Control of Self-Regulating Heating Cable for Use in Pipeline Heating Applications

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Abstract—**Self-regulating heating cable is an effective method of electrical heat tracing. The control of temperature without conventional sensors such as RTD's and thermocouples is described. The theory of temperature control using variable self-regulating cable is discussed. Characteristics unique to this method of heat tracing are detailed as is a controller specified to meet these requirements. Finally a cost-effective control system is described and laboratory results presented.**

I. Introduction

SELF-REGULATING heating cables produce heat from the flow of current through a polymer resistive element located between two parallel copper wires. The heating element possesses a positive change of resistance with temperature, thus limiting internal power dissipation and preventing destruction due to self-heating. It is the relationship of the heating element resistance to temperature that can be used to indicate pipeline temperature in lieu of dedicated sensors such as RTD's, thermostats, and thermocouples. A self-regulating heating cable can be visualized as an array of parallel resistors with each individual resistor having a value related to its temperature. As a result, the measurement of pipeline temperature by sensing cable resistance produces a value averaged over the length of the cable being used. The averaging effect is a desirable feature when one considers that individual heating zones can be longer than 200 ft and the pipeline temperature will vary along its length due to variations in thermal losses caused by such effects as valves, pipe supports, damp insulation, etc. The problem of positioning a single external sensor in the correct location along a pipeline is thus avoided.

A typical pipeline heating system consists of a self-regulating cable strapped to the lower quadrant of the pipe with both pipe and cable jacketed under a thick insulating blanket to minimize thermal losses to the environment. The inside diameter of the insulation should be larger than the pipe/cable diameter to provide an air chamber that acts as a convection oven to warm the pipe (Fig. 1). In a steady-state condition the heat produced by the cable balances the heat, which is lost by the system to its ambient temperature.

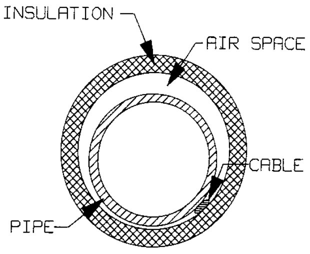

Fig. 1. Inside diameter of insulation showing air chamber relationship among insulation, pipe, and cable.

II. Theory

The relationship between pipeline and cable temperature is given in (1).

$$T_w = T_p + Q_w \times \Theta \tag{1}$$

where

T_w self-limiting cable temperature, °C
T_p pipe temperature, °C
Q_w heat energy produced per hour, W
Θ cable-to-pipeline coupling coefficient or thermal resistance, °C/W.

The cable temperature must exceed the pipe temperature if heat is to flow from cable to pipe. At equilibrium the heat being lost to the environment equals the product of the thermal resistance Θ and the heat energy produced per unit time or watts. In order to estimate the pipe temperature both the cable temperature and the thermal loss term must be evaluated.

The issue of cable temperature is examined first. The primary assumption is that the cable resistance can be used to determine its temperature. However, the cable resistance may not simply be a function of temperature. The voltage applied to the cable may also have an effect. A simple experiment was devised to test for voltage dependence. A 20-ft sample of self-regulating cable rated at 20 W/ft output was immersed in an ice bath. A variac was used to momentarily apply voltage to the cable and the current was recorded. Power was pulsed on for periods of 10 s while measurements were taken. A resting period of 5 min was maintained between readings to ensure that the cable remained at a constant temperature. The test was then repeated with a different sample of 20 W/ft cable. The results are presented in Tables I and II.

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TABLE I
Resistance-Voltage Dependence at Fixed Temperature

20W/ft @ 0°C		
Voltage, V	Current, A	Resistance, Ω
28.43	0.78	36.45
41.87	1.15	36.40
55.45	1.53	36.24
69.40	1.92	36.15
81.40	2.25	36.18
97.54	2.68	36.40
109.2	3.00	36.38

TABLE II
Resistance-Voltage Dependence at Fixed Temperature

15W/ft @ 0°C		
Voltage, V	Current, A	Resistance, Ω
28.47	0.75	37.96
41.06	1.10	37.32
49.89	1.35	36.96
53.93	1.44	37.45
62.07	1.79	36.51
69.24	1.82	38.04
95.32	2.56	37.23
110.4	2.95	37.71

The conclusion is that temperature is the dominant factor in cable resistance and the effect of voltage can be essentially ignored. A resistance-to-temperature relationship can be developed for each particular cable and this can be used to determine the cable temperature by measuring resistance.

The next point of discussion is the coupling constant Θ. Thermal coupling is influenced by the physical system. It changes with the method used to fasten the cable to the pipe, for example. Coupling constant Θ can be found for a given system by measuring the pipe and cable temperature and calculating it from (1). However, this would not be a practical method in the field when pipe and cable are sealed beneath an insulating blanket. An alternative approach is provided through the data supplied by the cable manufacturers. An example of the information provided is shown in Fig. 2.

If you examine Fig. 2 the self-limiting nature of the cable is evidenced by the negative slope that indicates decreasing power output with increasing temperature. The manufacturer's data are always provided with rated voltage applied to the cable. The depicted information contains an implicit assumption. It assumes that the cable was installed as per the manufacturers instructions since the pipe temperature is dependent on cable temperature *and* thermal losses or in other words for a given value of Θ. Typically the cable is strapped to the pipe every foot with both heating cable and pipe insulated from the ambient, which yields a value for Θ of approximately 5°C/W. Consider (2):

$$W_{\text{rated}} = c_1 \times T_p + c_0 \tag{2}$$

where

W_{rated} power output per foot of cable at rated voltage, W/ft

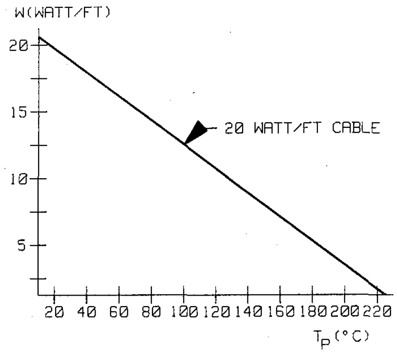


Fig. 2. Self-limiting nature of cable shown by negative slope indicating decreasing power output with increasing temperature.

T_p pipe temperature, °C
c_0, c_1 constants describing cable behavior, W/ft and W/ft °C.

Equation (2) is a first-order approximation to the cable output versus temperature curve supplied by the cable manufacturer for a specific cable type. Converting (2) to a resistance/temperature relationship is straightforward since

$$W = \frac{V^2}{R} \tag{3}$$

where

W power, W
V voltage, V
R resistance, Ω.

Combining (2) and (3) yields the result

$$R = \frac{V^2}{c_1 \times T_p + c_0}. \tag{4}$$

A plot of cable resistance versus temperature is shown in Fig. 3. The curves presented were developed for a 20-W/ft cable. The curve labeled "pipe temperature" is developed from (4). The curve labeled "delta" is the difference in temperature between the heating cable and the pipe caused by losses to the ambient (see (1)). The cable temperature is the sum of the delta and pipe temperature curves and is labeled as "cable temperature."

III. Control

Having established a mathematical model for the cable, we now discuss the issue of control. Since the pipe temperature is proportional to the cable resistance, the pipe temperature can be held constant by maintaining a constant cable resistance. Fig. 4 is a block diagram for a theoretical temperature controller. The inner loop is a power controller; its function is to maintain a constant power output whose reference is established by the resistance loop. The outer loop is the resistance loop. The cable model is used to compute the resistance at which the set point temperature will be achieved. This resistance is the reference for the resistance loop.

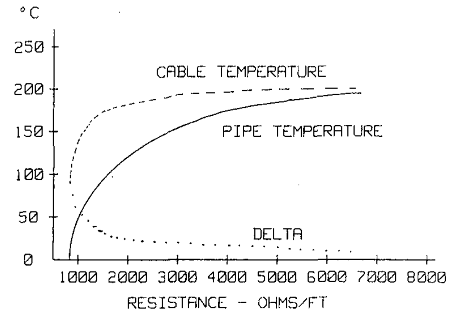


Fig. 3. Plot of cable resistance versus temperature. Curves presented are for a 20-W/ft cable.

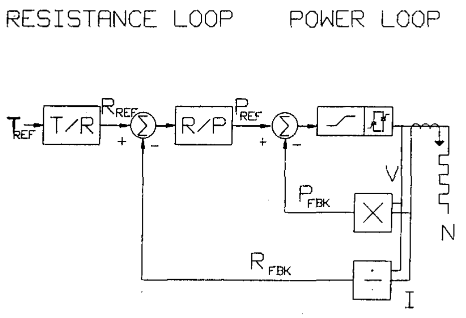


Fig. 4. Block diagram for a theoretical temperature controller. Inner loop is power controller. Outer loop is resistance loop.

There is a further complication caused by a significant transport delay in the self-regulating cable. Delays on the order of minutes exist from the time power is applied to the cable until its resistance stabilizes. The sluggish response makes attempts to control such a system with conventional PID control difficult. Superior control can be accomplished using non-PID control algorithms. Fast response is normally unimportant because of the thermal inertia of pipeline heating systems.

IV. Accuracy

At this point the accuracy of temperature measurement is addressed. The RTD and self-regulating cable both possess a temperature/resistance dependence. However, they differ significantly in their application and these differences illustrate the factors affecting the accuracy of temperature measurement.

RTD's are constructed to be interchangeable. The most common RTD used today is made of platinum. The temperature coefficient of the platinum is defined by DIN standards, which dictates the metal chemical purity. This is not true of self-regulating cable. Heating cable is produced to have a minimum wattage per foot of cable. The actual cable output is often higher than the published curves. In addition the cable output will also vary between production runs, which translates into poor interchangeability. This necessitates a calibration procedure for each heating zone to match the characteristics of a specific length of cable to the actual zone temperature.

The RTD is not a self-powered sensor. Low levels of dc current are used to excite the RTD. DC measurements are both simple and highly accurate, which allows the RTD resistance to be easily determined. This is not the case for self-regulating cable. Since its function is to provide heat, the cable is excited with high ac currents. Errors are introduced from inaccuracies in the rms measurement of the current and voltage that produce errors in resistance measurement. The errors are more significant when a phase-controlled current is fed into the cable due to the harmonic content of the waveform, making accurate rms measurement more difficult.

V. Test Data

An experiment to determine the accuracy of temperature measurement using a cable model was performed. Twenty-five feet of 1-in.-diameter schedule 40 steel pipe was enclosed inside a 1-in.-thick polyisocyanurate insulation jacket, which was preformed for a $1\frac{1}{4}$-in. pipe. Twenty watt/foot heating cable was strapped along the upper quadrant of the steel pipe inside the gap between pipe and insulation. A power controller employing phase-fired SCR's was connected to the cable at one end. Voltage, load resistance, and cable temperature at the pipe midpoint were recorded at several output voltages. The results along with the predicted values are given in Table III. The errors were not unexpected when one considers the sources of inaccuracies discussed earlier. At this point it was decided that this method could be used as a temperature-sensing technique.

VI. Controller Specification

With a reasonable algorithm in hand, the next problem is determining which features a hypothetical controller should incorporate to accomplish the goal of controlling a self-regulating heating cable. At this point a decision on control philosophy must be made as well. Should a controller be a $\frac{1}{4}$ DIN unit with external power controller or should power control be incorporated directly? For that matter, should the control of self-regulating cable be attempted at all since the cable will not destroy itself from self-heating?

A detailed treatment of the reasons [1] for using a controller on self-limiting cable will not be presented. The major points for doing so are summarized as follows:

1) On startup, cable resistance is lower and currents may exceed design limits. A current-limiting controller will prevent excessive currents.
2) An unregulated system will generate excess heat and is energy inefficient if the cable capacity exceeds the thermal losses of a system. This will always be the case since a good design will allow a safety margin in regard to heat capacity and the system will always be designed for worst-case conditions. Also note that self-regulating cables tend to produce more heat than manufacturers specify.
3) The use of a safety factor can lead to high pipe temperatures that can damage heat-sensitive materials inside the pipe or, in the case of safety showers, lead to scalding of personnel.

TABLE III
PREDICTED TEMPERATURE

Load Res., Ω	Load Voltage, V	Pretemp., °C	Meas. Temp, °C	Error, %
16	42.12	52.1	52.1	n/a
17	40.53	63.2	67.8	6.8
18	40.60	71.9	77.8	7.6
19	44.40	76.9	81.5	5.6
20	47.00	81.8	86.2	5.1
21	49.40	86.3	88.9	2.9
22	51.04	91.2	93.0	1.9
23	54.75	93.5	94.9	1.5
24	56.01	97.7	98.5	0.8

4) Monitoring fault conditions is required. Cable typically has a ground leakage of 8–12 mA/1000 ft at 240 V_{ac}. However wet insulation, improperly installed cable, or cable damage can lead to increased ground fault leakage with the danger of fire.

VII. DESIGN CONSIDERATIONS

A controller was to be designed that would regulate temperature using the algorithm described earlier. Since this device was to be application specific its design should take into account the criteria of practicality and simplicity of use.

A. Practicality

A system approach was to be taken from the onset. The envisioned system would consist of an integral power transformer, distribution panel, and up to 24 zones of controllers. Each individual controller would contain its own power controller and alarm relays.

B. Simplicity of Use

By providing a complete power distribution and controller package, field installation is simplified. The controller would be designed with a nonvolatile memory capability that allows each controller to be factory programmed to meet application requirements. Modular controllers would be capable of operating over a wide input voltage range that would allow interchangeability between controllers on zones with different voltages. A serial interface would be included to permit remote monitoring and programming. Field calibration would be a simple single-point calibration process with the goal of making the system as close to a turnkey operation as possible.

C. Solution

The result of the design criteria was a control system utilizing 24 individual controllers. Fig. 5 is a drawing of such a system. A standard system contains a 45-KVA 480–120/208 V_{ac} transformer with a 480–240 V_{ac} transformer available as an option. The system contains 24 double-pole circuit breakers individually rated at 25 A. Each zone can be easily converted from 208–120 V_{ac} by moving a single wire.

TABLE IV
SYSTEM TEST RESULTS

Target Temp., °F	Probe Temp., °F	Output Power, W	Outside Temp., °F
150	149.9	111	38
150	151.7	105	46
150	150.8	110	33
150	151.8	120	39
150	154.9	126	36
150	156.4	123	34
90	89.6	63	20
90	96.0	60	23
90	95.3	51	21
90	91.5	65	19
90	95.6	55	25
90	90.9	56	18
90	87.0	73	8
90	90.8	70	10
90	95.0	62	24

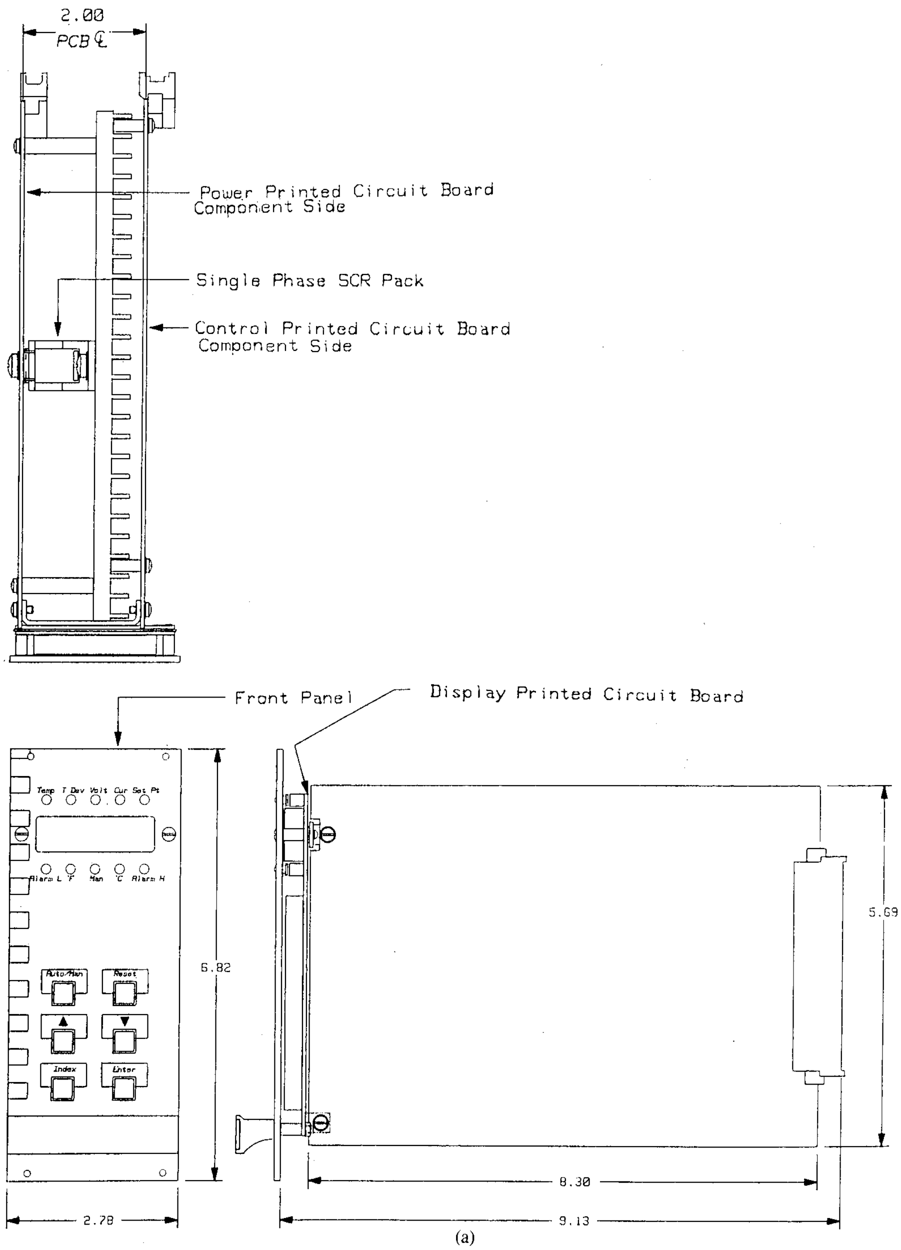
The controller is a plug-in module with an integral power controller capable of a 20-A output at up to 240 V_{ac}. It employs back-to-back SCR's that are protected by semiconductor fuses. The unit was designed to control self-regulating heating cables from its inception. It was equipped with circuitry specific to the requirements of implementing the measurement algorithm as described in this paper. Capabilities include the following:

1) Temperature measurement by resistance inference standard with options to use thermocouple or RTD sensors
2) true rms measurements of voltage, current, and ground-fault leakage
3) soft start to prevent high currents into low resistance loads
4) nonvolatile memory for storage of digital calibration constants and controller setup parameters
5) extensive monitoring functions with two alarm relays. There are 16 programmable alarm conditions: high temperature, high deviation, low temperature, low deviation, high heater resistance, low heater resistance, high ground fault current, high ambient temperature, blown fuse, over current, open thermocouple, shorted RTD, open RTD, data loss, manual mode, and watch dog timeout.
6) serial communications interface for remote monitoring
7) switch-mode power supply that operates from 100–260 V_{ac} at a line frequency of 50–60 Hz
8) optional 4–20 MA output for remote temperature monitoring.

A technical reference manual [2] is available that documents the operating features of the control system in greater detail.

VIII. SYSTEM TEST

The following test was performed with the controller to test its ability to control temperature in field conditions. Twenty-five feet of 1-in. schedule 40 pipe was fitted with 20 W/ft cable as per the manufacturer's instructions. The assembly was placed outdoors during the winter to allow the ambient conditions to change with the daily fluctuations in temperature. The heating cable was connected to the output of a controller. The unit was then put through a resistance/temperature measurement calibration cycle and the set point for pipe temperature established at various temperatures. The pipe temperature was measured near midpoint with a type K thermocouple. Two test runs were made at a different setpoint. The controller was calibrated at the beginning of each test. The results are shown in Table IV.



(a)

Fig. 5. Control system utilizing 24 individual controllers: (a) Control module; (b) main enclosure.

IX. ECONOMICS

The final point of discussion is an analysis of the costs to install an electrical tracing system at two plant sites. Each system was estimated using three different approaches: field-mounted thermostats, resistance controllers as described in this paper, and field-mounted sensors and controllers operating contactors.

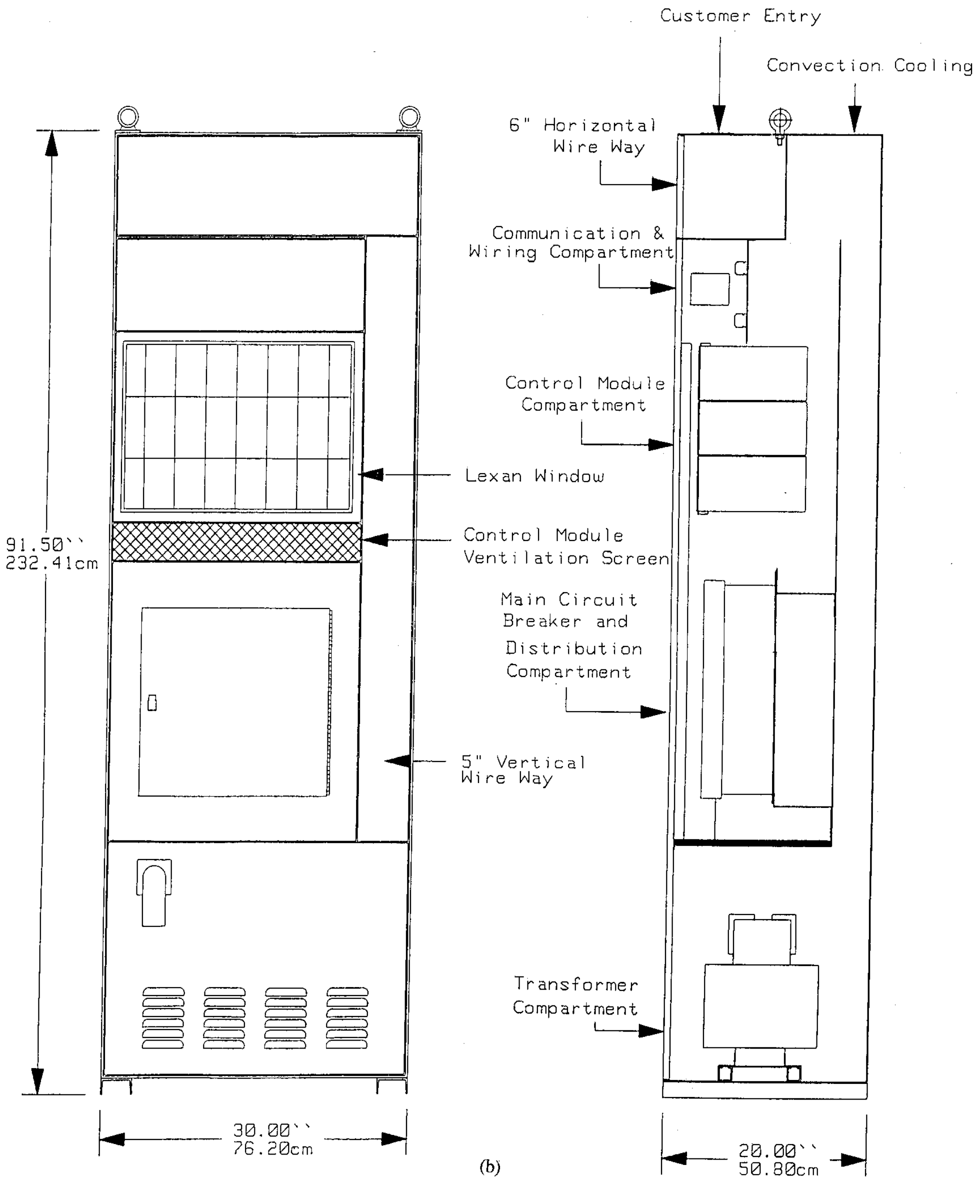
A. Estimate 1

A midwestern plant will use electrical tracing for both freeze protection and process heating. A total of 112 circuits with 9300 ft of cable mounted on 0.5–4 in.-diameter pipe. Self-regulating cable types range from 3–20 W/ft with a small length of constant wattage cable. The cost breakdown is as follows:

Type of Tracing	Electrical Costs, ft	Insulation Costs, ft	Total Costs, ft
1	31.21	19.60	50.81
2	36.81	19.60	56.41
3	40.17	19.60	59.77

B. Estimate 2

A Gulf Coast plant will use electrical tracing for process



(b)

Fig. 5. (*continued*)

heating. A total of 97 circuits with 5375 ft of cable mounted on 0.5-10 in.-diameter pipe. Self-regulating cable types range from 5-20 W/ft with a small length of constant wattage cable. The cost breakdown is as follows:

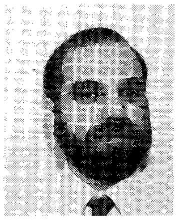
Type of Tracing	Electrical Costs, ft	Insulation Costs, ft	Total Costs, ft
1	59.16	19.02	78.21
2	67.31	19.02	86.33
3	75.67	19.02	94.69

Note that the thermostat approach is initially the least expensive, but it has some drawbacks. First, the thermostats are not centrally located but are scattered along the pipe. Second, there are no monitoring functions provided. As a result, maintenance costs will be higher. Monitoring has the advantage of providing a warning of system deterioration. A sudden increase in ground fault current or a change in cable resistance can signal a problem and preventative maintenance can be scheduled before a costly downtime occurs.

REFERENCES

[1] C. J. Erickson, "Reliable and cost-effective electrical heating of pipelines with self-regulating heating cables," Paper no. PCIC-87-21, 34th Annual Petroleum and Chemical Conference, 1987.

[2] *tcm120 Temperature Control Module Technical Reference Manual*, manual no. 1224, Val-Tech Inc., Newark, DE.



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