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Information Branch

Summary

A study has been made of the thermoelectric properties of 106 alloys of the nickel-base, iron-base, and cobalt-base groups. The motivation for the study was provided by the intended use of complex alloys in absolute and differential thermocouple circuits in turbine engine heat flux measurements and in other heat-transfer and temperature measurements. Since virtually all hot-section turbine engine alloys contain chromium for oxidation protection, all alloys selected for this study contained chromium, in the range 1 to 25 percent.

The thermoelectric properties were compared with the following material characteristics: atomic percent of the principle alloy constituent; ratio of concentration of two constituents; alloy physical property (electrical resistivity); alloy phase structure (percent precipitate or percent hardener content); alloy electronic structure (electron concentration).

Correlations of varying quality between thermoelectric properties and the material characteristics were observed. A distinction can be seen between solid-solution alloys and precipitation-hardenable alloys: For solid-solution alloys the most consistent correlation was obtained with electron concentration, with data following a smooth curve for each group and with a scatter of about ±10 percent; for precipitation-hardenable alloys of the nickel-base super alloy group, the thermoelectric potential correlated with hardener content in the alloy structure.

For solid-solution-type alloys no problems were found with thermoelectric stability to 1000° C. For precipitation-hardenable alloys, thermoelectric stability was dependent on phase stability. Maximum use temperature should give a useful indication of the stability range.

The effects of the compositional range of alloy constituents on temperature measurement uncertainty are discussed. The use of correlation parameters to determine the approximate thermoelectric properties of uncalibrated alloys whose composition is known is suggested.

Introduction

The thermoelectric properties of many binary alloy systems have been measured and reported. Reference 1 presented this information on several systems which are completely miscible. Certain binary alloys (for example, Chromel and Constantan) have been universally adopted as thermocouple alloys because of the magnitude and stability of their thermoelectric potential. Occasionally, more complex alloys have been developed in order to obtain superior thermoelectric properties. Alumel and Nicrosil are examples. In general, however, very few of the complex alloys in use have been evaluated for their thermoelectric properties.

Nickel-base, iron-base, and cobalt-base alloys are used in the hot sections of turbine engines. Accurate temperature measurements are of vital importance in the study of the heat-transfer characteristics of jet engine parts. The use of the engine hardware as a part of a thermocouple circuit enables differential temperature measurements to be made in the engine and improves temperature measurement accuracy. Also, by making the part one leg of a thermocouple circuit, only a single wire (or a single film) needs to be brought to the measuring junction for temperature measurements. It would therefore be of great interest to determine the magnitude and stability of the thermoelectric potential of jet engine alloys.

Since the majority of commercial alloys are permitted composition limits that are broader than those for thermocouple alloys, the effects of this allowable compositional variation on thermoelectric properties must be studied to determine the degree of uncertainty of temperature measurements caused by this variation.

One additional problem in bringing signals out from an engine part is that some of these materials are not available in wire form. Leadwire matching could be performed to solve this problem if matching materials could be found. A study of the thermoelectric properties of a large group of alloys could be helpful in the solution of this problem.

The purpose of this study was, not only to determine the thermoelectric properties of complex alloys of the type used in jet engines, but also to examine the underlying material characteristics that affect these properties. The information obtained from this study could help to determine the suitability of a particular alloy in a thermocouple application.

Database

Virtually all of the nickel-base, iron-base, and cobalt-base alloys used to form turbine-engine hot-section parts contain chromium for oxidation protection. Coincidentally, chromium has a profound influence on the thermoelectric characteristics of nickel and cobalt, as shown in the Ni–Cr and Co–Cr binary alloy curves of figure 1. The figure shows the thermoelectric potential of an alloy relative to platinum at 600° C as a function of chromium content. Small quantities of chromium transform the thermoelectrically negative nickel and cobalt elements into thermoelectrically positive alloys relative to platinum. On the basis of this behavior, all the alloys selected for this study contain chromium, ranging from 1 to 25 weight percent.

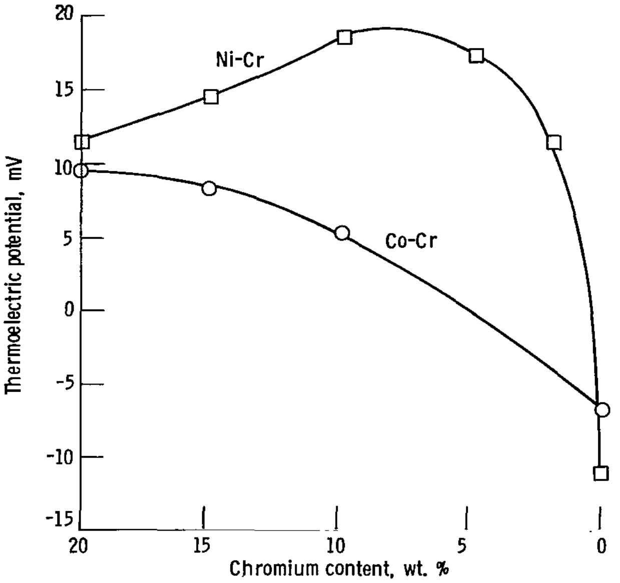


Figure 1. – Thermoelectric potential of Co-Cr and Ni-Cr solid-solution binary alloys versus platinum at 600° C as function of chromium content.

Table I lists the 106 alloys examined in this study. When calibrations of the same alloy by different sources are included, a total of 115 calibrations were examined in this study (82 from refs. 1 to 11 and 33 performed at Lewis (unpublished data of G. E. Glawe and this work)).

The 12 cobalt-base alloys include the following types: three members of the Co–Cr binary system; two commercial wrought superalloys; four Co–Cr–Mn alloys; one Co–Cr–Ta alloy; and two commercial cast superalloys.

The 18 iron-base alloys are composed of the following types: nine 300-series stainless steels; two Russian alloys; two precipitation-hardenable steels; and five other commercial steels.

The 76 nickel-base alloys are composed of the following types: 14 Nicrosil-type alloys, in which silicon and chromium were systematically varied; seven Ni–Cr–Mo alloys; 16 Ni–Cr alloys in which aluminum, silicon, manganese, and carbon were systematically varied; 12 superalloys; eight Inconels; four Russian alloys; three Hastelloys; and 12 commercial alloys used in strain gage, thermocouple, or electric-resistance applications.

Thermoelectric potentials are presented in table II, arranged in a format of values at 200°, 400°, 600°, 800°, and 1000° C where available. The data are presented relative to platinum and have been corrected to a common cold-junction temperature of 0° C where necessary. This correction is an approximation and has a negligible effect on the accuracy of the elevated temperature data used in the comparisons of this report.

To visualize the behavior of many different alloys, the thermoelectric potentials at 600° C have been selected for comparison. This intermediate temperature was chosen because data were available for most alloys at this temperature, because it was well below the melting points for all the alloys, and because it was well above the Curie temperature for most alloys. Additional analysis has demonstrated that the conclusions drawn in this report based on the 600° C data are valid for the entire calibration range.

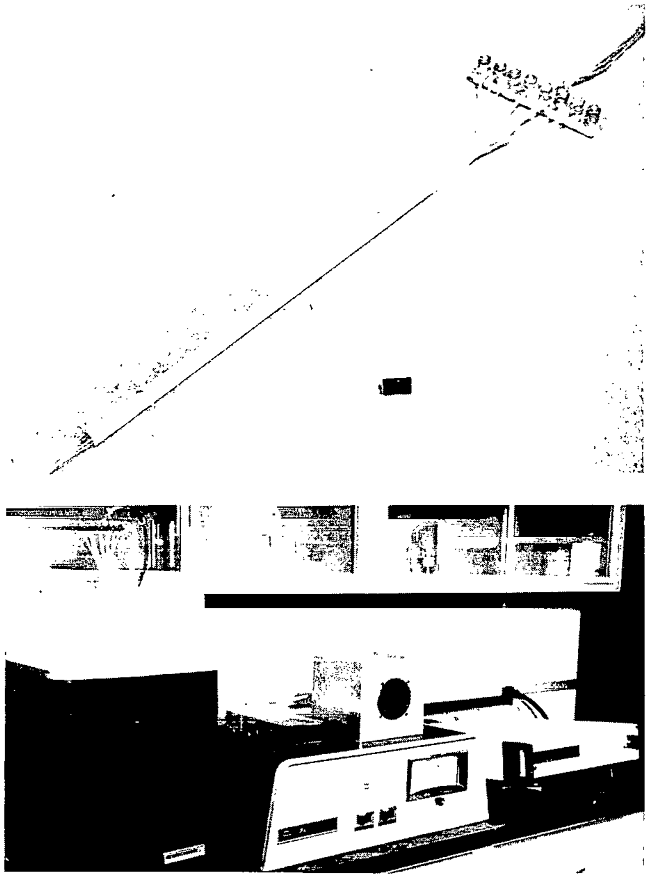
The data of references 2 and 8 were obtained by National Bureau of Standards with full documentation of methods and techniques and accuracy. Unfortunately, accuracy and experimental techniques of other literature sources were not always documented or specified, and occasionally the data were presented as several curves drawn on a small graph which was readable with a few percent uncertainty. For the purposes of this report, however, all sources were considered of sufficient quality to justify their use.

The degree of specification of alloy chemistry exhibited wide differences. In some cases, such as the National Bureau of Standards study of reference 8, each alloy constituent is specified to ±0.1 percent or better, with impurity content held to a negligible level. In other cases, such as commercial alloys, compositional tolerances are allowed for each constituent. For example, the nickel content of 316 stainless steel is allowed to vary from 10 to 14 weight percent. In most cases, the sources of emf data on commercial alloys presented in this study have not specified the composition of these alloys to any greater extent than these nominal values. The conclusions of this report are presented with these limitations taken into consideration. Where the composition of commercial alloys has not been specified, manufacturer's published data or the Metals Handbook, 9th edition, data (ref. 12) have been used. In addition, compositions of the Russian alloys were obtained from reference 13.

Test Apparatus and Experimental Techniques

Thermoelectric properties of 29 materials were obtained at Lewis Research Center as a part of this study. These materials are indicated in table II (G.E. Glawe's and author's data). The calibrations performed for this work in general followed the experimental methods and techniques outlined in reference 8.

Six materials were calibrated simultaneously. The materials were assembled in alumina tubing and welded together to form a common junction. Included in this junction was a 0.5-mm-diameter Pt–13Rh/Pt reference thermocouple. The materials were 46 cm long and varied in diameter, depending on the source of the available material. A calibration probe is shown in figure 2(a); the calibration furnace test setup is shown in figure 2(b). Potentials were measured with a digital voltmeter with a



(a) Probe.
(b) Furnace test setup.

Figure 2. – Calibration apparatus for thermoelectric measurements.

sensitivity of 1 μV and an accuracy of ±0.01 percent +5 μV. Cold junction temperature was recorded but not controlled, and the emf data were corrected to 0° C. Calibration data were obtained at 100° C intervals in both the ascending and descending temperature modes. The oven was stabilized at each temperature level and each material was in turn compared with the platinum leg.

The materials calibrated at Lewis were commercially available alloys, with one exception. The material Udimet 700-type is a low-cobalt version of Udimet 700 in which about 5 weight percent of the cobalt has been replaced with nickel. The exact composition of the following materials calibrated in this study was known: Udimet 700, Udimet 700-type, and Waspaloy. These values appear in table I correct to ±0.1 percent. The compositions of the remainder of the materials were obtained from manufacturer's data or from reference 12. The superalloy materials Udimet 700, Udimet 700-type, and René 41 were prepared from bar stock by swaging, followed by the appropriate heat-treatment process for each material to restore it to its precipitation-hardened condition.

Analysis of Database

Thermoelectric properties of complex alloys were compared with several material characteristics. These material characteristics were selected to represent the pertinent composition, property, and structure characteristics of these materials. They were (1) atomic percent of principal constituent, (2) ratio of concentration of constituents, (3) physical property, (4) phase structure, and (5) electronic structure.

The advantages and disadvantages of each material characteristic as a correlation parameter with thermoelectric properties will be discussed.

Atomic Percent Principal Constituent

There is an advantage of simplicity to the use of percent principal constituent. This has the effect of treating the total alloying constituents as a single solute, whose characteristics are thus averaged without weighting. For binary alloys, there is only one alloying constituent. As alloys becomes more complex, this correlation parameter become less reliable. Values for atomic percent principal constituent are listed in table III.

Ratio of Concentration of Two Constituents

A comparison of the ratio of a principal constituent with a secondary constituent is a good selection when these are the only constituents that vary in a family of otherwise identical alloys. The same argument can be used to justify the use of the ratio of two secondary constituents. The 300-series stainless steels are a good example of an alloy group that might correlate well when compared for these ratios. The following ratio values are listed in table III: Co/Cr for cobalt-base alloys and Ni/Cr for iron-base and nickel-base alloys.

Physical Properties

A correlation with another thermal or electrical property, such as electrical resistivity, thermal conductivity, or temperature coefficient of resistance, would make an excellent choice to compare with thermoelectric potential. The problems that arise are several: All these properties vary substantially with temperature; accuracy of measurement of some of these properties is not good; many nonstandard alloys used in this study do not have accompanying physical property data. Electrical resistivity was selected as the most desirable of this group, and values are listed in table III, where available.

Phase Structure

Factors that must be considered when comparing phase structure with thermoelectric characteristics is the stability of the phase structure with temperature and time and the quantity of each structural constituent. The temperature range of concern in this report is the calibration range of 0 to 1000° C. The time of concern is the calibration time, which is a maximum of a few hours.

The cobalt-base superalloys, with carbon content ranging from 0.1 to 0.6 percent by weight, consist of a solid-solution matrix with carbide precipitates. An analysis of these carbide structures is presented in reference 14. From this analysis it is seen that these carbide precipitates can constitute from 2 to 12 percent by volume of these alloys.

The Co–Cr binary alloys of reference 5 have a phase transition in the temperature range of concern in this report. This is a transition from one crystal structure to another.

The alloys 17–4 PH and 17–7 PH are the iron-base precipitation-hardenable alloys in this study. The 17–4 PH alloy is classified as a martensitic type, and the 17-7 PH a semiaustenitic type.

The nickel-base precipitation-hardenable alloys are the largest and most complicated group in this study. In these materials, the elements aluminum, titanium, niobium, and tantalum form γ and γ' precipitates, which are based on the intermetallic phase Ni_3Al, where titanium, niobium, and tantalum substitute for aluminum. In addition, carbides, borides, and other precipitate phases may be present. Other elements present may enhance or retard the solubility of these phases. One subgroup, the superalloys, contain from 25 to 65 atomic percent precipitates.

Because of this complexity, some simplifying approach is needed to analyze these complex alloys with respect to their thermoelectric properties. The quantity of $Al + Ti + Nb + Ta$ will be referred to here as the hardener content. Hardener content will be used to correlate phase structure with thermoelectric properties for the nickel-base precipitation-hardenable alloys. Values of hardener content are listed in table IV for the 29 nickel-base alloys containing aluminum, titanium, niobium, and tantalum.

Maximum use temperature and solutioning temperature will be examined to determine the effect of structural stability on thermoelectric stability. Maximum use temperature is a somewhat arbitrary value that can be defined differently for each individual use. The value chosen here is for 100-hr life at a stress of 136 MPa (20 000 psi). Solutioning temperature is the heat-treating temperature used to dissolve all precipitates in the alloy. Values of maximum use temperature and solutioning temperature for some superalloys are listed in table V, where available.

Electron Structure

In the discussion of thermoelectric potential, reference 15 states: "The potential occurs because the instantaneous spatial distribution of conduction electrons along a conductor is a function of temperature distribution. A nonuniform electron distribution results in a net potential difference that is the Seebeck emf." Thus, the electron structure of complex alloys was selected to compare with the thermoelectric potential.

It was concluded in reference 16 that the absolute thermoelectric power of the binary alloys of nickel is dependent on the electron concentration of the alloy. By electron concentration was meant the total electrons per atom in the unfilled bands. For the transition elements this quantity is equal to the sum of the electrons in the unfilled *d* and *s* bands of the atom. Based on this definition, electron concentration was computed for the solid-solution alloys of this report according to the formula

$$C = \sum_{i=1}^{n} A_i \frac{E_i}{100}$$

where

C	electron concentration
n	number of constituents in alloy
A_i	atomic percent of each constituent
E_i	number of electrons in the unfilled bands of each constituent

The values are listed in table III.

For solid solution alloys in which all constituents dissolve in a disordered array in the solvent, this parameter would, in theory, take into account every constituent with an individual weighting factor.

The formula for electron concentration would not apply to precipitation-hardenable alloys because the formation of precipitate compounds changes the electron structure of the alloy. As previously discussed under "phase structure," in many alloys of this type it is virtually impossible to know the exact precipitate structures that form and therefore the exact electron concentration.The following is an explanation of how this problem was handled for each alloy group:

(1) Cobalt-base superalloys—Haynes 25, Haynes 188, WI-52, and MAR-M 509 are the alloys in this group. The only precipitate formed by these alloys is carbides. Reference 14 presents a discussion of the various carbide forms that can result. On the basis of this discussion, a carbide structure was determined for each alloy. The electron concentration was then computed for the remaining solid solution matrix.

(2) Iron-base alloys—The alloys 17–4 PH and 17–7 PH were the only precipitation-hardenable iron-base alloys in this study. Because they were not thermoelectrically stable over the temperature calibration range of this effort, an electron concentration was not determined.

(3) Nickel-base alloys—The nickel-base precipitation-hardenable alloys of this study are based on the forma-

tion of the γ' precipitate. This phase structure was discussed in the previous section. Because of the extreme complexity of the internal structure of these alloys, it was considered impossible to compute an electron concentration based on an estimate of actual precipitate forms. Therefore, an electron concentration was computed by equation (1) based on the assumption of solid-solution to observe the effect of this assumption on the correlation with emf.

Results and Discussion

Iron-Base Alloys

Thermoelectric properties were obtained for 18 iron-base alloys. When repeated calibrations of the same material by different investigators are included in the tally, 23 sets of data are included in this group. Fourteen of these were obtained from the literature (refs. 1, 2, 4, and 7), and nine were obtained at Lewis.

The materials represented by these 23 calibrations were fourteen 300-series stainless steels; two precipitation-hardenable steels; two Russian steels; five miscellaneous steels with commercial or other designations. The chromium content ranged from 16 to 25 weight percent. Most of the iron-base alloys in this study are commercially available alloys whose physical properties are known. The 300-series stainless steels are a subgroup in which iron, nickel, and chromium vary against a stable background of manganese, silicon, potassium, sulfur, and carbon. Several other alloys in this group are closely related to the 300-series stainless steels.

Figure 3 presents nearly linear relationships between thermoelectric potential and atomic percent iron, Ni–Cr ratio, physical property (electrical resistivity), and electron concentration. The choice of Ni–Cr ratio instead of Fe–Cr ratio as a comparison with thermoelectric potential was made on the basis of a slightly better correlation coefficient.

Not included in these figures are the data for the precipitation-hardenable steels 17–4 PH and 17–7 PH. These alloys showed unstable thermoelectric properties that varied with time and temperature during calibration. This occurred because the solutioning temperature was exceeded during the calibration process and caused some precipitates to dissolve, changing the electronic structure and phase structure of the alloys. Physical property data for these two alloys shows that their electrical resistivity is different in the annealed and age-hardened conditions. For 17–4 PH, electrical resistivity is increased by annealing; for 17–7 PH, electrical resistivity is decreased. Changes in thermoelectric potential during calibration, which is also an annealing process, follow this pattern.

Nickel-Base Alloys

Thermoelectric properties from 80 nickel-base alloy calibrations were obtained from the literature search (58) and from the calibrations performed at Lewis (22). The nickel-base alloys are thus the largest and most diverse group in this study. In this group are these important subgroups:

(1) Fourteen Nicrosil-type alloys, in which silicon and chromium are systematically varied

(2) Seven Ni–Cr–Mo alloys

(3) Sixteen Ni–Cr alloys in which aluminum, silicon, manganese, and carbon were systematically varied

(4) Twelve superalloys, containing large amounts of γ' precipitate

(5) Eight Inconels

(6) Four Russian alloys, including one superalloy

(7) Six Hastelloys

(8) Thirteen commercial alloys used in strain gage, thermocouple, or electric-resistance applications.

The chromium content of these alloys varied from 1 to 25 weight percent.

The thermoelectric potentials of the nickel-base alloys are plotted in figure 4 against atomic percent nickel, Ni–Cr ratio, electrical resistivity, and electron concentration.

In figures 4(a) and (d), all the data follow a smooth curve with a shape similar to the Ni–Cr binary alloy curve, with the exception of the superalloys with high γ' precipitate content. The scatter in the data is approximately ±10 percent.

In figure 4(b), where thermoelectric potential is compared with Ni–Cr ratio, a similar pattern occurs but with exceptions. At low chromium content the data scatter broadly, and when a constituent other than nickel or chromium is systematically varied, the scatter is greater. This is particularly clear in the Ni–Cr–Mo and Nicrosil-type alloy groups.

Figure 4(c) compares thermoelectric potential with electrical resistivity. Fewer data are available here but a pattern can be seen. In general, emf decreases with increasing resistivity to an asymptotic value, with broad scatter in the 110 to 130 $\mu\Omega$-cm region. However, based on only one data point available for a superalloy with high γ' precipitate content, an exception is seen to this trend. The high γ' superalloy has high resistivity and high thermoelectic potential. Note that the value for electrical resistivity used here is the 20° C value for each material and that many of these materials have unusually shaped resistivity versus temperature curves (see, e.g., ref. 18).

The effect of precipitate content on the magnitude of thermoelectric potential for these nickel-base alloys can be summarized as follows: (1) For alloys with low precipitate contents (up to about 25 percent), the data generally follow the trends of the smooth curves of

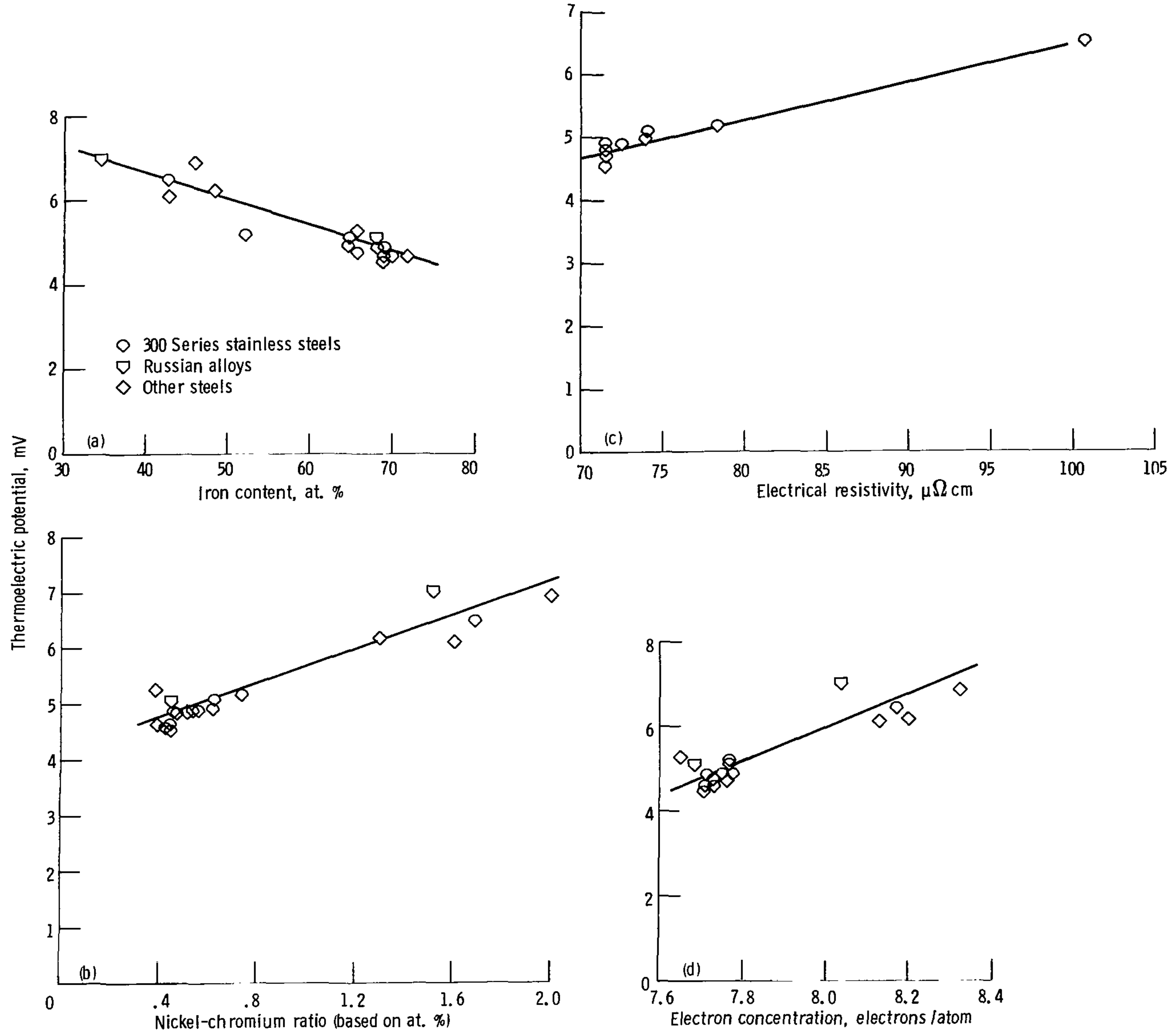


Figure 3. – Thermoelectric potential of iron-base alloys versus platinum at 600° C.

figures 4(a) and (d); (2) for alloys with high precipitate contents (from about 40 to 65 percent), the data do not conform to these trends.

These precipitation-hardenable alloys will be analyzed in more detail in the next section.

Nickel-Base Precipitation-Hardenable Alloys

As previously mentioned, the elements used to form precipitates in these nickel-base alloys are aluminum, titanium, niobium, and tantalum. The quantity Al + Ti + Nb + Ta is referred to here as the hardener content. Twenty-nine alloys in this study contained these elements (table IV). The data points which deviate from the curves of figure 4 are the alloys with the largest amount of hardener content. These are all members of the superalloy group.

Figure 5(a) is a plot of thermoelectric potential as a function of hardener content for the precipitation-hardenable alloys. While the data below 10 atomic percent hardener content are broadly scattered, the data above this value show a trend to high values of thermoelectric potential. In figure 5(b) the thermoelectric potential is plotted against the Al + Ti content. This graph shows a higher correlation between thermoelectric potential and hardener content than figure 5(a) for the superalloy group. It may be that these elements have the greater influence on thermoelectric properties.

The other aspect of concern, if we try to apply a precipitation hardenable alloy to temperature measure-

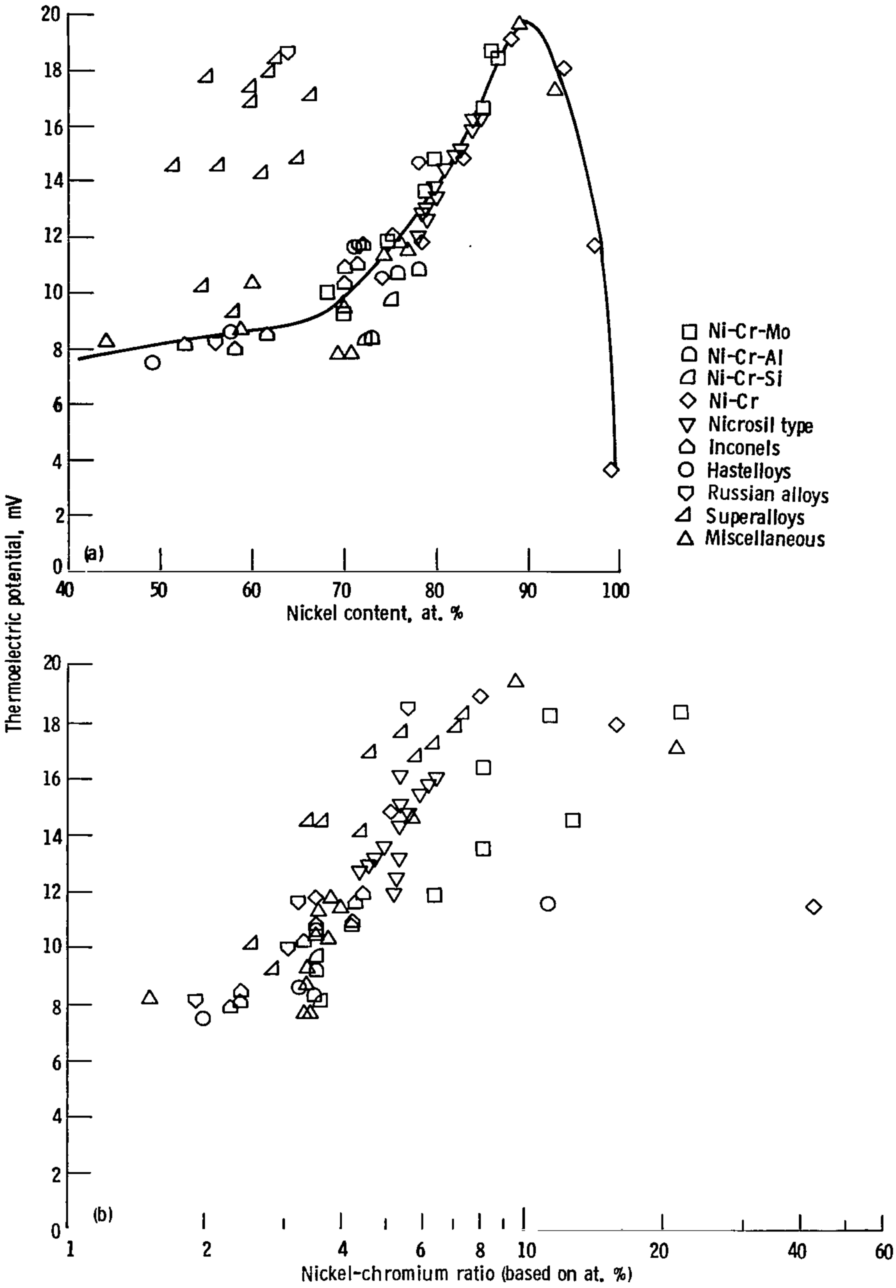


Figure 4. – Thermoelectric potential of nickel-base alloys versus platinum at 600° C.

ment of an engine part, is its thermoelectric stability. As precipitates form and dissolve, the electron structure changes and thus thermoelectric potential changes. This phenomenon was studied in the calibrations performed by this author. Table V lists a group of superalloys along with their hardener content, maximum use temperature, and solutioning temperature. Waspaloy, René 41, and Udimet 700 were calibrated in this work. The alloys were subjected to calibration cycles with progressively increasing maximum temperatures. While Waspaloy and René 41 showed thermoelectric instability at about 800° C, Udimet 700 remained thermoelectrically stable up to 1000° C. This is consistent with the higher solutioning temperature of Udimet 700. Figure 6 shows the relationship between Al + Ti content and solutioning temperature for Ni-Cr-base alloys (such as the Inconels) and Ni-Cr-Co-base alloys (such as the superalloys). By comparing curves such as these with thermoelectric calibration stability results, the temperature range of thermoelectric stability for different alloys can be inferred. In general, these alloys showed thermoelectric stability up to about maximum use temperature.

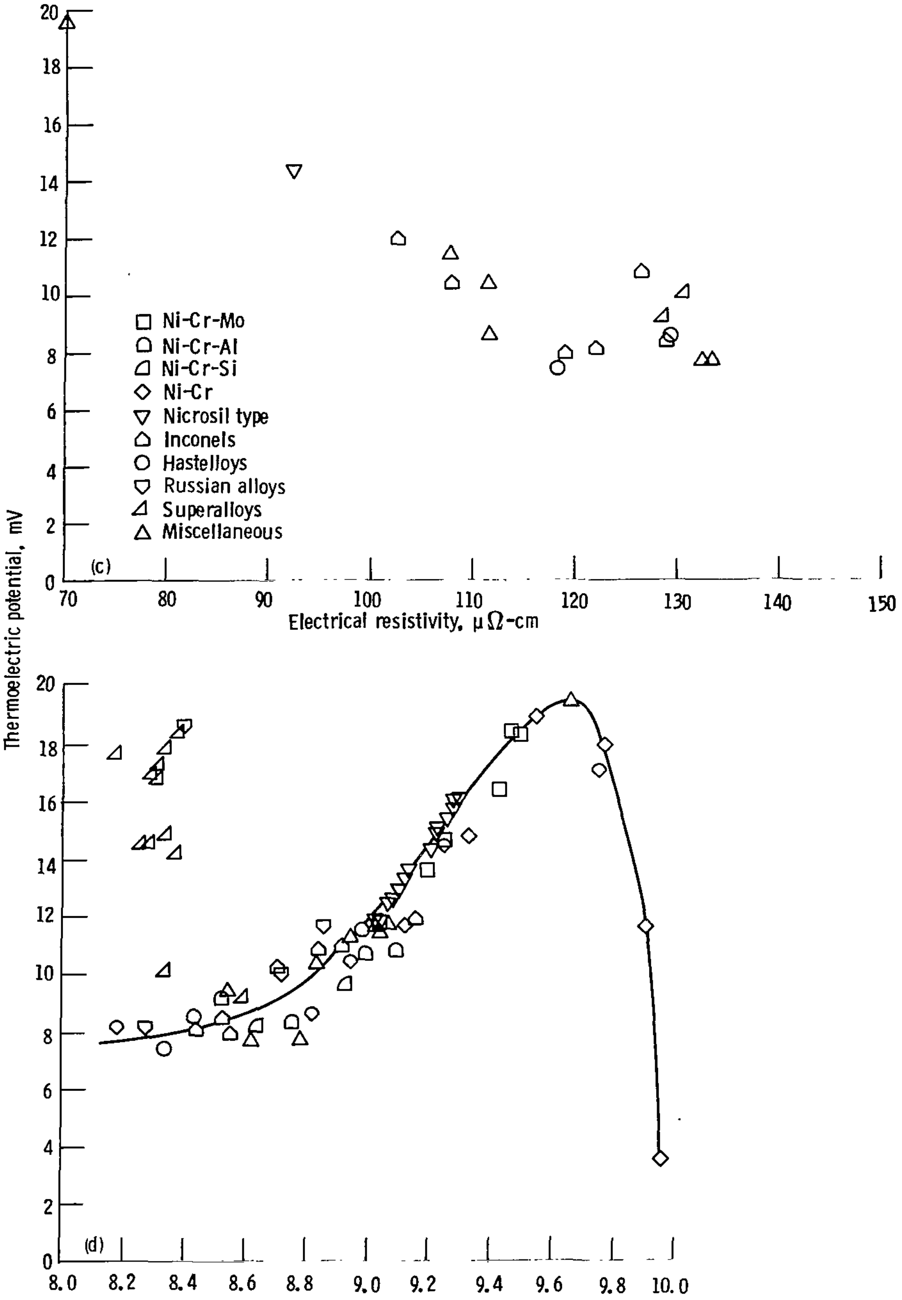


Figure 4. – Concluded.

Cobalt-Base Alloys

Thermoelectric properties were obtained for 12 cobalt-base alloys. Chromium content varied from 10 to 22 weight percent. Reference 5 provided data for three Co-Cr binary alloys, four Co-Cr-Mn alloys, and one Co-Cr-Ta alloy. Reference 11 was the source of data for MAR-M-509 and WI-52, both cast carbide-strengthened superalloys. Haynes 25 and Haynes 188, both carbide-strengthened wrought superalloys, were calibrated in this effort.

Physical property data were not available for most of these cobalt-base alloys. Comparison of thermoelectric potential against atomic percent cobalt is shown in figure 7(a), and a comparison based on Co-Cr ratio is shown in figure 7(b). Electron concentration and thermoelectric potential are plotted in figure 7(c).

The cobalt-base alloys are the smallest group in this study. Because of this, insufficient data are available to make definitive conclusions. The data are widely scattered in figures 7(a) and (b). The correlation batween

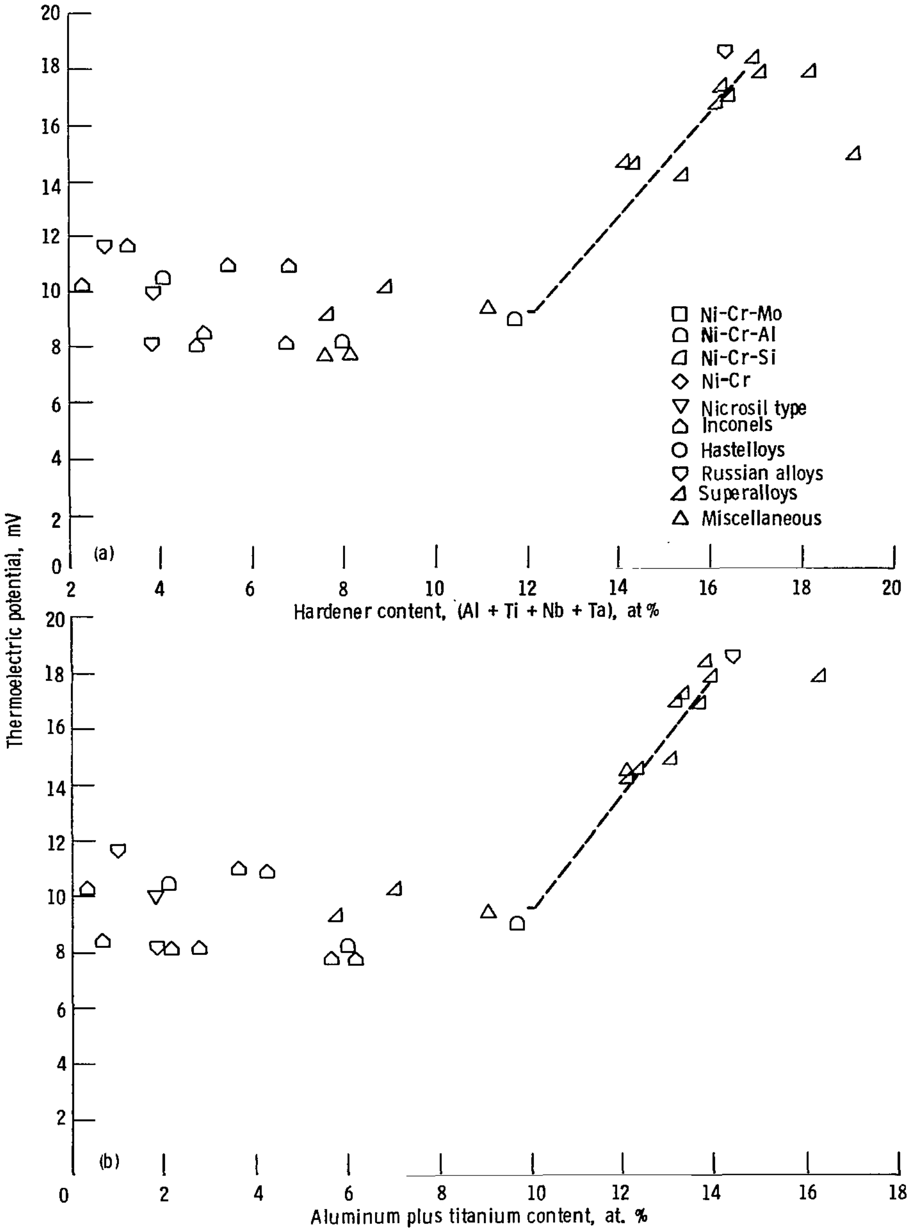


Figure 5. – Thermoelectric potential of nickel-base precipitation-hardenable alloys versus platinum at 600° C.

electron concentration and thermoelectric potential in figure 7(c) follows a smooth curve with a shape similar to the nickel-base alloy curve seen in figure 4(d). The data fall approximately within a 10 percent scatter band.

Maximum calibration temperature was 1100° C for the data of reference 5 and 1000° C for the data of reference 11 and this effort. No problems of thermoelectric instability were reported. This is true even though the Co-Cr alloys of reference 5 undergo a phase transition in the temperature range of this calibration.

Discussion of Results

The thermoelectric characteristics of 106 cobalt-base, iron-base, and nickel-base alloys, all containing chromium, have been investigated. The calibration curves fall within the bands shown in figure 8.

Figures 3, 4, and 7 show comparisons of thermoelectric properties of these materials with atomic percent principal constituent, ratio of two constituents, physical property (electrical resistivity), and electron concentra-

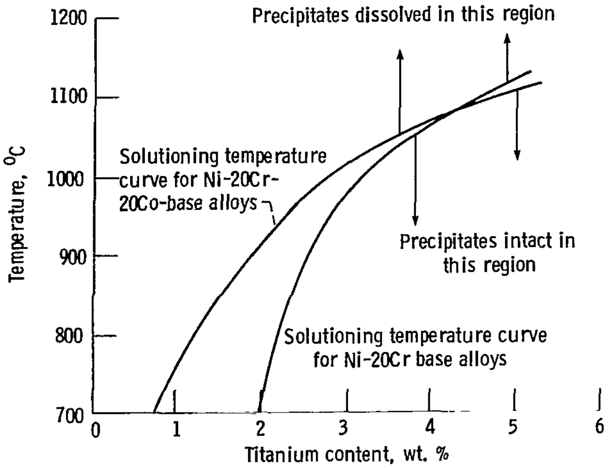


Figure 6. – Effect of composition on solutioning temperature for nickel-base precipitation-hardenable alloys. Titanium-aluminum ratio, 2/1.

tion. All of these figures show useful relationships between material characteristics and thermoelectric properties for these material groups. The electron concentration is the most consistent correlation parameter for the thermoelectric properties of these materials. Except for the highly precipitated alloys, the data lie on smooth curves (figs. 3(d), 4(d), and 7(c)) with a scatter of about ±10 percent.

From the slopes of these graphs the effect of the allowable variation of alloy constituents on measurement uncertainty can be examined. Using 304 stainless steel as an example, nickel content is allowed to vary from 8 to 10.5 weight percent and chromium content from 18 to 20 weight percent. From these variations, allowable ranges of Ni-Cr ratio, electron concentration, and iron content can be calculated. From the slopes of figures 3(d), 4(d), or 7(c) it was determined that about ±2 percent uncertainty in thermoelectric potential would result due to these allowable tolerances. This can be compared with the ANSI standard thermocouple materials with ±3/4 percent uncertainty tolerances.

For precipitation-hardenable alloys the presence of the precipitate phases changes the electronic structure of the alloy and affects the thermoelectric properties. For nickel-base superalloys a correlation was seen in figure 5 between thermoelectric potential and the hardener content in the alloy. Using Udimet 700 as an example, a computation of the uncertainty in measurement accuracy can be made based on the allowable variation in hardener content. Udimet 700 has compositional limits of 3.7 to 4.7 weight percent aluminum and 3 to 4 weight percent titanium. When these limits are converted to atomic percent and when the slope of the functional relation of figure 5(b) is used, the uncertainty of thermoelectric potential is determined to be about ±18 percent. This uncertainty is unacceptable for many applications;

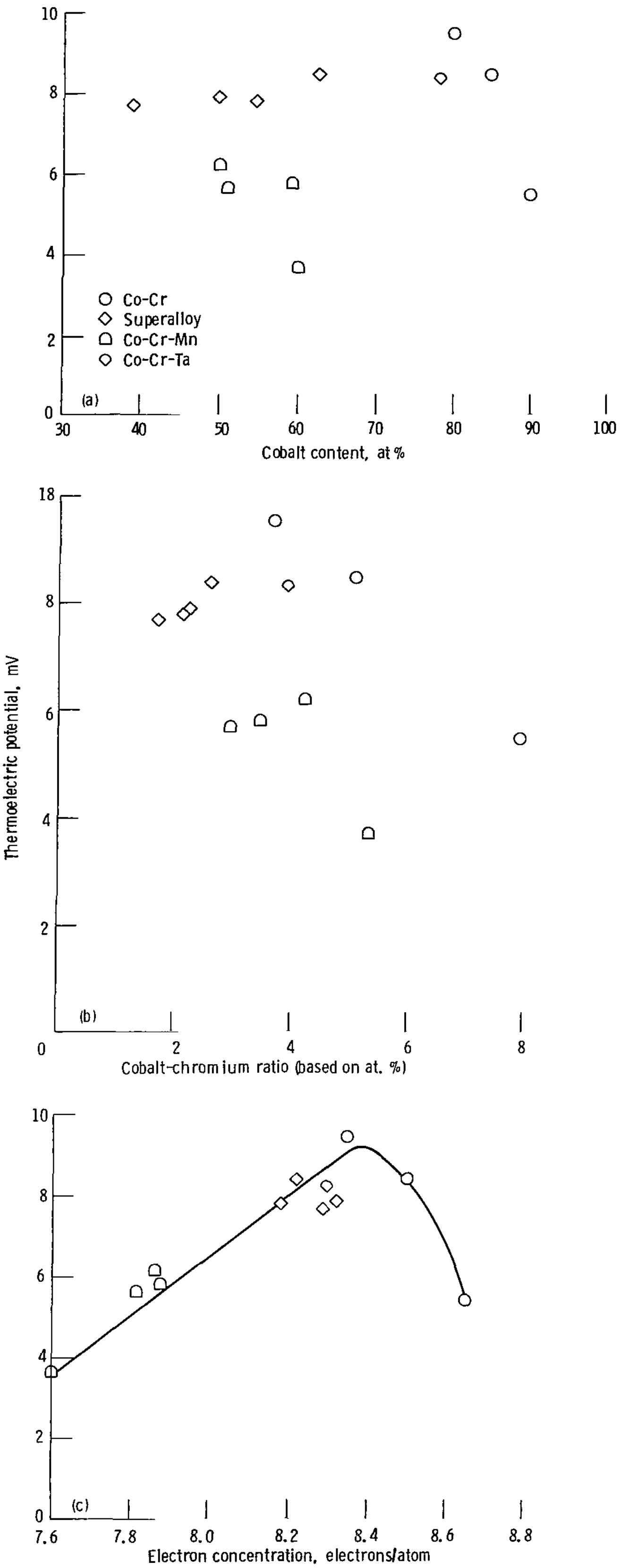


Figure 7. – Thermoelectric potential of cobalt-base alloys versus platinum at 600° C.

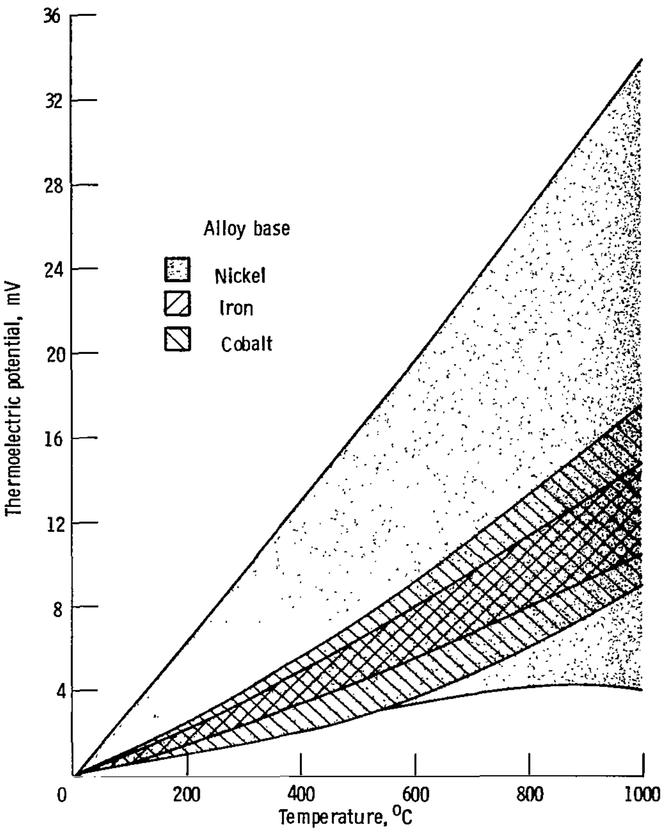


Figure 8. – Scatter bands of thermoelectric potential as function of temperature for nickel-base, iron-base, and cobalt-base alloys versus platinum.

however, it could be reduced if a more accurate compositional determination was made. Furthermore, some superalloys have tighter compositional limits on their constituents.

An examination was made of the thermoelectric stability of alloys calibrated in this study. For solid-solution-type alloys, no problems of thermoelectric instability were found up to 1000° C. For precipitation-hardenable alloys, thermoelectric stability was related to phase stability. Figure 6 showed the effect of composition on solutioning temperature for nickel-base precipitation-hardenable alloys. Table V lists solutioning temperature, maximum use temperature, and melting point for several nickel-base superalloys. For this group of alloys maximum use temperature is generally 100° to 200° C below solutioning temperature. These alloys showed thermoelectric stability up to about maximum use temperature.

One practical problem with the use of superalloys in thermocouple circuits is how to bring the signal out of the engine. Most superalloys are not fabricable in wire form. By coincidence, the emf curve of Udimet 700 matches closely the curve of Nicrosil II, a standard thermocouple material, while the Russian superalloy ZhS6k closely matches the Chromel calibration curve. Therefore, these standard thermocouple alloys could be used as leadwires for bringing the signal from turbine blades made from these superalloy materials. A study of a large body of data as presented in this report could aid in finding other leadwire matches. Also, the use of these correlation parameters could be useful in predicting the approximate thermoelectric properties of uncalibrated materials whose composition is known. Reference 19 reports on a commercial instrument that measures relative thermoelectric properties of alloys for use in alloy separation and identification. The information in this report can be used to enhance the use of such an instrument as well as to indicate the limitation in its use due to the effect of allowable compositional variation on alloy differentiation.

Conclusions

The information in this study should be useful in making temperature measurements in turbine engines in the following ways:

1. Engine parts can be used as one leg of a thermocouple in conjunction with a thin film or single-wire sheathed thermoelement.
2. Differential temperature measurements on engine parts can be made between any two points on the part which are each accessible to a single thermoelement attachment.
3. Knowledge of the shape of the thermoelectric potential versus material property function will aid in the determination of the thermoelectric properties of other uncalibrated materials.
4. Knowledge of the shape of the thermoelectric potential versus material property function will aid in the determination of the uncertainty of the thermoelectric potential caused by allowable composition variation of alloy constituents.
5. Electron concentration is the most consistent material property correlation function for the thermoelectric properties of solid-solution-type alloys in these material groups.
6. For nickel-base superalloys quantity of hardener content is a useful correlation function with thermoelectric potential.
7. For precipitation-hardenable alloys maximum use temperature should be a useful indication of thermoelectric stability range.
8. A large body of thermoelectric property data will provide a source for leadwire matching for materials not fabricable in wire form.

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Cleveland, Ohio, 44135, November 25, 1983

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TABLE I. - ALLOY COMPOSITION

(a) Cobalt-base alloys

Alloy	Alloy composition, wt %						
	Co	Cr	Mn	Si	Ni	Mo	Other
Cobalt-chromium binary alloys							
Co-10Cr	90	10	-----	----	--	---	----------------------------
Co-15Cr	85	15	-----	----	--	---	----------------------------
Co-20Cr	80	20	-----	----	--	---	----------------------------
Superalloys							
Haynes 25	52	20	1.5	0.5	10	---	1.5Fe, 15W, 0.1C
Haynes 188	39	22	.6	.3	22	---	1.5Fe, 14.5W, 0.1C, 0.09La
MAR-M-509	55	23	-----	----	10	---	3.5Ta, 7W, 0.5Zr, 0.2Ti, 0.6C
WI-52	63	21	.25	.25	--	---	2Ta+Nb, 11W, 2Fe, 0.45C
Cobalt-chromium-manganese alloys							
Co-Cr-Mn	51	15	34	----	--	---	----------------------------
Co-Cr-Mn	59.5	15	25.5	----	--	---	----------------------------
Co-Cr-Mn-Al	60	10	25	----	--	---	5Al
Co-Cr-Mn-Mo	50	10.2	35	----	--	4.8	----------------------------
Cobalt-chromium-tantalum alloys							
Co-Cr-Ta	78	20	-----	----	--	---	2Ta

(b) Iron-base alloys

Alloy	Alloy composition, wt %						
	Fe (a)	Ni (a)	Cr (a)	Mn (b)	Si (b)	C (b)	Other (a)
300-Series stainless steels							
302	71	9	18	2	1	0.15	----------------
304	70	9.25	19			.08	----------------
305	69	11.75	18			.12	----------------
308L	67	11	20			.03	----------------
310	52	20.5	25		1.5	.25	----------------
316	67	12	17		1	.08	2.5Mo
321	70	10.5	18		1		5x%C min. Ti
330	44	35.5	18.5		0.75-1.5		----------------
347	69	11	18		1		10x%C min. Nb+Ta
Precipitation-hardenable steels							
17-4 PH	74	4	16.5	1	1	0.07	4Cu, 0.30Nb+Ta
17-7 PH	74	7	17	1	1	.07	1.15Al
Commercial steels							
C-20	48	29	20	---	--------	----	3Cu
525	46	36.4	16	1.4	0.1	----	----------------
KA2	68	9.7	21.3	.5	.7	0.11	----------------
18-8	74	8	18	---	--------	----	----------------
RA-330	45	36	19	---	--------	.05	----------------
Russian steels							
EI703	35	37	21.5	0.7	0.8	0.10	1Ti, 3W, 0.5Al
1Kh18N9T	69	9.5	18.5	2	.8	.14	----------------

[a] Nominal values unless otherwise indicated.
[b] Maximum values unless otherwise indicated.

TABLE I. - Continued

(c) Nickel-base alloys

Alloy	Alloy composition, wt %							
	Ni	Cr	Fe	Mn	Si	Mo	Al	Others
Nicrosil-type alloys								
Ni-15.4Cr-1.5Si	83.0	15.37	0.06	----	1.47	-----	----	0.03Mg, 0.06C
Ni-15.8Cr-1.5Si	82.6	15.79	.06	----	1.49	-----	----	0.03Mg, 0.06C
Ni-16.3Cr-1.5Si	82.1	16.26	.05	----	1.49	-----	----	0.03Mg, 0.06C
Ni-16.9Cr-1.5Si	81.5	16.88	.05	----	1.50	-----	----	0.02Mg, 0.06C
Nicrosil II	84.3	14.2	.10	----	1.40	-----	----	0.03C
Ni-13.6Cr-1.5Si	84.8	13.60	.10	----	1.47	-----	----	0.02Mg, 0.02C
Ni-13.0Cr-1.5Si	85.5	12.98	.03	----	1.45	-----	----	0.01Mg, 0.02C
Ni-12.5Cr-1.5Si	86.0	12.50	.04	----	1.44	-----	----	0.02Mg, 0.02C
Ni-12.0Cr-1.5Si	86.4	12.04	.04	----	1.44	-----	----	0.02Mg, 0.01C
Ni-14.2Cr-0.5Si	85.1	14.16	.05	----	.61	-----	----	0.09Mg, 0.01C
Ni-14.2Cr-1Si	84.5	14.25	.04	----	1.09	-----	----	0.08Mg, 0.01C
Ni-14.2Cr-2Si	83.6	14.21	.07	----	2.08	-----	----	0.07Mg, 0.01C
Ni-14.2Cr-2.5Si	83.0	14.28	.08	----	2.60	-----	----	0.08Mg, 0.01C
Ni-14.2Cr-3Si	82.6	14.26	.06	----	3.04	-----	----	0.07Mg, 0.01C
Nickel-chromium-aluminum alloys								
Ni-20Cr-0.2Al	80	20	-----	----	----	-----	0.22	----------------------------------
Ni-19.8Cr-1Al	79.2	19.8	-----	----	----	-----	1.0	----------------------------------
Ni-19.4Cr-2.9Al	77.6	19.4	-----	----	----	-----	2.9	----------------------------------
Ni-19.4Cr-4.8Al	76.2	19.4	-----	----	----	-----	4.8	----------------------------------
Nickel-chromium-silicon alloys								
Ni-19.6Cr-2Si	78.4	19.6	-----	----	1.96	-----	----	----------------------------------
Ni-19.4Cr-4.8Si	76.2	19.4	-----	----	4.8	-----	----	----------------------------------
Nickel-chromium-molybdenum alloys								
Ni-9.4Cr-5Mo	84.6	9.4	-----	1	----	5	----	----------------------------------
Ni-6.6Cr-6.9Mo	86.5	6.6	-----		----	6.9	----	----------------------------------
Ni-8.9Cr-10Mo	80.0	8.9	-----		----	10	----	----------------------------------
Ni-3.2Cr-13.8Mo	83.0	3.2	-----		----	13.8	----	----------------------------------
Ni-8.4Cr-15Mo	75.5	8.4	-----		----	15	----	----------------------------------
Ni-10Cr-17.8Mo	71.2	10	-----		----	17.8	----	----------------------------------
Ni-5Cr-18.8Mo	75.2	5	-----		----	18.8	----	----------------------------------
Nickel-chromium binary alloys								
Ni-0.8Cr-0.4Mn	98.8	0.8	-----	0.4	----	-----	----	----------------------------------
Ni-2Cr-0.4Mn	97.6	2	-----		----	-----	----	----------------------------------
Ni-5Cr-0.4Mn	94.6	5	-----		----	-----	----	----------------------------------
Ni-10Cr-0.4Mn	89.6	10	-----		----	-----	----	----------------------------------
Ni-15Cr-0.4Mn	84.6	15	-----		----	-----	----	----------------------------------
Ni-20Cr-0.4Mn	79.6	20	-----		----	-----	----	----------------------------------
Miscellaneous nickel-chromium alloys								
Ni-5Cr-1Mn	94.0	5.0	-----	1.0	----	-----	----	----------------------------------
Ni-6.5Cr-1Mn-0.2C	92.49	6.45	-----	.88	----	-----	----	0.18C
Ni-8.7Cr-1Mn-0.2C	89.81	8.70	-----	1.30	----	-----	----	0.19C
Ni-9.6Cr-1Mn-0.2C	89.34	9.55	-----	.95	----	-----	----	0.16C
Hastelloys								
Hastelloy C	54.85	15	6	1	1	17	----	0.15C, 5W
Hastelloy W	61	5	5.5	----	----	24.5	----	0.06C, 0.6V, 2.5Co[a]
Hastelloy X	49	22	15.8	----	----	9	2	0.15C, 0.6W, 1.5Co[a]

[a] Maximum value.

[b] Low cobalt version of Udimet 700.

TABLE I. - Concluded

(c) Concluded

Alloy	Alloy composition, wt %							
	Ni	Cr	Fe	Mn	Si	Mo	Al	Others
Inconels								
Inconel 62	73	15.5	8	0.5	0.38	-----	----	0.25Cu, 2.25Nb
Inconel 69	72.44	15.5	7	.5	.25	-----	0.7	2.37Ti, 0.95Nb, 0.25Cu, 0.04C
Inconel 82	74.6	20	1.5	3	.25	-----	----	0.25Cu, 0.37Ti
Inconel 92	73.9	15.5	5	2.4	.2	-----	----	3Ti
Inconel 600	76	15.5	8	----	----	-----	----	0.25 Cu[a], 0.08C
Inconel 601	60.5	23	14.1	----	----	-----	1.35	0.5Cu[a], 0.05C
Inconel 625	61	21.5	2.5	1	.25	9	.2	3.6Nb+Ta, 0.2Ti, 0.05C
Inconel 718	52.5	19	18.5	.25	.37	3	.5	0.9Ti, 5.1Nb+Ta, 0.05C
Strain gage alloys								
Nichrome	62.11	14.93	21	2.02	0.35	-----	----	-----------------------------------
Nichrome V	79	18.85	.33	1	.69	-----	----	0.03C
Karma	74	19.5	3	.15	.30	-----	3	0.06C
Evanohm	74.5	20	-----	----	----	-----	2.75	2.75Cu
Moleculoy	75.5	20	-----	----	----	-----	4.5	-----------------------------------
Electric resistance alloys								
RA333	45	25	18	1.5	1.25	3	----	3Co, 3W, 0.05C
Nirex	80	13.15	5.58	1.02	.24	-----	----	0.05C
105	94	3.85	-----	2.11	.11	-----	----	-----------------------------------
80-20	80	20	-----	----	----	-----	----	-----------------------------------
Ni-16Cr-24Fe	60	16	24	----	----	-----	----	-----------------------------------
Thermocouple alloys								
Geminol	78	19	0.8	----	0.8	-----	----	-----------------------------------
Chromel	90	10	-----	----	----	-----	----	-----------------------------------
Russian alloys								
VZh98	54.1	25	4	0.5	0.8	-----	0.5	0.5Ti, 14.5W, 0.1C
ZhS6k	67.38	10.8	-----	----	----	4	5.3	2.8Ti, 5W, 4.5Co, 0.14C, 0.08B
EI435	75	21	1.78	.7	.8	-----	.2	0.4Ti, 0.12C
EI602	71.02	20.5	3	.4	.8	2	.55	0.55Ti, 0.08C, 1.1Nb
Superalloys								
Waspaloy	57	19.5	[a]2.0	----	----	4.3	1.4	3Ti, 13.5Co, 0.07C, 0.09Zr
René 41	55	19	.3	----	----	10	1.5	3.1Ti, 11Co, 0.09C
Udimet 700	55.49	14.71	.10	0.10	0.10	4.66	4.11	3.18Ti, 17.4Co, 0.06Zr, 0.06C, 0.03B
Udimet 700-type[b]	59.84	14.8	-----	----	----	5.1	4.03	3.56Ti, 12.6Co, 0.07C(a)
MAR-M-200 + Hf	59	9	-----	----	----	-----	5	2Ti, 10Co, 12W, 1Nb, 2Hf, 0.1C
B1900	64.8	8	-----	----	----	6	6	1Ti, 10CO, 4Ta, 0.1Zr
B1900 + Hf	64	8	-----	----	----	6	6	1Ti, 10Co, 4Ta, 1.5Hf, 0.1Zr
IN 713C	72.3	14	-----	----	----	4.5	6	1Ti, 2Nb+Ta, 0.1C, 0.1Zr,
IN792	61.2	12.4	-----	----	----	1.9	3.1	4.5Ti, 9Co, 3.8W, 3.9Ta, 0.1Zr, 0.1C
MAR-M-247	59.3	8.4	.5	----	----	.65	5.5	1Ti, 10Co, 10W, 3Ta, 1.4Hf, 0.05Zr
Alloy 454	62.5	10	-----	----	----	-----	5	1.5Ti, 5Co, 4W, 12Ta
IN 100	60	10	.6	----	----	3	5.5	4.7Ti, 15Co, 1V, 0.15C, 0.06Zr

[a] Maximum value.
[b] Low cobalt version of Udimet 700.

TABLE II. - THERMOELECTRIC POTENTIAL FOR HIGH TEMPERATURE ALLOYS VERSUS PLATINUM

[Cold junction corrected to 0° C.]

(a) Cobalt-base alloys

Alloy	Thermoelectric potential, mV					
	Reference	Temperature, °C				
		200	400	600	800	1000
Cobalt-chromium binary alloys						
Co-10Cr	5	1.2	3.0	5.5	8.4	11.8
Co-15Cr	5	2.2	5.1	8.5	12.2	16.7
Co-20Cr	5	2.4	5.7	9.5	13.3	17.6
Superalloys						
Haynes 25	(b)	1.9	4.6	7.9	11.9	16.5
Haynes 188[a]	(b)	1.8	4.5	7.7	11.7	16.3
MAR-M-509	11	2.0	4.7	7.8	11.5	15.7
WI-52	11	2.2	5.1	8.4	12.2	16.5
Cobalt-chromium-manganese alloys						
Co-15Cr-34Mn	5	1.2	3.1	5.7	8.7	12.7
Co-15Cr-25.5Mn		1.2	3.2	5.8	8.9	12.9
Co-Cr-Mn-Al		.8	2.0	3.7	5.9	9.0
Co-Cr-Mn-Mo		1.3	3.6	6.1	9.7	13.9
Cobalt-chromium-tantalum alloys						
Co-Cr-Ta	5	2.2	5.1	8.1	11.7	16.0

(b) Iron-base alloys

300-series stainless steels						
302	4	0.9	2.6	4.7	7.2	----
304	(c)	1.0	2.5	4.6	7.2	----
304	(b)		2.6	4.7	7.4	10.9
304	4		2.7	4.9	7.4	----
305	4		2.7	4.9	7.4	----
308L	(b)	1.1	2.7	4.8	7.5	11.1
310	4	1.2	2.9	5.2	8.1	----
316[a]	(c)	1.1	2.8	5.0	7.9	----
316[a]	(b)	1.1	2.8	5.1	7.9	11.6
316[a]	4	1.2	2.9	5.1	7.9	----
321	4	1.0	2.7	4.9	7.4	----
330	4	1.4	3.5	6.5	10.2	----
347	(c)	1.2	2.9	5.0	7.8	----
347	4	---	---	4.9	7.4	----
Precipitation-hardenable steels						
17-4 PH	(b)	2.4	5.3	9.2	12.0	16.3
17-7 PH	(b)	1.2	3.0	5.2	7.8	11.1
Commercial steels						
C-20	4	---	---	6.2	----	----
525	1	1.5	3.9	6.9	10.3	14.8
KA2	1	1.5	3.0	5.3	8.2	11.6
18-8	2	1.0	2.6	4.7	7.4	----
RA330	(b)	1.3	3.4	6.1	9.6	13.7
Russian steels						
EI703	7	1.9	4.0	7.0	10.8	15.1
1Kh18N9t	7	1.1	2.9	5.1	7.8	11.0

[a] Average of 2 samples.
[b] Author's data.
[c] Data of G. E. Glawe.

TABLE II. - Concluded.

(c) Nickel-base alloys

Alloy	Thermoelectric potential, mV					
	Reference	Temperature, °C				
		200	400	600	800	1000
Nicrosil-type alloys						
Ni-15.4Cr-1.5Si	8	---	----	[a]13.7	19.0	25.2
Ni-15.8Cr-1.5Si		---	----	[a]13.3	18.8	24.8
Ni-16.3Cr-1.5Si		---	----	[a]13.0	18.5	24.5
Ni-16.9Cr-1.5Si		---	----	[a]12.8	18.0	24.0
Nicrosil II		3.9	8.9	14.4	20.1	26.0
Ni-13.6Cr-1.5Si		---	----	[a]14.9	20.8	26.8
Ni-13.0Cr-1.5Si		---	----	[a]15.4	21.2	27.2
Ni-12.5Cr-1.5Si		---	----	[a]15.8	21.6	27.6
Ni-12.0Cr-1.5Si		---	----	[a]16.1	22.0	28.0
Ni-14.2Cr-0.5Si		---	----	[a]16.1	22.2	28.4
Ni-14.2Cr-1Si		---	----	[a]15.1	21.0	27.0
Ni-14.2Cr-2Si		---	----	[a]13.3	18.8	24.5
Ni-14.2Cr-2.5Si		---	----	[a]12.6	17.7	23.3
Ni-14.2Cr-3Si		---	----	[a]12.0	17.0	22.2
Nickel-chromium-aluminum alloys						
Ni-20Cr-0.2Al	3	---	----	10.9	----	21.7
Ni19.8Cr-1Al		---	----	10.8	----	21.3
Ni-19.4Cr-2.9Al		---	----	8.4	----	17.2
Ni-19.4Cr-4.8Al		---	----	9.2	----	17.6
Nickel-chromium-silicon alloys						
Ni-19.6Cr-2Si	3	---	----	9.7	----	18.9
Ni-19.4Cr-4.8Si	3	---	----	8.2	----	16.7
Nickel-chromium-molybdenum alloys						
Ni-9.4Cr-5Mo	3	---	----	16.5	----	30.2
Ni-6.6Cr-6.9Mo		---	----	18.3	----	33.5
Ni-8.9Cr-10Mo		---	----	----	----	29.9
Ni-3.2Cr-13.8Mo		---	----	18.5	----	34.6
Ni-8.4Cr-15Mo		---	----	13.7	----	28.0
Ni-10Cr-17.8Mo		---	----	11.9	----	25.0
Ni-5Cr-18.8Mo		---	----	14.7	----	29.7
Nickel-chromium binary alloys						
Ni-0.8Cr-0.4Mn	3	1.1	2.4	3.6	4.1	3.9
Ni-2Cr-0.4Mn		3.8	7.7	11.7	13.7	15.4
Ni-5Cr-0.4Mn		5.8	12.5	18.0	23.5	28.4
Ni-10Cr-0.4Mn		5.8	12.5	19.0	25.2	31.8
Ni-15Cr-0.4Mn		4.2	9.4	14.9	20.6	27.5
Ni-20Cr-0.4Mn		3.0	6.8	11.8	16.8	22.6
Miscellaneous nickel-chromium alloys						
Ni-5Cr-1Mn	3	---	----	----	----	26.6
Ni-6.5Cr-1Mn-0.2C		---	----	----	----	30.4
Ni-8.7Cr-1Mn-0.2C		---	----	----	----	30.2
Ni-9.6Cr-1Mn-0.2C		---	----	----	----	29.5
Hastelloys						
Hastelloy C	4	2.0	4.8	8.6	13.0	----
Hastelloy W	(c)	2.7	6.6	11.6	17.3	----
Hastelloy W	(b)	2.7	6.6	11.7	17.6	24.1
Hastelloy X[d]	(c)	1.7	4.3	7.5	11.5	----
Hastelloy X	(b)	1.6	4.2	7.4	11.4	16.0
Hastelloy X	9	1.5	4.0	7.2	11.2	16.0
Inconels						
Inconel 62	(b)	2.9	6.9	11.7	17.2	23.3
Inconel 69		2.7	6.5	10.9	16.0	21.5
Inconel 82		2.5	6.0	10.3	15.5	21.2
Inconel 92		2.6	6.4	11.0	16.4	22.0
Inconel 600	(c)	3.0	7.1	12.0	17.6	----
Inconel 601	(b)	1.8	4.6	8.0	12.1	17.1
Inconel 625	(b)	1.9	4.8	8.5	13.0	18.3
Inconel 718	(c)	1.8	4.6	8.1	12.5	----
Strain gage alloys						
Nichrome	1	3.2	6.4	10.4	15.0	20.5
Nichrome V	1	3.7	7.4	11.8	16.9	22.9
Nichrome V	(b)	2.9	6.7	11.3	16.4	22.1
Karma		1.9	4.7	7.8	12.0	16.6
Evanohm		1.8	4.5	7.8	12.0	16.7
Moleculoy		2.4	5.7	9.4	13.7	18.3
Electric resistance alloys						
RA 333	(b)	1.9	4.7	8.2	12.4	17.3
Nirex	1	4.1	9.2	14.7	20.7	27.4
105	1	5.3	11.3	17.1	21.6	25.9
80-20	2	2.6	6.3	10.5	15.4	20.9
Ni-16Cr-24Fe	2	2.0	5.0	8.7	13.1	18.1
Thermocouple alloys						
Geminol	10	3.1	6.9	11.3	16.9	22.5
Chromel	10	6.0	12.8	19.6	26.2	32.5
Russian alloys						
VZh98	7	2.3	5.1	8.1	12.3	17.1
ZhS6k		5.8	12.0	18.7	25.5	33.0
EI435		3.2	5.0	11.7	16.8	23.0
EI602		2.8	4.0	10.0	15.0	20.7
Superalloys						
Waspaloy	(b)	2.5	5.9	9.2	14.0	19.1
René 41		2.4	5.9	10.1	15.2	20.9
Udimet 700		3.8	8.8	14.6	21.0	27.4
Udimet 700-type[e]		3.8	8.8	14.6	21.0	27.4
MAR-M-200 + Hf	11	4.7	10.4	16.8	23.7	31.3
B1900		5.6	11.9	18.4	25.0	31.8
B1900 + Hf		5.1	11.3	17.9	25.1	32.7
IN 713C		5.1	10.9	17.0	23.5	30.3
IN 792		3.8	8.6	14.1	20.4	27.5
MAR-M-247		4.9	10.8	17.3	24.2	31.7
Alloy 454		4.0	9.0	14.9	21.5	29.0
IN 100	(b)	4.8	11.0	17.9	25.4	32.8

[a] Extrapolated from 800° to 1000° C data.
[b] Author's data.
[c] Data of G. E. Glawe.
[d] Average of two samples.
[e] Low cobalt version of Udimet 700.

TABLE III. - PROPERTY VALUES FOR HIGH TEMPERATURE ALLOYS

(a) Cobalt-base alloys

Alloy	Electron concentration (a)	Cobalt content, at. %	Co-Cr ratio (b)	emf at 600° C versus Pt, mV (c)
Cobalt-chromium binary alloys				
Co-10Cr	8.66	89	7.9	5.5
Co-15Cr	8.50	83	5.0	8.5
Co-20Cr	8.34	78	3.5	9.5
Superalloys				
Haynes 25	8.10	55	2.2	7.9
Haynes 188	8.22	41	1.6	7.7
MAR-M-509	8.01	56	2.1	7.8
WI-52	7.93	65	2.6	8.4
Cobalt-chromium-manganese alloys				
Co-15Cr-34Mn	7.81	49	3.0	5.7
Co-15Cr-25.5Mn	7.98	57	3.5	5.8
Co-Cr-Mn-Al	7.60	55	5.3	3.7
Co-Cr-Mn-Mo	7.84	49	4.3	6.2
Cobalt-chromium-tantalum alloys				
Co-Cr-Ta	8.30	77	3.9	8.3

(b) Iron-base alloys

Alloy	Electron concentration (a)	Iron content, at. %	Ni-Cr ratio (b)	emf at 600° C versus Pt, mV (c)	Electrical resistivity, μΩ-cm (d)
300-Series stainless steels					
302	7.73	70	0.44	4.7	72
304	7.71	69	.47	4.9	
305	7.78	68	.57	4.9	
308L	7.73	66	.49	4.8	
310	7.77	52	.73	5.2	78
316	7.78	68	.63	5.1	74
321	7.75	69	.52	4.9	72
330	8.17	43	1.70	6.5	101
347	7.76	68	.54	4.9	73
Precipitation hardenable steels					
17-4 PH	7.77	73	0.21	9.2	98
17-7 PH	7.61	72	.37	5.2	86
Commercial steels					
C-20	8.20	48	1.28	6.2	---
525	8.33	46	2.01	6.9	---
KA2	7.65	66	.40	5.3	---
18-8	7.77	73	.39	4.7	72
RA330	8.13	44	1.63	6.1	---
Russian steels					
EI703	8.04	35	1.52	7.0	---
1Kh18N9T	7.68	68	.45	5.1	---

[a] Electrons per atom.
[b] Based on atomic percent values.
[c] Cold junction temperature corrected to 0° C.
[d] At 20° C.

TABLE III. - Concluded.

(c) Nickel-base alloys

Alloy	Electron concentration (a)	Nickel content, at. %	Ni-Cr ratio (b)	emf at 600° C versus Pt, mV (c)	Electrical resistivity, μΩ-cm (d)
Nicrosil-type alloys					
Ni-15.4Cr-1.5Si	9.13	80	4.78	13.7	-----
Ni-15.8Cr-1.5Si	9.11	79	4.63	13.3	-----
Ni-16.3Cr-1.5Si	9.09	79	4.47	13.0	-----
Ni-16.9Cr-1.5Si	9.07	78	4.28	12.8	-----
Nicrosil II	9.20	82	5.30	14.4	93
Ni-13.6Cr-1.5Si	9.22	82	5.52	14.9	-----
Ni-13.0Cr-1.5Si	9.25	83	5.84	15.4	-----
Ni-12.5Cr-1.5Si	9.27	83	6.09	15.8	-----
Ni-12.0Cr-1.5Si	9.29	84	6.36	16.1	-----
Ni-14.2Cr-0.5Si	9.28	83	5.32	16.1	-----
Ni-14.2Cr-1.0Si	9.22	82	5.25	15.1	-----
Ni-14.2Cr-2.0Si	9.11	80	5.21	13.3	-----
Ni-14.2Cr-2.5Si	9.06	79	5.12	12.6	-----
Ni-14.2Cr-3.0Si	9.01	78	5.13	12.0	-----
Nickel-chromium-aluminum alloys					
Ni-20Cr-0.2Al	9.09	78	3.53	10.9	-----
Ni-19.8Cr-1Al	8.99	76	3.54	10.8	-----
Ni-19.4Cr-2.9Al	8.75	73	3.55	8.4	-----
Ni-19.4Cr-4.8Al	8.51	70	3.46	9.2	-----
Nickel-chromium-silicon alloys					
Ni-19.6Cr-2Si	8.92	75	3.54	9.7	-----
Ni-19.4Cr-4.8Si	8.63	70	3.46	8.2	-----
Nickel-chromium-molybdenum alloys					
Ni-9.4Cr-5Mo	9.42	85	8.0	16.5	-----
Ni-6.6Cr-6.9Mo	9.49	87	11.5	18.3	-----
Ni-8.9Cr-10Mo	9.30	82	8.0	----	-----
Ni-3.2Cr-13.8Mo	9.46	86	22.7	18.5	-----
Ni-8.4Cr-15Mo	9.18	79	8.0	13.7	-----
Ni-10Cr-17.8Mo	9.03	75	6.3	11.9	-----
Ni-5Cr-18.8Mo	9.23	80	13.3	14.7	-----
Nickel-chromium binary alloys					
Ni-0.8Cr-0.4Mn	9.95	99	110.9	3.6	-----
Ni-2Cr-0.4Mn	9.90	97	43.3	11.7	-----
Ni-5Cr-0.4Mn	9.76	94	16.7	18.0	-----
Ni-10Cr-0.4Mn	9.54	88	7.9	19.0	-----
Ni-15Cr-0.4Mn	9.32	83	5.0	14.9	-----
Ni-20Cr-0.4Mn	9.11	78	3.5	11.8	-----
Miscellaneous nickel-chromium alloys					
Ni-5Cr-1Mn	9.74	93	16.6	----	-----
Ni-6.5Cr-1Mn-0.2C	9.63	91	12.7	----	-----
Ni-8.7Cr-1Mn-0.2C	9.52	88	9.1	----	-----
Ni-9.6Cr-1Mn-0.2C	9.50	88	8.3	----	-----
Hastelloys					
Hastelloy C	8.42	58	3.24	8.6	129.2
Hastelloy W	8.97	67	11.5	11.6	-----
Hastelloy X	8.32	49	1.97	7.5	118.1
Inconels					
Inconel 62	9.01	72	4.17	11.7	-----
Inconel 69	8.83	70	4.14	10.9	127.2
Inconel 82	8.70	70	3.31	10.3	-----
Inconel 92	8.91	72	4.22	11.0	-----
Inconel 600	9.15	75	4.37	12.0	102.9
Inconel 601	8.54	58	2.35	8.0	119.0
Inconel 625	8.52	62	2.54	8.5	128.7
Inconel 718	8.44	53	2.54	8.1	122.3
Strain gage alloys					
Nichrome	8.82	60	3.66	10.4	112
Nichrome V	9.05	76	3.68	11.8	107.8
Nichrome V	8.93	74	3.54	11.3	107.8
Karma	8.63	69	3.36	7.8	133
Evanohm	8.77	71	3.30	7.8	134
Moleculoy	8.53	70	3.34	9.4	-----
Electric resistance alloys					
RA333	8.18	44	1.60	8.2	-----
Nirex	9.23	78	5.45	14.7	-----
105	9.75	93	21.6	17.1	-----
80-20	8.93	75	3.45	10.5	108
Ni-16Cr-24Fe	8.81	58	3.32	8.7	112
Thermocouple alloys					
Geminol	9.03	77	3.89	11.8	-----
Chromel	9.65	89	9.5	19.6	70
Russian alloys					
VZh98	8.27	56	1.92	8.1	-----
ZhS6k	8.29	64	5.53	18.7	-----
EI435	8.85	71	3.16	11.7	-----
EI602	8.71	68	3.07	10.0	-----
Superalloys					
Waspaloy	8.58	57	2.80	9.2	128
René 41	8.32	54	2.56	10.1	131
Udimet 700	8.25	52	3.34	14.6	-----
Udimet 700-type[e]	8.28	57	3.58	14.6	-----
MAR-M-200 + Hf	8.30	60	5.81	16.8	-----
B-1900	8.36	63	7.18	18.4	-----
B1900 + Hf	8.32	62	7.01	17.9	-----
IN 713C	8.28	67	4.57	17.0	-----
IN 792	8.36	61	4.37	14.1	-----
MAR-M-247	8.30	60	6.26	17.3	-----
Alloy 454	8.33	65	5.54	14.9	-----
IN 100	8.17	55	5.32	17.9	143

[a] Electrons per atom.
[b] Based on atomic percent values.
[c] Cold junction temperature corrected to 0° C.
[d] At 20° C.
[e] Low-cobalt version of Udimet 700.

TABLE IV. - HARDENER CONTENT IN NICKEL-BASE PRECIPITATION-HARDENABLE ALLOYS

Alloy	Al	Ti	Al+Ti	Nb+Ta	Al+Ti+Nb+Ta
	Content, at. %				
Nickel-chromium-aluminum alloys					
Ni-19.8Cr-1Al	2.10	----	2.10	----	2.10
Ni-19.4Cr-2.9Al	5.96	----	5.96	----	5.96
Ni-19.4Cr-4.8Al	9.65	----	9.65	----	9.65
Inconels					
Inconel 62	-----	----	-----	1.39	1.39
Inconel 69	1.46	2.80	4.26	.58	4.84
Inconel 82	-----	.42	.42	----	.42
Inconel 92	-----	3.56	3.56	----	3.56
Inconel 601	2.79	----	2.79	----	2.79
Inconel 625	.44	.25	.69	2.30	2.99
Inconel 718	1.08	1.10	2.18	2.48	4.66
Strain gage alloys					
Karma	6.11	----	6.11	----	6.11
Evanohm	5.66	----	5.66	----	5.66
Moleculoy	9.08	----	9.08	----	9.08
Superalloys					
Waspaloy	2.12	3.58	5.70	----	5.70
René 41	3.23	3.76	6.99	----	6.99
Udimet 700	8.43	3.68	12.11	----	12.11
Udimet 700-type[a]	8.30	4.13	12.43	----	12.43
MAR-M-200 + Hf	11.08	2.50	13.58	0.65	14.23
B1900	12.59	1.18	13.77	1.25	15.02
B1900 + Hf	12.72	1.20	13.92	1.26	15.18
IN 713C	12.18	1.14	13.32	1.18	14.50
IN 792	6.69	5.47	12.16	1.26	13.42
MAR-M-247	12.17	1.25	13.42	1.00	14.42
Alloy 454	11.25	1.90	13.15	4.03	17.18
IN 100	11.03	5.31	16.34	----	16.34
Russian alloys					
VZh98	1.14	0.64	1.78	----	1.78
ZhS6k	11.07	3.30	14.37	----	14.37
EI435	.42	.47	.89	----	.89
EI602	1.16	.65	1.81	----	1.81

[a] Low cobalt version of Udimet 700.

TABLE V. - HARDENER CONTENT, SOLUTIONING TEMPERATURE, MELTING TEMPERATURE, AND MAXIMUM USE TEMPERATURE FOR SEVERAL SUPERALLOYS

Alloy	Hardener content, at. %	γ' solutioning temperature, °C	Melting point, °C	Maximum use temperature[a] °C
Waspaloy	5.70	1024	1340	882
René 41	6.99	1052	1340	885
Udimet 700	12.11	1149	1300	954
Udimet 700 type[b]	12.43	1149	1300	954
MAR-M-200 + Hf	14.23	----	1340	1027
B1900	15.02	1190	1288	1016
B1900 + Hf	15.18	----	1288	1016
IN 713C	14.50	1120	1275	982
IN 792	13.42	1120	----	1010
MAR-M-247	14.42	----	----	1038
Alloy 454	17.18	----	----	----
IN 100	16.34	1149	1300	1010

[a] Based on 100-hr life at a stress level of 136 MPa (20 000 psi).
[b] Low cobalt version of Udimet 700.

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16. Abstract

A study has been made of the thermoelectric properties of 106 chromium-containing alloys of the nickel-base, iron-base, and cobalt-base groups. The chromium content ranged from 1 to 25 percent. The thermoelectric properties were compared with the following material characteristics: atomic percent of the principle alloy constituent; ratio of concentration of two constituents; alloy physical property (electrical resistivity); alloy phase structure (percent precipitate or percent hardener content); alloy electronic structure (electron concentration). Correlations between thermoelectric properties and these material characteristics are discussed. For solid-solution-type alloys the most consistent correlation was obtained with electron concentration, with data following a smooth curve for each group and a scatter within 10 percent; for precipitation-hardenable alloys of the nickel-base superalloy group, the thermoelectric potential correlated with hardener content in the alloy structure. For solid-solution-type alloys, no problems were found with thermoelectric stability to 1000° C; for precipitation-hardenable alloys, thermoelectric stability was dependent on phase stability. Maximum use temperature should give a useful indication of the stability range. The effects of the compositional range of alloy constituents on temperature measurement uncertainty are discussed.

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