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THERMISTOR ARRAY IMPEDANCE CONSIDERATIONS.(U)
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NORDA TECHNICAL NOTE 26

THERMISTOR ARRAY IMPEDANCE CONSIDERATIONS

CLIFFORD R. HOLLAND

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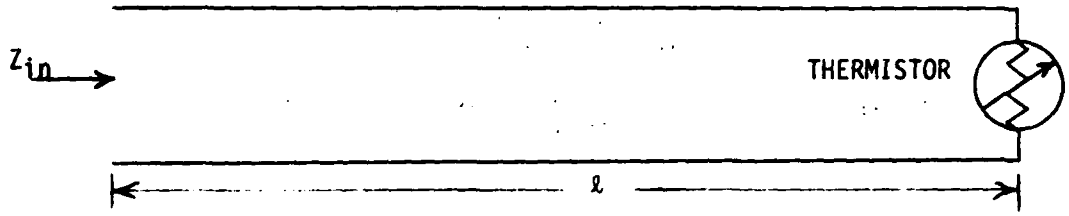
EXECUTIVE SUMMARY

This study examines the effects of cable resistance changes on temperature measurement accuracy when using a typical thermistor array for ocean temperature measurements. The analysis demonstrates that while some of the effects can be calculated or calibrated out, the major effects of insulation leakage can not be so corrected. Depending on choice of thermistor, measurement errors as large as a few degrees Celsius are possible, with errors of a few tenths of a degree Celsius likely. Even with great care, errors of a few hundredths of a degree Celsius are probable. To avoid sensitivity to cable impedance changes, it is strongly recommended that appropriate signal conditioning electronics be utilized at the thermistor sensor. The use of signal conversion and line driving electronics will insure that the accuracy of measured parameters will be maximally preserved during transmission to the output end of the array.

THERMISTOR ARRAY IMPEDANCE CONSIDERATIONS

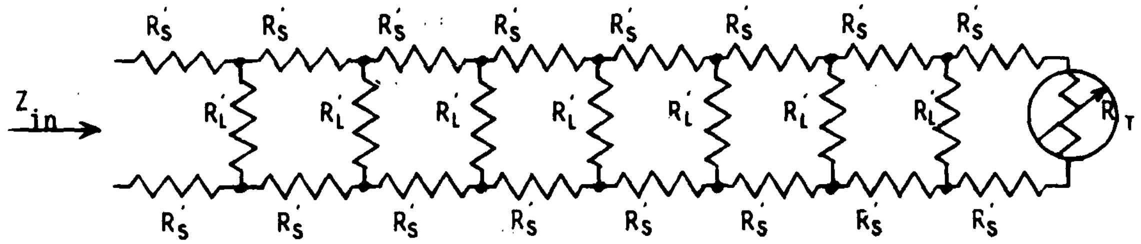
This analysis studies the effects of changing transmission line impedance on the accuracy of thermistor temperature data. Changes in transmission line impedance result primarily from temperature induced series resistance changes in the conductors and shunt resistance changes due to leakage of the conductor insulating jacket.

Consider the following thermistor array configuration and its distributed and lumped parameter equivalent circuits:



Typical of Each Array Element

ℓ = line length to Thermistor Element



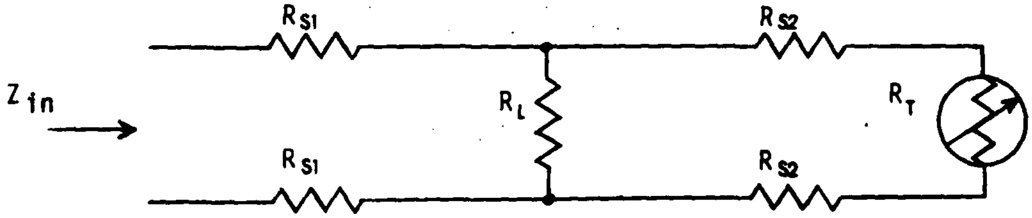
DISTRIBUTED PARAMETER EQUIVALENT

where:

R_S' = Elemental Series Resistance

R_L' = Elemental Shunt Resistance

R_T = Thermistor Resistance



LUMPED PARAMETER EQUIVALENT

WHERE:

R_{S1} = Series Resistance Between Output & Shunt Leakage

R_{S2} = Series Resistance Between Shunt Leakage & Thermistor

R_L = Shunt Leakage Resistance

R_T = Thermistor Resistance

Z_{in} = Combined Resistance of Cable and Thermistor. It is this resistance that will be interpreted as a measured temperature

The signal frequencies being dwelt with here are so low as to be essentially DC and so the analysis which follows is one of simple resistance dividers.

The "Ideal" Situation

In the ideal situation R_L is extremely high, $R_{S1} + R_{S2}$ is very very low, and R_T is in between. $R_{S1} + R_{S2}$ is determined by the material type and size selected for the conducting cables. Table 1 gives resistance values for copper wire of various sizes @ 20° D per 1000 linear feet.

* TABLE 1 - COPPER WIRE DC RESISTANCE

AWG SIZE	HARD DRAWN @ 20°C	MEDIUM DRAWN @ 20°C	SOFT DRAWN @ 20°C
20	10.5Ω	10.5Ω	10.1Ω
22	16.9Ω	16.8Ω	16.2Ω
24	26.7Ω	26.6Ω	25.7Ω
26	72.7Ω	42.4Ω	41.0Ω
28	67.9Ω	67.6Ω	65.3Ω

Let's assume our thermistor array will be approximately 1000 m (3000 ft.) long and that we will use AWG #22 wire for the thermistor signal transmission. The furthest thermistor from the readout end will "see" the greatest $R_{S1} + R_{S2}$ effect while the closest thermistor will "see" the least effect. If we wish our outputs to be reasonably independent of $R_{S1} + R_{S2}$ so as to avoid individual and unique calibration of each thermistor/cable combination, then R_T must be chosen such that:

$$\frac{R_T}{2(R_{S1} + R_{S2})} = 100 \text{ for a 1\% error (approx.)}$$

$$\frac{R_T}{2(R_{S1} + R_{S2})} = 1000 \text{ for a 0.1\% error (approx.)}$$

*Standard Handbook for Electrical Engineers, Tenth Edition, Pages 4-47, 4-48, McGraw-Hill 1969.

$$\frac{R_T}{2R_{S1} + R_{S2})} = 10{,}000 \text{ for a 0.01\% error (approx.)}$$

For the <u>furthest</u> thermistor then:

$R_{S1} + R_{S2} = 16.8\Omega^{*}\ (3) = 50.4\Omega$

and $2(R_{S1} + R_{S2}) = 100.8\Omega$

*AWG 22 Medium
drawn @ 20°C

For the nearest thermistor (assuming 50' below surface)

$$2(R_{S1} + R_{S2}) = 2(16.8)\ \frac{50}{1000} = 1.68\ \Omega$$

In order that $(R_{S1} + R_{S2}) \times 2$ be less than 1% of R_T, then R_T must = 50.4 X 100 = 5040 Ω or greater (1% effect) or R_T must = 50.4 x 1000 = 50KΩ for 0.1% effect or R_T must = 50.4 X 10,000 = 500 KΩ for 0.01% effect.

A reasonable compromise in selecting R_T would be a value between 10KΩ and 40KΩ at a temperature that is mid-scale of the measurement range. Two Ysi thermistors (type 44006 & 44008) satisfy this requirement. Their characteristic curves are shown in Figure 1 on the next page.

Let us further assume a measurement range of 0°C to 40°C; the thermistor resistance variation will be as follows (See Figure 1):

Type	0°C	10°C	20°C	30°C	40°C
44006	29.49KΩ	18.79KΩ	12.26KΩ	8194Ω	5592Ω
44008	94.98KΩ	58.75KΩ	37.30KΩ	24.27KΩ	16.15KΩ

One could also use the Ysi thermilinear element type 44212 in resistance mode where $R_T = (-129.163)T+13698.23$

Type	0°C	10°C	20°C	30°C	40°C
44212	13698.23Ω	12406.6Ω	11114.97Ω	9823.34Ω	8531.71Ω

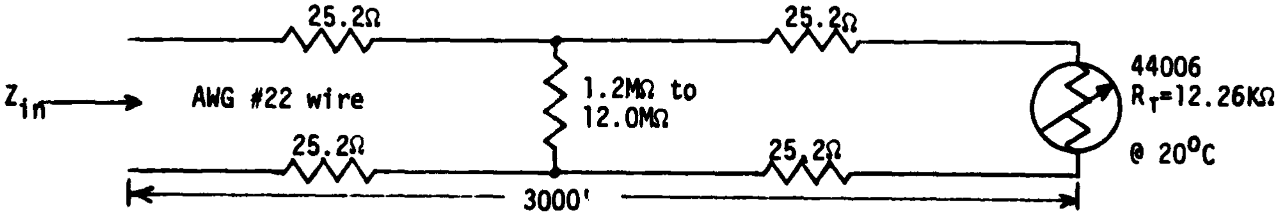
If a thermistor is chosen such that R_T @ 20°C is say 12KΩ, then R_L must be as follows:

R_L= 12KΩ (100) = 1.2MΩ for a 1% effect (approx.)

R_L = 12KΩ (1000) = 12.0MΩ for a 0.1% effect (approx.)

R_L = 12KΩ (10,000) = 120MΩ for a 0.01% effect (approx.)

In summary, then, we have the following initial thermistor array design using "rule of thumb" resistance loading considerations:



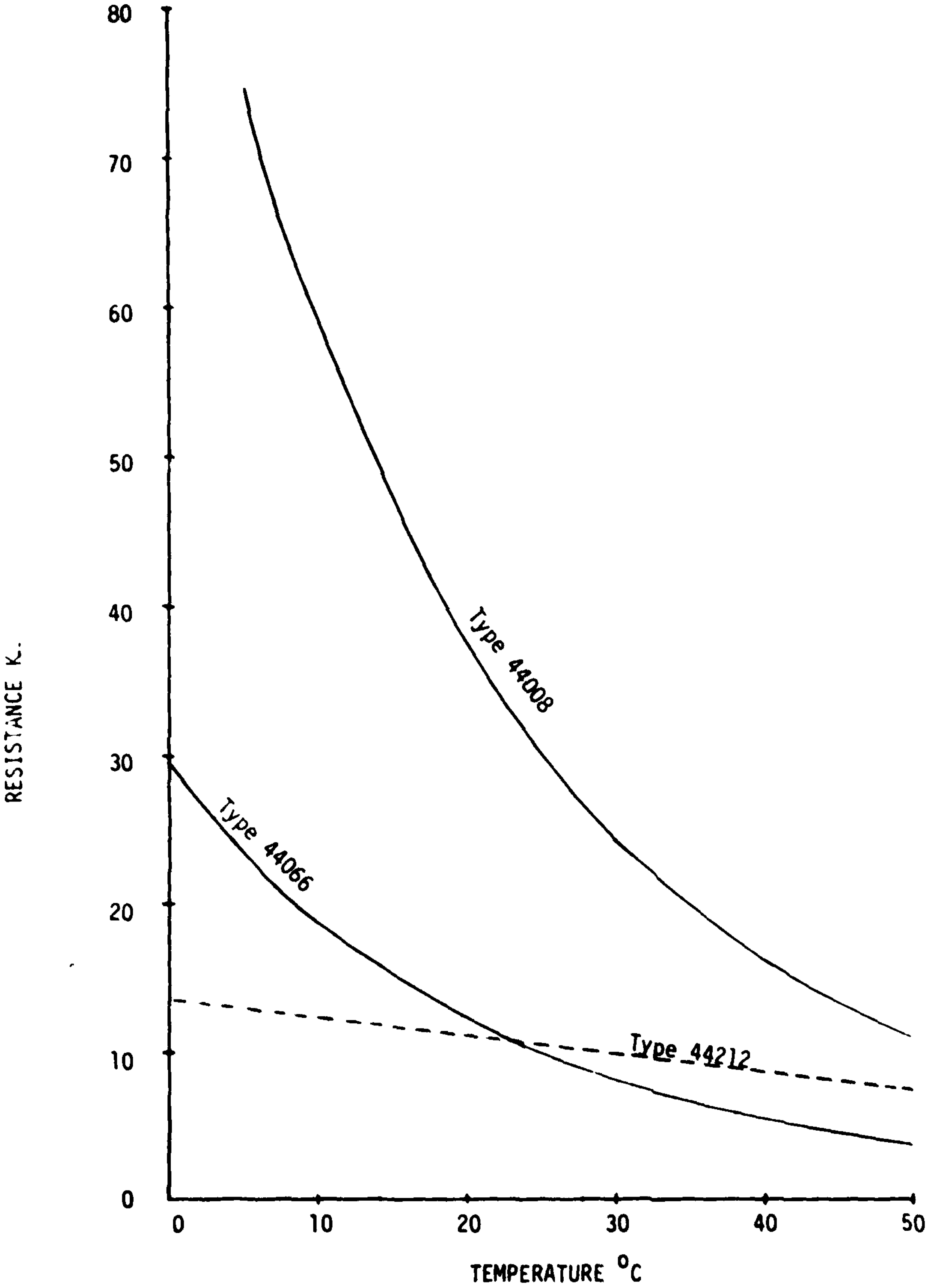


FIGURE 1 - Thermistor Curves

Now let's look at some parameter variations and the resultant effects on the accuracy of the signal output. The following tabulations illustrate the deviation from "normal" operation caused by the parameter change specified.

TABLE 2 - Zin AT VARIOUS CONDITIONS
OUTPUT RESISTANCE AT: (See code below)

Condition Code	0°C	10°C	20°C	30°C	40°C
1	29.49KΩ	18.79KΩ	12.26KΩ	8.194KΩ	5.592KΩ
2	29.50KΩ	18.86KΩ	12.35KΩ	8.288KΩ	5.690KΩ
3	28.74KΩ	18.54KΩ	12.21KΩ	8.227KΩ	5.661KΩ
4	27.94KΩ	18.21KΩ	12.06KΩ	8.161KΩ	5.630KΩ
5	22.85KΩ	15.90KΩ	11.01KΩ	7.667KΩ	5.391KΩ
6	28.80KΩ	18.60KΩ	12.27KΩ	8.286KΩ	5.720KΩ
7	28.89KΩ	18.69KΩ	12.36KΩ	8.380KΩ	5.814KΩ
8	13.613KΩ	12.354KΩ	11.092KΩ	9.828KΩ	8.559KΩ
9	12.137KΩ	11.128KΩ	10.094KΩ	9.037KΩ	7.954KΩ
10	13.698KΩ	12.407KΩ	11.115KΩ	9.823KΩ	8.532KΩ
11	13.780KΩ	12.492KΩ	11.203KΩ	9.914KΩ	8.625KΩ

Condition Code	Analysis Conditions
1	Type 4406 Thermistor alone (No loading)
2	Type 44006 with R_{S1} = R_{S2} = 25.2Ω (AWG #22) and R_L = 10M Ω
3	" " " " " " R_L = 1M Ω
4	" " " " " " R_L = 500KΩ
5	" " " " " " R_L = 100K Ω
6	" " " R_{S1} = R_{S2} = 39.9Ω (AWG #24) AND R_L = 1M Ω
7	" " " R_{S1} = R_{S2} = 63.6Ω(AWG #26) " "
8	Type 44212 with R_{S1} = R_{S2} = 25.2Ω (AWG #22) and R_L = 1MΩ
9	" " " " " " R_L = 100KΩ
10	Type 44212 Thermistor alone (No loading)
11	" " with R_{S1} = R_{S2} = 25.2 Ω (AWG #22) and R_L = 10MΩ

TABLE 3 - TEMPERATURE READING ERROR FOR TABLE 2

CONDITION CODE	MEASUREMENT ERROR AT THERMISTOR TEMP. OF: 0°C	10°C	20°C	30°C	40°C
1	0	0	0	0	0
2	-.07°C	-.08°C	-.17°C	-.29°C	-.46°C
3	+.56°C	+.31°C	+.10°C	-.10°C	-.32°C
4	+1.17°C	+.72°C	+.41°C	+.11°C	-.18°C
5	+4.59°C	+3.84°C	+2.62°C	+1.71°C	+.99°C
6	+.51°C	+.23°C	-.02°C	-.28°C	-.60°C
7	+.45°C	+.12°C	-.19°C	-.57°C	-.1.04°C
8	+.66°C	+.48°C	+.18°C	-.04°C	-.21°C
9	+12.09°C	+9.90°C	+7.90°C	+6.09°C	+4.47°C
10	0	0	0	0	0
11	-.63°C	-.66°C	-.68°C	-.70°C	-.72°C

In addition to series resistance and shunt leakage resistance effects, one should also consider cable resistance changes due to surrounding water temperature changes. The standard handbook for Electrical Engineers, Tenth Edition, Page 4-5 gives the following relationship between wire resistance and temperature:

$$R_{T2} = R_{T1} [1 + \alpha_{T1} (T_2 - T_1)]$$

where: R_{T2} = wire resistance at temperature T_2

R_{T1} = wire resistance at temperature T_1

α_{T1} = wire temperature coefficient at temperature T_1

$(T_2 - T_1)$ = temperature difference in ^{0}C

For 100% pure copper at 20^{0}C, $\alpha_{20^\circ C} = 0.00393$

For copper clad steel at 20^{0}C, $\alpha_{20^\circ C} = 0.00378$

Since the largest resistance change will occur for the biggest α_{T1} (for a given temperature difference), pure copper will be most affected. Using $\alpha_{20^\circ C}$ = 0.00393 and the medium drawn wire resistances of Table 1, we calculate the following table:

Table 4 - Temperature Effects on Wire Resistance

AWG Medium Drawn	0°C	20°C	40°C
20	9.66Ω	10.5Ω	11.34Ω
22	15.46Ω	16.8Ω	18.14Ω
24	24.47Ω	26.6Ω	28.73Ω
26	39.01Ω	42.4Ω	45.79Ω
28	62.19Ω	67.6Ω	73.01Ω

NOTES: 1. Resistance values are per 1000 linear feet of wire.
2. 20°C is considered the nominal design point for temperature operation.

From Table 4, we see that in using AWG #22 wire, the resistance change is less than 1.5Ω/1000' from nominal, or 9Ω/3000' array. Considering the Table 3 temperature errors for condition codes 3, 6, and 7, we see that a 9Ω resistance change due to wire temperature would be expected to change the output reading by about .04 to .06°C worst case. From Table 3 it can be seen that this effect is much less important than those of series and shunt resistance.

Now, let's assume that we are willing to calibrate each thermistor sensor and its associated cable individually. The major effects will now result from series resistance changes due to temperature changes and shunt resistance changes due to insulation leakage. Since the series resistance of the cable will be calibrated out (at any <u>one</u> temperature), a lower resistance thermistor can be used; thereby also reducing the effects of shunt resistance changes. The following circuit will be analyzed:

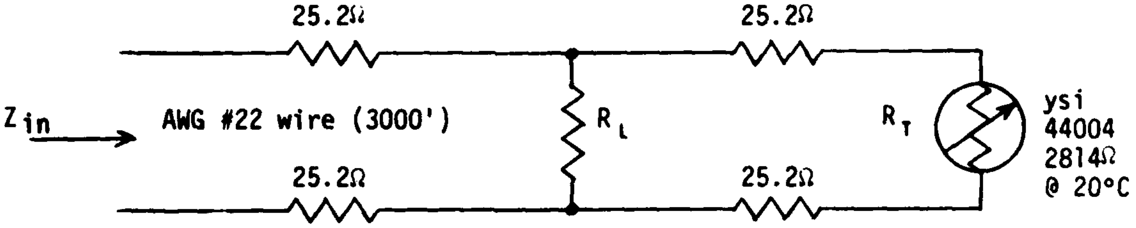


TABLE 5 - "CALIBRATED" OUTPUT OF THERMISTOR PLUS CABLE ARRANGEMENT @ 20°C

Temp °C	Type 44004 Thermistor	
	W/O Cable	W/Cable
0	7355Ω	7455.8Ω
1	6989Ω	7089.8Ω
2	6644Ω	6744.8Ω
3	6319Ω	6419.8Ω
4	6011Ω	6111.8Ω
5	5719Ω	5819.8Ω
6	5444Ω	5544.8Ω
7	5183Ω	5283.8Ω
8	4937Ω	5037.8Ω
9	4703Ω	4803.8Ω
+10	4482Ω	4582.8Ω
11	4273Ω	4373.8Ω
12	4074Ω	4174.8Ω
13	3886Ω	3986.8Ω
14	3708Ω	3808.8Ω
15	3539Ω	3639.8Ω
16	3378Ω	3478.8Ω
17	3226Ω	3326.8Ω
18	3081Ω	3181.8Ω
19	2944Ω	3044.8Ω
+20	2814Ω	2914.8Ω
21	2690Ω	2790.8Ω
22	2572Ω	2672.8Ω
23	2460Ω	2560.8Ω
24	2354Ω	2454.8Ω
25	2252Ω	2352.8Ω
26	2156Ω	2256.8Ω
27	2064Ω	2164.8Ω

TABLE 5 CONTINUED

Temp	W/O Cable	W/Cable
28	1977Ω	2077.8Ω
29	1894Ω	1994.8Ω
+30	1815Ω	1915.8Ω
31	1739Ω	1839.8Ω
32	1667Ω	1767.8Ω
33	1599Ω	1699.8Ω
34	1533Ω	1633.8Ω
35	1471Ω	1571.8Ω
36	1412Ω	1512.8Ω
37	1355Ω	1455.8Ω
38	1301Ω	1401.8Ω
39	1249Ω	1349.8Ω
+40	1200Ω	1300.8Ω
41	1152Ω	1252.8Ω
42	1107Ω	1207.8Ω

TABLE 6 - Z_{in} FOR "CALIBRATED" ARRANGEMENT @ VARIOUS TEMP.

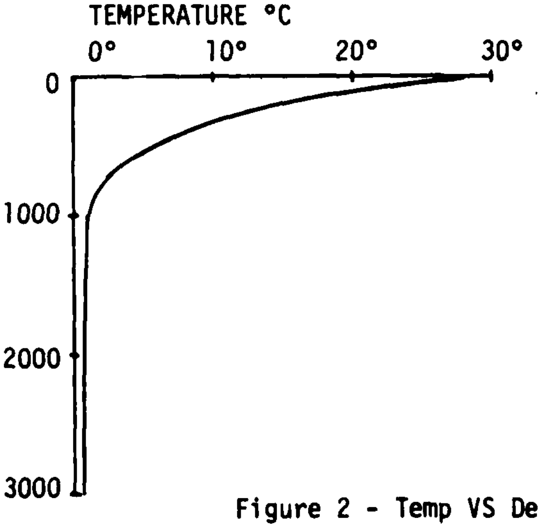
Condition Code	OUTPUT RESISTANCE AT: 0°C	10°C	20°C	30°C	40°C
A	7455.8Ω	4582.8Ω	2914.8Ω	1915.8Ω	1300.8Ω
B	7450.32Ω	4580.75Ω	2913.98Ω	1915.45Ω	1300.64Ω
C	7401.36Ω	4562.35Ω	2906.62Ω	1912.33Ω	1299.24Ω
D	7347.72Ω	4542.08Ω	2898.48Ω	1908.87Ω	1297.68Ω
E	6945.21Ω	4386.28Ω	2835.04Ω	1881.64Ω	1285.36Ω
F	7393.38Ω	4554.35Ω	2898.60Ω	1904.30Ω	1291.12Ω
G	7409.34Ω	4570.35Ω	2914.64Ω	1920.35Ω	1307.27Ω
H	7396.38Ω	-	-	-	-

Condition Code	ANALYSIS CONDITIONS
A	Type 44004 Thermistor W/Cable (AWG #22) and R_L = [illegible]
B	" " " " " " R_L = 10MΩ
C	" " " " " " R_L = 1MΩ
D	" " " " " " R_L = 500KΩ
E	" " " " " " R_L = 100KΩ
F	Type 44004 W/Cable (AWG #22) @ 0^{o}C and R_L = 1MΩ
G	" " " " @ 40^{o}C " R_L = 1MΩ
H	" " " " @Temp. Profile of Fig. 2 and R_L = 1MΩ

TABLE 7 - TEMPERATURE READING ERROR FOR TABLE 6

Condition Code	THERMISTOR TEMP. OF 0°C	10°C	20°C	30°C	40°C
A	0	0	0	0	0
B	+.015°C	+.010°C	+.007°C	+.005°C	+.003°C
C	+.149°C	+.098°C	+.066°C	+.046°C	+.033°C
D	+.295°C	+.195°C	+.132°C	+.091°C	+.065°C
E	+1.419°C	+.940°C	+.643°C	+.449°C	+.322°C
F	+.171°C	+.135°C	+.131°C	+.151°C	+.202°C
G	+.127°C	+.060°C	+.001°C	-.058°C	-.132°C
H	+.162°C	-	-	-	-

Since a thermistor has been chosen of fairly low OHMIC value, Z_{in} will be more sensitive to cable resistance changes due to temperatures different than 20°C. Conditions F&G investigate the extremes of cable temperature change while condition H analyzes a "typical" ocean temperature profile (see Fig. 2*). The tropical temperature profile was chosen for condition H since it represents the greatest temperature change with depth. Method of calculating each R_s are given after Fig. 2.



From Fig. 2

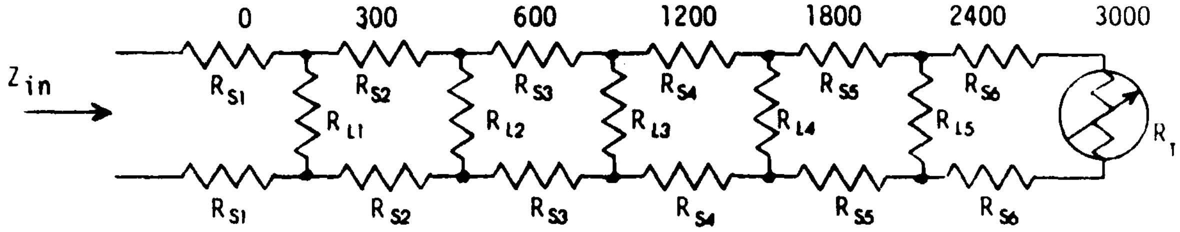
Depth (M)	Temp (°C)
0	27
100	20
200	13
400	6
600	3
800	2
1000	1

Figure 2 - Temp VS Depth Profile

* Source: Handbook of Ocean and Underwater Engineering, McGraw-Hill 1969, page 1-8, Fig. 1-4.

CALCULATIONS FOR ANALYSIS CONDITION H:

Depth in Feet (Not M)



Using the relationship: $R_{T2} = R_{T1} \; [1 + \alpha_{T1}(T_2 - T_1)]$

If R_T is at 0°C then $R_T = 7355\ \Omega$

$$R_{S1} = \frac{16.8\Omega}{1000'} \times 300' \quad [1 + .00393\ (23.5-20)] = 5.109\Omega$$

$$R_{S2} = \frac{16.8\Omega}{1000'} \times 300' \quad [1 + .00393\ (16.5 - 20)] = 4.971\Omega$$

$$R_{S3} = \frac{16.8\Omega}{1000'} \times 600' \quad [1 + .00393\ (9.5 - 20)] = 9.663\Omega$$

$$R_{S4} = \frac{16.8\Omega}{1000'} \times 600' \quad [1 + .00393\ (4.5 - 20)] = 9.465\Omega$$

$$R_{S5} = \frac{16.8\Omega}{1000'} \times 600' \quad [1 + .00393\ (2.5 - 20)] = 9.387\Omega$$

$$R_{S6} = \frac{16.8\Omega}{1000'} \times 600' \quad [1 + .00393\ (1.5 - 20)] = 9.348\Omega$$

Also: $\frac{1}{R_L} = \frac{1}{R_{L1}} + \frac{1}{R_{L2}} + \frac{1}{R_{L3}} + \frac{1}{R_{L4}} + \frac{1}{R_{L5}} = \frac{1}{1M\ \Omega}$

or $\quad R_{L1} = R_{L2} = R_{L3} = R_{L4} = R_{L5} = 5M\ \Omega$

Using the above calculated values:

Z_{in} @ $0^{\circ}C = 7396.38\ \Omega$

SUMMARY:

This analysis was designed to explore the temperature measurement errors induced by changes in array cable series and shunt (leakage) resistances. The analysis has indicated that shunt resistance changes produce the greatest detrimental effects. It is also true that the shunt or leakage resistance can change unpredictably with time, and measurements to determine the value will indicate only what it is now, not what it will be in the near or far future! Because the shunt resistance varies in an uncontrolled and unpredictable manner, the potential exists, and with high probability, that significant errors will be introduced into the temperature measurements without being detected. The major effect of this realization is to cast a doubt of credibility on all the collected data; i.e., which part is really true?

What then is the solution to this disturbing situation? The signal from the temperature sensing element(s) must be conditioned in such a manner that the values transmitted along the array cable are insensitive to cable parameter changes over a reasonably wide range. The necessary signal conditioning will require the use of electronic circuitry at the temperature sensor. Adequate signal conditioning techniques exist and modern, low power integrated circuits make their incorporation very beneficial.

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This study examines the effects of cable resistance changes on temperature measurement accuracy when using a typical thermistor array for ocean temperature measurements. The analysis demonstrates that while some of the effects can be calculated or calibrated out, the major effects of insulation leakage can not be so corrected. Depending on choice of thermistor, measurement errors as large as a few degrees Celsius are possible, with errors of a few tenths of a degree Celsius likely. Even with great care, errors of a few

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