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Low-Temperature Solder for Joining Large Cryogenic Structures

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John D. Buckley and Paul G. Sandefur, Jr.
Langley Research Center
Hampton, Virginia

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SUMMARY

Three joining methods were considered for use in fabricating cooling coils for the National Transonic Facility. After analysis and preliminary testing, soldering was chosen as the cooling-coil joining technique over mechanical force-fit and brazing techniques. Charpy V-Notch tests, cyclic thermal tests (ambient to 77.8 K) and tensile tests at cryogenic temperatures were performed on solder joints to evaluate their structural integrity. It was determined that low-temperature solder can be used to ensure good fin-to-tube contact for cooling-coil applications.

INTRODUCTION

It has been shown (ref. 1) that the cryogenic wind-tunnel concept permits high Reynolds numbers to be obtained at relatively low energy consumption levels compared to other high Reynolds number wind-tunnel concepts. However, despite this relatively economical use of energy, the overall consumption of energy in high Reynolds number tunnels is high, primarily because of the use of liquid-nitrogen injection for cooling (ref. 2). If a conventional chilled-water heat exchanger were used for cooling in the ambient temperature mode of operation instead of liquid-nitrogen injection, it has been estimated that the consumption of energy in this mode would be reduced by an order of magnitude. The cost of the energy would be reduced even further. In addition to the advantages in energy consumption, the benefits of using a conventional heat exchanger for cooling would also include the capability to use air as well as nitrogen as the test gas in the ambient temperature mode. Figure 1 shows the location of the cooling coil in the National Transonic Facility (NTF). It will be used when operating under ambient conditions using air; however, it will not be used when operating under cryogenic conditions. Tests performed on round and elliptical tube and fin cooling-coil specimens, measured as a function of Reynolds number based on tube hydraulic diameter, showed an apparent aerodynamic advantage of elliptical tube shape compared with round shape for pressure loss and turbulence characteristics (ref. 3). Figure 2 shows a segment of the cooling coil used in the NTF. The tube and fin structures are arranged in rows four deep in the direction of the fluid flow and are fabricated in gangs 0.914 m and 0.457 m across as shown in figure 3. The diameter of the cooling coil is approximately 12.1 m.

Upon completion of the design and definition of the expected thermomechanical and thermodynamic loads, when operating this tunnel, inquiries were made with industry having this expertise. Industry indicated that the uniqueness of this one-of-a-kind cooling-coil heat exchanger would require study and development. Because of the need for this heat exchanger in the NTF, Langley Research Center engaged in a study of the materials and fabrication technology as related to cooling coils exposed to cyclic cryogenic atmosphere. Two interdependent areas of concern became evident: (1) the 12.1-m diameter structure, suggesting the potential need for segmented lengths of cooling coil requiring tube-to-tube joints and (2) the effect of cyclic thermal excursions at cryogenic temperatures and the effect of cryogenic to ambient temperatures on joints and joint bonding materials.

JOINING METHODS AND MATERIALS

Table I shows the joining methods considered for fabricating the NTF cooling coils. Mechanical force fit is the technique most commonly used in industry to fabricate cooling coils. This method was ruled out early in the study when analysis indicated that thermal cycling in a cryogenic atmosphere would loosen the interface between the tube and fin components making up the cooling coil, thereby decreasing the heat transfer efficiency of the system. A second method eliminated early in the study was the dip brazing of aluminum (tables I and II). This technique was dropped because of corrosion experienced with aluminum tubing used in similar circumstances. Vacuum brazing of as-drawn (hard copper) oxygen-free copper (tables I and II) brazed with an alloy composed of 72 percent silver and 28 percent copper was accomplished in a vacuum braze furnace at 0.00133 newton/ meter^2 at a maximum temperature of 1097.6 K. Figure 4 shows the braze test specimen with fins, tubes, and joints. The joints were required in the specimen because joints would be needed in the full-scale cooling coil. There are no vacuum braze furnaces in the United States capable of brazing a cooling coil over 12.1 m in length with the configuration required for the NTF. Finally, two low-temperature solders (table II) were also evaluated for joining the as-drawn (hard copper) oxygen-free copper. The advantage of using low-temperature solder was the availability of furnaces that would allow for fabricating 12.5-m-long (diameter) cooling coils. The two solders evaluated were eutectic compositions as shown in figures 5 and 6. These eutectic alloys show melting temperatures of 494 K and 456 K, respectively, low enough not to deleteriously affect the mechanical properties of the hard copper tubes and fins being soldered. The low melting temperature of these alloys plus limited experience in their use at Langley were the reasons for evaluating them as candidate joining materials. A major disadvantage when using high tin solders is the brittleness of these solders when subjected to temperatures at and below their ductile-brittle transition temperature of 173.6 K (ref. 4).

TEST AND PROCEDURE

Because of the problem of brittleness with tin solder and limited data on materials subjected to the unique environmental regime of the NTF, a series of quality tests were undertaken. Tensile load tests were performed on copper tube specimens (fig. 7) joined at the center to evaluate solder alloy compositions (table II) in cryogenic atmospheres. Cryogenic tensile tests were performed in a cold-box tensile test facility. Cyclic cryogenic tests consisted of two steps. Tensile specimens (fig. 7) were submerged in liquid nitrogen, held in place until thermal equilibrium was reached, raised out of the nitrogen into a furnace at 355.6 K, and again held in position until thermal equilibrium was reached. Then the cycle was repeated for a predetermined number of cycles. Upon completion of the desired number of thermal cycles, the specimens were removed from the thermal cycling system and tested (ambient conditions) in tension in the tensile testing machine. Tensile tests were conducted at a strain rate of 0.51 mm per minute. Thermal cycle tests made on a segment of the NTF cooling coil to evaluate the integrity of the fin-to-tube bond used the thermal cyclic technique described previously for the tensile specimens (fig. 8). Upon completion of the thermal cycles, the specimen was examined with a metallograph to observe the presence of cracks at the fin-tube interface.

RESULTS AND DISCUSSION

As described previously in this paper, mechanical force-fit brazing and dip brazing were eliminated after analysis of these techniques. Upon completion of vacuum brazing a hard copper specimen brazed with 72 percent silver and 28 percent copper, this technique was dropped. The specimen shown in figure 9 was so ductile after brazing that it was determined that copper cooling coils fabricated using this technique would be considered structurally unacceptable. Because soldering would allow fabrication at low temperatures (453.6 K) and eliminate the need for joints, it was considered the most promising method for manufacture of the cooling coils. The solder material now had only one major function and that was to maintain its thermal interface between cooling-coil fin and tube when subjected, though not in use, to cryogenic cycling. The results of a literature search are summarized in table III. The data indicate that solder alloys having a major tin constituent become brittle and eventually crack when subjected to cyclic heating and cooling between 355.6 K and 77.8 K. Charpy V-Notch tests were performed on the two solder alloys chosen for this structure to substantiate data from the literature. The V-Notch tests showed both alloys had acceptable toughness at room temperature but had very low impact strength at 77.8 K.

Because the cooling coil would have no impact loads and would operate in ambient conditions, several additional tests were performed to evaluate the integrity of the tube-to-fin solder joint. Tensile load tests were performed on copper tube specimens (fig. 7) joined at the center with the solder alloy compositions shown in table II. Tensile tests were used as the criteria for solder joint acceptability since a cracked specimen, assuming a crack in the solder joint resulted from specimen exposure to cycling at cryogenic temperatures, would have a lower tensile strength than a specimen with no flaws. Figure 10 shows solder joint strength as a function of temperature. The curves show the expected increase in strength to the ductile-brittle transition temperature, where the strength then falls off (ref. 5). The important point observed in these curves was that the solder joint strength (low notch toughness, table IV) at cryogenic temperatures approximated or was stronger than the solder joint tested at room temperature (good notch toughness, table IV). Figure 11 shows joint strength of specimens pulled at ambient temperature after up to 5000 cyclic cryogenic exposures between 77.8 K and 355.6 K. Lines faired through data points for the two solder alloys evaluated showed no appreciable change in the strength of the solder joints. Finally, the typical segment of a fin-tube cooling coil (fig. 8) cycled 5000 times between 77.8 K and 355.6 K showed no cracks at the tube-fin interface when examined with a metallograph.

CONCLUSIONS

The results of this study indicate the following conclusions:

1. Cyclic cryogenic exposure did not affect the room-temperature strength of the low-temperature solder joint.

2. The low-temperature solders in the joints tested did not show cracking when submitted to cyclic exposure below their ductile-brittle transition temperature.

3. Low-temperature solder can be used to ensure good fin-to-tube contact for cooling-coil applications.

Langley Research Center
National Aeronautics and Space Administration
Hampton, VA 23665
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REFERENCES

1. Kilgore, Robert A.; Goodyer, Michael J.; Adcock, Jerry B.; and Davenport, Edwin E.: The Cryogenic Wind-Tunnel Concept for High Reynolds Number Testing. NASA TN D-7762, 1974.

2. Polhamus, E. C.; Kilgore, R. A.; Adcock, J. B.; and Ray, E. J.: The Langley Cryogenic High Reynolds Number Wind-Tunnel Program, Astronaut. & Aeronaut., vol. 12, no. 10, Oct. 1974, pp. 30-40.

3. Johnson, William G., Jr.; and Igoe, William B.: Aerodynamic Characteristics at Low Reynolds Numbers of Several Heat-Exchanger Configurations for Wind-Tunnel Use. NASA TM-80188, 1979.

4. Hansen, Max: Constitution of Binary Alloys. Second ed. McGraw-Hill Book Co., Inc., 1958.

5. Jaffee, R. I.; Minarcik, E. J.; and Gonser, B. W.: Low-Temperature Properties of Lead-Base Solders and Soldered Joints. Metals Progr., vol. 54, no. 6, Dec. 1948, pp. 843-845.

TABLE I.- JOINING METHODS

- MECHANICAL FORCE FIT
- BRAZING
  - A. DIP BRAZING
  - B. VACUUM FURNACE BRAZING
- SOLDERING
  - A. 95% TIN – 5% SILVER
  - B. 63% TIN – 37% LEAD

TABLE II.- COOLING-COIL MATERIALS

TUBE AND FIN ALLOYS	BRAZE ALLOYS	SOLDER ALLOYS	JOINING TECHNIQUES
6061 ALUMINUM	89% ALUMINUM 11% SILICON		DIP BRAZING
OXYGEN FREE COPPER	72% SILVER 28% COPPER		VACUUM BRAZE (HARD-COPPER)
OXYGEN FREE COPPER		95% TIN 5% SILVER 63% TIN 37% LEAD	LOW TEMPERATURE FURNACE SOLDER (HARD-COPPER)

TABLE III.- SOLDER DATA - ELECTRICAL CONNECTIONS

- TIN SOLDER TESTS
  - —63 TIN - 37 LEAD
  - —95 TIN - 5 ANTIMONY
- CYCLED BETWEEN 77.8 K AND 355.6 K
- SOLDER WIRE CONNECTIONS BECAME BRITTLE AND DEVELOPED CRACKS RESULTING IN NOISY ELECTRICAL OUTPUT

TABLE IV.- ASTM CHARPY V-NOTCH TEST DATA

SOLDER MATERIALS

TEMPERATURE, K	QUANTITY	95% TIN – 5% SILVER IMPACT VALUE, J	63% TIN – 37% LEAD IMPACT VALUE, J
ROOM TEMP.	6	51.68	25.84
355.6	6	51.68	25.84
77.8	6	.544	1.22

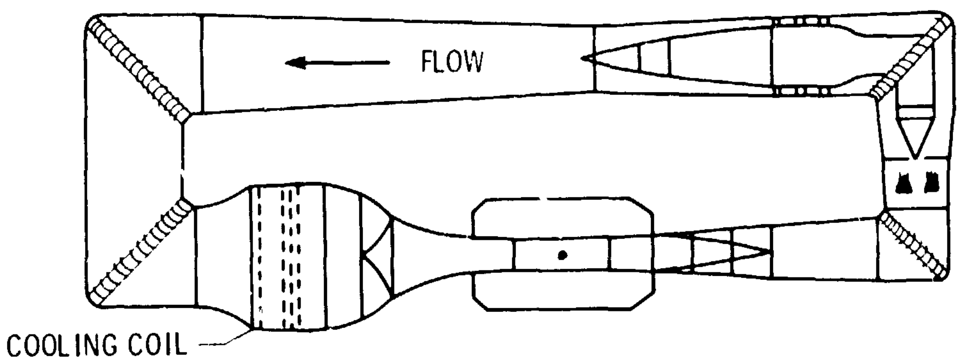

Figure 1.- Location of cooling coils in NTF.

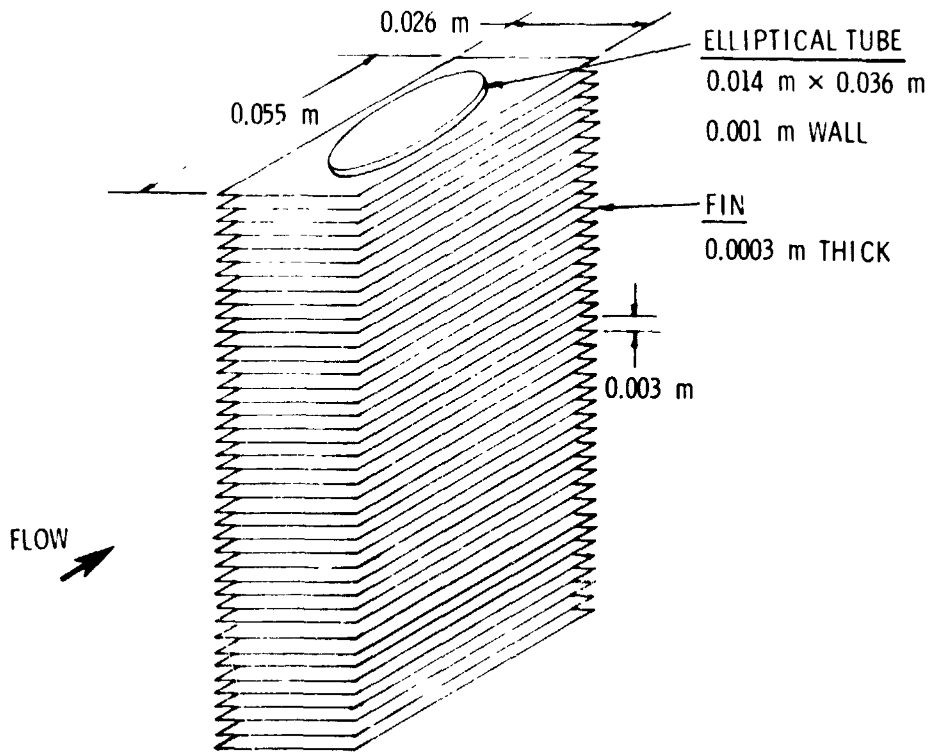

Figure 2.- Fin-tube concept showing section of NTF cooling coil.

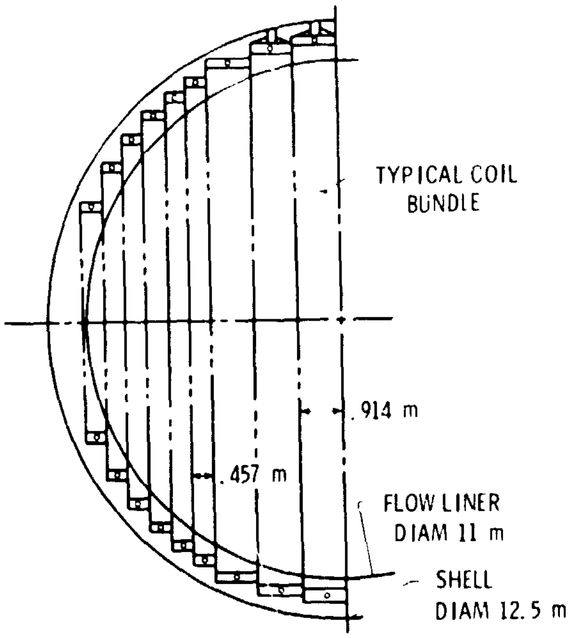

Figure 3.- Cross section of NTF tunnel showing cooling coil.

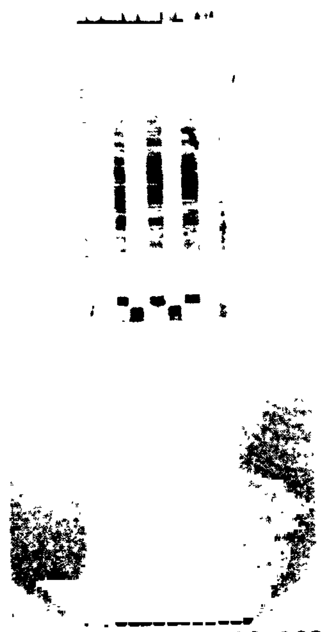

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Figure 4.- Braze test specimen showing fin-to-tube and tube-to-tube joints.

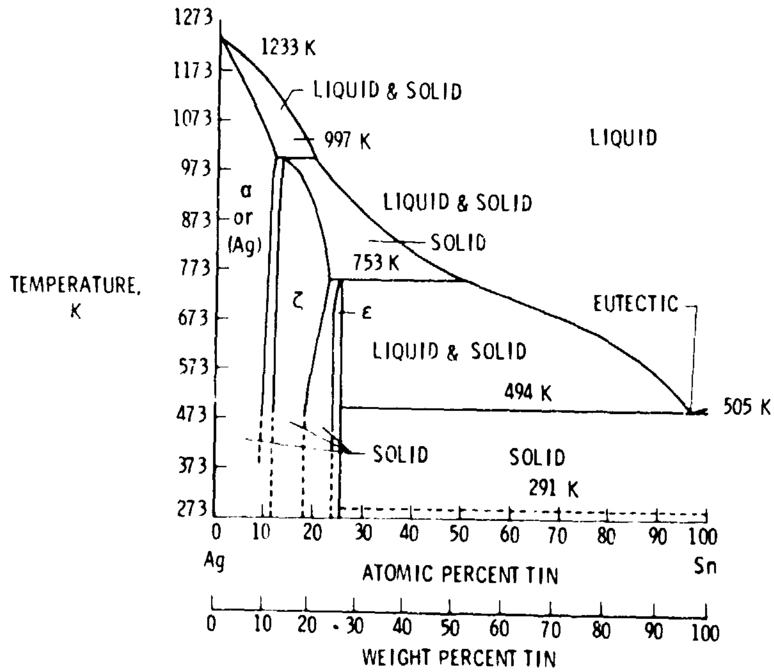

Figure 5.- Equilibrium phase diagram for silver-tin (ref. 4).

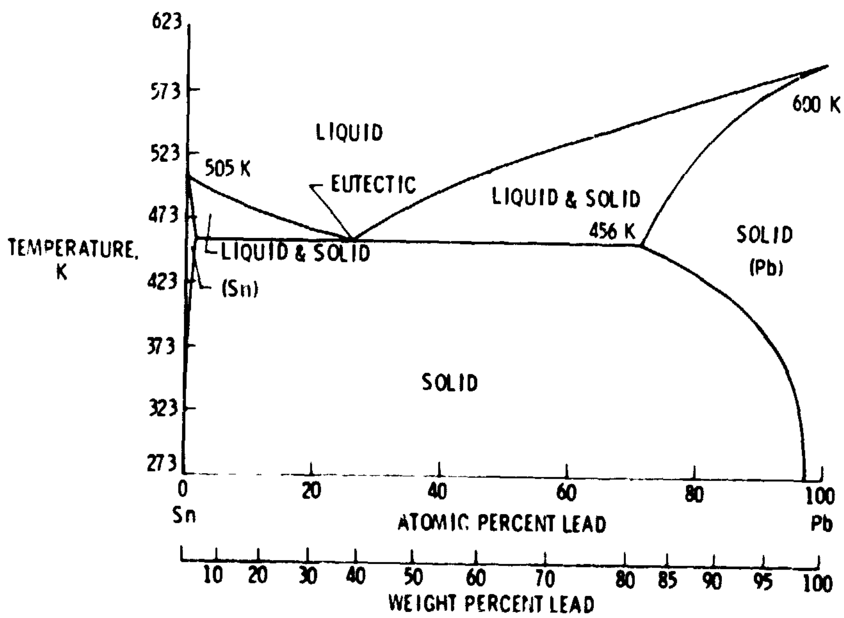

Figure 6.- Equilibrium phase diagram for tin-lead (ref. 4).

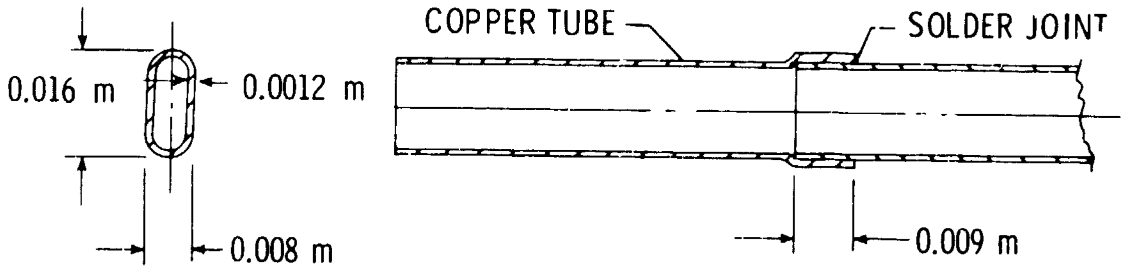

Figure 7.- Copper tube solder joint tensile load test specimen.

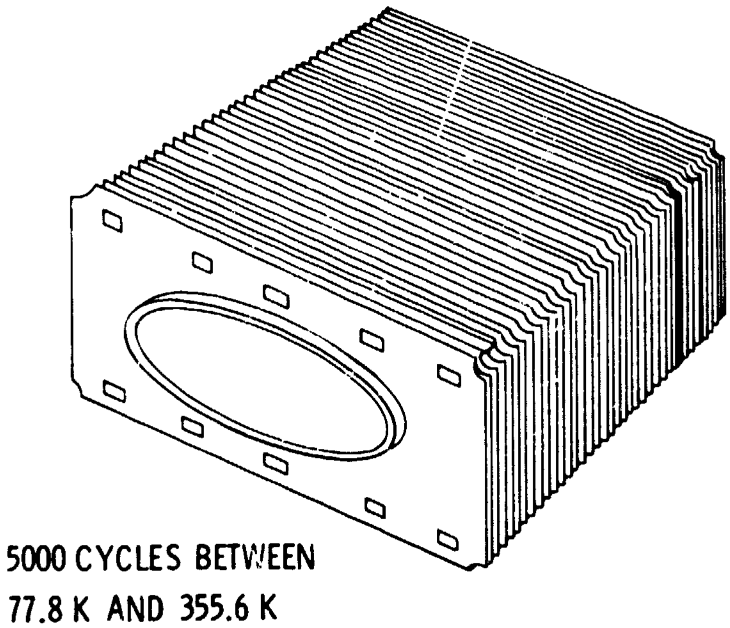

Figure 8.- NTF cooling-coil thermal-cycle test specimen.

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Figure 9.- Tube and fin specimen after vacuum braze at 1097.6 K.

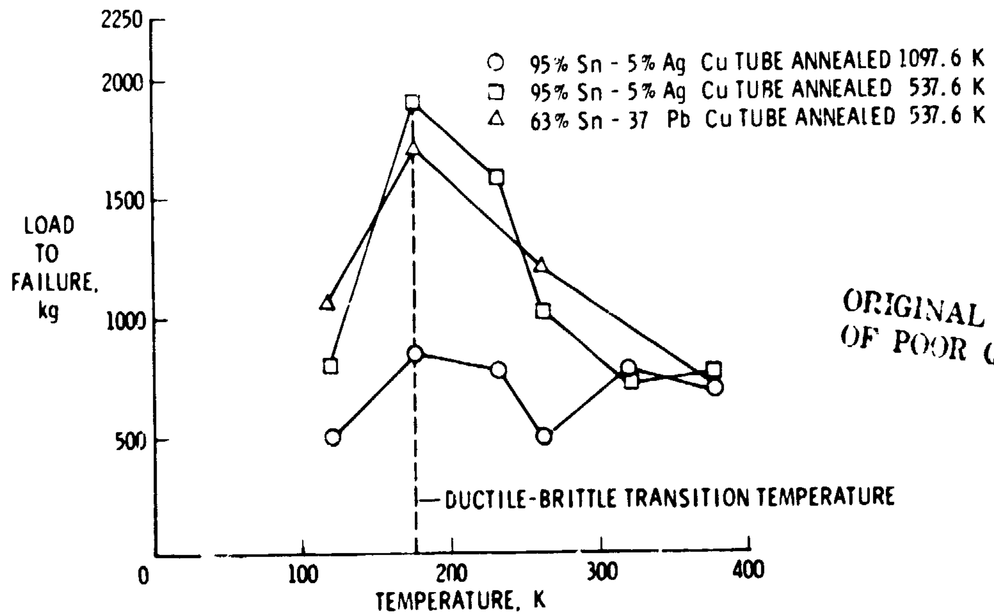

Figure 10.- Solder joint strength as a function of temperature.

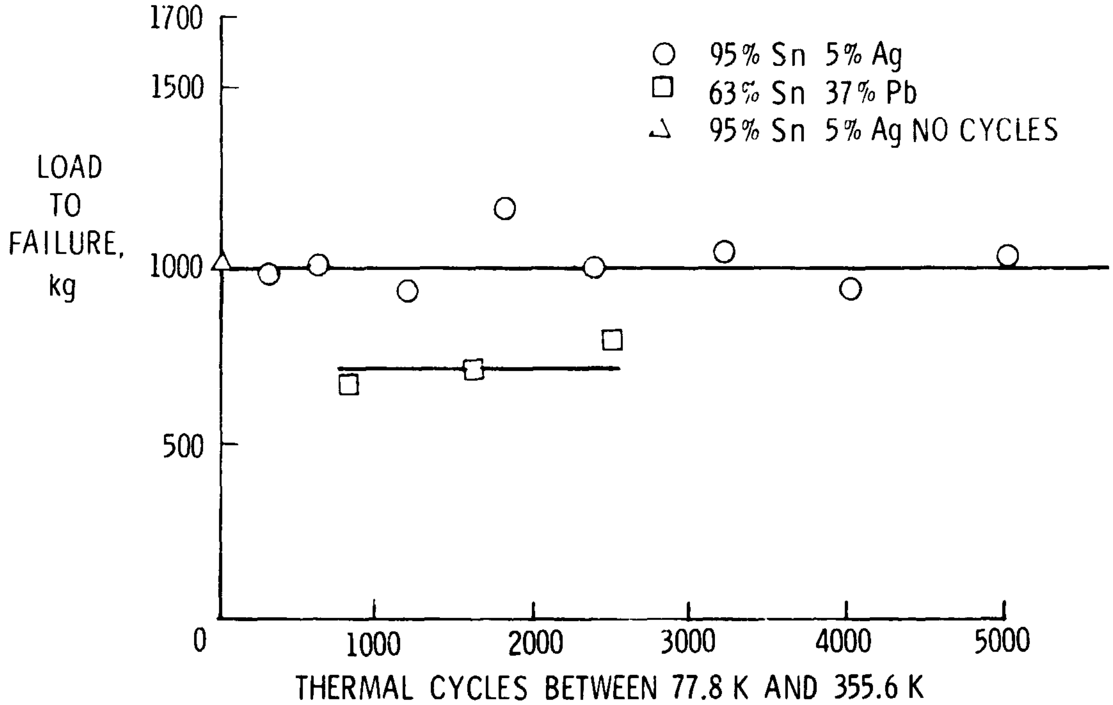

Figure 11.- Solder joint strength pulled at ambient temperature after thermal cyclic exposure between 77.8 K and 355.6 K.