

DESIGN, CONSTRUCTION AND COMMISSIONING OF  
AN IN-PILE BWR COOLANT CHEMISTRY LOOP

by

JOHN OGDEN OUTWATER, III

S.M., Massachusetts Institute of Technology (1989)  
B.S.E., Princeton University (1985)

Submitted to the Department of Nuclear Engineering  
in partial fulfillment of the requirements for the  
Degree of Doctor of Science in  
Nuclear Engineering

at the

Massachusetts Institute of Technology  
January 1991 A.D.

© Massachusetts Institute of Technology 1991. All rights reserved.

Signature of Author..

.....  
Department of Nuclear Engineering  
January, 1991

Certified by.....

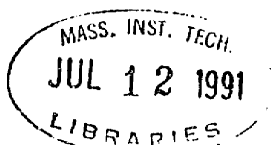
.....  
Michael J. Driscoll  
Professor Emeritus of Nuclear Engineering  
Thesis Supervisor

Certified by..

.....  
Otto K. Harling  
Professor of Nuclear Engineering  
Thesis Supervisor

Accepted by.....

.....  
Allan F. Henry  
Chairman, Department Committee on Graduate Students



ARCHIVES

DESIGN, CONSTRUCTION AND COMMISSIONING OF  
AN IN-PILE BWR COOLANT CHEMISTRY LOOP

by

JOHN OGDEN OUTWATER, III

Submitted to the Department of Nuclear Engineering  
on January 22, 1991 A.D. in partial fulfillment of the  
requirements for the Degree of Doctor of Science in  
Nuclear Engineering

ABSTRACT

An in-pile facility simulating BWR coolant chemistry has been designed, built, and put into operation in the MIT Reactor, and preliminary data has been collected. This facility closely simulates the radiation, thermal-hydraulic, and chemistry environments of BWR coolant. The principal function of this facility is to collect data on coolant radiolysis -- particularly hydrogen peroxide production, ECP (electrochemical potential), and N-16 behavior -- under different coolant chemistries, in support of efforts to minimize corrosion and radiation fields in BWR's.

The present work describes the design and operating characteristics of the BCCL (BWR Coolant Chemistry Loop), and presents results from the initial shakedown campaign of in-pile runs. Three different coolant chemistries were tested: NWC (normal water chemistry), with helium-saturated coolant; "HWC" (Hydrogen Water Chemistry), with hydrogen-saturated coolant; and NWC with the injection of KOH (potassium hydroxide) into the flow stream. The core section of the loop was saturated at 1000 psi, and the core exit quality was 15%.

These preliminary results provided the following information. HWC was found to decrease the hydrogen peroxide concentration in the outlet plenum by a factor of 3 (relative to the concentration under NWC), and to increase N-16 in the steam line by a factor of 4.5. NWC with KOH injection was found to decrease N-16 in the steam line by a factor of 3. Under single-phase NWC conditions, the concentration of hydrogen peroxide in the outlet plenum increased by a factor of 20.

**Thesis Supervisors:**

**Dr. Michael J. Driscoll**

**Title: Professor of Nuclear Engineering (Emeritus)**

**Dr. Otto K. Harling**

**Title: Professor of Nuclear Engineering**

## Acknowledgements

It is with pleasure that the author acknowledges the help of Professor Michael Driscoll, whose extraordinary consideration and hard work have made the task of writing this thesis much easier. In addition, the author would like to thank Professor Otto Harling and Dr. Gordon Kohse, the other principal investigators, who have made it possible for me to take part in this worthwhile project. The support of EPRI (the Electric Power Research Institute), ESEERCO (the Empire State Electric Energy Research Corporation) and the MIT EUP participants is gratefully acknowledged for their support of this project; as well as that of Hitachi, Toshiba, Tokyo Electric Power Company, and the MIT EUP participants (Boston Edison, PSE&G, and Northeast Utilities) who are supporting the next experimental campaign. The support of the GE research staff, for their technical advice and contribution of key instrumentation (the anion IC unit and the electrodes for ECP determination) is also gratefully acknowledged, as are the contributions of the Technical Advisory Committee convened by EPRI and ESEERCO, and the important input of our Japanese colleagues from Hitachi and Toshiba.

Credit is due to many people who contributed to the operation of the BCCL: Mike Ames, who designed and put together major portions of it; Don Mason, who designed the sampling system and developed BCCLMIT; Ernesto Cabello, who did the N-16 measurements; Phillippe Borys, who did the ion chromatograph measurements; Meng-Ruo Zhang, who mixed the injection chemistry and took peroxide data; Tom Ippolito, who set up the N-16 detector and took peroxide data; Mark Anderson, who designed, built and ran the level detector electronics; Steve Boerigter, who calibrated the gamma detector; John Chun, who, with Don Mason, helped develop BCCLMIT; Paul Menadier, who did the electrical work; and Paul Dozois, John Wasik, and Ron St. Jean, who did much of the machining. The craftsmen at Ramsay Welding, particularly Brent Marks, did the titanium welding. Gordon Kohse, whose contributions are too numerous to cite, is largely responsible for the success of the BCCL. He and Mike Ames brought much experience from the PCCL.

The author especially wishes to thank his friends and coworkers on the loop projects, who have made this difficult project a fun one.

Special thanks go to Tricia Normile, who did the painstaking work of assembling, and partly typing, this report. It is much the better for her efforts. Lenny Andexler contributed several of the figures and graphs.

The author wishes success to Rob Rozier, who will carry out the next experimental campaign with the BCCL.

Finally, the author would like to thank his parents, for whose constant love and support he is most grateful.

This thesis is dedicated to our Lord, the author of all good things.

## TABLE OF CONTENTS

	<u>Page</u>
COVER PAGE	1
ABSTRACT	2
ACKNOWLEDGEMENTS	4
TABLE OF CONTENTS	5
LIST OF FIGURES	13
LIST OF TABLES	16
1. INTRODUCTION	17
FOREWORD	17
BACKGROUND	18
ORGANIZATION OF THIS REPORT	22
2. DESCRIPTION OF SYSTEM	24
Introduction, and Overview of System	24
IN-PILE THIMBLE	25
Streaming Channel	25
In-Core Section	27
Flange	27
Pump Pod	28
Lid and Lid Penetrations	28
Helium Purge System and Pressure Relief System	29
THIMBLE INTERNALS	29
Fluid System	31
In-Core Section	31
Outlet Plenum/Steam Separator-Dryer	31
Downcomer Plenum	33

	<u>Page</u>
Sampling System and Cooling Block	34
Level Detector	36
Coils for Level Detector	38
Float for Level Detector	38
Electronics for Level Detector	39
In-Core Section	41
Titanium Test Tube	43
Zircaloy U-Tube	43
In-Core Heater	44
In-Core Lead Bath	44
Gravel Bed	44
Heater Lead Extensions	45
In-Pile Instrumentation	46
Thermocouples	46
Electrochemistry Probes	47
Gamma Detector	47
<b>OUT-OF-PILE FLUID SYSTEM</b>	<b>48</b>
Hotwell Tank	48
Feedwater Pump	51
Sample Injection System	51
N-16 Detector	52
Lead Shield Block	52
Detectors and Electronics	54
Steam Plenum	54
Heat Exchangers	54
Feedwater Heater	55

	<u>Page</u>
Steam Orifice Flowmeter	56
Hot Line Sampling System	56
HYDROGEN PEROXIDE MEASUREMENT METHOD	57
ON-LINE ION CHROMATOGRAPH	57
SHIELD RING PLUG	58
POWER SUPPLIES	59
DATA AQUISITION SYSTEM	59
ALARM SYSTEM	60
SUPPORT FACILITIES	61
SUMMARY: DESCRIPTION OF SYSTEM	62
3. FUNCTIONAL CHARACTERISTICS OF SYSTEM	63
THERMAL HYDRAULICS AND RADIATION DOSES	63
Calculation of Dose Rates to Coolant	63
Core Section: Calculation of Transit Time and Exit Quality	64
Outlet Plenum: Calculations of Water and Steam Transit Times	69
Downcomer Plenum: Calculation of Transit Time and Dose Rate	70
N-16 DETECTOR	71
SAMPLE COOLING BLOCK AND PEROXIDE MEASUREMENT SYSTEM	77
MODES OF OPERATION	77
Shutdown Mode	78
Standby Mode	78
Operating Mode	79

	<u>Page</u>
DYNAMIC STABILITY OF THE THERMAL HYDRAULIC SYSTEM	79
REACTIVITY TESTS	81
SUMMARY: FUNCTIONAL CHARACTERISTICS	82
4. IN-PILE TESTS AND RESULTS	83
INTRODUCTION	83
OPERATION OF THE BCCL	83
Thermal-Hydraulic Operation	85
Chemistry Sampling System	86
N-16 Detector Operation	87
Ion Chromatograph	88
RUN 1: HELIUM COVER GAS IN HOTWELL TANK	88
N-16 Measurements	88
Hydrogen Peroxide Measurements	91
Ion Chromatograph Measurements	91
Dissolved Hydrogen and Oxygen Measurements	92
Conductivity Measurements	92
Potential Measurements	92
RUN 2: HYDROGEN COVER GAS IN HOTWELL TANK	92
N-16 Measurements	93
Hydrogen Peroxide Measurements	95
Ion Chromatograph Measurements	95
Dissolved Hydrogen and Oxygen Measurements	96
Conductivity Measurements	96
RUN 3: HELIUM COVER GAS IN HOTWELL TANK, WITH KOH INJECTION	96



	<u>Page</u>
N-16 Measurements	97
Hydrogen Peroxide Measurements	100
Ion Chromatograph Measurements	100
Dissolved Hydrogen and Oxygen Measurements	101
Conductivity Measurements	101
Carryover Test Results	101
COMPARISON OF TEST RESULTS WITH CODE SIMULATIONS	103
SUMMARY: IN-PILE TESTS AND RESULTS	110
5. SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS FOR FUTURE WORK	112
INTRODUCTION	112
DESCRIPTION OF THE BWR COOLANT CHEMISTRY LOOP	112
IN-PILE EXPERIMENTS	115
Experimental Conditions	115
Principal Experimental Results	115
WORK IN PROGRESS	116
MODIFICATIONS	119
Glass Float Replacement	119
ECP Data Acquisition and Electrodes	119
Dissolved Gas Sensor Calibration	120
Heat Balance on Heat Exchanger to Determine In-Core Power	120
N-16 Detector Shielding and Discriminator Setting	121
Germanium N-16 Detector	121
In-Core Lead Bath: Replacement with Machined Block	122

	<u>Page</u>
Increasing the Thermal Inertia of the Fluid System	123
Decomposition of Peroxide and Organics	123
Outlet Plenum Separator and Steam Dryer Improvement	124
Sample Cooling Block Improvements	125
IC Detection for Transition Metals	125
Gas Pressure Maintenance in the Hotwell Tank	126
Updating the BCCLMIT Modelling Code	126
<b>POSSIBLE FUTURE EXPERIMENTS</b>	<b>126</b>
Coordinated BCCL and BCCL MIT (Code) Runs: Surface Effects	127
N-16 Carryover	127
Indirect G-value Measurements	127
Electrochemical Measurements of Dissolved Species	128
Conversion to A Recirculating Loop	128
<b>SUMMARY: CONCLUSIONS AND RECOMMENDATIONS</b>	<b>130</b>
<b>APPENDIX A</b>	<b>131</b>
<b>CONSTRUCTION DETAILS</b>	<b>131</b>
<b>IN-PILE THIMBLE</b>	<b>131</b>
<b>THIMBLE LID AND FEEDTHROUGHS</b>	<b>135</b>
<b>THIMBLE INTERNALS - FLUID SYSTEM</b>	<b>138</b>
In-Core Section	138
Outlet Plenum/Steam Separator-Drier	140
Simulated Downcomer Region	144
Sampling System and Cooling Block	144
Tubing and Fittings	146

	<u>Page</u>
Glass Float for Level Detector	146
LEVEL DETECTOR COILS	150
TITANIUM BATH CAN	151
GRAVEL BED CAN	154
HEATER LEADS	159
OUT-OF-PILE FLUID SYSTEM	159
Hotwell Tank	161
Steam Plenum	162
Additive Injection System	162
Hot Line Sample Taps	163
Heat Exchangers	163
Feedwater Heater	164
Proposed Metal Bath for Thermal Transient Damping	166
Steam Orifice Flowmeter	167
LEAD SHIELD BLOCK FOR N-16 DETECTOR	170
LEVEL DETECTOR ELECTRONICS	173
APPENDIX B	177
COMPONENT SUPPLIERS AND FABRICATORS	177
APPENDIX C	182
DATA FROM IN-PILE RUNS	182
NORMAL WATER CHEMISTRY	182
Hydrogen Peroxide Measurements	182
N-16 MEASUREMENTS	183
ECP MEASUREMENTS	183
APPENDIX D	184

	<u>Page</u>
CALCULATIONS OF NEUTRON ENERGY DEPOSITION RATES IN THE MIT REACTOR	184
APPENDIX E	188
ESTIMATION OF CARRYUNDER USING Ar-41	188
NOMENCLATURE	190
Abbreviations	190
List of Variables	191
REFERENCES	192

## LIST OF FIGURES

<u>Figure</u>		<u>Page</u>
Figure 1-1	Schematic of In-Pile Loop to Simulate BWR Coolant Chemistry	20
Figure 2-1	Schematic of In-Pile Thimble	26
Figure 2-2	Schematic of Lid for BCCL Thimble	30
Figure 2-3	Hydraulic Internals of BCCL Thimble	32
Figure 2-4	Schematic of Sample Cooling Block	35
Figure 2-5	Float Level Detector Assembly for BCCL	37
Figure 2-6	Block Diagram of Electronics for BCCL Level Detector	40
Figure 2-7	Calibration Curve for Float Level Detector	42
Figure 2-8	Calibration Curve for Ionization Chamber	49
Figure 2-9	Schematic of BCCL Out-of-Pile System	50
Figure 2-10	Gamma Background on MIT Reactor Top, With and Without Shielding	53
Figure 3-1	BCCL Core Transit Time and Quality Map	68
Figure 3-2	Water Transit Time From Core Exit to N-16 Detector	73
Figure 3-3	Steam Transit Time From Core Exit to N-16 Detector	75
Figure 4-1	Data Collection Points on BCCL	84
Figure 4-2	Normalized N-16 Dose Rate at Turbine as a Function of Hydrogen in Coolant ( <u>I-2</u> )	94

<u>Figure</u>		<u>Page</u>
Figure 4-3	N-16 Gas-to-Liquid Partition Ratio as a Function of pH (T-2)	99
Figure 4-4	Comparison of Code Results for the BCCL, Using Different Reaction Equation Sets (M-1)	106
Figure 4-5	Second Comparison of Code Results for the BCCL, Using Different Reaction Equation Sets (M-1)	107
Figure 4-6	Comparison of BCCL Data and Computer Model Results (M-1) for NWC	108
Figure 4-7	Comparison of BCCL Data and Computer Model Results (M-1) for HWC	109
Figure 5-1	Schematic of In-Pile Components of BCCL	113
Figure 5-2	Schematic of BCCL Out-of-Pile Components	114
Figure 5-3	Current Once-Through BWR Loop Configuration	129
Figure 5-4	Modified BWR Loop to Accommodate Recirculation	129
Figure A-1	Schematic of In-Pile Thimble	132
Figure A-2	Lower Flange for BCCL Thimble	133
Figure A-3	Upper Flange for BCCL Thimble	134
Figure A-4	Schematic of Lid for BCCL Thimble	137
Figure A-5	Hydraulic Internals of BCCL Thimble	139
Figure A-6	Endcaps for BCCL Plena	141
Figure A-7	Float Level Detector Assembly for BCCL	142
Figure A-8	Sample Cooling Block for BCCL	145

<u>Figure</u>		<u>Page</u>
Figure A-9	Titanium Glands for Parker Ultraseal O-Ring Fittings Used in BCCL	147
Figure A-10	Construction of Glass Float for BCCL Level Detector	148
Figure A-11	Spools for Winding Level Gauge Coils	152
Figure A-12	Cross Section of In-Core Titanium Bath Can	153
Figure A-13	Spacer Collar for Titanium Bath Can	155
Figure A-14	Schematic of Gravel Bed Cannister for BCCL	156
Figure A-15	Bottom Plate for BCCL Gravel Bed Cannister	158
Figure A-16	Schematic of BCCL Out-of-Pile System	160
Figure A-17	Regenerative Counterflow Heat Exchanger for BCCL	165
Figure A-18	Schematic of Proposed Metal Bath for Thermal Transient Damping	168
Figure A-19	Schematic of Orifice Flowmeter for BCCL	169
Figure A-20	Calibration Curve for Orifice Flowmeter	171
Figure A-21	Lead Shield Block for N-16 Detector	172
Figure A-22	Block Diagram of Electronics for BCCL Level Detector	175
Figure D-1	Neutron Dose Rate to Coolant in MIT Reactor (F-1)	187

## LIST OF TABLES

<u>Table</u>		<u>Page</u>
Table 1-1	Summary of Similarities and Differences Between BWR and PWR Loops	23
Table 2-1	Composition of Zircaloy-4 Used in BCCL	43
Table 3-1	Procedures for BCCL Operation	77
Table 4-1	Principle Characteristics of BCCL Runs	83
Table 4-2	Modified Burns and Marsh Reaction Equation Set ( <u>M-1</u> )	104
Table 4-3	Principal Results of In-Pile Runs	111
Table 5-1	Principal Results of In-Pile Runs	117
Table 5-2	BCCL Test Plan for 1991 Campaign	117
Table 5-3	Planned Additives for Investigating N-16 Holdback	118



# 1. INTRODUCTION

## FOREWORD

Much effort has been expended by the nuclear power industry over the last decade to reduce both the personnel radiation exposure and the downtime of LWR (Light Water Reactor) systems, both of which are closely linked to corrosion of plant materials, both localized and uniform, by reactor coolant. The complexity and diversity of these efforts are reflected in the proceedings of recent international conferences on reactor water chemistry (B-3, J-1). Our interest here is in BWR (Boiling Water Reactor) issues.

Major current efforts dealing with BWR problems are focused on SCC (stress-corrosion cracking) of BWR construction materials and on N-16 carryover (into the steam line). Substantial economic losses have been caused by SCC, and while the problem appears to be under control, there is a lack of fundamental understanding of the phenomenon. Furthermore, there is concern that IASCC (Irradiation-Assisted Stress-Corrosion Cracking) may be the cause of some failures of in-flux structural components in LWR's. SCC can be greatly reduced if the reactor coolant is reducing rather than oxidizing; this can be effected by adding hydrogen to the coolant, as is done in PWR's. Hydrogen injection greatly increases N-16 carryover, however, as reduced nitrogen species are gaseous, while oxidized nitrogen species remain in the liquid phase under BWR conditions. N-16 carryover increases personnel exposure, limits plant operating flexibility, and may constrain multi-unit siting. The two problems, SCC and N-16 carryover, are thus intimately interrelated through their dependence on coolant chemistry.

The degree to which BWR coolant is oxidizing or reducing is reflected in the ECP (electrochemical potential) of the coolant, and recent studies (U-1, E-1, and M-3) indicate that radiolytically-produced hydrogen peroxide (in addition to dissolved oxygen) is an important contributor to high coolant potentials and hence SCC. The production and decomposition of hydrogen peroxide in reactor systems is poorly understood, and theoretical understanding is lacking, partly because of the difficulty of collecting experimental data. Hence, calculational models are not yet adequate for the characterization of the BWR coolant chemistry environment. Experimental investigation must be the principal recourse, a difficult prospect on the full-scale BWR's used for commercial power production. This circumstance motivated MIT to develop the conceptual design for an in-pile BWR radiolysis chemistry test loop, with seed money provided by the MIT EUP (Electric Utility Program) sponsors, and subsequently, in the work described here, with EPRI and ESEERCO funding, to construct and operate the facility.

## BACKGROUND

During recent years, the effort to understand SCC-related phenomena in BWR systems has included the following lines of attack:

1. Identification of the material characteristics which affect susceptibility to SCC;
2. Calculation and measurement of radiolysis effects on BWR coolant;
3. Evaluation of the effect of HWC (Hydrogen Water Chemistry) on SCC and N-16 carryover;

4. Investigation of additives which might hold back N-16;
5. Improvement of BWR coolant chemistry to minimize corrosion and corrosion product transport, and
6. Improvement of decontamination techniques to remove crud and reduce personnel exposure.

Efforts have also been made to understand the theoretical basis of the phenomena in the above areas.

To assist these efforts, the Nuclear Reactor Laboratory at MIT has designed, built and put into operation an in-pile facility which closely simulates the coolant chemistry of a BWR. This facility, the BCCL (BWR Coolant Chemistry Loop), is capable of operating under a wide range of conditions relevant to BWR chemistry and can gather data on numerous factors, including ECP and hydrogen peroxide production. Together with the investigation of N-16 carryover, the collection of data on hydrogen peroxide production has been a major motivation for the development of the BCCL.

A schematic of the BCCL is shown in figure 1-1. The loop consists primarily of a coolant reservoir (the hotwell tank); a high-pressure pump, which pumps the water to the in-pile section; the in-pile section itself, where the coolant is irradiated; a steam separator-dryer; and heat exchangers, which cool the fluid before it is returned to the hotwell tank. In addition, there are cleanup systems for maintaining water purity, and sampling systems for analyzing the coolant before and after it is irradiated. There is also a chemical injection system, which can inject a stream of fluid into the coolant immediately before it enters the core section, and a sample extraction system, which takes and quickly cools fluid samples from the outlet and downcomer plena.

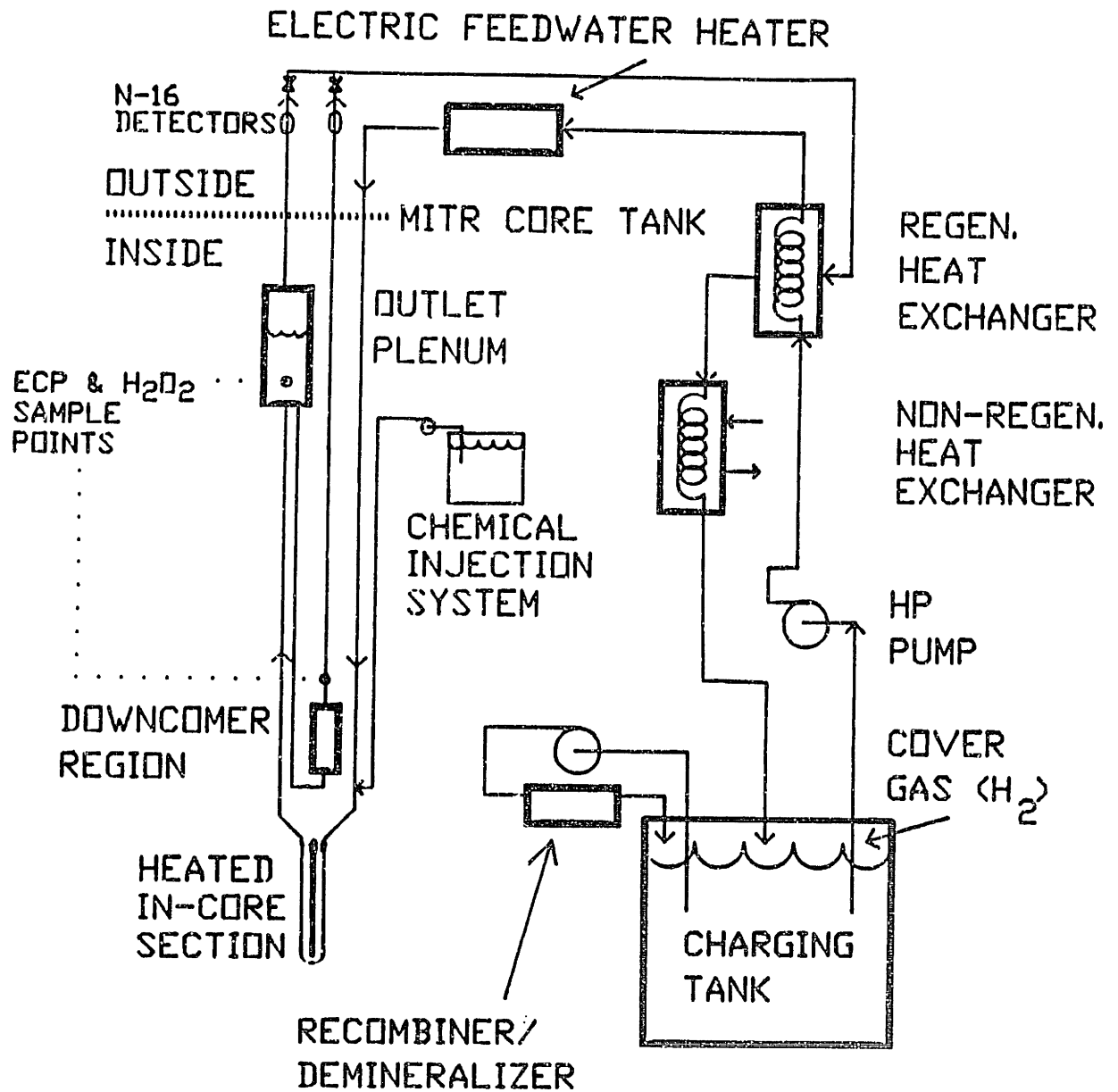


Figure 1-1 Schematic of In-Pile Loop to Simulate BWR Coolant Chemistry

The preliminary conceptual design of the BCCL is described in a report by Driscoll (D-1), and is further refined in a report by Outwater (O-3). The safety review is described in a report by Ames et al. (A-3). The development and out-of-pile tests of the basic design were presented in theses by Oliveira (O-1) and Baeza (B-1), who constructed and operated out-of-pile lab mockups. In the present work a number of refinements were made, and an in-pile version was constructed and operated.

In addition to the BCCL, a number of related projects are in progress at the MIT Nuclear Reactor Lab. These include the PCCL (PWR Coolant Chemistry Loop), involving an in-pile loop project investigating PWR corrosion product transport phenomena; the IASCC (Irradiation-Assisted Stress-Corrosion Cracking) project, with both dry irradiation and slow strain rate in-pile test facilities; and the sensor project, which will test in-pile crack-growth sensors for LWR's. The latter two projects are of particular interest here, because the BCCL facility will serve as a prototype for the coolant makeup and chemistry control systems for these facilities, and measurements on the BCCL will also be used to specify target in-core chemistry conditions for the operation of these facilities. Also relevant is the development of computational models of radiolysis chemistry described in theses by Mason (M-1) (BCCL coolant radiolysis chemistry), Chun (C-1) (BWR coolant radiolysis chemistry), Simonson (S-5) (general corrosion), and Psaila (P-2) (crack tip chemistry).

The PCCL project deserves special note here, since its completion preceded that of the BCCL, and many common design features were proven out on the PCCL. The thesis by Sanchez (S-1) describes the design, construction and operation of the PCCL at a level comparable to that of this

report for the BCCL. The major differences and similarities of the BCCL and the PCCL are summarized in Table 1-1.

The preliminary design of the BCCL was sponsored by the MIT EUP (Electric Utility Program); construction and initial operations were supported by EPRI and ESEERCO (the Empire State Electric Energy Research Corporation). Work currently underway or in an advanced stage of planning on the project is sponsored by EPRI, ESEERCO, Toshiba, Hitachi, the Tokyo Electric Power Co., and the MIT EUP.

## ORGANIZATION OF THIS REPORT

This report is divided into 5 chapters. Chapter 1 contains an outline of the problem which this project addresses, and briefly describes the relation of the project to other efforts. Chapter 2 contains a description of the physical system which has been built, including support facilities. Chapter 3 describes the functional characteristics of the system, and contains analyses of transit times for the loop (necessary for the evaluation of data). Operating modes are also described in Chapter 3. Chapter 4 describes the initial in-pile commissioning runs and compares the results with computer simulations (M-1). Chapter 5 contains a summary and conclusions, and discusses possible modifications and future experiments. It also contains a description of work currently in progress. The Appendices contain construction details of components, information on component suppliers and fabricators, data from in-pile runs, and neutron energy deposition calculations for the MIT Reactor.

Table 1-1

**SUMMARY OF SIMILARITIES AND DIFFERENCES  
BETWEEN BWR AND PWR LOOPS**

<u>Item</u>	<u>Similarities</u>	<u>Differences</u>
• Aluminum containment thimble	Same fill gas, pressure relief system, main structure components.	Flange in transition region, additional short elliptical section for enhanced streaming to plenum.
• In-core heater bath	Virtually identical; same heater, Ti sheath	Zircaloy-2 U-tube in place of Zircaloy-4
• Thimble internals		<ul style="list-style-type: none"> <li>• Larger exit plenum in BWR, with steam/water interface and level measurement system.</li> <li>• No recirculating pump in BWR loop.</li> <li>• Insulating shot (quartz gravel) in place of conducting shot (copper).</li> <li>• Local sample extraction taps for out-of-pile analysis.</li> </ul>
• Makeup/letdown system		<p><u>Substantially different:</u></p> <ul style="list-style-type: none"> <li>• BWR flow rate <math>\approx</math> 100x higher, and <math>\approx</math> 15 w/o of effluent is steam.</li> <li>• BWR has heat exchangers, feedwater heater.</li> </ul>
• Charging, discharge tanks	Similar tank construction.	<ul style="list-style-type: none"> <li>• Water is returned to charging tank through ion exchange beds and recycled.</li> <li>• Tanks are Acrylic plastic instead of Pyrex glass</li> </ul>
Operating conditions/procedures	$\approx$ same temperature	<p><u>Substantially different:</u></p> <ul style="list-style-type: none"> <li>• Steady-state boiling in-core</li> <li>• Substantially lower pressure (1000 psi vs. 2200 psi).</li> <li>• Shorter runs.</li> <li>• Attended runs.</li> </ul>
• Handling facilities and equipment	Identical	

## 2. DESCRIPTION OF SYSTEM

### Introduction, and Overview of System

The configuration of the BCCL used for the first campaign of in-pile experiments and the influence of the goals of the experiments on the design of the facility are discussed in this section.

The primary goal of the BCCL is to duplicate the water chemistry environment of a BWR, to allow the investigation of phenomena related to water radiolysis chemistry, and corrosion and radiation control. The primary parameters to be matched are the temperature distributions, the hydraulic conditions, the water chemistry, and the radiation fields.

This section describes the actual configuration of the system. Reference O-1 discusses the preliminary design and testing of a laboratory mockup of the system. Reference B-1 describes the refinement of the preliminary design and the development of the level detector. Reference M-1 describes the design and characterization of the coolant sampling apparatus, and a computer code modelling the radiochemistry of the BCCL. Finally, Reference S-1 describes the PCCL, an associated project which experimentally models the water chemistry environment of a PWR. The design of the BCCL relied heavily on experience gained during the PCCL work, and some of the facilities and components developed for the PCCL were used in the course of the work reported here.

The BCCL consists of two major systems: the in-pile thimble and its internals, and the out-of-pile fluid system (which supplies coolant to the thimble internals). In addition, there are a number of supporting



subsystems. The in-pile thimble, the thimble internals, the out-of-pile fluid system, the shield ring plug, the power supplies, the data acquisition system, the alarm system, and support facilities will be described in this section.

## **IN-PILE THIMBLE**

The in-pile thimble is shown in Figure 2-1. The purpose of this thimble is to provide an envelope isolating the components of the BCCL from the coolant water of the MIT Reactor. The tip, about 24 inches, of this thimble is inserted into the core of the reactor. The thimble has four main segments: the pump pod, the four-inch section, the in-pile elliptical section, and the streaming channel. The in-pile elliptical section and the streaming channel are both welded to the lower half of the flange, which attaches to the bottom of the four-inch section. These segments will be described in the following subsections. A detailed description may be found in Appendix A.

### **Streaming Channel**

The streaming channel extends from the bottom of the flange to a position 1/4 inch above the top of the core of the MIT Reactor. The purpose of this channel is to allow radiation to stream up from the core to the simulated downcomer region, which is situated immediately above the streaming channel. This channel is normally empty (except for helium gas), and displaces water, which would otherwise attenuate the radiation. The channel is designed, however, to accept lead disks, which allow the

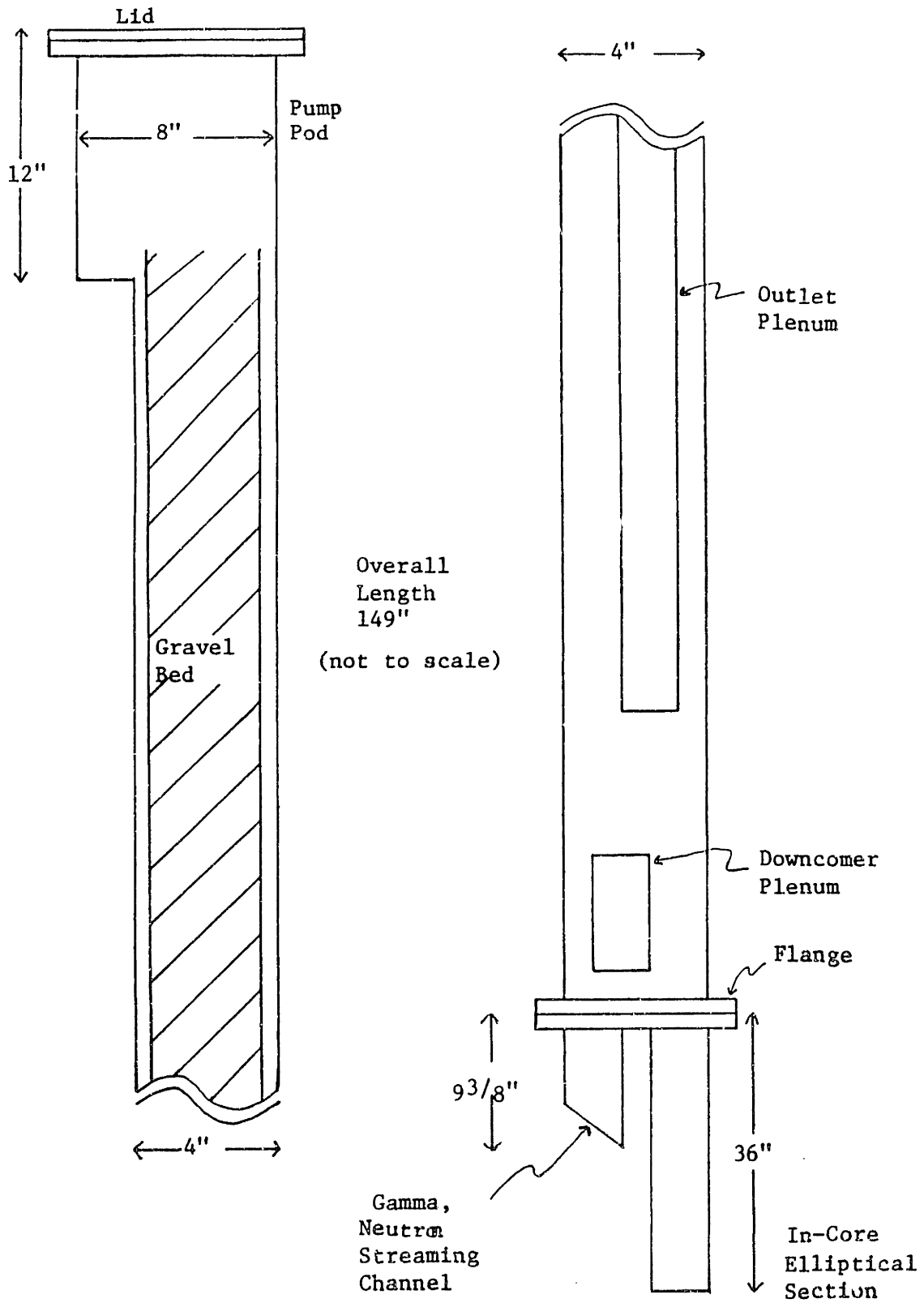


Figure 2-1: Schematic of In-Pile Thimble

radiation dose on the downcomer plenum to be varied. It is elliptical in cross section, and is fabricated from a 2 inch OD, 1-3/4 inch ID aluminum tube.

### In-Core Section

The in-core section extends 36 inches downward from the lower half of the flange, and is also elliptical in cross section. The bottom 24 inches of the in-core section are within the core of the MIT Reactor. Inside this section is a titanium can holding the Zircaloy in-core tubing (through which the coolant flows), an electric heater, and molten lead (for heat transfer). A thermocouple is placed in a well in the lead bath to monitor the in-core bath temperature.

### Flange

The purpose of the flange is to allow access to the internals of the thimble, for adjustment or repair, without removing all the internals from the thimble. To gain access to the lower internals, the flange bolts can be removed, the internals suspended, and the upper section of the thimble slid up several feet. This allows access to the most delicate of the internals, including the level detector and the sample cooling block, without their complete removal. The bottom ring of the flange is welded to the elliptical streaming channel and to the elliptical in-core section, and the top ring of the flange is welded to the four-inch section. The upper and lower flange

are held together by bolts, and a metal O-ring seal between the two faces provides sealing.

### Pump Pod

The pump pod is 12 inches long and 8 inches in diameter. All fluid and electrical lines have connections here, which can be undone so that the thimble lid may be removed completely. The pump pod can also hold a small pump, which may be used in the future when the BCCL is modified to allow recirculation. The bottom of the pump pod is welded to the four-inch section, and the top of the pump pod is flanged to accept the thimble lid. The flange of the pump pod also has threaded holes through which it is bolted into position onto the bridge which spans the core tank of the MIT Reactor.

### Lid and Lid Penetrations

The purpose of the thimble lid is to complete the envelope isolating the thimble internals from the primary coolant of the MIT Reactor. Since the thimble is internally pressurized with helium (to approximately 15 psig), the lid forms part of the pressure boundary, and it is necessary to pass a large number of fluid and electrical lines through this pressure boundary. Three of the fluid lines are at a temperature of 540°F, and three of the electrical lines are designed to carry 80 amperes. The lid is constructed of 1/4 inch thick stainless steel plate, and a number of female

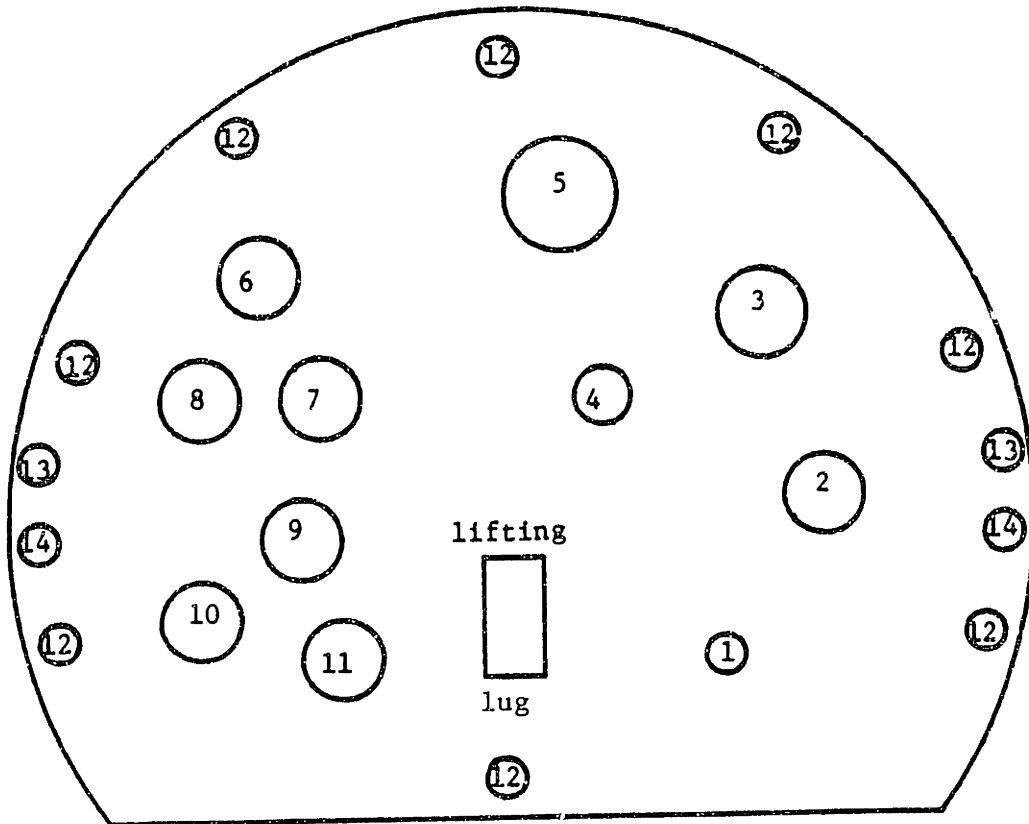
NPT, compression, and Ultratorr fittings are welded to pass through it. The lid is shown in Figure 2-2, and is further described in Appendix A.

### Helium Purge System and Pressure Relief System

To prevent overpressurization of the thimble, a 3/4 inch OD line was connected to one of the thimble lid penetrations. This line is connected to a rupture disk designed to rupture at 65 psig, well below the pressure to which the thimble was hydrostatically tested (150 psig). This 3/4 inch line also serves as a helium feed line. A small flowrate (approximately 1/2 ft<sup>3</sup>/hr) of helium is constantly flowed through the thimble during operation, in order to purge any moisture. The helium leaves the thimble through a 1/8 inch OD stainless steel tube which extends the length of the thimble starting at the level of the flange, and exits through the thimble lid. This line is connected to a humidity detector, which gives a good indication of the presence or absence of small leaks. It is anticipated that this helium purge line would also allow drainage of the thimble, should a major leak develop and the thimble flood with water.

### THIMBLE INTERNALS

The major systems and components in the thimble are the fluid system (which includes the level detector), the heater and its connections, and mechanical support components. These items are described in this section. Design specifications may be found in Appendix A.



1. Helium purge supply line.
2. Bleed line/overpressure relief.
3. Power lines for core heater.
4. Power lines for gravel bed heater.
5. Thermocouple feedthroughs.
6. Lines for level detector.
7. Sample and injection lines.
8. Electrode signal lines.
- 9, 10, 11. Hot fluid lines.
12. Lid bolts.
13. Holddown bolts.
14. Jacking bolts.

Figure 2-2: Schematic of Lid for BCCL Thimble

## **Fluid System**

In order to maintain high water purity, the hot portion of the fluid system is constructed entirely of titanium, except for the in-core section (Zircaloy) and fittings (stainless steel).

### **In-Core Section**

The in-core section of the fluid system, in which boiling takes place, is fabricated from a 6 foot length of 5/16 inch OD, 0.2565 inch ID Zircaloy-2 tubing which has been bent into a U. Connections are made to the ends of this tubing with compression fittings. The coolant water flows into the inlet of this tube from the inlet line, made of 1/4 inch OD titanium. From the outlet of this tube, the two-phase coolant flows (again, through a 1/4 inch titanium line) to the outlet plenum/ steam separator-dryer.

### **Outlet Plenum/ Steam Separator-Dryer**

As its name suggests, the function of the outlet plenum is to separate the two-phase mixture exiting the core into saturated water and saturated steam. This plenum in the BCCL corresponds to the outlet plenum and steam separator-dryer regions of a BWR. The outlet plenum, along with the downcomer plenum, is shown in Figure 2-3.

The outlet plenum is 20-1/2 inches long, 1-1/2 inches OD, 1.32 inches ID, and has a volume of 0.45 liters. Since the water level in this plenum is normally 50%, the nominal steam volume is 0.22 liters, and the

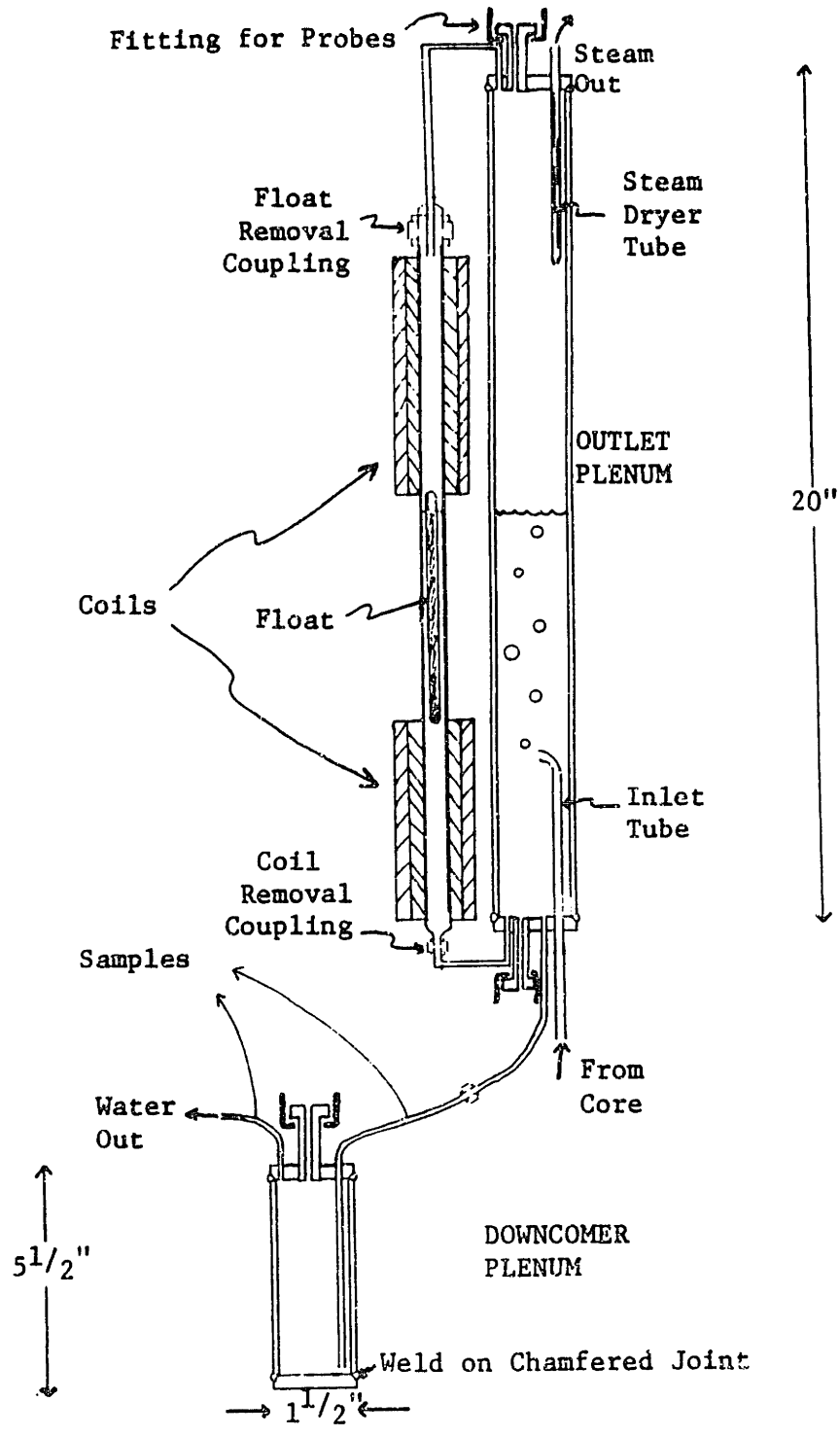


Figure 2-3 Hydraulic Internals of BCCL Thimble



nominal water volume is also 0.22 liters. Attached to the outlet plenum is a removable sidearm containing the level-measuring float. The sidearm communicates with the top and the bottom of the outlet plenum in a manner similar to that of a sight glass on a tank. The sidearm is surrounded by electrical coils, which monitor the position of the float. Inside the outlet plenum are two electrochemical probes, an Ag/AgCl reference electrode and a platinum counter-electrode. These probes are removable and replaceable. The outlet plenum is fabricated from titanium in order to maintain high water purity. The fittings are stainless steel. The steam exits the outlet plenum through the top of the plenum, and continues out of pile; the water exits the bottom of the outlet plenum, and flows to the downcomer plenum.

### Downcomer Plenum

The downcomer plenum of the BCCL is intended to correspond to the downcomer region and inlet plenum of a BWR. The downcomer plenum is shown in Figure 2-3.

The downcomer plenum is 5 1/2 inches long, 1-1/2 inches OD, 1.32 inches ID, has a volume of 0.11 liters, and is fabricated from titanium. It is located immediately above the streaming channel, in order to maximize the radiation incident on the plenum (approximating the radiation incident on the downcomer region of a BWR). It contains one removable electrochemical probe, a stainless steel counter-electrode. After the water exits the downcomer plenum, it flows out of pile through a 1/4 inch titanium tube.

## **Sampling System and Cooling Block**

**One of the primary objectives of the BCCL project is to accurately measure the quantity of various dissolved radiolytic species produced in water by the in-core radiation field. It is known that some radiolytic species of interest (e.g., hydrogen peroxide) decompose quickly if they come in contact with a hot metal surface. Thus, to measure the concentration of hydrogen peroxide in the coolant, it was necessary to build a compact sampling system which diverts a small stream of coolant and quickly cools it below the temperature at which decomposition takes place.**

**A schematic of this aluminum cooling block is shown in Figure 2-4. The two lower nipples are attached to the exit lines of the downcomer and outlet plena with titanium compression fittings, which are welded onto the lines and swaged onto the nipples. Drilled through the center of each nipple is a small hole, which extends the length of the block to another nipple at the top of the block. The fluid sample stream flows into the lower hole and through the block, cooling down in transit. The fluid stream then exits through the top nipple, onto which is swaged a fitting connected to a 1/16 inch OD, 0.020 inch ID stainless steel line which carries the sample stream up through the thimble to the pump pod. There, to carry the sample out of pile to the sample analysis equipment, a 1/16 OD, 0.010 inch ID PEEK (Polyetheretherketone) line is connected to the stainless steel sample line. The flowrate in each sample line is controlled by a flow control valve on the (out-of-pile) outlet of the PEEK sample line.**

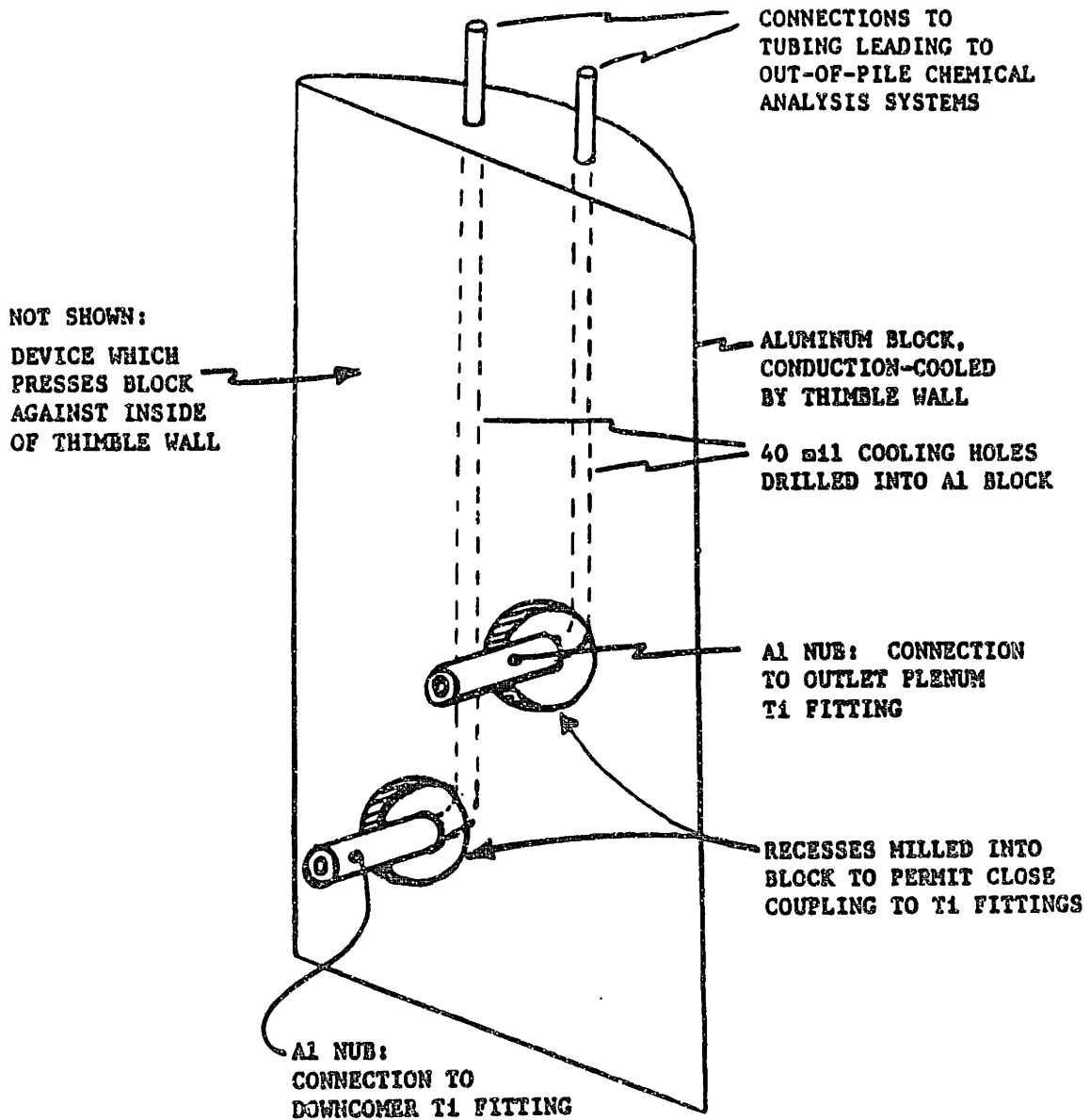


Figure 2-4 Schematic of Sample Cooling Block

In order to reject the heat imparted to the block by the fluid stream, the cooling block is pushed against the inner wall of the thimble (the outer wall of which is cooled by the water of the MIT Reactor) by a lever mechanism. The lever mechanism can be tightened or loosened by turning a threaded rod in the pump pod. This mechanism and the rest of the sampling system are described fully in Reference M-1. Detailed drawings may also be found in Appendix A.

### Level Detector

In order to maintain a constant water level in the outlet plenum, so that the steam flows out the top of the plenum and the water flows out the bottom, it is necessary to be able to control, and thus to measure, the level. Initial experiences with a heated-thermocouple type level-measuring device were not satisfactory, so a float-type level gauge was designed, built, and used.

This level gauge is shown schematically in Figure 2-5. It communicates, top and bottom, with the outlet plenum, and the water level in the sidearm is the same as the water level in the outlet plenum. The sidearm is constructed from a length of 5/8 inch OD, 1/2 inch ID titanium tubing, and several titanium O-ring fittings. Inside the tube is a glass float, which carries an iron wire up and down as the float moves with the water level. Surrounding the tube are two coils, each with concentric primary and secondary windings. The primary winding is excited with a constant, continuous alternating current. The voltage in the secondary winding is proportional to the length of iron wire (carried by the float) which is

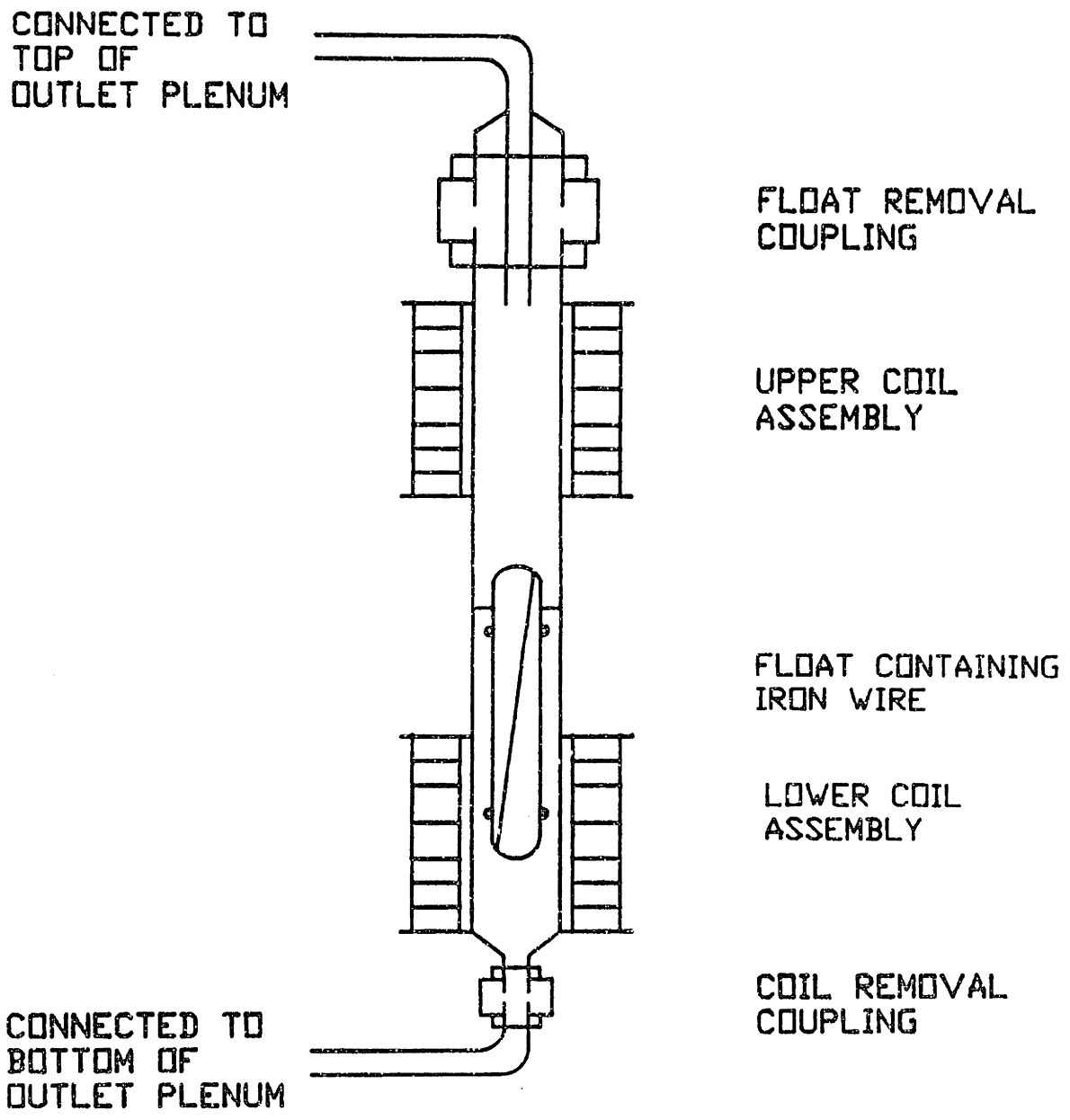


Figure 2-5 Float Level Detector Assembly for BCCL

inside the coils, and hence to the position of the float, and thus to the water level. This system is described in detail in Appendix A; a functional description of the major components follows. A patent application has been filed on this level-detecting device.

### **Coils for Level Detector**

Since the coils are in a relatively high radiation field and operate at a high temperature, it is necessary that no polymers be used in their construction. This difficult requirement was satisfied by winding them from 24 gauge aluminum wire (manufactured by Permaluster) which had been oxidized to form a tenacious, insulating coating of aluminum oxide. The resistance of coils wound from this wire was found to be strongly temperature-dependent. This temperature dependence is compensated for electronically. A more detailed description of the coils is found in Appendix A.

### **Float for Level Detector**

The purpose of the float is to carry the iron wire up and down with the water level. To do this, it is necessary that the float be able to withstand an external pressure of 1000 psi at a temperature of 540°F, and have a density of less than 0.7 g/cm<sup>3</sup>.

The float was made from a length of quartz tubing which had been sealed off at one end. A length of iron wire and a stainless steel weight were then inserted, bumps were melted onto the surface of the tube to

prevent it from sticking due to surface tension, and the other end of the tube was sealed in a flame. These floats were found to be simple to make and capable of withstanding very high external pressures. The collapse pressure was found to depend on the Ott number  $[(\text{modulus})/(\text{density})^3]$ . A complete description of the float fabrication procedure may be found in Appendix A.

### Electronics for Level Detector

The purpose of the level detector electronics is to convert the ac output of the level detector secondary coils to a signal which can be interfaced with a computer for display, datalogging and control functions. Their function is briefly outlined in this section, and is fully described in Appendix A. A block diagram of the circuit is shown in Figure 2-6.

The primary winding of each coil is excited with constant, continuous ac current. Each primary circuit has a coil trouble transducer, which detects an open circuit in the primary winding. If an open circuit is detected, an alarm is sounded to inform the operator that the level reading may be in error.

The output from the secondary windings is a noisy ac signal with a peak-to-peak voltage of between 0 and 500 millivolts (most of the noise originates in the heater power supply leads, which carry approximately 50 amperes of chopped ac current). This signal is filtered through a low-pass filter which strips it of the high-frequency noise, leaving only the 60-cycle signal from the coils. This "clean" signal then passes through a peak detector circuit, which effectively turns the ac signal into a dc signal, the

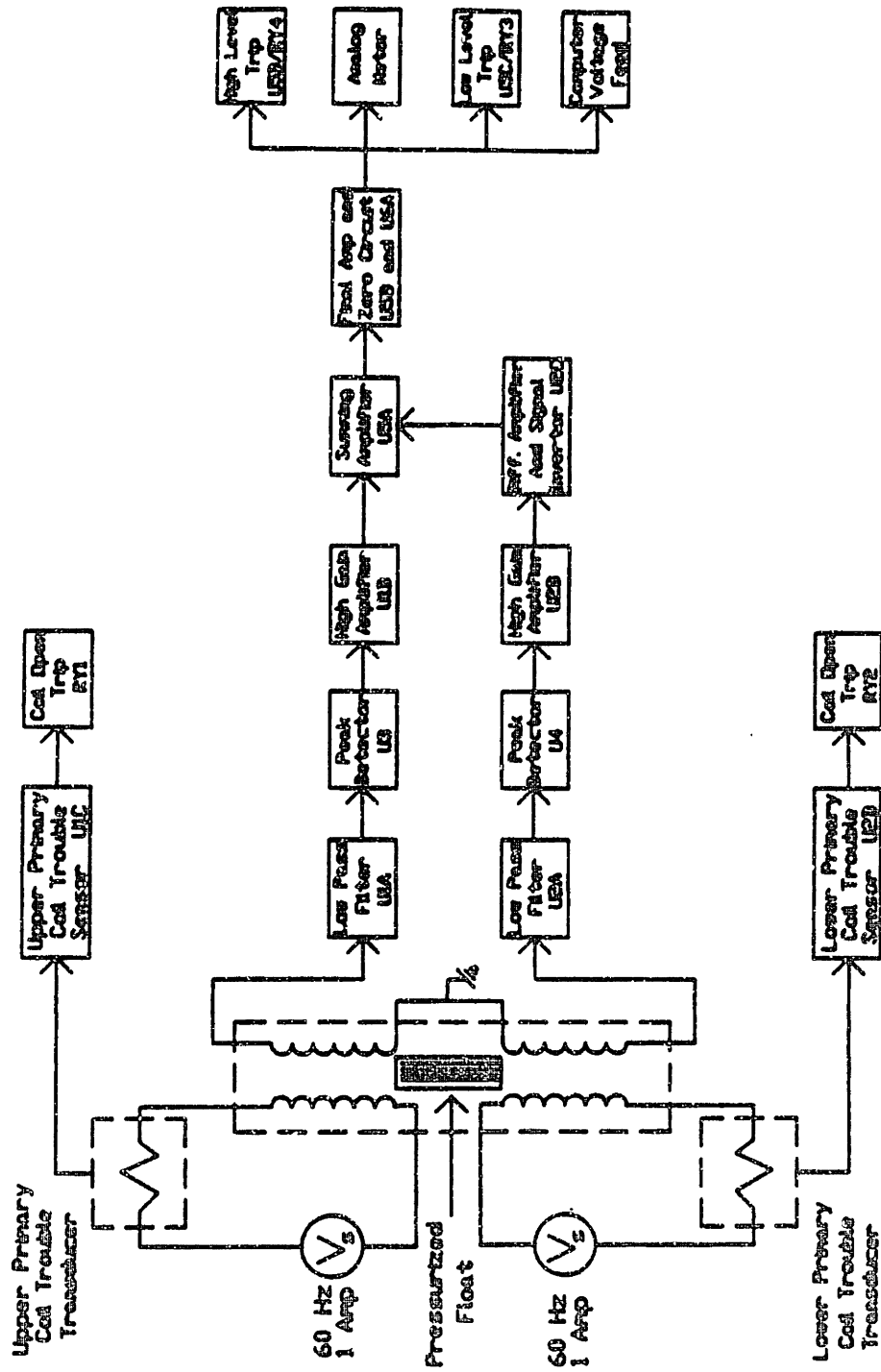


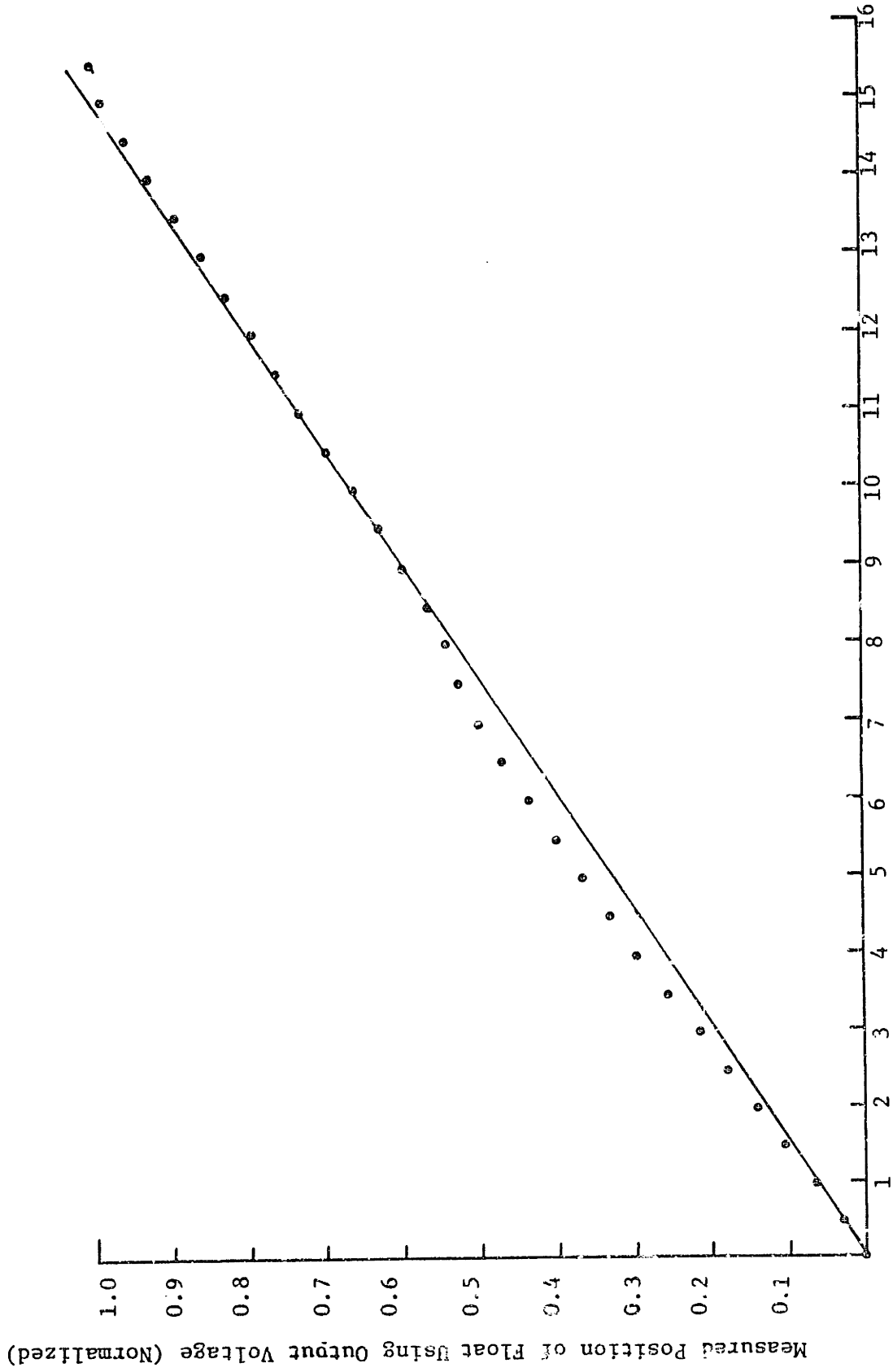
Figure 2-6 Block Diagram of Electronics for BCCL Level Detector



magnitude of which is proportional to the ac peak-to-peak voltage. This dc signal is then amplified with a high-gain amplifier. The amplified signal from the lower coil is inverted (the 0-5 volt range is changed to 5-0 volts), and the signals from the upper and lower coils are added in a summing amplifier. The result of this inversion and summing is a signal which varies linearly with the level. The calibration curve for the level detector (actual vs. measured position of float) is shown in Figure 2-7. The output voltage from the summing amplifier is 0 volts when the float is completely inside the lower coil, 5 volts when the float is between the coils, and 10 volts when the float is completely inside the upper coil. The output from this summing amplifier goes to another filter amplifier, and then to the computer and display interfaces. Adjustments of the various components are possible using trim potentiometers built into the circuit. The electronics were built using integrated circuit components, and rely on linear (i.e. op-amp) circuits rather than digital circuits.

### In-Core Section

The in-core section of the BCCL consists of a Zircaloy U-tube through which the coolant water flows; an electric heater; and a liquid lead bath thermally coupling these two components. The U-tube, the heater and the lead are contained in a titanium "test tube," which fits into the elliptical in-core section of the thimble. The titanium test tube and the elliptical in-core section are approximately 3 feet long, and the lower two feet of these components are within the core of the MIT reactor. The depth of the lead bath is approximately 25 inches (from the bottom of the titanium test tube).



Position of Float, Measured from Bottom (Inches)

Figure 2-7 Calibration Curve for Float Level Detector

## Titanium Test Tube

The major requirements for the in-core container for the liquid lead are that it maintain structural strength at a temperature of approximately 1200 F; that it not be attacked by liquid lead; and that it not be highly activatable in the radiation field of the core of a reactor. In addition, it should be corrosion-resistant in the presence of air and water. Titanium is one such material, and was used for the construction of the in-core test tube. The tube has a roughly elliptical cross section, with major and minor axes of approximately 1-3/4 inches and 3/4 inches, respectively. Details of construction are given in Appendix A.

## Zircaloy U-Tube

The Zircaloy U-tube simulates the in-core section of a BWR. It is made of a 6 foot length of seamless tubing, approximately 50.5 inches of which are within the core of the MIT Reactor, and 56 inches of which are submerged in the lead bath (and hence subjected to the heat flux). The tubing is 5/16 inch OD and 0.2565 inches ID, and the in-core fluid volume is thus 43 cm<sup>3</sup>. The tubing is made of Zircaloy-2, having a composition shown in Table 2-1.

Table 2-1: Composition of Zircaloy-2 Used in BCCL

(ppm)	Cr	Fe	Co	Sb	Hf	Ta	Ni	W
Zirc-4	1070 ± 20	2080 ± 90	0.68 ± 0.04	2.2 ± 0.02	54 ± 4	0.57 ± 0.06	<25	0.48

## **In-Core Heater**

The in-core heater has two legs, each approximately 48 inches long, which are joined in a junction box at the lower end. It is capable of delivering up to 20 kW; the heated length of each leg is approximately 21 inches. The sheath is fabricated from 1018 low-cobalt, low-carbon steel, and is insulated from the heating elements (a grounded-sheath design was not acceptable due to MIT Reactor technical specifications). The heating element is nichrome ribbon, and the insulation is magnesia. The heater was designed and fabricated by Delta M Inc., and uses the same basic design as other fuel pin simulators produced by Delta M.

## **In-Core Lead Bath**

The purpose of the lead bath is to thermally couple the in-core heater to the Zircaloy U-tube. In addition, the lead absorbs approximately 1 watt/gram of gamma energy when the reactor is at full power, and thus contributes approximately 7 kW of nuclear heat to the in-core region, in addition to the electric heat. To keep activation of the lead to a minimum, high purity lead (from Doe Run Corp.) was used.

## **Gravel Bed**

The purpose of the gravel bed is primarily to prevent streaming of neutron and gamma radiation up the thimble. In addition, it is designed to

insulate the hot outlet, steam and inlet lines from the (relatively cool) thimble wall.

The can holding the gravel is made of 3-1/4 inch OD, 2-3/4 inch ID aluminum tubing. It is designed to fit inside the thimble with a radial gap of approximately 1/8 inch. The gravel used for shielding is quartz of a type sold for use in swimming pool filters, which has been screened for size (to avoid any pieces small enough to fall between the fuel plates of the MIT Reactor) and sorted (to remove pieces known to be activatable). The volume of gravel in the bed is approximately 1-1/2 liters; most of the space inside the bed is taken up by electrical and fluid lines and their insulation.

### Heater Lead Extensions

The heater lead extensions used for the BCCL are constructed from M.I. (mineral-insulated) cable. This cable has a 1/8 inch copper conductor which is surrounded by magnesia insulation and clad with 1/4 inch OD carbon steel. These cables must be baked at a moderate temperature (350 F) for several hours before sealing the ends with epoxy or silicone rubber, as the magnesia is highly hygroscopic.

To connect the ends of the central conductor of the lead extensions to the heater leads, the male pins and female sockets of an Amphenol connector are removed. The male pin is brazed onto the heater, and the female socket brazed onto the central conductor of the heater lead extension. The result is an easily removable but electrically sound union.

## In-Pile Instrumentation

Inside the thimble are a large number of electrical measuring probes and instruments, including thermocouples, electrochemical probes, and a gamma detector (ionization chamber). These are described in the following sections.

### Thermocouples

Thermocouples are used to enhance safety, to facilitate control, and ensure accurate experimental results. All thermocouples are K-type chromel-alumel, and are clad in stainless steel sheaths. They were manufactured by Delta M Corp. and Omega.

A safety thermocouple probe (with two separate sensing elements) is placed in the in-core lead bath, with the sensing elements approximately 1 foot above the bottom of the bath (i.e., in the center of the core, where the gamma flux and nuclear heating are greatest). During operation, this thermocouple probe is at a temperature of approximately 860 F, and is used as part of a safety system which shuts down the in-core heater if it senses a temperature greater than 1275 F.

Control and experimental thermocouples probes, in compression fitting tees, are placed in the fluid streams entering and exiting the core. These thermocouples ensure that the water entering the core is at actual BWR inlet conditions, and that the fluid exiting the core is saturated. Each probe has two separate thermocouple junctions, so one signal may be used for control and one may be recorded. Two (single-element) thermocouple

probes are also placed in different positions in the aluminum sample cooling block, to confirm that the temperature of the block is not high enough to decompose the hydrogen peroxide present in the sample stream.

### Electrochemistry Probes

The purpose of the electrochemistry probes is to allow the collection of data related to ECP (electrochemical potential) and to correlate this data with various reactor conditions, particularly the concentration of radiolytic hydrogen peroxide. To effect this, a silver-silver chloride reference electrode and a platinum counter-electrode are inserted into the outlet plenum, and a stainless steel counter-electrode is inserted into the downcomer plenum. Compression fittings are used to clamp onto the stalks of these probes, and 1/16 inch M.I. cable is used to carry their signals out-of-pile to the datalogging system. All three electrodes were provided by GE, and are prototypes of units used in commercial practice for BWR service.

### Gamma Detector

The purpose of the gamma detector is to measure the gamma dose rate on the downcomer plenum, which is located directly above the elliptical streaming channel. The gamma detector, manufactured by LND (Model 5016), is a miniature ionization chamber with an active volume of 0.5 cm<sup>3</sup> filled with 1 bar of nitrogen gas. The electrical lead of the detector is similar to those of the electrochemical probes, consisting of 1/16

inch OD M.I. cable. The gamma detector is designed to operate at high temperature, and is placed directly beside the downcomer plenum.

The gamma detector was calibrated with a known Co-60 dose rate and different cathode (outer electrode) voltages at the University of Lowell gamma irradiation facility. The calibration curve is shown in Figure 2-8. As may be seen from this curve, the output current plateaus at a voltage lower than 100 volts. For an operating voltage of 250 volts, the efficiency is found to be  $3.3E-14$  amps/(K/hr).

## OUT-OF-PILE FLUID SYSTEM

A schematic of the out-of-pile fluid system is shown in Figure 2-9. It consists fundamentally of a feedwater pump, and a hotwell tank with a gas cleanup system and a water purification system. A functional description of the components is contained in the following sections; a more detailed description may be found in Appendix A.

### Hotwell Tank

The hotwell tank serves as a reservoir of clean water to supply the main feedwater pump and the in-pile section. It is constructed of acrylic tubing with glass-filled polycarbonate endcaps and has a volume of approximately 65 liters. It has been pressure-tested to 15 psig, and normally operates at a pressure of approximately 5 psig. The water level is normally approximately 50-55 liters, with 10-15 liters of cover gas.



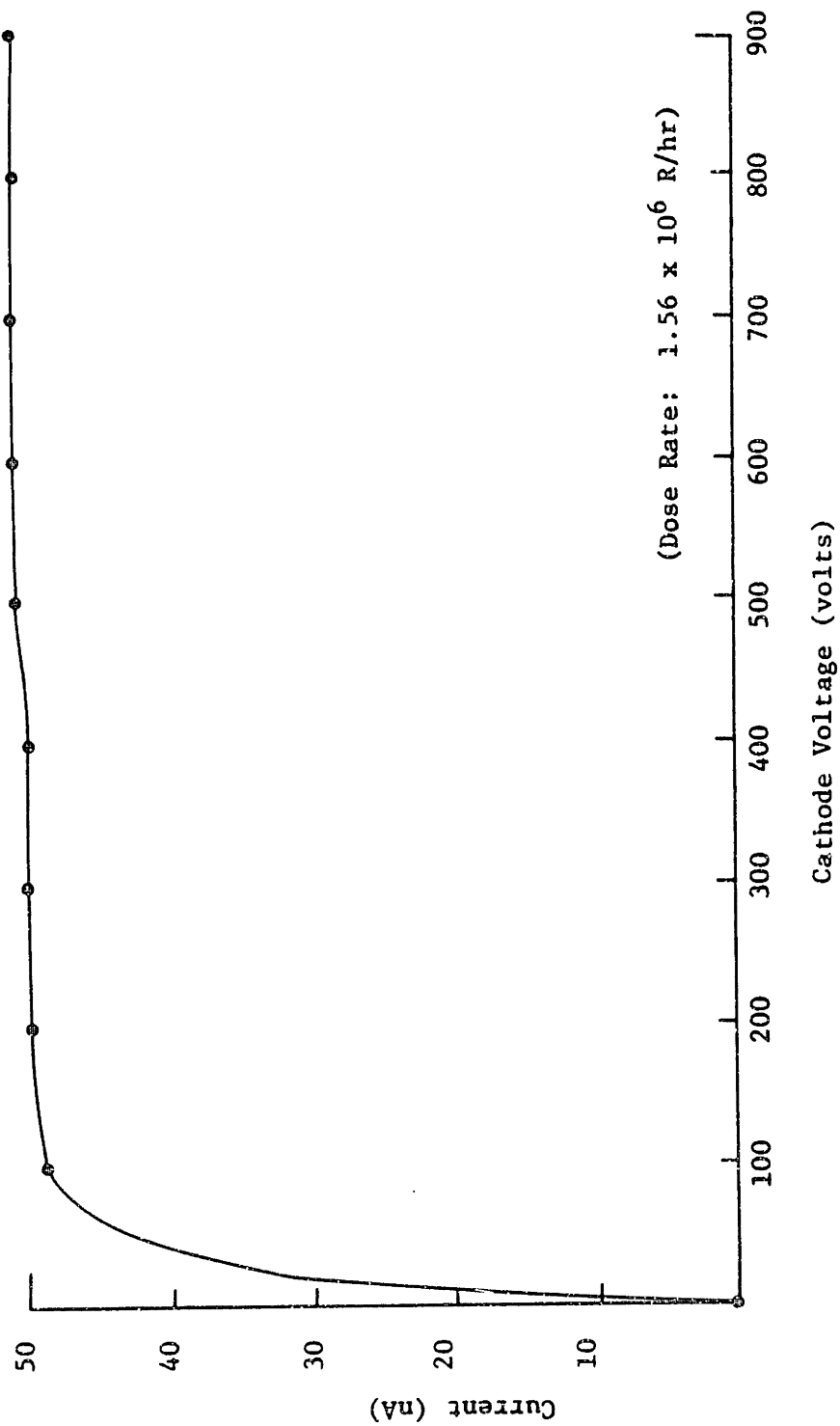


Figure 2-8 Calibration Curve for Ionization Chamber

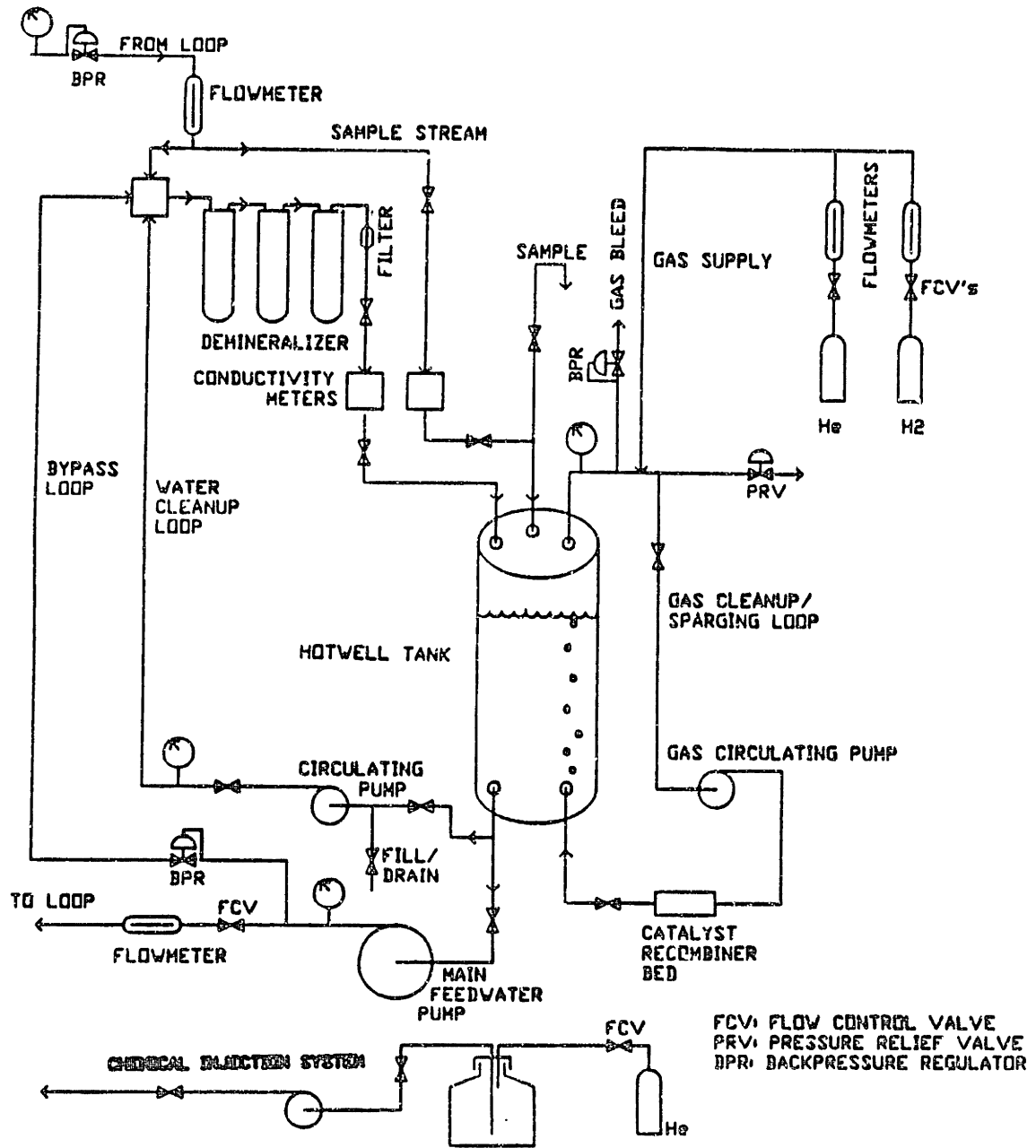


Figure 2-9 Schematic of BCCL Out-of-Pile System

## Feedwater Pump

The feedwater pump takes suction directly from the hotwell tank. The capacity of the feedwater pump is approximately 3 lpm at 1250 psi. This flowrate is essentially constant (although there is a slight pressure dependence), and part of the flow stream is bypassed back to the demineralizer. By increasing or decreasing the bypass flowrate, the flowrate to the in-pile section may be varied between 0 and 3 lpm. If desired, the flowrate could be increased substantially by changing the sheaves connecting the motor with the pump. The pump is a 3-piston model with stainless steel wetted surfaces and Viton and Teflon seals. It is manufactured by Cat Pump.

## Chemical Injection System

The purpose of the chemical injection system is to allow the injection of a small stream of additives into the coolant immediately before it enters the core. To effect this, a 1/16 inch stainless steel tube is connected to the flowpath just upstream of the core with a compression fitting. The tube extends the length of the in-pile thimble to the pump pod, where it is connected to a 1/16 inch PEEK line. This line passes through the thimble lid, and travels out-of-pile where it is connected to a valve. The chemical injection pump (MiniPump, manufactured by Milton Roy) shown in Figure 2-9, takes suction from the sample supply tank, and pumps the injection stream through this valve into the stainless steel injection line.

## N-16 Detector

The N-16 detector system is designed to monitor the N-16 activity in the water and steam exit lines. It consists of a large lead shield block (to reduce background radiation), two 3-inch NaI(Tl) scintillator crystals, and a MCA (multichannel analyzer). The scintillator crystals are placed in cavities in the lead block, the steam and water lines each pass in front of one of the NaI(Tl) scintillator crystals. The gamma rays emitted by the decay of N-16 in the fluid easily pass through the walls of the fluid lines and enter the crystal.

### **Lead Shield Block**

The lead shield block is designed to reduce the background radiation level at the scintillator crystals, to improve the precision with which N-16 measurements can be made. The block has two penetrations for the scintillator crystals and one penetration each for the steam and water lines. It has a minimum of 2 inches of lead shielding around each crystal, and reduces the incident radiation by a factor of approximately 50 in the N-16 energy range (near 6 MeV). The background gamma doses on the reactor top at the position of the lead shield block (2 feet in front of the shield ring plug), with and without lead shielding, are shown in Figure 2-10. The configuration and construction details of the lead shield block may be found in Appendix A.

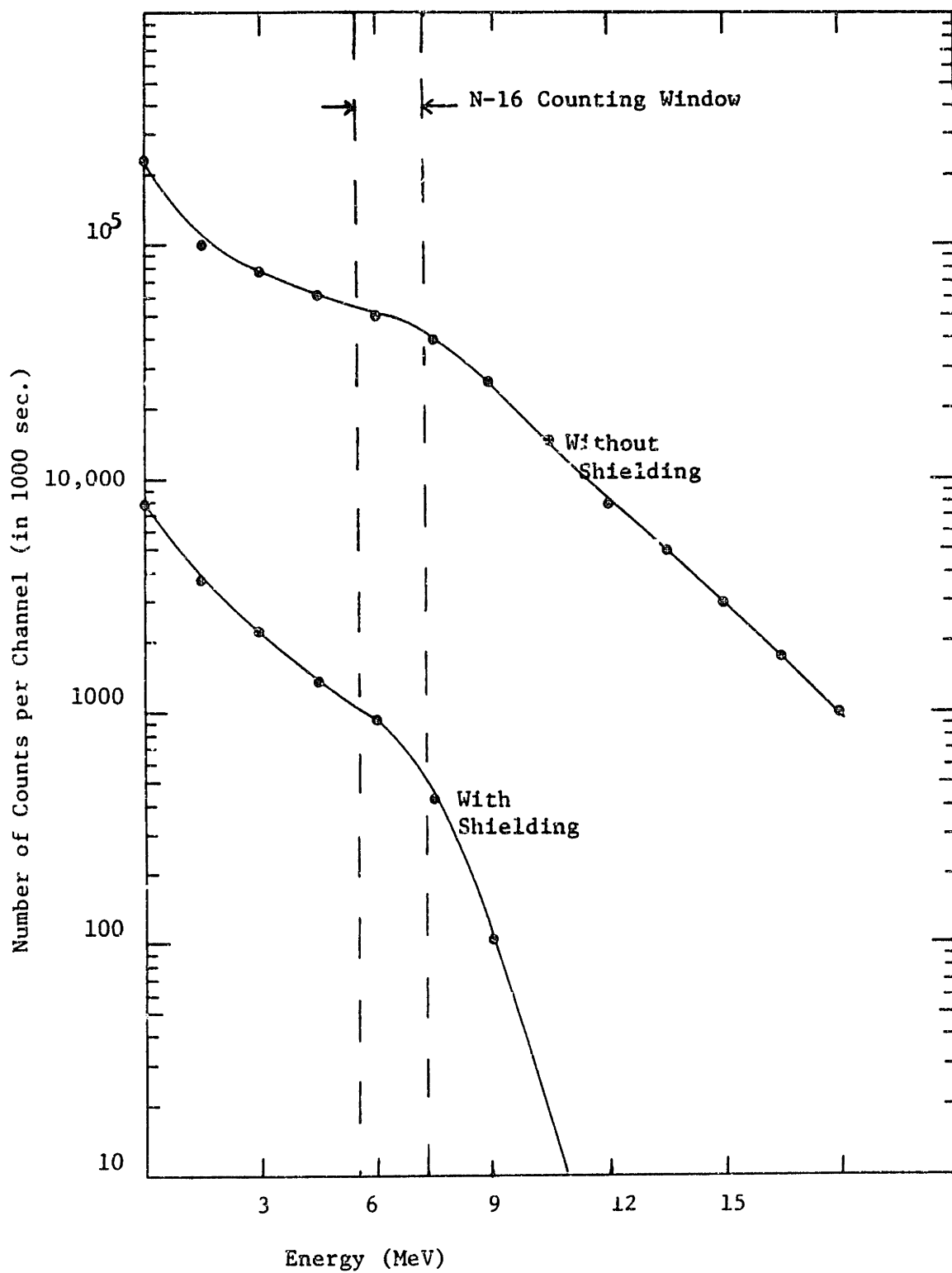


Figure 2-10 Gamma Background on MIT Reactor Top, With and Without Shielding

## **Detectors and Electronics**

The detection system used for the N-16 detector consists of a 2-inch NaI(Tl) scintillation crystal with a photomultiplier tube, and a MCA. Both the crystal (Model No. 802-4) and the MCA (Series 20) were manufactured by Canberra. The efficiency (intrinsic plus geometry) of the 2-inch NaI(Tl) crystal for 6 MeV gamma rays is approximately 0.03%.

## **Steam Plenum**

In order to increase the volume of steam inside the lead shield block and hence the N-16 gamma activity incident on the scintillator crystal, a small steam plenum was made from 5/8 inch OD, 1/2 inch ID titanium tubing. The internal volume of this plenum which shines directly onto the crystal is 12.0 cm<sup>3</sup>, approximately 6.64 times the corresponding volume of the 1/4 inch OD, 0.194 inch ID water line. The construction details of this steam plenum may be found in Appendix A.

## **Heat Exchangers**

The BCCL out-of-pile system has two heat exchangers, one regenerative (to transfer heat from the core outlet stream to the core inlet stream), and one non-regenerative (to reject heat from the fluid stream returning to the hotwell tank). The regenerative heat exchanger is constructed of titanium, and is of a counterflow tube-in-shell design. Its heat transfer length is approximately 20 feet; it is described more fully in

Reference B-1. The non-regenerative heat exchanger is of a similar design, but the shell is made from 3/4 inch OD copper pipe (rather than 1/2 inch OD titanium tubing). The secondary side coolant of the non-regenerative heat exchanger is supplied by the small centrifugal pump used to cool the water in the out-of-pile test tank. This pump circulates water from the test tank through a heat exchanger, the secondary side of which is cooled by the reactor secondary coolant system (connected to the cooling tower). Part of the return flow from this pump is passed through the BCCL non-regenerative heat exchanger, before discharging to the out-of-pile test tank. The construction of these heat exchangers is discussed in more detail in Appendix A.

### Feedwater Heater

After leaving the regenerative heat exchanger, the feedwater flows to the electric feedwater heater, the purpose of which is to heat the feedwater up to BWR core inlet conditions. This feedwater heater consists of a length of titanium tubing immersed in a tin-zinc eutectic bath. Three electric rod heaters are also immersed in the metal bath; the maximum electric power which is available with the current heaters and power supplies is approximately 7500 watts at 50 amperes. The input power for standard operating conditions is approximately 6 kW. The heaters are controlled by a thermocouple-based controller. After leaving the feedwater heater, the feedwater flows directly to the in-core section. This feedwater heater is described more fully in Appendix A.

## Steam Orifice Flowmeter

The steam orifice flowmeter is located on the steam line, after it exits the core tank and the lead shield block. The purpose of the orifice flowmeter is to measure the steam flowrate reliably and simply (at high temperature and pressure). It consists of a small plate with a (1/16 inch) center hole through which all the steam is forced to flow, and pressure taps upstream and downstream of the hole. The pressure drop of the steam flowing through the hole was correlated with the steam flowrate in a calibration experiment. This flowmeter is described more fully in Appendix A, and in Reference B-1. The calibration curve may also be found in Appendix A.

## Hot Line Sampling System

The hot line sample taps allow water and condensed steam samples to be drawn from the steam and water exit lines at a point immediately downstream of the N-16 detector and the orifice flowmeter. Each tap consists of a coil of 1/4 inch OD titanium tubing which is connected to the exit line by a tee compression fitting. This coil is submersed in an icewater bath, and the flow through the sample tap is controlled by a small valve at the free end of the titanium coil. This system is also described in Appendix A.



## HYDROGEN PEROXIDE MEASUREMENT METHOD

Hydrogen peroxide concentrations in the coolant were measured using a technique developed by Chemetrics Inc. The sample is first reacted with an acidic solution of potassium iodide. Any hydrogen peroxide present in the sample liberates free iodine which, in turn, reacts with the methyl-substituted DPD (N,N-diethyl-p-phenylene diamine) reagent. This reaction produces a blue-violet color in the sample, the darkness of which is proportional to the amount of hydrogen peroxide present initially. The blue-violet color is quantified by a Hach colorimeter (Model DR/2000), which passes a 565 nm beam of light through the sample and measures the absorption which takes place in the sample. The amount of light absorbed is proportional to the original hydrogen peroxide concentration. This method was found to be reliable and repeatable. The measuring range was 10 ppb to 2000 ppb, with an accuracy (at low ranges) of +/- 10 ppb. For samples above 2000 ppb, dilution brought them within range.

## ON-LINE ION CHROMATOGRAPH

The on-line ion chromatograph used was a GE-modified HPLC unit with a Dionex suppressor and a Waters anion column (a more sophisticated Waters unit capable of detecting anions, cations, and transition metals was available for use with grab samples, but was not used). The IC was capable of detecting F<sup>-</sup>, Cl<sup>-</sup>, Br<sup>-</sup>, NO<sub>3</sub><sup>-</sup>, NO<sub>2</sub><sup>2-</sup>, and SO<sub>4</sub><sup>2-</sup> at concentrations down to 5 ppb. The ion chromatograph required approximately 25 cm<sup>3</sup> samples for analysis; samples of the size taken for hydrogen peroxide analysis were

found to be ample. Alternatively, the ion chromatograph suction tube may be connected directly to the return line from the loop, or to the hotwell tank.

## **SHIELD RING PLUG**

The purpose of the shield ring is to isolate the top of the core tank (the space below the reactor lid and above the circulating reactor coolant water) from the reactor top area (which is accessible to personnel), while still providing substantial radiation shielding. The shield ring plug fits into a hole in the reactor shield ring which is designed to accept it. All the electrical and fluid lines of the in-pile thimble must pass through this plug. It is not a pressure boundary, but free gas flow past the plug is not permissible.

The plug is approximately 12 inches high, 8 inches deep, and 7 inches wide. It is made of 1/4 inch steel plate and is filled with lead. It has several 1 inch ID conduits, bent into arcs or sigmoids, running through it from the core tank to the reactor top, for feedthroughs. Straight feedthrough tubes were avoided to prevent radiation streaming. Most of the seals between the fluid lines and the penetration conduits are made with high-temperature silicone rubber caulking. This plug is the same unit as used for the PWR loop runs, and is described more fully in Reference S-1.

## **POWER SUPPLIES**

The BCCL uses two power supplies, one for the in-core heater and one for the feedwater heater. Both of these power supplies were manufactured by Delta M Corp., and are phase-firing SCR (silicon-controlled rectifier) devices. They operate by turning on the current at the start of each ac half-cycle, and turning off the current partway through each half-cycle, depending on how much power is demanded. Thus, the current is turned on and off 120 times each second, producing a relatively smooth power input to the heaters. The power supplies are controlled either manually, or by a thermocouple input. The main heater power supply is capable of delivering 150 amperes at 277 volts, and the power supply for the feedwater heater is capable of delivering 50 amperes at 277 volts. The power input for standard operating conditions is approximately 7 kW.

## **DATA AQUISITION SYSTEM**

The data aquisition system consists primarily of a PC XT with a color monitor, and appropriate input interfaces for the temperature, pressure, level and power transducers used in the BCCL. The software used is Labtech's "Notebook," which allows data analysis and manipulation with the spreadsheet program Lotus 1-2-3. This system is the same as used for the PWR loop, described in Reference S-1.

## **ALARM SYSTEM**

The purpose of the alarm system is to notify the loop and reactor operators of off-normal conditions which affect either safety or the proper functioning of the experiment. Display panels, on the instrumentation rack of the experiment and in the reactor control room, show the status of each alarm; when an alarm trips, the display light associated with the alarm comes on, and a buzzer sounds. Acknowledging (disabling) the alarm shuts off the buzzer and causes the light to flash. The display light continues to shine until the monitored variable returns to its normal range.

The BCCL alarms and setpoints are:

In-core lead bath. Set at 1275 F (normal operating temperature is 860 F). Sounds alarm and cuts off in-core heater.

Core outlet (coolant stream). Set at 575 F (normal operating temperature is 542 F). Sounds alarm and cuts off in-core heater.

Low pressure in loop. Set at 500 psi (normal operating pressure is 1000 psi). Sounds alarm.

Pressure relief valve lifted. Sounds alarm.

Low level in charging tank. Set at 20 liters (normal level is 55 liters). Sounds alarm.

High thimble humidity. Set at 40% (normal humidity level is 5%). Sounds alarm.

Low thimble pressure. Set at 10 psig (normal operating pressure is 14 psig). Sounds alarm.

Low heater current. Set at 1 kW (normal operating power is 7 kW). Sounds alarm.

Low level in out-of-pile test tank. Set at 12 feet (normal operating level is 15 feet). Sounds alarm and causes circulating pump to shut off.

Low level in outlet plenum. Set at 15% (normal operating level is 50%). Sounds alarm.

High level in outlet plenum. Set at 90% (normal operating level is 50%). Sounds alarm.

Open circuit in primary winding of level detector coils. Sounds alarm.

## SUPPORT FACILITIES

The most important support facility used for the BCCL work is the "test tank," a vertical cylindrical aluminum tank filled with water, into which the BCCL thimble fits. The tank is approximately 2 feet in diameter and 16 feet high. A pump is provided to circulate the water through a heat exchanger (connected to the reactor secondary coolant system), and another, smaller pump circulates the water through a demineralizer bed. This tank is used to simulate the in-core environment (except for the radiation) of the reactor, and is useful for hot testing of the loop.

In addition to the test tank, the other major piece of support equipment is the shield cask. The purpose of the cask is to shield the in-core section of the thimble while the thimble is being transferred from the reactor to the hot cell and storage area. This cylindrical cask is approximately 11-1/2 inches in diameter and 4 feet tall, and is constructed of lead-filled steel. It has a central hole 4-1/2 inches in diameter, and is built in two halves, hinged together, to allow it to open and shut. To

remove the thimble from the reactor, the reactor lid is removed, and a 1-inch thick steel plate with a large central hole is placed over the top opening. The thimble is then hoisted out of the reactor through the hole in the plate, and the shield cask is closed around the in-core section. Both the cask and the thimble are then lifted together, and the thimble is transferred to the hot cell or storage area.

The shield cask and the test tank are the same as used for the PWR loop experiments. A more detailed description of these items, and of the thimble transfer operation, may be found in Reference S-1.

#### **SUMMARY: DESCRIPTION OF SYSTEM**

The BCCL has two major subsystems, the in-pile thimble (and its contents) and the out-of-pile support facilities. The functioning of these subsystems and their components have been described in this section. Detailed descriptions and fabrication details have not been included; these may be found in Appendix A.

### 3. FUNCTIONAL CHARACTERISTICS OF SYSTEM

The functional characteristics of the BCCL experiment are described in this section. The physical system is described in the previous section; here the experimental parameters such as flow rates, radiation doses, transit times, and dynamic stability are addressed.

#### THERMAL HYDRAULICS AND RADIATION DOSES

To conduct a meaningful radiochemistry experiment, the core transit time and the in-core radiation dose rates must be known. When these parameters are known, the actual absorbed dose to the water may be calculated. This absorbed dose may then be correlated in a useful way with experimental results (e.g., the production of hydrogen peroxide).

#### Calculation of Dose Rates to Coolant

Most BCCL experiments were conducted with the reactor at approximately 4.2 MW, well below the 5 MW maximum, to allow a safety margin for reactivity insertions which may cause a sudden power rise. The average gamma radiation dose rate in the water in the core of the MIT Reactor is  $1.5 \times 10^5$  R/sec (reactor at 4.2 MW) (B-2), or  $1.5 \times 10^7$  ergs/g-sec. This was measured as described in Appendix A, using a small ionization chamber. To find the gamma dose to the coolant, this dose rate should be multiplied by the residence time of the coolant in the core radiation field.

The average fast neutron (>1 MeV) energy deposition rate in the water in the core of the MIT Reactor is 0.92 W/g (reactor at 4.2 MW) (E-

1, M-2), or  $9.2 \times 10^6$  erg/g-sec. The neutron energy deposition profile and a theoretical calculation are given in Appendix D. To find the integrated neutron dose to the coolant, this dose rate should be multiplied by the residence time of the coolant in the core radiation field.

### Core Section: Calculation of Transit Time and Exit Quality

The core section transit times and exit qualities are calculated in this section as functions of the inlet flow rate and the heat transferred to the coolant. The calculations are somewhat complex, and are reproduced in some detail here to facilitate application to revised system designs or operating conditions.

The following assumptions are made in these calculations:

1. Inlet and outlet temperatures are constant at  $277^\circ\text{C}$  and  $285^\circ\text{C}$ , respectively.
2. Pressure is constant and uniform at 6.9 MPa (1000 psi).
3. No slip (of steam relative to liquid).
4. Uniform heat flux.

#### 1) Calculation of Exit Quality as a Function of Heat Input and Flow Rate

We know that the heat input to the coolant is equal to the mass flow rate times the change in enthalpy of the coolant, or

$$\dot{q} = \dot{m} \cdot \Delta h \quad (3-3)$$

where  $\dot{q}$  = heat input (core section) to coolant;



$\dot{m}$  = mass flow rate; and

$\Delta h$  = change in enthalpy between the core inlet and the core outlet.

The change in enthalpy comprises an increase in the enthalpy of the liquid plus an enthalpy of evaporation, so

$$\dot{q} = \dot{m} \cdot (\Delta h_f + x_{out} \cdot h_{fg(285)}) \quad (3-4)$$

where  $\Delta h_f$  = the change in enthalpy of the fluid;

$x_{out}$  = the core outlet quality, and

$h_{fg(285)}$  = the enthalpy of evaporation at 285°C.

Since the change in enthalpy of the liquid is

$$\Delta h_f = h_f(285) - h_f(277) \quad (3-5)$$

where  $h_f(285)$  = the enthalpy of water at 285°C; and

$h_f(277)$  = the enthalpy of water at 277°C,

by combining eqs. 3-4 and 3-5 we get

$$\dot{q} = \dot{m} \cdot (h_f(285) - h_f(277) + x_{out} \cdot h_{fg(285)}) \quad (3-6)$$

which, when rearranged, gives

$$x_{out} = \frac{\frac{\dot{q}}{\dot{m}} - h_f(285) + h_f(277)}{h_{fg(285)}} \quad (3-7)$$

as the exit quality.

## 2) Calculation of Core Transit Time as a Function of Heat Input and Flow Rate

The total heated length,  $L$ , may be divided into a non-boiling length,  $L_{nb}$ , and a boiling length,  $L_b$ , so that

$$L = L_{nb} + L_b \quad (3-8)$$

Similarly, the heat added to the coolant,  $\dot{q}$ , may be divided into the quantity added in the non-boiling region,  $\dot{q}_{nb}$ , and the quantity added in the boiling

region,  $\dot{q}_b$ , so that

$$\dot{q} = \dot{q}_{nb} + \dot{q}_b \quad (3-9)$$

Assuming constant heat flux, the fraction of the total heat transferred to the coolant in the non-boiling region is equal to the non-boiling fraction of the total length, or

$$\frac{\dot{q}_{nb}}{\dot{q}} = \frac{L_{nb}}{L} \quad (3-10)$$

The heat needed to initiate boiling is given by

$$\dot{q}_{nb} = \dot{m} \cdot \Delta h_f = \dot{m} \cdot (h_f(285) - h_f(277)) \quad (3-11)$$

Combining and rearranging eqs. 3-10 and 3-11 gives

$$L_{nb} = L \cdot \frac{\dot{m} \cdot (h_f(285) - h_f(277))}{\dot{q}} \quad (3-12)$$

for the non-boiling length.

The average density of a two-phase mixture is (T-1)

$$\rho = \frac{\alpha}{x} \cdot \rho_g \quad (3-13)$$

where  $\rho_g$  = the density of the steam.

The void fraction,  $\alpha$ , is (T-1)

$$\alpha = \frac{x \cdot \rho_f}{x \cdot \rho_f + (1 - x) \cdot \rho_g} \quad (3-14)$$

Combining and rearranging eqs. 3-13 and 3-14 gives

$$\rho = \frac{\rho_g \cdot \rho_f}{x \cdot (\rho_f - \rho_g) + \rho_g} \quad (3-15)$$

for the average density of a two-phase mixture.

Since the quality varies linearly from the point at which boiling starts to the core exit, we can integrate this expression for the average density of a two-phase mixture from  $x=0$  to  $x=x_{out}$  to find the average density over the entire boiling region. The resulting expression for the average density of the coolant in the boiling region is

$$\bar{\rho}_b = \frac{1}{x_{out}} \cdot \frac{\rho_g \rho_f}{\rho_f - \rho_g} \cdot \ln \left[ \left( \frac{\rho_f}{\rho_g} - 1 \right) x_{out} + 1 \right] \quad (3-16)$$

The average density of the coolant over the entire core region (both boiling and non-boiling) is given by

$$\bar{\rho}_{tot} = \bar{\rho}_b \cdot \frac{L_b}{L} + \rho_f \cdot \frac{L_{nb}}{L} \quad (3-17)$$

The volumetric flow rate through the core is found by dividing the mass flow rate by the average density of the coolant:

$$\dot{v} = \frac{\dot{m}}{\bar{\rho}_{tot}} \quad (3-18)$$

The transit time,  $\tau$ , of the coolant through the core section is given by dividing the volume of the core by the volumetric flow rate:

$$\tau = v \cdot \left( \frac{1}{\dot{v}} \right) = v \cdot \left( \frac{\bar{\rho}_{tot}}{\dot{m}} \right) \quad (3-19)$$

This is the expression for the transit time. By substituting eq. 3-7 into eq. 3-16, eqs. 3-12, 3-8 and 3-16 into eq. 3-17, and eq. 3-17 into eq. 3-19, we get an explicit expression for the transit time as a function of the heat input and the mass flow rate. The transit times (eq. 3-19) and outlet qualities (eq. 3-7) are plotted in figure 3-1 for typical BCCL flow rates and heat inputs.

Several assumptions, in addition to those listed above, are implicit in this plot. The length of the heated section is taken as 50.5 inches, and the ID of this section is 0.2625 inches. The in-core section is approximately 2 inches shorter, and has a volume of  $v = 43 \text{ cm}^3$  (used in eq. 3-19). Thus, the plot is valid unless the diameter of the in-core section, or the depth of the in-core lead bath, are changed substantially.

The assumption of constant heat flux is not fully accurate, as the contribution from gamma heating is lower towards the ends of the core section. However, the heating is symmetrical with respect to the up and

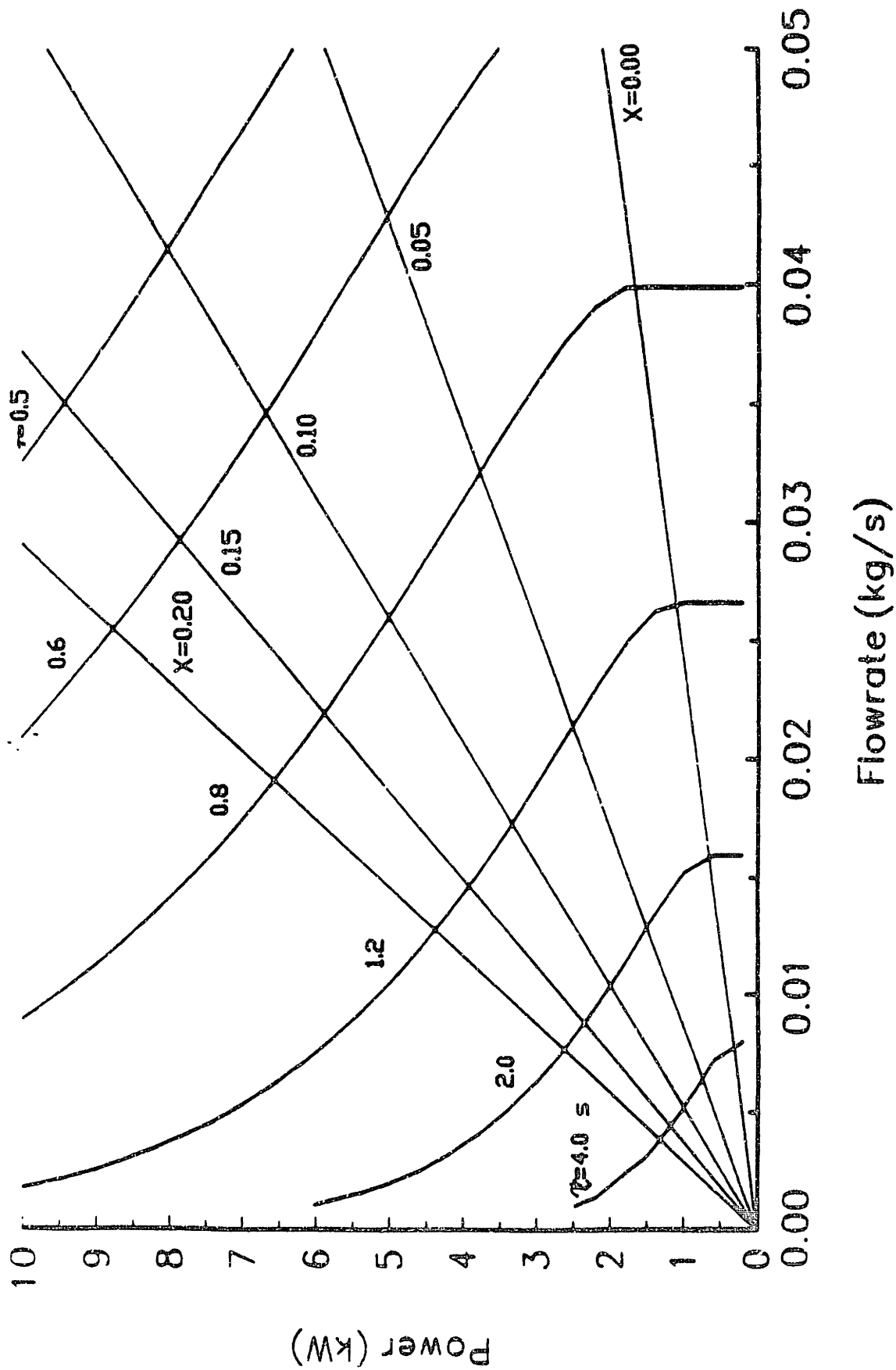


Figure 3-1 BCCL Core Transit Time and Quality Map

down legs of the core section, so this assumption should not introduce a large inaccuracy.

The homogeneous equilibrium flow model has been used for the relation between quality and void fraction (eq. 3-14); the assumption of no slip is a reasonably good one. Most of the BCCL mass flux conditions are near or within the region of applicability for this correlation (T-1). The maximum error introduced by this correlation is believed to be minor, perhaps on the order of 5%.

### Outlet Plenum: Calculation of Water and Steam Transit Times

The transit time for the steam and water through the outlet plenum are calculated as follows.

#### 1) Calculation of Water Transit Time Through Outlet Plenum

The volume of water in the outlet plenum is

$$v_w = v_o \cdot y \quad (3-20)$$

where  $v_o$  = the internal volume of the outlet plenum (0.45 liters), and

$y$  = the normalized level in the outlet plenum, which varies from 0 to 1.

The volumetric flow rate of water through the outlet plenum is

$$\dot{v}_w = \frac{\dot{m}}{\rho_f} (1-x) \quad (3-21)$$

where  $\dot{m}$  = mass flow rate (through the core);

$\rho_f$  = density of water (742 kg/m<sup>3</sup> at 285°C), and

$x$  = quality.

The transit time of water through the outlet plenum is then given by

$$\tau_w = \frac{v_w}{\dot{v}_w} = \frac{v_o \cdot \rho_f y}{\dot{m}(1-x)} \quad (3-22)$$

## 2) Calculation of Steam Transit Time Through Outlet Plenum

Similarly, the steam volume in the outlet plenum is

$$v_s = v_o \cdot (1 - y) \quad (3-23)$$

and the steam flow rate is given by

$$\dot{v}_s = \frac{\dot{m} \cdot x}{\rho_g} \quad (3-24)$$

where  $\rho_g$  = density of steam (36 kg/m<sup>3</sup> at 285°C).

The steam transit time through the outlet plenum is then

$$\tau_s = \frac{v_s}{\dot{v}_s} = \frac{v_o \cdot \rho_g \cdot (1 - y)}{\dot{m} \cdot x} \quad (3-25)$$

### Downcomer Plenum: Calculation of Transit Time and Dose Rate

Using the small gamma detector and the calibration curve, the gamma radiation dose rate on the downcomer plenum was found to be approximately  $9 \times 10^6$  R/hr (2500 R/s or  $2.5 \times 10^5$  ergs/g-sec) with the reactor at full power (5 MW). Corrected for the reactor power at which the experiments are run (4.2 MW), the gamma dose rate to the water in the downcomer plenum is approximately  $2.1 \times 10^5$  ergs/g-sec. This absorbed dose rate is found to scale approximately linearly with reactor power, and is roughly 1% of the in-core absorbed dose rate by the BCCL thimble internals.

The transit time is calculated as follows. The volume of the downcomer plenum is  $v_d = 0.11$  liters ( $0.11 \times 10^{-3} \text{ m}^3$ ). The volumetric flow rate of water through the downcomer plenum is

$$\dot{v}_d = \frac{\dot{m}}{\rho_f} (1-x) \quad (3-26)$$

where  $\dot{m}$  = the mass flow rate through the loop;

$\rho_f$  = density of water at  $285^\circ\text{C}$  ( $= 742 \text{ kg/m}^3$ ), and

$x$  = quality of the core outlet.

The transit time for the downcomer plenum is given by

$$\tau_d = \frac{V_d}{\dot{v}_d} \quad (3-27)$$

where  $V_d$  = volume of downcomer plenum. Combining eqs. 3-26 and 3-27 gives

$$\tau_d = \frac{V_d \cdot \rho_f}{\dot{m}(1-x)} \quad (3-28)$$

for the transit time in the downcomer plenum. The gamma dose to the downcomer water is found by multiplying the transit time by the dose rate.

## N-16 DETECTOR

The function of the N-16 detector is to determine how much N-16 is produced in the core radiation field, and how it is distributed between the water and steam phases. Since N-16 decays with a 7.13 second half-life, in order to determine the specific activity, it is necessary to know both the transit times between the core and the detector, as well as the volumes of water and steam which shine on the detector.

The transit time of the liquid from the core outlet to the N-16 detector is the sum of the transit times through the outlet plenum, the

downcomer plenum, and the tubing connecting these plena with the core and the detector. The length of this tubing is approximately 19 feet, with an internal volume of approximately  $v_{\text{wat}} = 110 \text{ cm}^3$ . Thus, the transit time for the water to pass through the tubing connecting the plena with the N-16 detector is

$$\tau_t = \frac{v_{\text{wat}}}{\dot{V}_t} \quad (3-29)$$

where  $v_{\text{wat}}$  = the volume of the tubing ( $110 \text{ cm}^3$ ), and

$\dot{V}_t$  = the volumetric flow rate through the tubing.

The transit time from the core to the detector is the sum of the transit times through the outlet plenum, the downcomer plenum, and the tubing. Using the transit times calculated in the previous sections, the total transit time for the water is

$$\tau_{\text{wat}} = \frac{\rho_f}{\dot{m} \cdot (1 - x_{\text{out}})} \cdot (v_o \cdot y + v_d + v_{\text{wat}}) \quad (3-30)$$

This water transit time is plotted for typical BCCL conditions in figure 3-2 as a function of mass flow rate, outlet plenum level, and core power input. Since the transit time is only slightly dependent on core power input, the curves for different plenum levels are plotted for maximum and minimum power levels (0 and 10 kW). The actual water transit time can be found by interpolation between the curves.

Similarly, the transit time for the steam is the sum of the outlet plenum transit time and the steam line transit time. The length of the steam line is approximately 13 feet, with an internal volume of  $v_{\text{stm}} = 76 \text{ cm}^3$ . Using the results from the previous section, the transit time for the steam from the core to the N-16 detector is

$$\tau_{\text{stm}} = \frac{\rho_g}{\dot{m} \cdot x} \cdot (v_o \cdot (1 - y)) + v_{\text{stm}} \quad (3-31)$$



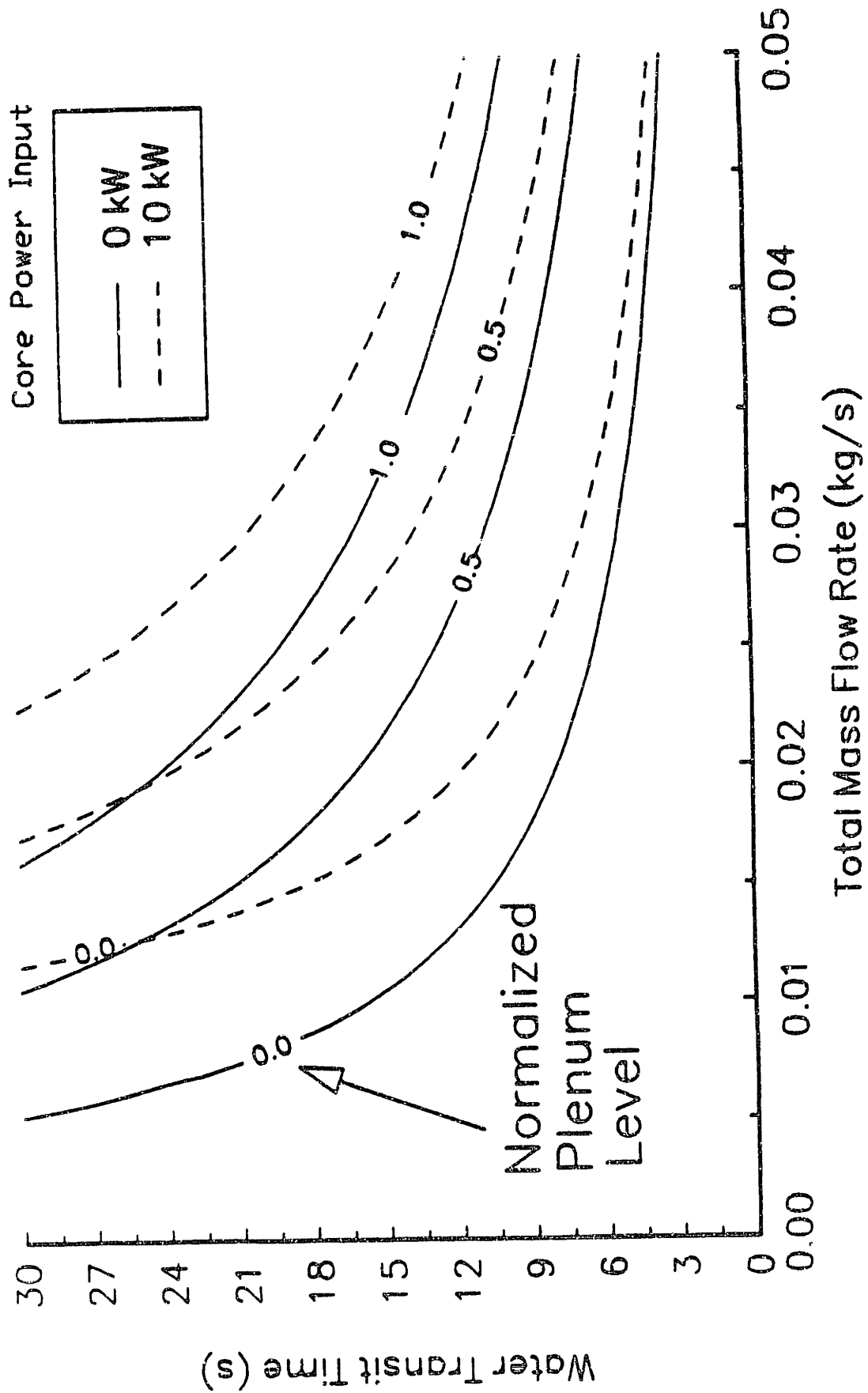


Figure 3-2 Water Transit Time From Core Exit to N-16 Detector

This steam transit time is plotted for typical BCCL conditions in figure 3-3. As before, the steam transit times may be found by interpolating between the curves representing plenum level.

The internal volumes of the steam and water chambers facing the the N-16 detectors have been previously calculated to be 12.0 cm<sup>3</sup> and 1.8 cm<sup>3</sup>, respectively. These chambers thus contain 0.43 gram of steam and 1.34 grams of water, respectively.

The N-16 activity measured at the detector is a function of the core transit time (production), the transit time of the fluid from the core to the detector, and the detector itself (intrinsic efficiency and geometry factor). The expected N-16 activity at the detector is calculated as follows.

The N-16 activity at the core outlet (in dps/cm<sup>3</sup>) is given by

$$A_{\text{core}} = \phi \cdot N \cdot \sigma \cdot \left[ 1 - \exp\left(-\frac{\tau \cdot \ln(2)}{T_{1/2}}\right) \right] \quad (3-32)$$

where  $\phi$  = average in-core fast neutron flux (n/cm<sup>2</sup>-sec);

$N$  = specific population of O-16 atoms (atoms/cm<sup>3</sup>);

$\sigma$  = O-16(n,p)N-16 capture cross section (cm<sup>2</sup>);

$\tau$  = transit time of fluid through core (sec), and

$T_{1/2}$  = half-life of N-16 (7.13 sec).

Since the flux is proportional to the reactor power (MW); the population of atoms is proportional to the average density of the coolant; and the capture cross section is constant, this expression may be simplified to the functional relationship

$$A_{\text{core}} = k \cdot P \cdot \bar{\rho}_{\text{tot}} \cdot \left[ 1 - \exp\left(\frac{\tau \cdot \ln(2)}{T_{1/2}}\right) \right] \quad (3-33)$$

where  $P$  = normalized reactor power, and

$k$  = an experimentally determined proportionality constant.

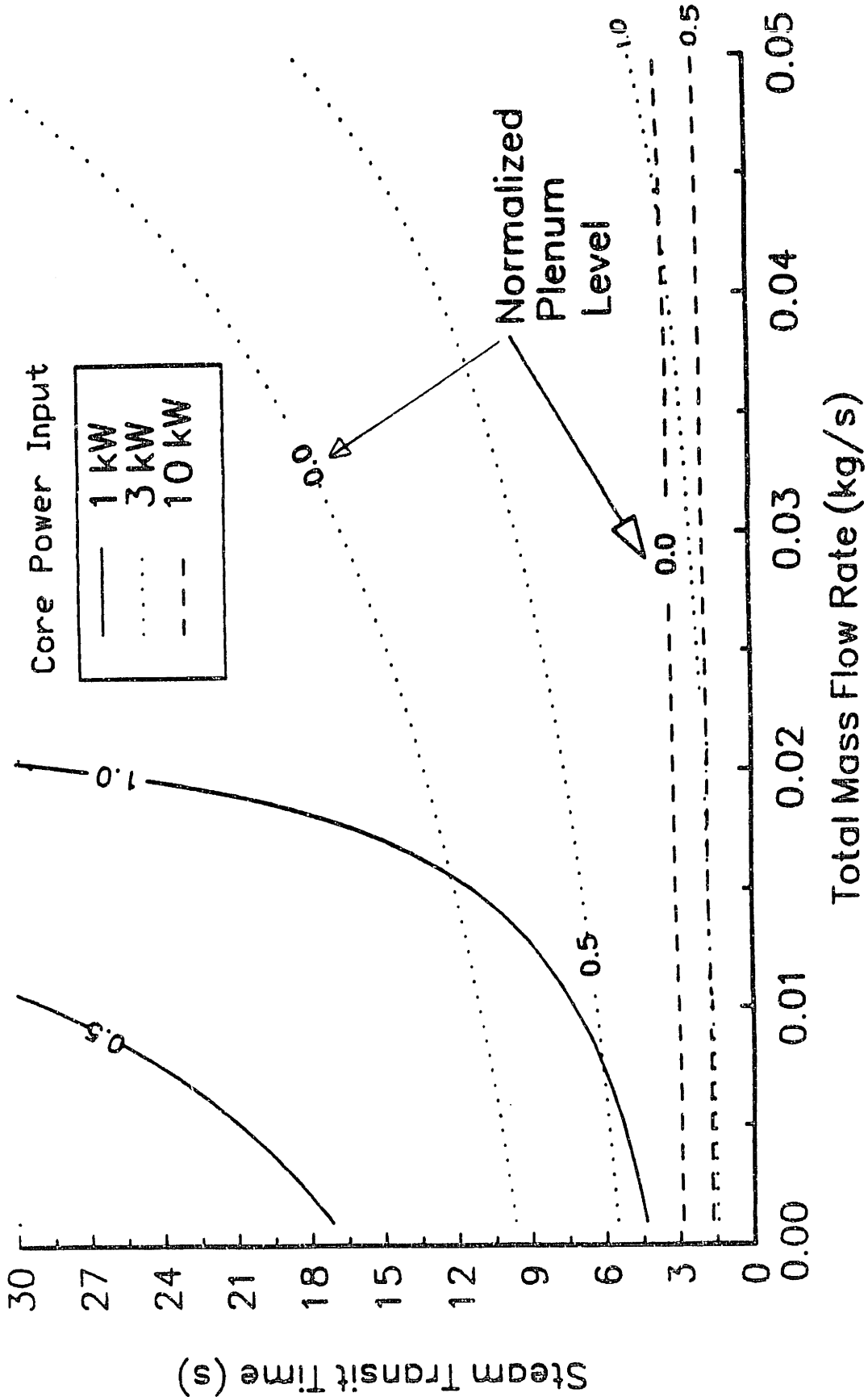


Figure 3-3 Steam Transit Time From Core Exit to N-16 Detector

The activity at the detector will be lower than the activity at the core, because of decay during transit:

$$A_{\text{det}} = A_{\text{core}} \cdot \exp\left(-\frac{\tau_i \cdot \ln(2)}{T_{1/2}}\right) \cdot f \quad (3-34)$$

where  $\tau_i$  = the transit time between the core and the detector, and

$f$  = the fraction of N-16 which remains in the water.

Since the two-phase mixture exiting the core is separated into steam and water, the observed activity at the detector must be corrected for the density change, and the functional relationship for the N-16 activity observed at the steam line is

$$A_{\text{det,stm}} = K'_{\text{stm}} \cdot P \cdot \bar{\rho}_{\text{tot}} \cdot (1-f) \cdot \left(\frac{\rho_{\text{stm}}}{\rho_{\text{tot}}}\right) \left[1 - \exp\left(-\frac{\tau \cdot \ln(2)}{T_{1/2}}\right)\right] \cdot \exp\left(-\frac{\tau_{\text{stm}} \cdot \ln(2)}{T_{1/2}}\right) \quad (3-35)$$

or

$$A_{\text{det,stm}} = K_{\text{stm}} \cdot P \cdot (1-f) \cdot \left[1 - \exp\left(-\frac{\tau \cdot \ln(2)}{T_{1/2}}\right)\right] \cdot \exp\left(-\frac{\tau_{\text{stm}} \cdot \ln(2)}{T_{1/2}}\right) \quad (3-36)$$

where  $K_{\text{stm}}$  is an experimentally determined constant which depends upon effective volume, the geometry factor, and the intrinsic detector efficiency.

Similarly, the functional expression for the N-16 activity observed at the water line is

$$A_{\text{det,wat}} = K_{\text{wat}} \cdot P \cdot f \cdot \left[1 - \exp\left(-\frac{\tau \cdot \ln(2)}{T_{1/2}}\right)\right] \cdot \exp\left(-\frac{\tau_{\text{wat}} \cdot \ln(2)}{T_{1/2}}\right) \quad (3-37)$$

where  $K_{\text{wat}}$  is a constant which must be determined during a calibration run.

## **SAMPLE COOLING BLOCK AND PEROXIDE MEASUREMENT SYSTEM**

The peroxide sampling system consists of a 7 inch long, 0.040 inch ID hole through an aluminum block, and approximately 20 feet of 0.010 inch ID PEEK tubing. For a typical sample flow rate of 5 cm<sup>3</sup>/min., the transit time is calculated to be 8.8 seconds. This system is described in detail by Mason (M-1).

### **MODES OF OPERATION**

The BCCL is run in one of three modes: shutdown mode, standby mode, or operating mode. These modes are described in this section. The documents addressing operation of the BCCL are listed in Table 3-1, and may be referred to for greater detail. Some of the documents listed address both the BCCL and the PCCL.

Table 3-1: Procedures for BCCL Operation

Maintenance of Schematic Diagrams	PCCL-1
General Safety Requirements	PCCL-2
Loop In-Core Installation	PCCL-3
Loop Removal From In-Core	PCCL-4
Hydrogen Inventory	PCCL-5
Rigging Checklist	PCCL-C1
Cask Cleanliness Checklist	PCCL-C2
Hydrogen Checklist	PCCL-C3
BCCL Preoperational Test Proced.	SR#-0-89-32
BCCL Startup Procedure	SR#-0-89-32
BCCL Startup to Standby Procedure	SR#-0-90-20
BCCL Operating Procedure	SR#-0-89-32
BCCL Abnormal Operating Proced.	SR#-0-89-14
BCCL Shutdown Procedure	SR#-0-89-32

CCL files are located in the project scientist's office, NW13-260, MIT.

SR files are located in the MITR Operations office, NW12-210, MIT.

Note: Installation, removal and some other operations were identical for the PCCL and the BCCL; the BCCL was installed, removed, etc. as per the appropriate PCCL procedure.

### Shutdown Mode

The BCCL is put in shutdown mode when the reactor is not operating. The main coolant pump is shut off, and the loop is depressurized to 5 psig, the pressure in the out-of-pile hotwell tanks. If the reactor is operating at greater than 100 kW, the BCCL must be put in standby mode.

### Standby Mode

When the reactor is at full power, but the BCCL is not being used to run experiments, it is necessary to remove approximately 7 kW of heat produced by gamma heating of the in-core lead bath. To accomplish this, a flow rate of 3 lpm is pumped through the loop at reduced pressure (300 psi) by the main coolant pump. The higher flow rate allows the system to run at lower temperatures, and the lower pressure reduces the stress on the pump. A pressure of 300 psi corresponds to saturation at 400°F, which is well above the typical standby core outlet temperature of 250°F.

## Operating Mode

The operating mode applies when experiments are being run on the BCCL. The pressure at the pump outlet is approximately 1250 psi; the pressure at the inlet to the loop is approximately 1050 psi; the pressure in the in-core section is 1000 psi; and the pressure at the return from the loop (downstream of the heat exchangers) is approximately 950 psi. The temperature of the fluid at the core inlet is 277°C, and the fluid at the core outlet is saturated at 285°C. For typical experimental conditions (flow rate of 1.8 lpm, quality of 15%), the electric feedwater heater is run at approximately 5.5 kW and the electric core heater is run at 7 kW.

## **DYNAMIC STABILITY OF THE THERMAL-HYDRAULIC SYSTEM**

During operation of the BCCL, it was found that the level in the outlet plenum is highly sensitive to small changes in the thermal-hydraulic configuration of the system, such as heater power and valve settings. Even a small change in heater power is sufficient to cause the level to rise or fall. An increase in the core heater power causes more steam to be generated, and hence the water level in the outlet plenum to fall; a decrease in the core heater power causes less steam to be generated, and hence the water level in the outlet plenum to rise. This behavior allows the level to be controlled on core heater power alone. However, the system as presently configured and operated tends to be unstable under certain operating conditions.

Problems arise when perturbations larger than a minor adjustment to the core heater power occur, such as drawing a sample from a sample tap or from the peroxide cooling device. After exiting the core, all fluid

normally passes through the regenerative heat exchanger, in which most of the heat from the return flow stream is imparted to the inlet flow stream. The removal of a sample from the return flow stream thus causes the loss of thermal energy to the inlet flow stream, due to the thermal coupling of the two streams by the regenerative heat exchanger. The electric feedwater heater (which is under automatic control on its fluid outlet temperature) should be able to compensate for this small change. Apparently, however, it is operating with such a large internal temperature gradient that the small change in the temperature of the water entering it is not enough to affect the heat flow which it imparts to the water. Thus, the small change in inlet temperature is not damped by the heater, and the thermal perturbation continues on through the system to alter the water level in the outlet plenum. A positive feedback effect is thus encountered with each disturbance. Since the electric feedwater heater slowly adjusts to the lower temperature of its outlet stream (by increasing power), the oscillation of the system increases. The system is unstable with respect to even small perturbations.

It is believed that adding a "thermal mass" to the system would greatly decrease its sensitivity to small disturbances. Such a mass would be similar in design to the electric feedwater heater, and would consist of a solid lead bath surrounding the tube through which the coolant water flows. Its function would be to absorb heat when the temperature of the feedwater rises, and to give up heat when the temperature of the feedwater falls. It would be placed in the flow stream between the regenerative heat exchanger and the feedwater heater. While the system would still suffer from the positive feedback introduced by the regenerative heat exchanger, this proposed thermal mass should lengthen the time constant enough so



that perturbations can be damped out by the automatically controlled feedwater heater. This proposed thermal mass is described in Appendix A.

Although the system is unstable as currently configured, operation is still possible. Care must be taken to minimize disturbances, and a skilled operator must continually adjust the core heater power. Automatic level control is desirable, however, and would reduce the number of personnel required to operate the BCCL. It is believed that the thermal mass described above would make automatic level control possible.

## REACTIVITY TESTS

Reactivity tests were conducted to ensure that the BCCL experiment does not violate the technical specifications of the MIT Reactor. To measure the maximum possible reactivity insertion due to a flooding of the BCCL thimble, both the in-core Zircaloy section and the space between the lead bath can and the aluminum thimble were flooded. The volume of the Zircaloy tube is 43 cm<sup>3</sup>; the volume of the space between the can and the thimble is approximately 232 cm<sup>3</sup>. The reactivity insertions due to flooding were found to be 0.0425 %  $\Delta k/k$  (+54 mbeta) for the Zircaloy section and 0.1425 %  $\Delta k/k$  (+181 mbeta) for the can/thimble gap (K-2). These insertions are below the maxima specified by the technical specifications of 0.2 %  $\Delta k/k$  (+254 mbeta) for movable experiments and 0.5 %  $\Delta k/k$  (+635 mbeta) for non-secured experiments, and it was concluded that the BCCL will not violate the reactivity specifications of the reactor. It should be noted that the flooded volumes and reactivity insertions quoted by Sanchez (S-1) are in error.

In addition, it was thought that the rapid reactivity changes caused by in-core boiling in the BCCL might affect control of the MIT Reactor. A boiling test was carried out at approximately 1000 psi and 57% quality, with the reactor at 10 kW. No reactivity noise was observed by the reactor operator, and it was concluded that boiling in the BCCL does not affect control of the reactor. No noise was observed during later experimental runs. Both the boiling test and the flooding reactivity test were carried out using the PCCL thimble, which has the same in-core configuration as the BCCL.

#### **SUMMARY: FUNCTIONAL CHARACTERISTICS**

The functional characteristics of the BCCL have been described in this section, particularly the thermal hydraulic characteristics of the system and the radiation fields, as well as the modes of operation. Formulae for the calculation of transit times have been developed which will be used in the following sections for analyzing the results. The problem of dynamic instability has been outlined, and a possible amelioration has been proposed.

## 4. IN-PILE TESTS AND RESULTS

### INTRODUCTION

In this chapter the procedures for running the in-pile tests are described, and the results of these tests are presented. Three sets of tests were run, each set using a different cover gas in the out-of-pile hotwell tank. Principal characteristics of each run are summarized in Table 4-1.

Table 4-1: Principle Characteristics of BCCL Runs

Run 1: NWC	Helium cover gas in hotwell tank
Run 2: HWC	Hydrogen cover gas in hotwell tank (18.4 ppm in coolant)
Run 3: NWC w/ KOH injection	Helium cover gas in hotwell tank, with $1.8 \times 10^{-4}$ M KOH in coolant

Common to all runs: 1.8 kg/min = mass flow rate;  
1000 psi at exit of core section;  
285°C = core exit temperature (saturated at 1000  
psi);  
15% quality at core exit.

### OPERATION OF THE BCCL

The points in the BCCL flow circuit at which information is gathered (e.g., thermocouples, electrodes, sample points, etc.) are shown in figure 4-1. This drawing may be referred to during the following discussion.

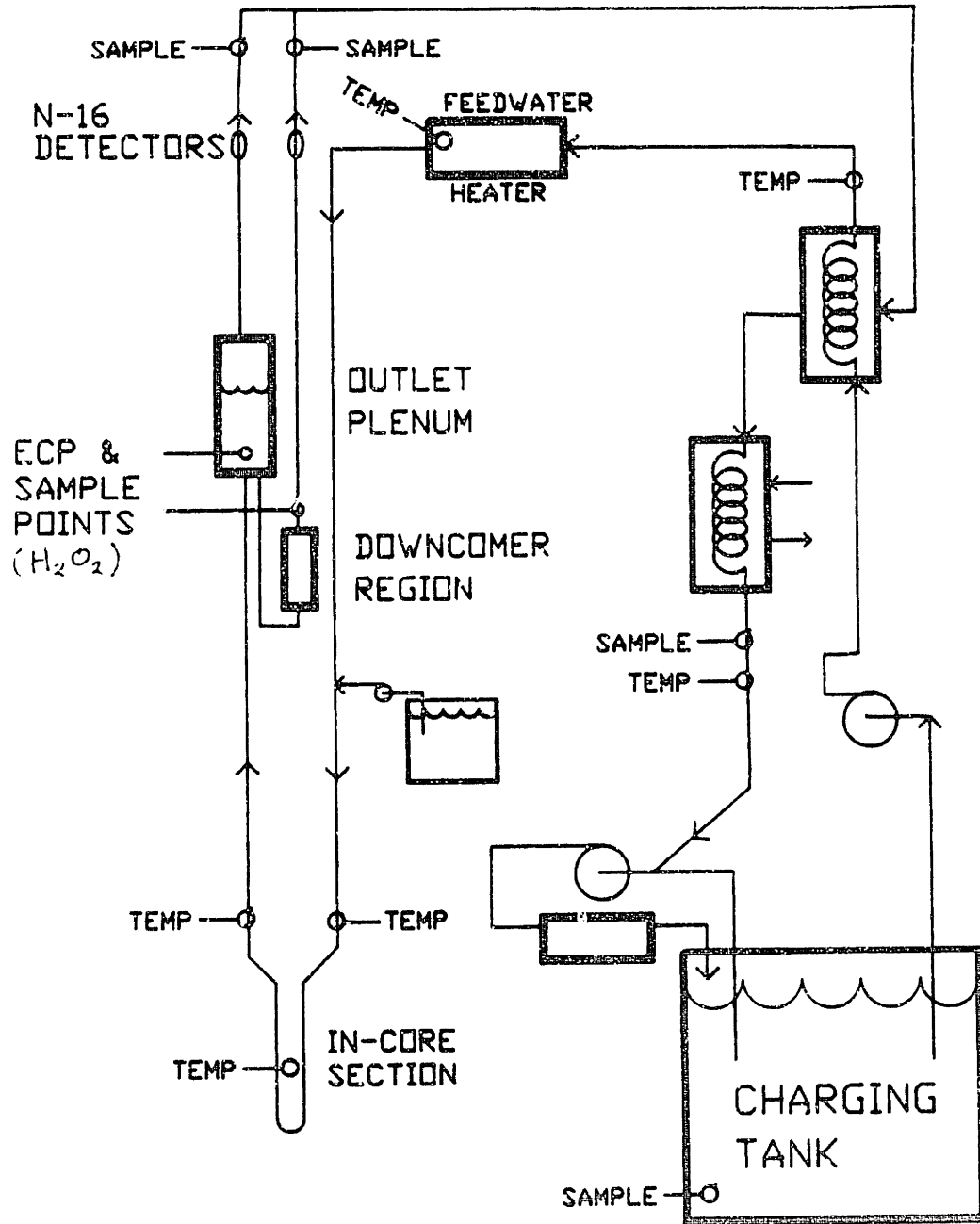


Figure 4-1 Data Collection Points on BCCL

## Thermal-Hydraulic Operation

The most difficult aspect of controlling the thermal-hydraulic operation of the BCCL is the initial transition from a single-phase (all water) to a two-phase (steam in the outlet plenum) condition. The following procedure is employed to accomplish this.

To draw a steam bubble in the outlet plenum, the main coolant pump and the electric feedwater heater are turned on. Refer to figure 1-1 for all components mentioned. The valve on the outlet of the steam line is opened approximately one turn, and the valve on the outlet of the water line is opened all the way. These valve settings remain unchanged throughout the run.

When the core inlet temperature has reached  $277^{\circ}\text{C}$ , the core heater is turned up slowly, allowing the automatic controller on the feedwater heater to turn down (most of the heat added in the core is returned to the inlet flow stream immediately upstream of the feedwater heater via the regenerative heat exchanger). A large amount of heat is stored in the feedwater heater bath, so the core heater power must be increased over a period of approximately 20 minutes. When the coolant exiting the core reaches saturation (that is, the temperature reaches  $285^{\circ}\text{C}$ ), the core heater power must be increased very slowly, and when a steam bubble first appears in the outlet plenum (as indicated by a drop in the level) the core heater power must be decreased slightly to allow for overshoot of the temperature ramp. Once a steam bubble has been established in the outlet plenum, the water level can be raised or lowered by decreasing or increasing the core heater power. When samples are drawn from any of the

sample lines, the core or feedwater heater power must be increased slightly to counterbalance the loss of enthalpy from the system.

### Chemistry Sampling System

When the BCCL is running, coolant samples may be taken using the coolant sampling system. Both the sample cooling block (which takes fluid streams from the downcomer and outlet plenum exit lines) or the out-of-pile sample taps (which take fluid streams from the steam and water lines immediately after they leave the core tank) may be used. With both sampling systems, the sample flowrate must be limited to approximately 5 cm<sup>3</sup>/min. (roughly one drop per second), to prevent the sampling system components from overheating. The temperature of the aluminum cooling block should not exceed approximately 170°F, to minimize peroxide decomposition; similarly, the sample streams exiting the sample taps should be kept as cool as possible (it was also observed that if the temperature of the cooling block exceeds 170°F, the thimble humidity increases shortly thereafter, then slowly decreases; apparently, higher temperatures caused a very small leak to open, which subsequently closed completely. This leak should be repaired before the loop is recommissioned). For hydrogen peroxide and other measurements, a 25 cm<sup>3</sup> sample is required.

Characterization tests of the hydrogen peroxide sampling system (M-1) determined that approximately 40% of the hydrogen peroxide in the coolant decomposes as a sample of the coolant passes through the sampling system. To correct for this, the measured values (for hot samples) of hydrogen peroxide concentration have been multiplied by 1.7 to arrive at the correct concentration. As noted in Section 5, a hot calibration run

(without radiation), with peroxide injection, should be performed to measure the actual fraction of hydrogen peroxide which decomposes in the sampling system.

### N-16 Detector Operation

To count N-16 activity in the steam and water exit lines, a one-minute count cycle was used. One minute is long enough to give good counting statistics, yet is short enough so that the conditions of the BCCL do not change during the count. The NaI(Tl) scintillation crystal is supplied with 800 V from the Canberra MCA. A single crystal was used, and was shifted back and forth between the two positions; thus, the steam line and water line results are directly comparable (without a calibration cross-check).

The expected activity at the detector is calculated as follows. For a mass flow rate of 0.028 kg/s, a core transit time of 0.7 sec., and a quality of 10%, the expected activity at the detector on the steam line is given as (Q-2) 170000 dps/cm<sup>3</sup>. The branching ratio for N-16 for 6.13 MeV is 55%. The efficiency of a 2-inch NaI(Tl) scintillator for a 6 MeV gamma ray point source at a distance of 3 inches is (K-1) 0.013. The volume of water seen by the detector is 1.45 cm<sup>3</sup>, so the expected count rate is (170000)x(0.55)x(0.013)x(1.45)x(60sec/min) = 106,000 counts/min. Actual one-minute counts on the water line were close to this value. The estimate is highly sensitive to efficiencies, discriminator settings, and geometry; in addition, the actual source configuration is a cylinder, not a point.

## Ion Chromatograph

The on-line ion chromatograph used was a GE-modified HPLC unit with a Dionex suppressor and a Waters anion column (a more sophisticated Waters unit capable of detecting anions, cations, and transition metals was available for use with grab samples, but was not used). The IC was capable of detecting F<sup>-</sup>, Cl<sup>-</sup>, Br<sup>-</sup>, NO<sub>3</sub><sup>-</sup>, NO<sub>2</sub><sup>2-</sup>, and SO<sub>4</sub><sup>2-</sup> at concentrations down to 5 ppb. The ion chromatograph required approximately 25 cm<sup>3</sup> samples for analysis; samples of the size taken for hydrogen peroxide analysis were found to be ample. Alternatively, the ion chromatograph suction tube may be connected directly to the return line from the loop, or to the hotwell tank. No samples were found to have the ions tested for, so contamination was apparently not a problem.

## **RUN 1: HELIUM COVER GAS IN HOTWELL TANK**

The initial reference run was made with a helium cover gas in the hotwell tank. The tank overpressure was approximately 5 psig, and had been maintained for several days before the run started. This cover gas was continuously bubbled through the water in the tank and circulated through a gas recombiner/catalyst bed. A helium purge flowrate of approximately 5 cm<sup>3</sup>/min. was bled through the tank.

## N-16 Measurements

The purpose of making N-16 measurements during the reference (helium) run was to verify the functioning of the detector and to produce



standard "benchmark" counts for later HWC and sample injection runs, during which it was anticipated that the fraction of N-16 in the steam would change. Counts with the original steam line setup were found to be lower than desirable, however, and after the NWC and HWC runs were completed, the steam plenum (which is seen by the detector) was enlarged.

A large number of counts of N-16 were made during the course of the experiment; an attempt will be made to condense the results into a compact, usable form, with a minimal loss of information. Actual experimental data from in-pile runs may be found in Appendix C.

With the loop operating at standard conditions ( $x = 15\%$ ,  $p_{core} = 1000$  psi,  $\dot{m} = 1.8$  kg/min), and the steam line (on the N-16 detector) valved out, the one-minute count at the steam line detector was  $3400 \pm 600$ . This is a reasonable approximation of the background at the detector, including crosstalk from the nearby water line. This average background count comprises 5 individual one-minute counts. The background at the water line is similar. The variation in the counts is larger than would be expected from statistical considerations; it is possibly due to minor thermal-hydraulic fluctuations in the loop.

To evaluate the count rates, eq. 3-36 is applied. Data from 12 counts are used. The average count was  $6906 \pm 1200$ , so when corrected for the background,  $A_{det,stm} = 3506 \pm 1342$ . The normalized reactor power was  $P = 4.2/5.0 = 0.84$ . If the fraction of N-16 normally in the steam is equal to the quality, then  $f = 0.85$ . The half-life of N-16 is  $T_{1/2} = 7.13$  sec. The outlet plenum level was 0.76, so from figures 3-1 and 3-3, the core transit time was 0.6 sec. and the steam line transit time was 4.5 sec. Substituting these values into eq. 3-36 gives the counting constant  $K_{stm} = 760600 \pm 291100$ . This constant should be valid for the steam line detector for all

conditions except a change in the operating temperature or pressure, a change in the dimensions of the steam plenum itself, or a change in the discriminator setting on the MCA.

It should be noted that the "normal" fraction of N-16 which goes into the steam is not necessarily equal to the quality (i.e., the steam mass fraction). The partition function of N-16 between the steam and water is strongly dependent on water chemistry, system geometry, and possibly reactor power (B-4); for "clean" water, values in the literature range from 0.01 (T-2, B-4) to near 1.0 (B-4). This can be easily determined with the BCCL, by taking a count at the water line with the coolant slightly subcooled (single phase) and the steam line valve shut off, and comparing it to a count at the water line with the system at standard two-phase conditions. This calibration was not accomplished during the present run, however, and should be performed when the loop is recommissioned.

The above calculation, when compared with the calculation in the following section, supports a "normal" partition ratio [(N-16 activity per g steam)/(N-16 activity per g water)] near 1. This is reflected in a decrease in the activity in the water (under HWC) which is offset by an equal increase in the activity in the steam (under HWC), relative to the activities under NWC.

Similarly, five one-minute counts on the water line averaged (corrected for background) 110000 +/- 3100. From eq. 3-37, the constant for the water line detector is  $K_{\text{wat}} = 12.8 \times 10^6 \pm 0.36 \times 10^6$ .

The ratio of counts in the steam line to counts in the water line is  $3506/110000 = 0.032$ .

## Hydrogen Peroxide Measurements

The hydrogen peroxide levels increased during the course of the run, because hydrogen peroxide produced by radiolysis did not decompose entirely before the coolant returned to the charging tank, and it was not removed by the ion exchange cartridges. During the early stages of the run, the concentration was found to be approximately 310 ppb (corrected from 180 ppb) at the downcomer and outlet plena; by the end of the run, the concentration had increased to approximately 360 ppb (corrected from 210 ppb), and the concentration in the charging tank (i.e., the inlet to the loop) was approximately 80 ppb. Samples from the sample taps (on the steam and water outlet lines) were not analyzed during this run.

Samples were also taken during NWC runs when the system was single-phase, and during cooldown and warmup of the loop, with the reactor at 4.2 MW. Very high concentrations of hydrogen peroxide were present under single-phase conditions, typically about 7 ppm (corrected from 5 ppm). These levels warrant investigation in future runs.

## Ion Chromatograph Measurements

Total ionic species in the loop effluent (and in the charging tank) were found to be less than 5 ppb, the lower detection limit of the IC. Gamma spectrum analyses were also run on the loop effluent and on the water in the hotwell tank; no gamma activity having a half-life greater than 10 minutes was detected in the samples.

## Dissolved Hydrogen and Oxygen Measurements

The oxygen concentration in the loop effluent (after the heat exchangers) was measured as 600 ppb, and the concentration in the charging tank water was measured as 400 ppb. Hydrogen levels in the charging tank were measured as 1.7 ppb. It is believed that the detectors were miscalibrated or were not functioning properly, and that these values are not correct.

## Conductivity Measurements

The resistivity of the water going into the loop remained fairly constant at 17.5 M $\Omega$ -cm. The resistivity of the effluent returning from the loop remained near 5.3 M $\Omega$ -cm. These and other resistivity measurements have been corrected to 25°C.

## Potential Measurements

The potential measurements taken during this run are not believed to be valid, but are reproduced in Appendix C.

## **RUN 2: HYDROGEN COVER GAS IN HOTWELL TANK**

After the helium test was completed, a HWC (Hydrogen Water Chemistry) test was run. The helium cover gas in the hotwell tank was replaced by hydrogen, which was bled into the tank at a flow rate of approximately 7 cm<sup>3</sup>/min. This purge flow was maintained overnight

before the run started, and was maintained throughout the run. The tank overpressure was approximately 5 psig, and the cover gas was continuously circulated through a catalytic gas recombiner and bubbled through the liquid in the hotwell tank.

### N-16 Measurements

With the loop operating at standard conditions ( $x=15\%$ ,  $p_{\text{core}} = 1000$  psi,  $\dot{m} = 1.8$  kg/min) under HWC, the average of 11 one-minute counts on the steam line (corrected for background) was 11909 +/- 3300. Using the value of  $K_{\text{stm}}$  found during the calibration (NWC) run, and with a steam line transit time corresponding to a normalized plenum level of 0.4, the fraction of N-16 in the water is given by eq. 3-36 as  $f = 0.4$ . Thus, the fraction of N-16 which goes into the steam has risen four-fold, from 0.15 (under NWC) to 0.6 (under HWC).

Similarly, for five counts on the water line under HWC the average count (corrected for background) was 82720 +/- 6040. The normalized plenum level was at 0.4, so eq. 3-37 gives as the fraction of N-16 remaining in the water as 0.447. This is in good agreement with the fraction calculated from steam line values, which confirms the validity of the transit time analysis in Chapter 3 of this report. In addition, the expected increase of N-16 in the steam phase under HWC was observed.

The ratio of counts in the steam line to counts in the water line is  $11909/83720 = 0.142$ . Thus, HWC increased the steam line activity by a factor of 4.4, which is in good agreement with the BWR plant data summarized in figure 4-2 (1-2). The point representing the BCCL under

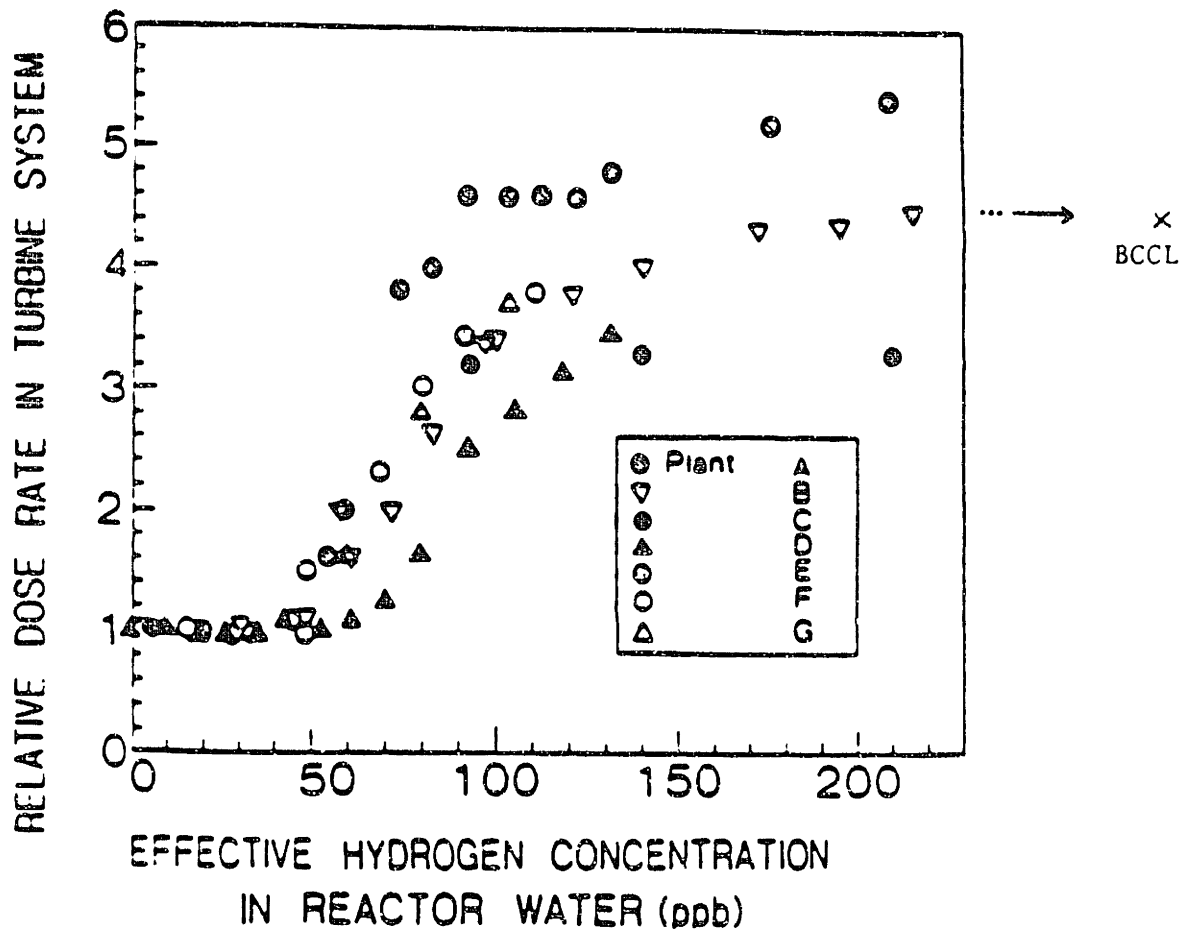


Figure 4-2 Normalized N-16 Dose Rate at Turbine as a Function of Hydrogen in Coolant (I-2)

HWC is shown at the right of the plot (the hydrogen concentration for the BCCL is 18.4 ppm).

### Hydrogen Peroxide Measurements

Hydrogen peroxide concentrations were lower under the HWC runs by roughly a factor of three; concentrations at the outlet and downcomer plena were approximately 110 ppb (corrected from 65 ppb) and 80 ppb (corrected from 45 ppb), respectively. The concentration in the hotwell tank was measured at 30 ppb. As mentioned above, the hydrogen peroxide did not completely decompose before the effluent returned to the hotwell tank, and the concentration in the hotwell tank increased as the run progressed. The HWC run followed the NWC run by one day; it is possible that some of the peroxide in the system remained from the earlier run. With the system not boiling, the concentration of hydrogen peroxide at the outlet and downcomer plena was approximately 190 ppb (corrected from 110 ppb). Thus, hydrogen peroxide concentration was again higher under single-phase conditions -- but the increase is far less than that under NWC.

### Ion Chromatograph Measurements

Total ionic species in the loop effluent (and in the charging tank) were found to be less than 5 ppb, the lower detection limit of the IC. Gamma spectrum analysis did not detect any activity.

## Dissolved Hydrogen and Oxygen Measurements

Dissolved oxygen in the charging tank was measured as 6 ppb, although this value may not be entirely reliable. The hydrogen meter was not functioning during the HWC run, but the calculated concentration of hydrogen gas dissolved in the coolant (at a pressure of 20 psia) is 18.4 ppm.

## Conductivity Measurements

The resistivity of the water going into the loop remained constant at 17.1 M $\Omega$ -cm. The effluent returning from the loop had a resistivity of 7.2 M $\Omega$ -cm, somewhat higher than that under NWC.

### **RUN 3: HELIUM COVER GAS IN HOTWELL TANK, WITH KOH INJECTION**

The purpose of this run was to investigate whether low concentrations of KOH in the coolant had an effect on the partition of N-16 between the steam and the water in the outlet plenum. The injected solution had a concentration of 0.02 M and a pH of 12. The injection flow rate was 980 cm<sup>3</sup>/hr, so for a coolant flow rate of 1.8 kg/min., the concentration of KOH in the coolant was  $1.81 \times 10^{-4}$  M (density at 25°C). The pH of the coolant (at 25°C) was near 10. The KOH solution was injected into the flow stream immediately before the coolant entered the core section. The carboy holding the KOH solution was capped, but did not have an inert helium cover gas; hence, the injected fluid would have had dissolved air in it.



When the loop had been operating in a stable fashion for several hours, but before the KOH injection started, the float in the level detector on the outlet plenum failed. The loop was kept at steady state during the injection run. The effect of the absence of level indication is noted below in the section on N-16 measurements.

After the HWC run was completed, the hotwell tank was purged with helium, which was bled into the tank at a flow rate of approximately 7 cm<sup>3</sup>/min. This purge flow, unfortunately, stopped for an unknown period of time during the night before the run (due to a malfunctioning backpressure regulator on the hotwell tank), but was restarted when the run commenced. Thus, it is possible that Run 3 was still under partial HWC. The pressure in the hotwell tank was approximately 5 psig, and the cover gas was continuously recirculated through a catalytic gas recombiner and bubbled through the liquid in the hotwell tank.

### N-16 Measurements

For approximately 20 minutes after KOH injection was initiated, the average of 9 one-minute counts on the steam line detector was (corrected for background) 7590 +/- 1500. Since the steam plenum size was increased by a factor of 6.64 before the injection run, the adjusted steam count was 1143 +/- 225. After this period, the average count went up to approximately 13000, probably due to water getting into the the steam line (no level indication was available). The average for 6 one-minute counts on the water line was (corrected for background) 113600 +/- 7300. Since the discriminator setting on the MCA was changed immediately before KOH injection commenced, use of eq. 3-36 to evaluate the carryover is not

possible, and a comparison of the activity ratios will be used instead. The ratio of the activity in the steam line to that in the water line was  $1143/113600 = 0.010$  (with KOH injection). For the NWC run, this ratio was  $3506/110000 = 0.032$ , and for the HWC run, this ratio was  $11909/83720 = 0.142$ . Thus, hydrogen addition increased the steam-to-water N-16 ratio by a factor of 4.4, and KOH injection decreased the ratio by a factor of 3, even though residual hydrogen was probably present during the KOH run. These ratios are not precise, as the plenum level during the KOH injection run was not known, and the plenum level was different during the NWC and HWC runs. The observed qualitative effect, however, is apparent: hydrogen increases N-16 in the steam line, and KOH decreases it.

This general trend, of higher coolant pH lowering the N-16 activity in the steam line, is confirmed by low-temperature, accelerator-irradiated experiments conducted by Hitachi. The results of these accelerator experiments are shown in figure 4-3 (T-2), and show the same qualitative result as found with the BCCL. It is possible, however, that the N-16 partition function is dependent on the coolant's redox potential (ECP) rather than pH; this is supported by the observation that the addition of hydrogen, which raises the redox potential but does not affect the pH, greatly increases N-16 carryover. The low-pH additives shown in figure 4-3 ( $\text{HNO}_3$ ,  $\text{H}_2\text{SO}_4$ ) are also highly oxidizing, and the high pH additives ( $\text{NH}_4\text{OH}$ ,  $\text{LiOH}$ ) are reducing. Low pH additives are usually oxidizing and high pH additives are usually reducing, but this is not always the case, and the proper dependence may be on redox potential. This dependence could be investigated further in future runs by injecting additives which are neutral in pH but are oxidizing or reducing. In addition, high and low pH

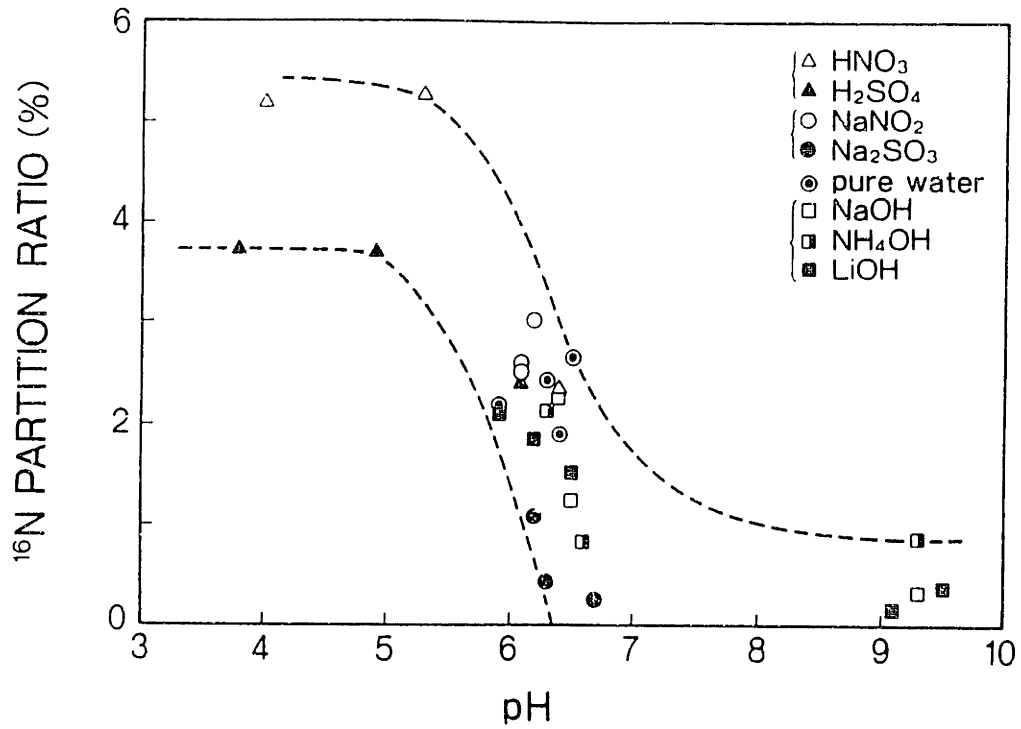


Figure 4-3 N-16 Gas-to-Liquid Partition Ratio as a Function of pH (T-2)

additives of a neutral redox potential would help resolve the question. In-line measurements using an ORP (Oxidation-Reduction Potential) electrode would also be useful.

### Hydrogen Peroxide Measurements

At standard conditions, before the KOH injection was initiated, the concentrations of hydrogen peroxide were found to be approximately 85 ppb (corrected from 50 ppb) in the outlet plenum and in the downcomer plenum. After KOH injection was initiated, the concentrations in the plena were found to be approximately 70 ppb (corrected from 40 ppb), and the concentrations in the water and steam outlet lines were 130 ppb (corrected from 75 ppb) and 100 ppb (corrected from 60 ppb), respectively. During cooldown (during KOH injection, when the loop was single-phase but still hot), the concentration of peroxide in the outlet plenum was 1360 ppb (corrected from 800 ppb). The hydrogen peroxide concentration in the hotwell tank was 10 ppb.

No interferences or false peroxide signals from KOH were detectable. The low concentrations of hydrogen peroxide prior to KOH injection may be due to residual hydrogen in the coolant, left over from the previous HWC run.

### Ion Chromatograph Measurements

Total anionic species in the loop effluent (and in the charging tank) were found to be less than 5 ppb, the lower detection limit of the IC. Tests were not made after the KOH injection was initiated, as the concentration

of KOH was far higher than the IC was capable of evaluating. Gamma spectrum analysis did not detect any activity with a half-life greater than 10 minutes except for K-42.

### Dissolved Hydrogen and Oxygen Measurements

The dissolved oxygen concentration in the loop effluent was measured to be between 600 and 700 ppb. The hydrogen meter was not functioning properly during this run. As before, these measurements may not be entirely valid.

### Conductivity Measurements

The resistivity of the water going into the loop remained constant at 17.7 M $\Omega$ -cm. The effluent returning from the loop had a resistivity of 5.3 M $\Omega$ -cm. This resistivity decreased to 0.025 M $\Omega$ -cm when KOH injection commenced. The calculated resistivity of a  $1.8 \times 10^{-4}$  M KOH solution (the calculated concentration of KOH in the coolant flowing through the core) is 0.022 M $\Omega$ -cm, which is in good agreement with the observed value.

### Carryover Test Results

Two methods were employed to estimate the carryover of water into the steam line in the BCCL: one using the ratio of conductivities of the steam condensate and the water, and the other using the ratio of the K-42 activities in the steam condensate and water. Steam and water grab samples were drawn from the sample taps, and were measured to have

conductivities of  $1.89 \times 10^{-6}$  S/cm and  $47.5 \times 10^{-6}$  S/cm, respectively. Since these were grab samples and hence air-saturated, the conductivity of air-saturated (but otherwise pure) water, approximately  $1 \times 10^{-6}$  S/cm, must be subtracted out. Assuming that all the (remaining) conductivity in the steam sample is due to entrained water (that is, that the steam itself carries no KOH), then the ratio of conductivities would approximate the carryover of water into the steam line. The carryover then would be  $(1.89 - 1)/(47.5 - 1) = 0.0190 = 1.9\%$  (by weight).

To estimate the carryover using K-42, the steam condensate and water samples were counted for gamma activity; the steam sample gave 17 cpm (+/- 58.5%), and the water sample gave 770 cpm (+/- 3.9%). Again, assuming that all the K-42 activity in the steam is due to water carryover, the carryover would be the ratio of the two counts, or  $17/770 = 0.022 = 2.2\%$  (by weight). The two methods were thus in good agreement.

As noted above, the N-16 activity in the steam line increased substantially 20 minutes after KOH injection commenced, probably due to water entering the steam line (no plenum level indication was available); hence, the high conductivity in the steam sample (which was taken after the count rate rose) is probably due to water entering the steam line directly, not by vapor-phase entrainment.

Carryover tests similar to the one described above should be run (without radiation) when the loop is recommissioned, and the level of the interface in the outlet plenum can once again be measured. The concentration of KOH in the steam under BCCL conditions should be approximately 0.3 ppb (C-3). If possible, the sample taps should be connected (through a cooling device) directly to the flow cell of the

conductivity meter. This would eliminate the background due to the high conductivity of air-saturated water.

A method of estimating the carryunder (of steam into the water line) using Ar-41 activity ratios is given in Appendix E. It was not successfully applied during these runs because the grab samples degassed during collection. Measurable Ar-41 levels were detected in both samples, however, so this method should work if on-line bomb samples are taken in future runs.

## COMPARISON OF TEST RESULTS WITH CODE SIMULATIONS

A radiolysis computer code modelling the aqueous environment of a BWR is described in the thesis by Simonsen ((S-5)), and was adapted by Mason ((M-1)) and Chun ((C-1)) to reflect the environment of the BCCL. A number of computer runs modelling the BCCL were made by Mason, which will be compared with data from the actual in-pile runs with the BCCL. It should be noted that a major impediment to accurate computer modelling is the lack of accurately-known g-values, or radiolysis production terms. In most cases, the high-temperature data which is available has been extrapolated from room-temperature measurements, and is quite inaccurate. This inaccuracy is reflected in the disparate results which are generated by using different standard reaction equation sets. A typical reaction equation set, the modified Burns and Marsh set, is shown in Table 4-2. The first and second columns of this equation set are the reactants, and the third, fourth, fifth and sixth columns are the reaction products. Water (H<sub>2</sub>O) is assumed to be present at unit concentration. The

Table 4-2 Modified Burns and Marsh Reaction Equation Set (M-1)

CHEMICAL REACTIONS, RATE CONSTANTS, AND ACTIVATION ENERGIES					
REACTIONS				RATE CONSTANT	ACTIVATION ENERGIES (KJ/MOL-K)
W 1	e-	>H	OH-	0.66D+03	0.13D+02
W 2	e-	H+	>H	0.24D+11	0.13D+02
W 3	e-	OH	>OH-	0.24D+11	0.13D+02
W 4	e-	H2O2	>OH	0.13D+11	0.13D+02
W 5	H	H	>H2	0.10D+11	0.13D+02
W 6	e-	HO2	>HO2-	0.20D+11	0.13D+02
W 7	e-	O2	>O2-	0.19D+11	0.13D+02
W 8	e-	e-	>OH-	0.28D+10	0.13D+02
W 9	OH	OH	>H2O2	0.45D+10	0.13D+02
W10	OH-	H	>e-	0.20D+08	0.19D+02
W11	e-	H	>H2	0.10D+13	0.13D+02
W12	e-	HO2-	>OH	0.14D+12	0.13D+02
W13	H	OH	>	0.20D+11	0.13D+02
W14	OH	H2	>H	0.34D+08	0.19D+02
W15	O	O	>O2	0.22D+11	0.13D+02
W16	H	O2	>HO2	0.19D+11	0.13D+02
W17	H	HO2	>H2O2	0.20D+11	0.13D+02
W18	H	O2-	>HO2-	0.20D+11	0.13D+02
W19	e-	O2-	>HO2-	0.53D+12	0.19D+02
W20	H	H2O2	>OH	0.90D+08	0.14D+02
W21	OH	H2O2	>HO2	0.27D+08	0.14D+02
W22	OH	HO2	>O2	0.12D+11	0.13D+02
W23	OH-	H2O2	>HO2-	0.50D+09	0.19D+02
W24	HO2-		>OH-	0.23D+08	0.19D+02
W25	H+	O2-	>HO2	0.50D+11	0.13D+02
W26	HO2		>H+	0.80D+06	0.13D+02
W27	HO2	O2-	>HO2-	0.15D+08	0.19D+02
W28	O2-	O2-	>H2O2	0.29D+11	0.19D+02
W29	HO2	HO2	>H2O2	0.27D+07	0.19D+02
W30	H+	OH-	>	0.15D+13	0.43D+02
W31			>H+	0.12D-01	0.34D+02
W32	OH	O2-	>O2	0.12D+11	0.13D+02
W33	H		>H2	0.33D+05	0.85D+02
W34	HO2	O	>O2	0.20D+11	0.13D+02
W35	OH	O	>H	0.10D+00	0.70D+02
W36	O		>OH	0.78D+05	0.41D+02
W37	OH	O	>HO2	0.20D+11	0.13D+02
W38	H2	O	>H	0.48D+04	0.35D+02
W39	H2O2	O	>HO2	0.13D+07	0.18D+02
W40	H	O	>OH	0.20D+11	0.13D+02
AB1	H2		>H2O	0.30D+02	-0.10D+01
AB1	H2O		>H2	0.10D+02	-0.10D+01
AB2	O2		>O2O	0.23D+02	-0.10D+01
AB2	O2O		>O2	0.12D+02	-0.10D+01
COR	H2O2		>O	0.53D-06	0.67D+02
CCL	H2O2		>O	0.53D-06	0.67D+02

+



seventh and eighth columns show the rate constants and the activation energies, respectively.

The results of Mason's code, BCCLMIT, are shown for two reference runs in figures 4-4 and 4-5, using different reaction equation sets. The runs both start with 200 ppb of hydrogen and oxygen in the coolant at the core inlet, yet give widely disparate concentrations of hydrogen peroxide at the core outlet. Mason's runs also show that exit composition is not a strong function of inlet composition; hence, we can apply his results here. While it is not possible at present to ascertain which reaction set is the most accurate, it is planned that future BCCL runs will resolve this issue.

The results of the code for NWC for the BCCL are shown in figure 4-6. The two measured values of hydrogen peroxide in the loop (at the outlet and downcomer plena) are shown as X's on the figure, and are close to the predicted results from the Burns and Marsh data. They are somewhat higher than the concentrations predicted by the standard reaction equation set, but not greatly so.

The results for HWC are shown in figure 4-7. As can be seen in the plot, the initial hydrogen and oxygen concentrations are 200 ppb; the concentration of hydrogen in the BCCL was much higher (18 ppm). The measured concentrations of hydrogen peroxide in the loop are shown as X's on the graph; they agree well with the results from the standard reaction equation set, but are much lower than those predicted from the Burns set. It is not possible to say from results currently available whether the measured concentration would be higher if the concentration of hydrogen in the feedwater was lower; future experiments with the BCCL should clarify this.

Chemical Species Concentration Profile from BCCLMIT  
Data From Table NEGGBH

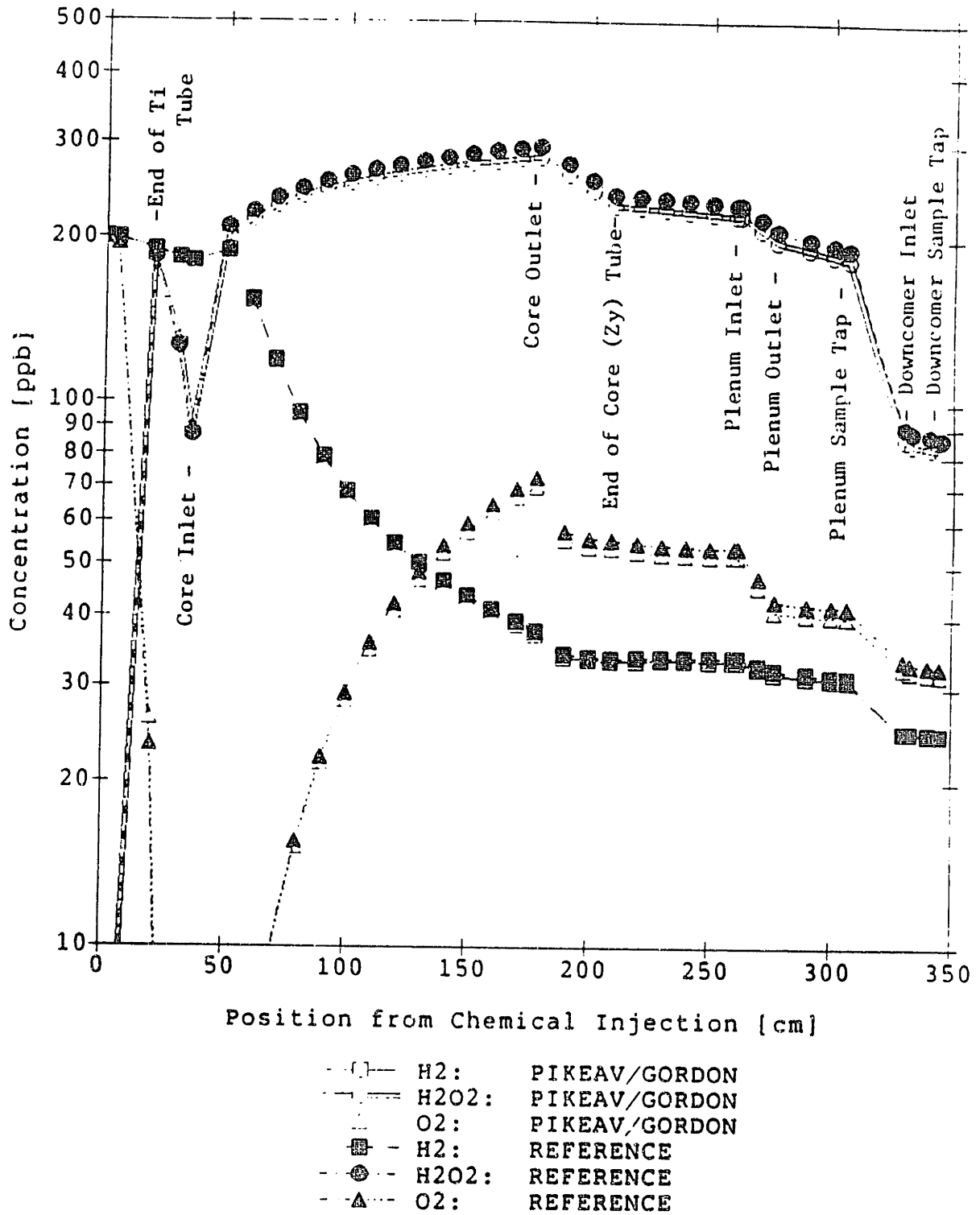


Figure 4-4 Comparison of Code Results for the BCCL, Using Different Reaction Equation Sets (M-1)

Chemical Species Concentration Profile from BCCLMIT  
Data From Table NEGGBH

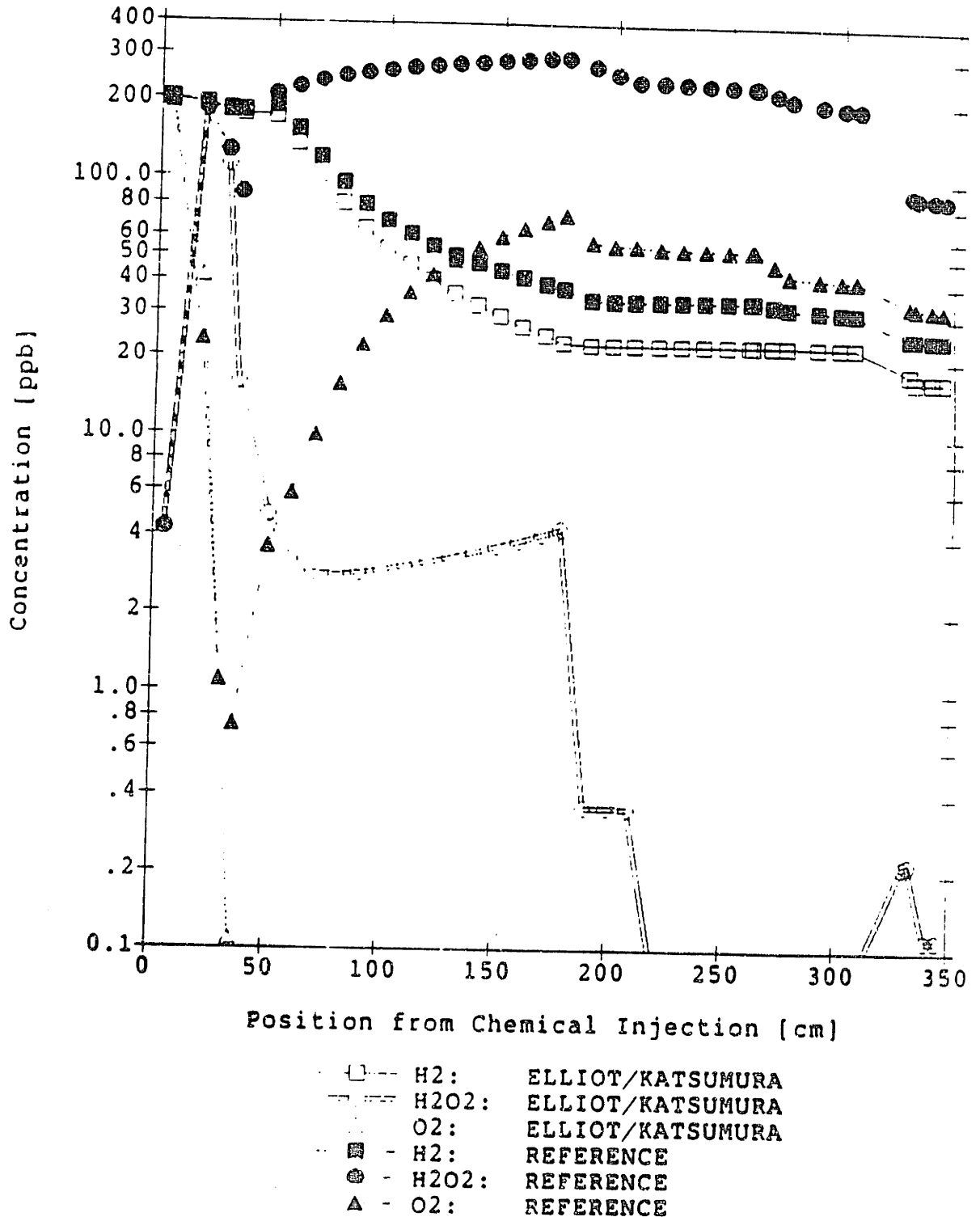


Figure 4-5 Second Comparison of Code Results for the BCCL, Using Different Reaction Equation Sets (M-1)

Chemical Species Concentration Profile from BCCLMIT  
Data From Table NELGB

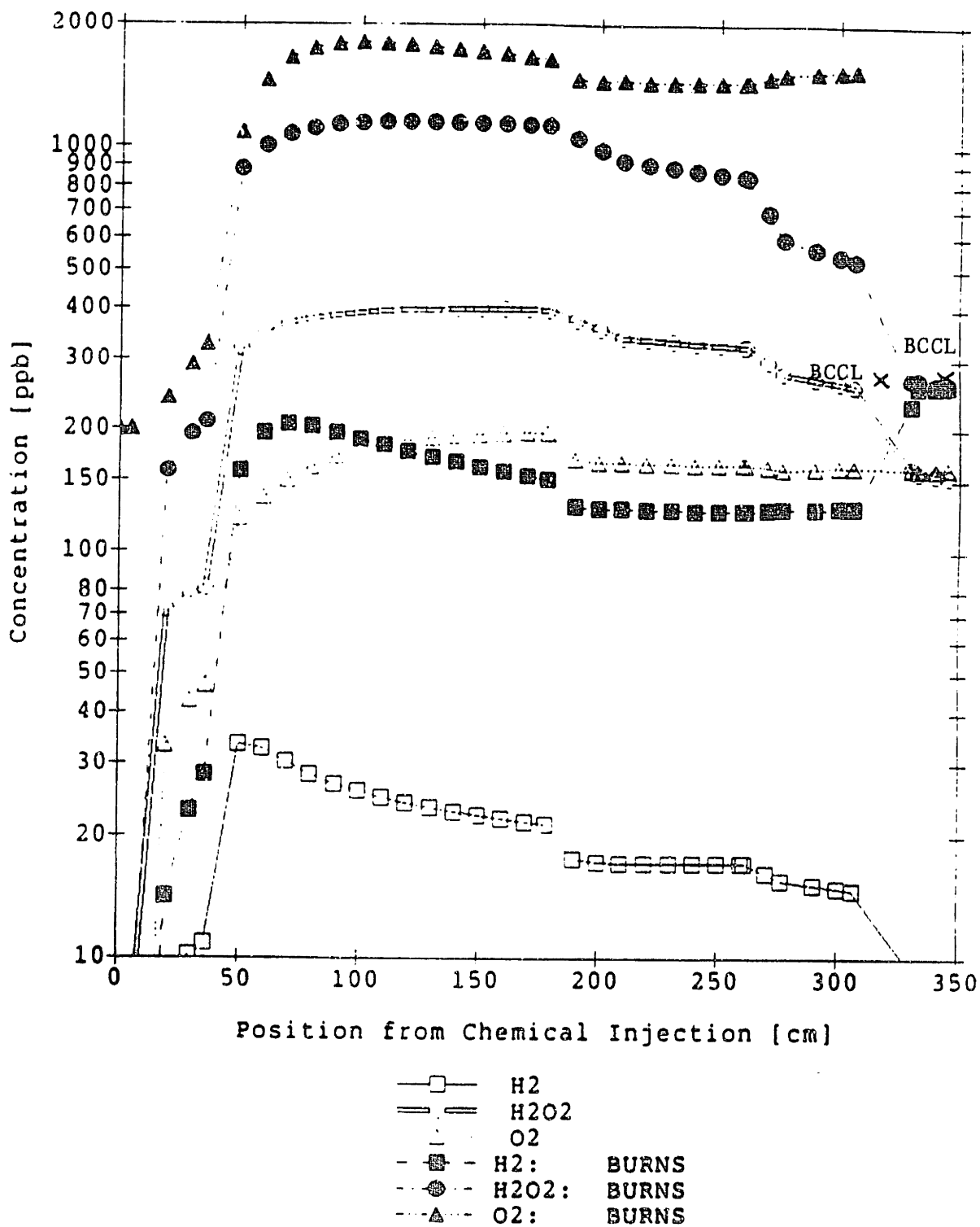


Figure 4-6 Comparison of BCCL Data and Computer Model Results (M-1) for NWC

Chemical Species Concentration Profile from BCCLMIT  
Data From Table NELGBH

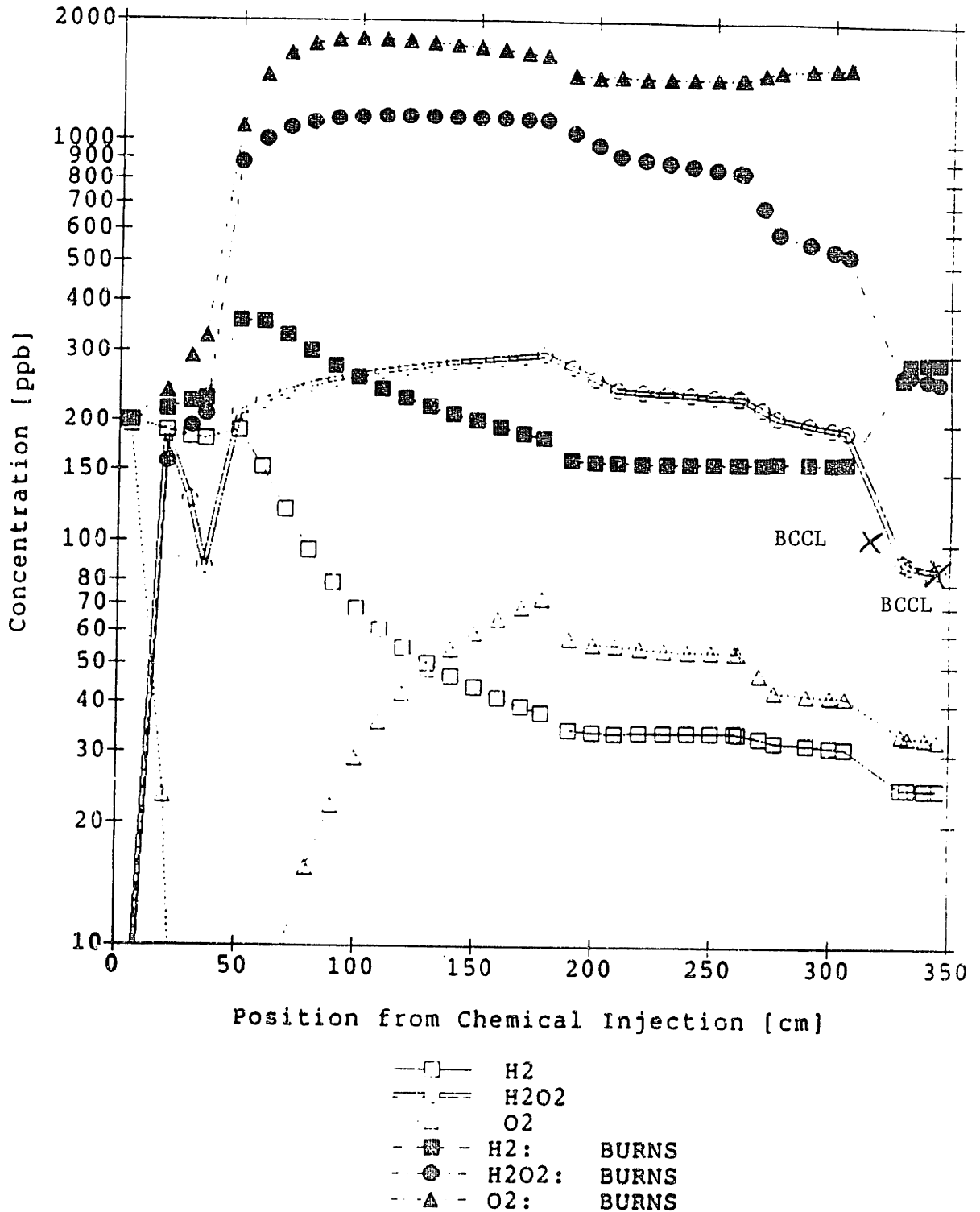


Figure 4-7 Comparison of BCCL Data and Computer Model Results (M-1) for HWC

One of the major uncertainties of BCCLMIT is the effect of surface decomposition on hydrogen peroxide concentration. The BCCL has a substantially higher surface-to-volume ratio than does a full-size BWR (although BCCL ex-core surfaces are titanium, rather than the stainless steel found in full-size BWR's). An investigation of this effect might be possible if the BCCL were run at lower temperatures (below the hydrogen peroxide decomposition temperature) but with a full radiation flux. The results from the BCCL could then be compared with the results from BCCLMIT (run at lower temperatures, for which it should be more accurate) and the effect of surface decomposition could thereby be clarified. In addition, the code should be run for single-phase conditions with NWC, to attempt to reproduce the extremely high concentrations of hydrogen peroxide which were measured under those conditions.

Well-coordinated runs with both the BCCL and BCCLMIT are necessary for these two tools to achieve their full, mutually-supporting predictive capacity.

## SUMMARY: IN-PILE TESTS AND RESULTS

Preliminary experiments with the BCCL were run with three different water chemistries, NWC (Normal Water Chemistry), "HWC" (Hydrogen Water Chemistry), and NWC with KOH injection. Hydrogen peroxide concentrations were measured at various points in the system, and N-16 counts on the steam and water lines were taken. The principal measured results are shown in Table 4-3.

As may be seen from the table, hydrogen in the feedwater decreased hydrogen peroxide concentrations and increased N-16 carryover into the

steam line; KOH decreased N-16 carryover. The concentration of hydrogen in the feedwater during the KOH injection run was not known, but is believed to have been non-zero. Impurity levels in the coolant were very low; ion chromatograph measurements gave levels of anions lower than 5 ppb. The resistivity of the loop effluent was greater than 5 MΩ-cm. Carryover (of water into the steam line) was estimated by two different methods (conductivity and K-42 ratios in steam and water samples) to be 2%, but this may be high. An unsuccessful attempt was made to measure carryunder (of steam into the water line) using Ar-42 activities.

The results of the in-pile runs were compared with calculated results from BCCMIT. Measured values correlated well with some of the calculated hydrogen peroxide concentrations, but more experimental benchmarking interaction is necessary for the code to reach its full predictive potential.

Table 4-3: Principal Results of In-Pile Runs

	NWC	HWC	NWC w/ KOH
H <sub>2</sub> O <sub>2</sub> in outlet plenum	310 ppb	110 ppb	70 ppb
H <sub>2</sub> O <sub>2</sub> in downcomer plenum	310 ppb	85 ppb	70 ppb
H <sub>2</sub> O <sub>2</sub> in outlet plenum with system single-phase	7000 ppb	190 ppb	1360 ppb
steam/water line N-16 ratio	0.032	0.142	0.010
KOH in feedwater	0	0	1.81x10 <sup>-4</sup> M
H <sub>2</sub> in feedwater	0	18.4 ppm	(low)

## 5. SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS FOR FUTURE WORK

### INTRODUCTION

In order to conduct BWR coolant radiation chemistry studies, an in-pile loop which is capable of closely simulating the aqueous environment of a BWR has been designed, built, and put into operation, and preliminary data has been collected. The goals of the first set of runs included general shakedown tests and system characterization studies; in addition, a preliminary investigation of the radiolytic production of hydrogen peroxide and a study of N-16 behavior were conducted, and preliminary ECP data were collected. The system characteristics, experimental results, plans for future work, and a number of possible improvements are outlined below.

### DESCRIPTION OF THE BWR COOLANT CHEMISTRY LOOP

A schematic of the in-pile portion of the BCCL is shown in figure 5-1, and the out-of-pile system is shown in figure 5-2. The out-of-pile system consists essentially of a (low-pressure, low-temperature) hotwell tank with associated gas and water cleanup systems and a cover gas control system; a high-pressure pump; and a trace element injection system. The BCCL is intended as a radiation chemistry experiment; hence, the core transit times and temperature fields closely match those of a BWR. The hot section is constructed entirely of titanium (except for fittings), and operates with water of a purity equal to that of the cleanest BWR's. The BCCL is capable



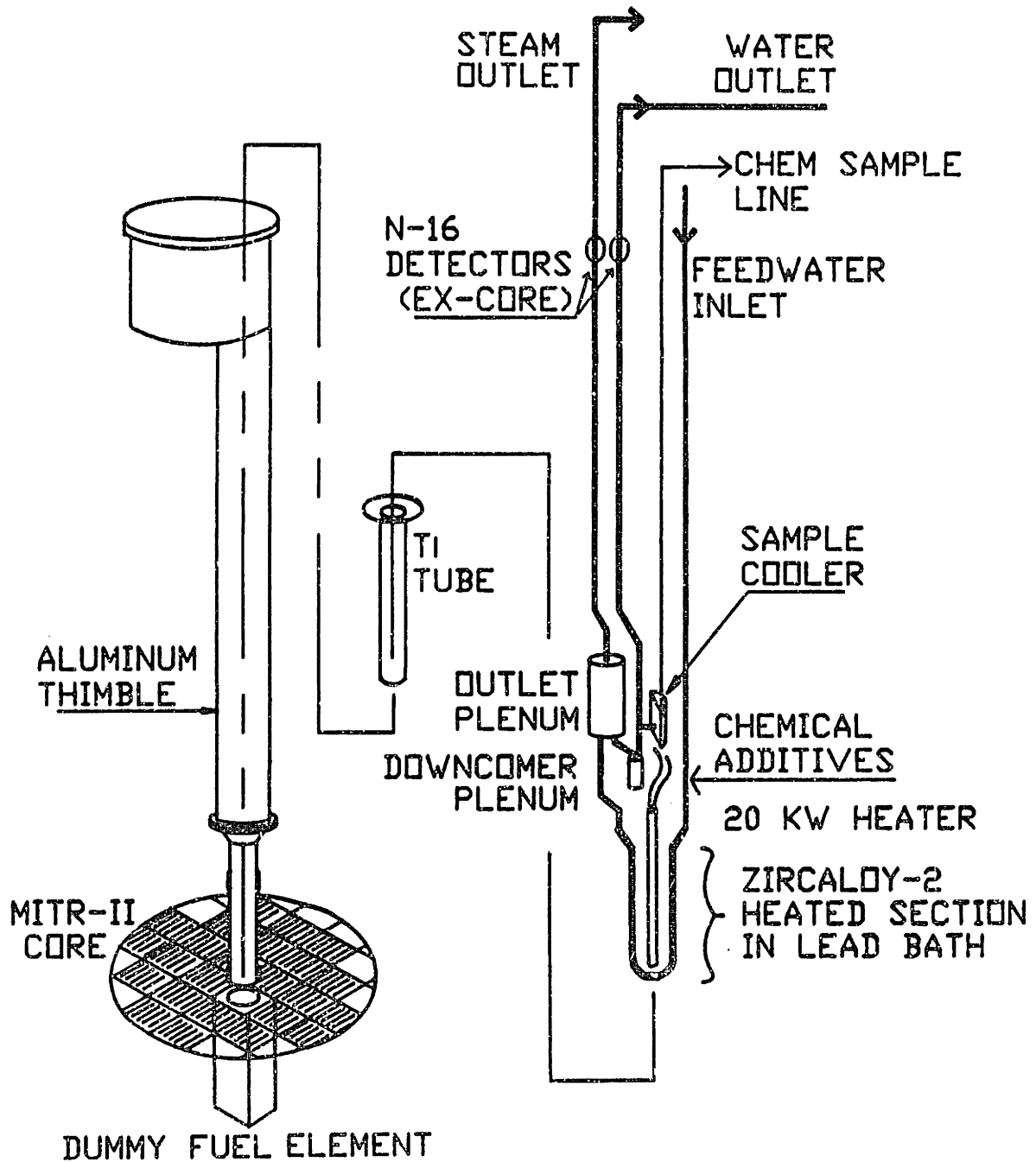


Figure 5-1 Schematic of In-Pile Components of BCCL

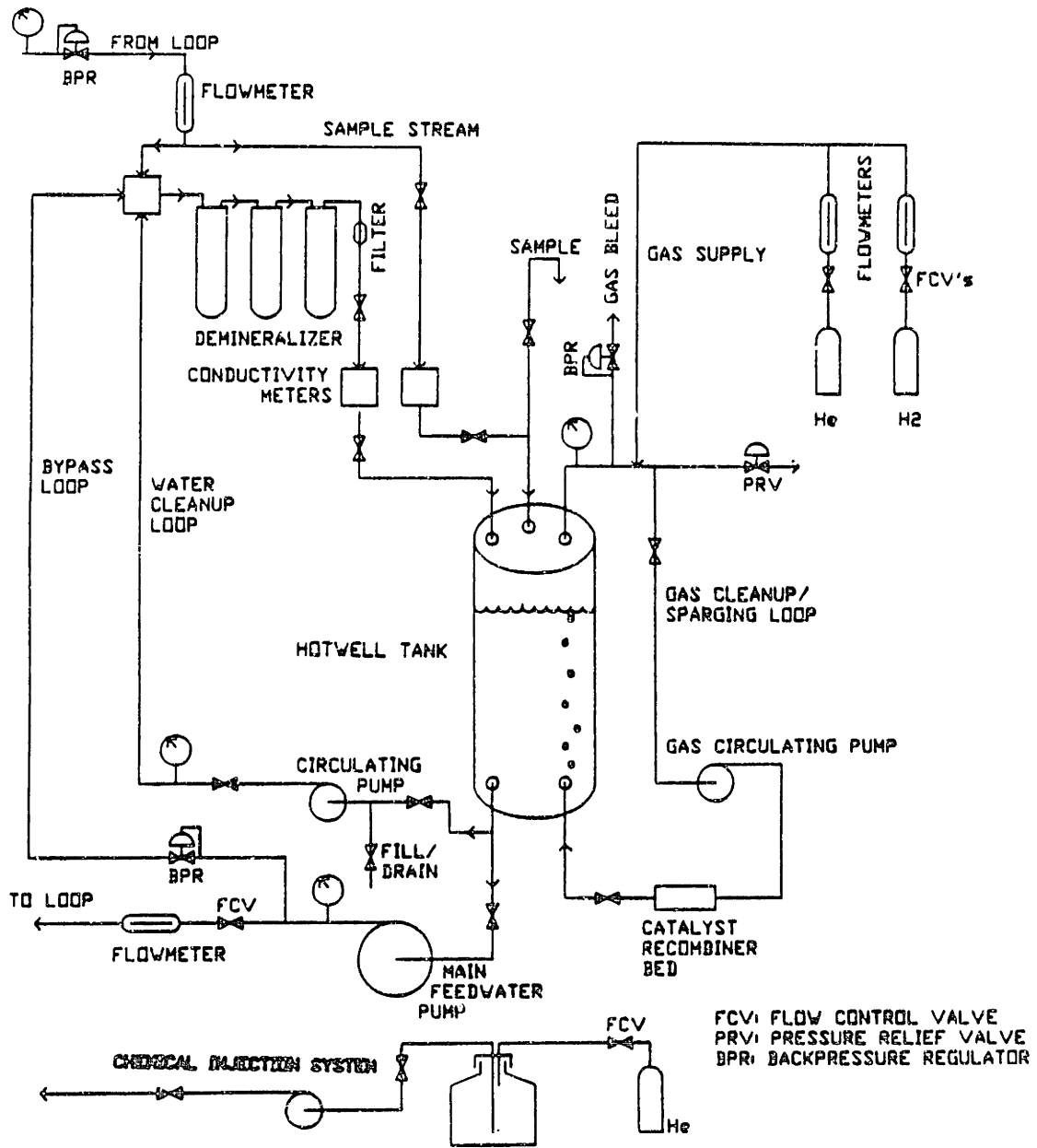


Figure 5-2 Schematic of BCCL Out-of-Pile Components

of simulating a wide range of BWR conditions; flow rates, core transit times, and radiation fluxes are all independently variable. The chemistry of the coolant may also be varied. The concentration of hydrogen in the coolant can be controlled, and trace elements can be injected into the coolant stream. Finally, samples of the coolant can be extracted immediately after the core section and quickly chilled, allowing accurate measurement of short-lived radiolytic species such as hydrogen peroxide.

## IN-PILE EXPERIMENTS

### Experimental Conditions

Three different experimental runs were conducted, each with a different coolant chemistry: a standard reference run, with helium as the cover gas in the hotwell tank; a "HWC" (hydrogen water chemistry) run, with hydrogen as the cover gas in the hotwell tank; and a trace element injection run, with helium as the cover gas in the hotwell tank and a small stream of KOH injected immediately upstream of the core section. The flow rate through the core section was 1.8 lpm; the pressure at the core section was 1000 psi; the core inlet temperature was 277°C; the core outlet temperature was saturated at 285°C; the core outlet quality was 15%; and the core transit time was 0.6 sec. for all runs.

### Principal Experimental Results

Most systems performed as expected. The feedwater purity was excellent; the full-flow ion exchanger gave water having a resistivity of

17.9 M $\Omega$ -cm at its outlet. The water returning from the loop had a resistivity of approximately 7 M $\Omega$ -cm; the impurity causing this decrease in resistivity was not determined. No gamma activities with a half-life greater than 10 min. were detected, except for Ar-41. The water level gauge (used to measure the level in the outlet plenum/steam separator-dryer) worked well. The pump and hydraulic system proved very reliable. The chemical injection system was successfully demonstrated, and KOH was found to reduce carryover of N-16 into the steam line by a factor of 3. The N-16 detection system on the steam and water effluent lines worked well; HWC increased the N-16 in the steam line by a factor of 4.5. Hydrogen peroxide was successfully measured; concentrations ranged from 30 ppb (during HWC runs) and 310 ppb (during NWC runs) to 7 ppm (during NWC runs, when the system was all liquid). The ECP electrodes gave stable outputs, although the results were not the values anticipated. Preliminary tests indicated that the carryover of water into the steam line may have been as high as 2%. The principal measured results are shown in Table 5-1.

## WORK IN PROGRESS

Another set of runs with the BCCL is planned, and work is currently underway to ready the loop for further operations. The goal of the next set of runs is to complete the original test matrix, which is summarized in Table 5-2.

Table 5-1: Principle Results of In-Pile Runs

	NWC	HWC	NWC w/ KOH
H <sub>2</sub> O <sub>2</sub> in outlet plenum	310 ppb	110 ppb	70 ppb
H <sub>2</sub> O <sub>2</sub> in downcomer plenum	310 ppb	85 ppb	70 ppb
H <sub>2</sub> O <sub>2</sub> in outlet plenum with system single-phase	7000 ppb	190 ppb	1360 ppb
steam/water line N-16 ratio	0.032	0.142	0.010
KOH in feedwater	0	0	1.81x10 <sup>-4</sup> M
H <sub>2</sub> in feedwater	0	18.4 ppm	(low)

Table 5-2: BCCL Test Plan for 1991 Campaign

Chemistry	Measurements
NWC	H <sub>2</sub> O <sub>2</sub> ECP N-16 in liquid and vapor phases
NWC with chemical injection	H <sub>2</sub> O <sub>2</sub> ECP N-16 in liquid and vapor phases
HWC	H <sub>2</sub> O <sub>2</sub> ECP N-16 in liquid and vapor phases
HWC with chemical injection	H <sub>2</sub> O <sub>2</sub> ECP N-16 in liquid and vapor phases

After this test matrix is completed, the effect of different chemical additives on N-16 behavior will be investigated, particularly the partition of N-16 between the steam and water effluent lines. In the N-16 runs, the additives will be injected immediately upstream of the core section using the sample injection system. Gaseous additives will be introduced by injecting water saturated with the desired gas; solid additives will be injected as a dilute solution. Planned additives are shown in Table 5-3.

Table 5-3: Planned Additives for Investigating N-16 Holdback

Chemical Species	Concentration in Coolant, g-mol/liter (a)
KOH	$10^{-4}$
NH <sub>4</sub> OH	$10^{-4}$
KNO <sub>3</sub>	$10^{-4}$
KNO <sub>2</sub>	$10^{-4}$
K <sub>2</sub> CO <sub>3</sub>	$10^{-4}$
C <sub>2</sub> H <sub>5</sub> OH (ethanol)	$10^{-4}$
NO (nitric oxide; gas)	$10^{-4}$ (b)
N <sub>2</sub> O (nitrous oxide; gas)	$10^{-4}$
CO <sub>2</sub> (gas)	$10^{-5}$ (c)
N <sub>2</sub> (gas)	$10^{-5}$ (c)

- (a) Each additive will be tested at the concentration listed, and, if effective, also at 1/10 this value.
- (b) Saturated at 3.2 atm.
- (c) A prohibitive 10 atm overpressure would be needed to reach  $10^{-4}$  g-mol/liter.

## MODIFICATIONS

Although the BCCL performed well, a number of modifications are suggested which would greatly improve its usefulness in experimental investigations. These improvements are described in this section.

### Glass Float Replacement

The glass float failed at the end of the experimental campaign. This float must be replaced with a new one, which should be made of quartz instead of borosilicate glass. The procedure for fabrication of the float is described in Appendix B. Annealing procedures for the float should also be investigated; it is probable that appropriate annealing would increase the life of the float. The possibility of fabricating a beryllium float should be considered.

### ECP Data Acquisition and Electrodes

It is not known why the data from the electrochemical probes were apparently not correct. It is possible that the data acquisition system was functionally inadequate (e.g., of an insufficiently high impedance) or incorrectly installed (e.g., incorrectly grounded), or that the probes themselves were not functioning properly. It may also be that the probes were not cleaned properly; standard procedures for electrode pre-run grooming should be developed.

### Dissolved Gas Sensor Calibration

Two Orbisphere electrodes and meters, one for oxygen and one for hydrogen, were used to measure these gases dissolved in the coolant. They were difficult to keep operating correctly; the hydrogen meter was particularly troublesome. Flow rate requirements for the meters were too high to allow them to be used in several positions of interest. Alternative methods of measuring dissolved gases should be investigated; before the next run, the detectors should at least be properly calibrated.

### Heat Balance on Heat Exchanger to Determine In-Core Power

Difficulty was encountered in trying to determine the heat transferred to the coolant in the core section of the loop. This heat contribution is particularly important because it directly influences the core transit time (via the mean void fraction), and hence the radiation dose received by the coolant. The electric power and gamma heat put into the lead bath are both known; what is not known is how much power is lost to the MIT Reactor coolant. The temperature of the coolant at the core outlet is not dependent on the power input since the coolant is saturated at this point.

To provide an alternate means of determining the actual heat transferred to the coolant in the core section, a pair of thermocouples should be placed on the regenerative heat exchanger so a heat balance on this section can be calculated. This would allow a verification of other estimates of the heat transferred to the coolant.



## N-16 Detector Shielding and Discriminator Setting

At low steam and water flow rates, the signal-to-noise ratios in the N-16 detector are low. Additional lead shielding should be placed around the N-16 detector shield block to lower the background noise, if low-flow runs are planned.

The correct discriminator setting on the MCA is of great importance, because only counts made with the same discriminator setting are comparable. The energies of the gamma signals near 6 MeV are as follows:

7.115 MeV N-16 first gamma

6.604 MeV N-16 first gamma single escape peak

6.129 MeV N-16 second gamma

6.093 MeV N-16 first gamma double escape peak

5.618 MeV N-16 second gamma single escape peak

5.298 MeV C-15 gamma

5.107 MeV N-16 first gamma double escape peak

4.787 MeV C-15 gamma single escape peak

4.276 MeV C-15 gamma double escape peak

To maximize the total N-16 counts and to reject the contribution from C-15, the MCA discriminator should be set with cutoffs from approximately 5.5 MeV to approximately 7.2 MeV.

## Germanium N-16 Detector

A germanium detector should be tested for possible use in the N-16 detector system in place of the NaI(Tl) crystal. Such a detector on the

steam and water lines would substantially improve the sharpness of the N-16 peaks; a disadvantage of using a germanium detector is the lower overall efficiency relative to a NaI(Tl) crystal.

### In-Core Lead Bath: Replacement with Machined Block

The current in-core design consists of an electric heater and a Zircaloy U-tube partially immersed in a liquid lead bath. The lead bath absorbs approximately 7 kW of gamma heat when the reactor is at full power. For many regimes of interest, however, 7 kW is far more power than is needed; this design effectively precludes long transit time simulations, which are particularly interesting in light of the high hydrogen peroxide concentrations observed in the single-phase regime.

To allow simulations involving long transit times, it is recommended that in place of the lead bath, an aluminum block be used. This block would be made in two halves, and would have four close-tolerance grooves machined down each half, for the legs of the heater and the Zircaloy U-tube. The two aluminum halves, with the heater and U-tube sandwiched inside, would be tack-welded together, or would be held together by bolts. This sandwich unit would fit in the same envelope that the current titanium can fit in, and would probably operate at a lower temperature than does the current lead bath. Fabrication would probably be no more expensive. With this design, a much wider range of transit times could be investigated since the gamma heating power would be reduced by the density ratio of lead to aluminum, a factor of 4. In addition, it is likely that it would improve the thermal hydraulic stability of the loop as a whole.

## Increasing the Thermal Inertia of the Fluid System

The thermal-hydraulic system of the BCCL is unstable due to the positive feedback caused by the regenerative heat exchanger. The system operates in a metastable mode, and requires continual minor adjustments to the core heater power. If the system is perturbed (e.g., a sample is drawn), a stable level in the outlet plenum is very difficult to maintain.

It is believed that a thermal mass, such as described in Section 3 and in Appendix B, would improve the stability of the loop so that it could operate under automatic control (the core heater should be controlled by the level in the outlet plenum, and the feedwater heat should be controlled by the core inlet temperature). This would allow experiments to be run more easily on the loop, and for longer periods of time.

An elementary control system analysis should be applied to the thermal hydraulic system to investigate whether a thermal mass would improve its characteristics (P-1). If the analysis indicates that it would help, the above-described thermal mass should be installed.

## Decomposition of Peroxide and Organics

It was found that under certain operating conditions, the hydrogen peroxide produced by radiolysis does not decompose completely, but circulates throughout the loop and builds up to relatively high levels in the condensate tank. Since hydrogen peroxide is not a gas, it is not removed by helium stripping of the water in the condensate tank, and is not affected by the gas-phase catalyst. It is therefore necessary to catalyze the decomposition of the dissolved hydrogen peroxide. This could probably be

accomplished by passing the flow stream returning from the loop through a palladium-plated tube, or through a sintered stainless steel filter (placed upstream of the ion exchange unit to avoid adding undesirable impurities to the water). A UV irradiation unit might also help in this regard. AECL also makes a catalyst capable of operating in water. These possibilities should be investigated, and one of them implemented, before the loop is recommissioned. It is not known why the peroxide is not decomposed in the many meters of hot tubing through which it passes.

Contamination by organics was initially found to be a problem, as evidenced by the increase in the conductivity of the water returning from the loop when the loop was run hot. The probable source of this contamination was the activated carbon filter which preceded the ion exchange columns in the demineralizer unit. The contamination problem was solved by removing the initial carbon filter and installing a final organics-removal cartridge in the demineralizer unit. The demineralizer consistently gave water of 17.9 to 18.2 M $\Omega$ -cm. A UV disintegration unit may also provide extra assurance of organic cleanup.

### Outlet Plenum Separator and Steam Dryer Improvement

Carryover of water droplets from the outlet plenum into the steam line was excessive -- possibly as high as 2%, enough to affect the results of anticipated N-16 carryover experiments. Carryover tests using conducting salt injection (similar to those described in Section 4) should be run (without radiation) when the loop is recommissioned, and the level of the interface in the outlet plenum can once again be measured. If possible, the sample taps should be connected (through a cooling device) directly to the

flow cell of the conductivity meter. This would eliminate the problem of the high conductivity of air-saturated water.

Carryunder should also be estimated, using the Ar-41 activity ratio method given in Appendix E. Sample bombs need to be designed and prepared to do this.

An improved steam separator should be installed, if carryover is found to be excessive. If possible, this should be installed on the steam line outside of the outlet plenum; if not, the plenum must be cut open and rewelded.

#### Sample Cooling Block Improvement

As noted in Section 4, a tiny leak developed at the cooling block when the temperature of the block rose above approximately 170°F. The fittings on the block should be tightened further to stop this leak before the BCCL is recommissioned.

#### IC Detection for Transition Metals

In order to determine the quantities of transition metals present in the loop, an IC transition metal detection system should be installed on the return line from the loop in parallel with the present anion IC unit. Such a system would allow accurate measurement of any transition metals present in the BCCL. This would be particularly useful if experiments with trace element injection are to be run.

## Gas Pressure Maintenance in the Hotwell Tank

Difficulty was encountered in maintaining a constant cover gas pressure in the hotwell tank. A low-flow pressure regulator was used on the bleed line of the tank to keep the pressure constant, and the cover gas (helium or hydrogen) was flowed into the tank at a low flow rate. It was found, however, that the pressure regulator did not let gas flow out at a constant rate, and the pressure in the tank varied between 0 and 7 psig. To keep the tank pressure constant, it is recommended that the backpressure regulator be replaced by a simple vertical ball-type check valve.

## Updating the BCCLMIT Modelling Code

The computer modelling code BCCLMIT (M-1), which numerically simulates the BCCL, should be made current with the latest improvements by Chun (C-1) before simulations are run modelling the next set of BCCL experiments. In particular, the possibility of using the Bankoff correlation for void and slip ratios should be investigated.

## POSSIBLE FUTURE EXPERIMENTS

A large number of interesting experiments are possible with the BCCL, some of them uniquely so. Several are outlined in this section.

## Coordinated BCCL and BCCLMIT (Code) Runs: Surface Effects

One of the major uncertainties of the code modelling the BCCL, BCCLMIT, is the effect of surface decomposition on hydrogen peroxide concentration. The BCCL has a substantially higher surface-to-volume ratio than does a full-size BWR. An investigation of this effect might be possible if the BCCL were run at lower temperatures (below the hydrogen peroxide decomposition temperature) but with a full radiation flux. The results from the BCCL could then be compared with the results from BCCLMIT (run at lower temperatures, for which it should be more accurate) and the effect of surface decomposition could thereby be clarified. In addition, the code should be run for single-phase conditions with NWC, to attempt to reproduce the extremely high concentrations of hydrogen peroxide which were measured under those conditions.

## N-16 Carryover

Preparations are currently underway to run experiments testing the effect of a number of additives on the partition of N-16 between the steam and the water in the outlet of a BWR. It is postulated that the partition depends on the pH of the coolant; these experiments will test whether this is so.

## Indirect G-value Measurements

The BCCL is well-suited (through comparison of calculated and measured concentrations of radiolytic species) to make indirect radiolytic

species production measurements, in addition to enthalpy- and entropy-of-reaction (activation energy) measurements, at both high and low temperatures. These quantities are not accurately known, and are hindering progress in some areas, such as modelling.

### Electrochemical Measurement of Dissolved Species

Work is underway elsewhere to allow the measurement of species such as oxygen and hydrogen peroxide in reactor coolant by electrochemical means (S-3). The BCCL could be an excellent means of testing and perfecting these methods, and adapting them to long-term use.

### Conversion to A Recirculating Loop

A study has been completed (I-1) which describes the steps necessary to convert the BCCL from a once-through system to a recirculating system. This would allow the loop to more closely model a BWR, and would permit a wider range of experiments and code validations to be run. A schematic of the current once-through design is shown in figure 5-3, and the design with recirculation is shown in figure 5-4.



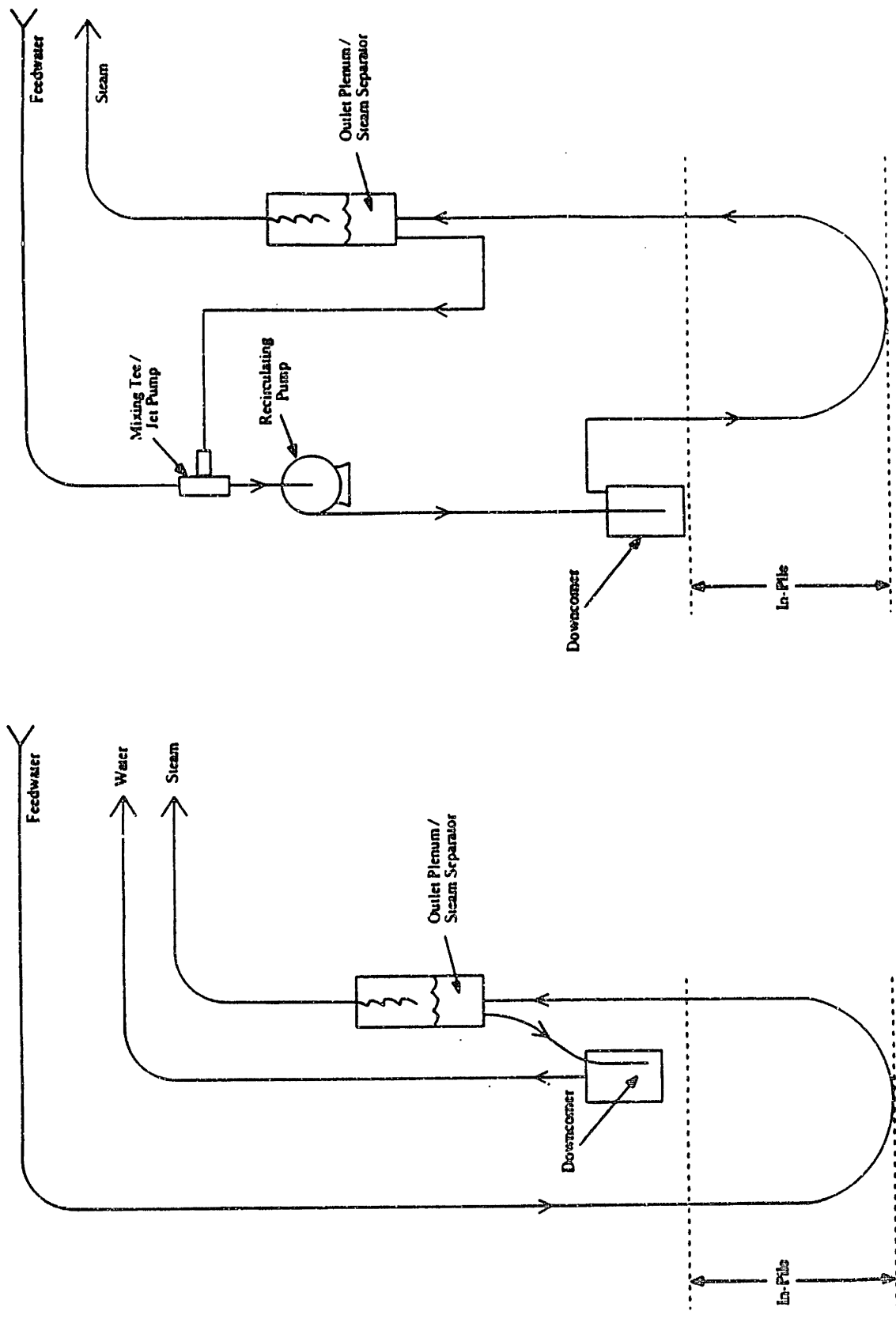


Figure 5-3 Current Once-Through BWR Loop Configuration Figure 5-4 Modified BWR Loop to Accommodate Recirculation

## **SUMMARY: CONCLUSIONS AND RECOMMENDATIONS**

**An in-pile loop simulating BWR coolant chemistry has been designed, constructed and operated. Basic feasibility and functional capabilities have been confirmed. Experimental results to date have been described. Work currently in progress has been outlined. A number of modifications to improve the usefulness of the BCCL have been suggested, and possible future experiments with the facility have been proposed.**

## APPENDIX A

### CONSTRUCTION DETAILS

#### IN-PILE THIMBLE

The thimble used for BCCL experiments is shown in Figure A-1. It consists of an elliptical in-core section, an elliptical streaming channel, a 4-inch O.D. component section, and an 8-inch O.D. pump pod. The elliptical sections are connected to the 4-inch section by a bolted flange, the construction drawings for which are shown in Figures A-2 and A-3. The portion of the thimble above the flange is the same as for the PWR Coolant Chemistry Loop (PCCL), which is described by Sanchez (S-1). Construction of the elliptical in-core section is also identical to that of the PCCL in-core section. As described in (S-1), the orientation of the major axis of the elliptical in-core section relative to the pump pod is 45°.

The flange is grooved to accept an O-ring or C-ring to provide a water-tight seal. Lead-plated metal C-rings (see Appendix B: C-rings) were used for in-pile runs, while rubber O-rings (see Appendix B: O-rings) were found to be satisfactory for out-of-pile tests.

The two halves of the flange are fastened together with 3/4-inch long stainless steel 10-24 capscrews. These capscrews may be purchased with holes crosswise through the heads (for a securing wire). This obviates the time-consuming procedure of drilling each screw.

The elliptical sections were fabricated from a round 2-inch O.D., 1/8-inch wall tube. The tube was crushed to approximately the correct dimensions in a press, then brought to the final dimensions by drawing a steel die through it. The die must be drawn using a threaded, high-strength

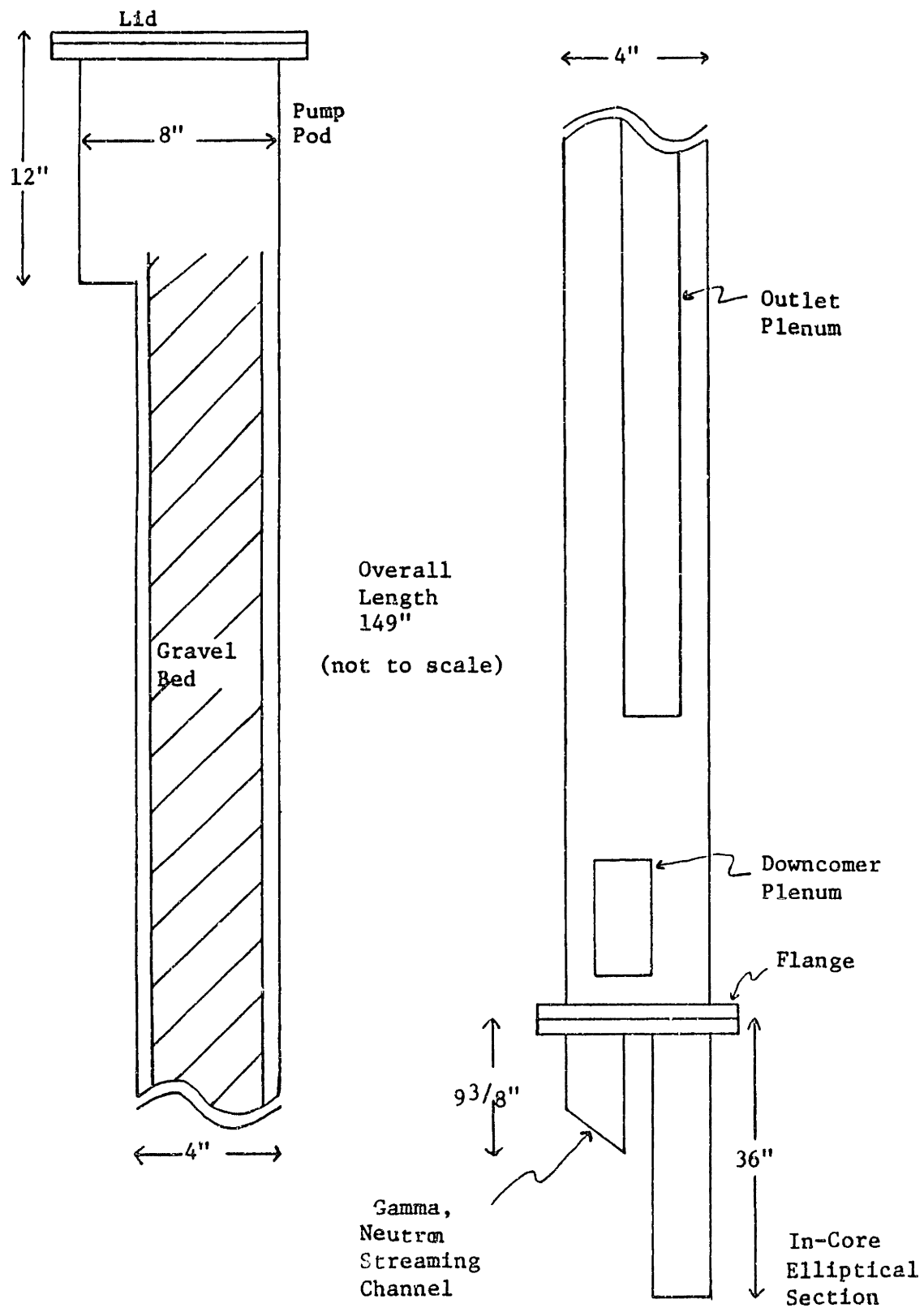


Figure A-1: Schematic of In-Pile Thimble

MATERIAL: ALUMINUM 6061

(DIM. INCHES)

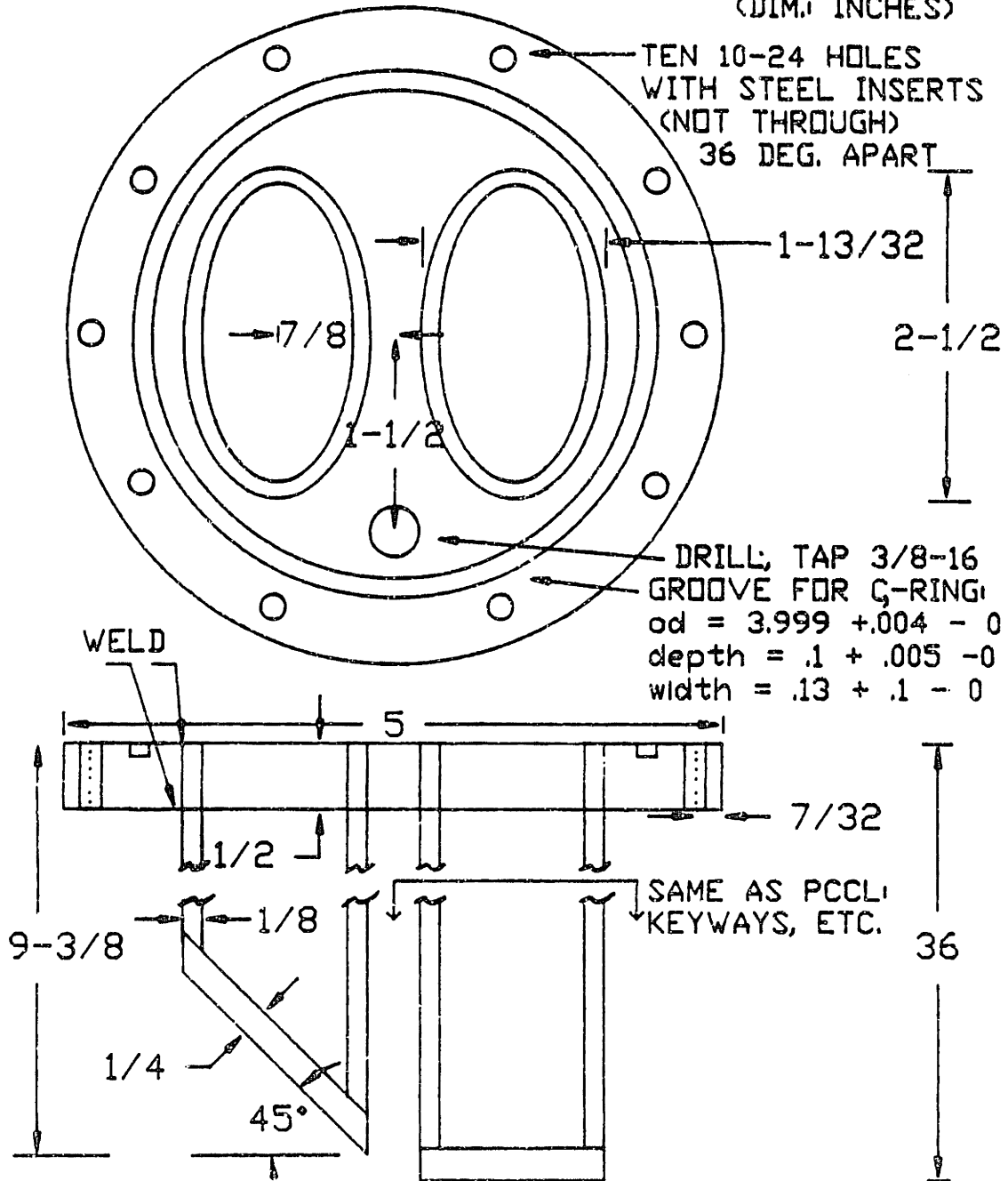


Figure A-2: Lower Flange for BCCL Thimble

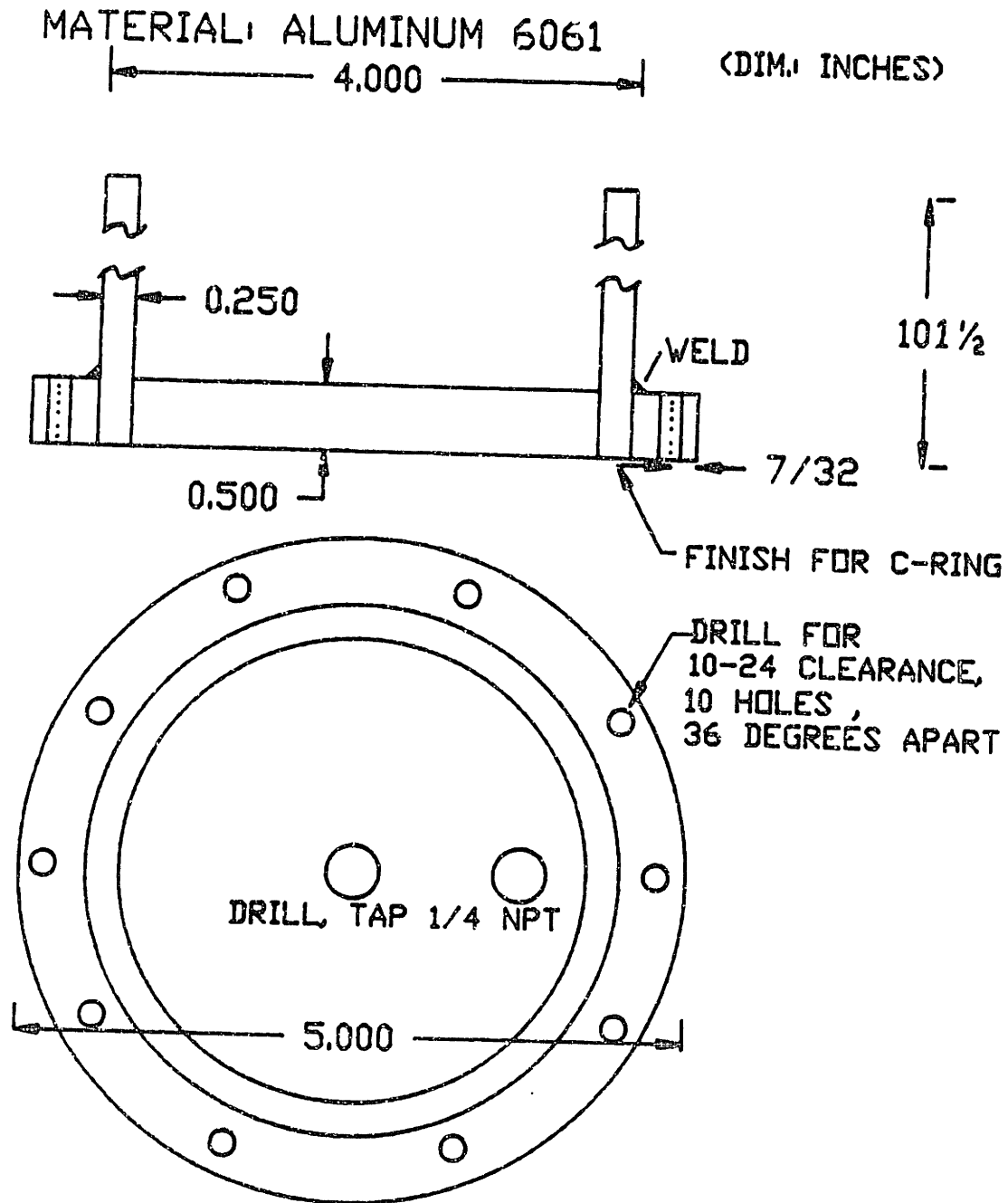


Figure A-3: Upper Flange for BCCL Thimble

(i.e., stainless, not mild) steel rod and a thrust bearing, and the die must be lubricated (e.g., with powdered soap). The die should first be polished to a mirror-smooth finish.

All sections of the thimble were fabricated from 6061-T6 aluminum. For the fabrication of future elliptical sections, it is strongly suggested that aluminum with a less-hardening heat treatment be used (e.g., 6061-T2), since severe difficulties were encountered in drawing the die through the 6161-T6 material.

To avoid excessive porosity in the aluminum welds, the following chemical cleaning procedure was found to be necessary before welding.

1. Immerse in 5 w% NaOH solution at 65°C (150°F) for 30-60 seconds.
2. Rinse in cold tap water.
3. Immerse in 1:1 (by volume) nitric acid/water solution at room temperature.
4. Rinse in hot water.
5. Hot air dry immediately.
6. Weld as soon as possible; no more than 48 hours later.

For bright, unoxidized aluminum, the NaOH bath may be omitted.

## THIMBLE LID AND FEEDTHROUGHS

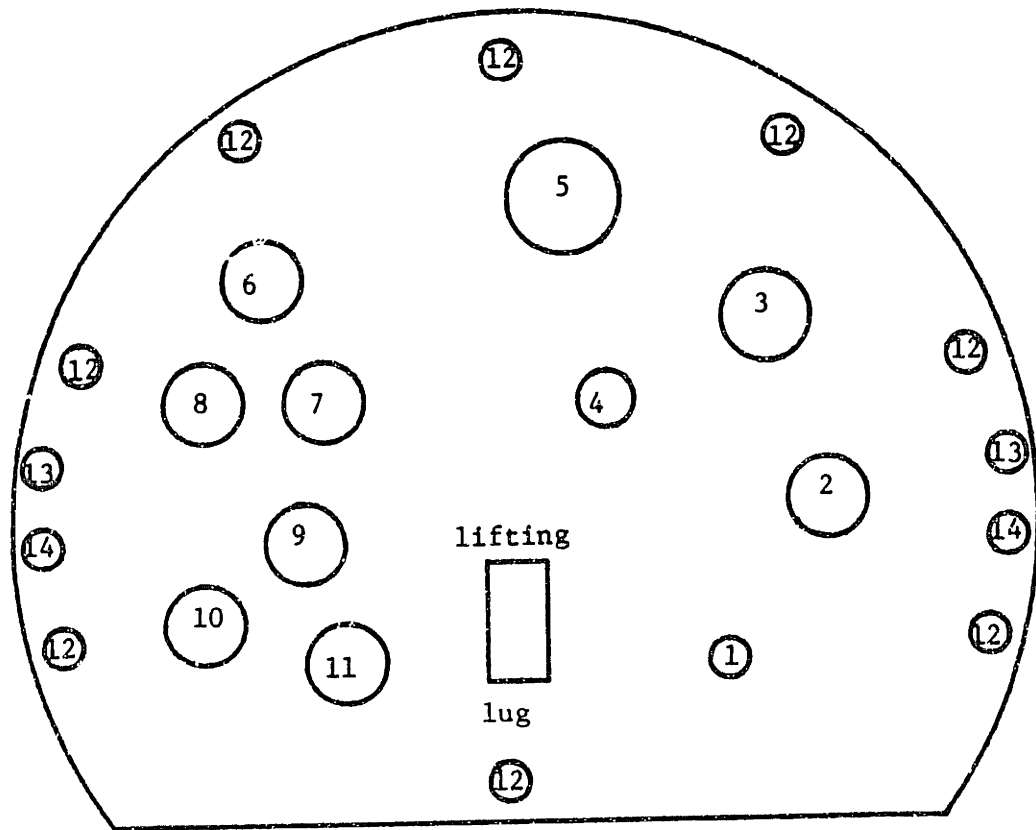
The BCCL thimble lid, made of 1/4-inch thick stainless steel plate, is identical in profile to that of the PCCL thimble lid, described in (§-1). The

array of penetrations, however, differs considerably. As shown in Figure A-4, a number of female NPT couplings and compression fittings were welded into holes drilled through the central portion of the lid. The lid constitutes part of the pressure boundary of the thimble, and the purpose of these fixtures is to hold feedthroughs which allow fluid and electrical lines to cross the pressure boundary without compromising its integrity.

Referring to Figure A-4, the feedthroughs are as follows:

1. 1/8-inch compression fitting. Helium purge supply line.
2. 3/4-inch compression fitting. Bleed line/over- pressure relief.
3. 3/4-inch NPT coupling. Holds Conax feedthrough for core heater power and ground lines (3).
4. 1/2-inch NPT coupling. Holds Conax feedthrough for gravel bed heater power lines (2).
5. 3/4-inch NPT. Holds feedthrough for thermocouples (8 pairs).
6. 1/2-inch NPT. Holds feedthrough for level detector power and signal lines (8).
7. 1/2-inch NPT. Holds feedthrough for sample and injection lines (3).
8. 1/2-inch NPT. Holds feedthrough for electrode signal lines (9).
- 9,10,11. 3/4-inch Cajon Ultra Torr fitting. Holds rounded Conax fitting for core inlet, steam, and downcomer outlet lines (3).
12. Bolts to hold thimble lid on thimble.
13. Holddown bolts (to hold thimble to bridge spanning reactor pool).





1. Helium purge supply line.
2. Bleed line/overpressure relief.
3. Power lines for core heater.
4. Power lines for gravel bed heater.
5. Thermocouple feedthroughs.
6. Lines for level detector.
7. Sample and injection lines.
8. Electrode signal lines.
- 9, 10, 11. Hot fluid lines.
12. Lid bolts.
13. Holddown bolts.
14. Jacking bolts.

Figure A-4: Schematic of Lid for BCCL Thimble

14. Jacking bolts (for fine adjustment of position of thimble relative to bridge).

The total number of electrical and fluid lines passing through the lid is, therefore, 38.

## THIMBLE INTERNALS - FLUID SYSTEM

The hydraulic internals of the thimble are depicted schematically in Figure A-5. A description of each of the components follows.

### In-Core Section

The in-core section consists of a  $5/16$ -inch (0.3125 inch) OD, 0.025-inch wall, (hence 0.263-inch ID) 6 foot long Zircaloy tube, bent into a U, with a  $5/8$ -inch inner bend radius. Connections are made to the ends of the U-tube with Parker compression fittings. This section is identical in design to that used in the PCCL, described in (S-1).

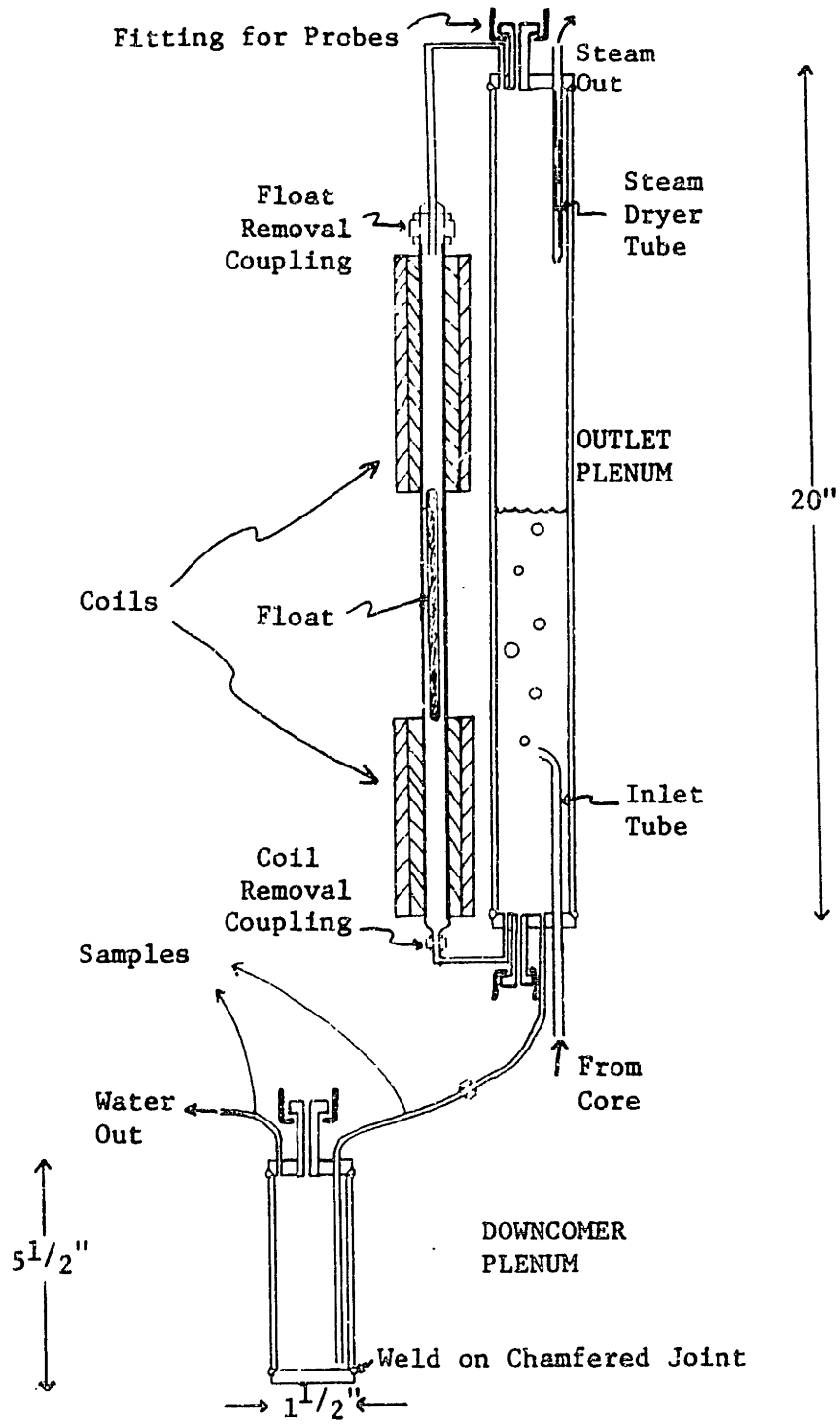


Figure A-5: Hydraulic Internals of BCCL Thimble

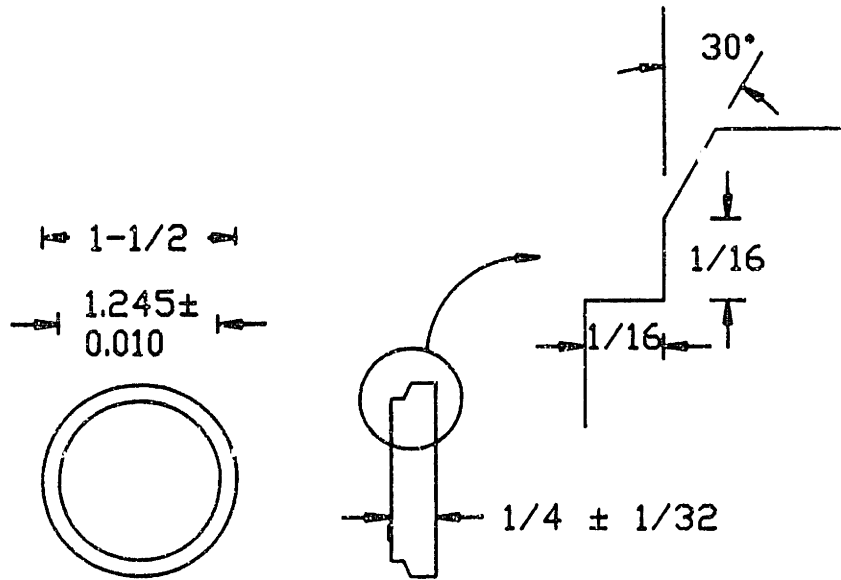
### Outlet Plenum/Steam Separator-Drier

The outlet plenum consists of a 1½-inch OD, 0.090-inch wall, (1.32-inch ID) 20-inch long titanium tube. This tube was cut to length, then a 1/16-inch chamfer was cut in its outer edge. Endcaps, as shown in Figure A-6, were machined from 1½-inch c.p. titanium rod stock. To accommodate the 1/4-inch fluid line penetrations, two No. F (0.2570 inch) holes were drilled in the central portion of the upper endcap, and three No. F holes were drilled in the central portion of the lower endcap. To accommodate 1/2-inch Parker Ultraseal O-ring fittings to hold the two electrochemical probes in the outlet plenum, a 41/64-inch hole was drilled into each endcap. The 1/4-inch tubes and the 1/2-inch O-ring seal glands (drilled out to 7/16-inch to accommodate the probes, and with the nuts in place) were then welded into the endcaps, and the endcaps were welded onto the ends of the 1½-inch titanium tube serving as the outlet plenum.

The outlet plenum is shown schematically in Figure A-5. The steam drier tube, at the top of the plenum, extends down into the plenum approximately 3½-inches. It was fabricated by machining six narrow grooves, each approximately 1/2-inch long, into the steam drier tube (1/4-inch OD, 0.028-inch wall, 0.222-inch ID c.p.titanium) with a narrow slitting saw. The end of the tube was then pinched nearly shut, in order to force the steam to enter the tube through the slots, but still allow for the drainage of condensate out the bottom of the tube.

The side arm containing the float for the level detector is shown in Figure A-7. It was fabricated from a 5/8-inch OD, 1/16-inch wall, 1/2-inch ID, 23¾-inch long c.p. titanium tube. A 1/2-inch titanium O-ring seal gland was welded to the top of the tube to allow insertion and removal of the float, while a 1/4-inch titanium O-ring seal gland was welded to the

MATERIAL: CP TITANIUM  
 DIMENSIONS IN INCHES



LAYOUT OF ENDCAP PENETRATIONS

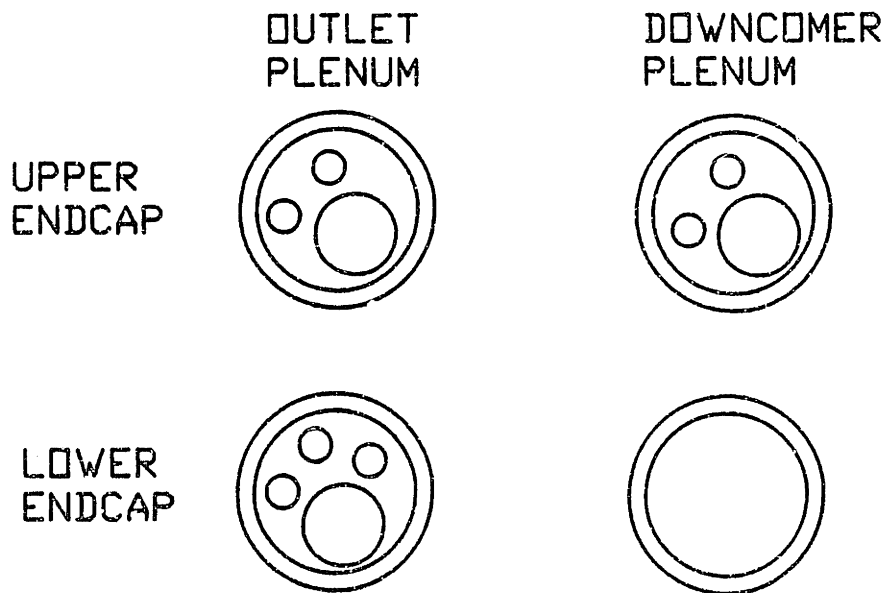


Figure A-6: Endcaps for BCCL Plena

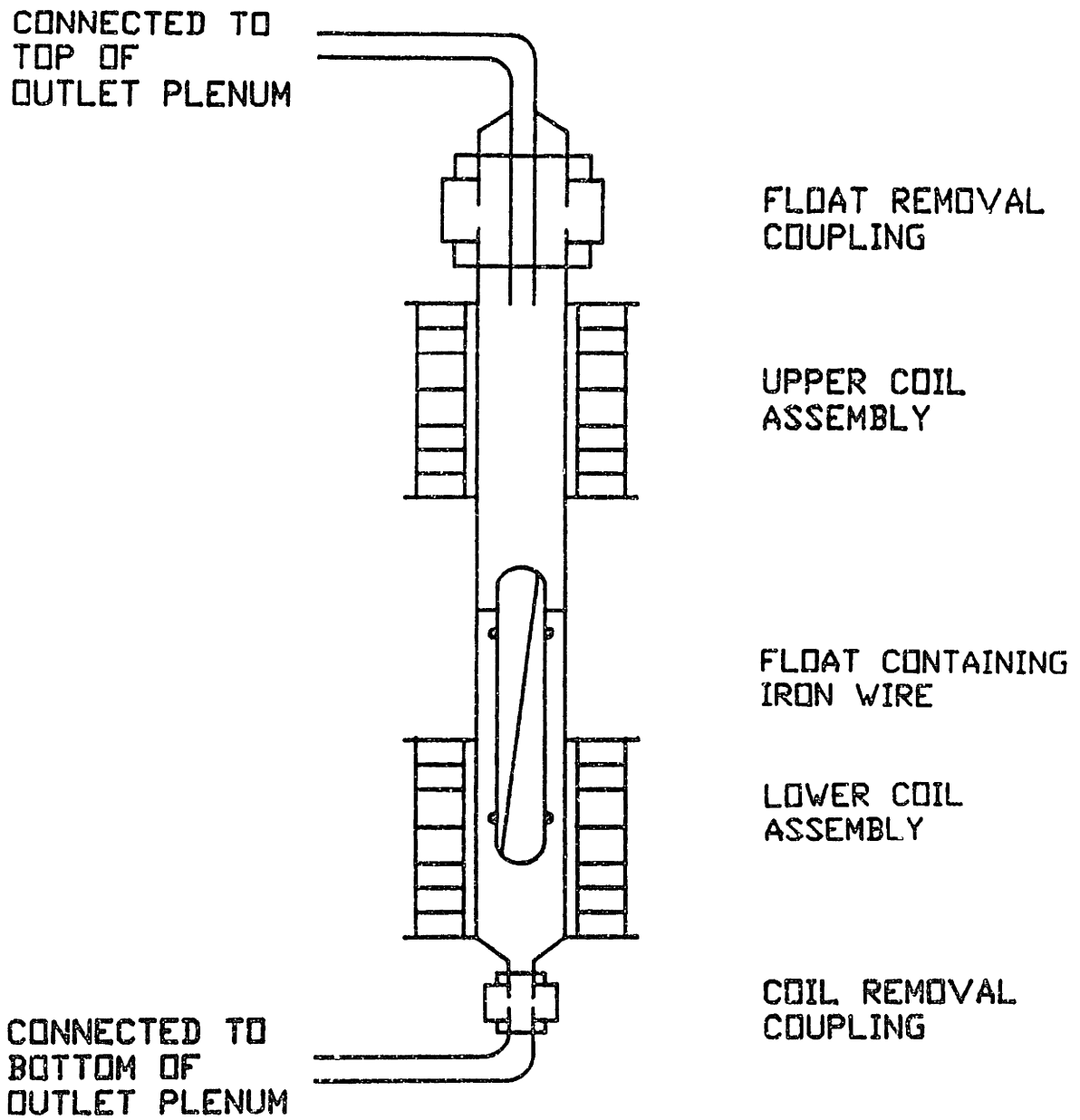


Figure A-7: Float Level Detector Assembly for BCCL

bottom of the tube to allow removal of the coils from the outside of this tube. The nut for the 1/4-inch O-ring seal was turned down on a lathe until its outer diameter was 5/8-inch, so that the coil assemblies could pass over it. The 1/4-inch OD tube which was welded to the top gland of the 1/2-inch fitting extends through the fitting and both glands, approximately 1/2-inch into the 5/8-inch tube. The purpose of this extension is to limit the travel of the float to that portion of the tube which is surrounded by the upper coil.

The inlet tube at the bottom of the outlet plenum is made of 1/4-inch OD titanium tubing, and extends approximately 3 1/2-inches into the bottom of the plenum. The free end of the tube bends sharply at a right angle in a direction parallel to the inner wall of the plenum, to exhaust the steam/water mixture without excessive agitation of the plenum inventory, and to help effect the separation of the phases.

The water outlet line of the outlet plenum is a 1/4-inch OD titanium tube, the free end of which is flush with the bottom endcap of the plenum. Like the other endcap penetrations, it is welded in place.

The welding procedure for titanium is similar to that for stainless steel, with one exception: it is critically important that the hot titanium never come in contact with air. If contact with air occurs, the titanium will be immediately nitrated and oxidized internally, causing extreme and permanent brittleness and weakness in the piece. For this reason, the welding of titanium must be done under inert conditions (i.e., argon or helium) in a glovebag or a glovebox, and any hollow piece must be flushed with approximately thirty volumes of inert gas before welding. It is recommended that the welding of titanium be done only by personnel who are trained and experienced with welding titanium. Visual inspection of a

welded joint gives some indication of its integrity; heavy discoloration, particularly if it is metallic blue, indicates a potentially brittle joint. The welding of BCCL components (after unsuccessful in-house attempts) was successfully done by Ramsay Welding and Fabrication of Woburn, MA.

### Simulated Downcomer Region

The simulated downcomer region is similar in form and construction to the outlet plenum. The body of the downcomer plenum consists of a 5-inch long, 0.090-inch wall, piece of 1½-inch OD, 1.32-inch ID titanium tubing, prepared with a 1/16-inch chamfer identical to that of the outlet plenum. The endcaps, shown in Figure A-6, are similar to those of the outlet plenum. The lower endcap of the downcomer plenum has no penetrations, while the upper endcap has three penetrations, as shown: Two N<sub>2</sub>F holes for the ¼-inch inlet and outlet tubes, and one 41/64-inch hole to accommodate a ½-inch O-ring fitting for an electrochemical probe. The inlet tube extends the length of the plenum to within ½-inch of the bottom endcap, to establish flow through the plenum. Welding details were similar to those for the outlet plenum.

### Sampling System and Cooling Block

The sampling system basically consists of a half-cylinder of aluminum with two long holes drilled through it, and nipples at the end of each hole to accept compression fittings to contain the fluid stream. The sample cooling block is shown in Figure A-8. The purpose of the aluminum block is to cool the sample streams flowing through it, and to



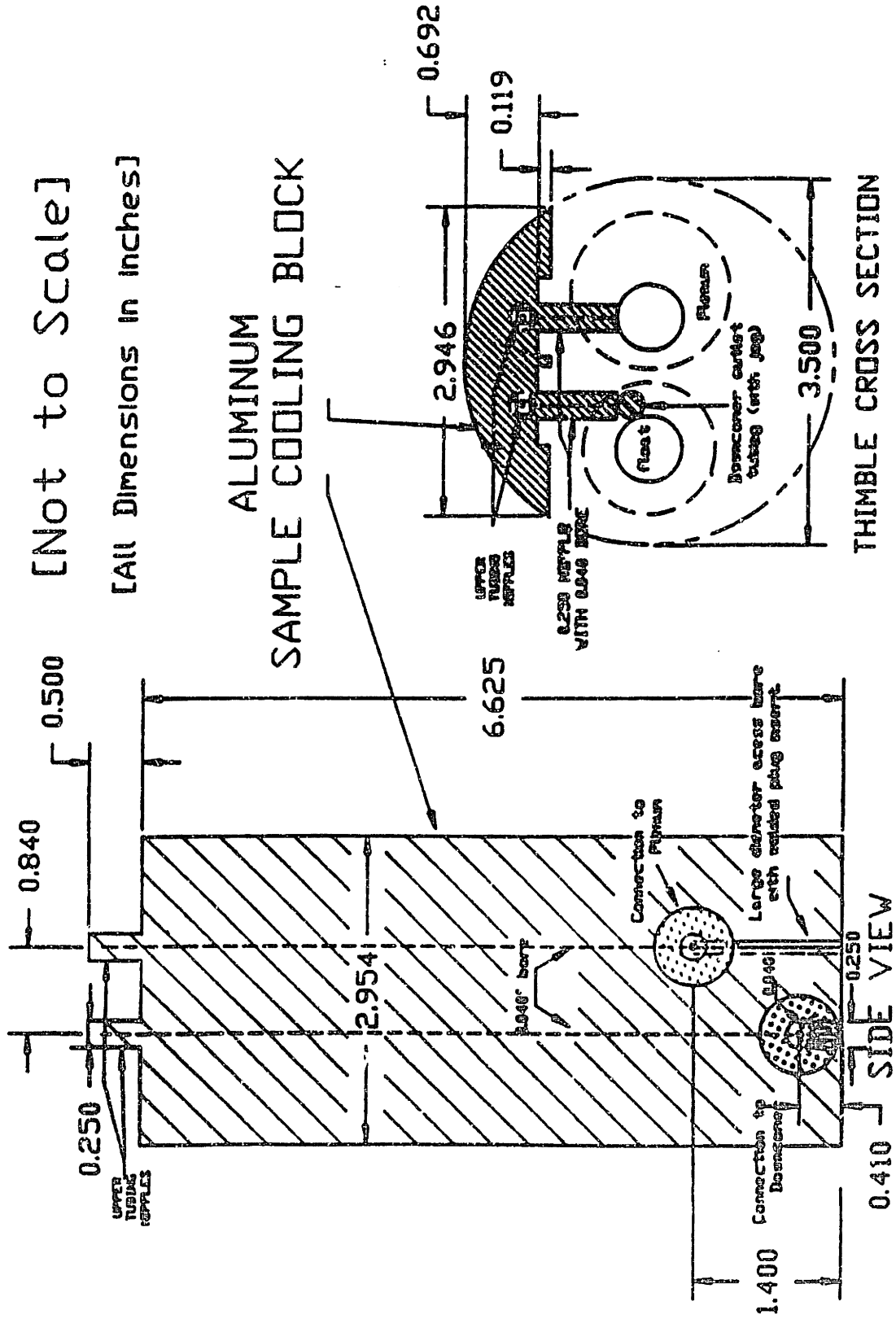


Figure A-8: Sample Cooling Block for BCCL

effect this it is held against the inside wall of the thimble by a manually tightened spring mechanism. This entire system is described thoroughly by Mason (M-1). The sample lines transporting the fluid from the outlet of the cooling block to out-of-pile were 1/16-inch OD, 0.020 inch ID, 316 stainless steel tubing.

### Tubing and Fittings

The tubing used to connect the thimble internals was (except for the Zircaloy core section) 1/4-inch OD, 0.028-inch wall, hence 0.194-inch ID), titanium tubing. The connections to the nipples on the aluminum cooling block were 1/4-inch titanium compression fittings; all other connections were made with O-ring fittings, with titanium glands, which were welded to the ends of the sections of titanium tubing. These glands, which had to be custom-machined from titanium rod stock, are shown in Figure A-9. The O-rings used for these fittings were nickel-plated stainless steel.

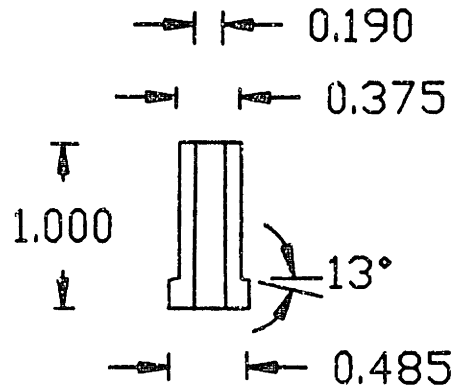
### Glass Float for Level Detector

The glass float for the level detector, and the steps for the construction thereof, are shown schematically in Figure A-10. The fabrication procedure is as follows:

1. Start with a type 7740 Pyrex test tube (e.g. tubing made for NMR spectroscopy work), 9 inches long, 10 mm diameter, 0.47 mm wall, 9.06 mm ID.
2. Using a length of thin, type 7740 Pyrex glass rod, melt on two rows of six bumps each, near the top and bottom of the float.

MATERIAL: CP TITANIUM  
DIMENSIONS IN INCHES

1/4" ULTRASEAL  
GLAND



1/2" ULTRASEAL  
GLAND

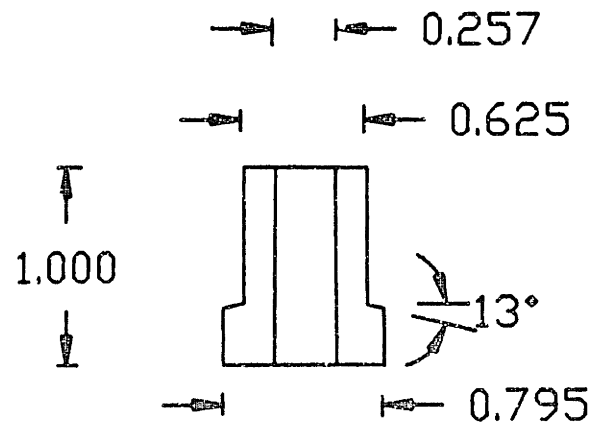


Figure A-9: Titanium Glands for Parker Ultraseal  
O-Ring Fittings Used in BCCL

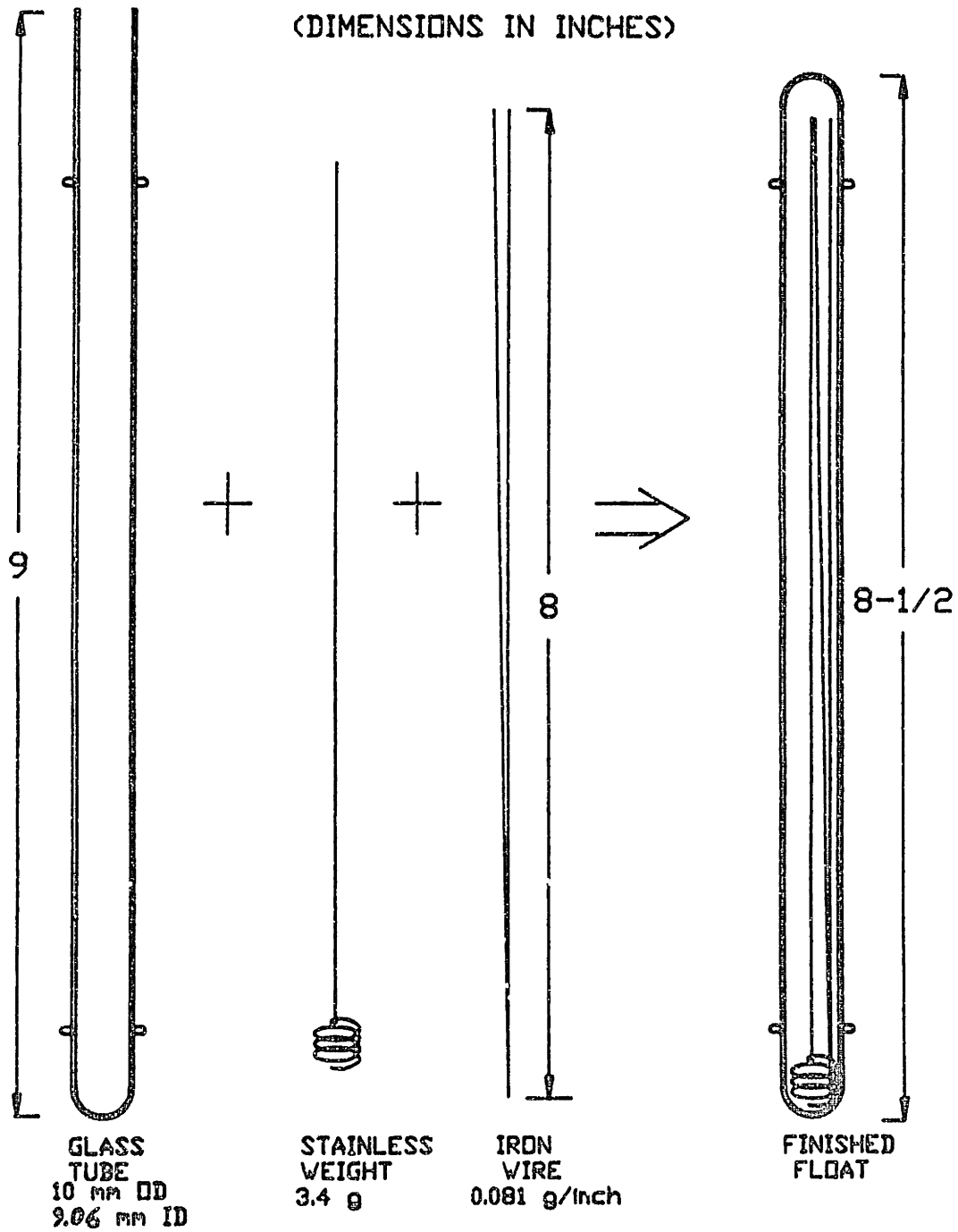


Figure A-10: Construction of Glass Float for BCCL Level Detector

The bumps should be  $1/16$ -inch high. Their purpose is to prevent the float from sticking (because of surface tension) to the wall of the metal tube in which it travels. If the bumps are too large, they can be sanded down with fine sandpaper.

3. Make a coil of  $1/16$ -inch OD, 0.010-inch wall, 0.042-inch ID, type 316 stainless steel tubing, leaving a long tail, as shown. This should weigh approximately 3-4 g. The purpose of this tubing is simply to provide ballast in the bottom of the float so it will float upright and not cock sideways, and also to provide weight so the float will not be held up by surface tension forces. The purpose of the long tail is so that when the float is inverted, the weight does not slide down the glass tube and crack the end of it.
4. Take a 16-inch length of 24 gauge (0.0201-inch diameter) pure iron wire. Such wire is used in iron-constantan thermocouple leads. Bend it double, so its overall length is 8 inches. This is the iron core which couples the detector coils, allowing position sensing.
5. Insert the iron wire and the stainless steel weight into the test tube.
6. Seal off the test tube approximately  $1/2$ -inch from the end in a methane-oxygen flame. The overall length of the float is now approximately  $8\frac{1}{2}$ -inches, and its total weight is approximately 11.5 g.

### Notes

- A. The diameter of the test tube is not critical; the only requirement is that the walls be thin enough so that the finished device will float in high temperature (i.e., specific density equal to 0.7) water. Fused silica (i.e., quartz) tubing may be substituted for Pyrex, in which case the bumps must also be made of fused silica (Pyrex is not satisfactory in high neutron flux conditions, but may be used temporarily). The length is determined by the coil dimensions.

- B. The weight must be of non-magnetic material and should be concentrated at the end of the float. Stainless tubing is one convenient option.
- C. The iron can be multiple wires, as the above design states, or may be a single wire. For our coils and electronics, a linear loading of 0.081 g/inch is desirable. This could be accomplished, for example, by a single length of 21 gauge (0.0285-inch diameter) iron wire.
- D. The finished float should float with its upper end approximately 1 inch above the surface when floated in methanol (which has nearly the same density as 285°C water). This can be tested before the tube is sealed, and the weight adjusted accordingly.
- E. If fused silica is used instead of glass, it is easier to seal off the tube at the end rather than 1/2-inch from the end. The initial length should then be 8 1/2-inches rather than 9-inches.

It is recommended that a fused silica float be used for actual in-pile runs (i.e., with a neutron flux present). The borosilicate glass float used in our first campaign operated for approximately 100 full power hours before failure. It was, however, subjected to considerable abuse during pre-operational testing.

## LEVEL DETECTOR COILS

Each level detector coil consists of an aluminum spool on which was wound an inner excitation coil of 335 turns, and an outer pickup coil of 1675 turns. The wire used is 24 gauge (0.0201 inch OD) aluminum wire with aluminum oxide insulation manufactured by Permaluster Inc. of Burbank, CA. Although the wire was fragile, it performed satisfactorily.

The winding of the coils was also done by Permaluster. It was found that broken aluminum lead wires could be repaired by carefully scraping off the aluminum oxide insulation, then brazing the two ends together using cadmium-zinc braze metal, an electric soldering iron, and an appropriate fluxing compound (available from Middlesex Welding Supply, Middlesex, MA). These brazed joints were able to withstand high temperatures. The aluminum winding wires were joined to copper lead wires with the same brazing procedure.

The dimensions of the spools on which the coils were wound are shown in Figure A-11. The spools were made of 6061 aluminum.

## TITANIUM BATH CAN

The function of the titanium bath can is to contain the lead bath. The liquid lead is the heat transfer fluid coupling the in-core heater and the in-core Zircaloy section.

The can is shown in cross section in Figure A-12. The flat sides are machined from 1/8-inch thick c.p. titanium sheet, while the half-round sides were fabricated by machining away half of two lengths of 7/8-inch OD, 0.061-inch wall, 0.753 inch ID, 6Al-4V titanium tubing. An endcap of the same cross-section as the can was machined from 1/8-inch thick titanium sheet. The four vertical seams were then welded, and the endcap was welded on. Distortion due to the welding caused the can to bow substantially (about 1/2-inch over its total length), and the can had to be bent back straight using a heavy hydraulic press. Finally, the corners of the 1/8-inch thick flat sides had to be filed down, so the can would fit into

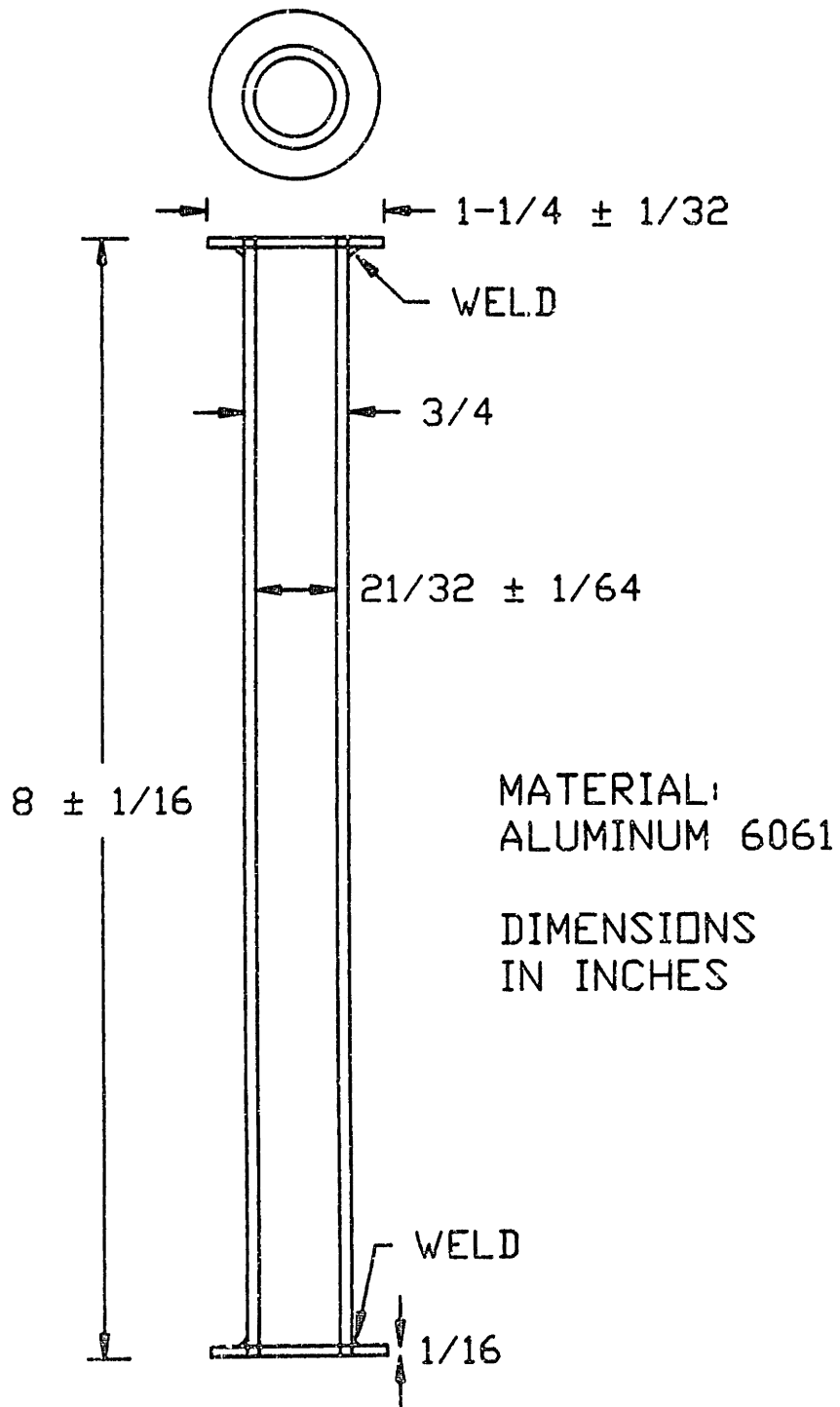
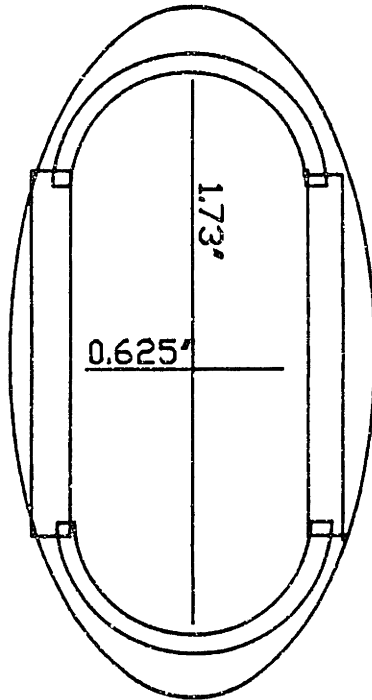


Figure A-11: Spools for Winding Level Gauge Coils



TUBE: 7/8" O.D., 0.061" WALL  
PLATE: 1/8" THICK, 1.17" WIDE,  
1/16" CORNER CUTOUT

LENGTH: 35-5/8"  
BOTTOM PLATE: 1/8" THICK



TOTAL LENGTH: 35-3/4"

Figure A-12: Cross Section of In-Core Titanium Bath Can

the elliptical section of the aluminum thimble. The length of the sides of the can is  $35\frac{5}{8}$ -inches; the bottom is  $\frac{1}{8}$ -inch thick. The overall length of the can is thus  $35\frac{3}{4}$ -inches. The welding was performed by Ramsay Welding and Fabrication of Woburn, MA.

A flat spacer collar, shown in Figure A-13, was machined from  $\frac{1}{8}$ -inch thick titanium plate and welded near the top lip of the can, so that the top of the can protruded  $\frac{1}{8}$ -inch past this collar. This collar rested on the bottom of the 4-inch section of the thimble and supported the titanium can. The purpose of the 135° profile of the collar was to prevent the collar from covering the elliptical streaming channel of the thimble. A  $\frac{1}{8}$ -inch thick,  $3\frac{1}{2}$ -inch diameter boral plate (with an elliptical hole through which the top of the titanium can protruded) was fastened to the top of this collar by a  $\frac{1}{4}$ -20 screw to attenuate the thermal neutron flux streaming up the thimble.

## GRAVEL BED CAN

The gravel bed can is shown in Figure A-14. Its purpose is twofold: to hold the gravel used to attenuate neutron and gamma streaming, and to serve as a framework from which the thimble internals such as the plena and piping could be supported.

The gravel bed was machined out of  $3\frac{1}{4}$ -inch OD,  $\frac{1}{4}$ -inch wall,  $2\frac{3}{4}$ -inch ID aluminum tubing. A  $\frac{1}{2}$ -13 hole was drilled and tapped across a diameter of the tube approximately  $\frac{1}{2}$ -inch from the top. A  $3\frac{1}{4}$ -inch length of  $\frac{1}{2}$ -13 threaded stainless steel rod (with a shallow slot at one end to allow use of a screwdriver) was inserted through this hole to form a lifting bar.

MATERIAL: 1/8 CP TITANIUM PLATE  
DIMENSIONS IN INCHES

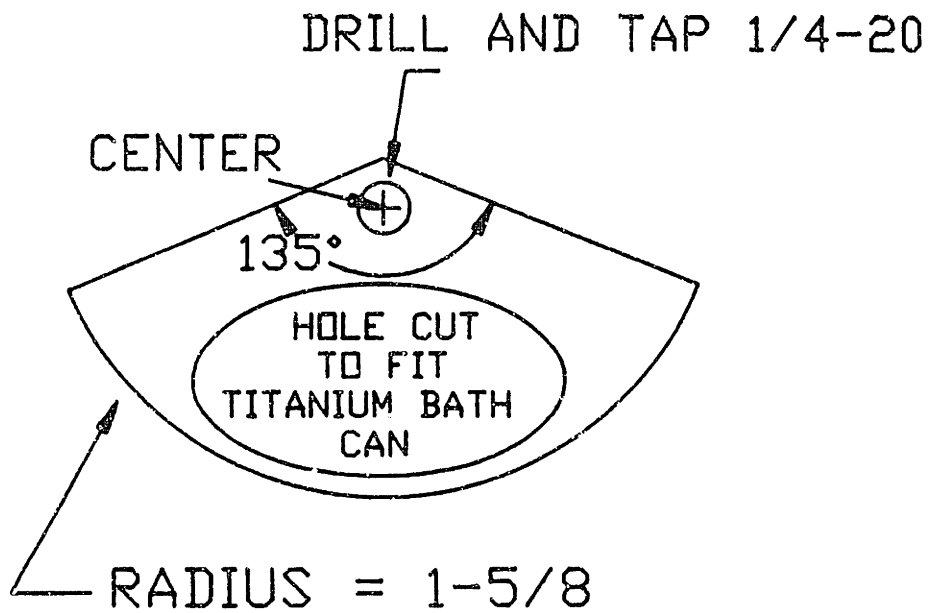


Figure A-13: Spacer Collar for Titanium Bath Can

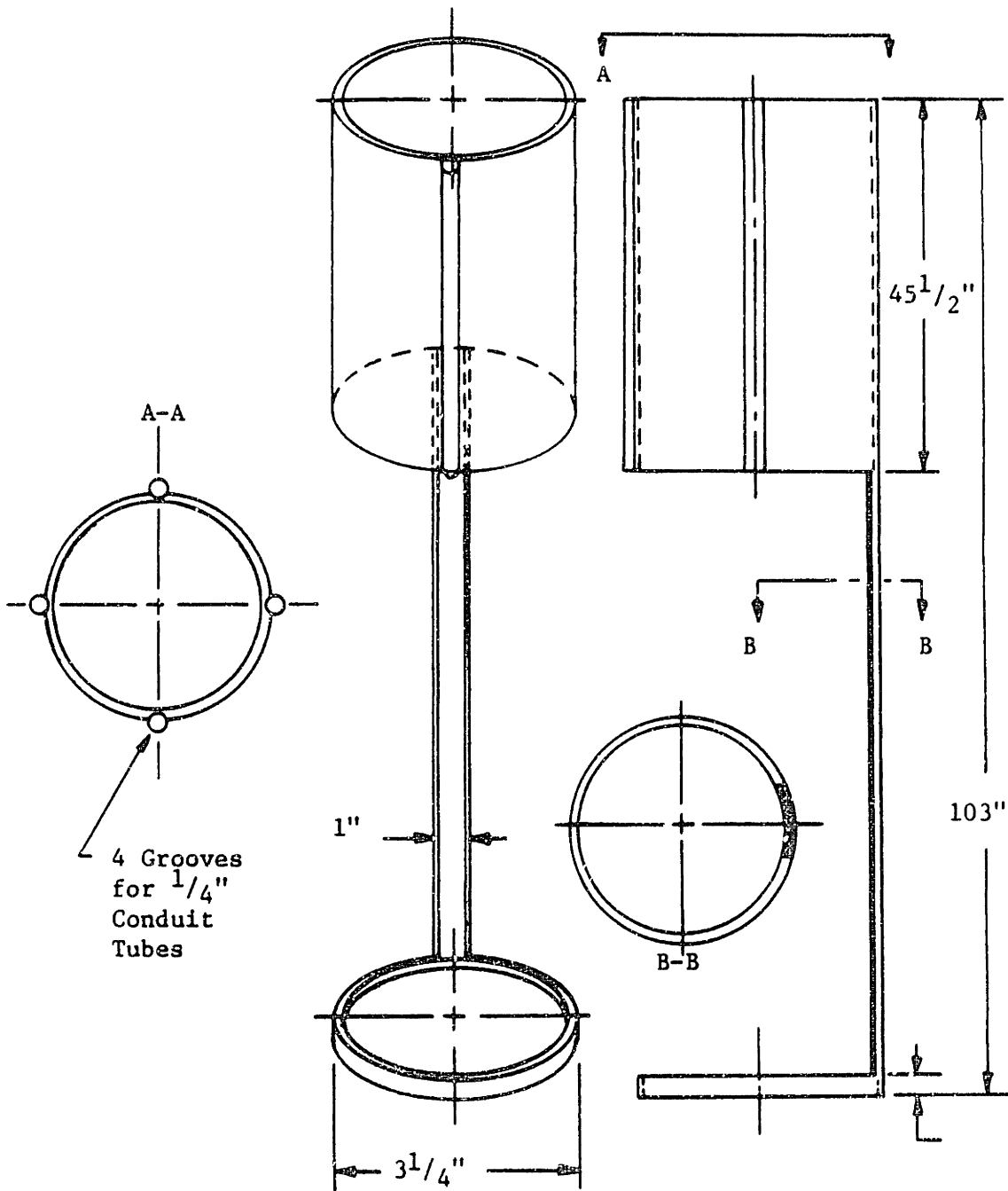


Figure A-14: Schematic of Gravel Bed Cannister for BCCL

Four vertical, hemispherical, evenly spaced grooves,  $\frac{1}{4}$ -inch diameter and  $\frac{5}{32}$ -inch deep, were machined the length of the upper enclosed portion of the gravel bed. Short  $\frac{1}{4}$ -inch diameter carbon rods were laid in these grooves approximately every foot, and a small aluminum weld bead was drawn nearly completely over the carbon rods. The carbon rods were then removed, and four  $45\frac{1}{2}$ -inch lengths of thin-walled  $\frac{1}{4}$ -inch OD stainless steel tubing were slid into the grooves. In this manner, the stainless steel tubes were mechanically fastened (by the non-bonding weld beads) to the aluminum can. These tubes served as conduits for chemical injection lines, sample lines, and electrical lines, and were found to stay relatively cool compared with the inside of the gravel bed. While this design was adequate, future gravel beds should be constructed with  $\frac{1}{8}$ -inch more (diametral) clearance between the stainless steel conduits and the thimble wall, to allow the gravel bed to move easily in and out of the thimble.

A thick weld bead was laid down on the inside of the lower lip of the enclosed portion of the can. On this lip rests the  $\frac{1}{4}$ -inch thick stainless steel plate shown in Figure A-15. Thin-walled stainless steel tubes extending the length of the enclosed portion of the gravel bed were welded into the  $\frac{3}{4}$ -inch and  $\frac{1}{4}$ -inch holes. These tubes serve as conduits through the gravel bed for the heater leads and the thermocouple leads. Bulkhead compression fittings were installed in the three  $\frac{29}{64}$ -inch holes. The three hot lines -- the feedwater, water outlet, and steam outlet lines -- pass through these fittings, which serve to support the lines, and form a gravel-tight seal around the lines.

The total volume of gravel in the gravel bed is approximately  $2\frac{1}{2}$  liters. The gravel used was a quartz gravel sold for swimming pool filters.

MATERIAL: S.S. 304 PLATE, 1/4" THICK  
(PRECISE PLACEMENT OF HOLES  
NOT CRITICAL)

(DIMENSIONS IN INCHES)

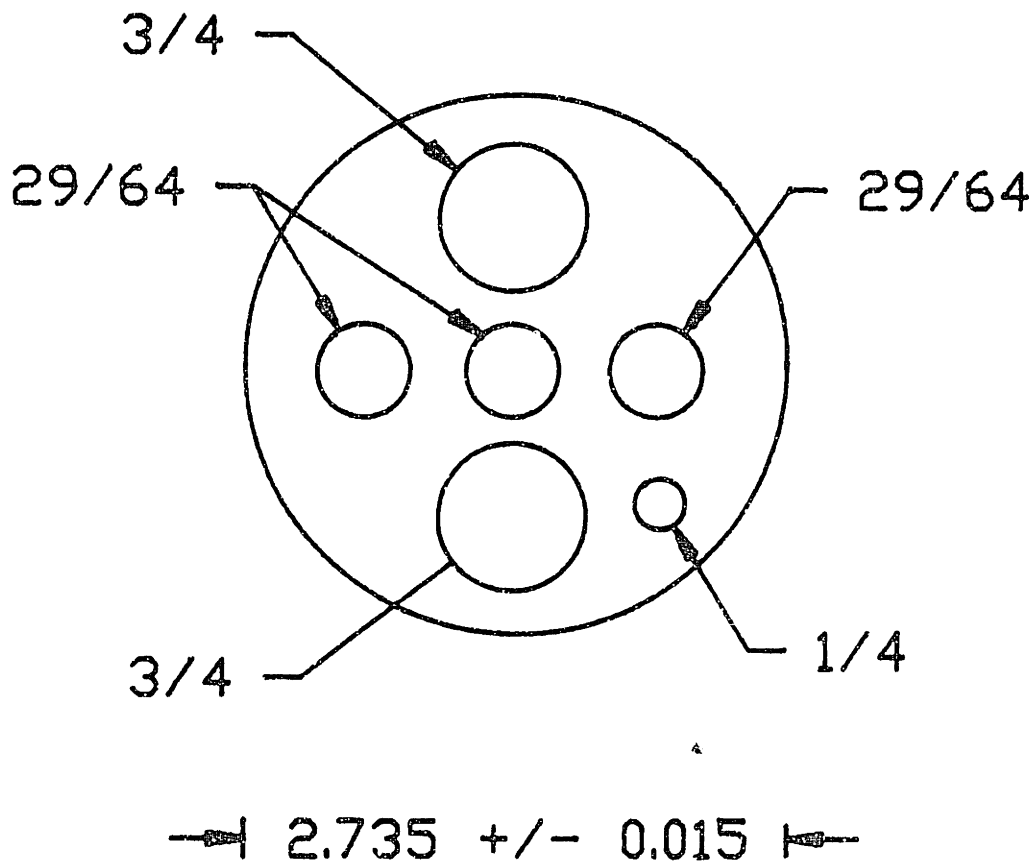


Figure A-15: Bottom Plate for BCCL Gravel Bed Cannister

A neutron activation analysis was performed to assay the constituents of the gravel, and it was determined that the dark colored pieces were activatable, while the light pieces were not. The gravel was then culled of dark pieces, sifted by size through wire mesh screens, washed in methyl alcohol, washed in deionized water, then dried, in preparation for use. The individual granules were approximately  $\frac{1}{8}$ -inch in diameter, and were roughly spherical. As in the case of the PCCL copper shot, small diameter particles were excluded, so that no particles small enough to pass between MITR fuel plates would be present.

## HEATER LEADS

The power leads for the in-core heater core made of  $\frac{1}{4}$ -inch OD, M.I. (mineral-insulated) cable. The electrical contact at the end of each length of M.I. cable had been removed from an Amphenol quick-connect connector, and brazed onto the end of the central conductor of the M.I. cable. Before use, the cables were baked in an oven at 350°F for several hours to drive off moisture, and the exposed magnesium oxide insulation was sealed with silicone rubber or high-temperature vacuum epoxy. These leads performed satisfactorily.

## OUT-OF-PILE FLUID SYSTEM

The out-of-pile fluid system is shown schematically in Figure A-16. It consists, essentially, of a supply tank (and associated cleanup systems), and a charging pump, which pumps water to the loop.

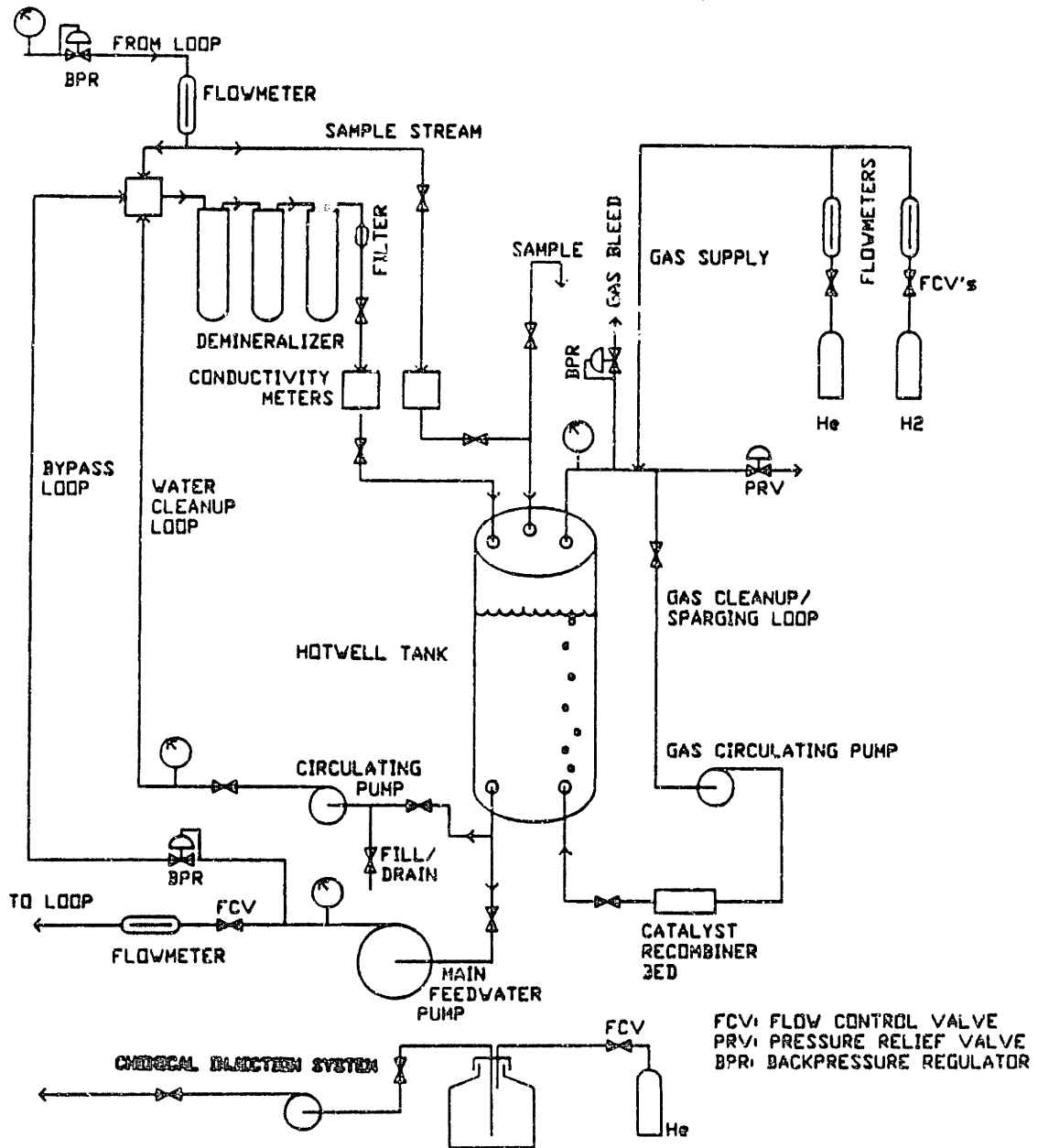


Figure A-16: Schematic of BCCL Out-of-Pile System



## Hotwell Tank

The hotwell tank is constructed of a 5 foot long, 10-inch OD, 1/4-inch wall, 9<sup>1</sup>/<sub>2</sub>-inch ID acrylic tube. The endcaps are flat pieces of 20% glass filled polycarbonate plate, 1 inch thick and 11 inches square (it is likely that titanium or electropolished stainless steel plates would also perform well as endcaps). These plates are held firmly against the ends of the cylinder by metal nuts on four threaded rods which extend the length of the tube. Flat rubber gaskets were used to seal the acrylic tubes to the end plates. Holes were drilled through the endplates for fluid penetrations, and tapped to accept NPT tapered fittings.

As shown in Figure A-16, the out-of-pile system has two cleanup loops, a gas cleanup loop and a water cleanup loop. The central element of the water cleanup loop is a 3-cartridge demineralizer unit manufactured by Barnstead (Nanopure model). It was found that two high-purity ion exchange cartridges followed by an organics removal cartridge performed satisfactorily.

The purpose of the gas cleanup loop is twofold: to recombine (with the hydrogen cover gas) any oxygen produced by radiolysis, and to bubble the cover gas through the liquid, so as to keep the dissolved gas levels in the liquid constant at their saturation values. To recombine the gases, a proprietary AECL teflon/platinum/carbon-matrix catalyst for wet gases was used.

The tubing and fittings used throughout were 1/4-inch nylon, to avoid metal contamination, and because of its relative ease of fabrication and modification. The only important exceptions were the gas supply lines, which were 1/8-inch nylon tubing; the bypass loop from the backpressure

regulator to the demineralizer, which was  $\frac{3}{8}$ -inch polyethylene tubing, chosen because of its flexibility and ability to absorb pressure pulsation; and the tubing from the tank to the main feed pump, which was  $\frac{3}{4}$ -inch OD,  $\frac{1}{2}$ -inch ID, clear PVC (polyvinyl chloride) resin tubing, selected for its flexibility. In addition, the inlet and outlet lines on the water circulating pump were  $\frac{1}{2}$ -inch OD,  $\frac{3}{8}$ -inch ID, clear PVC resin tubing. The valves used throughout the system were inexpensive polypropylene and PVC ball valves.

### Steam Plenum

The purpose of the steam plenum was to increase the volume of steam inside the lead shielding of the N-16 detector. This plenum was made from an approximately 9-inch length of  $\frac{5}{8}$ -inch OD,  $\frac{1}{2}$ -inch ID, titanium tubing. This length of tubing was bent downward at approximately  $20^\circ$  immediately after it exited the lead shield, to allow condensed steam to drain away from the section of tubing inside the lead shield. It was wrapped with  $\frac{1}{8}$ -inch thick woven glass tape, and coupled to the  $\frac{1}{4}$ -inch titanium steam line with compression fittings. This plenum greatly increased the sensitivity of measurements made with the N-16 detector system.

### Chemical Injection System

The additive injection system is shown at the bottom of Figure A-16. Its purpose is to allow the injection of small quantities of additives immediately upstream of the core section of the loop in order to evaluate their effect on BWR radiochemistry.

The fluid for injection is supplied from a polyethylene container equipped with a helium cover gas. The fluid flows to the injection pump through a 1/8-inch OD nylon line. The injection pump is a double-headed sapphire plunger metering pump of a type used for liquid chromatography, manufactured by Milton Roy (model No. 92014903), and is capable of delivering 920 ml/hr. at high pressure. The line at the pump outlet is a length of 1/16-inch OD, 0.010-inch ID PEEK (polyetheretherketone) tubing, which extends to the pump pod at the top of the thimble. The fluid is carried through 1/16-inch OD, 0.020 inch ID stainless steel tubing down the thimble, and is injected into the flow path of the coolant through a modified O-ring fitting just upstream of the core.

### Hot Line Sample Taps

The hot line sample taps allow samples to be drawn from the steam and water exit lines at a point outside of the core tank of the MIT reactor. Each sample tap consists of a four-turn, four inch-diameter helical coil of 1/4-inch OD, 0.194-inch ID titanium tubing, which communicates with the flow stream via a tee compression fitting. At the end of this coil is a low-flow flow control valve, out of which the sample is taken. The coils are arranged so that a box containing ice water can be placed around them, to cool the sample streams.

### Heat Exchangers

The BCCL contains two heat exchangers, a regenerative heat exchanger (to transfer heat from the fluid returning from the in-pile heated

section to the fluid flowing into the loop), and a non-regenerative heat exchanger (to reject excess heat from the fluid returning to the hotwell tank). The regenerative heat exchanger has approximately 20 feet of heat transfer length, and is of a counterflow tube-in-shell design. It is shown in Figure A-17. It was constructed with titanium as both the tube and the shell material, and is described by Baeza (B-1).

The non-regenerative heat exchanger is of a similar design, except that the shell side is 3/4-inch OD copper pipe. The secondary side flowrate is approximately 4 gpm, supplied from the reactor secondary side cooling system by a small centrifugal pump.

### Feedwater Heater

The purpose of the feedwater heater is to heat the water flowing into the in-pile section up to BWR core inlet conditions. It consists of a 3-inch OD, 1/8-inch wall, 2 3/4-inch ID, 3 foot long stainless steel tube, which has a cap welded onto the lower end. Three rod heaters (manufactured by Chromalox), each 2 1/2 feet long, 3/4-inch diameter, and with a resistance of 12 ohms, were inserted into this bath through holes in a steel cap. The feedwater line, made of 1/4-inch OD, 0.194-inch ID titanium, is bent into a zigzag "paper clip" configuration. It has 6 legs, each 2 1/2 feet long, and is inside the feedwater heater shell, entering and exiting through holes in the steel cap. The heat transfer fluid is a 89%-11% tin-zinc eutectic alloy with a melting temperature of 198°C. The three heaters are wired in parallel, and are capable of delivering a total of 7500 watts with a current of 50 amperes. After leaving the feedwater heater, the water flows directly to the in-pile section. This feedwater heater is described more fully in (O-1).

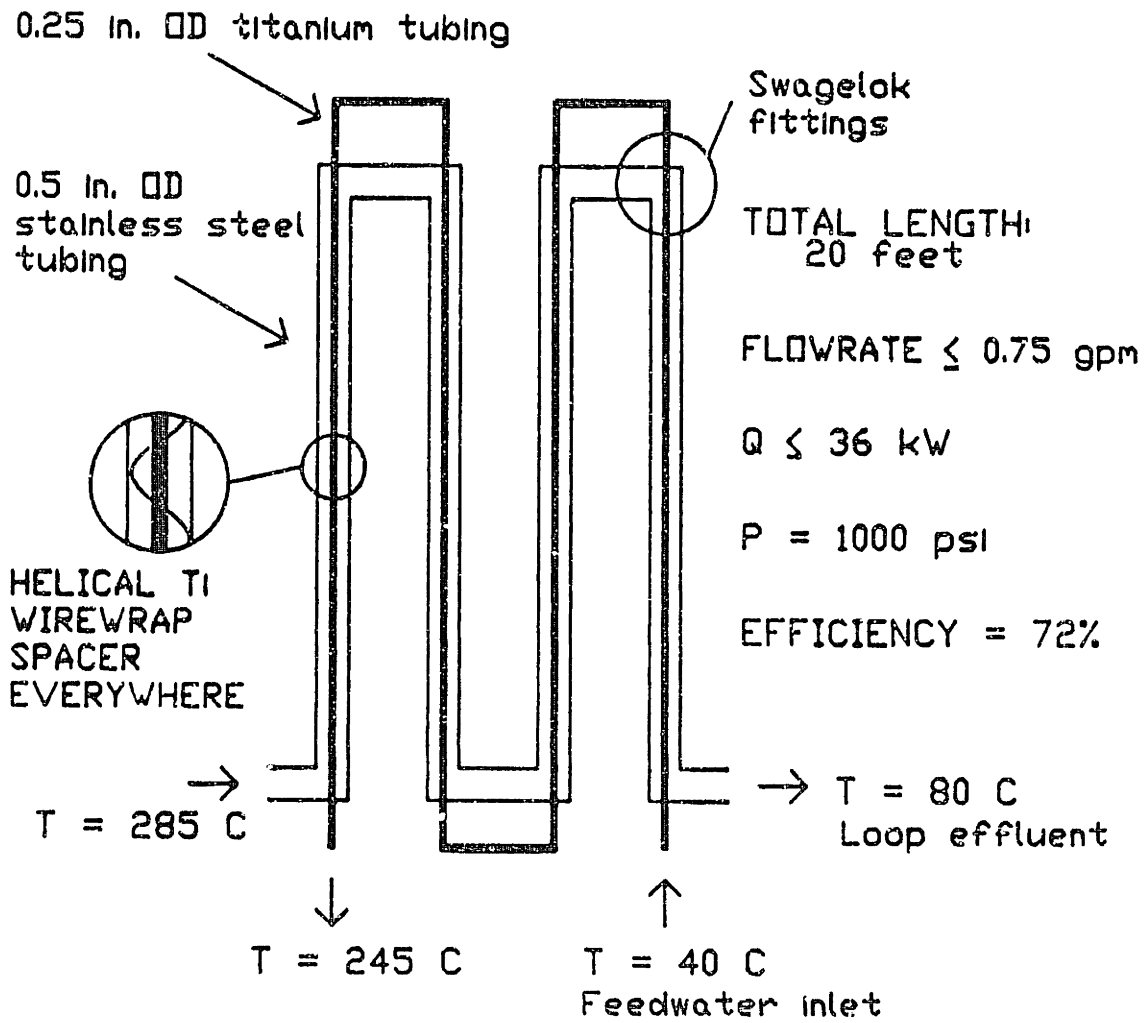


Figure A-17: Regenerative Counterflow Heat Exchanger for BCCL

## Proposed Metal Bath for Thermal Transient Damping

As described in Section 5, the fluid system was found to be highly sensitive to thermal-hydraulic transients. An increase in the steam flowrate from the in-core section to the regenerative heat exchanger increased the enthalpy of the feedwater leaving the heat exchanger and flowing to the feedwater heater and the in-core section. Since the feedwater heater and core heater temperature and heat fluxes were roughly constant on the time scale of this perturbation (approximately 3-5 minutes), the higher specific enthalpy of the water entering the core was translated into a higher core exit quality. This higher exit quality again tended to increase the specific enthalpy of the feedwater, via the heat exchanger; but meanwhile, both the feedwater and core heaters, under automatic control, were reducing power, exacerbating the disequilibrium. In short, the system was unstable.

According to the analysis of Section 4, it is believed that adding a thermal mass on the feedwater line between the regenerative heat exchanger and the feedwater heater would greatly increase the stability, and hence controllability, of the system.

Such a thermal mass would be similar in design to the feedwater heater, with suggested characteristics as follows, starting with a copper or steel tube 3 feet long and two inches in diameter, with a cap brazed or welded on the bottom end. A single stick heater, 2<sup>1</sup>/<sub>2</sub> feet long, is inserted into this shell, for initial heatup only. The feedwater line, made of 1/4-inch OD titanium tubing, is bent into a zigzag "paper clip" configuration, with four legs, each 2<sup>1</sup>/<sub>2</sub> feet long. The tube is filled with 25 pounds of lead (at the temperature of this bath, approximately 220°C, lead would be greatly preferable to tin-zinc alloy because lead (with a melting point of

327°C) would not require melting, and hence startup would be much faster). Ideally, the bath could be filled with an alloy with a melting point slightly above the operating temperature of the bath (i.e., the outlet temperature of the regenerative heat exchanger). Then, any temperature rise would be arrested by the phase transformation of the alloy. This would be difficult to achieve, however, as each different outlet quality at which the loop is run requires a different temperature at the regenerative heat exchanger outlet. Hence, a single-phase lead bath is probably more appropriate.

This proposed thermal mass is shown schematically in Figure A-18.

### Steam Orifice Flowmeter

The steam orifice flowmeter is designed to measure the steam flow rate from the outlet plenum, and is located on the steam line immediately after the line exits the N-16 detector. It consists of a small orifice through which the steam is forced to flow, and a differential pressure meter (manufactured by Orange Research; Model No. 1516DG-1C-2.5L-0-30 psid) which measures the pressure drop across the orifice. This pressure drop is then translated into a steam flow rate using a calibration curve.

The flowmeter is shown schematically in Figure A-19. The orifice disk itself is made of stainless steel or titanium, and is  $\frac{1}{4}$ -inch in diameter,  $\frac{1}{32}$ -inch thick, and has a  $\frac{1}{16}$ -inch hole drilled through its center. The disk is oriented so that the steam flows vertically down through it, to prevent water from building up behind it. The disk is held in place by two pieces of  $\frac{1}{4}$ -inch OD, 0.194-inch ID which are butted together. A small

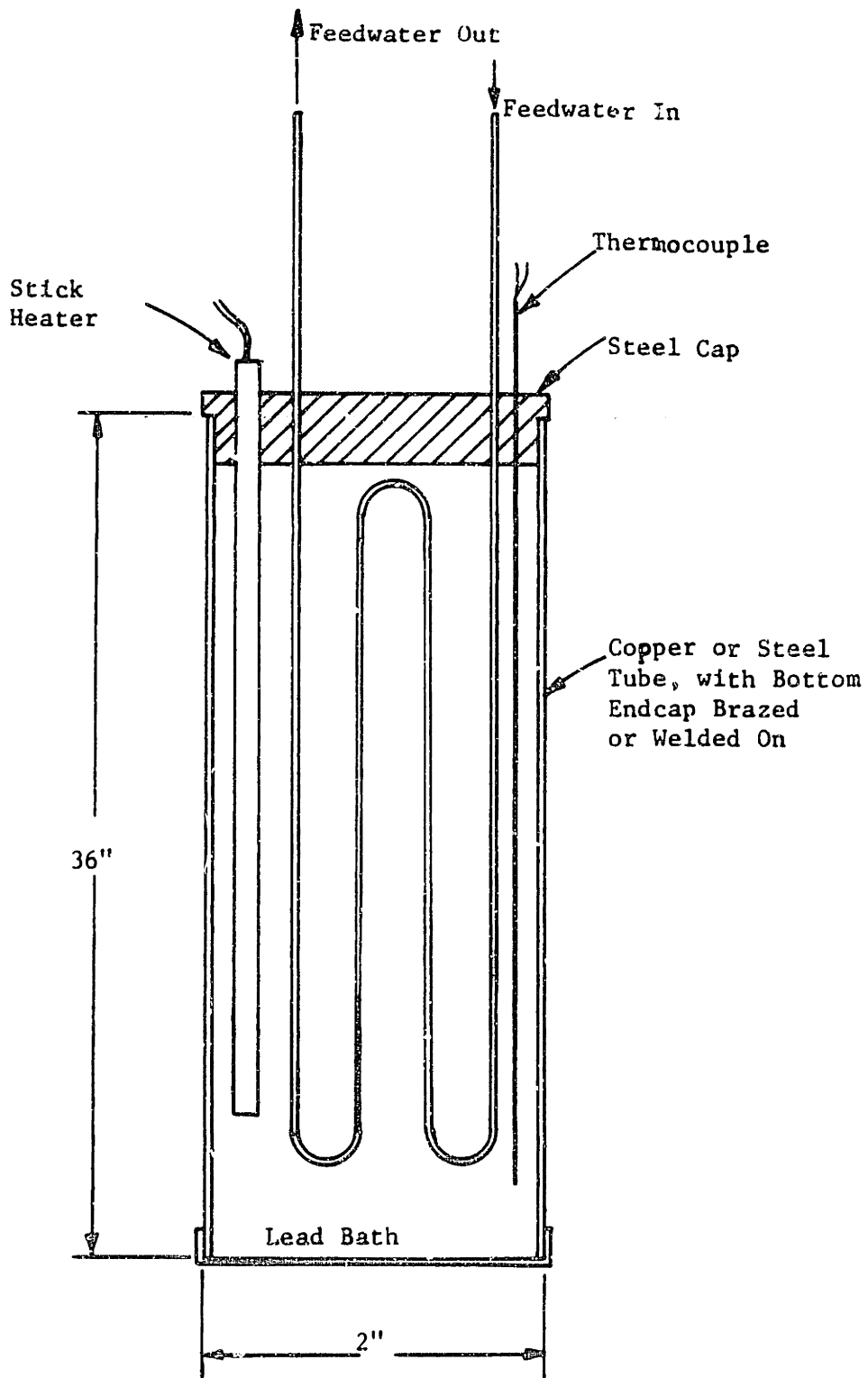


Figure A-18: Schematic of Proposed Metal Bath for Thermal Transient Damping



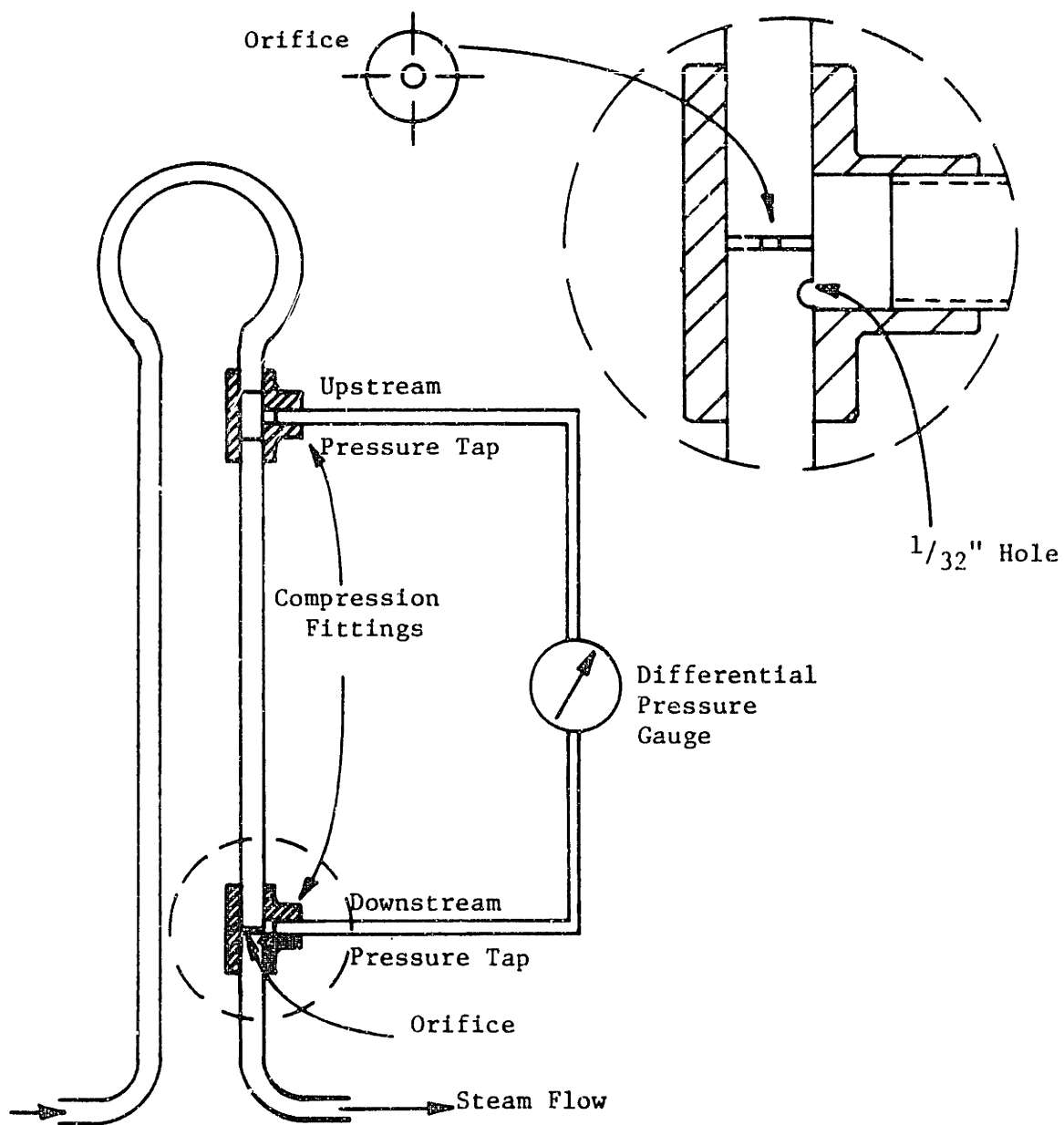


Figure A-19: Schematic of Orifice Flowmeter for BCCL

hole has been drilled in the tube immediately after the disk to allow communication with the downstream pressure tap.

The calibration curve for this flowmeter is shown in Figure A-20. This calibration curve was produced by passing different known steam flowrates through the orifice flowmeter, and measuring the corresponding pressure drops. Condensed (water) flowrates, were easily measured using a simple rotameter; the water flow, when evaporated and slightly superheated, gave a known steam flowrate.

A more complete description of the orifice flowmeter is given by Baeza (B-1). The outer shell of the flowmeter is constructed of two union tee compression fittings and 1/4-inch OD, 0.028-inch wall, 0.194-inch ID titanium tubing.

## LEAD SHIELD BLOCK FOR N-16 DETECTOR

The purpose of the lead shield block is to shield the NaI (TI) detector crystals from background radiation on the reactor top. The shield block weighs approximately 1000 lb., and is shown in Figure A-21.

As shown in the figure, the large cavities hold the detector crystals, and are capped at the end with removable lead plugs. Each plug has a wiring hole drilled through it at an acute angle, to prevent radiation from streaming into the cavity holding the detector. At the other end of each detector cavity, a smaller hole intersects the cavity at right angles. The steam and water lines pass through these holes, and thus shine directly onto the detector crystals. The block also has two 3/4-10 threaded rods which extend almost the entire height of the block. The block can be lifted using screw fittings threaded onto these rods.

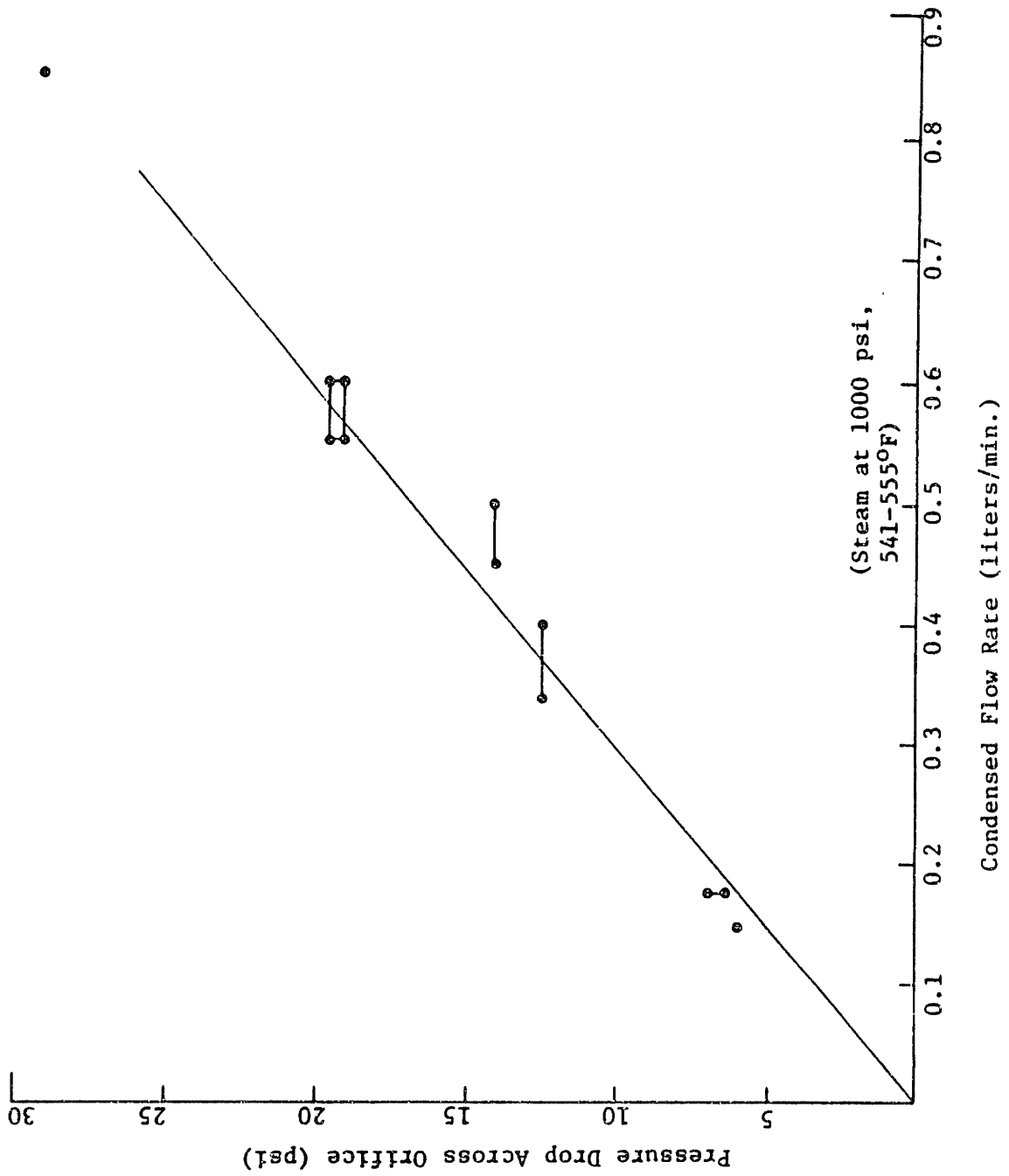


Figure A-20: Calibration Curve for Orifice Flowmeter

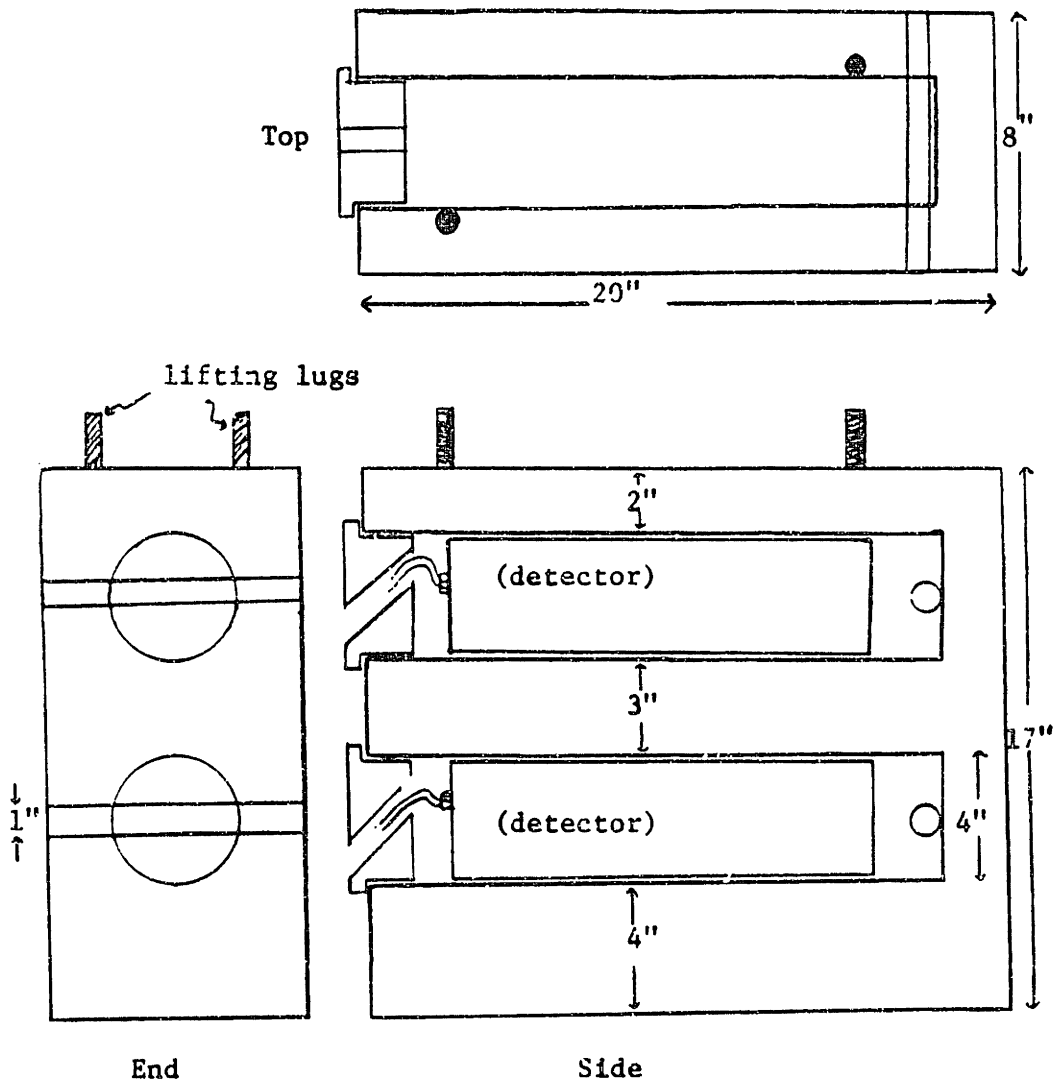


Figure A-21: Lead Shield Block for N-16 Detector

The mold for casting the block was made of 3/4-inch thick plywood, and had a double bottom (the block was cast on its side in order to minimize the hydrostatic pressure of the liquid lead, so the bottom of the mold corresponds to the side of the block). The 4 inch diameter cavities were formed by two lengths of 4 inch OD, 3 3/4-inch ID copper pipe with copper endcaps. The ends of these pipes were drilled through to accept two lengths of 1 inch pipe at right angles to their ends. Both assemblies were firmly bolted into the wooden mold at an appropriate position, and were filled with sand to prevent their filling with molten lead. The lifting rods were inserted through holes drilled in the side of the mold, and secured in place by iron wire. The seams of the wooden mold were caulked with furnace clay to prevent leakage. The actual pouring of the lead was done at Somerville (MA) Smelting, with the lead heated to a temperature of approximately 640°F, slightly above its melting point of 621°F. After pouring, the wood and sand were removed from the casting, and the casting was cleaned and painted.

## LEVEL DETECTOR ELECTRONICS

The purpose of the level detector electronics is to convert the variable ac waveform output of the secondary windings to a 0 to 10 volt dc signal which varies linearly with the position of the float. The circuitry has been designed with the following goals (A-2):

- Measurement over the 16-inch span of the plenum level.
- Minimization of penetrations for wiring.

- Ability to sense the failure of:
  - a) Either of the two coil voltage sources.
  - b) Step-down transformers.
  - c) Wiring to primary windings.
  - d) Primary windings themselves (i.e., an open circuit).
- Adjustable gain for both secondary winding signals.
- Adjustable overall gain.
- Adjustable High Level and Low Level alarm outputs.
- 0-100 mA output for a meter.
- 0-10 Vdc output for computer control and data-logging.
- Ability to test the full range of output and alarms without having to change actual plenum level (after initial adjustment).
- Immunity to extraneous electrical noise.

A block diagram of the electronics is shown in Figure A-22. Two power supplies have been provided for high reliability. Both upper and lower primary windings have trouble sensing circuits which activate relays if there is an open circuit. This has been provided since erroneous level readings will result upon failure of the primary windings. To provide immunity to electrical noise, the first signal processing stage is a Second-Order Butterworth low pass filter. The next signal stage is a peak-detection circuit whose output is a dc voltage proportional to the peak value of the ac voltage input. An adjustable-gain amplifier is the next block (this high-gain amplifier allows the use of a constant low gain in the peak-detection circuit). The lower coil signal is then inverted by a second

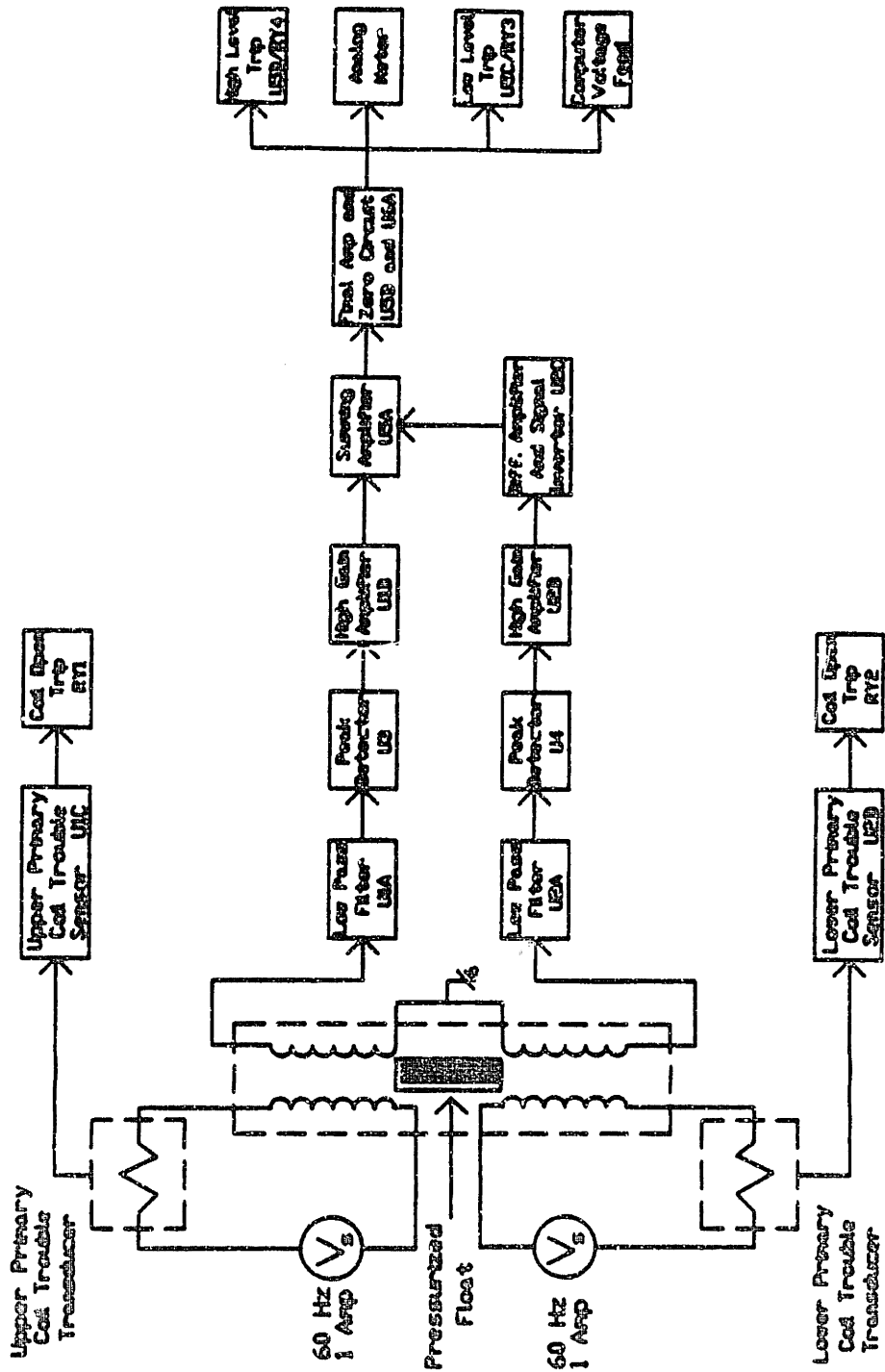


Figure A-22 Block Diagram of Electronics for BCCL Level Detector

amplifier (as its input goes from 0 to 5 volts, its output goes from 5 to 0 volts). The upper and lower coil signals are fed to the summing amplifier. An adjustable high gain amplifier follows the summing stage. The output of this stage is a 0 to 10 Vdc signal which varies approximately linearly with the plenum level. This signal drives a 100 mA meter and the 0 to 10 Vdc analog-to-digital converter board on the datalogging computer. Two full-range adjustable comparators are provided to give high- and low-level alarms with individual relays. A push-button test signal and a full-range, adjustable test signal are provided. These allow testing of the meter and the 0 to 10 Vdc computer input, as well as both the high and low level alarms, without changing the actual plenum level.



**APPENDIX B**  
**COMPONENT SUPPLIERS AND FABRICATORS**

Angle iron. Part No. 73-704AP. For making framework for out-of-pile system. C & H Distributors, Milwaukee, WI. (800) 558-9966.

Backpressure regulator. Part No. 102790. Low pressure; used on hotwell tank. J. H. Bertram & Co., Bloomfield, CT.

Backpressure regulators. 54-2124-W24. Manufactured by Tescom; distributed by Northeast Engineering, Falmouth, MA. (508) 540-9555.

C-rings, lead plated; Part No. ECI-003985-10-07-2-LPB. For flange of thimble. Advanced Products, North Haven, CT. (800) 243-6039.

Catalyst. "Wet-proofed" Catalyst. Used for catalytic gas recombiner. Commercial Operation Division, Chalk River Laboratories, Chalk River, Ontario, Canada. (613) 584-3311.

Conductivity meter and flow cell. Part No. N-05970-42. Used on out-of-pile system. Cole-Parmer, Chicago, IL. (800) 323-4340.

Copper tube with endcaps, 4 inch OD, 1/8 inch wall. For lead shield block for N-16 detector. Boston Pipe and Fitting, Cambridge, MA. (617) 876-7800.

Differential pressure gauge. 1516DG-1C-2.5L-0-30 psid. Used for orifice flowmeter. Orange Research, Milford, CT. (203) 877-5657.

## Electric connectors.

For heater leads. MS-3106-A-28-5-S. Manufactured by Amphenol.

For signal feedthroughs on lid. 38F302. Manufactured by Amphenol; distributed by Newark Electronics, Woburn, MA. (617) 932-9040.

## Fittings.

Ultratorr (rubber) O-ring fittings for thimble lid; snubbers for pressure gauges; nylon fittings for out-of-pile system; metal valves. Manufactured by Swagelok; distributed by Cambridge Valve and Fitting, Billerica, MA. (617) 272-8270.

Conax fittings. Used for lid feedthroughs. Manufactured by Conax, distributed by Charles T. Morgan Co., Hathorne, MA. (508) 774-3215.

Compression fittings, Ultraseal O-ring fittings. Manufactured by Parker, distributed by Harbor Controls, Chelmsford, MA. (508) 453-2323.

## Flowmeters.

High pressure. L-03209-02. Used on outlet of feedwater pump. Gas, low-flow. N-03219-50. Used on gas inlet to out-of-pile system.

Water. L-03232-25. Used on out-of-pile system. Cole-Parmer, Chicago, IL. (800) 323-4340.

Fuses. A50P50. For feedwater heater power supply. Hillco, Allston, MA. (617) 783-2600.

Glass for level detector float construction. 513-1PP-9; NMR sample tubes. Wilmad Glass, Buena, NJ. (609) 697-3000.

#### Heaters.

Cartridge. CIR-5300. Used for feedwater heater.  
Stick. TSSM-30. Used for gravel bed heater. Manufactured by Chromolox; distributed by Leo Pelkus Inc., Wellesley Hills, MA. (617) 235-8040.

Core heater and power supplies. Delta M Corp., Oak Ridge, TN. (615) 483-1569.

Hydrogen peroxide measuring ampoules. Part No. R-5503. Chemetrics Inc., Calverton, VA. (703) 788-9026.

Ionization chamber. 5016. Used for gamma detector. LND, Oceanside, NY. (516) 678-6141.

Lead casting. Used in fabrication of lead shield block. Somerville Smelting, Somerville, MA. (617) 623-0050.

Level detector coils, wire and winding. Permaluster, Burbank, CA. (213) 849-4543.

Mineral-insulated cable.  $1/4$  inch OD;  $1/16$  inch OD. Used for heater leads and electrochemical probe leads, respectively. Delta M Corp., Oak Ridge, TN. (615) 483-1569.

O-rings, nitrile. 2-240, 4 inch OD. Used for flange of thimble. I.B. Moore Co., Cambridge, MA (617) 491-0100.

Oxygen, hydrogen meters. Orbisphere, Emerson, NJ. (201) 265-4900.

## **Plastic.**

**Tube, acrylic; 10 inch OD, 1/4 inch wall. For hotwell tank.  
Plate, 20% glass-filled polycarbonate; 1 inch thick. Hotwell tank  
endcaps.**

**Tubing, nylon, Type H. For plumbing hotwell tank. AIN Plastics,  
Norwood, MA. (617) 769-9050.**

**PEEK (polyetherether ketone) tubing. Used for sampling system  
and sample injection system. Upchurch Scientific, Oak Harbor, WA.  
(800) 426-0191.**

**Valves. Used for out-of-pile system. Cole-Parmer, Chicago, IL.  
(800) 323-4340.**

**Pressure gauges. Manufactured by McDaniel; distributed by Northeast  
Engineering, Falmouth, MA. (508) 540-9555.**

## **Pumps.**

**Valveless pumps for out-of-pile system gas and water circulation.  
Part Nos. N-07114-76, N-07104-68. Cole Parmer, Chicago, IL  
(800) 323-4340.**

**Main feedwater pump. Model 290. Manufactured by Cat Pump;  
distributed by Previte Supply, Cambridge, MA. (617) 776-2200.**

**Injection metering pump. MiniPump. Model No. 92014903. Used  
for chemical injection. Manufactured by Milton Roy; distributed by  
Rainin, Woburn, MA. (617) 935-3050.**

**Quartz gravel. Used for gravel bed. Puraqua Pool Service Inc., 5 Central  
Avenue, Waltham, MA. (617) 893-6300.**

Rod, threaded; 1/2-13, stainless steel. For pulling die through elliptical section. Accurate Fasteners, South Boston, MA. (617) 268-8300.

Rod, threaded, 3/4-10, cadmium-plated steel. For lead shield block for N-16 detector. Boston Pipe and Fittings, Cambridge, MA. (617) 876-7800.

Stainless steel and aluminum tubing. Tubesales, Hartford, CT. (800) 243-0173.

Stainless steel tubing, 1/16 inch OD, 0.020 inch ID. Used for sample extraction and injection. Upchurch Scientific, Oak Park, WA. (800) 426-0191.

Thermocouples.

Long lead. Used in thimble. Delta M. Corp., Oak Ridge, TN. (615) 483-1569.

Short lead, thermocouple wire and connectors. Used in out-of-pile system. Omega Engineering, Stamford, CT. (800) 826-6342.

Titanium. President Titanium, Hanson, MA. (617) 294-0991.

Water purification system. N-01505-30. Manufactured by Barnstead; distributed by Cole-Parmer, Chicago, IL. (800) 323-4340.

Welding of titanium. Ramsay Welding and Fabrication, Woburn, MA. (617) 933-4900.

## APPENDIX C: DATA FROM IN-PILE RUNS

Representative data is presented in the extracts which follow; complete data sets from the in-pile runs are on file in the project office (NW13-260, MITNRL).

### NORMAL WATER CHEMISTRY

#### Hydrogen Peroxide Measurements

These are the measured concentrations, and have not been corrected for decomposition of the hot samples (Section 4). Approximately 40% of the hot samples decomposed when passing through the sampling device. The only samples in which decomposition did not take place are those taken from the charging tank.

	NWC	HWC	NWC w/ KOH
outlet plenum	219 ppb 138 ppb 71 ppb 190 ppb 175 ppb 117 ppb 87 ppb 80 ppb	120 ppb 55 ppb 66 ppb 45 ppb 90 ppb	50 ppb 17 ppb 38 ppb
downcomer plenum	200 ppb 153 ppb 203 ppb 219 ppb	42 ppb 47 ppb 50 ppb 37 ppb	45 ppb
steam line			62 ppb
water line			74 ppb
charging tank	175 ppb 115 ppb 87 ppb	27 ppb	10 ppb
outlet plenum: hot, single-phase loop operation	5000 ppb 4800 ppb	110 ppb 100 ppb	800 ppb

## N-16 MEASUREMENTS

The following counts are each for 1 minute. Typical values for the three runs are presented. These counts are not directly comparable, as the discriminator settings were changed between runs; ratios of counts from the same run, however, generally may be compared. The volume of the steam plenum (and hence the counts on the steam line) was increased by a factor of 6.64 before the KOH injection run commenced. The counts listed have not been corrected for background (approximately 3400 counts). Approximately 20 minutes after KOH injection was initiated, the counts in the steam line went up by approximately 50%; this is believed to have been caused by water entering the steam line (level indication was not available at that point).

NWC		HWC		NWC w/ KOH		(Comments)
water	steam	water	steam	water	steam	
114240	7655	78494	15942	93448	10877	Steam plenum was enlarged before KOH run
107951	6845	86036	12332	104240	11421	
111721	9808	85570	11391	104876	10498	
112837	5421	87821	13722	97022	10057	
114689	5732	92832	16286	92048	10487	
116925	9455		15440	106171	13760	
112652	6257		16322	107291	11251	
116410	6720		18025	105711	10079	
129896	6813		15586	102616	10561	
128191	7761		14344		17218	
	6310		19232		19976	
	4093				14642	
	6568				18833	

<sup>1</sup>Here steam line readings for the KOH run started to increase (increased water carryover into steam line suspected).

## ECP MEASUREMENTS

The ECP measurements are not believed to be accurate, for reasons discussed in Section 4. Typical measurements (platinum electrode vs. silver-silver chloride reference electrode) were, for the most part, approximately -0.007 V, although they drifted as high as 0.069 V immediately after KOH injection commenced. Major potential differences were not observed between the platinum, stainless steel and silver-silver chloride electrodes. Complete sets of ECP data are on file in the project office.

## APPENDIX D

### CALCULATIONS OF NEUTRON ENERGY DEPOSITION RATES IN THE MIT REACTOR

A simple energy balance should yield a fairly reliable estimate for the gamma and fast neutron dose rates in the MITR-II core, and hence in the in-pile loops inserted in it.

Let  $\bar{q}_z'''$  = axial average power density in MITR core,  
kw/liter (50)

$f_g, f_n$  = fraction of fission energy released as  
gammas and fast neutrons, respectively  
(0.10, 0.024)

$F_g, F_n$  = fraction of gamma and neutron energies  
absorbed in core water, respectively (0.23, 0.95)

$P_g, P_n$  = leakage probability from core for gammas  
and fast neutrons, respectively (0.05, 0.05)

$r$  = density of water in MITR core, g/cc (0.986)

Then the dose rate in water, whose radiolytic chemistry is the subject of present interest is as follows (in R/hr, where 1 R = 100 ergs/g = 0.01 Gray (Gy) =  $10^{-8}/3.6$  watts/g)

$$\bar{D}_z = 3.6 \times 10^8 \bar{q}_z''' f(1-P) F/r, \text{ R/hr}$$



Using the parameter values cited in parentheses above, we have the following mean axial dose rates in water:

$$\bar{D}_{Z, g, H_2O} = 4.0 \times 10^8 \text{ R/hr} \approx 1.1 \text{ watts/g H}_2\text{O}$$

$$\bar{D}_{Z, n, H_2O} = 4.0 \times 10^8 \text{ R/hr} \approx 1.1 \text{ watts/g H}_2\text{O}$$

Peak axial values are about 1.8 times the above, or ~2 watts/g H<sub>2</sub>O, in relatively good agreement with measured gamma heating in aluminum in the MITR-II (Z-1).

Notes:

- (1) Gammas include prompt and decay contributions plus, a capture contribution estimated as follows (A-1, S-4):

Total non-fission absorptions per fission  $\approx \xi-1 \approx 1.5$ .

Mean capture gamma energy in core material (principally U-235, Al, H)  $\approx 5 \text{ Mev}$

Thus, we have per fission:

Prompt g (U-235)	=	6.97 Mev
Delayed g (U-235)	=	6.33 Mev
Capture g	=	7.5 Mev
Total		20.8 Mev

Note that we have ignored gammas from inelastic scattering of neutrons. Thus, if total energy/fission  $\approx 200$  Mev, the fraction carried by gammas is 0.10.

- (2) The fraction of total gamma energy absorbed in water is just the mass fraction water in the core, if we assume that  $(\mu_a/\rho)$  is approximately the same for all core materials.
- (3) Neutron energy absorption is primarily in water because its value of  $\Sigma$  for elastic scattering is much larger than that of other core components.

$$(\Sigma)_{\text{H}_2\text{O}} \approx 1.53 \text{ cm}^{-1}$$

$$(\Sigma)_{\text{Al}} \approx 0.006 \text{ cm}^{-1}$$

Again, we ignore moderation by inelastic scattering.

In addition, approximately the same mean dose rates were arrived at using MCNP (E-1), a Monte Carlo neutron code. The neutron dose profile to the coolant calculated using this code is shown in Figure D-1, and is in good agreement with the calculation outlined above.

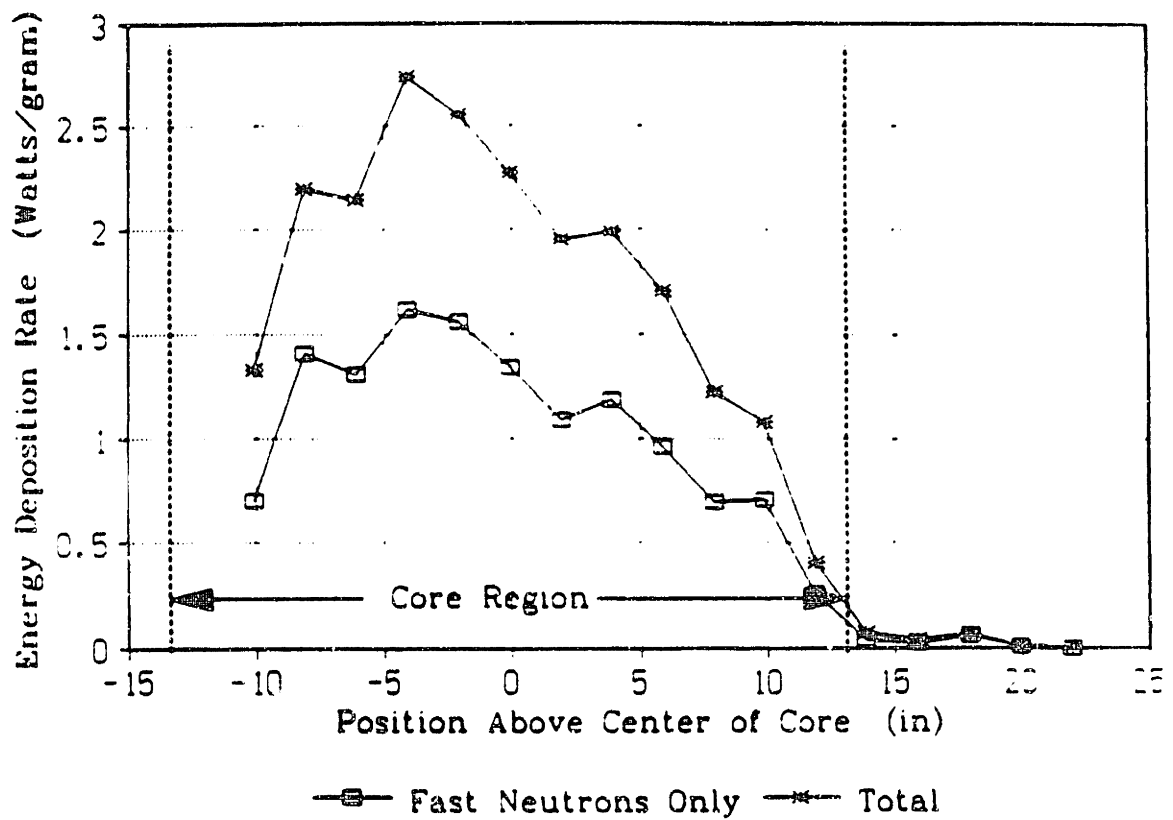


Figure D-1: Neutron Dose Rate to Coolant in MIT Reactor (F-1)

## APPENDIX E: ESTIMATION OF CARRYUNDER USING Ar-41

The carryunder of steam into the water line of the BCCL may be estimated using the ratio of Ar-41 activities in the steam condensate and in the water. It should be noted that Ar-41 is volatile, and tends to escape the samples unless they are kept under pressure during sampling and counting.

The ratio of the concentrations of dissolved gas per unit mass of vapor and liquid phases is (at equilibrium) given by Henry's law as

$$B = \frac{H}{p} \quad (E-1)$$

where  $H$  = Henry's law constant (values are available in the literature (H-1)), and

$p$  = system pressure.

For the BCCL,  $B = 115$  (approximately).

Let

$c$  = the equilibrium concentration of gas in the steam; then

$c/B$  = the equilibrium concentration of gas in the water.

For a steam-water mixture such as that expected in the water line due to carryunder, let

$w$  = the weight fraction of steam in the water sample (i.e., "carryunder").

Then the concentration of argon gas in the water sample will be

$$C = wc + (1-w)\frac{c}{B} \quad (E-2)$$

where the first term is the contribution from the entrained steam, and the second term is the contribution from the water. Rearranging gives

$$w = \frac{BC - 1}{B - 1} \quad (E-3)$$

The ratio  $C/c$  is the ratio of Ar-41 activities per gram of sample for the liquid line and steam line samples, respectively. Note that  $(C/c)B = 1$  only when carryunder is 0.  $(C/c)B$  cannot be less than 1 if the concentrations are at equilibrium.

An attempt was made to apply this equation to measurements made on the BCCL. The ratio  $C/c$  of Ar-41 activities was measured to be 0.154; application of eq. E-3 gives the carryunder as  $w = 0.147 = 14.7\%$ , which is much larger than plausible. It is considered highly likely that Ar-41 escaped from the condensed steam sample, which caused a substantial underestimate of  $c$ , and hence an overestimate of  $C/c$ .

Measurements could, in principle, be made using other gases, such as  $H_2$  or  $O_2$ . However, our Orbisphere meters require too high a sample flow rate to make this practical.

**Repeat of the Ar-41 ratio method is recommended using in-line bomb samples during the next several BCCL runs.**

## **NOMENCLATURE**

### **Abbreviations**

<b>AECL:</b>	<b>Atomic Energy of Canada, Limited</b>
<b>BCCL:</b>	<b>BWR Coolant Chemistry Loop</b>
<b>BWR:</b>	<b>Boiling Water Reactor</b>
<b>cpm:</b>	<b>Counts per minute</b>
<b>ECP:</b>	<b>Electrochemical Potential</b>
<b>EPRI:</b>	<b>Electric Power Research Institute</b>
<b>ESEERCO:</b>	<b>Empire State Electric Energy Research Corporation</b>
<b>EUP:</b>	<b>Electric Utility Program</b>
<b>GE:</b>	<b>General Electric</b>
<b>gpm:</b>	<b>Gallons per minute</b>
<b>HPLC:</b>	<b>High Performance Liquid Chromatography</b>
<b>HWC:</b>	<b>Hydrogen Water Chemistry</b>
<b>IASCC:</b>	<b>Irradiation-Assisted Stress Corrosion Cracking</b>
<b>IC:</b>	<b>Ion Chromatograph</b>
<b>lpm:</b>	<b>Liters per minute</b>
<b>LWR:</b>	<b>Light Water Reactor</b>
<b>MCA:</b>	<b>Multichannel Analyzer</b>
<b>MCNP:</b>	<b>Monte Carlo Neutron Package</b>
<b>MIT:</b>	<b>Massachusetts Institute of Technology</b>
<b>MITR:</b>	<b>Massachusetts Institute of Technology Reactor</b>
<b>NPT:</b>	<b>National Pipe Thread</b>
<b>NWC:</b>	<b>Normal Water Chemistry</b>
<b>ORP:</b>	<b>Oxidation-Reduction Potential</b>
<b>PCCL:</b>	<b>PWR Coolant Corrosion Loop</b>
<b>PEEK:</b>	<b>Polyetheretherketone</b>
<b>ppb:</b>	<b>Parts per billion</b>
<b>ppm:</b>	<b>Parts per million</b>
<b>psi:</b>	<b>Pounds per square inch</b>
<b>psia:</b>	<b>Pounds per square inch, absolute</b>
<b>psig:</b>	<b>Pounds per square inch, gauge</b>
<b>PWR:</b>	<b>Pressurized Water Reactor</b>
<b>SCC:</b>	<b>Stress-Corrosion Cracking</b>
<b>ss:</b>	<b>Stainless steel</b>
<b>UV:</b>	<b>Ultraviolet</b>

## List of Variables

A	Activity
f	Fraction of N-16 which remains in the water
$\Delta h$	Change in enthalpy of coolant
k	Proportionality constant
K	Proportionality constant
L	Heated length in core
$\dot{m}$	Mass flow rate
N	Specific atom population
P	Normalized reactor power
$\dot{q}$	Heat input to coolant
$T_{1/2}$	Half-life
v	Volume
x	Quality
y	Water level in outlet plenum
$\alpha$	Void fraction
$\rho$	Density
$\bar{\rho}$	Average density
$\sigma$	Cross section
$\tau$	Transit time
$\phi$	Neutron flux
B	Ratio of gas per unit mass in liquid and vapor phases
H	Henry's law constant
p	Pressure
c	Equilibrium concentration of gas in the condensed steam sample
C	Concentration of gas in the water sample
w	Weight fraction of steam in the water sample (carryunder)

## REFERENCES

- A-1 G. C. Allen. "The Reactor Engineering of the MITR-II Construction and Startup". Ph.D. Thesis. MIT Nuclear Engineering Department. June 1976.
- A-2 M. Anderson. "Intermediate Design Report: BCCL Plenum Level Circuitry". MIT Nuclear Reactor Laboratory. March 1989.
- A-3 M. R. Ames, J. L. Baeza, M. J. Driscoll, O. K. Harling, G. E. Kohse, and J. Outwater. "Safety Evaluation Report for the BWR Coolant Chemistry Loop". MITNRL-031. March 1989.
- B-1 J. Baeza. "Refinement of an In-Pile Loop Design for BWR Chemistry Studies". M.S. Thesis. MIT Nuclear Engineering Department. January 1990.
- B-2 S. Boerigter. "Report on the Result of the Gamma Scan Experiment Undertaken as Part of IASCC Project". MIT-Nuclear Reactor Laboratory. September 1989.
- B-3 Proceedings of the 4th International Conference on Water Chemistry of Nuclear Reactor Systems. BNES, London, 1986.
- B-4 C. R. Breden. "Boiling Water Reactor Technology Status of the Art Report". ANL-6562, Argonne National Laboratory, Argonne, Illinois. February 1963.
- C-1 J. Chun. "Modelling of BWR Chemistry". M.S. Thesis. MIT Nuclear Engineering Department. September 1990.
- C-2 Chemetrics, Inc. Literature Accompanying K-5503 Vacu-vials. Calverton, Virginia, 1989.
- D-1 M. J. Driscoll, W. Luangdilok, I. Kato, and C. Oliveira. Status Report on the Preliminary Conceptual Design of a General Purpose In-Pile Loop for Simulation of BWR Coolant Chemistry". MITNRL-018. February 1987.



## REFERENCES

- A-1 G. C. Allen. "The Reactor Engineering of the MITR-II Construction and Startup". Ph.D. Thesis. MIT Nuclear Engineering Department. June 1976.
- A-2 M. Anderson. "Intermediate Design Report: BCCL Plenum Level Circuitry". MIT Nuclear Reactor Laboratory. March 1989.
- A-3 M. R. Ames, J. L. Baeza, M. J. Driscoll, O. K. Harling, G. E. Kohse, and J. Outwater. "Safety Evaluation Report for the BWR Coolant Chemistry Loop". MITNRL-031. March 1989.
- B-1 J. Baeza. "Refinement of an In-Pile Loop Design for BWR Chemistry Studies". M.S. Thesis. MIT Nuclear Engineering Department. January 1990.
- B-2 S. Boerigter. "Report on the Result of the Gamma Scan Experiment Undertaken as Part of IASCC Project". MIT-Nuclear Reactor Laboratory. September 1989.
- B-3 Proceedings of the 4th International Conference on Water Chemistry of Nuclear Reactor Systems. BNES, London, 1986.
- B-4 C. R. Breden. "Boiling Water Reactor Technology Status of the Art Report". ANL-6562, Argonne National Laboratory, Argonne, Illinois. February 1963.
- C-1 J. Chun. "Modelling of BWR Chemistry". M.S. Thesis. MIT Nuclear Engineering Department. September 1990.
- C-2 Chemetrics, Inc. Literature Accompanying K-5503 Vacu-vials. Calverton, Virginia, 1989.
- D-1 M. J. Driscoll, W. Luangdilok, I. Kato, and C. Oliveira. Status Report on the Preliminary Conceptual Design of a General Purpose In-Pile Loop for Simulation of BWR Coolant Chemistry". MITNRL-018. February 1987.

## REFERENCES (CONTINUED)

- E-1 EPRI Report NP-5800M. "Hydrogen Water Chemistry to Mitigate Intergranular Stress Corrosion Cracking: In-Reactor Tests". Palo Alto, CA, 1988.
- F-1 J. Fox. "Modelling the Pressurized Chemistry Coolant Loop (PCCL) with MCNP". Report for 22.39. MIT Nuclear Engineering Department. December 1990.
- H-1 D. N. Himmelblau. "Solubilities of Inert Gases in Water". *J. Chem. Eng. Data*, 5, 10 (1960).
- I-1 T. Ippolito. "Modification of MIT BCCL to Include Recirculation". Report for Subject for 22.901, MIT Nuclear Engineering Department. October 1990.
- I-2 E. Ibe, *et. al* *J. Nucl. Sci. Technol.*, 26, p. 844 (1989).
- J-1 Proceedings of the 5th International Conference on Water Chemistry of Nuclear Reactor Systems. JAIF, Tokyo, Japan, 1989.
- K-1 G. F. Knoll. "Radiation Detection and Measurement". John Wiley and Sons, NY, 1979.
- K-2 K. Kwok. "PCCL Reactivity Measurement Results — Revision 1". Q/A File #M-89-2. MIT Nuclear Reactor Laboratory. January 28, 1988.
- M-1 V. Mason. "Chemical Characterization of Simulated Boiling Water Reactor Coolant". M.S. Thesis. MIT Nuclear Engineering Department. May 1990.
- M-2 R. Medina. "Measurement of Neutron Flux and Spectrum-Averaged Cross Sections for an In-Pile PWR Loop". S.M. Thesis. MIT Nuclear Engineering Department. May 1990.
- M-3 D. R. McCracken, J. B. Rasewich, and W. R. Shorter. "Coolant Radiolysis and Boiling in Water-Cooled Reactors", in *Water Chemistry in Nuclear Power Plants 5 (Proceedings of the 5th International Conference, Toyko, Japan, 1989)*. Vol. 1, JAIF, Tokyo, Japan, 1989.

## REFERENCES (CONTINUED)

- O-1 C. R. L. de Oliveira. "Design and Proof-of-Principle Testing of an In-Pile Loop to Simulate BWR Coolant Chemistry". N.E. Thesis. MIT Nuclear Engineering Department. December 1987.
- O-2 J. Outwater. "Design and Construction of an N-16 Monitor for the BWR Coolant Loop". Report for Subject for 22.59. MIT Nuclear Engineering Department. October 1988.
- O-3 J. Outwater, and M. J. Driscoll. "Prospectus for Construction of and Experiments With an In-Pile BWR Coolant Chemistry Loop". MITNRL-027. May 1988.
- P-1 R. H. Perry and C. H. Chilton. Chemical Engineer's Handbook, Chapter 22. Fifth Edition. McGraw-Hill Book Company, New York, NY, 1973.
- P-2 M. Psaila. "Modelling of Crack-Tip Chemistry". Ph.D. Thesis. MIT Nuclear Engineering Department, 1990.
- S-1 R. Sanchez. "Construction and Operation of an In-Pile Loop for PWR Dose Reduction Experiments". Ph.D. Thesis. MIT Nuclear Engineering Department. May 1990.
- S-2 Safety Review Forms for BCCL. SRF 0-90-14 to 0-90-22. MIT Nuclear Reactor Laboratory. September 1990.
- S-3 M. Sakai. Personal Communication. Hitachi Research Laboratory, Ibaraki, Japan. November 1990.
- S-4 R. Sher and C. Beck. "Fission Energy Release for 16 Fissioning Nuclides". EPRI NP-1771. March 1981.
- S-5 S. Simonsen. "Modelling of Radiation Effects on Nuclear Waste Package Materials". Ph.D. Thesis. MIT Nuclear Engineering Department, 1988.
- T-1 N. E. Todreas and M. S. Kazimi. Nuclear Systems I. Hemisphere Publishing Corporation, New York, NY, 1990.

## REFERENCES (CONTINUED)

- T-2 M. Takahashi. Personal Communication. Hitachi Energy Research Laboratory, Ibaraki, Japan. September 1990.
- U-1 M. Ullberg, T. Rooth, and B. Persson. "Hydrogen Peroxide in BWR's", in Water Chemistry of Nuclear Reactor Systems 4 (Proceedings of the 4th International Conference, London, 1986). Vol. 2, BNES, London, 1986.
- Z-1 M. Zaker. "Dose Rate Measurements in the MITR-II Facilities". S.M. Thesis. MIT Nuclear Engineering Department. May 1977.