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**BORON-11 NEUTRON FLUX MONITORS:
INTERIM REPORT**

APRIL, 1965

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INTERIM REPORT

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BORON-11 NEUTRON FLUX MONITORS: INTERIM REPORT

INTRODUCTION

There is an incentive to monitor continuously the flux distribution in most large power or production reactors to use fuel efficiently and thereby minimize production costs. Several monitoring techniques are employed for this purpose, but none is entirely satisfactory. Important parameters to consider in the selection of an in-core neutron flux monitoring system include: speed of response, stability under long irradiation, operation temperature, effect of temperature variations on operating characteristics, dynamic range, and physical dimensions of the detectors.

In theory, a B^{11} beta current generator provides reasonable compromise values for all the parameters. B^{12} , formed by neutron transmutation of the B^{11} in the detector, decays by high energy beta emission with a half-life of 20 msec and provides a signal proportional to the neutron flux; thus, speed of response is adequate for most conceivable applications (including reactor control). Because of the small absorption cross section of B^{11} , burnup is negligible, so the operating lifetime should be virtually unlimited in presently conceivable flux environments. Boron is stable at elevated temperatures and the reaction is not known to be temperature sensitive; therefore, temperature limitations are not apparent. The primary beta signal generated by the decay of B^{12} is not influenced by gamma background, but dynamic range can be limited by background current generated within the detector and cable. Although rela-

tively small B^{11} detectors are possible, miniaturization is limited by the small reaction cross section.

Because of the many desirable features of an in-core neutron flux detector employing B^{11} , investigations were begun to develop an operational device. This report summarizes the accomplishments to date and was prepared to provide information to the sponsors.

SUMMARY

A survey of the elements shows that B^{11} has excellent potential for use as the neutron sensitive isotope in a beta current type of in-core neutron flux monitor. Short half-life (prompt response), small cross section (negligible burnup) and high energy betas (collection efficiency) are major items of interest. A number of prototype detectors have been developed and irradiation tested in an effort to develop a practical monitor employing B^{11} . A primary difficulty was the background current induced in the connecting cable residing within the reactor flux. To overcome this problem, a digressive parametric study of cables was undertaken. Qualitative evaluation of the sources of background current has been achieved. Recent tests, using twin-wire cables, have demonstrated that background current can be effectively eliminated without close control of the composition of the environment, type of insulation, and dimensions of the sheath and wire. Efforts to incorporate twin-wire cables in an operational B^{11} prototype detector are continuing.

BACKGROUND INFORMATION

Continuous monitoring of the neutron flux distribution within a reactor is necessary for control purposes to achieve maximum efficiency and safety. Ideally, the system should provide absolute information independent of variations in environmental conditions. Limitations of present monitoring techniques make it necessary to compromise and to use systems whose favorable characteristics outweigh the unfavorable for the particular application. The following paragraphs briefly describe characteristics of several monitoring techniques.

Activation

Activation analysis of foils, ribbons, wires or gases can be used to determine the neutron distribution within the core. Using appropriate radioactivants, the neutron flux distribution can be measured precisely, and an evaluation can even be made of the energy spectrum. One major disadvantage of an activation system is the speed of response, since a significant delay occurs before the information is available for use. Usually, mechanical considerations also detract from practical application of the activation method.

Neutron Sensitive Ion Chambers

Ion chambers, coated with neutron sensitive material such as U^{235} or B^{10} , are employed for in-core neutron monitoring. A major limitation is the decrease in sensitivity caused by burnup (depletion) of the coating material. Calculations show that 10% of a B^{10} coating would be destroyed in about 3 days at a flux level of $10^{14} \text{ n}(\text{cm}^{-2})(\text{sec}^{-1})$. In the same flux, 10% burnup of a U^{235} coating would occur within 20 days. Sensitivity of fission-type chambers can be sustained for an extended period by use of regenerating coating material⁽¹⁾ which includes a reservoir of fertile atoms that become fissile by neutron absorption. By using an appropriate mixture of fertile and fissile isotopes, the sensi-

tivity (macroscopic fission cross section) of the chamber can be made relatively constant for extended exposures.^(2,3) Ion chambers with regenerating coatings appear to provide a practical solution for in-core monitoring.

Temperature Sensors for Neutron Flux Detection

Heat generation in a reactor core is proportional to the neutron flux so temperature sensors can be utilized for in-core flux monitoring. Primary limitations are slow response speed and limited dynamic range; thus, reactor damage could be sustained under certain conditions before such sensors responded sufficiently to indicate the danger.

Gamma Chambers

Gamma-sensitive ion chambers can provide a measurement of neutron flux and power distribution within a reactor core in some environments. Induced activity of the chamber components can be minimized by proper choice of materials to extend the dynamic range of the monitors.⁽⁴⁾ However, delayed components of the gamma flux following transient operating conditions tend to vitiate the signal. Also, in heterogeneous reactors with movable components, the local gamma intensity might not be as meaningful as direct neutron flux level information.

Beta Current Generators

An electrical current, proportional to the neutron flux, is generated by beta decay of an isotope produced by neutron activation. The signal is unaffected by gamma background or by temperature changes in the environment. Potential for this type of device as an in-core neutron flux monitor is good; therefore, investigations were initiated to develop a beta current generator employing the isotope B^{11} .

BASIS FOR BORON-11 SELECTION

The isotope for use in a neutron detector (beta current generator type) should decay

promptly by high energy beta emission for immediate response to changes in the neutron flux level. The reaction cross section should be adequate to provide a useful signal, yet should be small to insure negligible burnup (depletion) of the detecting material. No single isotope is ideal for all environments, and apparently, no isotope is completely ideal for any environment. Table I summarizes isotopes whose combined properties of half-life, cross section, and beta decay energy make them potentially useful in beta current neutron flux monitors.

TABLE I
POTENTIAL ISOTOPES FOR BETA CURRENT
NEUTRON FLUX DETECTION

	Cross Section, barns	Half- Life, sec	Maximum β Energy, MeV
Li ⁷	0.033	0.85	13.0
B ¹¹	<0.05	0.02	13.4
Al ²⁷	0.23	138	2.9
V ⁵¹	4.5	226	2.6
Tc ⁹⁹	22	16	3.4
Rh ¹⁰³	150	42 (and 264)	2.4

The half-life of the boron isotope is undoubtedly the most desirable for an in-core monitor used for reactor control purposes. The half-life of lithium might be acceptable for certain control purposes. The other isotopes could be used for flux monitoring in which speed of response was unimportant. Tc⁹⁹ was included even though it is radioactive and decays by emission of a 0.29 MeV beta with a half-life of about 2×10^5 yr. This half-life would limit the application to fluxes in excess of about $10^{10} \text{ n}(\text{cm}^{-2})(\text{sec}^{-1})$. Burnup of Li⁷ or B¹¹ would be negligible in a flux of $10^{14} \text{ n}(\text{cm}^{-2})(\text{sec}^{-1})$ for several years, while Rh¹⁰³ would be about 50% destroyed in 1 yr in that flux environment. Sensitivity

changes in vanadium and aluminum detectors, due to neutron transmutation, would be acceptable in most reactors, but the long half-life (slow response) would be undesirable for most applications.

Collection efficiency (the fraction of betas that escape the material to generate the desired signal) is a function of geometry as well as beta decay energy. The beta particles from a decay spectrum are attenuated nearly exponentially with a range characteristic of the maximum energy. For a given geometrical arrangement, collection efficiency will be higher for the higher energy beta spectrum. A study of collection efficiency has been made for cylindrical beta sources.⁽⁵⁾ The combined effects of collection efficiency and reaction cross section must be considered in determining the signal current from a given isotope.

The theoretical maximum current that can be generated per gram of detector isotope (neglecting collection efficiency) is simply the product of the neutron flux, the cross section, the number of atoms per gram, and the charge on an electron. For B¹¹, this current is calculated to be about $4.5 \times 10^{-22} \text{ A}(\text{nv})^{-1} \text{ g}^{-1}$. For boron encased in a stainless steel tube 0.218 cm in diam with 0.025 cm thick walls, the escape efficiency was calculated to be about $80\% \pm 10\%$. Therefore, currents in excess of $3 \times 10^{-8} \text{ A}$ could be expected per gram of B¹¹ in a flux of $10^{14} \text{ n}(\text{cm}^{-2})(\text{sec}^{-1})$.

Consideration of properties of isotopes in Table I indicates that no single isotope would find universal application as beta current generators for in-core neutron flux monitoring. Low flux applications, where burnup is unimportant, would require the use of rhodium to obtain sensitivity. Vanadium could be used in relatively high flux applications where speed of response was not important. Detectors employing rhodium and

vanadium have been investigated by Hilborn⁽⁶⁾ and are now available commercially. B^{11} has excellent potential for in-core applications in future high flux reactors where response speed is important and burnup cannot be neglected.

EXPERIMENTAL INVESTIGATIONS

Initial Experiments

A number of experimental detectors have been designed, fabricated and tested in an attempt to obtain a suitable working device. The first model, fabricated commercially to provided specifications, consisted of a 1 in. diam SS collector with magnesium oxide insulation between the collector and the B^{11} , which was contained in a stainless steel sleeve. The detector assembly was integrally connected to a solid sheath coaxial cable with stainless steel wire and sheath. When irradiated in a Hanford production reactor test facility, the signal from the assembly was much greater than expected from theoretical calculations. Data analysis revealed that the current was proportional to the integral of the neutron flux over the length of cable within the reactor rather than being proportional to the flux at the detector. It was concluded that the background signal generated in the cable was excessive because of the large dimensions (0.25 in. sheath diam, 0.065 in. wire diam), and possibly because of the presence of the magnesium oxide insulation.

A second experimental assembly was designed and fabricated locally, using a 3 mil SS wire supported by ceramic spacers located at 2 ft intervals. A second parallel lead wire (not connected to a beta current generator) was incorporated in the assembly to determine the background signal. Vibration of the assembly, induced by flow of the facility cooling water, caused intermittent shorting of the wires, and little information of value was obtained. When the assembly was

removed from the reactor, a large residual current remained. The signal decay was minor over a 3 day period. It was concluded that contact potentials or galvanic action might be responsible for the signals rather than induced radioactivity.

A third assembly was fabricated locally with great care being taken to clean components and to avoid the problems noted in the previous experiment. Three mil SS wire and continuous ceramic sleeve insulation was used (Figure 1), and the sample tube was sealed and evacuated. Vibration caused mechanical failure of the electrical portion soon after the assembly was charged into the reactor. The small amount of data showed that a significant (factor of ten) reduction in background signal had been achieved over that in the previous attempt. In addition, the background signal polarity was negative; whereas, it had been positive in the previous irradiation.

FIGURE 1

Third Experimental
 B^{11} Detector and Assembly
(B^{11} is encased in stainless steel with
ends supported by ceramic. Center wire
is 3 mil SS with continuous ceramic
insulation.)

Neg. 0640379-1

It was noted in the previous two irradiations that a component of the background signal generated in the lead wire exhibited a buildup and decay with a half-life comparable to that of aluminum. Each time, the assem-

blies were encased in a standard aluminum irradiation tube.

In the fourth experiment, the 3 mil SS lead wires were once again supported at intervals using ceramic spacers, but stainless steel sleeves were placed around the wires to shield them from the aluminum tube. Once again mechanical vibrations disturbed the signal from the B¹¹ detector, but intermittent data obtained from the cable indicated background current had been reduced.

After the four described assemblies had been irradiated, a review of the results was conducted to determine the approach for further work. The mechanical vibration failures caused by cooling water flow dictated that solid sheathed coaxial cables be used rather than the supported wires with segmented insulation. The second conclusion was that the background signal generated within the cable needed to be significantly suppressed before a practical, operational B¹¹ detector could be achieved. Previous cable studies did not provide parametric evaluations to permit selection of cable dimensions and materials to achieve specific, predictable behavior. Therefore, a parametric evaluation of irradiated coaxial cable signals (background) was started.

Cable Investigations

Background currents generated within a cable located in a reactor environment are summarized in Figure 2. A series of cables were obtained from a commercial supplier to study the effects of the following parameters: outer diameter of the sheath, diameter of the center conductor wire, and type of insulation. Stainless steel was chosen as the sheath and wire material on the basis of physical properties, and the two insulations were aluminum oxide and magnesium oxide. Sheath diameters of 20, 40, and 125 mils were selected. Wire diameters of 1.5, 3, and 10 mils were

requested, but the cables received had wire diameters of 2, 3, 9, and 12 mils.

- Positive current defined as transfer of negative charge (electrons) from central wire to sheath (ground).
- Negative current defined as transfer of negative charge (electrons) from sheath (ground) to central wire.

Electrons can be ejected with sufficient energy to effect transfer by photons (Compton scattering process) or by neutrons (activation to beta decaying isotope).

FIGURE 2

Generation of Background Current in Cables

Irradiation testing of the cables was delayed by out-of-reactor tests because of mislabeling discovered by capacitance and resistance measurements. The cables were sealed assemblies, and it was desired to non-destructively measure the diameter of the central lead wire and establish its continuity. Resistance and capacitance measurements varied greatly between cables (ostensibly of the same type), and this initially caused concern that the center wires might be broken. Pulse-echo techniques, frequently used with ordinary RG-type cables (having high-conductance central wires and low-loss dielectrics), were not successful with these particular cables. Radiographs revealed that several of the cables labeled as having 3 mil central wires actually had 12 mil wires. A partial summary of the test data is shown in Table II and radiographs of the cables are shown in Figure 3. Validity of the planned irradiation experiments would have been lost if the in-laboratory testing had not revealed the inconsistencies and established the actual parameters.

In the first of this series of irradiations, five types of cables were included in the test assembly with the fifth B¹¹ experimental detector as shown in Figure 4. The test objective was to study parametrically the

TABLE II
CABLE TEST DATA INFORMATION

Cable Type	Piece	Specified Dimensions, mils		Best Estimate Actual Wire Diam	Measured Capacitance, pF	Calculated Capacitance with Specified Dimensions	Resistance, Ω at 500 V	Remarks
		OD	Wire					
1	1	20	3	3	1360	1200	3×10^{11}	Resistance measured @ 50 V *
2	1	40	1.5	3.3	1000	700	2×10^{11}	Resistance measured @ 50 V *
2	2	40	1.5	2	10	700	5×10^8	Center wire apparently not connected
2	3	40	1.5	2.3	255	700	1×10^8	
3	2	40	3	2.8	340	800	1×10^{11}	
3	3	40	3	12	2400	800	4×10^9	Wire much larger than specified
3	4	40	3	12	2400	800	3×10^9	Wire much larger than specified
3	5	40	3	12	2400	800	9×10^8	Wire much larger than specified
4	2	40	10	9.5	1800	1500	7×10^8	Resistance measured @ 50 V *
5	2	125	3	3	520	+	10^{13}	B ¹¹ detector attached
5	4	125	3	3	505	+	4×10^{10}	Resistance measured @ 50 V *
7	1	40	3	3	725	800	1×10^{12}	
7	2	40	3	12	2400	800	3×10^9	Wire much larger than specified

* Items used in assembly of Figure 4

† Capacity values of Type 5 cable were used to estimate dielectric constant

FIGURE 3

Enlargements of Radiographs
of Coaxial Cables for Use
in B¹¹ Detector Experiments
Neg. 0650458

FIGURE 4

Fifth B¹¹ Detector Assembly
with Five Cables Used
for Parametric Study of Background Effects
Neg. 0642586-3

background signal generated and to choose the most suitable cable type for use with the B^{11} detector. Several cables were exposed simultaneously to the same flux so comparative data could be obtained without the need of measuring the actual flux or flux distribution. The irradiation was made in the same water-cooled facility used previously. Great precautions were taken to stabilize the aluminum sample tube within the facility, minimizing vibrations that had affected earlier experiments.

For this fifth experiment, the B^{11} was contained within rolled stainless steel shim stock that was subsequently soldered with pure lead. The boron-filled tube was supported at each end by quartz insulators that positioned the sleeve within the stainless steel collector (Figure 5). A spring was used to firmly stabilize the detector. A large (125 mil) cable was attached to the detector, and the entire assembly was evacuated. Resistance between the sheath and wire of the cable and

detector assembly improved considerably during the initial stages of the evacuation process; the removal of moisture that had entered the cable during the fabrication process accounted for the change. Resistance of the evacuated system was greater than a teraohm, which exceeded that of any of the cables as received from the vendor. This prototype failed shortly after insertion into the reactor core, apparently due to a seal failure that allowed gas into the evacuated region. This failure made the detector behave like a simple ion chamber.

Much information was gained from the cable irradiation performed simultaneously with the fifth B^{11} detector. The geometrical relationship of the five cables is shown schematically in Figure 6, which illustrates the large differences in the parameters. To a first approximation, the background currents in the cables could be correlated with cable dimensions; however, a large transient signal

FIGURE 5

Components for B^{11} and Cable Studies
Neg. 0641877

FIGURE 6

Relative Dimensions of Wire, Insulation,
and Sheath of the Cable Types Used
in the Fifth Irradiation Series

(with the half-life of aluminum) seemed to bias the results. Later tests in a Co^{60} gamma facility showed that the cable signal could be increased by wrapping lead foil around the cable. It was assumed Compton electrons generated in the lead entered the wire and provided a negative current. The gamma field data revealed the importance of electrons generated external to the wire; thus, another in-core cable irradiation was completed in which betas from the aluminum environment were, at times, intercepted by a stainless steel sheath. The data clearly disclosed the importance of the beta particles emitted from the aluminum tube.

Data from a typical reactor irradiation in the fifth series are plotted in Figure 7. The assembly was charged into and withdrawn from the reactor in the same two steps. The three negative-going curves represent cables

FIGURE 7

Typical Cable Currents,
Fifth Irradiation Series

of 40 mils in diam and smaller, and the positive-going curves represent a cable of 125 mils diam.

All cable current data show build-up and decay transients that are primarily characteristic of aluminum. Both the sample tube (surrounding all of the cables) and the insulation contained within each individual cable sheath contain aluminum. It is not possible to infer from the data the true magnitude of the positive and negative components of current contributed by the aluminum, since only the resultant is measured. Individual substitution of an element other than aluminum in each of the two positions would be required.

The Type 4 cable exhibited a pronounced prompt current component in a positive direc-

tion during charging and in a negative direction during discharging. The prompt change is about 45% of the eventual change achieved after the transient signal comes into equilibrium. This prompt component is attributed to the equilibrium gamma field existing within the reactor. The apparent absence of the prompt transients from the cables with 3 mil wires is probably because the mass of these wires is less than a tenth of the mass of the Type 4 wire (Figures 3 and 6). The prompt positive signal is thought to be caused by electrons being driven from the wire (and the immediately surrounding insulation) by gamma rays, so the mass of the wire is of primary importance.

FIGURE 8

Current from Cables, Type 3 and 4,
During Charging and Discharging
(Cable 4-2, 40 mil OD, 9 mil wire; Cable
3-3, 40 mil OD, 12 mil wire; data of
11-9-64)

The insulation of Type 5 cable is more than five times as thick as that of the Type 4, thus attenuating this prompt signal. Also, the aluminum signal in the Type 5 cable has the same polarity as the prompt signal, tending to mask the magnitude, if any, of the prompt signal. With the smaller cables (Types 1 and 2) some recorder traces show a slight indication of a prompt signal. Residual currents, after about 10 min out of the reactor, are attributed to Mn^{56} . It should be noted that the polarity of some cables changes during decay. The prompt component in Cable 3-3 is more clearly shown in Figure 8 and is estimated to be 60% of the eventual change in signal.

For these irradiation data, the amount of aluminum in the assembly is large, and most of it is external to the cables in the form of the surrounding sample tube and the central rod which supports the cables. This mass of aluminum cannot be considered as the equivalent of an aluminum channel in the reactor because it is not at nuclear equilibrium, but is undergoing buildup and decay simultaneously with the cables. It became clear that this strong changing aluminum signal could not be tolerated, so sample tubes of other materials were procured for later experiments.

From Figure 8, when the assembly was discharged into the reactor shield, the negative signal from the Type 3 cable decayed through zero, became slightly positive, and then decayed with the 2.6 hr half-life characteristic of manganese. The presence of a strong manganese component was demonstrated separately by gamma ray spectrum analysis of cables during test-reactor experiments.

In addition to measuring the direct current generated by the cables, a series of current readings were taken for each cable as a function of impressed voltage. These V-I data were used to determine the effective resistance of the cables under various condi-

tions, to investigate the possibility of there being potential sources in the cables, and as an indicator of possible ion chamber currents. Typical resistance values are shown in Table III and typical V-I curves are shown in Figure 9. These plots are interpreted to indicate that the currents are typical of those from high-voltage sources, and not like ion chamber currents or simple resistive leakage caused by input offset voltages of the readout instruments. Such currents are expected from high energy sources like beta particles and Compton electrons. The leakage resistance of the cable acts like a shunt across the resultant of many current sources. The plots cross

TABLE III
CABLE RESISTANCE IN GIGAOHMS

Cable	Preirradiation	During Irradiation	Postirradiation
1-1	300	11.6	240
2-1	200	1	90
3-3	4	1.6	22
4-2	0.7	0.5	45
5-4	40	2.6	100
5-2 (B11 Chamber)	2000	0.001	0.4

FIGURE 9

Current versus Voltage Curves of Cables
(Data taken 11-5-64 after manganese activity was saturated)

the zero-current axis at a voltage value representing the open circuit voltage of the cable. This value is inversely dependent on the cable leakage resistance and not dependent on a true potential source within the cable. The plots cross the zero-potential axis at a current that represents the actual resultant of the currents generated in the cable. To read this current with reasonable accuracy, the input offset voltage of the readout device must be limited to a minor fraction of a volt, and must be only a few millivolts when the currents are much smaller (when the reactor is shut down). Currents due to interstitial ionization would introduce a component like the "S-shaped" curve shown. To make these measurements at small current levels (such as 10 pA), either the voltage source or the picoammeter must have an extremely high resistance to ground (such as a teraohm).

Cables were irradiated in a Co^{60} gamma facility to compare the induced currents with those obtained within the reactor. It was hoped that gamma observations could be used to help predict the in-reactor performance. A study of the effect of the reactor materials environment was begun by wrapping thin layers of lead around the cables. These sleeves would be expected to increase the electron intensity within the cable (due to Compton reactions in the sheath) while slightly reducing the gamma intensity. Typical measurements are plotted in Figure 10, clearly showing an effect caused by the change of the material immediately surrounding the smaller cables. The radius of the 125 mil cable is large enough that the effect of the external sleeves is greatly attenuated. The cables and sleeves were in air within a 2 in. diam SS pipe in the water-filled Co^{60} facility. All cables produced negative-polarity currents in the gamma facility, but the prompt effect in the reactor was of positive polarity. This anomaly may be due to differences in the energy spectra, but this has not been confirmed.

FIGURE 10
Cable Currents in Co^{60} Gamma Field
at 2.4×10^6 R/hr

Charge and discharge transient currents from a Type 7 cable are shown in Figure 11. The bipolar logarithmic readout is shown with increasing positive polarity currents at the top of the figure and increasing negative currents at the bottom of the figure. Between the two is an indeterminate "zone" in which the amplifier was inaccurate or unstable at the extremely small currents. The use of this readout prevented the loss of data during exploratory test runs, and shows predominant half-lives during decays without replotting.

The necessity of identifying sources of cable current prompted a shrouding technique wherein a stainless steel tube (0.065 in. wall, 0.375 in. OD) was interposed at will between the cables and the aluminum sample tube that forms the water jacket. In this first test, the shroud was used immediately after the assembly was withdrawn from the reactor to avoid any effect of activation of the shroud. The test results are shown in Figure 12. The prompt component during charging and discharging is shown, followed by shrouded and unshrouded decay curves show-

FIGURE 11

Charge and Discharge Transients of Current
from Cable, 0.040 in. OD, 0.012 in. Wire;
Bipolar Log Display

FIGURE 12

Effect of a Stainless Steel Shroud
Shielding Cable from the Surrounding
Aluminum Sample Tube

ing domination by aluminum in the early stages. The magnitude of the aluminum contribution from the alumina cable insulation was to be determined by comparing these data with those from a similarly-dimensioned cable made with magnesia insulation. However, the sets of data were so nearly identical that the cable insulation was analyzed at the conclusion of the irradiations. The analysis disclosed that the manufacturer had erred and had made both cables with alumina. Consequently, it is not known at this time what fraction of the current is from aluminum in the cable insulation, and what fraction is from the sample-tube aluminum gamma penetrating the shroud or driving Compton electrons from the shroud.

Figure 13 shows that the buildup curves in the reactor are also dominated by aluminum, both shrouded and not shrouded.

INSTRUMENTATION

Instrumentation used in the investigations was progressively expanded and improved to meet the needs disclosed by experience gained at each stage of the work. During the earlier tests, data were taken principally with a battery-powered picoammeter (Hexem Model 124) using meter readings, and with a current-to-pulse converter (Dymec Model 2210) using a digital printer. These instruments were accurate, but the transient nature of the currents during assembly insertion or removal from the reactor core demonstrated the need to record continuously each of the assemblies under test. During later irradiations, as many as six channels were used with separate current amplifiers and recorders. Typical transient data obtained with these systems are presented in Figures 7 and 8. Another instrument was designed and fabricated

FIGURE 13

Cable Current Buildup in Reactor,
Showing Effect of Stainless Steel Shroud

to explore any apparent potentials of the current sources and to measure the effective resistance of the assemblies during irradiation and in the presence of the radiation-induced currents.

All current amplifiers selected were the feedback type so the inputs were within a millivolt of ground at all times. This minimized possible cable leakage currents caused by an input offset voltage.

Major changes were incorporated in the readout instrumentation because of the experience gained in the fifth series of irradiations. The large changes in magnitude and polarity led to the development of three different types of readouts. The first used a log count-rate meter on the output of a current-to-frequency converter, automatically resulting in a multidecade logarithmic recording of currents of either polarity. The second type was an operational amplifier with back-to-back logarithmic feedback elements, providing a "center zero" display with several decades of each polarity increasing in magnitude toward the edges of the chart. The third type was a true center-zero linear display of picoammeter outputs. Typical recorded data are shown in Figures 11 and 12.

PRESENT AND FUTURE EFFORT

The irradiations have demonstrated the importance of aluminum on the background current induced in cables in reactor environments. In recent irradiations, the standard aluminum sample tube was replaced by titanium to evaluate the effect of the environs on the magnitude of the induced current. In addition, an irradiation was conducted comparing the induced currents in cables with similar dimensions using aluminum oxide and magnesium oxide insulation to determine the effects of these materials on the induced current. Solid sheathed cables with twin central wires have been irradiated and demonstrate potential for eliminating the induced background current.

Design of the detector was modified to utilize twin-wire cables in an effort to separate the desired signal from the background current.

As a result of this work now in progress, it is thought that the proper combination of materials, dimensions, and geometrical arrangement will eventually result in a fully operational B¹¹ detector. Further effort will be required to develop a practical in-core neutron flux monitor.

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APPENDIXSUMMARY RESULTS AND COMMENTS
FOR INITIAL EXPERIMENTSFirst Experimental Assembly

The first assembly was commercially fabricated (to provided specifications) with 0.25 in. SS cable.

- The B^{11} detector and cable provided 8.7×10^{-7} A (positive polarity).
- The blank cable provided 9.2×10^{-7} A (positive polarity).

Second Experimental Assembly

B^{11} was in a stainless steel sheath supported on ceramic insulators with a connecting wire of 3 mil SS supported on ceramic insulators mounted in an aluminum tube.

- The B^{11} detector and wire provided about 2×10^{-6} A (positive polarity).
- The blank wire provided about 6×10^{-7} A (positive polarity).

Residual currents 3 days after discharge of assembly from the reactor were about 2×10^{-6} A (for B^{11} portion) and 1×10^{-8} A (wire); therefore, the conclusion was that some effect other than irradiation (such as contact potential, galvanic action, etc.) was causing the current.

Third Experimental Assembly

B^{11} was contained as above; however, the 3 mil wire was insulated (continuous fashion) by ceramic material supported in an aluminum sample tube (evacuated).

- The B^{11} detector and wire provided about 6×10^{-7} A (positive polarity).
- The blank wire provided about 8.5×10^{-8} A (negative polarity).

The combination of evacuation and continuous insulation reduced the "wire current" by about a factor of 10. The detector signal appeared to act as a voltage source rather than a current source and was erratic.

Fourth Experimental Assembly

B^{11} was contained in a sheath as above with the 3 mil connecting wire supported at intervals by ceramic insulators. A stainless steel sheath was placed between the aluminum sample tube and the wires. The assembly was evacuated.

- The B^{11} detector and wire provided about 5×10^{-7} A (positive polarity).
- The blank wire provided about 2×10^{-7} A (positive polarity).

The stainless sheath "changed" the blank wire current from negative polarity (in third assembly) to positive polarity in this assembly. However, the cable currents still exceeded the current from the B^{11} detector thus making it impossible to measure the detector (only) current. One day after the assembly had been withdrawn from the reactor, the detector-portion current had reversed polarity and had increased to 2.5×10^{-6} A.

Fifth Experimental Assembly

The B^{11} was contained in steel shimstock rolled and soldered with lead, supported by quartz insulators. Negative polarity currents approaching 10^{-6} A were recorded as the assembly was inserted into the reactor; however, a sudden polarity reversal occurred and the magnitude became about 2×10^{-7} A. Tests indicated that simple ion chamber operation was being observed. In the same test, the same type of cable with no attached detector produced a current of about 3×10^{-8} A (positive polarity).

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