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EVALUATION OF A COMPUTER SIMULATION OF THE RADIANT HEAT CURING PROCESS FOR PRIMARY URD ELECTRICAL CABLE

An independent research project
submitted in partial fulfillment of
the requirements for the MBA degree

by
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INTRODUCTION

It is the intent of this paper to compare the predictions of an in-house developed computer model, of the radiant heat curing process for plastic insulated electrical cable, with data gathered both from trials in a pilot facility and from actual production in a full scale manufacturing plant. First, background explanations of the product and the manufacturing process are given. Then the thermodynamic and chemical basis of the computer model are discussed in some detail. The model predictions of product temperatures during processing are then compared to the results obtained during trials at the pilot facility. Next, degree of cure data from actual plant production runs is compared to the values generated by the computer model. Finally, conclusions are drawn concerning the overall accuracy of the model predictions and suggestions are made for areas that should be examined if improvement in predictions is desired.

PRIMARY URD CABLE

To get their product to the customer most companies use a delivery channel consisting of various combinations of manufacturers, wholesalers, retailers and the like. The delivery system for electricity utilizes electrical cables as the connection between the manufacturing utility and the customer. Just as there are many types of marketing distribution channels for the more standard goods and services depending on which system best fits the need, there are many different types of electrical cables, depending on such things as how much power must be delivered, who the customers are, where they live, and how reliable the power must be.

In this paper we are concerned primarily with a particular class of plastic insulated cables known as primary Underground Residential Distribution (URD) cable [2]. These cables are typically buried in the ground to provide an intermediate link in the electricity distribution chain. In general, the amount of power that can be conveyed by the cable is proportional to the product of its voltage and current ratings. The larger the electrical conductivity and cross-sectional area of the conductor and the thicker the insulation, the more power can be delivered by the cable.

Of course, there is the usual trade off that more capability means more cost. For illustration purposes, an electrical system can be compared to a water supply system. The generator is analogous to a pumping station. The cables are like pipes, the voltage like water pressure, and the current like water flow. Pipes with larger cross sectional areas can carry more flow and pipes with thicker walls can handle higher pressures. Similarly, cables with larger conductors can carry more current and cables with thicker insulations can handle higher voltages.

The components of a typical primary URD cable are shown in Figure 1. Working from the inside out, The first object

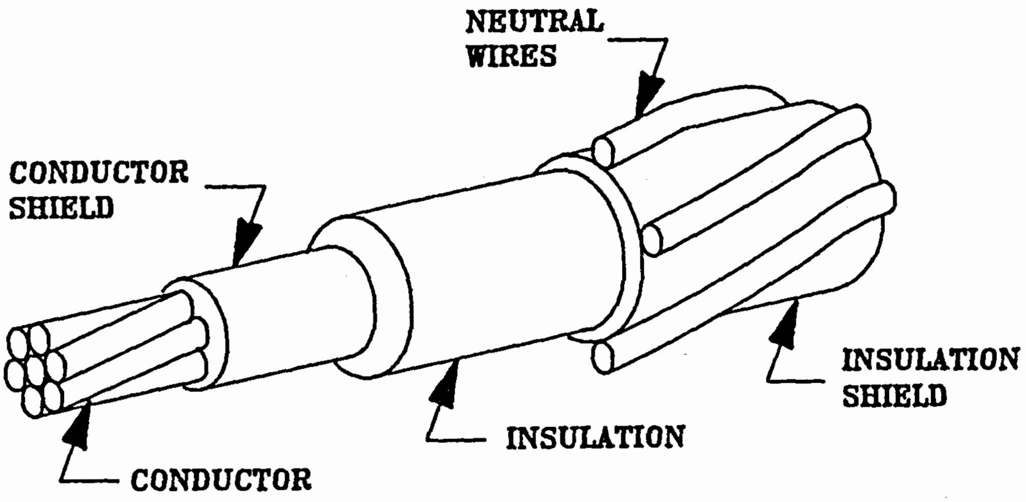

FIGURE 1: TYPICAL PRIMARY URD CABLE

is the metallic conductor. This is the supply pipe through which the current going to the end user flows. It is usually aluminum for this application due to the combination of low cost, light weight, and moderately high electrical conductivity, approximately 62% of that of copper of equal size. Conductors are designated by cross-sectional area and number of individual wires twisted together to make them up. The cross-sectional area unit of measure is a circular mil, abbreviated "cmil". A cylindrical conductor whose diameter is one mil (0.001 inches) has an area of one circular mil. Typical sizes for primary URD cable range from approximately 26 thousand circular mils (26 kcmil) to 1000 kcmil. For conductor sizes less than 250 kcmil, the American Wire Gauge (AWG) is usually used to describe the conductor size [19]. Table 1 below shows the common AWG sizes used for primary URD cable and the corresponding kcmil sizes [19]:

<u>Table 1</u>: Common primary URD conductor sizes

AWG	kcmil
#2	41.74
#1	66.36
#1/0	105.6
#2/0	133.1
#3/0	167.8
#4/0	211.6

Conductors may be made up of from one to 61 wires. The larger the number of wires, the more flexible the finished product will be. The more flexible strandings are usually used for the larger size conductors in order to make them easier to handle during installation.

The layer closest to the conductor is called the conductor shield. It is an extruded layer of partially conducting plastic called semi-conducting crosslinked polyethylene. It serves two purposes [5]. First it provides a smooth surface over which the electrical stresses are uniformly distributed [5]. It is vital to the long term performance of the cable that this layer be very smooth. Discontinuities on the surface can be sources of higher than normal electrical stress and thus premature failure in service. Second, the conductor shield provides a surface for close bonding to the insulating plastic layer to avoid gaps between the two plastic layers [5]. These gaps can lead to internal electrical discharge which eventually can destroy the integrity of the insulation layer and create an electrical short circuit [5].

Just over the conductor shield is the extruded insulation layer. This allows the conductor to be held at very high electrical potentials. It keeps the power from "leaking out" before it gets to the customer. It is essential that this layer be microscopically clean and homogeneous. Even very small imperfections can lead to distorted electrical stresses and subsequent early failure of a cable. Just as pipe walls must be thicker to accommodate higher water pressures, insulation must be thicker to allow higher voltages. Typical thicknesses range from 0.175 inches for 15000 volt applications to 0.345 inches for 35000 volts [4]. Another must for the insulation material is that it be able to withstand the heat generated by the conductor as it carries current. The electrical resistance of the conductor generates heat proportional to the square of the current. The majority of primary URD cables in use today have insulation which is capable of operating at conductor temperatures up to 90 C. This is achieved by blending a catalyst with the thermoplastic polyethylene such that when the material is subjected to heat during cable manufacturing, the insulation material is cured. This curing, called crosslinking, imparts improved physical and electrical properties to the insulation [5]. This curing process is the subject of the model which is under investigation herein.

The last plastic layer is the insulation shield. Like the conductor shield, it also has two purposes [5]. First, it provides a smooth surface to which the insulation can be mated to avoid gaps and subsequent detrimental electrical discharges [5]. Secondly, in conjunction with the metallic neutral wires it confines the high energy electrical fields within the insulation and provides safety from shock hazard [5].

The concentric neutral wires shown in Figure 1 can be thought of as the return pipe in the water system analogy. They are typically made of copper due to its high electrical conductivity and the fact that it generally has better corrosion resistance than aluminum in the presence of water and minerals in the ground. The neutral wires both help the insulation shield provide containment for the electric fields and provide the return path for the electrical current to get back to the generating source.

Figure 2 shows the typical stages in the processing of a primary URD cable with an aluminum conductor and extruded crosslinked polyethylene insulation. Generally cable manufacturers would start with the electrical rod as a raw material, produce smaller size wires by drawing it through dies with successively smaller holes, and then twist them together in the stranding operation to form the finished metallic conductor.

The continuous extrusion/curing/cooling operation for the plastic materials is diagrammed in more detail in Figure 3. The conductor shield, insulation and insulation shield, are each applied to the conductor in an extrusion process. Figure 4 shows a cutaway side view of a typical extruder for the application of a single layer of plastic. The polyethylene, in pellet form, is fed onto a rotating screw where it is pushed through the heated barrel and melted. The pumping and mixing action of the screw acts to homogenize the molten plastic and move it to the front of the extruder where it enters the crosshead, so called because in it the melted plastic makes a right angle turn from parallel to the

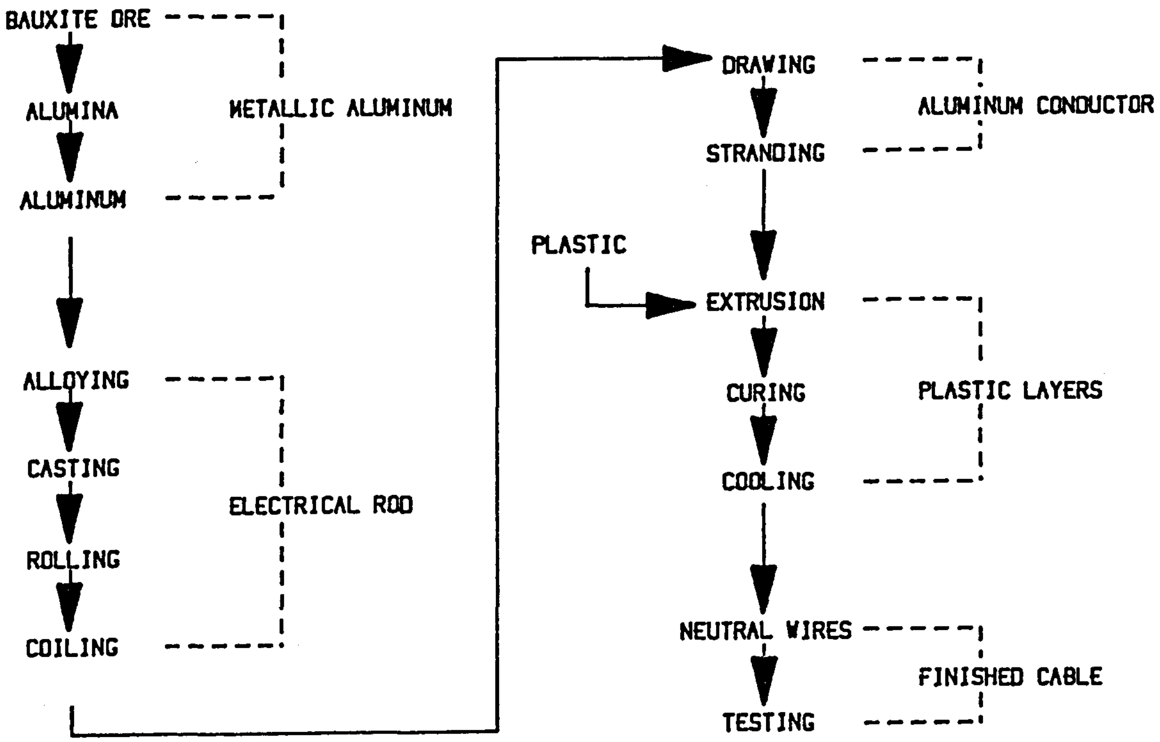

FIGURE 2. MANUFACTURING STEPS FOR PRIMARY URD CABLE

extrusion screw to parallel to the incoming conductor. Here the melted plastic wraps around the conductor and forms a hollow tube over it as they exit the crosshead together. Typically the layout of the extruders is as shown in Figure 3. The conductor shield is applied first, by itself, followed generally by a few feet of air cooling. The insulation and insulation shields are then applied by two

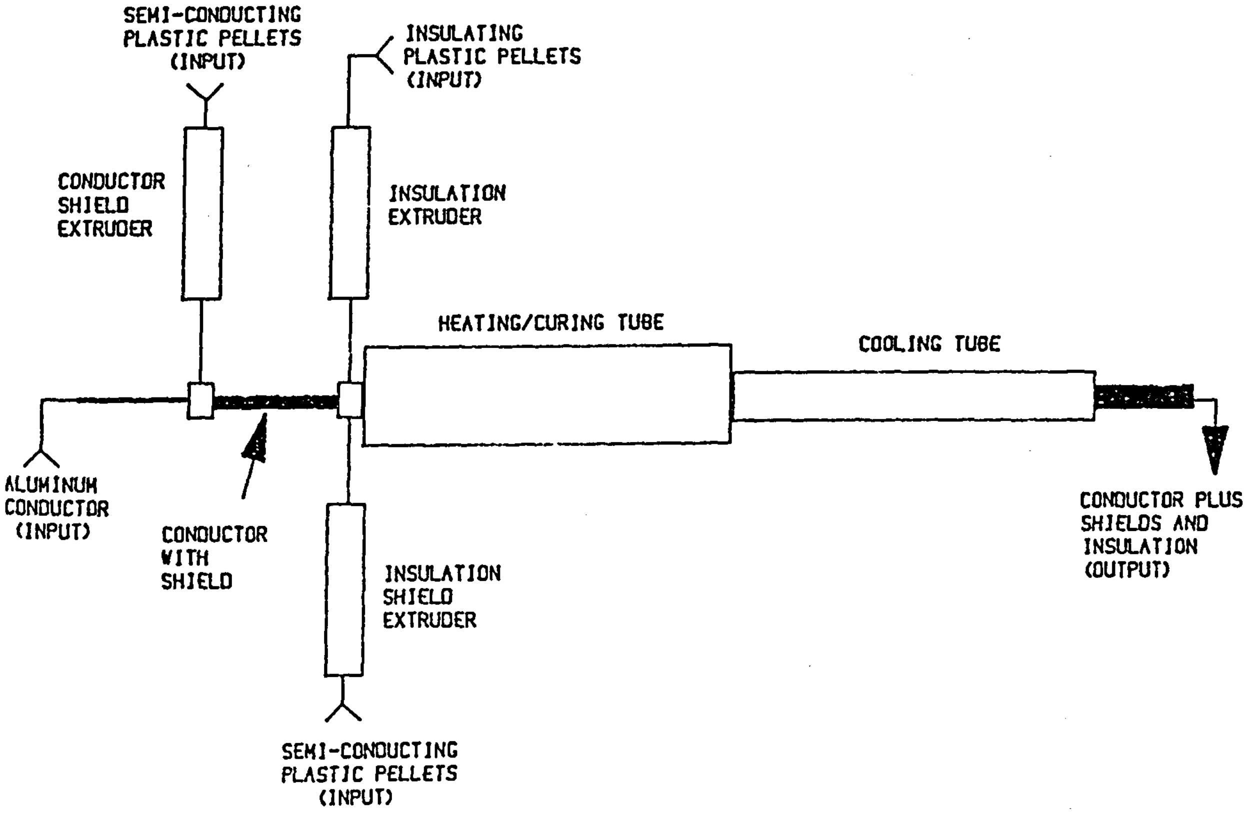

FIGURE 3. EXTRUSION, RADIANT HEAT CURING, COOLING PROCESS FOR URD CABLE

separate extruders feeding them through one common crosshead.

Immediately as the metallic conductor and plastic layers emerge from the insulation-insulation shield crosshead they enter the curing tube. As they travel through it, they are heated in a pressurized nitrogen atmosphere to a temperature sufficient to initiate the curing process. The nitrogen primarily serves two purposes. First it prevents gaseous

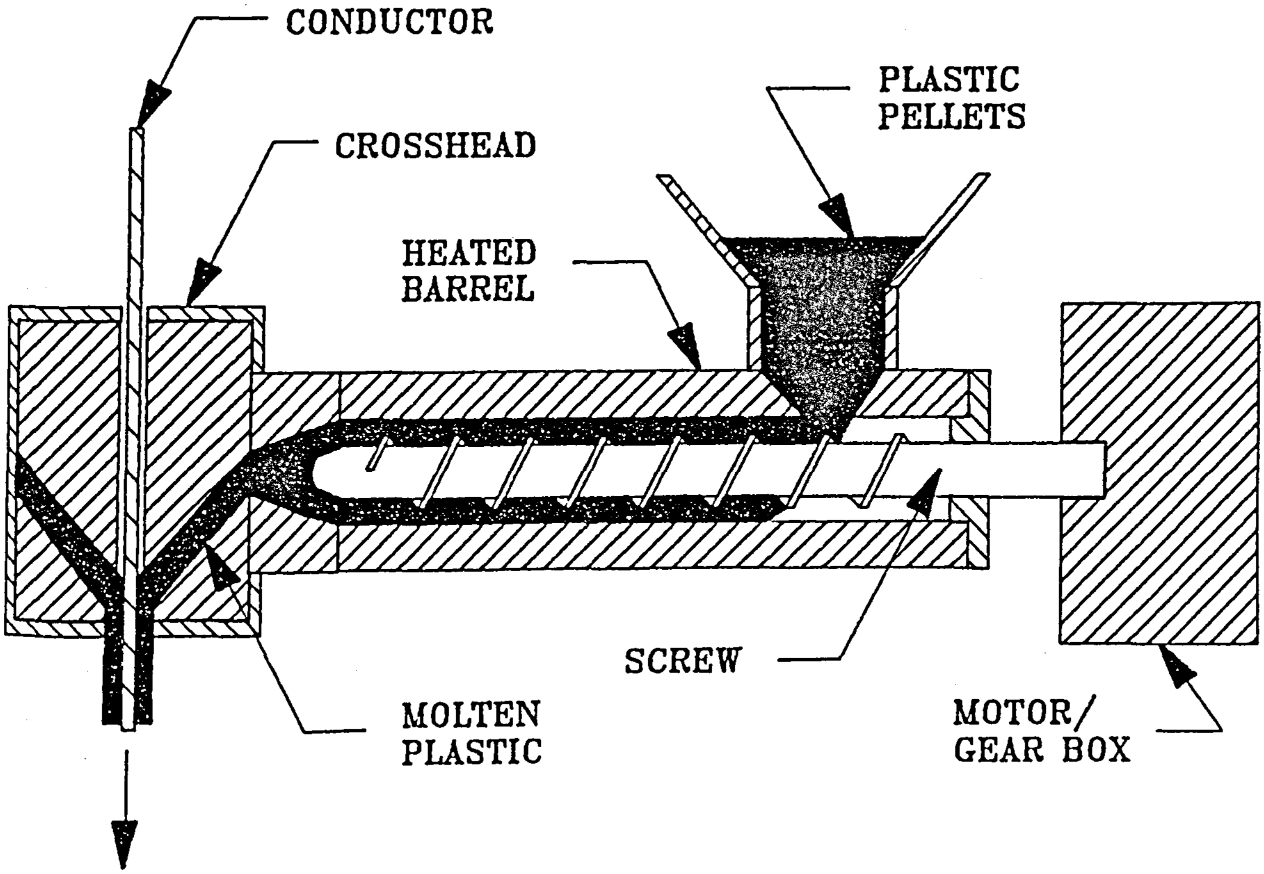

FIGURE 4. PLASTIC EXTRUDER

by-products of the curing process from bubbling up and creating voids within the insulation. Second, it provides an inert atmosphere so unwanted chemical reactions do not take place during the curing. In the radiant heat/cure process, the heat is provided by passing electrical current through the walls of the stainless steel pipes enclosing the nitrogen. A typical system will have one to ten individually controllable heating zones to accommodate the varying heating requirements for different conductor size and plastic layer thickness combinations.

As the product leaves the heated pipe, it passes directly into a water filled cooling pipe where it is kept at the same pressure as in the heating pipe. Before the cable can exit the pressurized system, the plastic must be sufficiently cooled to prevent voids from forming due to gaseous by products of the curing process. Once cooling is complete, the product exits the curing/cooling system through a water seal and is wound up onto reels for further processing.

Returning to Figure 2, we see that next the neutral wires are twisted around the partially completed product. Finally, electrical and mechanical testing takes place before shipment to the customer to assure that specification requirements are being met.

There are currently two manufacturing facilities which use the computer model discussed herein to simulate their radiant heat curing process lines. Each plant has one production line similar in layout to that shown in Figure 3. The lines represent approximately two thirds of the total primary URD cable manufacturing capacity at each plant. There are ten heated zones on each line with a total curing length of approximately two hundred feet per line. The cooling portion of the individual lines is roughly three hundred feet long.

In addition to the two production facilities making use of the model, there is one research and development location with a scaled down radiant cure line for testing of products and processes. This pilot line has three heated curing zones totalling around twenty feet and a cooling section about fifty feet long.

Two industry associations publish standards which dictate the requirements for mechanical and electrical properties of crosslinked polyethylene used in primary URD cable. The first of these, the Insulated Cable Engineer's Association, consists of a group of cable manufacturers that publish standards that may be referenced by utilities in their own purchase specifications [12]. The second group, the Association of Edison Illuminating Companies, is a group of cable users, primarily utilities, that publish standards which any utility may reference or adopt as their own [4]. In addition to these industry standards, utilities, especially the larger ones, write their own specifications for physical and electrical properties and cable performance.

One requirement of many of these specifications is a minimum degree of cure as measured by either a solvent extraction test or a hot creep test [12]. In the solvent extraction test a sample of the cured polyethylene is weighed, boiled in a solvent, and weighed again to determine the amount of plastic dissolved away [12]. The more plastic boiled away, the less cured the material is. ICEA limits the maximum plastic boiled away to thirty percent of the initial weight [12]. In the hot creep test a sample of the cured plastic is heated in an oven while being held under tension [12]. The amount of elongation and permanent stretch cannot exceed 175 percent and 10 percent, respectively. As the degree of cure is a function of the time and temperature to which the cable was subjected during curing these tests limit the maximum speed at which the cable can be processed [11].

Another limit on the maximum processing speed is the length of time required to cool the cable. As stated before, to prevent the formation of voids, the hottest part of the cable insulation must be cooled sufficiently before exiting the pressurized system. A generally accepted industry value for this maximum temperature at exit from the pressurized cooling system is approximately 200 degrees Fahrenheit. The hottest area normally occurs in the innermost layer since the cooling water cools the cable from the outside to the inside. Indirectly, two specification requirements call for this limitation on maximum exit temperature. First AEIC has requirements for maximum size and number of voids allowed in the insulation [4]. Second, both AEIC and ICEA have limitations on the amount of partial discharge allowed in a cable [4,12]. Partial discharge is electrical noise generated within voids in the cable insulation when voltage is applied to it. It is used as an indicator of the presence of voids.

In the case of the radiant heat curing process, there is also a limitation on the minimum speed at which a primary URD cable can be processed. This is due to the high cable surface temperatures which can be encountered as a result of the 750 to 850 degree Fahrenheit curing pipe temperatures. The polyethylenes used for the insulation shield begin to show deterioration at approximately 575 degrees Fahrenheit. If the cable is allowed to remain in the curing pipe too long, the surface can heat beyond this temperature and cause damage to the insulation shield material.

Outside of the curing/cooling process limitations, there exist others that control how a primary URD cable production line can be operated. Among these are the minimum and maximum output volumes of the extruders, and the maximum linear speeds at which the other machines in the production line can be operated.

MODELLING THE PRODUCTION PROCESS

The algorithm used to model the radiant curing and water cooling portions of the primary URD cable manufacturing process is based on work reported by Boysen in 1970 [6]. He describes a method for computer modelling a similar curing/cooling process, only using steam as the heat source. In Boysen's model, the curing tube is divided into a number of sections along its length, and the plastic extrusion thickness is divided into a number of annular rings. For instance, if the pipe were one hundred feet long, it might be divided into one hundred one foot increments for the model. The length of the increment selected is influenced by two opposing factors. First, it must be small enough to avoid large temperature changes in any of the plastic rings as the cable moves from one section of the heating tube to another. Too large a temperature change would invalidate the assumption Boysen makes that the temperature throughout the incremental element of plastic is constant [6]. This in turn would severely affect the accuracy of the model. The second factor to be considered in choosing an appropriate increment length is calculation time. The smaller the increment, the more of them there must be, and subsequently the more calculations that must be made. At some point the practical limits on the time that can be spent doing the calculations will force a lower bound on the increment size.

The temperatures of each of the annular rings on the inside of the cable, in Boysen's algorithm, are recalculated at every section of the heating pipe. The new temperature is based on the temperature of the ring as it exits the previous heating section, the amount of heat being conducted into it and out of it by the ring inside and outside of it, and its own internal energy change over the time spent in the section. The time spent in each section, of course, is a function of the speed at which the cable is travelling through the process. The outer ring, the one exposed to the steam, is assumed to always have a surface temperature equal to that of the steam, due to the condensation of the steam on the surface of the cable. The remainder of the heat transfer occurs similarly to the other rings. The metallic conductor receives its heat from the inner plastic ring. The equations for the heat flow from Boysen are summarized below [6]:

Equation 1) Heat Conduction from ring to ring

$$Q = K A \quad \Delta T / \Delta L$$

Equation 2) Change in internal energy of material from heating section to heating section

$$C_p = (1/M) \quad \Delta Q / \Delta T$$

where:

Q= heat flow from ring to ring

ΔT= temperature difference

ΔL= distance in direction of ΔT

A= area normal to direction of plastic flow

K= thermal conductivity of plastic

M= mass of plastic

ΔQ= heat flow difference

C_p= specific heat capacity of plastic

As Boysen explains, if the temperatures of the cable components as they exit the extrusion operation and enter the curing and cooling phases are known, the above equations, along with the concept of energy balance between the rings and sections, can be used to calculate a new temperature for each ring in each heating section [6]. The equation for the new temperature of a given ring is shown below [6]:

<u>Equation 3)</u> $T_n = T_o + (Q_2 - Q_1)t/M/C_p$

where:

T_n= new temperature of ring
T_o= old temperature of ring
Q_2= heat flow into/out of outer edge of ring
Q_1= heat flow into/out of inner edge of ring
t= length of time for ring to travel through heating increment
M= mass of plastic flowing through heating increment
C_p= specific heat capacity of plastic

Once the temperature of all the rings has been calculated for a given heat section, the degree of curing that has taken place as a result of the heating is then figured. The crosslinkable polyethylenes typically used for cable applications cure by means of the decomposition of a peroxide catalyst in a first order rate reaction [11]. In a first order rate reaction the time required, at a given temperature, to reduce the amount of catalyst by half is a constant [9]. Figure 5 shows a typical "half-life" time

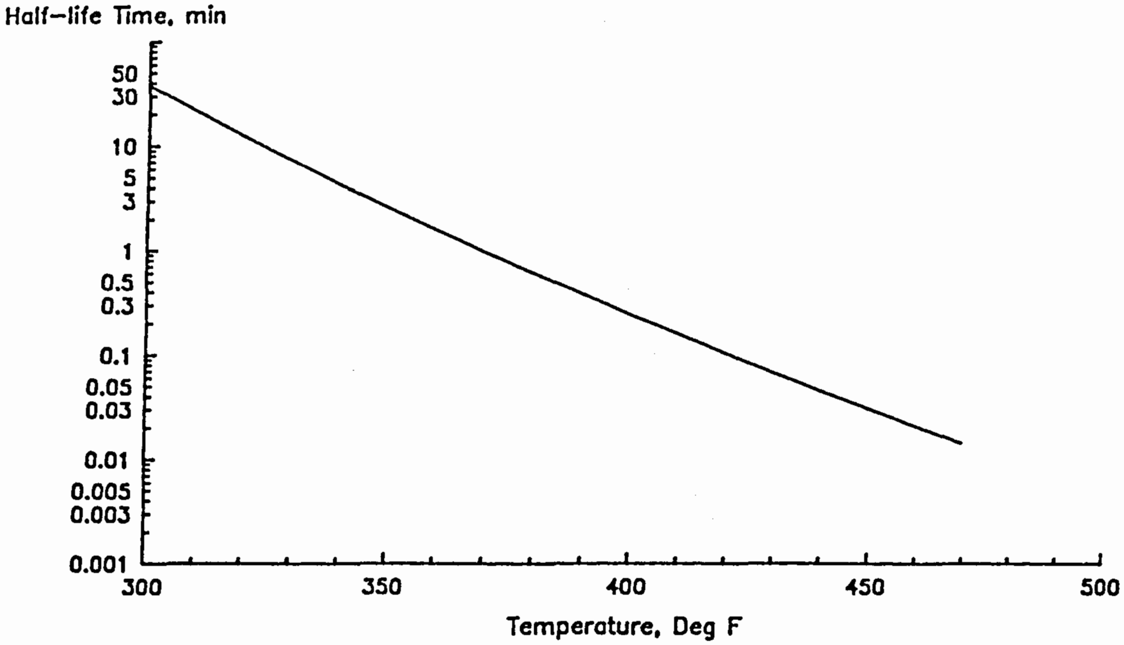

FIGURE 5. HALF LIFE TIME VS TEMPERATURE FOR TYPICAL CROSSLINKING PROCESS

versus temperature curve for a crosslinkable polyethylene. With the temperature of each ring having already been calculated, the half-life time can be determined from Figure 5. The number of half-lives is then readily calculated by dividing the time the plastic ring has been at the temperature of interest. Once the number of half-lives is known, the amount of peroxide decomposed during the time period of interest can then be determined by the following relationship:

Equation 4: $P= \{1-(1/2)^{N}\}$

where:

P= fraction of peroxide decomposed in N half lives

N= number of half-lives

Figure 6 is a graphical representation of this relationship. Once the amount of peroxide decomposed is known, the degree of crosslinking is also known since they are proportional [11].

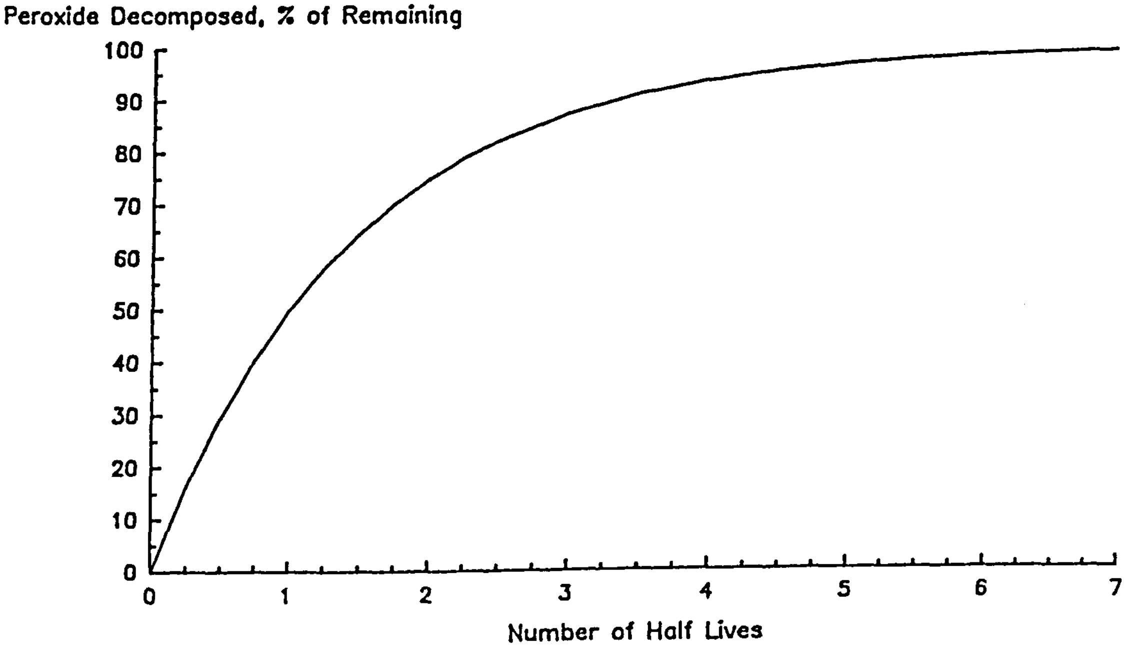

FIGURE 6: PEROXIDE DECOMPOSED VS NUMBER HALF LIVES FOR FIRST ORDER RATE REACTION

An additional calculation related to degree of cure is performed by the model. As was mentioned in the above section on industry and customer specification requirements, the solvent extraction test requires a thirty percent maximum level for dissolved plastic. The model includes a "percent extractibles" calculation which is an empirical attempt to estimate the amount of plastic that can be dissolved after all processing has taken place.

In Boysen's model the temperature and peroxide calculations for the cooling zone are essentially the same as those for the heating zone, except the heat flows are reversed since the outer medium is now cooler than the cable. The model under study here generally utilizes the same assumptions and thermodynamic equations for heat transfer as explained by Boysen, once the heat has reached the surface of the cable. There are a few minor differences, primarily refinements. The thermal conductivities for the various materials are allowed to vary with temperature. In addition, in an attempt to empirically account for differences between actual and predicted values of heat transfer and cure rate, an artificial thermal resistance between the inner layer of plastic and the metallic conductor was added to the model during it initial development.

The primary difference in calculations occurs in the method used to get the heat to the cable. Recall that the Boysen model assumes that since the steam condenses rapidly and directly on the surface of the cable, that the temperature of the surface of the cable is the same as the steam [6]. In the case of the radiant cure process, the heat is transferred from the heated pipe to the cable surface primarily by radiation. Itaka et al have described typical radiant heat transfer equations as follows [13]:

<u>Equation 5</u>) $$Wr = \frac{S\,(T_2^4 - T_1^4)\,A_1}{1/E_1 + A_1/A_2\,(1/E_2 - 1)}$$

where:

Wr= heat transferred by radiation

S= Stefan Boltzman constant

T_1= absolute temperature of cable surface

T_2= absolute temperature of pipe

A_1= surface area per unit length of cable

A_2= surface area per unit length of pipe

E_1= emissivity of cable

E_2= emissivity of pipe

An additional mode of heat transfer to the cable is by convection. Again, Itaki et al have described typical heat transfer equations for this situation [13]. The form is as follows:

Equation 6)
$$W_c = \frac{K_o P^{0.6} d_1^{3/4} (T_2-T_1)^{5/4}}{\{\ln(d_2/d_1)+a\} \{1+(d_1/d_2)^{3/5}\}^{5/4}}$$

where:

W_c= heat transferred by convection

K_o= constant, 14.9 for nitrogen gas

P= gas pressure

d_1= cable diameter

d_2= pipe diameter

T_1= absolute cable surface temperature

T_2= absolute pipe temperature

a= constant, 2.2

Another variation that our model has from the Boysen model is the use of from one to ten insulated heating pipes, each of which can have its own length and temperature settings, and the use of a short, variable non-heated zone between the last heating zone and the cooling zone. The model allows the lengths to be input by the user. The customarily used lengths are based on actual physical length of the pipes less some allowance for non-insulated sections of the pipe where internal temperatures may be considerably lower than in the insulated sections.

Why is it important to know how well a computer program models the radiant curing process for the production of electrical cable? The answer lies in the potential applications for the model and their possible benefits. Boysen identifies three categories of applications for a model of a curing process [6]. One of these is the prediction of optimum operating conditions for the production line [6]. Processing problems, product quality problems and productivity considerations are the primary issues in this case. Processing problems would include temporary limitations imposed due to equipment failures such as the loss of a heating zone or the reduction in output of an extruder to which the curing/cooling process must be matched. The model could be used to determine the temporary curing, cooling and line speed conditions necessary to match the limits.

Product quality problems for which the model could be a useful investigation tool would be where the cable failed to meet specification requirements and would require scrapping or reprocessing. Examples of scrap generating problems are overheated cables with scorched surfaces and undercooled cables with internal voids as evidenced by partial discharge measurements at the final electrical testing stage of production. The model could be used to examine the actual processing conditions used such as cure tube temperature, cooling water temperature, etc., as determined by production records, to determine if any variation in standard procedures that might be present were sufficient to have caused the problem. For product quality problems like undercuring, the model could not only be used to determine the possible reasons for the problem but also the conditions necessary for potential scrap reducing remedies like recuring by passing the cable through the curing/cooling process again.

As Bartnikas points out, due to the amount of capital typically required to build this type of production line, it is economically essential that a company maximize productivity by maximizing production speeds [5]. The model can be used to assist in developing target production rates used to establish industrial engineering standards and subsequent standard costs of production, even for products which have never actually been produced.

A second application of cure calculation models cited by Boysen is the prediction of cure performance of new materials without the need for expensive plant trials [6]. This is particularly valuable when production capacity is limited and profit making production must be forgone to accommodate experiments on new products. In the case of an organization with pilot facilities where material characteristics can be determined on small scale prototype equipment, the model can then be used to predict full scale production performance of the candidate materials.

The final application referred to by Boysen is the prediction of optimum process design [6]. Here we are dealing with the design of new production facilities or the upgrade of current facilities. By being able to reasonably accurately predict production speeds for various combinations of curing and cooling lengths and temperatures, the outputs of these parts of the production process can be closely matched to the extruder outputs. This helps to minimize the capital investment necessary to achieve desired production rates. It also may help to maximize productivity for an entire cable production facility since the curing/cooling process is typically the bottleneck operation.

The ability to predict production speeds through the use of the model has other potential applications in addition to those mentioned by Boysen. For instance, estimates can be made of production costs. Once the costs are predicted, business problems like how many of which products are best to make, what is the potential return on the capital investment, and what are the best ways in which to schedule production of orders, may be examined.

RESULTS

Since the first step in calculating the degree of cure is to calculate the appropriate temperatures, it seems logical that if there were a way to actually measure temperatures inside the cable as it is being produced, this would be the place to start examining the capabilities of the model. Mitchell [14-16] and Robbins [17] report methods for measuring the temperature of the cable surface and of the interface between the conductor shield and insulation during experimental runs on a pilot radiant heat, dry cure extrusion line. The surface temperature is measured with an infrared pyrometer through quartz glass inspection ports at the end of each of the three heating zones on the line. This measurement method is subject to considerable variability and error since it depends on calibration of the system to the quality of the optics being used and the emissivity and surface condition of the material being measured [7].

The measurement of the internal temperature is accomplished by placing a thermocouple on the surface of the conductor shield just before the cable enters the crosshead where the insulation and insulation shield layers are applied. A thermocouple measures temperature by generating an electrical signal proportional to the temperature at which it is being held [8]. The signal generated must be sent to a display device which converts it to a readable temperature. In trials described here, the thermocouple is attached to the readout device through a sufficient length of lead wire such that the wire can be fed into the crosshead as the cable travels through the pilot production line. In this way the temperature at the interface between the conductor shield and insulation can be read at any point along the process. Measurement errors for the type of thermocouples used in these studies are generally believed to be plus or minus four degrees Fahrenheit [3].

All of the trials reported by Mitchell [14-16] and Robbins [17] were done on #1/0 AWG solid aluminum conductors with 0.260 inches of crosslinked insulation. These trials are listed in Tables 2 through 9 as T1 through T7. They represent minor variations in processing variables such as line speed and cooling water temperature. Trial T8 was on a #1/0 AWG 19 strand aluminum conductor with .175 inches of insulation and Trial T9 was on a #2 AWG 7 wire aluminum conductor with 0.175 inches of insulation. Tables 2 through 6 compare the conductor shield/insulation interface temperature data collected during the trials with the predictions of the computer model. Tables 2 through 4, show the errors in the calculated values through the three heating zones are relatively small, less than ten percent. Tables 5 and 6 show the errors start increasing in the neutral zone and then become quite significant, up to thirty seven percent, after the cooling zone.

TABLE 2: Conductor Shield / Insulation Interface Temperature Data from Thermocouple Trials - End of Heat Zone 1

Trial	Meas.	Calc.	Error
T1	264	270	2.3%
T2	256	265	3.5%
T3	263	266	1.1%
T4	251	270	7.6%
T5	249	270	8.4%
T6	251	269	7.2%
T7	250	269	7.6%
T8	270	274	1.5%
T9	258	267	3.5%

TABLE 3: Conductor Shield / Insulation Interface Temperature Data from Thermocouple Trials - End of Heat Zone 2

Trial	Meas.	Calc.	Error
T1	314	317	1.0%
T2	306	314	2.6%
T3	312	317	1.6%
T4	291	304	4.5%
T5	290	304	4.8%
T6	304	313	3.0%
T7	303	313	3.3%
T8	334	329	-1.5%
T9	313	313	0.0%

TABLE 4: Conductor Shield / Insulation Interface Temperature Data from Thermocouple Trials - End of Heat Zone 3

Trial	Meas.	Calc.	Error
T1	349	357	2.3%
T2	340	355	4.4%
T3	343	358	4.4%
T4	336	346	3.0%
T5	335	346	3.3%
T6	360	368	2.2%
T7	359	368	2.5%
T8	386	379	-1.8%
T9	363	360	-0.8%

TABLE 5: Conductor Shield / Insulation Interface Temperature Data from Thermocouple Trials - End of Neutral Zone

Trial	Meas.	Calc.	Error
T1	348	363	4.3%
T2	340	361	6.2%
T3	340	364	7.1%
T4	351	384	9.4%
T5	351	384	9.4%
T6	384	417	8.6%
T7	388	417	7.5%
T8	386	409	6.0%
T9	378	395	4.5%

TABLE 6: Conductor Shield / Insulation Interface Temperature Data from Thermocouple Trials - End of Cooling Zone

Trial	Meas.	Calc.	Error
T1	133	147	10.5%
T2	140	144	2.9%
T3	142	145	2.1%
T4	158	167	5.7%
T5	158	141	-10.8%
T6	205	172	-16.1%
T7	210	181	-13.8%
T8	192	121	-37.0%
T9	146	124	-15.1%

Tables 7 through 9 compare the surface temperature data collected during the trials with the calculated values from the model. There is considerable variation in errors with values ranging up to approximately twenty-two percent. It must be remembered, though, that this particular measurement itself is subject to substantial errors.

TABLE 7: Cable Surface Temperature Data from Thermocouple Trials - End of Heat Zone 1

Trial	Meas.	Calc.	Error
T1	425	400	-5.9%
T2	435	397	-8.7%
T6	510	427	-16.3%
T7	510	428	-16.1%

TABLE 8: Cable Surface Temperature Data from Thermocouple Trials - End of Heat Zone 2

Trial	Meas.	Calc.	Error
T1	435	463	6.4%
T2	440	461	4.8%
T6	548	502	-8.4%
T7	548	502	-8.4%

TABLE 9: Cable Surface Temperature Data from Thermocouple Trials - End of Heat Zone 3

Trial	Meas.	Calc.	Error
T1	320	390	21.9%
T2	330	389	17.9%
T4	473	489	3.4%
T5	473	489	3.4%
T6	540	556	3.0%
T7	540	556	3.0%

To test the ability of the model to predict cure results on products made on full scale factory production equipment, the products shown in Table 10 were selected for testing. They represent as wide a range of products as could be chosen given the production schedules in effect during the time frame of this research.

TABLE 10: Product Descriptions for Cure Test Samples

Sample	Description
1	#4/0 AWG 19 wire aluminum, .175" insulation
2	500 kcmil 37 wire aluminum, .175" insulation
3	750 kcmil 61 wire aluminum, .175" insulation
4	#4/0 AWG 19 wire aluminum, .220" insulation
5	#1/0 AWG 19 wire aluminum, .260" insulation
6	#1/0 AWG solid aluminum, .260" insulation
7	#4/0 AWG 19 wire aluminum, .260" insulation
8	500 kcmil 37 wire aluminum, .260" insulation
9	#1/0 AWG solid aluminum, .345" insulation
10	750 kcmil 61 wire aluminum, .345" insulation

Two sets of cure related tests were performed on the samples. The first was the normal solvent extraction test, on a specimen taken from the inner twenty-five percent of the insulation thickness, required by industry and customer specifications as described previously. The results of the tests and the model predictions are shown in Table 11. As the table shows, there is considerable variation between predicted and actual. In most cases the model predicts more cure than actually exists, but in some cases, such as Sample #3, the model predicts substantially less cure. As Adams [1] has shown in a series of round-robin solvent extraction tests, the variation in actual test results is typically four percent. This accounts for only a small part of the large discrepancies seen here.

TABLE 11: % Extractables, Inner 25% of Insulation Plant Samples, Plant Measurements

Sample	Meas.	Calc.	Error
#1	17.4	13.5	-22.4%
#2	20.2	11.3	-44.1%
#3	21.1	36.0	70.6%
#4	16.7	16.6	-0.6%
#5	16.6	19.2	15.7%
#6	18.0	18.6	3.3%
#7	18.6	12.5	-32.8%
#8	16.8	11.3	-32.7%
#9	17.6	11.3	-35.8%
#10	18.3	12.4	-32.2%

The second set of cure tests performed on the cable samples were done using HPLC (High Performance Liquid Chromatography) analysis as described by Hercules [10]. In these, samples of the uncured plastic are collected as the cables are being manufactured. HPLC analysis is performed on the uncured samples to determine the concentration of the peroxide catalyst present. Then HPLC analysis is performed on the cured samples, also to determine the level of peroxide present. The percent of original peroxide remaining in the cured samples is then calculated.

The results of the HPLC measurements and the computer model predictions are shown in Tables 12 through 14. Insulation ring one is the innermost one-eighth of the insulation thickness. The measured values shown are questionable since they don't show the expected decrease in cure as the sample position gets nearer to the inside. The very small sample quantities available for each ring quite likely contributed to the experimental error. Another factor which may have affected the results is the length of time that elapsed between the time the cables were produced and the time the ring samples were cut from them. Robbins [18] suggests that the concentrations of the peroxide catalyst may tend to equalize across the insulation wall as time passes. His best estimate of a time frame is a few weeks. The samples in this study typically were not cut up for four to eight weeks after production.

TABLE 12: Percent Remaining Peroxide, Insulation Ring 1 Plant Samples, Lab HPLC Measurements

Sample	Meas.	Calc.	Error
#1	1	0	-100%
#2	7	0	-100%
#3	1	77	7600%
#4	3	19	533%
#5	2	28	1300%
#6	1	24	2300%
#7	4	5	25%
#8	5	0	-100%
#9	0	0	0%
#10	0	0	0%

TABLE 13: Percent Remaining Peroxide, Insulation Ring 2 Plant Samples, Lab HPLC Measurements

Sample	Meas.	Calc.	Error
#1	1	4	471%
#2	7	0	-100%
#3	1	57	5082%
#4	4	10	186%
#5	2	16	662%
#6	2	15	838%
#7	2	2	25%
#8	2	0	-100%
#9	0	0	0%
#10	0	0	0%

TABLE 14: Percent Remaining Peroxide, Insulation Ring 3 Plant Samples, Lab HPLC Measurements

Sample	Meas.	Calc.	Error
#1	1	1	67%
#2	-	0	-
#3	1	28	3900%
#4	4	3	-14%
#5	-	5	-
#6	2	7	338%
#7	2	0	-100%
#8	2	0	-100%
#9	0	0	0%
#10	0	0	0%

CONCLUSIONS

Comparisons to reasonably accurate temperature measurements performed during experimental trials on a pilot line show the model to have conductor shield/insulation interface temperature calculation errors ranging from -37.0 percent to +10.5 percent. Measurement of the cable surface temperatures during the trials indicate errors ranging from -16.9 percent to + 21.9 percent. The measurements themselves, however, may contain considerable error due to their inherent inaccuracy. The solvent extraction data from plant production records show the model to be substantially more deficient in percent extractibles, with probable errors ranging from -44.1 percent to +15.7 percent. The results of HPLC analysis were inconclusive due to a substantial probability of high experimental error. It is not possible, therefore, to draw conclusions directly, based on the data presented herein, about the ability of the model to predict percent remaining peroxide. It is probable, however, that since the percent remaining peroxide calculation is dependent on the temperature calculations, the errors will be about the same at best.

As a consequence of the results reported above, substantial caution should be exercised in the application of the model. It is probably most useful for making relative comparisons of the results of small changes in operating parameters.

There are numerous potential sources of the large errors exhibited by the model. Basically it is a combination of theoretical thermodynamic equations and empirical parameters attempting to provide a "best fit" model. Either of these two areas contain possible problem sources.

A possible theoretical problem might be the equations for heat exchange between the curing pipe and the cable surface. The equations used include heat exchange by radiation and natural convection. Natural convection is the mode of heat transfer when there is little or no relative movement between the gas pressurizing medium and the surface of the cable such as in the gas spacer cable described by Itaki, et al [13]. In the case of a radiant heat curing production line, however, the cable may be moving through the line at speeds in excess of one hundred feet per minute. It may be necessary to include a heat transfer component for the forced convection mode of heat transfer such as is typically done for bare electrical conductors installed outdoors and exposed to the wind [2].

Another possible theoretical problem is the heat transfer function used between the conductor shield and the aluminum conductor. The model has built in an equation which creates an artificial resistance to heat transfer at this point. This was originally done in an attempt to account for differences between measured and calculated temperatures in early development work on the model. Perhaps another method of accounting for the differences might yield better results. For instance, the model contains no provision for the increase in strand shield material volume that exists on stranded conductors versus solid conductors due to the strand interstices. Accounting for this material volume difference in conjunction with other potential sources of error might improve the accuracy of the model, particularly for stranded conductors.

Empirical parameters which might be sources of error are the variables and constants in the equations which either cannot be directly measured or derived from accepted physical constants. Such error sources would include items like pipe and cable emissivities, and the effective heated length of the heating pipes which are not insulated over their entire length.

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