Thermocouples without tears — 1

Most electronics people know very little about thermocouples, although they're still the simplest and most practical way to measure temperatures above about 150°C. Here's the first of two articles explaining how thermocouples work, the types that are available, and how you can put them to use.

by JIM ROWE

A few months ago I began working on a small hobby project that involved turning and milling some metal parts. The job called for a couple of special cutters, and the only feasible way to get these was to make them myself. This involved turning and milling them from "silver steel" (a high carbon steel with manganese and chromium added), followed by quench hardening and annealing.

For quench hardening, silver steel must be heated up to a temperature of about 780°C, held at this temperature for a short time, and then dropped into water (or brine, or oil) to cool it down suddenly. This causes the formation of a highly stressed crystal structure called Martensite, which is extremely hard.

The temperature the steel is heated to before quenching is fairly critical. If it's too low or too high, the steel won't harden properly. The traditional way for hobbyists to gauge the temperature is to go by its colour: 780°C is midway between "blood red" and "cherry red", for example.

Frankly, when I tried doing this, I got very mixed results indeed. One cutter turned out fine, but another didn't harden properly at all and I had to make a new one all over again. The problem seems to be that it's *very* hard to accurately judge the right colour for 780°C, even when you have a printed colour chart as a guide.

The obvious solution was to find a way to measure the temperature more accurately. Ah, I thought, what about thermocouples? They're supposed to be just the shot for measuring high temperatures. Surely EA had discussed how they work and how to use them, at some stage in the past . . .

It was then that I discovered the sad truth. We only seem to have talked about them and described a project using them once, in October 1984. And that was a project using an iron-constantan thermocouple, designed to measure temperatures only up to about 400°C. So for measuring up to around 800°C, I was on my own.

There was nothing for it but to search out the information myself, ringing up people who design them, make them or sell them, and picking their brains. Funny how one job can lead to another!

Actually the more I found out about thermocouples, the more interesting it became. So much so that before long, I realised the logical thing would be to turn what I'd learned into a couple of articles, to make it available to readers. I hope you find it all as interesting as I have, and can put it to practical use.

Right then, to begin. The principle of the thermocouple is quite old. It was discovered way back in 1821 by the

INTERNATIONAL CODE	METALS USED	TEMPERATURE RANGE	COMMENTS
S	Rhodium (+) vs Platinum 10%	0 — 1400°C	Very stable, but expensive
R	Rhodium (+) vs Platinum 13%	0 — 1400°C	Similar to type S
J	Iron (+) vs Copper-Nickel (Constantan)	0 — 800°C	Iron rusts if not protected
K	Nickel-Chromium ("Chromel") (+) vs Nickel-Aluminium ("Alumel")	0 — 1100°C	Suitable for oxidising atmospheres
T	Copper (+) vs Copper-Nickel (Constantan)	—200 — 400°C	Generally used for low and sub-zero temperatures
E	Nickel-Chromium ("Chromel") (+) vs Copper-Nickel (Constantan)	0 — 800°C	Accurate and stable, low cost
N	Nickel-Chromium-Silicon ("Nicrosil") (+) vs Nickel-Silicon ("Nisil")	0 — 1250°C	Very stable at high temperatures

TABLE 1: The main kinds of thermocouple in use

German physicist Thomas Johann Seebeck, who found that a small electric current was generated in a circuit formed from two different metals, provided that one of the two junctions between the metals was raised to a higher temperature than the other junction.

It turned out that the current was produced by an electromotive force, since dubbed the Seebeck EMF, whose voltage is roughly proportional to the temperature difference between the two junctions.

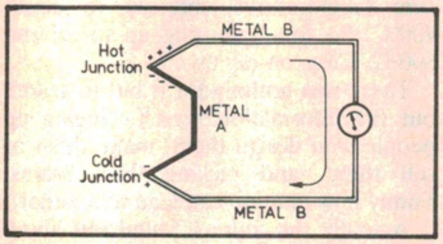

Fig.1: In its most basic form, a thermocouple consists of a circuit made from two metals. When one junction is made hotter than the other, a current flows.

The basic idea is shown in Fig.1. In reality there are two different Seebeck voltages generated, one at each junction and with opposing polarities, with the voltage produced by the hotter junction greater than that produced by the cold junction. The resultant voltage is therefore the difference between the two.

By the way, we're talking about quite small voltages here — typically only a few tens of millivolts. The actual voltage level depends on the two metals used to make the junctions. A number of different metal combinations have been used over the years, for thermocouples designed for different applications. The main types used are shown in Table 1. Each combination of metals gives a different relationship between temperature and Seebeck output voltage, and has features which make it suitable for different kinds of use.

Note especially the type N thermocouple, which is the most recent type to be developed and largely supersedes many of the earlier types. It uses Nickel-Chromium-Silicon alloy ("Nicrosil") and Nickel-Silicon-Magnesium alloy ("Nisil"), which give excellent temperature stability and long working life at temperatures up to about 1230°C. It also has considerably higher output than the precious metal types S and R, and is also much lower in cost.

The type N thermocouple became an international standard type in 1984, after its development by Australian scientist Dr Noel Burley.

EMF in Absolute Millivolts — **Reference Junctions at 0 C**

THERMOELECTRIC VOLTAGE IN ABSOLUTE MILLIVOLTS

DEG C	0	1	2	3	4	5	6	7	8	9	10	DEG C
0	0.000	0.039	0.079	0.119	0.158	0.198	0.238	0.277	0.317	0.357	0.397	0
10	0.397	0.437	0.477	0.517	0.557	0.597	0.637	0.677	0.718	0.758	0.798	10
20	0.798	0.838	0.879	0.919	0.960	1.000	1.041	1.081	1.122	1.162	1.203	20
30	1.203	1.244	1.285	1.325	1.366	1.407	1.448	1.489	1.529	1.570	1.611	30
40	1.611	1.652	1.693	1.734	1.776	1.817	1.858	1.899	1.940	1.981	2.022	40
50	2.022	2.064	2.105	2.146	2.188	2.229	2.270	2.312	2.353	2.394	2.436	50
60	2.436	2.477	2.519	2.560	2.601	2.643	2.684	2.726	2.767	2.809	2.850	60
70	2.850	2.892	2.933	2.975	3.016	3.058	3.100	3.141	3.183	3.224	3.266	70
80	3.266	3.307	3.349	3.390	3.432	3.473	3.515	3.566	3.598	3.639	3.681	80
90	3.681	3.722	3.764	3.805	3.847	3.888	3.930	3.971	4.012	4.054	4.095	90
100	4.095	4.137	4.178	4.219	4.261	4.302	4.343	4.384	4.426	4.467	4.508	100
110	4.508	4.549	4.590	4.632	4.673	4.714	4.755	4.796	4.837	4.878	4.919	110
120	4.919	4.960	5.001	5.042	5.083	5.124	5.164	5.205	5.246	5.287	5.327	120
130	5.327	5.368	5.409	5.450	5.490	5.531	5.571	5.612	5.652	5.693	5.733	130
140	5.733	5.774	5.814	5.855	5.895	5.936	5.976	6.016	6.057	6.097	6.137	140
150	6.137	6.177	6.218	6.258	6.298	6.338	6.378	6.419	6.459	6.499	6.539	150
160	6.539	6.579	6.619	6.659	6.699	6.739	6.779	6.819	6.859	6.899	6.939	160
170	6.939	6.979	7.019	7.059	7.099	7.139	7.179	7.219	7.259	7.299	7.338	170
180	7.338	7.378	7.418	7.458	7.498	7.538	7.578	7.618	7.658	7.697	7.737	180
190	7.737	7.777	7.817	7.857	7.897	7.937	7.977	8.017	8.057	8.097	8.137	190
200	8.137	8.177	8.216	8.256	8.296	8.336	8.376	8.416	8.456	8.497	8.537	200
210	8.537	8.577	8.617	8.657	8.697	8.737	8.777	8.817	8.857	8.898	8.938	210
220	8.938	8.978	9.018	9.058	9.099	9.139	9.179	9.220	9.260	9.300	9.341	220
230	9.341	9.381	9.421	9.462	9.502	9.543	9.583	9.624	9.664	9.705	9.745	230
240	9.745	9.786	9.826	9.867	9.907	9.948	9.989	10.029	10.070	10.111	10.151	240
250	10.151	10.192	10.233	10.274	10.315	10.355	10.396	10.437	10.478	10.519	10.560	250
260	10.560	10.600	10.641	10.682	10.723	10.764	10.805	10.846	10.887	10.928	10.969	260
270	10.969	11.010	11.051	11.093	11.134	11.175	11.216	11.257	11.298	11.339	11.381	270
280	11.381	11.422	11.463	11.504	11.546	11.587	11.628	11.669	11.711	11.752	11.793	280
290	11.793	11.835	11.876	11.918	11.959	12.000	12.042	12.083	12.125	12.166	12.207	290
300	12.207	12.249	12.290	12.332	12.373	12.415	12.456	12.498	12.539	12.581	12.623	300
310	12.623	12.664	12.706	12.747	12.789	12.831	12.872	12.914	12.955	12.997	13.039	310
320	13.039	13.080	13.122	13.164	13.205	13.247	13.289	13.331	13.372	13.414	13.456	320
330	13.456	13.497	13.539	13.581	13.623	13.665	13.706	13.748	13.790	13.832	13.874	330
340	13.874	13.915	13.957	13.999	14.041	14.083	14.125	14.167	14.208	14.250	14.292	340
350	14.292	14.334	14.376	14.418	14.460	14.502	14.544	14.586	14.628	14.670	14.712	350
360	14.712	14.754	14.796	14.838	14.880	14.922	14.964	15.006	15.048	15.090	15.132	360
370	15.132	15.174	15.216	15.258	15.300	15.342	15.384	15.426	15.468	15.510	15.552	370
380	15.552	15.594	15.636	15.679	15.721	15.763	15.805	15.847	15.889	15.931	15.974	380
390	15.974	16.016	16.058	16.100	16.142	16.184	16.227	16.269	16.311	16.353	16.395	390
400	16.395	16.438	16.480	16.522	16.564	16.607	16.649	16.691	16.733	16.776	16.818	400
410	16.818	16.860	16.902	16.945	16.987	17.029	17.072	17.114	17.156	17.199	17.241	410
420	17.241	17.283	17.326	17.368	17.410	17.453	17.495	17.537	17.580	17.622	17.664	420
430	17.664	17.707	17.749	17.792	17.834	17.876	17.919	17.961	18.004	18.046	18.088	430
440	18.088	18.131	18.173	18.216	18.258	18.301	18.343	18.385	18.428	18.470	18.513	440
450	18.513	18.555	18.598	18.640	18.683	18.725	18.768	18.810	18.853	18.895	18.938	450
460	18.938	18.980	19.023	19.065	19.108	19.150	19.193	19.235	19.278	19.320	19.363	460
470	19.363	19.405	19.448	19.490	19.533	19.576	19.618	19.661	19.703	19.746	19.788	470
480	19.788	19.831	19.873	19.916	19.959	20.001	20.044	20.086	20.129	20.172	20.214	480
490	20.214	20.257	20.299	20.342	20.385	20.427	20.470	20.512	20.555	20.598	20.640	490
500	20.640	20.683	20.725	20.768	20.811	20.853	20.896	20.938	20.981	21.024	21.066	500
510	21.066	21.109	21.152	21.194	21.237	21.280	21.322	21.365	21.407	21.450	21.493	510
520	21.493	21.535	21.578	21.621	21.663	21.706	21.749	21.791	21.834	21.876	21.919	520
530	21.919	21.962	22.004	22.047	22.090	22.132	22.175	22.218	22.260	22.303	22.346	530
540	22.346	22.388	22.431	22.473	22.516	22.559	22.601	22.644	22.687	22.729	22.772	540
550	22.772	22.815	22.857	22.900	22.942	22.985	23.028	23.070	23.113	23.156	23.198	550
560	23.198	23.241	23.284	23.326	23.369	23.411	23.454	23.497	23.539	23.582	23.624	560
570	23.624	23.667	23.710	23.752	23.795	23.837	23.880	23.923	23.965	24.008	24.050	570
580	24.050	24.093	24.136	24.178	24.221	24.263	24.306	24.348	24.391	24.434	24.476	580
590	24.476	24.519	24.561	24.604	24.646	24.689	24.731	24.774	24.817	24.859	24.902	590
600	24.902	24.944	24.987	25.029	25.072	25.114	25.157	25.199	25.242	25.284	25.327	600
610	25.327	25.369	25.412	25.454	25.497	25.539	25.582	25.624	25.666	25.709	25.751	610
620	25.751	25.794	25.836	25.879	25.921	25.964	26.006	26.048	26.091	26.133	26.176	620
630	26.176	26.218	26.260	26.303	26.345	26.387	26.430	26.472	26.515	26.557	26.599	630
640	26.599	26.642	26.684	26.726	26.769	26.811	26.853	26.896	26.938	26.980	27.022	640
650	27.022	27.065	27.107	27.149	27.192	27.234	27.276	27.318	27.361	27.403	27.445	650
660	27.445	27.487	27.529	27.572	27.614	27.656	27.698	27.740	27.783	27.825	27.867	660
670	27.867	27.909	27.951	27.993	28.035	28.078	28.120	28.162	28.204	28.246	28.288	670
680	28.288	28.330	28.372	28.414	28.456	28.498	28.540	28.583	28.625	28.667	28.709	680
690	28.709	28.751	28.793	28.835	28.877	28.919	28.961	29.002	29.044	29.086	29.128	690
700	29.128	29.170	29.212	29.254	29.296	29.338	29.380	29.422	29.464	29.505	29.547	700
710	29.547	29.589	29.631	29.673	29.715	29.756	29.798	29.840	29.882	29.924	29.965	710
720	29.965	30.007	30.049	30.091	30.132	30.174	30.216	30.257	30.299	30.341	30.383	720
730	30.383	30.424	30.466	30.508	30.549	30.591	30.632	30.674	30.716	30.757	30.799	730
740	30.799	30.840	30.882	30.924	30.965	31.007	31.048	31.090	31.131	31.173	31.214	740
750	31.214	31.256	31.297	31.339	31.380	31.422	31.463	31.504	31.546	31.587	31.629	750
760	31.629	31.670	31.712	31.753	31.794	31.836	31.877	31.918	31.960	32.001	32.042	760
770	32.042	32.084	32.125	32.166	32.207	32.249	32.290	32.331	32.372	32.414	32.455	770
780	32.455	32.496	32.537	32.578	32.619	32.661	32.702	32.743	32.784	32.825	32.866	780
790	32.866	32.907	32.948	32.990	33.031	33.072	33.113	33.154	33.195	33.236	33.277	790
800	33.277	33.318	33.359	33.400	33.441	33.482	33.523	33.564	33.604	33.645	33.686	800
810	33.686	33.727	33.768	33.809	33.850	33.891	33.931	33.972	34.013	34.054	34.095	810
820	34.095	34.136	34.176	34.217	34.258	34.299	34.339	34.380	34.421	34.461	34.502	820
830	34.502	34.543	34.583	34.624	34.665	34.705	34.746	34.787	34.827	34.868	34.909	830
840	34.909	34.949	34.990	35.030	35.071	35.111	35.152	35.192	35.233	35.273	35.314	840
850	35.314	35.354	35.395	35.435	35.476	35.516	35.557	35.597	35.637	35.678	35.718	850
860	35.718	35.758	35.799	35.839	35.880	35.920	35.960	36.000	36.041	36.081	36.121	860
870	36.121	36.162	36.202	36.242	36.282	36.323	36.363	36.403	36.443	36.483	36.524	870
880	36.524	36.564	36.604	36.644	36.684	36.724	36.764	36.804	36.844	36.885	36.925	880
890	36.925	36.965	37.005	37.045	37.085	37.125	37.165	37.205	37.245	37.285	37.325	890
900	37.325	37.365	37.405	37.445	37.484	37.524	37.564	37.604	37.644	37.684	37.724	900
910	37.724	37.764	37.803	37.843	37.883	37.923	37.963	38.002	38.042	38.082	38.122	910
920	38.122	38.162	38.201	38.241	38.281	38.320	38.360	38.400	38.439	38.479	38.519	920
930	38.519	38.558	38.598	38.638	38.677	38.717	38.756	38.796	38.836	38.875	38.915	930
940	38.915	38.954	38.994	39.033	39.073	39.112	39.152	39.191	39.231	39.270	39.310	940
950	39.310	39.349	39.388	39.428	39.467	39.507	39.546	39.585	39.625	39.664	39.703	950
960	39.703	39.743	39.782	39.821	39.861	39.900	39.939	39.979	40.018	40.057	40.096	960
970	40.096	40.136	40.175	40.214	40.253	40.292	40.332	40.371	40.410	40.449	40.488	970
980	40.488	40.527	40.566	40.605	40.645	40.684	40.723	40.762	40.801	40.840	40.879	980
990	40.879	40.918	40.957	40.996	41.035	41.074	41.113	41.152	41.191	41.230	41.269	990

TABLE 2: Seebeck Voltage vs Temperature (°C) for a type K Thermocouple (Chromel/Alumel)

The relationship between the temperature differential of the two junctions of a thermocouple and the resulting output voltage is not linear. In fact it's close to a parabolic curve. This tends to complicate matters a little, as we'll see shortly.

To make it easier to use thermocouples made from each combination of metals, the manufacturers provide calibration tables showing the Seebeck output voltage against junction temperature. Table 2 shows the calibration table for a type K thermocouple, which is one using Nickel-Chromium alloy ("Chromel") and Nickel-Aluminium alloy ("Alumel") as the two metals.

To use a thermocouple for measuring temperature, one of the two junctions is arranged to be held at a known "reference" temperature while the other junction is used as the measuring or "active" junction. The differential Seebeck voltage produced (Vm) is then measured.

For really accurate measurements, the reference junction should be held at an accurately controlled temperature, say by placing it in a container of melting ice (0°C). However for many purposes it is sufficient to have the reference junction at room temperature, provided that this can be measured fairly accurately using a normal thermometer.

Now if the relationship between temperature and Seebeck voltage were linear, we could work out the true temperature of the active junction by looking up the temperature difference corresponding to Vm, and then simply add the temperature of the reference junction to this. However because the relationship is parabolic rather than linear, this method is not accurate (see Fig.2). So instead we have to use:

$$Va = Vm + Vr$$

where Va is the Seebeck voltage which corresponds to the true temperature of the active junction, Vm is the measured differential voltage Vm, and Vr is the reference junction Seebeck voltage — looked up from the table after measuring the temperature of the reference junction using a thermometer.

In other words, we have to measure Vm, and add this to the reference junction voltage Vr looked up from the table. This gives the Va actually being produced by the active junction. Then we go back to the table with Va, to find the actual temperature Ta of the active junction.

There's another small complication. In practice, it's not really feasible to have the thermocouple measurement circuit wired entirely using the two metals used in the thermocouple itself. So the reference junction tends to get "split in two" by the external circuit — see Fig.3. The two resulting halves of the junction are where each of the two active junction metals are joined to the external wiring (Jr1 and Jr2). This causes no problems, provided that the two reference half-junctions are held at the same temperature, and the leads used to connect them to the external circuit are made from the same metal.

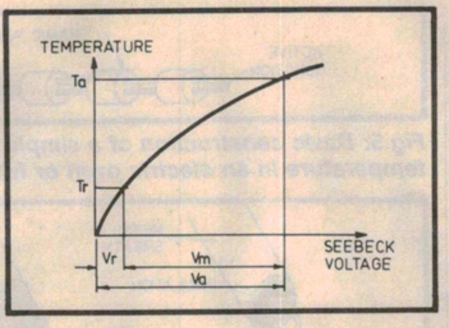

Fig.2: The relationship between temperature and the Seebeck voltage generated is not linear, but parabolic. This causes a few complications, as explained in the text.

Over the years, thermocouples have been used for various things — mainly for measuring high temperatures, but not exclusively. Fig.4 shows a small non-inductive resistor/thermocouple combination housed in a glass vacuum envelope, and used for measuring the power produced by RF oscillators. The power is fed into the resistor, whose temperature naturally rises proportional to the RMS power level. The thermocouple output can thus be calibrated in terms of RF power level, knowing its Seebeck voltage characteristic. This kind of RF power measurement technique can be quite accurate and was fairly widely used before other methods were developed.

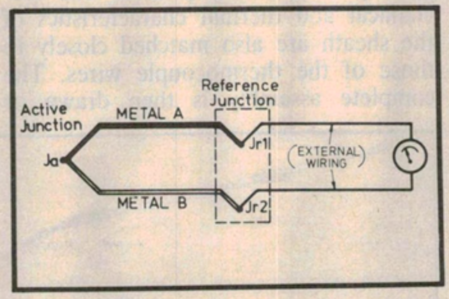

Fig.3: In practice, the reference junction is split into two half junctions Jr1 and Jr2, where the thermoelectric metals are joined to the external circuit.

Practical thermocouples for measuring high temperatures directly tend to take a variety of forms. In the simplest case, they may be little more than a thin wire of each metal, fed through beads of ceramic insulator and spot-welded together to form the active junction (Fig.5). This kind of thermocouple can be used to measure the temperature in a small pottery kiln, for example.

For measurements in very corrosive or reactive environments, such as chemical vapours, molten metals or flames, it becomes necessary to encase the basic thermocouple with a protective sheath. As this must generally be made of metal, the thermocouple wires themselves must be encased in an insulating material inside the sheath.

There are three normal ways of doing this, shown in Fig.6. The first method (a) leaves the active junction itself exposed, in order to get a fast response time for measurements. However this cannot be used in highly corrosive or reactive environments.

The second method (b) encases the junction itself in insulation and sheath, as well as the leads. This gives good protection, but slows down the response to temperature changes because of the thermal resistance of the sheath and (more importantly) the insulation.

This shortcoming is overcome in the third method (c), where the junction is bonded to the inside of the sheath. This gives fast response, along with full protection.

A small low-cost type K thermocouple with a stainless steel sheath is shown in Fig.7. This measures 4mm in diameter and is 150mm long, with leads 520mm long. Designed for measurements to about 900°C, it was made by local firm Richard Foot of 26-30 Tepko Road, Terrey Hills, NSW 2084.

Typically and until very recently the

Fig.4: A small vacuum-enclosed thermocouple and load resistor combination, of the type used to measure RF power.

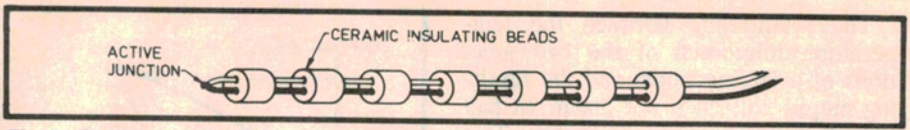

Fig.5: Basic construction of a simple thermocouple suitable for measuring temperature in an electric oven or furnace.

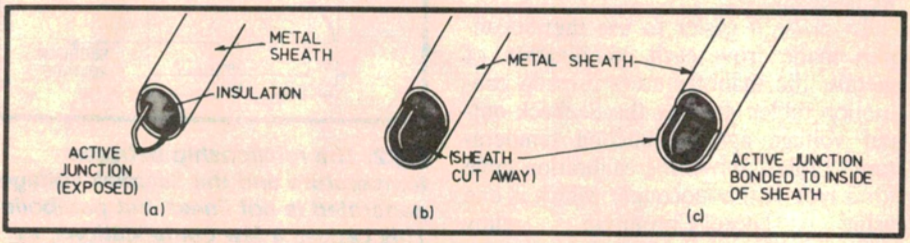

Fig.6: The three traditional ways of protecting a thermocouple in highly corrosive or reactive environments. Method (a) leaves the junction itself exposed, while (b) and (c) include it inside the sheath.

sheath was made from stainless steel, inconel or ceramic materials. However more recently, special alloys like Nicrosil (Nickel-Chromium-Silicon) have been used. These offer distinct advantages in terms of matching the temperature expansion coefficient of the actual thermocouple metals, and minimising thermal stresses. Australian scientist Dr Noel Burley has again pioneered in this area, and has just announced the development of an improved sheath alloy called Nicrobell.

Dr Burley is general manager of R&D at Bell-IRH, of 32 Parramatta Road, Lidcombe NSW 2141. In addition to the development of the type N thermocouple and Nicrobell sheath material, he has also been responsible for much of the development of the so-called "MIMS" or mineral insulated, metal sheathed construction shown in Fig.8. This is rapidly becoming the preferred construction for all high temperature thermocouples.

A feature of MIMS construction is that the insulation between the actual thermocouple wires and the metal sheath is formed from a material such as magnesium oxide powder, which is initially only loosely packed. The mechanical and thermal characteristics of the sheath are also matched closely to those of the thermocouple wires. The complete assembly is then drawn or swaged down to the required final diameter, rather like drawing wire or optical glass fibre.

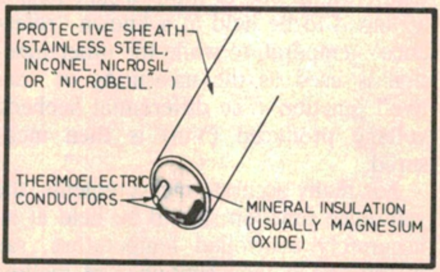

Fig.8: Construction of the mineral insulated, metal sheathed or MIMS type of thermocouple, which can be drawn down to diameters as low as 0.5mm. (Courtesy Bell-IRH)

This allows the production of highly stable and rugged thermocouples with diameters as small as 0.5mm!

For basic temperature measurement using thermocouples, very little electronics is required. Apart from the actual thermocouple itself, all that is needed is a DC millivoltmeter capable of allowing accurate measurements up to about 75mV. Next month I hope to describe a simple and low cost high temperature thermometer, using a type K thermocouple, and suitable for measuring temperatures up to around 900°C. Just the shot for checking the temperature of small heat treatment furnaces, as it happens!

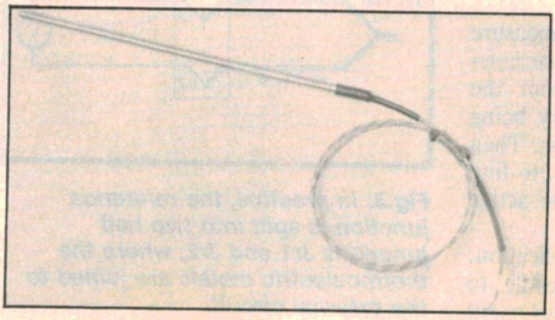

Fig.7: A small low-cost type K thermocouple in a stainless steel sheath, made locally by the firm Richard Foot.