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MANDRELS FOR FILAMENT WINDING

ROCKETDYNE
A DIVISION OF NORTH AMERICAN AVIATION, INC.

INTERIM CONTRACT: AF33(600)-43594
ASD PROJECT: 7-880a

IM TECHNICAL ENGINEERING REPORT
9 NOVEMBER 1961 TO 9 FEBRUARY 1962

THIS INTERIM TECHNICAL ENGINEERING REPORT (NO. 2) IS A SUMMARY OF LABORATORY AND SMALL-SCALE MANDREL EVALUATIONS PERFORMED AS PART OF PHASE II INVESTIGATIONS. SEVERAL MANDREL MATERIALS AND CONCEPTS ARE BEING EVALUATED IN LIGHT OF SEVERAL PARAMETERS.

MANUFACTURING TECHNOLOGY LABORATORY
AERONAUTICAL SYSTEMS DIVISION
UNITED STATES AIR FORCE
WRIGHT-PATTERSON AIR FORCE BASE, OHIO

ABSTRACT - SUMMARY ASD Interim Report 7-880a(2)

Interim Technical Progress Report

MANDRELS FOR FILAMENT WINDING

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et al

Rocketdyne

This interim technical engineering report (No. 2) is a summary of laboratory and small-scale mandrel evaluations performed as part of Phase II investigations. Several mandrel materials and concepts are being evaluated in light of several parameters. Mandrel material properties and the effects of winding and curing operations on these materials during the fabrication of a filament-wound structure are discussed. Status of current small-scale mandrel investigations and the projected plan of action are presented.

Laboratory and small-scale mandrel evaluations show that Navmold (carbohydrate-based material) mandrel material has comparatively good shrinkage and thermal expansion properties. But, as noted for other hot-melt, water-soluble materials in the literature survey of Phase I, radial deformation due to the winding and curing operation was excessive.

MANDRELS FOR FILAMENT WINDING

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A Division of North American Aviation, Inc.

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Manufacturing Technology Laboratory
Aeronautical Systems Division
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FOREWORD

This Interim Technical Progress Report covers the work performed under Contract AF33(600)-43594 from 9 November 1961 to 9 February 1962. It is published for technical information only and does not necessarily represent the recommendations, conclusions, or approval of the Air Force.

This contract with Rocketdyne Engineering, Canoga Park, California, was initiated under ASD Manufacturing Technology Project 7-800a,"Mandrels for Filament Winding." It was administered under the direction of Leo J. Conlon, Project Engineer of the Chemical Engineering Branch, Manufacturing Technology Laboratory, Aeronautical Systems Division, Wright-Patterson Air Force Base, Ohio.

Mr. Elden L. Hawkinson of Rocketdyne Engineering, Supervisor, Structural Components Development Unit, was the engineer in charge. Others who cooperated in the expediting of laboratory and engineering study tasks discussed in this report were: I. L. Tubb, Senior Research Engineer, C. B. Kaylor, Senior Design Engineer, and M. Varlas, Specialist Research. This report has been given the Rocketdyne Engineering internal number R-3338-2.

PUBLICATION REVIEW

Approved by: R. Lorey

Approved by: D. M. Leitch

TABLE OF CONTENTS

Foreword v

Phase II, Laboratory and Small-Scale Mandrel Investigations 1

Introduction 1

Laboratory Evaluations 1

Small-Scale Mandrel Evaluations 2

Laboratory Evaluations 3

Soluble Mandrel Materials 3

Mechanical Breakout Mandrel Materials 12

Summary 13

Small-Scale Mandrels 17

Soluble Navmold Mandrels 18

Analysis 24

Preliminary Calculation of Mandrel Stress and Deflection 24

Soluble Sand/PVA-Type Mandrel 26

Soluble Plaster Mandrel 27

Mechanical Breakout Plaster Mandrel 28

Collapsible Segmented Aluminum Mandrel 30

Summary of Small-Scale Mandrel Evaluations 31

Scheduled Work for Next Quarterly Period 31

Distribution List 33

LIST OF ILLUSTRATIONS

1. Mandrel Schematic 2
2. Split Mold for Navmold-Fabricated Mandrels 18
3. Electrical Melt-Mix Pot 20
4. Navmold Mandrel Deflections During Case Winding and Cure 22
5. Collapsible Segmented Aluminum Mandrel 30

LIST OF TABLES

1. Properties of Navmold Material 4
2. Properties of Paraplast 33 8
3. Properties of Kerr DMM Plaster 9
4. Properties of Duplitool Plaster 11
5. Properties of Hydrocal B-11 Plaster 14
6. Status of Small-Scale Mandrel Evaluations 17
7. Diameter Deflections on Navmold Mandrel From Winding, Curing, and Mandrel Removal Operations 21

PHASE II, LABORATORY AND SMALL-SCALE MANDREL INVESTIGATIONS

INTRODUCTION

The objective of this phase is to evaluate, in the light of several parameters, a number of mandrel materials and mandrel concepts for filament-winding applications. The areas that will be used as a basis for comparison for each mandrel material or concept in the final analysis are:

1. Size range
2. Cost
3. Production rate adaptability (1 to 1000 units)
4. Stability
   a. Rigidity
   b. Compatibility with resins used in filament-winding process
   c. Temperature resistance
   d. Storage and handling
5. Weight
6. Ease of removal
7. Compatibility with insulation

LABORATORY EVALUATIONS

Preliminary investigations to determine mandrel materials properties were performed in the laboratory. Establishing the degree of correlation between material properties and design allowables used in the construction of small- or large-scale winding mandrels is being attempted. The mechanical properties of the mandrel materials at elevated temperatures was given particular emphasis in the evaluation of the various materials considered to date. The effect of environmental conditions such as humidity on the physical and mechanical properties was also determined by laboratory evaluations.

SMALL-SCALE MANDREL EVALUATIONS

The development of design criteria for the various mandrel materials and concepts is being accomplished by noting dimensional changes in the winding mandrels during the winding and curing of a simple filament-wound structure. These results are then compared with those analytically determined. The basic mandrel size being used in this phase of the contract is 24 inches in diameter and 36 inches in length (Fig.1).

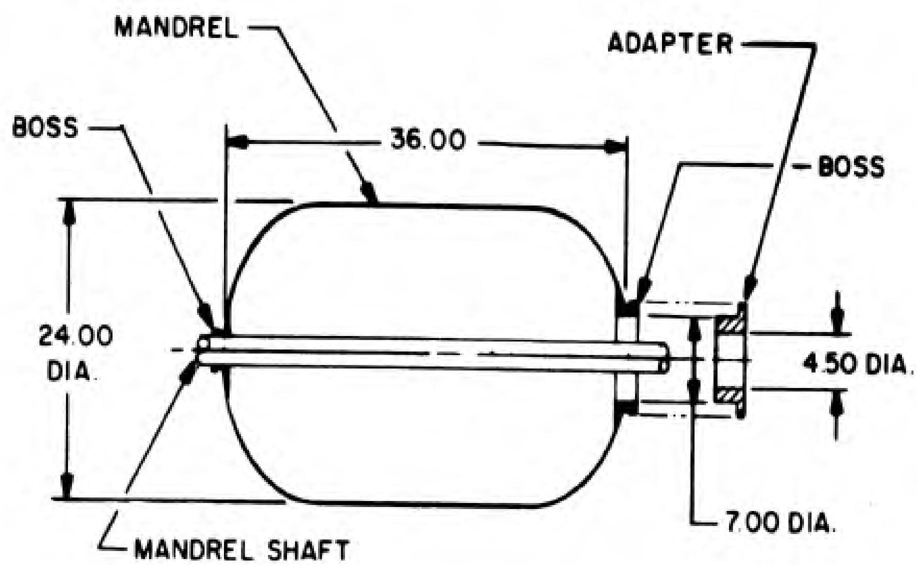

Figure 1. Mandrel Schematic

LABORATORY EVALUATIONS

Mandrel materials for various types of mandrels (soluble, mechanical-breakout, plastic, etc.) are being evaluated in the laboratory to (1) screen out those materials whose physical or mechanical properties are not suited to winding mandrel applications (2) select several mandrel material-design concepts, and (3) yield data for analytically determining mandrel-design limitations. Those mandrel materials that warrant further evaluation after the initial screening tests are then considered in the design and construction of small-scale winding mandrels used to evaluate the effect of winding and curing of a filament-wound structure.

A discussion of the laboratory results noted for each of the various mandrel materials will be presented according to the mandrel removal method usually considered for the particular material.

SOLUBLE MANDREL MATERIALS

The literature search concluded in Phase I indicated that most soluble-type mandrel materials have strength and rigidity limitations at elevated temperatures. The following discussion is of soluble-type mandrel materials evaluated in the laboratory thus far during Phase II of this development program.

Navmold

Navmold is a carbohydrate-based mandrel material of the hot-melt, water-soluble variety. It is a three-part mixture, using silica as one of the fillers. The mixture may be blended dry and then heated to temperatures between 325 F and 350 F to form a pourable liquid of thin, syrup-like consistency.

A summary of the physical and mechanical properties determined for Navmold is given in Table 1.

TABLE 1

PROPERTIES OF NAVMOLD MATERIAL

(Source: North American Aviation, Inc.)

Physical and Mechanical Properties

Compressive strength, room temperature, lb/sq in.	4832, $E_c = 2.42 \times 10^5$
Compressive strength, 250 F, lb/sq in.	2221, $E_c = 7.6 \times 10^4$
Compressive strength, 300 F, lb/sq in.	1148, $E_c = 4.1 \times 10^4$
Compressive strength after 95 percent relative humidity, 100 F test	3735
Flexural strength, room temperature, lb/sq in.	1062
Tensile strength, room temperature, lb/sq in.	706, $E_t = 4.7 \times 10^3$
Density, lb/cu ft	109
Moisture pickup, percent by weight, 95 percent relative humidity, 100 F, 30 hours	0.9
Heat distortion point, 264 psi	180 F
Melting range, F	325 to 329
Water solubility rate	moderate
Coefficient of thermal expansion/C	1.362×10^{-6}
Shrinkage, in./in.	0.00005

Preparation of Specimens. The test specimens were prepared by melting the mix at approximately 340 F, then pouring the mix into the molds. Individual specimens were then machined to dimension from the cast material. This material was relatively hard, and the specimens had to be ground to obtain flat and parallel surfaces.

Physical Properties. The physical properties of the Navmold material are good for a hot-melt, soluble-type mandrel material. This material has better shrinkage, thermal expansion, and humidity resistance characteristics than those noted for other hot-melt,soluble-type mandrel materials.

A special mold (12 x 3/4 x 1/2 inches) was used to determine the shrinkage rate (in./in.) after casting the mix. The mold was tapered in width to provide sufficient draft and lined with silicone-treated cellophane. One end of the mold was open and fitted with a freely moving piston equipped with a dial gage. The shrinkage in in./in. of material was 0.00005.

The effect of humidity on the compressive strength properties of the Navmold material was determined. Dried specimens were placed in a humidity chamber at approximately 95 percent relative humidity and 100 F for a period of 30 hours. The specimens were weighed immediately after the 30-hour exposure time to determine the amount of moisture pickup. Compression strength (room temperature) was approximately 9 percent lower because of the humidity exposure.

Mechanical Strength Properties. The mechanical strength properties were determined at room temperature, 250 F and 300 F. Compression strength at room temperature was lower than those noted for other hot-melt, water-soluble mandrel materials.

Heat Resistance. The compression strength properties at 300 F were approximately 25 percent lower than those measured at room temperature. The heat distortion temperature as determined under a constant load of 264 psi was 180 F.

Paraplast 33. Paraplast 33 is a hot-melt, water-soluble material (probably an inorganic salt) that melts at approximately 310 F. Higher melting point Paraplast materials (36 and 55) are being considered. Improved resistance to deformation at elevated cure temperatures are expected from them.

A summary of physical and mechanical properties for Paraplast 33 are given in Table 2 .

Preparation of Specimens. The specimen castings were made by melting the Paraplast 33 material at approximately 310 F and pouring the hot melt into the molds. Some difficulty was noted during the sawing and grinding (clogging, material fracturing and melting) of individual specimens from the castings. The specimens were kept in a desiccator until tested.

Physical Properties. High shrinkage and poor resistance to humidity are two primary physical property limitations. It is possible that a coating may be sprayed on Paraplast winding mandrels to act as a moisture barrier and release agent.

Mechanical Strength Properties. The compression strength of Paraplast 33 specimens tested at room temperature was approximately 13,000 psi. Modulus of elasticity in compression was slightly lower than values noted for the Navmold material.

Heat Resistance. Mechanical strength properties dropped off rapidly at elevated temperatures. Compression strength at 200 F was less than 50 percent of room temperature strength.

The heat distortion temperature as determined under a constant load of 264 psi was 215 F.

Kerr DMM Plaster

This plaster is soluble in a 15 percent solution of acetic acid when mixed and dried properly (48 hours or longer at 140 F to 150 F is recommended for drying).

A summary of physical and mechanical properties for this material is given in Table 3.

Preparation of Specimens. Castings were prepared by mixing 2-1/4 parts by weight of Kerr DMM plaster with 1 part by weight of water and pouring the mix into test specimen molds. Individual specimens were then machined from the castings. All of the specimens were dried in an oven at 125 F (for approximately 24 hours) before testing.

Physical Properties. In general, the physical properties of Kerr DMM are not significantly different from other plasters noted in the literature survey or laboratory evaluations, except resistance to humidity was significantly better. Essentially no change in compressive strength at room temperature was obtained after the specimens were subjected to the 30-hour, 95 percent relative humidity, 100 F environment.

Mechanical Properties. The mechanical strength properties noted in this laboratory evaluation were lower than those reported from literature sources in Phase I. This was believed due to drying the specimens at 125 F instead of 140 to 175 F.

Heat Resistance. No reduction in compression strength at 250 F was noted.

TABLE 2

PROPERTIES OF PARAPLAST 33
(Source: Rezolin, Incorporated)

Physical and Mechanical Properties

Compressive strength, room temperature, lb/sq in.	13,120, $E_c = 2.35 \times 10^5$
Compressive strength, 225 F, lb/sq in.	3001, $E_c = 5.9 \times 10^4$
Flexural strength, lb/sq in.	472
Tensile strength, lb/sq in.	1006
Heat distortion point, 264 psi	215 F
Moisture pickup, percent by weight, 70 percent relative humidity, 100 F, 30 hours	86.5
Density, lb/cu ft	125
Melt-point range, F	306 to 315
Water solubility rate	moderate
Cost, pound	0.49

TABLE 3

PROPERTIES OF KERR DMM PLASTER
(Source: Kerr Manufacturing Company, Detroit, Michigan)

Physical and Mechanical Properties*

Compressive strength, room temperature, lb/sq in.	648, $E_c = 1.13 \times 10^5$
Compressive strength, 250 F, lb/sq in.	776, $E_c = 5.71 \times 10^4$
Compressive strength, 300 F, lb/sq in.	411, $E_c = 3.70 \times 10^4$
Compressive strength, room temperature, after 95 percent relative humidity, 100 F, 30 hours	716
Moisture pickup percent, 95 percent relative humidity, 100 F, 30 hours	0.065
Density, lb/cu ft	70
Solubility (15 percent solution acetic acid)	slow
Cost, pound	0.165

*Mechanical properties are believed low because of improper dryout procedure.

Duplitool Plaster

This plaster has been used in thick-walled winding mandrels (18-inch diameter x 24 inches long) at Rocketdyne; however, difficulty in dissolving the mandrels in water has been experienced. Improper dryout cycle may affect the solubility characteristics of this plaster mix.

A summary of physical and mechanical properties is shown in Table 4.

Preparation of Specimens. The castings were prepared by mixing three parts, by weight, of Duplitool plaster and two parts, by weight, of water and pouring the mix into the molds. The individual specimens were then sawed from the cast material. Flat and parallel surfaces were obtained by hand finishing. All specimens were dried at 125 F before testing.

Physical Properties. The physical properties of this plaster material were not fully determined because of the low mechanical strength properties (compression, flexural, etc.) noted in the laboratory tests at room temperature. Poor resistance to humidity was noted. (16 percent moisture absorption by weight was measured; more than 20 percent decrease in compression strength was obtained after the humidity exposure.)

Mechanical Properties. A compression strength of 249 psi at room temperature for this plaster was the lowest measured for the soluble-type materials evaluated.

Heat Resistance. Physical and mechanical properties at elevated temperatures were not determined for the reasons mentioned.

Sand/PVA

This mandrel material system consists of five constituents of which more than 95 percent by weight is fine sand (usually 52 grit). PVA in an

TABLE 4

PROPERTIES OF DUPLITOOL PLASTER
(Source: Kirkhill Rubber Company, Brea, California)

Physical and Mechanical Properties

Compression strength, room temperature, lb/sq in.	249, $E_c = 1.22 \times 10^4$
Compression strength, 250 F, lb/sq in.	143, $E_c = 3.01 \times 10^3$
Compression strength, room temperature, after 95 percent relative humidity, 100 F, 30 hours	194
Moisture pickup, 95 percent, 100 F, 30 hours	15.8
Density, lb/cu ft	61
Water solubility rate	slow
Cost, pound	0.20

alkaline water solution is used as a binder. The laboratory tests may not reflect the actual limitations for using this material as a winding mandrel since a solid mandrel (with stovepipe for lightening), rather than one of a shell construction, is normally used.

Preparation of Specimens. The PVA was dissolved in water and thoroughly blended. An alkaline solution was then added and mixed in thoroughly. The liquid mixture was then blended into the sand in the same manner as concrete aggregates are mixed until the sand was thoroughly wet. The sand/PVA mixture was then tamped into a mold and cured several hours at 225 F, plus several hours at 275 F. Individual compression specimens were then cut from the cast sample.

Physical Properties. An extensive laboratory evaluation of the sand/PVA material system has not been completed. This material system should not be exposed to high humidity since the PVA-modified binder is readily soluble in water. The cured specimens had a density of 113 lb/cu ft.

Mechanical Properties. The average compression strength at room temperature was 2165 psi, with a decrease of 58 percent at 200 F.

Heat Resistance. The heat-distortion point will be determined.

MECHANICAL BREAKOUT MANDREL MATERIALS

The properties of one plaster (Hydrocal B-11) that can be used for mechanical breakout-type mandrels is discussed. The use of pullout chains, wires, and mechanical chipping is usually required for removal of a winding mandrel made from this plaster.

Hydrocal B-11 Plaster

The literature survey in Phase I indicated that the physical and mechanical properties of Hydrocal B-11 are comparably good, although lack of solubility in usable materials was a limitation.

A summary of physical and mechanical properties is given in Table 5 .

Preparation of Specimens. Castings were prepared by mixing the Hydrocal B-11 with water, using a weight ratio of approximately 1:1. The plaster mix was then poured into molds, and the individual specimens were cut from the castings. This material machined easily and flat, parallel surfaces were obtained with no difficulty. All specimens were dried at 125 F (for approximately 24 hours) before testing.

Physical Properties. Shrinkage and humidity resistance properties were similar to those noted for the Kerr DMM plaster. The compressive strength (room temperature) after humidity exposure was 2172 psi.

Mechanical Properties. Mechanical properties of this plaster were superior to any of the soluble-type materials, evaluated from a stability standpoint. The measured compressive strength, 1248 psi at room temperature (control specimens), was not believed valid since significantly higher values were noted at elevated temperatures up to 300 F.

SUMMARY

The following conclusions are based on observations made in the preparation of the test specimens, and test results shown in Tables 1 through 5.

TABLE 5

PROPERTIES OF HYDROCAL B-11 PLASTER
(Source: U.S. Gypsum Company, Los Angeles, California)

Physical and Mechanical Properties

Compressive strength after humidity exposure test, lb/sq in.	2172
Compressive strength, 250 F	2621, $E_c = 1.06 \times 10^5$
Compressive strength, 300 F	1450, $E_c = 6.6 \times 10^4$
Flexural strength, room temperature	973
Moisture pickup, percent, after 95 percent relative humidity, 100 F, 30-hour humidity exposure	0.45
Density, lb/cu ft	86
Cost, pound	.045

Navmold

This material system has better physical characteristics than other types of hot-melt, water-soluble systems (inorganic salts) noted in the literature search of Phase I. However, as with the inorganic salts, poor resistance to deformation at high temperatures is a limitation that must be considered when using this material as a winding mandrel.

Paraplast 33

Paraplast 33 is not recommended as a material for winding mandrels for filament-wound cases requiring close dimensional tolerances, because of poor resistance to humidity and/or excessive deformation at temperatures above 200 F. Humidity resistance may be improved by the use of sealer coating on the outside surface of a winding made from this material.

Kerr DMM Plaster

The Kerr DMM Plaster is believed the best of the soluble-type systems evaluated. Limitations related to size and repeatibility will be determined from results noted on small-scale mandrels.

Duplitool Plaster

This plaster material system is not recommended for general use in fabricating winding mandrels because of properties related to dimensional stability. Physical and mechanical properties are poor at room temperature. Also, greater sensitivity to humidity was observed when compared with the Kerr DMM plaster or the Navmold mandrel material systems. Thick-walled winding mandrels could be fabricated from the Duplitool material that would probably satisfy some filament-winding applications. Low density and low cost would be two attributes to consider.

The spraying of a sealer coating on the outside mandrel surface may minimize the effect of high humidity on this type of mandrel.

Hydrocal B-11 Plaster

The measured mechanical properties of Hydrocal B-11 were superior to other materials evaluated, but difficulty in removal when used as a winding mandrel is a limitation that must be considered. The use of this plaster in the construction of a winding mandrel in combination with a soluble-type plaster is being evaluated. Further discussion is given in the section entitled Small-Scale Mandrels.

SMALL-SCALE MANDRELS

Several material systems are being evaluated as winding mandrels, using the standard 2-foot-diameter x 3-foot-long mandrel size. Evaluation of each system is not completed at this time. A comparison of design allowables established by laboratory test results and actual mandrel stresses resulting from the winding and curing operation will be made.

The status (percent complete) of the material systems or concepts being evaluated at this time is shown in Table 6.

TABLE 6

STATUS OF SMALL-SCALE MANDREL EVALUATIONS
(Percent Complete)

Material and/or Concept	Tooling	Mandrel Fabrication	Winding of Case	Mandrel Removal	Analysis
Navmold	C*	C	C	C	C
Kerr DMM	C	I**	--	--	--
Sand/PVA	C	I	--	--	--
Mechanical Breakout (Kerr/Hydrocal/pullout chains) Mandrel	C	C	10	--	--
Collapsible Segmented Aluminum Mandrel	60	--	--	--	--
Low Melting Metal Alloys	45	--	--	--	--

* C denotes 100 percent completion
**I denotes phase is in process

SOLUBLE NAVMOLD MANDRELS

Two standard small-scale mandrels were cast from the hot-melt, water-soluble Navmold material. Only one was evaluated since the Navmold used in the second mandrel had become contaminated and degraded before casting was completed.

The effect of the winding and curing operations on the Navmold mandrel was determined before a proper theoretical analysis could be made. However, radial deflection because of the curing operation was measured and could have been reduced if the wall thickness had been significantly greater than one inch.

Tooling

A split mold of glass-fabric, reinforced-plastic construction (Fig. 2) was used for the fabrication of mandrels from Navmold (and plaster materials).

Mandrel Fabrication

A fill-and-drain technique was used for casting the standard small-scale mandrels from the Navmold material.

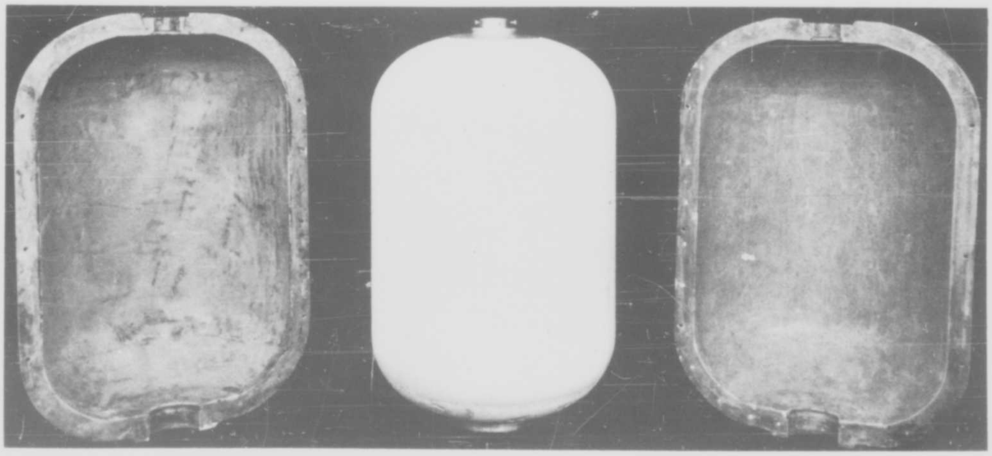

Figure 2. Split Mold for Navmold-Fabricated Mandrels

Mixing. The constituents of the Navmold material were blended together in the electrical, melt-mix pot shown in Fig. 3 . The carbohydrate-base granular material was poured into the mixing pot and melted at approximately 335 F. The other two constituents were then added to the molten carbohydrate material, with lumps broken up as they formed. The melting of the carbohydrate-based material, and adding and blending of the other two constituents to form a homogeneous mixture (approximately 900 pounds) took less than four hours. (The Navmold material began to degrade after two days at 335 F.)

Casting. The molten Navmold mixture was then cast into the assembled split-plastic mold. Shielded thermocouples (glass fabric/aluminum tape), attached to the exterior surface of the split plastic mold, were used to check the mold temperature before draining the excess Navmold. The excess Navmold material was drained (after approximately 45 minutes) when the exterior mold temperature was 140 to 160 F. The standard small-scale mandrel had a fairly uniform wall thickness of approximately 1 inch. The total operation of casting and removing the Navmold mandrel from the reinforced plastic mold took approximately 8 man hours.

Contour Check. A template was used to indicate the uniformity of the dimensions of the cast Navmold mandrel. No shrinkage could be noted.

Effect of Winding and Curing Conditions

Mandrel deflections, due to the winding and curing operation, were taken by using micrometer calipers to measure diametrical changes between metal probes (thumb tacks) embedded in the mandrel. Two pairs of probes were located 90 degrees apart at the tangent points and the midpoint of the cylindrical section (Table 7). Change in total length after fabrication processing was also measured.

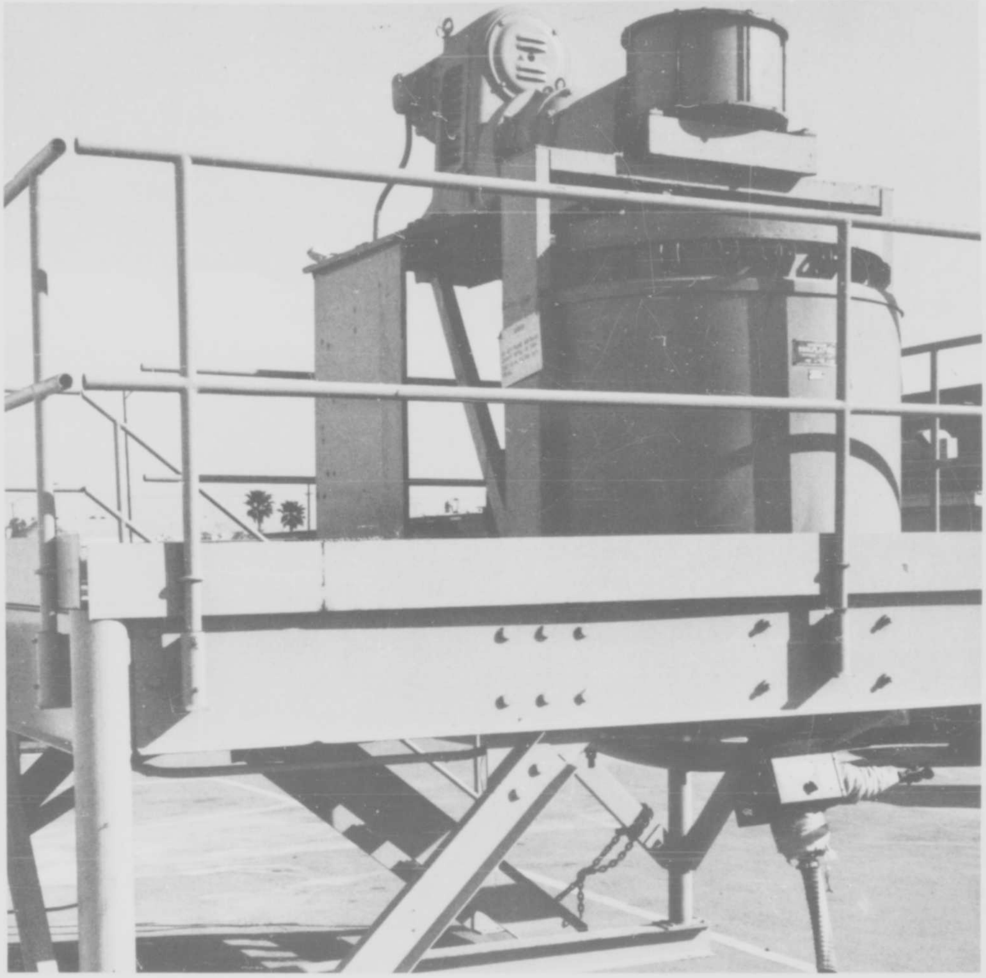

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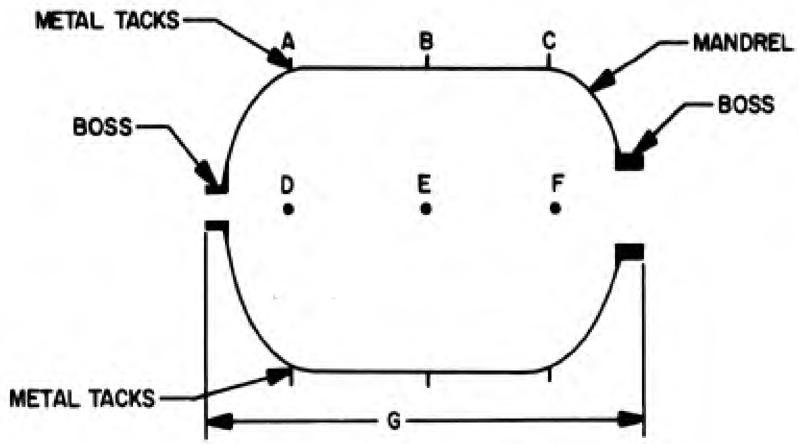
Figure 3. Electrical Melt-Mix Pot

TABLE 7

DIAMETER DEFLECTIONS ON NAVMOLD MANDREL FROM WINDING, CURING, AND MANDREL REMOVAL OPERATIONS



Operation	Deflection, Inches						
	A	B	C	D	E	F	G*
Winding							
First hoop winding	0.009	0.012	0.008	0.008	0.014	0.013	--
First polar winding	0.014	0.021	0.017	0.012	0.019	0.013	0.095
Second hoop winding	0.026	0.026	0.021	0.020	0.030	0.021	0.119
Second polar winding	0.023	0.028	0.024	0.021	0.027	0.018	0.102
Third hoop winding	0.027	0.027	0.026	0.025	0.035	0.021	0.073
Fourth hoop winding	0.036	0.047	0.032	0.033	0.043	0.027	0.002
Curing							
Two hours at 200 F +							
Two hours at 250 F +							
Eight hours at 300 F	0.148	0.160	0.138	0.144	0.165	0.143	0.262
Mandrel Removed	--	--	--	--	--	--	0.677

*The starting length is the measurement taken after the initial hoop winding was applied, since the total length (G) before beginning the winding operation was not recorded. Also, the unusual pattern noted for the change in length values measured during the winding operation may have been due to inaccurate measurements.

Winding Operation. The winding operation consisted of applying four layers of hoop windings with two revolutions of polar windings (four layers) interplied between the hoop windings. U.S. Polymeric 20-end E-787/801 preimpregnated glass roving was used as the filament-reinforcement system. A tension of 0.8 to 1.0 pound per end of roving was used during the winding of the filament structure.

Deflection During Winding. Micrometer caliper measurements were taken after each complete polar- and hoop-winding step. Diametrical deflections after the winding operation ranged from 0.029 to 0.047 inch. Increase in average diametrical deflection, as the filament layers were added, is shown in Fig. 4.

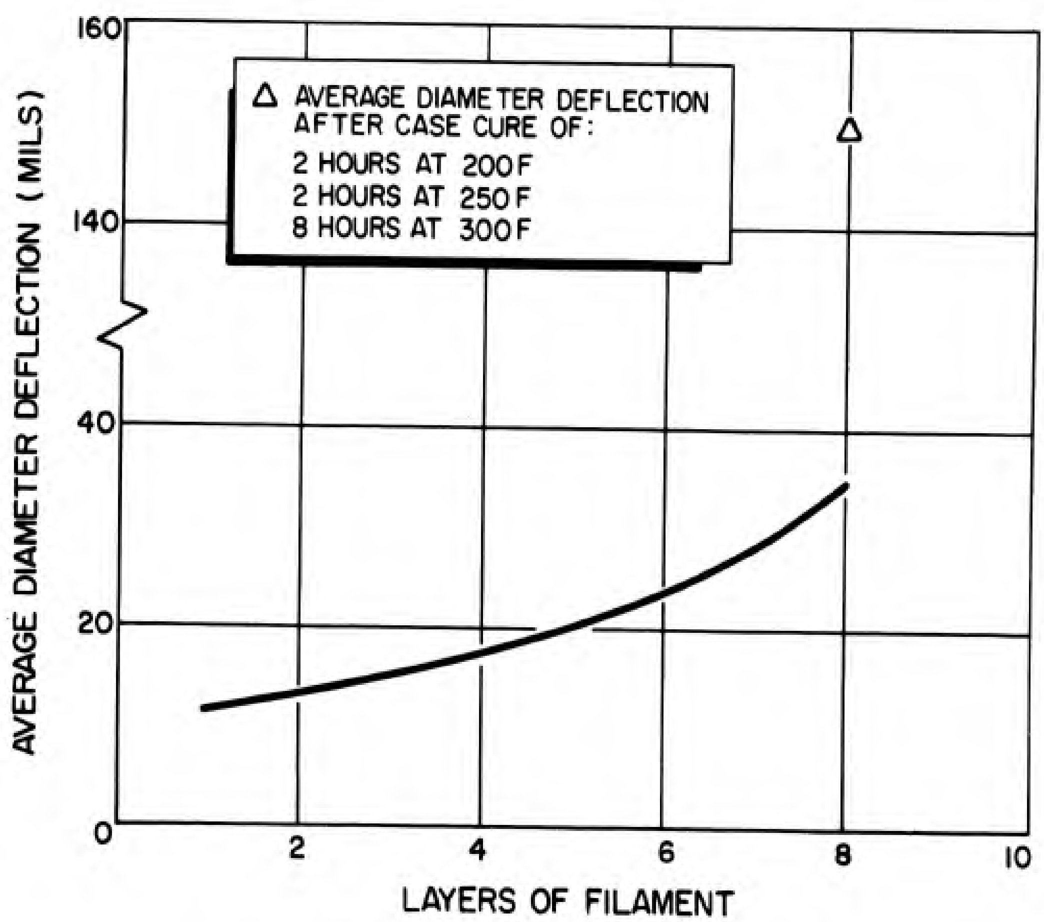


Figure 4. Navmold Mandrel Deflections During Case Winding and Cure

Deflection Due to Cure Cycle. The cure schedule for the case laminate was 2 hours at 200 F, 2 hours at 250 F, and 8 hours at 300 F. Micrometer caliper measurements taken after the laminate cure cycle showed that diametrical deflection had increased 0.111 to 0.113 inch for a total deflection after the winding and curing operations of 0.138 to 0.160 inch. This is believed chargeable to a loss of strength of the Navmold material at the curing temperatures.

Mandrel Removal. The Navmold mandrel was easily removed in less than 6 hours by dissolving it in hot water. A significant reduction in total chamber length was measured after the mandrel was removed. This "spring-back" effect caused an additional 0.415-inch reduction in the total length. This effect was approximately 60 percent greater than deflection noted after the winding and curing operations. Relieving of residual stresses that were built into the case laminate during the winding and curing operations may be an explanation for the large reduction in length after mandrel removal. Additional data and further analysis are required for verification of this belief.

ANALYSIS

As expected, the ultimate mechanical strength properties (Table 1) of the approximately 1-inch-thick Navmold mandrel were high enough to sustain the ultimate compressive loads encountered during the winding and curing of the filament-wound structure. However, the heat distortion point of the Navmold material is too low to resist radial deformation under the constant loading conditions that resulted from the winding and curing operations. This radial deformation could have been significantly reduced if a 2-inch wall thickness had been used in the Navmold mandrel. However, a weight penalty would have resulted.

PRELIMINARY CALCULATION OF MANDREL STRESS AND DEFLECTION

An analytical solution is presented for determining the stress and deflection in a mandrel from winding filaments over it. Tests will be performed in the laboratory and applicable data will be taken to correlate results. An initial analysis is outlined below, with a discussion of refinements to be made included.

General Analysis

These symbols are used in the analysis:

- dR_m radial deflection in the mandrel due to winding tension, inches
- E_{mc} compressive modulus of elasticity of mandrel, psi
- f_{mc} compressive stress in mandrel due to winding tension, psi
- P radial pressure between mandrel and filaments due to winding tension, psi
- R_{1m} inside radius of mandrel, inches
- R_{mm} mean radius of mandrel, inches

R_{om} outside radius of mandrel, inches

t_m thickness of mandrel, inches

T tension load on glass filaments, lb/in. of width

u Poisson's ratio

The radial pressure is

$$P = \frac{T}{R_{om}}$$

The average compressive stress is

$$f_{mc} = \frac{PxR_{mm}}{t_m}$$

The radial deflection of the outside radius is

$$dR_m = \frac{PxR_{om}}{E_m} \left(\frac{R_{om}^2 + R_{im}^2}{R_{om}^2 - R_{im}^2} - u \right)$$

<u>Navmold Mandrel Analysis</u>

Analysis for the case wound on the Navmold mandrel is

$E_{mc} = 242{,}000$ psi

$R_{1m} = 11.0$ inches

$R_{om} = 12.0$ inches

$t_m = 1.0$ inches

$T = 300$ lb/in.

$R_{mm} = 11.5$ inches

$u = 0.25$

The radial pressure is

$P = 25$ psi

The compressive stress is

$$f_{mc} = 287.5 \text{ psi}$$

Radial deflection

$$dR_m = 0.014 \text{ inch}$$

represents a diametral change of 0.028 inch while the measured diametral deflection was 0.011 inch. This was measured by micrometer calipers.

Reasons for lack of correlation between the analytical analysis and the micrometer deflection measurements include possible errors in the values used in the equation. The equation used is accurate for small deflections. Here the deflections predicted by the equation are relatively large. Consideration of the inherent assumptions in using these equations may well account for the lack of correlation. First, the expression for the radial pressure assumes that there is no strain reduction in the filaments after they are wound on the mandrel. This is true if the mandrel is rigid or there are no edge effects. In fact, the filaments are in small-band width; therefore, there is an edge effect. The mandrel deflection is incremental. If the filaments were placed on a very wide band with some overlap,the edge effect would not be significant. The pressure between filaments and mandrel would be $P = T/R$. This edge-effect phenomenon will be investigated further in the next quarterly period.

SOLUBLE SAND/PVA-TYPE MANDREL

A small-scale mandrel will be fabricated from the sand/PVA formulation. Except for the stove pipe used for lightening purposes, this mandrel will be solid.

Mandrel Fabrication

Using the reinforced plastic split mold, the sand/PVA will be tamped into each mold section. The stove pipes will be located as the material is packed into the molds.

Each sand/PVA section, while still in the mold, will be baked for 12 to 16 hours at 275 F to remove excess water and to consolidate the binder. The two halves of the sand/PVA hand-tamped castings will then be bonded together, using the Bondmaster 611/DTA (8PHR) adhesive system. The mold sections will be removed after curing the bond between the two solid halves.

Effect of Winding and Curing Conditions

The procedure previously described for determining the effect of winding and curing operations, as related to mandrel deflections, will be used.

Mandrel Removal

The sand/PVA mandrel is expected to dissolve readily when soaked in warm water.

SOLUBLE PLASTER MANDREL

A small-scale, soluble-type mandrel is being fabricated using Kerr DMM plaster. The mandrel will consist of two bathtub halves bonded together. This mandrel is being fabricated to determine deflections under winding and curing conditions, and,also, ease of removal.

Mandrel Fabrication

The reinforced plastic split mold was used in the fabrication of the bathtub plaster sections. Two bathtub halves of approximately 2-inch wall thicknesses were built up inside the plastic mold sections. After drying each plaster half in an oven at 140 to 150 F for 24 hours, the sections were bonded together, using a Bondmaster 611/DTA (8 PHR) adhesive system. The bonded Kerr DMM plaster halves were then put back in the oven for an additional 24 hours at 140 to 150 F for further dryout.

Effect of Winding and Curing Conditions

The same procedures used with the Navmold mandrel to determine the effect of winding and curing operations will be used for this particular mandrel.

Mandrel Removal

The removal of the Kerr DMM plaster mandrel will be attempted by filling the hollow mandrel with a 15-percent solution of acetic acid and allowing it to soak for 12 to 24 hours before draining. Circulating the acetic acid under low pressure may also be used as a method of removing the Kerr DMM plaster.

MECHANICAL BREAKOUT PLASTER MANDREL

A small-scale, mechanical breakout-type mandrel was fabricated, using a composite structure consisting of a thin outer shell of Kerr DMM plaster and thicker inner shell of Hydrocal B-11 plaster, with chains imbedded in the latter.

Mandrel Fabrication

Using the reinforced plastic split mold, a buildup of approximately 3/8-inch-thick Kerr DMM plaster was swept into the female molds to form the outer shell of the mandrel.

After drying the Kerr DMM plaster shell at 175 F for 12 hours, an approximate 2-1/2-inch buildup of Hydrocal B-11 plaster was swept over the inner surface of the Kerr DMM plaster. Chain was laid in during the buildup of the Hydrocal B-11 section to expedite mandrel removal.

After drying the composite plaster sections at 175 F for 12 hours, the two halves were bonded together, using a low-temperature-curing epoxy adhesive. The female mold halves were removed and the bonding adhesive was allowed to cure at room temperature for several hours.

The completed mandrel assembly was then placed in an oven at 175 F for further drying of the plaster materials. During the dryout cycle, the outer shell of Kerr DMM plaster delaminated from the Hydrocal B-11 portion and cracked in several areas. The delamination and cracking was believed due to either too high a dryout temperature for the thin Kerr DMM shell and/or the difference in thermal expansion characteristics of the two plaster materials.

Effect of Winding and Curing Conditions

The same basic procedure that was used to evaluate the Navmold mandrel will also be used for this particular mandrel.

Mandrel Removal

Removal of the plaster sections will be attempted in two steps:

1. Pulling the breakout chains to fracture and break up the Hydrocal B-11 plaster portion of the mandrel (some chipping may be required)

2. Dissolving the Kerr DMM plaster portion with a 15-percent solution of acetic acid.

COLLAPSIBLE SEGMENTED ALUMINUM MANDREL

The basic mandrel concept to be evaluated is shown in Fig. 5. This mandrel will be constructed from a series of parts capable of being easily removed. The following description of this mandrel will cover its general design.

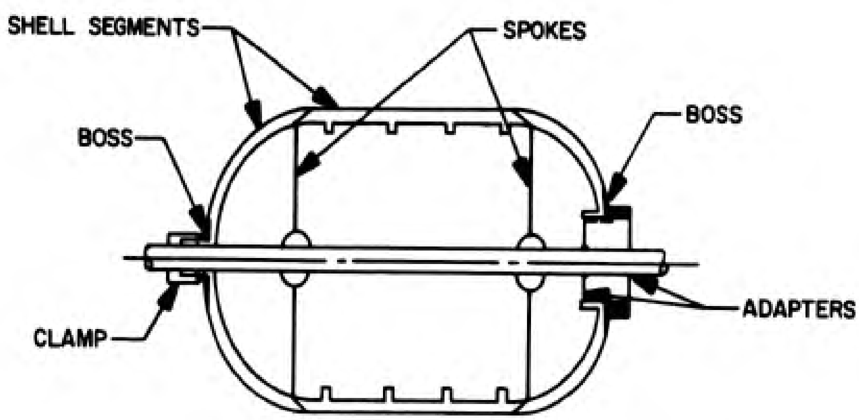


Figure 5. Collapsible Segmented Aluminum Mandrel

Design

The mandrel shaft will have a series of spokes mounted on it by means of a hinge mechanism. These spokes serve to support the mandrel shell segments and are capable of pivoting in relation to the shaft axis. They can be locked in a perpendicular position, thus eliminating mandrel collapse during winding. Mechanical means will be used to operate them. This feature of spoke mounting will permit easy removal of both shaft and spokes as one unit. Two of these spoke sets will be used in the standard small-scale mandrel to support the longitudinal shell segments. There are 16 segments around the shell periphery, 15 of which are identical and interlocked to provide a tight body surface. The sixteenth segment is a "key" which locks and completes the contour. It is the first piece removed when dismantling the series of shell segments. Each end of the mandrel is formed by another series of identical segments. These segments are pie shaped, interlocked, and mechanically attached to the mandrel shaft. The case end bosses are located against the outside surface of these segments and held concentrically to the mandrel shaft with locking adapters to maintain the mandrel length. The possibility of voids exists at each segment joint; however, voids may be eliminated by filling them with plaster or other expendable filler material to provide a smooth, continuous surface for wrapping.

SUMMARY OF SMALL-SCALE MANDREL EVALUATIONS

Since the small-scale mandrel investigations are only partially complete, a final summary cannot be made at this time. The final summary will be based on the objectives outlined for Phase II and will include a design analysis procedure. This summary will be presented at the end of the next quarterly period.

SCHEDULED WORK FOR NEXT QUARTERLY PERIOD

To fulfill the objectives of the Phase II investigations, a 90-day extension has been requested for this phase to permit the evaluation and completion of those items:

1. Complete fabrication of components for collapsible, segmented aluminum mandrel (small-scale), assembling, and evaluation by winding and curing a filament-wound structure on it
2. Complete fabrication of split metal mold for casting small-scale winding mandrels from low melting metal alloys
3. Complete evaluation of small-scale mandrels fabricated from plasters, sand/PVA material systems, low-melting metal alloys, plaster mechanical breakout concept, and inflatable/soluble

material design concept (Each mandrel will be designed for a nominal deflection range that will be determined analytically.)

4. Final analysis of mandrel materials and/or concepts evaluated in Phase II, and selection of two or three showing the most desirability for use in mandrel applications 25 feet long by 5 feet diameter that will be demonstrated in Phase III.

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