METAL FABRICS FOR AEROSPACE EXPANDABLE STRUCTURES

W. D. Freeston, Jr.
Fabric Research Laboratories, Inc.
Dedham, Massachusetts

Many aerospace structures under current development require utilization of flexible, textile-like fabrics having high strength at elevated temperatures. To minimize form-drag during launch, these aerospace structures must have a small pre-deployment volume. Thus, the fabric must be capable of being folded, packaged, and subsequently deployed without suffering damage.

The most suitable candidate materials available in filament form at the present time are the superalloys and the refractory metals and their alloys. Under the sponsorship of the Fibrous Materials Branch of the Air Force Materials Laboratory, the feasibility of weaving fabric from multifilament yarns, composed of metal filaments as fine as 0.0005 inch in diameter, on modified, power textile equipment has been demonstrated.

The properties of the fabrics are compared to those of a typical, equally strong, commercial fabric woven from single wires. The superior flexibility, crease recovery, fold endurance and tear strength of multifilament metallic-yarn fabrics are shown.

The tensile properties, tear strength, creep and fold endurance of a multifilament-yarn fabric in air at temperatures to 2000°F are given.

Joining panels of metal fabric by conventional sewing with threads composed of a large number of fine metal filaments is discussed.

INTRODUCTION

Many aerospace structures under current development, such as re-entry drag and lift-drag vehicles, require utilization of flexible, textile-like fabrics having high strength at elevated temperatures. To minimize form-drag during launch, these aerospace structures must have a small pre-deployment volume. Thus, a fabric used in these structures must be capable of being folded, packaged, and subsequently deployed without suffering damage.

The temperature and tensile load that the fabric in a particular aerospace application will experience depends on the design and mission of the structure. For instance, it is estimated that the temperature of the fabric in a paraglider returning from an orbiting space station with a launch weight of 1000 pounds can be kept below 1000°F by utilizing a "skip-glide" re-entry and an ablative fabric coating, such as silicone rubber. The required fabric strength would be over 200 lbs/inch at the 1000°F temperature level[10]. Systems of greater weight intended for other missions may encounter temperatures in the 1500°F to 2500°F range.

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Trailing, aerodynamic, decelerator systems capable of stabilizing and decelerating supersonic and hypersonic airplanes, aerospace vehicles and ejected payloads are also under development. One of the designs being evaluated by the Air Force at the present time is the Hyperflo canopy. It has a conical-frustrum shaped, canopy configuration, some portions of which may be exposed to temperatures of 600°F to 1800°F.

The textile-like materials potentially useful in these aerospace structures, i.e., the materials available in fiber form that are flexible and exhibit high strength at elevated temperatures, are the superalloy and refractory metals, ceramics (oxide fibers, including glass) and carbonaceous residues. Considerable research effort is being expended on fibers in all three classifications. Noteworthy progress has recently been made in the carbonaceous-fiber area. However, the most suitable candidate materials available at the present time for use at 1000°F, and above, are the superalloy metal filaments.

Metal filaments are, inherently, many times stiffer in tension than organic filaments. Therefore, in order to obtain a metal fabric whose bending flexibility approaches that of an organic-fiber fabric, the metal fabric must be woven from yarns composed of a large number of very fine metal filaments.

Assuming complete freedom of filaments to bend individually, yarn rigidity is proportional to the square of the filament diameter for equally strong yarns. Since metal filaments, as a class, are ten to twenty times stiffer in bending than organic filaments, metal filaments have to be drawn to less than one-quarter the diameter of organic filaments to achieve equal yarn rigidity at equal yarn strength.

The diameter of typical organic filaments is approximately 1.0 - 1.5 mils. The diameter of metallic filaments necessary to achieve equal yarn rigidity at equal strength would, therefore, be on the order of 0.3 mil. And there must be about 600 - 2400 metal filaments per yarn compared to 50 - 150 organic filaments[2].

The finest wires commercially available in quantity are 0.5 mil (0.0005 inch) in diameter. This wire is not supplied by the manufacturers in multifilament-yarn form since high-strength wire cannot be melt-extruded, as can polymeric fibers, but must be drawn through diamond dies with only a small area reduction on each pass. The fine wire must be twisted into a yarn in a subsequent operation.

However, during the past year limited quantities of metal yarns composed of a large number of fine wires and produced by a multifilament drawing process have become available. This is of considerable economic importance. Singly-drawn, 0.5-mil diameter, superalloy wire costs from roughly $1,000 (Chromel R) to $3,000 (René 41) per pound. However, the price of multi-drawn wire yarn (composed of 0.5-mil wires) is $25 (stainless steel) to $210 (Chromel R) per pound.

Hoskins Manufacturing Company has produced multifilament yarns composed of fine, nickel-base alloy, metal filaments by placing large-diameter metal filaments in a formed-up ribbon of iron and drawing the composite to a small diameter. The iron sheath is then dissolved and the yarn twisted[7].

Brunswick Corp. produces a similar product by imbedding large metal filaments in a metal matrix and drawing the composite to a small diameter. The matrix is subsequently dissolved(11).

Multi-drawn, metal yarn can be drawn such that the individual filament size is smaller than 0.5 mil and, undoubtedly, yarn can be produced with 600 to 2400 filaments. Thus, it should be possible in the near future to produce a metal fabric having the same flexibility for the same fabric strength as conventional, synthetic-fiber fabrics.

MULTIFILAMENT FINE-WIRE YARN FABRIC

The technology required to wind and twist fine wire into yarn and weave the yarn into fabric has been developed using modified textile equipment(3,5). A ring-twister specifically modified to twist, ply, and cable wires having diameters from less than 0.5 mil to 1.5 mils into yarns with 0.1 to 50 turns per inch twist was recently constructed. The design incorporates the necessary-type creel and guides, and an electronic stop motion that detects the rupture of a single, 0.5-mil diameter, metal fialment(6).

The fine-wire, multifilament-yarn, metal fabrics woven to date have been designed for maximum translation of filament and yarn strength into fabric strength, and for maximum fabric flexibility, crease recovery, fold endurance and tear strength. The success of these efforts is demonstrated by comparing the fine-wire, multifilament-yarn fabric to a typical, monofilament wire screen. The above-mentioned properties of the multifilament-yarn fabric are considerably superior to those exhibited by wire screen and approach those of conventional organic-fiber textiles(5).

The averages of the warp and filling properties of a series of multifilament-yarn, fine-wire fabrics are summarized in Table 1. The properties of a typical commercial fabric of equal strength woven from single wires are also given. As shown, the multifilament-yarn fabrics weigh approximately the same, yet have air permeabilities approaching one one-hundredth that of the monofilament-fabric. The multifilament yarn fabrics also have tear strengths from two to four times, and fold endurances from twenty to one hundred times those of the typical monofilament fabric. The monofilament fabric exhibits essentially no wrinkle recovery, while the multifilament yarn fabrics exhibit recoveries up to 33%. (The methods used to measure the permeability, tensile properties, tear strength, fold endurance and wrinkle recovery are outlined below.)

As also shown in Table 1, a 50% decrease in fabric air permeability, a five-fold increase in fold endurance and a two-fold increase in wrinkle recovery can be realized by weaving a fabric from multifilament yarns composed of 0.5-mil diameter wires rather than from equally strong yarns composed of 1.0-mil diameter wires.

TABLE 1

FABRIC PROPERTIES

Wire Diameter (mils)	Material	Filaments per Yarn	Weave Pattern	Ends per Inch	Picks per Inch	Weight (oz/yd^2)	Permeability ($ft^3/min/ft^2$)	Tear Strength (lbs) average	MIT Folding Endurance (cycles) average	Tensile Rupture Load (lbs/inch) average	Monsanto Wrinkle Recovery (%) average
0.5	Chromel A*	100	two-by-two basket	81	81	21.2	18-21	12.7	999	216	32
0.5	Chromel A	100	three-by-four twill	81	82	21.2	21-22	17.5	1201	215	33
0.7	Chromel A	49	two-by-two basket	82	119	23.9	8-11	8.7	437	213	13
1.0	Chromel A	25	two-by-two basket	81	81	20.1	47-57	8.3	232	205	16
1.0	Chromel A	25	three-by-five twill	81	81	20.0	54-57	14.7	265	199	25
5.0	304 Stainless	Mono-filament	plain	90	92	20.7	828	3.5	11.5	181	~0

*Registered trademark, Hoskins Manufacturing Co., Detroit, Michigan; 80 Ni, 20 Cr.

CHROMEL R WIRE FABRIC

Seven yards of eighteen-inch wide fabric were woven from a twisted, multi-filament yarn containing fully annealed, 0.5-mil diameter, superalloy, Chromel R* wire[3]. The fabric was woven from Chromel R wire because it is readily available in 0.5-mil diameter filaments and because it has excellent high-temperature properties[8,9]. The construction, weight, air permeability, wrinkle recovery, tensile properties, tear strength, and fold endurance of the fabric at 70°F are given below. The tensile properties of the fabric at temperatures from 70°F to 2000°F, and at jaw speeds of 0.5 inch/minute and 5.0 inches/minute are also given, as are the tensile strength of creased fabric samples, and the fabric tear strength and fold endurance. The fabric creep at 50% of the at-temperature rupture load at temperatures from 1000°F to 2000°F is also given[4]. In addition, the fabric tensile properties at -110°F and -320°F are noted.

The tensile properties of the 0.5-mil, Chromel R wire at ambient temperatures are given in Table 2. These properties were determined with an Instron tensile-testing machine using a ten-inch gauge length and a jaw speed of 0.5 inch/minute. The wires were mounted in standard fiber jaws faced with masking tape. A typical, although not necessarily average, stress-strain diagram is given in Figure 1.

TABLE 2

TENSILE PROPERTIES OF 0.5-MIL CHROMEL R WIRE

Yield Load (gm)	Yield Elongation (%)	Rupture Elongation (%)	Rupture Load (gm)
11.4	0.57	6.97	13.5

The 0.5-mil, Chromel R wire was twisted and plied into a one-hundred filament yarn. Ten ends of the individual strands of wire were twisted 3.0 Z turns per inch and ten ends of the twisted yarn were then plied 3.0 S turns per inch. (This yarn construction is denoted by: 10/10/0.5 mil/3.0 S/3.0 Z.) The yarn is balanced, i.e., torque free.

The yarn was woven into a two-by-two basket-weave fabric. The pick-and-end count, weight, thickness and air permeability of the fabric are given in Table 3. The fabric permeability was measured with a Frazier Permeometer, using 0.5 inch of water-pressure drop across the fabric.

TABLE 3

PROPERTIES OF 0.5-MIL CHROMEL R WIRE FABRIC

Weave Pattern	Ends per Inch	Picks per Inch	Weight (oz/yd^2)	Thickness (inch)	Permeability ($ft^3/min/ft^2$)
Two-by-two basket	80-81	80-81	19.9	0.0077	2.1

*Registered trademark, Hoskins Manufacturing Co., Detroit, Michigan; 73 Ni, 20 Cr, 3 Al, 3 Fe, 0.5 Si, <0.05 C.

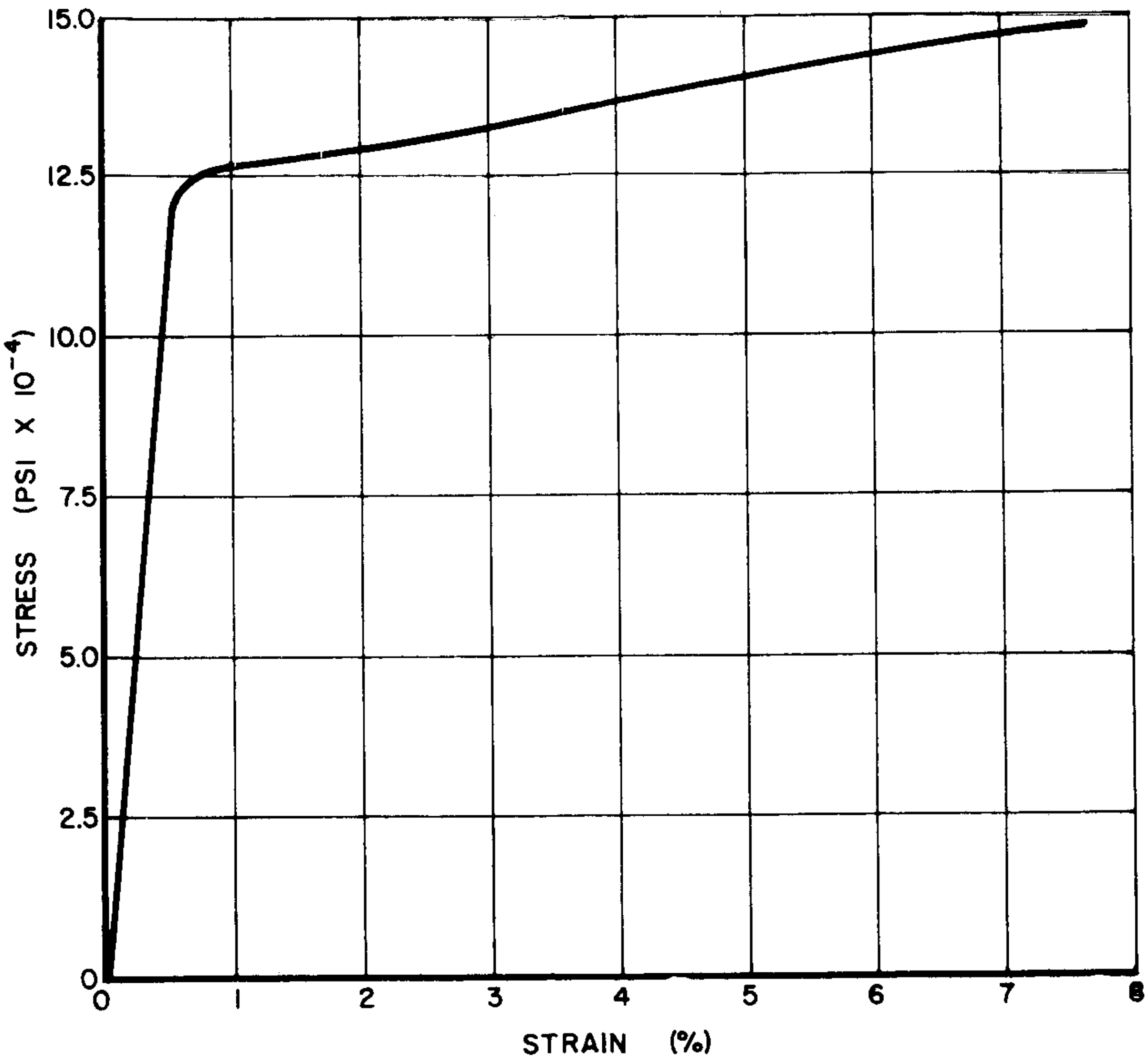

FIGURE 1. STRESS - STRAIN DIAGRAM OF 0.5-MIL CHROMEL R WIRE.

The average tensile properties of the multifilament-yarn, 0.5-mil Chromel R wire fabric are given in Table 4. Specimens in both the warp and filling directions were tested on an Instron tensile tester. One-inch wide, ravel-strip specimens, 3.5-inches gauge length, 0.5 inch per minute jaw speed, and flat, leather-lined, serrated jaws were used. The tensile moduli values given represent the slope of the initial linear portion of the fabric load-elongation curves in pounds per inch width of fabric per unit strain.

TABLE 4

TENSILE PROPERTIES OF 0.5-MIL CHROMEL R WIRE FABRIC

Yield Elongation (%)		Yield Load (lbs/inch)		Rupture Elongation (%)		Rupture Load (lbs/inch)		Modulus (lbs/inch x 10^{-3})	
Warp	Fill	Warp	Fill	Warp	Fill	Warp	Fill	Warp	Fill
4.0	1.4	198	213	9.5	7.2	226	245	109	210

The tongue tear strength of the Chromel R wire fabric in the warp and filling directions (breaking filling and warp yarns respectively) is given in Table 5. Specimens 3-inches wide and 4.5-inches long were used. They were cut lengthwise along their center-line for a distance of approximately 2 inches. A one-inch length of each cut end was placed into Instron jaws, one in the upper jaw and one in the lower. The specimens were subjected to a constant rate of extension of 2 inches/minute for approximately 2 inches of tear, and the load recorded.

The load-elongation curve obtained in a tear test is sawtoothed, each peak representing one or several yarn breaks. The tear-strength values given in Table 5 are the visual averages of the peak values of the tests.

TABLE 5

TEAR STRENGTH, WRINKLE RECOVERY AND FOLD ENDURANCE OF 0.5-MIL CHROMEL R WIRE FABRIC

Tear Strength (lbs)		Monsanto Wrinkle Recovery (%)		MIT Fold Endurance (cycles)	
Warp	Filling	Warp	Filling	Warp	Filling
17.7	14.5	33.3	30.0	968	992

The wrinkle recovery of the Chromel R wire fabric in the warp and filling directions is given in Table 5. It was measured with the Monsanto Wrinkle Recovery Tester (ASTM D1295-53T). In this test 1.5 by 4.0-centimeter test specimens are folded 180° with a 0.01-inch thick, metal shim between the two fabric surfaces. A load of 1.5 pounds applied for five minutes is used to crease the specimens(3). The recovered angle is measured after a five-minute free-recovery time and its percentage of 180° is calculated, i.e., the percent wrinkle recovery equals Recovered Angle/180° x 100. Specimens in both the warp and filling directions, bent against the direction of curl and with the direction of curl, were tested and the results averaged.

The fold endurance of the Chromel R wire fabric in both the warp and filling directions is also given in Table 5. It was measured with the MIT Folding Endurance Tester (ASTM D643-43, Method B). In this test both ends of the fabric are clamped in jaws. The lower jaw is subjected to a rotary, oscillating, bending movement such that the fabric is folded through an angle of 135 ± 5 degrees to both the right and left of the center-line position, 180 times per minute. The folding surfaces of the jaw have a radius of curvature of approximately 0.015 inch. A tension of 1.5 kg was applied to the test specimens at the upper jaw. The opening width of the jaw was 0.01 inch.

Test specimens 0.59-inch wide and 4.5-inches long were used. The results given in Table 5 are the averages of the tests.

The elevated-temperature tensile tests of the Chromel R wire fabric were performed on an Instron tensile tester using a resistance-heated, clam-shell oven. The test specimens were gripped with jaws fabricated from Inconel '702'. The jaws extended into the heated zone of the clam-shell oven thereby enabling material elongations to be recorded directly on the Instron chart.

Jaw breaks and jaw slippage were prevented by lining the serrated jaw faces with two layers of 181 quartz fabric. New linings were used for each test.

Test specimens 1-1/8-inches wide and 6-inches long were cut from the fabric in both the warp and filling directions. These strips were ravelled to a 1.0-inch width immediately prior to testing. A gauge length of approximately 3.5 inches was used.

In all elevated-temperature tests the test specimens were held at temperature for 15 minutes prior to testing. Since the oven cools down somewhat as the jaws and sample are being inserted, the time between insertion of the test specimen and the test was roughly 17 minutes at 1000°F and 20 minutes at 2000°F.

The length of the fabric between the jaws in each test was only approximately 3.5 inches due to the lack of precision of the clamping procedure. In a 70°F tensile test, the jaws are set a fixed distance apart, namely 3.25 inches, at the start of the test. The exact gauge length is then determined by adding to this fixed distance the amount of jaw travel, as given on the Instron chart, from the start of the jaw travel until a load rise is indicated.

This procedure cannot be used for the tests performed at elevated temperatures due to the thermal expansion of the jaw assembly. Also, this thermal expansion is difficult to either measure or calculate accurately. Therefore, in all elevated-temperature tests, the gauge length GL used to calculate percent elongation and modulus values was taken as the average sample gauge length of the 70°F tests, 3.52 inches, plus the calculated thermal expansion of the fabric, i.e.,

$$GL = 3.52\,(1 + \alpha\Delta T)$$

where $\Delta T = T - T_o$, T is the test temperature, $T_o = 70°F$, and α is the coefficient of thermal expansion of the material being tested. This expression assumes that the percent crimp in the fabric is the same at all temperatures. At 2000°F, the gauge-length correction is less than 2%.

The rupture loads of the Chromel R wire fabric are plotted in Figure 2 as a function of test temperature and testing speed.

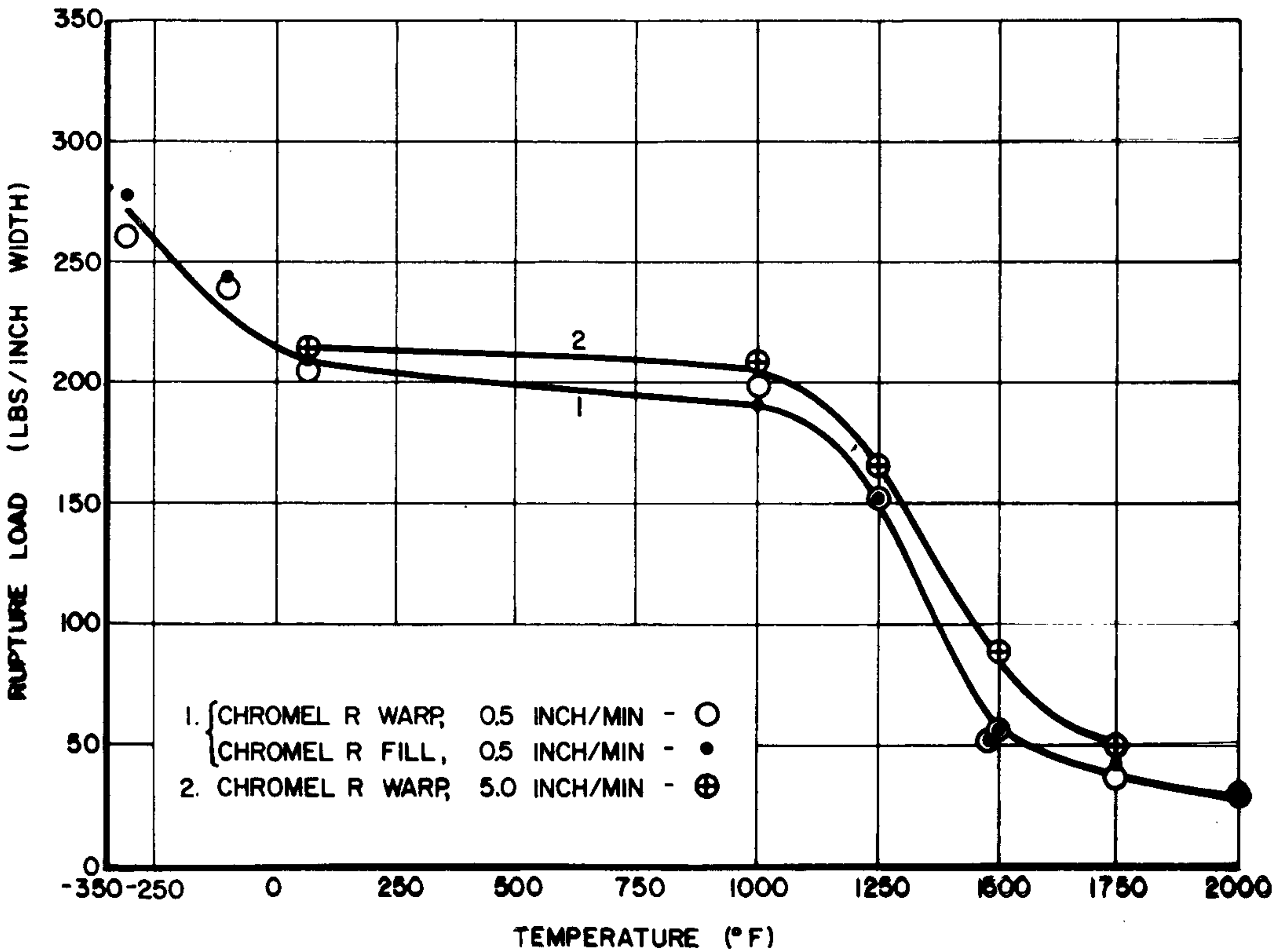

FIGURE 2. CHROMEL R WIRE FABRIC RUPTURE LOAD AS A FUNCTION OF TEMPERATURE.

The tensile strength of the Chromel R fabric decreases rapidly in the 1100°F to 1700°F temperature range. The strength of the fabric at 2000°F is 15% of the strengths at 70°F in the warp and filling directions. Also, the strength of the fabric increases with increasing testing speed, particularly at the elevated temperatures.

The rupture elongation of the Chromel R fabric is plotted in Figure 3 as a function of test temperature. As shown, the elongation remains roughly constant over the temperature range of 70°F to 1250°F, increases sharply near 1500°F and then decreases rapidly beyond 1500°F. The fabric rupture elongation at 1500°F is greater than at 70°F. This is probably a result of the wire being annealed, the work-hardening caused by twisting and weaving being removed. The decrease in fabric elongation beyond 1500°F evidently results from oxidation hardening of the wire. The 0.5-mil wire is particularly susceptible to this because of its large surface-to-volume ratio.

Typical, warp load-elongation diagrams of the Chromel R wire fabric at a jaw speed of 0.5 inch/minute and test temperatures from 70°F to 2000°F are given in Figure 4. Similar diagrams for the filling direction are given in Figure 5.

The creep, extension under a constant load, of the Chromel R wire fabric in the warp direction was measured on the Instron at elevated temperatures. The loads used were one-half of the average, at-temperature, fabric-warp, rupture loads, i.e., 100 lbs at 1000°F, 77 lbs at 1250°F, 28 lbs at 1500°F and 15 lbs at 2000°F. The test specimens were exposed to the desired temperature for 15 minutes prior to the start of the test and the creep was measured for 15 minutes. A jaw speed of 0.1 inch/minute was used to maintain the desired specimen loading. The results were corrected for the jaw creep. However, this was a small correction.

The fabric creep at 1000°F and 2000°F is low, less than 2% in 15 minutes. At temperatures between 1000°F and 2000°F the creep increases to about 10% in 15 minutes. The low creep at 2000°F is probably due to oxidation hardening of the fine wire.

The tensile properties in the warp direction of Chromel R wire-fabric test specimens creased at 70°F were measured at temperatures from 70°F to 1750°F. The following procedure was used to crease the fabric (Standard Method for Static Fold Resistance of Fiberglass Decorative Fabrics, OCF Test No. DF 505). Fabric test specimens 1-1/8-inches wide by 6-inches long were folded in half and placed under a 10-lb weight for 10 minutes. One square inch of folded fabric was placed under the weight. The face of the weight in contact with the fabric measured 2 inches by 4-3/8 inches. The specimens were ravelled to a one-inch width prior to testing. As in previous tests, the specimens were held at temperature for 15 minutes before testing.

The tests showed that creasing the fabric decreases the strength by only a small amount up to 1500°F. However, at 1750°F the tensile strength of the creased fabric is only two-thirds that of the uncreased fabric.

The tongue-tear strength of the Chromel R wire fabric was measured in the warp direction (breaking filling yarns) at temperatures from 70°F to 2000°F. The specimens were held at temperature for 15 minutes prior to testing. Specimens 3-inches wide by 4-inches long were used. They were cut lengthwise along

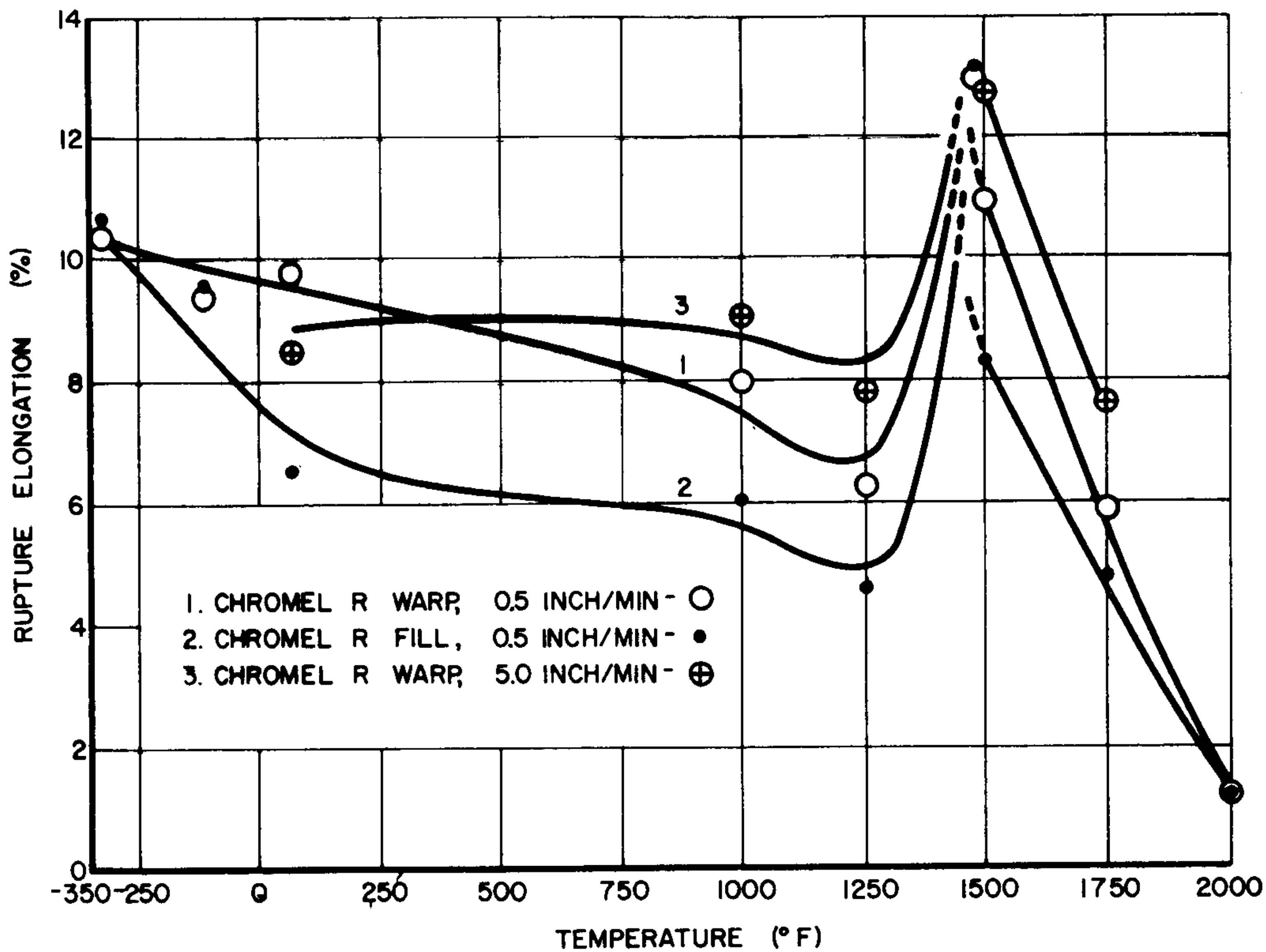

FIGURE 3. CHROMEL R WIRE FABRIC RUPTURE ELONGATION AS A FUNCTION OF TEMPERATURE.

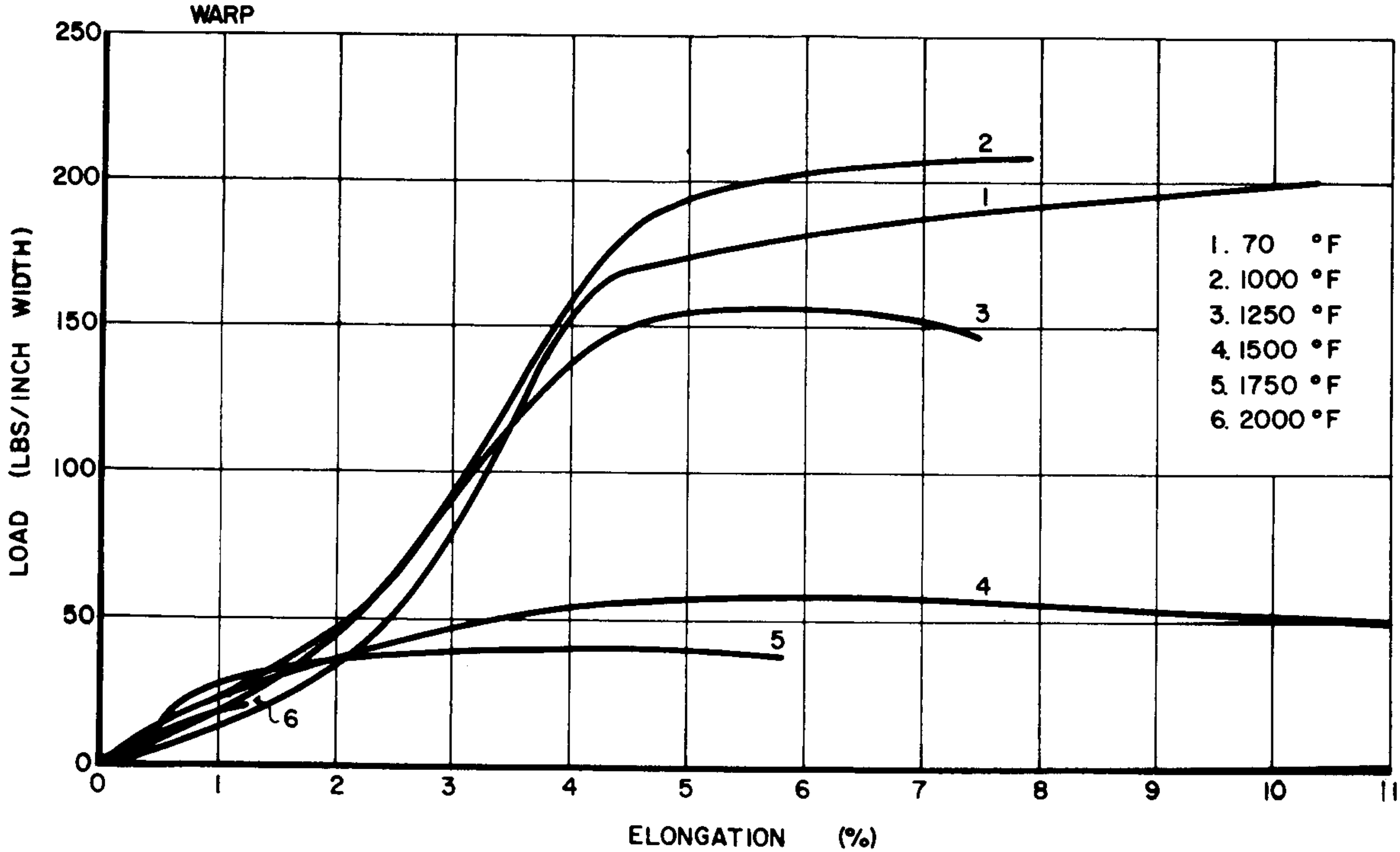

FIGURE 4. TYPICAL WARP LOAD-ELONGATION DIAGRAMS OF CHROMEL R WIRE FABRIC AT A JAW SPEED OF 0.5 INCH/MIN AND TEMPERATURES FROM 70° F TO 2000° F

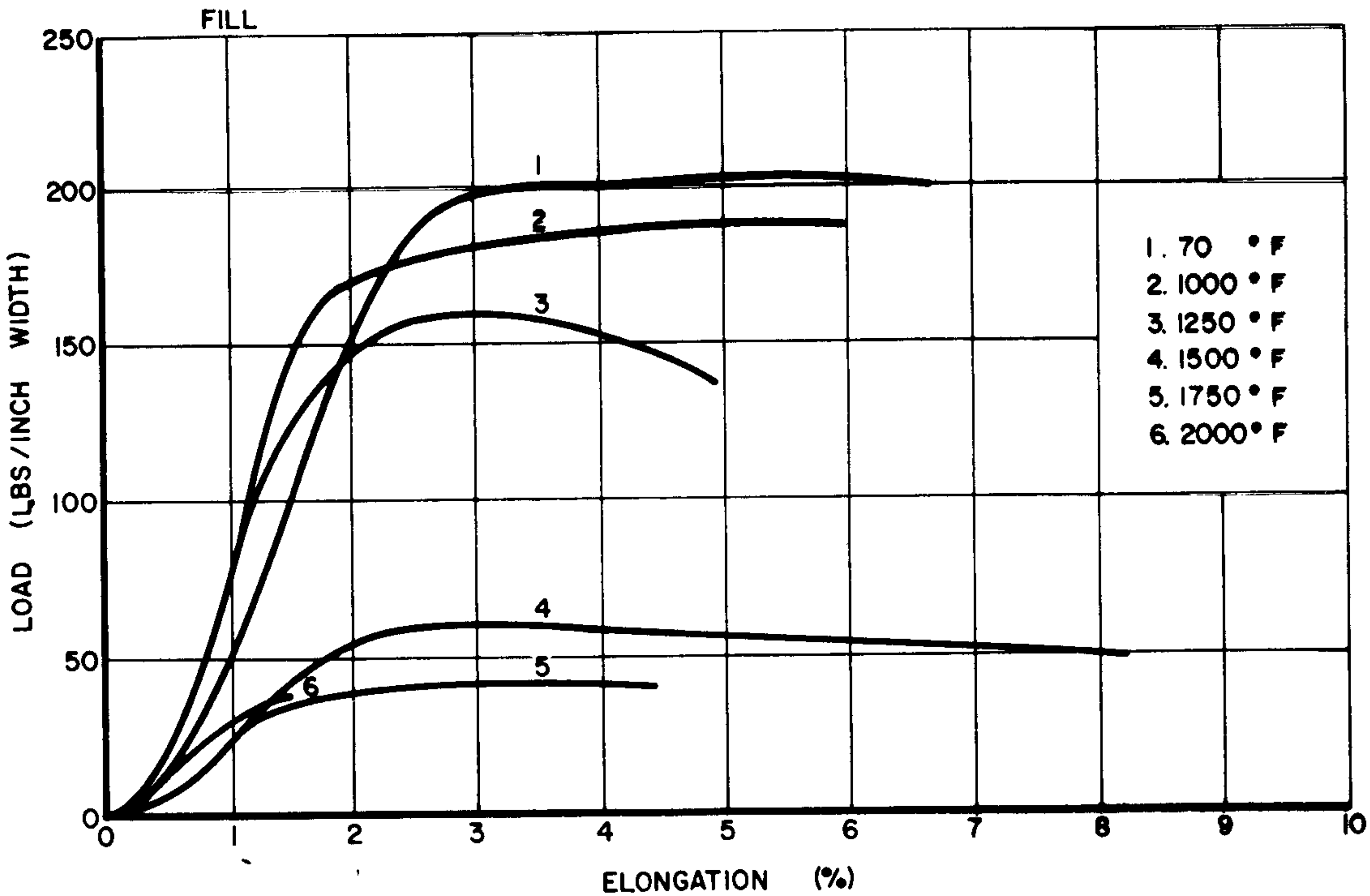

FIGURE 5. TYPICAL FILLING LOAD-ELONGATION DIAGRAMS OF CHROMEL R WIRE FABRIC AT A JAW SPEED OF 0.5 INCH/MIN AND TEMPERATURES FROM 70°F TO 2000°F.

their center-line for a distance of approximately 2 inches. One inch of each of the two portions of the cut end were placed into the Inconel jaws, one in the upper jaw and one in the lower jaw. The specimens were subjected to a constant rate of extension of 2 inches/minute for approximately 1-1/2 inches of tear.

The tear strength of the fabric is plotted in Figure 6 as a function of test temperature. The values plotted are the visual averages of the peak values.

The fold endurance of the Chromel R wire fabric was measured at elevated temperatures in a kiln. The results are plotted in Figure 7 as a function of test temperature. As shown, the fold endurance of the fabric is almost zero at 1750°F to 2000°F.

CORELESS CORD

The designs of some aerospace systems require that one component of the system be attached to another component by a flexible line or cable with high-temperature durability, for instance, the joining of the payload to the canopy of the Hyperflo parachute. Therefore, the feasibility of braiding fine wire into coreless cord was investigated. The cord was braided from a metal yarn composed of 75 ends of 1.0-mil, Chromel A wire on a #1 New England Butt Braider with Mossberg carriers. The cord construction and weight are given in Table 6[3]. The cord is very flexible, indicating that 0.5-mil wire is not necessary in such structures.

TABLE 6

CORELESS METAL CORD

Number of Carriers	Type of Stitch	Wire Diameter (mils)	Filaments per Yarn	Picks per Inch	Ends per Carrier	Total Ends	Weight (yds/lb)
16	regular (two over and two under)	1.0	75	10.0	6	96	13.5

The average breaking strengths of the cord at 70°F, 1000°F and 1500°F are given in Table 7[4]. Two-inch diameter capstan jaws and a jaw speed of 2.0 inches/minute were used. The strength of the cord at 1000°F and 1500°F was measured using a clam-shell oven with the jaws outside the oven. The cord elongation to rupture at 70°F is approximately 16 percent.

TABLE 7

BREAKING STRENGTH OF 1.0-MIL, CHROMEL A WIRE, CORELESS CORD AT ELEVATED TEMPERATURES

Temperature (°F)	Rupture Load (lbs)
70	677
1000	530
1500	164

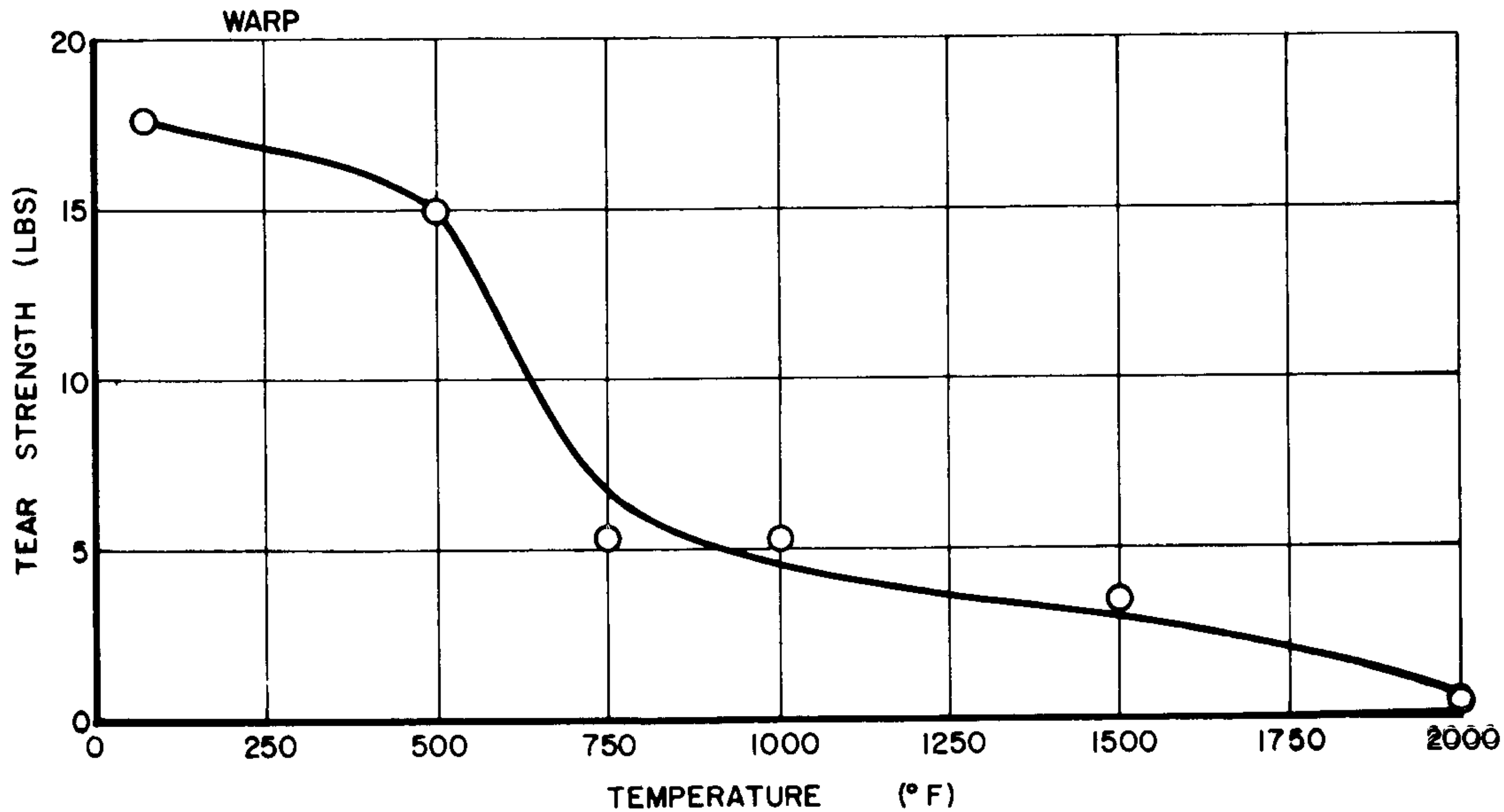

FIGURE 6. CHROMEL R WIRE FABRIC TEAR STRENGTH AS A FUNCTION OF TEMPERATURE

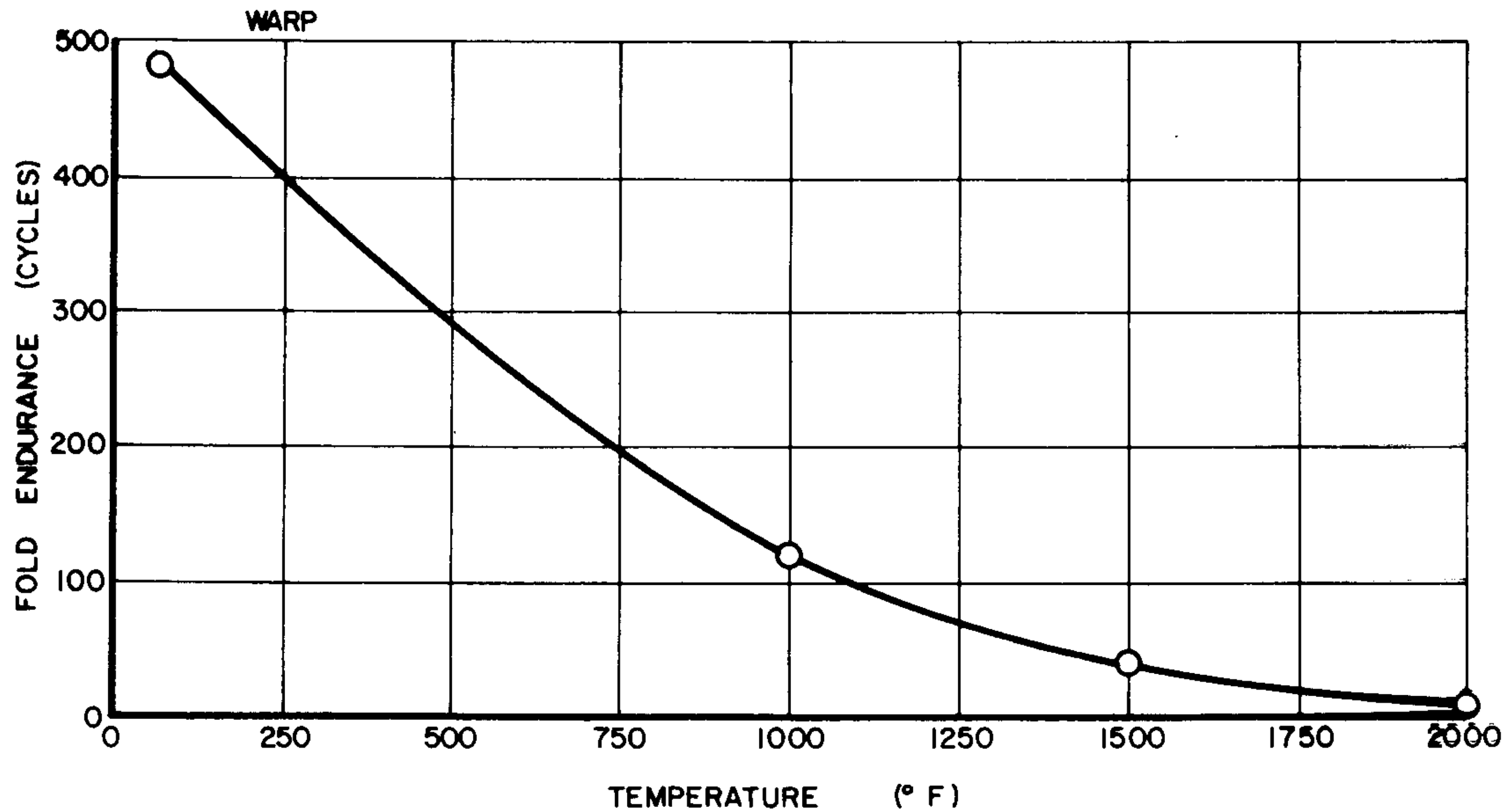

FIGURE 7. CHROMEL R WIRE FABRIC FOLD ENDURANCE AS A FUNCTION OF TEMPERATURE.

SEAMING OF METAL FABRIC

The development and evaluation of flexible, high-strength, thermo-durable, fibrous structures are only the first steps toward the utilization of such materials in an aerospace system. The fibrous structures, fabrics, must be tailored into the required configuration and the mechanical properties of the resulting configuration must be determined. An investigation of the joining of panels of multifilament-yarn, fine-wire, metal fabrics by sewing was, therefore, undertaken.

A metal sewing thread was designed[1] and twisted from five hundred, 0.5-mil, Chromel R wires for the study. To prevent the occurrence of broken filaments during the sewing operation, the thread was coated with Teflon.

No difficulties were encountered in the sewing operation itself. A standard, industrial sewing machine was used. Various combinations of seam types, stitches per inch, rows of stitches, gauge, and sewing-thread tension have been tried[3,4]. Seam efficiencies of 65% have been obtained consistently using an integral LS-2 seam and four rows of stitches. Work in this area is continuing and it is anticipated that higher seam efficiencies are possible.

CONCLUSION

Flexible, high-strength, thermally durable, textile-like fabrics have been developed. They are capable of being folded, packaged and subsequently deployed without suffering damage. These multifilament, fine-wire yarn fabrics are being considered for several aerospace structures at the present time and undoubtedly will find application in many more in the next few years.

The major shortcomings of a fine-wire, multifilament-yarn, metal fabric for aerospace applications is its weight. The Chromel R wire fabric discussed herein weighs 20 oz/yd^2. However, even on a strength-to-weight basis, these metal fabrics are superior to fabrics woven from other fibrous materials at the present time, including glass and quartz, at temperatures of 1000°F and above.

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