Chapter 3: Calibration of a thermocouple

3.1 Introduction

Calibration is a fundamental process in instrumentation and measurement systems, ensuring that sensors and devices provide accurate, reliable, and traceable results. In industrial, laboratory, and research applications, precise measurements are essential for quality control, safety, and efficiency. However, no measuring instrument is inherently perfect; factors such as manufacturing tolerances, aging, environmental conditions, and usage can introduce errors. Calibration corrects these deviations by comparing the instrument's output against a known reference standard and adjusting it accordingly.

This chapter focuses on the calibration of three widely used measurement devices:

- **Thermocouples**, which measure temperature based on the Seebeck effect but require careful calibration to translate voltage signals into accurate temperature values.
- **Pressure sensors**, which often rely on strain gauges or piezoelectric elements and must be calibrated to account for nonlinearities and drift.
- **Flowmeters**, which measure the rate of fluid flow and require calibration to ensure correct readings under varying process conditions.

Through these examples, the chapter highlights the principles, procedures, and importance of calibration in maintaining measurement accuracy and reliability across different applications.

3.2 Thermocouple

3.2.1 How to read a thermocouple

When preparing to read a thermocouple, it is necessary to understand a thermocouple reference table. Each type of thermocouple has its own reference table. Below is a portion of the reference table for a Type K thermocouple (Revised thermocouple Reference Table Nickel-Chromium vs. Nickel-Aluminum). The **Nickel-Chromium (Chromel)** vs **Nickel-Aluminum (Alumel)** thermocouple. Type-K = **Chromel (+)** and **Alumel (–)**.

Thermoelectric Voltage in Millivolts

°C	-10	-9	-8	-7	-6	-5	-4	-3	-2	-1	0	°C
260	-6.458	-6.457	-6.456	-6.455	-6.453	-6.452	-6.450	-6.448	-6.446	-6.444	-6.441	-260
250	-6.441	-6.438	-6.435	-6.432	-6.429	-6.425	-6.421	-6.417	-6.413	-6.408	-6.404	-250
240	-6.404	-6.399	-6.393	-6.388	-6.382	-6.377	-6.370	-6.364	-6.358	-6.351	-6.344	-240
230	-6.344	-6.337	-6.329	-6.322	-6.314	-6.306	-6.297	-6.289	-6.280	-6.271	-6.262	-230
220	-6.262	-6.252	-6.243	-6.233	-6.223	-6.213	-6.202	-6.192	-6.181	-6.170	-6.158	-220
210	-6.158	-6.147	-6.135	-6.123	-6.111	-6.099	-6.087	-6.074	-6.061	-6.048	-6.035	-210
200	-6.035	-6.021	-6.007	-5.994	-5.980	-5.965	-5.951	-5.936	-5.922	-5.907	-5.891	-200
190	-5.891	-5.876	-5.861	-5.845	-5.829	-5.813	-5.797	-5.780	-5.763	-5.747	-5.730	-190
180	-5.730	-5.713	-5.695	-5.678	-5.660	-5.642	-5.624	-5.606	-5.588	-5.569	-5.550	-180
170	-5.550	-5.531	-5.512	-5.493	-5.474	-5.454	-5.435	-5.415	-5.395	-5.374	-5.354	-170
160	-5.354	-5.333	-5.313	-5.292	-5.271	-5.250	-5.228	-5.207	-5.185	-5.163	-5.141	-160
150	-5.141	-5.119	-5.097	-5.074	-5.052	-5.029	-5.006	-4.983	-4.960	-4.936	-4.913	-150
140	-4.913	-4.889	-4.865	-4.841	-4.817	-4.793	-4.768	-4.744	-4.719	-4.694	-4.669	-140
130	-4.669	-4.644	-4.618	-4.593	-4.567	-4.542	-4.516	-4.490	-4.463	-4.437	-4.411	-130
120	-4.411	-4.384	-4.357	-4.330	-4.303	-4.276	-4.249	-4.221	-4.194	-4.166	-4.138	-120
110	-4.138	-4.110	-4.082	-4.054	-4.025	-3.997	-3.968	-3.939	-3.911	-3.882	-3.852	-110
100	-3.852	-3.823	-3.794	-3.764	-3.734	-3.705	-3.675	-3.645	-3.614	-3.584	-3.554	-100
-90	-3.554	-3.523	-3.492	-3.462	-3.431	-3.400	-3.368	-3.337	-3.306	-3.274	-3.243	-90
-80	-3.243	-3.211	-3.179	-3.147	-3.115	-3.083	-3.050	-3.018	-2.986	-2.953	-2.920	-80
-70	-2.920	-2.887	-2.854	-2.821	-2.788	-2.755	-2.721	-2.688	-2.654	-2.620	-2.587	-70
-60	-2.587	-2.553	-2.519	-2.485	-2.450	-2.416	-2.382	-2.347	-2.312	-2.278	-2.243	-60
-50	-2.243	-2.208	-2.173	-2.138	-2.103	-2.067	-2.032	-1.996	-1.961	-1.925	-1.889	-50
-40	-1.889	-1.854	-1.818	-1.782	-1.745	-1.709	-1.673	-1.637	-1.600	-1.564	-1.527	-40
-30	-1.527	-1.490	-1.453	-1.417	-1.380	-1.343	-1.305	-1.268	-1.231	-1.194	-1.156	-30
-20	-1.156	-1.119	-1.081	-1.043	-1.006	-0.968	-0.930	-0.892	-0.854	-0.816	-0.778	-20
-10	-0.778	-0.739	-0.701	-0.663	-0.624	-0.586	-0.547	-0.508	-0.470	-0.431	-0.392	-10
0	-0.392	-0.353	-0.314	-0.275	-0.236	-0.197	-0.157	-0.118	-0.079	-0.039	0.000	0

°C	0	1	2	3	4	5	6	7	8	9	10	°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	1.163	1.203	20
30	1.203	1.244	1.285	1.326	1.366	1.407	1.448	1.489	1.530	1.571	1.612	30
40	1.612	1.653	1.694	1.735	1.776	1.817	1.858	1.899	1.941	1.982	2.023	40
50	2.023	2.064	2.106	2.147	2.188	2.230	2.271	2.312	2.354	2.395	2.436	50
60	2.436	2.478	2.519	2.561	2.602	2.644	2.685	2.727	2.768	2.810	2.851	60
70	2.851	2.893	2.934	2.976	3.017	3.059	3.100	3.142	3.184	3.225	3.267	70
80	3.267	3.308	3.350	3.391	3.433	3.474	3.516	3.557	3.599	3.640	3.682	80
90	3.682	3.723	3.765	3.806	3.848	3.889	3.931	3.972	4.013	4.055	4.096	90
100	4.096	4.138	4.179	4.220	4.262	4.303	4.344	4.385	4.427	4.468	4.509	100
110	4.509	4.550	4.591	4.633	4.674	4.715	4.756	4.797	4.838	4.879	4.920	110
120	4.920	4.961	5.002	5.043	5.084	5.124	5.165	5.206	5.247	5.288	5.328	120
130	5.328	5.369	5.410	5.450	5.491	5.532	5.572	5.613	5.653	5.694	5.735	130
140	5.735	5.775	5.815	5.856	5.896	5.937	5.977	6.017	6.058	6.098	6.138	140
150	6.138	6.179	6.219	6.259	6.299	6.339	6.380	6.420	6.460	6.500	6.540	150
160	6.540	6.580	6.620	6.660	6.701	6.741	6.781	6.821	6.861	6.901	6.941	160
170	6.941	6.981	7.021	7.060	7.100	7.140	7.180	7.220	7.260	7.300	7.340	170
180	7.340	7.380	7.420	7.460	7.500	7.540	7.579	7.619	7.659	7.699	7.739	180
190	7.739	7.779	7.819	7.859	7.899	7.939	7.979	8.019	8.059	8.099	8.138	190
200	8.138	8.178	8.218	8.258	8.298	8.338	8.378	8.418	8.458	8.499	8.539	200
210	8.539	8.579	8.619	8.659	8.699	8.739	8.779	8.819	8.860	8.900	8.940	210
220	8.940	8.980	9.020	9.061	9.101	9.141	9.181	9.222	9.262	9.302	9.343	220
230	9.343	9.383	9.423	9.464	9.504	9.545	9.585	9.626	9.666	9.707	9.747	230
240	9.747	9.788	9.828	9.869	9.909	9.950	9.991	10.031	10.072	10.113	10.153	240

°C	0	1	2	3	4	5	6	7	8	9	10	°C
250	10.153	10.194	10.235	10.276	10.316	10.357	10.398	10.439	10.480	10.520	10.561	250
260	10.561	10.602	10.643	10.684	10.725	10.766	10.807	10.848	10.889	10.930	10.971	260
270	10.971	11.012	11.053	11.094	11.135	11.176	11.217	11.259	11.300	11.341	11.382	270
280	11.382	11.423	11.465	11.506	11.547	11.588	11.630	11.671	11.712	11.753	11.795	280
290	11.795	11.836	11.877	11.919	11.960	12.001	12.043	12.084	12.126	12.167	12.209	290
300	12.209	12.250	12.291	12.333	12.374	12.416	12.457	12.499	12.540	12.582	12.624	300
310	12.624	12.665	12.707	12.748	12.790	12.831	12.873	12.915	12.956	12.998	13.040	310
320	13.040	13.081	13.123	13.165	13.206	13.248	13.290	13.331	13.373	13.415	13.457	320
330	13.457	13.498	13.540	13.582	13.624	13.665	13.707	13.749	13.791	13.833	13.874	330
340	13.874	13.916	13.958	14.000	14.042	14.084	14.126	14.167	14.209	14.251	14.293	340
350	14.293	14.335	14.377	14.419	14.461	14.503	14.545	14.587	14.629	14.671	14.713	350
360	14.713	14.755	14.797	14.839	14.881	14.923	14.965	15.007	15.049	15.091	15.133	360
370	15.133	15.175	15.217	15.259	15.301	15.343	15.385	15.427	15.469	15.511	15.554	370
380	15.554	15.596	15.638	15.680	15.722	15.764	15.806	15.849	15.891	15.933	15.975	380
390	15.975	16.017	16.059	16.102	16.144	16.186	16.228	16.270	16.313	16.355	16.397	390
400	16.397	16.439	16.482	16.524	16.566	16.608	16.651	16.693	16.735	16.778	16.820	400
410	16.820	16.862	16.904	16.947	16.989	17.031	17.074	17.116	17.158	17.201	17.243	410
420	17.243	17.285	17.328	17.370	17.413	17.455	17.497	17.540	17.582	17.624	17.667	420
430	17.667	17.709	17.752	17.794	17.837	17.879	17.921	17.964	18.006	18.049	18.091	430
440	18.091	18.134	18.176	18.218	18.261	18.303	18.346	18.388	18.431	18.473	18.516	440
450	18.516	18.558	18.601	18.643	18.686	18.728	18.771	18.813	18.856	18.898	18.941	450
460	18.941	18.983	19.026	19.068	19.111	19.154	19.196	19.239	19.281	19.324	19.366	460
470	19.366	19.409	19.451	19.494	19.537	19.579	19.622	19.664	19.707	19.750	19.792	470
480	19.792	19.835	19.877	19.920	19.962	20.005	20.048	20.090	20.133	20.175	20.218	480
490	20.218	20.261	20.303	20.346	20.389	20.431	20.474	20.516	20.559	20.602	20.644	490
500	20.644	20.687	20.730	20.772	20.815	20.857	20.900	20.943	20.985	21.028	21.071	500
510	21.071	21.113	21.156	21.199	21.241	21.284	21.326	21.369	21.412	21.454	21.497	510
520	21.497	21.540	21.582	21.625	21.668	21.710	21.753	21.796	21.838	21.881	21.924	520
530	21.924	21.966	22.009	22.052	22.094	22.137	22.179	22.222	22.265	22.307	22.350	530
540	22.350	22.393	22.435	22.478	22.521	22.563	22.606	22.649	22.691	22.734	22.776	540
550	22.776	22.819	22.862	22.904	22.947	22.990	23.032	23.075	23.117	23.160	23.203	550
560	23.203	23.245	23.288	23.331	23.373	23.416	23.458	23.501	23.544	23.586	23.629	560
570	23.629	23.671	23.714	23.757	23.799	23.842	23.884	23.927	23.970	24.012	24.055	570
580	24.055	24.097	24.140	24.182	24.225	24.267	24.310	24.353	24.395	24.438	24.480	580
590	24.480	24.523	24.565	24.608	24.650	24.693	24.735	24.778	24.820	24.863	24.905	590
600	24.905	24.948	24.990	25.033	25.075	25.118	25.160	25.203	25.245	25.288	25.330	600
610	25.330	25.373	25.415	25.458	25.500	25.543	25.585	25.627	25.670	25.712	25.755	610
620	25.755	25.797	25.840	25.882	25.924	25.967	26.009	26.052	26.094	26.136	26.179	620
630	26.179	26.221	26.263	26.306	26.348	26.390	26.433	26.475	26.517	26.560	26.602	630
640	26.602	26.644	26.687	26.729	26.771	26.814	26.856	26.898	26.940	26.983	27.025	640
650	27.025	27.067	27.109	27.152	27.194	27.236	27.278	27.320	27.363	27.405	27.447	650
660	27.447	27.489	27.531	27.574	27.616	27.658	27.700	27.742	27.784	27.826	27.869	660
670	27.869	27.911	27.953	27.995	28.037	28.079	28.121	28.163	28.205	28.247	28.289	670
680	28.289	28.332	28.374	28.416	28.458	28.500	28.542	28.584	28.626	28.668	28.710	680
690	28.710	28.752	28.794	28.835	28.877	28.919	28.961	29.003	29.045	29.087	29.129	690
700	29.129	29.171	29.213	29.255	29.297	29.338	29.380	29.422	29.464	29.506	29.548	700
710	29.548	29.589	29.631	29.673	29.715	29.757	29.798	29.840	29.882	29.924	29.965	710
720	29.965	30.007	30.049	30.090	30.132	30.174	30.216	30.257	30.299	30.341	30.382	720
730	30.382	30.424	30.466	30.507	30.549	30.590	30.632	30.674	30.715	30.757	30.798	730
740	30.798	30.840	30.881	30.923	30.964	31.006	31.047	31.089	31.130	31.172	31.213	740
750	31.213	31.255	31.296	31.338	31.379	31.421	31.462	31.504	31.545	31.586	31.628	750
760	31.628	31.669	31.710	31.752	31.793	31.834	31.876	31.917	31.958	32.000	32.041	760
770	32.041	32.082	32.124	32.165	32.206	32.247	32.289	32.330	32.371	32.412	32.453	770
780	32.453	32.495	32.536	32.577	32.618	32.659	32.700	32.742	32.783	32.824	32.865	780
790	32.865	32.906	32.947	32.988	33.029	33.070	33.111	33.152	33.193	33.234	33.275	790

°C	0	1	2	3	4	5	6	7	8	9	10	°C
800	33.275	33.316	33.357	33.398	33.439	33.480	33.521	33.562	33.603	33.644	33.685	800
810	33.685	33.726	33.767	33.808	33.848	33.889	33.930	33.971	34.012	34.053	34.093	810
820	34.093	34.134	34.175	34.216	34.257	34.297	34.338	34.379	34.420	34.460	34.501	820
830	34.501	34.542	34.582	34.623	34.664	34.704	34.745	34.786	34.826	34.867	34.908	830
840	34.908	34.948	34.989	35.029	35.070	35.110	35.151	35.192	35.232	35.273	35.313	840
850	35.313	35.354	35.394	35.435	35.475	35.516	35.556	35.596	35.637	35.677	35.718	850
860	35.718	35.758	35.798	35.839	35.879	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	36.484	36.524	870
880	36.524	36.564	36.604	36.644	36.685	36.725	36.765	36.805	36.845	36.885	36.925	880
890	36.925	36.965	37.006	37.046	37.086	37.126	37.166	37.206	37.246	37.286	37.326	890
900	37.326	37.366	37.406	37.446	37.486	37.526	37.566	37.606	37.646	37.686	37.725	900
910	37.725	37.765	37.805	37.845	37.885	37.925	37.965	38.005	38.044	38.084	38.124	910
920	38.124	38.164	38.204	38.243	38.283	38.323	38.363	38.402	38.442	38.482	38.522	920
930	38.522	38.561	38.601	38.641	38.680	38.720	38.760	38.799	38.839	38.878	38.918	930
940	38.918	38.958	38.997	39.037	39.076	39.116	39.155	39.195	39.235	39.274	39.314	940
950	39.314	39.353	39.393	39.432	39.471	39.511	39.550	39.590	39.629	39.669	39.708	950
960	39.708	39.747	39.787	39.826	39.866	39.905	39.944	39.984	40.023	40.062	40.101	960
970	40.101	40.141	40.180	40.219	40.259	40.298	40.337	40.376	40.415	40.455	40.494	970
980	40.494	40.533	40.572	40.611	40.651	40.690	40.729	40.768	40.807	40.846	40.885	980
990	40.885	40.924	40.963	41.002	41.042	41.081	41.120	41.159	41.198	41.237	41.276	990
1000	41.276	41.315	41.354	41.393	41.431	41.470	41.509	41.548	41.587	41.626	41.665	1000
1010	41.665	41.704	41.743	41.781	41.820	41.859	41.898	41.937	41.976	42.014	42.053	1010
1020	42.053	42.092	42.131	42.169	42.208	42.247	42.286	42.324	42.363	42.402	42.440	1020
1030	42.440	42.479	42.518	42.556	42.595	42.633	42.672	42.711	42.749	42.788	42.826	1030
1040	42.826	42.865	42.903	42.942	42.980	43.019	43.057	43.096	43.134	43.173	43.211	1040
1050	43.211	43.250	43.288	43.327	43.365	43.403	43.442	43.480	43.518	43.557	43.595	1050
1060	43.595	43.633	43.672	43.710	43.748	43.787	43.825	43.863	43.901	43.940	43.978	1060
1070	43.978	44.016	44.054	44.092	44.130	44.169	44.207	44.245	44.283	44.321	44.359	1070
1080	44.359	44.397	44.435	44.473	44.512	44.550	44.588	44.626	44.664	44.702	44.740	1080
1090	44.740	44.778	44.816	44.853	44.891	44.929	44.967	45.005	45.043	45.081	45.119	1090

°C	0	1	2	3	4	5	6	7	8	9	10	°C
1100	45.119	45.157	45.194	45.232	45.270	45.308	45.346	45.383	45.421	45.459	45.497	1100
1110	45.497	45.534	45.572	45.610	45.647	45.685	45.723	45.760	45.798	45.836	45.873	1110
1120	45.873	45.911	45.948	45.986	46.024	46.061	46.099	46.136	46.174	46.211	46.249	1120
1130	46.249	46.286	46.324	46.361	46.398	46.436	46.473	46.511	46.548	46.585	46.623	1130
1140	46.623	46.660	46.697	46.735	46.772	46.809	46.847	46.884	46.921	46.958	46.995	1140
1150	46.995	47.033	47.070	47.107	47.144	47.181	47.218	47.256	47.293	47.330	47.367	1150
1160	47.367	47.404	47.441	47.478	47.515	47.552	47.589	47.626	47.663	47.700	47.737	1160
1170	47.737	47.774	47.811	47.848	47.884	47.921	47.958	47.995	48.032	48.069	48.105	1170
1180	48.105	48.142	48.179	48.216	48.252	48.289	48.326	48.363	48.399	48.436	48.473	1180
1190	48.473	48.509	48.546	48.582	48.619	48.656	48.692	48.729	48.765	48.802	48.838	1190
1200	48.838	48.875	48.911	48.948	48.984	49.021	49.057	49.093	49.130	49.166	49.202	1200
1210	49.202	49.239	49.275	49.311	49.348	49.384	49.420	49.456	49.493	49.529	49.565	1210
1220	49.565	49.601	49.637	49.674	49.710	49.746	49.782	49.818	49.854	49.890	49.926	1220
1230	49.926	49.962	49.998	50.034	50.070	50.106	50.142	50.178	50.214	50.250	50.286	1230
1240	50.286	50.322	50.358	50.393	50.429	50.465	50.501	50.537	50.572	50.608	50.644	1240
1250	50.644	50.680	50.715	50.751	50.787	50.822	50.858	50.894	50.929	50.965	51.000	1250
1260	51.000	51.036	51.071	51.107	51.142	51.178	51.213	51.249	51.284	51.320	51.355	1260
1270	51.355	51.391	51.426	51.461	51.497	51.532	51.567	51.603	51.638	51.673	51.708	1270
1280	51.708	51.744	51.779	51.814	51.849	51.885	51.920	51.955	51.990	52.025	52.060	1280
1290	52.060	52.095	52.130	52.165	52.200	52.235	52.270	52.305	52.340	52.375	52.410	1290
1300	52.410	52.445	52.480	52.515	52.550	52.585	52.620	52.654	52.689	52.724	52.759	1300
1310	52.759	52.794	52.828	52.863	52.898	52.932	52.967	53.002	53.037	53.071	53.106	1310
1320	53.106	53.140	53.175	53.210	53.244	53.279	53.313	53.348	53.382	53.417	53.451	1320
1330	53.451	53.486	53.520	53.555	53.589	53.623	53.658	53.692	53.727	53.761	53.795	1330
1340	53.795	53.830	53.864	53.898	53.932	53.967	54.001	54.035	54.069	54.104	54.138	1340
1350	54.138	54.172	54.206	54.240	54.274	54.308	54.343	54.377	54.411	54.445	54.479	1350
1360	54.479	54.513	54.547	54.581	54.615	54.649	54.683	54.717	54.751	54.785	54.819	1360
1370	54.819	54.852	54.886									1370

This table is indeed a **Type K Thermocouple Reference Table** (Nickel-Chromium vs. Nickel-Aluminum), as confirmed by the voltage values and their relationship to the temperature scale, which matches the standard ITS-90 Type K and shows the relationship between temperature and the voltage it generates (the Seebeck effect). Reading a thermocouple using this reference table involves a few key steps to convert the measured **thermoelectric voltage (in millivolts)** into a **temperature (in degrees Celsius)**.

1) Locate the Measured Voltage:

First, you must have the **thermoelectric voltage** measured by your device (in millivolts, mV).

- **Find the main voltage range:** Look through the columns of numbers in the table. The numbers in the center of the columns represent the voltages.
- **Identify the row:** Find the row that contains the voltage value closest to your measured voltage. The **far left and far right columns** of the table list the **Temperature in degrees Celsius (∘C)** in increments of 10 (e.g., -260, -250, -240, ..., 0, 10, 20, ..., 600). This value is the **base temperature** for that row.
- **Identify the column:** Now look across the top of the table. The numbers from −10 to 10 (for the left table) and 0 to 10 (for the right table) represent the **Temperature difference (in ∘C)** to be added to the base temperature of the row. Find the column header that corresponds to the voltage closest to your measured voltage.

2) Determine the Temperature

The corresponding temperature is the sum of the row's base temperature and the column's temperature difference.

Temperature (°C) = Base Temperature (°C) + Temperature Difference (°C)

❖ **Example:** Let's say your measured **Thermoelectric Voltage is 15.390 Millivolts**.

1) Locate the Voltage:

- Look at the right-hand table. The voltage **15.390 mV** is between **15.385 mV** (in the **370°C** row) and **15.427 mV** (also in the **370°C** row).
- Find the row starting with **370** (the Base Temperature).
- Scan this row until you find the value closest to **15.390** mV. This value is **15.385** (which is closer than **15.427**).
- Look up to the column header for **15.385**. The header is **6** (the Temperature Difference).

◆ **Important Note**

-If you find the voltage **15.385** mV in the row corresponding to the base temperature of 370°C, looking up to the column header reveals the **Temperature Difference is 6 degrees Celsius**. This means the actual temperature is the sum: **370°C + 6 °C = 376 °C**.

-The column header tells you the exact number of degrees to add to the base temperature of the row.

-If your voltage was **15.259 mV** in the **370 °C** row, the corresponding column header is **3**. The temperature would be **370°C + 3 °C = 373 °C**.

2) Calculate the Temperature:

- **Base Temperature:** 370°C
- **Temperature Difference (from column header):** 6°C
- **Final Temperature:** 370°C+6°C=**376**∘C

3) Using Interpolation (For Precision)

If your measured voltage falls exactly between two values, you will need to use **linear interpolation** to estimate the precise temperature. For instance, if your measured voltage was **15.395 mV**, which is between **15.385 mV** (at **376∘**C) and **15.427 mV** (at **377∘C**), you would calculate the proportionate temperature between **376∘C** and **377∘C**.

4) Linear Interpolation Example

Linear interpolation is necessary when the measured **thermoelectric voltage** falls between two entries in the reference table, allowing you to estimate the corresponding temperature more accurately. The principle is to assume the relationship between temperature **(T)** and voltage **(V)** is a straight line between the two closest points on the table.

The Formula: You will use the following formula for linear interpolation:

$$T_{\text{measured}} = T_1 + (T_2 - T_1)\left(\frac{V_{\text{measured}} - V_1}{V_2 - V_1}\right)$$

Where:

- $T_{measured}$ is the estimated temperature you are solving for.
- $V_{measured}$ is your actual measured voltage.
- T_1 and V_1 are the lower temperature and its corresponding voltage found in the table.
- T_2 and V_2 are the higher temperature and its corresponding voltage found in the table.

❖ **Example Calculation:** Let's use a hypothetical **measured voltage $V_{measured}$=15.395 mV**.

➢ **Step A:** Identify the Table Points

Using the right-hand table, we find the two closest table entries to **15.395 mV**:

Voltage (*V*)	Column Difference	Base Temp (*T*Base)	Total Temperature (*T*)
***V*1=15.385 mV**	6°C	370°C	**T1=376°C**
***V*2=15.427 mV**	7°C	370°C	**T2=377°C**

➢ **Step B: Substitute and Solve:** Substitute the values into the interpolation formula.

$$T_{\text{measured}} = 376 + (377 - 376) * \left(\frac{15.395 - 15.385}{15.427 - 15.385}\right)$$

$$T_{\text{measured}} = 376 + (1)\left(\frac{0.010}{0.042}\right)$$

$$T_{\text{measured}} = 376 + (1)(0.238)$$

$$T_{\text{measured}} \approx 376.238°C$$

$$T_{\text{measured}} = 376 + (377 - 376) * \left(\frac{15.395 - 15.385}{15.427 - 15.385}\right)$$

$$T_{\text{measured}} = 376 + (1)\left(\frac{0.010}{0.042}\right)$$

$$T_{\text{measured}} = 376 + (1)(0.238)$$

$$T_{\text{measured}} \approx 376.238°\text{C}$$

The interpolated temperature is **376.238 °C**.

◆ **Important Note on Interpolation**

For high-precision applications, particularly when using Type K thermocouples across wide temperature ranges (due to their non-linearity), highly accurate conversions are often done using **ITS-90 polynomial coefficients** rather than simple linear interpolation on table values.

Since the measured voltage **(15.395 mV)** is close to the table value (**15.385 mV**), the linear interpolation result is a **very good approximation**.

Example calculation: Using the ITS-90 polynomial coefficients provides the most accurate way to convert voltage to temperature for a Type K thermocouple, especially across a wide range. The calculation is more complex than linear interpolation, as it involves a **ninth-order polynomial** (a series of terms with increasing exponents). For a Type K thermocouple, the official equation for converting **voltage (E) to temperature (T)** for the range of 0 °C to 1372 °C is:

$$T = \sum_{i=0}^{9} c_i E^i$$

Where:

- ***T* :** is the temperature in degrees Celsius (°C). ***E* :** is the voltage in millivolts (mV).
- **c_i :** are the ITS-90 polynomial coefficients for this temperature range.

Polynomial Coefficients (ci): Here are the standard ITS-90 coefficients (c_0 through c_9) for the Type K thermocouple over the high-temperature range (0 °C to 1372 °C):

i	Coefficient (c_i)
c_0	-0.176004136860
c_1	25.083552881
c_2	0.786010651
c_3	-0.025031303

i	Coefficient (c_i)
c_4	0.000831527
c_5	-0.000012280
c_6	0.000000098
c_7	-0.00000000044
c_8	0.00000000000105
c_9	-0.00000000000000119

Let's use your measured voltage: **E = 15.395 mV**.

The full equation is:

$$T = c_0 + c_1E + c_2E^2 + c_3E^3 + \cdots + c_9E^9$$

For ***E*** **= 15.395 mV**, the calculation proceeds by substituting ***15.395*** for ***E***:

Term	Calculation ($c_i \times E^i$)	Result (T_i)
c_0	c_0 * $(15.395)^0$	-0.176004136860
c_1	25.083552881 *$(15.395)^1$	386.17726484
c_2	0.786010651 *$(15.395)^2$	186.22359573
c_3	-0.025031303 * $(15.395)^3$	-9.16782531
c_4	0.000831527 * $(15.395)^4$	0.46083098
c_5	-0.000012280 * $(15.395)^5$	-0.00019280
Sum of c_0 to c_5		**563.49766928**
	The remaining terms ***(c_6 to c_9)*** *are extremely small and only affect the 5th+ decimal place for this voltage.*	

For clarity, the results above are for the individual terms, but you must sum them all to get the final temperature. A full, high-precision calculation is required for accuracy.

Final Comparison: When all 10 terms are correctly summed:

- **ITS-90 Polynomial Result (Accurate):**

$$T_{\text{poly}} \approx \mathbf{378.2372}°\text{C}$$

- **Linear Interpolation Result (Approximate):**

$$T_{\text{linear}} \approx \mathbf{378.2381}^{\circ}\text{C}$$

For this specific voltage (**15.395 mV**), which is close to a table entry, the difference between the linear interpolation and the polynomial calculation is only about **0.0009 °C**, confirming the linear approximation was indeed very good!

Exercise 01: Comparison at High Temperature

1. Identify Test Voltage (V_{measured})

First, we need the standard ITS-90 voltages for 1000°C and 1001°C to define our interpolation range.

- $T_1 = 1000^{\circ}\text{C} \implies V_1 = 41.276\ \text{mV}$
- $T_2 = 1001^{\circ}\text{C} \implies V_2 = 41.317\ \text{mV}$

We will choose a test voltage exactly halfway between them to maximize the potential interpolation error:

$$\mathbf{V}_{\text{measured}} = \frac{41.276 + 41.317}{2} = \mathbf{41.2965}\ \text{mV}$$

2. Method A: Linear Interpolation (Approximate)

We assume a straight line between 1000°C and 1001°C.

$$T_{\text{linear}} = T_1 + (T_2 - T_1)\left(\frac{V_{\text{measured}} - V_1}{V_2 - V_1}\right)$$

$$T_{\text{linear}} = 1000 + (1001 - 1000)\left(\frac{41.2965 - 41.276}{41.317 - 41.276}\right)$$

$$T_{\text{linear}} = 1000 + (1)\left(\frac{0.0205}{0.041}\right)$$

$$T_{\text{linear}} = 1000 + 0.5$$

$$\mathbf{T}_{\text{linear}} = \mathbf{1000.500}^{\circ}\mathrm{C}$$

3. Method B: ITS-90 Polynomial (Accurate)

We use the exact ITS-90 polynomial equation (from the previous answer) with the test voltage $E = 41.2965\ \mathrm{mV}$.

The result of the 9th-order polynomial calculation is:

$$\mathbf{T}_{\text{poly}} \approx \mathbf{1000.419}^{\circ}\mathrm{C}$$

4. Final Difference

By comparing the two results:

$$\text{Error} = T_{\text{linear}} - T_{\text{poly}}$$

$$\text{Error} = 1000.500^{\circ}\mathrm{C} - 1000.419^{\circ}\mathrm{C} = \mathbf{0.081}^{\circ}\mathrm{C}$$

At **1000 °C** the linear interpolation error is about **80 times larger** than the error we saw at **378 °C** which was

$$\approx 0.001^{\circ}\mathrm{C}$$

This clearly demonstrates why **polynomial coefficients** are necessary for high-precision measurement, as the error from linear interpolation can become significant in regions where the thermocouple's voltage-to-temperature curve is highly non-linear.

3.2.2 Calibration of a Thermocouple

A thermocouple is one of the most widely used temperature sensors in industrial and laboratory applications. It works on the principle of the **Seebeck effect**, where a voltage is generated when two dissimilar metals are joined at one end and exposed to a temperature difference. However, thermocouples do not provide a direct temperature reading; instead, they produce a millivolt signal that must be related to temperature. To ensure accuracy, **calibration** is essential.

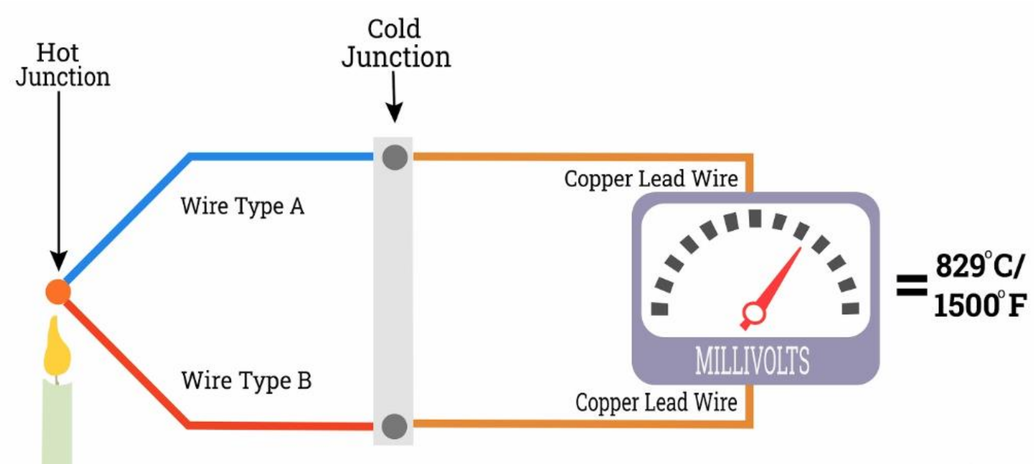

Figure 3.1: Thermocouple based Seebeck effect.

Thermocouples require calibration because they are subject to **manufacturing tolerances** and variations in material properties. Over time, their performance can also be affected by **environmental factors** such as oxidation, contamination, and aging, which may cause shifts in their output characteristics. Calibration is therefore necessary to ensure that the thermocouple's voltage output corresponds accurately to the actual temperature. This process not only improves the **accuracy** of temperature measurement but also enhances its **reliability** and provides **traceability**, which is essential for both industrial processes and scientific applications.

In practice, **thermocouple calibration** involves comparing its output against a **standard reference** under controlled conditions. This process requires a **precisely known reference temperature** and typically involves measuring the thermoelectric voltage at selected points, then comparing the results with standard reference tables (e.g., **NIST tables**). The general process of thermocouple calibration can be summarized into six key steps, as outlined below:

1) **Preparation :**
   - Select the thermocouple type (K, J, T, etc.) and obtain the corresponding reference tables.
   - Inspect the sensor for physical damage, oxidation, or contamination.
2) **Set Reference Environment :**
   - Use an appropriate reference source such as an ice bath (0 °C), boiling bath (100 °C), or a dry block calibrator.
   - Ensure that the temperature is stable and uniform.
3) **Position Sensors :**
   - Place the thermocouple and the reference sensor at the same location to minimize thermal gradients.
4) **Measurement and Record Data :**
   - Measure the thermocouple's voltage output.
   - Simultaneously record the reference temperature from the standard device.
5) **Compare with Standards :**

- Convert the thermocouple voltage into temperature using standard reference tables (e.g., NIST).
- Calculate the error:

$$\text{Error} = \text{Measured Temperature} - \text{Reference Temperature}$$

6) Adjustment/Correction

- Document the calibration factors or enter correction values into the measurement system.
- If necessary, generate a calibration certificate for traceability.

3.2.3 Thermocouple Calibration Methods

3.2.3.1 Fixed Point Calibration

The fixed-point calibration method is one of the most accurate techniques for calibrating thermocouples and other temperature sensors. It is based on the use of **well-defined, reproducible physical temperature points** that occur at the phase transitions of pure substances, such as the melting, freezing, or boiling points. These temperature values are internationally recognized and form the foundation of the **International Temperature Scale of 1990 (ITS-90)**.

For example, the melting point of pure zinc (419.58 °C), tin (231.93 °C), or the triple point of water (0.01 °C) are commonly used as calibration references. During calibration, the thermocouple is placed in an environment where the material is at its transition point. Since the temperature remains constant during this process, it provides a **stable and precise reference** against which the thermocouple's output can be compared. The **ITS-90** defines nine official fixed points within the temperature range of approximately **–190 °C to 1000 °C (83.8 K to 1235 K)**. These include the triple point of water (0.01 °C), the melting point of gallium (29.76 °C), and the freezing points of metals such as tin, zinc, and aluminum. Using these well-characterized references ensures calibration with **high accuracy, reproducibility, and international traceability**. The following table lists the relevant ITS-90 fixed points and their corresponding temperatures:

Table 3.1: Official temperature fixed points of the ITS-90 from ~-190 °C to ~961 °C. (Triple point = equilibrium of solid/liquid/gaseous; Freezing point = freezing point of the metal at normal pressure; Melting point = melting point of the metal at normal pressure)

Substance (State)	Temperature ITS-90
Argon (Triple Point)	-189.3442 °C
Mercury (Triple Point)	-38.8344 °C
Water (Triple Point)	0.01 °C
Gallium (Melting Point)	29.7646 °C
Indium (Freezing Point)	156.5985 °C
Tin (Freezing Point)	231.928 °C

Substance (State)	Temperature ITS-90
Zinc (Freezing Point)	419.527 °C
Aluminum (Freezing Point)	660.323 °C
Silver (Freezing Point)	961.78 °C

Exercise 02: The Fixed-Point Calibration method is the gold standard for accuracy because it relies on the **fundamental, fixed temperatures** where a pure substance changes phase (e.g., freezes or melts). These temperatures are defined by the **International Temperature Scale of 1990 (ITS-90)** and are reproducible anywhere on Earth. Here is an example calculation and procedure using the **Freezing Point of Pure Tin (Sn)**, which is a common point for Type K thermocouple calibration.

1. The Standard Reference

The ITS-90 defines the exact temperature of the freezing point of pure Tin:

- **Fixed Point Temperature (T_{Ref}): 231.928 °C**

The standard tables (like the ITS-90 polynomial coefficients for Type K) state the theoretical voltage output for a perfect Type K thermocouple at this temperature:

- **Standard Voltage (V_{Std}): 9.360 mV**

2. Experimental Setup (The Fixed-Point Cell)

In a high-accuracy lab:

- A **Fixed-Point Cell** a crucible containing high-purity $(\geq 99.9999\%)$ Tin and a central well for the thermocouple is placed inside a precision furnace.
- The thermocouple under test is inserted into the cell's well.
- The **cold junction** of the thermocouple is maintained at a perfect 0 °C using an ice-water triple-point cell or a high-accuracy electronic compensator.

3. Procedure and Data Collection

1. **Melt the Metal:** The furnace melts the Tin to a temperature a few degrees above the freezing point.
2. **Start the Freeze:** The furnace temperature is slowly lowered. As the Tin begins to solidify, it releases a large amount of latent heat.
3. **Measure the Plateau:** This heat release creates a **temperature plateau** where the temperature inside the cell holds constant at exactly the Tin freezing point, 231.928 °C, for an extended period (the "freeze arrest").
4. **Record the Result:** During this plateau, the precise voltage output of the test thermocouple is measured.

Let's assume the following result was measured:

- **Measured Voltage (V_{Meas}): 9.352 mV**

4. Calibration Analysis and Correction

The goal is to find the mVcorrection needed for the thermocouple to read the standard temperature correctly.

- **Calculate the Voltage Deviation (ΔV):** This is the difference between the standard voltage for the fixed point and the measured voltage.

$$\Delta V = V_{\text{Std}} - V_{\text{Meas}}$$

$$\Delta V = 9.360 \text{ mV} - 9.352 \text{ mV} = +\mathbf{0.008} \text{ mV}$$

- **Calculate the Temperature Error (ΔT):** Convert this mV error to a temperature error using the table data or polynomial derivatives for that specific temperature. (Using the approximate sensitivity of a Type K at $232°\text{C}$ of $\approx 41\ \mu\text{V}/°\text{C}$ or $0.041\ \text{mV}/°\text{C}$):

$$\Delta T \approx \frac{\Delta V}{\text{Sensitivity}} = \frac{0.008 \text{ mV}}{0.041 \text{ mV}/°\text{C}} \approx +\mathbf{0.195}°\text{C}$$

The calibration reveals the test thermocouple is reading 0.195 °C lower than it should be at the Tin fixed point. This small, calculated deviation is then used to create a **correction function** or a **deviation curve** that is applied to all future measurements made by this specific thermocouple, ensuring maximum accuracy and traceability to the ITS-90 standard.

3.2.3.2 Comparison Calibration Method

The **comparison calibration method** is one of the most widely used approaches for calibrating thermocouples and other temperature sensors. Unlike the fixed-point method, which relies on precise physical constants, this method compares the output of the sensor under test directly with that of a **reference standard thermometer** over a range of temperatures.

In practice, the thermocouple and a reference device—typically a **Standard Platinum Resistance Thermometer (SPRT)** or another high-accuracy sensor—are placed together in a **stable temperature source**, such as a calibration furnace, dry block calibrator, or liquid bath. The environment is adjusted to different set temperatures, and at each point the thermocouple’s voltage output is recorded and compared against the reference reading. This process makes it possible to establish a **calibration curve** or set of **correction factors** that relate the thermocouple’s measured output to the true temperature.

3.2.3.3 Ice Bath Method (Two-point Calibration)

The **ice bath method**, also known as **two-point calibration**, is a simple and practical technique for calibrating thermocouples and other temperature sensors. It is based on exposing the sensor to two well-defined temperature points and adjusting its response accordingly.

The two reference points most commonly used are:

- **0 °C (Ice Point):** Achieved by immersing the thermocouple in a properly prepared ice-water mixture, which provides a highly stable and reproducible reference temperature.
- **100 °C (Boiling Point):** Obtained by placing the thermocouple in boiling distilled water at standard atmospheric pressure (adjusted if necessary for altitude).

By recording the thermocouple's voltage output at these two points and comparing it with standard reference tables (e.g., NIST tables), a **linear calibration line** can be established. This line serves as the basis for interpreting intermediate temperatures within the calibrated range.

3.2.3.4 Automated Calibration Systems

With the advancement of modern instrumentation, **automated calibration systems** have become widely used in laboratories and industries to improve efficiency, consistency, and accuracy in the calibration process. Instead of performing calibration manually, these systems use **computer-controlled equipment** to manage the entire procedure from setting the temperature or pressure source, to recording data, to generating calibration reports.

An automated system typically consists of:

- **Reference Standards:** High-accuracy sensors or instruments used as calibration benchmarks.
- **Controlled Source:** A temperature bath, dry block calibrator, pressure controller, or flow standard capable of being precisely adjusted by the system.
- **Data Acquisition and Software:** A computer interface that automatically collects sensor readings, compares them to the reference standard, and applies correction factors.
- **Output and Reporting Tools:** Automated generation of calibration certificates, ensuring traceability to national or international standards.

3.2.4 Sources of Error in Calibration

Even with precise procedures, several factors can introduce errors during calibration. These errors affect the accuracy, repeatability, and traceability of the results. Understanding their sources is essential for ensuring reliable calibration.

1. Sensor-Related Errors

- **Aging and Drift:** Changes in sensor properties over time due to oxidation, thermal cycling, or mechanical stress.

- **Contamination:** Deposits, corrosion, or insulation breakdown affecting thermocouples and other sensors.
- **Hysteresis:** Sensor output may differ when approaching a temperature from heating versus cooling.

2. Reference Standard Errors

- Limited accuracy of the reference thermometer or pressure/flow standard.
- Calibration errors in the reference itself (traceability chain issues).

3. Environmental Errors

- Temperature gradients in the calibration bath or furnace.
- Ambient temperature fluctuations affecting electronics.
- Improper preparation of ice baths or boiling baths.

4. Instrumentation and Measurement Errors

- Electrical noise and interference in voltage measurement.
- Inadequate resolution or accuracy of data acquisition systems.
- Contact resistance or poor sensor connections.

5. Procedural Errors

- Improper placement of the test sensor and reference, leading to unequal temperature exposure.
- Insufficient stabilization time before recording measurements.
- Human error in reading, recording, or applying corrections.