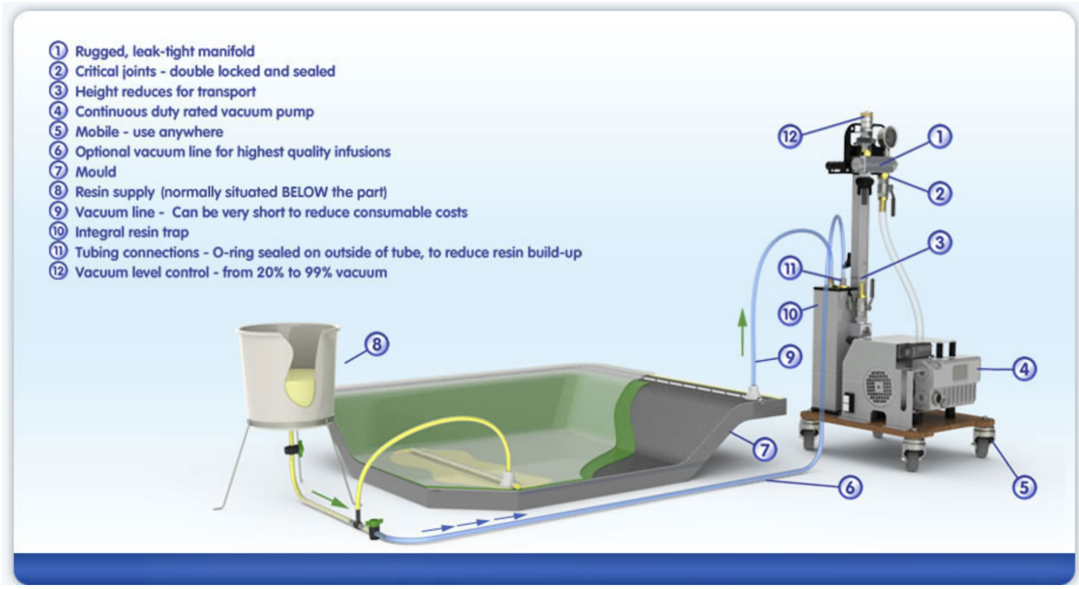

Figure 6. Basic Infusion Process [15]

A complex part made with infusion processing is shown in Figure 7.


Figure 7. Complex, Net Shape Part made with Vacuum Assisted Resin Transfer Molding (VARTM) Processing [16]

The disadvantage of infusion type processing is that tooling can be very expensive, and it is not the best for high viscosity resins such as toughened epoxies.

Manufacturing and Testing Screening Laminates

Once there has been a discussion as to whether any materials/laminates would be precluded for reasons other than structural performance, and a group of three specific facesheet/core combinations should be chosen and manufactured. Where and how these laminates are manufactured may be of interest to streamline the procurement process if a decision to go into production manufacturing is made. That is to say, many laboratories could produce the laminates for the testing described in Tables 7 and 8, but it may be wise to chose manufacturers which most closely resemble practical, full scale production.

One could have the laminates made by a company which would be a candidate for a production contract. Since the properties of composites are a combination of materials and manufacturing, this could be a way to determine if candidate manufacturing processes have any deleterious effects on performance with respect to requirements for any composite aerospace structures. Manufacturers could be any of those listed in Table 9 below. Most of these have testing capabilities as well.

Table 9. Potential Suppliers for Hand Laid Alternative Material Shell Prototype Structures

Supplier	Comments
Alliant TechSystems (ATK), Clearfield, UT	Very familiar with aerospace structures, have extensive experience in a variety of manufacturing with specialties in filament winding and fiber placement.
Lockheed Martin	Prime Contractor for aerospace systems
Boeing	Very familiar with a wide variety of composite material structures from commercial aircraft to space structures. Most extensive experience in fiber placement
Northrop Grumman	Prime contractor, familiar with DOD requirements for advanced composite structures.
Hexcel	Hexcel makes fairings and engine nacelles in its engineering products division. It is also a supplier of some of the materials in Table 6. http://www.hexcel.com/Products/Engineered+Products/
Gougeon Brothers	This is a relatively strange recommendation, but it has some history. Gougeon Brothers know a tremendous amount about wooden boatbuilding and understand the transition from laminated wooden boats to modern composite boats. The laminating materials West System may be owned by another parent company, but engaging former employees from Gougeon Brothers early on could have merit. http://www.westsystem.com/ss/ http://www.macnaughtongroup.com/gougeon_brothers_on_boat_construction.htm http://www.epoxyworks.com/24/pdf/Gougeon_Technical_Staff.pdf
Advanced Composites Group (ACG)	http://www.advanced-composites.co.uk/aerospace_archived_news_index_2008.html#Complex_Aircraft_Primary

	Another company relatively unknown to the US composites industry. ACG is based in the UK and has expertise in large composite shell structures. Hence, ACG warrants consideration as a supplier.

A purely composites testing laboratory such as Delsen Testing Laboratories (http://www.delsen.com/index.html) could be commissioned to manufacture the laminates and test them with very good ASTM controls. The downside is that these type of laboratories can be expensive, and there is a moderate "disconnect" between the manufacturing processes and the laminate performance. This disconnect may not be a concern if one is only looking to screen and compare materials.

A hybrid approach wherein some form of "round-robin" manufacturing and testing could be done by sharing manufacturing and testing responsibility with duplicity across a variety of suppliers and testing facilities.

References

1. US Navy, Weapon Specification SSP WS14593A, Veneer, Sitka Spruce, 1998, supersedes a 1977 document.

2. http://www.centennialofflight.gov/essay/Aerospace/Hughes/Aero44G1.htm

3. Alexander, Ron, **Aircraft Wood**, http://www.sportair.com/articles/Aircraft%20Wood%20-%20Part%20One.html

4. FAA Advisory Circular AC 43.13-1B, 1998.

5. Bannister, J., Curtis, K., Barber, V., *A mechanical evaluation of Alaska grown Sitka spruce*, **Forest Products Journal**, September, 2008. Available on the web at http://www.allbusiness.com/education-training/academic-standards-testing-academic/11677688-1.html

6. Barbero, Ever J., ***Introduction to Composite Materials Design***, Taylor & Francis, Philadelphia, PA, 1998.
7. CYTEC Incorporated http://www.cytec.com/engineered-materials/film-adhesives.htm

8. http://www.compositesworld.com/columns/sandwich-panel-test-methods.aspx

9. http://www.compositesworld.com/articles/testing-tech-shear-testing-of-sandwich-panel-core-materials.aspx

10. Cairns, D.S. and Adams, D.F., "Moisture and Thermal Expansion of Composite Materials," Proceedings of the **JANNAF Composite Motor Case and Structures and Mechanical Behavior Meeting**, Hill Air Force Base, April 1982.

11. Cairns, D.S. and Adams, D.F., "Moisture and Thermal Expansion of Unidirectional Composite Materials and the Epoxy Matrix," **Journal of Reinforced Plastics and Composites,** Vol. 2, Technomic Publishing Co., Westport, CT, October, 1983, pp. 239-255.; reprinted as a book chapter in **Environmental Effects on Composite Materials**, Edited by George Springer, Technomic Publishing Co., Westport, CT, 1984.

12. http://www.vtcomposites.com/Vermont_Composites_Capabilities/Manufacturing_Capabilities.aspx

13. http://www.freepatentsonline.com/7124797-0-large.jpg

14. http://www.engr.ku.edu/~rhale/ae510/compintr/sld022.htm

15. http://www.vacmobiles.com/welcome_panel_lager.jpg

16. http://www.compositesworld.com/articles/inside-analysis-simulating-vartm-for-better-infusion.aspx