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DEVELOPMENT OF A TEMPERATURE MONITOR FOR LARGE REACTORS

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DEVELOPMENT OF A TEMPERATURE MONITOR
FOR LARGE REACTORS

by

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ABSTRACT

A temperature monitor was designed to measure
the temperature rise of coolant flowing through each
fuel channel of a nuclear reactor. Although the
monitor was intended for use with a large heavy
water-cooled reactor, the design principles are
generally applicable to large power and production
reactors that employ forced flow of coolant.

A scanning monitor was chosen because it has
more economic and operational advantages than a
continuous monitor. Digital circuitry permits
automatic programming, arithmetic operations, and
visual displays. Arguments are presented for types
of alarms which should be provided.

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DEVELOPMENT OF A TEMPERATURE MONITOR
FOR LARGE REACTORS

INTRODUCTION

Temperature monitoring of the fuel coolant is an essential feature of almost all designs for high power reactors. However, the complexity of the monitoring system and the extent to which the safety and efficiency of the reactor are made to depend upon this system can vary greatly between different designs. During the past several years, the authors have been involved in the design of an advanced type of monitor for the coolant temperatures in a large heavy-water-cooled reactor. This report gives the design philosophy which was evolved in the course of this project. It is believed that these ideas have applications considerably beyond the immediate reactor type for which they have been developed.

SUMMARY

The basic philosophy behind the temperature monitor design was that the detailed measurement of fuel coolant temperatures provides an accurate, reliable, and reasonably available diagnostic tool for determining the reactor performance. Specifically, this data can be used to indicate unsafe reactor operation, to provide a basis for detailed reactor control, and to warn of fuel element failures. The safety requirements necessitate extensive and rapid sampling of the full range of coolant temperatures while the control requirements invite the use of digital circuitry and visual display to put the temperature data into a useful form.

A major design decision for the temperature monitor involves the choice between a scanning monitor covering many temperature sensors or a continuous system for each sensor. The scanning systems were judged superior for any large reactor. Fast acting switches are now available which permit the scanning of the temperature sensors at speeds that are in general greater than the response time of the sensor. These sequential data are then in the ideal form for operation of the digital circuits. Discussions of the various alarm requirements are given as well as methods for their implementation in both the digital-circuitry design and the read-out devices. The discussion is carried to the point of presenting a conceptual design of a monitor which meets the requirements developed in this report.

DISCUSSION

Fuel elements must be operated at high temperatures for economical operation of power and production reactors, and the margin between the operating temperature and the limiting safe temperature is usually very small. The flow of coolant through a fuel element may be partially blocked by a swollen fuel element or accidental intrusion of a foreign object. Such a restriction of flow may cause the fuel element to melt.

Accidents of this type can be avoided by monitoring the temperature of the fuel elements with sufficient precision. This could be accomplished by means of temperature sensors located on or in the fuel elements, but this method cannot be employed, particularly with water-cooled reactors, because of the risk of impairing the integrity of the fuel elements and the connect-disconnect problems during the charging and discharging operations. Therefore, the fuel temperatures are monitored indirectly by measuring the temperature increase of the coolant with sensors at the inlet and outlet ends of each coolant channel. Since fuel elements usually have a common coolant inlet, only a few inlet temperature sensors are required. The temperature increase (ΔT) across the fuel element is then an indirect measure of the fuel element temperature, provided the coolant flow is constant and the shape of the axial neutron flux is known. These provisions usually apply in the case of large reactors, because constant flow is maintained and the axial flux is monitored with either activated wire or internal flux monitors[1].

INSTRUMENT CONSIDERATIONS

General reactor considerations usually determine the form and specific features of a temperature monitor. These considerations should be apparent, but have not been discussed previously in the literature.

Temperature Sensors

The designer must choose either thermocouples or resistance thermometers. For optimum sensitivity the exit coolant sensors should be located as close as possible to the end of the fuel channel. This of course implies that the sensor will be subjected to radiation from within the reactor. Experience indicates that only thermocouples can survive this environment for extended periods. Resistance thermometers can be used, however, in lesser radiation fields. Mineral-insulated thermocouples of both chromel-alumel and iron-constantan materials, enclosed in stainless steel sheaths, have been used successfully for the temperature range of 100 to 600°C. The output of these thermocouples is about 50 μV/°C.

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The response time of the thermocouple (and the associated monitoring equipment and trip circuits) should be short compared with the time in which a fuel element would melt as the result of a temperature transient. Fuels consisting of enriched alloys of uranium and other metals, for example, can melt in a relatively short time due to their small heat capacity, whereas melting would require a longer period with solid uranium or oxide-type fuel elements, which have an inherently greater heat capacity. If a very short time response is required, the thermocouple junction should be grounded to the enclosing sheath. Response times of about 0.1 second can be achieved in this manner.

Junction Compensation

Cold junction errors can be handled in a number of ways[2]; however, in the case of a temperature monitor in which hundreds or thousands of thermocouples must be dealt with, it is more economical to employ a single common compensating unit for all thermocouples. It is common practice to join the thermocouple leads to pairs of copper wire that can be routed some distance to the temperature monitor, which is usually located in a radiation-free region such as a control room. One method of compensating for the cold junction error is to enclose the junctions in a large, temperature-controlled oven, but this method requires fairly elaborate thermostating and associated control systems and a large oven requiring considerable power. Most of these difficulties can be overcome with a scanning-type system that employs multi-input switches to sequentially route a large number of thermocouple signals into a common output channel. The scanning system permits the use of a common compensating oven.

The preferred compensation system employs an isothermal box to maintain all junctions at the same (but not constant) temperature. This arrangement permits temperature variations to be compensated by one unit. The isothermal box is relatively simple and eliminates the numerous problems associated with the thermostated oven.

Monitor Type (Scanning vs. Continuous Monitoring)

The small DC output voltages of the thermocouples must be amplified before they can be used. Since a large reactor of the type under discussion will normally use 200 to 2000 thermocouples, a considerable quantity of electronic equipment will be required. The monitor can take one of two basic forms: it may be a continuous system that uses a separate amplifier plus associated equipment for each thermocouple to be monitored,

or it may be a scanning system that uses multi-input switches to sequentially route a number of thermocouple voltages through a single amplifier and associated circuitry. The difference between these two systems is shown schematically in Figure 1 for a rudimentary temperature monitor that provides an alarm if any thermocouple voltage exceeds a fixed alarm setting.

The continuous system provides data continuously. The same protection can be provided by the scanning system if the multi-input switch is fast enough that each thermocouple voltage is measured in less time than the response time of the thermocouples. For example, if the response time of the thermocouples was 1 second and each thermocouple was read 10 times per second, the scanning monitor would provide essentially continuous process protection.
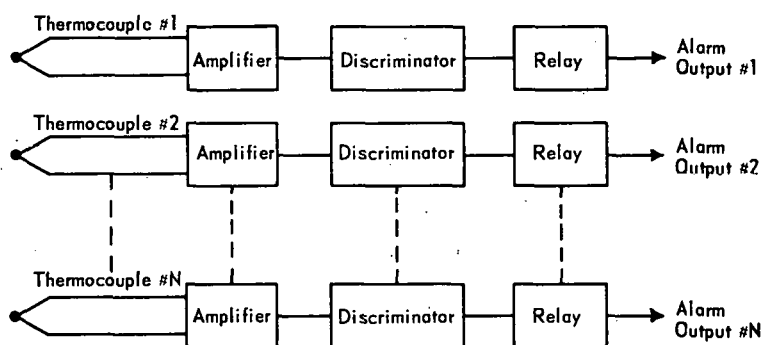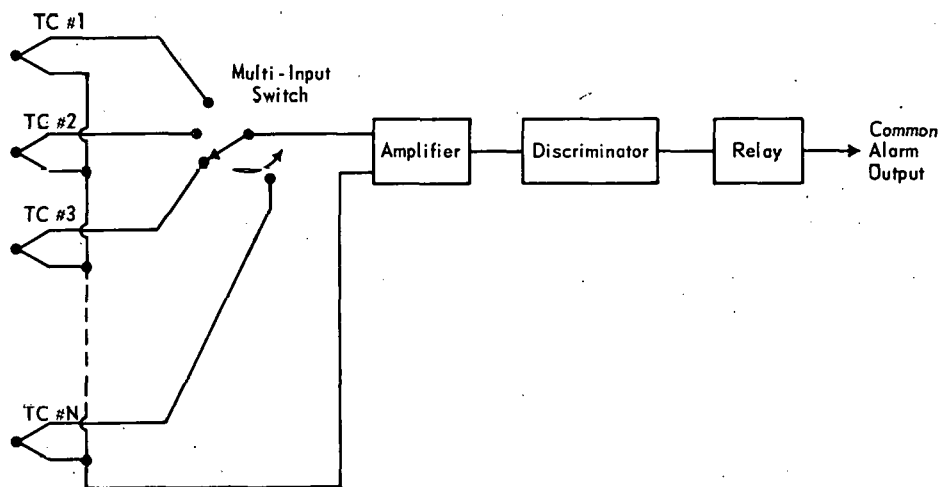

FIG. 1A CONTINUOUS TYPE MONITOR

FIG. 1B SCANNING TYPE MONITOR

Continuity of operation is thus not a consideration in selecting between the two systems if multi-input switches with sufficient speed are available. Perhaps the most important difference between the two rudimentary systems of Figure 1 is the matter of economics. If, for example, a multi-input switch with n inputs can be obtained for less than the cost of the (n-1) amplifiers and discriminators that it replaces (other things being equal), then the scanning system is preferable to the continuous system. In practice, it is usually found that for a small number of inputs the continuous system is more economical, but for a large number of inputs, as in the case of a large reactor, the scanning system is more economical. The general relationship between the cost and the number of monitored inputs is shown in Figure 2.

Other considerations that tend to favor the use of a scanning monitor are shown in the following section.
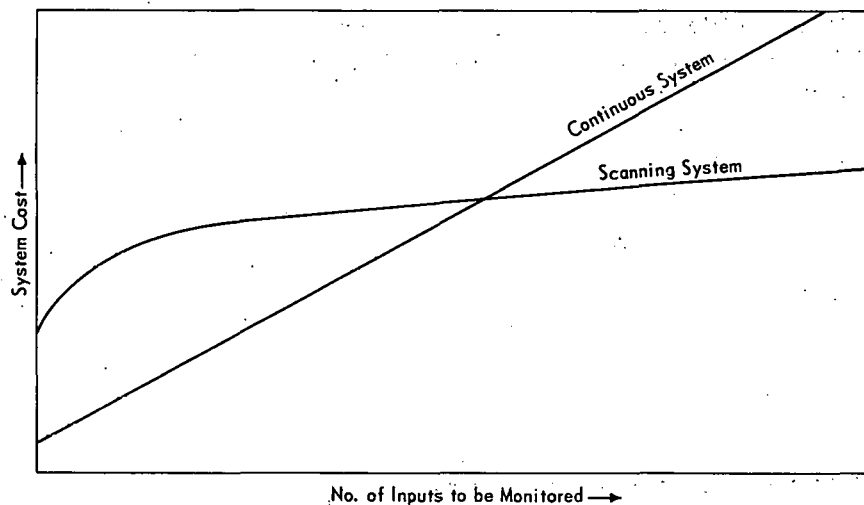
FIG. 2 SYSTEM COST VS. NO. OF INPUTS

DATA UTILIZATION

Only a rudimentary system that provides limited process protection has been considered. In practice, a temperature monitor may be called upon to provide much more protection and information for control purposes.

Alarms

As previously noted, certain conditions lead to temperature increases; in certain circumstances the rise may be rapid enough that the operator does not have sufficient time to manually prevent damage to the reactor. For the protection

of the reactor, several types of alarms should be provided. Of primary importance is an alarm that will be actuated if the temperature of the coolant approaches some limiting value.

This limiting value might be the temperature at which bulk boiling of coolant occurs in a liquid-cooled fuel element. Since this limiting value is a fixed temperature, the temperature monitor should provide one set of output signals that are proportional to the absolute outlet temperature of the coolant. Since the reactor will almost certainly be damaged if this temperature is exceeded, this output alarm should be connected to the automatic shutdown circuits that insert the safety rods.

A second alarm is desirable at a lower temperature level to permit the initiation of lesser corrective action such as the slow insertion of the control rods to reduce the reactor power to a safe level. It would be possible to use the absolute temperature signal previously cited and to have the associated circuitry arranged to provide an alarm if any temperature exceeded a certain fixed value that was less than the limiting temperature (e.g., the alarm level might be set $5^{\circ}C$ less than the limiting temperature alarm level). Unfortunately, this arrangement does not provide for the earliest recognition of a rising temperature for all fuel positions in the reactor. If, for example, the radial temperature profile across the reactor is as shown in Figure 3a and the second alarm level is set a constant amount below the limiting temperature alarm level, the temperature of a fuel channel in the outer regions of the reactor would have to rise a considerable amount, as contrasted with one near the center, before it actuated the second level alarm.

It would be preferable for the temperature monitor to provide an alarm level that parallels the reactor temperature profile as shown in Figure 3b; this level could be $5^{\circ}C$ greater than the temperature of any channel in a "normal" reactor temperature profile.

In the case of the continuous system, the voltage difference between each thermocouple signal and an individually adjustable reference voltage is fed to a discriminator. In the case of the scanning system, a second bank of switches, phased with the input bank, connects each thermocouple signal with its respective adjustable reference voltage. The difference voltages are fed to a common discriminator.

Both of these systems share the same significant deficiency, namely, the need for manual adjustment of the 200 to 2000 reference potentiometers. If the monitor is to provide the desired second level protection and not generate false alarms, it is necessary to readjust all of the

reference voltage potentiometers several times during a power ascension and periodically after full power is attained, due to the changes in the radial temperature profile that occur during a fuel cycle. These adjustments may require as much as an hour, during which time the monitor must be disconnected from the automatic control rod insertion circuits to avoid false insertions.

The loss of the protection of the temperature monitor during these periods is undesirable and a method is needed for rapidly and automatically adjusting the reference voltages or for performing the equivalent function. It is not obvious how such a scheme could be applied to the continuous system other than by means of a very complex electro-mechanical servo system. The scanning monitor, however, lends itself quite readily to automatic adjustment (i.e., programming). It is possible, for example, to sequentially record all of the amplified thermocouple voltages on magnetic tape at some instant when the reactor temperature profile is considered to be normal. This can be accomplished in a relatively short time. The recorded temperatures can then be sequentially "read" off of the tape by conventional techniques, and compared with current temperatures at a later time. If any voltage difference exceeds a fixed discriminator setting, an alarm is generated as before. Those who are familiar with modern digital data handling systems will recognize that the magnetic tape scheme can be performed even more rapidly with memory devices of the type exemplified by the magnetic drum[3] or the core-store matrix[4] to provide even faster programming and comparison. The adaptability of the scanning system to automatic programming is thus another of the important advantages of scanning systems over continuous systems.

A third alarm level should be included for taking corrective manual action when the temperature rise is slow enough to permit such action. This alarm need only actuate an annunciator and/or light to call attention to the abnormal condition. A convenient way of providing this alarm is to route the signal employed for the second-level alarm to a discriminator that is set to actuate the annunciator if any coolant channel temperature increases a small amount ($2^{\circ}C$) above normal.

Operational Displays

The temperature monitor is important in reactor operation. The coolant temperatures can be used to optimize the radial temperature profile of the reactor by adjustment of the various control rods. In large reactors, in which the central zone temperatures can be flattened, the number of fuel elements operated at maximum temperature can be maximized.

Limiting
Temperature

Limiting Temperature Alarm Level

Possible Second Alarm Level

Radial Temperature Profile of Reactor

Temperature

a.

Periphery
of Reactor

Center of
Reactor

Periphery
of Reactor

Limiting
Temperature

Limiting Temperature Alarm Level

Preferable Second Alarm Level

Radial Temperature Profile of Reactor

Temperature

b.

Periphery
of Reactor

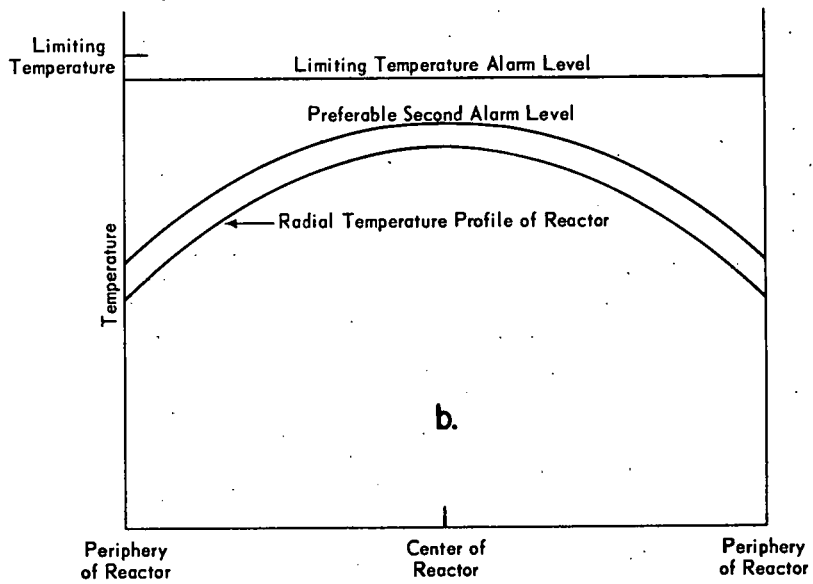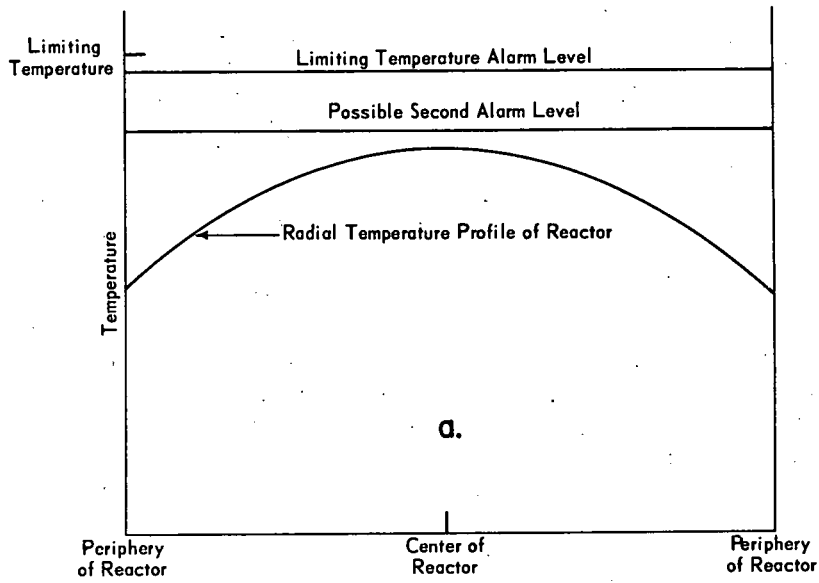Center of
Reactor

Periphery
of Reactor

FIG. 3 CONSIDERATIONS IN ESTABLISHMENT OF SECOND ALARM LEVEL

A visual display is the most efficient way of presenting this temperature information to the operator; a display that shows the coordinates (address) of each fuel element and provides a visual (not numerical) indication of temperature is probably the most useful. Although actual three-dimensional displays are difficult to construct, two-dimensional displays of various types can be constructed that are adequate to meet operating needs. (By analogy, a topographical map is just about as useful as a three-dimensional model.)

A visual display may be generated by the monitor, or the monitor may merely supply temperature data from which a display can be generated manually. The latter method was employed at an early date and is still in use. The manual method involves determination of the temperature rise (ΔT) of each fuel channel, which can be done by connecting a millivoltmeter, in turn, to each of the process thermocouples and an inlet reference thermocouple so as to obtain the ΔT's. The temperatures are transcribed to a coordinate map of the reactor and each coordinate is colored-in by hand to indicate the incremental range of temperature. Red can be used to indicate the hottest increment, orange the next, and so on through the spectrum. This results in a simple visual display, but contains some deficiencies. It is tedious and time consuming and does not allow the operator to see immediately the consequences of moving the control rods. Electronic techniques now available make it unlikely that the manual method will receive any serious consideration in the future.

The automatically generated visual display can take a number of forms. A color television presentation is certainly feasible and can provide the equivalent of the manually generated display. However, no such display has been built. A black and white television presentation, where the various shades of gray correspond to temperature increments, is equally feasible and somewhat easier to accomplish[5]. Electroluminescent screens with larger displays offer future promise.

All of these displays have (in theory at least) the potentiality of displaying simultaneously the incremental temperature of each fuel channel, but none can present more than a limited number of temperature increments. The black and white television presentation, for example, is limited by the number of shades of gray the eye can distinguish (i.e., about 7 shades). Another type of display - the bulb panel display - offers an unlimited number of increments, but only one increment can be viewed at a time.

The bulb panel has small electric lights disposed in a two-dimensional array so that each bulb represents a particular

fuel channel coordinate. Suitable discriminators switch the bulbs "on" or "off" depending upon the temperature of the fuel channels. The discriminators may be varied over wide limits to examine the temperature profile of the reactor in detail, but not all of the fuel channels can be viewed simultaneously.

The displays mentioned are not all-inclusive, but are indicative (with the exception perhaps of the electroluminescent screen) of what can be accomplished automatically today. These readouts are only practical with scanning monitors-- a result of the sequential train of signals available from a scanning monitor. These signals can then be passed through the same common discriminator(s) in order to modulate the intensity of the electron beam of the television tube or to light or extinguish bulbs.

The panel can also show which fuel channel produced an alarm.

Detecting and Locating Failed Fuel Elements

In some multichannel reactors, temperature monitors can detect and locate failed fuel elements if the reactor has: (1) relatively small coolant channels, (2) a sufficiently large temperature increase across the fuel channel, and (3) fuel elements that swell when coolant interacts with fuel. Under these conditions, the initial swelling of the fuel element is often sufficient to impede coolant flow slightly and to produce a small increase in coolant temperature. A common discriminator usually cannot be set at some alarm level to detect these initially small temperature increases because they are of the same magnitude as normal variations. It would be unsafe to wait until the swelling of the fuel element is sufficient to exceed an alarm level that is significantly in excess of the background variations.

At least two methods are recognized for handling this special problem. The first uses conventional recording of temperature vs. time, coupled with the ability of the human eye to perceive small but significant changes in temperature in one of many slowly undulating recordings. One such system, which employs segmental recorders, has been used successfully at this site for a number of years. The segmental recorder is unique in that it permits the intermittent recording of signals from more than 500 thermocouples for 24 hours without replacement of the chart paper[6]. The obvious disadvantage of the recording method is the need for continual surveillance.

Automatic detection of fuel failures offers considerable promise, but to date it has been evaluated only to a limited extent by calculation. This method assumes that the temperature difference between the ΔT of a given fuel channel and the average of all other fuel channel ΔT's in the same fuel element will be essentially constant, under normal conditions, during the fuel cycle. If one takes the indicated temperature difference at some time zero (e.g., after the first attainment of power) and then compares subsequent values during the fuel cycle with the initial value by taking a second difference, then the second difference should remain essentially constant (or at worst vary within certain small limits). If, however, a fuel failure occurs and the fuel swells, thereby constricting and increasing the ΔT of the channel, the second difference will tend to change in value and will increase markedly. This method has been applied, in hand-calculated form, to long-term temperature data from fuel elements that subsequently failed, and from all indications the method is applicable. The results indicate that this system should make it possible to detect fuel failures as soon as they are now detected with activity monitors. An example of the method, for a fuel element with four flow channels, is given in a classified version of this report (DP-810). An alarm can be obtained automatically from the monitor if certain simple computational and memory features which perform the indicated hand calculations by electronic means are incorporated. Such features can be provided easily if the monitor is of the scanning type and employs digital data-handling circuitry (i.e., if the analog voltage signals from the thermocouples are digitized with an analog-to-digital converter and subsequently handled in the digitized form).

The location (address) of the failed fuel element can be suitably displayed with additional circuitry.

Computations

The operation of a reactor often requires periodic hand computation of certain values such as hydraulic limits and burnout safety factors. Since many of these computations involve temperature data already available in the monitor, plus some small amount of data from other sources, it is not unreasonable to incorporate the necessary computational ability within the monitor. This facility can probably be added to the monitor for only a slight additional expense in the case of a scanning monitor that employs digital circuitry.

Data Readouts

It is often desirable to monitor the temperature of a given fuel channel for some short period of time or on a continuous basis. This can be done simply by providing jacks on each thermocouple pair to permit connection of a milli- voltmeter or recorder, or it can be done more elaborately by presenting a °C reading on "Nixie"-type bulbs in response to punching in of the address of the desired thermocouple.

Data Loggers

It should not be necessary to continuously record all of the reactor temperatures. The data obtained from recorders or printers are in a form that cannot be conveniently utilized. It should be possible to present worthwhile data in the form that can lead to the required operator action, as discussed previously. However, the designer cannot foresee all future eventualities, and it may be desirable to obtain logs of the temperature data under altered conditions. A visual readout of individual temperatures could be used to provide these data, but the data would not necessarily be time-concurrent. Therefore, plug-in provisions should be made for the later addition of an automatic printer[7], even though the printer is not included in the original equipment.

CONCEPTUAL DESIGN FOR A TEMPERATURE MONITOR

A general-purpose temperature monitor can be designed on the basis of the previous discussions and conclusions (see Figure 4). For the reasons previously stated, the monitor is of the scanning type. Digital circuitry is employed for convenience in the storage of data and the performance of computations. This conceptual design can be modified to suit most reactor temperature monitoring require- ments.

The inlet and outlet thermocouples are terminated at an isothermal panel located near the reactor. These signals, plus the signal from a thermocouple that measures the isothermal panel temperature, are brought out on long copper pairs that lead to the temperature monitor (located in or near the control room of the reactor) and are terminated at the input to the scanning switches. The signals at the input to the scanning switches are:

(1) Coolant outlet signals (t_1-t_{iso}), (t_2-t_{iso}), (t_1-t_{iso})

(2) Coolant inlet signal (t_r-t_{iso})

(3) Reference signal $(t_{iso}-r)$

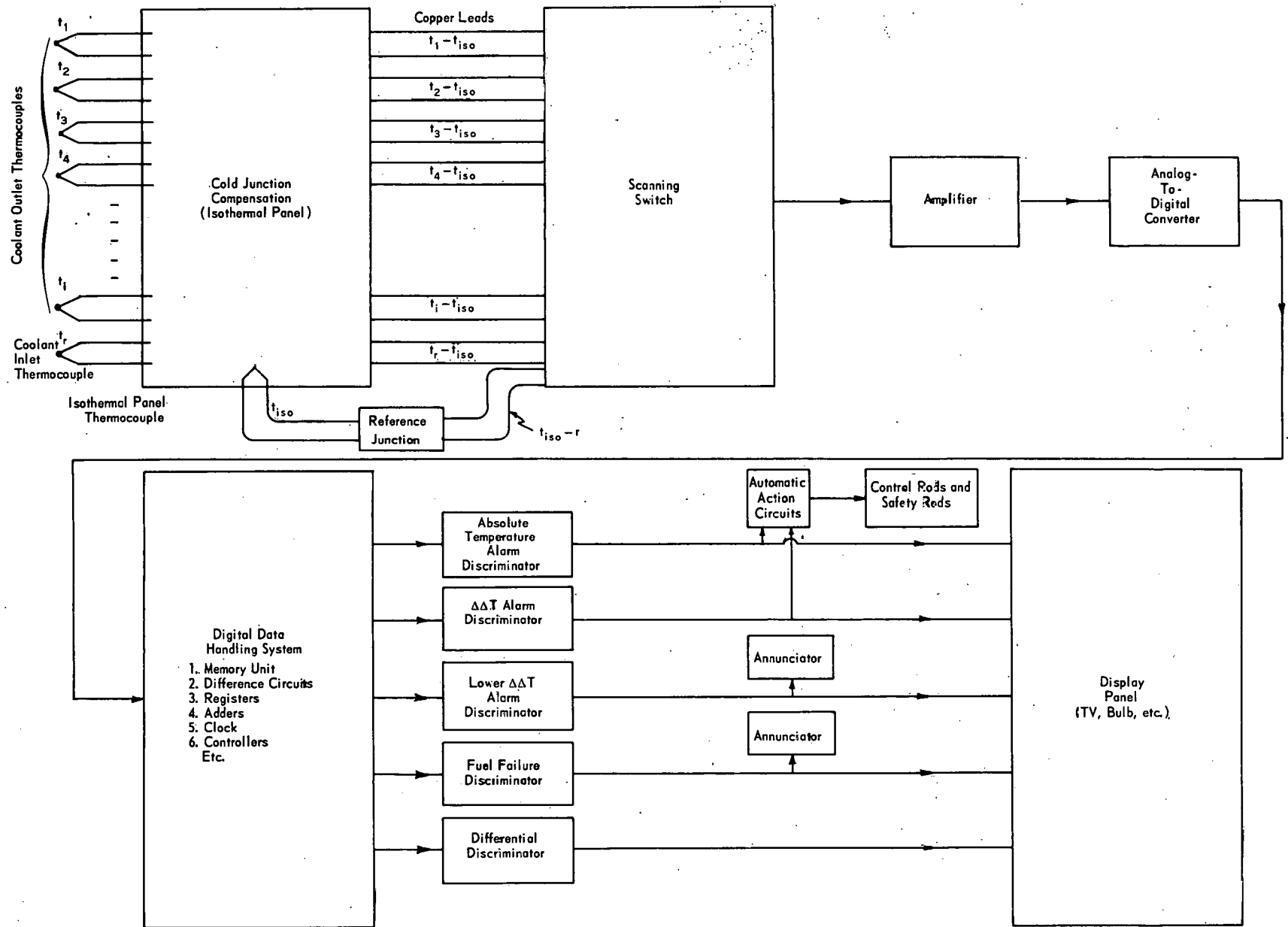where r is an internally generated reference signal.

FIG. 4 CONCEPTUAL DESIGN FOR A TEMPERATURE MONITOR

The type of switch depends upon the rapidity with which temperature transients or accidents can occur within the reactor. Stepping switches could be employed for times of the order of minutes and either fast relays or transistor switches for times of the order of 0.1 second.

After suitable amplification, the thermocouple signals are converted to digital form with an analog-to-digital converter, giving the digitized signals (T_1-T_{1so}), (T_R-T_{1so}), and $(T_{1so}-R)$.

Within the digital system, the absolute temperature is obtained by subtracting $(T_{1so}-R)$ from each of the (T_1-T_{1so}) values to yield (T_1-R), i.e., the absolute temperature minus a constant. These values are then fed to an alarm discriminator, which institutes automatic action if any value exceeds the absolute temperature discriminator setting, and to the display panel, which permits the coordinates (address) of any alarm to be determined.

In similar fashion the ΔT across each fuel element is determined by subtracting (T_R-T_{1so}) from each (T_1-T_{1so}) to yield (T_1-T_r) or ΔT_1. The initial ΔT_1 values, i.e., ΔT_{1o} are stored in the memory unit when the reactor reaches full power, and are read off each cycle of the scanner for comparison with the current ΔT_1 values. If the difference $(\Delta T_1-\Delta T_{1o})$ or $\Delta\Delta T_1$ exceeds the temperature rise discriminator setting, an alarm is generated. An approach discriminator, set at a lower level, provides an annunciator indication that alerts the operator and permits him to take corrective manual action.

The fuel failure feature operates from either the (T_1-R) or the ΔT_1 values. As an example, the (T_1-R) values for all of the channels of a fuel element can be summed and divided by the number of fuel channels to give $(T_1-R)_{avg}$ for that fuel element. This value is then subtracted from each of the channel (T_1-R)'s to give a difference denoted as D_{jk}, where j = the particular fuel channel number of fuel element number k. The initial values $D_{jk}(o)$ are stored at the attainment of full power and are compared with current values $D_{jk}(t)$ to give the second difference ΔD_{jk}. If any ΔD_{jk} value exceeds the fuel failure discriminator setting, the operator is alerted by an annunciator.

The visual display for flattening and optimizing the radial flux of the reactor can be generated by passing the ΔT_1 values to suitable discriminators, differential or otherwise, to either light bulbs or modulate the beam intensity of a TV tube.

Other features, such as the decimal readout of a particular fuel channel temperature can also be conveniently provided. The digital data can be utilized in a computer section if such requirements exist.

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