NUCLEAR
ENGINEERING
MONOGRAPHS

NUCLEAR REACTOR INSTRUMENTATION

BY

M. W. JERVIS

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"NUCLEAR ENGINEERING" MONOGRAPHS

This series of monographs on nuclear engineering subjects is intended for university and technical college students, research assistants and qualified technicians who require a broad understanding of those topics of nuclear engineering outside their own field of study. The depth of treatment in the specialist works currently available is too great and the cost too high for this category of reader and in producing this relatively inexpensive series of monographs in association with their monthly journal, *Nuclear Engineering*, the Publishers have aimed at meeting the requirement of low cost and, at the same time, providing a broad treatment ranging from elementary principles to up-to-date summaries of more advanced theories.

"NUCLEAR ENGINEERING" MONOGRAPHS

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Preface

This monograph is primarily intended for engineers and physicists engaged in nuclear engineering and for post-graduate or final-year students who wish to add a study of the more specialized field of nuclear reactor instrumentation to their general knowledge of instrumentation and nuclear radiation detection. This volume is therefore complementary to Sharpe's *Nuclear Radiation Measurement* in this series.

At some time, most of those concerned in nuclear engineering come into contact with measurements and instrumentation. Though excellent accounts of such instrumentation are available in various technical papers, reports and textbooks, the author has found a demand for an integrated treatment of the subject. In the short compass of this monograph great detail is not possible, but the basic descriptions are augmented by references to readily available sources of information.

Although many techniques have been available since the early days of reactor development, the subject is in a continuous state of change. This arises partly from new requirements and partly from a continual quest for simplification and reduction in cost. Any treatment, therefore, can be a statement valid only at the time of writing, but in the monograph an indication of new trends of development is given where this is appropriate.

Acknowledgment is due to the Publishers of *Nuclear Power* for permission to reproduce Figs. 22 and 23. Tables 1 and 5 are reproduced by courtesy of The Institute of Physics and The Physical Society.

The author wishes to thank the Management of The Nuclear Power Group for permission to publish this monograph, and his colleagues for constructive criticism.

April 1961 M. W. JERVIS

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Chapter One

INTRODUCTION

The instrumentation of nuclear reactors is installed to provide permanent records of the variables of the plant and to give immediate information for its safe and efficient operation by manual or automatic control. The automatic control includes the auto-shutdown of the reactor if a serious fault condition arises. In general, these requirements are met by making measurements of the following:

The reactor power by inference from instruments outside the reactor core.
Neutron flux within the core.
Temperature of fuel and moderator.
Flow, temperature, pressure and activity of the coolant.
Detection and location of faulty fuel elements.
Detection of leaks between coolant and steam circuits.
Closed circuit television.
Miscellaneous measurements, mainly temperature of pressure vessel, biological shield, etc.
In power reactors, conventional boiler and turbine measurements.

In all but the simplest experimental installations, the display equipment associated with reactor measurements is centralized in a control area. This centralized control feature of nuclear power station operation is necessary because of the large number of instruments and the complexity of the instrumentation and control. It is, however, uneconomic and unnecessary to transmit all information to the control room, and some instruments are installed in local panels. For example, in Berkeley Nuclear Power Station, control of the gas circulators and heat exchangers is effected from panels near the gas circulators, with only the more important controls in the central control room. There is, however, a modern tendency towards complete centralized control of all important plant items in nuclear power stations.

Cost of Instrumentation

It is interesting to consider the cost of instrumentation and its relation to that of the remainder of the plant items. For the instrumentation listed in the previous section the cost is in the region of £M 1·5–2 for a nuclear power station using two gas-cooled reactors. The total cost of such a station is about £M 50 so that instrumentation accounts for a figure in the rang. of 3 to 4 per cent of the total cost. For a research reactor the cost of instrumentation is a much greater proportion and for a "Merlin" swimming pool type is a much higher percentage of the total.

Elementary Reactor Kinetics

A substantial proportion of the instrumentation is associated with reactor power measurement, and it is relevant to consider the range to be covered and the rate at which it can change.

The kinetics of nuclear reactors has been dealt with in many publications to which the reader is referred for detailed information.[1–4] The following elementary account is a simplified statement intended only to illustrate the problems from the instrumentation viewpoint.

If k_{eff} is the effective neutron reproduction constant then in one generation the number of neutrons increases by a factor $(k_{eff}-1)$ since one neutron is used for the next fission. If n neutrons are present, the rate of generation is:

$$\frac{dn}{dt} = \frac{n(k_{eff}-1)}{\tau} = \frac{nk_{ex}}{\tau}$$

where τ = average lifetime between generations and $k_{ex} = k_{eff}-1$.

In general, a source of neutrons is present either due to spontaneous fission or to one artificially introduced. If this source supplies S neutrons/sec,

then
$$\frac{dn}{dt} = \frac{n(k_{eff}-1)}{\tau}+S.$$

The criticality of the reactor is controlled by alteration of k_{eff} and the following cases apply.

Reactor subcritical

$k_{eff} < 1$, then dn/dt is negative and the reactor will stabilize when $dn/dt = 0$, i.e. $\frac{n(k_{eff}-1)}{\tau}+S = 0$,

therefore,
$$n = \frac{\tau S}{1-k_{eff}}.$$

It can be seen that the reactor is now a neutron multiplier, the source being increased by a factor

$$\frac{1}{(1-k_{eff})}$$

e.g. $k_{eff} = 0{\cdot}98$, multiplication = 50 times.

Reactor critical

$$k_{eff} = 1, \quad \text{therefore, } dn/dt = S.$$

In practice this is a very slow rate.

Reactor supercritical

$$k_{eff} > 1, \quad \text{therefore, } \frac{dn}{dt} = \frac{n(k_{eff}-1)}{\tau} + S.$$

Integrating,

$$n = \left(n_0 + \frac{S\tau}{k_{ex}}\right) \exp(k_{ex}t/\tau) - S\frac{\tau}{k_{ex}}$$

where n_0 = number of neutrons initially.
In practice, the term due to the source is rapidly swamped and the expression becomes a pure exponential

$$n = n_0 \exp(k_{ex}t/\tau)$$
$$\text{i.e.} \quad n = n_0 \exp(t/T) \quad \text{or} \quad n = n_0 \exp(0{\cdot}693\, t/T_D)$$

where T = reactor period
and T_D = doubling time = $\ln 2 \times$ period = $0{\cdot}693\, T$.

Nuclear reactors are different from other forms of heat-producing plant in that the fuel is normally permanently installed in the reactor. Thus, if the reactor is allowed to become critical and the power increase, a dangerous condition might conceivably arise. For example, a reactor with a full power rating of 500 MW would typically have a shutdown power of 10 W. Such a power level might be considered completely negligible but facilities must be provided for monitoring it, since even 10 W represents a large number of neutrons. Should a fault occur in which this number were allowed to multiply, the power might increase to a dangerous level if no monitoring system were provided to give alarms or initiate automatic safety action. We therefore have the fundamental concept that neutron levels must be monitored at all times and at all powers including shutdown.

The scale of the problem from the viewpoint of instrumentation is illustrated by the example of the Calder Hall reactors.[5] In this case the thermal power at 100 per cent rating is 200 MW. The power at shutdown is that provided by an artificial neutron source and amounts to about 2 W. Thus, the range to be covered between shutdown and full power is 10^8. This is a very wide range and one which is not commonly met in the instrumentation of other types of plant. As will be discussed in Chapter Three this power range can be covered only by the nuclear instrumentation. On the other hand, the temperature measurements described in Chapter Two and telemetering equipment, Chapter Seven, are required to be operative over a range of about 1–120 per cent of normal values.

Chapter Two

REACTOR TEMPERATURE INSTRUMENTATION

GENERAL

Apart from research reactors intended only as neutron sources, most reactors are used to produce heat for conversion via steam to electrical energy. This involves a large number of temperature measurements of the reactor coolant, the moderator, the steam circuits and the fuel elements themselves. The latter are particularly important since the life of the fuel element sheath, containing the highly radioactive fission products, is sensitive to temperature. For maximum power output from the reactor the fuel elements are run at as high a temperature as possible, and the temperature margin between operating temperature and maximum safe temperature must be known accurately. This requires precise measurement of fuel element temperatures. Temperatures of the coolant in the ducts and leaving fuel element channels, are also measured, as these give an indication of the fuel element temperatures. In graphite moderated reactors, energy is stored in the graphite due to the Wigner effect and can be released with resultant temperature surges. Such temperature excursions can have serious consequences, and since the Wigner storage is temperature dependent, it is important to measure and record continuously graphite moderator working temperatures.

Temperature measurements of components of the reactor structure, such as pressure vessel, biological shield, etc, are required to check calculated figures, and to ensure that during start-up specified rates of rise of temperature are not exceeded.

INITIATING DEVICES

Choice of type

In some cases, such as duct gas temperature measurements, either thermocouples or resistance thermometers can be used. The advantages of one type as opposed to the other are marginal. In general, a compromise is reached between sensitivity, size and speed of response in relation to the indicating or recording instruments used. The resistance thermometers are usually of the types which have become conventional in the pyrometry field,[1–3] though special types have been developed for reactor use.[4]

In other cases, for example, for fuel element temperature, thermocouples are preferred, mainly on the grounds of known performance under neutron and gamma irradiation, and for physical convenience.

Thermocouples

The temperature range is typically 100° to 600°C, and for metallurgical and nuclear reasons, chromel–alumel couples are used. They take the form of mineral-insulated pairs enclosed in a stainless-steel sheath. In order to reduce both the neutron absorption and the cost of the thermocouples inside the reactor, the diameter of the sheath is made as small as practicable, i.e. about $\frac{1}{8}$ in. This implies a fairly high resistance, about 2 Ω/yd. This resistance, together with any compensating cable which may be used, gives a maximum total resistance in the region of 200 Ω, the output being about 40 μV/°C, i.e. 16 mV at 400°C.

In a typical, large, gas-cooled reactor there may be in the region of 1,000 thermocouples.

Cold-junction errors

The thermocouples are brought through the pressure vessel by special glands, and thereafter there is a choice of methods used to eliminate cold-junction errors.[1] One is to join the thermocouple cable to copper cables, the chromel–copper and alumel–copper junctions being enclosed in small temperature-controlled ovens or in one large cabinet. The output is then in the form of copper pairs which can be passed through jumper boards, resulting in a very convenient system of routing thermocouples without error. A further advantage is that the copper cable resistance is low so that the loop resistance is minimized. The main difficulty with this arrangement is the relatively large power and space used by the ovens, and the fact that a monitoring scheme must be incorporated to check the electrical supply and correct operation of the thermostats in the ovens. This is particularly important in thermocouples used for safety purposes. A rise in temperature of the oven is equivalent to a fall in reactor temperature so preventing the reactor trip occurring at the correct temperature. The alternative is to use the conventional copper–constantan compensating cable, and incorporate individual cold-junction compensating circuits of the type used in conventional measuring devices.

In multipoint scanning devices such as multipoint recorders and automatic loggers, considerable economy can be effected by having one compensating unit or oven fitted after the scanning, i.e. a common unit for all points.

A further possibility is the use of an isothermal box which maintains all junctions at the same temperature, the value of which can vary. These variations can then be compensated by a single compensation unit.

Measuring Instruments

General

The loop resistance of reactor thermocouples is relatively high, 100–200 Ω: it is variable from one to another, and varies with reactor temperature.

Although, in principle, the thermocouple output can be measured by classical instruments such as reflecting galvanometers, these are unsuitable for installation in power stations. Such an application necessitates the display of information on large easily-read indicators or its recording on large pen recorders or electric typewriters. In addition to display or recording it is often necessary for the measured variable to operate an alarm or safety circuit if it goes outside its normal operating limits in either an upward or downward direction.

Large indicators, recorders, and relays in alarm circuits require relatively large operating forces, and it is necessary to interpose some form of d.c. power amplifier between the detector and the display equipment or alarm and safety system. A large range of d.c. power amplifiers is available for the purpose. If a permanent record is required, a recorder of the potentiometric, self-balancing type gives a better overall performance than an amplifier followed by a moving-coil recorder.

Potentiometric servo-operated recorders and indicators

In these devices, a d.c. to a.c. conversion device and a.c. amplifier are followed by a phase-sensitive electric motor. This motor is made to operate a slidewire, and the voltage tapped off is fed back to oppose the input voltage as shown in Fig. 1. It will be seen that if the a.c. amplifier gain is high, the motor will rotate until it finds a position where the difference between feedback and input voltage is small. At this point the motor stops and the position of the slidewire will be related to the input voltage. If the slidewire is linear and the current is maintained constant, the position of a pointer moved by the motor will be proportional to the input. Damping is provided by derivative feedback from a tachogenerator. Non-linearity of thermocouples can be corrected by suitably-graded slidewires. With recorders the pointer also carries a pen

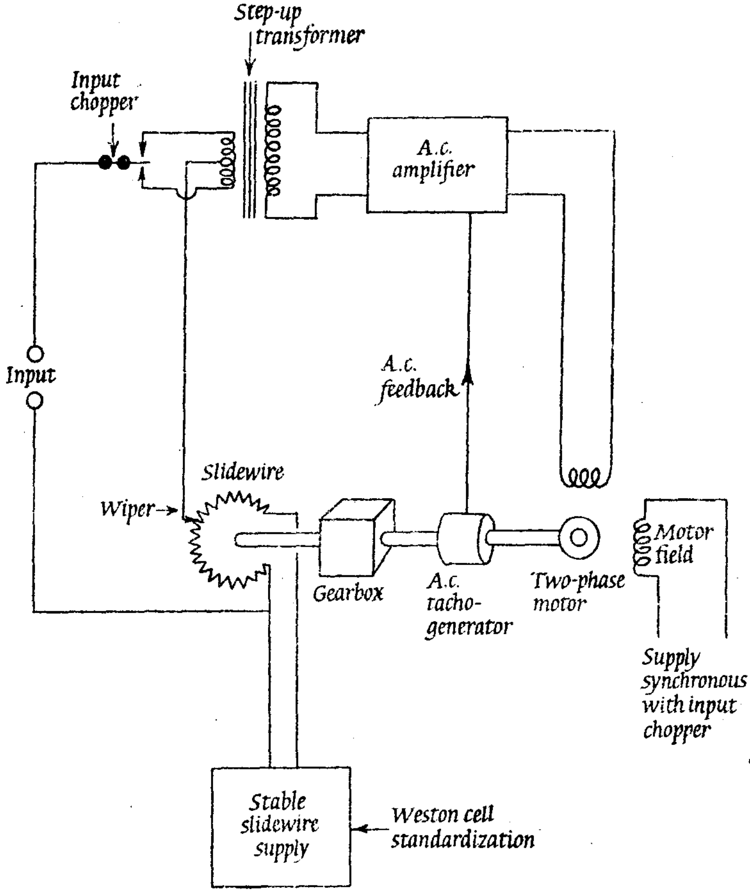

FIG. 1. Schematic diagram of potentiometric recorder

moving over a chart, and by suitable switching multipoint recording is performed.

It will be seen that the device is a self-balancing potentiometer and that the current is very small at balance, so that the voltage measurement is made without loading the input circuit. This property together with its high stability and accuracy makes it ideal for use with thermocouples. The balance is not perfect, however, and above a certain value the resistance of the input circuit causes a "dead spot" with subsequent loss of accuracy. Details of design and performance of servo-operated recorders are given in extensive reviews by Maddock[5] and by Medlock and Kealy.[6]

Typical recorders have scale lengths in the range 4–10 in. and are single trace with a time for full-scale travel of 1–2 sec. Multipoint versions are available covering numbers of points of 32 or greater with times per point of 5 sec. The limitation of the number of points scanned is fixed partly by the time to scan all the points and partly by the difficulty in reading the resultant chart. With large numbers of points reading the same value and slow chart speeds, records tend to become superimposed. Modern recorders incorporate mains-driven zener diode stabilizers for the slidewire current so that the only electrical maintenance is that of checking the stability of this source at infrequent intervals, e.g. 1,000 hr. The recorders provide sufficient operating force to operate switches which can be used for high and low alarms or electrical interlocking functions. By fitting re-transmitting slidewires, remotely-operated indicators, or small recorders can be used to show the same indication as the recorder.

Potentiometric indicators employ the same mechanism as the recorder, a suitable pointer and scale being fitted instead of the pen carriage and chart.

Automatic data loggers[7–10]

An example will now be considered of 1,000 thermocouples installed in a reactor, with 600 as the number required to be continuously observed, 240 being particularly important.

Since temperature transients can occur quickly, it is essential that changes be followed with a minimum of delay. This implies a short scanning cycle for the multipoint recorders, say 1 min. For the 240 points at 5 sec per point, a reasonable installation would have 20 recorders each of 12 points. Such a scheme is unattractive both from the viewpoint of panel space and manpower required to observe it. The clarity of the display leaves much to be desired. A further problem is that although alarm facilities can be fitted to recorders it is difficult to arrange for these to be individually adjustable, as the recorder scans its 12 points, i.e. a common alarm level has to be used.

The fundamental point is that with recorders of the usual type, all information is recorded so that when the plant is running normally, much redundant information has to be dealt with. Thus, when an "off normal" condition arises, the situation is somewhat confused by the unnecessary information presented. This situation can be improved by the use of automatic data loggers which suppress the print out of information and release it only for "off normal" conditions, on demand by the operator or at pre-set intervals. This arrangement also has the

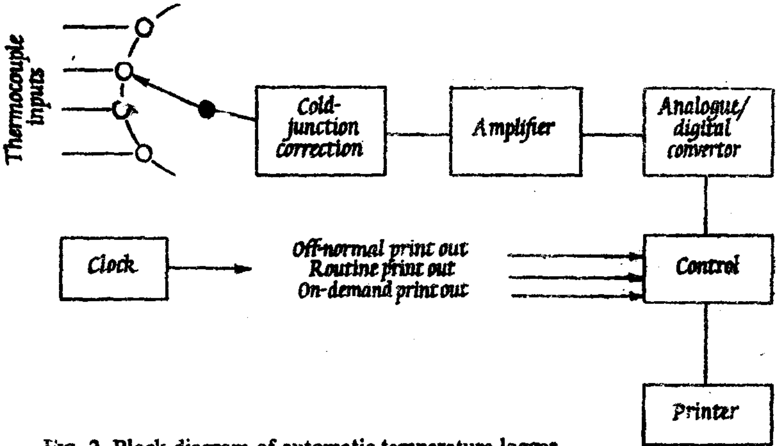

FIG. 2. Block diagram of automatic temperature logger

advantage of reducing data storage space, since the records produced fill up the surface of the paper with significant information only.

In a typical scheme illustrated in Fig. 2, the thermocouples are scanned by rotating switches or relay contacts and the signals amplified to a level where they can be checked for "off normal" conditions, and the non-linearity of the thermocouple corrected. The voltage is converted to digital form, a variety of circuits being available for this purpose, and the digital signals fed to the printer. The print-out can be initiated for "off normal" conditions on demand by the operator or at preset intervals, e.g. every 8 hr. The record takes the form of a printed sheet giving time, point number, temperature and when the printer has been initiated by an "off normal" condition.

Excess Temperature Shutdown Amplifiers

Protective equipment is required which, when fed from certain thermocouple signals, for example, fuel elements, will operate contacts in the safety circuit. Thus, an abnormal temperature initiates alarms and safety action is taken, if necessary.

The essential feature of such shutdown amplifiers is extreme reliability coupled with "fail safe" features. As discussed in Chapter Four, this means that should any fault arise in the equipment, e.g. due to valve failure, the fault will make itself evident by giving an alarm or trip. Alarms are also initiated by open-circuit thermocouples. The amplifier should also be fitted with a trip-margin indicator showing the