ARGONNE NATIONAL LABORATORY
P. O. Box 299
Lemont, Illinois

NUCLEAR INSTRUMENTATION AND CONTROL
OF THE
D₂O-MODERATED THORIA-URANIA CRITICAL ASSEMBLY (ZPR-VII)

by

C. A. Pesce

Reactor Engineering Division

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ABSTRACT

The design criteria and operation of seven nuclear instrumentation channels and safety interlocks employed for initial measurements on heavy-water moderated thoria-urania lattices of interest to power reactors is described. The mechanical design features of the various control mechanisms and components are illustrated or described briefly where necessary to clarify the over-all instrument-control scheme. The basic start-up sequence is given.

I. INTRODUCTION

The ZPR-VII is a versatile zero power reactor designed to facilitate a comprehensive experimental program to establish the nuclear properties of thoria-urania-heavy water systems. The immediate objective of the program is to evolve a range of concentrations and lattices for detailed investigation in connection with the design of a second core loading for EBWR. This immediate use has, to a large extent, influenced the design of ZPR-VII; however, sufficient flexibility has been incorporated to facilitate subsequent research on other reactor systems using light or heavy water.

This report describes the initial nuclear instrumentation and control interlocks employed for measurements on thoria-urania-heavy water systems. Accordingly, the mechanical design features of the various control mechanisms and components are limited to illustrations or brief descriptions where necessary to clarify the over-all instrument-control scheme.

A detailed description of the ZPR-VII concept, and the proposed long-range experimental program to be conducted, has been published in ANL-5715.*

The ZPR-VII Facility (Fig. 1) is located in Cell No. 1 of the Critical Assembly Building (Fig. 2) on the site of Argonne National Laboratory. Construction started early in March, 1957. The reactor first achieved criticality on July 3, 1957.

*W. C. Redman, J. A. Thie, and L. R. Dates, "Hazards Summary Report on the Oxide Critical Experiments," ANL-5715, April, 1957.

FIG. 1
THORIUM-URANIUM OXIDE CRITICAL FACILITY

FIG. 2
REACTOR CELLS IN BUILDING 316

II. CONTROL ROOM

Operation of the reactor is controlled from the console and adjacent nuclear instrumentation panel located in the control room.

A. Control Console

The control console (Fig. 3) was designed so that all recorders, switches, and annunciator lights important to reactor control are within convenient reach and view by the operator. The reactor Interlock Bypass key switches (described later) were installed high on the console in full view of all personnel participating in the experiments.

The control scheme is designed to facilitate changes in control circuits consistent with the type of experiment to be performed, and with a minimum of re-construction "tie-up-time." This is accomplished at a master terminal board (Fig. 4) located in back of the control console. The connections for all control components are made at this board. A given control circuit may be wired in by means of jumper connections between the various terminals. The power panel (shown partially on Fig. 4) contains all line fuses for the various interlock circuits.

Shielded wire is used for all inter-connections between the master terminal board and the nuclear instrumentation panel.

B. Nuclear Instrumentation

The nuclear instrumentation system (Fig. 5) consists of seven channels: five for neutron flux level, and two for gamma flux level measurement. Reactor shutdown trip signals are derived from neutron flux level, period measurement, and gamma level. Each channel overlaps the previous channel to the extent that information is displayed on the instrumentation panel at all times for any point within the operating neutron flux range (Fig. 6).

Power to the instrument panel is furnished by two a-c voltage regulators. A-C voltage regulators are used to ensure a constant output voltage to the various nuclear instruments regardless of the variations in the input voltage or load current.

The power inputs to the various amplifiers and power supplies are distributed between the two voltage regulators as a precaution against complete loss of nuclear instrumentation in the event of a voltage regulator failure. The nuclear instrumentation can be considered "fail safe" in the sense that failure of supply voltage to any one of the amplifiers, trip circuits, or power supplies will cause a reactor shutdown.

1. Channel Description

Figure 7 shows the respective channel instrumentation mounted on the panel adjacent to the control console.

a. Channels 1, 2 - Start-up

Channels 1 and 2 are used primarily for start-up monitoring. Each channel features a BF_3 proportional counter detector which transmits approximately 4 pulses per second per unit thermal neutron flux input to a pre-amplifier. The pre-amplifier consists of one cathode follower stage so that pulses can be transmitted through a long coaxial cable to the nuclear instrumentation panel with a minimum effect on waveshape and amplitude. The cathode follower is used as an impedance-matching device.

The output from the pre-amplifier is fed into a linear amplifier. The linear amplifier has an "adjustable" discriminator circuit such that pulses due to gamma or spurious noise can be amplitude-discriminated and only pulses due to neutrons are passed and appear in output from the amplifier. This output is fed into an electronic decade-type scaler which provides an integrated mechanical count of the pulses. The output from either linear amplifier can be switched to a log count rate and period amplifier circuit.

The output of the period amplifier provides a period signal to period meters on the panel and control console, and also to a period trip circuit. The log count rate circuit provides a neutron level signal to a log count rate strip chart recorder on the control console.

Either of the start-up channels can be switched to an audible count rate monitor to assist the operator during start-up operations.

The normal operating reactor level is well above the range of these channels; therefore, the high voltage to the BF_3 detectors must be manually turned off before the counting channels reach their maximum counting rate. If the high voltage is not turned off, the counting rate will exceed the resolution capability of the linear amplifier; this will cause amplifier blocking due to the "pile-up" of pulses. The "pile-up" will tend to build up and then collapse; this will produce erratic counting rate and period measurements that would cause a trip and shut down the reactor. Reliable operating information from the higher flux channels is available before this condition exists.

b. Channels 3, 4 - Linear Flux Level

Each of these channels uses a neutron-sensitive ionization chamber (not gamma compensated) to drive a vibrating reed electrometer. The current from the ionization chamber is fed to a shunt

1. LOG COUNT RATE RECORDER (CHANNEL 1 OR 2)	15. SPARE SWITCH
2. CLOCK	16. CONTROL ROOM TO REACTOR ROOM INTERCOM
3. LOG FLUX LEVEL RECORDER (CHANNEL 5)	17. SOURCE DRIVE CONTROLS
4. ROD DROP SWITCHES	18. PERIOD METER AND SWITCH
5. INTERLOCK BY-PASS KEY SWITCHES AND INDICATORS	19. CONTROL ROD SELECTOR SWITCH
6. SOURCE AND CONTROL ROD CLUTCH POWER INDICATORS	20. REACTOR SHUTDOWN BUTTON
7. LINEAR FLUX LEVEL RECORDER (CHANNEL 4)	21. CONTROL ROD DRIVE SWITCHES
8. CONTROL ROD POSITION INDICATORS	22. STANDPIPE DRIVE CONTROLS
9. LINEAR FLUX LEVEL RECORDER (CHANNEL 3)	23. DUMP VALVE CONTROLS
10. CONTROL CIRCUIT INTERLOCK TRIP INDICATORS	24. REACTOR WATER FLOW CONTROLS
11. CONTROL CIRCUIT INTERLOCK TRIP INDICATORS	25. PUMP CONTROL
12. NUCLEAR INSTRUMENT POWER CONTROL SWITCHES	26. HEATER SWITCHES
13. CONTROL POWER KEY SWITCHES	27. 4-POLE CONTROL RELAY
14. CHANNEL 1 AND 2 PROPORTIONAL COUNTER HV SWITCH	28. 6-POLE CONTROL RELAY

FIG. 3
CONTROL CONSOLE

POWER PANEL

FIG. 4
ONE SECTION OF THE MASTER TERMINAL BOARD

FIG. 5
NUCLEAR INSTRUMENTATION SYSTEM

FIG. 6
RANGES OF NUCLEAR INSTRUMENTATION

input resistance in the vibrating reed electrometer pre-amplifier to develop a d-c voltage. This voltage is fed into the main amplifier unit located in the instrumentation panel. The main amplifier drives a panel milliammeter, trip circuit, and strip chart recorder. The strip chart recorder for each channel is located on the control console. Both channels are very important for constant monitoring of the flux level by the operator.

c. Channel 5 - Log Level Flux

This channel uses a neutron-sensitive ionization chamber (not gamma compensated). The current from the chamber is fed through a "low-noise" coaxial cable into a pre-amplifier located in the reactor room. The pre-amplifier is close (approximately 3 feet) to the chamber. This channel will give period measurement; therefore, "low-noise" cable was used to reduce the spurious signals that may be caused by shock or vibration to the cable. In the pre-amplifier the current signal is fed into a circuit containing several series-connected selected diodes to obtain an output voltage proportional to the logarithm of the input current. This output voltage is amplified and fed to a cathode follower stage so that a signal could be fed to a long coaxial cable between the pre-amplifier in the reactor room and the main amplifier in the control room. From the main amplifier, the signal is fed to a log level meter on the instrument panel, to a strip chart recorder on the control console, to a log level trip circuit, and to a differentiation circuit. The signal out of the differentiation circuit is amplified and fed to a period meter and period trip circuits. The period meter is duplicated on the control console.

d. Channel 6 - Fast Period Trip

This channel uses a gamma scintillation counter for a detector. The phototube circuit is designed to provide a varying d-c voltage to the phototube such that the current from the tube is constant. Under this condition, the applied voltage which is generated by an oscillator-rectifier circuit bears a very nearly logarithmic relationship to the incident flux over a range of several decades. The logarithmic signal drives a conventional period amplifier and period trip circuit. This channel operates at higher flux levels only. The inherent circuit delay is very low.

e. Channel 7 - Fast Power Level Trip

This channel also uses a gamma scintillation counter for a detector. Direct-current derived from the phototube is supplied to a feedback amplifier and a trip circuit. The primary purpose of this channel is to provide fast linear level measurement. It is designed to operate only at high flux levels. The circuit has very low time delay and serves as a reliable and fast high level trip.

1	2	3	4
	5	6	7
8	9	10	11
12	13	14	15
			16
17	18	19	20
21	22		23
24	25	26	27
28	29	30	31

1. REACTOR WATER TEMPERATURE RECORDER 2. AUDIBLE PULSE COUNT RATE MONITOR (CHANNEL 1 OR 2) 3. BLANK PANEL 4. POSITIVE HV SUPPLY (CHANNEL 1) 5. DUAL LINEAR TRIP CIRCUITS (CHANNELS 3 AND 4) 6. SCINTILLATION PERIOD TRIP CIRCUIT (CHANNEL 7) 7. POSITIVE HV SUPPLY (CHANNEL 2) 8. LOG COUNT RATE AND PERIOD CIRCUITS (CHANNELS 1 AND 2) 9. VIBRATING REED ELECTROMETER (CHANNEL 3) 10. LINEAR SCINTILLATION TRIP CIRCUIT (CHANNEL 6) 11. POSITIVE HV SUPPLY (CHANNEL 3) 12. DUAL ELECTRONIC DECADE SCALER (CHANNEL 1 AND 2) 13. VIBRATING REED ELECTROMETER (CHANNEL 4) 14. SAFETY ROD INTERLOCK CIRCUIT 15. POSITIVE HV SUPPLY (CHANNEL 4) 16. SPARE POSITIVE HV SUPPLY	17. LINEAR AMPLIFIER (CHANNEL 1) 18. LOG PERIOD CIRCUIT (CHANNEL 5) 19. SPARE - AUXILIARY CHAMBER POWER SUPPLY 20. NEGATIVE HV SUPPLY (CHANNEL 6) 21. LINEAR AMPLIFIER (CHANNEL 2) 22. BLANK PANEL 23. BLANK PANEL 24. CONTROL RODS AND SOURCE ARMATURE POWER SUPPLY WITH SPEED CONTROL KNOB 25. A-C VOLTAGE REGULATOR NO. 1 26. A-C VOLTAGE REGULATOR NO. 2 27. CONTROL RODS AND SOURCE FIELD POWER SUPPLY 28. AIR BLOWER AND FILTER NO. 1 29. AIR BLOWER AND FILTER NO. 2 30. AIR BLOWER AND FILTER NO. 3 31. AIR BLOWER AND FILTER NO. 4

FIG. 7
NUCLEAR INSTRUMENTATION PANEL

2. Nuclear Instrument Trip - Shutdown System

The nuclear instrument trip-shutdown system (Fig. 8) involves all seven channels.

a. Channels 1, 2 - Start-up Pulse Channels

The pulse output from either channel may be switched to a log count rate circuit where reactor period is derived. Period trip circuit is set at a period of + 3 sec. When the counters reach a level just below their maximum counting rate, the log count rate period trip is shorted out.

b. Channels 3, 4 - Linear, Wide Range Operating

The signal from the main amplifier is used to drive an adjustable trip circuit on a separate chassis. Both channels provide trip contacts for reactor shutdown. Since the trip circuit is fed from the panel milliammeter circuit of the vibrating reed electrometer, it is necessary that the reactor operator switch the amplifier ranges at the proper

times as the reactor level rises to avoid incurring a shutdown. The trip point on the panel milliammeter can be adjusted from one-tenth to full-scale meter indication.

c. Channel 5 - Logarithmic Level

Both log level and period trips are obtained from this ionization chamber channel. The period trip circuit contacts are shorted until the chamber current reaches 1×10^{-10} amp. At this point a log level trip shorts out the log count rate period trip contacts from channels 1 and 2, and opens the short across the period trip contacts from this channel. The log level trip is indicated by a light on the instrument panel and on the control console. The log level trip does not shut down the reactor. It is only used for shorting out the period trip at low chamber currents where the period fluctuations, due to pile statistics, are large.

d. Channel 6 - Fast Period Trip

This channel provides a fast period trip that is set at a period of +4.5 sec.

e. Channel 7 - Fast High Level Trip

This channel provides a fast high level gamma trip that is set at 1 R/hr.

III. REACTOR ROOM

Figure 9 shows the wire and coaxial cable duct work interconnecting

the control room and reactor room. The coaxial cables for the nuclear instrumentation are isolated as much as possible from all wires carrying a-c power, switching, and relay circuits in order to reduce the amount of "pickup" due to induced voltage surges or electrical noise. Within the reactor room, the duct work extends upward to a horizontal "ring" duct which encircles the reactor at about the core center height.

FIG. 9
WIRE AND COAXIAL DUCTS INTERCONNECTING CONTROL AND REACTOR ROOMS

Power cables from the control room are embedded in separate concrete trenches in the

shield wall. The wiring for all control components in the reactor room is interconnected with the control room at a terminal panel in the reactor room. Heavy breakers and control switches are installed on all circuits that require a large amount of a-c power.

A. Detectors

The detectors for all channels are mounted on short, vertical steel members ("Unistrut") attached to the outer surface of the reactor vessel. The effective area of all detectors is on a plane equal to the horizontal centerline of the core. However, the method of mounting is such that their position can be varied vertically over two feet from the core centerline. During initial loading and start-up operations, the detector for Channel 2 was installed in a special dummy element in the core to monitor the initial neutron multiplication.

Figure 10 shows how the cables from the "ring" duct are connected to a detector mounted on the vessel wall (Channel 4 is shown). All pre-amplifiers are shock-mounted to prevent noise pickup due to vibration, and protected with an aluminum shield from damage by tools or debris falling on them from the steel walkway encircling the top of the reactor.

FIG. 10
TYPICAL DETECTOR - PRE-AMPLIFIER INSTALLATION
(CHANNEL 4)

B. Mechanical Control Systems

There are basically five different mechanical drive circuits. They are used for positioning the start-up source and the control rods in the nuclear system; and the dump valve, the adjustable weir standpipe, water pump and heaters in the water system.

1. Start-up Source Positioning Mechanism

The start-up source drive (Fig. 11) is a variable speed,

FIG. 11
START-UP SOURCE POSITIONING MECHANISM

95-volt d-c reversible motor coupled with a 90-volt d-c magnetic clutch to the drive mechanism. The speed is controlled manually by a variable transformer mounted on the instrument panel in the control room. The source travel is limited by micro-switches and is interlocked with the control rod release mechanism so that the rod-actuating clutch cannot be energized initially until the source is in the inserted position.

2. Control Rod Drives

There are nine aluminum-clad cadmium control rods. Each rod is suspended from a cable attached to a drive mechanism (Fig. 12) which features a 95-volt d-c reversible motor and a 90-volt d-c magnetic clutch.

Figure 13 shows a drive mechanism and method of attachment to the control rod. Each rod is serviced by two selsyn position indicators: one synchro dial has a full-scale calibration of 1 in.; the other has a full-scale calibration of 72 in.

3. Pump Drive

The heavy-water circulating system is operated at atmospheric pressure and at room temperature except for experiments involving temperature coefficient measurements.

FIG. 13
CUTAWAY OF TANK SHOWING CORE AND CONTROL MECHANISM

With reference to Fig. 14, the D_2O is pumped from the dump tank to the reactor tank by means of a 440-volt a-c motor-driven centrifugal pump submerged in the dump tank. The flow rate is accomplished by a system of valves controlled by a rotary switch on the control console. Three flow rates are available: (1) "Off" (in this position, the water is circulated from the dump tank, through the bypass line, and back to the dump tank); (2) "Low" (0-10 gpm); and (3) "High" (160 gpm).

The flow valves are operated electrically against a normal air pressure of 20 psi. If the air supply to the valves is exhausted, the flow valves will relax to a condition such that the operator would only be able to circulate the water in the dump tank.

4. Adjustable Standpipe Drive

During reactor operation, the water level within the reactor tank can be raised or lowered to satisfy experimental conditions. This is accomplished by means of an adjustable standpipe with a weir flange (Fig. 15). The standpipe is raised or lowered by a 440-volt a-c, 3-phase reversible motor mounted on the reactor top flange. The height of the weir, and thus the water level, is indicated in the control room by a double selsyn unit. One synchro dial has a full-scale calibration of 1 in.; the other has a full-scale calibration of 80 in. The surplus water passes over the weir and downward through the standpipe and into the dump tank.

FIG. 15
ADJUSTABLE STANDPIPE AND OVERFLOW

5. Dump Valve Drive

Water is removed from the reactor tank by tripping the butterfly dump valve located in the 12-inch discharge pipe below the tank. With reference to Fig. 16, the circular vane, hinged along its diameter, seats against a rubber-lined body and is held closed against the water head by a 90-volt a-c magnetic clutch. The clutch is secured to a 115-volt a-c, single-phase, non-reversible drive motor and gear reduction unit. The armature of the clutch is secured to a weighted lever which, in turn, is fastened to the butterfly valve stem. The magnet side of the clutch is attached to the shaft of the reduction unit.

Power to the motor and clutch is supplied by depressing a switch at the control console. The valve is closed by the motor which rotates the clutch and valve stem until the lever trips the micro-switches that automatically stop the drive and operate valve position indicator lights on the control console. The clutch remains energized during reactor operation. It is de-energized either automatically at shutdown or on power failure, or at will by the operator.

6. Water Heater Circuits

For temperature coefficient measurements the D_2O in the dump tank will be heated by two 440-volt a-c, 3-phase immersion heating elements. Heater operation with water temperature above 200°F, or with water level below that required to cover the heaters, is prevented by thermostatic and float switch interlocks.

C. System Interlocks

The following description of system interlocks is made with reference to Fig. 17.

1. Pre-start-up Tests

For certain pre-startup testing, portions of the interlock circuit can be bypassed. Power to the drive circuits can be obtained through a bypass key switch No. 1 located on the control console. When key bypass No. 1 is used, the reactor door interlock is shorted, and the source and dump valve clutch circuits are opened automatically. This prevents reactor personnel from raising the source or pumping water into the reactor with the reactor room door open. However, it does allow operation of any of the drive circuits for maintenance or test purposes. Bypass switch No. R 1 is paralleled with switch No. 1 but it is located by the reactor door inside the reactor room. It is the responsibility of anyone entering the reactor room to use the No. R 1 bypass switch for his protection.

FIG. 16
 DUMP VALVE AND ACTUATING MECHANISM

NOTE:

KEY BYPASS 1A, 1B, AND 1C ARE PART OF ONE SWITCH. BYPASS SWITCH R1A, R1B, AND R1C ARE PART OF ANOTHER SWITCH. WHEN 1A AND/OR R1A ARE CLOSED, 1B, AND/OR R1B AND 1C AND/OR R1C ARE OPENED. KEY BYPASS 1, 2 AND 3 ARE IN CONTROL ROOM. BYPASS R1 IS IN REACTOR ROOM.

Each time a key switch is used to bypass an interlock, a red light flashes on the console along with an audible clicking alarm.

2. Basic Start-up Sequence

The following is the sequence of operations that must be performed, in the order as shown, during reactor start-up.

- (1) Turn on instrument power.
- (2) Reset nuclear instrument trips.
- (3) Check to see that no one is in reactor room.
- (4) Close reactor room door.
- (5) Operate both control power key-operated switches simultaneously.
- (6) Raise source into the reactor.

- (7) Raise (one at a time) two control rods designated as safety rods to their upper limit out of the core.
- (8) Close dump valve.
- (9) Operate pump.
- (10) Place flow rate switch in "High" position.
- (11) Raise weir standpipe.
- (12) Near the normal operating water level operate the flow rate switch to the "Low" position.
- (13) Raise control rods to go critical.
- (14) After critical has been obtained, operate bypass key switch No. 2.
- (15) Lower the source out of the reactor.
- (16) Operate control rods to raise flux level to desired level..

3. Operational

The interlock circuit is designed such that the source must be in the reactor before the two control rods designated as safety rods can be raised. By means of a key switch on the control console, the operator can bypass the source upper limit switch interlock in order to remove the source after the reactor is critical.

Any two of the nine control rods can be used as safety rods. The two rods selected are raised to their upper limit out of the reactor core during operation. When the rods are so positioned the dump valve can be closed, the weir standpipe can be operated, and water can be pumped into the reactor vessel. The pump drive can be operated any time after power has been made available to the control console. However, unless the latter condition has been satisfied, the water can only be circulated in the storage tank.

The flow interlock is dependent on neutron multiplication and is designed to prevent the reactor from becoming critical on a high D_2O flow rate (160 gpm). Normally, the operator will initiate high flow in filling the reactor tank and will switch to low flow when approaching the desired water level. Should the reactor inadvertently be in a condition where criticality could occur before normal water level is reached, a scram can occur if the water flow rate is high. The multiplication-water flow interlock will prevent this condition by automatically stopping the high flow rate (if the flow switch is on "high"), when the neutron level reaches a multiplication level just below critical. This is initiated by a normally closed switch actuated by the slide-wire mechanism on the

log level recorder. This switch can be adjusted to operate anywhere over the log level range. If the flow is in the "Low" condition, no action takes place, and the flow continues. The rate of flow is sufficiently slow that normal operator attention can effect the necessary control.

On a shutdown signal, either from the nuclear instrumentation or by manual operation, the magnetic clutches holding the two safety rods, control rods, and dump valve are de-energized. This allows the rods to free-fall under gravity into the reactor core and the dump valve to spring open, thereby dumping the water out of the reactor and causing shutdown.

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