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DEVELOPMENT OF A BORON

CONCENTRATION METER

FINAL REPORT

April 1969

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

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ABSTRACT

Two prototype meters for monitoring reactor coolant boron concentration were developed and evaluated. One meter employs the mannitol-conductance technique for determining boron concentration; the other employs the neutron-absorption technique. Both meters are capable of quickly determining boron concentration in the reactor coolant, and both may be operated continuously, if desired.

This report summarizes the development, operation, and evaluation of the prototype meters, and includes a description of each meter.

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SECTION 1

PROGRAM SUMMARY AND CONCLUSIONS

A. G. Opitz

1.1 INTRODUCTION

This is the final report for the USAEC-EURATOM sponsored program on the development of a boron concentration meter for monitoring reactor coolant boron concentration. This work was accomplished under AEC Contract AT(30-1)-3690 with Westinghouse Electric Corporation, Pressurized Water Reactor Systems Division.

1.2 PREVIOUS REPORTS

Previous reports issued under this program are:

EURAEC-1722	"Development of a Boron Concentration Meter, Technical
WCAP-3690-1	Progress Report for the Period Ending September 30, 1966"
EURAEC-1778	"Development of a Boron Concentration Meter, Technical
WCAP-3690-2	Progress Report for the Period Ending January 31, 1967"
EURAEC-1827	"Development of a Boron Concentration Meter, Technical
WCAP-3690-3	Progress Report for the Period Ending December 31, 1967"
EURAEC-1972	"Description and Evaluation of the Boron Concentration
WCAP-3690-4	Meter Utilized at the SENA (Franco-Belge) Reactor Plant"
EURAEC-2005	"Development of a Boron Concentration Meter, Technical
WCAP-3690-5	Progress Report for the Period Ending March 31, 1968"
EURAEC-2042	"Development of a Boron Concentration Meter, Technical
WCAP-3690-6	Progress Report for the Period Ending June 30, 1968"

1.3 ACCOMPLISHMENTS

Two prototype boron concentration meters were developed and evaluated. One meter employs the mannitol-conductance technique for determining boron concentration; the other employs the neutron-absorption technique. Both units meet requirements for a meter which can quickly determine boron concentration in reactor coolant, and which can be operated continuously, if desired. Tables 1-1 and 1-2 compare the characteristics of each meter with characteristics established for them prior to development.

Section 2 of this report is a detailed discussion of the development, operation, and evaluation of the mannitol-conductance boron meter.

Section 3 is a detailed discussion of the development, operation, and evaluation of the neutron-absorption boron meter.

Section 4 is a brief summary of the evaluation of the boron concentration meter used at the SENA (Franco-Belge) reactor plant. A detailed description and evaluation of this meter is contained in a topical report issued as EURAEC-1972 (WCAP-3690-4).

1.4 CONCLUSIONS AND RECOMMENDATIONS

Both meters were evaluated at the Saxton Nuclear Reactor, but because of schedule limitations, only the neutron-absorption meter was evaluated at a large reactor plant, precluding a direct comparison of the two meters under identical conditions at such a plant. While the continued satisfactory operation of the neutron-absorption meter at Connecticut Yankee recommends this type of meter for use in other plants, it is noted that the testing accomplished under this program indicates that both meters are, in fact, suitable for such use.

1.4.1 Mannitol-Conductance Boron Meter

1. A mannitol-conductance boron concentration analyzer has been fabricated using commercially available components where possible, and has been operationally tested. The principal characteristics of this meter are shown in Table 1-1.

TABLE 1-1
CHARACTERISTICS OF MANNITOL-CONDUCTANCE
BORON CONCENTRATION METER

<u>Characteristic</u>	<u>Desired</u>	<u>Prototype Meter</u>
Range, ppm Boron	0 - 3500	0 - 3500
Precision	0.3% or 2 ppm Boron (which- ever is greater)	
100 ppm Boron		±0.8% (0.8 ppm)
1000 ppm Boron		±0.23% (2.3 ppm)
3200 ppm Boron		±0.13% (4.2 ppm)
Response Time		
(Analyzer Inlet to Readout), Min	1	
Sample Flow Rate of 35 cc/Min		3
Sample Flow Rate of 50 cc/Min		2
Initial Cost (Materials), Dollars	5,000 - 10,000	
With Digital Readout		8,100 (est.)
Without Digital Readout		4,600 (est.)
Operating Cost for Mannitol (Based on 77¢/lb.), Dollars		
2-hours/shift Operation		1,600/year
Continuous Operation		6,500/year

TABLE 1-2

CHARACTERISTICS OF NEUTRON-ABSORPTION BORON
CONCENTRATION METER

<u>Characteristic</u>	<u>Desired</u>	<u>Prototype Meter</u>
Range	0-5000 ppm Boron in 4 ranges	0-5000 ppm Boron in one range
Precision		
25 - 500 ppm	± 2 ppm	} ±2.8 ppm
250 - 1250 ppm	± 5 ppm	
1000 - 2500 ppm	± 5 ppm	
2500 - 5000 ppm	±25 ppm	±7.1 ppm
Drift	less than 10 ppm/week	Negligible
Time between readouts	5 minutes	
0 - 2500 ppm		2 minutes
2500 - 3000 ppm		3 minutes
Initial Cost (Materials)		\$8,000 (est.)
Operating Cost (Neutron Source Rental Fee)		\$150 per year

2. Waste disposal requirements for fluids from the meter should not present any significant problem. For continuous operation, total liquid output from the meter is approximately 32 gallons per day.
3. Maintenance requirements, based on operating two hours per shift, are as follows:

Chemical renewal

Mannitol solution every 10 days

Resin replacement every 20 days

Recorder chart paper every 27 days

Platinize electrodes every 6 months

4. The total cost of the meter components is about \$4,600 excluding digital readout and 8,100 with digital readout.
5. A desirable meter improvement would be the incorporation of a millivolt-to-boron-concentration converter to provide direct readout in units of ppm boron.
6. A recommended modification would be the addition of an automatic self-compensating sensitivity adjustment for the conductivity monitor. In the opinion of Beckman Instruments, Inc., this modification could be added for about \$100.

1.4.2 Neutron Absorption Boron Meter

1. A neutron-absorption boron concentration analyzer that has a four place ppm readout has been fabricated and tested in operating reactor plants. The principal characteristics of the prototype meter are presented in Table 1-2 together with the original design specifications.
2. No significant problems were encountered in installing and making the meter operational at both the Saxton and Connecticut-Yankee reactor plants.

3. Reliability records at both the Saxton and Connecticut-Yankee plants have been excellent, with no maintenance requirements after initial setup.
4. In the prototype meter, the ppm boron readout is printed out continuously on paper tape. The addition of a timer or timing marker would help in correlating the meter readings to plant operations.

SECTION 2

MANNITOL-CONDUCTANCE BORON METER

W. D. Fletcher, J. E. Bulkowski, D. D. Whyte

2.1 INTRODUCTION

The mannitol-conductance boron concentration analyzer rapidly, accurately, and automatically determines the boron content of solutions typical of those found in pressurized water reactors. The basic analytical principle involves the measurement of the solution electrical conductivity after adding a polyhydroxyl alcohol. The specific complexation reaction of the di-ol with the borate species enhances the solution conductivity and, consequently, leads to increased instrument sensitivity.

The desired characteristics of the device were established at the beginning of the program:

Boron concentration range	0 to 3500 ppm
Precision	0.3% or 2 ppm (whichever is greater)
Response time (from analyzer inlet to readout)	1 minute

Also, the boron meter system must not respond to changes in other variables associated with reactor coolant solutions. These solutions may normally contain:

1. Strong base (KOH or LiOH) in the range 0 to 3×10^{-4} molar, and/or ammonia up to 6.7×10^{-4} molar
2. Dissolved hydrogen gas at from 15 to 50 standard cubic centimeters per kilogram of water
3. Traces of fission products and corrosion products

The only significant contaminants are the added bases, and these are readily removed to a sufficiently low level by circulating the solution through a cation exchange resin prior to analysis.

To increase the conductivity of the solution in a manner specific to boric acid, use is made of the fact that boric acid forms relatively strong complex acids with most cis 1,2 - and 1,3 - di-ols which are themselves nonconductors. The overall reaction is:^[1]

and

or in abbreviated form

The equilibrium expression for these reactions is

$$K_n = \frac{[\text{BM}_n^-]}{(\text{B}^-)(\text{M})^n}, \quad n = 1 \text{ or } 2$$

assuming concentrations are equal to activities, and the water activity is essentially constant.

For mannitol, K_1 and K_2 have been reported to be 3.0×10^2 and 5.1×10^4 respectively, [1] assuming the first ionization constant for boric acid is 6.4×10^{-10} to 1.2×10^{-9} .

The larger these equilibrium constants, the greater the conductivity of a given boron solution and the greater the change in conductivity per unit change in boron concentration with resulting higher instrument sensitivity and potential accuracy. In practice, saturation of a 2800 ppm boron solution with mannitol increases the 25°C conductivity from about 2.5 to 800 micro-mho per cm with even greater relative changes at lower concentrations.

The following sections will describe the work accomplished under the various subtasks of the mannitol meter development program. They will include the laboratory studies, design and construction of the prototype, evaluation of the prototype, and conclusions and recommendations.

2.2 LABORATORY STUDIES

This subtask of the boron meter development program consisted primarily of laboratory testing to better define the variables relating to measurement of boron concentration by the mannitol-conductance technique. This work also evaluated the possible use of pH as a means of detecting the amount of boron present in the solution stream by investigating the effect of various di-ol complexing agents on the boric acid solution conductivity and pH. These studies included the effect of temperature and the amount of complexing agent required to give maximum conductivity or minimum pH. Other factors pertaining to design, such as cost, instrumentation requirements, etc., were also looked at in this phase of the project.

2.2.1 Summary

The following is a summary of the results obtained during this subtask.

1. The basic principle of measuring the boron concentration by measuring the conductivity increase of a boric acid solution with added mannitol or fructose is sound.
2. Reproducibility of pH measurements under controlled conditions at several temperatures were generally no better than 0.05 pH units, resulting in an error of about ± 2 to 3 percent in estimating boron concentration.
3. The use of conductivity measurements for boron concentration determination appeared superior to pH measurements.
4. Twenty-four grams of mannitol were required to obtain maximum conductivity at 25°C for 100 grams of a 3500 ppm boron as boric acid solution, while about 36 grams of fructose were required for maximum conductivity.
5. Glycerol was much less effective than fructose or mannitol in increasing the boric acid solution conductivity.
6. Of the complexing agents, other than mannitol or fructose, which were evaluated, only catechol appears to have the desired complexing properties with boric acid solutions.
7. With either excess mannitol or fructose at room temperature the conductivity of the boric acid solutions varied at nearly the square root of the boric acid concentration.
8. The conductivity change of the mannitol-boric acid solution appeared to vary linearly with temperature between 19 and 35°C; then decreased fairly rapidly, at least up to 49°C. The conductivity increase with temperature appears to be quite dependent on the boron concentration, with slight variation at low boron concentrations and greater variations at higher boron concentrations.
9. The use of low temperature operation of the boron concentration meter reduces the quantity of mannitol (or fructose) required for measurement of the boron concentration, but also decreases the

measurement accuracy. The quantity of mannitol or fructose required for a 2°C solution would be about 40 percent less than that required for a 20°C solution.

10. Conductivity measurements of boron solutions containing mannitol or fructose at saturation levels (maximum conductivity or minimum pH) indicated about a 20 percent reduction in value as the temperature was lowered from 20 to 2°C, resulting in an error increase of about 20 percent.
11. A delay time of one minute can be met, although in some applications, delay times of greater than one minute are suitable.
12. The materials cost of the boron concentration meter using conductivity measurements will be about \$4,600 without digital readout, and about \$8,100 with digital readout.
13. Contacts with plant operating personnel indicate that a boron meter is desired by plant operators, and that the instrument have the following characteristics:

Chemical type (implies high operating cost)

Readout time of from 1 to 15 minutes

Accuracy of ± 1 to ± 3 percent of boron present

Initial cost of between \$5,000 and \$10,000

On-demand operation for spot analysis; continuous operation if required

2.2.2 Experimental Results

Laboratory testing on the effects of di-ols on the conductivity and pH of boric acid solutions was performed using ACS-grade boric acid, Fisher* certified D-Mannitol (Fisher Catalog No. M-120), Fisher reagent grade D-Fructose (Fisher Catalog No. L-95) and high quality demineralized water (less than

* Fisher Scientific Company, Pittsburgh, Pennsylvania

2 $\mu\text{mho/cm}$ conductivity). All other chemicals were Fisher reagent grade materials. Conductivity was measured with a Leeds and Northrup electrolytic conductivity bridge (Catalog No. 4866) with an error limit of ± 0.3 percent of its 1-12 range, and platinized conductivity cells with cell constants of either 1.029 or 0.660. The pH of the solutions was measured with a Beckman Expandomatic pH meter, using a silver chloride glass electrode and a calomel reference electrode. This instrument is capable of reading out to 0.005 pH units. Solution temperatures were maintained constant to $\pm 0.1^\circ\text{C}$ in a constant temperature bath. All measurements were made in open polyethylene bottles.

2.2.2.1 Mannitol and Fructose

a. Effect of Di-ol Concentration on pH and Conductivity

The effect of solid mannitol and fructose addition upon conductance, for various concentrations of boron as boric acid solution at 19.2°C , is presented in Figure 2-1 and Table 2-1. No corrections were made for the effect of dilution of the boric acid solution by the mannitol or fructose. The dilution effect of mannitol on 100 cc of a 1.8×10^{-3} molar sodium chloride solution (about 100 micromhos/cm conductivity) was determined to be 1.2 μmho per cm per gram of mannitol. The total mannitol required to obtain maximum conductivity for all boron concentrations at 19.2°C was about 20 grams per 100 grams of initial solution; for fructose, about 35 grams per 100 grams of solution was required.

Addition of mannitol to demineralized water resulted in the conductivity curve presented in Figure 2-2. The increase in conductivity of the solution is quite small (~ 10 $\mu\text{mhos}/24$ gm M per 100 grams of solution). The reason for the initial higher increase is probably due to low solubility impurities in the mannitol.

b. Boron Concentration versus pH and Conductivity with Excess Di-ol

The changes of pH and conductivity of boric acid-mannitol or boric acid-fructose solutions with changes in boron concentration, when

Figure 2-1. Effect of Di-ol Addition on Conductivity of Boric Acid Solutions

Figure 2-2. Effect of Mannitol Addition on Conductivity of Pure Water

TABLE 2-1

CONDUCTIVITY AND PH OF BORIC ACID SOLUTIONS WITH ADDITION OF DI-OL AT 19.2°C

Grams Mannitol Per 100 gms of Original Solution	pH, ppm boron						Conductivity, micromhos/cm, ppm boron					
	0	249	1014	1524	2538	3552	0	249	1014	1524	2538	3552
0	6.05	5.41	4.99	4.84	4.59	4.38	0.1	1.6	4.0	5.0	9.0	15.3
2.9	6.73	3.81	3.48	3.38	3.26	3.19	8.1	74.9	147	174	214	239
5.7		3.58	3.23	3.13	3.00	2.92		133	258	309	385	431
8.6	6.90	3.46	2.99	2.89	2.73	2.63	10.0	177	345	417	515	584
11.5		3.50	2.84	2.75	2.64	2.57		210	414	497	622	701
14.3		3.49	2.81	2.69	2.57	2.49		236	464	561	702	797
17.2	6.98	3.47	2.73	2.63	2.50	2.42	10.6	254	501	607	761	870
20.1		3.01	2.68	2.56	2.43	2.35		261	522	635	803	924
22.9	6.98	3.09	2.66	2.55	2.42	2.33	11.8	258	519	635	804	931
24.3		3.11	2.68	2.55	2.43	2.34		258	517	633	794	930

Grams Fructose
Per 100 gms of
Original Solution

pH
3412
ppm boron

Conductivity,
micromhos/cm
3412, ppm boron

0	4.40	14
14.3	3.58	917
20.0	3.31	1109
22.9	2.27	1175
25.8	2.22	1228
28.6	2.18	1267
31.5	2.13	1294
34.3	2.10	1313
37.2	2.07	1320
40.0	2.07	1320

excess di-ol is present, is shown in Tables 2-2 and 2-3 and Figures 2-3, 2-4, 2-5, and 2-6. Excess di-ol is defined as an amount slightly in excess of the amount required to attain maximum conductivity or minimum pH of the boric acid solution tested.

The conductivity versus boron concentration for the LOT 2 data on boric acid-mannitol solutions at 19.2°C can be described by the equation $K = 1.68 \times 10^{-5} C^{0.484}$, where K is the specific conductivity in mhos per centimeter and C is the concentration of boron in ppm in the original boric acid solution. LOT 1 data at 19°C for boric acid-mannitol solutions indicated that the equation for the conductivity versus boron concentration was $K = 1.61 \times 10^{-5} C^{0.500}$. The difference in the slopes of the two curves can possibly be attributed to the difference in purity of the two different lots of mannitol used for the two series of tests. The equation for the conductivity versus boron concentration of boric acid-fructose solutions at 19.2°C is $K = 2.53 \times 10^{-5} C^{0.469}$.

The equations to describe the variation of pH with changes in boron concentrations at 19.2°C are presented below:

1. $C_B = 1.175 \times 10^7 \exp (-3.74 \text{ pH})$	LOT 1 Mannitol-Boric Acid Solutions
2. $C_B = 2.41 \times 10^7 \exp (-3.80 \text{ pH})$	LOT 2 Mannitol-Boric Acid Solutions
3. $C_B = 1.26 \times 10^7 \exp (-4.01 \text{ pH})$	Fructose-Boric Acid Solutions

The difference between the equations for the LOT 1 mannitol data and LOT 2 mannitol data is probably due to a difference in mannitol purity, plus a possible difference due to use of different pH meters and probes in the two tests. The use of pH for determining boron concentration appears doubtful since a change from 2.100 to 2.105 pH units (limit of accuracy) corresponds to about a 2.0 percent change in boron concentration at about 3500 ppm boron; and about a 1.6 percent change in boron concentration for a pH change from 2.900 to 2.905 (~ 500 ppm boron).

Figure 2-3. Conductivity versus Original Boron Concentration for Mannitol Saturated Boric Acid Solutions at 19°C, 10°C, and 2°C

Figure 2-4. Conductivity versus Original Boron Concentration for Fructose Saturated Boric Acid Solutions at 19°C, 10°C, and 2°C

Figure 2-5. pH versus Original Boron Concentration for Mannitol Saturated Boric Acid Solutions at 19°C, 10°C, and 2°C

Figure 2-6. pH versus Original Boron Concentration for Fructose Saturated Boric Acid Solutions at 19°C, 10°C, and 2°C

TABLE 2-2
CONDUCTIVITY AND PH OF BORIC ACID SOLUTIONS WITH EXCESS MANNITOL
VERSUS BORON CONCENTRATIONS AT VARIOUS TEMPERATURES

Boron Concentration (Prior to Mannitol Addition, ppm)	pH				Conductivity, micromhos/cm						
	2°C	10°C	19°C	30°C	2°C	10°C	19°C	30°C	35°C	40°C	49°C
0			6.98				10				
108			3.12 ^a				167 ^a	172 ^a	175 ^a	174 ^a	
249	2.93	2.94	3.01		228	244	261				
492			2.71 ^a				364 ^a	380 ^a	384 ^a	381 ^a	
971			2.52 ^a				517 ^a	540 ^a	542 ^a	536 ^a	
1014			2.68				522				
1472			2.40 ^a				631 ^a	660 ^a	664 ^a	655 ^a	
1524			2.56				635				
2433			2.28 ^a				804 ^a	835 ^a	837 ^a	829 ^a	
2538			2.42				804				
3435			2.20 ^a				942 ^a	965 ^a	870 ^a	959 ^a	900 ^a
3552	2.43	2.38	2.33	233	770	844	931	1056			

a. Indicates data obtained using LOT 1 of mannitol - others are mannitol LOT 2.

TABLE 2-3
 CONDUCTIVITY AND PH OF BORIC ACID SOLUTIONS WITH EXCESS FRUCTOSE
 VERSUS BORON CONCENTRATIONS AT VARIOUS TEMPERATURES

Boron Concentration (Prior to Fructose Addition, ppm.)	pH				Conductivity, micromhos/cm				
	2.0°C	10.5°C	19.2°C	25.6°C	2.0°C	10.5°C	19.2°C	25.6°C	30°C
0		6.98				12			
103				2.80				209	
249	2.70	2.71	2.70		259	300	360		
492				2.42				471	
971								675	
1472				2.29				840	
2433				2.19				1081	
3412	2.13	2.07	2.07		964	1090	1320		1459
3435				1.98				1286	

c. Conductivity and pH of Pure Boric Acid Solutions (No Di-ol Added)

The variation of the pH and conductivity with boron content of a pure boric acid solution at 19.2°C is presented in Table 2-4 and Figures 2-7 and 2-8. The conductivity of the pure boric acid solution appears to approach a linear function with respect to boric acid content at low boron concentrations but increases at a slightly greater rate with increasing concentrations. This is due to the effect of multiple equilibrium reactions that occur in the ionization of boric acid. Since the conductivity of a 3500 ppm boric acid solution is only about 15 micromhos per cm, any ionic contamination remaining in the solution to be measured would cause large errors in the boron concentration determination. For example, the conductivity of an 0.8 ppm hydrochloric acid solution is 10 micromhos per cm.

The log of the boron concentration also does not vary linearly as the pH, and again this is due to the multiple equilibrium reactions of boric acid solutions.

The slope of the pH versus boron concentration for various boric acid solutions is shown in Table 2-5. From this data, it can be concluded that the sensitivity for pH measurements is about the same whether or not a di-ol is added to the boric acid solution. Thus, it again appears that pH is too insensitive to use for determining boron concentration; and that the additional error added to the pure boric acid pH measurements by contaminants at the near neutral pH values (low boron concentrations) would make this method even less applicable.

d. Temperature Dependence

Results of the changes in conductivity and pH of boric acid-mannitol or fructose solutions with changes in solution temperature are presented in Tables 2-2 and 2-3 and Figures 2-9 and 2-10. The conductivity increase with temperature appears to be linearly dependent on boron concentration, with an increase of 10.3 ($\mu\text{mho}/\text{cm}$) per

Figure 2-7. Conductivity versus Boron Concentration for Boric Acid Solutions with No Added Di-ol

Figure 2-8. pH versus Boron Concentration for Boric Acid Solutions with No Added Di-ol

Figure 2-9. Effect of Temperature on Conductivity of Di-ol Saturated Boric Acid Solutions

Figure 2-10. Effect of Temperature on pH of Di-ol Saturated Boric Acid Solutions

TABLE 2-4

CONDUCTIVITY AND PH OF BORIC ACID SOLUTIONS AT VARIOUS CONCENTRATIONS
(No Added Di-ol)

Boron Concentration, ppm	pH			Conductivity, micromhos/cm		
	2°C	10°C	19.2°C	2°C	10°C	19.2°C
249			5.41	1.14	1.47	1.49
1014			4.99			3.81
1524			4.84			5.33
2538			4.59			9.44
3412	4.29	4.37	4.40	9.91	11.5	14.1
3552	4.44	4.33	4.34	11.1	12.5	

TABLE 2-5

SLOPE OF BORON VERSUS PH CURVE AT 19.2°C (NO DI-OL)

Boron Concentration C_B ppm	Slope (- log ppm Boron), pH	Actual pH	$\pm$ pH Units/ $\pm$ 1% C_B	pH Units/ppm B
3500	.621	4.400	0.0070	2.00×10^{-4}
2500	.805	4.600	0.0054	2.16×10^{-4}
1500	1.039	4.840	0.0042	2.79×10^{-4}
500	1.498	5.223	0.0029	5.80×10^{-4}
250	1.634	5.410	0.0027	10.64×10^{-4}
100	1.880	5.630	0.0023	23.10×10^{-4}

degree centigrade observed for a 3550 ppm boron solution with excess mannitol. An increase of only 2.1 ($\mu\text{mho}/\text{cm}$) per degree centigrade was observed with a 249 ppm boron solution with excess mannitol. The same effect is noted for the boric acid solutions with excess fructose, with an increase of 16.7 ($\mu\text{mho}/\text{cm}$) per degree centigrade for 3412 ppm boron solution and 5.3 ($\mu\text{mho}/\text{cm}$) per degree centigrade for a 249 ppm boron solution. The slope of the conductivity versus temperature curve for a 3435 ppm boron solution obtained on LOT 1 of mannitol was 2 ($\mu\text{mho}/\text{cm}$) per degree centigrade, or only about 20 percent of that observed in the LOT 2 tests. This difference in slope may be due to the different methods used for bringing the solutions to temperature. In the LOT 1 test, one boric acid solution was used for all temperature measurements. Sufficient mannitol, as a slurry, was added at the lowest temperature condition to maintain solid mannitol in the boric acid solution even at the highest temperature condition. In the LOT 2 test, separate boric acid solutions were used for each temperature condition and mannitol was added to each container until maximum conductivity or minimum pH was attained.

The changes in pH with temperature are quite small with the greatest change being observed for the 3500 ppm boron solution. At this boron concentration, the pH decrease with temperature was about 0.005 pH units per degree centigrade over the range from 0 to 30°C for both mannitol and fructose. The pH change with changes in temperature of a 250 ppm boron solution was 0.000 pH units per degree centigrade over the temperature range of 2 to 20°C with excess fructose, and the pH appeared to increase with increasing temperature with excess mannitol at about 0.005 pH unit per degree centigrade. The reason for the increase is not obvious but may well be in the limit of reproducibility of the pH readings.

The amount of mannitol or fructose required for maximum conductivity or minimum pH for a 3500 ppm boron solution at several temperatures is presented in Table 2-6 and Figure 2-11. It can be seen from

Figure 2-II. Quantity of Di-ol Required for Maximum Conductivity versus Temperature

Figure 11 that the quantity of either mannitol or fructose required to reach maximum conductivity or minimum pH is a linear function of the temperature of the boric acid solution. The quantity of mannitol required for a 3552 ppm boron solution increased with temperature by $0.50 \frac{\text{grams M}}{100 \text{ grams Soln.}}$ per degree centigrade between 0 and 30°C. The quantity of fructose required for a 3412 ppm boron solution increased with temperature by $0.58 \frac{\text{grams F}}{100 \text{ grams Soln.}}$ per degree centigrade between 0 and 30°C.

TABLE 2-6

DI-OL REQUIREMENTS FOR MAXIMUM CONDUCTIVITY AT VARIOUS TEMPERATURES
GRAMS DI-OL/100 GRAMS OF ~ 3500 PPM BORON SOLUTION

	0.2°C	2.0°C	10.0°C	10.5°C	19.2°C	30°C
Mannitol		14.30	18.58		22.90	28.71
Fructose	28.60			34.30	40.04	45.72

2.2.2.2 Other Compounds

In addition to mannitol and fructose, other poly-ols were evaluated as to complex formation with boric acid. The particular materials tested are presented in Table 2-7 along with their specific conductivity for one addition of the poly-ol. It can be seen from this data that only catechol appeared promising. Therefore, data was obtained at room temperature on the change of conductivity of a 3412 ppm boron (as boric acid) solution with increasing amounts of catechol. These data are presented in Table 2-8 and Figure 2-12, and 2-13. Catechol appears to be about as effective as fructose or mannitol in forming the complex acid with the borate ion but the cost would be much higher for reagent grades.

In addition to the Fisher reagent grade fructose, a commercial solution of 65 w/o fructose was checked for impurity effect on conductivity. The

Figure 2-12. Effect of Catechol Addition on Conductivity of Boric Acid Solutions

Figure 2-13. Conductivity versus Original Boron Concentration for Catechol Saturated Boric Acid Solutions

TABLE 2-7

EFFECT OF SEVERAL POLY-OLS ON SOLUTION CONDUCTIVITY AT $23 \pm 1^\circ\text{C}$

Complexing Agent	Pure Water		3412 ppm B Solution	
	Grams Added to 100 gm of Sol.	Conductivity, Micromhos/Cm	Grams Added to 100 gm of Sol.	Conductivity, Micromhos/Cm
Dextrose	28.573	120	28.573	127
Catechol	5.761	6.0	5.761	464
Resorcinol	9.508	6.0	9.508	25
Tartaric Acid	28.57	10,600 (pH = 1.88)	28.57	10,600

TABLE 2-8

CHANGE IN CONDUCTIVITY WITH INCREASING CATECHOL CONTENT AT 23°C

Grams of Catechol per 100 Grams Original Solution	Conductivity, Micromhos/Cm		
	Water	3412 ppm Boron Solution	249 pp, Boron Solution
0	0.005		
4.3		399	
5.7		477	
8.6	0.07	601	
11.4		696	147
14.3	0.09	776	
17.1		832	
20.0		898	200
22.8	0.09	937	
25.7		983	210
28.5	0.09	993	
31.4		1003	
34.2		1023	211
37.1		1030	
39.9		1036	
42.8		1040	
45.6		1030	211

conductance at 22°C of a solution containing 26.5 grams fructose per 100 grams of pure water was determined to be 663 μmho per cm and the pH to be 3.71. After ion exchanging this solution with washed XE-150 mixed bed ion exchange resin, the conductance only improved to 280 μmho per cm and the pH to 3.70. Thus, this solution does not appear to be a candidate for complexing the borate without making considerable effort to remove impurities.

The effect of glycerol on the conductivity of a 3435 ppm boron solution was also evaluated. The minimum pH of a 3435 ppm boron solution with glycerol addition was 3.10. It was obvious that glycerol was much less effective than fructose or mannitol in increasing the conductivity of boric acid solutions so no additional work was performed with glycerol.

2.2.2.3 Calculation of the Electrical Conductivity of Mannitol Saturated Boric Acid Solution from Equilibrium Data

The equilibria involved are:

where B^- = borate ion, M = mannitol molecule.

The equilibrium equations, charge, and mass balances are

$$(\text{H}^+)(\text{B}^-) = K_B (\text{HB}) \quad (1)$$

$$(\text{BM}^-) = K_1 (\text{B}^-) (\text{M}) \quad (2)$$

$$(\text{BM}_2^-) = K_2 (\text{B}^-) (\text{M})^2 \quad (3)$$

$$(\text{H}^+)(\text{OH}^-) = K_w \quad (4)$$

$$(\text{H}^+) = (\text{B}^-) + (\text{BM}^-) + (\text{BM}_2^-) + (\text{OH}^-) \quad (5)$$

$$(\text{A}) = (\text{HB}) + (\text{B}^-) + (\text{BM}^-) + (\text{BM}_2^-) \quad (6)$$

$$(\text{F}) = (\text{M}) + (\text{BM}^-) + 2 (\text{BM}_2^-) \quad (7)$$

where () indicates molarity and (A) = gross boric acid molarity and (P) = gross mannitol (poly-ol) molarity.

For mannitol saturated solutions (M) is constant, taken as the saturation value 0.737 molar. Calculations are easily carried out then by

- a. Picking a value for (H^+) .
- b. Evaluating in order the following quantities

$(B^-) = \left[(H^+) - \frac{K_w}{(H^+)} \right] / \left[1 + K_1 (M) + K_2 (M)^2 \right]$	$3.67 \times 10^{-5} \left[(H^+) - \frac{K_w}{(H^+)} \right]$
$(BM^-) = K_1 (B^-) (M)$	$221 (B^-)$
$(BM_2^-) = K_2 (B^-) (M)^2$	$2.72 \times 10^4 (B^-)$
$(HB) = (H^+) (B^-) / K_B$	$8.34 \times 10^8 (H^+) (B^-)$
$(A) = (HB) + (B^-) + (BM^-) + (BM_2^-)$	
$(P) = (M) + (BM^-) + 2 (BM_2^-)$	

The initial equation for (B^-) is obtained by substituting Equations 2 and 3 in Equation 5.

To relate A, the boron molarity in the saturated solution, to the boron concentration in the solution prior to mannitol addition, additivity of volumes is assumed and a density of 1.489 g/cm^3 and a molecular weight of 182.2 for mannitol and 1.435 g/cm^3 and 10.8 molecular weight for boron are used. This yields:

$$C_b \cong 1.192 \times 10^4 A$$

where C_b = initial boron concentration in ppm.

The conductivity, K mho/cm is then calculated from

$$K = 10^{-3} \sum_i c_i \lambda_i$$

where c_i = gram equivalents per liter of ith ion

λ_i = equivalent conductance of ith ion

$$\lambda_i = \lambda_i^o - (30.17 + 0.23 \lambda_i^o) \sqrt{c_i} \quad [2]$$

using $\lambda_{H^+}^o = 350 \text{ mho/cm}^2$

$\lambda_{-}^o = 30 \text{ mho/cm}^2$ for all negative ions [3]

(OH^- content negligible)

The results of the calculations, given in Table 2-9 and compared with measurement in Figure 2-14, show quite satisfactory agreement. The small systematic deviation is probably due to uncertainties in the equilibrium constants.

2.3 DESIGN AND CONSTRUCTION OF PROTOTYPE

This subtask of the boron meter development program involved the complete design and construction of a boron analyzer prototype that would be suitable for reactor plant use. This section of the report is a detailed account of the design and construction phase of the work. It includes results obtained from the first working model and a complete description of the actual design, operation, and bench testing of the as-built chemical meter.

2.3.1 First Working Model

A first working model was constructed to provide information for design of a meter that would not involve saturating the boron solution with mannitol. This conceptual design would eliminate the problems associated with adding a highly concentrated mannitol feed solution, eliminate heat tracing of lines

Figure 2-14. Conductivity vs. Initial Boron Concentration for D-Mannitol Saturated Boric Acid Solutions

TABLE 2-9

CALCULATION OF ION CONCENTRATIONS AND CONDUCTIVITY OF BORIC ACID
SOLUTIONS SATURATED WITH MANNITOL

$(H^+)^a$	(B^-)	(BM^-)	(BM_1^-)	(HB)	(A)	C_b , ppm	K, mho/cm
3×10^{-3}	11.0×10^{-8}	24.3×10^{-6}	29.9×10^{-4}	0.275	0.275	3,280	11.2×10^{-4}
1×10^{-3}	3.67×10^{-8}	8.12×10^{-6}	9.97×10^{-4}	0.0306	0.0316	376	3.75×10^{-4}
6×10^{-4}	2.20×10^{-8}	4.86×10^{-6}	5.96×10^{-4}	0.0110	0.0116	138	2.26×10^{-4}
3×10^{-4}	1.10×10^{-8}	2.43×10^{-6}	2.99×10^{-4}	0.00275	0.00305	36.4	1.13×10^{-4}

a. See text for meaning of symbols.

to keep the mannitol in solution, and reduce the possibility of deposition of solid mannitol through the instrument.

Results obtained from the first working model indicated that a boron concentration meter operating with an unsaturated mannitol-boron solution was feasible and of simpler design than a saturated mannitol system. Since the data obtained for conductivity versus flow ratio (cc boron solution/cc mannitol solution) in Figures 2-15 through 2-18 show that conductivity is not greatly dependent on flow ratio, the mixing of a precisely fixed ratio of boron solution to mannitol solution, is not critical. However, by using a duplex diaphragm pump, such as the Clark-Cooper utilized in the first working model, a flow ratio can be set and be expected to remain constant even with a varying electrical supply. Also, the data indicate that 0.70 cc of boric acid solution will require 1.00 cc of 14.5 w/o mannitol solution. For a flow of 50 cc per minute of reactor coolant sample through the meter, a flow of 71.5 cc per minute of 14.5 w/o mannitol solution is required, consuming about 11 grams per minute of mannitol.

The conductivity of the unsaturated mannitol-boron solution was shown to decrease with an increase in solution temperature. This observation differs from previous test results with the saturated mannitol-boron solutions where the increase in conductivity appeared to be directly proportional to the temperature. This effect may be due to the temperature dependence of the multiple equilibrium reactions that occur in the ionization of boric acid and the complexing of the boron with the cis di-ol. The test data suggested that temperature should be controlled at a value of from 15 to 20°C for maximum conductivity for a meter employing the unsaturated mannitol-boron principle.

The bench testing of the first working model of the boron concentration meter was performed using Atlas Chemical Reagent Grade D-mannitol, ACS-grade boric acid, and high quality demineralized water. Conductivity was measured with a Leeds and Northrup electrolytic conductivity bridge (Catalog No. 4866) with an error limit of ± 0.3 percent of its 1-12 range, and a platinized flow conductivity cell with a cell constant of 0.629. The pump was a Clark-Cooper duplex diaphragm precision metering pump (Model No. 7131 D). Temperature was controlled to $\pm 0.1^\circ\text{C}$ in a constant temperature bath. Flow data for the

Figure 2-15. Conductivity versus Boron-Mannitol Flow Ratio at 17.5°C Referred to 25°C

Figure 17

Figure 16

Figures 2-16 and 2-17. Conductivity versus Boron-Mannitol Flow Ratio at 22°C and 43°C

Figure 2-18. Conductivity versus Boron-Mannitol Flow Ratio at 43°C Referred to 25°C

precision metering pump was obtained through careful calibration. In certain tests wherein the pump was not used, gravity-feed was employed for boric acid and mannitol solutions and flow rates were determined using calibrated rotameters.

2.3.1.1 The Effect of Flow Mixing Ratio, Mannitol Concentration, and Temperature on Conductivity

The effect of mixing a 14.5 w/o mannitol solution with various concentrations of boron solution at 17.5°C* is presented in Figure 2-15. The conductivity is shown as a function of flow ratio (cc boron solution/cc mannitol solution) for the various boron concentrations. A 14.5 w/o mannitol solution was employed since it is soluble at 20°C and does not require heat tracing of the mannitol feed lines. Figures 2-16 and 2-18 present conductivity versus flow ratio at 22°C* and 43°C*, respectively, for addition of a 14.5 w/o mannitol solution. For a 22 w/o mannitol feed solution, Figure 2-17 shows the variance of conductivity with flow ratio for various boron concentrations.

2.3.1.2 Conductance Relationships for Mannitol-Boric Acid Solutions

Conductivity is plotted as a function of boron concentration in Figure 2-19 for flow ratios resulting in maximum conductivity readings. Equations were determined which describe the conductivity as a function of original boron concentration and the sensitivity of the measurements. These relationships, along with test conditions, are presented in Table 2-10. The conductivity versus boron concentration at 17.5°C* and a flow ratio of 0.70 cc of boron solution per cc of 14.5 w/o mannitol solution is described by the equation $K = 1.14 \times 10^{-5} C^{0.481}$ where K is the specific conductivity in mhos/cm and C is the original boric acid concentration in ppm boron. Previous data at 19.2°C for a mannitol-saturated boron solution is described by a similar equation for the conductivity versus boron concentration, which is $K = 1.79 \times 10^{-5} C^{0.485}$. Also, the sensitivity equations for the same two

* Values referred to conductivity at 25°C.

Figure 2-19. Conductivity versus Original Boron Concentration for Mannitol-Boron Solutions Referred to 25°C

TABLE 2-10

CONDUCTANCE RELATIONSHIPS FOR MANNITOL-BORIC ACID SOLUTIONS

Run	Temp. ^a °C	$\frac{F_M}{F_B}$	Mannitol Conc. Weight Percent	Conductivity Equation, mhos/cm	Sensitivity, $\frac{dK}{dC} = \frac{\text{mhos}}{\text{cm}}/\text{ppm}$	Comments
-	19.2	0	Saturated	$K = 1.79 \times 10^{-5} C^{0.485}$	$8.68 \times 10^{-6} C^{-0.515}$	-----
1	22.0	1.43	14.5	$K = 1.19 \times 10^{-5} C^{0.458}$	$5.45 \times 10^{-6} C^{-0.542}$	Gravity flow model meter
2	43.0	1.43	14.5	$K = 5.97 \times 10^{-6} C^{0.484}$	$2.89 \times 10^{-6} C^{-0.516}$	Gravity flow model meter
3	43.0	1.25	22	$K = 7.06 \times 10^{-6} C^{0.500}$	$3.53 \times 10^{-6} C^{-0.500}$	Gravity flow model meter
4	25.5	1.25	22	$K = 1.20 \times 10^{-5} C^{0.489}$	$5.87 \times 10^{-6} C^{-0.511}$	Gravity flow model meter
5	17.5	1.43	14.5	$K = 1.14 \times 10^{-5} C^{0.481}$	$5.48 \times 10^{-6} C^{-0.519}$	Pump flow model meter

a. Temperature referred to conductivity reading at 25°C.

K = Specific Conductivity in mhos/cm.

C = Boron Concentration in ppm.

comparisons were determined to be $dK/dC = 5.48 \times 10^{-6} C^{-0.519}$ and $dK/dC = 8.68 \times 10^{-6} C^{-0.515}$, respectively.

2.3.1.3 Temperature Effect

It was previously determined that maximum conductivity values were obtained for a flow mixing ratio of 0.7 cc of boric acid solution per cc of 14.5 w/o mannitol solution. Conductivity measurements were made for these boric acid-mannitol solutions as a function of temperature. The results are presented in Figure 2-20 and Table 2-11. It is seen that the effect of temperature on the conductivity is negligible in the range 15 to 20°C. This information indicates that automatic temperature compensation is not required for an accurate measurement of the conductivity; the temperature bath will be more than adequate for temperature control (control sensitivity is ± 0.02 percent).

2.3.1.4 Accuracy and Error Calculations

The precision of measurement for the test conditions described previously are presented in Table 2-12 and Figure 2-21 for a few selected boron concentrations. The sensitivity is reduced by less than a factor of two when the conductivity of an unsaturated mannitol-boron solution is measured compared to the saturated mannitol-boron solutions.

The sensitivity of the conductance measurements for a ± 1.0 percent change in the boron concentration is presented in Table 2-13.

2.3.2 Description of the Prototype Meter

The prototype 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 2-14. Other components that were designed and constructed specifically for the meter are as follows:

- a. 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.

Figure 2-20. Effect of Temperature on Conductivity of Boric Acid-Mannitol Solutions with 0.7 cc Boron Solution/cc 14.5 w/o Mannitol Solution

Figure 2-21. Sensitivity of Conductivity Measurements

TABLE 2-11

EFFECT OF TEMPERATURE ON CONDUCTIVITY FOR BORIC ACID-MANNITOL SOLUTIONS

Temperature, °C	Original Boron Concentration, ppm					
	3085	2055	1030	515	103	58
9.6	404 ^a	333	242	172	75.8	52.5
14.9	407	335	243	172	76.4	53.2
25.0	401	332	241	171	76.3	53.1
35.0	389	322	234	167	75.3	52.8
45.0	370	307	222	159	72.1	50.7

a. Conductivity readings are in micromho/cm at the temperature stated.

TABLE 2-12

SENSITIVITY OF CONDUCTIVITY MEASUREMENTS

Boron Concentration, ppm	Precision of Measurements $\frac{dK}{dC}$ in $\frac{\mu\text{mhos}}{\text{cm}}/\text{ppm B}$					
	Saturated	1	2	3	4	5
	19.2°C	22°C	43°C	43°C	25.5°C	17.5°C
100	0.810	0.450	0.270	0.350	0.559	0.503
1000	0.248	0.130	0.082	0.112	0.173	0.153
2000	0.174	0.089	0.058	0.079	0.121	0.107
3500	0.129	0.066	0.043	0.060	0.091	0.079

1, 2, and 5. 14.5 w/o Mannitol Solution

3 and 4. 22 w/o Mannitol Solution

Flow Systems

TABLE 2-13

REQUIRED SENSITIVITY OF CONDUCTIVITY MEASUREMENTS

Boron Concentration, ppm	Sensitivity of Measurements at $\pm 1.0\% C_B$ in $\mu\text{mhos/cm} \pm \mu\text{mhos/cm}$					
	Saturated	1	2	3	4	5
	19.2°C	22°C	43°C	43°C	25.5°C	17.5°C
100	167 $\pm$ 0.81	95 $\pm$ 0.45	56 $\pm$ 0.27	79 $\pm$ 0.35	118 $\pm$ 0.56	107 $\pm$ 0.50
1000	510 $\pm$ 2.48	280 $\pm$ 1.30	168 $\pm$ 0.82	227 $\pm$ 1.12	350 $\pm$ 1.73	312 $\pm$ 1.53
2000	720 $\pm$ 3.48	385 $\pm$ 1.78	236 $\pm$ 1.16	311 $\pm$ 1.58	485 $\pm$ 2.42	430 $\pm$ 2.14
3500	910 $\pm$ 4.51	485 $\pm$ 2.31	296 $\pm$ 1.51	390 $\pm$ 2.10	610 $\pm$ 3.19	540 $\pm$ 2.77

1, 2, and 5. 14.5 w/o Mannitol Solution

3 and 4. 22 w/o Mannitol Solution

Flow Systems

TABLE 2-14
COMMERCIALY AVAILABLE COMPONENTS

<u>Component</u>	<u>Description</u>	<u>Manufacturer</u>
Conductivity Monitor	Type R13 Conductivity Indicator, AC Wheatstone Bridge Circuit 0-500 $\mu\text{mho/cm}$ 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. per hour	Leeds and Northrup Co.
Dual Head Precision Metering Pump	Model "A" Cyclo/Fram Duplex Controlled Volume Diaphragm Pump, Teflon Diaphragm, 316 SS Pump Heads, capacity 1.3 gph, 58 strokes per min	Yarway Corp.
Constant Temperature Bath	Forma-Temp Jr. Bath and Circulator, Model-2095-I, Temp. Range 15 to 70°C , heat removal capacity 1000 Btu per hr	Forma Scientific Inc.
Conductivity Cells	2 Small Glass Conductivity Cells with 316 SS Threaded Fittings; cell constants of 0.1 cm^{-1} and 1.0 cm^{-1}	Beckman Instruments Inc.
Cabinet	Bud 19 in. Cabinet Rack, Panels, and Accessories	Bud Cabinets
Mannitol Mixing and Storage Tank and Agitator	50 gal. Capacity, Stainless Steel Construction, Sight Glass, Hinged Cover, Suction Piping with Strainer and Suction Valve Agitator: Single Phase, 60 cps, 115 v with SS Shaft and Impellor	Pittsburgh Process Equipment Company
Quick-Connects	Double-End Shut-Offs, 316 SS, Tube-to-Tube for $1/4$ in. OD Tube	Swagelok

TABLE 2-14 (Continued)

<u>Component</u>	<u>Description</u>	<u>Manufacturer</u>
Miscellaneous Fittings	Stainless Steel Unions, Connectors, Reducers, Solenoid Valves, Throttle Valve, Check Valves, etc.	-
Miscellaneous Electrical Components	Relays, Switches, Connectors, Blower Motor, etc.	-

- b. Heat exchangers for temperature control of the mannitol and sample solutions shortly after entering the meter and before mixing.
- c. Cation resin column for removing highly conductive species such as lithium in reactor coolant samples.
- d. Mixing chamber for rapid and complete mixing of the boric acid and mannitol solutions.
- e. 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-inch rack panel to form the boron meter. The meter measures the conductivity of a controlled blend, the conductivity being 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 2-22. The corresponding electrical and signal diagrams for the instrument are given in Figures 2-23 and 2-24, respectively.

The solution to be analyzed enters the system through a solenoid valve, flow control valve, and degasser connected in series. The degasser removes 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. The sample solution then flows through a heat exchanger to the suction side of one pump head of a dual-head precision metering pump. From the pump outlet, the sample stream goes through a check valve to a cation exchange resin column which removes interfering (conducting) cations such as lithium from the solution. The boric acid solution is then directed through a reference conductivity cell to the mixing chamber.

A tank is provided for the mixing and storage of the mannitol feed solution. The mannitol solution flows from the tank through a heat exchanger to the pump suction of the second pump head. The pump effluent stream is then directed through a check valve to the mixing assembly.

Figure 2-22. Boron Meter Flow Diagram

Figure 2-23. Boron Meter Electrical Diagram

Figure 2-24. Boron Meter Signal Diagram

The boric acid solution contacts the mannitol feed solution in the mixing chamber where the two streams are rapidly and completely mixed. The blend then passes through a temperature control heat exchanger to the flow conductivity cell.

A conductivity meter receives signals from the flow conductivity cell which is connected to a remote operating readout device. Provisions are made for determining the base conductivity of the coolant sample before mixing with the mannitol solution, by utilizing the first conductivity cell.

The instrument is completely self-contained and requires only a sample source, sample drain, and power source of 115 v, 60 cps. The instrument console has a local readout and a local strip chart recorder for visual and continuous 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 is also provided by a signal supplied from the console to a digital voltmeter or recorder.

Photographs of the meter are presented in Figures 2-25 through 2-28.

Diagrams of the degasser unit and the mixing chamber are presented in Figures 2-29 and 2-30. Diagrams of the cell holder, heat exchanger, and resin column are shown in Figures 2-31, 2-32, and 2-33, respectively.

2.3.3 Operation of the Boron Meter

Operating parameters of the boron meter are presented in Table 2-15.

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

2.3.3.1 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 is made up to be in the operational range of the meter.

Figure 2-25. Boron Meter-Front View

Figure 2-26. Boron Meter-Rear View

Figure 2-27. Degasser Assembly

Figure 2-28. Mannitol Mixing and Storage Tank

Figure 2-29. Degasser Unit

Figure 2-30. Mixing Chamber

CELL HOLDER COOLING COIL

Figure 2-31. Plexi-Glass Cell Holder

Figure 2-32. Heat Exchanger

Figure 2-33. Resin Column

TABLE 2-15
BORON METER - OPERATING PARAMETERS

<u>Power Requirements</u>	110 v, 60 cps AC 2.2 K watts max.
<u>Flow Rates</u>	
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
<u>Chemicals Consumption</u>	
Mannitol	7.3 gm/min
Cation Exchange Resin	8.1×10^{-3} cc/min ^a
<u>Electrical Signal</u>	
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
<u>Chemical Renewal</u>	
Mannitol Solution	Every 10 days ^b
Resin	Approximately every 20 days ^c

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

b. Based on operating 2 hours per 8 hour shift.

c. Based on chemical criteria.

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

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

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:

a. Prepare the following reagents:

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

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

3. 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 demineralized water and dilute to 500 cc. Calculate the normality as follows:

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

- b. Standardize the pH meter with buffer, pH 9.
- c. Dilute an aliquot of sample to 50 cc with demineralizer water.

<u>Approx. ppm boron</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

- d. Add 1 gram of mannitol and mix.
- e. Titrate to pH 8.5 with sodium hydroxide using the pH meter.
- f. Add an excess of mannitol and titrate to pH 8.5.
- g. Calculate the boron concentration in the following manner:

$$\text{ppm boron} = \frac{\text{cc NaOH} \times \text{normality of NaOH} \times 10,810}{\text{cc of Sample}}$$

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 2-34), 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 43.6 cm mark.
3. Calculate the amount of mannitol to be added from

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

which is in kilogram units.

Convert to pounds by multiplying by 2.2.

4. Weight the amount of mannitol calculated above and add it to the tank.

Figure 2-34. Mannitol Tank Calibration

5. Add 300 cc of 30 w/o reagent grade formaldehyde for each 100 liters 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:

1. Prepare a standard 3000 ppm boron 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 2-35.

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

2.3.3.2 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:

W/O MANNITOL IN ORIGINAL SOLUTION
WITH 0.1% FORMALDEHYDE

Figure 2-35. Mannitol Determination Calibration Chart

1. Energize the meter by placing the main power switch on the console control panel, Figure 2-36, 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 per cc mannitol solution is obtained and lock the controls by means of the locking screws provided. (This means that the boric acid side of the pump should be set at 35 cc per min and the mannitol side of the pump set at 50 cc per min. The pump calibration curve is included in Figure 2-37.)
3. Start the constant temperature bath operating by means of 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 temperature in the bath is 20°C. Allow ample time for bath to stabilize at 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 a operation. The excess flow should be about 35 cc per min for a total inlet flow of 70 cc per min of reactor coolant solution.

2.3.3.3 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

*~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.

Figure 2-36. Boron Meter Console Control Panel

Figure 2-37. Pump Calibration

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. Determine the boron concentration by taking the digital voltmeter reading and converting it to ppm boron from the set of calibration tables provided in Appendix A, or from the calibration curve shown as Figure 2-38.

2.3.3.4 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 2-39. The base line check is performed by depressing the switch labeled "cell" at either the local or remote location. An amber light will indicate that the reference conductivity is being measured.

BORON CONCENTRATION, PPM B

Figure 2-38. Boron Meter Calibration Curve

Figure 2-39. Boron Meter Output for Boric Acid Solutions with No Added Mannitol

2.3.4 Laboratory Testing of the Prototype Meter

Bench testing of the prototype was conducted to determine accuracy, time response, and reliability of the as-built meter. To provide a simulated reactor coolant source to the prototype meter, 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 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 analyses of various boric acid solutions by the meter. These values are presented in Table 2-16. An equation was determined to describe the boron concentration as a function of millivolt readings. This relationship was found to fit the expression

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

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 to 3200 ppm boron.

From the above expression, it follows that

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

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

TABLE 2-16

BORON METER CALIBRATION DATA

Boron Concentration ppm	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

This expression will give the sensitivity of the meter in terms of change in boron concentration per change in millivolt reading. The following data can be obtained:

<u>Boron Concentration</u>	<u>Millivolt</u>	<u>Δ ppm Boron/Δ Millivolt</u>
57 ppm	107	0.9
114 ppm	153	1.5
531 ppm	337	3.2
1000 ppm	462	4.6
1863 ppm	593	6.0
2651 ppm	735	7.6
3188 ppm	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 ± 0.5 millivolts. The meter accuracy was found to be:

<u>Boron Concentration</u>	<u>Accuracy</u>
50 ppm	± 0.5 ppm = $\pm 1.0\%$
100 ppm	± 0.8 ppm $\pm 0.8\%$
500 ppm	± 1.5 ppm $\pm 0.30\%$
1000 ppm	± 2.3 ppm $\pm 0.23\%$
1700 ppm	± 3.0 ppm $\pm 0.17\%$
2000 ppm	± 3.8 ppm $\pm 0.14\%$
2300 ppm	± 4.2 ppm $\pm 0.13\%$

The output signal was completely free of noise during the bench testing. Long term drifting of electronics was not noticed during the bench testing and the meter ran continuously for periods up to forty-eight hours with no observable drifting.

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 at the boron meter inlet two minutes after the change.

2.4 EVALUATION OF THE PROTOTYPE METER

The purpose of this subtask of the program was to evaluate the long-term performance of the boron concentration analyzer while operating in a nuclear power plant. Consequently, the meter was installed as an integral part of the Saxton reactor plant sampling system. The coolant contained boric acid, lithium as an alkali control agent, and radioactive fission and corrosion products. When the Saxton plant shut down for refueling operations, the meter was returned to the Forest Hills Site for continued operation from a simulated reactor coolant source. The following sections report in detail the results of the meter operation at Saxton and Forest Hills.

2.4.1 Operations at Saxton

The boron meter was installed in the auxiliary building of the Saxton Nuclear Experimental Corporation's reactor plant near the sample room. The meter was connected such that it would receive a reactor coolant sample from the plant sampling system downstream of the "let-down" valve and the regenerative heat exchanger. The sample was provided at an approximately constant pressure by the sampling system booster pump. An electrical control signal from the system sampling valve energized a solenoid valve allowing the reactor coolant sample to enter the meter and, at the same time, start the instrument. Upon

closing the sampling valve the boron meter shut off and the solenoid valve closed. The excess flow above that required for the analyzer (35 cc/min) was directed to the waste disposal system along with the meter effluent. The excess reactor coolant solution could have been returned to the primary surge tank and eventually back to the reactor coolant system. A vacuum line was connected to the degasser housing so that radioactive gases stripped from the influent would be removed to the site radioactive gas decay system. A remote control panel and signal readout device were located in the Saxton experimental equipment room which is situated next to the reactor control room approximately 100 feet away from the analyzer. The readout device employed during this testing was a digital voltmeter with printout. The meter was controlled from the remote location during plant operation and all boron concentration measurements other than instrument calibrations, were recorded at the remote location. Instrument calibrations were performed locally at the meter. Piping arrangements, as well as the electrical control and signal leads, are illustrated in the simplified schematic in Figure 2-40.

The meter was operated for a total of 172.5 hours under various plant operating conditions including reactor coolant boron concentration changes, hot standby, and at-power operations. In addition, the boron meter was operated for 51 hours using a standard boron source when reactor coolant samples were not available from the reactor primary system. The plant boron concentrations ranged from 250 to 694 ppm, and the meter accuracy was within ± 2.0 ppm in those instances where the boron concentration was essentially constant during the intervals of boron follow. The accuracy of the boron concentration measurement, determined by the analyzer, corresponded to the accuracy previously stated in the laboratory evaluations.

A sequence of boron additions to the reactor coolant was followed to evaluate the meter performance in a dynamic situation. Three boron additions were made, raising the reactor coolant boron concentration from 263 ppm to 633 ppm. Each addition raised the reactor coolant boron concentration approximately 125 ppm. The reactor coolant was sampled periodically during the boron additions, and boron concentrations were determined by manual analysis. The results of this test are presented in Figure 2-41. It can be seen that there

Figure 2-40. Piping Arrangement for Boron Meter at Saxton

Figure 2-41. Boron Meter Boron Addition Follow

is a delay time of about ten minutes from the time the injection was initiated to the time the boron meter responded to show an increase in the boron concentration. Previously, it had been shown that the meter has an internal delay time of about three minutes, so that there is a seven minute time lag from the reactor coolant to the meter inlet. Thus, boron concentrations determined by both the meter and by analysis are compared at times corrected for the delay. The following results were obtained:

<u>Event</u>	<u>Mannitol Meter</u>	<u>Chemical Analysis</u>
Base Line	263 ppm boron	263 ppm boron
After 1st Addition	394 ppm boron	396 ppm boron
After 2nd Addition	530 ppm boron	526 ppm boron
After 3rd Addition	642 ppm boron	633 ppm boron

The deviations in the boron concentrations after the third addition were due to a drifting in flow from one side of the duplex metering pump which would change the flow mixing ratio and consequently the boron concentration. It is also noted in Figure 2-41 that the meter indicates that the boron concentration peaks after the addition and then drops to the equilibrium value. This effect is probably due to incomplete initial mixing of the reactor coolant with dead volumes in the system such as that which is contained in the pressurizer.

2.4.2 Operations at Forest Hills

The boron meter was returned to the Forest Hills Site where the pump problem was investigated in detail. All testing was conducted using a boric acid source tank adjusted with lithium to simulate the reactor coolant influent solutions. It was found that operations at higher flow rates than were used in previous operations (greater than 50 cc/min reactor coolant and 71.5 cc/min mannitol solution) produced a stable flow mixing ratio. The meter operated continuously at the higher flow rates for 100 hours with no indication of flow problems.

At this time, the one pump side which had been operating erratically at the lower flow rates again showed a decreasing flow rate. The pump was returned to Yarway Corporation for repair, and factory performance testing was conducted in a loop set up to simulate conditions found in the boron meter. The abrupt decrease in flow was due to a defective air escape shaft clutch in the hydraulic fluid air vent mechanism. This part was replaced. It was also found that by reducing the replenishing valve tension settings, the pump would perform stably at the lower flow rates. The lower settings resulted in less bubble formation and oil vaporization in the hydraulic side of the pump.

The pump was reinstalled in the meter and operated trouble-free for 120 hours. Again, the air escape shaft clutch malfunctioned and had to be replaced by the vendor. The meter has operated for over 400 hours with stable flow and no further indication of pump problems. The operation has been trouble-free and meter accuracy is within the range determined previously in runs at Forest Hills.

A typical dilution test for the boron analyzer is indicated by the recording presented in Figure 2-42. The strip chart recorder is employed to provide a record of the changes in boron concentration. To obtain the sensitivity required, the readout is taken from a digital voltmeter.

The following list describes the meter operation presented on the strip chart recording:

1. initial steady-state condition
2. check standard solution
3. check reference cell
4. return to reactor coolant solution
6. check reference cell
7. commence first dilution
9. commence second dilution
11. commence third dilution
13. commence fourth dilution
15. commence fifth dilution

Figure 2-42. Boron Dilution Test

17. check reference cell
18. check standard solution
20. check reference cell
21. commence boron addition

The meter performance is listed in Table 2-17. It is seen that the meter accuracy is within the ± 2 ppm or 0.3 percent.

TABLE 2-17
METER PERFORMANCE

Time Designation	Digital Voltmeter, mv	Boron Concentration, ppm	Analyzed Boron Concentration, ppm
1	573.8	1572	1570
3	71.8	----	----
4	471.2	1042	1042
5	573.7	1572	1570
6	105.0	----	----
8	560.4	1494	1491
10	542.7	1397	1396
12	479.2	1079	1080
14	412.3	799	797
16	200.3	192	191
17	35.0	----	----
19	471.0	1042	1042
20	71.5	----	----
22	432.4	879	878

2.5 CONCLUSIONS AND RECOMMENDATIONS

A summary of conclusions based on the foregoing work along with recommendations for the mannitol-conductance boron analyzer are as follows:

1. The boron concentration analyzer has been fabricated using commercially available components where possible and has been operationally tested.
2. Accuracy analysis of data obtained from testing of the instrument has shown the following:

Boron Concentration	Accuracy
100 ppm	± 0.8 ppm = $\pm 0.8\%$
1000 ppm	± 2.3 ppm = $\pm 0.23\%$
3200 ppm	± 4.2 ppm = $\pm 0.13\%$

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

3. 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.
4. 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 \$1600.00 per year.
5. Waste disposal requirements for fluids from the meter should not present any significant problem. For continuous meter operation, the total liquid output from the meter is approximately 32 gallons per day.
6. The following maintenance requirements are based on operating two hours per shift:

Chemical renewal	
Mannitol solution	Every 10 days
Resin replacement	Every 20 days

* Whichever is greater.

[†] Based on cost of mannitol at 77¢/lb.

Recorder chart paper	Every 27 days
Platinize electrodes	Every 6 months

7. The actual operational times during which the meter was recording boron concentration of an influent solution are:

Saxton	223.5 hours
Forest Hills	395 hours

8. The total cost of the meter components is about \$4600 excluding digital readout, and \$8100 including digital readout.
9. A desirable meter improvement would be the incorporation of a millivolt-to-boron concentration converter to provide direct readout in units of ppm boron.
10. A recommended modification would be the addition of an automatic self-compensating sensitivity adjustment for the conductivity monitor. Beckman was contacted concerning this modification and their opinion is that it could be provided.

APPENDIX A
CALIBRATION TABLES

0-99

Millivolts	0	1	2	3	4	5	6	7	8	9
0										
10										
20										
30										
40										
50	13.7	14.2	14.7	15.3	15.8	16.4	16.9	17.5	18.1	18.7
60	19.3	19.9	20.5	21.1	21.8	22.4	23.1	23.7	24.4	25.1
70	25.8	26.5	27.2	27.9	28.6	29.4	30.1	30.8	31.6	32.4
80	33.1	33.9	34.7	35.5	36.3	37.2	38.0	38.8	39.7	40.5
90	41.4	42.2	43.1	44.0	45.8	46.7	47.6	48.6	49.5	50.4

CALIBRATION TABLES (Continued)

100-199

Millivolts	0	1	2	3	4	5	6	7	8	9
100	50	51	52	53	54	55	56	57	58	59
110	60	61	62	63	65	66	67	68	69	70
120	71	72	73	74	76	77	78	79	80	81
130	83	84	85	86	88	89	90	91	92	94
140	95	96	98	99	100	102	103	104	105	107
150	108	109	111	112	114	115	116	118	119	121
160	122	123	125	126	128	129	131	132	134	135
170	137	138	140	141	143	144	146	147	149	150
180	152	154	155	157	159	160	162	164	166	167
190	169	171	173	175	176	178	180	182	184	186

CALIBRATION TABLES (Continued)

200-299

Millivolts	0	1	2	3	4	5	6	7	8	9
200	188	189	191	193	195	197	199	201	203	205
210	207	209	211	213	215	217	219	221	223	225
220	227	229	231	233	235	237	239	242	244	246
230	248	250	252	255	257	259	261	263	266	268
240	270	272	274	277	279	281	283	285	288	290
250	292	294	297	299	301	304	306	308	311	313
260	315	318	320	322	325	327	330	332	334	337
270	339	342	344	346	349	351	354	356	359	362
280	364	367	370	372	375	378	381	383	386	389
290	391	394	397	400	403	405	408	411	414	417

CALIBRATION TABLES (Continued)

300-399

Millivolts	0	1	2	3	4	5	6	7	8	9
300	419	422	425	428	431	434	437	440	443	445
310	448	451	454	457	460	463	466	469	472	475
320	478	481	484	488	491	494	497	500	503	506
330	509	513	516	520	523	526	529	532	536	539
340	542	546	549	552	555	559	562	565	569	572
350	575	579	582	586	589	592	596	599	603	606
360	610	613	617	620	624	627	631	634	638	641
370	645	648	652	655	659	663	666	670	674	677
380	681	685	688	691	695	699	702	706	709	713
390	717	720	724	727	731	735	738	742	746	750

CALIBRATION TABLES (Continued)

400-499

Millivolts	0	1	2	3	4	5	6	7	8	9
400	753	757	761	764	768	772	776	779	783	787
410	791	795	798	802	806	810	814	818	822	825
420	829	833	837	841	845	849	853	857	861	865
430	869	873	877	881	885	889	893	897	901	905
440	909	913	917	921	925	929	934	938	943	946
450	950	954	958	963	967	971	975	980	984	988
460	992	997	1001	1005	1009	1014	1019	1023	1028	1032
470	1037	1041	1046	1050	1055	1060	1064	1069	1074	1078
480	1083	1083	1092	1097	1102	1106	1111	1116	1121	1125
490	1130	1135	1140	1145	1149	1154	1159	1164	1169	1174

CALIBRATION TABLES (Continued)

500-599

Millivolts	0	1	2	3	4	5	6	7	8	9
500	1179	1183	1188	1193	1198	1203	1208	1213	1218	1223
510	1229	1233	1238	1243	1248	1253	1258	1263	1268	1273
520	1278	1283	1288	1294	1299	1304	1309	1314	1319	1325
530	1330	1335	1340	1345	1351	1356	1361	1366	1372	1377
540	1382	1388	1393	1398	1404	1409	1414	1420	1425	1430
550	1436	1441	1447	1452	1458	1463	1469	1475	1480	1486
560	1492	1497	1503	1509	1515	1520	1526	1532	1538	1544
570	1550	1556	1561	1567	1573	1579	1585	1590	1597	1602
580	1608	1614	1620	1626	1632	1638	1644	1650	1656	1662
590	1668	1674	1680	1686	1693	1699	1705	1711	1717	1723

CALIBRATION TABLES (Continued)

600-699

Millivolts	0	1	2	3	4	5	6	7	8	9
600	1729	1735	1742	1748	1754	1760	1766	1773	1779	1785
610	1791	1798	1804	1810	1817	1823	1829	1836	1843	1848
620	1854	1861	1868	1874	1880	1887	1893	1900	1906	1913
630	1919	1926	1932	1939	1945	1952	1958	1965	1972	1978
640	1985	1991	1998	2004	2011	2018	2025	2031	2038	2045
650	2051	2058	2066	2073	2080	2087	2093	2100	2107	2114
660	2121	2127	2134	2141	2148	2155	2162	2169	2176	2183
670	2190	2197	2204	2211	2218	2225	2232	2239	2246	2253
680	2260	2267	2274	2281	2289	2296	2303	2310	2317	2325
690	2332	2339	2346	2353	2361	2368	2375	2383	2390	2397

CALIBRATION TABLES (Continued)

700-799

Millivolts	0	1	2	3	4	5	6	7	8	9
700	2404	2412	2419	2427	2434	2441	2449	2456	2464	2471
710	2478	2486	2493	2500	2508	2516	2524	2532	2540	2548
720	2557	2565	2573	2581	2589	2597	2605	2614	2622	2630
730	2638	2646	2654	2662	2671	2679	2687	2696	2704	2712
740	2720	2729	2737	2746	2754	2762	2771	2779	2788	2796
750	2805	2813	2822	2830	2839	2847	2856	2864	2873	2882
760	2890	2899	2908	2916	2925	2933	2942	2951	2960	2968
770	2977	2986	2995	3003	3013	3021	3030	3039	3048	3056
780	3066	3074	3083	3092	3101	3110	3119	3128	3137	3146
790	3155	3164	3175	3184	3193	3202	3211	3220	3229	3238

CALIBRATION TABLES (Continued)

800-899

Millivolts	0	1	2	3	4	5	6	7	8	9
800	3247	3256	3263	3271	3278	3285	3293	3300	3307	3314
810	3321	3329	3336	3343	3351	3358	3366	3373	3380	3387
820	3395	3402	3410	3417	3424	3432	3439	3448	3454	3461
830	3469	3476	3484	3491	3498	3506	3514	3521	3528	3536
840	3543	3551	3558	3566	3573	3580	3589	3597	3604	3611
850										
860										
870										
880										
890										

SECTION 3

NEUTRON-ABSORPTION BORON METER

V. Rajagopal

3.1 INTRODUCTION

The boron absorption meter is an electro-nuclear device for measuring the concentration of absorbers in the reactor coolant water. Since the absorbers are essentially boron, the concentration is hereafter referred to as the boron concentration. Boron has a high probability of absorbing slow neutrons and this property provides the basis of the meter. The slow neutrons are generated by slowing down fast neutrons from a neutron source (α, n), through collisions with hydrogen nuclei in light water. The neutrons are then detected by a proportional counter. Coolant water, whose boron concentration is to be measured, is contained in an annulus region around the neutron detector. The larger the boron content of the water, the smaller the neutron counting rate in the detector. The electronic section of the meter then converts this detector counting rate to a direct reading of boron concentration in parts per million (ppm).

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

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

where C is the counting rate for a given sample, C_0 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 nonlinear 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 were implemented to read time to a present count rather than counts over a fixed time, the function consistently approached a linear function without nonlinear circuits.

As a result of this hyperbolic characteristic, the electronics were 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 nonlinear function.

3.2 GENERAL DESCRIPTION OF THE NEUTRON ABSORPTION METER

The neutron meter consists of two parts. The sample tank, and the electronics readout drawer. Figure 3-1 is a photograph of the entire system.

Figure 3-2 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. Three heaters equally spaced around the tank and approximately 3 inches from the bottom 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.

Figure 3-1. Boron Concentration Meter Based on the Neutron Absorption Principle

Figure 3-2. General Layout of Neutron Absorption Meter

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 3-1.

3.3 COMPARISON OF THE NEUTRON ABSORPTION METER WITH DESIGN SPECIFICATIONS

3.3.1 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; and 2500-5000 ppm ± 25 ppm.
2. Readout: digital in terms of ppm of natural boron (based on 19.7% of boron-10) for visual indication and for a process computer.
3. Readout Option: an additional analog signal for a recorder.
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 minutes.

3.3.2 Bench Test Results

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

1. Accuracy: 25-500 ppm ± 3 ppm; 250-1250 ppm ± 5 ppm; 1000-2500 ± 5 ppm; and 2500-5000 ppm ± 7.1 ppm. One additional accuracy point was investigated. With pure H₂O the accuracy is ± 2 ppm.
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; and 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 feet. 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.	6- 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 was within specifications.
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.

3.4 ANALYSIS OF OPERATING CHARACTERISTICS OF BORON CONCENTRATION METERS

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. These 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 to 3/4 inches; 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 inches; and water or paraffin moderators ranging in size from a block 12 by 12 by 6 inches, to a cylinder 22 inches in diameter by 26 inches high. Experimental data are 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.

3.4.1 Data from Earlier Concentration Meters

3.4.1.1 DeFord and Braman Data

DeFord and Braman^[4] present data on a boron concentration meter whose annulus is the concentric region between standard 1-inch and 2-inch polyethylene pipes. Figure 3-3 shows their arrangement. The neutron 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 by 12 by 6 inches.

The data on counting rate versus/boron concentration are shown in Table 3-1. 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 3-2 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.

Figure 3-3. Arrangement of Components for Boron Concentration Determination by DeFord and Braman

TABLE 3-1

COUNTING RATE VERSUS CONCENTRATION DATA BY DEFORD AND BRAMAN

Boron Concentration Gram Atoms per Liter	Counts Recorded in 10 Minutes, 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 3-2

TIME TO ACCUMULATE 10^5 COUNTS VERSUS

BORON CONCENTRATION, DEFORD AND BRAMAN DATA

Boron Concentration, Grain Atoms per Liter	ppm	Count Rate, $\text{Min}^{-1} \times 10^{+2}$	Time to Accumulate 10^5 Counts, 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

The data from Table 3-2 are plotted in Figures 3-4 and 3-5. Figure 3-4 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 3-5 where the data available in the range of interest are plotted on an expanded scale. A straight line has been eye-fitted to the data points.

3.4.1.2 Eastman Data

Four sets of data are available from Eastman's work. [5, 6] These data are given by the four curves shown in Figure 3-6 and 3-7.

The data shown in Figure 3-6 are taken using an arrangement similar to that shown in Figure 3-3. The annulus thickness of the absorption cell, designated A, was 1/2 inch.

Table 3-3 shows data read from Figure 3-6. In addition, the times to accumulate 100,000 counts are shown.

Figure 3-8 shows a plot of the data from Table 3-3. 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 are shown in Figure 3-7. Again, the arrangement was similar to that shown in Figure 3-3. 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 3-7.

Table 3-4 shows the data on count rate versus boron concentration as read from Figure 3-7. In addition, the times to accumulate 100,000 counts are shown. These data have been plotted in Figures 3-9 and 3-10 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

Figure 3-4. Time to Accumulate 10^5 Counts versus Boron Concentration, DeFord and Braman Data

Figure 3-5. Time to Accumulate 10^5 Counts versus Boron Concentration, DeFord and Braman Data

Figure 3-6. Counting Rate versus Boron Concentration for Cell A,
Eastman Data, 1/2-Inch Annulus

Figure 3-7. Counting Rate versus Boron Concentration for Cell B, Eastman Data, 7/8-inch Annulus

Figure 3-8. Time to Accumulate 10^5 Counts versus Boron Concentration, Eastman Data, Cell A, 1/2-inch Annulus

Figure 3-9. 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 3-10. 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

TABLE 3-3

TIME TO ACCUMULATE 100,000 COUNTS VERSUS BORON CONCENTRATION,
EASTMAN DATA ON CELL A WITH 1/2-INCH ANNULUS

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

TABLE 3-4

TIME TO ACCUMULATE 100,000 COUNTS VERSUS BORON CONCENTRATION,
EASTMAN DATA ON CELL B WITH 7/8-INCH ANNULUS

Boron Concentration, ppm	Count Rate, Min ⁻³	Time to Accumulate 100,000 Counts, 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
1,000	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

5/8 inch and 1-1/2 inch. The data points for the 3-inch spacing, as shown in Figure 3-11, do not appear to be along a straight line.

3.4.2 Experimental Data Obtained during Meter Development

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

Figure 3-12 shows the arrangement of components used for experiments performed during the development of the concentration meter. The neutron detector was a boron-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 are shown in Figures 3-13, 3-14, and 3-15. 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 3-13) does not display a linear relationship between T and C .

The data for the 0.600 inch annulus (Figure 3-14) does display a linear relationship to $C = 3500$ ppm. The point at 5,000 ppm lies below the extrapolation of the linear data.

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

Figure 3-12. Arrangement of Components for Experiments for Boron Concentration Meter

Figure 3-13. Time to Accumulate N Counts versus Boron Concentration for 0.473-inch Annulus

Figure 3-14. Time to Accumulate N Counts versus Boron Concentration for 0.600-inch Annulus

Figure 3-15. Time to Accumulate N Counts versus Boron Concentration for 0.875-inch Annulus

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.

3.4.3 Discussion of Experimental Data

The data of DeFord and Eastman as represented in Figures 3-9 and 3-10 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 (12 by 12 by 6 inch) moderator block.

The complete DeFord data displayed in Figure 3-4 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 3-16 shows the neutron flux^[7] 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 3-3 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 3-4.

The Eastman data for 3-inch spacing between the source and cell wall as shown in Figure 3-11 does not appear to give a linear relationship between T and C. Figure 3-16 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.

Figure 3-16. Distribution of Thermal Neutrons from a Point Source Immersed in Water

The present data improve in linearity as the annulus thickness is increased from 0.473 inch (Figure 3-13) to 0.875 inch (Figure 3-15). 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

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

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.

3.4.4 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 3-16 to one as shown in Figure 3-17. 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_0) by a flux depression factor, F.

$$\phi_0 = F\phi_s \quad (2)$$

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

Figure 3-17. Depressed Neutron Flux Distribution Around Annulus Filled with Borated Water

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

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., $\frac{\mu x}{2} = 0$.

An analytical expression for F is needed. Such an expression does not exist for the geometry used in boron concentration meters. However, Bothe^[3] has developed an expression for F , which is a spherical shell of radius R . We shall use his expression as a rough approximation to the correct one. His expression^[9] 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, x is the total absorption thickness, and $\text{Ei}(-\mu x)$ is the "exponential" integral function available in Tables.^[10]

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

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

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

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

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 percent 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 nonuniform flux. However, the analysis does demonstrate the plausibility of the linear relationship between T and C.

3.4.5 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 a 12 by 12 by 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 in diameter by 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 0.875 inch the linear relationship is very good up to 5,000 ppm.

3.5 DEVELOPMENT OF PROTOTYPE MODEL

3.5.1 Construction and Initial Experiments

Figure 3-18 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 outside diameters of 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 outside diameter of the detector tube, therefore, made up the inside diameter of the annulus.

Figure 3-18. Jig for Neutron Absorption Experiments for the Boron Concentration Meter

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 of 5,000, 1,250, 625, 312.5, 156.25, and 78.125 ppm were obtained. A second master of 3,500 ppm was mixed 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 3-19 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 of the physics analysis,^[11] 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 time 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 3-20) for the various annuli and these were compared to an exponential curve to determine the magnitude of the nonlinearity 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 normal or gaussian as expected. This confirmed the operation of the electronics system. During this period in the development program, the measurements were all made in counts per unit time.

3.5.1.1 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 were taken on this system for both modes of operation with a 0.6-inch annulus and the plot of time to a

Figure 3-19. Block Diagram of Electronics for Neutron Attenuation Experiments

Figure 3-20. Boron Concentration Meter Breadboard System Counts versus Boron Concentration.

preset count curve approximated a straight line. Data were collected and curves generated for the 0.473- and 0.875-inch annuli. The results of these tests are shown on Figures 3-21 and 3-22.

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 per 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 set up, 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 ensure that the variation in the output indication was correct, that is, that the 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.

3.5.1.2 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 kept the detector cable leads short.

The pre-amplifier output was 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 pre-amplifier while voltage regulator "A" drives a conventional dc-to-dc inverter and double circuit. The

Figure 3-21. Boron Concentration Meter Counts versus Boron Concentration for Various Annulus Thicknesses

Figure 3-22. Boron Concentration Meter Breadboard System Time to Preset Count versus Boron Concentration for Various Annulus Thicknesses

output of the voltage doubler was filtered and supplied the high voltage to the detector. The power supply has the following characteristics:

Output

Voltage:	+700 to +900 V
Current (HV):	up to 2 milliamperes
(10V):	up to 60 milliamperes
Line Regulation:	Better than 0.5 percent for line voltage
Temperature:	0.1 percent (0 to 75°C)
Ripple and Noise:	Less than 0.003 percent
Overload:	Both supplies are current limited to protect against load faults.

The power supplies were tested to insure they met all of the above characteristics except for a temperature test over the full range. The temperature of the entire annulus system was 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 was 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 the adjustment is set for a given cable, it will not be changed.

The other assembly for the boron meter is the electronics chassis. This chassis contained the power supplies 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 were card mounted in the chassis. Figure 3-23 is a block diagram of the logic circuits. Modules A through D are binary counters. The A and B units

Figure 3-23. Logic Circuits Block Diagram, Boron Concentration Meter

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 were selectable by means of the mode control switch, -- events per 10 seconds, ppm, and Time. In the Events per 10 seconds position, the readout indicated the total counts from the discriminator per 10 seconds. In this mode, the system operated as a conventional electronic counter. In the Time mode, the readout displayed the time in seconds to reach the preset count. This preselected count was derived from the counters via Gate E_2 from B_3 of the counter string. In the ppm mode, which was the normal mode of operation, the readout displayed parts per million boron directly. Figure 3-24 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 resulted in at least 100 hours operating time on the entire system, and infant mortalities which could have occurred were weeded out.

3.5.2 Model Testing and Test Results

3.5.2.1 Circuit Modifications

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

1. Installation of a new thermostat controller for regulating tank temperature. This controller has a dead band of about 0.5°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 supplies with fixed precision resistors.
4. High voltage inverter and bleeder resistors changed to precision low temperature coefficient types.

Figure 3-24. Electronic Readout Chassis Boron Concentration Meter

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.

3.5.2.2 Final Meter Checkout

The test setup shown in Figure 3-25 was used to obtain data for the final laboratory checkout of the boron meter. Several tests were performed. These tests confirmed 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 per degree Fahrenheit. This indicated that an extreme temperature transient (much worse than would be expected in actual 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 3-5, are plotted in Figure 3-26.

Following the completion of laboratory checkout, the meter was installed in the Saxton nuclear facility for an extended in-plant evaluation of its performance. The configuration of the meter as installed at Saxton and Connecticut Yankee reactor plants is shown in Figure 3-27.

3.6 EVALUATION OF PROTOTYPE NEUTRON-ABSORPTION BORON METER

3.6.1 Performance Evaluation at Saxton

Figure 3-25. Boron Concentration Meter Test Set-up

Figure 3-26. Boron Concentration Meter Final Laboratory Calibration Test Results

Figure 3-27. Boron Absorption Meter Functional Block Diagram

TABLE 3-5

NEUTRON ABSORPTION METER CALIBRATION TEST

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

3.6.1.1 Installation

The boron absorption meter was installed in the nuclear reactor system at the Saxton Nuclear Experimental Corporation (SNEC) plant in July, 1968. The results stated here are based on the operating data obtained from that plant. The tank section of the unit, the high voltage, the preamplifier, amplifier and discriminator were installed in the auxiliary building while the readout, printout and BATU sections were installed in the instrumentation room. A sketch of the location of the absorption meter in relation to the overall plant layout is shown in Figure 3-28.

3.6.1.2 Static Performance

Computation of the static accuracy of the absorption meter is based on using the chemical analysis as a standard. Usually a sample is taken and is analyzed once per day. The static accuracy was determined about three levels of concentration and the results summarized in Table 3-6.

TABLE 3-6

BORON ABSORPTION METER STATIC ACCURACY

Analysis ppm	Data Mean, ppm	Data Standard Deviation, ppm	Data Limit Deviation, ppm
258	259	± 2.5	± 5
313	312	± 2.5	± 5
621	622	± 2.8	± 6

The levels of concentration in Table 3-6 were predominant levels of operation of the Saxton Site during the month of September, 1968.

Figure 3-28. Connection of Absorbtion Meter in Saxton Plant

To obtain some information concerning the statistical nature of the data, twelve hours printout from the boron absorption meter was analyzed using the MAX/RAN Amplitude Statistics. The results of this analysis are shown in Figure 3-29. The probability density of the data shown in Figure 3-29 does not follow a gaussian fit.

3.6.1.3 Dynamic Performance

The dynamic response of the boron absorption meter for a linear dilution rate is demonstrated in Figures 3-30 and 3-31. Figure 3-30 shows boron concentration by chemical analysis and by absorption meter reading versus time. Figure 3-31 is an enlarged portion of Figure 3-30 which allows more detail. A dynamic lag of approximately seven minutes between the boron meter reading and the chemical sample is apparent from Figure 3-30. This lag can be explained by the time required to fill the annulus with reactor water (2 minutes) time to read the boron concentration (2 minutes) and the time difference in sample lines (3 minutes).

The dynamic response of the absorption meter when the boron content of the main coolant (Saxton Reactor) was raised from 263 to 633 ppm is shown in Table No. 3-7 and Figure No. 3-32 and 3-33. This boration was accomplished by the addition of 240 gallons of Boric Acid in 3 batches of 80 gallons each. Odd numbered samples were taken after 40 gallons had been added (i.e. halfway through the addition). Even numbered samples were taken after the batch had thoroughly mixed with the Main Coolant and approximately 10 minutes before the next addition. The following table lists the vital data.

Figure 3-29. Amplitude Statistics Analysis

Figure 3-30. Boron Concentration Versus Time

Figure 3-31. Boron Concentration versus Time

Figure 3-32. Boron Absorption Meter Dynamic Response

Figure 3-33. Boron Absorbion Meter Dynamic Response

TABLE 3-7
BORON ABSORPTION METER DYNAMIC RESPONSE

<u>Sample Number</u>	<u>Time</u>	<u>Neutron Absorption</u>	<u>SNEC Chemist</u>
Base	1039	263	263
1	1523	271	350
2	1551	399	396
3	1608	394	447
4	1638	529	526
5	1720	527	569
6	1811	630	633

The addition of 80 gallons of boric acid took about 7 minutes. The first indication of a change occurred in the Neutron Absorption unit about 7 minutes after the start of the addition and the unit stabilized about 10 minutes later.

3.6.2 Performance at Connecticut-Yankee Atomic Power Plant

The following paragraphs give a brief description of the installation, calibration and testing of the boron absorption meter at Connecticut-Yankee.

The meter was installed at Connecticut-Yankee on February 19, 1969.

3.6.2.1 Installation

The absorption analyzer was installed in the Connecticut-Yankee plant in parallel with the primary coolant radiation monitoring unit. The primary coolant was throttled such that a pressure drop of 2.5 psi across the analyzer

was obtained. According to the flow calibration curve (Figure 3-34) this would produce a flow of 0.45 gpm which is less than the analyzer maximum of 2 gpm. The inlet coolant temperature was about 115°F and the outlet about 130°F.

3.6.2.2 Calibration

The absorption analyzer was filled with clean water and two calibration sleeves (0.6 inch and 0.3 inch) were used to adjust the analyzer reading at three points (0, 824 and 1230 ppm). The primary coolant flow was then connected to the analyzer and the necessary small calibration adjustments (high voltage) were made at the plant operating point. The final settings of the boron analyzer are given in Table 3-8. Figure 3-35 shows the detector high voltage characteristics.

3.6.2.3 Performance Evaluation

Observation of the analyzer readings indicated that the static accuracy was approximately the same as that obtained at the Saxton Plant (± 5 ppm limit). Table 3-9 summarizes the comparison between the boron meter readings and chemical analyses over a period of one month. No drift was observed in the boron meter and agreement with the chemical analyses was excellent.

3.7 CONCLUSIONS AND RECOMMENDATIONS

1. A neutron-absorption-boron concentration analyzer that has a four place ppm readout has been fabricated and tested in operating reactor plants. The principal characteristics of the prototype meter are presented in Table 1-2 together with the original design specifications.
2. No significant problems were encountered in installing and making the meter operational at both the Saxton and Connecticut-Yankee reactor plants.

Figure 3-34. Boron Analyzer Calibration

Figure 3-35. High Voltage Characteristics for Boron Analyzer Detector

TABLE 3-8

CONNECTICUT YANKEE BORON METER DATA

Data Set	Boron Analyzer Settings						Boron Analyzer Readings		
Set Number	High Voltage	Pre-Amplifier	Amplifier Coarse	Fine	Discriminator	Calibr. Sleeve in.	RIDL Time	BA Time	BA ppm
1	830	1	1/8	1	0.49	AL	38.5	77.5	-
	830	1	1/8	1	0.49	0.3	47.9	-	909
	830	1	1/8	1	0.49	0.3	47.9	-	910
	830	1	1/8	1	0.49	0.6	52.5	-	1360
	830	1	1/8	1	0.49	0.6	52.5	-	1364
	830	1	1/8	1	0.49	0.6	52.4	-	1357
2	830	1	1/8	1	0.40	AL	37.6	75.7	-
	830	1	1/8	1	0.40	AL	37.5	75.6	-
	830	1	1/8	1	0.40	0.3	46.8	-	799
	830	1	1/8	1	0.40	0.3	46.8	-	801
	830	1	1/8	1	0.40	0.6	51.0	-	1225
	830	1	1/8	1	0.40	0.6	51.1	-	1230
3	830	10	1/8	1	0.40	AL	41.8	84.1	310
	830	10	1/8	1	0.40	0.3	50.0	-	1128
	830	10	1/8	1	0.40	0.6	54.0	-	1519
4	830	1	1/8	1	0.30	AL	36.8	74.1	-
	830	1	1/8	1	0.30	0.3	45.5	-	684
	830	1	1/8	1	0.30	0.6	49.8	-	1100
5	830	1	1/8	1	0.20	AL	36.3	73.5	-
	830	1	1/8	1	0.20	0.3	44.8	-	604
	830	1	1/8	1	0.20	0.6	48.8	-	1000

TABLE 3-8 (Continued)

Data Set		Boron Analyzer Settings					Boron Analyzer Readings		
Set Number	High Voltage	Pre-Amplifier	Amplifier Coarse	Fine	Discriminator	Calibr. Sleeve in.	RIDL Time	BA Time	BA ppm
6	830	10	1	1	0.20	AL	43.0	86.6	-
	830	10	1	1	0.20	0.3	51.0	-	1229
	830	10	1	1	0.20	0.6	54.5	-	1607
7	830	1	1	1	0.60	AL	36.2	73.0	-
	830	1	1	1	0.60	0.3	44.2	-	559
	830	1	1	1	0.60	0.6	48.1	-	943
8	830	1	1/8	1	0.60	AL	39.6	79.9	-
	830	1	1/8	1	0.60	0.3	49.5	-	1067
	830	1	1/8	1	0.60	0.6	54.3	-	1541
9	925	1	1/8	1	0.20	AL	35.6	71.8	-
	925	1	1/8	1	0.20	0.3	43.5	-	485
	925	1	1/8	1	0.20	0.6	47.3	-	863
10	900	1	1/8	1	0.20	AL	35.6	71.8	-
	900	1	1/8	1	0.20	0.3	43.7	-	500
	900	1	1/8	1	0.20	0.6	47.4	-	871
11	900	1	1/8	1	0.25	AL	35.6	72.0	-
	900	1	1/8	1	0.25	0.3	43.7	-	495
	900	1	1/8	1	0.25	0.6	47.4	-	869

TABLE 3-8 (Continued)

Data Set	Boron Analyzer Settings						Boron Analyzer Readings		
Set Number	High Voltage	Pre-Amplifier	Amplifier Coarse	Fine	Discriminator	Calibr. Sleeve in.	RIDL Time	BA Time	BA ppm
12	900	1	1/8	1	0.30	AL	35.6	71.8	-
	900	1	1/8	1	0.30	0.3	43.7	-	494
	900	1	1/8	1	0.30	0.6	47.4	-	875
13	900	1	1/8	1	0.40	AL	35.6	71.8	-
	900	1	1/8	1	0.40	0.3	43.7	-	509
	900	1	1/8	1	0.40	0.6	47.6	-	892
14	900	1	1/8	1	0.50	AL	35.7	72.1	-
	900	1	1/8	1	0.50	0.3	43.9	-	524
	900	1	1/8	1	0.50	0.6	47.9	-	917
15	900	1	1/8	1	0.60	AL	35.9	72.5	-
	900	1	1/8	1	0.60	0.3	44.1	-	551
	900	1	1/8	1	0.60	0.6	48.2	-	944

Final Meter Settings at C-Y

						RIDL Time	BA Time	ppm
HV 900	PA 1	A 1/8; 1	Disc 0.60	AL		36.0	72.6	-
				0.3 inch		-	-	842
				0.6 inch		-	-	1237

HV Changed to 855 Based on Chemistry and Water No. Set at 72.0 sec.

TABLE 3-9

BORON METER PERFORMANCE AT CONNECTICUT-YANKEE

Analyzer Average of Six Readings, ppm	Titration Average of Three Readings, ppm
835	837
824	826
795	791
773	778
760	764
756	757
752	754
785	788
748	746
740	739
737	740
735	735
734	732
730	727
719	716

3. Reliability records at both the Saxton and Connecticut-Yankee plants have been excellent, with no maintenance requirements after initial setup.
4. In the prototype meter, the ppm boron readout is printed out continuously on paper tape. The addition of a timer or timing marker would help in correlating the meter readings to plant operations.

SECTION 4
EVALUATION OF THE BORON CONCENTRATION METER
USED AT THE SENA REACTOR PLANT

W. D. Fletcher

4.1 INTRODUCTION

The objective of this task under the boron concentration meter development program was to obtain detailed operating methods and characteristics of the SENA (Franco-Belge) reactor plant's meter for comparison with the overall program objectives, and the desired characteristics established at the beginning of this program for a boron concentration meter.

4.2 ACCOMPLISHMENTS

To obtain detailed operating characteristics of the SENA meter, a trip was made to the SENA reactor plant at Chooz, France. Operating records of the meter were reviewed, in-place operation was witnessed, technical discussions were held with plant personnel, and a report "Description and Evaluation of the Boron Concentration Meter Utilized at the SENA (Franco-Belge) Reactor Plant" (EURAE-1972, WCAP-3690-4) was issued in January 1968. This report and evaluation contains a detailed description of the SENA meter.

4.3 SUMMARY AND CONCLUSIONS

Based on observations and appraisal of operational characteristics of the SENA meter, the following conclusions were reached in the report:

1. The boron instrument has been operational and was used at SENA for monitoring reactor coolant system boron concentrations.
2. Operational characteristics of the meter require considerable maintenance and inspection. The basic instrument assembly relies on

trouble-free operation of four fundamental systems: chemical, mechanical, optical, and electronic. A malfunction which appears in any one of the four will result in spurious signals or significant deviations in meter reading from the true boron concentration.

3. Errors in measurements from the true boron concentration, taken from selected data points when the meter was known to be operating in an acceptable manner, average ± 1.3 percent. Sporadic deviations from the normal readings are not included in this determination of average error.
4. Persistent troubles which affect reliability and precision include: electronic/optical noise, electronic drift, mechanical deterioration of tubing used to pump chemicals, air bubble entrapment in the optical system, and loss of automatic standardization.
5. Waste disposal requirements from the meter should not present any significant problem. Total fluid flow is approximately 50 gallons per day -- most of which will be excess reactor coolant.
6. Cost of chemicals for the SENA meter is estimated by SENA personnel to be small, i.e., less than 500 U.S. dollars per year.
7. Time delay from meter inlet to steady recorder readings is approximately 12 minutes minimum as presently installed.

SECTION 5

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