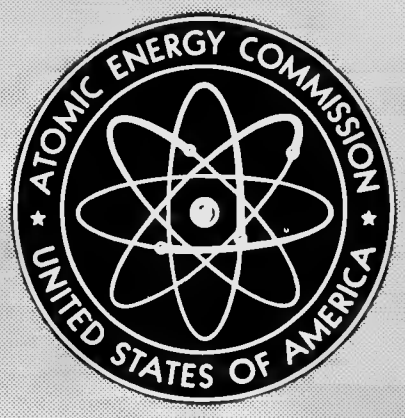

NMI-1252

STABILITY OF THE HIGH TEMPERATURE BETA PHASE IN BERYLLIUM AND BERYLLIUM ALLOYS

Final Technical Report for the Period July 1, 1960
Through June 30, 1961

By
J. J. Pickett
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September 11, 1961

Nuclear Metals, Inc.
Concord, Massachusetts

UNITED STATES ATOMIC ENERGY COMMISSION • DIVISION OF TECHNICAL INFORMATION

USAEC Division of Technical Information Extension, Oak Ridge, Tennessee

FUNDAMENTAL AND APPLIED RESEARCH AND DEVELOPMENT IN METALLURGY

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ABSTRACT

The discovery of a high-temperature phase in beryllium has opened a new field of study in beryllium metallurgy. Studies in this field have been carried out over the past year. Differential thermal analysis (DTA) to determine equilibrium phase boundaries has been applied to alloys of beryllium in each of the following systems: barium, cerium, cobalt, copper, lanthanum, manganese, platinum, silver, nickel-cobalt, nickel-iron, nickel-copper, nickel-cobalt-iron, and nickel-cobalt-manganese. The boundaries of the beta beryllium regions in the systems beryllium-cobalt and beryllium-copper have been fairly well established; the remaining systems require further study using additional test methods. The beryllium-nickel system, studied previously, and the beryllium-cobalt and beryllium-copper systems enlarge the beta field and lower the beta-to-alpha transus temperature, thus making these systems suitable for further study of the beta phase. A correlation was found between the beta-alpha upper solvus transition temperatures and electron-to-atom ratios for alloys of beryllium with cobalt, copper, iron and nickel. Application of this relationship to ternary and quaternary alloys met with some success.

Lowering of the beta-alpha transformation temperature by quenching from the beta phase was attempted on beryllium-cobalt and beryllium nickel alloys using a modified Greninger helium-gas quenching apparatus. Initial cooling rates up to 60,000^{o}C/sec have been observed with the transformation temperature lowered to 242^{o}C. Suppression of the alpha phase, as measured by X-ray diffraction, has not been observed.

On the basis of a few tests, the beta phase structure appears to be more ductile than the alpha phase structure at elevated temperature. A Be-8 ^{a}/o nickel alloy exhibited 20 percent reduction in area in tensile tests at 1070^{o}C (at which temperature the alloy is mostly beta). Unalloyed beryllium exhibited zero reduction in area at this temperature.

I. INTRODUCTION

The existence of a high temperature phase in beryllium[1,2,3] has opened up new avenues of approach for circumventing the brittleness of the metal. This phase, which is body-centered cubic, would be expected to be more ductile than the hexagonal phase. A program to investigate this possibility was started in fiscal 1960 (sponsored by the AEC Reactor Division), and the first year's work was reported in NMI-1218[4] which describes the background and theory. The present report covers the second year's effort on this program.

The objectives of the second year's work were to determine the composition and temperature range of the beta phase in those beryllium alloy systems that offered promise of having a wide beta field, to determine the mechanical properties of the beta phase, and to attempt to retain this phase to room temperature by quenching. The systems investigated were: binary alloys of beryllium with cobalt, manganese, copper, platinum, silver, cerium, lanthanum and barium; ternary alloys of beryllium with nickel and copper, nickel and cobalt, and nickel and iron, and quaternary alloys of beryllium with nickel, cobalt and iron, and nickel, cobalt and manganese.

II. BETA-PHASE BOUNDARIES

A. Specimen Preparation

The composition and temperature range of the beta beryllium phase in the various alloy systems were determined by thermal analysis. The specimens for thermal analysis were prepared by first cold compacting 20 grams of Pechiney beryllium flake at 25 tsi. The alloys were then induction melted in vacuum in BeO crucibles specially fabricated with an inverted thermocouple well at the bottom. When the alloying element was in powder form, the required amount was added to the beryllium flake during compacting. When the alloying addition was in the form of lumps or pellets, it was added separately to the melting crucible. No susceptor was used so that maximum stirring could be obtained in the melt. All alloys were melted at least twice and were thoroughly cleaned between melts by etching in

concentrated nitric acid containing 1 to 2% concentrated hydrofluoric acid. The analysis of the beryllium and the alloying metals is given in Table I.

B. Equipment

A three-zone platinum-wound furnace and power supply were used for the thermal analysis. A schematic cross section of the furnace with a specimen in place is shown in Fig. 1.

The crucible containing the specimen is positioned slightly above the center line of the furnace. The crucible rests on the "standard" block of molybdenum, which is positioned in the furnace by appropriate alumina, K-30 brick, and beryllia spacers. Leads for a thermocouple pass through a series of central holes in the spacers and standard block, and the couple is located in the crucible thermocouple well. A second thermocouple is placed off-center in a blind hole in the standard block. Purified argon, constantly flowing, is introduced at the top of the furnace through a molybdenum tube which extends along the side of the spacers, standard block and specimen crucible. The top of this tube is above the specimen. The gas leaves the furnace muffle through a port at the bottom. A gas pressure slightly above one atmosphere absolute is maintained in the furnace.

The specimen heating and cooling rates were about $3^{\circ}C$ per minute, and the specimen temperature was measured by a platinum-platinum-10% rhodium thermocouple. When the value of this temperature was desired, the thermocouple was connected to a Leeds and Northrup Speedomax Type G Recorder (Azar); the accuracy of the specimen temperature is estimated to be $\pm 5^{\circ}C$.

Prior to use, the furnace was calibrated; it was found that an axial temperature gradient of less than $\pm 2^{\circ}C$ could be maintained over the region of specimen and standard block in the temperature range 1000 to $1400^{\circ}C$.

C. Test Method

For differential thermal analysis, the EMF of the platinum-platinum-10% rhodium thermocouple inserted in the standard block was bucked against the specimen thermocouple EMF, and the resulting voltage difference measured by a Keithley Model 150 Microvolt-Ammeter. The output of the Keithley instrument was fed to an Esterline-Angus Recording Millivoltmeter. As the standard-block temperature changed uniformly with changes in furnace temperature, rapid changes in the EMF difference signal indicated the start and end of phase transformations in the specimen. The bucking circuit appeared to be more sensitive to the start of transformations. However, by using it in conjunction with direct temperature measurement, the temperature ranges of thermal effects could be determined more closely.

Thermal analysis was performed on each specimen from below the alpha-beta transformation temperature to above the liquidus. All samples were cycled twice through the transformations. Unless otherwise noted, only the data from the second cycle have been reported. The second cycle data is preferred because, prior to the initial melting in the cycling crucible, poor contact between the alloy and crucible resulted in poor thermocouple response and associated temperature measurement.

D. Results

A total of 19 binary, 9 ternary, and 11 quaternary beryllium alloys, representing 8 binary, 3 ternary and 2 quaternary alloy systems, was examined during the past year by thermal analysis. For reference, a specimen of pure beryllium from the lot used for alloy fabrication was also analyzed. The results of these runs are given in Table II. Chemical analysis results of the cobalt, copper and manganese alloys are given in Table III.

Figures 2(a), 2(b), and 2(c) show suggested beryllium-rich portions of the phase diagrams of beryllium with, respectively, cobalt, copper, and chromium.

The binary systems may be divided into two general groups. The first group contains the systems in which the beta field is closed by small amounts of solute, and therefore presents little possibility for retaining the beta phase to ambient temperature. The second group contains the systems in which the beta field is enlarged and the beta-to-alpha transition temperature is lowered. This group offers the best possibility for beta-phase retention.

In the first group are the systems beryllium-silver, beryllium-chromium, and beryllium-silicon, systems which were examined previously and reported in NMI-1218. The second group includes beryllium-cobalt and beryllium-copper. The systems beryllium-barium, beryllium-cerium, beryllium-lanthanum, and beryllium-platinum may also belong in the second group, but additional thermal analysis with samples of higher alloys must be performed to confirm this hypothesis.

The system beryllium-manganese was examined, but insufficient data were obtained to define the beta field.

Both the beryllium-cobalt and beryllium copper systems exhibited an enlargement of the beta field, similar to that shown by the beryllium-nickel system (NMI-1218). In the former, beryllium-cobalt, the beta-to-alpha transformation temperature is lowered 140°C at the eutectoid composition, while the solidus rises continuously over the same composition range. In the latter, beryllium-copper, the beta-to-alpha transformation temperature is lowered 150°C at the eutectoid composition, while the solidus temperature decreases very slowly over the same composition range.

Heat-treatment studies on the beryllium-chromium system confirmed the general shape of the system initially proposed in NMI-1218, a peritectic-eutectic system.

The approximate upper solvus lines for the beta-to-alpha transformation in several beryllium alloys as a function of atomic concentration of solute is shown in Fig. 3. A relationship is indicated between the extent of beta stabilization and the position of the solute in the periodic table. At the end of the first transition series, it is observed that solutes of higher atomic number are weaker beta stabilizers.

Rationalization of the observations may be made in terms of the change in electron-to-atom ratio in beryllium alloys as solute is added. Raynor[5] suggested that, when transition elements are added to high valence solvents, electrons are transferred from the conduction band of the solvent to the 3d band of the transition solute atoms. For aluminum alloys with transition metals, this behavior was confirmed by Raynor,[5] who assumed that the number of aluminum valence electrons that can be accommodated by a transition metal atom is equal to the Pauling 3d vacancy.[6] For iron, cobalt and nickel, these vacancies are 2.66, 1.71 and 0.61 respectively.

It has not been shown that beryllium, or other divalent solvents, behave in a similar manner. Such an interaction, however, appears to take place in beryllium alloys since, as shown in Fig. 4, there is a correlation between the extent to which electrons are removed from the beryllium conductior band and the degree of beta stabilization. A single upper beta-to-alpha solvus line can be drawn through the data points for iron, cobalt, nickel and copper when the compositions are plotted as electron-to-atom ratios, calculated on the basis of the 3d vacancies given above. On the basis of binary alloy systems, it appears that the beta-to-alpha transus can be significantly lowered by alloying beryllium with solutes that produce a large decrease in the electron-to-atom ratio. Unfortunately, for solutes that are most effective in decreasing the electron-to-atom ratio on an atom basis, the eutectoid (beta-to-alpha plus gamma) occurs at lowest solute concentrations.

It was hypothesized that Fig. 4 could be extrapolated to more complex alloys which might stabilize the beta phase to even lower temperatures. For example, an alloy containing 4 ^{a}/o nickel, 3.5 ^{a}/o cobalt and 1.0 ^{a}/o iron has a calculated electron-to-atom ratio of 1.72. If it is assumed that solute-solute interactions are negligible, the curve of Fig. 4 may be extrapolated to a predicted solvus temperature of approximately 940^{o}C, more than 125^{o}C lower than the best binary composition (8.0 ^{a}/o nickel).

On this basis, a series of ternary and quaternary alloys were prepared and examined by differential thermal analysis (see Table II). The binary alloys were beryllium-nickel-cobalt, beryllium-nickel-ccpper, and beryllium-nickel-iron; and the quaternary alloys were beryllium-nickel-cobalt-iron and beryllium-nickel-cobalt-manganese. In all instances, the alloys obeyed the hypothesis until the electron-to-atom ratio approached 1.79. Below this electron-to-atom ratio, the observed temperatures remained at about 1060 to 1080°C, (minimum 1030°C), due possibly to the existence of a new phase.

III. MECHANICAL TESTS

Both elevated-temperature tensile tests and hot hardness tests were used to determine mechanical properties of the beta phase.

A. Tensile Tests

1. Specimen Preparation

For the tensile tests, a Be-8 ^{a}/o nickel alloy was chosen because of the extended temperature range and low transformation temperature of the beta phase. The alloy was fabricated by extruding a mixture of -200 mesh Brush QMV beryllium and 9 micron carbonyl nickel powders. The powders were mixed for 24 hours by tumbling with Teflon cubes in a glass container. The mixture was cold compacted in a steel extrusion can to 60 percent theoretical density and subsequently extruded at 2100°F to a reduction in area of about 30:1. Samples were selected from sound sections of the resultant 1/2-inch diameter rod. An unalloyed -200 mesh Brush QMV beryllium compact was extruded into rod under similar extrusion conditions.

2. Procedure

Tensile specimens, prepared by grinding, were uniform rods 1/4-inch diameter by 3 inches long. Tensile tests were performed on a rapid heating-rate, high-temperature tensile machine at the Rensselaer Polytechnic Institute, Troy, New York. Tests were conducted at 1060

and 1070°C (eutectoid temperature 1065°C) employing a heating rate of 260°C/sec. Above 1070°C the chromel-alumel thermocouples exhibited a tendency to break away from the specimens, preventing higher temperature tests. Specimens were held at temperature for 2.5 seconds and then broken in tension at a platen speed of 0.03 in/sec. As the hot zone was approximately 0.4-inch long, this platen speed corresponds to a strain rate of about 5 in./in./sec. Reduction in area at the point of fracture was employed as a measure of ductility. The results are given in Table IV.

It must be noted that subsequent chemical analysis showed the actual composition of the nominal Be-8 a/o nickel alloy to be 7.36 a/o nickel. This placed the alloy at the 1070°C test temperature in the two-phase alpha-plus-beta field (about 65 percent beta).

3. Results

Unalloyed beryllium of 1070°C showed a tensile strength of 8,000 psi and no ductility. The Be-8 a/o nickel alloy, on the other hand, exhibited a 19 percent reduction in area at 1070°C. Although the data are limited, this increase in ductility is believed to be due to the body-centered cubic structure.

Additional data on the Be-8 a/o nickel alloy could not be obtained because of the extreme brittleness of the material below the eutectoid temperature. Four specimens fractured outside the hot zone during heating. These failures have been attributed to slight misalignment of the specimens in the chucks, which produced nonaxial loading by thermal and mechanical stress during heating.

B. Hot Hardness

1. Specimen Preparation

Alloys for hot hardness testing were prepared by casting in the same manner used to make the alloys for thermal analysis. Cast ingots of pure beryllium (Pechiney flake), Be-3.8 a/o nickel and Be-8 a/o nickel were produced. Sample discs 1/4-inch by 1/8-inch thick were ground from castings. Because of the brittleness of the alloy, no suitable samples could be made from the Be-8 a/o nickel alloy.

2. Method

Three samples each of the beryllium and the 3.8 ^{a}/o nickel alloy were placed in the hot hardness tester which was then sealed, evacuated, and back filled with "purified" argon. Except during actual testing, when a static condition prevailed, a constant argon flow was maintained.

Tests were performed at three temperatures, 1273, 1254 and 1100^{o}C. For close and accurate temperature measurement, a plutonium-plutonium-10% rhodium thermocouple was cemented with a BeO slurry into a recess in the specimen holder. The system with all samples in place was heated to the maximum temperature and a sample each of beryllium and of alloy tested. The remaining sample pairs were tested at the lower temperatures during the cooling cycle. The tests were performed with a 136^{o} pyramid sapphire indenter at a 2-1/2 Kg load.

3. Results

Upon examination after test, no evidence of a hardness impression could be found on either the samples or the sample holder. A thin film was observed on the sample surfaces. The film from one sample was examined chemically and found to be high (141 ppm), in nitrogen. Since beryllium-nitride has a hardness equivalent to sapphire, the indenter material, it is assumed that the film inhibited the formation of an impression under the test load used.

IV. BETA PHASE RETENTION

A. Test Equipment and Procedure

Rapid-quenching experiments were performed on several beryllium-nickel alloys and a beryllium-cobalt alloy in a modified Greninger apparatus[7] using helium as the quenching medium. The nominal and actual compositions of the alloys tested are listed in Table V. The alloys were prepared in the same manner as for thermal analysis.

In these experiments, the specimen was spot welded to a platinum-platinum-13% rhodium thermocouple (0.008-inch wire) and heated into the beta field in a slow flowing helium atmosphere. During heating, the thermocouple EMF was measured by a potentiometer; when the test temperature was reached, the thermocouple was connected to a Tektronix 531A Oscilloscope with a Type D High Gain Preamplifier. The quench was initiated by dropping the furnace winding away from the specimen. This action triggered a microswitch which shut off the furnace power and opened a solenoid valve introducing high-pressure helium gas into the system. The cooling curve was recorded by photographing the oscilloscope trace. The samples used in these tests were approximately 0.030-inch diameter by 0.010-inch thick.

B. Results

Initial tests were performed on a nominal Be-8 $^{a}/_{o}$ nickel alloy with initial cooling rates ranging from 210°C/sec to over 12,000°C/sec. Figure 5 is a collection of cooling curves obtained on the alloy at several initial cooling rates. The EMF of the measuring thermocouple is plotted vs log time. As can be seen from the graph, at slow cooling rates the eutectoid transformation is pronounced. Initially, two breaks in the cooling curve are seen with a linear curve between them. As the cooling rate increases, the linear portion disappears and only one discontinuity remains. At still higher cooling rates a smooth curve is produced without any indication of transformation. On the basis of X-ray examination complete beta retention was not achieved; however, in one sample, a reduction in the amount of alpha beryllium present with respect to an equilibrium sample was noted by X-ray diffraction.

The family of curves shown in Fig. 5 is typical of those attained for all the alloys investigated in the quenching apparatus.

Subsequent to these tests it was found that the Be-8 $^{a}/_{o}$ nickel alloy was hypereutectoid. It was highly possible that many of these samples were heated into and quenched from the two-phase beta-plus-gamma field instead of the single-phase beta field. Therefore, another alloy, nominally

Be-7.5 ^{a}/o nickel, was produced and tested. The initial cooling rates ranged up to 27,000°C/sec and the maximum temperature to 1193°C. Subsequent analysis showed that this alloy also was hypereutectoid (see Table V) and subject to the same limitations as the nominal 8 ^{a}/o nickel alloy. Again complete beta retention was not obtained, based on X-ray data. Most samples, cooled over a range of initial rates, up to 27,000°C/sec, did not exhibit any discontinuities in the recorded cooling curves. However, a suppression of the beta-to-alpha transus temperature down to 242°C was observed at an initial cooling rate of 14,000°C/sec from 1186°C.

In both the above series of tests, the maximum rated flow rate of the gas regulator used was 75 cfh at 40 psi. Another series of tests used a new helium regulator rated at 3225 cfh at 50 psi. In addition, the piping was revised to increase the line sizes. With these modifications, samples from a third alloy, nominally Be-7 ^{a}/o nickel, were prepared and quenched from approximately 1185°C at initial rates up to 60,000°C/sec. The measured gas-flow rate was 1560 cfh. No discontinuities were observed in the rapid-quench cooling curves, implying retention of the beta phase; however, X-ray diffraction study revealed the presence of gamma phase in the quenched sample. Typical examples of these cooling curves are shown in Fig. 6.

In order to test the response of the experimental set-up, a series of tests were performed using titanium samples. The samples were about 0.030-inch diameter by 0.011-inch thick. Initial cooling rates ranging from 1700°C/sec to 10,200°C/sec were used. In all tests the beta-to-alpha transus could be detected on the cooling curves and only slight suppression of the transus temperature was indicated.

A final series of tests were performed on a nominal Be-5 ^{a}/o cobalt alloy. Samples were quenched from 1200°C at initial cooling rates ranging from 750°C/sec to 16,000°C/sec. X-ray diffraction study of the sample quenched at 16,000°C/sec showed gamma (Co_5Be_{21}) and possibly alpha, indicating that the eutectoid transformation had not been completely suppressed.

To obtain a basis of comparison of X-ray diffraction patterns, a sample of the Be-5 ^{a}/o cobalt alloy was heat treated for 120 hours at 900^{o}C and water quenched. The sample was crushed and X-rayed twice (Debye-Scherrer technique). The lines obtained for the compound, assumed to be Co_5Be_{21}, indexed identically with $FeBe_{11}$. The source material was examined for iron by X-ray fluorescence and only a trace was found. A third sample was X-rayed by the Debye-Scherrer method and, again, the compound lines corresponded to $FeBe_{11}$. No explanation for this has been determined.

V. SUMMARY

The existence of an allotropic transformation in beryllium and the identification of the high-temperature phase as body-centered cubic has made necessary a re-examination of the beryllium-rich portion of beryllium alloy phase diagrams. Because of the possibility of improved mechanical properties in beta-phase alloys, an alloy program was performed to locate beryllium alloy systems in which the temperature of the beta phase is lowered.

Of the systems studied this year, expansion of the beta field and lowering of the transformation temperature occurred in the systems beryllium-cobalt and beryllium-copper.

Limited elevated tensile test data of a beta-phase Be-8 ^{a}/o nickel alloy at 1070^{o}C indicate that the beta phase may be more ductile than alpha-phase beryllium at 1070^{o}C or alpha-plus-gamma phase beryllium-nickel at 1060^{o}C.

Quenching studies, undertaken in an attempt to retain the beta phase of beryllium-nickel alloys to room temperature, were not successful, but the beta-to-alpha transus was lowered from 1065^{o}C to as low as 242^{o}C. Similar tests on a beryllium cobalt alloy gave no indication of a lowering of the beta-to-alpha transus temperature.

VI. TABLES AND FIGURES

TABLE I

Analysis of Materials

(Spectrographic analysis in ppm by weight unless otherwise specified.)

1. Beryllium Flake

   Al 80, Ca <50, Cu 75, Fe <190, Mg 75, Mn 15, Ni 190, Si <25

2. Barium

   99 +%

3. Cerium

   99.5 + %

4. Cobalt

   Lot I: Al 2, Fe <5, Si 1, Cu <1, Mg <1, Ca <1, Na <1, Ni nd

   Lot II: Al n.d., Fe 3, Si <1, Cu <1, Mg 1, Ca 1, Na 1, Ni 5

5. Copper

   Sb 100, As 10, Fe 40, Pb 100, Sn 100

6. Iron

   Electrolytic, estimated 99.8% pure

7. Lanthanum

   Si 115, Ti 9, Fe 1470, Ca 65, Al 58, Zr 33, Ni <24, Cr <20, Mg <29, Mn 23, Cu 16, B <1.5, Cl 1700, O 110, N 63, Na 45, other rare earths 2100

8. Manganese

   99.9 + %

9. Nickel

   C 160-200, Fe 320-420, Co undetected

10. Platinum

    Thermocouple grade

11. Silver

    Cl 50, Cu 10, Heavy metals (as Pb) 20, Fe 20, SO_4 600

TABLE II

Temperature of Thermal Effects for Some Beryllium Alloys

Beryllium Alloy (^{a}/o addition)	Temperature of Thermal Effect(^{o}C)		Remarks
	Heating	Cooling	
0.1 Ba	1268-1274 1286-1302	1261 1276-1281	Recorder malfunction - data questionable
0.5 Ba	No data	1249-1250 1268- ?	Recorder malfunction - thermocouple failure - data questionable
8.0 Ba	No data	1268 1247-1250	Thermocouple failure - data from first melting and cooling curves
2.5 Ce	1253-1260 1268-1275	1241-1245 1257-1264	
10.0 Ce	No data	No data	Heated to 1450^{o}C without exhibiting melting
0.5 Co	1254-1262 1278-1287	1239-1244 1264-1274	
1.0 Co	1253-1265 1289-1299	1234-1264 1280-1290	
2.5 Co	--- 1144-1233 1291-1299	1111 1139-1210 1284-1294	
5.0 Co	1126-1127.5 1147 1313-1322	1118-1121 1128 1311-1321	
1.0 Cu	1274-1276 1281-1285	1269-1272 1279-1283	Prior year's data. Reported earlier in NMI-1218
5.0 Cu	1252-1265 1275-1282	1243-1259 1268-1276	Prior year's data. Reported earlier in NMI-1218
10.0 Cu	1109-1118 1202 1251-1265	1102-1103 1184 1250-1255	

TABLE II (Continued)

Beryllium Alloy (^{a}/o addition)	Temperature of Thermal Effect(^{o}C)		Remarks
	Heating	Cooling	
15.0 Cu	1109-1113 1152 1225-1242	1102-1103 1143 1228-1240	
2.5 La	No data	No data	Sample did not melt
0.5 Mn	1186-1194 --- ---	1179-1180 1243-1350 1255	
1.0 Mn	1189-1195 --- 1271	1180-1183 1237 1250	
1.75 Mn	1190-1196 1248	1179-1181 1235	
2.5 Mn	1201-1205 1230	1200-1202 1234	
5.0 Mn	1184-1199 1219	1160-1170 1195	
5.0 Pt	No data	No data	Excessive Pt segregation
5.0 Ag	--- 1028 ? -1272	977 1028 1231-1245	
4.0 Ni-2.5 Co	--- 1340-1371	1083-1097 1315-1343	
4.0 Ni-3.0 Co	1127-1134 1210 1324-1346	1118-1123 1180 1311-1333	
4.0 Ni-3.5 Co	1101-1109 1328-1340	1077-1077 1314-1328	
4.0 Ni-0.5 Fe	1234 1312-1336	1202 1298-1321	

TABLE II (Continued)

Beryllium Alloy (^{a}/o addition)	Temperature of Thermal Effect(^{o}C)		Remarks
	Heating	Cooling	
4.0 Ni-1.0 Fe	1084-1091 1148 1191 1289-1334	1079-1081 1111-1117 1159 1297-1324	
4.0 Ni-1.5 Fe	--- 1157 1275-1328	1128-1133 1150 1261-1318	
4.0 Ni-2.0 Fe	1167 1265-1323	1138-1139 1254-1314	
8.0 Ni-0.1 Cu	1053-1058 --- 1368-1380	1039-1044 1046 1355-1370	
8.0 Ni-0.2 Cu	1036-1046 1078 1353-1366	1022-1029 1040 1339-1354	
4 Ni-2.5 Co-0.5 Fe	1109-1118 1327-1354	1081-1090 1311-1341	
4 Ni-2.5 Co-1.0 Fe	1110-1115 1314-1343	1085-1085 1309-1338	
4 Ni-2.5 Co-1.5 Fe	1122-1127 1323-1340	1092-1095 1284-1330	
4 Ni-3.5 Co-0.5 Fe	--- ---	1127-1134 1310-1335	Data from first cycle - thermocouple failed prior to start of second cycle
4 Ni-3.5 Co-1.0 Fe	1100-1128 1336-1365	1053-1059 1336-1365	
6 Ni-2.5 Co-0.5 Fe	1102-1104 1197-1201 1347-1367	1079 1185-1186 1341-1364	
6 Ni-2.5 Co-1.0 Fe	1338-1371	1330-1364	

TABLE II (Continued)

Beryllium Alloy (^{a}/o addition)	Temperature of Thermal Effect(^{o}C)		Remarks
	Heating	Cooling	
6 Ni-3.5 Co 0.5 Fe	1098-1101 1341-1357	1055-1060 1335-1357	
6 Ni-3.5 Co-1.0 Fe	1330-1360	1320-1350	
6 Ni-3.5 Co-1.5 Fe	---	1342-1366	Poor data - heat effects could not be found on DTA curves
4 Ni-2.5 Co-0.1 Mn	1111-1119 1201 ---	1108-1111 1182-1183 1322-1353	Not melted during second cycle - melting and solidification data from first cycle.
Pure beryllium (Pechiney flake)	1257-1259 1271-1276	1250-1252 1265-1269	

TABLE III

Chemical Analysis of Some Beryllium Alloys

Sample No.	Nominal Content (a/o)	Analyzed Content (a/o)	
		Top	Bottom
1160-BCu-1	1.0	1.10	1.10
1160-BCu-2	5.0	5.10	5.17
1160-BCu-3	10.0	9.73	10.12
1160-BCu-4	15.0	15.2	15.8
1174-BCo-1	0.5	0.57	0.64
1174-BCo-2	1.0	1.11	1.26
1174-BCo-3	2.5	2.50	2.67
1174-BCo-4	5.0	5.26	5.34
1174-BMn-1	0.5	0.46	0.68
1174-BMn-3	1.0	0.84	1.20
1174-BMn-5	1.75	1.20	1.46
1174-BMn-2	2.5	2.20	3.17
1174-BMn-4	5.0	4.61	5.25

TABLE IV

Elevated Temperature Mechanical Properties of Beryllium and a Be-8 a/o Ni Alloy

Specimen	Nominal Composition	Peak Temp (°C)	Ultimate Tensile Strength (psi)	Percent Reduction in Area
B-3	Be	1070	8000	0
B-4	Be	1070	not measured	0
N-1	Be-8 a/o Ni	1070	5000	19
N-6	Be-8 a/o Ni	1060	4000	0

TABLE V

Analysis of Beryllium-Nickel Alloys Used in Quenching Tests

Sample No.		Nominal Composition (a/o)	Actual Composition (a/o)
1160-BN-4:	Top	8.0	8.69
	Bottom	8.0	8.95
1174-BN-75:	Top	7.5	8.46
	Bottom	7.5	8.46
1174-B7N-Q:	Top	7.0	6.96
	Middle	7.0	7.01
	Bottom	7.0	7.13
1174BCo-4:	Top	5.0	5.26
	Bottom	5.0	5.34

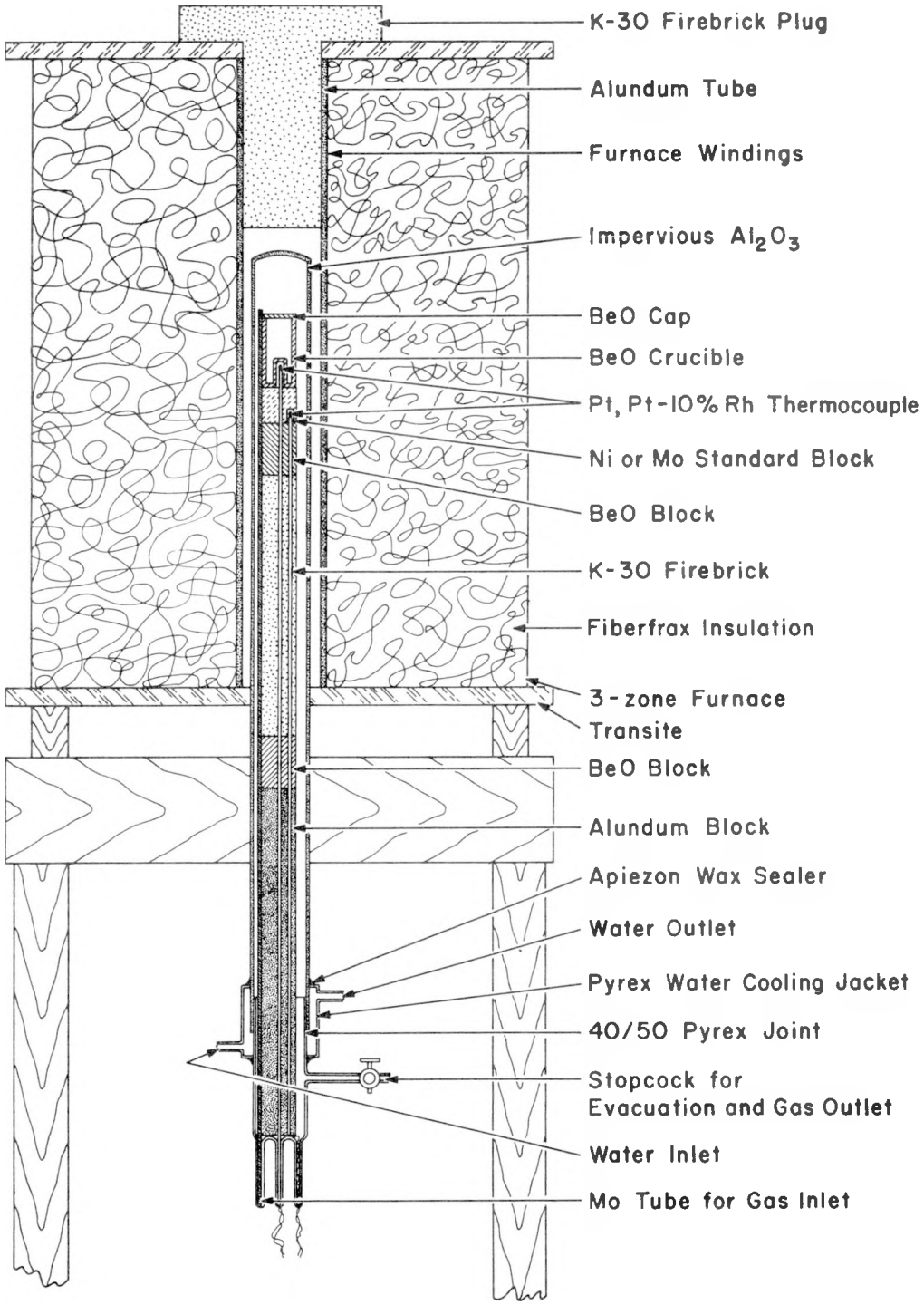


Fig. 1 - Schematic diagram of thermal analysis furnace.
Drawing No. RC-1041

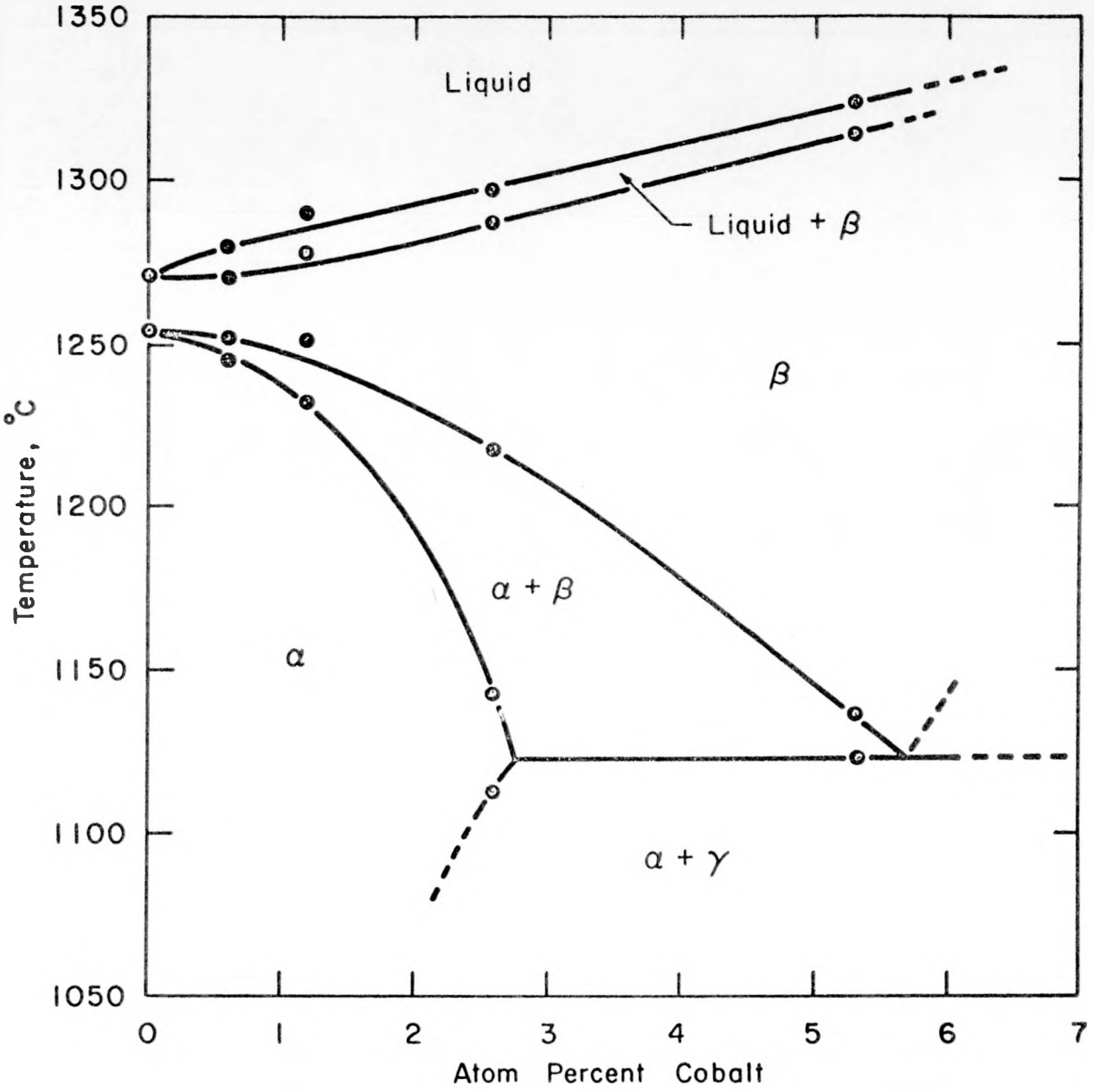


Fig. 2(a) - Beryllium-rich portion of the beryllium-cobalt phase diagram. Drawing No. RA-1804

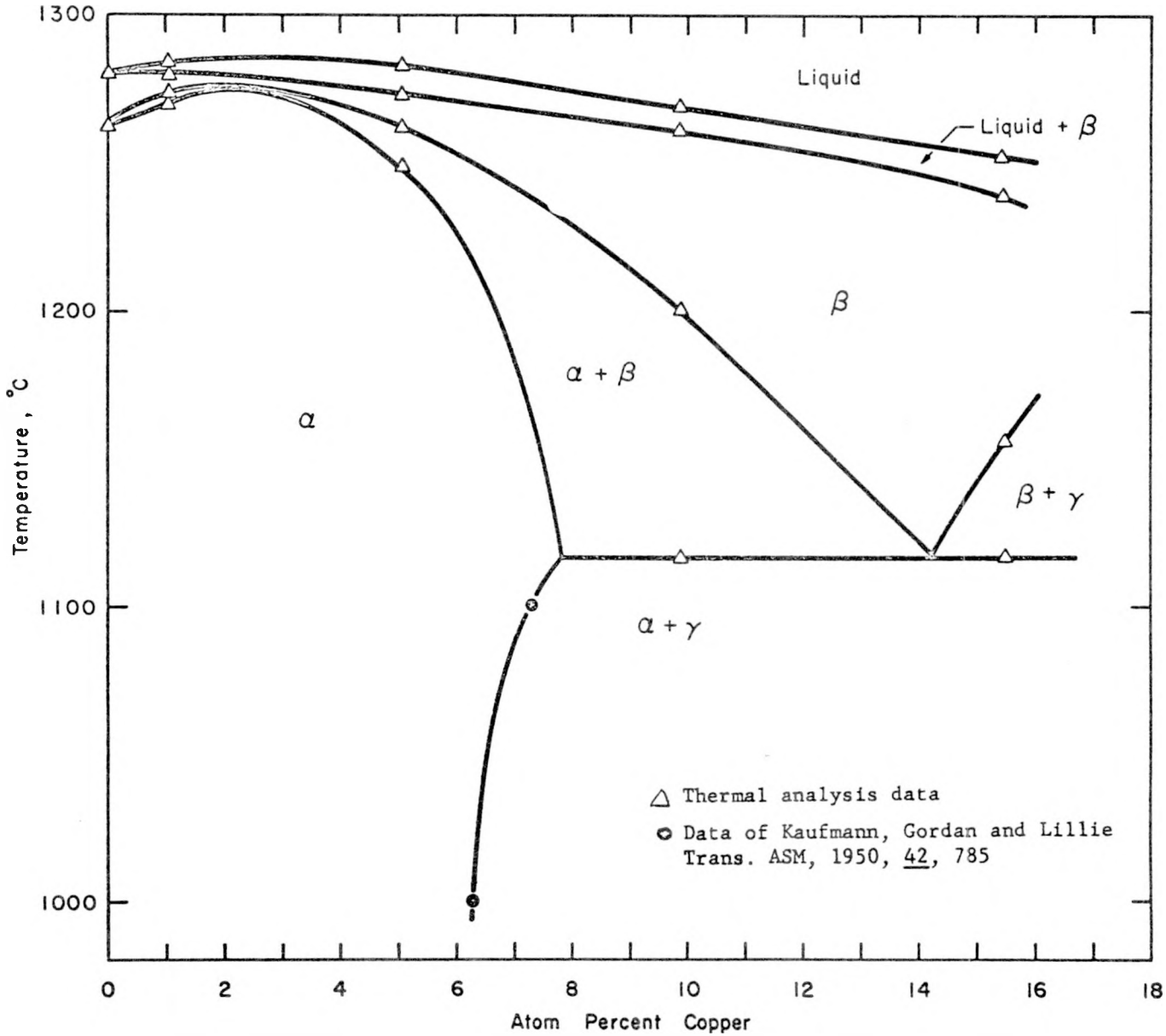


Fig. 2(b) - Beryllium-rich portion of the beryllium-copper phase diagram. Drawing No. RA-1844

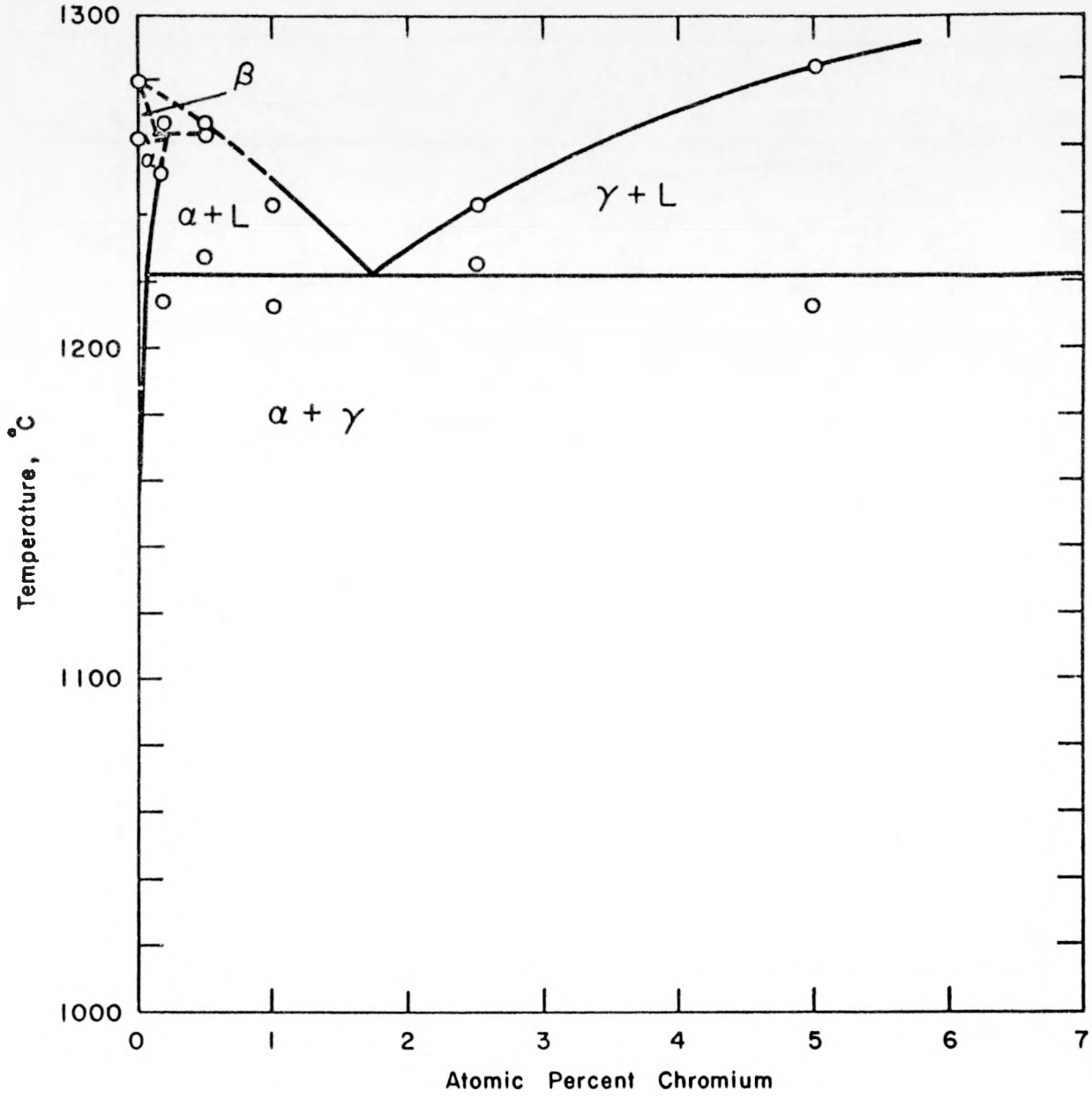


Fig. 2(c) - Beryllium-rich portion of the beryllium-chromium phase diagram. Drawing No. RA-1716

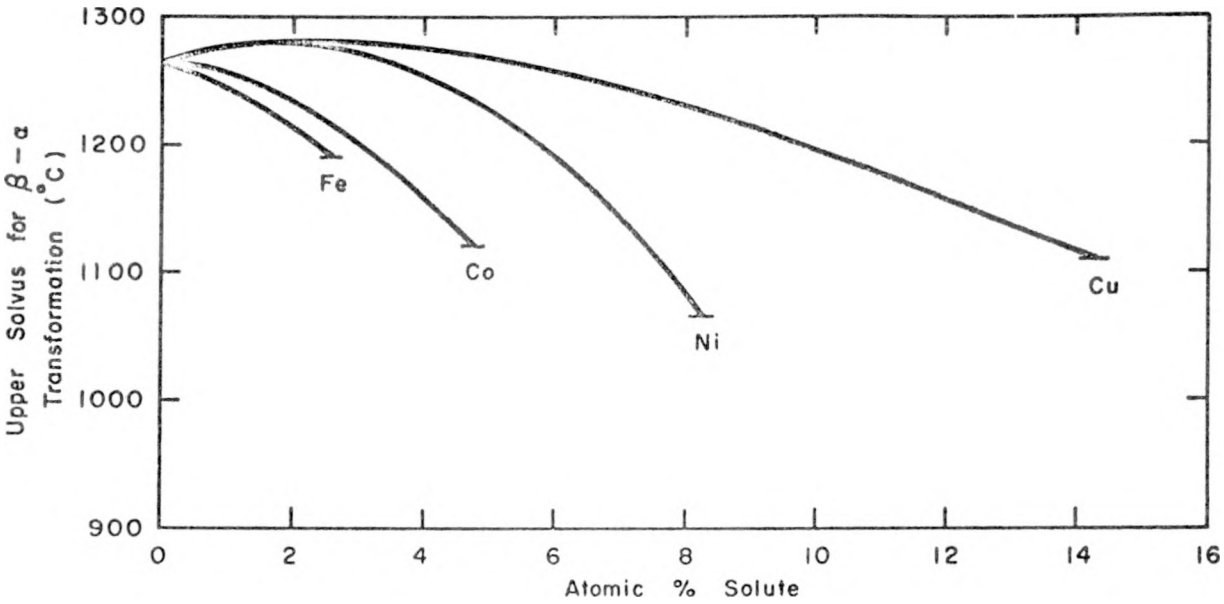


Fig. 3 - $\beta \longrightarrow \alpha$ upper solvus lines in beryllium alloys. Drawing No. RA-1966

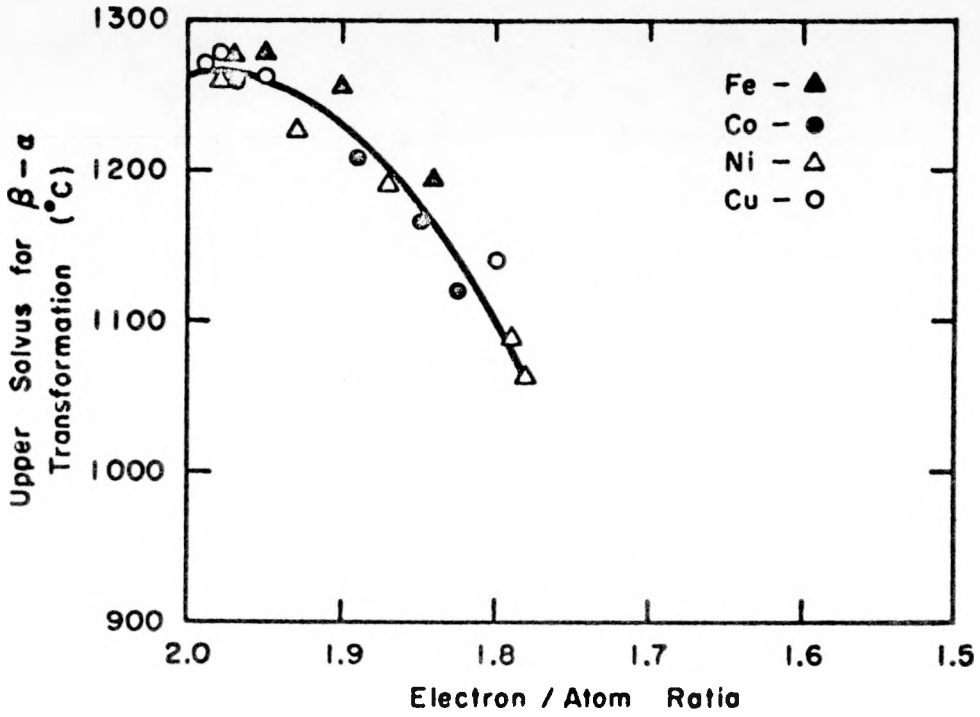


Fig. 4 - $\beta \longrightarrow \alpha$ upper solvus as a function of electron/atom ratio. Drawing No. RA-1967

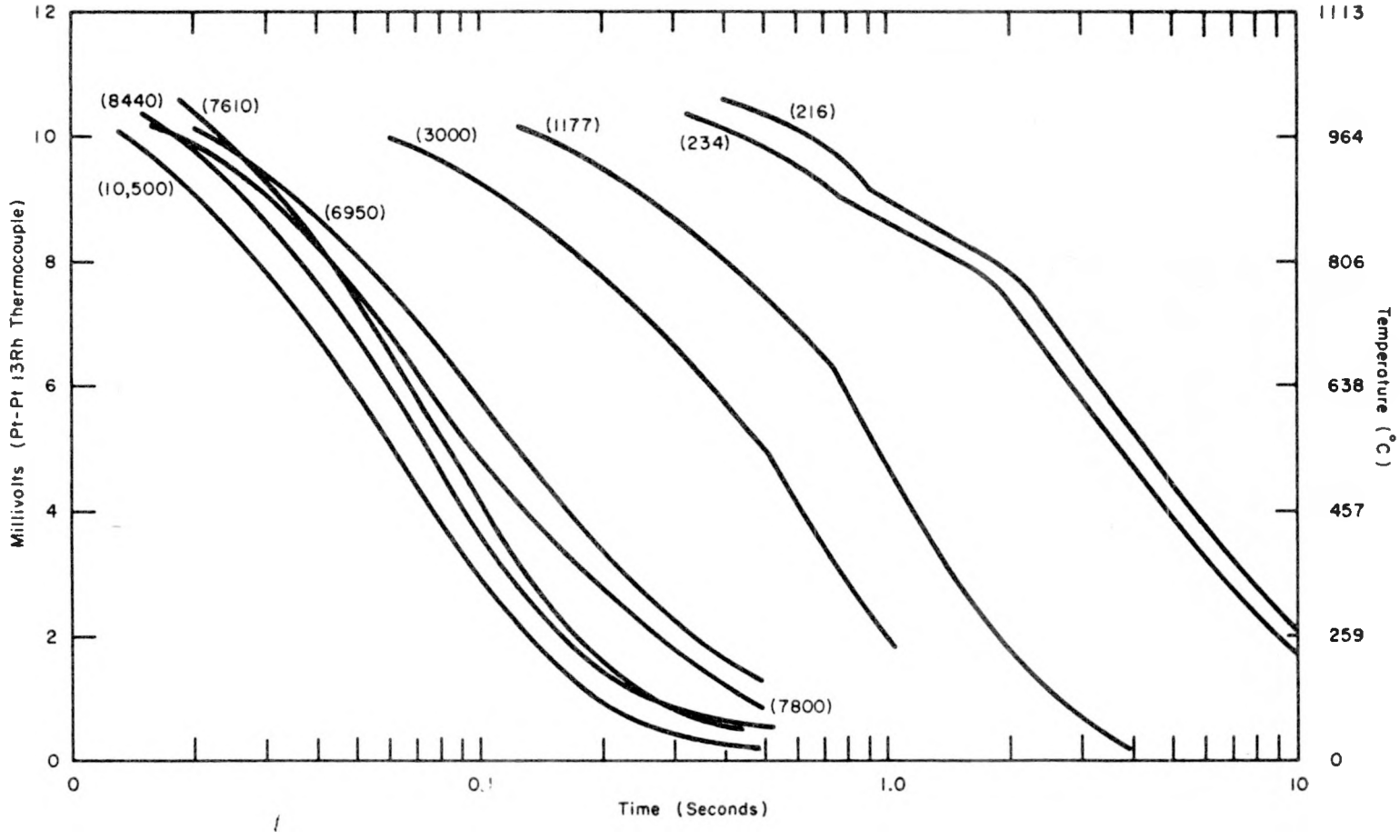
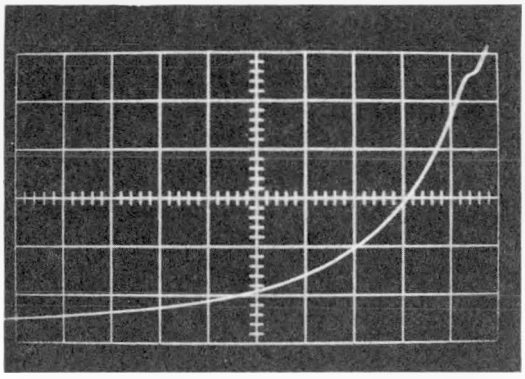
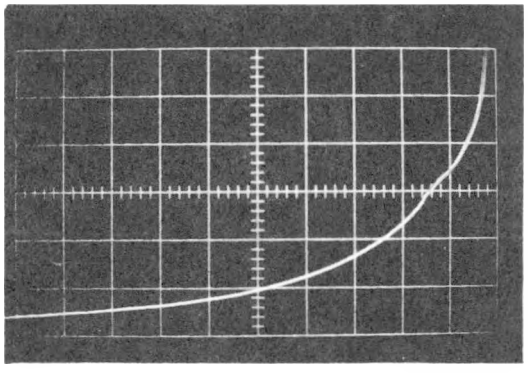


Fig. 5 - Family of cooling curves - Be-8.0 ^{a}/o Ni alloy. Figures in parenthesis are initial cooling rates in ^{o}C/sec. Drawing No. RB-1131



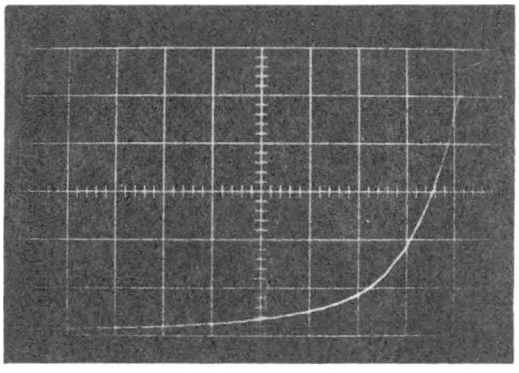
1174-90

(a) Be-7 ^{a}/o Ni alloy quenched from 1186°C. Initial cooling rate: 750°C/sec. Transus temperature: 1044-1050°C.



1174-62

(b) Be-7.5 ^{a}/o Ni alloy quenched from 1193°C. Initial cooling rate: 3700°C/sec. Transus temperature: 651-710°C.



1174-120

(c) Be-7.0 ^{a}/o Ni alloy quenched from 1205°C. Initial cooling rate: 14,000°C/sec. Transus temperature: ?

Fig. 6 - Examples of cooling curves on nickel-beryllium alloys.

VII. REFERENCES

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