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DEVELOPMENT OF A

BORON CONCENTRATION METER

TECHNICAL PROGRESS REPORT

FOR THE PERIOD ENDING

JUNE 30, 1968

MASTER

NOTICE

This report was received under the provisions of the arrangement and is subject to the terms thereof.

J. L. O'Brien, Jr.
Project Engineer

Prepared for the New York Operations Office
U. S. Atomic Energy Commission
Under AEC Contract AT(30-1)-3690

August 1968

WESTINGHOUSE ELECTRIC CORPORATION
Atomic Power Divisions
PWR Plant Division
Box 355
Pittsburgh, Pennsylvania 15230

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PROGRAM DESCRIPTION

The increasing application of Chemical Shim Control to Pressurized Water Reactors (PWR's) has emphasized the need for a means to monitor accurately and automatically the concentration of boric acid in aqueous solution.

The overall objective of this program is to develop, design, test and evaluate the performance of two prototype boron concentration meters. One meter under investigation is based on conductivity measurements of a boric acid solution with mannitol added. The second is based on the neutron absorption principle.

The program can be divided into the following tasks:

A. Laboratory Studies

Experimental and analytical work was conducted to determine whether the design objectives can be attained for meters based on these principles. This task has been completed.

B. Meter Design

Prototype meters have been designed using, where possible, standard commercially available components.

C. Prototype Construction

Prototype meters have been constructed. Laboratory tests of the meters' sensitivity and reliability have been conducted. Further testing will determine the final characteristics of the prototype instruments.

D. In-Plant Evaluation

The final prototype boron meters will be installed and tested in a typical closed-cycle chemical-shim water reactor. The meters will be evaluated side-by-side for a comparison of the meters' sensitivity, reliability, accuracy, maintainability, etc.

E. Design, Operation and Evaluation

A final review and evaluation of the two separate boron meter designs will be prepared. This will compare the performance of the two separate designs and identify any modifications found necessary as a result of in-plant tests. A final report will be prepared documenting all the information developed during the program.

In addition, a review was conducted of the boron concentration meter presently in use at the SENA reactor. Available data was reviewed as to the meter's reliability, maintenance requirements, accuracy and precision, chemicals makeup requirements, operating costs, time delay, waste disposal requirements and other particulars. A topical report was prepared summarizing this evaluation.

(WCAP-3690-4, "Description and Evaluation of the Boron Concentration Meter Utilized at the SENA (Franco-Belge) Reactor Plant".)

EUBM-100 - Program Management (Summary of Progress)

J. L. O'Brien, Jr., Project Engineer

This is the fifth technical progress report on a USAEC-EURATOM joint program for the development of a boron concentration meter. The previous reports were:

EURAEC-1722 WCAP-3690-1	"Development of a Boron Concentration Meter, Technical Progress Report for the Period Ending September 30, 1966".
EURAEC-1778 WCAP-3690-2	"Development of a Boron Concentration Meter, Technical Progress Report for the Period Ending January 31, 1967".
EURAEC-1827 WCAP-3690-3	"Development of a Boron Concentration Meter Technical Progress Report for the Period Ending December 31, 1967".
EURAEC-2005 WCAP-3690-5	"Development of a Boron Concentration Meter Technical Progress Report for the Period Ending March 31, 1968".

In addition, the following topical report was published under this contract:

EURAEC-1972 WCAP-3690-4	"Description and Evaluation of the Boron Concentration Meter Utilized at the SENA (Franco-Belge) Reactor Plant".
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Program management is not discussed in this technical progress report, since separate reports emphasizing the administrative aspects of the project are published monthly for limited distribution.

Progress for the period April 1, 1968 through June 30, 1968 may be summarized as follows:

1. The final design of two boron concentration meters, one based on the mannitol conductance and the other on the neutron absorption principle, has been completed.
2. The meters have demonstrated reliable and accurate operation during repeated laboratory testing.

3. The accuracy of the mannitol meter can be shown by the following tabulation:

<u>Boron Concentration (ppm)</u>	<u>Accuracy (ppm)</u>
100	± 0.8
1,000	± 2.3
3,200	± 4.2

4. Successive readings of a known boron solution with the neutron absorption meter have demonstrated the following results:

<u>Boron Concentration (ppm)</u>	<u>Maximum Deviation from Average (ppm)</u>
141	+4, -3
573	+3, -3
1,960	+6, -4
2,950	+7, -6

5. Laboratory checkout of the meters has been completed and they are presently undergoing an extended in-plant evaluation at the Saxton nuclear reactor site.

EUBM-200 - Laboratory Studies - Mannitol Meter

W. D. Fletcher, Manager, Chemistry

This task has been completed. The results have been reported in EURAEC-1722 - WCAP-3690-1, "Development of a Boron Concentration Meter - Technical Progress Report for the Period Ending September 30, 1966" and EURAEC-1778 WCAP-3690-2 "Development of a Boron Concentration Meter - Technical Progress Report for the Period Ending January 31, 1967".

EUBM-300 - Boron Concentration Meter - Design and Construction of
Prototype Mannitol Meter

W. D. Fletcher, Manager, Chemistry

INTRODUCTION

The Westinghouse Electric Corporation, Pressurized Water Reactor Division, has fabricated a boron meter prototype which employs the mannitol conductance technique for continuous monitoring of the reactor coolant boron concentration. This work has been sponsored by EURATOM Contract AT(30-1)-3690. Previous work completed under Sub-Task EUBM-200 of this program has shown that a chemical meter is, indeed, feasible and the results of this investigation have been presented in earlier reports.* That is, it was demonstrated that a meter could be built to analyze boric acid specifically, utilizing the well known complexing ability of mannitol to cause complete and quantitative ionization of the normally weak acid. Recent work has involved the design, construction, and bench testing of the prototype meter which has been accomplished under Sub-Task EUBM-300 of the development program.

This report is a detailed account of the design and construction phase of the work. It includes a complete description, operation, and bench testing results of the as-built chemical meter. Plans for installation and field testing of the prototype meter are also included.

The meter is to be evaluated for in-plant reliability and accuracy at the Saxton Nuclear Experimental Corporation's reactor plant. The evaluation will indicate areas of improvement required to render the first meter more suitable for plant use.

* EURAEC-1722 (WCAP-3690-1), "Development of a Boron Concentration Meter - Technical Progress Report for the Period Ending September 30, 1966", dated October, 1966.

EURAEC-1778 (WCAP-3690-2), "Development of a Boron Concentration Meter - Technical Progress Report for the Period Ending January 31, 1967", dated February, 1967.

Description of the Boron Meter

The boron concentration meter has been constructed almost entirely from commercially available components. The basic components along with a description and manufacturer are given in Table 1. Other components that were designed and constructed specifically for the meter are as follows:

- degasser for removal of dissolved gases such as hydrogen which are normally found in the reactor coolant and which could be released in the meter leading to erratic recording of the boron concentration.
- heat exchangers for temperature control of the mannitol and sample solutions shortly after entering the meter and before mixing.
- a cation resin column for removing such highly conductive species as lithium found in reactor coolant samples.
- a mixing chamber for rapid and complete mixing of the boric acid and mannitol solutions.
- conductivity cell holders to position the cells in a precisely controlled temperature environment.

All of these components, with the exception of the mannitol storage tank, are assembled in a standard 19" rack panel to form the boron meter. The meter measures the conductivity of a controlled blend of boric acid and mannitol solution providing a signal which is directly proportional to the boron concentration. To accomplish sample acceptance, flow control, reagent mixing, standardization, and conductivity measurements, a system has been fabricated as shown in Figure 1. The corresponding electrical and signal diagrams for the instrument are given in Figures 2 and 3 respectively.

The instrument is completely self contained and requires only a sample source, sample drain, and power source of 115 v, 60 cps AC. The instrument console has a local readout and a local strip chart recorder for visual and continuous

Table 1

Commercially Available Components

<u>Component</u>	<u>Description</u>	<u>Manufacturer</u>
Conductivity Monitor	Type RI3 Conductivity Indicator, AC Wheatstone Bridge Circuit 0-500 μ mho/cm range based on cell const. of 1.0 cm^{-1} , 115 v 60 cps, 0-1 VDC output	Beckman Instruments Inc.
Strip Chart Recorder	Speedomax H Strip Chart Single Pen Recorder, 0-10 mv input, 115 v 60 cps, chart speed 6 in./hour	Leeds and Northrup Co.
Dual Head Precision Metering Pump	Model "A" Cyclo/Fram Duplex Controlled Volume Diaphragm Pump, Teflon Diaphragm, 316 S/S Pump Heads, capacity 1.3 gph, strokes/min - 58	Yarway Corp.
Constant Temperature Bath	Forma-Temp Jr. - Bath and Circulator, Model-2095-I, Temp. Range - 15°C to 70°C , heat removal capacity - 1000 Btu/hr	Forma Scientific Inc.
Conductivity Cells	2 Small Glass Conductivity Cell with 316 S/S Threaded Fittings; cell constants of 0.1 cm^{-1} and 1.0 cm^{-1}	Beckman Instruments Inc.
Cabinet	Bud 19" Cabinet Rack, Panels, and Accessories	Bud Cabinets
Mannitol Mixing and Storage Tank and Agitator	Capacity 50 gal., Stainless Steel Construction, Sight Glass, Hinged Cover, Suction Piping with Strainer and Suction Valve. Agitator: Single Phase, 60 cps, 115 v with S/S Shaft and Impellor	Pittsburgh Process Equipment Company
Quick-Connects	Quick-Connects with Double-End Shut-Offs, 316 S/S, Tube to Tube for $1/4$ " O.D. Tube	Swagelok
Miscellaneous Fittings	Stainless Steel Unions, Connectors, Reducers, Solenoid Valves, Throttle Valve, Check Valves, etc.	-
Miscellaneous Electrical Components	Relays, Switches, Connectors, Blower Motor, etc.	-

FIGURE 1

BORON METER ~ FLOW DIAGRAM

FIGURE 2

BORON METER ~ ELECTRICAL DIAGRAM

FIGURE 3

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BORON METER ~ SIGNAL DIAGRAM

monitoring of the boron concentration. Instrument control is provided by a switch panel mounted on the console and, in addition, provisions are made for remote control of the meter. Remote readout of the boron concentration is also provided by a signal supplied from the console, to a digital volt-meter or recorder.

Photographs of the meter are presented in Figures 4 through 7.

Diagrams of the degasser unit and the mixing chamber are presented in Figures 8 and 9 respectively.

OPERATION OF THE BORON METER

Operating parameters of the boron meter are presented in Table 2.

The operating procedure for the meter is divided into separate categories which consist of solution preparation, initial startup, normal operation, and calibration.

Solution Preparation

Solutions required for the operation of the meter are a 14.5 w/o mannitol solution and a standard boron solution. The boron solution is prepared from boric acid and the concentration should be made up to be in the operational range of the meter.

The quantity of reagent grade boric acid needed to prepare the standard solution can be calculated by the following equation:

$$\frac{\text{Wgt. of H}_3\text{BO}_3}{\text{kg of Solution}} = \text{ppm B} \times 5.715 \times 10^{-3}$$

where the weight of boric acid is in grams.

After preparation of the standard solution, it must be analyzed to determine the exact boron concentration. The procedure for determining the boron concentration is as follows:

Figure 4

Boron Meter-Front View

Figure 5

Boron Meter-Rear View

Figure 6

Degasser Assembly

Figure 7

Manitol Mixing and Storage Tank

FIGURE 8

SECTION A~A

DEGASSER UNIT

FIGURE 9

MIXING CHAMBER

Table 2

Boron Meter - Operating Parameters

Power Requirements	110 v, 60 cps AC 2.2 K watts max.
Flow Rates	
Reactor Coolant to Meter	70 cc/min
Excess Reactor Coolant	35 cc/min
14.5 w/o Mannitol Solution	50 cc/min
Total Flow to Waste	120 cc/min
Chemicals Consumption	
Mannitol	7.3 gm/min
Cation Exchange Resin	8.1×10^{-3} cc/min*
Electrical Signal	
Remote Readout	0 - 1 VDC (requires shielded conductor)
Remote Control	110 v, 60 cps. (requires 10 conductor lead wire)
Control Signal	110 v, 60 cps
Chemical Renewal	
Mannitol Solution	Every 20 days**
Resin	Approximately every 20 days***

* Based on reactor coolant Li concentration of 3×10^{-4} molar.

** Based on operating 2 hours/8 hour shift.

*** Based on chemical criteria.

1. Prepare the following reagents:

- a. Standard buffer solution, pH 9.
- b. Sodium hydroxide. Dissolve approximately 3.2 grams of NaOH in water and dilute to one liter. Standardize as follows: dilute 5 ml of KAP to 100 ml and titrate to pH 8.5 with NaOH using the pH meter.

$$\text{NaOH Normality} = \frac{5 \text{ ml} \times \text{KAP Normality}}{\text{ml NaOH Used}}$$

- c. Potassium acid phthalate. Dry approximately 10 grams of KAP for one hour and allow to cool in a dessicator. Weigh to the nearest 0.1 mg. Dissolve in D.I. water and dilute to 500 ml. Calculate the normality as follows:

$$\text{KAP Normality} = \frac{\text{g KAP}}{102.114}$$

2. Standardize the pH meter with buffer, pH 9.
3. Dilute an aliquot of sample to 50 ml with demineralized water.

<u>Approx. ppm B</u>	<u>ml of Sample</u>
1000 - 16000	3
600 - 1000	5
400 - 600	7
200 - 400	10
100 - 200	25
50 - 100	50
0 - 50	100

4. Add 1 gram of mannitol and mix.
5. Titrate to pH 8.5 with sodium hydroxide using the pH meter.
6. Add an excess of mannitol and titrate to pH 8.5.

7. Calculate the boron concentration in the following manner:

$$\text{ppm B} = \frac{\text{ml NaOH} \times \text{N NaOH} \times 10,820}{\text{ml of Sample}}$$

The mannitol solution is prepared using Reagent Grade D-Mannitol and demineralized water by the following procedure:

1. Read the solution level in the mannitol tank and using the calibration curve (Figure 10) determine the solution volume, V_1 .
2. Subtract V_1 from 160 to obtain V_2 , the quantity of water to be added and fill the tank to the 42.8 cm mark.
3. Calculate the amount of mannitol to be added from

$$\text{Weight (Mannitol)} = 0.170 V_2$$

which is in kg units.

Convert to lbs. by multiplying by 2.2.

4. Weigh the amount of mannitol calculated above and add it to the tank.
5. Add 100 cc of reagent grade formaldehyde for each 100 l of water added in preparing the mannitol. (This is a preservative to prevent mildew and mold from forming in the solution.)
6. Mix the solution with the agitator until it is clear (about 15 minutes).
7. Remove the agitator from the tank and cover the lid opening with the form fitted insert that is provided.

After preparation of the 14.5 w/o mannitol solution, the solution concentration should be determined. A simple procedure for checking the mannitol concentration utilizes the conductivity principle employed by the meter. The procedure is as follows:

FIGURE 10
MANNITOL TANK CALIBRATION

1. Prepare a standard 3000 ppm B solution from reagent grade boric acid as indicated in the previous method.
2. Mix 50 cc of the mannitol solution with 50 cc of the standard boron solution.
3. Measure the conductivity of the mixture at 25°C and read the mannitol concentration from Figure 11.

This method is accurate to 0.05 w/o mannitol or 0.3%.

Initial Startup

In preparation for the initial startup of the boron meter, all piping and electrical contacts must be connected as shown in the preceding diagrams. This includes reactor coolant sample inlet line, standard inlet line, mannitol inlet line, and waste outlet line. The instrument should be connected to a 110 v AC, 60 cps power line and the control signal attached to the connection provided.

Once the meter has been connected and the solutions prepared, the constant temperature bath should be filled to the mark on the level indicator through the connection provided. At this point, the meter is ready for startup and the procedure is as follows:

1. Energize the meter by placing the main power switch on the console control panel, Figure 12, in the "on" position. The red light will indicate that power is being supplied to the instrument.
2. Adjust the pump controls so that a 0.7 cc boric acid/cc mannitol solution is obtained and lock them by means of the locking screws provided. This means that the boric acid side of the pump should be set at 35 cc/min and the mannitol side of the pump set at 50 cc/min.
3. Start the constant temperature bath operating with the controls provided on the bath. The main power, heater, refrigeration, and circulation pump switches should be in the "on" position. Adjust the temperature controller inside the cabinet such that the tempera-

MANNITOL DETERMINATION CALIBRATION CHART
FIGURE 11

W/D MANNITOL IN ORIGINAL SOLUTION
WITH 0.1% FORMALDEHYDE

FIGURE 12

BORON METER CONSOLE CONTROL PANEL

*~TOGGLE SWITCH

#~ INDICATOR LIGHT

NOTE:

CELL #1 MEASURES THE CONDUCTIVITY OF THE BORON SOLUTION AFTER MANNITOL ADDITION. CELL #2 MEASURES THE CONDUCTIVITY OF THE BORON SOLUTION PRIOR TO MANNITOL SOLUTION.

ture in the bath is 20°C. Allow ample time for bath to maintain this temperature.

4. Check to see that the switches inside the recorder and the conductivity monitor are in the "on" position and that each of these components are operating.
5. Adjust the flow control valve on the degasser assembly so that a level is maintained in the degasser with the metering pump in operation. The excess flow should be about 35 cc/min for a total inlet flow of 70 cc/min of reactor coolant solution.

Normal Operation

The boron meter is now ready for normal operation. The meter should be left in this condition with the main power "on", the bath maintaining a constant temperature, and the recorder and conductivity meter energized. The instrument can now be operated locally or remotely to read the boron concentration.

To determine the boron concentration, simply perform the following:

1. Start the pump by depressing the pump switch on either the local or remote control panels. The red light will indicate that the pump is operating. (NOTE: The instrument is provided with an interlock to prevent operation of the meter when the sampling system is inoperative. A switch inside the cabinet will permit overriding this interlock.)
2. Check to see that the standardize switch is in the "reactor coolant" position. This will be indicated by an amber light on the local and remote control panels.
3. Check to see that the cell selection switch is in the "cell #1" position on the local or remote control panels. This will be indicated by an amber light.
4. Read out the boron concentration by taking the digital voltmeter reading and converting it to ppm B from the set of calibration tables provided, or from the calibration curve shown as Figure 13.

Calibration

The boron meter is calibrated by the following:

1. With the pump operating, depress the "standardize" switch on either the local or remote console. The amber light should indicate "standard".
2. The boron meter should now be adjusted to read out in millivolts the value corresponding to the standard solution stored in the standard tank. This adjustment is made with the calibration dial located inside the door of the conductivity monitor

Another feature of the boron meter prototype is the ability to check the base line conductivity of reactor coolant solutions prior to mixing with mannitol. In this way, the ion exchange resin can easily be checked for depletion by comparing this conductivity value with determined conductivity values of pure boric acid solutions. These values can be obtained from Figure 14. The base line check is performed by depressing the switch labelled "cell" at either the local or remote location. An amber light will indicate that the reference conductivity is being measured.

Laboratory Evaluation of the Prototype Meter

Bench testing of the prototype was conducted to determine accuracy, time response, and reliability of the as-built meter. A system was constructed to provide a simulated reactor coolant source to the prototype meter. That is, a recirculating tank was set up in which various boron solutions could be prepared and directed to the meter for analysis. The results from the meter were then compared with boron concentration values from titration analyses. Also, the meter was run over long intervals to observe whether there was any electronic drifting or other unforeseen malfunctions. Another mode of operation consisted of examining the meter as it received a signal from a timer which automatically started and stopped the meter at intervals of one hour. The timer simulated the signal that would be provided from the sample booster pump at the Saxton facility.

A calibration curve was obtained from analysis of various boric acid solutions by the meter. These values are presented in Table 3. An equation was deter-

FIGURE 14

BORON METER OUTPUT FOR BORIC ACID SOLUTIONS WITH NO ADDED MANNITOL

Table 3

Boron Meter Calibration Data

Boron Concentration (ppm B)	Digital Voltmeter (Millivolts DC)
3188	801.3
2873	760.4
2651	734.8
1230	509.9
1221	507.0
998	461.8
913	440.2
528	336.8
355	274.6
114	153.0
57	107.0

mined to describe the boron concentration as a function of millivolt readings. This relationship was found to fit the expression

$$\text{ppm B} = 2.937 \times 10^{-3} (\text{millivolt})^{2.0779}$$

for meter conditions described in the previous section.* The correlation for the fit of this equation to the data was 0.99992 for boric acid concentrations from 350 ppm B to 3200 ppm B. For boron concentration less than 350 ppm, an expanded graphical analysis of the data was performed.

From the above expression, it follows that

$$\frac{\Delta \text{ ppm B}}{\Delta \text{ millivolt}} = 6.11 \times 10^{-3} (\text{millivolt})^{1.078}$$

will give the sensitivity of the meter in terms of change in boron concentration per change in millivolt reading. The following list can be prepared:

<u>Boron Concentration</u>	<u>Millivolt</u>	<u>$\Delta \text{ ppm B} / \Delta \text{ millivolt}$</u>
57 ppm B	107	0.9
114 ppm B	153	1.5
531 ppm B	337	3.2
1000 ppm B	462	4.6
1683 ppm B	593	6.0
2651 ppm B	735	7.6
3188 ppm B	801	8.4

The digital voltmeter output from the boron meter is readable to one tenth of a millivolt and readings were always reproducible to within one millivolt. Thus, the meter accuracy can be stated to be

<u>Boron Concentration</u>	<u>Accuracy</u>
50 ppm B	$\pm 0.5 \text{ ppm B} = \pm 1.0\%$
100 ppm B	$\pm 0.8 \text{ ppm B} = \pm 0.8\%$
500 ppm B	$\pm 1.5 \text{ ppm B} = \pm 0.30\%$
1000 ppm B	$\pm 2.3 \text{ ppm B} = \pm 0.23\%$ (Continued)

* $T = 20^\circ\text{C}$, $F_B/F_M = 0.7 \text{ cc B/cc M}$

(Continued)

<u>Boron Concentration</u>	<u>Accuracy</u>
1700 ppm B	$\pm 3.0 \text{ ppm B} = \pm 0.17\%$
2650 ppm B	$\pm 3.8 \text{ ppm B} = \pm 0.14\%$
3200 ppm B	$\pm 4.2 \text{ ppm B} = \pm 0.13\%$

The output signal has been completely free of noise during the bench testing. Long term drifting of electronics has not been noticed during the bench testing. The meter has run continuously for periods up to forty-eight hours with no observable drifting. The in-plant testing will provide additional data in this area.

The time response of the boron meter, for the conditions specified in the operating parameters is about three minutes for a step-change at the analyzer inlet. Faster response times can be obtained by increasing the flow rates to the meter. However, a trade-off must be made concerning mannitol consumption, resin replenishment, and disposal of waste solution, all of which will be increased with an increased flow rate. For a flow rate of 50 cc* of reactor coolant entering the meter, a change in millivolt output will be observed two minutes after the change, at the boron meter inlet.

Reliability information is not complete at present. The meter has run a total of over 300 hours, with no serious problems. Again, in-plant testing will provide more information in this area.

Installation at Saxton

The instrument will be installed in the auxiliary building of the Saxton Nuclear Experimental Corporation's reactor plant near the sample room. The meter will receive a reactor coolant sample from the plant sampling system downstream of the "let-down" valve and the regenerative heat exchanger. The sample will be provided at an approximately constant pressure by the sampling system booster pump. An electrical control signal from the booster pump controller will open a solenoid valve allowing the reactor coolant sample to enter the meter and,

* As opposed to 35 cc/min specified previously.

at the same time, start the instrument. Upon de-energizing the booster pump, the boron meter will shut off and the solenoid valve will close. The excess flow, that is, above that required for the analyzer (35 cc/min) will combine with the meter effluent and be directed to the waste disposal system. Piping arrangements, as well as the electrical control and signal leads, are illustrated in the simplified schematic in Figure 15.

Summary and Conclusions

Based on the foregoing description and characteristics, conclusions regarding the prototype meter are as follows:

1. The boron meter prototype has been completely assembled using commercially available components where possible and is presently operational.
2. The instrument requires trouble-free operation of three fundamental systems, which are chemical, mechanical, and electronic. All of which have proven to be quite reliable during the bench testing of the prototype.
3. Accuracy analysis of the data obtained from the laboratory evaluation has shown the following

<u>Boron Concentration</u>	<u>Accuracy</u>
100 ppm B	± 0.8 ppm B = $\pm 0.8\%$
1000 ppm B	± 2.3 ppm B = $\pm 0.23\%$
3200 ppm B	± 4.2 ppm B = $\pm 0.13\%$

which is less than the ± 2 ppm or $\pm 0.3\%$ * over the range specified for the operational meter.

4. Waste disposal requirements for fluids from the meter should not present any significant problem. Total liquid output from the meter is approximately 45 gallons per day.

* whichever is greater.

FIGURE 15

34

PIPING ARRANGEMENT FOR BORON METER

5. Cost of mannitol for the prototype meter will be approximately \$6500.00 per year of continuous operation. Based on operation of two hours per shift, the total cost would be \$1625.00 per year.
6. A change in boron concentration at the meter inlet is observed approximately three minutes later with a sample flow rate of 35 cc/min. The time response for a reactor coolant inlet flow rate of 50 cc/min is about two minutes.
7. Maintenance requirements will be the following based on operating two hours per shift:
 - Chemical renewal
 - Mannitol Solution Every 20 days
 - Resin Replacement Every 20 days
 - Recorder chart paper Every 27 days
8. The boron meter prototype will be installed for in-plant evaluation at the Saxton nuclear facility.

EUBM-400 - Evaluation of Prototype Mannitol Meter

W. D. Fletcher, Manager, Chemistry

Effort under this task has not yet been initiated.

EUBM-500 - Evaluation of the SENA Boron Meter

W. D. Fletcher, Manager, Chemistry

This effort has been completed and was reported in EURAEC-1972,
WCAP-3690-4 "Description and Evaluation of the Boron Concentration
Meter Utilized at the SENA (Franco-Belge) Reactor Plant".

EUBM-600 - Development of a Neutron Absorptiometer

V. Rajagopal, Manager, Instrumentation and Control Development

INTRODUCTION

Previous work on this type boron analyzer centered around the transmission of a thermal neutron beam through a slab of borated water or a linear geometry. Such a geometry, with a well collimated thermal neutron beam would obey the following equation

$$C = C_0 E^{-AX}$$

Where C is the counting rate for a given sample, C₀ is the counting rate for a sample containing no boron, E is the macroscopic cross section of the sample and is directly proportional to the boron concentration in the sample, X is the sample thickness, and A is a constant related to the area of the apparatus. Pursuing this linear model permitted a definition of counting rates required to obtain the defined accuracies, an estimate of the sample thickness to produce the required accuracy, and an estimate of the radiation shielding required for the system. The linear approach indicated that the characteristic would approach an exponential. For this reason, original test setups and concepts were based on using a non-linear circuit in the electronics system to achieve a direct readout of boron concentration. Later tests consistently showed a hyperbolic characteristic for counts versus boron concentration and because the electronics was implemented to read time to a preset count rather than counts over a fixed time, the function consistently approached a linear function without non-linear circuits.

As a result of this hyperbolic characteristic, the electronics was simplified to essentially a scaler timer which is offset from zero time by the time to a preset count in water and proportional to time thereafter. This being the case, no error is introduced in the electronics by virtue of synthesis of a non-linear function.

GENERAL DESCRIPTION OF THE NEUTRON ABSORPTION METER

The neutron meter consists of two parts. The sample tank, and the electronics readout drawer. Figure 16 is a photograph of the entire system.

Figure 17 is a drawing of the sample tank showing the essential parts. The borated sample water flows through a heat exchanger in the tank, then through the annulus surrounding the neutron detector and back into the supply via the outlet. The tank, which is 30 inches in diameter and stands 44 inches to the top cover, contains water which acts as a radiation shield and temperature stabilizer for the annulus water as well. Three heaters, equally spaced around the tank and approximately 3 inches from the bottom act to maintain the shield water temperature constant by means of a controller located on the side of the tank. The heat exchanger through which the borated water passes transfers heat either into or out of the sample water to condition it prior to entry into the annulus. The sample water is held within $\pm 4^{\circ}\text{F}$ for any combination of flow and inlet temperature by this means. Normal controller cycling causes less than a 2°F variation in the annulus temperature, and this variation is included in the $\pm 4^{\circ}\text{F}$ figure given above.

Also included as a part of the sample tank, and shown on the figure, are the source, detector, high voltage power supply, and pre-amplifier; all of which will be discussed in detail in later sections. The electronics readout drawer, is also shown in the photograph in Figure 16.

COMPARISON OF THE NEUTRON ABSORPTION METER WITH DESIGN SPECIFICATIONS

The following are the design specifications to which the meter was designed.

1. Ranges and Accuracies: 25-500 ppm ± 2 ppm; 250-1250 ppm ± 5 ppm; 1000-2500 ppm ± 5 ppm; 2500-5000 ppm ± 25 ppm.
2. Readout: digital in terms of ppm of natural boron (based on 19.7% of B^{10}) for visual indication and for a process computer.
3. Readout Option: an additional analog signal for a recorder.

Figure 16

Boron Concentration Meter Based on the Neutron
Absorption Principle

PARTS ON TANK ROTATED INTO SECTION

Figure 17. General Layout of Neutron Absorption Meter

4. Operating Conditions - pressure: 15 to 150 psi
temperature: 70 to 140°F
sample flow rate: 0.5 to 2 gpm.
5. Distance to Readout from Sample Location: up to 1000 feet.
6. Shielding: dose rates near the cell should be less than 1 mr/hr.
7. Calibration: facilities should be provided to check the electronics and to adjust overall calibration based on chemistry measurements and/or metallic shim corresponding to 100 ppm of boron change.
8. Calibration Option: check of overall calibration by use of pure water and metallic shims (one for each range) without chemistry support.
9. Drift: equipment drift should be less than 10 ppm in a one week period.
10. Maximum Time Interval Between Readouts: five (5) minutes.

Following is a summary of the bench test results on the model.

1. Accuracy

25-500 ppm $\pm$ 3 ppm; 250-1250 ppm $\pm$ 5 ppm; 1000-2500 $\pm$ 5 ppm; 2500-5000 ppm $\pm$ 7.1 ppm. One additional accuracy point was investigated. With pure H₂O the accuracy is $\pm$ 2 ppm. The model met the accuracy requirements everywhere except in the 50 to 500 range.

2. Readout

The readout of the model is on a four digit nixie tube readout on the front of the electronics chassis. Also available at the rear of the chassis is the readout in terms of a BCD output code which can be used to drive a printer or computer. Caution should be observed in the use of this output so as not to overload the operating circuits.

3. Readout Option

No optional output is included on the model, however, an analog signal proportional to the indication can be derived from the BCD output.

4. Operating Conditions

Pressure - the sample water circuit has been tested to 150 psi

Temperature - a sample water variation of 70 to 140°F

Sample flow rate - the model can accept any flow rate up to 2 gallons per minute.

For best accuracy, however, the flow rate should be held as low as possible. Since the instrument reads out approximately every 200 seconds the sample water need only be changed in this time. The sample system holds approximately 2 liters so a flow rate of 0.2 gpm will change the water in the annulus as often as the instrument can read. Flow rates in excess of this will cause the annulus temperature to fluctuate and, therefore, add error without adding anything in terms of performance.

5. Distance from Sample Tank to Readout

The distance from the sample tank location to the readout chassis can be anywhere from 0 to 1000 ft. The pre-amplifier gain adjust must be used to adjust the operation of the model for the specific length of cable. The cable between the sample tank should have a characteristic impedance of 75 ohms and low capacitance. RG 59U cable is advised for this purpose. Standard BNC connectors are used to terminate the cable at both ends.

6. Shielding

A dose rate survey was made around the tank with a 10 curie source installed in the source chamber. The dose rates measured are as follows:

	<u>Maximum Top or Bottom</u>	<u>Maximum on Sides</u>
Fast Neutrons	25 n/cm ² -sec.	20-22 n/cm ² -sec.
Thermal Neutrons	90 n/cm ² -sec.	60 n/cm ² -sec.
mr/hr	2 mr/hr	1.5 mr/hr

These dose rate figures will be reduced directly as the source size. For a 5 curie source the maximum dose rate on the surface of the tank will, therefore, be less than 1.0 mr/hr.

7. Calibration

A calibration sleeve can be slipped down around the detector without taking the system out of operation. This calibration sleeve is equal to approximately 100 ppm. It can be used for both setup and calibration.

8. Calibration Option

The nature of the operation of the system precludes errors in one part of the instrument range without error on all ranges. As such, no multiple range calibrations are required.

9. Drift

The long term drift on the equipment is expected to be within specifications. Twenty-four hour drift tests have been conducted. Long term drift did not show up on these tests. Field testing will be required in this area.

10. Maximum Time Between Readings

The maximum time between readouts on the unit is approximately 3.5 minutes. Readings can be obtained with some loss of accuracy at 5 times the normal test rate.

ANALYSIS OF OPERATING CHARACTERISTICS OF BORON CONCENTRATION METER

This section correlates, analyzes, and attempts to explain the performance of several boron concentration meters, some of which have been the subject of earlier study.

All of the above mentioned meters use neutron absorption by boron as the basic mechanism for measuring boron concentration. Each consists of a neutron detector surrounded by an annulus containing the boron solution to be measured, a radioactive neutron source outside the annulus, and a neutron moderator for thermalizing the neutrons. The analysis in this section converts data relating "neutron counting rate" to "boron concentration" to data relating "time-to-achieve a fixed number of counts, N_0 " to "boron concentration". An explanation is developed for the resulting relationship.

The work presented here is limited to: annulus thicknesses in the range 7/16 inch to 3/4 inch; boron-water solutions with the boron concentration in the range 0 to 5000 ppm; neutron-source to annulus spacings from 0 to 1-1/2 inch; and water or paraffin moderators ranging in size from a block 12 inches by 12 inches by 6 inches to a cylinder 22 inches in diameter by 26 inches high. Experimental data is used in the analysis of the relationship between "time-to-achieve N_0 counts" and "boron concentration". Theoretical arguments are used to explain the observed relationship.

The purposes of this section are two-fold: first, to demonstrate that a linear relationship may be expected between "time-to-achieve N_0 counts" and "boron concentration"; second, to demonstrate that such a relationship is reasonable.

Data from Earlier Concentration Meters

1. DeFord and Braman Data

DeFord and Braman⁽¹⁾ present data on a boron concentration meter whose annulus is the concentric region between standard 1 inch and 2 inch polyethylene pipes. Figure 18 shows their arrangement. The neutron

¹Donald D. DeFord and Robert S. Braman, "Study of Neutron Absorptiometry and Its Application to the Determination of Boron," Analytical Chemistry, Volume 30, p. 1765 (1958).

Figure 18. Arrangement of Components for Boron Concentration Determination by DeFord and Braman

detector was a 1 inch diameter by 27 inch long boron trifluoride counter. The neutron source was 10 mr radium-beryllium. The moderator was a block of paraffin 12 inch x 12 inch x 6 inch.

The data on counting rate versus boron concentration are shown in Table 4. Boron concentrations are in gram atoms per liter. The counting rate is tabulated as the number of counts recorded in a 10 minute counting period.

Table 5 shows the same data converted to the units used in this report. The conversion from gram atoms per liter to ppm was made using the relation 1 gram atom per liter equals 10,800 ppm.

The data from Table 5 are plotted in Figures 19 and 20. Figure 19 shows the entire range of the available data. The relationship between T, the time to accumulate 10^5 counts, and C, boron concentration, is not linear over this broad range. However, there is a suggestion of linearity in the range of interest in this report, 0-5000 ppm.

This suggestion of linearity is confirmed in Figure 20 where the data available in the range of interest is plotted on an expanded scale. A straight line has been eye-fitted to the data points.

EASTMAN DATA

Four sets of data are available from Eastman's work.^(2,3) These data are given by the four curves shown in Figures 21 and 22.

The data shown in Figure 21 are taken using an arrangement similar to that shown in Figure 18. The annulus thickness of the absorption cell, designated A, was 1/2 inch.

² R. Eastman, "Continuous Measurement of Soluble Neutron Poison Concentration" from WCAP-3708, "Large Closed-Cycle Water Reactor Research and Development Program Progress Report for the Period December 1, 1961 to February 28, 1962", N. R. Nelson.

³ R. Eastman and J. W. Power, "Continuous Measurement of Soluble Neutron Poison Concentration" from WCAP-3710, "Large Closed-Cycle Water Reactor Research and Development Program for the Period March 1, 1962 to June 30, 1962", N. R. Nelson.

Table 4

Counting Rate Versus Concentration Data by DeFord and Braman

<u>Boron Concentration</u> (Gram atoms per liter)	<u>Counts Recorded in 10 Minutes</u> (Counts $\times 10^{-3}$)
0	297.0
0.01739	280.8
0.05277	254.2
0.1021	224.8
0.1182	217.0
0.2362	169.3
0.3169	149.6
0.6338	102.7
1.2677	65.6
2.5353	40.65

Table 5

Time to Accumulate 10^5 Counts Versus
Boron Concentration, DeFord and Braman Data

<u>Boron Concentration</u> (Grain atoms per liter)		<u>Count Rate</u> ($\text{Min}^{-1} \times 10^{-2}$)	<u>Time to Accumulate 10^5 Counts</u> (Sec)
0	0	297.0	202
0.01731	188	280.8	213
0.05377	570	254.2	236
0.1021	1,103	224.8	267
0.1182	1,278	217.0	276
0.2362	2,550	169.3	354
0.3169	3,420	149.6	401
0.6338	6,840	102.7	584
1.2677	13,680	65.6	915
2.5353	27,350	40.65	1,480

Figure 19. Time to Accumulate 10^5 Counts Versus Boron Concentration, DeFord and Braman Data

Figure 20. Time to Accumulate 10^5 Counts Versus Boron Concentration, DeFord and Braman Data

Figure 21. Counting Rate Versus Boron Concentration for Cell A, Eastman Data, 1/2-Inch Annulus

Figure 22. Counting Rate Versus Boron Concentration for Cell B, Eastman Data, 7/8-Inch Annulus

Table 6 shows data read from Figure 21. In addition, the times to accumulate 100,000 counts are shown.

Figure 23 shows a plot of the data from Table 6. A straight line has been fitted to the data points. It appears that there is a linear relationship between T and C.

The other three sets of data available from the Eastman work⁽³⁾ are shown in Figure 22. Again, the arrangement was similar to that shown in Figure 18. The annulus thickness was 7/8 inch for the absorption cell designated as Cell B. The distance from the neutron source to the outer wall of the sample cell was used as a parameter in these experiments. Three separation distances were used giving the three curves shown in Figure 22.

Table 7 shows the data on count rate versus boron concentration as read from Figure 22. In addition, the times to accumulate 100,000 counts are shown. This data has been plotted in Figures 24 and 25 and eye-fitted with a straight line indicating the validity of a linear relationship between T and C for the 7/8 inch annulus with source-to-cell wall spacings of 5/8 inch and 1-1/2 inch. The data points for the 3 inch spacing as shown in Figure 26 do not appear to be along a straight line.

Current Data

The boron concentration meter developed under this program differs in three ways from the earlier concentration meters. First, the height of the sample cell and of the moderator has been increased substantially to eliminate the possibility of neutrons reaching the detector without passing through the sample cell. Second, the neutron source strength has been increased by about a factor of 100 to reduce the statistical fluctuations in the counting rate, and thus improve the accuracy of the meter. Third, the output is in terms of time to accumulate a fixed number of counts rather than counting ratio.

³R. Eastman and J. W. Power, "Continuous Measurement of Soluble Neutron Poison Concentration" from WCAP-3710, "Large Closed-Cycle Water Reactor Research and Development Program for the Period March 1, 1962 to June 30, 1962", N. R. Nelson.

Table 6

Time to Accumulate 100,000 Counts Versus Boron Concentration,
Eastman Data on Cell A with 1/2 Inch Annulus

<u>C</u> <u>Boron Concentration</u> (ppm)	<u>R</u> <u>Count Rate</u> (Min ⁻¹)	<u>T</u> <u>Time to Accumulate 100,000 Counts</u> (Sec)
11/22 data 0		
0	74,600 $\pm$ 157	80.5 $\pm$ 0.2
100	73,300 $\pm$ 156	81.9 $\pm$ 0.2
250	71,600 $\pm$ 153	83.8 $\pm$ 0.2
500	67,900 $\pm$ 150	88.5 $\pm$ 0.2
1,000	62,300 $\pm$ 144	96.3 $\pm$ 0.2
1,500	57,400 $\pm$ 138	104.8 $\pm$ 0.3
11/21 data 0		
0	74,800 $\pm$ 157	80.3 $\pm$ 0.2
100	73,600 $\pm$ 157	81.5 $\pm$ 0.2
250	71,300 $\pm$ 154	84.1 $\pm$ 0.2
500	68,100 $\pm$ 150	88.1 $\pm$ 0.2
1,000	62,500 $\pm$ 145	96.0 $\pm$ 0.2
1,500	57,700 $\pm$ 139	104.0 $\pm$ 0.2
11/27 data		
0	75,200 $\pm$ 158	79.9 $\pm$ 0.2
100	73,000 $\pm$ 156	82.2 $\pm$ 0.2
250	71,200 $\pm$ 154	84.4 $\pm$ 0.2
500	68,000 $\pm$ 151	88.3 $\pm$ 0.2
1,000	62,600 $\pm$ 145	95.9 $\pm$ 0.2
1,500	58,000 $\pm$ 139	103.5 $\pm$ 0.3

Figure 23. Time to Accumulate 10^5 Counts Versus Boron Concentration, Eastman Data, Cell A, 1/2-Inch Annulus

Table 7

Time to Accumulate 100,000 Counts Versus Boron Concentration,
Eastman Data on Cell B with 7/8 Inch Annulus

<u>Boron Concentration</u> (ppm)	<u>Count Rate</u> (Min ⁻³)	<u>Time to Accumulate 100,000 Counts</u> (Sec)
-------------------------------------	---	---

5/8 inch spacing from neutron source to cell wall

0	54,500 ± 234	110 ± 0.5
500	46,500	129.1
1,000	39,750	151.2
1,500	34,750	173
2,000	31,000	194
3,000	25,250 ± 159	238.5 ± 1.5

1-1/2 inch spacing from neutron source to cell wall

0	39,700	151
500	34,500	176.5
1,000	29,000	207
1,500	25,500	235
2,000	21,000	286
3,000	18,500	324

3 inch spacing from neutron source to sample wall

0	17,000 ± 130	353 ± 3
500	14,750 ± 121	406 ± 3
100	13,000 ± 114	461 ± 4
1,500	11,000 ± 105	545 ± 5
2,000	9,000 ± 95	666 ± 7
3,000	8,250 ± 91	728 ± 8

Figure 24. Time to Accumulate 10^5 Counts Versus Boron Concentration, Eastman Data, 7/8-Inch Annulus, 5/8-Inch Spacing from Source to Cell Wall

Figure 25. Time to Accumulate 10^5 Counts Versus Boron Concentration, Eastman Data, 7/8-Inch Annulus, 1-1/2 Inch Spacing from Source to Cell Wall

Figure 26. Time to Accumulate 10^5 Counts Versus Boron Concentration, Eastman Data, 7/8-Inch Annulus, 3-Inch Spacing from Source to Cell Wall

This change was made to provide for a direct readout of boron concentration.

Figure 27 shows the arrangement of components used for experiments performed during the development of the concentration meter. The neutron detector was B^{10} lined unit. Plastic rods filled the voids below and above the detector. Concentric tubes were used to form the sample cell. Three annulus thicknesses were used: 0.473 inch, 0.600 inch, and 0.875 inch. The neutron source was 10 curies of plutonium mixed with beryllium. The source was always positioned adjacent to the outer wall of the sample cell. A plastic rod filled the void above the source to provide neutron moderation and prevent fast neutron leakage. The moderator was water contained in a 55 gallon drum. Clear plastic was used as the construction material.

The data obtained with this arrangement is shown in Figures 28, 29, and 30. The number of counts accumulated, N , is fixed for each curve, but varies from curve to curve. N is in the order of 10^6 counts.

The data for the 0.473 inch annulus (Figure 28) does not display a linear relationship between T and C .

The data for the 0.600 inch annulus (Figure 29) does display a linear relationship to $C = 3500$ ppm. The point at 5,000 ppm lies below the extrapolation of the linear data.

This curve was the first indication that a linear relationship might be expected and was the provocation of the data examination presented in this report.

The data for the 0.875 inch annulus displays a linear relationship between T and C over the entire range of interest 0 to 5,000 ppm.

DISCUSSION OF EXPERIMENTAL DATA

The data of DeFord and Eastman as represented in Figures 24 and 25 displays a linear relationship between T and C over the concentration range from 0 to 3,000 ppm. This relationship holds for annulus thicknesses ranging from less than 1/2 inch (DeFord) to 7/8 inch (Eastman) and for source to cell wall spacings up to 1-1/2 inches. All of this data was taken with a rather small moderator block, 12 inches x 12 inches x 6 inches.

Figure 27. Arrangement of Components for Experiments for Boron Concentration Meter

Figure 28. Time to Accumulate N Counts Versus Boron Concentration for 0.473-Inch Annulus

Figure 29. Time to Accumulate N Counts Versus Boron Concentration for 0.600-Inch Annulus

Figure 30. Time to Accumulate N Counts Versus Boron Concentration for 0.875-Inch Annulus

The complete DeFord data displayed in Figure 19 shows that a departure from linearity can be expected at concentrations above 3,000 ppm. Such a departure may be caused by thermal neutrons leaking from the upper and lower surfaces of the moderator block. Figure 31 shows the neutron flux⁽⁴⁾ as a function of distance from a point neutron source immersed in water. The distribution would be about the same in paraffin. The upper and lower surfaces in Figure 18 are only 3 inches from the source. Hence an appreciable neutron leakage flux can be expected from these surfaces. These neutrons can reach the neutron detector without passing through the sample cell. At low concentrations of boron in the sample cell, the leakage neutrons account for only small fractional increases. This increase in importance of the leakage neutrons with increase in boron concentration would cause the T versus C curve to bend in the direction shown in Figure 19.

The Eastman data for 3 inch spacing between the source and cell wall as shown in Figure 26 does not appear to give a linear relationship between T and C. Figure 31 shows that the thermal neutron flux at the detector has been greatly reduced by moving the source away. Hence it would be expected that undesired leakage neutrons would interfere with proper operation of the concentration meter.

The present data improves in linearity as the annulus thickness is increased from 0.473 inch, Figure 28 to 0.875 inch, Figure 30. The 0.473 inch annulus is too thin. The 0.600 inch annulus gives a good linear relationship up to 3,600 ppm. The 0.876 inch annulus gives a linear relationship between T and C over the entire range from 0 to 5,000 ppm.

On the basis of the experimental data it is clear that a linear relationship between T and C of the form

$$T = T_0 (1 + \beta C) \quad (1)$$

⁴Neutron Sources and Their Characteristics," Technical Bulletin NS-1, Atomic Energy Ltd., Commercial Products Division.

Figure 31. Distribution of Thermal Neutrons from a Point Source Immersed in Water

can be expected under a variety of geometries. The annulus thickness should be at least 0.6 inch and preferably 0.875 inch. When the moderator and cell height are small, as in the DeFord and Eastman geometry, leakage neutrons may limit the linear range to 0 to 3,000 ppm.

THEORETICAL CONSIDERATIONS ON THE LINEAR RELATIONSHIP BETWEEN T AND C

It is not obvious that a linear relationship should exist between T and C. The purpose of this section is to make this relationship plausible.

When a neutron absorbing object is placed in a neutron moderating region, the neutron flux about the object is reduced. For example, when the borated water annulus is placed next to the neutron source, the neutron flux may be depressed from a distribution such as shown in Figure 31 to one as shown in Figure 32. The depth of the flux depression will be dependent on the boron concentration in the annulus. The average flux on the surface of the annulus, ϕ_s can be related to the average flux in the same location without boron present, ϕ_o by a flux depression factor, F.

$$\phi_o = F\phi_s \quad (2)$$

The neutron counting rate in the detector, R, should be proportional to the surface flux times an exponential attenuation factor which accounts for absorption of neutrons in passing through the annulus. Thus

$$R = \frac{\xi\phi_o e^{-\frac{\mu x}{2}}}{F} = \frac{R_o e^{-\frac{\mu x}{2}}}{F} \quad (3)$$

where ξ is a constant related to the efficiency of the counter for detecting neutrons, μ is the absorption coefficient of boron in cm^2/gm , $\frac{x}{2}$ is the thickness of the annulus in gm/cm^2 and R_o is the counting rate when there is no boron in the annulus, i.e., $\frac{\mu x}{2} = 0$.

Figure 32. Depressed Neutron Flux Distribution Around Annulus Filled with Borated Water

An analytical expression for F is needed. Such an expression does not exist for the geometry used in boron concentration meters. However, Bothe⁽⁵⁾ has developed an expression for F, a spherical shell of radius R. We shall use his expression as a rough approximation to the correct one. His expression⁽⁶⁾ is

$$F = 1 + \frac{\alpha}{2} \left[\frac{3R}{2\lambda_{tr}} \frac{L}{R+L} - 1 \right] \quad (4)$$

where λ_{tr} is the transport mean free path (0.425 cm for water). L is the neutron diffusion length (2.76 cm in water), and

$$\alpha = 1 - e^{-\mu x} (1 - \mu x) + \mu^2 x^2 \text{Ei}(-\mu x)$$

in which μ is the neutron absorption coefficient and x is the total absorption thickness, and Ei (- μx) is the "exponential" integral function available in Tables.⁽⁷⁾

Using Bothe's expression for F, the counting rate to be expected in the boron concentration meter is

$$R = \frac{R_o e^{-\frac{\mu x}{2}}}{1 + K \{1 - e^{-\mu x} (1 - \mu x) + \mu^2 x^2 \text{Ei}(-\mu x)\}} \quad (5)$$

where

$$K = \frac{1}{2} \left[\frac{3R}{2\lambda_{tr}} \frac{L}{R+L} - 1 \right] \quad (6)$$

⁵W. Bothe, "Zur Methodik der Neutronensonde," Z. Physik, Vol. 120, p. 437, (1943); English translation in CP-2964, (1945).

⁶L. F. Curtis, "Introduction to Neutron Physics", D. Van Nostrand, Princeton, New Jersey, (1959), p. 148.

⁷E. Jahnke, F. Emde, and F. Losch, "Tables of Higher Functions", McGraw Hill Book Company, New York, (1960).

Multiplying the numerator and denominator by $e^{\frac{\mu x}{2}}$, expanding the resulting exponential terms in series, and collecting terms up to order $\mu^2 x^2$ the rate becomes

$$R = \frac{R_o}{1 + \mu x \left(\frac{1}{2} + 2k\right) + \mu^2 x^2 \left\{\frac{1}{8} - k/2 + kEi(-\mu x)\right\}} \quad (7)$$

The last term in the denominator is largest when the boron concentration is largest. For 5,000 ppm boron and an annulus thickness of 0.6 inch, this term contributes only 16% to the value of the denominator. Hence, this term will be neglected. Then R becomes

$$R = \frac{R_o}{1 + \mu x \left(\frac{1}{2} + 2k\right)} \quad (8)$$

Now μx is proportional to boron concentration, C, and k is a constant, so R may be rewritten as

$$R = \frac{R_o}{1 + \beta C} \quad (9)$$

where

$$\beta = \left(\frac{1}{2} + 2k\right) \text{ and } C = \mu x$$

This expression for counting rate as a function of boron concentration can be used to determine the time, T, required to accumulate N counts,

$$T = \frac{N}{R_o} (1 + \beta C) \quad (10)$$

Letting T_o be the time required when $C = 0$,

$$T = T_o (1 + \beta C) \quad (11)$$

This is the relationship which is observed experimentally, Equation (1).

The preceding theoretical analysis cannot be expected to produce an accurate value of β because the flux depression factor used was for a spherical shell in a non-uniform flux. However, the analysis does demonstrate the plausibility of the linear relationship between T and C.

CONCLUSIONS

The following conclusions can be drawn from this discussion:

1. Experiments show that a linear relationship exists between the time, T, to achieve a fixed number of counts and the boron concentration, C, in the annulus cell for a variety of experimental geometries.
2. Theoretical arguments can be made which indicate that such a relationship is plausible.
3. For 12 inch x 12 inch x 6 inch moderator block, the linear relationship holds for annulus thickness between 1/2 inch and 7/9 inch and for concentrations below 3,000 ppm.
4. For large moderator volumes, e.g. 22 inches diameter x 28 inches high, the relationship improves in linearity as the annulus thickness is increased from 0.473 inch to 0.600 inch to 0.875 inch. At 0.876 inch the linear relationship is very good up to 5,000 ppm.

DEVELOPMENT PROGRAM RESULTS

Construction and Initial Experiments

Figure 33 is a sketch of the jig which was constructed to perform the initial experiments on neutron attenuation. All of the parts in the jig were made of lucite and the entire assembly was made to fit into a standard 55 gallon drum. The source tube and source were fixed in location, and the experiments conducted by changing the size of the annulus by changing the annulus assembly. Four annuli were made with the following outside diameters 2.5, 3.5, 4.5, and 5.5 inches. The detector tube and detector fit into the annuli cups and were centered by a centering pin at the bottom of the annulus cup. The

Figure 33. Jig for Neutron Absorption Experiments for the Boron Concentration Meter

outside diameter of the detector tube therefore, made up the inside diameter of the annulus.

Various boron concentrations were made up by dissolving Borax in distilled water to make a 5,000 ppm master solution and then making a series of dilutions by weight. In this manner the following concentrations were obtained 5,000, 1,250, 625, 312.5, 156.25, and 78.125 ppm. A second master was mixed of 3,500 ppm and a second series of dilutions provided 1,750, 875, 437.5, 218.75, 109.375, and 54.687 ppm. Tests were conducted by filling the annulus with these solutions in rotation and reading the count rate through the solution.

In the early experiments standard electronics were used. Figure 34 is a block diagram of the system listing the equipment which was used. The results of the tests on this setup were in general agreement with the expectations per the physics analysis,⁽⁸⁾ however, the results were masked somewhat by the drift and noise in the electronics circuits. The discriminator, which was tube type was replaced by a tunnel diode discriminator. In addition, the pulse amplifier was replaced. Finally the scaler timer was replaced with an electronic counter.

From this setup curves were generated of counts versus boron concentration, an example of which is shown on Figure 35, for the various annuli and these were compared to an exponential curve to determine the magnitude of the non-linearity problem. At this same time, checks were made on the stability of the system by accumulating a significant number of readings for each concentration and determining the standard deviation. Comparison between the standard deviations of the measured values confirmed that the pulse distribution was as expected, Normal or Gaussian. This confirmed the operation of the electronics system. During this period in the development program, the measurements were all made in counts/unit time.

⁸J. E. Faulkner, "Physics Considerations in the Design of a Boron Concentration Analyzer", WANL TME-1770, Westinghouse Astronuclear Laboratory Report.

Figure 34. Block Diagram of Electronics for Neutron Attenuation Experiments

Figure 35. Boron Concentration Meter Breadboard System
Counts Versus Boron Concentration

Breadboard Linear Electronics

A scaler-timer breadboard was constructed using microelectronic circuits. Using this breadboard, two modes of operation became possible. The unit would count the input pulse over a selected time period, or measure the time for the counter to reach a preselected count. Data was taken on this system for both modes of operation with a 0.6 inch annulus and the plot of time to a preset count curve approximated a straight line. Data was taken and curves generated for the 0.473 and a 0.875 in annuli. The results of these tests are shown on Figure 36 and 37.

The counting circuit accomplishes the following: after a preset time has past, i.e., the time for the count to reach a preset count level with water in the annulus, 50 cycles/second is gated into the quasar unit. The quasar unit accumulates the 50 counts per second until the counter reaches the preset count level at which time it stops and holds this count. By selecting the preset count, the preset time, and the input count rate, the readout on the display is directly in parts-per-million of boron in the annulus.

Once the system is initially setup, the preset count and preset time are fixed (hard wired in) and the count rate is then used to calibrate the system. Tests were made on the system at this point in the program to insure that the variation in the output indication was correct, that is, this variation was consistent with the normal pulse distribution from the source. In addition, the stability (24 hours) of the breadboard was checked. All of these were satisfactory and showed that the operation of the breadboard was satisfactory.

Model Evaluation

The sample tank can be located as far as 1,000 feet from the electronics readout and for this reason the high voltage power supply for the detector and a preamplifier to amplify the detector output pulses were placed on the top of the annulus assembly. This keeps the detector cable leads short.

Figure 36. Boron Concentration Meter Counts Versus Boron Concentration for Various Annulus Thicknesses

Figure 37. Boron Concentration Meter Breadboard System
Time to Preset Count Versus Boron Concentration
for Various Annulus Thickness

The preamplifier output is transformer coupled to the line to prevent noise pickup in the signal return via grounds at both ends of the long line.

The 60 cycle input for the high voltage regulator is full wave rectified and filtered and fed to a pair of microelectronic voltage regulators. Voltage regulator "B" supplies the -10VDC to the preamplifier while voltage regulator "A" drives a conventional DC to DC inverter and doubler circuit. The output of the voltage doubler is filtered and supplied the high voltage to the detector. The power supply has the following characteristics:

Output

Voltage:	+700 to +900 VDC
Current (HV):	up to 2 milliamperes
(10V):	up to 60 milliamperes
Line Regulation:	Better than 0.5% for line voltage
Temperature:	0.1% (0 to 75°C)
Ripple and Noise:	Less than .003%
Overload:	Both supplies are current limited to protect against load faults.

The power supplies were tested to insure they meet all of the above characteristics except for a temperature test over the full range. The temperature of the entire annulus system is maintained at approximately 50°C via the temperature control in the tank. No changes were observed in either power supply with changes in tank temperature.

The card mounted preamplifier is located in the same chassis with the power supply. The circuitry for this amplifier is conventional, it uses RC coupled amplifiers, each stage of which has a gain of approximately 4. The output stage is an emitter follower which drives the isolating pulse transformer. The turns ratio on the transformer is 1 to 4. The potentiometer in the emitter circuit of the follower provides a gain adjustment. This

adjustment is used to produce approximately a 0.5 volt pulse height at the end of the long line cable. Once it is set for a given cable, it will not be changed.

The other assembly for the boron meter is the electronics chassis. This chassis contains the power supplied to drive the nixie tube readout and provide power for the digital logic circuits and the logic circuits themselves, including the pulse height discriminator. All of the logic circuits are card mounted in the chassis. Figure 38 is a block diagram of the logic circuits. Modules A through D are binary counters, the A and B units make up the eight decade counter and C and D, the eight decade count down circuit from the 100 kc oscillator, makes up the timer.

Three modes of operation are selectable by means of the mode control switch, Events per 10 seconds, ppm, and Time. In the Events per 10 seconds position, the readout indicates the total counts from the discriminator per 10 seconds. In this mode, the system operates as a conventional electronic counter. In the Time mode, the readout displays the time in seconds to reach the preset count. This preselected count is derived from the counters via Gate E_2 from B_3 of the counter string. In the ppm mode, which is the normal mode of operation, the readout displays parts per million boron directly. Figure 39 is a photograph of the entire electronics rack.

All of the assemblies of the boron meter were tested separately, and these tests compared with the operation of the like unit in the breadboard system. The checkout of the system has resulted in at least 100 hours operating time on the entire system, and infant mortalities which could have occurred have been weeded out.

MODEL TESTING AND TEST RESULTS

Circuit Modifications

As a result of the preliminary trouble shooting tests, the following changes were made in the meter model:

Figure 38. Logic Circuits Block Diagram Boron Concentration Meter

Figure 39

Electronic Readout Chassis Boron Concentration Meter

1. Installation of a new thermostat controller for regulating tank temperature. This controller has a dead band of about $1/2^{\circ}\text{F}$ and maintains annulus temperature to within 1°F under steady state conditions.
2. Encapsulation of the discriminator card to provide thermal insulation from ambient air current gradients.
3. Replacement of potentiometer adjustment controls of low voltage and detector high voltage power supplied with fixed precision resistors.
4. High voltage inverter and bleeder resistors changed to precision low temperature coefficient types.
5. Elimination of detector and preamplifier grounds from the tank.
6. Rework of grounding of pulse amplifier card and socket to eliminate ringing of output pulse.
7. Operation of entire system on a regulated supply line.

Final Meter Checkout

The test setup shown in Figure 40 was used to obtain data for the final laboratory checkout of the boron meter. Several tests were performed. These tests confirm the stability of the system, the temperature sensitivity of the tank, and the linearity of the system.

During the stability tests, the temperature of the tank was held constant, and readings over a thirty minute period were taken. For 2,000 and 800 ppm test solutions, the maximum deviations were ± 10 ppm and ± 4 ppm, respectively.

The temperature coefficient was found to be higher than the calculated value. The tests show the coefficient to be -4.5 ppm/ $^{\circ}\text{F}$. This indicates that an extreme temperature transient (much worse than would be expected in actual

Figure 40. Boron Concentration Meter Test Set-Up

operation) could change the output of the meter from the true value by less than ± 2.2 ppm. Under normal operating conditions the variation about the true value is estimated to be ± 0.9 ppm.

In all the testing completed, the meter exhibited linearity in the region of interest. As an example, the results of one of the calibration tests, shown in Table 8, are plotted in Figure 41.

Following the completion of laboratory checkout, the meter was installed in the Saxton nuclear facility for an extended in-plant evaluation of its performance.

Table 8

Neutron Absorption Meter Calibration Test

<u>Solution Concentration (Chemical Analysis)</u>	<u>Time to Preset Count</u>	<u>No. of Readings</u>	<u>Maximum Deviation from Average (ppm)</u>	<u>Tank Temp. (°F)</u>
4,900 ppm	157	14	+13,-15	109
3,938 ppm	136	12	+10,-11	109
2,950 ppm	115	16	+7,-6	109
1,960 ppm	96	13	+6,-4	109
1,461 ppm	87	18	+7,-6	109
962 ppm	77	17	+6,-3	109
573 ppm	70	18	+3,-3	110
284 ppm	65	21	+3,-5	110
141 ppm	62	13	+4,-3	110

Figure 41. Boron Concentration Meter Final Laboratory Calibration Test Results

EUBM-700 - Evaluation of Prototype Neutron Absorptiometer

V. Rajagopal, Manager Instrumentation and Control Development

Effort under this task has not yet been initiated.