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MANUFACTURING METHODS TECHNOLOGY (MM/T) FOR BALLISTIC-TOLERANT FLIGHT CONTROL COMPONENTS

R. L. VanAuken

Whittaker Corporation

Prepared for:

Army Air Mobility Research and Development Laboratory

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EUSTIS DIRECTORATE
U. S. ARMY AIR MOBILITY RESEARCH AND DEVELOPMENT LABORATORY
FORT EUSTIS, VIRGINIA

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WHITTAKER CORPORATION
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13. ABSTRACT

The objective of this program was to develop manufacturing methods and technology for producing glass reinforced plastic, ballistic-tolerant flight control components with a high degree of reliability while utilizing low-cost fabrication techniques. This objective was achieved through development of component designs to obtain simplicity and ease of manufacture. Maximum use was made of commercially available, finished material forms which required a minimum of additional processing. Matched die molding processes were developed which allowed rapid manufacture of parts to final net dimensions. Assembly techniques were developed which utilized adhesive bonding in precision fixtures and allowed a high degree of reproducibility and reliability of the finished component.

Eight complete sets of components, consisting of a connecting link, an idler arm, and two bell cranks, were prepared for an extensive verification testing program which included mechanical, environmental, and ballistic impact testing. Material, process, fabrication, and quality control specifications were prepared.

Details of illustrations in this document may be better studied on microfiche.

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FORT EUSTIS, VIRGINIA 23604

The work reported herein was performed under Contract DAAJ02-71-C-0062 with the Whittaker Corporation, Research and Development Division.

This report contains the results of the effort to develop manufacturing methods technology (MM&T) and the capability of producing ballistic-tolerant flight control components using low-cost fabrication techniques. Further objectives were to develop manufacturing processes, quality assurance methods, and a manufacturing technology data package to assure repeatable production of fiberglass-reinforced composite material flight control components with inherent high-reliability characteristics.

This report has been reviewed by the Eustis Directorate, U.S. Army Air Mobility Research and Development Laboratory and is considered to be technically sound. It is published for the exchange of information and the stimulation of future development.

This program was conducted under the technical management of Major Llayll A. Fry, Technology Applications Division.

Project 1F162208A170
Contract DAAJ02-71-C-0062
USAAMRDL Technical Report 73-20
May 1973

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Final Report

By

R. L. Van Auken

Prepared by

Whittaker Corporation
Research and Development Division
San Diego, California

for

EUSTIS DIRECTORATE
U. S. ARMY AIR MOBILITY RESEARCH AND DEVELOPMENT LABORATORY
FORT EUSTIS, VIRGINIA

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The objective of this program was to develop manufacturing methods and technology for producing glass reinforced plastic, ballistic-tolerant flight control components with a high degree of reliability while utilizing low-cost fabrication techniques. This objective was achieved through development of component designs to obtain simplicity and ease of manufacture. Maximum use was made of commercially available, finished material forms which required a minimum of additional processing. Matched die molding processes were developed which allowed rapid manufacture of parts to final net dimensions. Assembly techniques were developed which utilized adhesive bonding in precision fixtures and allowed a high degree of reproducibility and reliability of the finished component.

Eight complete sets of components, consisting of a connecting link, an idler arm, and two bell cranks, were prepared for an extensive verification testing program which included mechanical, environmental, and ballistic impact testing. Material, process, fabrication, and quality control specifications were prepared.

FOREWORD

This final technical report covers the work performed by the Whittaker Research and Development Division, San Diego, California, under Contract DAAJ02-71-C-0062, Project 1F162208A170 ("Manufacturing Methods Technology (MM&T) for Ballistic Tolerant Flight Control Components"), from June 1971 through January 1973. The program was accomplished under the technical direction of Major Llayll A. Fry, Technology Applications Division of the Eustis Directorate, USAAMRDL, Fort Eustis, Virginia.

The following Whittaker R&D personnel contributed in the capacities indicated. Mr. R. L. Van Auken was Program Manager and also responsible for process development. Mr. R. A. Anderson was responsible for design refinements and tool design, and Dr. K. R. Berg for experimental verification. Mr. L. Blake was in charge of component fabrication and Mr. D. Tripp was in charge of in-house testing.

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INTRODUCTION

The objective of this program was to develop manufacturing methods technology and the capability of producing ballistic-tolerant flight control components using low-cost fabrication techniques to manufacture these components from glass reinforced composite material. Further objectives were to specify manufacturing processes and quality assurance methods, and to prepare a manufacturing technology data package to assure repeatable production of composite material flight control components with an inherent reliability characteristic.

The initial phase of the program was made up of several study tasks involving configuration design refinements, manufacturing methods evaluation, materials evaluation, and tooling development. In order to meet the objective of low cost, these four tasks were performed concurrently as information regarding materials and manufacturing methods had direct input to the conceptual component designs and tooling studies.

During the course of these tasks, simplicity in design, availability of materials, and ease of manufacturing were the primary considerations. As a result, it was possible to design each of the four components from standard commercially available materials. Materials were selected that required minimum in-house reprocessing. One very significant contributor to the low cost was the availability of NEMA-grade glass reinforced round and square tubing stock and flat sheet stock which could be directly incorporated into the component design. The more complex shapes, such as needed for the end fittings and pivot fittings, were matched metal die molded from an epoxy bulk molding compound (BMC). The assembly of the stock NEMA-grade details and the in-house molded fittings was accomplished by locating them in precision bonding fixtures.

The second phase of the program dealt with the selection and preparation of quality assurance requirements for the fabrication of the ballistic-tolerant flight control components. Due to the simplicity of design and the availability of stock materials making up the components and the ability to inspect each detail prior to its installation into an assembly, the quality assurance provisions pertain only to the inspection of incoming materials, process control, and inspection of the final component.

The fabrication phase of the program dealt with the manufacture of eight sets of components to be used for the verification testing program. The developed low cost manufacturing methods and materials were used to fabricate these components. Manufacturing and process specifications were prepared and cost analyses were made of each component.

A verification test program was conducted at the conclusion of the fabrication phase. The test series included fit and function tests and combined environmental, structural, and ballistic impact tests. The results of these tests established that the performance of each of the components is more than adequate for the operational loads.

COMPONENT MANUFACTURING DEVELOPMENT

PROGRAM OBJECTIVES

The vulnerability of present-day metallic flight control systems for Army helicopters to ballistic impact damage from small-arms fire has led to the investigation of materials and designs which are less sensitive to ballistic damage. Typical flight control systems consist of control rods acting through leverage components which determine the movement of the rotor and the rotor blades. The components investigated in this program were a connecting link which imparts pitch to the blades, an idler arm which works in series with the controls rod for input to the aft rotor, a forward bell crank which provides input to the controls on the forward rotor, and an aft bell crank which provides input to the aft rotor.

A solution to the ballistic sensitivity problem has been found in the development of lightweight flight control components made from fiber glass reinforced nonmetallic composite materials. The initial work, performed by Boeing-Vertol Company under Contract DAAJ02-67-C-0092, established that the multipath load capability of GRP composite materials results in components which continue to function even after ballistic hits from small-arms fire. While the initial components fabricated under the aforementioned contract established a sound materials and design philosophy for these components, the manufacturing costs, weight, and reproducibility were unattractive compared to the metallic counterparts. The objective of this program was therefore to provide manufacturing methods technology and the capability of producing replacement ballistic-tolerant flight control components for the CH-47 helicopter, using low-cost fabrication techniques. This involved the establishment of appropriate manufacturing processes, quality assurance methods, and a manufacturing technology data package to assure repeatable production of flight control components with inherent high reliability and quality characteristics.

PROGRAM APPROACH

Design Considerations

In order to accomplish the above objectives, it was necessary to coordinate very closely the design, materials, and manufacturing efforts. Basically, the design considerations were:

1. Ballistic tolerance
2. Structural adequacy
3. Manufacturability
4. Weight

Material Considerations

The major considerations for selection of materials were not only their cost per pound but also how readily these materials could be processed into an end item. The development of specific materials for this application was not part of this program. A minimum of in-house materials processing would be required to meet the low-cost objective. Therefore, materials which were available as commercial stock items were highly desirable.

Manufacturing Considerations

The manufacturing process was the major developmental portion of this program. The main consideration for the manufacturing process was the utilization of manufacturing techniques requiring a minimum of hand labor for the fabrication of details and the assembly of final components.

REVIEW OF PREVIOUS DESIGN

The initial task of the program was to review the Boeing-Vertol design, analysis, and test program which had been reported under Contract DAAJ02-67-C-0092. This report provided the load and load introduction requirements necessary for the redesign and selection of materials to be accomplished later. The report also defined the envelope dimension of each component, and defined and described deficiencies of the previously fabricated components as well.

A review of the manufacturing procedures specified in this report revealed extensive use of in-house processing, hand labor, and machining which all contributed to high costs.

MATERIALS EVALUATION AND SELECTION

As previously mentioned, it is not possible to consider materials for a specific application without also considering the design and manufacturing process to be utilized. The materials selected must complement both the design and the manufacturing process if the objectives of low cost, ballistic tolerance, and reproducibility are to be achieved. A major consideration in the selection of materials, which is brought out more fully in the Design Refinement section, involves the complex geometry of parts of the flight control components. Producing complex geometries from continuous fibrous composite materials very often results in excessive labor costs and poor reproducibility. The development of semiautomated techniques to fabricate the intricate geometries of the subject components was beyond the scope of this work. As will be seen from discussions in later paragraphs, many of the semiautomated methods are not applicable to the low-cost fabrication of the subject components. On the other hand, prefabricated shapes made from composite materials are commercially available from a number of suppliers. Examples of these are the well-known NEMA-grade flat sheet stock and tubular shapes. These stock items are produced by continuous laminating processes in large quantities, and their cost per pound is substantially lower than similar custom fabrication articles.

The design refinement study showed that tubular shapes and flat sheet stock made to NEMA certifications for the G-11 FR4 grade would be a suitable structural material for portions of three of the components. There still remained, however, a material to be selected for the fittings of three components and the entire fourth component. There were no materials or material forms containing continuous glass filament which could be readily fabricated into the complex geometry of these details. The use of chopped glass molding compounds was considered a very practical materials approach for these fittings. This material would satisfy the low-cost manufacturing requirements for the fabrication of the detailed fittings. Transfer or compression molding in matched metal dies with a commercially available molding compound would be well within the objectives of the program. However, little was known of the ballistic impact sensitivity of these materials and their ability to meet the structural requirements of the components. In order to establish their applicability, two material forms from various suppliers were obtained: chopped glass/epoxy bulk molding compound (BMC) and random glass fiber/polyester sheet molding compound (SMC). For the BMC material, both 1/4-inch and 1/2-inch fiber lengths were evaluated. The two material forms were checked first for their structural adequacy. Large flat panels were molded to obtain tensile specimens for testing. These specimens were cut from the center portion of the panel to avoid the preferred orientation at the edges. The BMC tensile strength values averaged 10.7 ksi and the SMC 17.1 ksi.

Next, manufacturability of the two systems was investigated. Samples were molded in a tool simulating a component socket fitting. The SMC moldings were not successful. The cavity was not filled and the moldings contained large voids. The BMC material was very successful. Cavity fill was obtained and highly detailed parts were molded. Based on this evaluation, the SMC was eliminated from the program.

Ballistic tests were performed on several molded sheets of the various BMC materials to determine the best performance during ballistic impact. Specimens were preloaded to 50%, 60%, and 67% of tensile ultimate and impacted with an untumbled cal .30 projectile. No failures were incurred at 50% and 60% on the material selected. At 67% the specimen failed in tension. USAAMRDL reported a 30% strength retention on the same material impacted with a tumbled cal .30 projectile. These values were determined to be more than adequate based on the design allowables being used in the component design.

As a result of these evaluations, the BMC material designated EMC 7302 transfer grade with 1/2-inch fiber reinforcement was selected as the best candidate for molding the complex details.

MANUFACTURING METHODS STUDIES

The manufacturing studies dealt with methods to fabricate the individual component details and methods to assemble these details. The primary considerations in each case were low-cost techniques and high degree of reproducibility. Details of all four components could be fabricated from matched metal molded BMC, NEMA-grade sheet stock, and round or rectangular commercial tubing. Since the details which consisted of the NEMA-grade stock materials would require only cutting to the proper dimension and configuration, the emphasis was placed on the development of a suitable manufacturing process for the BMC molded details.

The bulk molding material as received has a bulk factor of approximately 12 to 1. While the material is readily molded in this form, the cavity volume to contain the initial charge must be excessively large to hold the full quantity. A method whereby the bulk factor, and in turn the volume of the initial charge, can be reduced is by low temperature preforming. This method consists of compacting the bulk material into pellets or rods at a low temperature and pressure. The developed technique produced preforms with a bulk factor of approximately 3 to 1 without destroying the natural flow properties of the material. It was also found to be a more reliable method of charging the tool and controlling the initial charge weight.

The development of a molding process initially followed the prescribed molding procedure. The tool is heated to between 300°F and 320°F. The ram is removed from the tool and a preform charge placed in the ram cavity. Immediately the ram is engaged in the tool and forced downward approximately two-thirds of the stroke. At this point a 1-minute hold is necessary to allow the BMC material to heat up throughout its cross section and permit the material to flow evenly throughout the cavity. At the end of this 1-minute period the ram is slowly closed over a period of approximately 15 seconds. Normally, approximately 1000 to 1500 psi is required to fully close the die and achieve optimum density (1.86 gm/cc) of the molded part. The mold is left in a closed position for 30 minutes to achieve the proper degree of cure. While still hot, the ram is withdrawn from the tool and the female cavity opened to permit removal of the molded detail. Immediately after removal, the molded detail is placed in a 300°F oven and postcured for an additional 2 hours to achieve the optimum cured properties. This process was highly successful and was used throughout the program.

The one remaining task to be studied was the assembling of the individual details for each of the four components. In keeping with the low-cost manufacturing techniques, as well as the part-to-part reproducibility, a method using a combined assembly jig and cure fixture which would properly align and locate each of the details was selected. A major portion of this task was the design and development of assembly fixtures which would accommodate rapid and accurate assembly and bonding of the components.

The fixtures were also used for dimensional inspection as go/no-go gauges. The fixtures which were developed are discussed in more detail in the Fabrication section of this report.

CONFIGURATION REFINEMENT STUDY

Since the objective of this program was to develop a high-volume, low-cost manufacturing method for each of the four components, the design refinement study utilized to the fullest the information contained in the Boeing-Vertol report. It was obvious from the standpoint of cost that vacuum bagging and autoclaving, which was used as the fabrication method in the Vertol program, would have to be eliminated. Further, if permissible, the aluminum honeycomb and polyurethane foam were to be eliminated also.

Information obtained from the materials evaluation studies indicated that wide use could be made of prepared epoxy/fiber glass sheet and tubular stock of the NEMA-grade variety. Attachment fittings and pivot fittings, as well as the ball and socket joint assemblies, could be fabricated from a bulk molding compound consisting of epoxy resin and 1/2-inch glass fibers. For specific reinforcement, epoxy impregnated 143-style (unidirectional) fabric could be utilized.

Based on these assumptions, preliminary design concepts for each of the four components were prepared. These preliminary design concepts are shown in Figures 1 through 4.

As shown in Figure 1, the connecting link assembly consists of four separate pieces: a NEMA-grade epoxy/glass fabric tube, two BMC fittings, and one continuous epoxy/fiber glass reinforcing strap. Also shown are the steel bearing support and the bearing. Essentially, no modification was made to the existing Vertol design for the connecting link. In order that all of the environmental requirements for the connecting link could be met, fire-retardant materials were specified.

The forward bell crank assembly shown in Figure 2 consists of NEMA-grade epoxy/fiber glass square tubing, two flat face sheets, and three epoxy BMC molded fittings. Comparing this design with the Vertol design, the foam core has been removed from the center of the bell crank, the fittings are molded to the final configuration instead of being machined, and the continuous fiber glass reinforced elements are obtained as precured stock shapes and sheets.

Figure 3, the aft bell crank assembly, consists of two molded ball rod ends, three sections of NEMA grade epoxy/fiber glass rectangular tubing, two epoxy BMC socket fittings, one epoxy BMC pivot fitting, and two NEMA-grade epoxy/fiber glass face sheets. Comparing this with the Vertol design, the internal foam core has been removed; all ball and socket joints and pivot fittings are matched metal die molded to the final configuration rather than filament wound or machined.

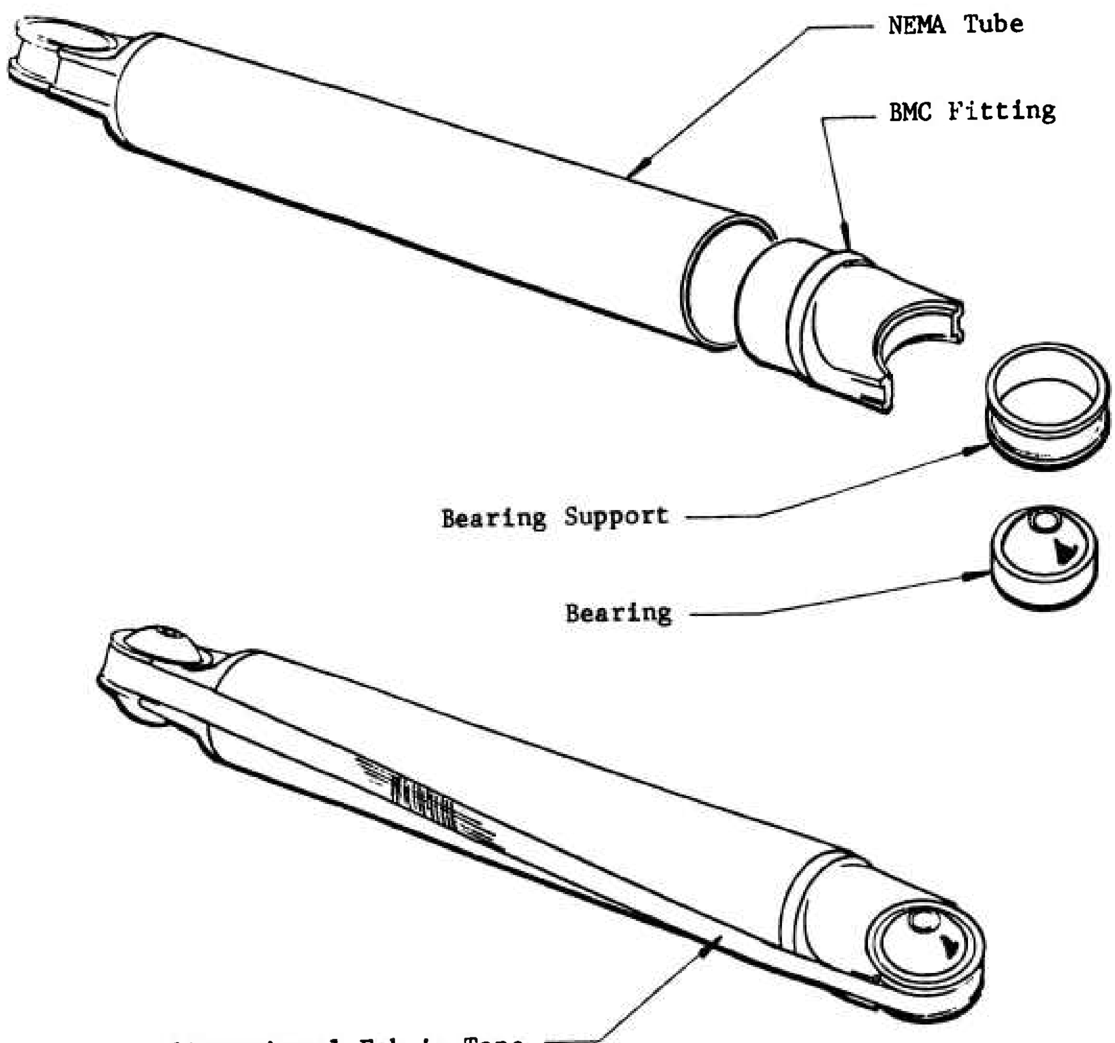


Figure 1. Connecting Link Assembly.

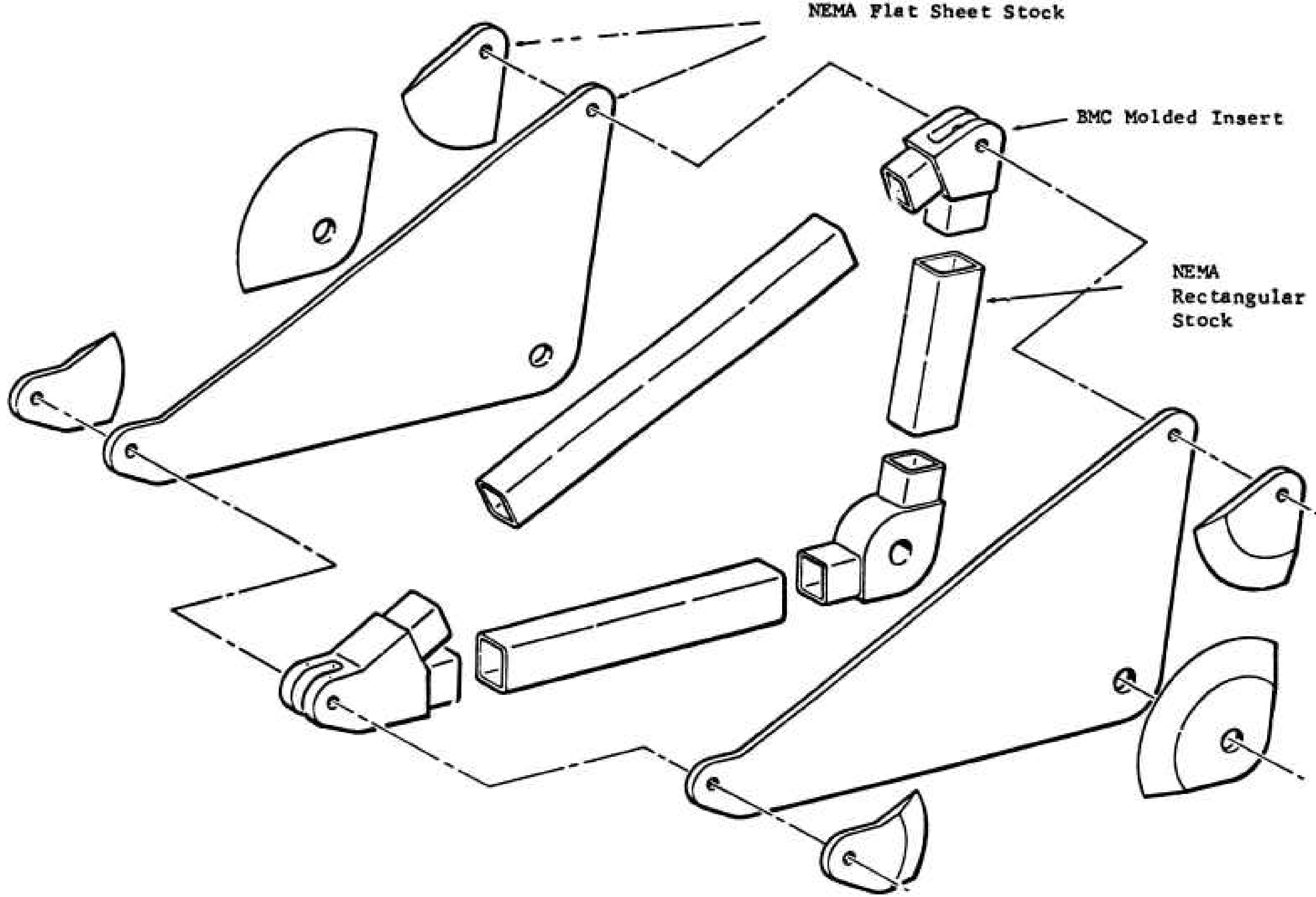


Figure 2. Exploded View of Forward Bell Crank.

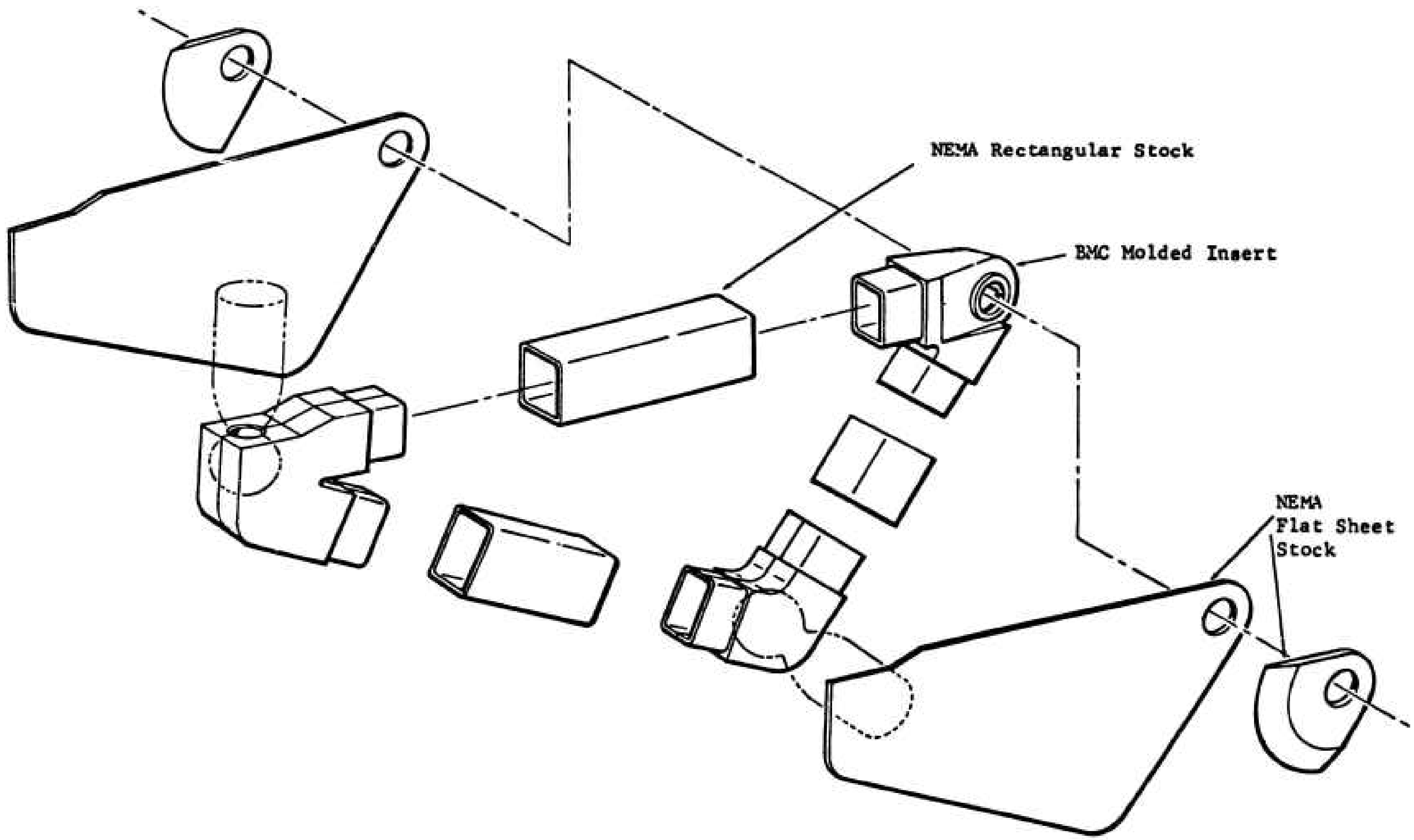


Figure 3. Exploded View of Aft Bell Crank.

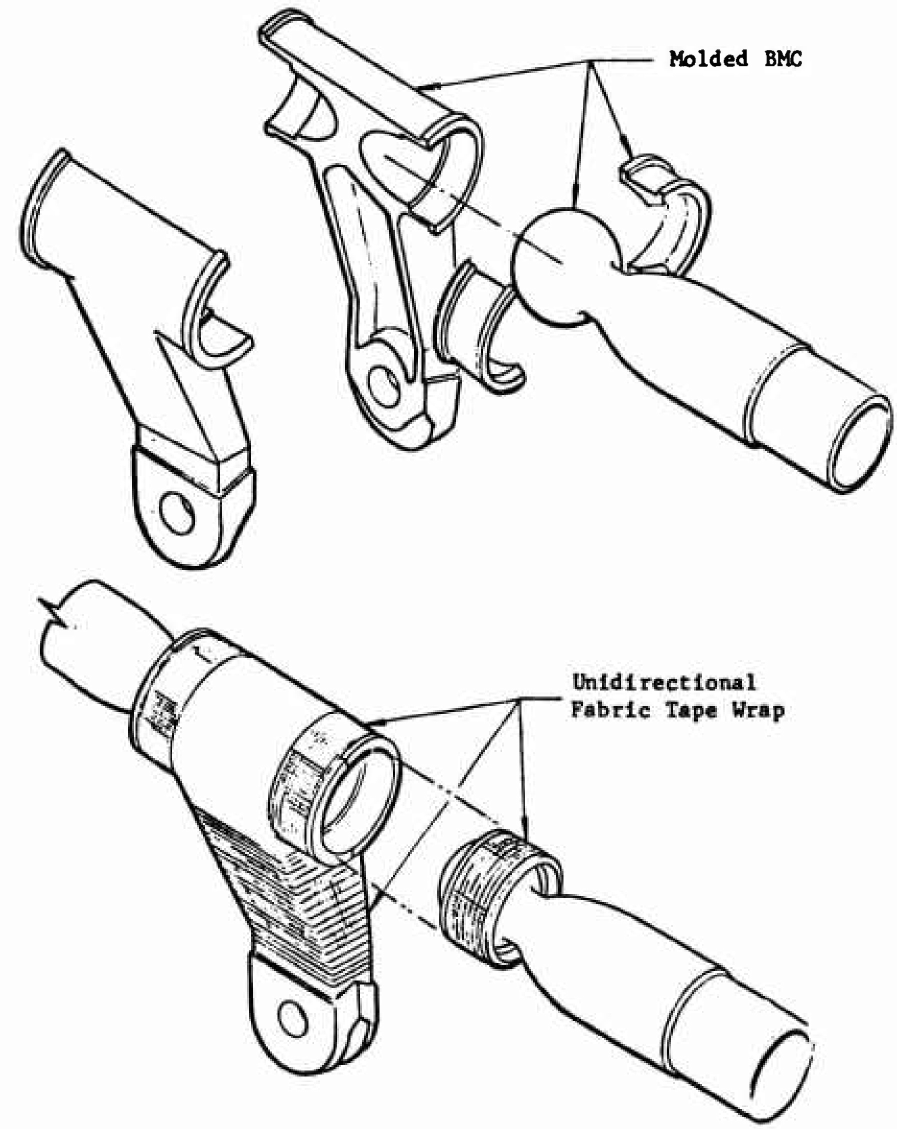


Figure 4. Exploded View of Idler Arm and Rod End Assembly.

Figure 4, which shows the concept for the design of the idler arm and rod end assembly, consists of two BMC molded rod end ball and socket details, an epoxy BMC idler arm assembly, and a unidirectional epoxy/fiber glass tape overwrap around the idler arm and the ball and socket joint. Comparing this design with the Vertol designs, the ball rod ends are matched metal die molded rather than filament wound, and the idler arm assembly does not contain foam and has been overwrapped with continuous glass fabric tape rather than unidirectional fiber glass roving.

In reviewing the design refinement study which was performed on each of the four components, it can be readily determined that three of the components - the two bell cranks and the rod end idler arm assembly - have been greatly simplified from a design, materials, and manufacturing standpoint. Having already established the structural capability of each of the four components, a preliminary estimate of the manufacturing cost for each of the components was made to assure that these manufacturing costs had been substantially reduced and made competitive with the metallic counterparts. This analysis was made on the basis of fabricating lots of 100, 500, and 1000 units. Table I provides certain assumptions regarding cost, which were used to prepare the cost analysis for each component. Tables II through V detail the specific cost items for the manufacture of each of the components.

MANUFACTURING PLAN

The manufacturing plan for the fabrication of the four components consisted of four primary tasks. First was the molding of the fittings or details for each of the components. The second task was the cutting of the NEMA-grade tubular and sheet stock. The third task was the assembly of each of the details for each component into the assembly fixture and subsequent bonding. The fourth task was the installation and bonding of the bearing inserts, bearings, and bushings into each of the components.

This manufacturing plan was found to be extremely cost effective and highly reliable. The outstanding advantage was the minimum of material processing steps; that is, the only material which requires some in-house reprocessing is the epoxy bulk molding compound. Another specific advantage of this manufacturing plan is the ability to inspect each detail of each component prior to its installation into the final assembly. During the course of this program no components were rejected after final assembly. However, several molded details were found not to be acceptable, particularly the first or second articles fabricated. The use of assembly and bonding fixtures for each of the components was largely responsible for the successful fabrication of each component.

TABLE I. ASSUMPTIONS FOR COST PROJECTION

Based on 1000 Quantity

80% Learning Curve Used to Adjust Labor

No Learning Curve on Material

Rates Considered

Laminator/Assembler	$2.75/hr
Inspector	$3.00/hr
Engineer	$6.50/hr
Overhead	150%
G & A	12%
Profit	10%

TABLE II. COST PROJECTION - CONNECTING LINK

Direct Material

(1)	2.0 lb	NEMA Tube	@ $4.50/lb	= $ 9.00
(2)	1.5 lb	BMC	@ $1.90/lb	= $ 2.85
(3)	0.5 lb	Prepreg	@ $4.00/lb	= $ 2.00
(4)	0.1 lb	Adhesive	@ $4.00/lb	= $ 0.40
(5)	2 ea	Bearing Races	@ $1.50/ea	= $ 3.00
(6)	2 ea	Bearings	@ $9.00/ea	= $18.00
			Material Cost	= $35.25

Labor

Laminator/Assembler

(1)	Cut Tube to Length	0.1 MH
(2)	Mold 2 Inserts	0.4 MH
(3)	Assemble and Bond	0.6 MH
(4)	Strap Overwrap	0.2 MH
(5)	Cure and Clean Up	0.2 MH

Total Laminator/Assembler	1.5 MH
Inspector	0.2 MH
Engineering	0.1 MH

Total Costs	100 Units	500 Units	1000 Units
Labor Cost	$11.03	$ 6.73	$ 5.38
Labor Overhead	$16.55	$10.10	$ 8.07
Material	$35.25	$35.25	$35.25
G & A/Profit	$14.62	$12.08	$11.29
Projected Cost	$77.45	$64.16	$59.99

TABLE III. COST PROJECTION - FORWARD BELL CRANK

Direct Material

(1)	0.4 lb NEMA Sheet Stock (Face Sheets)	@ $3.00/lb =	$ 1.20
(2)	0.5 lb NEMA Tube Stock (Frame)	@ $6.00/lb =	$ 3.00
(3)	1.5 lb BMC (Inserts)	@ $1.90/lb =	$ 2.85
(4)	0.3 lb Adhesive	@ $4.00/lb =	$ 1.20
(5)	Bearings, Bushings, and Spacers		$ 6.00
		Material Cost =	$14.25

Labor

Laminator/Assembler

(1)	Saw Plates and Doublers	0.3 MH	
(2)	Route Doublers	0.4 MH	
(3)	Cut Frames to Length	0.2 MH	
(4)	Mold 3 Inserts	1.5 MH	
(5)	Assemble and Bond	1.0 MH	
(6)	Install Bearings	0.5 MH	
(7)	Cure and Clean Up	0.6 MH	
	Total Laminator/Assembler		4.5 MH

Inspector	0.4 MH
Engineering	0.2 MH

Total Costs	100 Units	500 Units	1000 Units
Labor Cost	$ 33.08	$19.85	$15.88
Labor Overhead	$ 49.62	$29.77	$23.82
Material	$ 14.25	$14.25	$14.25
G & A/Profit	$ 22.49	$14.81	$12.51
Projected Cost	$119.44	$78.68	$66.46

TABLE IV. COST PROJECTION - BELL CRANK W/BALL SOCKETS

Direct Material

(1)	0.25 lb NEMA Sheet Stock (Face Sheets)	@ $3.00/lb	=	$ .75
(2)	0.3 lb NEMA Tube Stock (Frame)	@ $6.00/lb	=	$ 2.00
(3)	1.5 lb BMC (Inserts)	@ $1.90/lb	=	$ 2.85
(4)	1.0 lb BMC (2 Balls)	@ $1.90/lb	=	$ 1.90
(5)	0.1 lb Tape (2 Balls)	@ $4.00/lb	=	$ .40
(6)	0.3 lb Adhesive	@ $4.00/lb	=	$ 1.20
(7)	Ball Coating		=	$ .75
(8)	Bearings and Spacer			$ 9.00
		Material Cost	=	$18.85

Labor

Laminator/Assembler

(1)	Saw Plates	0.3 MH	
(2)	Cut Frames to Length	0.2 MH	
(3)	Mold 3 Inserts	1.5 MH	
(4)	Mold 2 Balls	1.0 MH	
(5)	Mold 4 Retainers	0.4 MH	
(6)	Assemble and Bond Bell Crank	1.0 MH	
(7)	Install Rod Ends	0.5 MH	
(8)	Cure and Clean Up	0.4 MH	
	Total Laminator/Assembler		5.3 MH
	Inspector		0.4 MH
	Engineering		0.2 MH

Total Costs	100 Units	500 Units	1000 Units
Labor Cost	$ 35.05	$21.03	$16.82
Labor Overhead	52.58	31.55	25.23
Material	18.85	18.85	18.85
G & A/Profit	24.71	17.96	14.12
Projected Cost	$131.19	$89.39	$75.02

TABLE V. COST PROJECTION - IDLER AND ROD END

Direct Material

(1)	0.6 lb BMC (Socket w/Hub Block)	@ $1.90/lb	= $ 1.14
(2)	0.3 lb Tape	@ $4.00/lb	= $ 1.20
(3)	1.0 lb BMC (2 Balls)	@ $1.90/lb	= $ 1.90
(4)	0.1 lb Tape (2 Balls)	@ $4.00/lb	= $ .40
(5)	0.1 lb Adhesive	@ $4.00/lb	= $ .40
(6)	Ball Coating		= $ .75
(7)	Bearings and Spacer		= $ 9.00
		Material Cost	= $14.79

Labor

Laminator/Assembler

(1)	Mold 2 Half-Sockets	0.4 MH	
(2)	Mold 2 Balls	1.0 MH	
(3)	Mold 4 Retainers	0.4 MH	
(4)	Prepare Ball and Socket Surface	0.5 MH	
(5)	Assemble Socket/Balls/Insert	0.5 MH	
(6)	Tape Wrap	0.3 MH	
(7)	Cure and Clean Up	0.3 MH	
(8)	Install Bearings	0.3 MH	
	Total Laminator/Assembler		3.7 MH
	Inspector		0.4 MH
	Engineering		0.2 MH

Total Costs	100 Units	500 Units	1000 Units
Labor Cost	$26.41	$15.85	$12.68
Labor Overhead	39.61	23.77	19.02
Material	14.79	14.79	14.79
G & A/Profit	18.75	12.62	10.79
Projected Cost	$99.56	$67.03	$57.28

TOOLING

Tooling developed during the program consisted of matched metal dies for the molding of the epoxy BMC material and of fixtures for the assembly of the component details.

Matched Metal Dies

A total of 11 matched metal dies were designed and fabricated to mold the complex details from BMC material. The dies were machined from a mild steel alloy so that many parts could be molded without deterioration of the tooling. With the exception of five tools, the molds were fabricated to the final configuration of the part. These five tools, which include the two clevis fittings on the forward bell crank, the two idler halves, and the pivot fitting on the aft bell crank required secondary processes to drill bearing and bushing holes in the moldings which could not be provided by the dies.

For the work performed on this program, the tools were more than adequate. The details molded in each of the cavities were of excellent dimensional and physical quality. However, operational difficulty was incurred with some tools which required a long entry stroke. The difficulty was galling of the plunger and throat. While every precaution was taken to avoid galling and enhance smooth operation, it was apparent that the softness of the mild steel in the plunger and throat areas of the tools was such that galling could occur if abrasives were trapped. It is believed that the galling is promoted by glass fibers becoming lodged between the throat and the plunger surfaces. It only occurred on tools which required a stroke between 3 and 5 inches. It is recommended that future tools for this application be prepared from a material with a harder surface to avoid such galling.

No galling or wear of the internal cavity surfaces was experienced on any of the tools. The bulk molding compound was nonabrasive to these surfaces.

Assembly Fixtures

Assembly fixtures were prepared for each of the four components. These fixtures were designed such that they could hold each of the individual details for each component in the right position for bonding. The fixtures contain clamping devices to apply pressure during the adhesive curing operation. The design of the fixtures is such that they will not accept the component details which are not dimensionally accurate. Thus the final bonding assembly was always dimensionally accurate after cure. The assembly fixture was therefore used as an inspection device consisting of a series of go and no-go gages for each individual component detail and its location.

FABRICATION OF COMPONENTS

The Ball Rod End Assembly

The ball rod end assembly was made from two composite materials. The inner surface of the ball rod end was comprised of unidirectional glass reinforcement, three plies in thickness, with a changing cross section as it extended from the shank portion down into the neck and into the ball area. The outer shell and the ball portion are fabricated from moldeu epoxy BMC material.

It was the intention at the start of the program that this inner unidirectional shell and the BMC material be integrally molded in one operation. Several attempts to utilize this fabrication method were unsuccessful. The force required to mold the BMC material was sufficient to distort and physically move the inner unidirectional uncured layer. The attempts at making this fabrication method successful included the B-staging of the epoxy resin in the unidirectional prepreg to a point where it had sufficient structural integrity to withstand the molding process. It was not possible to achieve this B-staged state repeatedly, and a different fabrication method had to be used.

A subassembly technique proved to be extremely successful. The layers of the unidirectional prepreg were applied to a mandrel, shown in Figure 5, and cured in place. This shell (Figure 6) was then removed and sandblasted on the outer surface, followed by MEK solvent degreasing, and inserted into the matched metal tool. The molding operation with the BMC material was then accomplished with the unidirectional shell already cured. Figure 7 shows a molded rod end. The reliability and reproducibility of this two-step process for fabricating the ball rod end were well within the 5% scrap factor normally used in a fully operational manufacturing line. While the developed two-step fabrication process would appear to involve additional man-hours for the fabrication of the rod end detail, the layup of the three plies of unidirectional tape had to be performed whether it would be an integral molding operation or a two-step molding operation. The only additional time required was the labor to remove the cured shell from the mandrel and perform the sandblasting and solvent degreasing operations. In comparison to the results in developing an integral molding process, the reproducibility and reliability of the two-step process are very successful.

After molding of the rod end assembly, the ball end of the detail is fine honed to a true spherical radius, as shown in Figure 8. After accomplishing this, the honed surface is cleaned and degreased in MEK and spray-coated with multiple layers of Teflon loaded polyurethane paint to reduce the friction between the ball and socket interfaces (Figure 9). In order that the tolerance of the fit between the ball and socket be maintained, an overthickness of paint is applied to the ball rod end. This overthickness is then honed to a true spherical radius after the paint has been fully cured (Figure 10).

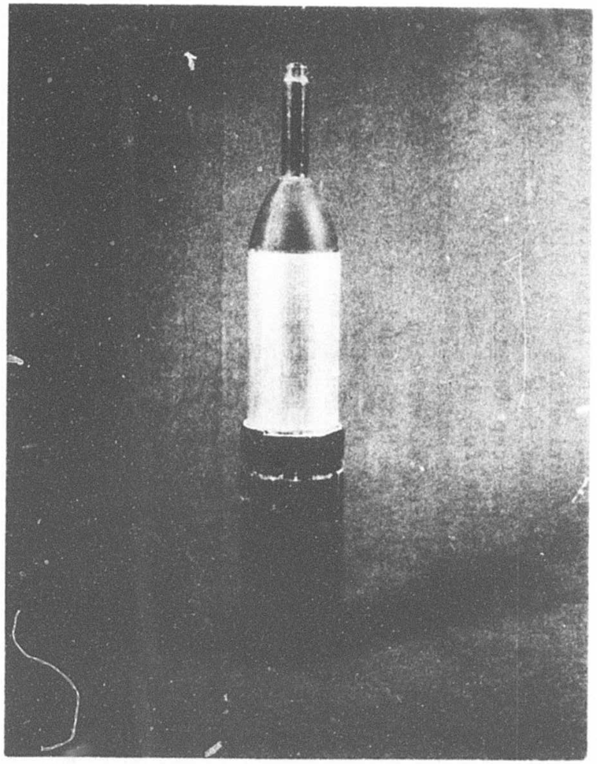


Figure 5. Mandrel for Unidirectional Shell.

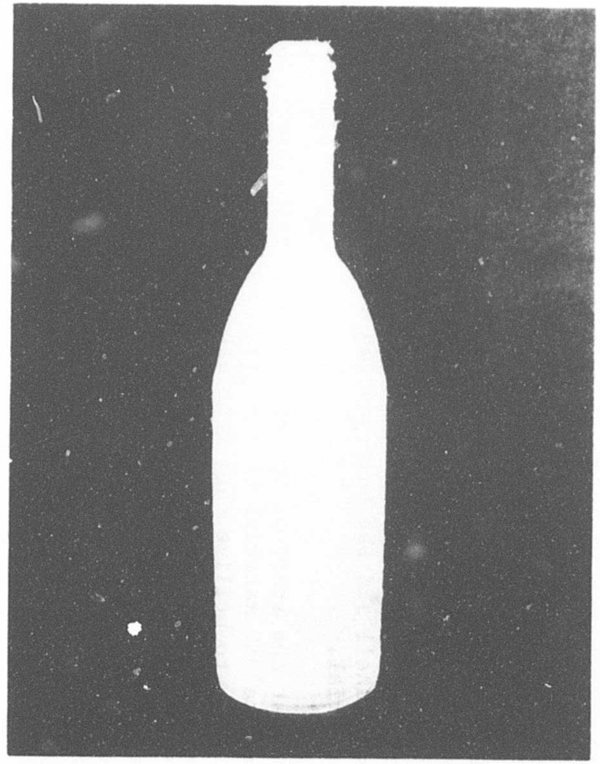


Figure 6. Cured Shell With Rough Bonding Surface.

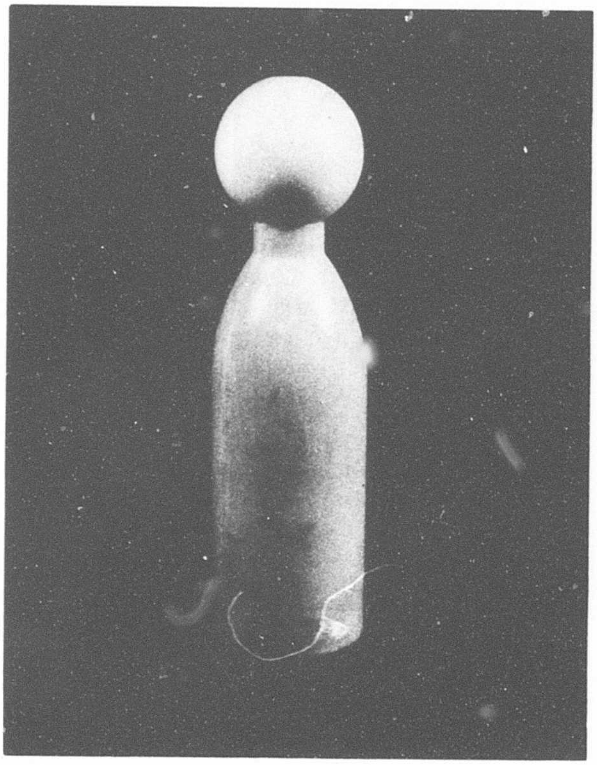


Figure 7. Molded Rod End.

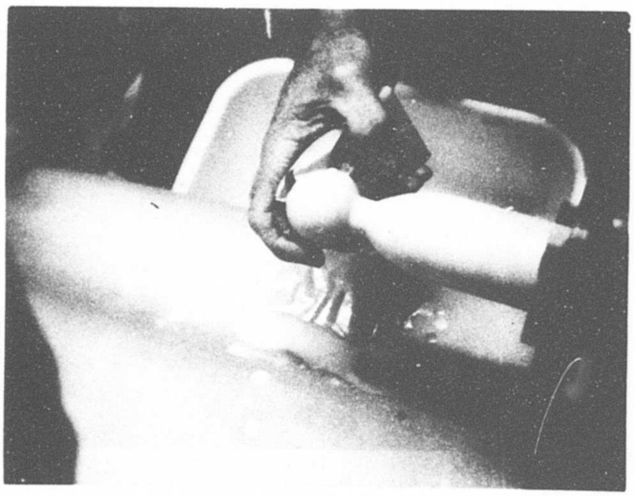


Figure 8. Honing to True Sphere.

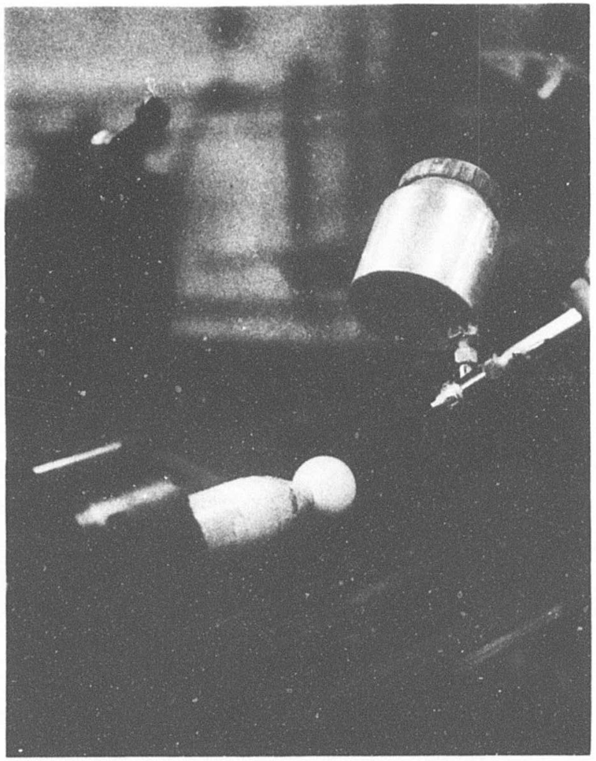


Figure 9. Applying Paint to Ball Surface.

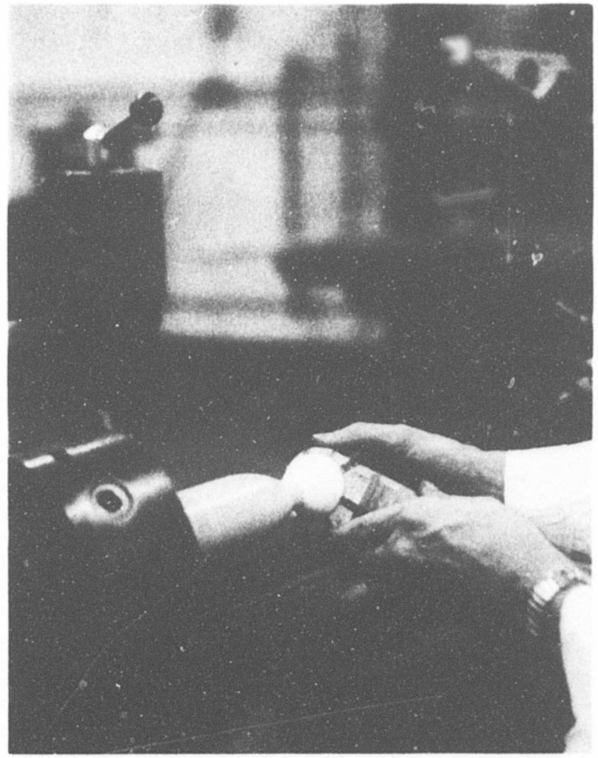


Figure 10. Honing Painted Surface.

After final honing of the painted ball surface, the retainer ring halves are positioned around the neck of the ball socket and overwrapped with two layers of epoxy impregnated 143-style glass fabric. The retainer ring halves are positioned in a fixture which holds them in a true circular alignment (Figure 11). The ball is permitted to locate on the mating retainer surfaces and is forced against the retainer to maintain proper fit. Once this has been accomplished, the two layers of prepreg tape are wrapped in the recess of the retainer and overwrapped with cellophane shrink tape. The entire assembly is placed in an oven and cured for 1 hour at 250°F.

Idler Arm Assembly

As shown in Figure 4, the idler arm consists of two molded BMC halves which, when assembled, are overwrapped with unidirectional, epoxy impregnated fabric tape both around the arm section and around the outboard edges of the socket joint.

The fabrication of the two idler halves is performed by matched metal die molding with the epoxy BMC material (Figure 12). The two halves are assembled with the ball socket fixtures, which are a part of the aft bell crank assembly fixture (Figure 13). These serve to position and align the socket half during the bonding of the idler arm. Subsequent to the bonding, the areas which are to receive the unidirectional reinforcement are sandblasted and MEK degreased. A fabric tape pattern is cut from the broadgoods material and wrapped around the three areas shown. Three plies of fabric are used to accomplish this task. The wraps around the outboard socket ends of the idler arm are simply overwrapped with three layers of cellophane shrink tape. The arm assembly, which contains four flat edges, is covered in these flat areas with 1/4-inch cork material which is chamfered at the corners to prevent wrinkling during cure. This in turn is overwrapped with three layers of cellophane shrink tape.

The cured idler arm assembly (Figure 14) is positioned back on the curing fixture, and the hole which will contain the bearings and bearing spacer is drilled.

The final operation on the idler arm assembly is the honing of the socket surface to a true sphere. This operation is shown in Figure 15.

Assembly of the Ball Rod End and Idler Arm Details

The assembly of the rod end and idler arm details consists of installing rod end assembly and retainer into the idler arm socket. This is accomplished by adhesive bonding in a fixture, as shown in Figure 16.

The final assembly on the rod end idler arm component is the installation of the bearings. The two bearings and the spacer are bonded into the hole at the lower portion of the idler arm detail. Figure 17 is a picture of a fully assembled rod end idler arm assembly.

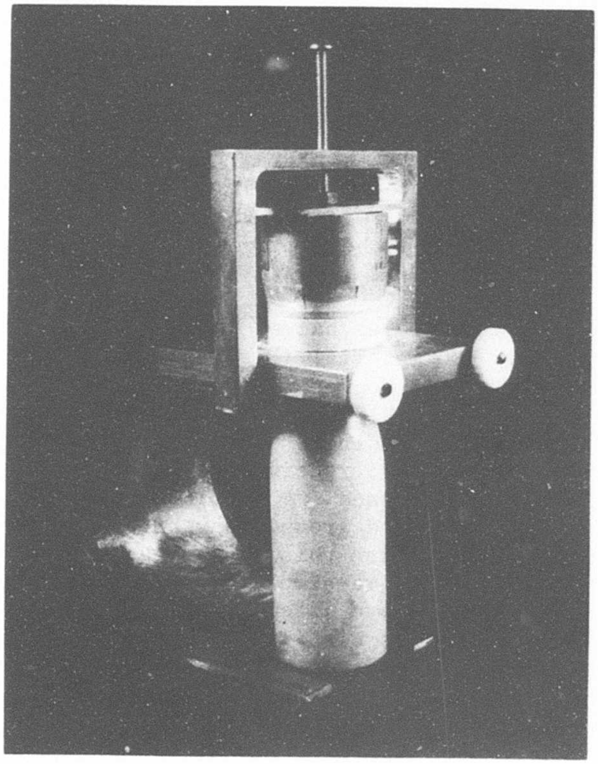


Figure 11. Installing Retainer Ring Around Ball Rod End.

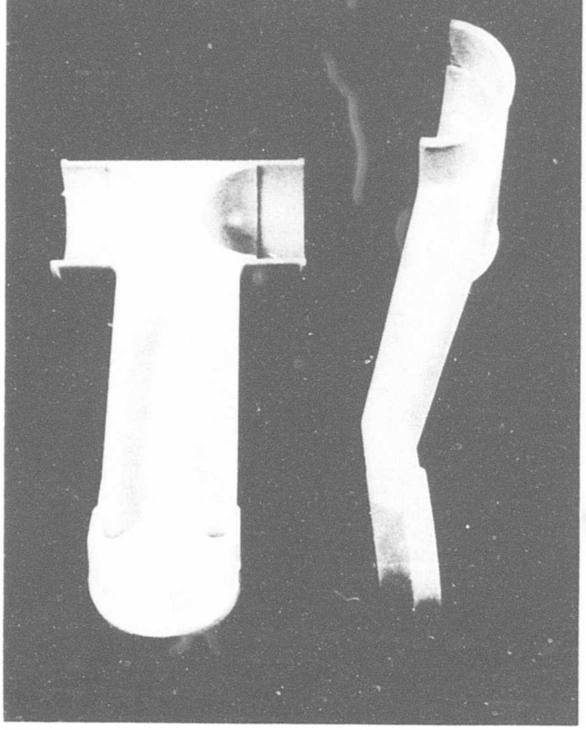


Figure 12. Molded Idler Arm Halves.

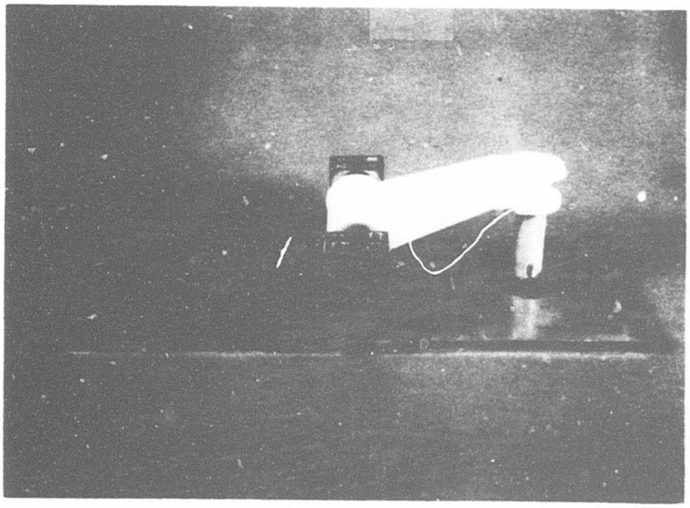


Figure 13. Bonding Idler Arm Halves.

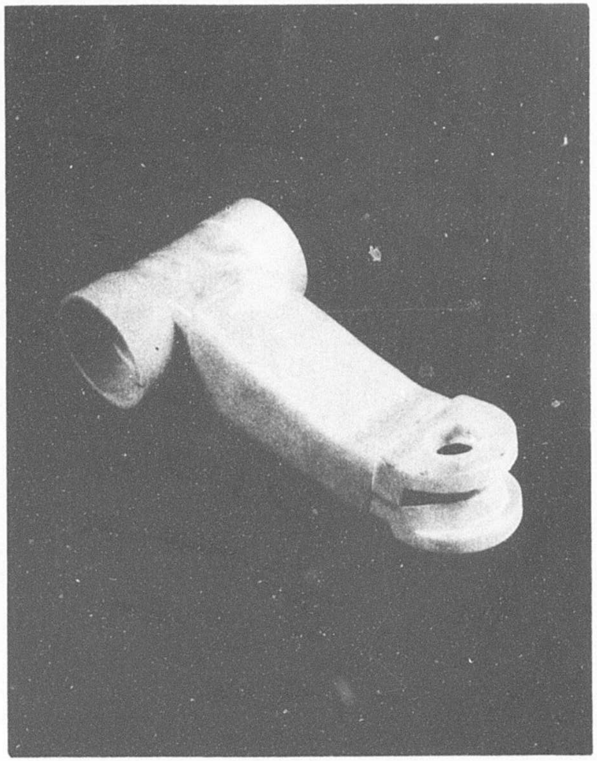


Figure 14. Cured Idler Arm.

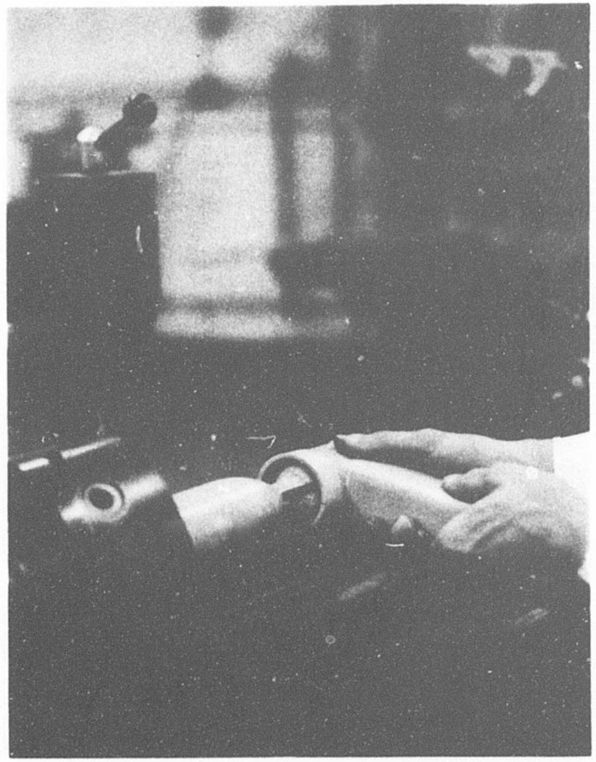


Figure 15. Honing of Idler Arm Socket.

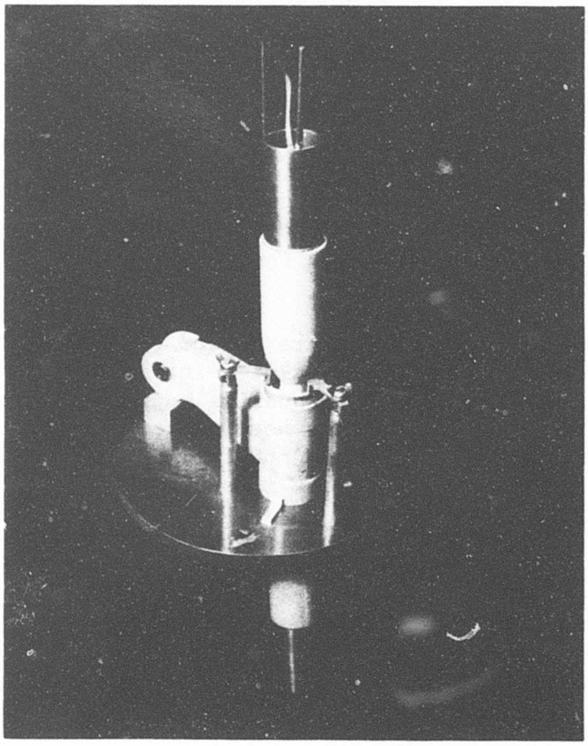


Figure 16. Assembly of Rod End Idler Arm.

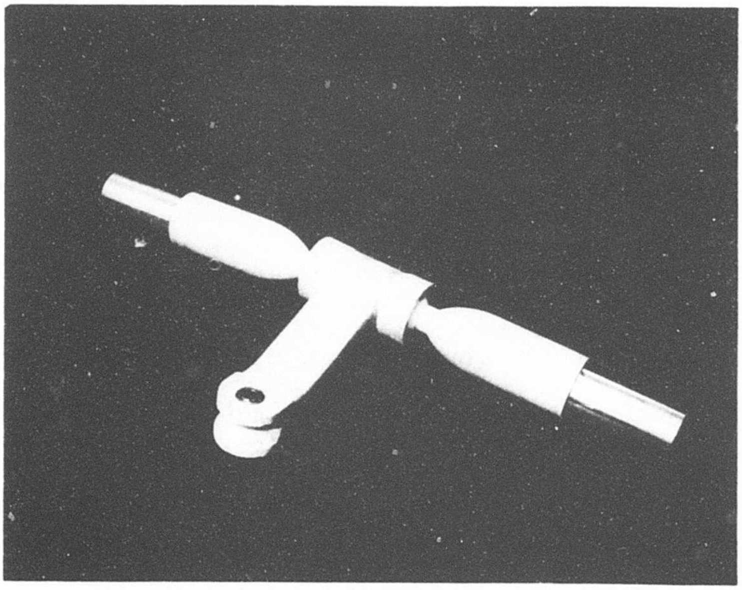


Figure 17. Full Assembled Rod End Idler Arm Component.

Aft Bell Crank Component

Figure 3 is an exploded view of the details comprising the aft bell crank assembly. Basically, the aft bell crank consists of a triangular box to which two rod end/retainer assemblies are installed. The triangular box consists of three epoxy BMC molded fittings, two of which contain sockets for the ball rod ends and the third a pivot fitting. Between each of the three fittings are three rectangular NEMA-grade tubes. Covering both sides of the triangular box are sheets of NEMA-grade sheet stock. On each side of the pivot fitting surfaces and around the bearing support is a NEMA-grade flat sheet stock doubler.

The three corner fittings for the bell crank box are molded from epoxy BMC material. The two fittings which contain a socket joint are molded as one final detail. The hole which contains the bearing support tube in the pivot fitting is drilled after the molding has been prepared. The NEMA-grade flat sheet stock and tubular shapes are cut from stock material to the desired configuration. Typical assembly is shown in Figure 18.

The assembly of the main bell crank triangular box is accomplished by adhesive bonding all details in an assembly and bonding fixture shown in Figure 19. Figure 20 shows the bell crank installed in the fixture during the bonding operation.

After the bonding of the bell crank box has been completed, the rod end/ retainer ring assemblies are installed into the socket fittings by adhesive bonding. The last and final operation is the installation of the bearing support, bearings, and bearing spacer. The bearing support is first installed into the access hole in the pivot fitting and bonded. The two bearings and the bearing spacer are then installed into the bearing support tube and bonded.

Figure 21 is a picture of a fully assembled aft bell crank assembly.

Forward Bell Crank Component

Figure 2 is an exploded view of the details comprising the forward bell crank assembly. As shown, the forward bell crank is a triangular box containing three epoxy BMC fittings at three corners. Two of the fittings are clevis-type fittings and the third a pivot fitting. Between the three fittings are three square NEMA-grade glass/epoxy tubes. Covering the two sides of the triangle are sheets of NEMA-grade sheet stock and NEMA-grade doublers at the fitting locations.

The three fittings are matched metal die molded from an epoxy BMC material in their final configuration, with exception of the clevis-type fittings which do not contain the holes in the molding operation. These holes are drilled after molding in a drill fixture. The hole in the pivot fitting is molded in.

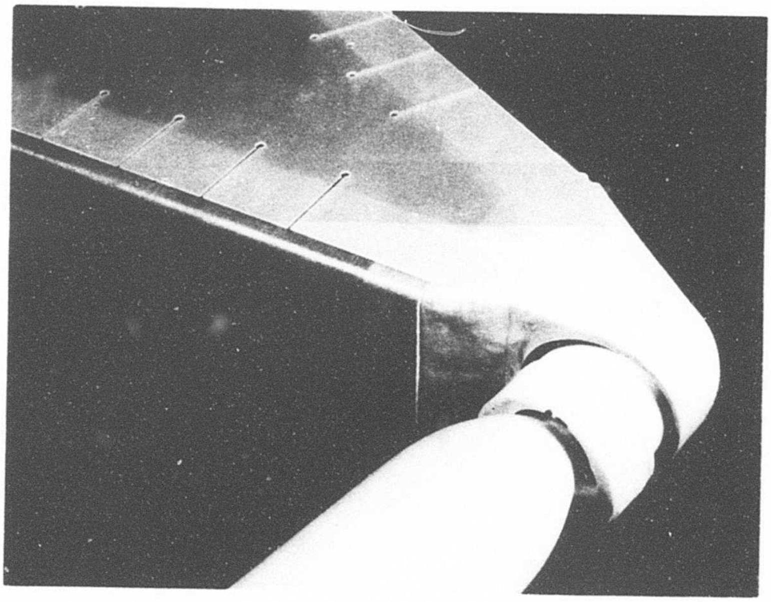


Figure 18. Typical Assembly of Aft Bell Crank Details.

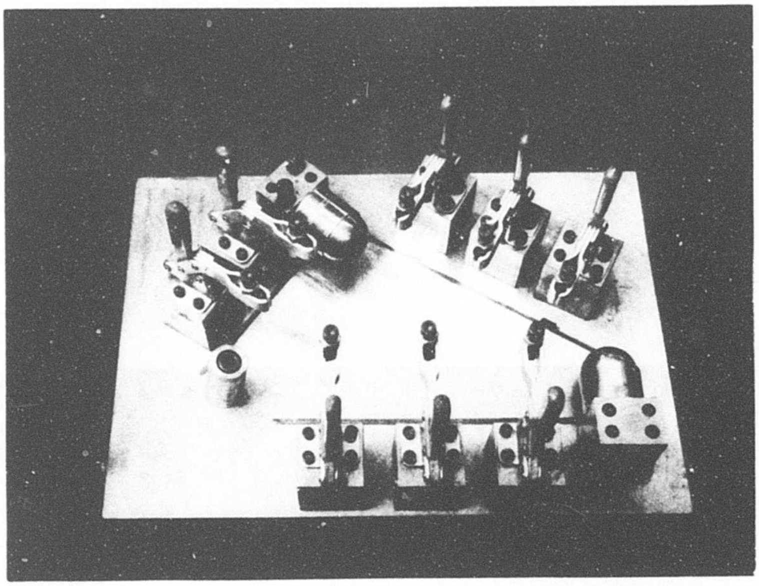


Figure 19. Aft Bell Crank Assembly Fixture.

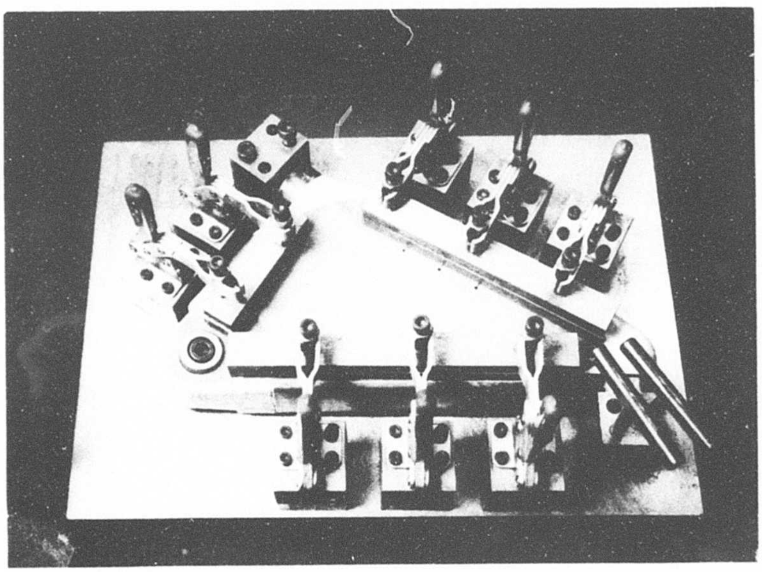


Figure 20. Bonding of Aft Bell Crank Box.

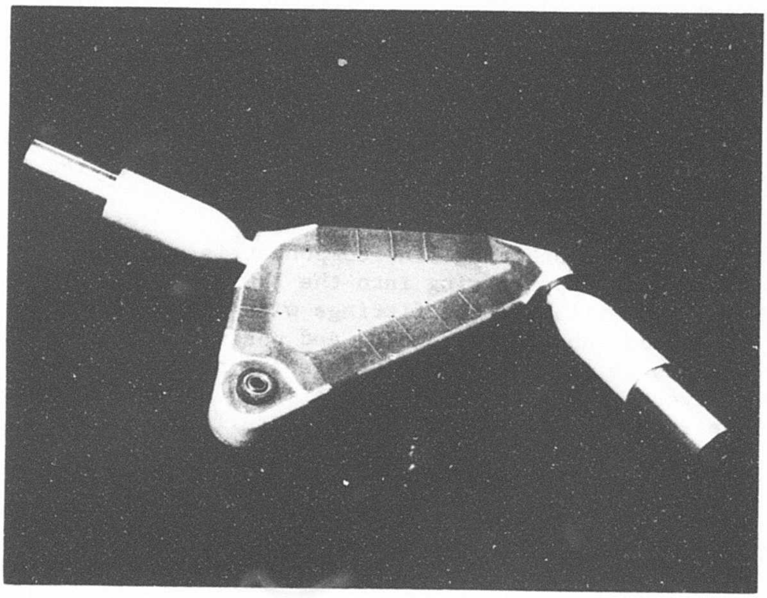


Figure 21. Fully Assembled Aft Bell Crank Component.

The NEMA-grade face sheets, doublers, and tubes are cut from stock tube and sheet material and assembled to the fittings, as shown in Figures 22, 23, and 24.

The assembly of the details is accomplished in the assembly and bonding fixture shown in Figure 25. Figure 26 is a view of the fixture containing the forward bell crank assembly during the bonding operation. Figure 27 is a picture of the fully assembled forward bell crank component.

Connecting Link Assembly

Figure 1 is a view of the details comprising the connecting link component. It consists of two epoxy BMC molded end fittings, one NEMA-grade round tube, two bearing supports and swivel bearings, and a unidirectional epoxy/glass fabric strap.

The two identical epoxy BMC end fittings are matched metal die molded to their final configuration. The NEMA-grade tube is prepared from stock tubular material.

The assembly of the connecting link component is performed first by bonding the bearing support ring into the BMC fittings (Figure 28). While this is being accomplished, the fittings with the bearing support ring and the NEMA-grade tube are assembled and positioned in the fixture, as shown in Figures 29 and 30. The fittings are bonded inside the tube and the unidirectional glass fabric tape is wound around the end of the bearing support rings and laid on the tube surface.

Curing of the unidirectional glass strap is accomplished by first applying cork dams on either side of the strap and overwrapping with cellophane shrink tape (Figure 31). The entire assembly is then placed in a 250°F oven and cured for 1 hour. After curing, the cellophane shrink tape and cork dams are removed and the detail deflashed prior to press fitting the swivel bearings.

Figure 32 is a picture of a fully assembled connecting link component.

Fabrication of Modified Aft Bell Crank Assembly

A modified aft bell crank was designed and fabricated to better satisfy the fit and function requirement. The redesign involved the ball rod end attachment only. As discussed in the Test section, the aft bell crank assembly could not be installed due to the excessive length of the two ball rod end assemblies attached as appendages to the bell crank box. The redesign incorporated a different method of attachment between the ball rod ends and the connecting rods which they actuate. Figure 33 is a schematic of the typical modified ball rod end. It is approximately 10 inches shorter than the previous rod end design. It

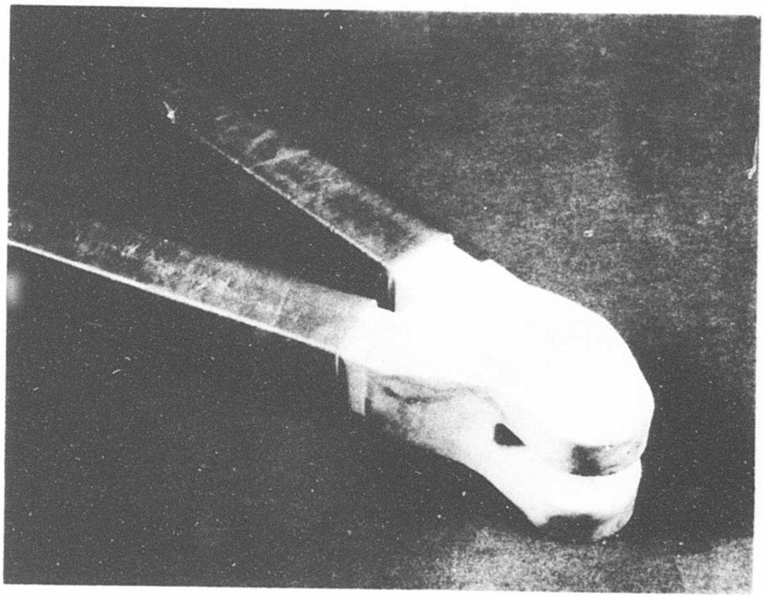


Figure 22. Typical Tube Fitting Assembly.

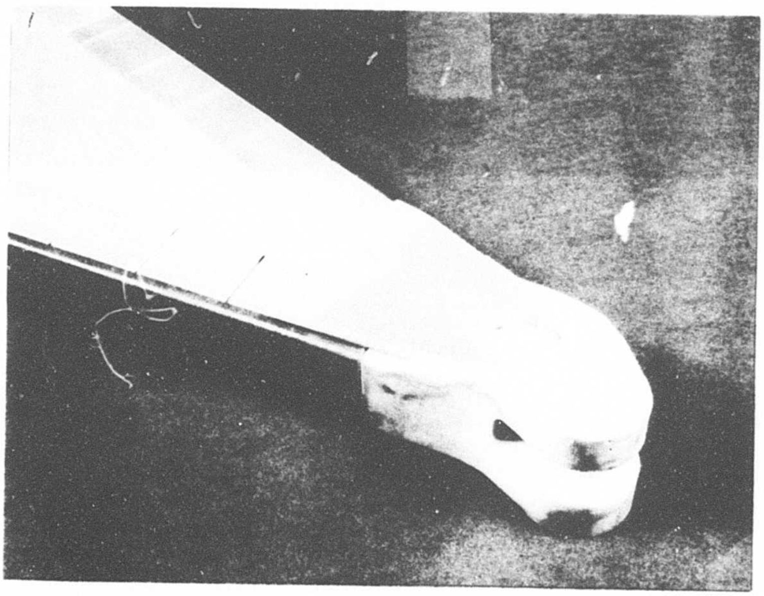


Figure 23. Installation of Face Sheet and Doubler.

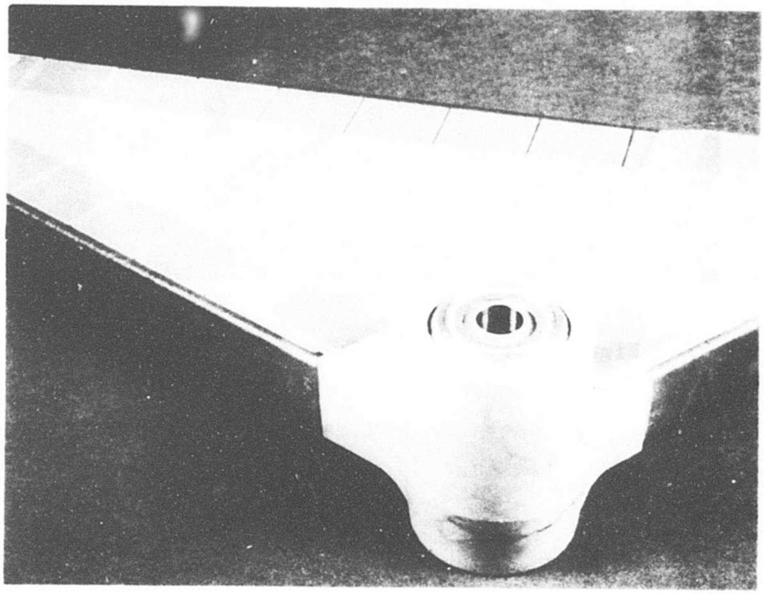


Figure 24. Pivot Fitting Installation.

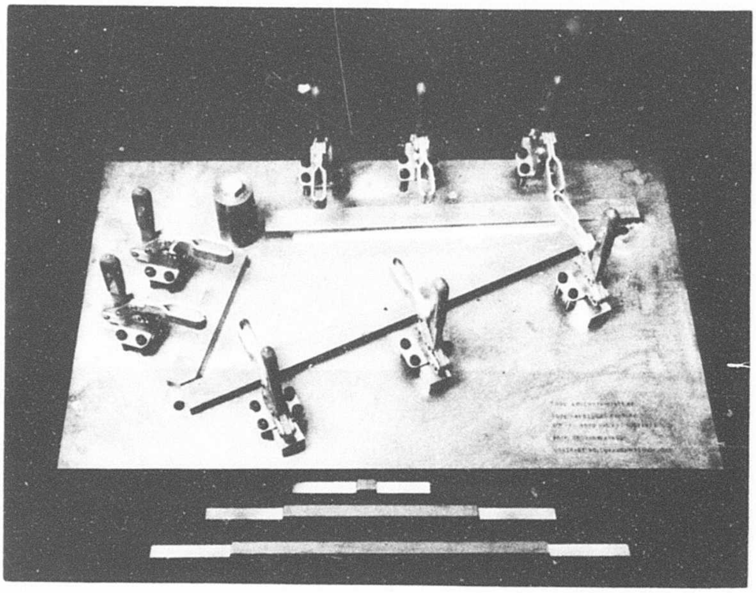


Figure 25. Forward Bell Crank Bond Fixture.

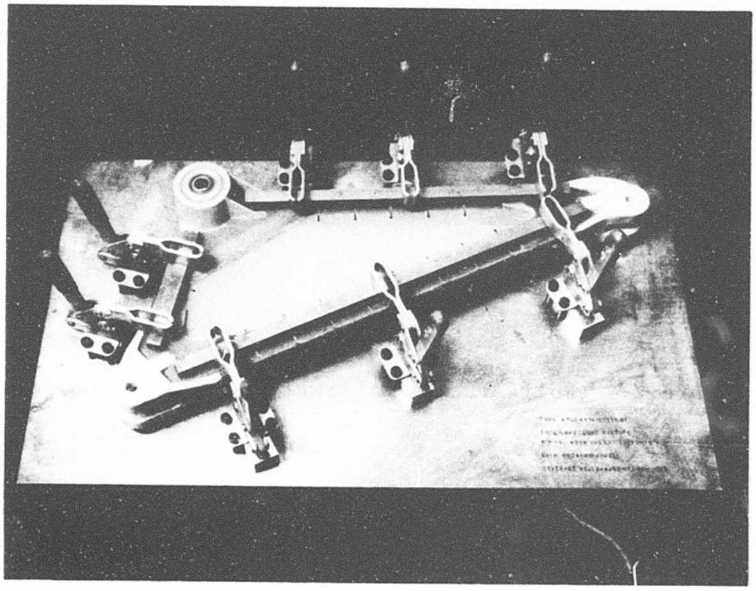


Figure 26. Assembly of Forward Bell Crank.

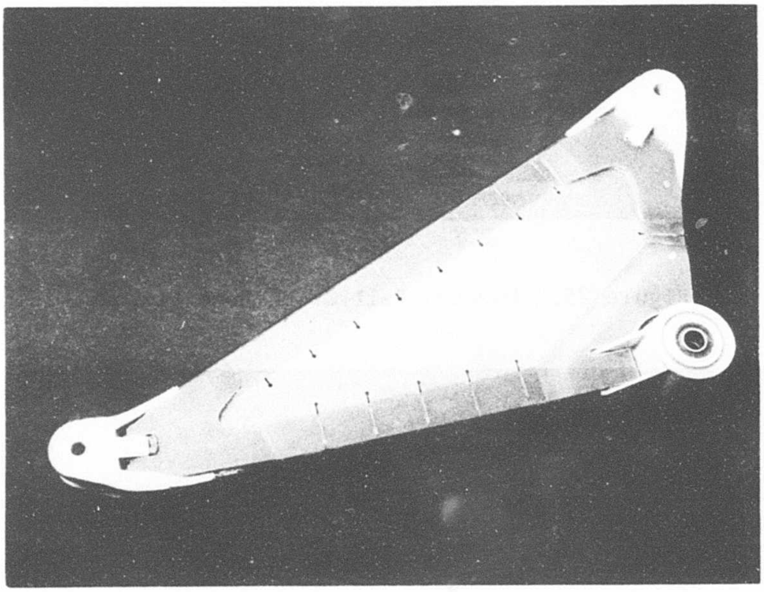


Figure 27. Full Assembled Forward Bell Crank Component.

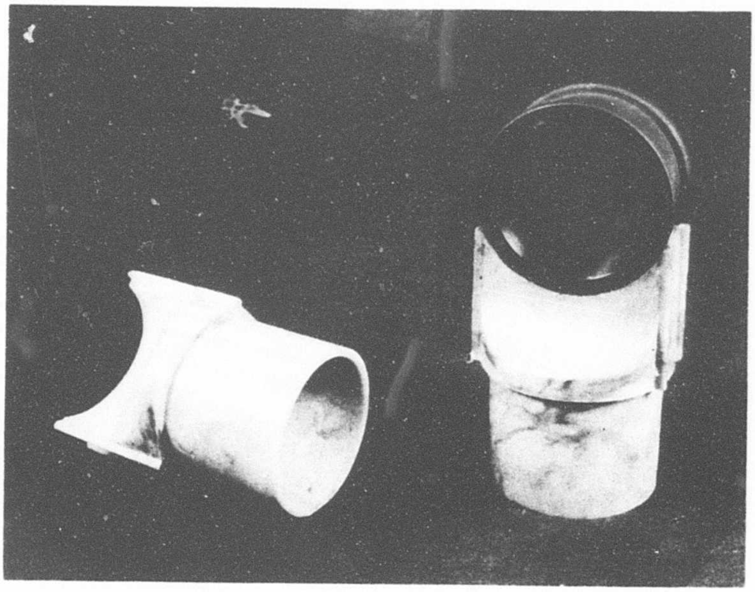


Figure 28. Fitting and Bearing Support.

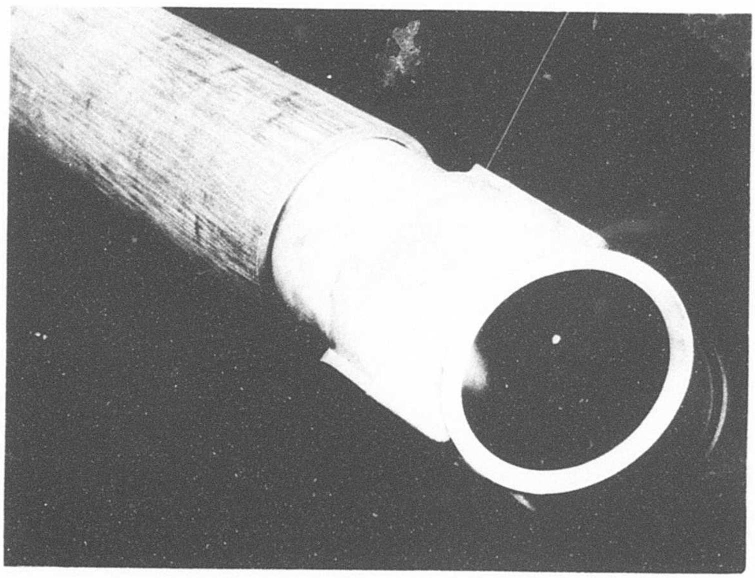


Figure 29. Installation of Tube and Fitting.

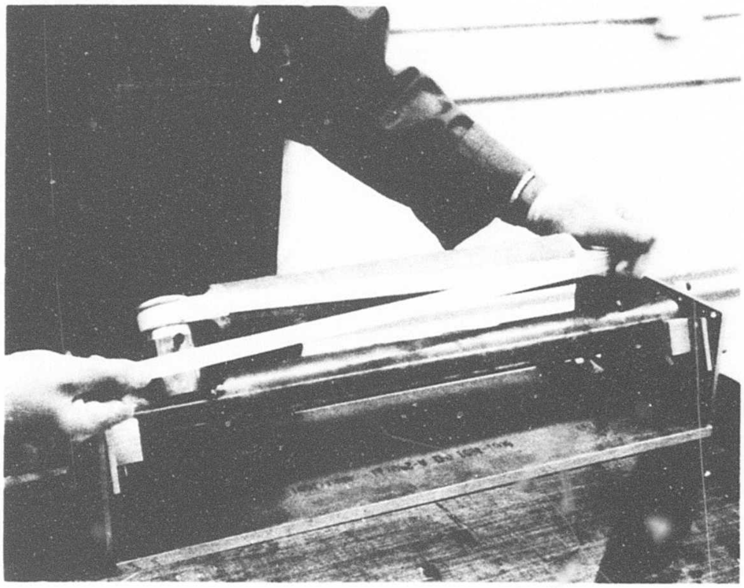


Figure 30. Assembly of Connecting Link.

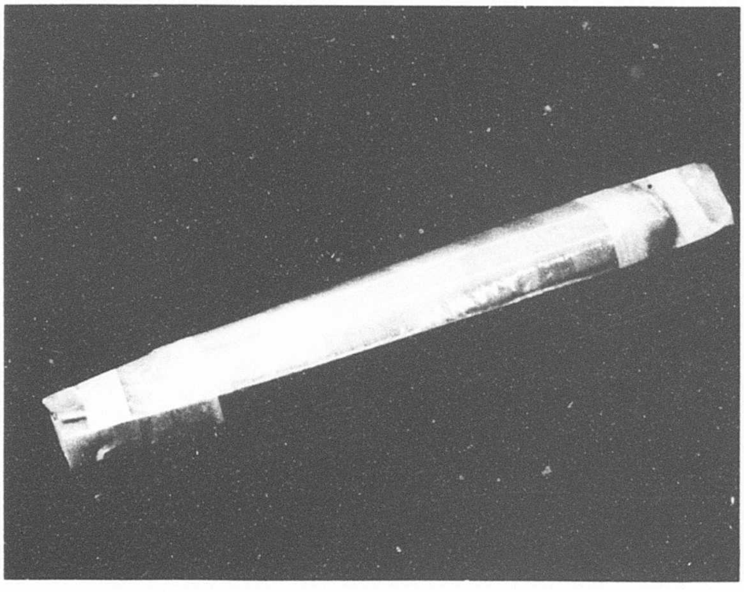


Figure 31. Connecting Link Wrapped With Shrink Tape Prior to Cure.

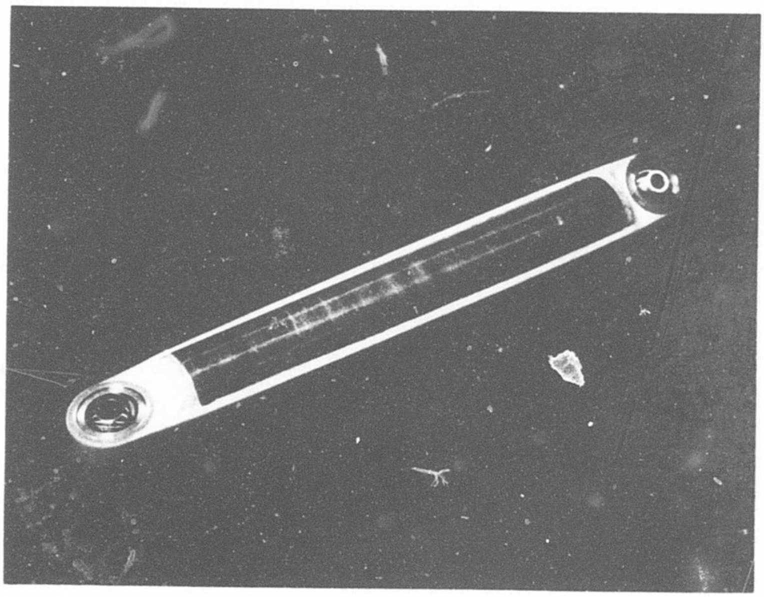


Figure 32. Full Assembled Connecting Link Component.

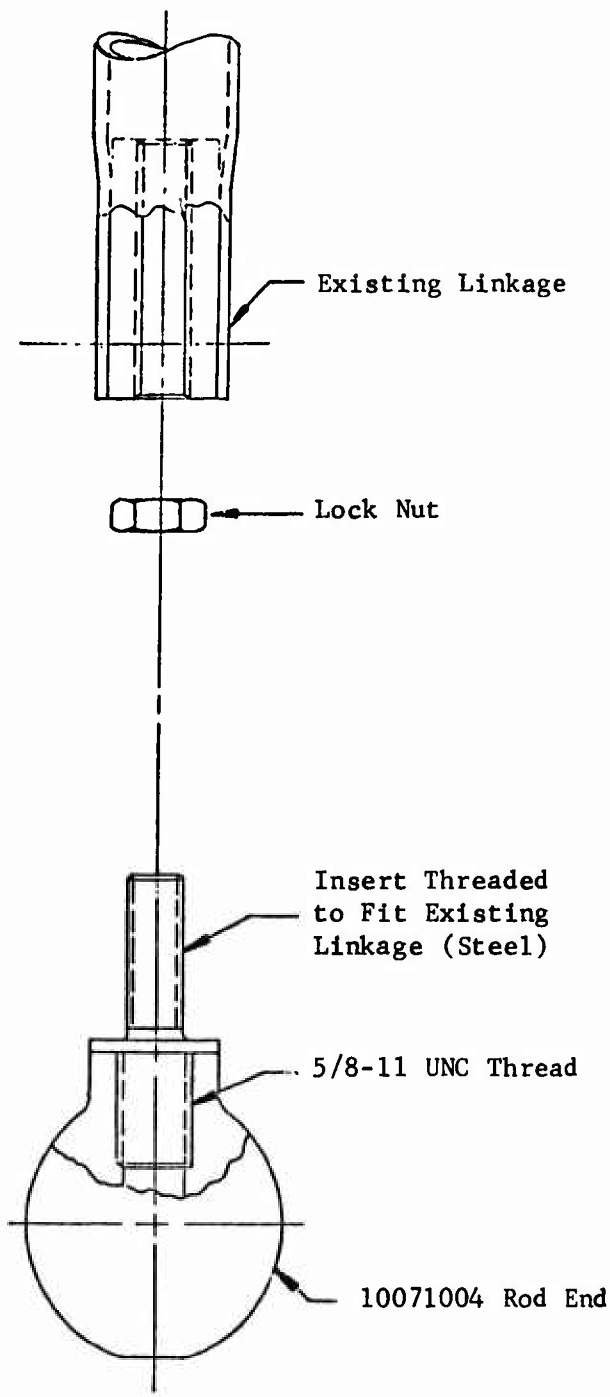


Figure 33. Modified Ball Rod Ends for the Aft Bell Crank Assembly.

incorporates a direct attachment to the connecting rods through a metallic insert threaded and bonded directly into the center of the ball. Since the shaft and thread dimensions for the two ball rod ends were different for the input and output ball and socket joints, two adapters needed to be fabricated. Figure 34 is a view of the two modified ball rod ends which were incorporated in the modified aft bell crank assembly.

It was noted during the fabrication of the modified aft bell crank that the installation of the ball rod ends was considerably simplified over the previous rod end design. This added simplicity was the result of not having to install the retainer ring assemblies around the neck of the ball rod end. The retainers could be fabricated as a subassembly and installed over the modified ball rod ends without interference from the larger diameter rod portion of the previous design. Thus, one complete step was eliminated from the assembly process.

The attachment of the modified aft bell crank ball rod ends is also greatly simplified in that direct attachment is now possible without an adapter linkage as was required on the previous rod end design.

VERIFICATION TESTING

The testing conducted during the course of this program was comprised of three separate tasks. The first was the fit and function test, the second a series of combined mechanical and environmental tests, and the third a ballistic impact test. Eight duplicates of each of the four components were fabricated for this test series. Table VI details the test series and sequence for each of the individual components. It should be noted that one set consists of one each of the four different components.

Shown below are the different agencies which conducted the verification testing.

USAAMRDL	Fit and Function
Approved Engineering Test Laboratories Chatsworth, California	Environmental: Altitude, Humidity, Sand and Dust, Fungus Resistance, Salt Spray, Ultraviolet Radiation Structural: Vibration
General Dynamics/Convair San Diego, California	Ballistic
Whittaker Research and Development San Diego, California	Environmental: High Temperature Exposure, Temperature Shock, Low Temperature Exposure, Fuel and Oil Resistance, Fire Resistance Structural: Static Loading, Fatigue and Load Cycling, Static Failure Load/Deflection

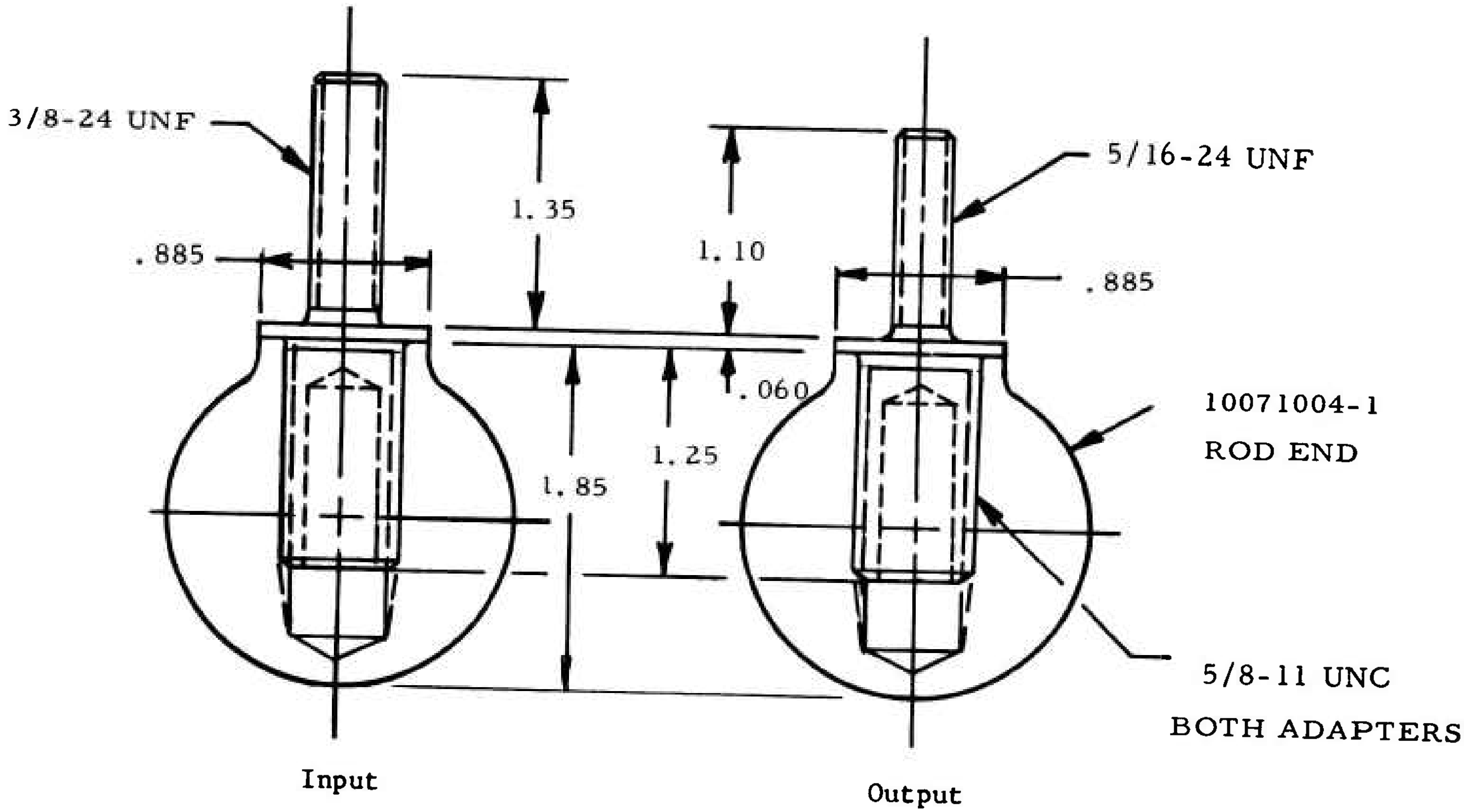


Figure 34. Modified Ball Rod Ends With Adapters.

TABLE VI. HELICOPTER CONTROL COMPONENTS VERIFICATION TEST PROGRAM

TEST NO.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
SET NO.	Fit & Function	Cyclic Loading A (E) $5 \cdot 10^6$ Cycles	Static Loading (B)	Ballistic Test Under Load (D)	Cyclic Loading B (E) 2,000 Cycles	Static Failure Load/Deflection	High Temperature Procedure II	Temperature Shock Procedure I	Low Temperature Procedure II	Altitude Procedure VI	Sand & Dust Procedure I	Humidity Procedure I	Fungus Procedure I	Salt Spray Procedure I	Vibration Procedure XII	Cyclic Loading C (C) $10 \cdot 10^6$	Ultraviolet Radiation Procedure I	Fuel & Oil Resistance Fed Test Std 406 Method 7011	Fire Resistance Fed Test Std 406 Method 2021
1	1	Spare																	
2	1	2		GD 3	4	5													
3	1		2			4													3
4		5				6	1	2	3	AETL 4									
5		5				6					AETL 1	AETL 2	AETL 3	AETL 4					
6						3									AETL 1	2			
7						2											AETL 1		
8						2												1	

NOTE: Number in table is order of test specimens.

C = Completed ST = Stores TEST = Test Group
GD = General Dynamics AETL = Approved Engineering Test Laboratory

Fit and Function Test

The first three sets of components fabricated during the manufacturing phase of the program were installed for operation aboard a CH-47 helicopter. The purpose of this test was to determine the retrofit capability of the newly designed components, as well as their ability to function correctly in the flight control system.

The results and findings of the fit and function tests are detailed below for each of the individual component types.

Idler Arm Rod End Assembly

The function of the rod end idler arm assembly is to transfer pilot control input to a series of tubular connecting rods, which subsequently apply input to the flight control components of the aft rotor. When installing the ballistic-tolerant rod end idler arm assembly, it was found that there was not adequate clearance on the bearing end of the idler arm section. Before the idler arm was able to fit with proper clearance, approximately 0.200 inch of nonessential material had to be removed from the outer periphery on the bearing support end.

The actual function of the rod end idler arm assembly as part of the control system was not accomplished. In order to do this, major modification is required of the existing metal connecting rods and various sizes of adopters would have had to be made. In lieu of this, with the component installed, measurements were made to assure adequate clearance and degree of freedom with the ballistic-tolerant component. These measurements proved that there was adequate clearance between all surrounding hardware and covers through full travel of the component. But some concern was expressed about the degree of freedom in a ball and socket joint. While the present configuration did permit adequate ball joint movement, any accumulated tolerance on installation could possibly cause binding. As a result, it was recommended that the retainer rings be ground in an oval configuration to permit more lateral movement of the arm.

At the conclusion of the fit and function test of the idler arm assembly, two modifications were made on all future units. The first was to remove from the lower end of the idler arm assembly approximately 0.200 inch of nonessential material. The second was to provide an oval clearance in the retainer ring to permit more lateral movement of the ball rod end detail.

Aft Bell Crank Assembly

The fit and function test of the ballistic-tolerant aft bell crank with rod ends as designed and built was found to be unsatisfactory from an installation and freedom of operation standpoint.

The surrounding bulkheads, hydraulic cylinders, and tubing did not allow adequate clearance for field installation of the bell crank with the rod end attached. This was not the result of an out-of-tolerance condition, as the bell crank was made to the previously approved design drawings. It was a matter of a lack of space to permit ease of installation and complete freedom of operation of the bell crank within the helicopter system, without removing hydraulic cylinders and tubing.

As a result of this finding, the ball rod ends were cut off approximately 1 inch aft of the ball socket. This did permit easy installation of the main bell crank body. Had there been provisions for connecting the remaining ball rod ends to the connecting rods, a function test could have been performed.

A second discrepancy was a slight interference with a bracket and the inboard cover sheet as the bell crank pivoted. This condition was easily alleviated by repositioning the bearing support tube in the pivot fitting.

As a result of the unsatisfactory fit and function of the aft bell crank assembly, it was requested that the ball rod end connections be redesigned to permit easier installation of the aft bell crank. This was accomplished, and one aft bell crank incorporating the modified design was submitted for a fit and function test and was successfully installed and operated. The design and fabrication of the modified aft bell crank are discussed later in more detail.

Forward Bell Crank Assembly

The ballistic-tolerant forward bell crank was installed easily and functioned without any problems.

Connecting Link

The function of the connecting link is to effect pitch movement to one of the helicopter rotor blades. At the pilot input end, it is connected by means of a clevis fitting. At the output end, it is attached inside a rectangular cavity which is part of the helicopter hub. During the fit and function test the connecting link could be fitted into the clevis end and into the cavity end. However, the fit in the cavity was so tight that little or no movement of the connecting link could be accomplished without interference. No measurement of the pitch angle obtainable was made with the connecting link; however, it can be considered negligible.

The drawing and the original Boeing-Vertol made ballistic-tolerant connecting link were reviewed to determine if the unit was dimensionally accurate. It was found to be according to the approved drawings and essentially identical to the Vertol part.

Thus, it was concluded that the connecting link as presently designed will satisfy the fit requirement, but it will not function properly.

A satisfactory fit and function of the connecting link assembly would require that an entirely new design be conceived. Due to the magnitude of this effort, it was decided not to redesign the connecting link, but to continue with its fabrication as is in order to accomplish the verification testing task on a typical, highly loaded connecting link.

Environmental Testing Results

Component sets no. 3 through 8 were exposed to a series of environmental test conditions prior to the final structural test series. The following paragraphs briefly describe the tests which were conducted and the results which were obtained for each of the conditions.

High Temperature Exposure

The high temperature exposure test was conducted on component set no. 4 in accordance with MIL-E-5272C, Procedure II. The test consisted of installing one each of the four components in a suitable chamber with the temperature raised to 160°F at a relative humidity of less than 15%. The duration of the test was 48 hours. At the conclusion of the test, the temperature was returned to ambient and the components were removed from the chamber. A visual examination of the components did not reveal any evidence or damage as a result of the test. Manual operation of the idler arm and aft bell crank ball and socket joints did not reveal any change in their frictional characteristics.

Thermal Shock

A thermal shock test was conducted in accordance with MIL-E-5272C, Procedure I. The test consisted of placing the same set of four components that were exposed to the high temperature condition in a suitable test chamber and raising the temperature to 185°F for a period of 4 hours. At the conclusion of this elevated temperature time period, the temperature in the chamber was reduced to -40°F within a period of 5 minutes. The test articles remained at this temperature for a period of 4 hours. At the conclusion of this time period, at the low temperature, the test articles were returned to 185°F within 5 minutes. Three cycles as described above were performed on the set of components. At the conclusion of the three cycles, the chamber was returned to ambient temperature conditions and the components were removed.

Inspection of the components revealed no visual degradation as a result of this test. A manual operation of the idler arm and aft bell crank ball and socket joints revealed that the friction at these points was somewhat reduced. While extremely slight, there was possibly some permanent set taken at the low temperature exposure. However, the operational characteristics of the ball and socket joints were still considered excellent.

Low Temperature Exposure

A low temperature test was conducted in accordance with MIL-E-5272C, Procedure II. The same set of components which had been exposed to the thermal shock test were positioned in a chamber and the temperature lowered to -80°F. The components were maintained at this temperature for 48 hours. At the conclusion of the test, the test chamber was returned to ambient temperature conditions and the components were removed. A visual observation of the components revealed no evidence of damage as a result of this test. Again, the aft bell crank and idler arm ball and socket joints were manually operated. The frictional characteristics of each of the joints were unchanged and fully acceptable.

Altitude Test

The altitude test was conducted in accordance with MIL-E-5272C, Procedure VI, Condition C. The same set of components previously exposed to the low temperature were subjected to the altitude test environment in a test chamber. The temperature was reduced to -65°F and the pressure was reduced to 3.44 inches of mercury simulating an altitude of 50,000 feet. These conditions were maintained for 1 hour; then the test chamber was returned to ambient conditions. At the conclusion of the test, the test articles were removed from the chamber and inspected. A visual inspection revealed no damage or adverse effects as a result of this test. Manual operation of the idler arm and aft bell crank assemblies indicated that there was no change in the operational characteristics of these joints.

Humidity Test

Set no. 5 consisting of one each of the four component configurations was exposed to the humidity test in accordance with MIL-E-5272C, Procedure I. The test consisted of placing the components in a vented test chamber capable of maintaining 95% relative humidity through a temperature range of 100°F to 160°F. Ten cycles between these two temperatures and at a relative humidity of 95% were completed during a 240-hour period. At the conclusion of this time, the chamber was returned to ambient conditions and the test articles were removed. A visual inspection of the tested components revealed that the only damage to the components was slight rusting of the bearings in the connecting link assembly. Manual operation of the idler arm and aft bell crank ball and socket joints determined that there was no noticeable change in the operational characteristics.

Sand and Dust Test

The sand and dust tests were performed on the same set of four components which had been exposed to the high humidity test. The test was conducted in accordance with MIL-E-5272C, Procedure I. The articles were placed in a test chamber and the sand and dust density raised to 0.45 gram per cubic foot. The relative humidity throughout the test was less than 30%. The chamber temperature was adjusted to 77°F and the air velocity controlled at 280 feet per minute. The sand and dust environment was maintained under these conditions for a period of 6 hours. At the conclusion of this time, the temperature was increased to 160°F and maintained for an additional 6 hours.

At the conclusion of the test, the chamber was allowed to cool to ambient and the test articles were removed. After removing accumulated dust, the components were inspected but revealed no evidence of damage or deterioration as a result of the test. The ball and socket joints of the idler arm and aft bell crank assembly were manually operated to determine any change in frictional characteristics; however, none was found.

Fungus Resistance Test

The fungus resistance test was conducted in accordance with MIL-E-5272C, Procedure I. The same set of four components that had been tested in the sand and dust environment were also used for the fungus resistance test. The test consisted of spraying each of the components with a suspension of viable fungus spores. After spraying the components, they were placed in a chamber which maintained an internal temperature of 86°F and a relative humidity of 95%. They remained in this test chamber under these conditions for a total of 28 days. At the end of this period, the chamber was returned to ambient conditions and the components inspected for fungus growth and material deterioration. The results are given below:

1. Connecting Link - no fungus growth
2. Aft Bell Crank - very light scattered spots on NEMA-grade tubes
3. Idler Arm - very light growth on ball and socket antifriction coating
4. Forward Bell Crank - very light scattered spots on NEMA-grade tubes

Salt Spray Exposure

The salt spray test was conducted on the same set of components that had been exposed to the fungus environment. The test was conducted in accordance with MIL-E-5272C, Procedure I. It consisted of placing the components in a salt spray chamber for a period of 50 hours. The conditions within the salt spray chamber are as follows:

Salt concentration	-	5%
Temperature	-	95°F
Salt fallout	-	1.4 ml/hr/80 cm^2

At the conclusion of the exposure period, the components were removed from the chamber and rinsed thoroughly with distilled water. The visual examination of the components revealed that the only damage was corrosion of the metal bearings. Manual operation of the idler arm and aft bell crank assembly ball and socket joints did not show any change in operational characteristics.

Ultraviolet Radiation Tests

Ultraviolet radiation tests were conducted on component set no. 7 in accordance with MIL-E-5272C, Procedure I. The four components were placed in a chamber and subjected to a radiant energy at the rate of 100-140 watts per square foot. During the tests the chamber was maintained at a temperature of 113°F. The components were exposed to this environment for 48 hours. At the conclusion of the tests, the components were returned to ambient conditions and visually inspected. The inspection revealed no evidence of damage as a result of the tests. Manual operation of the idler arm and aft bell crank ball and socket joints indicated they were fully operational and unchanged in their frictional characteristics.

Fuel and Oil Resistance Tests

Component set no. 8 was exposed to the fuel resistance test environment per Federal Test Standard 406, Method 7011. The test consisted of submerging the components for a period of 7 consecutive days in each of three test fluids. The components were exposed first to a hydraulic fluid designated Aeroshell Fluid No. 4. The second exposure fluid was Brayco 932 Hydrocarbon Iso-Octane Fluid. The third and final fluid was Shell Aircraft Turbine Oil No. 307.

At the conclusion of the three 7-day exposures, the components were visually examined for degradation as a result of this exposure. After each of the exposures, there were no obvious detrimental effects to the surfaces of the components resulting from the exposures. Also after each fluid exposure, the idler arm assembly and aft bell crank ball and socket joints were manually operated. In each case there was a noticeable reduction in friction in the ball and socket joints; however, after thoroughly cleaning them with an alcohol solution, the frictional characteristics of these joints returned to their original state.

Fire Resistance Tests

Component set no. 3 was exposed to the fire resistance test. This fire resistance test was conducted in accordance with a test plan which was designed to simulate an on-board helicopter fire. The test consisted of placing the components in an open natural gas flame for an exposure period of 2 minutes. The flames were allowed to impinge directly onto the component. A thermocouple placed in an area of flame contact was used to monitor the temperature rise. At the conclusion of the 2-minute period, the component was removed from the test and visually observed. During the course of the test the components were observed for ignition and, if ignition resulted, for self-extinction.

Idler Arm Rod End Assembly

The idler arm rod end assembly was positioned so that the two ball and socket joints were exposed to the flame. They remained in the flame for the full 2 minutes without igniting. At the conclusion of the test, visual observation showed some evidence of surface char on the BMC material and also on the reinforcing straps. There were no other obvious damaged areas. The temperature in these areas was measured at 659°F. Immediately after removing from the fire, the ball and socket joints were manually operated. They were extremely tight but could be moved manually.

Connecting Link Assembly

The connecting link assembly was positioned such that one end of approximately 4 inches was exposed to the flame. The results were exactly as those obtained on the idler arm, with the exception that the temperature over a 2-minute period rose only to 464°F, probably due to the massive metal bearing acting as a heat sink. It was noted at the conclusion of the test that the NEMA-grade tube directly above the fitting had softened slightly. The temperature in this area was approximately 370°F.

Aft Bell Crank Assembly

The aft bell crank assembly was positioned such that the outward ball and socket joint was immersed in the flame. After 1 minute 50 seconds, the rectangular NEMA-grade tubing, which had reached a temperature of 690°F, ignited. It was immediately removed from the flame but did not self-extinguish. It continued to burn slowly, and it appeared that the burning gases were coming from within the laminate wall. The flame had to be manually extinguished. Observations at the conclusion of the test indicated that there was severe burning only in the area of the NEMA-grade rectangular tubing. The ball and socket joint, while difficult to move, could be manually operated.

Forward Bell Crank

The forward bell crank assembly was positioned such that the output clevis fitting was immersed in the flame for approximately 4 inches, totally encapsulating the fitting and a portion of the bell crank body. Again, after 1 minute 50 seconds, and a temperature rise to 700°F, the NEMA-grade rectangular tubing ignited. It, too, had to be extinguished manually.

It was determined later that the NEMA-grade tubes had ignited because they were coated with a non-flame-retardant epoxy resin for the purpose of sealing all machined and sanded surfaces. The as-received uncoated NEMA-grade tubing did not ignite.

Structural Testing Results

After the environmental test series was completed, component sets no. 2 through 8 were subjected to various structural tests. Set no. 2 was the only set which had not been exposed to environmental testing.

Static Load Tests

The static load test was performed on component set no. 2. The test consisted of mounting each of the components in a suitable test fixture and loading the component to the static load condition. During the application of load a continuous plot of applied load and deflection was recorded. The results are listed in Table VII.

All of the four components withstood the static load condition. The only evidence of degradation during the static loading test was on the idler arm assembly, when a crack developed in an adhesive bond line between the two reinforcing straps around the ball and socket

TABLE VII. RESULTS OF STATIC LOAD TEST			
Component	Static Compressive Load (lb)	Total Deflection at Static Load (mil)	Permanent Deflection (mil)
Connecting Link	-4,060	30.5	~1.4
Idler Arm Assembly	-4,013	30.0	0
Forward Bell Crank	-2,070	102.0	6.0
Aft Bell Crank	-4,013	154.0	~4.0

joints. It was not determined whether this was the result of a poorly bonded interface or the result of the test load. However, the component continued to take load up to the 4,013-lb requirement without any change in deflection. A second run on the same component produced the same deflections, indicating the crack did not significantly affect the test results.

Fatigue and Cyclic Loading Tests

The fatigue tests were conducted on set no. 6, as shown in Table VIII, column B. Component sets no. 2, 4, and 5 were cyclic loaded for a total of 5,000,000 cycles. The loads are listed in Table VIII, column D. Each of the components which had been ballistically impacted was cyclic loaded for 2,000 cycles and tested with loads as shown in Table VIII, column D. Figures 35 through 38 show the test setup for each of the components.

At the conclusion of the fatigue and cyclic tests, each component was examined for damage resulting from the test. The only damage incurred during those tests was deterioration of the Teflon/glass composite retainer in the bearing of the connecting link assembly. It was noted early during the fatigue test that particles of brown material were dislodged from the bearing. The deterioration of this material caused excessive deflection of the connecting link during the test and a separation between the bearing retainer and the molded BMC fitting. The test had to be discontinued because excessive deflections caused the fatigue tester to shut down. All other components were undamaged. A manual operation of the idler arm and aft bell crank ball and socket joint revealed no change in their operational characteristics, although some heat was generated during the test.

Vibration Testing

Component set no. 6 was exposed to the vibration environment. The vibration tests were conducted in accordance with MIL-E-5272C, Procedure XII. Each specimen was mounted in a magnesium test fixture on the vibration excitor. Each specimen was then subjected to a search for resonance over a frequency range of 5 to 500 Hz in a sweep period of 8 minutes. Once these resonant frequencies had been established, the component was exposed to that frequency for a 15-minute period, followed by a 15-minute period under applied double amplitude of 0.036 inch up to a limiting value of 10 g peak at 500 Hz. Each specimen was then stabilized at a temperature of 160°F and subjected to 15 minutes of resonance dwell at each of the resonant frequencies, and then subjected to a sinusoidal cycle. Visual examination at the completion of the test revealed no damage or other adverse effects. The operational characteristics of the ball and socket joints on the idler arm and aft bell crank assemblies were unchanged.

TABLE VIII. SUMMARY OF STRUCTURAL TEST CONDITIONS (LB)

Component	A Static Base Line	B* Fatigue	C Static Preload for Ballistic Test	D** Cyclic Loading
Connecting Link	-4060	-1110 ± 2960	-4060	-1110 ± 2960
Aft Bell Crank	-4013	± 310	-310	± 310
Forward Bell Crank	-2070	± 310	-310	± 310
Idler Arm	-4013	± 600	-600	± 600

* 10,000,000 cycles
** 5,000,000 cycles after environmental
2,000 cycles after ballistic

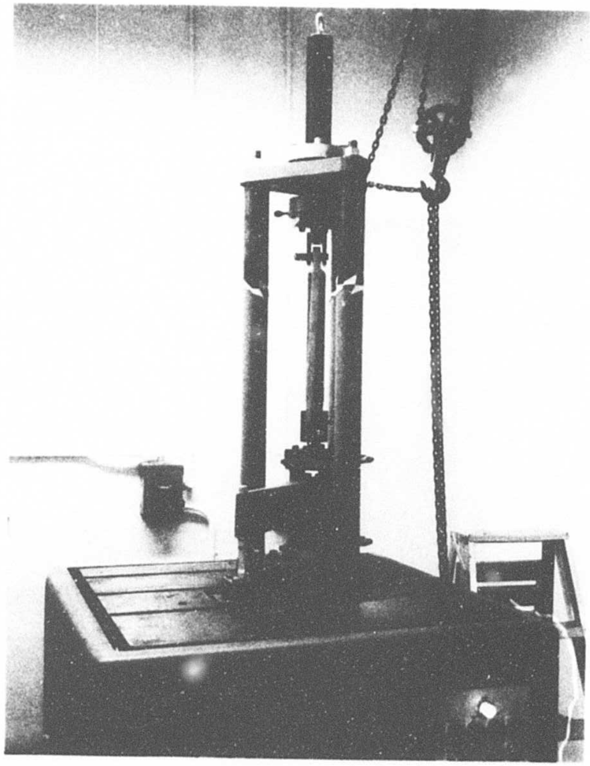


Figure 35. Cyclic Loading of Connecting Link.

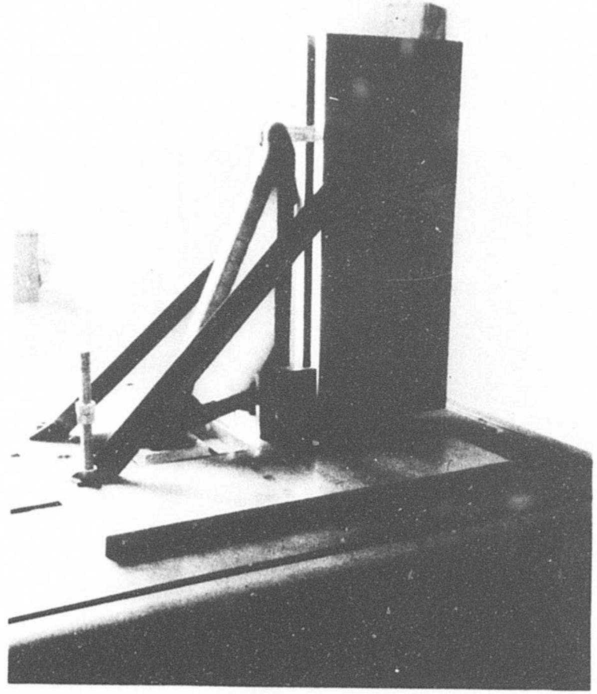


Figure 36. Cyclic Loading of Forward Bell Crank.

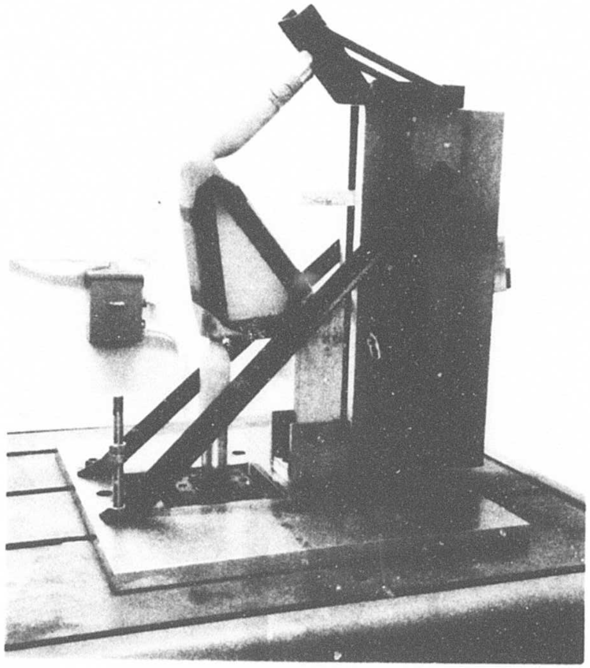


Figure 37. Cyclic Loading of Aft Bell Crank.

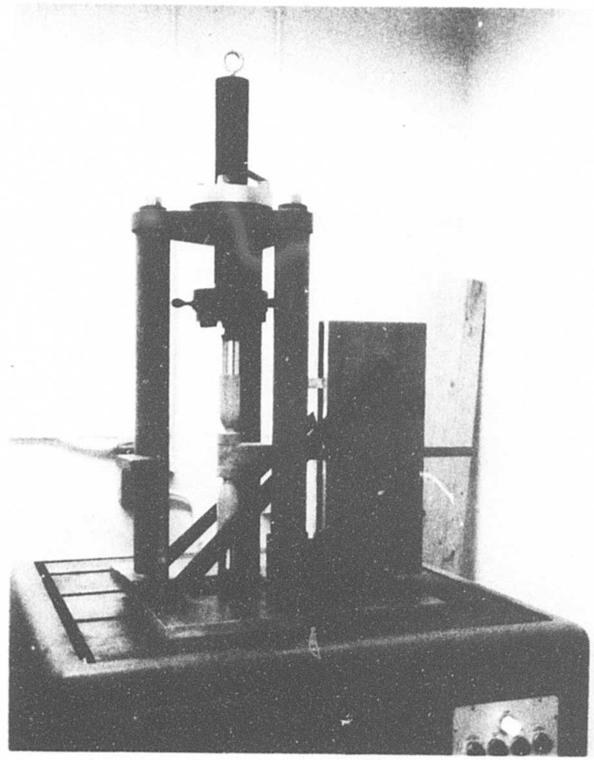


Figure 38. Cyclic Loading of Idler Assembly.

Static Failure Load/Deflection

Component sets no. 2 through 8 were loaded to failure and the load/deflections monitored for each test. These tests were conducted at the conclusion of the environmental, cyclic loading, fatigue, and vibration testing. The results of the static failure load/deflection tests are discussed below for each of the components.

Connecting Link Assembly

Figure 39 shows a typical static loading test being performed on a connecting link assembly. The detail at the right-hand portion of the assembly is an extensometer for measuring load/deflection during the test. Figure 40 shows a typical failure of the connecting link.

The base line static load requirement of the connecting link assembly was -4,060 lb. The lowest failure load was from set no. 2, which had been ballistically impacted. The failure load for this component was 6,700 lb, with a total deflection of 0.052 inch. All other failing loads were in excess of 300% of the base line requirement. The test reports show that the temperature cyclic test series and ultraviolet radiation tests appear to have the least effect on the performance of the component. Both of these components failed in excess of 500% of the base line requirement. The two components which were exposed to the fire resistance and the fuel and oil resistance tests are in excess of 400% of base line. The components which were exposed to the environments of sand and dust, humidity, fungus, and salt spray, and the component which was exposed to the vibration environment failed at over 300% of the base line requirement.

Forward Bell Crank Assembly

The base line requirement for the forward bell crank assembly is a compressive load of -2,070 lb. Figure 41 shows the typical installation of the forward bell crank in the test fixture. In the front left portion of the picture is the extensometer which is mounted directly at the pivot fitting for measuring load/deflection during the test. Figure 42 shows a typical failure of the connecting link assembly. All components tested met or exceeded the base line ultimate load requirements. Set no. 2, which had been ballistically impacted, failed at 2,080 lb, just slightly above the base line requirement. All other components failed in excess of 200% of the base line load. The spread for the remaining components was between 4,000 and 4,900 lb.

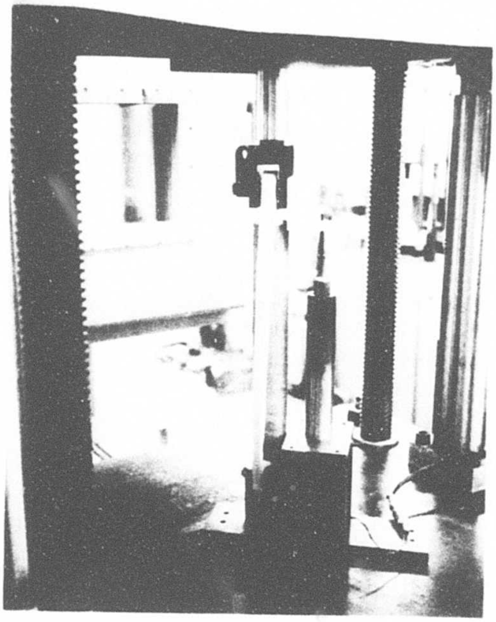


Figure 39. Test Setup for
Connecting Link.

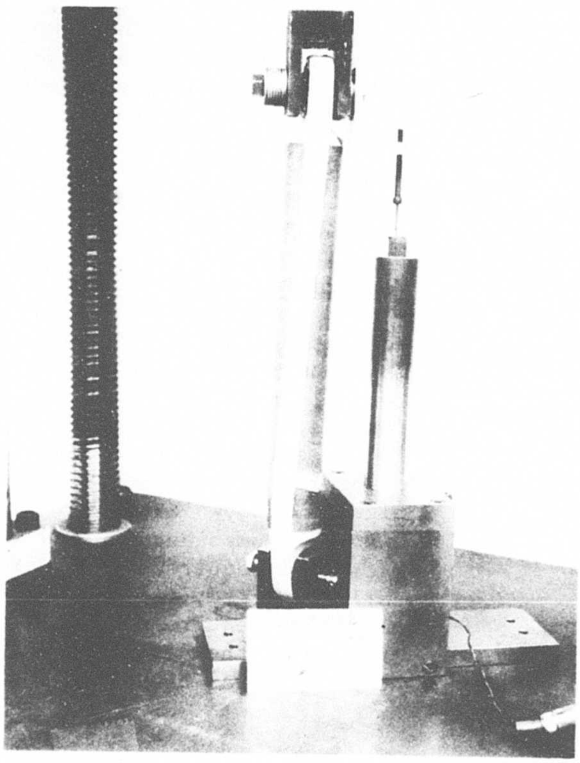


Figure 40. Failed Connecting
Link.

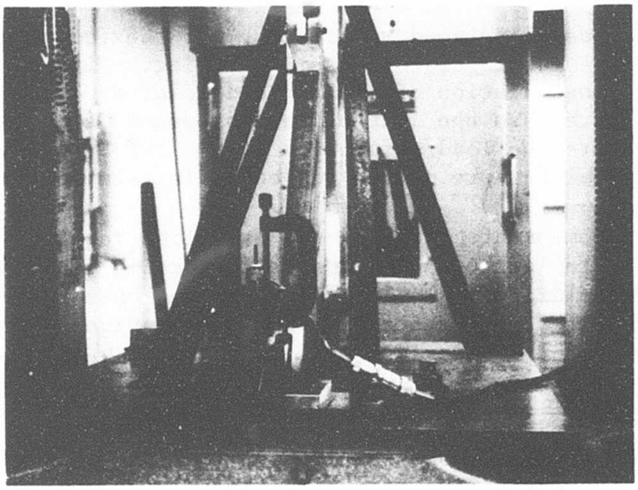


Figure 41. Test Setup for Forward Bell Crank.

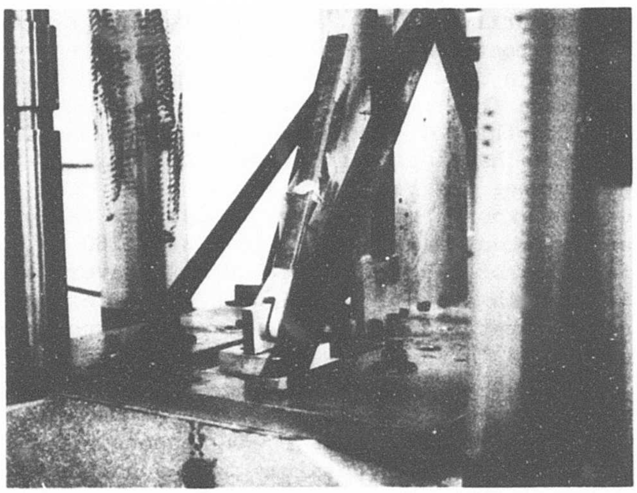


Figure 42. Failed Forward Bell Crank.

Rod and Idler Arm Assembly

The base line load requirement for the rod end idler arm assembly is -4,013 lb compressive loading. Figure 43 shows a typical installation of the rod end idler arm assembly in the test fixture. To the left of the component is the apparatus used to measure the load/deflection during the test. Figure 44 is a typical failure of the rod end idler arm assembly.

All components exceeded the base line requirement at failure. With the exception of the ballistically impacted component, which failed just slightly above the base line requirement, all other components exceeded the requirement by at least 150% of the base line load.

Aft Bell Crank Assembly

The base line load requirement for the aft bell crank assembly is -4,013 lb compressive loading. Figure 45 shows the typical installation of the aft bell crank assembly for static failure loading test and one of the types of failures. Figure 46 shows another type of failure in the rod end detail.

Some components failed to meet the static base line requirement. Two of these, the component that had been through ballistic impact test and that which had been exposed to the fire resistance tests, were not expected to perform satisfactorily due to the excessive damage incurred by the previous tests. The ballistically impacted component withstood a load of -1060 lb and had high deflections. The reason for this was the removal of approximately three-fourths of the socket portion of the input fitting; there also had been considerable fracture of the face sheet bonds during the ballistic impact test. The component which had been exposed to the fire resistance test performed better than expected, failing at a load of 3,280 lb, with a total deflection of 136 mil. There was, however, an unexpectedly low failure with set no. 5, which had been through the humidity, sand and dust, fungus, and salt spray exposures. This component failed in the rod end fitting at the pilot input end. Its failure mode is shown in Figure 46. The deflections were in line with the best performing components, and it is suspected that a manufacturing defect was responsible for this low failure load (2,290 lb), possibly poor adhesion between the BMC and the unidirectional insert. Failures in this same area occurred in the rod ends of the idler arm but at much higher loads.

The other three components failed at loads between 4,720 lb and 4,820 lb, or at approximately 125% of the base line requirement. It is apparent from these results that the aft bell crank as designed has the least margin of safety.

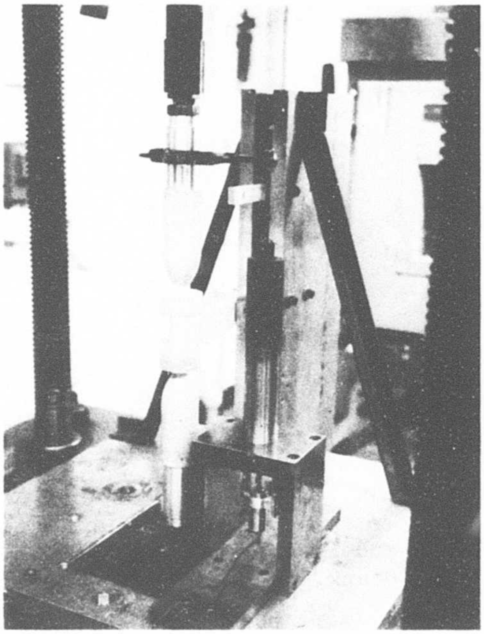


Figure 43. Test Setup for Idler Assembly.

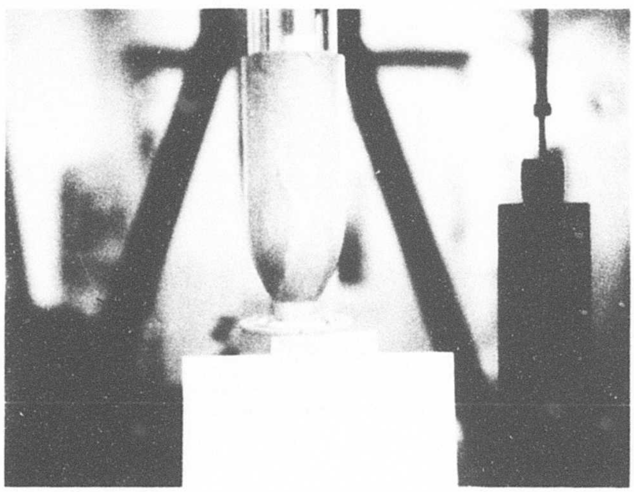


Figure 44. Typical Failure of Idler Assembly.

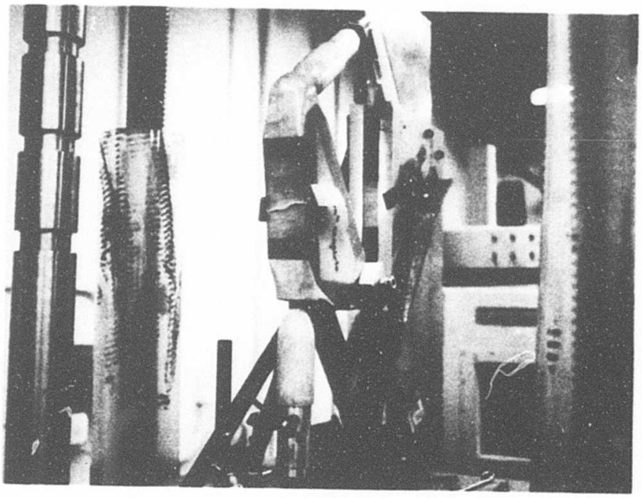


Figure 45. Test Setup and Type Failure of Aft Bell Crank.

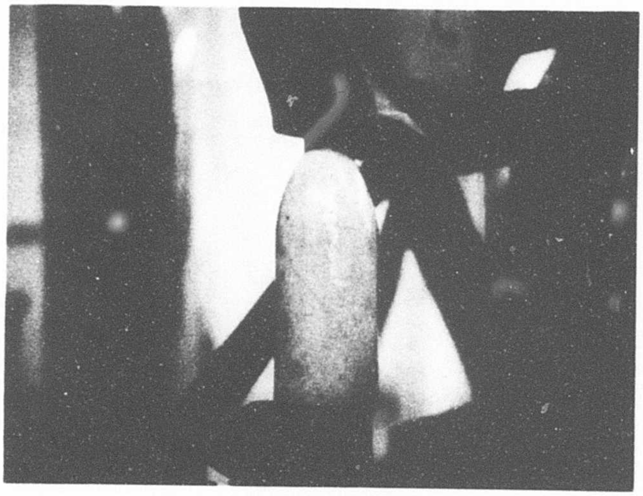


Figure 46. Failure in Rod End of Aft Bell Crank.

Ballistic Tests

A ballistic impact test was conducted on each of the four components. The test consisted of mounting the component in a suitable fixture and preloading to the load shown in column C of Table VIII. Loads and deflections were measured during the preloading phase of the component. The temperature of the component was reduced to -80°F before the components were impacted with a fully tumbled caliber .30 projectile at a velocity of 1800 feet per second. The projectile was tumbled by means of an aluminum tipping plate placed in the path of the projectile prior to impacting the specimen. The results of the ballistic test are given below for each of the components.

Forward Bell Crank

The target area for the ballistic impact on the forward bell crank assembly was the rectangular tube between the pivot fitting and the outboard clevis fitting. The objective was to sever one-half of the rectangular tube cross section. Figure 47 shows the bell crank installed in the fixture, and Figure 48 shows the damage to this area after ballistic impact. The test was successful and the component maintained the initial preload.

Rod End Idler Arm Assembly

The rod end idler arm assembly was positioned in a fixture and loaded as shown in Figure 49. The target for the ballistic impact was the very center of the ball and socket joint on the lower side. The test was successful in that the tumbled projectile hit nearly dead center, as shown in Figure 50. However, the projectile ricocheted off the ball, severing a portion of the molded idler arm assembly. The component withstood the impact and was still operational.

Aft Bell Crank Assembly

The aft bell crank assembly was positioned in the fixture and loaded as shown in Figure 51. The target for the ballistic impact was the center of the ball and socket joint at the input fitting. In the first test, the projectile hit approximately 0.4 inch below in a tumbled fashion. In this area it impacted the retainer ring and completely severed it from the rest of the assembly. No further damage was incurred; however, the ball was completely loose from the socket and would not permit further testing. Observation of the failure indicated that the projectile, when penetrating the retainer ring, had made contact with the unidirectional glass wrapped reinforcement around the retainer and appeared to have unwrapped this reinforcement on its path through the part. A second test was performed

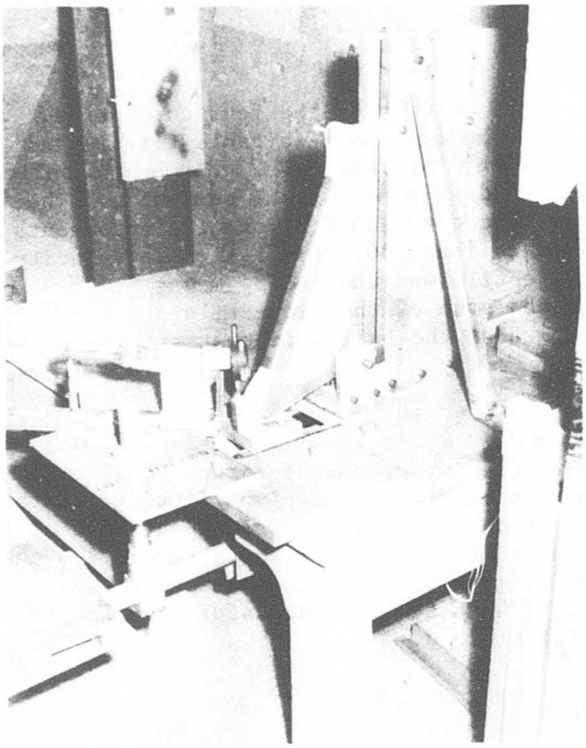
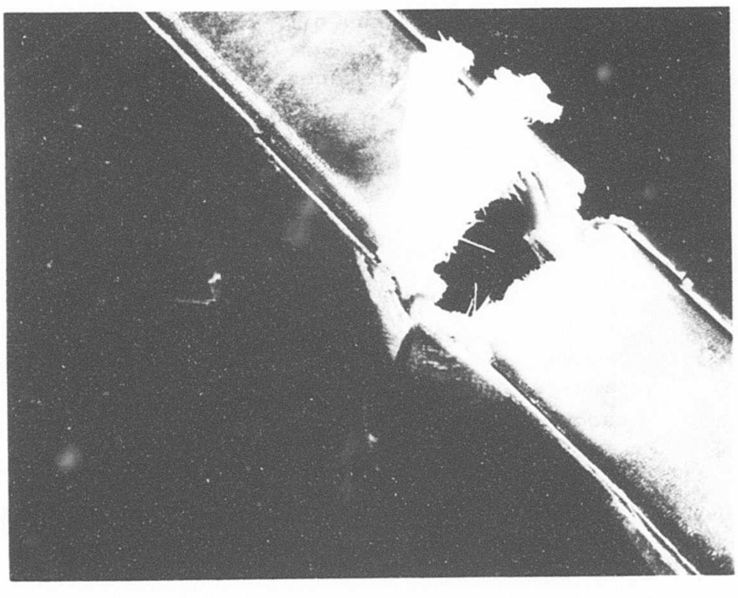


Figure 47. Forward Bell Crank Before Impact.

Figure 48. Impacted Forward Bell Crank.



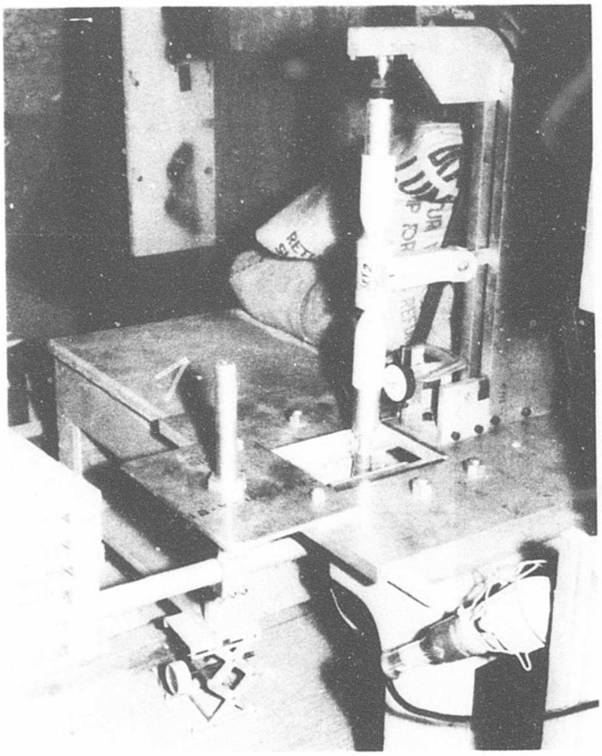


Figure 49. Rod End Idler Arm Before Impact.

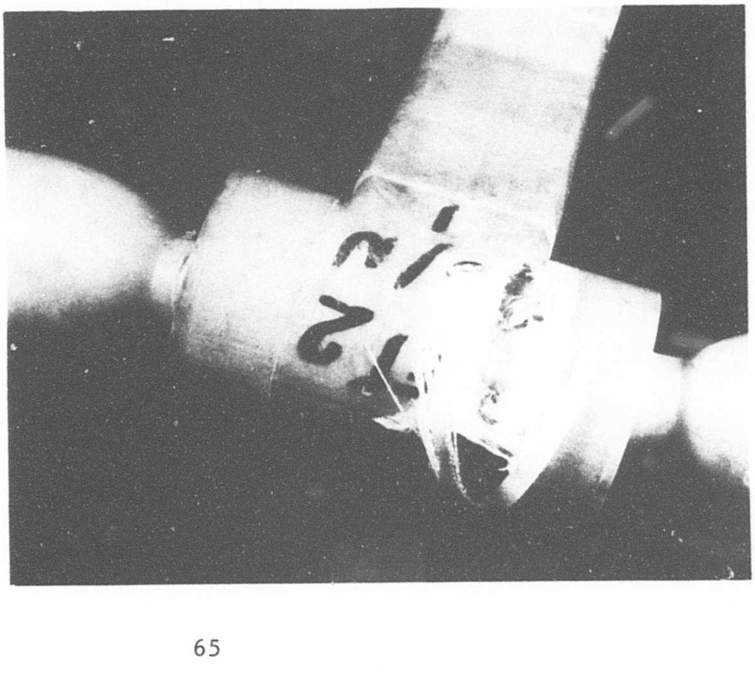


Figure 50. Rod End Idler Arm After Impact.

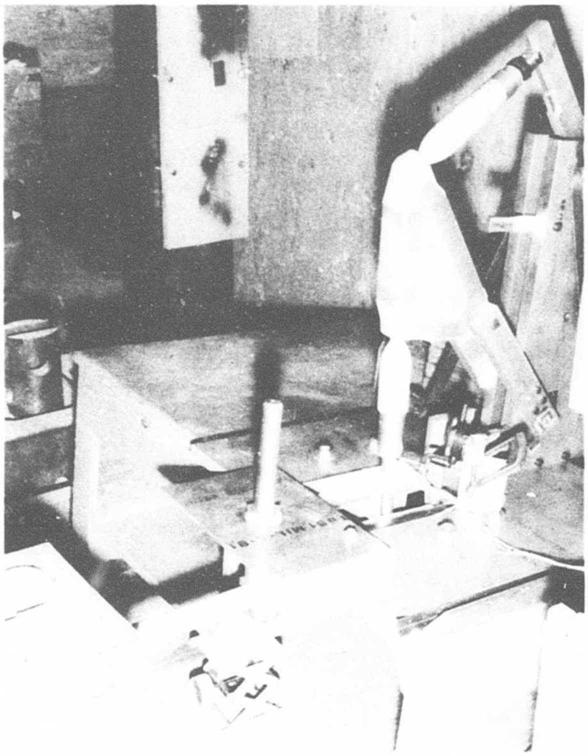


Figure 51. Aft Bell Crank
Before Impact.

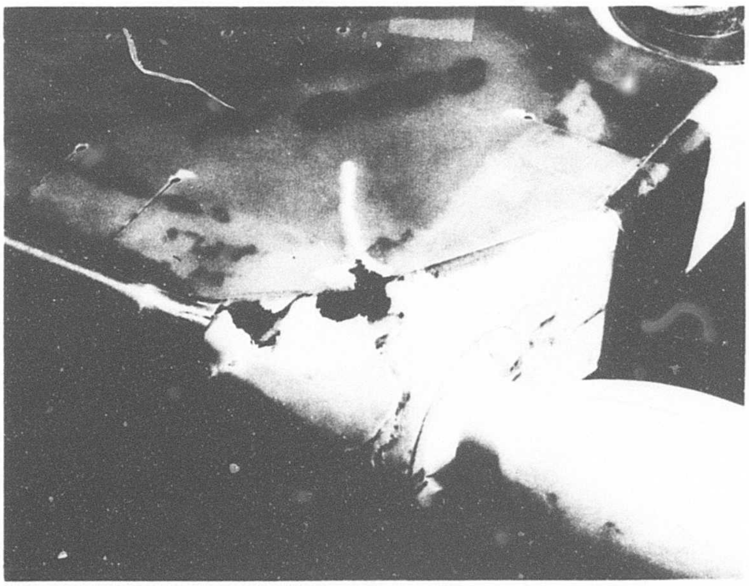


Figure 52. Aft Bell
Crank
After
Impact.

in an attempt to achieve a hit more centered on the ball and socket joint. The component for this test was the aft bellcrank assembly that had been exposed to the ultraviolet radiation condition. During the second test, the tumbled projectile hit directly on the center of the ball and socket joint and ricocheted inward. While there was minimal damage to the ball itself, it did stop the projectile, leaving the jacket and lead fragments inside the bell crank cavity. While absorbing this impact, considerable damage was incurred in the molded fitting. However, the bell crank was still operational. Figure 52 is a picture of the damage incurred on the second ballistic test.

Connecting Link Assembly

The connecting link was assembled and positioned in a fixture. The target for the ballistic impact was to be such that the tumbled projectile would hit one of the reinforcing straps, penetrate it, and exit through the tubular wall on the back side. This particular connecting link was impacted three times because the projectile did not tumble. Since the load/deflection on the three shots was negligible, a fourth shot was attempted. On this fourth hit, the projectile did tumble and completely destroyed the component. The tumbled hit appears to have impacted the same general area as the three previous hits and impacted a portion of both straps. The component failed during the test and was not suitable for further testing.

A second connecting link was positioned in the fixture and was impacted with a nontumbled projectile such that the strap portion was penetrated properly. The second test was successful in that the bullet cleanly penetrated the reinforcing strap and cleanly exited through the back side of the wall. Figure 53 is a picture of the damage incurred on the second connecting link and the failure after static loading. The test was successful in that after impact the component continued to carry the initial preload.

Results of the Cyclic Loading Test After Ballistic Impact

Each of the four components which were ballistically impacted were cyclic loaded for a total of 2,000 cycles at the loads described in Table VIII. Each of the four components withstood this cyclic loading without further damage to the component.

Static Failure Load/Deflections on Ballistically Impacted Components

Table V tabulates the results of the static failure tests of the impacted components.

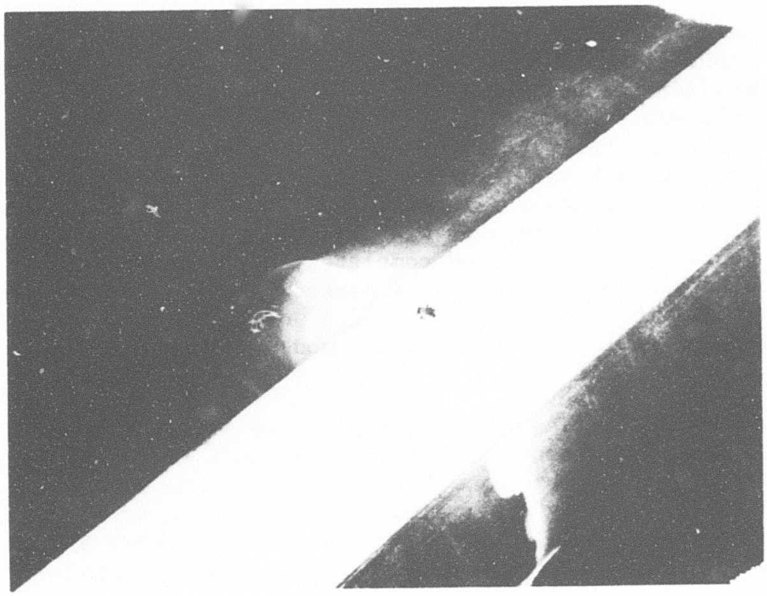


Figure 53. Connecting Link After Ballistic Impact and Static Failure Test.

TABLE IX. SUMMARY OF STATIC FAILURE RESULTS OF IMPACTED COMPONENTS

Component	Base Line Load Requirements (lb)	Typical Deflections of Nonimpacted Component at Base Line (in.)	Failure Load After Impact (lb)	Deflection at Base Line Load (in.)
Connecting Link	-4060	0.026	-6700	0.030
Forward Bell Crank	-2070	0.082	-2080	0.080
Aft Bell Crank	-4013	0.154	-1060	0.100*
Idler Arm	-4013	0.029	-4100	0.037
* at -1060 load lb				

CONCLUSIONS AND RECOMMENDATIONS

The results and findings of this program permit the following conclusions and recommendations regarding the design, fabrication, and performance of ballistic-tolerant flight control components fabricated from fiber glass reinforced plastics.

1. The materials selected for the fabrication of the ballistic-tolerant components met all the requirements for ballistic tolerance, structural capability, and resistance to all of the environments tested. The materials and material forms greatly enhanced the simplicity of design and the ease with which the component details were assembled into their final configuration.

2. The design of the four components is greatly simplified compared to previous designs of these components from composite materials.

3. The manufacturability of the four component assemblies is greatly simplified compared to previous manufacturing methods.

4. The matched die molding of epoxy bulk molding compound for the complex details of the components proved to be a cost effective and highly reliable method of producing these details.

5. The use of assembly fixtures to locate and bond the individual details of each component proved not only to be cost effective but was an in-process method of inspecting each of the details prior to installation and the inspection of the final cured assembled component.

6. The weights of the individual components compare favorably with the previous Boeing-Vertol design.

7. The structural adequacy of the components as designed is considered to be excellent. With the exception of the aft bell crank, the components are somewhat over-designed, indicating that additional weight savings could have been realized.

8. The materials selected for the fabrication of the components exhibited excellent resistance to all of the environments to which they were exposed. The only deteriorative results were the exposure to the simulated on-board fire and the fungus resistance test.

9. On future efforts to fabricate the ballistic-tolerant composite flight control components it is recommended that an adhesive material with a less brittle failure mode be used to assemble the component details.

10. The bonds between the BMC fittings and the NEMA-grade tubing would be enhanced if the ends of the tubes were slotted into tab forms. A slotted tube attachment would provide a means of applying positive external pressure to the glue lines during cure.

11. The ballistic tolerance of the ball and socket joint could probably be improved. Since no structural failures were incurred by the ball rod ends, it appears the cross section in the immediate ball area could be reduced by making it more hollow. This would have no effect on the frictional or operational characteristics of the ball, but it would possibly enhance its ballistic tolerance characteristics.

12. A simple clevis-type fitting, such as was used on the forward bell crank, would greatly reduce the cost and weight of the idler arm and aft bell crank assemblies.

13. The ballistic tolerance of the retainer ring area would be improved if the reinforcing strip was removed from the retainer or reduced to a single ply of a nonstructural thin glass prepreg.