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WANL-TME-1742

January 22, 1968

Westinghouse Astronuclear Laboratory

**THE THEORY AND OPERATION
OF INDUCTOTHERM ELEMENT
COATING FURNACES**

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Westinghouse Astronuclear Laboratory

THE THEORY AND OPERATION OF INDUCTOTHERM ELEMENT COATING FURNACES

(TITLE UNCLASSIFIED)

SPECIAL REVIEW
DETERMINATION
Class: U
Revisions: KAW Class: U Date: 4-13-82

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ABSTRACT

A test and analysis program was performed to determine a method for obtaining large temperature gradients necessary in the preparation of fuel elements for nuclear reactors. The information obtained from this program is presented in this report as a manual for the operation of Inductotherm element-coating furnaces. In addition, the contents can be utilized by non-electrical engineers. The information develops the theory on: 1) the operation of an induction furnace, 2) the use of capacitors in the control console, and 3) the temperature profile control by the use of shunting saturable reactors. An operating procedure for the control of furnace zone temperatures is presented by explaining the results of an actual furnace test. In conclusion, steep profiles can be obtained by the addition of two inexpensive components in the control console, and with no furnace modifications. The temperature control procedure permits the control of temperature to a precision of $\pm 10^{\circ}\text{C}$.

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1.0 INTRODUCTION

New processes for the coating of fuel elements require a larger temperature gradient between the ends of the element than can be obtained with the present furnace coils and furnace controls. A test and analysis program was carried out to determine how these large temperature gradients might be obtained with a minimum of modifications to the furnace coils, fixtures, and controls.

In the process of testing and analyzing, further knowledge was gained in the theory of furnace operation and should have been included in the manufacturer's Operation and Maintenance Manual. In addition to the theory of furnace operation, theory is included involving equipment additions necessary to obtain steep temperature profiles. Also, the report describes the theory of a new furnace operating procedure for improving the accuracy of temperature control.

This report is written so that it may be understood by those who are not electrical engineers. A companion report, TME-1743, "The Measurement of the Impedances of the Inductotherm Element Coating Furnaces, " presents a rigorous analysis of the furnace and its controls as an AC-circuit problem and describes the procedures which were used to measure the furnace impedances. This report is completely self-contained and may be read without referring to the companion report.

The discussions in this report apply quantitatively to all the element coating furnaces at Westinghouse Nuclear Core Operations (WNCO) and to the pilot plant element coating furnaces at WANL. They apply only qualitatively to the large graphitizing furnace at WNCO.

2.0 THEORY AND OPERATION OF THE GENERATOR AND FURNACE SYSTEM

(U) The theory of the Inductotherm furnace is covered in two steps. First, the generator-furnace system is described with the supposition that the furnace is a single coil without taps. Secondly, the use of the saturable reactors for the control of the power going into each of the furnace zones is described.

(U) Figure 1 is a simplified circuit diagram of the complete furnace system. It is composed of the adjustable voltage generator, the untuned iron-core tapped autotransformer, the power factor adjusting capacitors, the furnace coil, and the furnace susceptor.

2.1 THE INDUCTION FURNACE IS A CURRENT TRANSFORMER

(CRD) In all types of electric furnaces heat is developed by the flow of current through an electrical resistance. In the process of tip brazing at radio frequencies, the electrical resistance is the workpiece. In an arc furnace it is the resistance of a column of ionized gas. In the element coating furnaces, nearly all of the resistance is a hollow carbon cylinder called the susceptor. The load fixture (a very small portion of the resistance) is contained inside the susceptor. It conducts very little current and is heated almost completely by radiation and conduction from the susceptor. The purpose of the generator, transformer, capacitors, and furnace coil is merely to generate the very high currents needed to develop the required heat in the very low resistance susceptor. Typical currents at various points in the system are:

(U)	Output of generator	220 amperes
	Output of transformer	540 amperes
	Furnace coil current	3,000 amperes
	Susceptor current	30,000 amperes

(U) The susceptor is designed as a hollow cylinder because it must completely surround the load fixture in order to heat it uniformly by radiation. The cylinder is made of carbon because it is the only inexpensive conducting material which will operate at these furnace temperatures. The high currents required to heat the susceptor could be generated

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Figure 1. Simplified Diagram of Furnace System

Figure 2. Diagram Showing Furnace Coil with Resistance and Inductance in Series

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outside the furnace and applied by making an electrical connection at each end of the cylinder. It is very difficult, however, to make good electrical connections at the required high temperatures and currents. The currents are therefore generated in the hollow cylinder by placing it in an alternating magnetic field where it acts as a short circuited turn.

The magnetic field is provided most efficiently by placing the susceptor inside an air core coil. The coil and susceptor thus become the primary and secondary (respectively) of an air core transformer. The magnitude of the current generated in the susceptor depends on the strength and frequency of the magnetic field. The magnitude of the field is, in turn, fixed by the number of turns in the coil, the dimensions of the coil, and the current flowing in the coil. The Inductotherm Company has provided a coil which requires a current of approximately 3,000 amperes at 960 cps to develop the desired temperature in the susceptor.

2.2 THE FURNACE COIL IS AN INDUCTANCE

If all the magnetic flux lines generated by the furnace coil passed through the hole in the susceptor, the resistance of the susceptor would be reflected back to the generator as a pure resistance load and the power factor at the generator would be 1.0. Actually, a significant portion of the flux generated by the coil does not pass through the hole in the susceptor, but passes in an axial direction through the thermal insulation between the inside of the coil and the outside of the susceptor. This flux does not cause any voltage to be generated in the susceptor, but it does cause a voltage to be generated in the coil itself. The coil, therefore, looks like an inductance. Actually, it is best to consider the furnace an inductance with a small amount of transformer action rather than a transformer with a small amount of series inductance.

2.3 CAPACITIVE CURRENT CANCELS INDUCTIVE CURRENT

The 3,000 amperes required in the coil could be obtained from the step-down transformer by applying the present furnace voltage across the furnace coil. This would require a generator and transformer combination rated at 3,000 amperes instead of the present 540 amperes. Fortunately, this high current can be obtained less expensively by using capacitors to create the phenomena of resonance.

The actual circuit of the furnace coil is shown in Figure 2 where the coil resistance is in series with the coil inductance. The resistance, R , represents all the power dissipated in the furnace. The KW read on the furnace control panel is the product of the coil current, I_F^2 times this resistance.

$$KW = I_F^2 R \times 10^{-3} \quad (1)$$

The inductance is assumed to have no losses.

The phenomena of resonance can be most easily understood if the series resistance and inductance of the coil is replaced by an equivalent parallel combination of resistance and inductance shown in Figure 3. The current in the resistance can be calculated by ohms law.

$$I_{R_E} = \frac{V_F}{R_E} \quad (2)$$

Likewise, the current in the inductance can be calculated by an AC-circuit equivalent to ohms law which is used with inductances.

$$I_{L_E} = \frac{V_F}{X_{L_E}} = \frac{V_F}{2\pi f L_E} \quad (3)$$

where f is the frequency of the generator; i. e., 960 cycles per second.

Because these currents are 90 degrees out of phase with each other, they cannot be added directly, but must be added graphically as in Figure 4. The line lengths are drawn to scale to show the true furnace conditions.

The current total, I_F , is the same current that flows in the series circuit of Figure 2. It is the 3,000 amperes which we desire.

If we now put capacitors in parallel with the resistance and the inductance, we have a third current which can be calculated by another AC-equivalent to ohms law for capacitors.

$$I_c = \frac{V_F}{X_C} = \frac{V_F}{\frac{1}{2\pi f C}} \quad (4)$$

Figure 3. Diagram Showing Furnace Coil with Resistance and Inductance in Parallel

Figure 4. Graphical Addition of Resistive and Inductive Currents

This current must be added graphically to the currents in the resistance and inductance as shown in Figure 5. Actually, the current in the capacitor subtracts directly from the current in the inductance. In other words, the capacitor current cancels out the inductive current. If the size of the capacitor is correct, the total current, I_T , drawn from the transformer is only the current going into the resistor branch. This current in our example is 540 amperes instead of 3,000 amperes. This is the condition known as "resonance."

Furthermore, the current that flows in the resistor circuit is in phase with the voltage applied across it so that the power factor is 1.0. The power factor is the cosine of the phase angle between the current and the voltage.

For a power factor of 1.0, the furnace KW is the product of the furnace voltage and the total current I_T . Note that there is no meter on the control panel to read I_T , I_C , or I_F . Since the tapped transformer is a nearly perfect voltage and current ratio device, the KW can be calculated equally well from the generator voltage, generator current, and the power factor. This information is displayed on meters on the control panel. Unfortunately, the power factor meter has a very large error for any power factor other than 1.00. This is caused by the poor voltage and current waveshapes which are characteristic of this type of generator. The KW meter is not subject to this error and is accurate. This permits an accurate calculation of power factor to be made by the following equation,

$$\text{P. F.} = \frac{\text{KW} \times 10^{-3}}{I_G V_G} \quad (5)$$

The power factor meter accuracy is adequate to indicate when capacitors should be switched to maintain a power factor of 1.00.

2.4 THE PRODUCT OF INDUCTANCE AND CAPACITANCE IS CONSTANT AT RESONANCE

At the condition of resonance, $I_C = I_{L_E}$, suppose we set I_C calculated by equation (4) equal to I_{L_E} calculated by equation (3).

Figure 5. Graphical Addition of Resistive, Inductive and Capacitive Currents

$$I_C = \frac{V_F}{\frac{1}{2\pi fC}} = I_{L_E} = \frac{V_F}{2\pi fL_E}$$

$$X_C = \frac{1}{2\pi fC} = 2\pi fL_E = X_{L_E} \quad (6)$$

NOTE: V_F is the voltage read on the meter FURNACE VOLTAGE.

$$CL_E = \frac{1}{(2\pi f)^2}$$

$$CL_E = K \text{ (a constant)} \quad (7)$$

Thus, when the inductance is decreased, the capacitance must be increased to maintain resonance. This is exactly what happens when the saturable reactors are adjusted to shunt current around portions of the furnace coil in order to adjust furnace zone temperatures.

Figure 6 shows graphically the solutions of equation (6) for the full range of the value of the furnace inductance. This figure is used as follows.

Start from the point on the L_E curve which corresponds to the furnace operating conditions. Drop down vertically to the X axis and read the value of X_{L_E} . At resonance, this must also be the value of X_C . From the point on the C curve corresponding to this value of X_C , move horizontally to the left and read the value of capacitance which must be used for resonance. The solid curve is the range of capacitance which is available at the M furnace control console. Note that there is not quite sufficient capacitance to obtain unity power factor for top and center reactors saturated, and there is nowhere near enough capacity to obtain unity power factor for the top reactor saturated with the center reactor shorted out. If an inductance is put in series with the furnace, there is more than adequate capacitance when the top and center reactors are saturated.

Each unit of capacitance at the capacitor toggle switches corresponds to 52.5 microfarads. To this value must be added a fixed value of 1102.5 microfarads for L and M furnace, or 472.5 for C and F , or 1312.5 for S and T furnaces. The capacitor switch numbers to give the indicated value of capacitance for M furnace are shown along the Y axis on Figure 6.

Figure 6. Reactance vs Inductance and Capacitance

2.5 THE TAPPED TRANSFORMER PERMITS THE GENERATOR TO OPERATE WITHIN RATINGS

The purpose of the tapped transformer is to permit the maximum power rating of the generator to be used. This maximum power is attained when the generator voltage is at the rated 800 volts and the generator current is at the rated 220 amperes.

$$KW = V_G \times I_G \times 10^{-3} = 800 \times 220 \times 10^{-3} = 175 \text{ KW} \quad (8)$$

With this power into the furnace, the furnace voltage will not be 800 volts, but will be some different voltage which may be calculated by the equation:

$$V_F = \sqrt{KW \times R_E \times 10^{-3}} \quad (9)$$

The tapped transformer is a voltage changing device that permits the furnace to be operated at the required voltage even though this voltage is different from the generator voltage. The value of R_E changes with the saturable reactor operating conditions just as L_E did in Figure 6. Thus, the value of V_F is not a constant but will vary with the saturable reactor operating conditions. This means that the transformer voltage ratio must be changed if the maximum KW of the generator is to be attained.

In contrast to the furnace coil which is a very poor transformer, this transformer has an iron core and may be considered a perfect ratio device. Referring to Figure 1,

$$V_F = \frac{N_1}{N_2} \times V_G \quad (10)$$

$$I_T = \frac{N_2}{N_1} \times I_G \quad (11)$$

Figure 1 shows that the value of N_2 can be changed by the tap changing switch, thus changing the current and voltage ratios.

If in the process of making coil voltage adjustments the generator voltage should reach the red line value, then a larger number coil tap should be used. This reduces N_2 and thereby makes V_F larger for the fixed maximum value of V_G .

If in the process of making coil voltage adjustment the generator current should reach the red line value, then a smaller coil tap should be used. This increases the value of N_2 and thereby makes I_G larger for the fixed maximum value of I_G .

If both the generator voltage and the generator current simultaneously reach the red line values, this means that the best possible transformer tap is being used and that the generator is operating at its full power rating. This assumes, of course, that the capacitors have been adjusted so that the generator is operating at a power factor of 1.00.

If the rated KW cannot be attained for any tap of the transformer, this means that the value of R_E is either too large or too small. There is nothing wrong with operating the generator and furnace at less than maximum KW. Usually maximum KW is used only during startup. If maximum KW cannot be used, the startup just takes longer.

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3.0 THEORY AND OPERATION OF SATURABLE REACTORS FOR TEMPERATURE PROFILE CONTROL

3.1 TEMPERATURE CHANGE ALONG SUSCEPTOR LENGTH DEPENDS ON ZONE POWER

The manufacturing processes for which the inductotherm furnaces are used at Cheswick require that the temperature at various points along the length of the load fixture be adjustable to some desired value. The plot of temperature versus distance along the axis of the load fixture is known as the temperature profile. The furnace fixture temperatures can only be measured at the four sight ports which penetrate the susceptor. Because heat flows from high to low temperature along the length of the susceptor, the temperature cannot change abruptly along the susceptor. For this reason, a smooth curve drawn through the temperatures of the four sight ports, as in Figure 7, is very close to the true temperature profile. This figure is drawn to scale to show the correct relationship between the sight ports and the taps on the furnace coil.

It will be assumed that everyone will accept intuitively the statement that the more power that is put into a one-foot length of susceptor the hotter that one-foot length will be; therefore, if the temperature is to vary along the length of the susceptor, provision must be made to vary the power input per foot along the length of the susceptor. The manufacturer has determined that this can be done adequately by dividing the furnace coil into three zones with adjustable power going into each zone.

A test was made in which practically no power was put into zone two. This gave the temperature profile shown by the solid curve of Figure 7.

The dashed part of the curve is the probable actual profile in those parts of the susceptor where the temperature cannot be measured because there are no sight ports. The temperature at sight port No. 2 was found to be almost completely fixed by the power going into Zone No. 1 and to be influenced very little by the power going into Zone No. 2 or 3. The temperature at sight port No. 3 is determined by the flow of heat along the length of the susceptor and the load fixture from Zone No. 3 to Zone No. 2 since no heat is being developed in this center zone of the susceptor. The temperature at sight port No. 3 can be adjusted by putting some power into the center zone to get temperature profiles like the one shown by the dotted line in Figure 7.

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(CRD) Figure 7. Temperature Profiles (U)

In summary, the power into Zone 1 should be used to fix the temperature at sight port No. 2, the power going into Zone 2 should be used to fix the temperature at sight port No. 3, and the power going into Zone 3 should be used to fix the temperature at sight port No. 4.

3.2 TAPPED FURNACE COIL PROVIDES MEANS FOR ADJUSTING ZONE POWER

The control of the power into each of the three furnace zones could be accomplished by the use of three electrically independent coils each with its own capacitor and generator, but the expense of the equipment would be prohibitive. The advantages of this approach would be that the power into each zone could be adjusted without causing any change in the power going into the other zones.

The manufacturer has chosen the less expensive approach of using a single coil divided into three zones by two taps with saturable reactors shunting each zone. For the purpose of this discussion, the saturable reactors are considered to be pure inductances which can be adjusted by the operator. The circuit diagram for this approach is shown in Figure 8. The disadvantage of this is that the adjustment of the inductance of any one saturable reactor (to adjust the power into that zone of the furnace) results in a change of power into each of the other two zones of the furnace. For example, an adjustment to correct the temperature in one zone of the furnace will cause a temperature error to appear in each of the other furnace zones. Fortunately, the simple operating procedure described in the following sections overcomes this disadvantage.

3.3 SIMPLIFYING APPROXIMATION TO THE REAL CIRCUIT MAY BE USED

The procedure for adjusting the power into each of the furnace zones is more readily understood if the circuit of Figure 8 is replaced with the approximate circuit of Figure 9. This circuit emphasizes two facts: 1) the total furnace current is constant through the entire series circuit; 2) each coil zone and its parallel saturable reactor may be treated as an independent parallel combination.

Figure 8. Tapped Furnace Coil with Shunting Saturable Reactors for Furnace Coil Current Adjustment

Figure 9. Approximate Circuit for Tapped Furnace Coil with Shunting Saturable Reactors

The latter statement can be made because the inductive coupling between the coil zones is very small. The poor transformer action of the furnace coil was discussed in paragraph 2.2. This method of control could not be used with an iron core transformer which has good coupling.

The power going into Zone 1 of the furnace may be calculated by this following equation:

$$KW_1 = I_1^2 Z_1 \cos \theta_1 \times 10^{-3} \quad (12)$$

where Z_1 is the impedance of Zone 1 and $\cos \theta_1$ is the power factor of Zone 1. These values are fixed by the mechanical dimensions and materials of the coil and susceptor. A similar equation can be written for Zone 2 and Zone 3. This equation shows that the KW going into a zone can be regulated by adjusting the current in that zone of the coil.

A more useful alternate method for calculating the zone KW can be derived by using a relationship involving ohms law for an AC circuit.

$$I_1 = \frac{V_1}{Z_1} \quad (13)$$

Substituting $\frac{V_1}{Z_1}$ for I_1 in the above equation for KW gives:

$$KW_1 = \frac{V_1^2}{Z_1} \cos \theta_1 \times 10^{-3} \quad (14)$$

Either method of calculating the zone KW will give the same results; however, since it is impossible to place an ammeter in series with the coil to measure the current in Zone 2, the current equation can not be used. Actually, three voltmeters are clipped to the furnace leads to measure zone voltages V_1 , V_2 and V_3 . Note that the equation states that the zone KW is constant if the zone voltage is maintained constant.

3.4 CURRENT IN COIL ZONE ADJUSTED BY SHUNTING CURRENT THROUGH SATURABLE REACTOR OR BY GENERATOR FIELD CONTROL

Assume that the furnace current, I_F , is kept constant. The current through the saturable reactor is adjusted by varying the inductance of the saturable reactor. This current, I_{S1} , can be calculated in the same way that the current in the coil zone is calculated.

$$I_{S1} = \frac{V_1}{Z_{S1}} \quad (15)$$

Impedance of the saturable reactor, Z_{S1} , is not constant but decreases as the control current in the reactor is increased.

Since the total current I_F is maintained constant, I_1 must decrease as I_{S1} increases. In other words, some of the total current is shunted past the coil. If the control current in the saturable reactor is zero, Z_{S1} is very large and I_{S1} is practically zero.

The temperature required at each sight port will determine the KW to be applied to each furnace zone. Equations (12) and (14) will permit each zone current and zone voltage to be calculated. If the total furnace current, I_F , is made equal to the largest zone current, say I_3 , then the reactor for that zone must have zero current through it. This is accomplished by setting the reactor control current at zero. This amounts to removing that zone reactor from the circuit. The Zone 3 saturable reactor is shown as a dotted line in Figure 9 to illustrate this. The only control that is available to adjust the total furnace current, I_F , is the generator field current which adjusts the voltage V_F applied across the three furnace zones in series. This is the voltage read on the FURNACE VOLTAGE meter at the control console.

3.5 ANY SET OF ZONE VOLTAGES CAN BE OBTAINED BY SUCCESSIVE READJUSTMENTS

It has been found by experiment that the following procedure will permit any set of furnace zone voltages to be established by making only a few readjustments.

- 1) Adjust the generator field to obtain the desired voltage across that zone of the furnace which should have the largest current, say zone 3 for example.
- 2) Adjust one of the reactor currents to obtain one of the desired zone voltages, say zone 1. This will cause the voltage across zone 3 to change.
- 3) Readjust the generator field to obtain the desired voltage across Zone 3.
- 4) Repeat this procedure until both V_3 and V_1 are correct.
- 5) Repeat Steps, 2, 3, and 4 for the second reactor. It should not be necessary to go back and readjust the first reactor.

3.6 VOLTAGE CORRECTION PROPORTIONAL TO TEMPERATURE ERROR

Each temperature profile will have a corresponding set of voltages V_1 , V_2 , and V_3 . They are determined by experimental operation of the furnace or by previous experience with the profile. These voltages are the nominal voltages at which the furnace is to be operated.

If these voltages are set up for a run, it is almost certain that the sight port temperatures will not be exactly the desired value. This temperature error may be caused by changes in the cooling water temperature, changes in the process gas flows, or changes in the effectiveness of the thermal insulation.

To bring the temperatures to exactly the desired value, a small correction voltage must be added to or subtracted from the nominal voltage. It will be assumed that everyone will accept intuitively that it is reasonable to make the correction voltage large for large temperature errors and small for small temperature errors. Figure 10 shows a curve for correction voltage versus temperature error which worked well for all three zones in the furnace test of Figure 11. This curve is based on one volt of correction for each five degrees of temperature error.

Figure 10. Nominal Voltage Correction vs Temperature Error

(CRD) Figure 11. Test Run on M Furnace Using the Procedure of Paragraph 3.6 (U)

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To save the labor of adding and subtracting during a furnace run, a table, such as Table 1, can be made up in advance using Figure 10.

3.7 FURNACE CONTROL CIRCUIT MODIFICATIONS REQUIRED FOR STEEP TEMPERATURE PROFILES

The Inductotherm furnaces were designed to provide only flat temperature profiles. In this type operation, the center coil zone of thirteen turns was meant to provide the major power input to the furnace. The end coil zones of three turns each were supposed to put in only enough power to control the end heat losses so that adjustment could be made for a flat profile. With this type operation, the center reactor is operated unsaturated so that the center zone has a high inductance, the furnace current (I_F) is small, and only a small number of capacitors are required to obtain a power factor of 1.00. (See Figure 6.)

When a steep profile is desired, a large number of kilowatts must be put into one of the end coil zones having only three turns. Thus the furnace current, I_F , must be very large.

This table was used on M furnace to obtain the dotted profile of Figure 7.

The procedure for using this table in the operation of the furnace is as follows:

- 1) At the scheduled time, read all three sight port temperatures.
- 2) Go to the table and determine the zone voltages corresponding to the temperatures which were read.
- 3) Immediately readjust the zone voltages to the values obtained from the table using the procedure described in Section 3.5.

If the temperature should level off at a value higher or lower than the desired temperature, it means that the nominal value of voltage on which the table was based is in error. The nominal voltage should be corrected by exactly the amount of the correction voltage at which the temperature leveled out. A new table should be made using the corrected nominal voltage. The furnace run should be continued using the new table. The temperature should level out at exactly the desired value if all furnace conditions remain constant. A change in gas flow or water temperature will cause such a "temperature offset" to occur.

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TABLE 1

EXAMPLE OF FURNACE ZONE VOLTAGE CHART

Temperature	Sight Port No. 2 (Zone No. 1)		Sight Port No. 3 (Zone No. 2)		Sight Port No. 4 (Zone No. 3)	
	Temp.	Voltage	Temp.	Voltage	Temp.	Voltage
20° Low	1360	39	1500	79	1790	50
15° Low	1365	38	1505	78	1795	49
10° Low	1370	37	1510	77	1800	48
5° Low	1375	36	1515	76	1805	47
Desired Temp.	1380	35	1520	75	1810	46
5° High	1385	34	1525	74	1815	45
10° High	1390	33	1530	73	1820	44
15° High	1395	32	1535	72	1825	43
20° High	1400	31	1540	71	1830	42

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In order to keep the other two coil zones from being overheated, the saturable reactor must be adjusted to shunt most of the current past the other two coil zones. This means that the inductive reactance, X_L , of these two zones is low, and a large number of capacitor sections must be used to obtain a power factor of 1.00. (See Figure 6.) Very often the required number of capacitors is not available.

The most obvious solution would be to install more capacitors. In some practical cases, it would require the present number of capacitors to be doubled. Not only is such a number of capacitors expensive but there is no space for them in the console. A much simpler solution is to place a fixed inductance, L_S , in series with the furnace to substitute for the furnace coil inductance shorted out by the saturable reactors. The capacitors normally installed are then adequate to resonate the furnace. Figure 12 shows the location of this coil.

Accessory coils of this type are being built to be installed in each control console for regular furnace use. The presence of this coil does not change the furnace operating procedure in any way. It may be left in place for all of the present furnace operations. It would be necessary to move the coil only if one of the following two events occur: 1) the power factor is still positive, i. e., leading, when all of the capacitors are switched out. (See Paragraph 2.4.); 2) full generator KW cannot be attained even though the tapped transformer is operating at Tap No. 8. (See Paragraph 2.5.)

3.8 MINIMUM IMPEDANCE OF CENTER REACTOR IS TOO HIGH FOR A STEEP PROFILE

In establishing very steep profiles, very little power is required in the center zone. This means that the saturable reactor when fully saturated must shunt most of the current around the center zone of the coil. The present 360 KVA reactors rated at 240 volts have such a high minimum impedance that they cannot do this adequately.

This problem is overcome by placing two paralleled 75 KVA reactors in parallel with the present 360 KVA reactor; thus providing a very minimum impedance to shunt the coil. One 75 KVA reactor might be adequate for the job from the standpoint of minimum impedance, but since it is rated at only 1000 amperes it might very easily be overheated. Two 75 KVA reactors in parallel appear to be capable of carrying 3,000 amperes if supplied with adequate cooling water. Figure 12 shows the location of these accessory reactors.

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Figure 12. Furnace Circuit Showing the Fixed Series Inductance and the Paralleled 75 KVA Reactors Shunting the Center Zone Which Must Be Added to Obtain Steep Temperature Profiles

It will be necessary to watch the voltage, V_2 , which appears across these reactors. If the voltage exceeds the rated value of 80 volts, these reactors will begin to shunt current around the center zone even though the reactor control current is zero. This situation is very likely to occur during startup when the maximum possible number of KW is being put into the furnace. If this happens, one lead to the paralleled 75 KVA reactors should be disconnected. When the center zone has reached temperature, the lead must be reconnected so that the center zone temperature may be controlled to the desired value.

3.9 CONTROL MODIFICATIONS MAKE POSSIBLE GREAT PROFILE FLEXIBILITY

The addition of the series inductance and the additional saturable reactors across the center zone permit the furnaces to be adjusted for any desired profile between a flat profile and a profile nearly as steep as the solid line profile of Figure 7.

Also, these profiles can be inverted so that the high temperatures will be at the top of the furnace instead of the bottom of the furnace.

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4.0 CONCLUSIONS

The desired temperature profiles can be obtained with no modifications to the furnace coils or furnace fixtures. All that is needed is the addition of one series inductance and two 75 KVA reactors to the present furnace control console.

By means of a new furnace operating procedure, the temperature at each sight port can be maintained within $\pm 10^{\circ}\text{C}$.

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