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LOW–COST, LIGHTWEIGHT THERMOPLASTIC ALTERNATIVES TO TRADITIONAL METALLIC HELICOPTER COMPONENTS

BY

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Abstract

This paper assesses the application of advanced thermoplastics in rotorcraft components, by presenting an overview of three of the current thermoplastic programs being developed at Bell Helicopter Textron, Inc. These programs utilize three totally different manufacturing methods of fabricating thermoplastic components for three significantly different types of components: (1) injection-molded nonstructural components (drive system, rotors, etc.), (2) a diaphragm-formed Model 212/412 baggage door (secondary structure), and (3) an *in situ* consolidated Model 206/OH-58 tailboom (primary structure). The primary objectives of these programs, however, are the same: to reduce weight, to reduce cost, and to decrease manufacturing cycle time, while improving reliability and maintainability. Development of these programs is described, including materials and processing, design considerations, fabrication techniques, and test methods.

1. Introduction

The aircraft industry has a great desire to take advantage of the lightweight, corrosion resistant, durable components that composite materials provide, compared to metal. Bell, as did most major aerospace companies, invested a significant amount of time and money in the research and development of thermoset materials. However, many of the fabrication techniques utilized in the production of thermoset parts proved to be quite labor intensive, with long production cycle times. As a result, the widespread use of composites has been impeded due to the high cost associated with the manufacture of composite structure. Therefore, while customers would like to take advantage of the life-cycle costs reductions resulting from reduced corrosion, improved fatigue life, and toughness of composites, they consider the acquisition cost of composites to be prohibitive.

To attack this problem of acquisition cost, research was initiated to identify new materials and processing technology that could provide high-quality structure at a cost-effective price. Because of their heat-formability and rapid cycle times, thermoplastic materials were identified as a front runner in achieving this goal. Past experience with thermoplastics had surfaced concerns over tooling requirements, material cost, and high-temperature processing requirements. Thermoplastics suffered initially in research programs, due to early attempts to make "black aluminum" components. In other words, early design concepts were based on sheet metal technology, which necessitated labor-intensive fabrication methods similar to those used for thermosets. In order to take advantage of thermoplastics, new design and processing techniques were developed that allowed automation and capitalized on the formability of the material and its ability to cure in place immediately during fabrication.

Bell initiated several research and development programs with one overall objective: to develop advanced thermoplastic components in order to validate cost reductions relative to existing metallic components.

Bell utilized a multipronged approach to meet this objective. Concurrent engineering teams were formed to evaluate new design concepts, materials and fabrication techniques. Numerous components were reviewed to identify parts that would take advantage of automated thermoplastic fabrication techniques. Potential candidates were not limited to one type of component, one specific manufacturing approach, or function. Candidates covered a wide range of applications, environments, and challenges.

The components utilized advanced thermoplastic resins such as polyetheretherketone (PEEK) and polyethersulfone (PES). The fiber types, lengths, and forms were chosen based on the structural requirements and processing techniques utilized. Three types of components with different applications are discussed in this paper:

a. Injection-molded thermoplastic fuel and drive system components.

b. A continuous carbon-fiber-reinforced baggage door that utilized a diaphragm-forming technique.

c. A continuous carbon-fiber-reinforced helicopter tailboom that utilized "cure-on-the-fly" technology.

For each type of component, the development, cost/weight benefits, and lessons learned are discussed.

The result has been a family of parts where fabrication labor and assembly time have been significantly reduced, providing finished products that were cost competitive with their metallic counterparts.

2. Injection-molded Components: Drive System

The first application to be discussed will address injection molding of discontinuous fiber-filled polyetheretherketone (PEEK) material for drive system components. These components were one-to-one replacements of aluminum cast and machined parts. This application was particularly aggressive due to the stringent environment associated with drive system applications, such as high operating temperatures, hot oil exposure, and a requirement to survive oil-out run-dry conditions for 30 minutes minimum. The objective of this program was to take advantage of the toughness, corrosion resistance, and high temperature characteristics of the PEEK resin to save cost and weight in helicopter drive systems.

The initial plan consisted of the following steps:

a. Identify potential candidate components and select parts.

b. Injection-mold the component using PEEK.

c. Evaluate the component in realistic conditions by testing in a drive system test stand "slave unit."

d. Based on the results from these tests, perform mechanical and chemical test to verify the material properties.

Component Selection

The program was approached from the start as a concurrent engineering effort. The team identified a number of metal components as potential thermoplastic replacement candidates. Two components were chosen for further development and are discussed later in this section of the paper:

a. A bearing input idler jet assembly.

b. An oil jet assembly.

The components selected met all the required criteria established by the team. Both components were lightly loaded nonstructural aluminum components that represented significant molding challenges. Both components required a repeatable, highly precise fabrication technique due to the components' applications on the aircraft.

Once the components were chosen, molding of the parts was scheduled at Prototype Plastic and Mold Company (PPM) in Middletown, Connecticut. Bell requested that Prototype mold the component as close to net dimensions as possible. The objective was to buy a part that required no additional machining by Bell with the exception of drilling the oil jet orifices.

A list of technical concerns was also developed to assist in planning the required tests needed to verify the material properties. Mechanical and fatigue testing at elevated temperatures in various fluids was planned, as well as chemical exposure, corrosion compatibility testing to ensure mating in the aluminum gearbox would be acceptable, and finally, component testing.

Material Selection

Bell evaluated several of the advanced thermoplastic injection-molding-grade materials. Screening tests were performed, which resulted in the selection of Victrex's injection-molding-grade PEEK. The carbon fiber-filled material was of particular interest in areas where higher strength and stiffness were required for a component. The fiberglass fiber-filled material was chosen for applications where the thermoplastic component would be attached to an aluminum component. The glass was preferred due to its lack of galvanic reaction to the aluminum.

Both materials were subjected to tensile static (ASTM D 638) and fatigue tests (Bell Test Method Specification 299-947-299, Method 616) at temperatures of −55°C through 177°C (−67°F through 350°F), in both dry and wet (saturated) conditions. The results of the fiberglass-filled material and static tests are shown in Table 1. These properties were used to evaluate the chosen components to ensure the material was adequate to meet performance requirements for the selected components.

Table 1. Results of the tensile testing of S-2/PEEK

Conditioning			Strength		Strain	Modulus	
(°C)	(°F)	**	(MPa)	(ksi)	(%)	(Pa)	(Msi)
−55	−67	dry	182	26.4	2.11	115	1.67
RT*	RT*	dry	147	21.3	1.92	107	1.56
RT*	RT*	wet	113	16.4	1.50	100	1.45
82	180	dry	116	16.8	1.62	101	1.46
82	180	wet	85	12.4	1.22	92	1.33
121	250	dry	91	13.2	1.61	89	1.29
121	250	wet	67	9.71	1.24	75	1.09
177	350	dry	38	5.47	NR	NR	NR

* RT = 24°C (75°F)
** Dry condition = no conditioning
Wet condition = saturated

In addition, both materials were tested using flexure coupons (ASTM D 790) for chemical, hot oil, fuel, and water exposure. This was undertaken as a comparative test to determine the effect of these solutions on the physical properties of the materials. The results of these tests are shown in Fig. 1. As can be determined from this figure, the material degradation was primarily an effect of temperature increases, as would be expected. There was minimal degradation associated solely with any of the fluid conditions. In some cases, the properties even increased slightly (similar to the annealing process in metals).

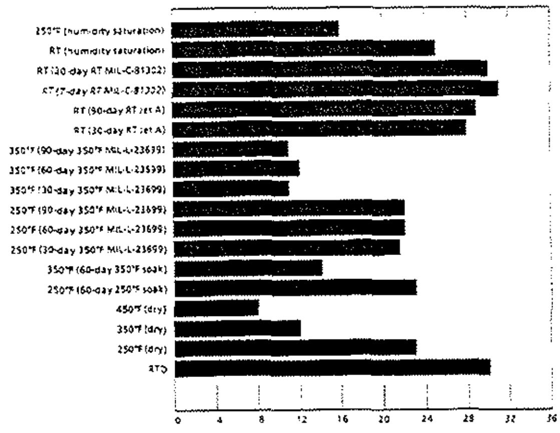

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Fig. 1. Physical properties test results.

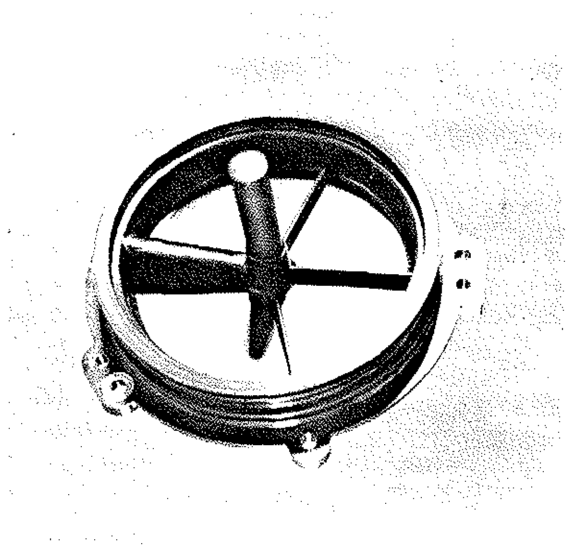

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Fig. 2. Bearing input idler assembly.

Bearing Input Idler Jet Assembly

The bearing input idler jet assembly required molded-in-place inserts, an internal oil passage, and tight dimensional tolerances. The part is shown in Fig. 2.

Component Fabrication. Minor design changes were made to the component consisting primarily of slight radius changes. PPM produced the part with O-ring grooves molded to near-net dimensions,, molded in inserts, and internal oil passages. The O-ring grooves required some machining by PPM to bring them into drawing tolerance.

The components were sent to the machine shop at Bell for drilling of three oil orifices that are used to deliver the oil to the appropriate areas of the drive system. After the orifices were drilled and targeting accuracy verified, the jets were submitted for testing.

Slave Unit Testing.

50-Hour Rig Endurance Test. The molded components were placed in a unit that simulates usage on the aircraft. These parts were tested under typical drive system operating conditions for 50 hours.

The bearing input idler jets passed the 50-hour endurance tests, which were designed to simulate flight conditions, and met all functional requirements. The components were examined for any anomalies. Small cracks were found in some of the jets on one sharp radius of the small ribs on the inside top of the cover (Fig. 3).
Based on the test results, it was determined that while sharp corners were not desirable in any injection-molded component, they were highly undesirable in parts subjected to repeated thermal cycles. All designs, both current and present, should be designed with as generous a radius as possible. The only areas allowing sharp radii were O-ring grooves or similar sections that require tight tolerances because of sealing.

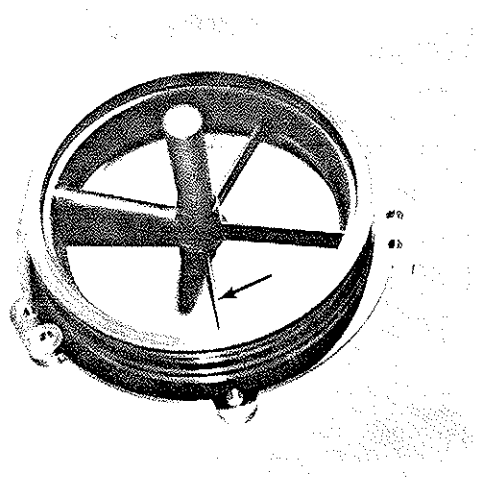

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Fig. 3. Small cracks in radius of bearing input idler jet.

Oil Jet Assembly

The oil jet assembly required a precision oil passage and screen mesh that would be molded in place, as well as tight dimensional tolerances, as shown in Fig. 4.

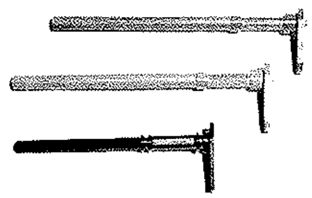

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Fig. 4. Oil jet assembly.

Component Fabrication. Minor changes were made to the design to simplify the tool construction. The screen material to provide filtering of the incoming oil was revised to be located on the inside of the jet and molded in place, in lieu of requiring a secondary operation to bond the screen externally. The number of oil intake slots was changed from three slots to two for ease of tool construction. The total area of oil intake remained the same by increasing the size of the slots. In addition, the internal screen configuration was the easiest to mold, offering greatly reduced mold tooling costs as well as lower unit costs. The inclusion of two oil feed slots, in lieu of the traditional three slots, was found to be more cost effective for both recurring and nonrecurring costs. Three slots required removable sections of the mold and, consequently, would make it more labor intensive to remove parts from the mold.

It was determined that "tube-type" oil jets could be molded from thermoplastic materials with little or no difficulty. The length of the part should not be a detriment to producing molded jets.

The overall molding results verified that molded thermoplastic oil jets were practical and cost effective, as well as lightweight. The parts were molded to near-net dimensions with the finishing operations performed by Bell. The orifice holes and timing hole in the tab were drilled using conventional techniques. No unusual machining difficulties or tool life was experienced. It was learned, however, that the orifice holes tend to close slightly after drilling.

The deburring or "tweaking" of the orifices proved to be more difficult than similar operations in aluminum jets. The toughness of the material is blamed for more difficult deburring. It was apparent that improved deburr methods will be required for production.

Tests. The methods used to flow test the completed jets were the same as those used for any oil jet. No adjustments or changes were necessary to successfully flow test the thermoplastic jets.

Flow test. The jets were subjected to typical flow tests required for metal jets during qualification. Examination of the orifices under magnification and dimensional verification of sizes leads to the conclusion that flow testing was consistent with metal jet results.

Arctic Cold Start. Some concern was initially expressed that the jet design with the inlet screen on the inside of the jet body would not withstand the spikes of high-pressure cold oil experienced during arctic start conditions. It was determined that, as part of this evaluation, one thermoplastic jet would be subjected to severe cold start to provide initial data to relieve or verify the concern.

Following one of the flow tests, the jet was left in the fixture and the fixture and jet placed in the dry box deep freezer at −40°C (−40°F). The MIL-L-7808 oil and sump to be used in the test was also placed in the deep freezer. All items (oil, jet, fixture, etc.) were left in the freezer overnight.

After the overnight soak at temperature, the fixture, jet, oil, and sump were connected to the flushing test stand. The test stand uses the ship's oil pump as part of the stand, driven by a hydraulic motor. The stand was started and the cold oil was pumped through the jet, by the oil pump, at elevated pressure. The entire test ran approximately 20 minutes until the oil temperature had risen to −23°C (−9°F). The flow was observed to remain a tight stream and fully within the target.

The condition of the screen and jet body was visually evaluated following the test. No apparent damage or distortion could be found on or to the screen body. Fig. 5 is a photograph of the jet as removed from the cold test fixture, after cleaning and drying. As witnessed by the photographs, no evidence of collapse of the screen, distortion, or other damage could be located.

Thread Strength Test Results. An additional issue to be addressed during this evaluation was the strength of threaded thermoplastic jets. It was a concern that field or depot removal of jets from the drive system assembly might result in the threads being stripped by the mechanic's technique for removal. The test devised was to evaluate whether further tests were required and whether the concern was with or without merit.

To establish a baseline and accurate comparison, an aluminum jet was pulled prior to testing the thermoplastic jet. The aluminum jet failed at 8,585 N (1,930 lbf) without damage to

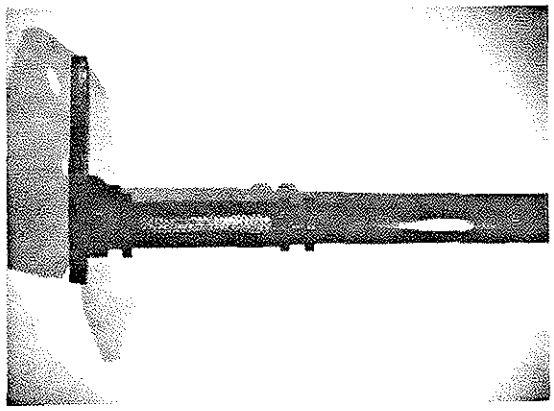

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Fig. 5. Oil jet after removal from test fixture.

the threads. The area of failure was at the tube end of the inlet area at a cross-section of 0.406 cm^2 (0.063 in^2). The thermoplastic jet was tested in the same manner as the aluminum jet with nearly the same results. The jet failed at 2,335 N (525 lbf) without damage to the threads. The area of failure was at the tube end of the inlet area at an O-ring groove at a cross-section of 0.253 cm^2 (0.039 in^2).

Fig. 6 shows both failed jets, with the thermoplastic jet at the upper half of the figure and the aluminum jet in the lower half of the figure. The test confirmed that thermoplastic oil jets were durable enough that concerns about damage of threads by mechanic at removal were unsubstantiated.

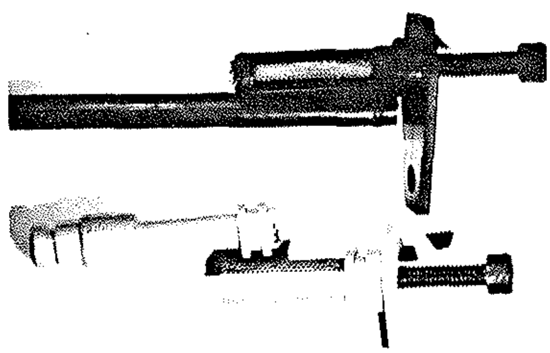

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Fig. 6. Thermoplastic and aluminum oil jets after testing to failure.

Cost/Weight Benefits for Injection-molded Components

The primary cost benefits for the injection-molded components versus cast and machined aluminum parts were obtained from the elimination of expensive machining labor. While metal or cast parts require hours of machine labor to produce a finished part to the tight dimensions required for drive system components, the injection-molded components can be fabricated to near-net dimensions in one operation with minimal machining. The estimate shows that approximately 75% of the machine labor is removed through this fabrication technique. This results in significant cycle time reduction both in the actual molding fabrication of the component, as well as in the elimination of machining time at Bell.

Material cost of the thermoplastic components is significantly higher than for the aluminum, approximately 10 times more. However, it has become apparent that material cost is insignificant compared to the cost associated with labor, as can be seen in Fig. 7.

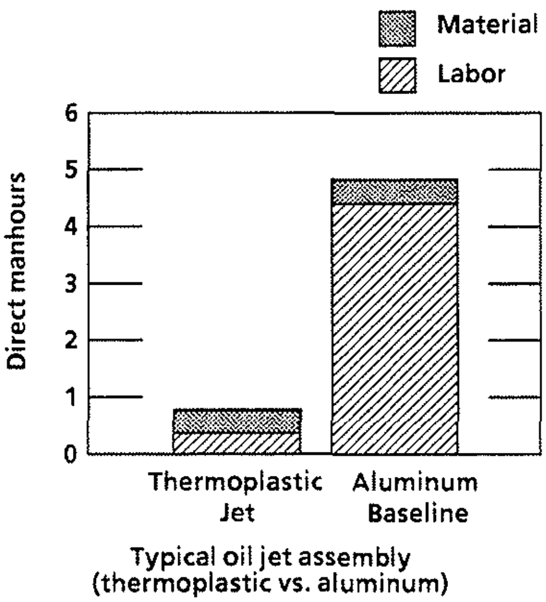

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Fig. 7. Material cost and labor cost for *thermoplastic and aluminum* components.

The negative cost impact of injection molding thermoplastic components was the up-front cost associated with matched steel tooling. An increase in tooling cost of approximately 20% was incurred. However, typical components, such as the oil jet assembly, show that the part savings were significant enough that break-even will be achieved as early as 25 ship sets for some components in production.

In addition, there is a life-cycle cost benefit that will be realized. The current model components require maintenance to keep corrosion in check, as well as periodic replacement caused by corroded parts. The thermoplastic jets are not affected by corrosion; therefore, this cost is significantly reduced.

The weight benefit was achieved as a result of the lower density of thermoplastic material. The component's load requirements were so low that one-to-one replacement was acceptable. As a result, a typical part such as the oil jet assembly was 30% lighter. Since Bell has plans to utilize approximately 90 parts in one ship, there is an estimated savings of 1.81 kg (4 lb).

Lessons Learned on Injection-molded Components

a. Injection-molded thermoplastics reduce cost by reducing cycle time and machining operations.

b. Injection-molded thermoplastics reduce life-cycle cost.

c. Injection-molded thermoplastics result in weight reduction.

3. Diaphragm-formed Component: Baggage Door

The 212/412 Baggage door is a secondary structural application using ICI's intermediate thermoplastic amorphous (ITA) AS4 fiber-reinforced plainweave fabric. Bell was able to take advantage of the forming characteristics of thermoplastics and utilize diaphragm-forming technology to provide a simple two-piece (inner and outer skin) door construction. The doors were fabricated in-house and proved to be cost effective compared to the metallic baseline, a honeycomb/skin construction. These doors are currently being recommended for production applications on new ships and for spares.

Design

The concurrent engineering team selected the Model 212/412 baggage door from a list of components identified as potential thermoplastics candidates. The objective was to produce a composite door to replace an existing metal honeycomb design at a cost-competitive price. After the component was selected, the part had to be redesigned as a thermoplastic component. ICI Advanced Materials assisted in both the part design and the tooling design. The design team developed a two-piece outer skin and hat-stiffened inner skin design that exploited the formability of thermoplastic (see Fig. 8).

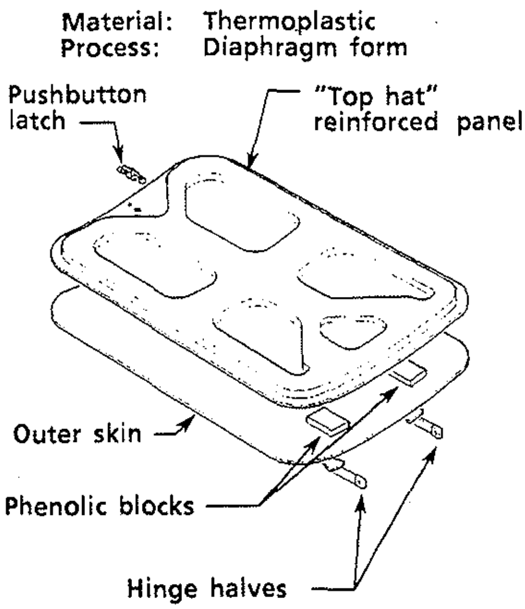

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Fig. 8. Two-piece thermoplastic door design.

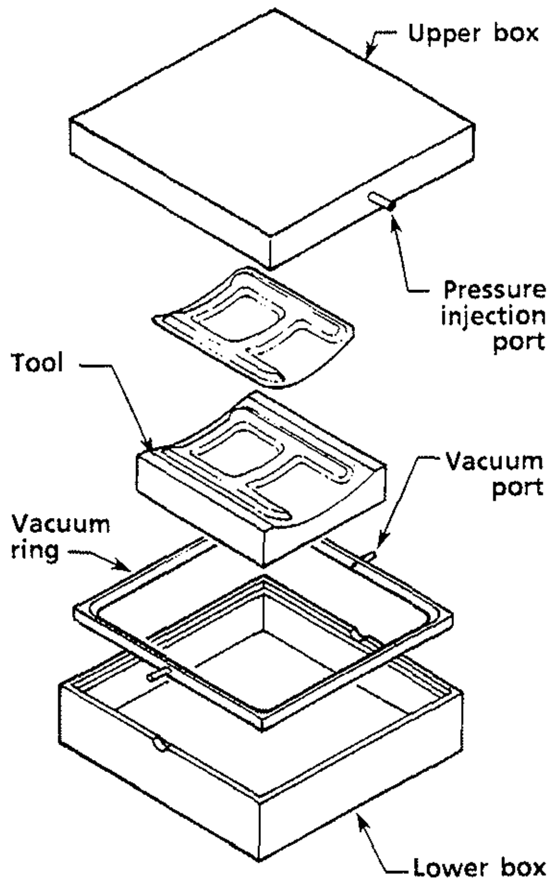
Both the inner and outer skin were 4-ply configurations. A CATIA drawing was completed and lines produced to assist in tool design.

The baggage door was subjected to higher service temperatures (177°C/350°F) compared to most helicopter airframe structure. This was due to its location on the tailboom where it is subjected to engine exhaust impingement. As a result, several new higher-temperature thermoplastic material systems were evaluated. ICI's ITA with T300 carbon fiber in a plainweave fabric was chosen. Material properties at 177°C/350°F and relative low cost were the main drivers in the selection of the ITA material.

Fabrication

Tool design completed the tooling drawing for a diaphragm-formed two-piece steel tool as shown in Fig. 9. The tool was carefully controlled to ensure that it would be a production-quality tool and meet all production requirements, in anticipation of Bell using the tool to make production doors for the Model 212/412, if all testing were acceptable.

Once the tool was completed, initial manufacturing trial runs were performed to optimize production techniques for the production-quality doors. The most critical manufacturing items of concern were as follows:



4G756
Fig. 9. Diaphragm-formed tool.

a. High-temperature forming press for press consolidation.

b. Requirement for even cool-down rates for the part and tool.

c. Equipment capable of reaching and maintaining maximum pressure in the range of 861 kPa (125 psi) or greater.

d. Evacuation method for removing volatile materials from the ITA.

After completion of the trials, multiple skin components were fabricated using a diaphragm-forming technique as shown in Fig. 10. Nondestructive inspection (NDI) was performed to determine the quality of the finished components. NDI showed that the skins were fully consolidated. In addition, it was determined that in skin sections, this thin porosity in the skins could be detected through visual examination.

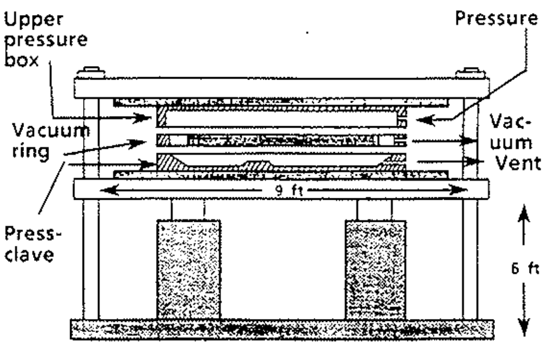


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Fig. 10. Diaphragm-forming technique.

The NDI panels were then grit blasted and cleaned prior to bonding. The panels were bonded in an autoclave for 90 minutes. The adhesive system utilized was 3M's AF191 film adhesive (service temperature rated at 177°C/ 350°F). The adhesive and bonding techniques were established through coupon level bond tests previously performed in the program.

Tests

Three test doors were fabricated to production standards as shown in Fig. 11. One door was subjected to static testing to ensure that the doors meet required structural loads. The static test unit failed at 720% of limit load or 64% ultimate load at temperature. To adjust for the environmental conditions (service temperature) a statistical correction of 2.94 was utilized to account for property degradation of the adhesive.

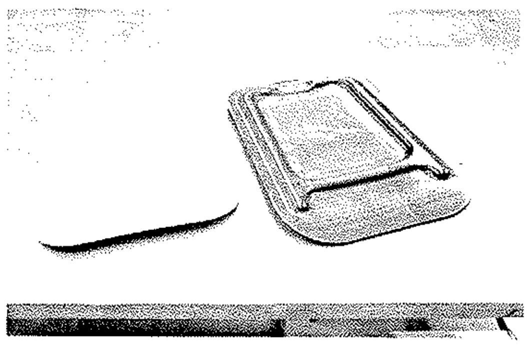

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Fig. 11. Test doors.

Based on the static test, Bell was granted FAA approval to test the door in the field. Primary flight time has been achieved on a door installed in a customer aircraft operating on the Louisiana Gulf Coast. The door has accumulated more than 2,000 flight-hours and shows no signs of delamination, corrosion, damage, etc. The customer was very pleased to have a product that will lower life-cycle costs.

Cost/Weight Benefits for Baggage Door

The primary cost benefit of diaphragm-formed thermoplastic components, such as the baggage door, was achieved from a labor reduction. The actual hand labor required to lay up the part was reduced due to the simplicity of thermoplastic ply layup. This thermoplastic component was designed in such a manner that darting, pleating, or splicing would not be required; this was possible because the components take advantage of the formability of the material.

Material cost of the thermoplastic component was significantly higher than the metal component. However, the reduction in labor-related man-hours (cutting, bonding, insert potting) proved to be significant enough to outweigh the material cost increase (as shown in Fig. 12).

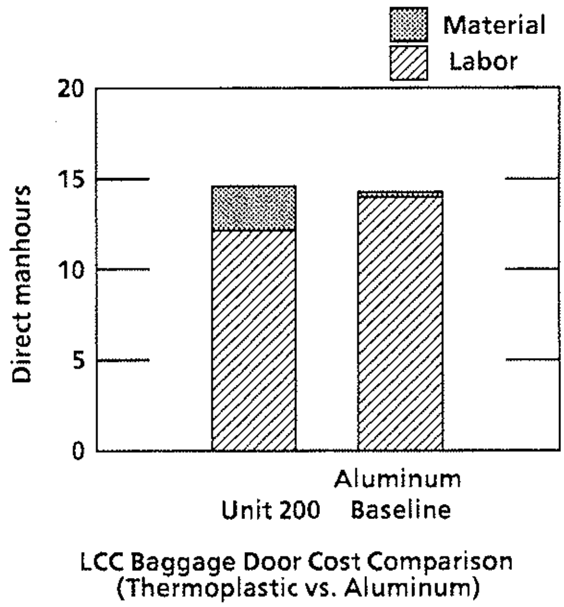

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Fig. 12. Material cost and labor cost for thermoplastic and aluminum door designs.

The initial components would be more expensive than the current door that has been in production 27 years. However, once the learning curve was developed, it became apparent that the cost would be reduced to match that of the metal door by Ship Set 200 (see Fig. 13). This was significant, since the current metal door is considered to be one of the cheapest, easiest metal constructions: metal and honeycomb bonded together. In addition, the current metal

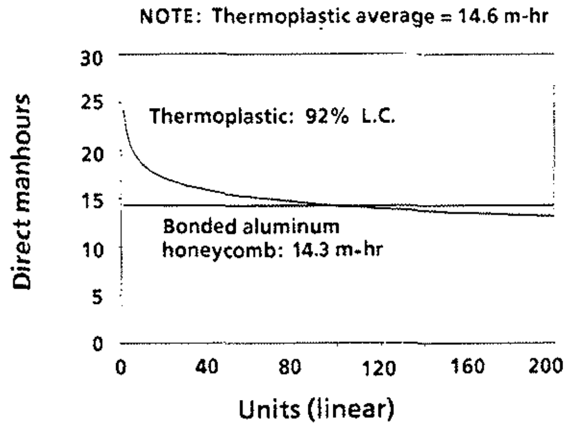

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Fig. 13. Comparison of cost for metal door and thermoplastic door over time.

door was fabricated outside Bell at lower labor rates.

Finally, the thermoplastic Model 212/412 Baggage Door should show reduced life-cycle cost. The new design has yet to develop any problems, and the nature of the thermoplastic material should preclude typical problems associated with metal doors, such as damage, abuse, damage from temperature fluctuations, and corrosion.

The savings were derived totally from the material change. The same phenolic block and hardware was used on both doors; therefore, the lighter composite material and reduction in potting requirements of the honeycomb reduced the weight. When both doors were weighed, the metal door weighed 1.5 kg/3.3 lb and the thermoplastic door weighed 1.18 kg/2.6 lb.

Lessons Learned on the Baggage Door

a. A two-piece bead-stiffened design can be cost competitive with a metal honeycomb design.

b. The diaphragm-forming process offers a cost-effective method for producing integrally stiffened structure.

c. The thermoplastic door provides a structure that saves weight compared to honeycomb structure.

4. "Cure-on-the-Fly" Component: Tailboom

The OH-58D/206 tailboom is a primary structural application using ICI's aromatic polymer composite (APC-2A) with AS4 fibers. Bell chose as the manufacturing method *in situ* consolidation using slit tape. This allows maximum use of automation with the fiber placement technique and eliminates the downstream bagging and autoclave cure cycles that are very costly in typical composite fabrication.

Automated Dynamics Corporation (ADC) of Schenectady, New York, was selected as subcontractor to fabricate the component. A 1.83-m (6-ft) section representing the aft portion of the tailboom was fabricated and delivered to Bell for testing. The unit was torsion tested to 2.75 times ultimate load, then tested in bending to failure.

Design

Based on the success of the Model 212/412 baggage door, the decision was made to include primary airframe structure when evaluating potential candidate components. The objective was consistent with the door: cost competitive structure, enhanced damage tolerance, improved corrosive resistance, and decreased life-cycle cost through improved reliability and maintainability. As various components were reviewed the following criteria were followed:

a. Component would be relatively easy to remove and replace on existing structure.

b. Component would utilize automated processing techniques currently available in the market.

c. Component would present technical challenge for fabrication.

During the evaluation, the requirement for "remove and replace" became a driving factor in the decision. Typical primary airframe structure is not easily replaced for short-term flight evaluation. The component that best met all the requirements was an OH-58D/206 tailboom.

The OH-58/206 tailboom is a relatively simple lightweight monocoque circular structure that is 3.66 m (12 ft) in length, consisting of an outer shell of sheet metal and numerous internal components, as shown in Fig. 14.

The structure is a cone that lends itself to automated manufacturing procedures such as fiber placement or *in situ* consolidation for thermoplastics. *In situ* consolidation has also been

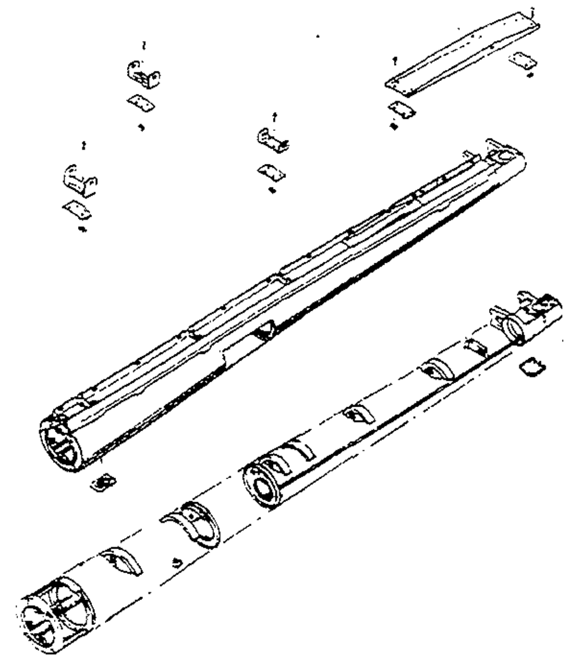

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Fig. 14. OH-58/206 metal tailboom.

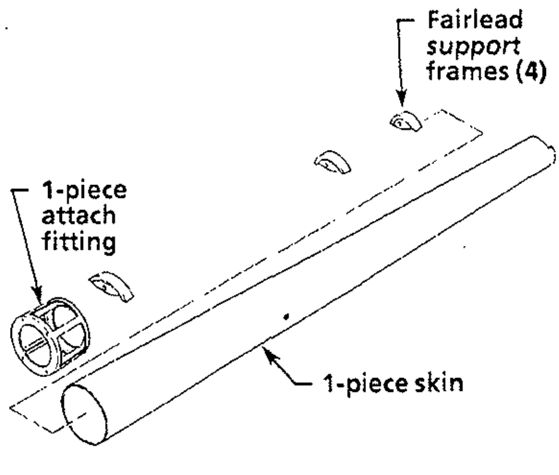

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Fig. 15. Revised tailboom design.

referred to as "cure-on-the-fly" and, simply stated, uses fiber placement type equipment to melt strips of thermoplastic tape together. This process will be discussed in greater detail later in this paper.

The tailboom also represented a manufacturing challenge, since a conical structure requires ply dropoffs as the cone tapers while maintaining a constant wall thickness. Fiber placement using the *in situ* consolidation allowed the design to follow a nongeodesic path and terminate plies as required through the use of a computer program.

The tailboom was redesigned as a thermoplastic component, based on the loads and requirements of the OH-58D. However, the stiffness was increased so minimal internal structure would be required and the part count could be reduced. The tailboom utilized a layup consisting of 0-deg, 90-deg, and ±45-deg plies. In addition, the design was developed to utilize the capability of the *in situ* process to form a hot bond to other thermoplastic components as processed to minimize secondary assembly operations. The final design will eliminate some features (multiple fasteners), utilize some of the existing features, and redesign other features using like thermoplastic materials. The revised design is depicted in Fig. 15.

The major emphasis on part count assembly and co-consolidation was driven by cost reduction. Assembly cost, not part cost, is the dominant factor in the tailboom. The objective was to minimize the number of secondary assembly steps, in particular to reduce the number of components that must be fastened to the structure.

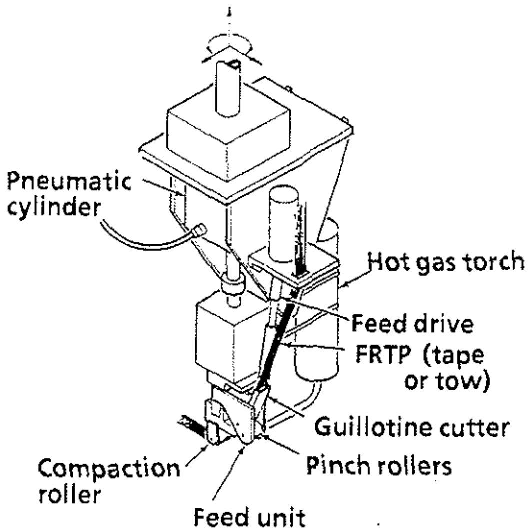
Material

The material selected for the tailboom was ICI's aromatic polymer composite carbon fiber reinforced APC-2/AS4 1/4-inch slit tape. This material was chosen based on the material property data base, past experience at Bell, and development work previously completed utilizing the APC-2S/AS4 slit tape for *in situ* consolidation. In addition, the material offers nuclear, biological, and chemical (NBC) warfare resistance and suffers minimal property degradation in hot/wet environments. The hot/wet condition has been a major design driver with thermosets.

Fabrication

The team decided to initially fabricate a 1.83-m (6-ft) section of the OH-58D tailboom as an element test to determine if the basic structural integrity and manufacturing costs would be acceptable.

ADC was selected as subcontractor to fabricate the demonstration article. ADC has developed a hot-gas torch process for the fiber placement and *in situ* consolidation of thermoplastic materials. Machine speeds, feeds, path, etc. are computer controlled. A hot gas stream is utilized to soften the resin in the tape and on the surface of the existing composite layer previously placed on the mandrel. A compaction roller, immediately following the fiber placement head (Fig. 16), consolidates the new piece of tape to the existing material.



4G763
Fig. 16. Fiber placement head.

ADC developed a computer program to control the winding, evaluated compaction roll geometry, and established the basic process requirements. Once the parameters were established, ADC produced a 1.83-m (6-ft) conical section of the OH-58D tailboom, as shown in Fig. 17.

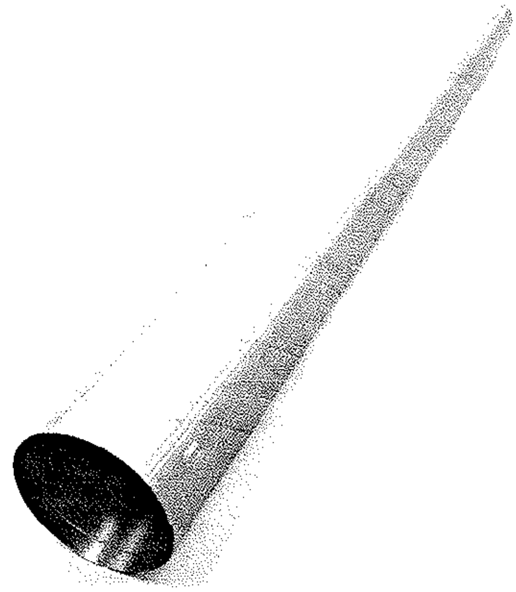


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Fig. 17. Conical section of OH-58D tailboom.

Tests

Ballistic Test. One of the primary concerns with thermoset materials has been their reaction to various types of damage. Material test data was available for standard damage tolerance tests such as compression-after-impact (CAI) to establish the APC-2A performance. However, we were interested in evaluating the material in a real life situation such as a typical ballistic impact. A cylindrical specimen using the same ply arrangement as the boom was fabricated and tested using a 12.7-mm tumbled round at 762 m/sec (2,500 ft/s). NDI was performed to determine the internal damage to the part. The damage was limited to the immediate vicinity of the entry and exit points as shown in Fig. 18.

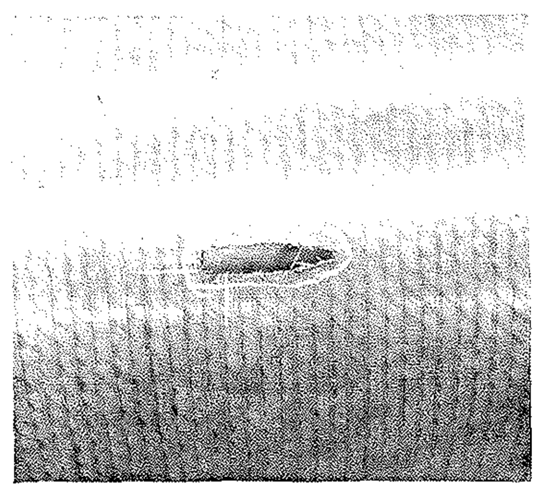

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Fig. 18. Ballistic damage to cylindrical tailboom test section.

Static Test. The 1.83-m/6-ft section previously shown in Fig. 17 was tested in bending and tension. The OH-58D loads were used as the goal. The torsion test was terminated at 2.75 times ultimate load. The tailboom was tested to failure in bending, which occurred at 2.0 times ultimate load.

Failure was due to a local buckling instability,and resulted in a clean break with no associated delamination. It was very similar to the crack one would expect to see in a metal structure, but did not exhibit permanent deformation of the crack edge. This should make repair of the damage simple (Fig. 19).

Status

Currently a full-size tailboom design is nearing completion. Development is addressing all

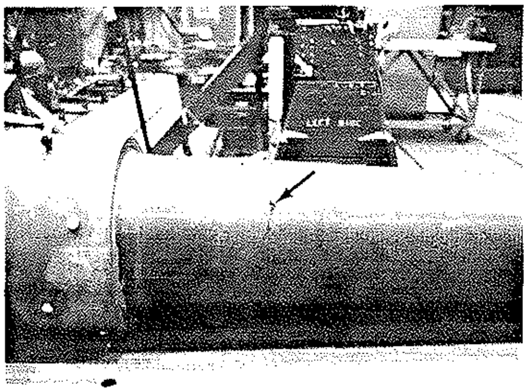

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Fig. 19. Tailboom damage.

productions features, including fuselage attachment, horizontal attachment, vertical attachment, and drive shaft support. Once this design is completed, a production quality tailboom will be fabricated and tested.

Cost Benefits of Tailboom

The cost benefit for the tailboom will be achieved through part count reduction and reduced assembly manhours. The *in situ* process is an automated process that allows co-consolidation of components, thereby minimizing touch labor.

Material cost of the thermoplastic skin is more expensive than the metal skin. However, the skin is only one part of the overall cost.

As previously mentioned, one of the primary cost drivers was fabrication cost for individual parts. Part costs for the tailboom features were mixed. As the design developed, it became clear that some components would stay the same. For example, we plan to use the same vertical attachment casting. Other components will be designed more efficiently, still using metal, by reducing multiple-piece sheet metal components to one-piece castings. This will provide (1) a cost lower than the original design through part-count reduction and (2) reduced assembly time through simplified installation. Small metal components will be molded using thermoplastic resins, which will reduce the part cost. Overall piece part costs will decrease slightly compared to the metal-design cost of these parts and allow co-consolidation during the hot winding of the skin.

After taking all this into account, the preliminary cost benefit analysis determined the thermoplastic design will be approximately the same cost as the metal tailboom, as shown in Fig. 20 (Ref. 1). In addition, life-cycle costs should be reduced due to the inherent nature of the material (as previously discussed in this paper). A full life-cycle analysis has not been completed.

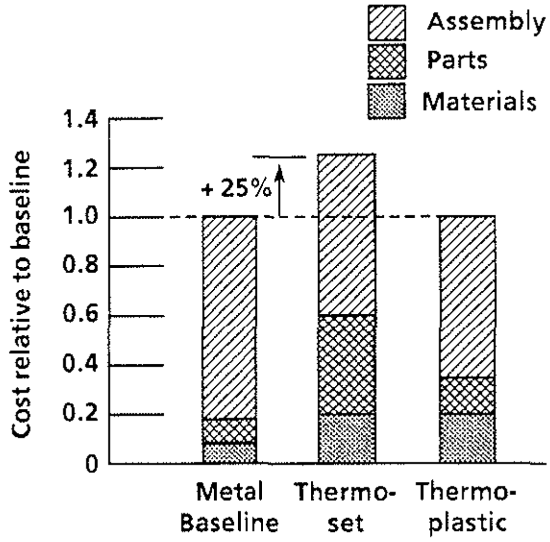

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Fig. 20. Comparison of cost for tailboom.

Lessons Learned on Tailboom

a. Part count and assembly time must be reduced to be competitive.

b. New composite structures can be intermingled with existing structure efficiently.

5. Conclusions

Composite materials offer many benefits relative to metals, such as damage tolerance, corrosion resistance, enhanced fatigue properties, etc., that typically result in life-cycle cost. However, production costs must be comparable to metals for composites to be practical in the marketplace. Thermoplastics offer the potential to reduce production costs and cycle times. Three types of components with different applications were have been discussed in this paper, and conclusions for each component are detailed below:

Injection-molded Components: Drive System

a. The economics associated with use of thermoplastics make incorporation most desirable. No technical cause could be found to eliminate fiber-reinforced thermoplastics as the material of choice.

b. The injection molding of thermoplastics led to reduced cycle time. This was achieved by molding complex shapes with precise dimensions to a finished component of near-net dimensions, including molded-in insets and bushings.

c. In addition to the reduced cost benefit and ease of manufacture, the use of thermoplastic material will provide an advantage of approximately 30% in weight over aluminum.

Diaphragm-formed Component: Baggage Door

a. The door, while slightly more expensive for the initial units, will match the cost of the current production door by Ship Set 200.

b. The weight of the component was decreased by 0.7 lb.

c. Life-cycle costs are predicted to be lower due to problem-free service to date.

"Cure-on-the-Fly" Component: Tailboom

a. Based on the program results to date, a thermoplastic tailboom appears to be a good candidate for a production helicopter from a structural and cost standpoint.

b. The *in situ* process offers a cost-effective automated processing option when properly utilized.

c. Components must be evaluated and redesigned to ensure cost effective structure.

6. Concluding Remarks

The research programs discussed in this paper have shown that successfully replacing aluminum parts with fiber-reinforced thermoplastics depends on following a basic methodology. This became apparent as these programs evolved and is outlined below:

a. Not all components are ideal candidates for composites. To ensure utilization of composites in a cost-effective manner requires choosing the right material and fabrication technique for the component. To achieve this goal, concurrent engineering teams must be formed that include design engineers, stress engineers, material and process engineers, and fabrication engineers.

b. The teams must remain open-minded and not fall into the trap of making composite structures that are just like their metal counterparts (i.e., "black aluminum"). These teams must be willing to accept new design approaches.

c. The teams must identify the cost drivers for a component and utilize design and fabrication techniques to reduce these costs (e.g., part count reduction to decrease assembly time).

d. The teams must be adaptable and willing to incorporate the strengths of the materials and processes into designs in order to take advantage of automation and unique manufacturing capabilities.

The acceptance of composite substitutes depends critically on achieving part costs comparable to metal. This cannot be achieved unless the right parts are matched to the right materials and the right fabrication processes.

7. Acknowledgements

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8. References

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