SAFETY ASPECTS OF NUCLEAR REACTOR CONTROL

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A B S T R A C T

Reactor control and safety systems are discussed with emphasis on safety considerations. Consideration is given to the importance of reactor characteristics, control and safety system characteristics, the operational program of the reactor, and credible accidents, in a determination of safety of operation.

Experience with research reactor control and safety systems has led to the development of certain general principles that determine reactor safety. These principles, with suitable modifications, should be applicable to establishing the safety of control and safety systems for other reactor types including present power reactors and advanced designs.

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Introduction

An important consideration in the design of a control system for a nuclear reactor is provision for safe operation. Most reactor control systems are divided into two distinct sections, one of which provides for routine operation and one designed to provide for emergency situations. The latter is frequently called a safety system.

Safe operation of a nuclear reactor requires an adequate safety system. It also requires careful design of the routine control system for startup and power level operation. In addition, careful attention must be given to operating practices.

This paper points out some of the important aspects of control of nuclear research and power reactors. The literature contains numerous descriptions and discussions of instruments used in reactor control; relatively little has been published on the subject of safety considerations in reactor control system design. Although most of the discussion here is based on experience with research reactors, most of the underlying principles are valid for power reactors. However, the final designs and the resulting hardware for the two classes of reactors may be significantly different.

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Reactor Characteristics Important in Control System Design

An important problem in reactor control system design is the requirement that the instrumentation and control equipment be capable of operating over an unusually wide range. Ranges of 10 to 11 decades are not uncommon. Figure 1 shows typical reactor startup and operating ranges. Appropriate instrumentation is indicated. It is necessary to use several different types of detecting equipment to provide valid information throughout the entire startup. From shutdown or source level to about three decades above, proportional counters are used. Over the next two to three decades, fission chambers are employed. By moving these chambers away from the reactor core the effective range can be extended to provide information up to full power. Compensated ionization chambers, if properly adjusted, can be used from about six decades below up to full power. Uncompensated chambers provide information from three decades below up to and somewhat above the full power rating of the reactor. These detectors are usually employed in the safety system.

For safe operation of a nuclear reactor a knowledge of the rate of change of power level as well as the power level itself is required. Since in most cases the nuclear instruments sense the neutron population within the reactor, rate of change of neutron population can be derived. The rate of change of neutron population is usually described in terms of the reactor period. Reactor period is defined as the time required for the neutron flux to change by a factor of e. Figure 1 indicates that period information is usually available from six decades below up to full power. Instrumentation exists which will provide period information from the low level counting channels.[1]

Period information is used for control purposes during startup. It is fed to the safety system both during startup and operation at fixed power. The safety system thus protects against short reactor periods in addition to excessively high power levels.

Kinetic Behavior of Reactors

The response of a reactor to a change in excess reactivity is an important factor in the successful performance of a control system. This response is strongly dependent both upon the operating power level and the amount of excess reactivity present. If the excess reactivity of the reactor is such that it is delayed critical, that is the contribution of delayed neutrons is necessary to produce criticality, its behavior depends almost entirely on the delayed neutrons. In a thermal reactor using Uranium 235 the average generation time for neutrons is then about 0.1 seconds and the response of the reactor to changes in excess reactivity is relatively sluggish. However, should the excess reactivity in the reactor exceed the delay fraction β, the generation time is determined by prompt neutrons and is of the order of microseconds. For instance, for the swimming-pool-type research reactor the generation time under these circumstances would be about 5×10^{-5} seconds. On fast reactors these times may be of the order of 10^{-7} seconds. These short generation times produce correspondingly more rapid changes in power level in response to a change in reactivity.

It is seen that those reactors in which excess reactivities are maintained at less than their delay fractions, will be relatively easier to control. Once beyond the delay fraction the control requirements become quite severe because of the fast response required of the control system. Reactors designed so that delayed neutrons do not contribute to criticality may place severe requirements on a control system.

Reactor Protection

Emergency shutdown of a reactor may be accomplished by rapid insertion of neutron absorbing materials into the core, by rapid removal of fuel or by a rapid change of the neutron leakage from the core.

Most research reactors and many power reactors employ absorbing rods containing cadmium or boron. Some of these rods are used to make small slow changes in reactivity for control. The others are inserted or dropped into the reactor when an emergency condition arises. The process of dropping or rapidly inserting safety rods into a reactor is often referred to as "scramming" the reactor.

In addition to changes in reactivity made externally, internal changes in core composition or structure may occur. For example, a change in power level may cause a change in neutron absorption or leakage thus changing the excess reactivity. Such changes may be caused by changes in temperature or pressure which produce corresponding changes in core density or structure. If an increase in temperature decreases reactivity, the reactor is said to have a negative temperature coefficient of reactivity. Conversely if an increase in temperature produces an increase in reactivity, the coefficient is said to be positive. Clearly, a negative temperature coefficient of reactivity which remains negative over the entire range of operating temperatures provides a degree of self-protection. The size and time of lag of the coefficient and thus the degree of protection depends on the reactor type. For instance, a homogeneous reactor has a much larger negative temperature coefficient than the swimming-pool-type reactor.

Other phenomena, such as the Doppler effect and void formation, contribute to changes of reactivity. If these effects tend to reduce the reactivity inherent protection exists. The response time of these effects are of extreme importance in determining the protection they afford. The existence of a net positive temperature coefficient in a reactor system is usually considered intolerable.

Safety Systems

Two safety systems which have been widely used are the "auctioneering" type and the "coincident" type. The MTR-ORNL safety system[2] is an auctioneering type. The instrument block diagram of this system is shown in Figure 2. This system employs several complete channels that monitor the neutron or power level as well as the reactor period during all phases of reactor operation. These channels feed information to a common bus, known as the Sigma bus, which in turn monitors the mechanisms which hold the safety rods. Coupling between the electronic instrumentation and the safety rods is accomplished by specially designed electromagnets. When the period or neutron level reach certain pre-selected values the Sigma bus acts to decrease the current in the electromagnets thus releasing the safety rods which then fall into the reactor.

Since all channels are connected to the Sigma bus, any single channel is capable of dropping all rods into the core. On most installations employing the MTR-ORNL type safety system, the rods fall under the influence of gravity. Because of its extremely short response time and its auctioneering arrangement (the control of the safety rods goes to the highest bidder) it provides a maximum of protection. This system was developed primarily for research reactors whose operational and experimental characteristics are frequently changed. Although any malfunction or false signal, in any single channel of the system will shutdown the reactor, this is usually more of an inconvenience than a disadvantage on a research reactor.

Power reactors cannot usually withstand physically or tolerate operationally unnecessary shutdowns. The coincident type safety system[3] is designed to reduce such shutdowns to a minimum. In this system, which also uses a multiplicity of channels, two or more channels must agree that an emergency condition exists before a reactor scram is initiated. This system, although it provides for continuity of reactor operation does not generally offer the same degree or reliability of protection as the auctioneering type. There are two reasons for this:

(1) the requirement that two or more channels concur usually introduces delays in the initiation of safety action, and

(2) additional equipment is required which increases the probability of component failure. Siddall has shown,[4] however, that if properly selected and arranged in a suitable complex, the addition of components can enhance rather than diminish the reliability of a system.

Although many safety systems fall into one of the two categories discussed above it is generally true that both the characteristics of the individual reactor and its operational requirements strongly influence the choice of an appropriate safety system. Thus some modification of one of the above systems may be used or some entirely different scheme may be employed.

No matter what type of safety system is chosen, the response time of the system is of primary importance.[5] A quantitative value of time response may be difficult to establish. The response time must generally be evaluated separately for each type of reactor accident considered. Response time may be defined as the total elapsed time from the existence of an emergency condition to the time the reactor power level (or period) is brought to a prescribed value. Response time defined in this way is critically dependent on the type of accident, the type of reactor, and the design of the safety system itself. For example, if an amount of reactivity equal to β is suddenly inserted into the reactor, making it prompt critical, a meaningful definition of response time is the elapsed time from the insertion of the positive reactivity to the time that the reactor power level ceases to increase. In other cases we may wish to define the response time as that time required by the safety system to reduce the power to a prescribed value. Under either of the definitions above, the response time depends on the time constants of the instrumentation, the release time of the electromagnets, or similar devices, the effectiveness of the safety rods, or their equivalent, and the inherent characteristics of the reactor.[5]

The time response required of a safety system must be determined during the initial design stages of the reactor and its control system. Establishing the requirements of a system requires detailed examination of reactor response. For instance, if we postulate the sudden insertion of 2β of positive reactivity, it might be expected that 2β of negative reactivity would have to be inserted rapidly to stop the power excursion. Actually, if approximately 1β is inserted quickly, the reactor power will level off momentarily while waiting for the delayed neutrons. This delay gives additional time for the remaining necessary negative reactivity to be inserted. Figure 3 clearly demonstrates this point.[5]

A fact often overlooked in the consideration of a safety system is that safety rods, an important part of the safety system, may be a source of potential danger. Indeed in some cases the potential danger may be the only thing provided by the so-called safety system.

As an example, suppose one postulates a pressurized reactor wherein the safety rods must act against a high pressure in order to shutdown the reactor. If the response time of this system is long compared to probable accidental reactor periods, then little or no protection is offered. Should the forces that hold or drive the safety rods fail, the only place for the rods to go is out of the reactor. Thus, the only role the safety rods can play in this case is that of getting the reactor into trouble or compounding an existing trouble. If this is the situation, the reactor would be better off without any external safety system whatsoever.

Since the speed of response of any safety system is limited, certain emergency situations may arise in which protection is provided only by the inherent characteristics of the reactor itself. If investigation indicates that the resulting protection is insufficient or unreliable the proposed reactor design is certainly questionable.

Those reactors in which a credible accident can be brought under control only by some inherent characteristic of the reactor itself, such as a fast negative coefficient of reactivity can employ a safety system that brings the reactor under control after the inherent characteristic of the reactor has delayed or stopped an excursion. Thus the fast acting inherent characteristic limits the early part of any rapid power excursion until slower corrective action can be taken by an external safety system. It should be emphasized that in such cases the safety system must be carefully studied in order that no situation arise in which the safety system itself represents a potential hazard to the reactor.

The rapid shutdown or scramming of the reactor by dropping all safety rods into the reactor is a drastic form of corrective action. In order to avoid this action for minor power level excursions, other forms of corrective action by the control system are employed. Automatic insertion of the safety rods into the reactor by suitable mechanisms, can in most instances handle minor excursions. This type of corrective action is frequently called Reverse or Automatic Rundown. Some reactors employ fast reverses, slow reverses, or even partial reverses, depending on the power excursion to be handled. These actions must in no way compromise the protection offered by the safety system.

Startup Considerations

Starting the reactor from shutdown level and raising it to full power covers a wide range of operation. During startup safety rods are withdrawn, introducing positive reactivity. If this reactivity is introduced rapidly, the reactor gets on a short period and rises to a high power level in a short interval of time. If this period is short compared to the response time of the safety system, the reactor may be damaged or destroyed before the safety system has time to take corrective action.

To avoid this situation, withdrawal rates are restricted such that if an accident occurs in which all of the safety rods are withdrawn simultaneously at the maximum possible speed, the resulting period and power excursion fall well within the capabilities of the safety system. Newson's criterion[1,2] has been used on several reactors in establishing the rate of insertion of reactivity consistent with the response time of the safety system. This criterion was established for a heterogeneous-light-water-moderated research reactor. This or similar criteria should be envoked for other reactor types.

Power Level Consideration

For automatic operation of a research reactor at rated power level a simple on-off type servo control unit is frequently employed. The servo controls a neutron absorbing regulating rod which is inserted or withdrawn from the core in order to maintain a prescribed power level. In most cases the reactivity of the regulating rod is small enough so that if the control rod is accidentally withdrawn completely, the reactor will not become prompt critical. The internal factors that influence reactivity are generally more numerous and may produce larger effects in power reactors. Thus the automatic control system will be correspondingly more complicated.

From a safety point of view, the problem is that of establishing how much reactivity is placed at the disposal of the servo control unit at any given time. The larger this amount of reactivity, the more important becomes the reliability of the automatic control system.

Some reactor control systems use an automatic control system to compensate for the effect of xenon buildup and burnup on reactivity. In such systems caution must be exercised to insure that no large quantity of positive reactivity can be inserted rapidly due to malfunctioning of the system.

Conclusion

Out of experience with reactors now in operation, a philosophy of control and safety is developing for these particular reactor types. At present, these control systems have many features in common. Extensions of present systems will probably be applied to reactors of many types for research and for power. Fundamental principles of reactor control, which will serve as the foundation for control and safety criteria, must be carefully developed in the design and specification of reactor control systems of the future.

BIBLIOGRAPHY

(1) E. P. Epler and S. H. Hanauer, "Control and Automatic Startup of the Geneva Conference Reactor," IRE Convention Record, Pt. 9, 90-8 (1956).

(2) T. E. Cole, E. E. St. John, and S. H. Hanauer, "The MTR Safety System and Its Components," ORNL-1139, April 4, 1952.

(3) A. Linford, "Instrumentation in Nuclear Power Plants," Nuclear Energy, Vol. 12, No. 19, April, 1958.

(4) E. Siddall, Chalk River Project, AECL Private Communication.

(5) F. P. Green, Ed., "Reactor Safety System Response," ORNL-2318, February 14, 1958.

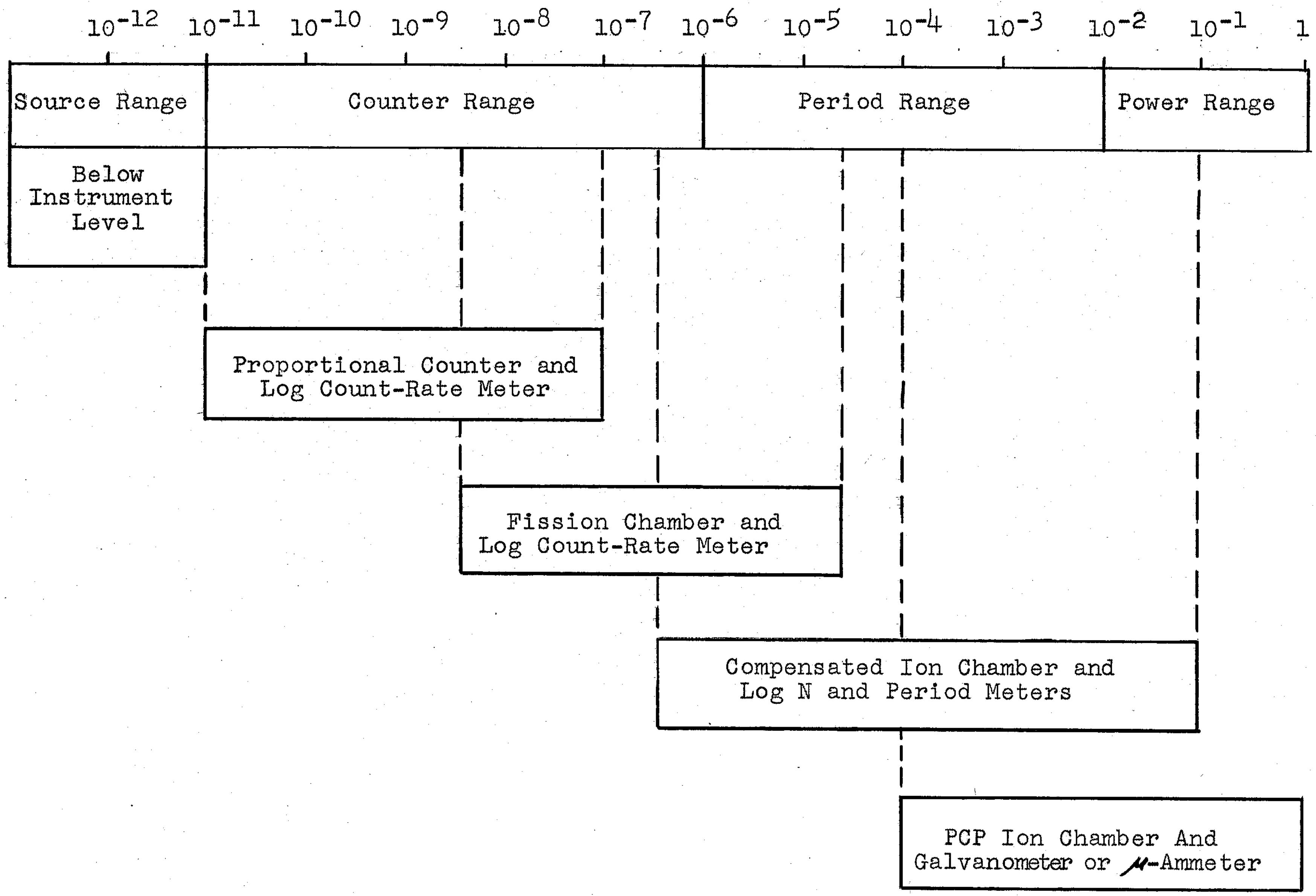

Figure 1. Reactor Startup and Operating Ranges With Appropriate Instrumentation.

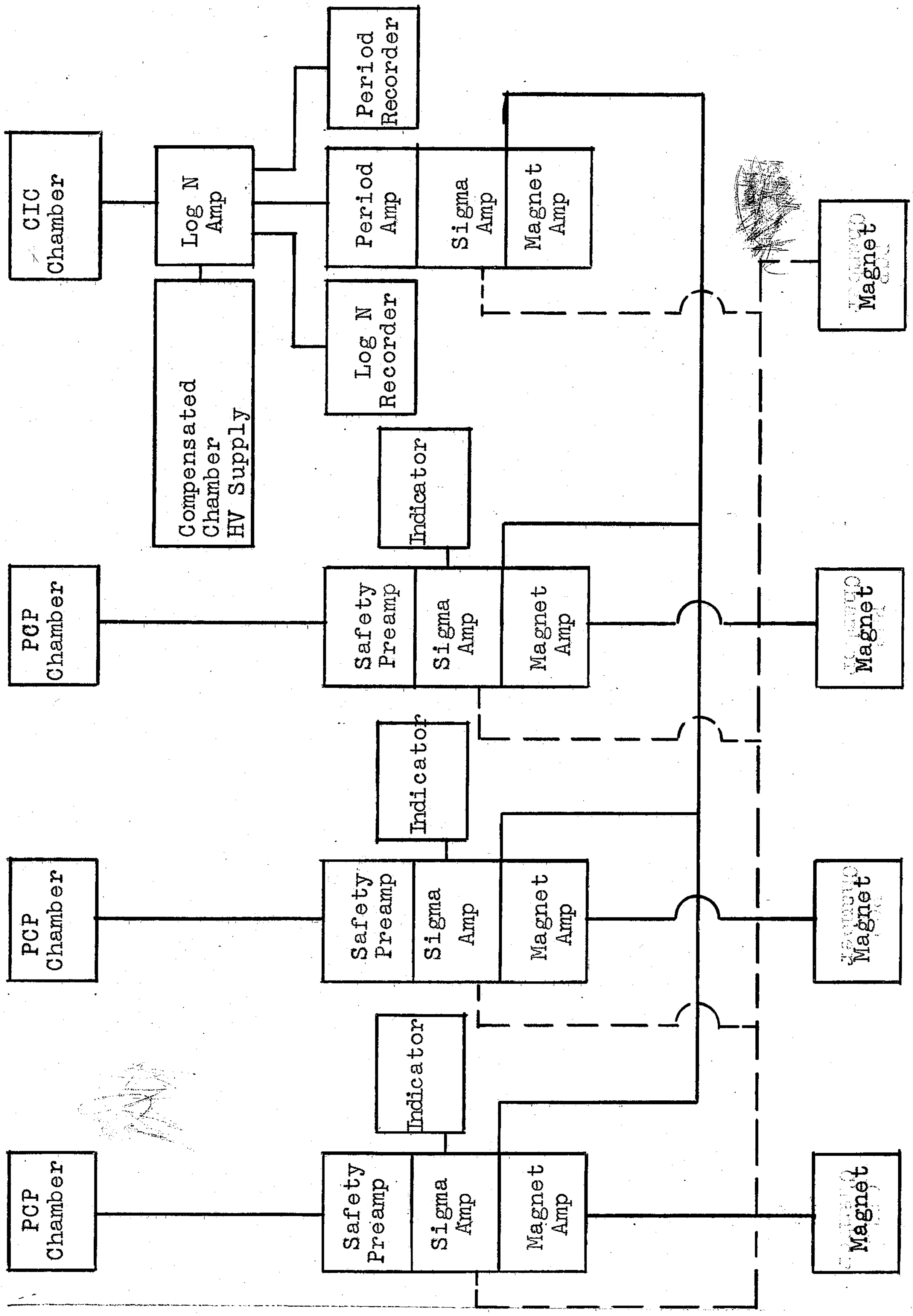

Fig. 2 Instrument Block Diagram, Safety Channels.

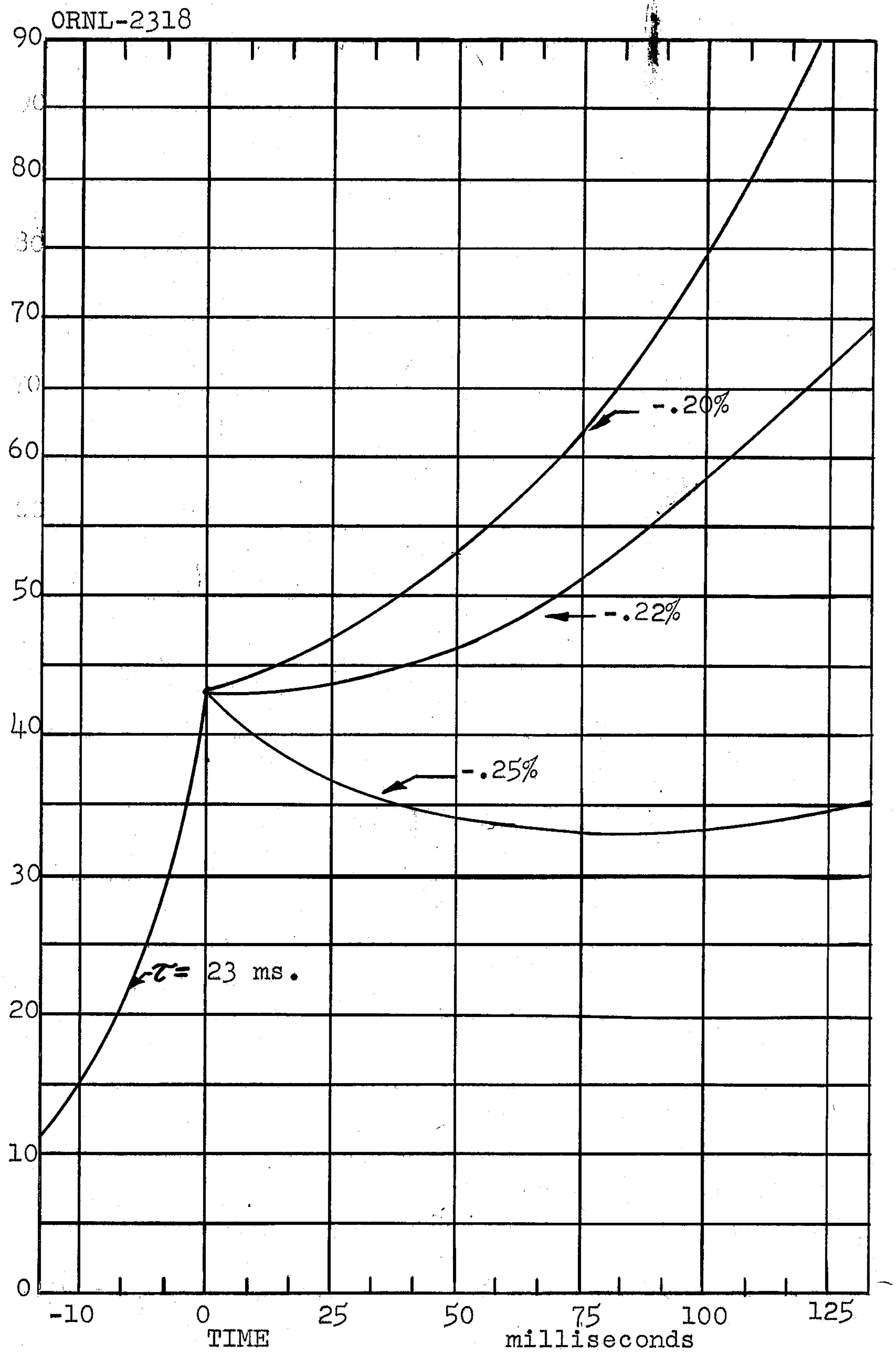

Fig. 3 Flux Response for a Single Step in Reactivity as Corrective Action.