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ADVANCED COMPOSITE AIRFRAME PROGRAM - TODAY'S TECHNOLOGY

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ABSTRACT

The Advanced Composite Airframe Program (ACAP) was undertaken by the Aviation Applied Technology Directorate, US Army Aviation Research and Technology Activity (AVSCOM) to demonstrate the advantages of the application of advanced composite materials and structural design concepts to the airframe structure on helicopters designed to stringent military requirements. The primary goals of the program were the reduction of airframe production cost and airframe weight by 17% and 22% respectively.

The ACAP effort consisted of a preliminary design phase, detail design and design support testing, full-scale fabrication, laboratory testing, and a ground/flight test demonstration. Since the completion of the flight test demonstration programs follow-on efforts have been initiated to more fully evaluate a variety of military characteristics of the composite airframe structures developed under the original ACAP advanced development contracts.

This paper provides an overview of the ACAP program and describes some of the design features, design support testing, manufacturing approaches, and the results of the flight test evaluation, as well as, an overview of Militarization Test and Evaluation efforts.

INTRODUCTION

The ACAP began in 1979 when the US Army awarded contracts to the five major US helicopter manufacturers to conduct a preliminary design of an all composite helicopter airframe for a utility class helicopter with a gross weight under 10,000 lbs. The helicopter was to be designed for a 2.3 hour mission endurance and a 2000 ft - 95^{0} F hover capability. Dynamic systems and subsystem components were to be existing qualified military or commercial components. The results of these five preliminary design studies indicated that the 22% reduction in weight and 17% reduction in production cost could be met or exceeded while at the same time improving military characteristics such as crashworthiness, reliability, maintainability, and survivability.

At the completion of the preliminary design studies the Army proceeded with a two-phased effort to conduct detail design and design support testing and to fabricate, laboratory test and flight test the ACAP helicopter. In March 1981 the Army selected both Bell Helicopter Textron and Sikorsky Aircraft to proceed with the detailed design of their respective ACAP helicopters.

ACAP HELICOPTER DESCRIPTION

The Bell ACAP Helicopter designated, the Model D292, is shown in Fig. 1. The gross weight of the D292 is 7525 lbs. The dynamic systems including the engines, rotors, transmissions and flight controls are taken from the Bell Model 222 commercial helicopter. The Sikorsky S-75 ACAP helicopter shown in Fig. 2. has a gross weight of 8470 lbs. and utilizes the dynamic systems and subsystems of the Sikorsky S-76 commercial helicopter.

AIRFRAME DESIGN

The design of the ACAP airframes was driven to a large extent by requirements other than flight loads. The primary design drivers were the crashworthiness requirements of MIL-STD-1290. As shown in Fig. 3 significant portions of the airframe cockpit, cabin and transition section were designed by crash conditions. The tail sections of the airframes were designed primarily by flight loads in a ballistically damaged condition while the doors, fairings, and portions of the empennage were designed by airloads.

During the design phase numerous trade-offs were made to select the most effective materials and structural configurations for the various airframe components and assemblies in order to provide designs that were structurally and environmentally sound and at the same time light weight, low cost and producible. As the airframe designs evolved a variety of materials and design configurations were used to meet the program goals of reduced airframe production cost and weight and to enhance the military characteristics over those of existing military helicopters. The airframe structural designs make use of a variety of composite materials including graphite, Kevlar, fiberglass, epoxy, and polyimides and structural configurations including skin/stringer; integrally stiffened panels; solid laminates; and sandwich beams, frames, and longerons. A breakout of the major structural components is shown in Fig. 4. Graphite is utilized in areas where high strength and stiffness are required, such as longerons, frames and beams; Kevlar is used predominantly for both primary and secondary skin panels; and fiberglass is utilized on surfaces subjected to high wear such as floors. In some airframe applications, however, composites were not considered practical. These areas included transparancies, some attachment hardware, door latches, and fasteners. Fig. 5 shows the utilization of materials in the composite airframes of each manufacturer.

Cost effective producible design required that particular attention be given to the airframe breaks and sizing of the major components and subassemblies. The preliminary design studies had shown that, in general, to meet the program cost savings goals, it was essential to minimize the total number of parts and fasteners. However, experience has shown other factors such as tool size, complexity, accessability and turn around time must be considered, as well.

The basic approach to the design by each manufacturer was significantly different and resulted from many factors including each contractor's background and experience with other composite designs. The Bell ACAP airframe assembly approach utilizes two large half shell fuselage sections which are bonded together to form the basic airframe shell from the nose to bulkhead where the tail boom is attached. Sikorsky Aircraft, on the other hand, elected to use a number of modules or subassemblies, which are mechanically fastened to form the basic airframe shell. In each case the manufacturer reduced the number of parts and fasteners substantially in comparison with their respective metallic baseline airframe.

The ACAP detail design represents the first US military helicopter structural design to be developed using Computer Aided Design. The aircraft lines were developed from CAD terminals as were a major portion of the airframe detail design drawings. The CAD system provided a common data base for the aircraft lines, detail design, and structural analysis. Not only did the CAD system provide the designer with a rapid visualization of his design, it also provided rapid turn around time thus allowing greater flexibility to optimize the part.

The use of CAD did not stop with the designer and analyst, however. The design data base was used by the manufacturing engineers as well to develop tool designs, flat pattern layouts, and tapes for numerically controlled machines such as the Gerber cutter, tape laying machines, and filament winders. From the tool designers viewpoint, a major benefit of the common data base and the CADAM system was the ability to incorporate shrink factors in the tool design to compensate for differential thermal expansion during the cure cycle.

DESIGN SUPPORT TESTING

Prior to committing to full-scale airframe manufacturing each contractor conducted a significant design support test program to verify the structural integrity of the critical components of the airframe. The objectives of these tests were to demonstrate that the structural concepts were properly designed and to compare the results to the design criteria. These tests ranged from coupon and panel tests to substantiate design allowables for specific materials and laminate configurations to static and fatigue tests of major joints, attachments and full-scale components to verify structural integrity. A one-fifth scale model wind tunnel test was conducted to assess the drag and stability characteristics of the ACAP helicopter configurations. Additionally, testing was conducted to assess the crashworthiness, damage tolerance and lightning strike protection of the airframe design.

TOOLING CONCEPTS

The tooling philosophy for the ACAP placed emphasis on controlling dimensional accuracy, stability, and repeatability of the composite components being fabricated. The resulting primary tooling concept used by each of the contractors, however, is quite different. Bell Helicopter elected to fabricate the basic ACAP fuselage shell in two halves, thereby minimizing the number of major assemblies. To minimize the differential thermal expansion between the part and the tool during autoclave curing Bell elected to use graphite tooling. Figure 6 shows the left-hand fuselage shell mold with the initial ply layups in place. The completed fuselage half-shell is shown in Fig. 7.

Sikorsky, on the other hand elected to use metal tooling for their large skin molds. They accounted for the differential thermal expansion in the design of the tool - a task that was greatly simplified by the use of CADAM. The large skin mold tools were made by forming a thin steel shell to the aircraft contour followed by welding studs on the shell mold for attachment to the mold base through the contoured headers. The headers were cut on a numerical control machine utilizing aircraft lines data from the CADAM data base. Figure 8 shows the completed mold with the formed steel shell in place. The posts at the corners of the mold base are used to stack tools for multiple autoclave curing.

Other components with critical dimensions such as ribs, frames, bulkheads, and beams, are fabricated on steel tooling like that shown in Fig 9. Electroplated nickel and fiber reinforced composite tools were also used for some components where dimensional control was less critical.

MANUFACTURING METHODS

Each contractor developed a manufacturing plan considering both existing and developmental manufacturing methods and technologies which could impact favorably on the manufacturing cost of the composite airframe. Autoclave curing was used for fabrication of the large skin sections. Filament winding was used to fabricate the Bell truss tailcone and the Sikorsky tailcone and vertical pylon spar. The graphite windshield post on the Sikorsky ACAP was fabricated using the pultrusion process. Computer generated pattern books (Fig. 10) were used to aid shop layup. Computer controlled rapid ply pattern cutting (Fig. 11) was used to prepare composite laminae for layup kits. Water jet trimming (Figure 12) of precured parts was also utilized.

Various computer aided and robotic manufacturing methods which were under investigation at the time were identified as potentially promising methods for factories-of-the-future. However, where the technology had not matured to the point it could be demonstrated under the ACAP contract it was not included in the manufacturing cost analysis. Each contractor was required to conduct a production cost analysis to compare the direct labor and material cost of the advanced composite airframe to the equivalent metallic baseline airframe. This cost comparison was based on FY 80 dollars and a production run of 1000 aircraft at a rate of 14 aircraft per month. Figure 13 shows a comparison between the ACAP airframe production costs and the metallic baseline in terms of materials and labor. It can be seen that the cost savings achieved is due to the labor cost reduction. The material costs for the airframe are significantly higher than for the metallic airframe despite the reduction in the weight of the airframe. Hopefully, future volume production of composite raw materials will result in lower prices and thus increase the cost savings on future aircraft systems.

Each contractor fabricated three airframes. The first airframe was used for proofing the tooling concept. The Tool Proof Airframes (TPA) shown in Figs. 14 and 15 were ballistically tested at the AATD Ballistics Test Range at Ft. Eustis, VA. The second airframe fabricated was designated the Static Test Article (STA). The STA was used both for static testing and shake testing. The third airframe fabricated was assembled with all the dynamic systems, subsystems and landing gear to produce a complete flightworthy Flight Test Vehicle (FTV).

During the fabrication effort the contractors were required to track the weight of the composite airframe and to compare the weight to that predicted both for the baseline metal and composite airframes. Figure 16 compares the weight of a composite airframe to a metal baseline from the preliminary design to the completion of the fabrication of the three airframes.

STATIC TEST PROGRAM

Static testing was conducted on the STA's to verify the structural integrity of the ACAP airframes for the applied design loads. The contractors selected the design loading conditions based on their NASTRAN model results. In the case of Sikorsky several critical load conditions were tested to insure that the most critical loading conditions were introduced to each section of the airframe. The flight and landing load conditions tested are shown in Table 1. Bell Helicopter also choose critical flight conditions which would introduce critical loading in each section of the airframe. Table 2. summarizes the flight and landing loading conditions applied in the Bell static test program.

AMCP 706-203 states that thermal environmental effects shall be accounted for in static testing by: (1) application of the operational environment, or (2) by accelerating the applied loads to account for the environmental degradation. This requirement was extended in the ACAP static test program to include the effect of moisture on composites as well as temperature. This requirement presented a dilemma for the contractors because conditioning of the entire airframe, particularly, moisture conditioning was considered impractical. On the other hand, full load acceleration to account for environment could impact too severely on environmentally insensitive components. The approach taken, therefore, was to test at elevated temperature with loads accelerated to account for moisture degradation. Figures 17 and 18 show the Sikorsky and Bell airframes in static test, respectively.

FLIGHT TEST PROGRAM

The structural substantiation process was continued throughout the flight test program to verify that the applied design loads were not exceeded during flight. The flight test vehicles were intrumented with strain gages to monitor flight loads during the test program. Safety of flight monitoring of the strain levels was a major concern. Since using design allowables as flight allowables would only guard against "failure under the gage", the flight strain allowables were based on the full scale static test results. In this manner the strain gages are monitored as "load cells" to assure that the loads substantiated in static testing were not exceeded in flight. The "Do Not Exceed" (DNE) flight strains were based on measured static strains reduced to appropriate safe flight levels by:

$$\epsilon_{\text{DNE}} = \epsilon_{\text{STATIC}} \times 2/3 \times 1/\text{LAF} \times \text{K}$$

Where:

ϵ STATIC = Peak Static Test Strain
2/3 = Ultimate to Limit Safety Factor
LAF = Load Acceleration Factor
(eg. Temperature/humidity effects)
K = Other Appropriate Factors

For those areas of the structure that were statically tested at elevated temperature the LAF was based on the ratio of room temperature dry to room temperature wet design allowables. When the critical area was not tested at elevated temperature then the LAF was based on the ratio of room temperature dry to elevated temperature wet design allowables. Early in the flight test program a K factor of 0.8 was used as added conservatism.

The Sikorsky S-75 ACAP made its first flight (Fig. 19) in July 1984 at the Sikorsky Aircraft Flight Test Facility in West Palm Beach, Florida. The FTV completed a 43 hour flight test program which included a 5 hour Government Pilot Evaluation in March of 1985. The S-75 flight envelope established, which was limited by the dynamics system installed, is shown in Table 3.

In September 1985 the Bell D-292 made its first Flight (Fig. 20) at the Bell Flight Test Center in Ft. Worth, Texas. The Bell FTV completed 25 hours in July 1986. The D-292 flight envelope established is shown in Table 5.

ACAP MILITARIZATION TEST AND EVALUATION

Although the basic ACAP program included an evaluation of some of the military characteristics of the airframes developed there were some areas that either were not evaluated completely or were not examined at all. In September of 1985 contracts were awarded to both Bell and Sikorsky to conduct additional test and evaluation of the ACAP airframes. These efforts included the following areas of interest: (1) landing gear/airframe crashworthiness, (2) repairability and inspectability, (3) lightning strike protection, and (4) internal acoustic noise.

The landing gear for the ACAP helicopters were designed in concert with the airframe design because the ability of the helicopter to meet the requirements established for crashworthiness is dependent on the ability of the total system to absorb crash energy. The airframe, landing gear and seats all play a role in the safety of the crew and troops in a crash. Drop testing of the main and auxiliary landing gear at sink speeds up to 20 fps was included in the original contract. The original contract also included a full-scale drop test of the complete airframe, landing gear and seat system. In order to preserve the assets for other testing it was decided to delete the full scale drop testing from the original contract. Therefore, the testing was picked up in the follow-on ACAP Militarization Test and Evaluation (MTE) Programs. In addition, to insure that both the main and auxiliary landing gear would function as designed, drop testing at sink speeds up to 42 fps was included in the MTE programs. Drop testing of the landing gear at sink speeds up to 42 fps is in progress now and the full-scale aircraft drop tests are scheduled for mid-1987.

Analyses of the reliability and maintainability characteristics of the ACAP airframes were conducted during the basic ACAP program. In addition, limited repair demonstrations were made. In the MTE program each contractor is further developing field repair techniques and procedures compatible with the personnel skills, materials and equipment expected to be available for field (AVIM level) repairs. These repair techniques and procedures to be demonstrated on the tool-proof and static test airframes will be completed early in 1987.

Lightning strike test of composite panels were conducted as a part of the ACAP design support test program to provide comparative test data to aid in the selection of a means for protecting the Kevlar skin from lightning strikes. Although the panel test results were favorable it was desirable to evaluate the performance of the lightning strike protection system on a full scale airframe. The testing included both direct and indirect lightning strikes. Testing of the Sikorsky ACAP was successfully conducted at the McDonnell Douglas Facilities in St. Louis, MO. The Bell ACAP lightning strike testing was conducted by Boeing Aircraft in Seattle, WA. This testing was conducted in cooperation with the Air Force's Atmospheric Electrical Hazards Protection (AEHP) program. In addition to the evaluation of the effects of lightning strike on the airframe structure, a variety of electrical and avionics components were installed onboard the Bell ACAP to enable the evaluation of electromagnetic compatibility and interference characteristics. Shown in Fig. 21 is the Bell tool-proof airframe being subjected to a direct lightning strike.

The transmission of internal acoustic noise in an all composite airframe has been a concern from the standpoint of increased sound pressure levels in both the cockpit and crew compartments. During the initial flight test evaluation of the Sikorsky S-75 ACAP and Bell D292 ACAP the pilots' qualitative reports were that the noise and vibration levels were about the same as in the parent S-76 and Model 222 helicopters. The ACAP MTE program included a 5-hour flight test evaluation to measure sound pressure levels and accelerations in an effort to quantitatively assess the internal acoustic noise. In addition, noise predictions were made using a computer code originally developed by Cambridge Collaborative for a Sikorsky S-76 helicopter under a NASA Langley Research Center contract. The acoustic flight testing of the Sikorsky S-75 ACAP was conducted in April 1986. Figure 22 shows a typical comparison of the acoustic noise data measured on the S-75 ACAP with data measured on the metal S-76. The Bell D292 ACAP is scheduled for acoustic flight testing in early 1987.

Finally, under separate contract competitively awarded to Bell Helicopter in September 1986, a full suite of communications and navigation equipment commensurate with the Army's UH-60 BLACK HAWK helicopter is being installed on the Bell FTV. The Bell ACAP FTV will be used as a flying test bed to evaluate the electromagnetic compatibility and interference characteristics and operational performance levels of a full-up avionics suite on-board an all composite airframe.

CONCLUSIONS

The Advanced Composite Airframe Program has successfully demonstrated the feasibility of applying advanced composite materials to the airframe of military helicopters. The ACAP has greatly reduced the risk of introducing composites into next generation helicopter full-scale engineering development programs. The primary goals for weight and cost reductions have been achieved and both a cost and weight data base have been established. The benefits of composites technology for enhanced military characteristics have or are being demonstrated through test and evaluation of the ACAP airframes.

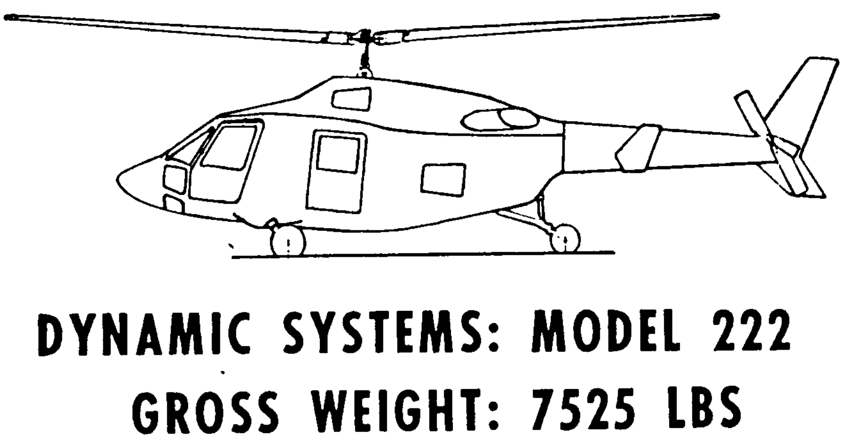

Figure 1. Bell D292 ACAP Helicopter

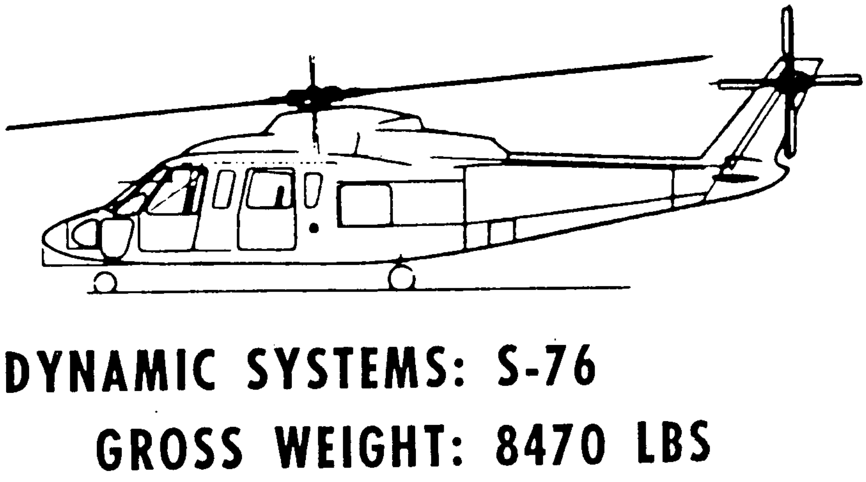

Figure 2. Sikorsky S-75 ACAP Helicopter

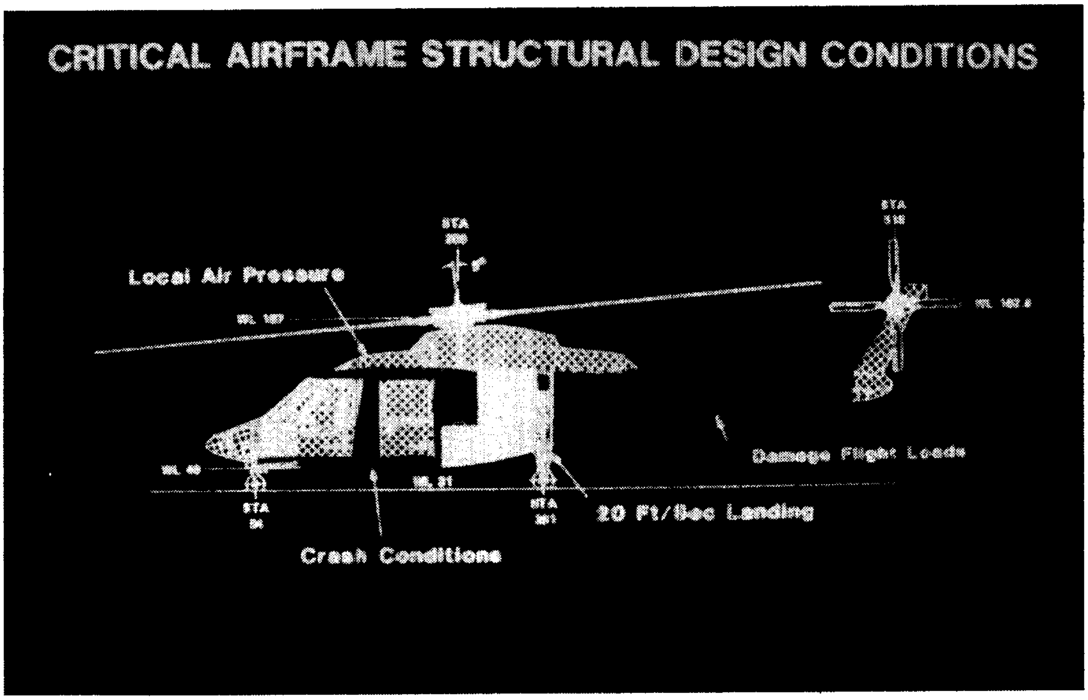

Figure 3. ACAP Helicopter Design Drivers

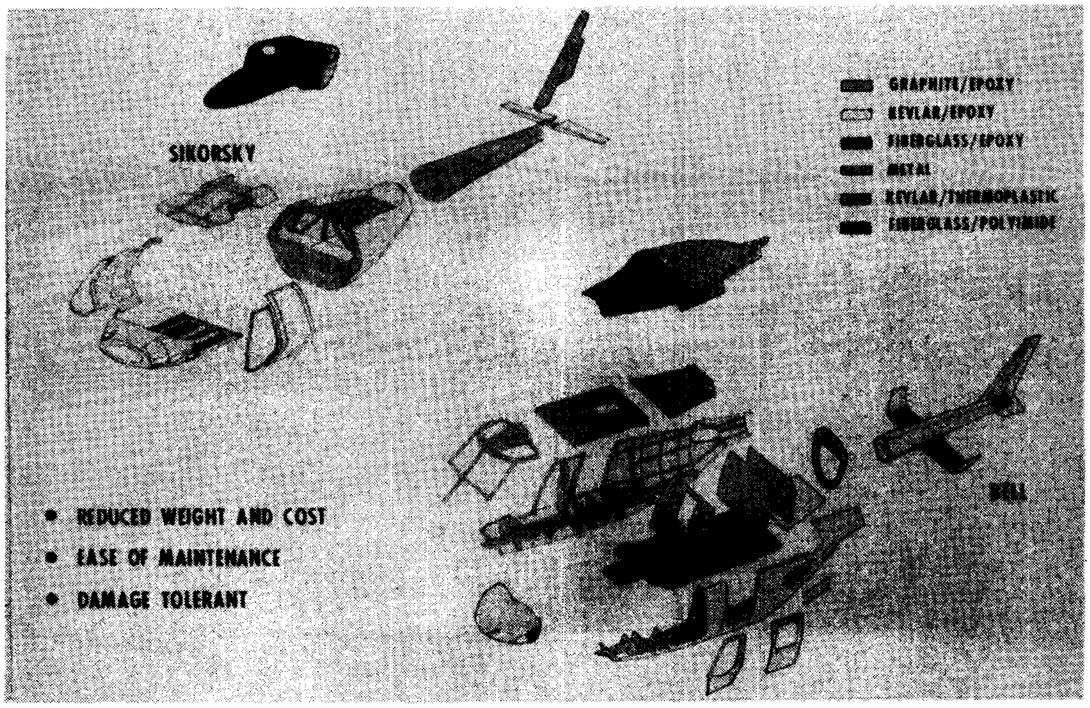

Figure 4. ACAP Helicopter Structural Arrangement

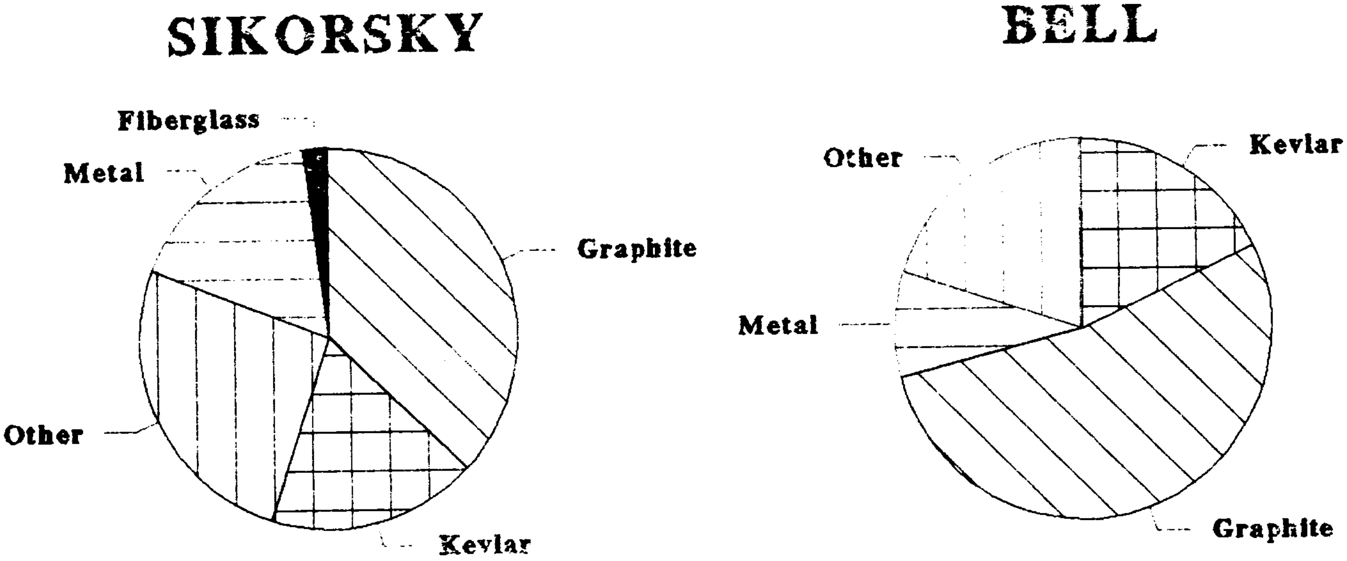

Figure 5. ACAP Material Utilization

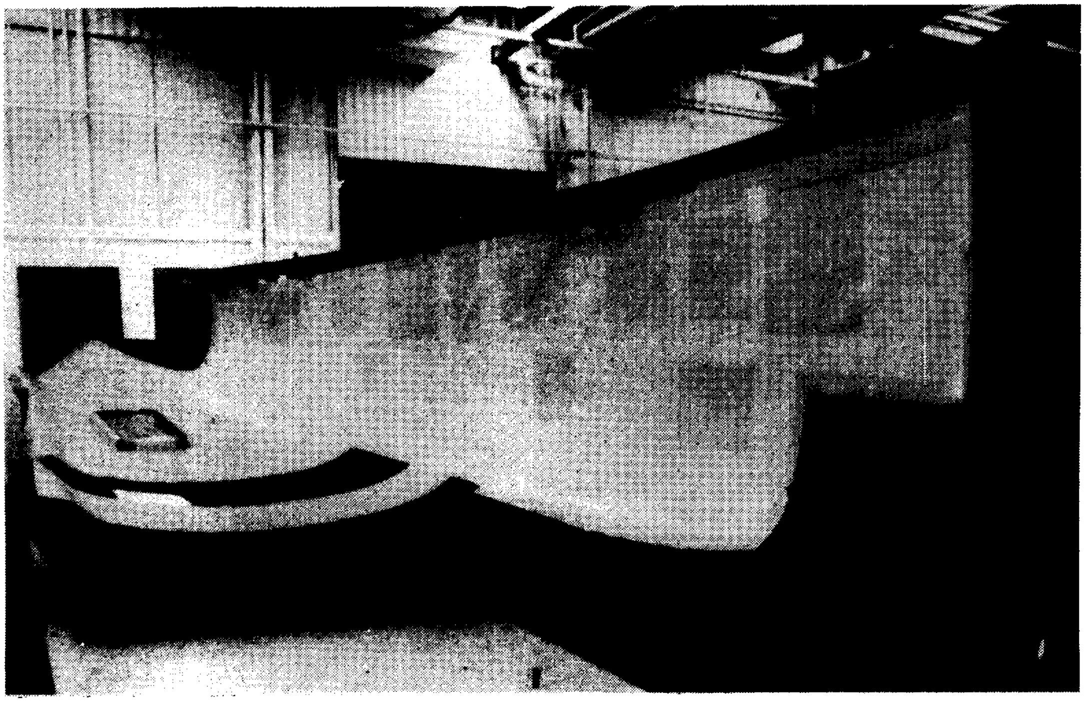

Figure 6. Bell ACAP Half-Shell Tool

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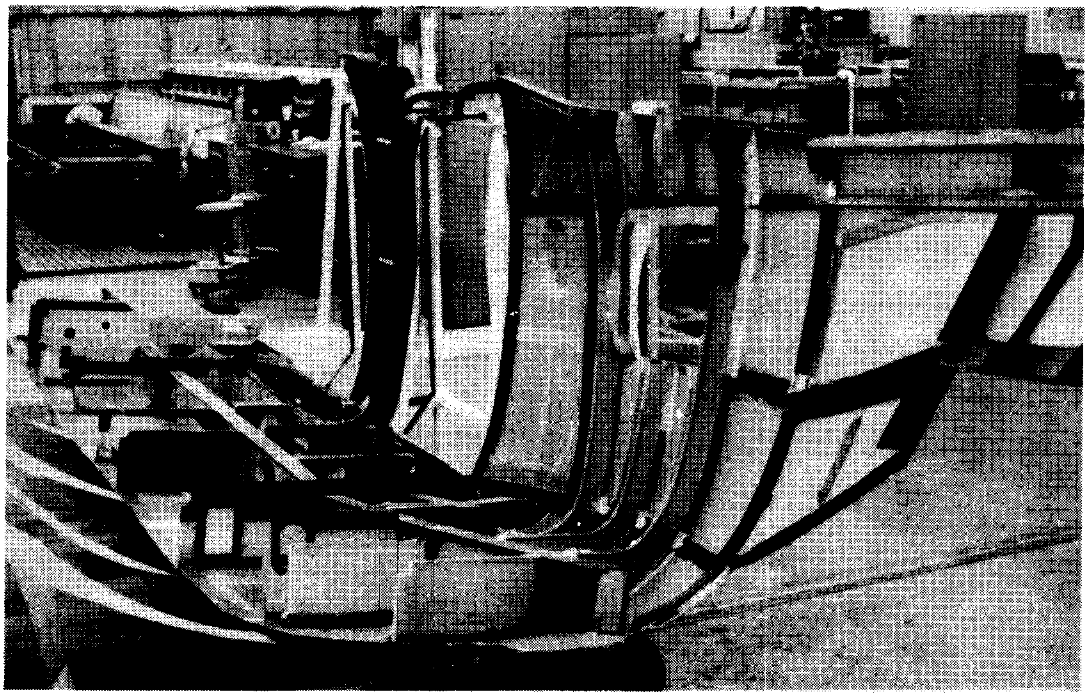

Figure 7. Bell Fuselage Half-Shell

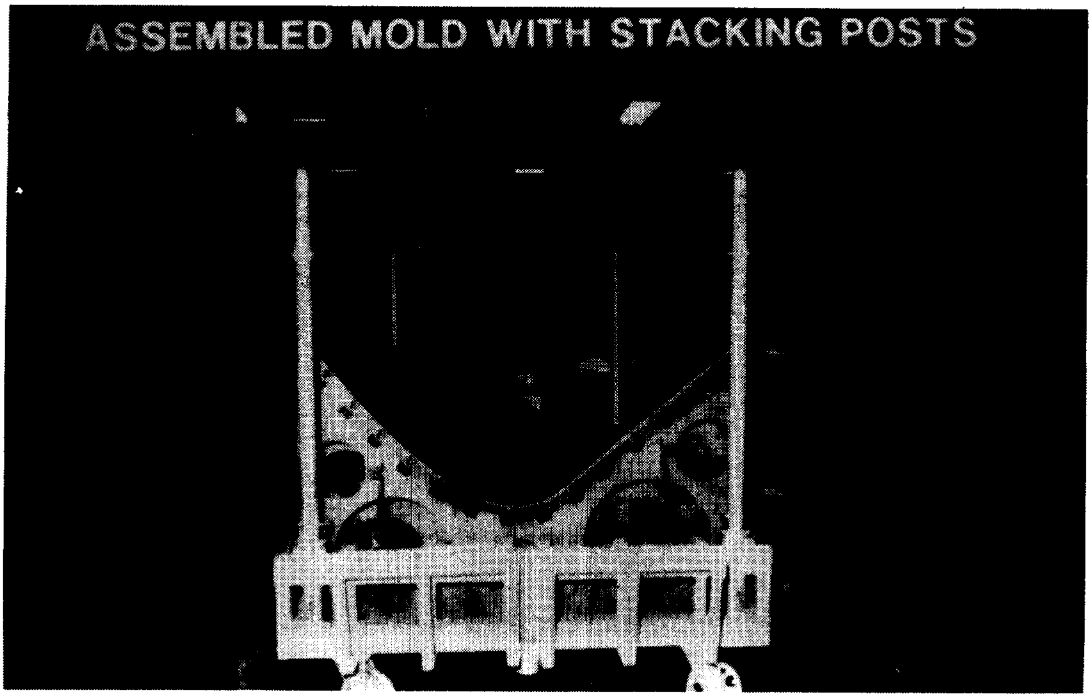

Figure 8. Sikorsky Steel Shell Mold Tool

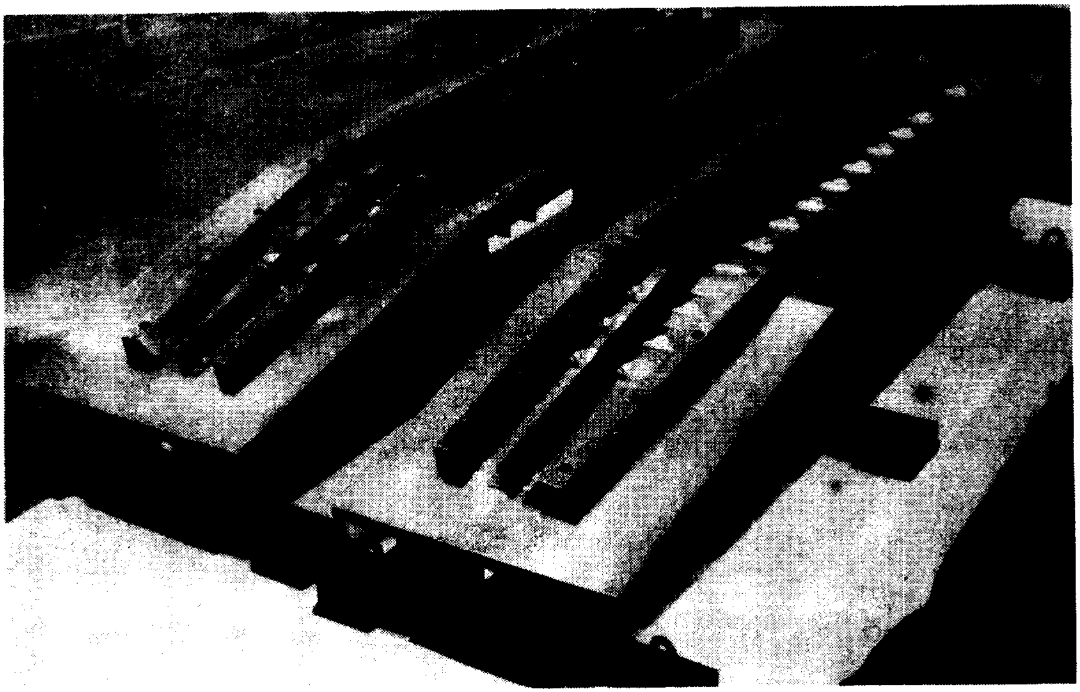

Figure 9. Typical Steel Frame Tool

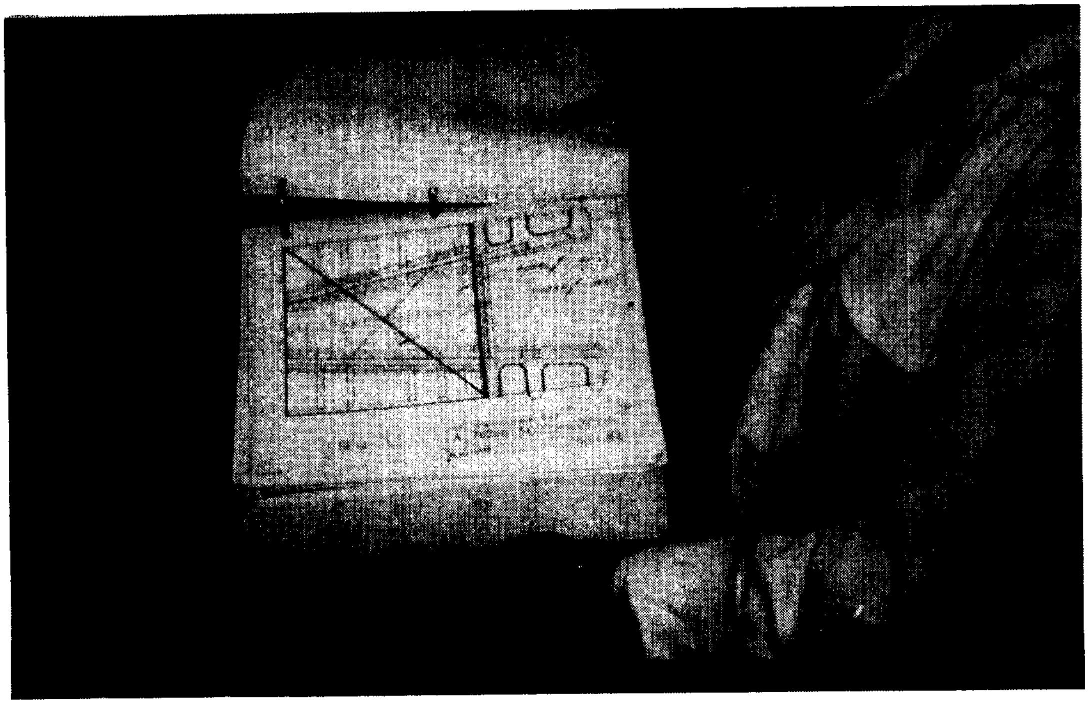

Figure 10. Computer Generated Composite Ply Layup Book

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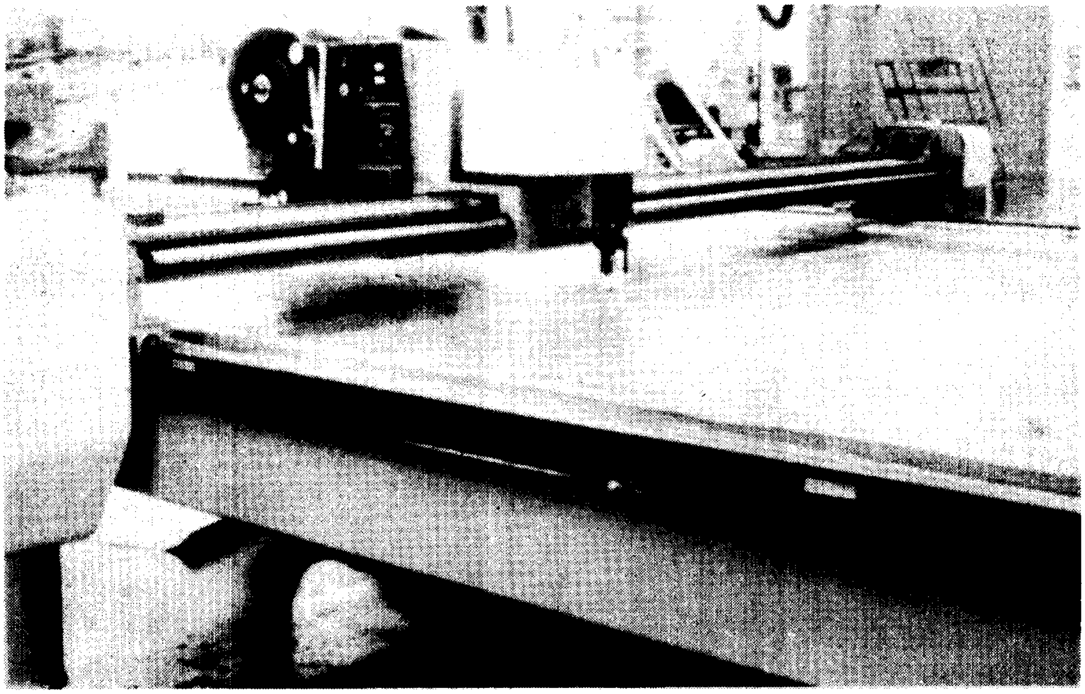

Figure 11. Computer Controlled Rapid Ply Cutting

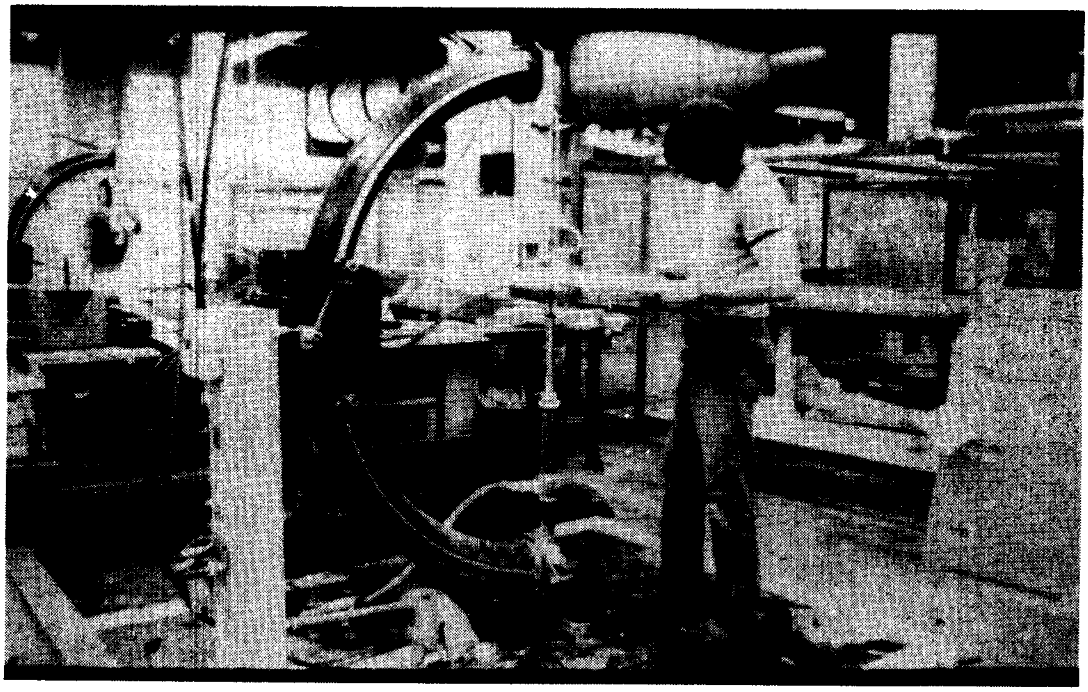

Figure 12. Water Jet Trimming

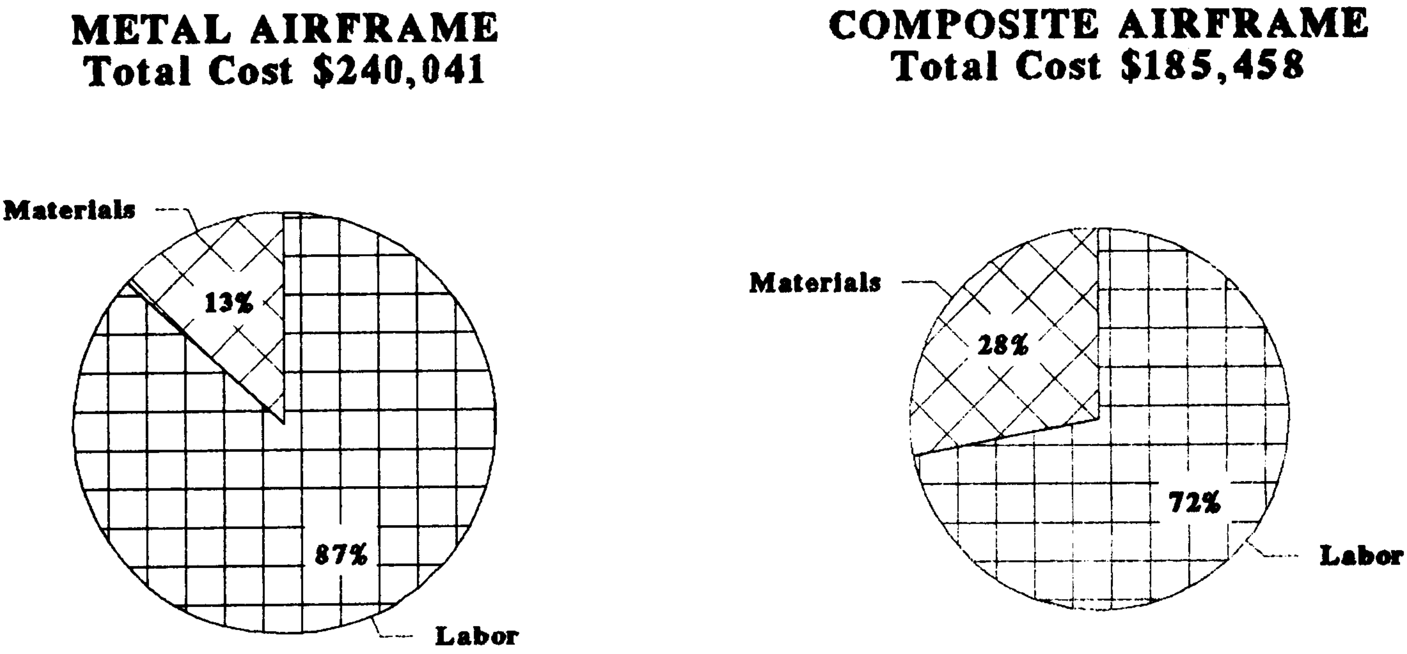

Figure 13. Comparison of Composite and Metal Airframe Cost

Figure 14. Bell ACAP Tool Proof Article

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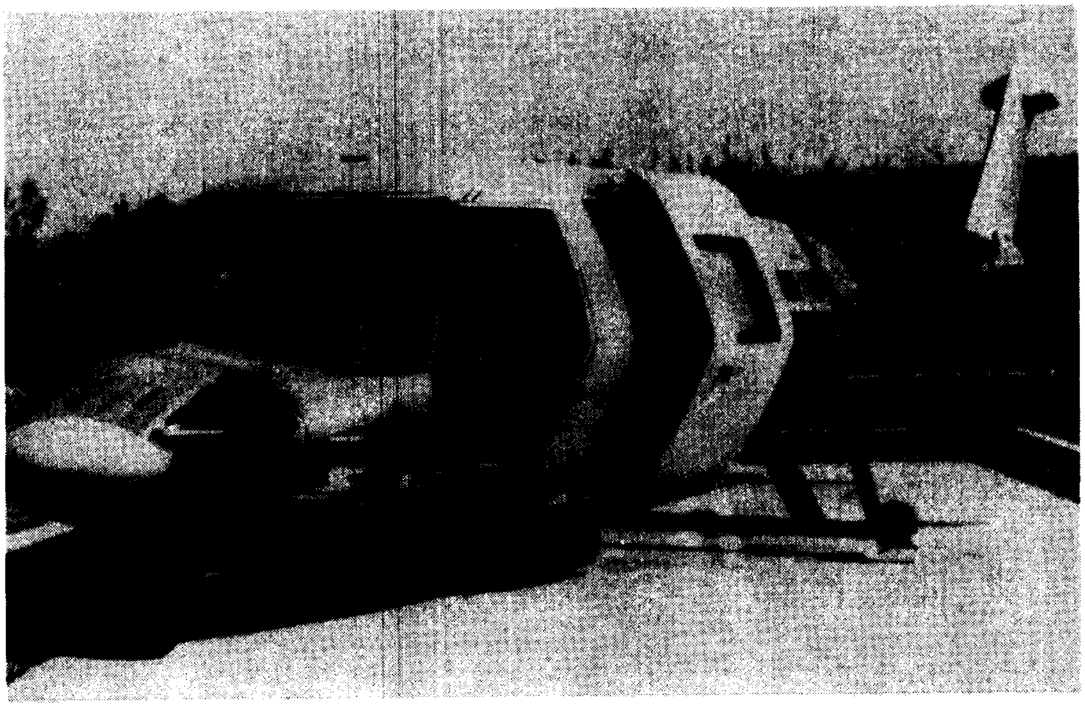

Figure 15. Sikorsky ACAP Tool Proof Article

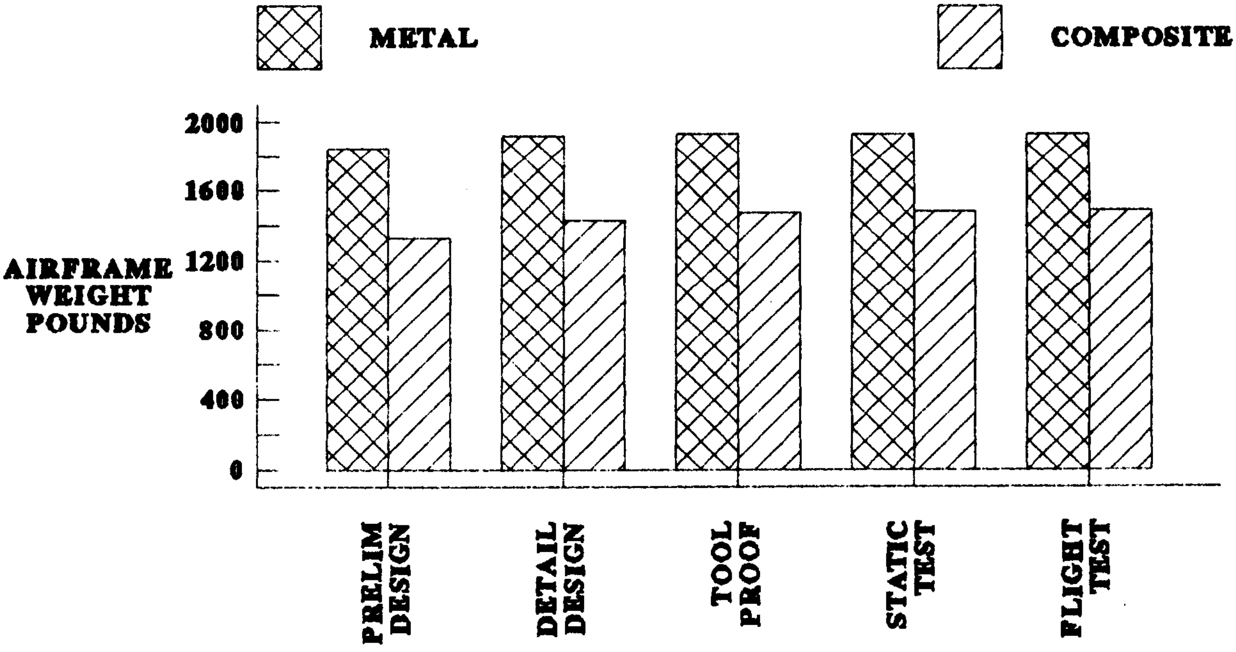

Figure 16. ACAP Airframe Weight Trends

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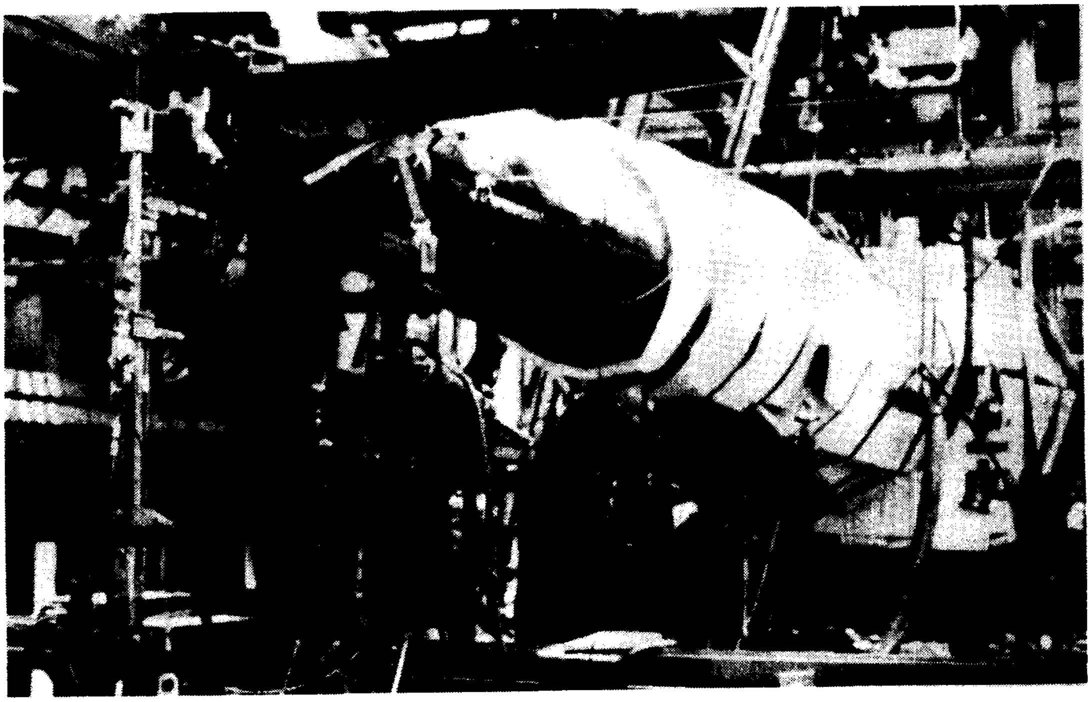

Figure 17. Sikorsky ACAP Airframe in Static Test

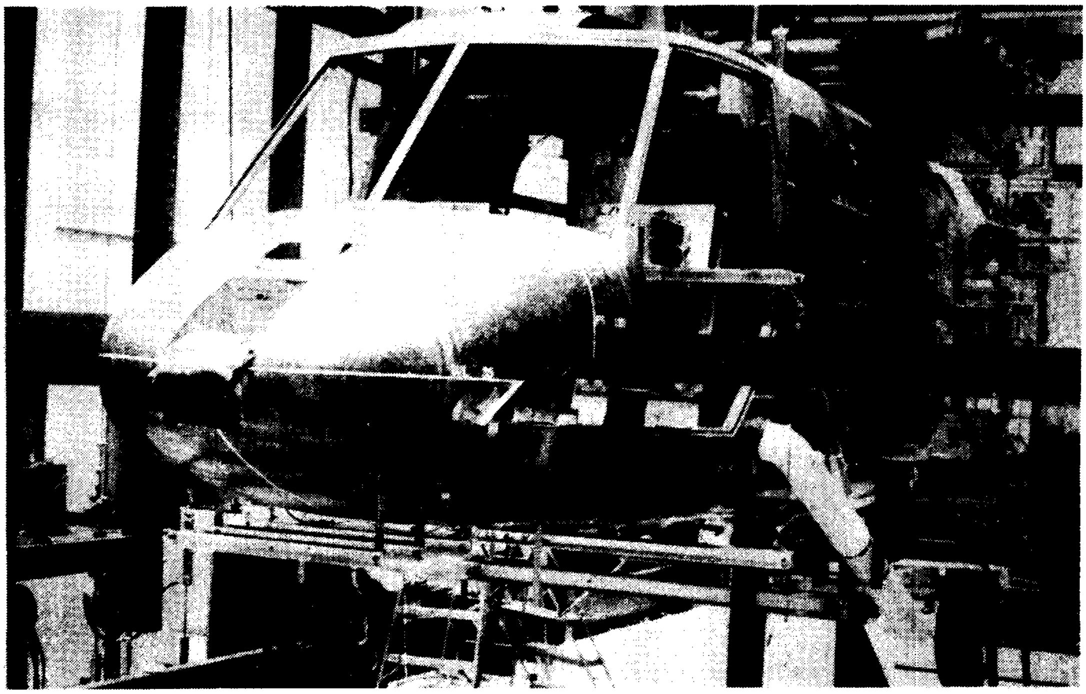

Figure 18. Bell ACAP Airframe in Static Test

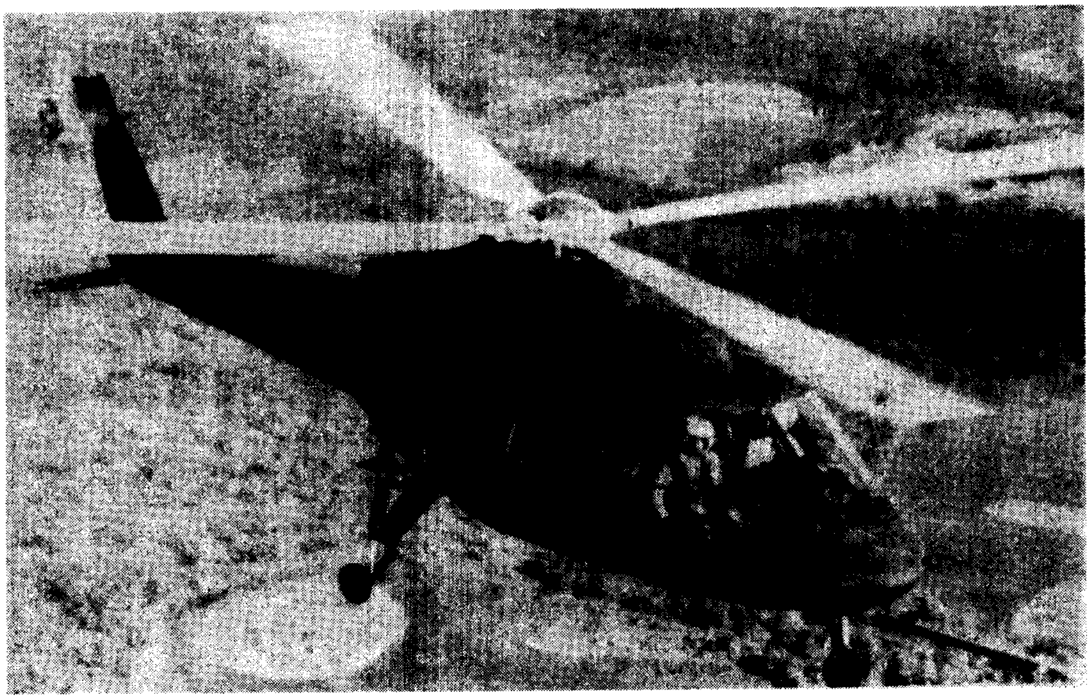

Figure 19. Sikorsky Flight Test Vehicle

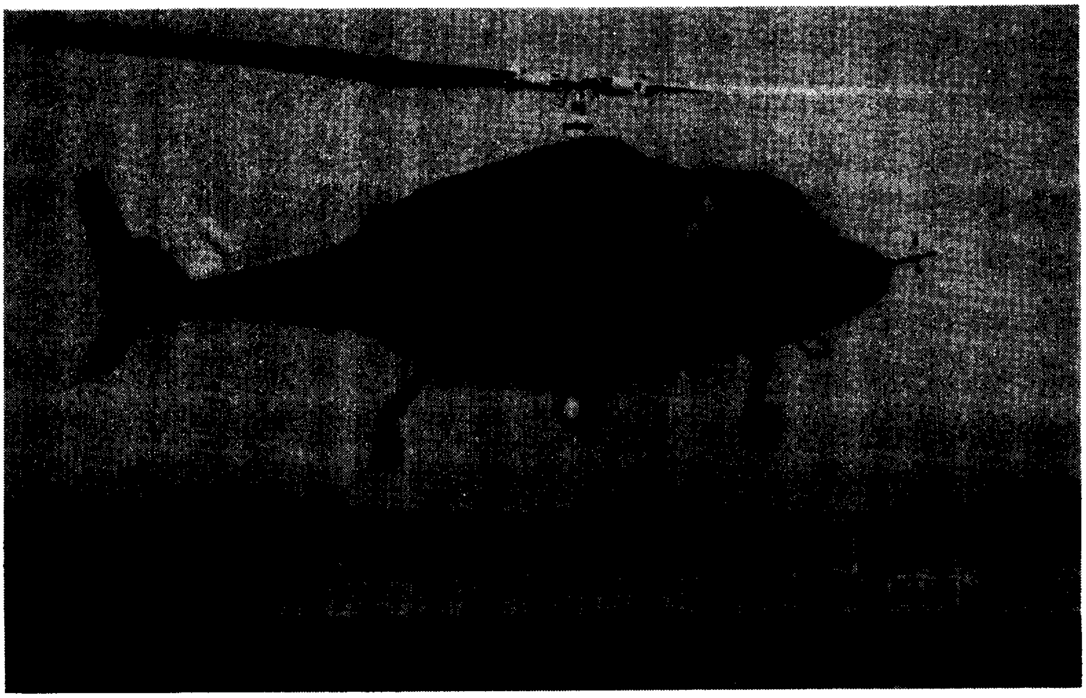

Figure 20. Bell Flight Test Vehicle

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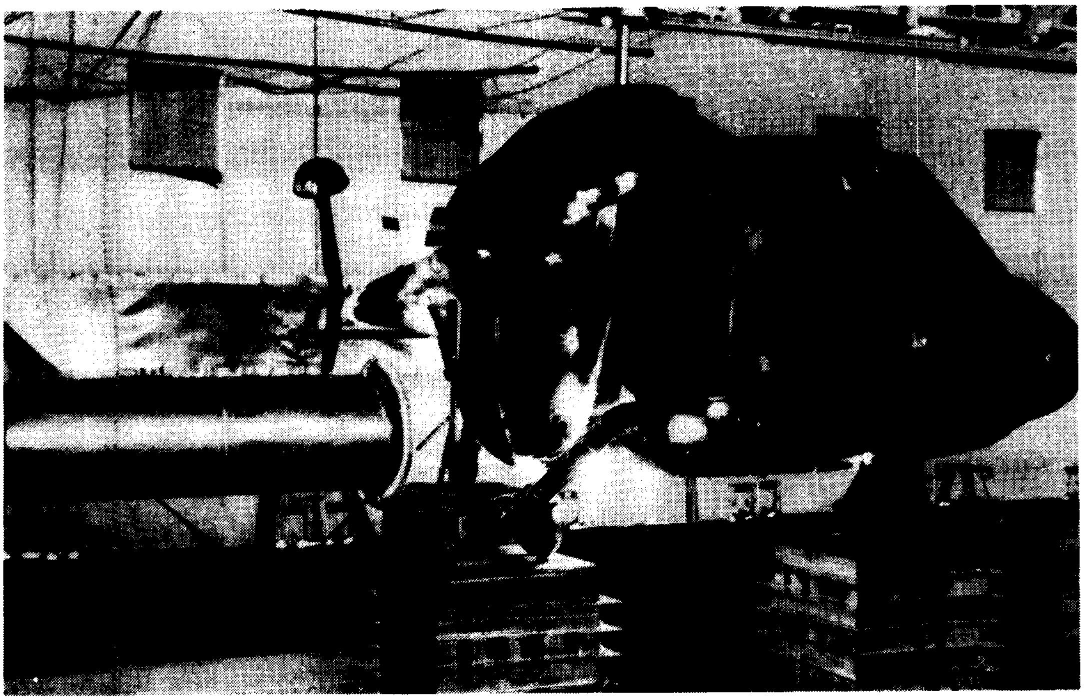

Figure 21. Lightning Strike Test of Bell ACAP Airframe

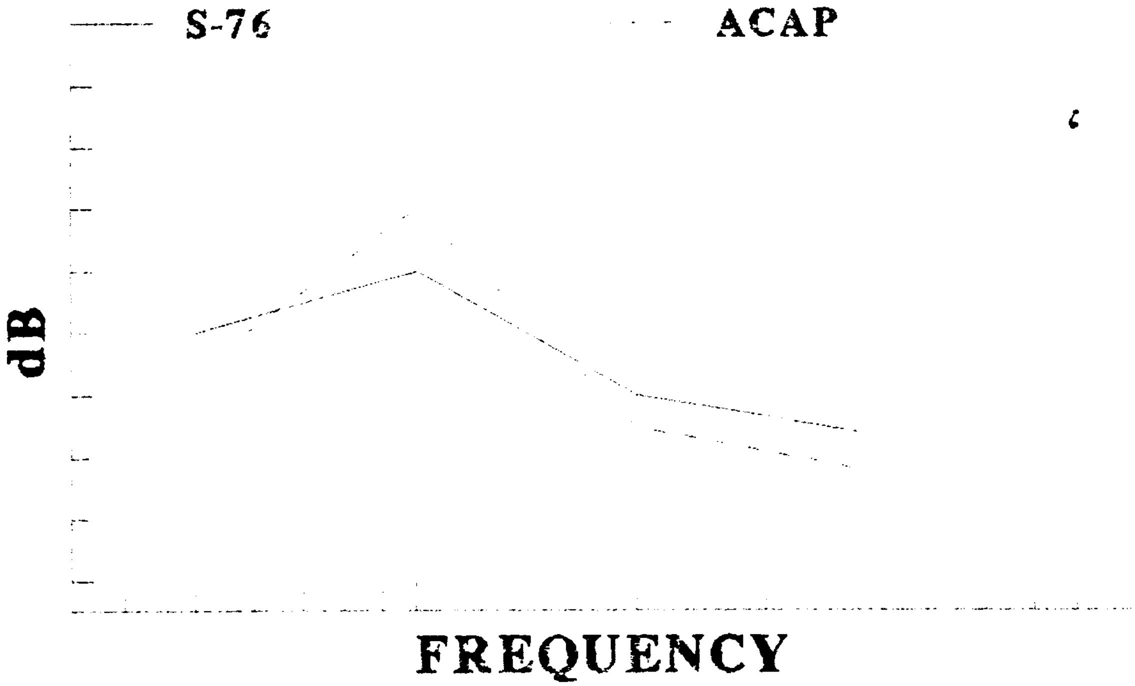

Figure 22. Comparison of ACAP and S-76 Internal Noise Levels

Table 1. Bell Static Test Conditions

Cond. No.	Description
1	Symmetrical Pull Out
2	15^{o} Yaw Left Return
3	15^{o} Yaw Right Return
4	Vertical Jump Take-Off
5	20 fps, 2 Point Landing
6	Vertical Fin, 15^{o} Yaw Trim
7	Horizontal Stabilizer, 15^{o} Yaw Trim
8	Horizontal Stabilizer, Sym. Pull Out

Table 2. Sikorsky Static Test Conditions

Cond. No.	Description
1	Horizontal Stabilizer, Asymmetrical Airloads
2	Horizontal Stabilizer, Symmetrical Airloads
3	Empennage, Rolling Pull Out
4	Empennage, Right Yaw Kick
5	Mid Cabin, Rolling Pull Out
6	Mid Cabin, Symmetrical Pull Out
7	Forward Fuselage, 20 fps
8	Rear Fuselage, 20 fps
9	Windshield/Crew Door, Dive, Airloads

Table 3. Bell D292 Flight Test Envelope

Flight Condition	Level Demonstrated
Forward Flight	120 Kts
Rearward Flight	35 Kts
Sideward Flight	15 Kts
Bank Angle	60^{o}
Load Factor	0.5 to 2.0 g

Table 4. Sikorsky S-75 Flight Test Envelope

Flight Condition	Level Demonstrated
Forward Flight	141 Kts
Rearward Flight	35 Kts
Sideward Flight	35 Kts
Bank Angle	60^{o}
Load Factor	-0.2 to 2.75 g