INL/EXT-07-13121

HTIR-TC Compensating Extension Wire Evaluations

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Idaho National Laboratory

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ABSTRACT

In an effort to reduce production costs for the doped molybdenum/niobium alloy High Temperature Irradiation Resistant Thermocouples (HTIR-TCs) recently developed by the Idaho National Laboratory, a series of evaluations were completed to identify an optimum compensating extension cable. As documented in this report, results indicate that of those combinations tested, two inexpensive, commercially-available copper nickel alloy wires approximate the low temperature (0 to 500 °C) thermoelectric output of KW-Mo (molybdenum doped with tungsten and potassium silicate) versus Nb-1%Zr in HTIR-TCs. For lower temperatures (0 to 150 °C), which is the region where soft extension cable is most often located, results indicate that the thermocouple emf is best replicated by the Cu-3.5%Ni versus Cu-5%Ni combination (measured emfs were within 4% at 100 and 150 °C). At higher temperatures (300 to 500 °C), data suggest that the Cu-5%Ni versus Cu-10%Ni combination may yield data closer to that obtained with KW-Mo versus Nb-1%Zr wires (measured emfs were within 8%).

1. Introduction

Currently, the Idaho National Laboratory (INL), in conjunction with the University of Idaho (UI), is exploring options to enhance the INL-developed High Temperature Irradiation Resistant Thermocouple (HTIR-TCs).[1] As discussed in References 2 and 3, initial INL results indicate that thermocouples constructed with doped molybdenum (KW-Mo) and alloyed niobium (Nb-1%Zr) thermoelement wires may be the optimum design. These materials are relatively expensive. At low temperatures (0 to 500 °C), extension wires composed of copper/nickel alloys may be used to replace these expensive molybdenum and niobium wires. Two alloys must be identified which will duplicate the low temperature thermoelectric output of the KW-Mo and Nb-1%Zr thermoelement wires.

2. Background

A literature review identified two prior efforts to select appropriate extension cable for molybdenum/niobium thermocouples. As discussed in this section, neither effort was focussed on the doped molybdenum/niobium alloy thermocouples pursued by INL.

2.1. Pratt Whitney

References 4 and 5 explore various extension wire material that could be used for a molybdenum versus niobium thermocouple. These efforts were based on the output of a Mo-0.5%Titanium/Niobium-1%Zirconium thermocouple between 16 and 100 °C. As shown in Figure 1, this effort used a "trial and error" approach, which evaluated the output of a wide range of combinations (Chromel/Constantan, Iron/Constantan, Copper/Constantan, Chromel/Alumel, Copper-3% Nickel/Constantan, Iron/Alumel, Chromel/Copper-3%Nickel, Alumel/Constantan, Copper/Alumel, Chromel/Copper, Iron/Copper-3%Nickel, Copper-3%Nickel/Alumel, Chromel/Iron, Iron/Copper, Copper/Copper-3%Nickel (Type R/S extension cable). Results (see Figure 2) indicate that the least error would be incurred with Copper/Copper-3%Nickel as extension cable.

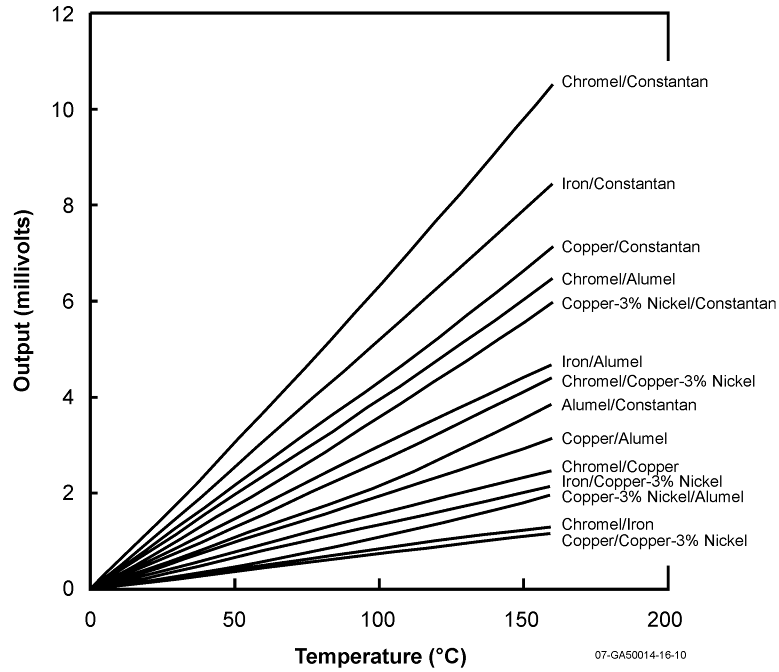


Figure 1. Emfs reported in References 4 and 5 for candidate extension wire combinations.

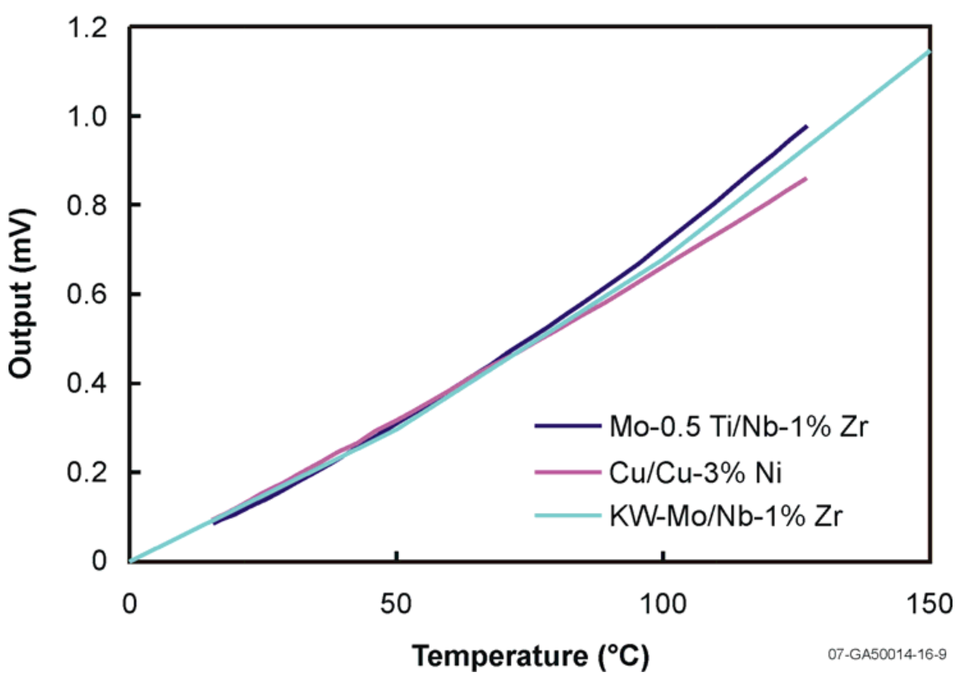


Figure 2. Comparison of emf for Cu/Cu-3%Ni and Mo-0.5%Ti/Nb-1%Zr combinations with KW-Mo/Nb-1Zr used in HTIR-TCs.

2.2. Institut National Polytechnique de Nancy

Reference 6 reports results from an investigation at the Institut National Polytechnique de Nancy (INPdN) of various copper/nickel alloys that could be used as extension cable for molybdenum/niobium thermocouples. Table 1 lists the alloys investigated by INPdN. For these tests, INPdN fabricated 0.6 mm (0.024 inch) diameter wire by three arc melt passes of pressed powder, followed by drawing to the final wire diameter.

Table 1. Copper-nickel alloy wires investigated by INPdN.

Wire	Predrawn Chemical Analysis %Ni	Chemical Analysis %Ni
Copper/3%Nickel	3%Ni	NA
Copper/5%Nickel	5%Ni	5.00
Copper/7%Nickel	6%Ni	6.67
Copper/10%Nickel	10%Ni	8.40
Copper/20%Nickel	20%Ni	16.62
Copper/30%Nickel	30%Ni	NA

INPdN obtained emf data from thermocouples composed of each of the above copper alloys mated with pure molybdenum and pure niobium at temperatures ranging from 46 to 288 ^{o}C. Tables 2 and 3 list results obtained for the copper alloy paired with pure molybdenum and pure niobium, respectively.

Table 2. Voltage from thermocouples containing copper alloy paired with molybdenum.

Temperature, ^{o}C	Mo/Cu, mV	Mo/Cu-10%Ni, mV	Temperature, ^{o}C	Mo/Cu-5%Ni, mV	Mo/Cu-7%Ni, mV	Temperature, ^{o}C	Mo/Cu-20%Ni, mV	Mo/Cu-30%Ni, mV
46	0.170	1.115	52	1.155	1.265	58	1.695	2.080
94	0.350	2.590	127	3.050	3.325	118	3.845	4.940
183	0.960	5.745	244	6.900	7.405	184	6.730	7.925
288	1.730	10.085	359	11.500	12.375	267	10.812	12.925

Table 3. Voltage from thermocouples containing copper alloy paired with niobium.

Temperature, °C	Nb/Cu, mV	Nb/Cu-10%Ni, mV	Temperature, °C	Nb/Cu-5%Ni, mV	Nb/Cu-7%Ni, mV	Temperature, °C	Nb/Cu-20%Ni, mV	Nb/Cu-30%Ni, mV
46	-0.100	0.665	52	0.735	0.870	58	1.215	1.510
94	-0.255	1.625	127	2.085	2.280	118	2.965	3.830
183	-0.540	3.780	244	4.680	4.970	184	5.280	6.390
288	-0.990	6.505	359	7.435	8.150	267	8.315	10.455

In Reference 6, Table 2 and 3 data were plotted to obtain the curves shown in Figures 3 and 4. Then, these voltage versus temperature curves were used to develop "equal voltage" curves for each temperature as a function of nickel content in the copper alloy versus molybdenum thermocouple and of nickel content in the copper alloy versus niobium thermocouple. As shown in Figure 5, these curves appear to cross for a composition of 4.2% nickel in the copper wire paired with molybdenum and 12.8% nickel in the copper wire paired with the niobium thermoelement. Note that these curves were obtained using the measured wire compositions and interpolating to obtain the values for 100 and 250 °C (because the data in Tables 2 and 3 were obtained at temperatures above and below these values).

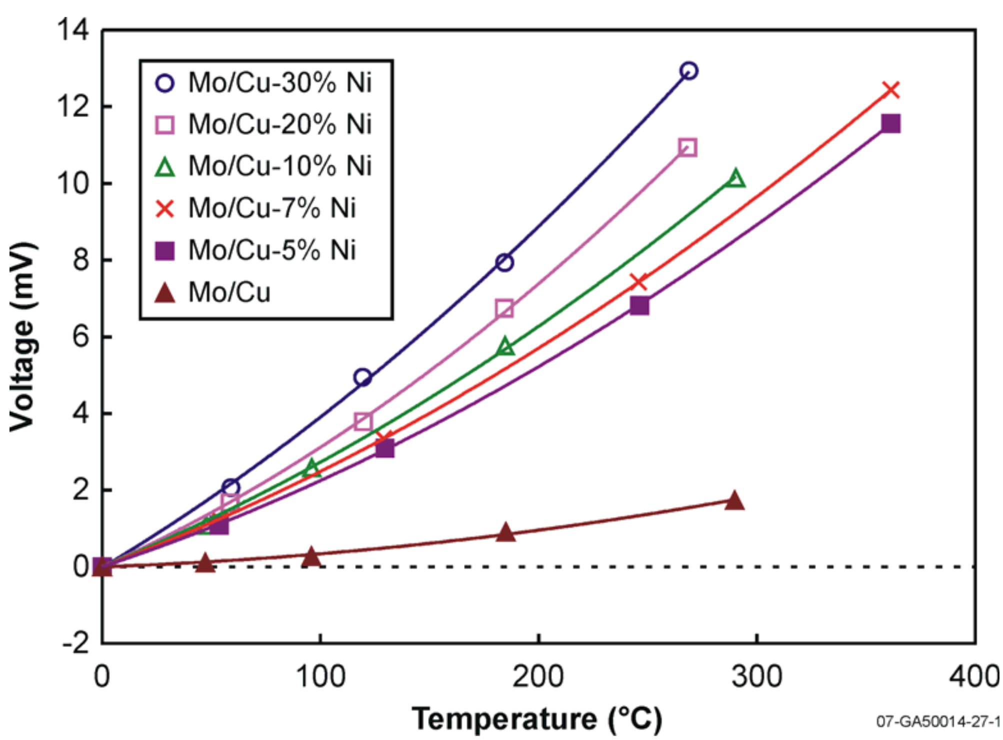


Figure 3. INPdN plot showing measured emf for Mo versus Cu-Ni alloys.

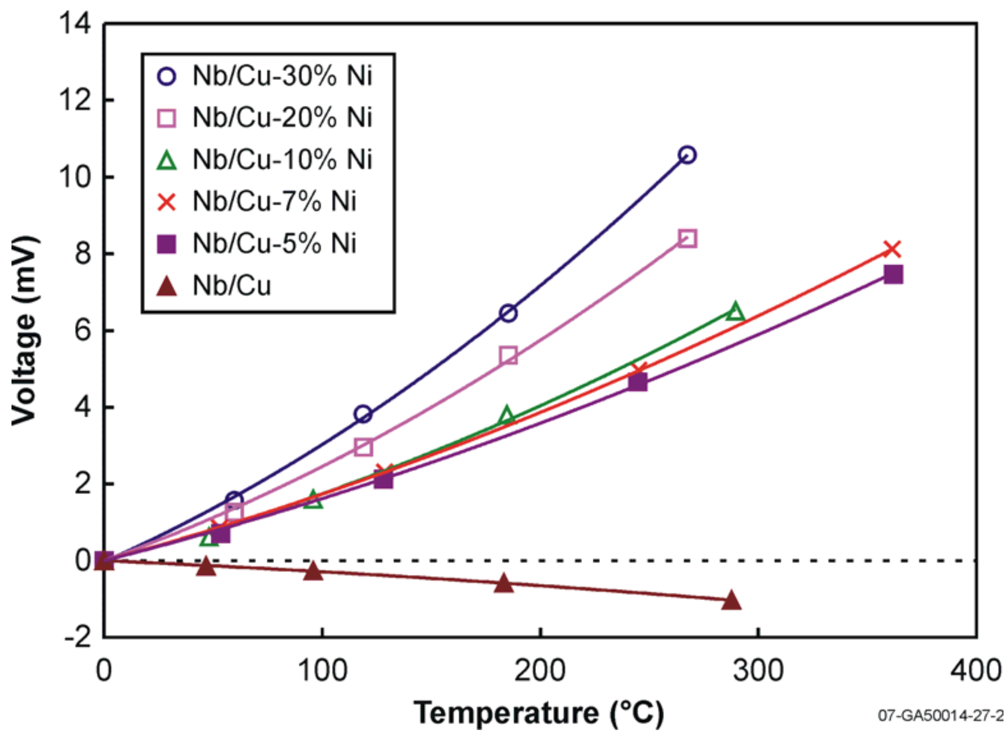


Figure 4. INPdN plot showing measured emf for Nb versus Cu-Ni alloys.

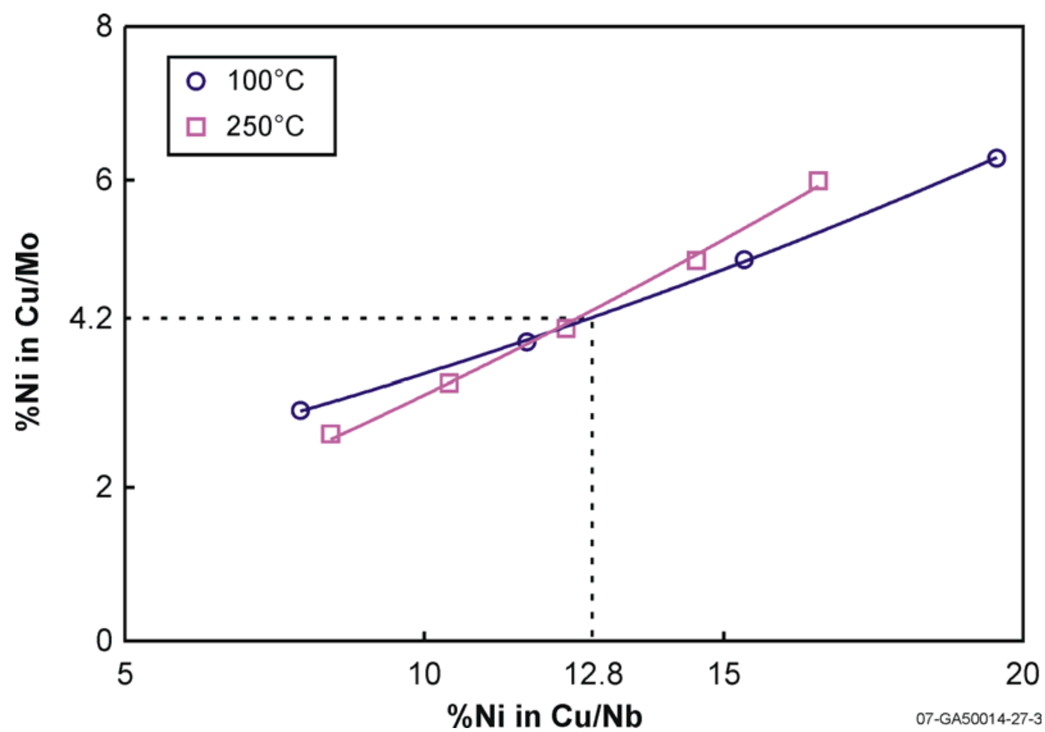


Figure 5. Determination of optimum composition based on "equal voltage" curves at 100 and 250 ^{O}C.

Finally, Reference 6 presents the curves shown in Figure 6. Curves in Figure 6 were generated by plotting the voltage obtained as a function of nickel content in the thermocouples paired with the molybdenum and niobium thermoelements for data obtained at approximately 100, 170, and 250 ^{o}C. Again, data were plotted for the measured compositions after the wire was drawn and by interpolating for values at these temperatures. The lines shown in black in Figure 6 correspond to the voltages for compositions of nickel, 4.3 and 12.8%, in the copper. The lines imply that these two alloys yield the same voltage if the wires are paired with molybdenum or niobium for all temperatures between 100 and 250 ^{o}C. Hence, Reference 6 authors conclude that these two copper alloys may be used as extension wires for molybdenum/niobium thermocouples for all temperatures between 100 and 250 ^{o}C.

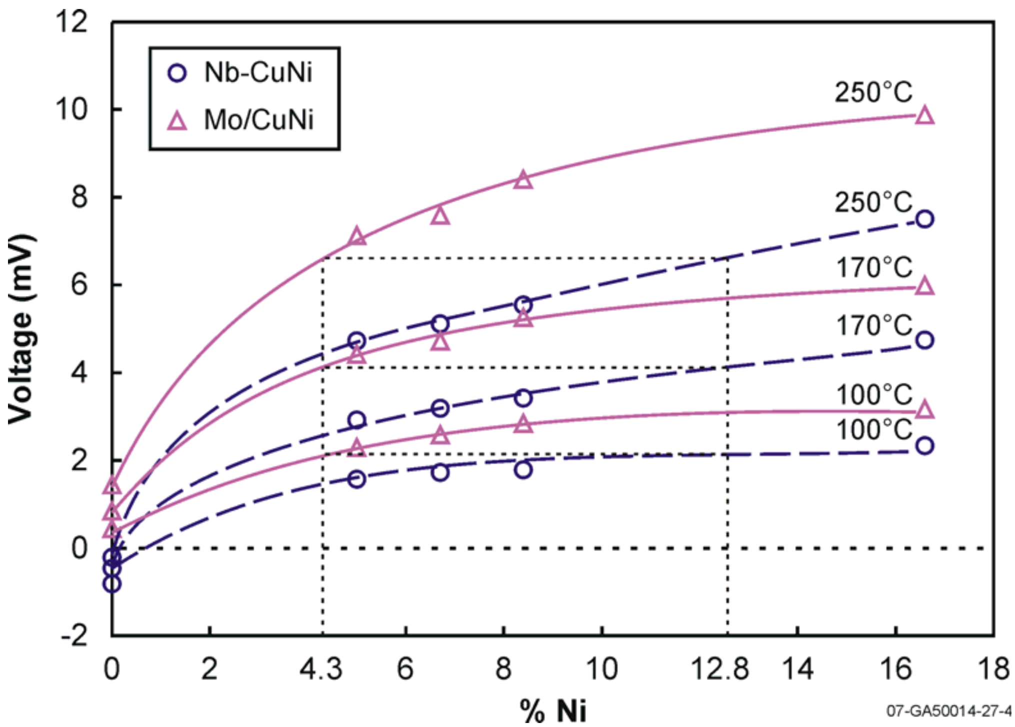


Figure 6. INPdN verification of optimum copper alloy compositions between 100 and 250 ^{o}C.

The required interpolations made it difficult to verify the INPdN approach. Hence, the data in Tables 2 and 3 were used to "recreate" Figures 3 through 6. Curves shown in Figure 7 and 8 appear very similar to those shown in Figures 3 and 4 developed by INPdN. Efforts to recreate Figure 5 required several assumptions. First, it was assumed that INPdN omitted data from wires containing 30%nickel (because the compositions for these wires weren't obtained after drawing). Second, although various types of curvefit options were available, it was judged that a 3rd order polynomial yielded the best result. Results shown in Figure 9 indicate that the compositions where the 100 and 250 ^{o}C curves intersect are different than values shown in Figure 5. Specifically, curves shown in Figure 9 appear to cross at compositions of Cu3.5%Ni and Cu 7.8%Ni.

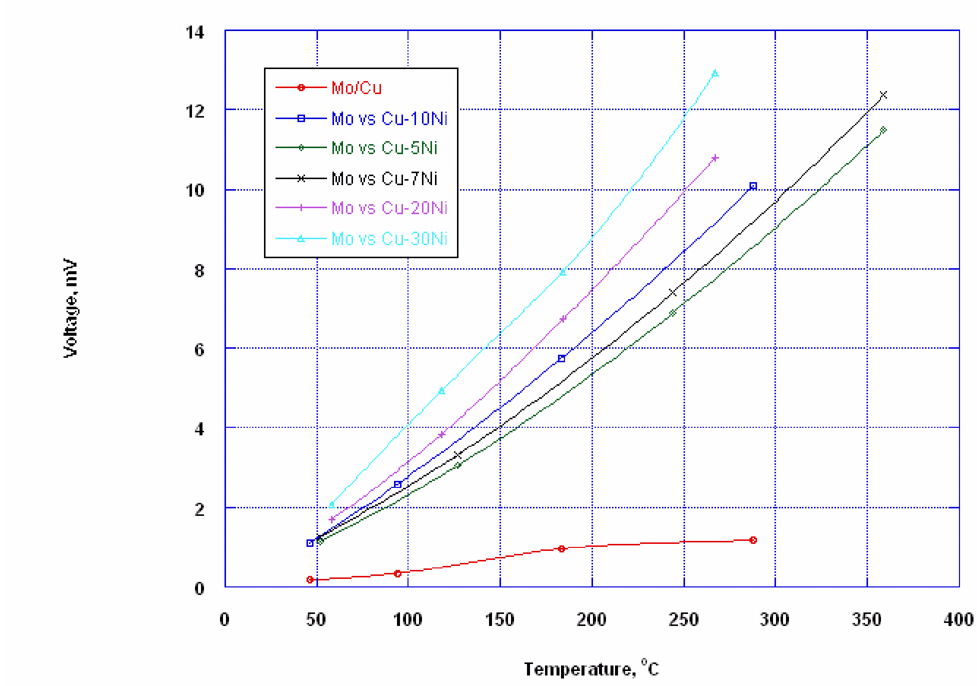


Figure 7. INL/UI recreation of INPdN curve showing measured emf for Mo versus Cu-Ni alloys.

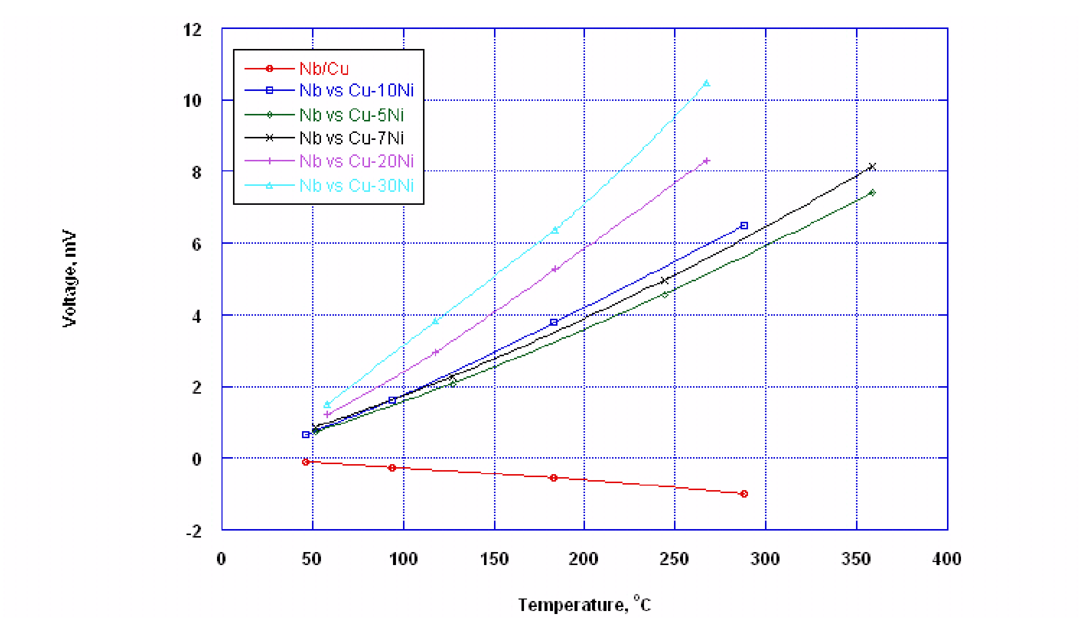
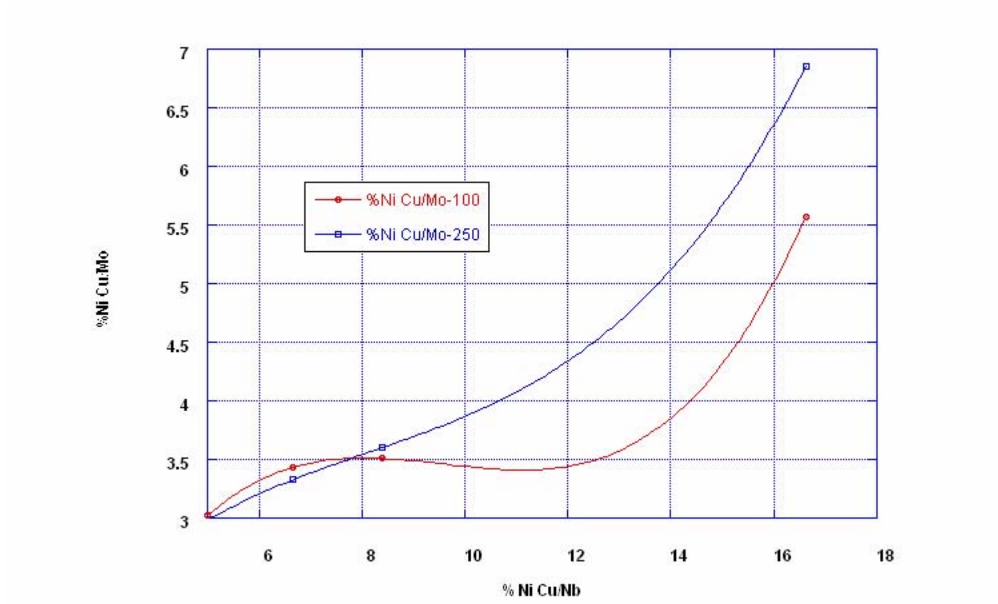
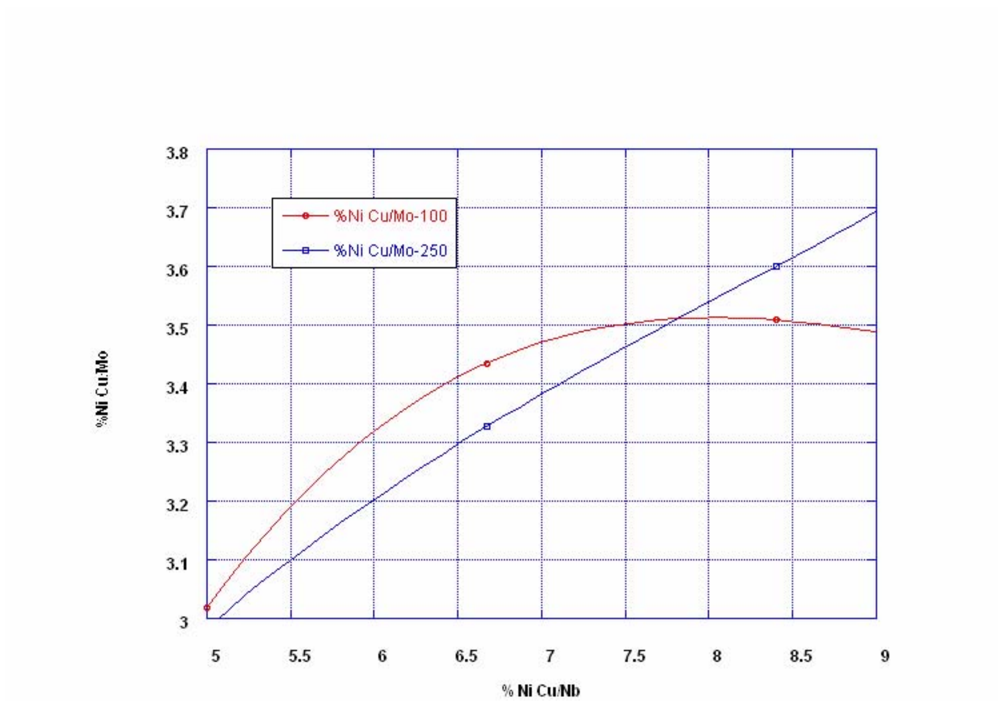


Figure 8. INL/UI recreation of INPdN curve showing measured emfs for Nb versus Cu-Ni alloys.

Figure 10 was developed to verify if the "optimum" compositions suggested in Figure 9 yielded similar voltage differences (as suggested by results in Figure 6). As indicated by the black



(a) all available data for interpolation



(b) close-up of intersection

Figure 9. INL/UI recreation of "equal voltage" curves at 100 and 250 ^{O}C.

lines in Figure 10, similar voltages were also obtained for curves at each temperature for combinations containing 3.1% and 7.8% nickel (slightly different compositions than values predicted using Figure 9).

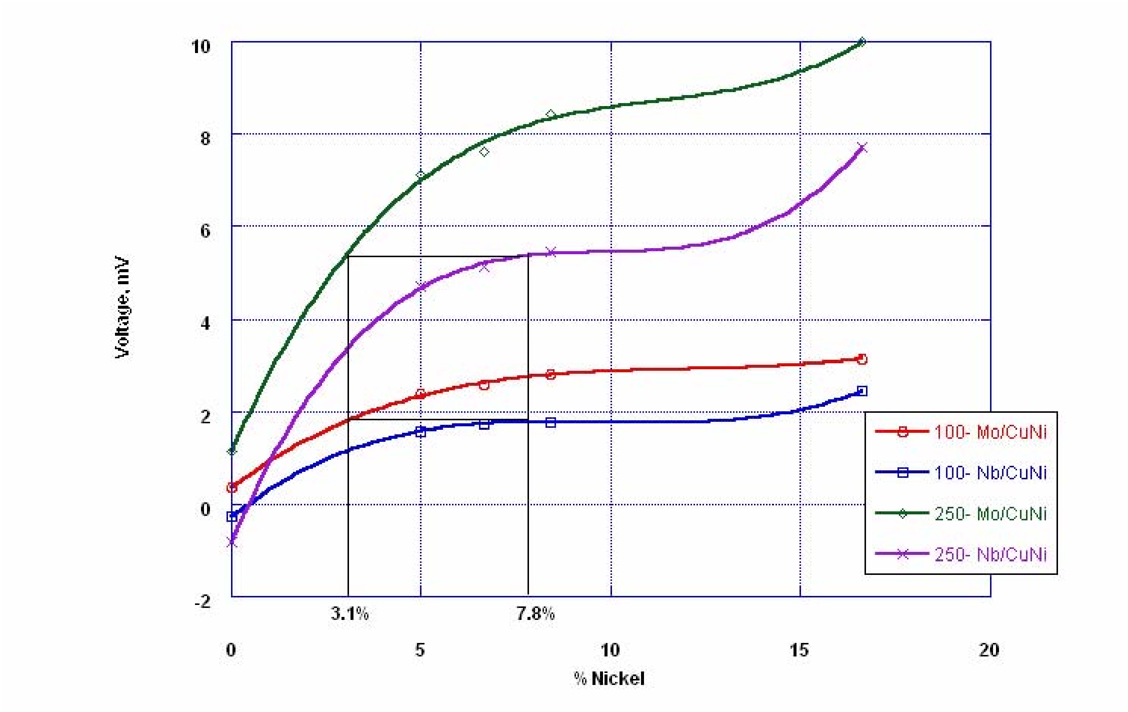


Figure 10. INL/UI recreation of curves to verify optimum copper alloy compositions between 100 and 250 ^{o}C.

2.3. Summary

In summary, prior work to develop extension wire for molybdenum-niobium thermocouples has been performed by Pratt-Whitney and by INPdN. However, this review indicates that neither could be directly applied to the INL-developed HTIR-TCs. Previous work had been performed for Mo-0.5%Ti/Nb-1%Zr and pure Mo/Nb thermocouples, rather than the KW-Mo and Nb1%Zr combination used in HTIR-TCs. In addition, the suggested copper alloy compositions from prior work differed. Finally, re-evaluation of the INPdN data yielded different copper alloy compositions than they obtained with their analysis. Hence, a new effort was undertaken to identify copper-nickel alloy extension wires for HTIR-TCs.

3. Methodology

This effort initially applied the approach suggested by INPdN in which copper alloy wires were paired with molybdenum and niobium wires. When results made it impossible to obtain conclusions about an "optimum" copper-nickel alloy combination, the data were used to predict combinations that yield voltages similar to a KW-Mo/Nb1%Zr thermocouple. These results were then confirmed by testing the predicted thermoelement wire combinations.

Fifteen bare wire thermocouples were initially constructed using wires composed of KW-Mo, Nb-1%Zr, and various copper-nickel alloys. This effort was limited to copper alloys available from commercial vendors. The composition of the copper-nickel wire after being drawn was verified using chemical analysis. As shown in Table 4, Inductively Coupled Plasma (ICP) results indicate compositions similar to the chemistry results on the original redraw stock.

Table 4. Copper-nickel alloy wires investigated.

Wire	Vendor[a]	Redraw Stock Chemical Analysis %Ni	Finished Wire Chemical Analysis %Ni
Copper 3.5%Nickel	California Fine Wire	3.50%Ni	3.6
Copper 5.0%Nickel	California Fine Wire	4.95%Ni	5.1
Copper 6.5%Nickel	California Fine Wire	6.49%Ni	6.6
Copper 10%Nickel[b]	California Fine Wire	10.00%Ni	10
Copper 11%Nickel	California Fine Wire	10.63%Ni	11
Copper 22%Nickel	California Fine Wire	23.83%Ni	22
Copper 30%Nickel	H. Cross	30.90%Ni	30
Copper 99.9%	California Fine Wire	NA	NA

a. All California Fine Wire alloys were "annealed". The Cu30%Ni from H. Cross was "as drawn temper."
b. Because the Cu10%Ni wire was similar in composition to the Cu11%Ni wire, it was not included in initial tests.

3.1. Experimental Setup

The test setup is shown in Figure 11. A test furnace and fixturing that accommodates up to five prototype thermocouples at a time was used. The test furnace utilizes two type-K thermocouples for monitoring and controlling test temperatures. This furnace contains a large Inconel equalizing block. This block provides a significant amount of thermal inertia, which helps maintain very stable temperatures over the desired test range (50 to 500 ºC for these tests).

Fifteen thermocouples were initially tested in three groups of five thermocouples. The thermocouples were connected to ice point probes, which were installed in ice point cells. The ice point cells maintain a constant temperature of 0 ºC. This allows the thermocouples to measure temperature directly, without needing compensation for ambient conditions. The thermocouples, through the ice point probes, were then connected to a LabView based data acquisition system (DAS), that recorded the output data from the thermocouples.

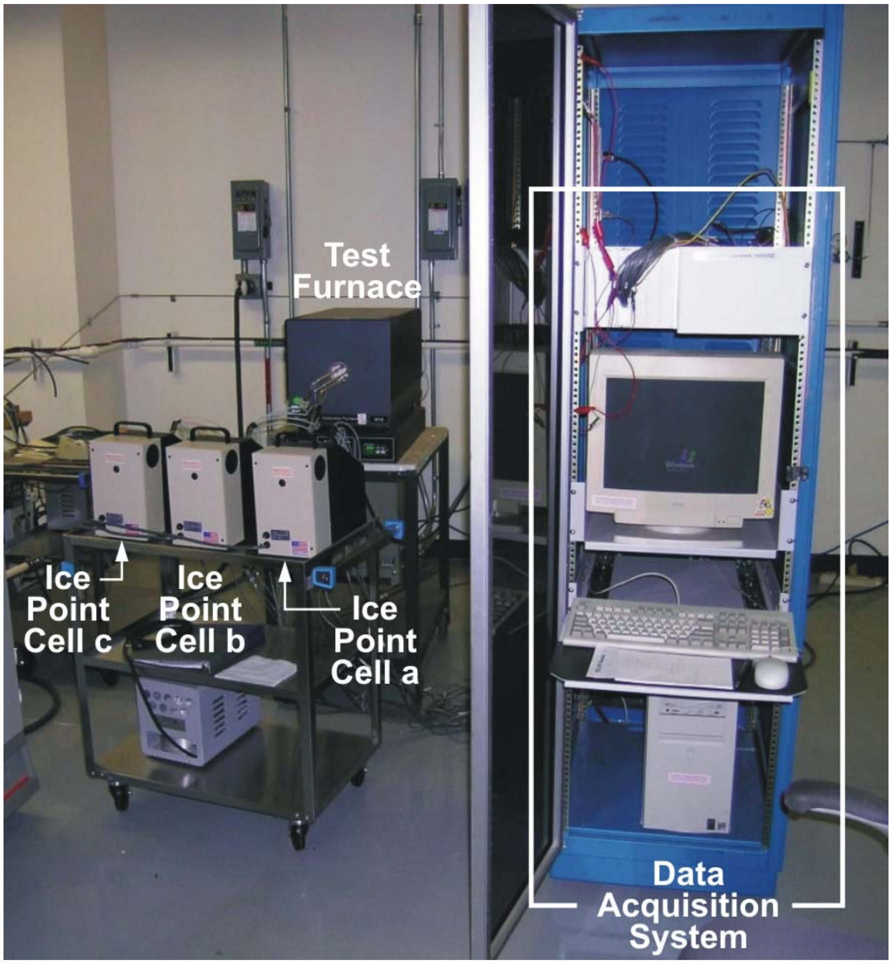


Figure 11. Experimental setup.

3.2. Ice Point Cell Probe and Thermocouple Fabrication

Ice point cells were used to maintain a constant “cold junction” temperature of 0 ºC. In order to use the cells, ice point probes for each type of test thermocouple were constructed. An ice point probe, as shown in Figures 12 and 13, joins the test thermocouple to the DAS. The probes were constructed by joining wires (approximately 16 inches in length) of the same composition as the thermoelement wires to pure copper extension wires (approximately 16 inches in length). This created two junctions per probe, one for each thermoelement. Junction welds were made using a LaserStar welding system, shown in Figure 14. Necessary welding parameters were developed to facilitate this process; the parameters are shown in Table 5. The weld is made by first twisting the two wires together, as seen in Figure 15. The wires are then welded using a rotary fixture (see Figure 14).

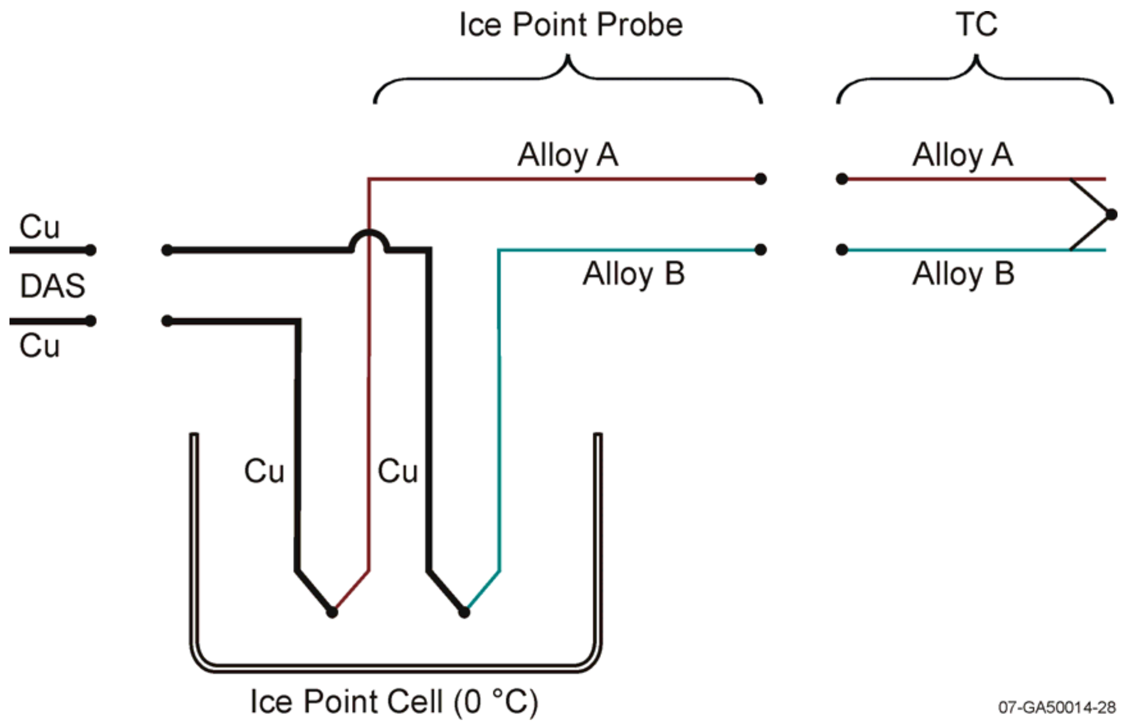


Figure 12. Ice point cell functional schematic.

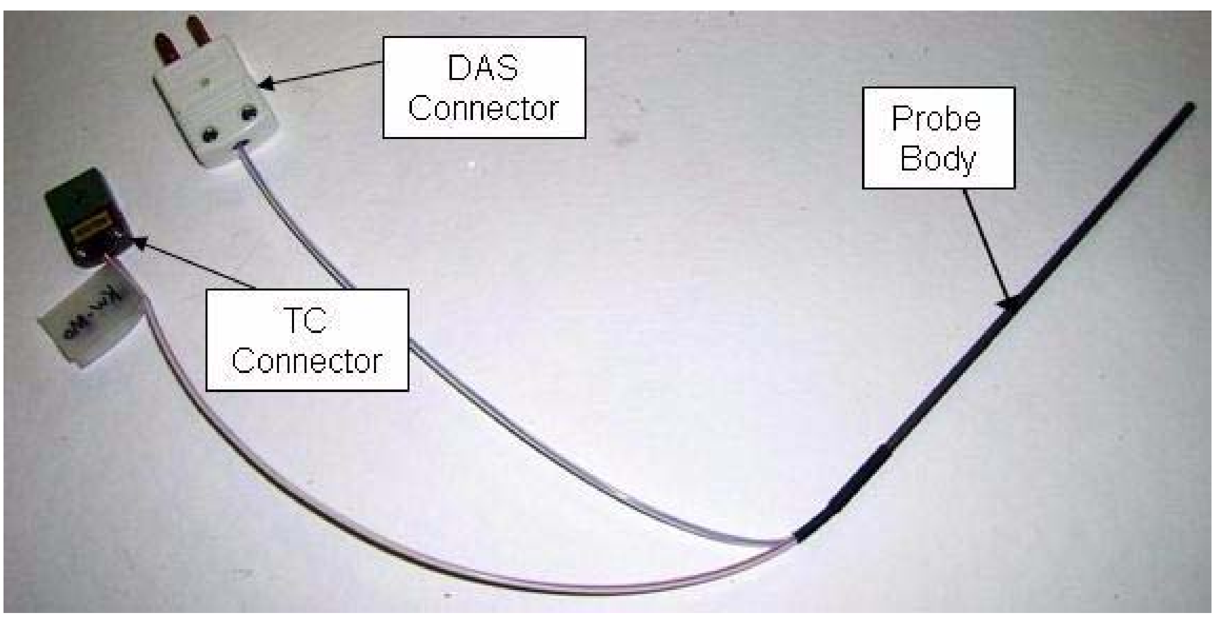


Figure 13. Finished ice point probes used for cold junction temperature maintenance.

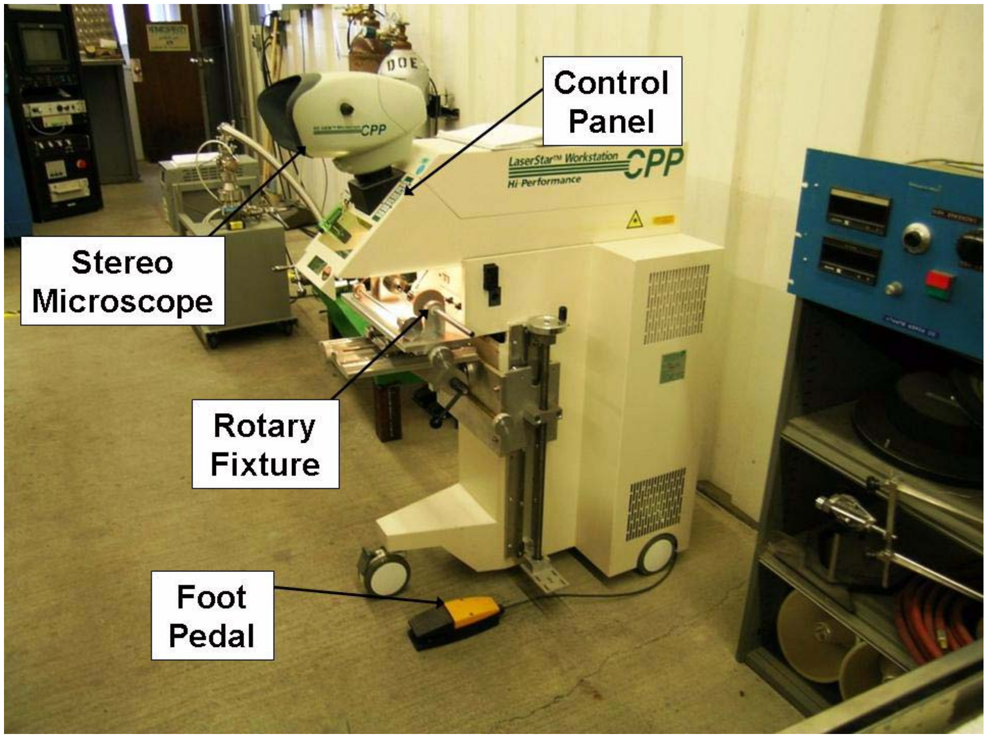


Figure 14. LaserStar welding system used for creating junctions for ice point probes and thermocouples.

Table 5. Weld parameters for copper-nickel alloys.

	KW-Mo	Nb1Zr	Cu99.99%	CuNi3.5%	CuNi5%	CuNi6.5%	CuNi10%	CuNi11%	CuNi22%	CuNi30%
KW-Mo										
Nb1Zr	200V 10 spot Gas flow must be very close to wires									
Cu99.99%	230V 15 spot	220V 10 spot								
CuNi3.5%	230V 15 spot	220V 15 spot	310V 15 spot							
CuNi5%	235V 15 spot	210V 10 spot	305V 15 spot	265V 15 spot						
CuNi6.5%	235V 15 spot	210V 15 spot	295V 15 spot	255V 15 spot	250V 15 spot					
CuNi10%	230V 15 spot	205V 15 spot	290V 15 spot	250V 15 spot	245V 15 spot	240V 15 spot				
CuNi11%	230V 15 spot	205V 15 spot	280V 15 spot	250V 15 spot	245V 15 spot	235V 15 spot	225V 15 spot			
CuNi22%	215V 15 spot	195V 10 spot	240V 15 spot	240V 15 spot	230V 15 spot	225V 15 spot	215V 15 spot	215V 15 spot		
CuNi30%	210V 15 spot	200V 15 spot	235V 15 spot	220V 15 spot	210V 15 spot	210V 15 spot	210V 15 spot	200V 15 spot	200V 15 spot	

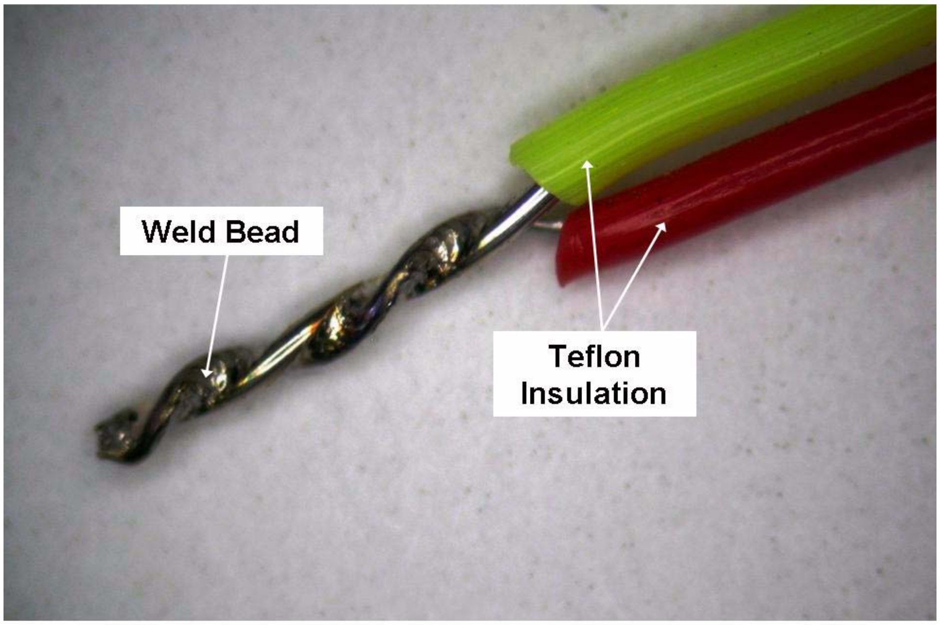


Figure 15. Twisted, welded junction used in ice point probes.

The exposed wires were threaded through Teflon insulation in order to maintain wire loop separation. A thin coating of epoxy was applied to each junction, also for electrical isolation. Once the epoxy was dry, the wire loops were threaded through a metallic (Inconel or tantalum) sheath, about six inches in length and 3/25 inch in diameter, that will fit into the existing ports of the ice point cell. The junctions were extended beyond the end of the sheath, and more epoxy was applied to them. The probes were hung vertically while the epoxy dried. The junctions were then pulled back into the sheath, the epoxy forming a hemispherical end cap once dry. PVC insulation was threaded onto the thermoelement ends as well as the copper extension wire ends. The PVC insulation was connected to the sheath using shrink wrap. A molybdenum/niobium connector were then attached to the thermocouple alloys, and a copper extension connector was attached to the pure copper alloys. A mating molybdenum/niobium connector (Figure 16), which was specially-made for the doped molybdenum/niobium alloy thermocouples, was attached to the thermocouple. These connectors were specially made by procuring commercial thermocouples (Type S, in this case) and replacing the metal pins (connector pins are shown in Figure 16) with molybdenum and niobium foil that has been machined to the proper dimensions. The molybdenum pin was used for positive thermoelements, whether doped molybdenum or one of the copper alloys, and the niobium pin was used for negative thermoelements, whether niobium-1% zirconium or one of the copper alloys. Care was taken in ensuring that the connector polarity was correct. The finished ice point probes were then installed into the ice point cells.

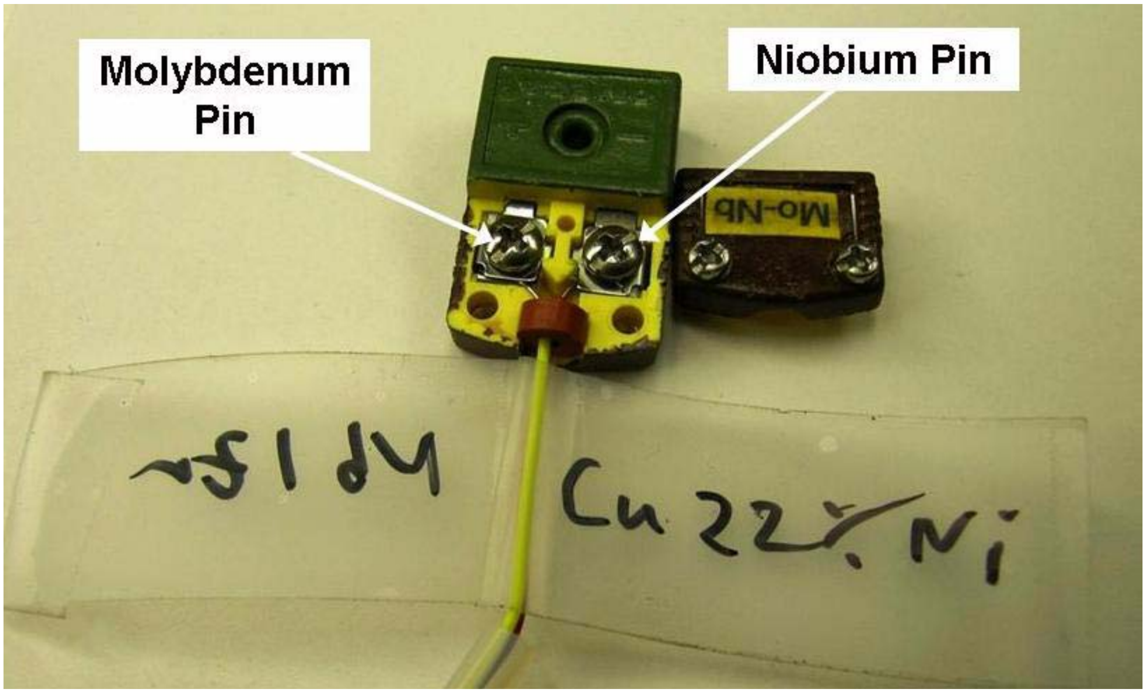


Figure 16. HTTL made connector used for prototype thermocouples.

Test thermocouples (see Figure 17) were constructed by laser welding the ends of thermoelement wires in the combinations of interest. These welds were made using the same techniques and parameters as those used for ice point probes (see Figure 15 and Table 5). Doped molybdenum positive thermoelements were joined with copper-nickel alloy negative thermoelements and copper-nickel positive thermoelements were joined with niobium-1% zirconium negative thermoelements.

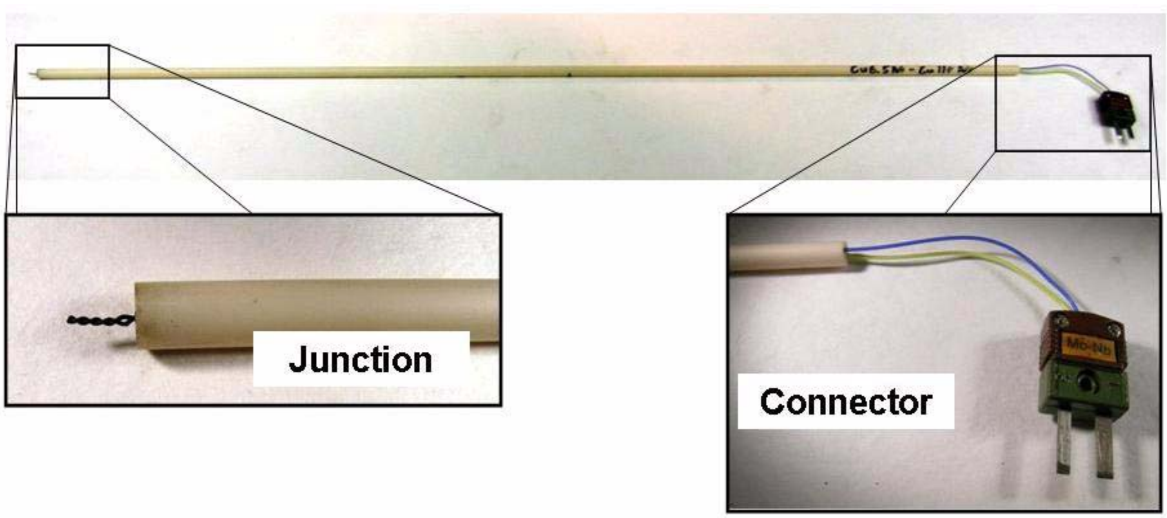


Figure 17. Bare wire test thermocouple.

The wires were then threaded into double-bore hard-fired alumina tubes. Teflon insulation was threaded onto the unwelded wire ends. The teflon was threaded so that a small amount was within the alumina tube, ensuring electrical isolation. The wire ends were then connected to molybdenum-niobium connectors in the same manner as for the ice point probes.

3.3. Initial Evaluations

Fifteen thermocouples were tested, so that each of the six copper-nickel alloy and pure copper wire could be paired with doped molybdenum and niobium-1%zirconium (along with one doped molybdenum/niobium-1%zirconium thermocouple). As noted in Table 1, the copper-10%nickel wire was omitted from the initial tests because its composition was similar to the copper-11%nickel wire. The fifteen test thermocouples were divided into three groups (a,b, and c) because the test furnace only accommodates five thermocouples at a time. The test groups are shown in Table 6.

Table 6. Compensating extension wire test thermocouples.

Group	Number	Designator	Positive Thermoelement	Negative Thermoelement
a	1	Mo-Nb	KW-Mo	Nb-1%Zr
	2	KW-Mo Cu99%	KW-Mo	Cu 99.99%
	3	KW-Mo Cu3.5%Ni	KW-Mo	Cu-3.5%Ni
	4	Kw-Mo Cu5%Ni	KW-Mo	Cu-5%Ni
	5	KW-Mo Cu6.5%Ni	KW-Mo	Cu-6.5%Ni
b	1	KW-Mo Cu11%Ni	KW-Mo	Cu-11%Ni
	2	KW-Mo Cu22%Ni	KW-Mo	Cu-22%Ni
	3	KW-Mo Cu30%Ni	KW-Mo	Cu-30%Ni
	4	Cu99% Nb1%Zr	Cu 99.99%	Nb-1%Zr
	5	Cu3.5%Ni Nb1%Zr	Cu-3.5%Ni	Nb-1%Zr
c	1	Cu5%Ni Nb1%Zr	Cu-5%Ni	Nb-1%Zr
	2	Cu6.5%Ni Nb1%Zr	Cu-6.5%Ni	Nb-1%Zr
	3	Cu11%Ni Nb1%Zr	Cu-11%Ni	Nb-1%Zr
	4	Cu22%Ni Nb1%Zr	Cu-22%Ni	Nb-1%Zr
	5	Cu30%Ni Nb1%Zr	Cu-30%Ni	Nb-1%Zr

The furnace temperature was increased in fifty degree increments, starting at 50 ^{o}C. The temperature was held constant while data were recorded for all three test groups. Thermocouples from one group were inserted into the furnace and allowed to stabilize, data were recorded during stabilization and for an hour while stable. Once sufficient data was collected, the next group was inserted. After data was recorded for each group, the temperature was increased. This process was repeated for all temperatures of interest.

4. Results

Initial tests were conducted using an approach based upon that used by INPdN for the thermoelements listed in Table 6. Based on results obtained from these initial tests, several copper alloy thermoelement combinations were tested. Results from these tests are presented below.

4.1. Initial Tests

Figures 18 and 19 compare the emfs measured for the doped molybdenum versus copper - nickel alloy wire and niobium versus copper-alloy thermocouples, respectively. In general, the results obtained from these tests are consistent with INPdN results (e.g., the measured emf increases with nickel content in the copper alloy). It should be noted that the difference between the wires containing 22% and 30% nickel were less than anticipated. It is suspected that this may be due to different wire manufacturers or the fact that the 30% nickel wire wasn't annealed.

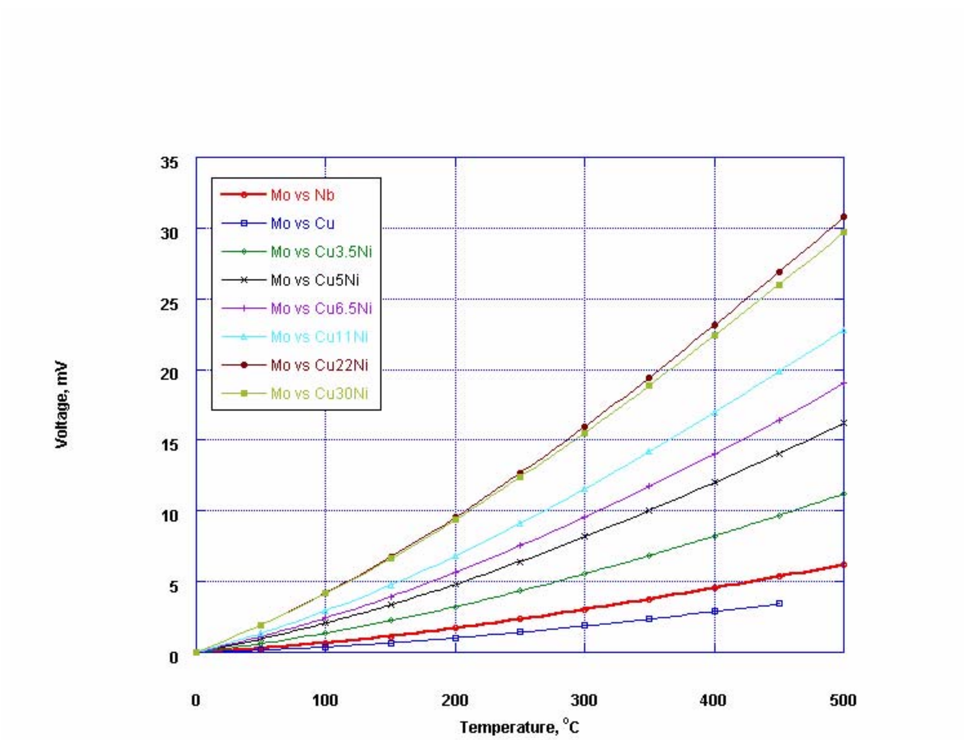


Figure 18. Emf for doped molybdenum thermoelement paired with various copper alloys.

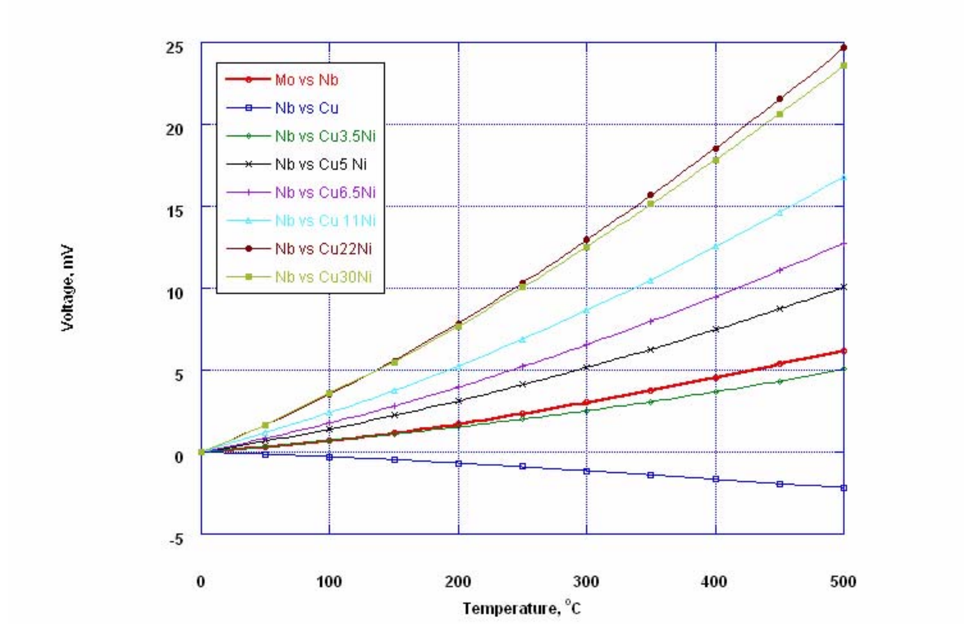
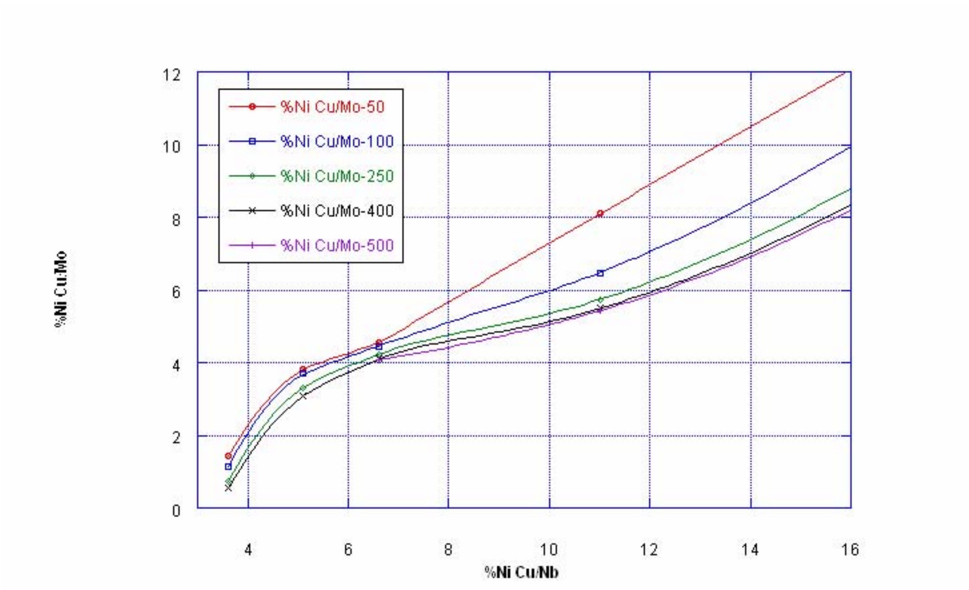


Figure 19. Emf for niobium-1%zirconium thermoelement paired with various copper alloys.

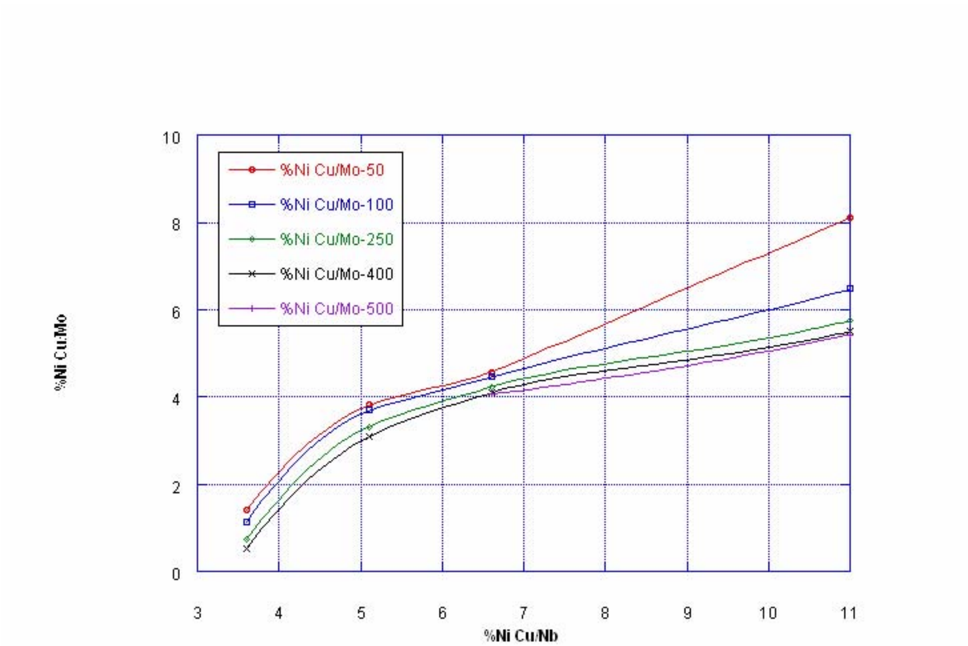
Results in Figures 18 and 19 were used to obtain insights about an optimum combination of copper-nickel alloys that would yield an emf similar to emf of a KW-Mo/Nb1%Zr thermocouple. Following the approach used to obtain Figure 5, "equal voltage" curves were obtained for selected temperatures by interpolating between the curves shown in Figures 18 and 19. Note that the "interpolation fits" for these curves do not cross (as occurred with the curves obtained with INPdN data). Although the lower composition nickel alloy curves lie close together, this approach does not provide insight about an "optimum" copper-nickel alloy combination for KW-Mo/Nb1%Zr thermocouples because none of the curves intersect.

Using the approach suggested in Reference 6 to develop Figure 6, emf versus nickel content curves are plotted for 100 and 250 ^{o}C in Figure 21 to determine if any combination of copper alloys might yield similar emfs for this temperature range. Lines in Figure 21 suggest that only low compositions of copper-nickel alloys (e.g., perhaps Cu-Cu3.5%Ni versus Cu-Cu2%Ni) will yield equal emfs in the 100 to 250 ^{o}C temperature range (e.g., nearly equal emfs occur for these combinations over this temperature range).

An alternate approach was then tried, in which the emfs obtained for various copper-nickel thermocouple combinations were calculated using data obtained in these initial tests. Measured emfs that were nearest to the values measured for KW-Mo/Nb1%Zr thermocouples are shown in Figure 22. As anticipated, copper alloy combinations shown in this figure generally yield similar emfs irrespective of whether the alloy is paired with a KW-Mo or a Nb1%Zr thermoelement wire (e.g., emfs for the Mo-Cu11%Ni versus Nb-Cu5%Ni combination are similar to the Nb-Cu11%Ni versus Mo-Cu5%Ni combination). Results in Figure 22 suggest that several combinations yield emfs that are similar to the values obtained for the doped molybdenum versus niobium-1% zirconium thermocouple.



(a) all available data for interpolation for selected temperatures



(b) close-up of region where curves lie close

Figure 20. "Equal voltage" curves at selected temperatures for INL/UI data.

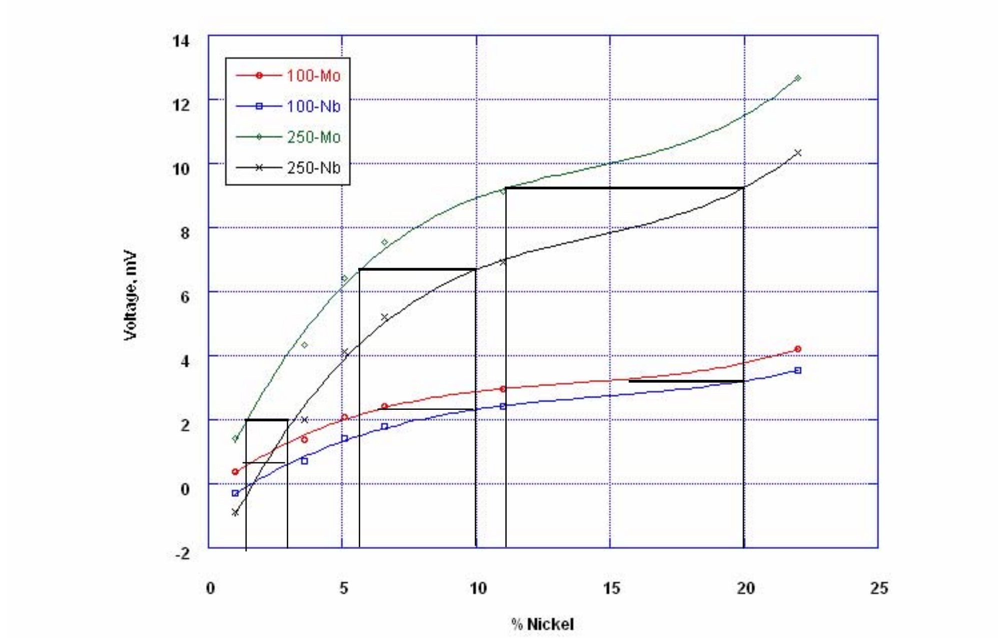


Figure 21. Emf versus nickel content curves for INL/UI data at 100 and 250 ^{o}C.

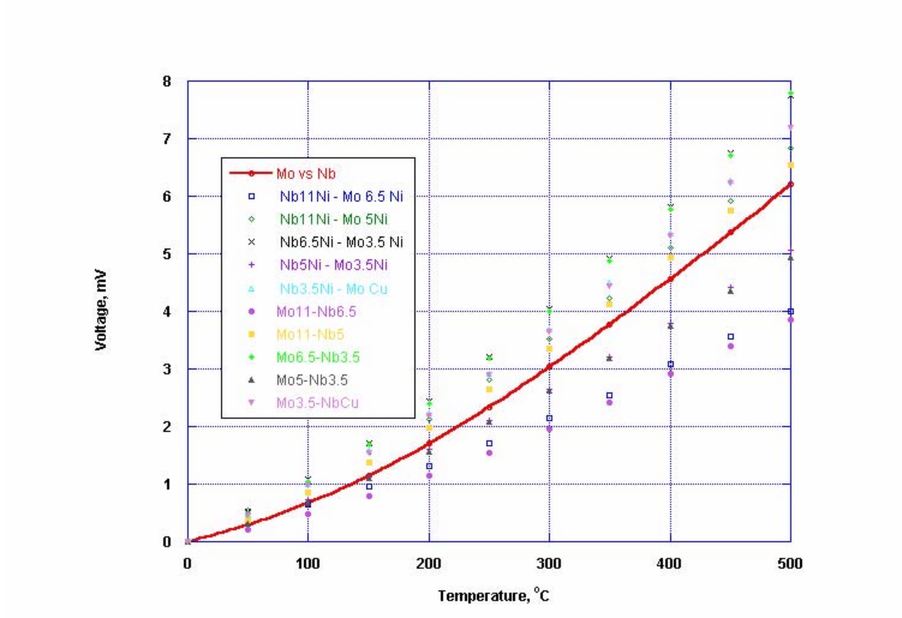


Figure 22. Calculated emfs similar to KW Mo/Nb-1%Zr thermocouple.

- Cu-5%Ni versus Cu-3.5%Ni
- Cu-3.5%Ni versus Cu
- Cu-11%Ni versus Cu-5%Ni
- Cu-11%Ni versus Cu-6.5%Ni

To verify results from these calculations, copper-nickel alloy thermocouples were fabricated and tested for each of the above combinations. In addition, results suggest that the combinations containing Cu-11%Ni would be closer if Cu-10%Ni wire were tested. Although this composition of wire was also commercially available from California Fine Wire, it was not included in the initial tests because it was so close in content to the Cu-11%Ni wire. However, subsequent tests included thermocouples containing Cu-10%Ni wire paired with Cu-5%Ni and Cu-6.6%Ni wire. Finally, because the combination of Cu-Cu3.5%Ni is so close to the combination recommended by Pratt-Whitney (Cu-Cu3%Ni), some Type S extension cable was also tested. Section 4.2 presents results from evaluating these combinations of copper-nickel alloys.

4.2. Confirmatory Tests

Using the data collected from the first set of fifteen thermocouples, new thermoelement combinations were determined and tested under the same conditions. The chosen thermoelement combinations are shown in Table 7.

Table 7. Confirmatory test combinations.

Group	Number	Designator	Positive Thermoelement	Negative Thermoelement
d	1	KW-Mo Nb-1%Zr	KW-Mo	Nb-1%Zr
	2	Cu-5%Ni Cu10%Ni	Cu-5%Ni	Cu-10%Ni
	3	Cu5%Ni / Cu11%Ni	Cu-5%Ni	Cu-11%Ni
	4	Cu6.5%Ni /Cu10%Ni	Cu-6.5%Ni	Cu-10%Ni
	5	Cu6.5%Ni / Cu11%Ni	Cu-6.5%Ni	Cu-11%Ni
e	1	KW-Mo / Nb-1%Zr	KW-Mo	Nb-1%Zr
	2	Cu / Cu-3.5%Ni	Cu99.99%	Cu-3.5%Ni
	3	Cu / Cu-3%Ni (Type S)[a]	Cu99.99%	Cu-3%Ni
	4	Cu3.5%Ni / Cu-5%Ni	Cu-3.5%Ni	Cu-5%Ni
f	1	Cu / Cu-3.5%Ni[b]	Cu99.99%	Cu-3.5%Ni
	2	Cu / Cu-3%Ni (Type S)[c]	Cu99.99%	Cu-3%Ni

a. Wire was drawn down from 0.020" to 0.015" (without annealing) so that it could fit into ice point cell probe tubes.
b. To better understand differences between Cu-Cu-3.5%Ni and Cu-Cu-3%Ni wires tested in Group 3, wire was drawn from 0.015" to 0.010" (without annealing).
c. Wire was drawn down from 0.020" to 0.015" (with annealing) so that it could fit into ice point cell probe tubes.

Figure 23 shows results from these evaluations. Figure 24 provides a view of thermocouples found to match the low temperature (less than 150 °C) response of the KW Mo/Nb1%Zr thermocouple, and Figure 25 provides a view of thermocouples found to best match the higher temperature response of the KW Mo/Nb1%Zr thermocouple. As shown in these figures, the Cu3.5%Ni versus Cu5%Ni yields emf values that most closely match that of the KW-Mo versus Nb1%Zr thermocouple, especially for temperatures less than 150 °C, which is the temperature range most anticipated for locations where soft extension thermocouple cable is needed. For higher temperatures, the Cu5%Ni versus Cu10%Ni may yield a closer emf. In addition, trends in Figure 24 and 25 suggest that Cu5%Ni paired with a copper-nickel alloy with a slightly lower nickel content (e.g, 9%nickel) may yield a closer emf. However, such alloys were not commercially available at the start of this project.

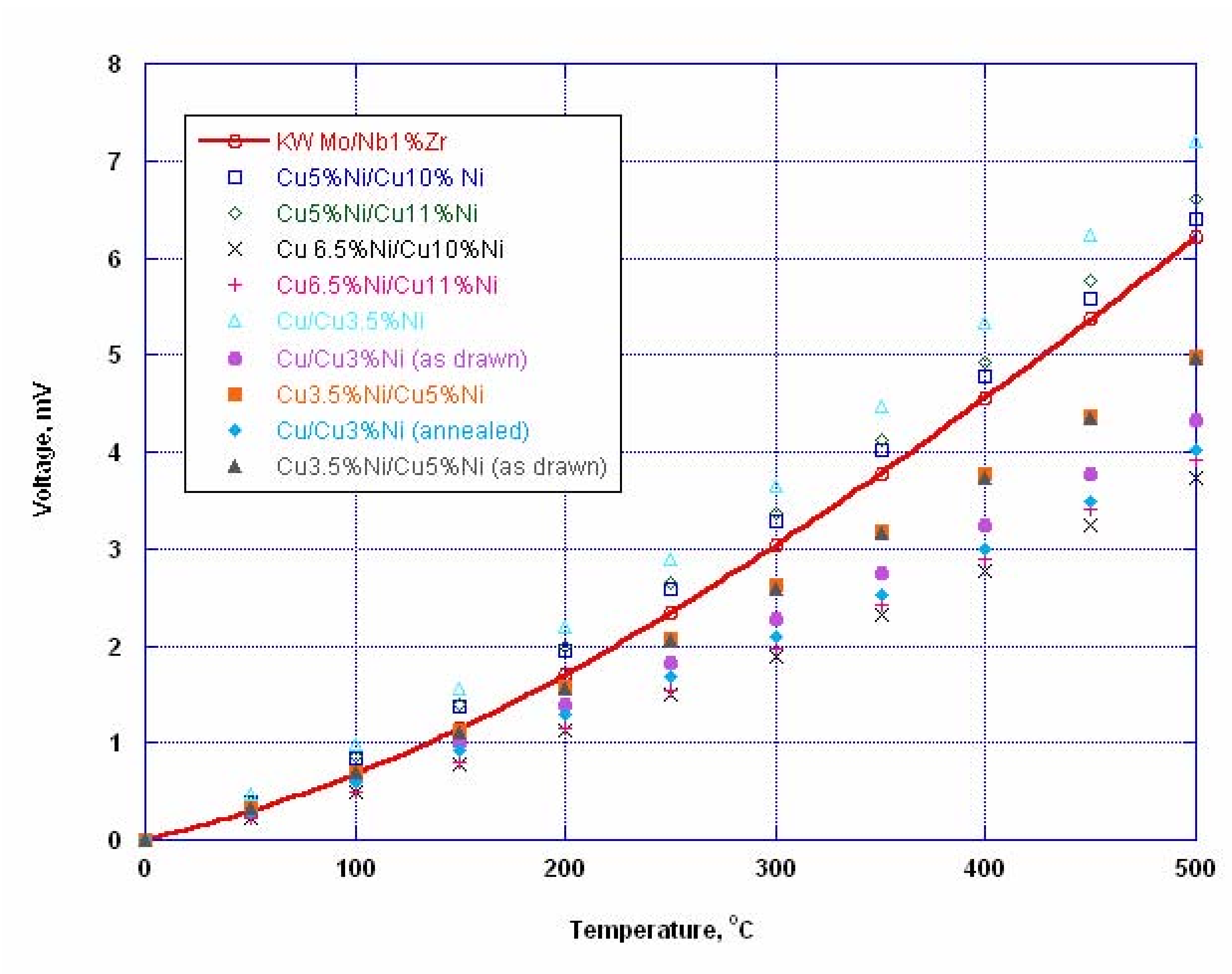


Figure 23. Measured emfs for selected copper-nickel alloy combinations.

Table 8 lists percent differences from the KW Mo/Nb1%Zr emf for the Cu3.5%Ni versus Cu5%Ni and the Cu5%Ni versus Cu10%Ni combinations. Values in this table are consistent with results shown in Figures 23 through 25. For lower temperature regions (e.g., less than 150 °C), the Cu3.5%Ni versus Cu5%Ni duplicates the KW Mo/Nb1%Zr emf within 12%. It should be noted

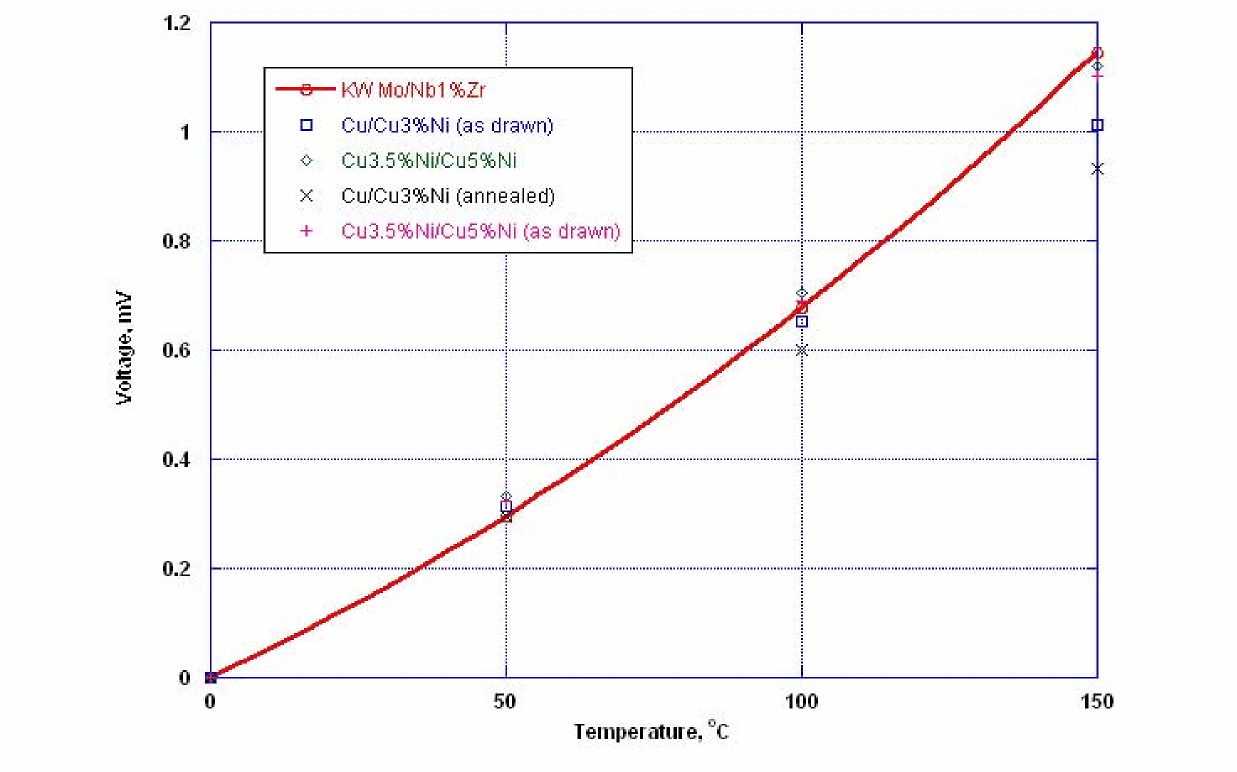


Figure 24. Measured emfs for selected copper-nickel alloy combinations in low temperature region.

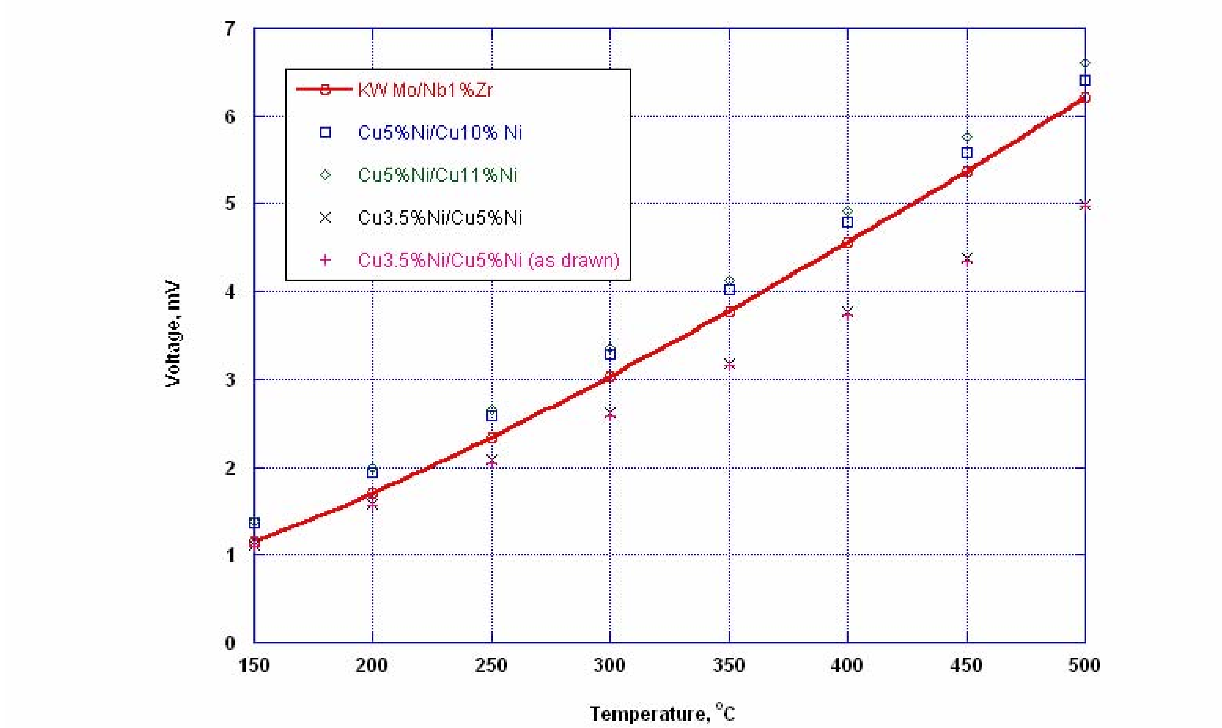


Figure 25. Measured emfs for selected copper-nickel alloy combinations in high temperature region.

that for temperatures greater than 50 °C, the emf values were within 4%. Because it is more difficult for the calibration furnace to maintain a temperature of 50 °C, it is suspected that there is more scatter in data obtained at this lower temperature. For high temperatures, especially for temperatures greater than 300 °C, the Cu5%Ni versus Cu10%Ni extension wires better match the emf from KW Mo versus Nb1%Zr thermocouples (emf values were within 8%).

Table 8. Calculated difference between candidate copper-nickel wires and KW Mo/Nb1%Zr.

Temperature, ^{o}C	% Difference from KW Mo/Nb1%Zr emf	
	Cu5%Ni/Cu10%Ni	Cu3.5%Ni/Cu5%Ni
0	0	0
50	32	12
100	25	4
150	19	2
200	14	7
250	11	11
300	8	14
350	6	16
400	5	17
450	4	18
500	3	20

5. Summary and Conclusions

Tests were completed to identify two inexpensive, commercially-available copper nickel alloy wires that approximate the low temperature (0 to 500 ^{o}C) thermoelectric output of KW-Mo versus Nb-1%Zr in INL-developed HTIR-TCs. For lower temperatures (0 to 150 ^{o}C), which is the region where soft extension cable is most often used, results indicate that the thermocouple emf is best replicated by the Cu3.5%Ni versus Cu5%Ni combination (measured emfs were within 4% at 100 and 150 ^{o}C). At higher temperatures (300 to 500 ^{o}C), test data suggest that the Cu5%Ni versus Cu10%Ni combination may yield data closer to that obtained with KW-Mo versus Nb-1%Zr wires (measured emfs were within 8%). Further, test results suggest that a combination containing a negative thermoelement with slightly lower nickel content, such as Cu5%Ni versus Cu9%Ni, may yield more representative data if extension cable is needed for these higher temperatures.

6. References

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