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INFLUENCE OF FIBER ASPECT RATIO ON THE STRESS-RUPTURE LIFE OF DISCONTINUOUS FIBER COMPOSITES

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16. Abstract

An investigation of the effect of critical aspect ratio on the stress-rupture life of discontinuous fiber reinforced composites was carried out. Pull-out specimens of tungsten wire and copper were tested at 1200° and 1500° F (649° and 816° C) for nominal stress-rupture times of 1, 10, and 100 hr. The observed critical aspect ratios were greater than in short-time tensile tests but were within the same order of magnitude at temperatures as high as 1500° F (816° C). Failure time of the specimens was controlled by the properties of the matrix (copper) at ratios less than the critical aspect ratio and by the properties of the fiber (tungsten) at aspect ratios greater than the critical aspect ratio.

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SUMMARY

Effects of time and temperature on the critical aspect ratio of fibers in discontinuous fiber reinforced composites were studied. Pull-out specimens of tungsten wire and copper were used.

The critical aspect ratio was determined for both short-time tensile tests and stress-rupture tests at 1200° and 1500° F (649° and 816° C). At 1200° F (649° C), the critical aspect ratio for short-time tensile tests was 15.0. For an average stress-rupture life of 35.43 hours at 1200° F (649° C), the critical aspect ratio was 17.0. This increased to 19.2 for an average stress-rupture life of 79.26 hours at the same temperature. At 1500° F (816° C), the critical aspect ratio was 19.8 for short-time tensile tests. This increased to 20.0 for an average stress-rupture life of 1.37 hours, and 23.0 and 27.5 for average lives of 10.33 and 42.31 hours, respectively. Extrapolation of these data indicated that for 1000 hours life the critical aspect ratio at 1200° F (649° C) would be 26.0 and at 1500° F (816° C) 33.0. The critical aspect ratio in stress-rupture was well within the limits for successful fabrication of practical components.

Failure time of the specimens was controlled by the properties of the matrix (copper) at aspect ratios less than the critical. The fiber (tungsten wire) properties controlled the time to failure at aspect ratios greater than the critical aspect ratio.

INTRODUCTION

Fiber reinforced composites, as a means for providing high-strength materials for critical aircraft and spacecraft applications, continue to be the subject of intensive investigation. Many of the projected applications for such composites involve use-temperatures at which failure in creep or stress-rupture could be the factor limiting their useful life. Stress-rupture and creep of fiber reinforced composites has been studied in several investigations (refs. 1 to 5). The reinforcing fibers used in the composites in references 1 to 4 were, in most cases, long lengths or continuous through the length of the specimen and demonstrated that the superior stress-rupture properties of fibers could be utilized in composites. The results in references 1 to 3 indicate that practical composite materials could be developed using long-length fibers and practical matrix alloys. Reference 4 is an analytical study of tungsten fiber-copper composites and relates the stress-rupture and creep properties of the constituents to those of the composite.

Except for references 1 and 5, little has been published concerning the stress-rupture or creep properties of short-length or discontinuous fiber reinforced composites. Short-length fiber composites are interesting for several reasons. Not all high-strength fibers are available as continuous lengths and, if they are to be utilized, it must be as discontinuous fibers. Also, long fibers could be broken during fabrication of the composites so that they are essentially discontinuous fiber composites. Furthermore, joints and holes destroy the continuity of the fibers in a composite, resulting in short-length fibers.

The present understanding of the failure behvaior of discontinuous fiber composites tested in creep is based on the data in reference 5. These data and previous tensile data (ref. 6) indicate that the length of fiber necessary for reinforcement in creep or stress-rupture applications is an area for concern. Tensile data have been obtained (ref. 7) which indicate that short-length fibers can be effectively used in fiber reinforced composites. However, the strength of fibers in discontinuous fiber composites is utilized by transfer of load from one fiber to the next by shear through the matrix provided that the fibers are sufficiently long. Therefore, any conditions, such as increased temperature and/or creep, that reduce the shear strength of the matrix result in property degradation of the composite. Failure occurs by fibers being pulled out of the matrix rather than by transverse fracture of the composite. The data in reference 5 indicate that pull-out only was observed in creep of short-length fiber composites. The fiber lengths used in the composites in reference 5 were chosen to be near the minimum necessary for short-time tensile failure of the fiber at the test temperature. Changing the test method from short-time tensile to creep led to the conclusion that the matrix controlled the creep rate of the composite and failure occurred by pull-out of the fibers.

Thus, both types of fiber reinforced composite have been investigated: long or continuous fiber reinforcement where transverse fracture of both fiber and matrix occurred and the fiber properties were utilized effectively, and very short-length fiber reinforcement where fiber pull-out failure occurred as a result of matrix shear at a stress below that for fiber failure. An analytical study of stress-rupture or creep of composites for the range of fiber lengths between these extremes has not been reported in the literature. It is possible that the required fiber lengths could be greater than could be readily obtained with some fibers. Reference 6 reported on the rapid increase in fiber length necessary to avoid failure by pull-out as the temperature of short-time tensile tests increased. These data (refs. 5 and 6) emphasize the need for a study of the fiber length required for reinforcement in composites intended for stress-rupture or creep applications.

The objective of this present program was to study the effect of temperature and time on the aspect ratio of fibers necessary for reinforcement in stress-rupture and compare it to the required aspect ratio in short-time tensile tests. A model system of tungsten wire as the fiber and copper as the matrix was used. Pull-out specimens designed to simulate the conditions around one fiber in a composite were tested in short-time tensile tests at 1200° and 1500° F (649° and 816° C). Stress-rupture tests were conducted on the same type of specimen at these temperatures; the critical aspect ratio was determined for nominal failure times of 1, 10, and 100 hours.

MATERIALS, APPARATUS, AND PROCEDURE

Specimen Configuration

In composites containing discontinuous, uniaxially oriented fibers such as those shown in figure 1(a), the fibers are surrounded by the matrix. Their long axis is oriented parallel to the long axis of the specimen. The fibers are bonded to the matrix and separated from each other by matrix. Ideally, the fibers overlap each other uniformly so that there is no more than one fiber end at any cross section and the fibers are arranged with a hexagonal array.

Figure 1(b) is a sketch of the pull-out specimen used in this investigation, which, with the exception of the grip, is the same as specimens used in previous pull-out experiments (ref. 6). It is an attempt to simulate the conditions occurring around one fiber in a composite containing about 70 volume percent fibers. In the figures l refers to the length of the fibers in a composite and L to the embedded length of the fiber in the pull-out test specimen. The length of the fiber in the test specimen L is equal to one-half the length of the fiber in an actual composite l. The reason for this is that in the test specimen the load is applied to the fiber by gripping one end of the fiber. In the composite, load is applied to the composite and transmitted to the fiber from both ends by shear through the matrix. The diameter of the fibers is represented by D in both cases. In the remainder of this report, the aspect ratio L/D are those of the pull-out specimen and must be doubled when referring to an actual composite. The interfiber distance (IFD) is the thickness of the matrix between fibers. Here a slight difference exists between the pull-out specimen and an actual composite. In the pull-out specimen the nearest neighbor fibers are represented by the surface of the hole drilled in the button. The distance between the fiber surface and the hole surface is constant and therefore the IFD is constant. In a composite containing fibers which are circular in cross section, and arranged in a hexagonal array, the IFD varies as shown in figure 1(a) and is not as easily defined as in the pull-out specimen. However, the trends observed by using the pull-out specimen should be helpful in understanding the behavior in an actual composite.

With the button held in a special fixture and the load applied from the free end of the wire, specimen failure took place by one of two modes: failure of the wire or pull-out, that is, shear failure either in the infiltrant or at the matrix-fiber interface. Specimens with an aspect ratio less than the critical aspect ratio failed by pull-out. Those having an aspect ratio greater than the critical aspect ratio failed in the wire. Figures 2(a) to (c) show a specimen prior to testing, a specimen which has failed in the wire ($L/D > L_c/D$), and a specimen which has failed by pull-out ($L/D < L_c/D$).

Specimen Preparation

Pull-out specimens. - Tungsten was used for the wire and button, and copper as the infiltrant (matrix). Their use was based upon their relative insolubility. Also, much previous data were already available for this model system and comparisons could be more easily made.

Figure 3 shows a specimen prior to infiltration. The unsintered button, was 7/16 inch (1.11 cm) in diameter and was made from 5-micrometer tungsten powder cold pressed to about 75 percent full density. A hole 0.0135 inch (0.0343 cm) in diameter was drilled in the button sintering. Both the thickness of the button and the hole diameter were oversize. This was done so that, after sintering, the button had shrunk to the desired thickness and hole diameter.

Buttons were presintered for 2 hours at 2200° F (1204° C) in vacuum to remove the binder and sintered for 4 hours at 4000° F (2204° C) in hydrogen to 91 percent full density. Final hole size was 0.0125 ± 0.0002 inch (0.0317 ± 0.0005 cm) which, when used with 10-mil- (0.0254-cm-) diameter wire resulted in an interfiber distance of 1.3 mils (0.0033 cm). Hole diameters were checked with a tapered pin gage, and buttons with oversize or undersize holes were rejected.

The button, 10-mil (0.0254-cm) diameter wire, and oxygen-free high-conductivity (OFHC) copper infiltrant were assembled as shown in figure 3. Infiltration was carried out for 15 minutes at 2100° F (1149° C) in flowing hydrogen (2 liters/hr).

Shear specimens. - In addition to the pull-out specimens, OFHC copper was tested in shear stress-rupture. The specimen used is shown in figure 4. Specimens were annealed for 1 hour at 1500° F (816° C) in hydrogen before testing.

Testing

Short-time tensile pull-out tests. - Tungsten wire - copper pull-out specimens were tested in short-time tension at 1200° and 1500° F (649° and 816° C). Tests were conducted using a screw-driven constant-crosshead-speed tensile machine. Crosshead speed was 0.05 inch (0.127 cm) per minute. A furnace equipped with quartz heating lamps was used. This heating source brought the specimen to temperature within 1 minute. This, in addition to a protective blanket of flowing helium, helped to minimize specimen oxidation. The specimens were held at the test temperature for 5 minutes prior to the application of load. Results from these tests could then be compared to the results from the stress-rupture tests.

Stress-rupture pull-out tests. - A general view of the stress-rupture test equipment used for the pull-out tests is shown in figure 5. The equipment was designed so that the long-time tests could be conducted in vacuum ($\sim 10^{-3}$ mm Hg) to limit specimen oxidation. Conventional stress-rupture equipment was impractical because of the low loads necessary. Direct loading was used.

Figure 6 is a detailed sketch of the apparatus. The pull-out specimen was mounted in a holder and the weight attached to the free end of the wire. This was enclosed in a chamber which was evacuated by using a mechanical vacuum pump. The weight was held by the retractable weight pan until the specimen was heated to the test temperature. Retracting the weight pan loaded the specimen. Failure time was recorded to the nearest 0.01 hour by the timer when the falling weight actuated the microswitch. Specimen temperature was monitored by thermocouples buried in the specimen holder. During testing, the specimen temperature was held to $\pm 5^{\circ}$ F (2.8° C) of the set point. Temperature variation along the test length of the specimen (i.e., the button and 1 in. (2.54 cm) of the wire), was $\pm 2^{\circ}$ F (1.1° C).

Stress-rupture shear tests. - Stress-rupture shear tests were run at 1200° and 1500° F (649° and 816° C). Standard constant-load machines were used. The specimens were tested in vacuum ($\sim 10^{-5}$ mm Hg) to prevent oxidation. Temperature was monitored by a thermocouple attached to the specimen. During testing, the specimen was held to $\pm 8^{\circ}$ F ($\pm 4.4^{\circ}$ C) of the set point, and the temperature variation over the test length of the specimen was $\pm 5^{\circ}$ F ($\pm 2.8^{\circ}$ C).

RESULTS

Elevated-Temperature Short-Time Tensile Tests

Results of short-time tensile pull-out tests conducted at 1200° and 1500° F (649° and 816° C) are listed in table I and plotted in figure 7. In this figure the horizontal lines are the average failure load for 10-mil- (0.0254-cm-) diameter tungsten wire at temperature. The aspect ratio at the "knee" of the curve is taken as the critical aspect ratio L_c/D. Its numerical value is the aspect ratio corresponding to the intersection of two lines. The horizontal line is the average failure load for the wire. The inclined line is drawn from the origin to the point of last wire failure (i.e., the smallest aspect ratio for wire failure).

The results show that for the tungsten wire - copper specimens tested the critical aspect ratio in short-time tension was 15.0 at 1200° F (649° C). At 1500° F (816° C), the critical aspect ratio was 19.8.

Stress-Rupture Tests

Table II(a) lists the results of stress-rupture tests run at 1200° F (649° C) on tungsten wire-copper specimens. These data are plotted in figure 8(a).

The definition of the critical aspect ratio in stress-rupture is the same as for the short-time tensile tests. It is that aspect ratio where as the aspect ratio of the specimen is decreased the failure mode changes from wire failure to pull-out. The major difference is that for the short-time tensile pull-out specimens (fig. 7) the load for failure varies and the time to failure is nearly constant. In the stress-rupture pull-out tests (fig. 8), the load is constant and the time varies. The numerical value of the critical aspect ratio in stress-rupture is the L/D of the smallest specimen which failed in the wire. At 1200° F (649° C), the critical aspect ratio was 17.0 (fig. 8(a-1)) for an average time to rupture of 35.43 hours. At an average rupture time of 79.26 hours, the critical aspect ratio was 19.2 (fig. 8(a-2)).

Results of the stress-rupture pull-out tests conducted at 1500° F (816° C) are tabulated in table II(b) and plotted in figure 8(b). When the average time to rupture was 1.37 hours, the critical aspect ratio, as shown in figure 8(b-1), was 20.0. For an average time to rupture of 10.33 hours (fig. 8(b-2)), the critical aspect ratio was 23.0. Similarily, for a rupture time of 42.31 hours the critical aspect ratio was 27.5, as shown in figure 8(b-3). The results of these tests, as well as of the tensile tests, are summarized in table III.

Results of shear stress-rupture tests on bulk samples of OFHC copper in the annealed condition are listed in table IV and shown graphically in figure 9. These data were obtained so that the stress-rupture properties of copper in the bulk form could be compared to the properties of the copper in the pull-out specimens. Also shown are the shear stress-rupture properties of OFHC copper obtained from copper failures in pull-out specimens.

DISCUSSION

Results of this investigation show that the critical aspect ratio necessary for reinforcement in a discontinuous fiber composite of tungsten wire - copper increases with time as well as with temperature. A summary of the results of stress-rupture tests performed at 1200° and 1500° F (649° and 816° C) are shown in figure 10. At 1200° F (649° C), the critical aspect ratio in short-time tension was 15. For the same material combination to have a stress-rupture life of 79 hours it was necessary to increase the fiber aspect ratio to 19.

A similar trend was observed at 1500° F (816° C). At this temperature the critical aspect ratio for stress-rupture failure in 42 hours increased by almost 39 percent over that required in short-time tensile tests.

It might be expected that the critical aspect ratio in stress-rupture would be different than in tension. It is interesting to note the relatively small change in critical aspect ratio required for a rupture life of 100 or even 1000 hours. The use of tungsten wire in copper was intended as a model system and not for use at elevated temperature because of the low strength of copper. Yet, at 1500° F (816° C), which is 80 percent of the melting point of copper, the critical aspect ratio for a 100-hour stress-rupture life was only 27.5 and extrapolates to 33 for 1000 hours life. Assuming that a tungsten wire 10 mils (0.0254 cm) in diameter is used in a copper matrix to make a composite, it need be only 0.66 inch (1.68 cm) long to provide reinforcement for 1000 hours. Previously, it had been estimated that a much higher aspect ratio would be required.

It would be desirable to compare the observed critical aspect ratios with predicted values based upon the known properties of the constituents. A fiber reinforced composite is made up of three major parts: the fiber, the matrix, and the interface between them. The properties of all three, as they exist in the composite, should be known.

Tests can be made on fibers which have been heat treated to duplicate the thermal history of the fibers in the composite. Fibers may also be tested after removal from an already fabricated composite. Both methods have been used with considerable success by various investigators.

Determination of the properties of the matrix is somewhat more difficult. Transfer of the load from one fiber to the next is by shear through the matrix. Accurate determination of the shear properties without error due to tensile or compressive stresses is difficult (ref. 8). In fiber reinforced composites tested in creep or stress-rupture, the matrix is subjected to shear creep. Data on shear creep are not available in the literature.

Additionally, the effect of the bond or interface between the fibers and matrix may alter the matrix properties. It was shown in reference 6 that a region in the matrix adjacent to the fiber was restrained and had properties considerably different from the bulk properties of the matrix. Any such change would have a pronounced effect on the critical aspect ratio (ref. 6).

In this investigation, a comparison was made of the shear stress-rupture properties of copper from the pull-out specimens and copper tested separately (fig. 9). This was intended as a first step towards comparing the observed critical aspect ratio to the calculated critical aspect ratio based upon the properties of the materials tested separately. As can be seen in figure 9, the agreement at 1200° F (649° C) was fair, particularly with regard to the rate of change. The results of tests at 1500° F (816° C) show no such agreement. The reasons for this lack of agreement are probably the failure to test the copper in pure shear stress-rupture and the inability to account for differences in the properties of the copper in a restrained form such as occurred in the pull-out specimens. More useful data relating to the effects of restraint on the matrix and more data on shear stress-rupture are necessary before a detailed comparison can be made.

Figure 11 shows the family of curves for tungsten-copper which illustrates how the critical aspect ratio changes as a function of temperature. The conditions shown are for stress-rupture lives of 1, 10, 100, and 1000 hours. This shows the moderate aspect ratios necessary to accomplish reinforcement for stress-rupture life of as much as 1000 hours. Also important is the change in the critical aspect ratios as the temperature is increased. Different combinations of fiber and matrix will result in different values and rates of change, depending on the properties of the constituents used in the composite.

An illustration of the change in critical aspect ratio for different materials combinations is shown in figure 12. It has been assumed that the same fiber was used in each case. Matrix I is a material which shows a rapid decrease in stress-rupture life as the applied stress is increased. The slope of the stress-time curve for this material would be much steeper than the slope of the curve for the fiber. These two materials in combination would exhibit a rapid increase in critical aspect ratio as the time to failure increased. This is comparable in behavior to the tungsten-copper system. The curve for the system utilizing matrix II is illustrative of a system such as tungsten-nickel, assuming the effects of alloying are not considered. The slope of the matrix curve would more nearly match that of the fiber, and therefore the critical aspect ratio would not change as rapidly. In the third combination, matrix III, the slope of the matrix curve is parallel to that of the fiber. For a combination of this sort, there would be no change in the critical aspect ratio as the time to failure was changed. A system such as tungsten fiber in molybdenum or in a ceramic might exhibit such behavior. A fourth possible combination in which the slope of the matrix curve would be less than that of the fiber could also be visualized, but such a combination is unlikely.

The stress-rupture properties of the fiber and matrix not only determine the critical aspect ratio, but the stress-rupture properties of the composite itself. In reference 5, which was a study of tungsten reinforced silver, it was concluded that the matrix controlled the creep rate of a discontinuous fiber reinforced composite. Although the present investigation used pull-out specimens to examine stress-rupture failure, which is a creep-related phenomenon, the results indicate that such a conclusion must be modified. When the aspect ratio of the fiber in a pull-out specimen is below the critical aspect ratio and the stress on the matrix is sufficiently high to cause matrix shear failure, pull-out occurs (figs. 8(a) and (b)). The time required is a function of the stress on the matrix and its creep rate. At fiber lengths greater than the critical length and where fiber fracture occurs, the fiber properties control the rupture behavior of the composite. This has already been shown for continuous length fiber composites (ref. 4). The fiber length selected for specimens in reference 5 was near that necessary for short-time tensile pull-out. As would be expected with lengths less than the critical length for rupture tests, the specimens failed by pull-out, with the matrix controlling the failure time.

CONCLUDING REMARKS

The results of this study indicate that the critical aspect ratio for stress-rupture times as long as 1000 hours is relatively small; the critical fiber lengths necessary for adequate reinforcement are comparatively short. This finding adds promise for the use of discontinuous length fiber composites for long-time tensile (stress-rupture) applications. However, the critical length is the minimum fiber length required to cause tensile failure of the fiber in a composite. In composites with fiber lengths equal to, or only slightly greater than, the critical length, the strength is considerably below that for continuous length fibers. Fiber lengths several times the critical length are required so that the effective strength of the composite is a high percentage of the fiber strength. Consideration of the effect of increased fiber length on the effective stress-rupture strength of a composite has not appeared in the literature. The discussion which follows is an attempt to extrapolate the results of this investigation to more practical systems.

As such, this extrapolation may be considered a first approximation of the fiber length required to realize large fractions of the fiber strength during long-time service.

The effect of variations in fiber length greater than the critical fiber length has been studied for short-time tensile applications (ref. 9). The load-carrying efficiency, the ratio of average fiber tensile stress to fiber tensile strength, can be calculated for short-time tensile failure by using the following equation from reference 10:

$$\beta_{eff} = \left(1 - \frac{l_c}{2l}\right) \times 100$$

where

β_{eff} load-carrying efficiency, percent

l_c critical fiber length

l actual fiber length

To make an approximation of fiber efficiency for stress-rupture such as can be made for short-time tensile tests, detailed data on the creep of the fiber and the matrix, as well as restraining effects within the composite, would be required. Such data are not available. Therefore, all approximations were made using the equations for short-time tensile failure.

A fiber reinforced composite of 15- mil- (0.0381-cm) diameter tungsten - 2-percent-thoria wire in a nickel alloy matrix (refs. 3 and 11) is attractive for application temperatures of 2000° and 2200° F (1093° and 1204° C). Figure 13 shows the results of calculations made of the load-carrying efficiency of various-length fibers in this system by using short-time tensile and shear data from references 3 and 11.

The calculated critical fiber length in short-time tension at 2000° F (1093° C) is 0.18 inch (0.46 cm). For a 1000-hour stress-rupture life at the same temperature, the critical fiber length increases to 0.45 inch (1.14 cm). But fibers of the critical length are only 50 percent efficient. To increase the efficiency to 95 percent, the fibers need only be 1.81 inches (4.60 cm) long for short-time tensile applications or 4.53 inches (11.51 cm) long for a usable life of 1000 hours at 2000° F (1093° C). These fiber lengths are within the normal dimensions of many components.

High-efficiency joints can be made in this material by using relatively short fiber lengths. In the case of a simple scarf joint, assuming a good metallurgical bond at the interface, an overlap of 0.90 inch (2.28 cm) would be sufficient for a joint efficiency of 95 percent for short-time tensile applications at 2000° F (1093° C). An overlap of 2.27 inches (5.87 cm) would be required for a 1000-hour stress-rupture life at 2000° F (1093° C). These approximations assume a uniform temperature over the entire length of the component or joint. In reality, a turbine blade, for example, operating at 2000° F (1093° C) would be expected to be cooled at its base. Such a condition would result in a much shorter length of overlap at the base.

CONCLUSIONS

Investigation of the influence of fiber aspect ratio on the stress-rupture life of simulated discontinuous fiber reinforced composites has led to the following conclusions:

1. The critical aspect ratio of fibers used to reinforce composites for long-time tensile applications at elevated temperature is greater than the critical aspect ratio for short-time applications. The difference, however, is comparitively small. At 1500° F (816° C), the critical aspect ratio in tension was 19.8, while for a stress-rupture life of 10.33 hours the critical aspect ratio increased to 23. The critical aspect ratio in stress-rupture, though greater than that for short-time applications, is within the same order of magnitude, and well within practical limits for successful component fabrications. At 1500° F (816° C), the critical aspect ratio for a tungsten-copper specimen containing 10-mil- (0.0254-cm-) diameter wire tested in tension was 19.8 (or 0.198 in. (0.503 cm)). For a stress-rupture life of 1000 hours at the same temperature, the extrapolated critical aspect ratio is 33 (or 0.330 in. (0.838 cm)), an increase of 67 percent.

2. When the length of the reinforcing fibers are below the critical length, time to failure of the composite is controlled by the properties of the matrix (copper). When they are longer than the critical length, failure time of the composite is determined by the properties of the fiber (tungsten).

Lewis Research Center,
National Aeronautics and Space Administration,
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TABLE I. - RESULTS OF ELEVATED-TEMPERATURE SHORT-TIME TENSILE TESTS ON TUNGSTEN WIRE - COPPER PULL-OUT SPECIMENS

Test temperature		Failure mode	Aspect ratio	Failure load	
^{o}F	^{o}C			lbf	N
1200	649	Pull-out	9.5	7.00	31.15
			9.5	7.80	34.71
			10.5	9.30	41.38
			10.5	9.80	43.61
			11.5	11.00	48.95
			11.5	10.00	44.50
			12.8	11.70	52.06
			13.0	10.50	46.72
			13.5	12.50	55.62
		Wire	14.7	13.47	59.94
			15.7	13.80	61.41
			16.0	13.50	60.07
			16.5	13.76	61.23
			17.5	13.44	59.80
			19.0	13.00	57.85
			22.1	14.79	65.81
1500	816	Pull-out	9.0	7.52	33.46
			11.5	7.75	34.48
			15.1	8.60	38.27
			16.5	9.60	42.72
			17.0	11.50	51.17
			20.0	11.50	51.17
		Wire	21.2	12.80	56.96
			22.0	12.50	55.62
			24.2	11.00	48.95
			24.2	12.00	53.40
			26.0	12.10	53.84
			29.0	12.08	53.75

TABLE II. - RESULTS OF STRESS-RUPTURE TESTS ON TUNGSTEN WIRE - COPPER PULL-OUT SPECIMENS

(a) Specimens tested at 1200° F (649° C)

Wire stress, psi	Wire stress, N/cm²	Aspect ratio	Failure mode	Time, hr	Shear stress, psi	Shear stress, N/cm²
155 600	107 271	5.3	Pull-out	(a)	7300	5033
		7.2	Pull-out	(a)	5400	3723
		12.5	Pull-out	0.18	3100	2137
		68.8	Wire	28.07	550	379
		10.5	Pull-out	.08	3700	2551
		17.0	Wire	37.60	2300	1586
		48.3	Wire	33.17	800	551
		13.4	Pull-out	11.50	2900	1999
		15.0	Pull-out	10.27	2600	1792
		16.9	Pull-out	40.56	2300	1586
		27.0	Wire	43.65	1450	1000
		17.8		45.67	2200	1517
		33.7		22.16	1200	827
		39.9		37.71	1000	689
155 100	106 926	10.5	Pull-out	7.54	3700	2251
		12.5	Pull-out	23.07	4000	2758
		17.0	Pull-out	140.11	2300	1586
		28.0	Wire	65.86	1400	965
		18.8		65.83	2050	1413
		48.0		122.39	800	551
		19.5		78.99	1900	1310
		21.7		70.14	1800	1241
		17.6	Pull-out	84.46	2200	1517
		5.9	Pull-out	(a)	6600	4550
		7.4	Pull-out	(a)	5250	3619
		39.4	Wire	72.43	1000	689

(b) Specimens tested at 1500° F (816° C)

Wire stress, psi	Wire stress, N/cm²	Aspect ratio	Failure mode	Time, hr	Shear stress, psi	Shear stress, N/cm²
140 100	96 585	13.6	Pull-out	(a)	2600	1792
		-20.0	Pull-out	0.36	1750	1206
		25.7	Wire	1.60	1350	931
		16.7	Pull-out	.95	1900	1310
		14.6	Pull-out	.23	2200	1517
		39.3	Wire	1.00	850	586
		19.6	Pull-out	.22	1650	1137
		19.6	Wire	1.06	1650	1137
		18.9	Pull-out	(a)	1700	1172
		17.9	Pull-out	1.28	1800	1241
		16.7	Pull-out	1.53	1900	1310
		21.6	Wire	1.92	1500	1034
		18.9	Pull-out	(a)	1700	1172
131 250	90 484	33.9	Wire	8.29	950	655
		15.0	Pull-out	1.19	2200	1517
		20.0	Pull-out	1.93	1650	1137
		28.0	Wire	8.96	1150	793
		26.9		5.53	1200	827
		27.0		4.92	1200	827
		39.8		4.15	800	551
		10.6	Pull-out	.02	3100	2137
		13.6	Pull-out	(a)	2400	1655
		48.5	Wire	13.81	700	483
		17.0	Pull-out	.73	1950	1344
		28.0	Wire	4.12	1200	827
		29.7		23.01	1100	758
		24.0		14.48	1400	965
		48.0		16.06	700	482
		23.2		9.61	1450	1000
		21.6		5.08	1500	1034
		45.0		16.29	750	517
		21.6	Pull-out	6.80	1500	1034
119 750	82 560	17.9	Pull-out	4.11	1700	1172
		25.3	Pull-out	41.15	1200	827
		33.7	Wire	40.89	900	620
		27.7	Wire	40.35	1100	758
		15.3	Pull-out	1.95	1950	1344
		27.5	Wire	40.26	1100	758
		22.1	Pull-out	19.14	1350	931
		39.3	Wire	47.77	750	517
		21.8	Pull-out	8.76	1350	931

[a]Broke on loading.

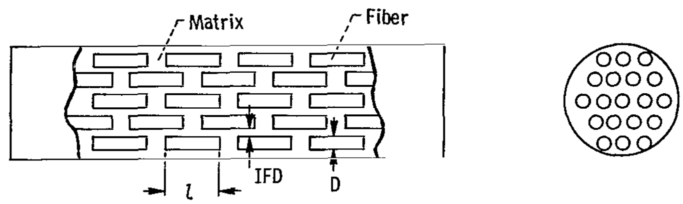
TABLE III. - SUMMARY OF OBSERVED CRITICAL ASPECT RATIOS OF TUNGSTEN WIRE - COPPER COMPOSITES IN SHORT-TIME TENSILE AND STRESS-RUPTURE TESTS

Temperature		Test	Time, hr	Critical aspect ratio
^{o}F	^{o}C			
1200	649	Short-time tensile	-----	15.0
		Stress-rupture	35.43	17.0
			79.26	19.2
1500	816	Short-time tensile	-----	19.8
		Stress-rupture	1.37	20.0
			10.33	23.0
			42.31	27.5

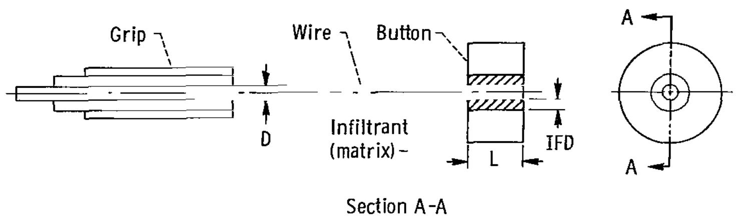
TABLE IV. - RESULTS OF STRESS-RUPTURE TESTS ON OFHC COPPER

[Copper annealed 1 hr at 1500^{o} F (816^{o} C) in hydrogen; test condition, shear.]

Test temperature		Stress		Life, hr
^{o}F	^{o}C	psi	N/cm^2	
1200	649	2250	1550	2.8
		2060	1419	15.1
		1900	1309	22.6
		1500	1033	173.0
1500	816	1500	1033	0.3
		1250	861	.6
		1000	689	.5
		750	517	2.4
		500	344	7.3

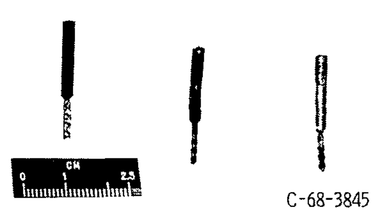


(a) Idealized short fiber composite.



(b) Test specimen.

Figure 1. - Comparison of test specimen and short fiber composite.



(a) Before test. (b) Wire failure. (c) Pull-out.

Figure 2. - Stress-rupture specimens.

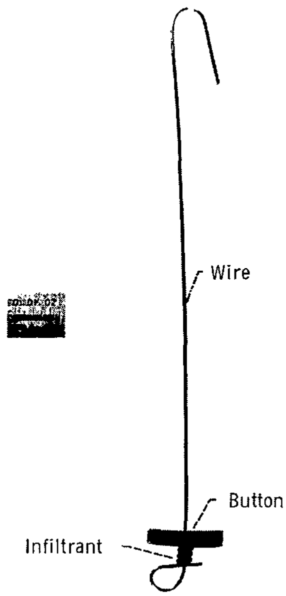


Figure 3. - Pull-out specimen prior to infiltration.

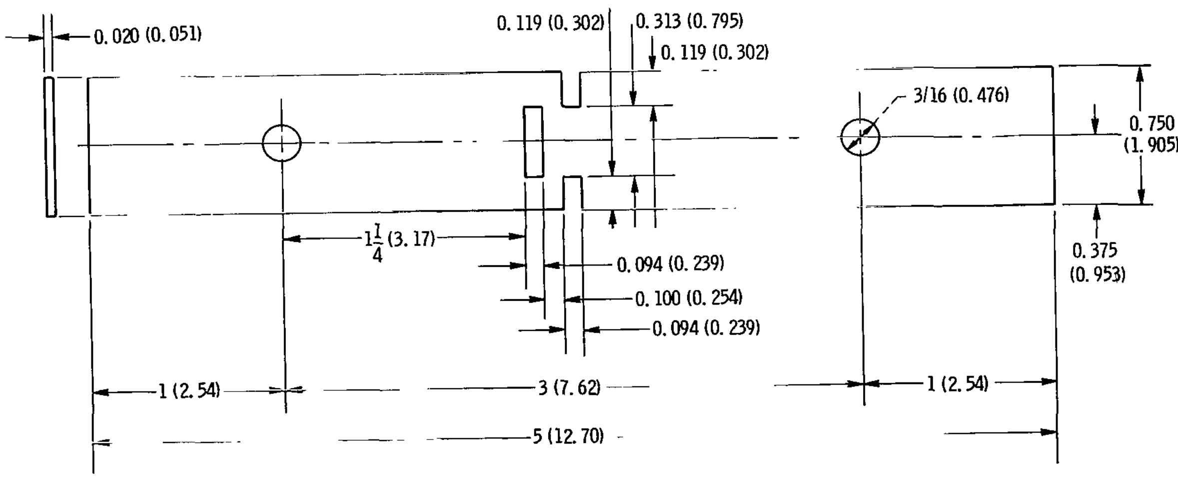


Figure 4. - Shear specimen. (Dimensions are in inches (cm). All fractions, ±1/64 (0.040); all decimals, ±0.0005 (0.0013).)

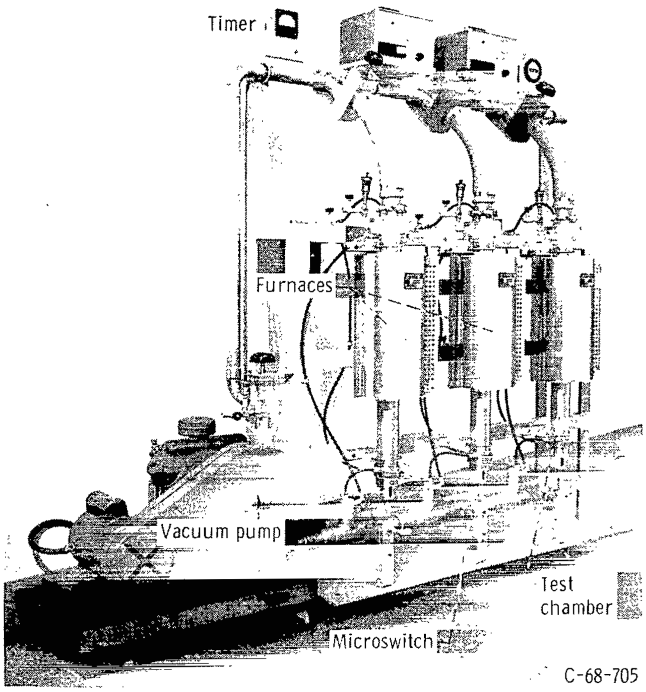


Figure 5. - General view of stress-rupture equipment.

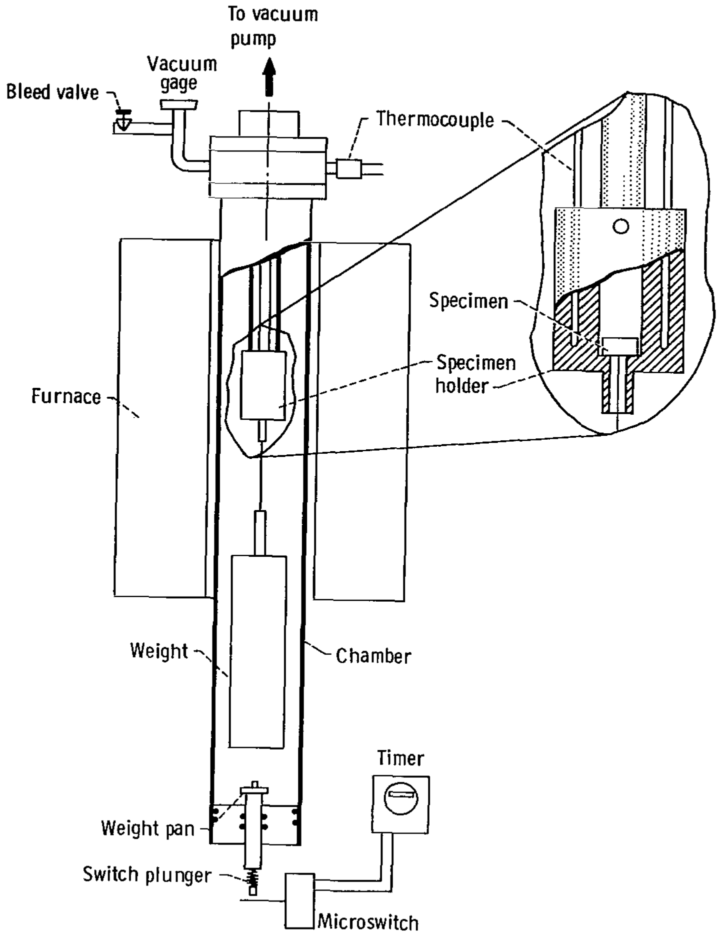


Figure 6. - Layout of vacuum stress-rupture test equipment (inset) detail of specimen and specimen holder.

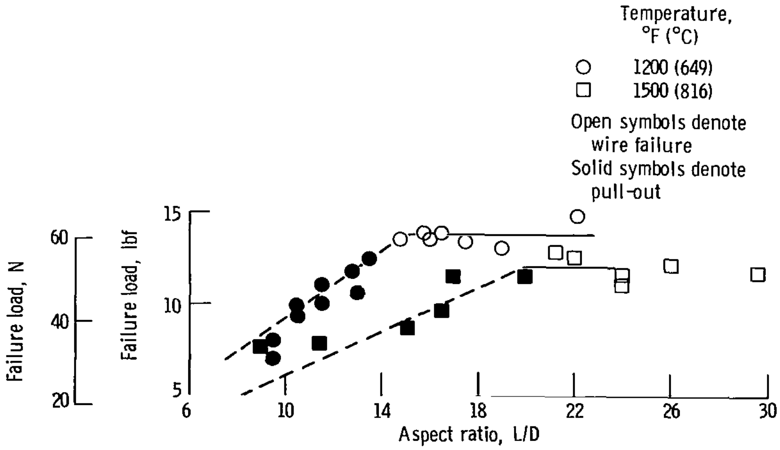
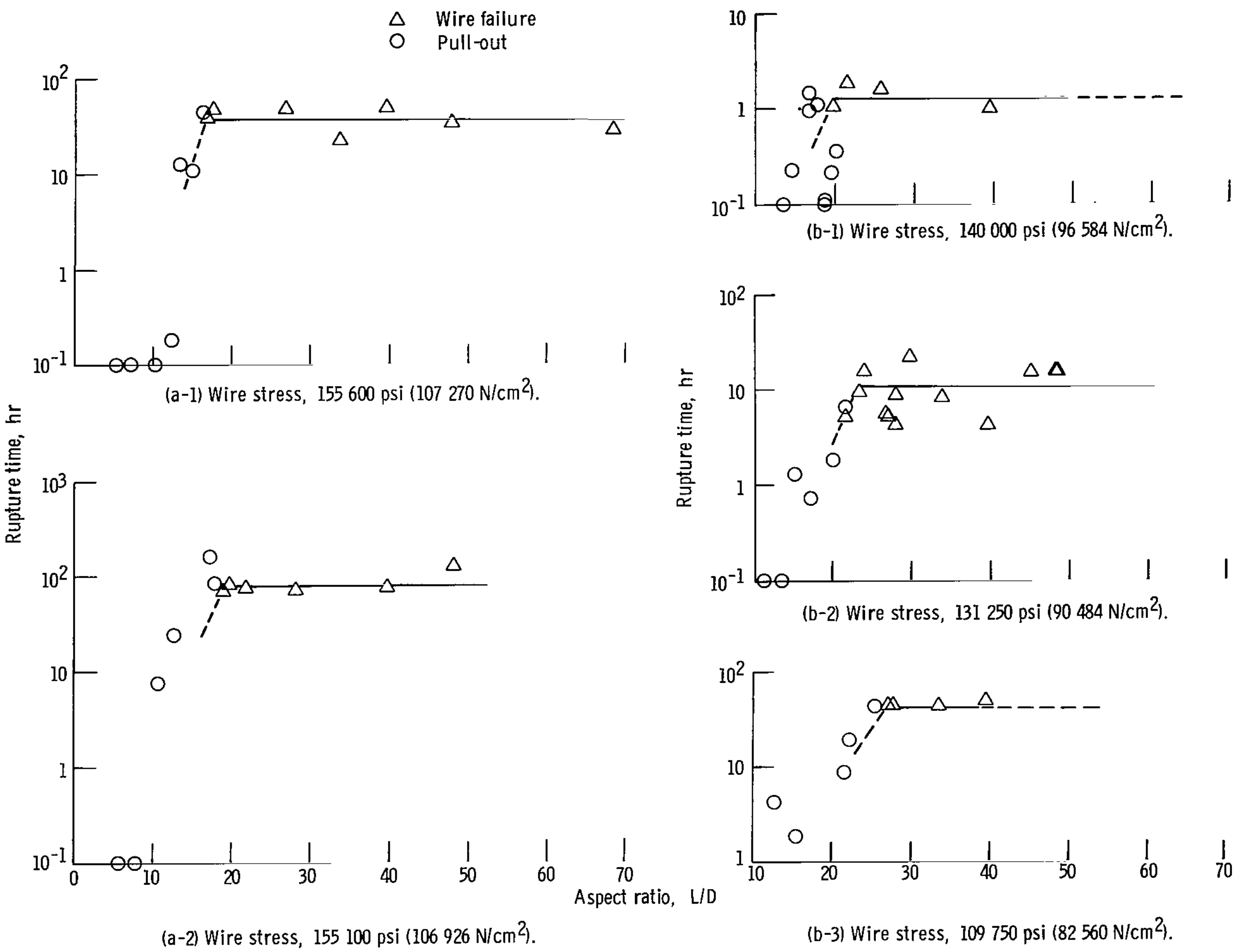


Figure 7. - Failure load and mode at various aspect ratios for tungsten wire - copper, short-time tensile tests.



(a) Temperature, 1200° F (649° C).

(b) Temperature, 1500° F (816° C).

Figure 8. - Failure time and mode at various aspect ratios for tungsten wire - copper.

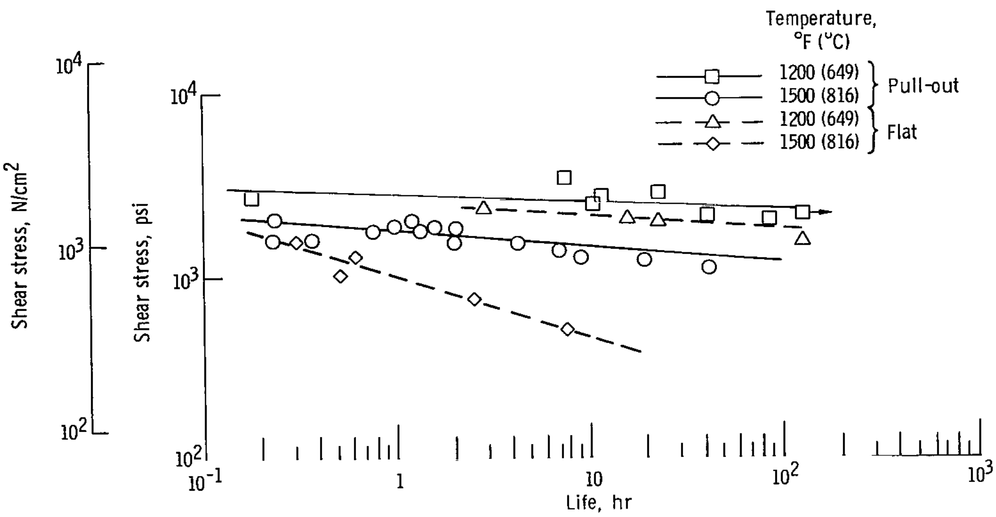


Figure 9. - Shear stress-rupture properties of copper at 1200° and 1500° F (649° and 816° C). Comparison of results from pull-out shear and flat shear specimens.

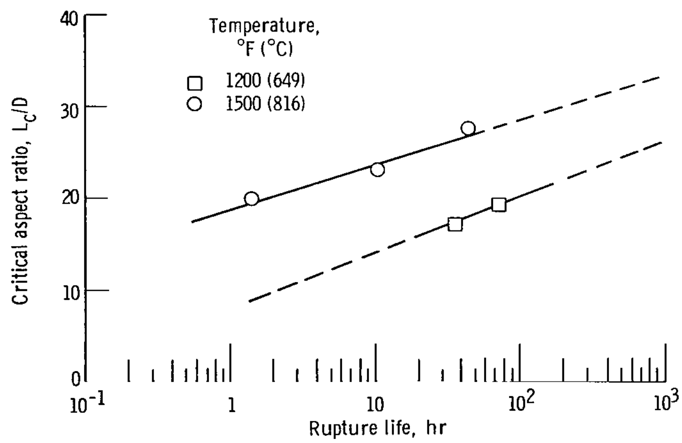


Figure 10. - Critical aspect ratios of tungsten wire - copper pull-out specimens tested in stress-rupture at 1200° and 1500° F (649° and 816° C).

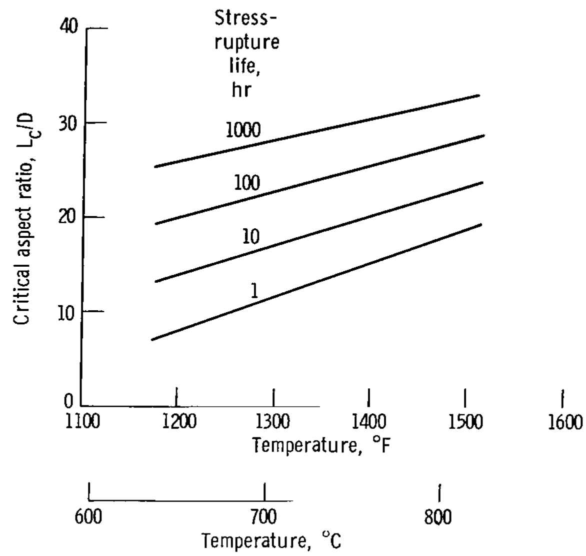


Figure 11. - Calculated critical aspect ratios of tungsten wire - copper pullout specimens in stress-rupture at 1200° and 1500° F (649° and 816° C).

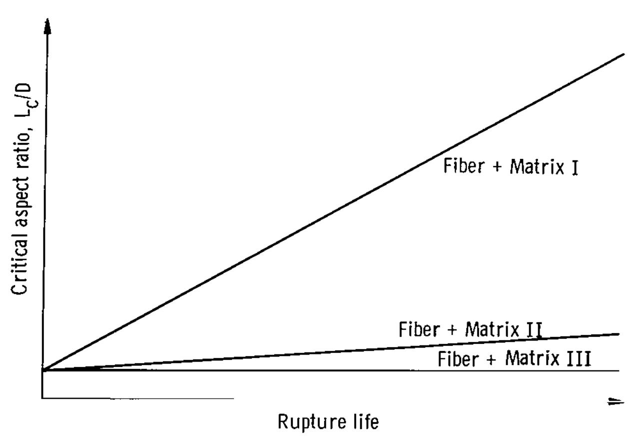


Figure 12. - Critical aspect ratios for various hypothetical fiber-matrix combinations.

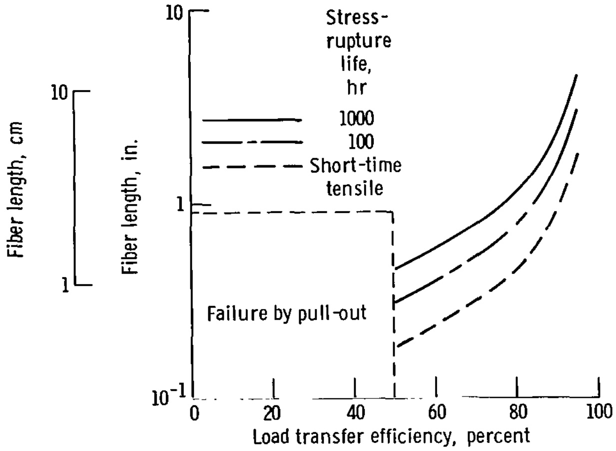


Figure 13. - Calculated load transfer efficiency of various length tungsten - 2-percent-thoria fibers in a nickel alloy (Ni-25W-15Cr-2Al-2Ti) at 2000° F (1093° C). (Material properties from refs. 3 and 11.)

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