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RESEARCH MEMORANDUM

A MULTIPLE-RANGE SELF-BALANCING THERMOCOUPLE POTENTIOMETER

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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SUMMARY

A multiple-range potentiometer circuit is described that provides automatic measurement of temperatures or temperature differences with any one of several thermocouple-material pairs. Techniques of automatic reference-junction compensation, span adjustment, and zero suppression are described that permit rapid selection of range and wire material, without the necessity for restandardization, by setting of two external tap switches.

INTRODUCTION

The design of centralized instrumentation for rocket research at the NACA Lewis laboratory required that there be made available in a central instrument room means for recording accurately a number of temperatures and temperature differences as measured by thermocouples located in the various test cells. The method of operation required that, within a few minutes, the central instruments be disconnected from one test installation and connected to another and that the ranges of the instruments be altered to suit the needs of the new installation. The new ranges required might differ a great deal from the preceding set because the types of test conducted in the various cells were of radically different natures.

The requirements for this instrumentation were met in part by the provision of a group of 12 multiple-range single-point strip-chart recording thermocouple potentiometers located in the instrument room. The terminals of these instruments were made available in each test cell by use of multiple-pole switches and of cables leading from the central room to each test cell. Ranges were changed by manually setting one or two knobs on the front of each instrument. These potentiometers have the following features:

(1) Several direct-reading temperature ranges are provided for use with a variety of thermocouple materials.

(2) Several millivolt ranges are provided for temperature-difference measurements.

(3) Several steps of zero suppression (shift of lower limit) are provided on the millivolt ranges.

(4) Automatic reference-junction compensation is provided on all direct-reading temperature ranges.

(5) Restandardization is unnecessary when the range is changed.

Potentiometers possessing some or all the features itemized have been obtainable, generally on special order, from commercial manufacturers of industrial potentiometers. The noteworthy characteristics of the Lewis laboratory instruments are the techniques of reference-junction compensation and of simultaneous span alteration that permit rapid selection of any one of a large number of ranges. The basic principles used in the measuring-circuit design and the circuit details of the particular 31-range units that were constructed are described herein. The instruments have been in use since September 1947.

DESCRIPTION

A commercial high-speed strip-chart recording potentiometer (fig. 1) that uses a synchronous chopper and electronic amplifier as the null-balance detector was adapted to fulfill the necessary requirements. The measuring circuit of the commercial instrument was replaced by a new measuring circuit housed in an auxiliary box attached to the top of the original instrument. The dry cell, the standard cell, and the balancing slide-wire used in the original instrument were retained. The principle of the new circuit is explained more clearly by first reviewing the standard measuring circuit (fig. 2) of a typical industrial recording potentiometer.

Unless otherwise indicated in figures 2 and 3, the heavy dots at each end of a resistor denote the terminals between which the resistance is measured, the heavy lines connecting the dots denote copper-wire connections of negligible resistance, and the light lines denote wire connections that may possess appreciable resistance.

The span of an instrument is defined as the difference between the emf's corresponding to the two ends of the scale. The slide-wire r_2 has a potential drop approximately equal to the span. The mechanical length of the slide-wire, and consequently its electric resistance, are generally such that the potential drop is approximately 4 percent greater than the exact span in order to allow slight mechanical adjustment of the zero position of the instrument. The resistance of the slide-wire that corresponds to the span is $r_2 - 2\Delta$. For convenience, the increment 2Δ

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is considered to be divided equally between the two ends of the slide-wire. A more precise term than "zero" is "lower limit" and "lower limit" will be used herein. The span is therefore the difference between the upper and lower limits of the range.

The current through the slide-wire is set to the proper value by throwing the standardizing switch S1 to the STD position and adjusting rheostat r_0 until the null detector indicates that the potential drop $i_4 r_4$ across the resistance r_4 equals the standard-cell voltage e_{sc}. If the value of r_3 has been properly selected, the slide-wire current i_1 will then be such that $i_1(r_2 - 2\Delta)$ is equal to the required span e_{sp}.

All resistors except r_5 have zero temperature coefficients of resistance. The thermocouple wires are brought to junctions adjacent to resistor r_5 and connected to copper wires that lead to the rest of the circuit. The reference junction (cold junction) thus formed is then at the same temperature as the resistor r_5. The resistor r_5 is made of material of high temperature coefficient of resistance, such as copper or nickel, and is so chosen that the rate of change of potential drop $i_4 r_5$ with respect to temperature is equal to the thermoelectric power Q_0 (emf/deg) of the thermocouple at the expected mean operating temperature T_0 of the resistor r_5. If $r_1 + \Delta$ is chosen so that the potential drop $i_1(r_1 + \Delta)$ is equal to the potential drop $i_4 r_5$ at the lower limit of the range, reference-junction compensation is obtained and the lower limit is correctly set. The value of r_5 is made sufficiently low compared with the value of r_4 so that variations in the temperature of r_5 produce negligible variations in the potential drop $i_4 r_4$. Consequently, the bridge, once standardized, remains standardized even if the reference-junction temperature changes.

Basic Multiple-Range Circuit

The basic principle of the multiple-range potentiometer is shown in figure 3(a). In order to provide a variety of spans, the current i_2 through the slide-wire r_2 is changed by varying r_3 in order to satisfy the condition

$$i_2(r_2 - 2\Delta) = e_{sp} \tag{1}$$

The resistance r_6 is varied simultaneously to maintain currents i_1 and i_0 unchanged. Then

$$\frac{r_6(r_2 + r_3)}{(r_2 + r_3 + r_6)} = \text{constant} \tag{2}$$

and standardization is maintained when the span is changed. The resistances r_3 and r_6 are made sufficiently high so that contact resistance exercises negligible effect upon the span. In order to simplify construction, the lower limit of the instrument scale is set at the extreme left end of r_2, and therefore the entire increment 2Δ appears at the upper-limit end, adjacent to r_3.

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The reference-junction compensating resistors are designated r_7 and r_8. The resistors are of copper or other material having a high temperature coefficient of resistance. The condition for reference-junction temperature compensation is

$$\frac{d}{dT}(i_4r_8 - i_1r_7) = Q_0 \tag{3a}$$

where T represents temperature. If α_0 is the temperature coefficient of resistance of the material of r_7 and r_8 at the expected mean operating temperature T_0 of these resistors, equation (3a) becomes

$$i_4r_{8,0} - i_1r_{7,0} = \frac{Q_0}{\alpha_0} \tag{3b}$$

where $r_{7,0}$ and $r_{8,0}$ are the values of r_7 and r_8 at the temperature T_0 at which Q and α are evaluated. The resistors r_7 and r_8 are the only resistors in the circuit that are not of negligible temperature coefficient.

For each pair of values of $r_{7,0}$ and $r_{8,0}$, corresponding to a particular pair of thermocouple materials, the values of r_1 and r_9 are so chosen that the lower limit of the instrument is at the proper value. Denote this lower limit as T_L and the thermocouple emf corresponding to a temperature difference $(T_0 - T_L)$ as $e_{0,L}$. Then $e_{0,L}$ is the net voltage generated by a thermocouple, at lower-limit temperature T_L, connected to an instrument containing the reference junction at temperature T_0. In order that balance may be obtained when the slide-wire contact is at the lower limit of scale indication, it is necessary that

$$i_1(r_1 + r_{7,0}) + e_{0,L} = i_4(r_{8,0} + r_9) \tag{4}$$

Furthermore, no solutions of equation (4) may yield negative values of r_1 or of r_9. Hence, from equation (3b), r_1 must be chosen so that $i_1 r_1$ is at least as great as the highest value of $(Q/\alpha) - e_{0,L}$ that might be encountered. The value of r_1 having thus been selected, the value of r_9 is computed from equation (4).

In order to eliminate effects of contact resistance, resistors r_7, r_8, and r_9 are wired as voltage dividers (as shown in fig. 3(a)) so that

$$\left.\begin{aligned} r_7 + r_8 &= \text{constant} \\ r_9 + r_{10} &= \text{constant} \end{aligned}\right\} \tag{5}$$

The resistances r_7 and r_8 are made sufficiently small in comparison with r_3 and r_4 so that temperature changes do not appreciably alter currents i_1 and i_4.

The preceding equations may be utilized for direct voltage measurement by simply setting Q_0 equal to zero in equation (3) and setting $-e_{0,L}$ in equation (4) equal to the lower limit of voltage.

Design Procedure

The conditions outlined in the preceding discussion, together with Kirchhoff's equations for the loop, yield the following design equations for a typical situation:

Given $e_{0,L}$, e_{sp}, e_{sc}, Q_0, α_0, r_2, and Δ which are fixed by the measurement problem and the available equipment, choose convenient values of i_1, i_4, and $r_{7,0} + r_{8,0}$. Then r_1, r_3, r_4, r_6, $r_{7,0}$, r_9, r_{10}, and the intermediate quantity i_2 are given by

$$r_4 = \frac{e_{sc}}{i_4} \quad \text{(standardization)} \quad (6a)$$

$$r_{7,0} = \frac{\left[i_4(r_{7,0} + r_{8,0}) - (Q_0/\alpha_0)\right]}{(i_4 + i_1)} \quad \text{(temperature compensation)} \quad (6b)$$

$$r_1 \geq \frac{\left[(Q_0/\alpha_0) - e_{0,L}\right]_{max}}{i_1} \quad \text{(lower limit)} \quad (6c)$$

$$r_9 = \frac{\left[i_1 r_1 - (Q_0/\alpha_0) + e_{0,L}\right]}{i_4} \quad \text{(lower limit)} \quad (6d)$$

$$(r_9)_{max} \leq (r_9 + r_{10}) \quad (6e)$$

$$i_2 = \frac{e_{sp}}{(r_2 - 2\Delta)} \quad \text{(span)} \quad (6f)$$

$$r_3 = \frac{\left[e_{sc} + (Q_0/\alpha_0) + i_4\,(r_9 + r_{10}) - i_1 r_1\right]}{i_2} - r_2 \quad \text{(span)} \quad (6g)$$

$$r_6 = \frac{(r_2 + r_3)\,i_2}{(i_1 - i_2)} \quad \text{(constant total current)} \quad (6h)$$

Practical Multiple-Range Circuit

In the practical realization of the basic circuit just outlined, a multiple-pole, multiple-position tap switch is used to select appropriate simultaneous values of r_3, r_6, (r_7/r_8), and (r_9/r_{10}).

The contacts in series with r_3 and r_6 must not introduce sufficient resistance to affect appreciably the lower limit position or the span voltage across r_2. If δe_{sp} and $\delta e_{0,L}$ are the permissible errors in e_{sp} and $e_{0,L}$, respectively, differentiation and combination of equations (6a) to (6h), and neglect of nonsignificant terms show that the permissible contact resistances δr_3 and δr_6 are given substantially by:

$$\delta r_3 < \frac{r_2 e_{sc} \delta e_{sp}}{{e_{sp}}^2} \qquad (7a)$$

$$\delta r_6 < \frac{r_2 e_{sc} \delta e_{sp}}{(i_1 r_2 - e_{sp})^2} \qquad (7b)$$

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The contact that selects r_7/r_8 is in series with the battery; the condition that the resistance δr_7 of this contact shall introduce negligible error is

$$\delta r_7 < \frac{E(\delta e_{sp}/e_{sp})}{(i_1 + i_4)} \qquad (7c)$$

where E is the battery voltage.

The contact that selects r_9/r_{10} carries no current except during the balancing operation. It is necessary that negligible thermal emf relative to the span potential e_{sp} shall be introduced and that the resistance of this contact shall be small compared with the input resistance of the null detector.

The details of the instrument actually used are shown in figure 3(b). Provision is made for three iron-constantan ranges (0°-400° F, 0°-800° F, and 0°-1200° F), two chromel-alumel ranges (0°-1600° F, and 0°-2400° F), one 13-percent rhodium platinum - platinum range (0°-3000° F), and 25 millivolt ranges. The large number of millivolt ranges was not intentional, but merely a fortuitous result of the technique used to obtain a few desired millivolt ranges by independent selection of span and of lower limit.

All thermocouple ranges are selected by a single span switch S2 with four decks (a) to (d) simultaneously selecting the proper values of r_3, r_6, r_7/r_8, and r_9/r_{10}. Only three values of r_9/r_{10} are needed for the thermocouple ranges because the lower limit happens to be 0° F on all ranges of a given thermocouple material.

The span switch S2 also selects five millivolt spans (10, 20, 30, 40, and 50 mv). For these span switch settings, the lead that would ordinarily be connected to R9 is connected instead to a second lower limit tap switch S3, which is used independently to select any one of five values of R9 corresponding to lower limits of 0, 10, 20, 30, and 40 millivolts. This technique is used to minimize the number of positions required on a single switch and to provide greater versatility in the selection of millivolt ranges.

In order to maintain constant detection sensitivity on all ranges and thereby to avoid sluggishness or hunting when the span is altered, a fifth deck (e) is added to switch S2. This deck introduces shunting resistances (R11 to R14) across the amplifier when the span is appreciably greater than 10 millivolts. The values of R11 to R14 listed in table I are for an amplifier having an effective input resistance of approximately 1000 ohms.

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The null-detecting amplifier of the potentiometer utilizes a 60-cycle chopper and phase-sensitive output circuit to achieve stability and high signal-to-noise ratio. All controls are on the front panel of the attached measuring-circuit box. These controls include (fig. 1) the switches for amplifier and chart power as they are used in the central instrumentation system. These switches are not relevant to the present discussion.

Connections from external thermocouples or from other voltage sources are brought to a 6-point terminal strip at the rear of the instrument on the outside of the attached box. In order that the reference-junction compensator is permanently enclosed, it is mounted inside the attached box, and thermocouple extension leads are permanently wired from the rear terminal strip in the manner shown in the insert in figure 3(b), to the common junction points (+) and (-) adjacent to the resistor group R7-1 to R7-5. The extension leads used for chromel-alumel thermocouples CA are copper and constantan; for the 13-percent rhodium platinum - platinum thermocouples Pt the extension leads are copper and a copper alloy. Thus, the constant wire serves both for iron-constantan IC and for chromel-alumel thermocouples. Similarly, one copper lead serves both for the platinum thermocouple and for millivolt MV measurements. As long as only a single pair of wires is connected to the terminal strip, accurate reference-junction compensation is obtained, and no interference results by having all leads of the same polarity permanently connected together at the (+) and (-) terminals.

A resistance-capacitance filter R16-C1 at the reference junction and condenser C2 at the amplifier input serve to suppress 60-cycle pickup that might overload the amplifier.

In order to allow rapid check calibration, a microphone jack mounted on the front of the panel permits insertion of leads from a precision potentiometer and injection of known potentials in place of the external thermocouple emf's.

Tables I and II list ranges, circuit constants, and tolerances used in the potentiometer shown in figures 1 and 3(b).

The standardization of battery current is normally manually performed about twice a day. When a new battery is installed, more frequent standardization is required until stability has been reached. The life of the No. 6 dry cell is substantially its shelf life.

Range changes are performed by resetting the span and lower-limit switches as required. Because such changes may be performed several times an hour, it has been found most convenient to retain at all times a chart and scale graduated linearly from 0 to 100. The charts are direct reading when the millivolt span is 10, 20, or 50 millivolts. For other millivolt ranges and for all thermocouple ranges, a set of clear plastic scales is provided, graduated directly in millivolts or in degrees Fahrenheit. The appropriate scale is placed directly over the chart at the time the chart is read, so that reference to calibration curves or tables is unnecessary.

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TABLE I - SWITCH POSITIONS AND RANGES

(a) Switch S2 - Span

Switch position	Span	Thermocouple	Equivalent millivolts	Switch connections				
				Deck a (R3)	Deck b (R6)	Deck c (Tap on R7)	Deck d (Tap on R9)	Deck e (amplifier shunt)
1	0-400° F	Iron-constantan	11.94	R3-1	R6-1	f	q	---
2	0-800° F	Iron-constantan	24.23	R3-2	R6-2	f	q	R11
3	0-1200° F	Iron-constantan	39.96	R3-3	R6-3	f	q	R13
4	0-1600° F	Chromel-alumel	36.88	R3-4	R6-4	g	t	R13
5	0-2400° F	Chromel-alumel	53.63	R3-5	R6-5	g	t	R14
6	0-3000° F	13 percent Rh-Pt/Pt	19.43	R3-6	R6-6	h	u	R11
7	10 mv.	---------------	10.00	R3-7	R6-7	k	To arm of S3	---
8	20 mv.	---------------	20.00	R3-8	R6-8	k		R11
9	30 mv.	---------------	30.00	R3-9	R6-9	k		R12
10	40 mv.	---------------	40.00	R3-10	R6-10	k		R13
11	50 mv.	---------------	50.00	R3-11	R6-11	k		R14

(b) Switch S3 - Lower Limit

Switch position	Lower limit	Switch connection (Tap on R9)
1	0 mv.	m
2	10	n
3	20	p
4	30	s
5	40	v

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TABLE II - PARTS LISTING

Element	Value (ohms)	Tolerance (percent)	Material	Element	Value (ohms)	Tolerance (percent)	Material
R0-1[a]	20	10		R6-9	707.6	0.05	Manganin
R0-2[a]	100	10		R6-10	1107.6	.05	Manganin
R1	13.333	.05	Manganin	R6-11	2547	.05	Manganin
R2[b]	19.6+0.4	.1		R7-1	.284[c]	1	copper
R3-1	1642.9	.05	Manganin	R7-2	.612[c]	1	copper
R3-2	799.5	.05	Manganin	R7-3	1.792[c]	1	copper
R3-3	476.9	.05	Manganin	R7-4	.312[c]	1	copper
R3-4	516.8	.05	Manganin	R7-5	4.500[c]	1	copper
R3-5	349.2	.05	Manganin	R9-1	5.000	.1	Manganin
R3-6	990.0	.05	Manganin	R9-2	5.000	.1	Manganin
R3-7	1940.0	.05	Manganin	R9-3	4.300	.1	Manganin
R3-8	959.8	.05	Manganin	R9-4	.70	.25	Manganin
R3-9	633.2	.05	Manganin	R9-5	.57	.25	Manganin
R3-10	469.9	.05	Manganin	R9-6	3.77	.1	Manganin
R3-11	371.9	.05	Manganin	R9-7	.67	.25	Manganin
R4	509.5	.05	Manganin	R11	1000	10	Manganin
R6-1	434.0	.05	Manganin	R12	680	10	Manganin
R6-2	593.0	.05	Manganin	R13	560	10	Manganin
R6-3	1119.7	.05	Manganin	R14	390	10	Manganin
R6-4	951.3	.05	Manganin	R15	22	10	Manganin
R6-5	487.5	.05	Manganin	R16	100	10	Manganin
R6-6	512.9	.05	Manganin	C1	500 (mfd)	20	electrolytic, 6v[d]
R6-7	410.9	.05	Manganin				
R6-8	519.9	.05	Manganin	C2	.25 (mfd)	20	paper, 400 v

Additional Elements

S1 3-pole, 2-position lever switch.

S2 5-pole, 11-position rotary tap switch. Shorting contacts. Decks (a) and (b), 0.002 ohm nominal contact resistance; decks (c), (d), and (e), 0.1 ohm nominal contact resistance.

S3 1-pole, 5-position rotary tap switch, shorting contacts, 0.1 ohm nominal contact resistance.

External terminal strip: 6-point, molded-bakelite barrier strip.

[a]Material: Any having low temperature coefficient of resistance. R0-2 may be 3-turn helical rheostat potentiometer or the standardizing rheostat normally supplied with the potentiometer.

[b]Potentiometer slide-wire.

[c]At 75° F.

[d]Nonpolarized. Not over 5 microvolts output into potentiometer measuring circuit.

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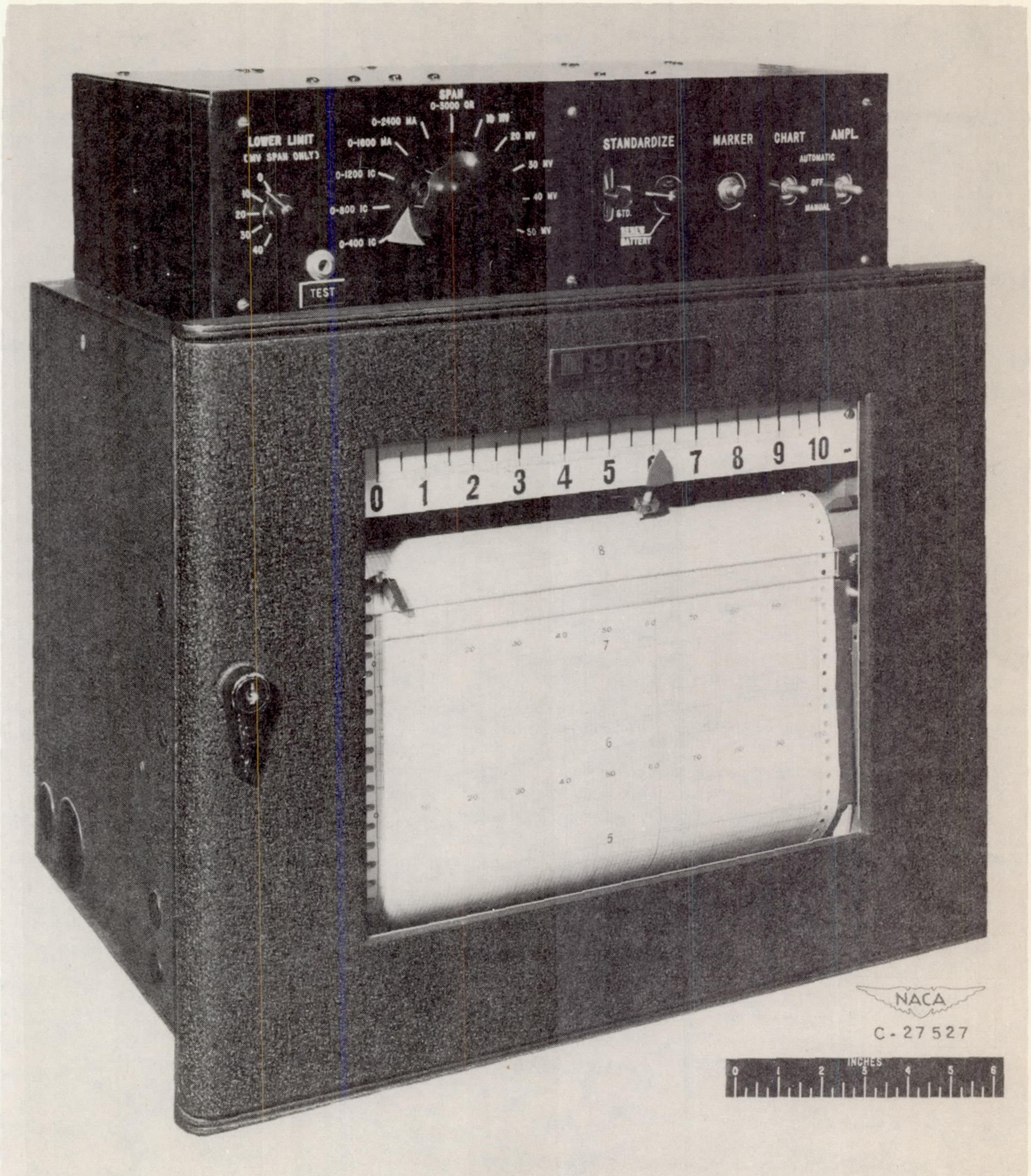

Figure 1. - Multiple-range self-balancing potentiometer.

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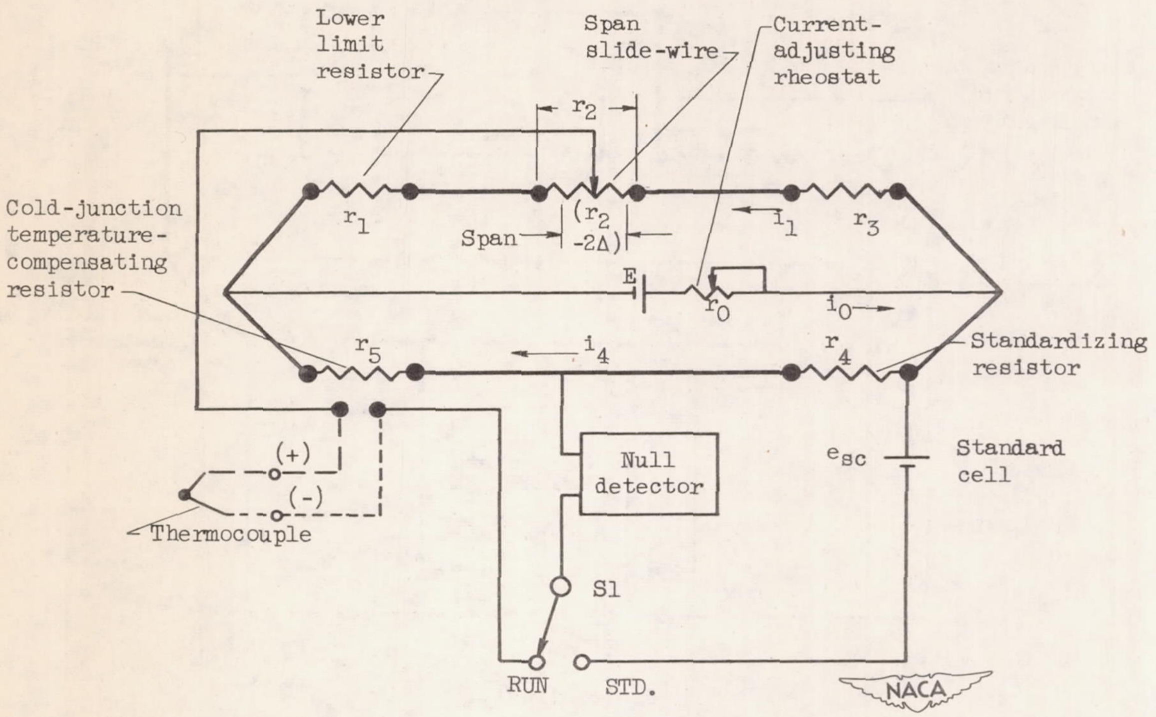
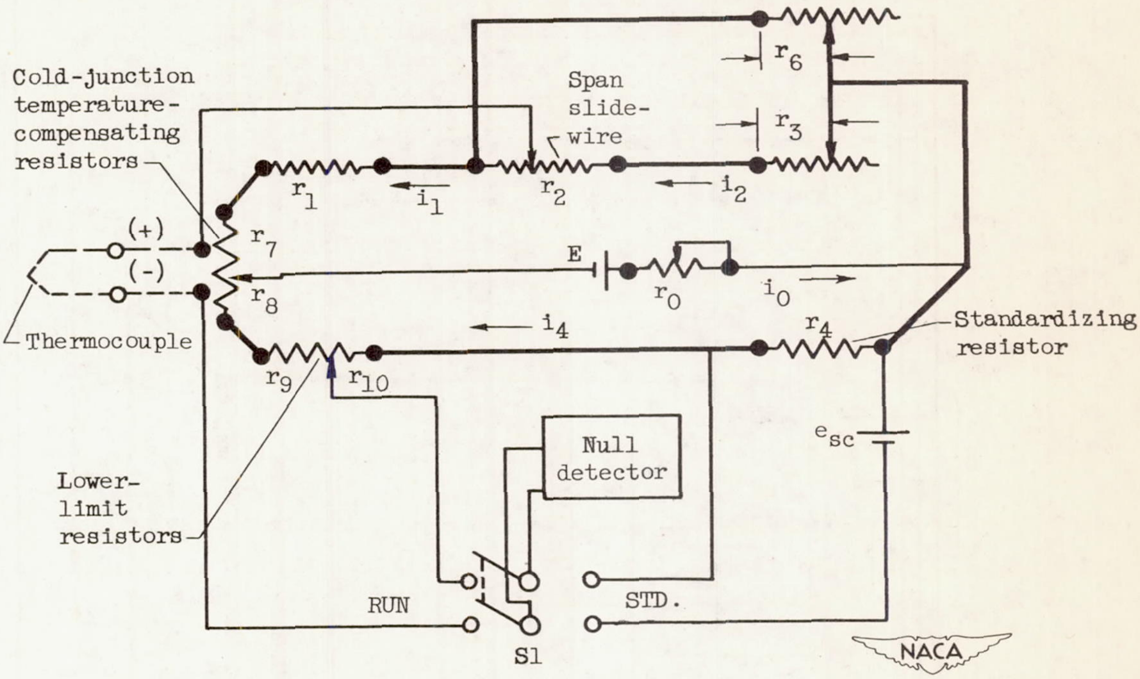


Figure 2. - Conventional industrial potentiometer circuit. The heavy dots at each end of a resistor denote the terminals between which the resistance is measured, the heavy lines connecting the dots denote connections of negligible resistance, and the light lines denote wire connections that may possess appreciable resistance.



(a) Basic circuit.

Figure 3. - Multiple-range potentiometer circuit. The heavy dots at each end of a resistor denote the terminals between which the resistance is measured, the heavy lines connecting the dots denote connections of negligible resistance, and the light lines denote wire connections that may possess appreciable resistance.

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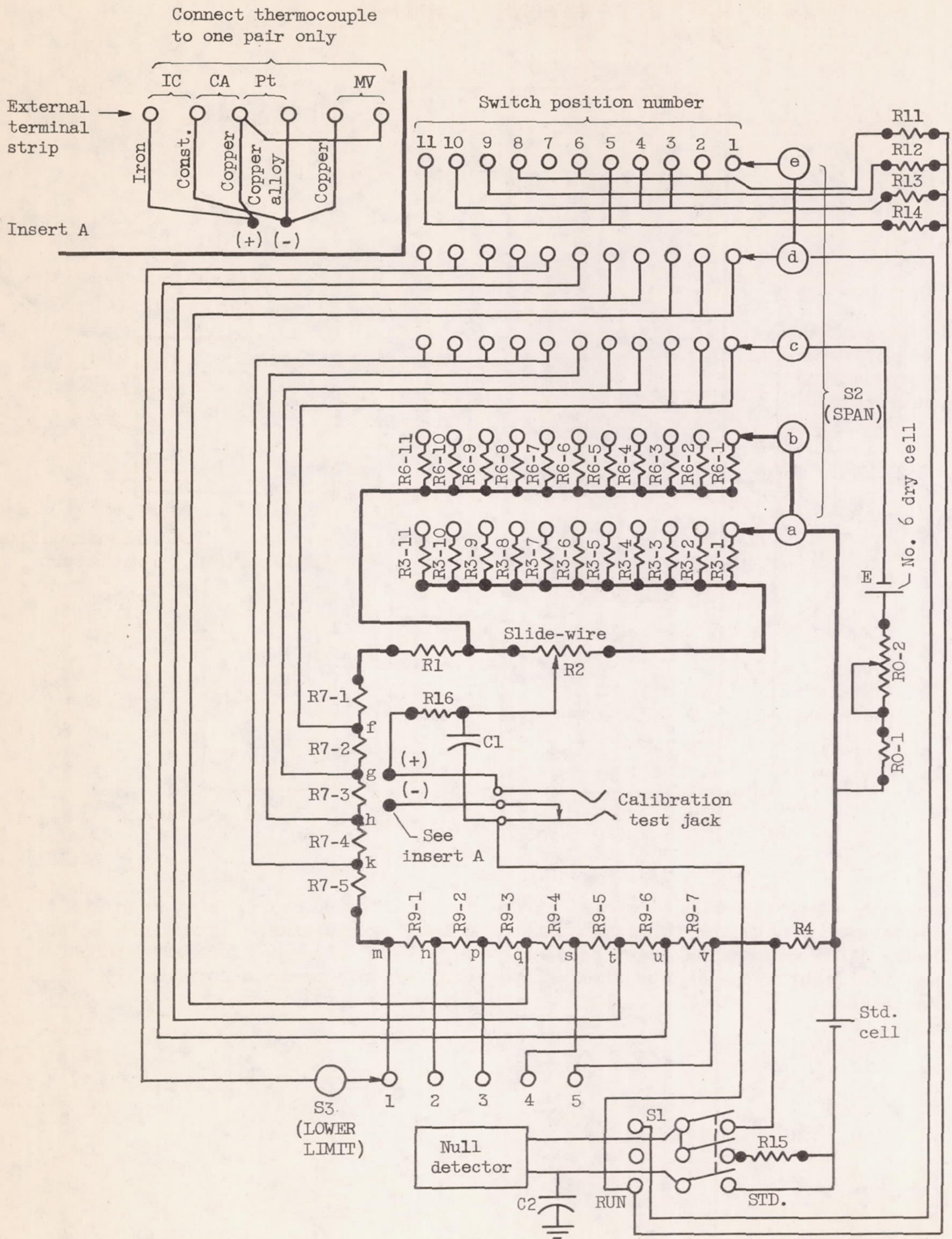

(b) Practical circuit.

Figure 3. - Concluded. Multiple-range potentiometer circuit. The heavy dots at each end of a resistor denote the terminals between which the resistance is measured, the heavy lines connecting the dots denote connections of negligible resistance, and the light lines denote wire connections that may possess appreciable resistance.

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