BWR COOLANT CHEMISTRY STUDIES USING A RECIRCULATING IN-PILE LOOP

by

Bronislav Guimpelson

Submitted to the Department of Nuclear Engineering
in Partial Fulfillment of the Requirements for the
Degree of

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in
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ABSTRACT

An in-pile loop to simulate the BWR coolant chemistry environment was substantially redesigned to allow operation in both once-through and recirculation modes. Runs were made to obtain comparative radiolysis data while the loop was run in both modes of operation, and to verify and extend N-16 data from the past campaigns.

Modernizations included a recirculation capability, new steam separator plenum to reduce water carryover and steam carryunder, relocation of the hydrogen peroxide sampling system to reduce gamma dose, installation of a new hydrogen peroxide sampler to reduce peroxide decomposition, a new in-core section to allow operation at reduced loop flow rates, relocation of in-thimble ECP sensors to a separate ECP plenum, replacement of titanium with stainless steel as the basic material of loop construction, employing Ge detectors for N-16 measurements and the Luminol method for peroxide measurements.

Baseline data were obtained for the recirculation mode of operation (normal water chemistry only) and once-through mode of operation (both normal and hydrogen water chemistry). The upgraded BCCL configuration now generates radiolysis products in better agreement with computer code predictions; but in general measured yields are about twice those predicted.

N-16 spectra were measured using Ge detectors on both water and steam lines. N-16 photopeaks were clearly distinguished from those of C-15; the maximum contribution of C-15 to total activities was shown to be 30%, although in most cases it is lower than 10%.

Carryover tests using chemical and radiochemical methods, demonstrated less than 0.1% carryover. Measurements of the ionic form of N-16 showed that N-16 is in cation form in steam and anion form in water.

A number of chemical additives were injected into the loop to investigate their effect on N-16 carryover and radiolysis product formation in the loop, as well as to verify data obtained during the previous BCCL campaigns. It was found that computed concentrations of H_2O_2 in the return streams are by a factor of 2 less than the measured values, suggesting the radiolysis yield G-values and chemical kinetics data may need some adjustment.

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I would especially like to thank my parents for their endless love, spiritual support, and understanding.

I dedicate this thesis to all nuclear professionals from the countries of the former Soviet Union.

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CHAPTER 1 INTRODUCTION

1.1 OBJECTIVE OF PRESENT RESEARCH

1.1.1 Foreword

Over the past several years an in-pile loop for simulation of the thermal hydraulic and radiolytic environment of a BWR has been designed, constructed and operated in the MIT Nuclear Reactor. Principal radiolysis product concentrations (O_2, H_2, H_2O_2) as well as N-16 activity in the water and liquid phases can be measured, as can be the electrochemical corrosion potential of materials exposed to the loop aqueous environment. For the first three campaigns the loop was operated in a once-through mode, whereas the fourth campaign-the subject of the present report-involved both once-through and recirculation modes. The development of the facility and previous BCCL campaigns are described in the theses by J. Outwater (O-1), B. Rozier (R-1), B. Hilton (H-1), and in a comprehensive EPRI/ESEERCO/HITACHI/TOSHIBA summary report (E-1).

1.1.2 Current Experimental Campaign

The objectives of the subject 1993/94 Campaign were as follows:

1. To obtain comparative radiolysis data while the loop is run in both once-through and recirculation modes.
2. To verify and extend N-16 data from past BCCL Campaigns with new data obtained using Ge detectors.
3. To implement loop modifications to more closely simulate BWR conditions.

Several significant modernizations were implemented in the BCCL for the 1993/94 Campaign. In particular, the loop was equipped with the capability for both once-through and recirculation modes of operation, and titanium was replaced with

316SS as the principal material of construction. The loop recirculation capability was successfully tested at the end of the 1992 Campaign, and some minor refinements were made prior to the 1993/94 recirculation runs. The main differences between the once-through and recirculation configurations are shown in Figures 1-1 and 1-2.

During the first half of 1993, loop design changes were developed and their feasibility was confirmed by appropriate tests. In the latter part of 1993 the new rig was assembled, carefully tested and, prior to in-pile runs, a series of out-of-pile tests were completed. Loop shakedown runs followed installation of the thimble with internals in the MITR core tank. During the first part of the 1993/94 experiments, loop characterization in its once-through mode of operation was carried out. Failure of the plenum level float interrupted the course of the experiments for more than one month following which recirculation mode runs were conducted. Considerable effort was devoted to loop baseline characterization during recirculation to match actual BWR conditions as closely as possible. After the recirculation baseline was established, different chemical additives were injected to study their effect on the behavior of N-16, radiolysis product generation, and electrochemical corrosion potential. When this part of the campaign was completed, the loop was switched back to once-through operation and additional chemical compounds of interest were injected.

1.2 REVIEW OF PAST BCCL WORK AND MODERNIZATION

1.2.1 System Design

Conceptual design of the BCCL and its modifications are described in detail in previous reports and theses. For the 1993/94 Campaign the design of the BCCL was further improved, so that the current loop configuration shown in Figure 1-2 represents a significant difference in comparison with the versions used in the 1990-1992 Campaigns. Before 1993 the loop was constructed of titanium (to reduce the background

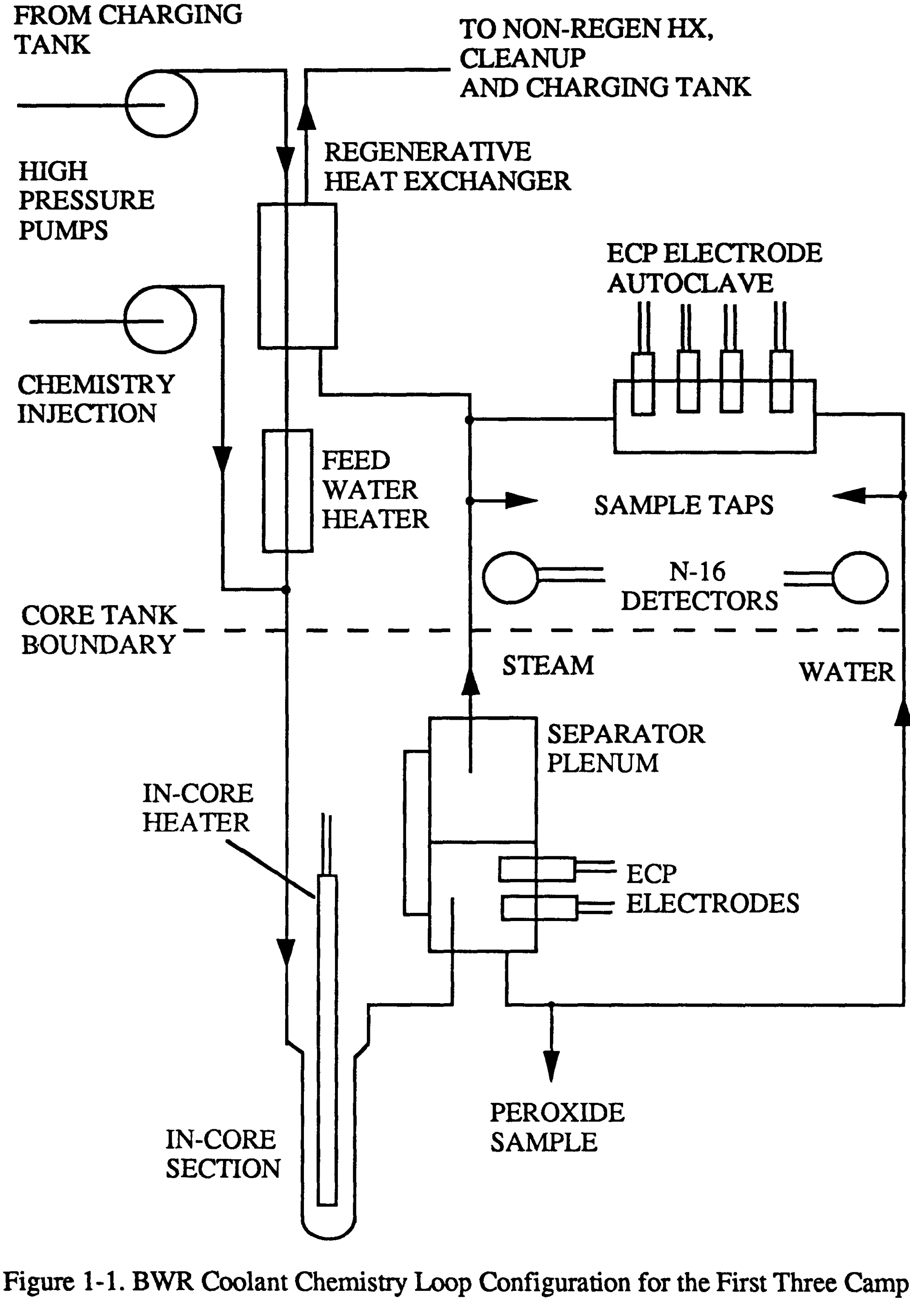


Figure 1-1. BWR Coolant Chemistry Loop Configuration for the First Three Campaigns

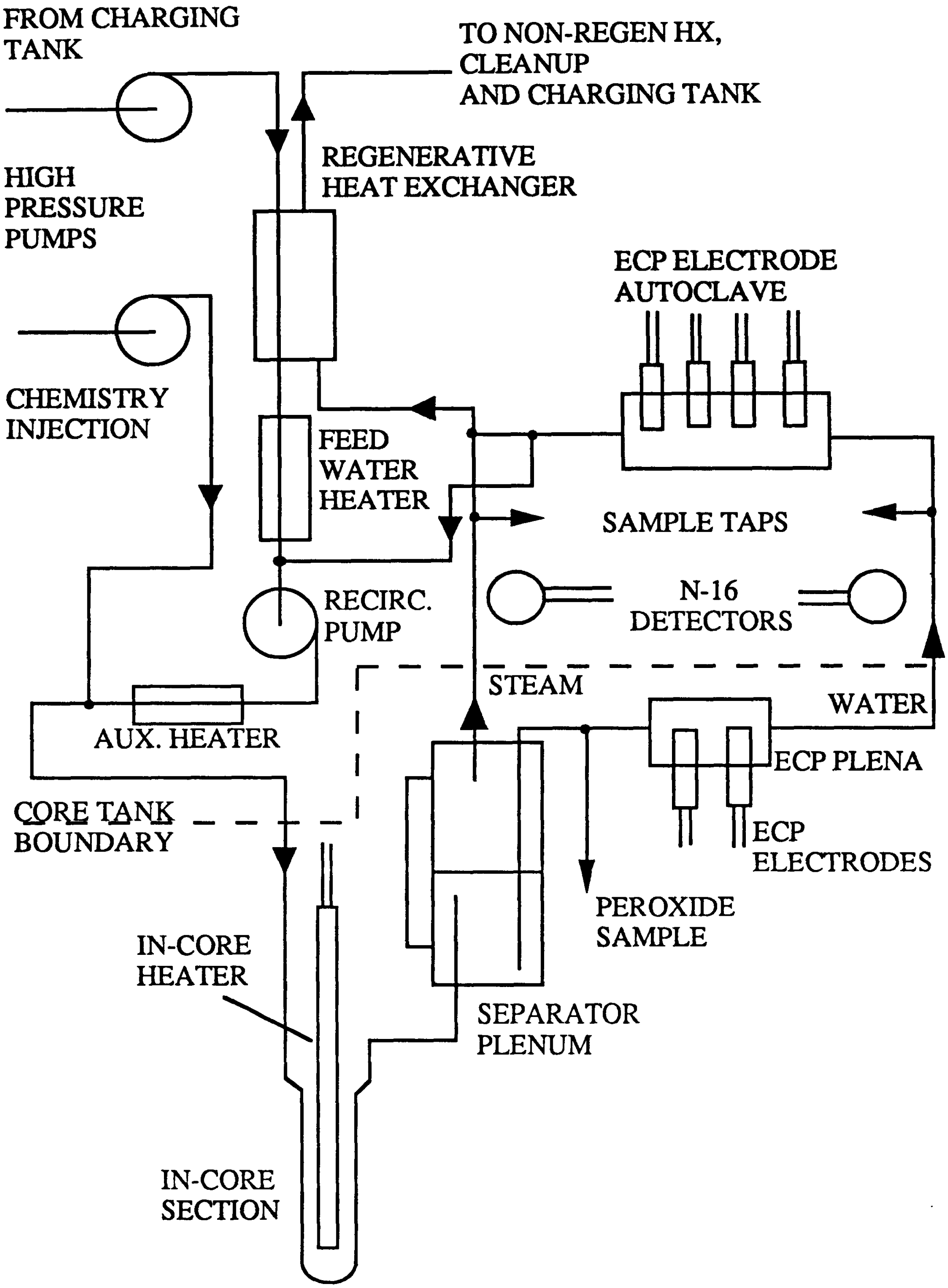


Figure 1-2. BWR Coolant Chemistry Loop Configuration for the 1993/94 Campaign

concentrations of transition metals in the coolant) and was operated in a once-through mode without recirculation. Transition from titanium to stainless steel and operation in the recirculation mode were major changes implemented for the 1993/94 Campaign. Several other modifications were also introduced in the current design:

1. Modified steam separator plenum. The separator configuration was changed to reduce water carryover and steam carryunder.
2. The hydrogen peroxide sampling system was relocated above the separator to reduce its ambient gamma dose.
3. A new hydrogen peroxide sampler was designed to reduce peroxide decomposition, by decreasing the length of contact of coolant with hot tube walls.
4. The reference ECP electrodes were moved from the steam separator to the water letdown line. This increased the water flow rate past the electrodes, and avoided electrode operation in two-phase flow.
5. The in-core section mass was reduced using an aluminum block, with a minimum amount of molten lead, to thermally couple the Zircaloy water channel with the in-pile electrical heater. This decreased nuclear heating and allowed operation of the loop at a reduced flow rate, hence higher integrated dose to the coolant.
6. A new recirculation pump and an auxiliary heater were installed to better support the recirculation mode.
7. Ge gamma detectors were added for N-16 counting to replace the NaI detectors used in the past.

Special attention was also given to H_2O_2 measurements. For this purpose a more precise technique (Luminol method) was tested, so that the validity of the CheMetrics® method used in earlier BCCL Campaigns could be checked and supplemented.

1.2.2 Experimental Results

Three campaigns were completed prior to the one reported here. In these runs data on ECP, H_2, O_2, H_2O_2, and N-16 were collected under both normal (NWC) and hydrogen (HWC) water chemistry in a once-through mode. The effect of adding different chemicals on suppression of N-16 activity in the steam line was carefully investigated. In general, adding hydrogenous organic compounds to the feedwater brought about an increase of N-16 carryover to the vapor phase, similar to that measured following hydrogen addition. In the final chapter of this report prior data will be integrated with the new results in the form of a comprehensive summary.

1.3 ORGANIZATION OF THIS REPORT

This report presents the results of the 1993/94 Campaign for the BCCL operated in its once-through and recirculation modes under normal water chemistry, hydrogen water chemistry, and chemical injection. A detailed loop description is presented here only for those components which were significantly changed since the previous campaign, as well as for new components. Only brief and very general attention is given to the loop elements which remained the same as before. Chapter 1 introduces the work and presents the main objectives of the current research. Chapter 2 describes the loop facility following the new modifications. Chapter 3 deals with experiment procedures. While operation in the once-through mode did not change significantly since the last campaign, the recirculation mode of operation was introduced, and its detailed description is presented in this chapter. Chapter 4 gives a description of the out-of-pile tests and their results. Results of the recirculation mode of operation are discussed in Chapter 5. And finally, results of loop once-through operation are presented and analyzed in Chapter 6. Conclusions and recommendations for future BCCL activity are given in Chapter 7. Details of measurements and data analysis are contained in the appendices.

CHAPTER 2 FACILITY DESIGN

2.1 INTRODUCTION

This chapter describes in detail only those loop modifications which were developed and implemented for the latest version of the facility. All other loop components and systems which remained unchanged are described at a more general level, since the details can be found in previous theses and reports.

The main loop modernizations were already pointed out in the introduction. They were done in support of several specific goals: to enable a recirculation mode of operation, to reduce water carryover into the steam line, and to decrease gamma heat to allow operation at reduced loop flow rates, etc. Here all changes will be presented in full. Many loop elements remained the same as during the previous campaigns: most of the out-of-pile system, and support systems comprising the sample and data acquisition systems. A list of the facility modernizations is presented in Table 2.1. Table 2.2 shows references where a detailed description of BCCL systems and components can be found.

2.2 OUT-OF-PILE SYSTEM

The loop out-of-pile system consists of the charging tank system, pump cabinet, heat exchangers, steam and liquid letdown lines, return line transit section, including the recirculation line, the return water cleanup system, and the chemical injection system. The tube internal diameter remained the same as during the previous campaigns (0.48 cm), although the connecting tubes were made of stainless steel instead of titanium. Employing stainless steel allowed simulation of BWR fluid systems more realistically. The principle differences between the design of the out-of-pile fluid system for current and past campaigns are shown in Figure 2-1 and Figure 2-2.

Table 2.1. List of Facility Modernizations

LOOP SYSTEM	**BCCL CAMPAIGN**	
	1992	**1993/94**
MAKEUP/ LETDOWN	-Replaced feedwater heater -IX cleanup on return stream only	-Ditto -IX cleanup on return and charging tank streams -Installed: recirculation pump, venturi flowmeter, auxiliary heater, low flow rate charging pump, advanced chem. injection pump
IN THIMBLE	-Grounded sheath heater	-Ditto -Aluminum block in-core section, ECP plenum, enlarged steam/separator plenum, new H_2O_2 sampler, new ECP electrodes SS instead of Ti
INSTRUMENTATION	-Cherenkov detector for N-13 -Ion Chromatograph -NaI Detectors for N-16	-No Cherenkov detector for N-13 -No Ion Chromatograph -Ge detectors for N-16 and C-15
SAMPLING/ ANALYSIS	-HYDRAN® H_2 meter -Orbisphere® O_2 low flow meter for water letdown line	-Ditto -Ditto -New design of the H_2O_2 sampler -Luminol method

New and redesigned components include the recirculation line, recirculation pump, auxiliary heater, new charging tank system, and pump cabinet.

Table 2.2. List of the BCCL Components and References

LOOP COMPONENT	**REFERENCE**
OUT-OF-PILE SYSTEM	
Charging Tank System	
Charging tank	O-1 (p.48)
Recombiner	R-1 (2.2.1)
Gas sparging pump	R-1 (2.2.1)
Cover gas flowmeters	R-1 (2.2.1)
Ion exchange columns	O-1 (p.161)
UV tube	H-1 (2.2.6)
Back-pressure regulator	O-1 (p.161)
Pump Cabinet	* (2.2.2)
CAT pump	O-1 (p.50)
American LEWA pump	* (2.2.2)
Micro pump	* (2.2.2)
Back-pressure regulators	O-1 (p.177)
Flowmeters on inlet lines	R-1 (2.2.2),* (2.2.2)
Return water flowmeters	O-1 (p.178)
Ion exchange columns	O-1 (p.161)
Filter on return line	H-1 (2.2.6)
O_2 Orbisphere sensor	R-1 (3.3.3)
H_2 Orbisphere sensor	R-1 (3.3.3)
HYDRAN	H-1 (3.3.3)
Conductivity meter	R-1 (2.6.3)
Flowmeter on the sensor line	* (2.2.6)
Non-regenerative heat exchanger	O-1 (p.54)
Regenerative heat exchanger	O-1 (p.54)
Thermal mass	R-1 (2.2.3)
Feedwater heater	O-1 (p.164)
AE recirculation pump	* (2.2.4)
Venturi flowmeter	* (2.2.4, 5.2)
Auxiliary (copper) heater	* (2.2.3)
Steam orifice	O-1 (p.167), * (5.2)

ECP electrode autoclave	H-1 (2.5.2), * (2.5.2)
CHEMICAL INJECTION SYSTEM	
PulsaFeeder pump	*(2.2.6)
Flowmeter on the PulsaFeeder pump suction line	H-1 (2.2.7)
THIMBLE AND INTERNALS	
Thimble	O-1 (p.25)
In-core section	*(2.3.3)
In-core electrical heater	H-1 (2.3.3)
Outlet plenum/steam separator	H-1 (2.3.4), *(2.3.4)
ECP plenum	*(2.3.5)
LEVEL CONTROL SYSTEM	O-1 (p.36)
Float	R-1 (2.7.1), *(App. H)
Coils	O-1 (p.38)
Electronics	O-1 (p.39)
ECP MEASUREMENT SYSTEM	
ECP electrodes	*(2.5.1)
ECP autoclave	*(2.5.2)
Data acquisition system	*(2.5.3)
HYDROGEN PEROXIDE SAMPLE SYSTEM	
Sample cooler	*(2.8.1)
Mixed cooling injection system	H-1 (2.8.2)
Sample tap	H-1 (2.8.3)
CONTROL/POWER/DA SYSTEM	H-1 (2.9)
N-16 MEASUREMENT SYSTEM	
Shielding blocks	O-1 (p.52)
Detectors	*(2.4.1)
Electronics	O-1 (p.54)

* In this report

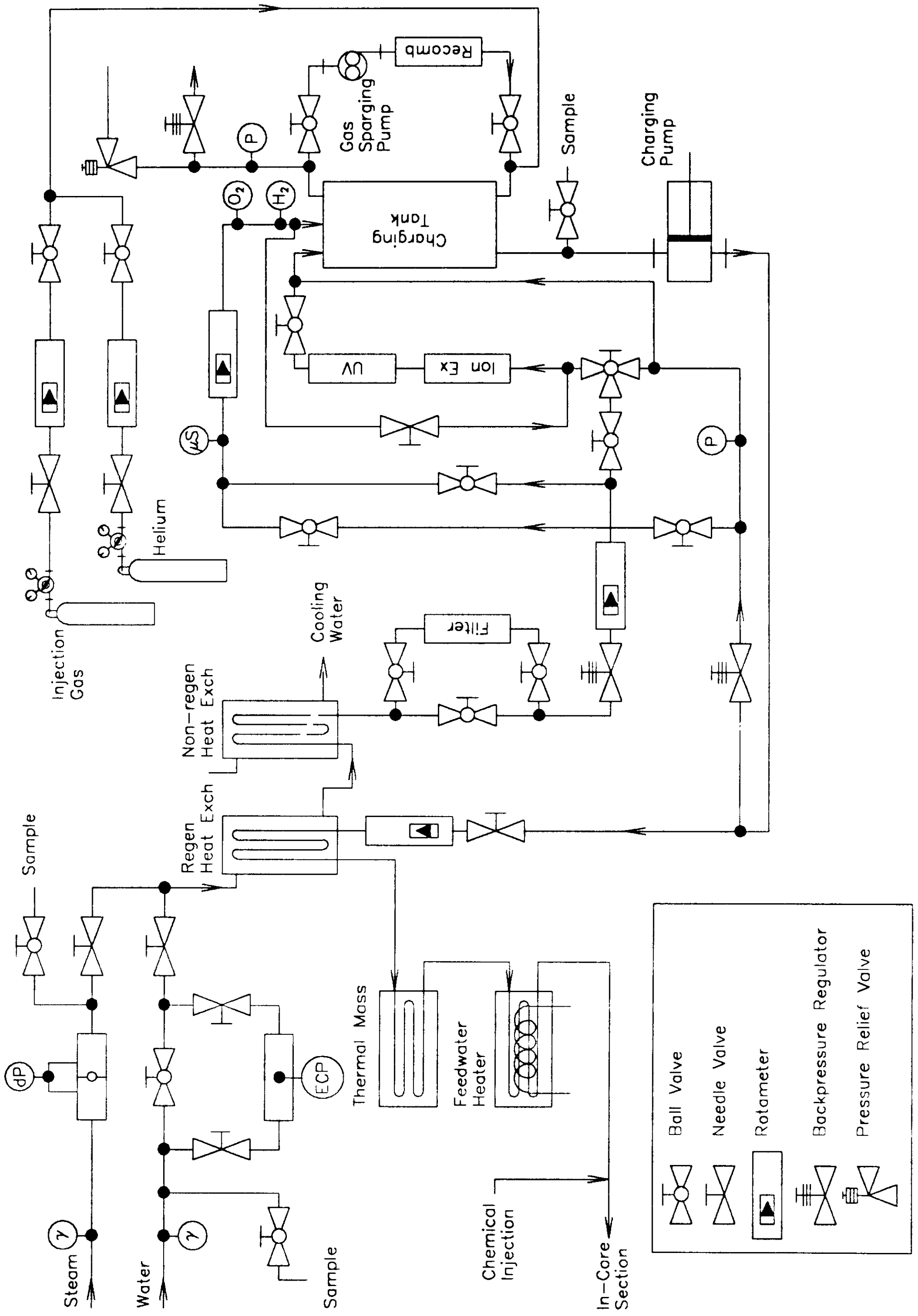


Figure 2-1. Out-of-Pile Fluid System Schematic.

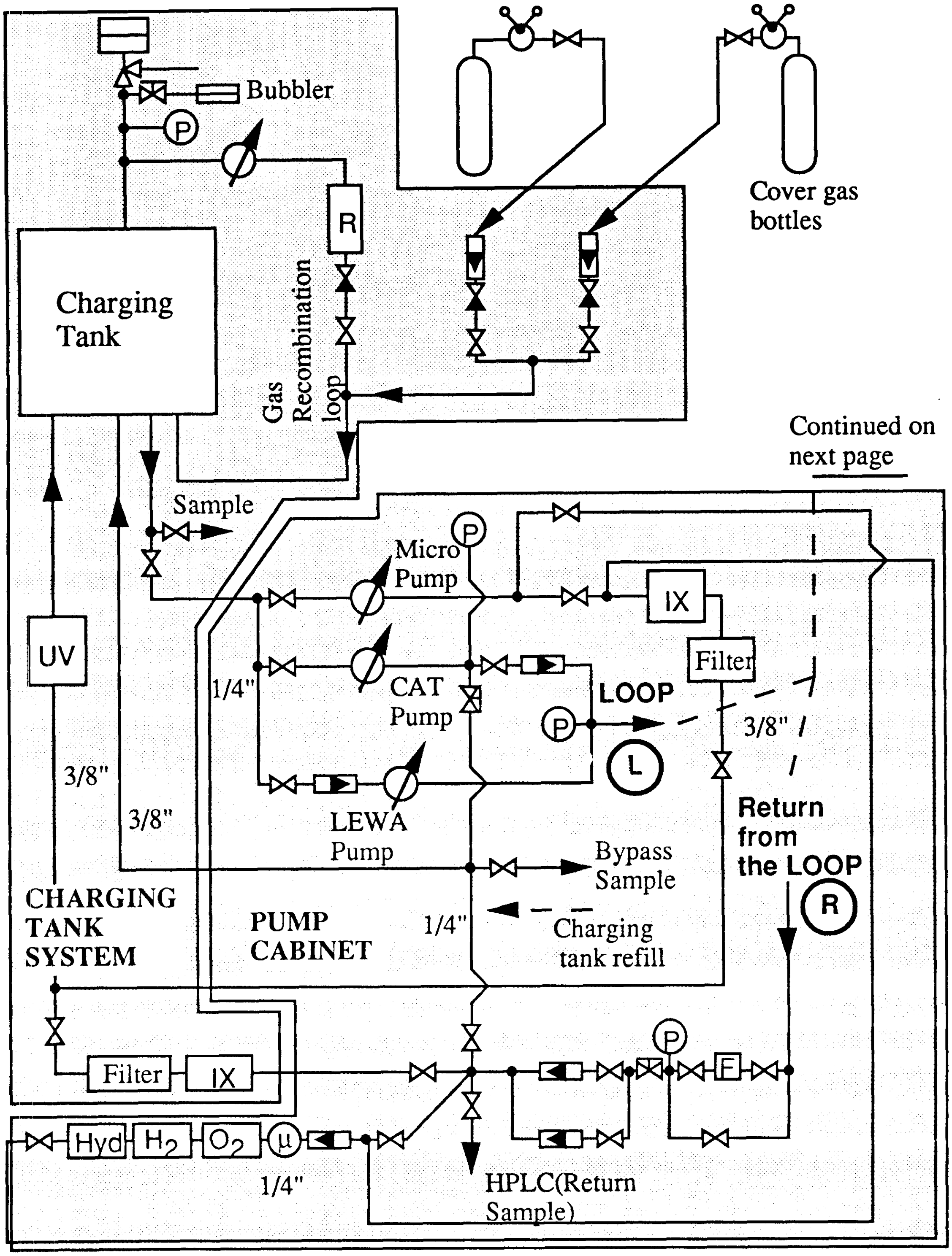


Figure 2-2. BCCL Out-of-Pile System in the 1993/94 Campaign

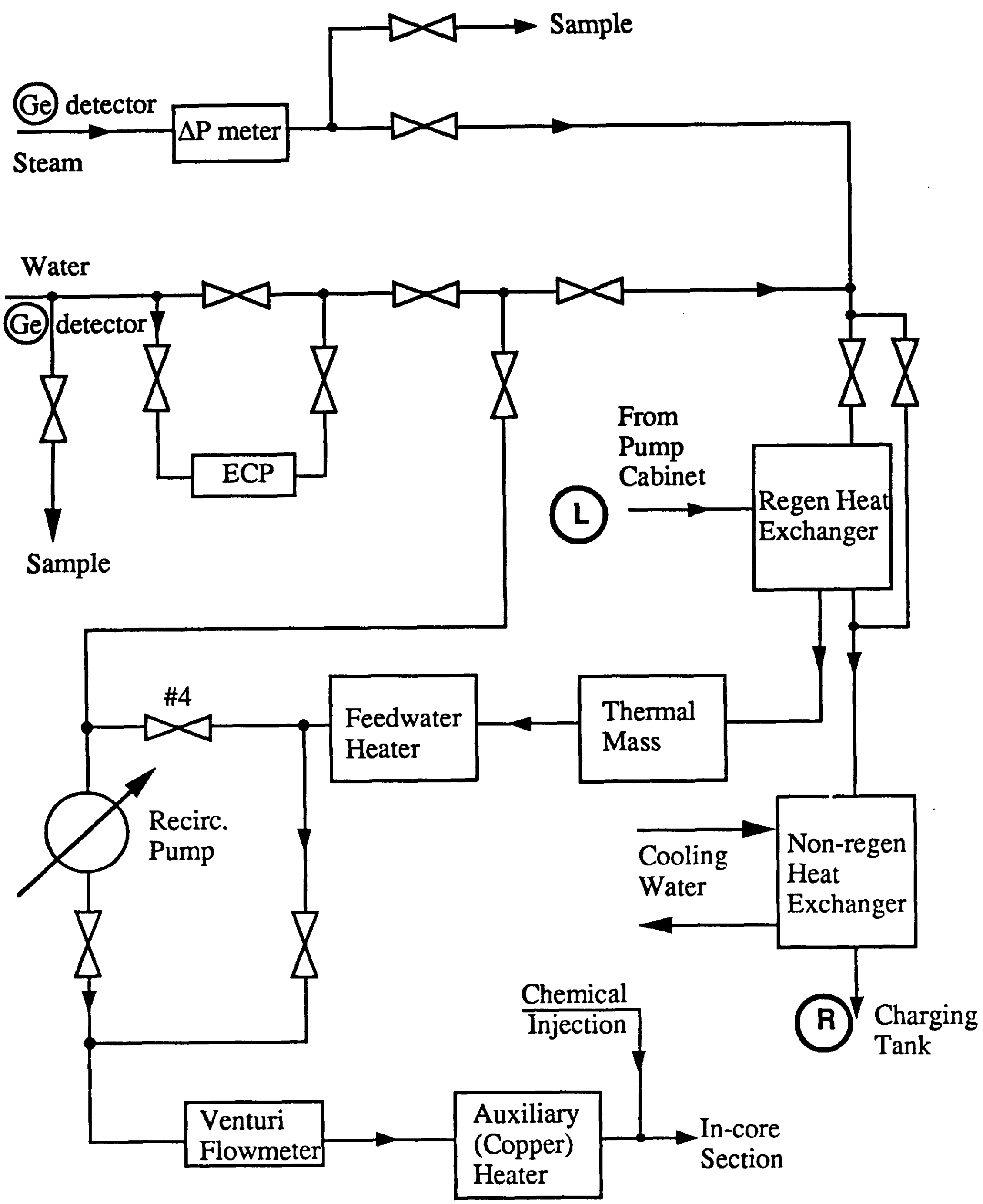


Figure 2-2. BCCL Out-of-Pile System in the 1993/94 Campaign (continued)

2.2.1 Charging Tank System

The charging tank system, which is shown in Figure 2-2, was entirely rebuilt to simplify system operation, to make operation more reliable, and to provide more space in which to install new elements. The old charging tank system was disassembled, and new lines and valves were installed. It was also decided to take several system components out of the charging tank and to integrate them into the pump cabinet.

In order to support the recirculation mode of operation, a charging pump capable of providing low flow rates (50-200 cc/min) had to be installed. During the recirculation run shakedown at the end of the 1992 Campaign, the required low feedwater flow rate (150 cc/min) could be supplied by the main charging pump, but stability problems associated with flow oscillations were observed and attributed to operating the pump below its stability range. Hence, a new charging pump was obtained, and both the old and new pumps were installed together in a separate cabinet. From an operation standpoint, the new charging tank design did not introduce any differences from past practice.

The charging tank system comprises a reservoir of clean water, a cover gas injection and purge system, and a gas recirculation system that recombines dissolved oxygen and hydrogen. A detailed description of these systems is given in (H-1). A shelf was mounted on the charging tank to hold the installed oxygen and hydrogen Orbisphere® meters, and a HYDRAN® hydrogen meter.

2.2.2 Pump Cabinet

As has previously been mentioned, both the new and old charging pumps were installed in the subject cabinet. The pump cabinet built for the 1993/1994 Campaign includes three pumps: a high capacity charging pump-CAT® piston pump (nominal flow rate of 5000 cc/min)- which is operated to provide feedwater for the once-through mode, an American LEWA® diaphragm pump (flow rate up to 220 cc/min) which provides feedwater during recirculation mode operation, and a Micro® circulation gear pump to circulate charging tank water through dedicated ion exchange columns. The pump cabinet layout is shown in Figure 2-2.

There is a common feedwater line coming out of the charging tank reservoir and going to the distribution cross. Three lines start from the cross and go to either the CAT® pump, LEWA® pump, and/or circulation-Micro®-pump. There is also a 3-way valve on the cleanup line in the cabinet used to fill the feedwater reservoir from a deionized water supply. All pump suction lines are equipped with shutoff valves to allow pump maintenance in-situ. In order to monitor flow rate, several flowmeters were installed on the pump cabinet. They are: a high capacity return line flowmeter (up to 2000 cc/min) and an inlet line flowmeter (up to 9000 cc/min) to measure flow rates when the loop is operated in its once-through mode, a low capacity return line flowmeter (up to 200 cc/min) to measure the return flow rate when the loop is operated in the recirculation mode, and a low capacity flowmeter on the LEWA® pump suction line to measure feedwater flow rate (up to 200 cc/min), again during recirculation mode operation. Two back pressure regulators and flow control valves are installed to control operational loop pressure and flow rate. A description of the system operation is given in Chapter 3.

2.2.3 Heat Exchangers

Several heat exchangers are employed in the loop. Their purpose is to bring water up to the desired temperature prior to the core section inlet. A detailed description of the ex-core heat exchangers has been given in previous reports and theses. Table 2.2 indicates where such information can be found. An extra heater was installed in the loop to support the recirculation mode operation.

At the very end of the last BCCL Campaign, the feasibility of loop operation in a recirculation mode was demonstrated. The only problem was relatively low core inlet temperature, which leads to an extension of the non-boiling length in the core. Therefore to achieve a more realistic performance, a new heater was installed in the line leading to the MITR core tank. An additional benefit of this extra heater is that it allowed us to decrease the load on the feedwater heater and to permit its operation even in case of failure of one heating element. This is a very worthwhile advantage, since heating elements have a tendency to fail at high load.

The design of the new heater is shown in Figure 2-3. It consists of a copper block cut in halves and machined with grooves to contain two electrical heaters, and three passes of stainless steel tube. Heat is transferred from the surface of the heating elements to the water flowing inside the stainless steel tube. To provide reliable heat transfer, to avoid heating element failure, and to increase the thermal efficiency of the heater, a copper grease (see G-1) was applied to the outer surface of the tube and heating elements to couple them with the copper block. This auxiliary heater was thermally insulated and installed inside a support frame on the reactor top. Electrical connections were made to tie the heater in with the loop control system on the front mezzanine of the MITR-II.

2.2.4 Recirculation Pump

The recirculation pump, which allows recirculation mode of operation, was installed on the reactor top immediately downstream of the mixing Tee connecting the feedwater line and the recirculation line. The pump was mounted in a separate (from the main feedwater) line to permit maintenance while the loop is operated (in the once-through mode). An Autoclave Engineering® pump (see G-1) was chosen for this purpose. Since in the recirculation mode a large fraction of the return water stream is directed back to the in-pile thimble, the flow rate through the in-core section cannot be measured the same way as during the once-through mode using the return water flowmeter. To serve this goal, a venturi flowmeter was installed between the recirculation pump and auxiliary (copper) heater (see Figure 2-2). This flowmeter has a

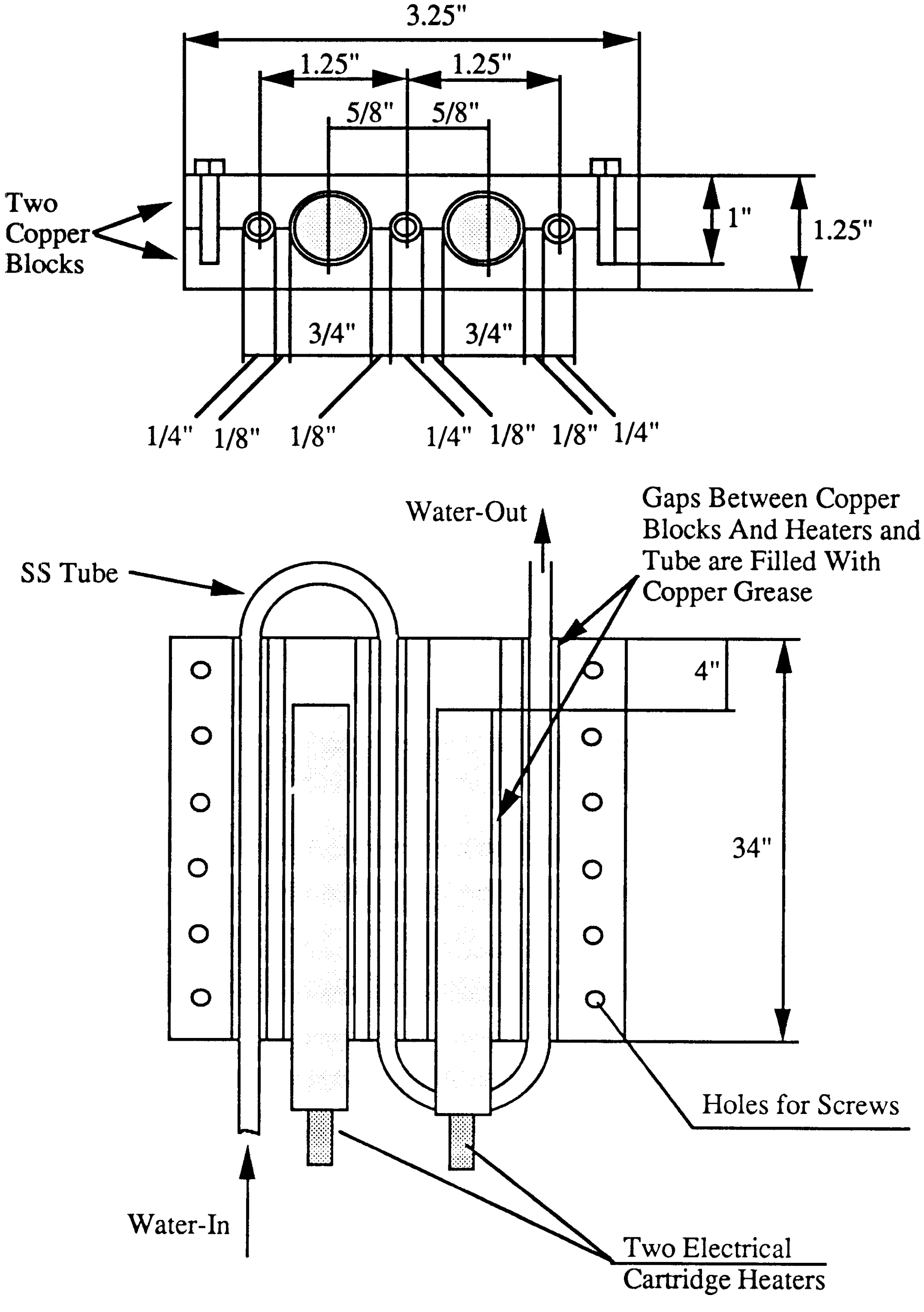


Figure 2-3. Auxiliary (Copper) Heater

range of 0-5 psi for normal operating parameters (maximum flow rate 1500 cc/min), and it was used directly during recirculation mode runs, and to verify the pump cabinet flowmeter during the once-through mode runs.

2.2.5 Return Line Transit Section

A detailed description of the return line transit section can be found in the previous reports and theses, e.g. (H-1). During preparations for the 1993/94 Campaign several changes were implemented to allow operation in a recirculation mode. For this purpose a new line (see Figure 2-2) was installed to connect the existing water return line, right after the N-16 measurement system, to the feedwater line going to the in-pile thimble. Several shutoff valves were installed to easily switch from once-through to recirculation modes of operation. The steam orifice (maximum pressure drop of 5.0 psi), that was used in the previous campaigns, was calibrated both under atmospheric conditions and at nominal loop parameters (see Section 4.3 of Chapter 4).

2.2.6 Return Water Cleanup System

The return water cleanup system is shown in Figure 2-2. A set of ion exchange columns was installed in this subsystem. These columns are used to clean up loop return flow. In the 1993/94 Campaign once-through mode of operation, the return water flow rate was 1500 cc/min. A small fraction of the return flow is directed through a flowmeter and then through oxygen and hydrogen sensors mounted on the pump cabinet. After passing the sensors, the water flows through the columns before returning to the charging tank. This column was also used to purify the circulating water in the charging tank cleanup line. To avoid complications with operation and to simplify maintenance, a minimum number of valves are used. These valves are installed on a shelf on the pump cabinet. Several sample taps are provided to monitor the quality of charging tank water, return water, and circulation water.

2.2.7 Chemical Injection System

The chemical injection system was not changed since the last BCCL Campaign. It comprises a chemical injection pump, a flowmeter, bottles containing chemicals of interest, and a line going from the back mezzanine to the place on the reactor top where this line merges with the loop before entering the thimble. A detailed description of the system can be found in the references listed in Table 2.2. A new PulsaFeeder® pump replaced the older Milton-Roy® pump (see G-1). Its maximum capacity is 180 cc/min. Pump flow rate can be varied either by changing piston stroke or by changing current frequency. The chemical injection system is shown in Figure 2-4.

2.3 THIMBLE AND INTERNALS

Many changes were introduced in the design of the thimble and its internals during preparation for the 1993/94 Campaign. To decrease gamma heating of the in-core section and, therefore, to allow operation at reduced flow rates, the average density of the in-core section had to be reduced. As a result, lead was replaced by aluminum. The design of the new in-core section is described in Section 2.3.3 in greater detail. New internals were also designed to reduce potential water carryover into the steam line, the ECP electrodes were moved into a special plenum to avoid their operation in two-phase flow, and to decrease hydrogen peroxide decomposition.

2.3.1 Thimble

The BCCL thimble is designed to provide support for internals and to separate MITR coolant water from the loop coolant. Since the 1992 Campaign no significant changes in the thimble design have been introduced. A detailed description of the thimble design can be found in Ref. (H-1). Thimble dimensions can be found in (R-1).

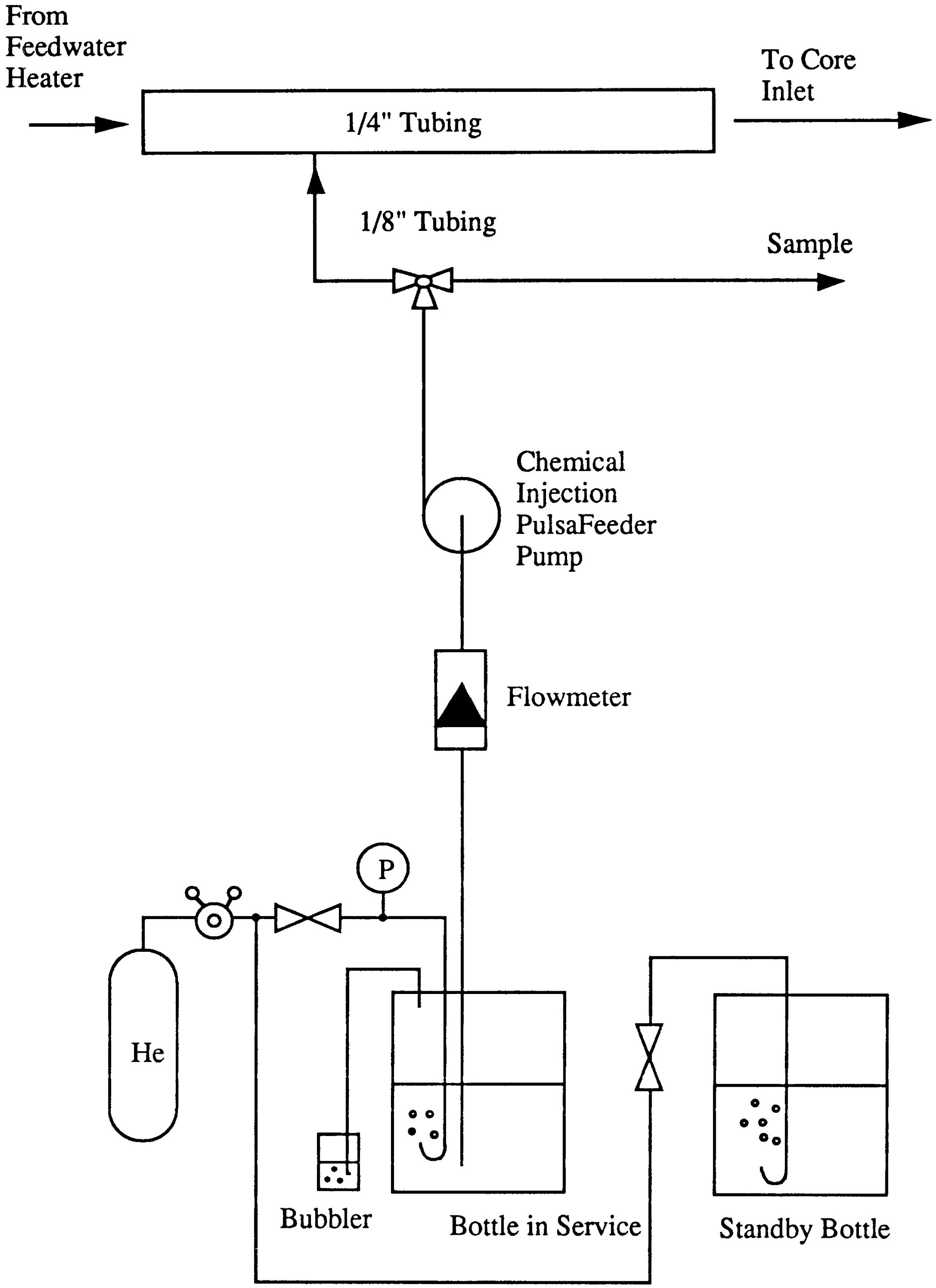


Figure 2-4. Chemical Injection System

2.3.2 In-Pile Fluid System

The in-pile fluid system is made up of the same components as in previous campaigns. This system is shown in Figure 2-5. However, there are a number of differences implemented in the current design that allow closer simulation of the radiolysis chemistry of a BWR. First of all, all elements of the in-pile fluid system (except the in-core section) are made of stainless steel. Some design changes were also incorporated to place ECP electrodes inside a separate plenum ("ECP plenum"), and the peroxide sampler was completely redesigned to minimize peroxide decomposition in the sampling device. To decrease water carryover into the steam line, the steam separator plenum was significantly modified. The sections which follow focus on the following features:

1. Change from Ti to SS.
2. New peroxide sampler.
3. A plenum for ECP electrodes.
4. New steam separator plenum.
5. Features to reduce carryover.

2.3.3 In-Core Heated Section

One of the goals of the present campaign was to conduct experiments at reduced flow rates. For this purpose the in-core section was redesigned to generate less gamma heat than during previous campaigns. Since the main source of the gamma heating was the lead coupling the electrical heating elements with the in-core Zircaloy tube, lead was replaced by aluminum. After several unsuccessful attempts to create reliable thermal coupling between a slotted aluminum block and the electrical heating elements and Zircaloy tube it was found necessary to use a thin film of lead to fill in the remaining gap. This design allowed reduction of the lead mass by a factor of six and, therefore to decrease gamma heating by approximately 50%. The design of the new in-core section is

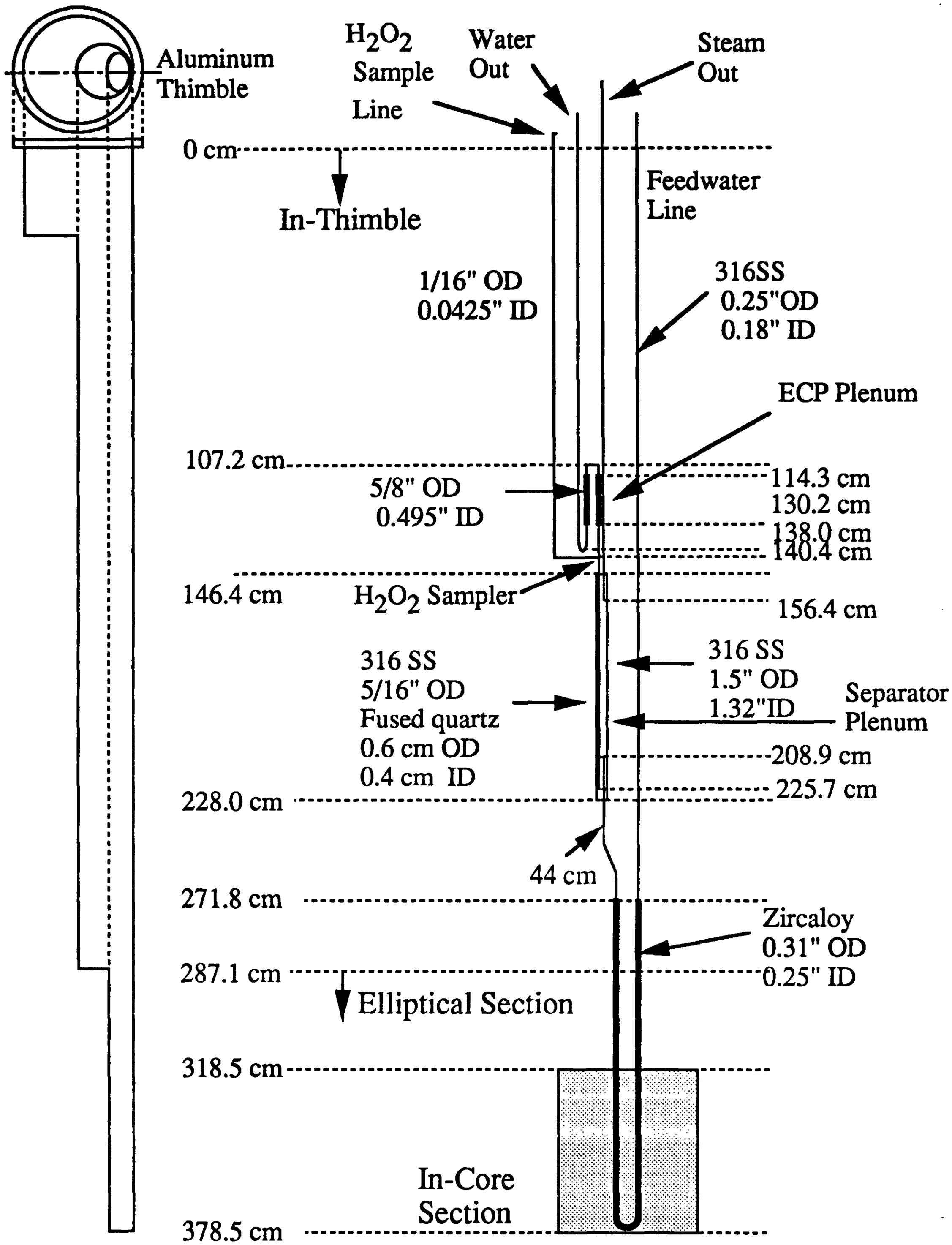


Figure 2-5. In-Pile Fluid System

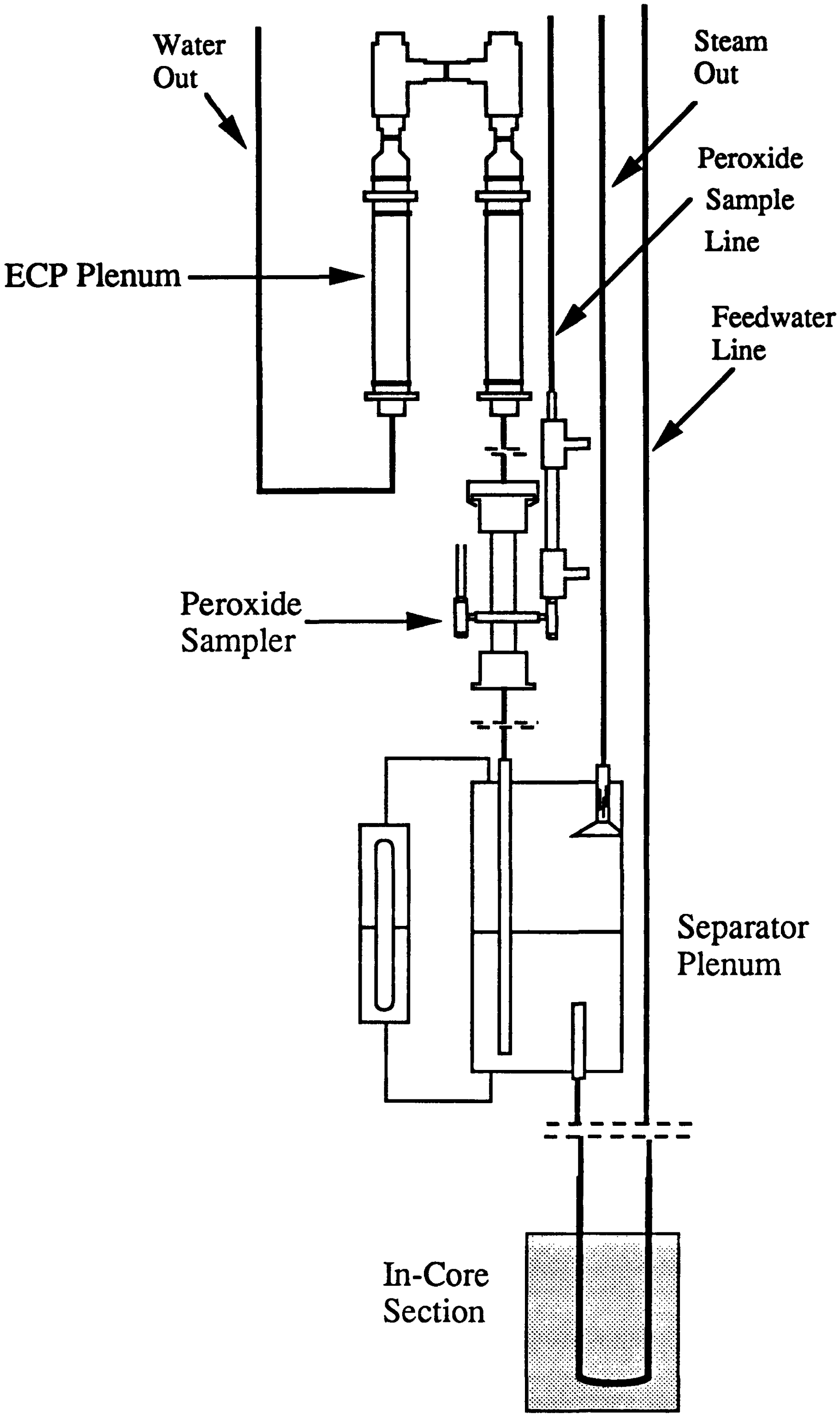


Figure 2-5a. In-Pile Fluid System Assembly Schematic Showing Major Components

shown in Figure 2-6. Details of the new in-core section design can be found in the Safety Evaluation Report (S-1) presented to the MITR Safeguards Committee. All other elements, the Zircaloy tube and the heating element, were the same as before. During the campaign no failure of, or other problems with the new in-core section occurred.

2.3.4 Outlet Plenum/ Steam Separator

The BCCL outlet plenum/steam separator separates water from steam in the two-phase flow exiting the in-core section. It corresponds to the separator and dryer regions of a full scale BWR. The new plenum features an extended length (82 cm compared to 52 cm) to allow more volume for separation and to assure that water carryover into steam is less than 0.1%. For this purpose the steam exit tube was equipped with an impingement cone to prevent carryover of water droplets directed at the tube. The water exit line path was also redesigned to decrease the effect of gamma dose on either hydrogen peroxide production or decomposition. A quartz tube was introduced inside the water exit line to help reduce peroxide decomposition by elimination of water contact with a hot metal wall. The design of the new plenum is shown in Figure 2-7, and the differences in dimensions between the past and current designs are demonstrated in Figure 2-8.

2.3.5 Instrumentation

The two in-thimble ECP probes were removed from the outlet plenum and installed in a special ECP plenum designed to allow the probes to operate in a single phase medium. The ECP plenum design is shown in Figure 2-9. The two ECP probes used in the 1993/94 runs were provided by Toshiba Corporation.

A number of thermocouples were installed to measure in-core section inlet and outlet temperatures, lead bath temperature (to protect the aluminum block from excessive softening and failure), and to monitor peroxide sampler temperatures.

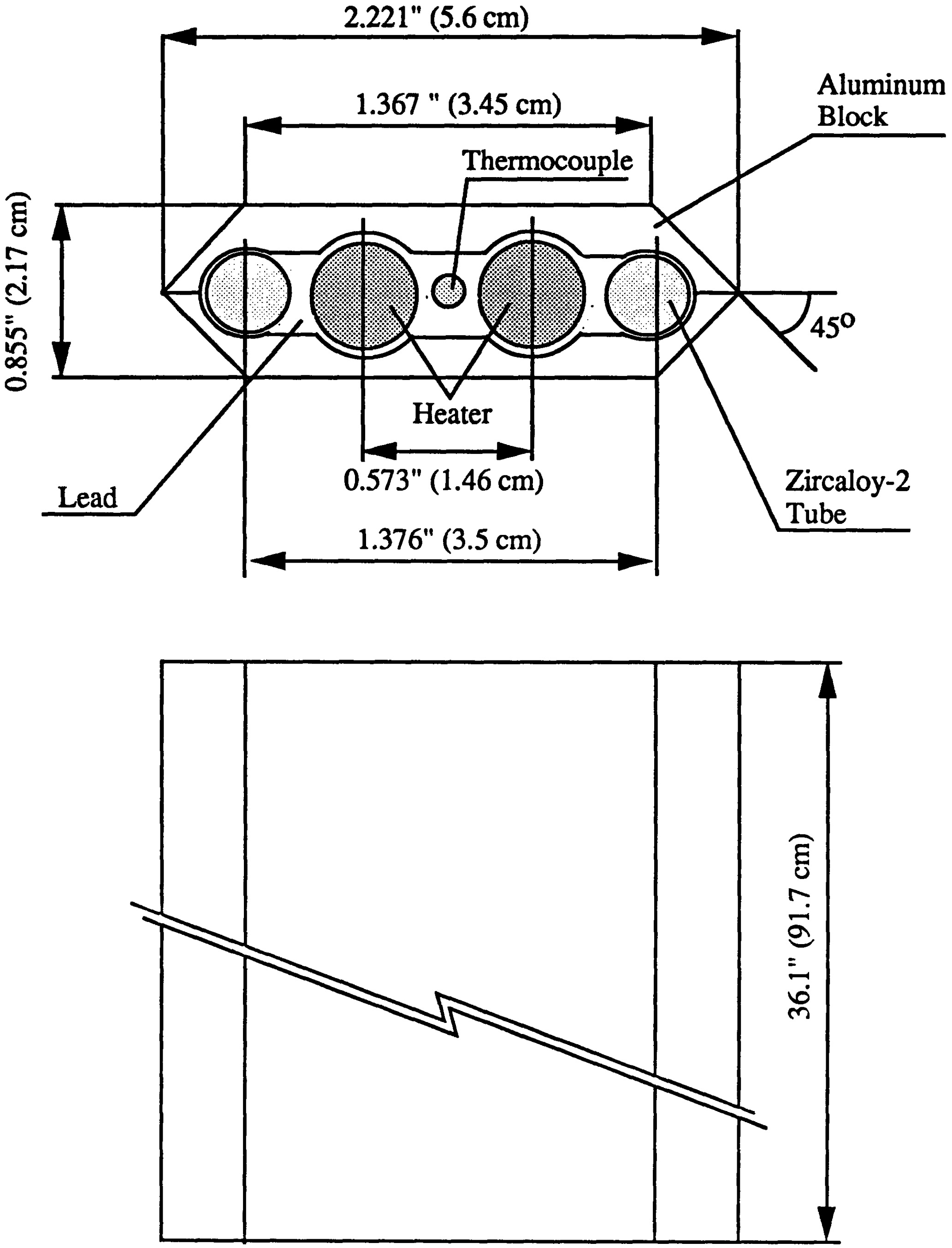
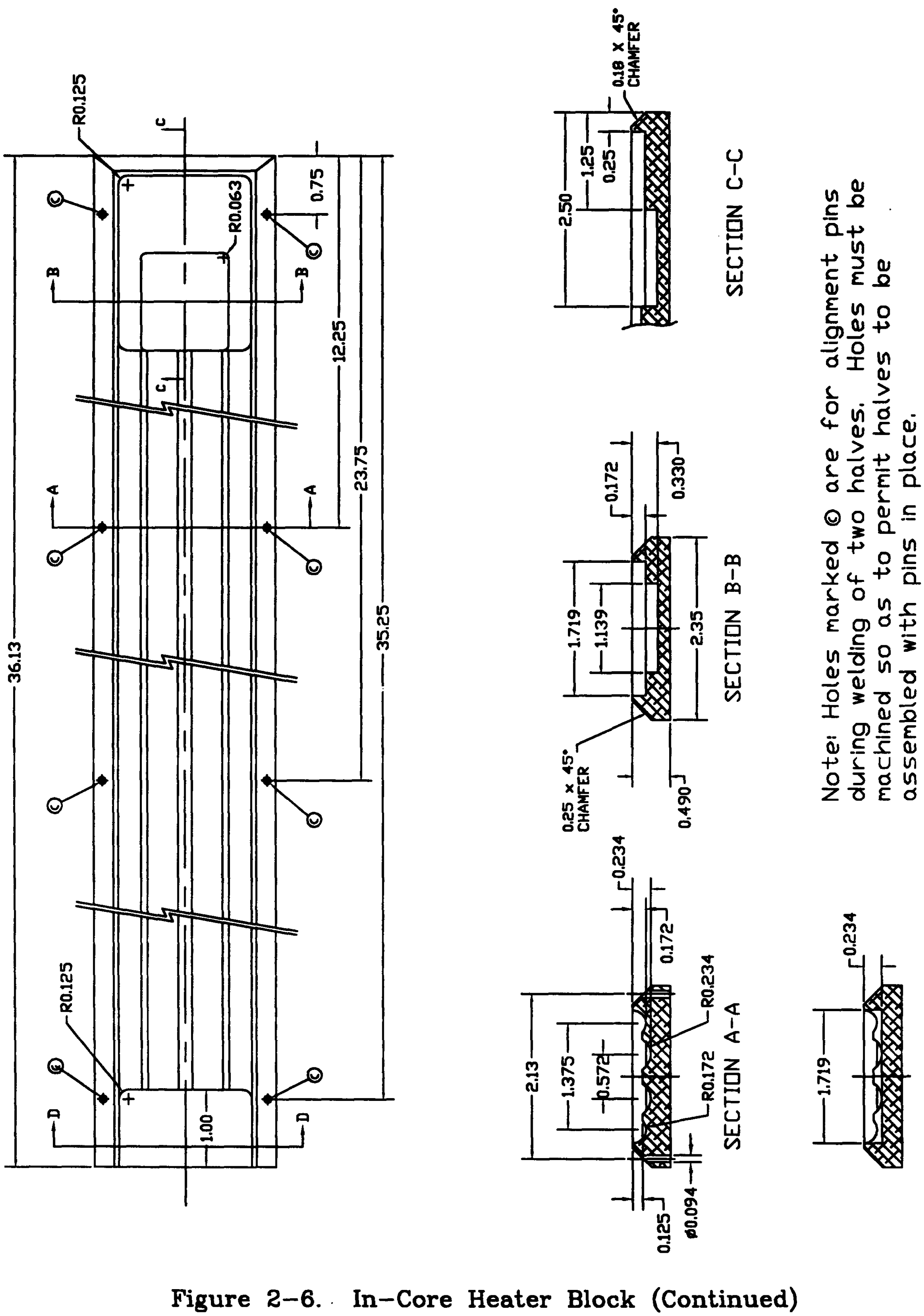


Figure 2-6. In-Core Heater Block



Note: Holes marked © are for alignment pins during welding of two halves. Holes must be machined so as to permit halves to be assembled with pins in place.

Figure 2-6. In-Core Heater Block (Continued)

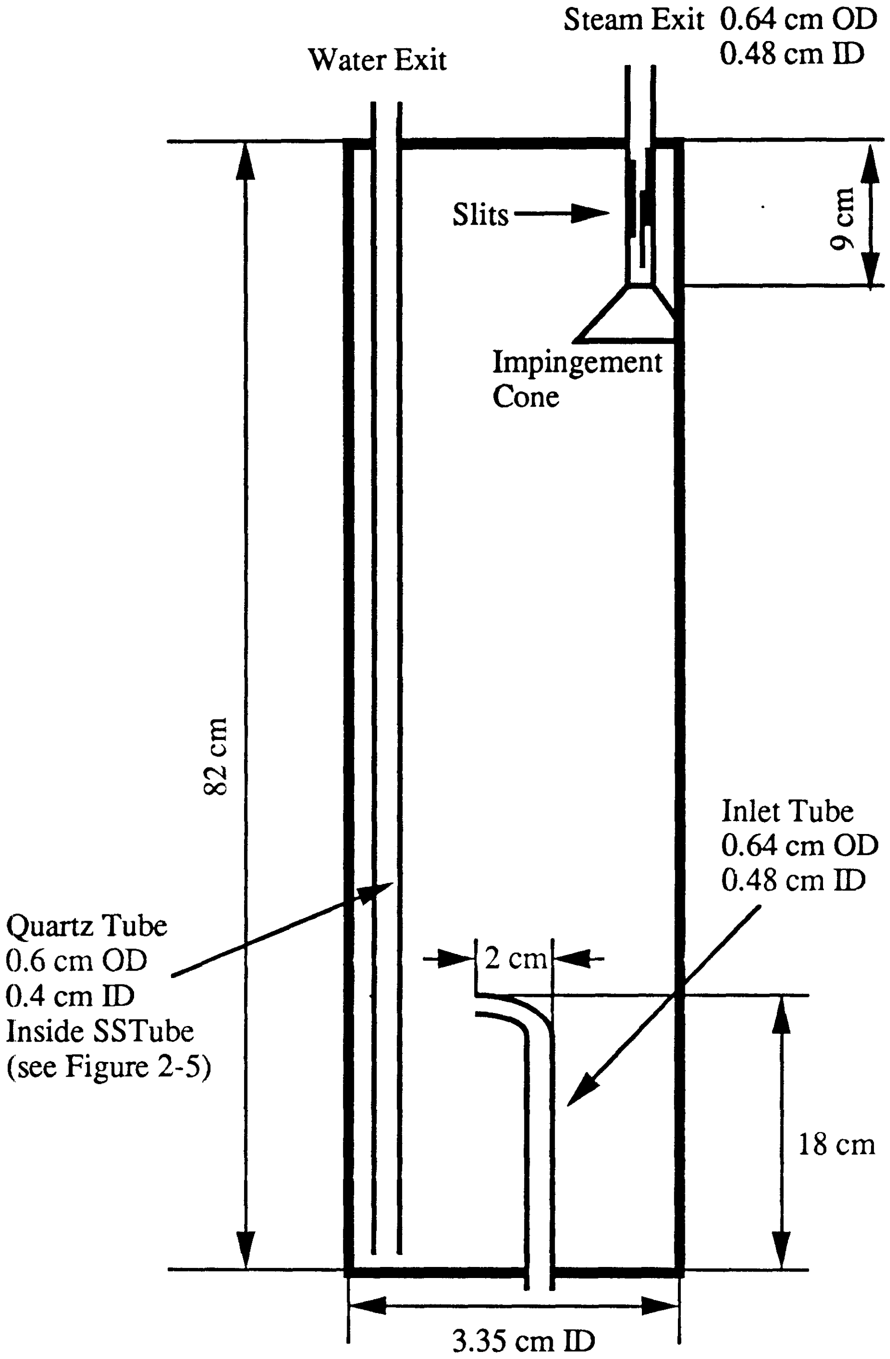


Figure 2-7. New Steam Separator Plenum Design

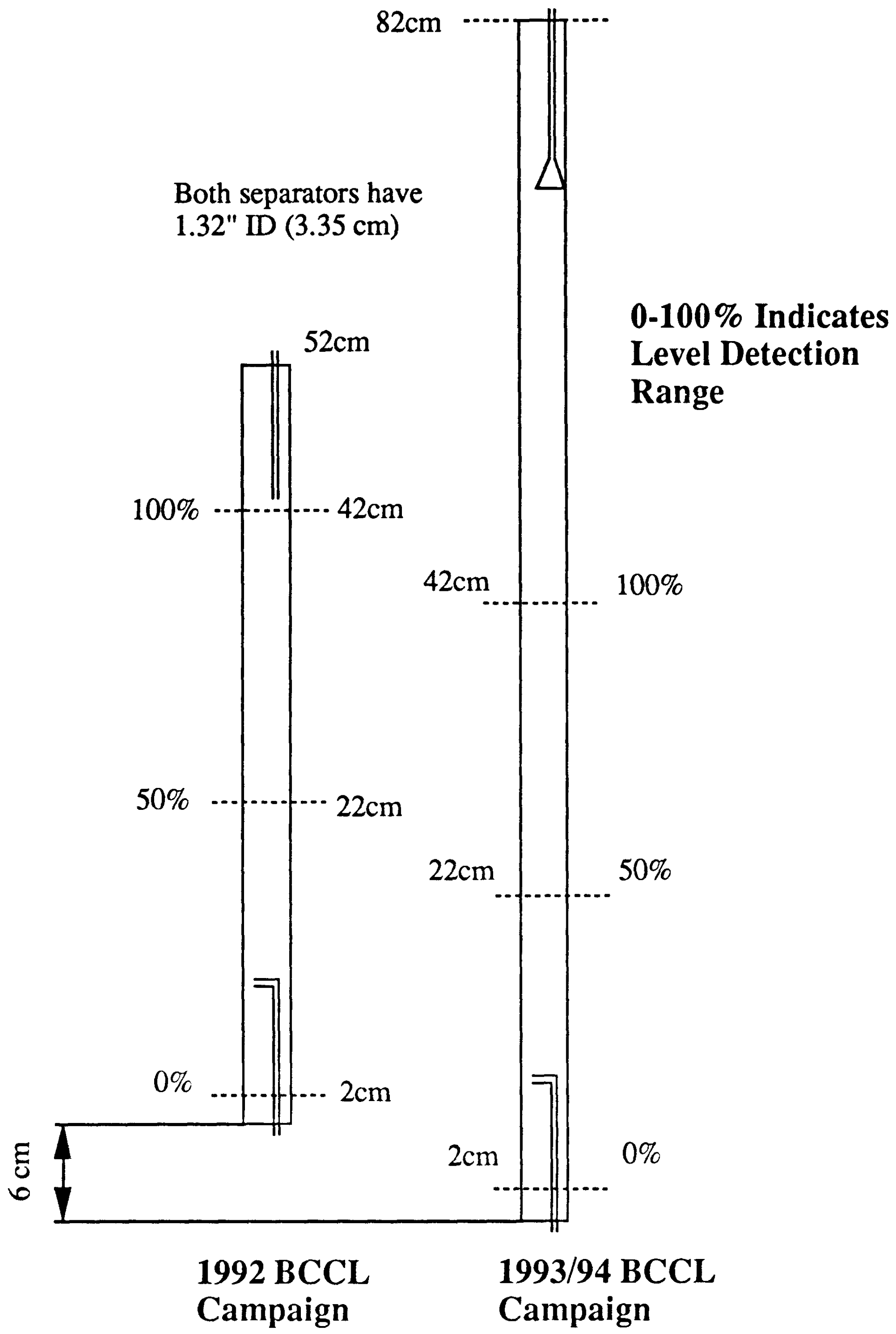


Figure 2-8. Comparison Between Plenum Designs
for 1992 and 1993/94 BCCL Campaigns

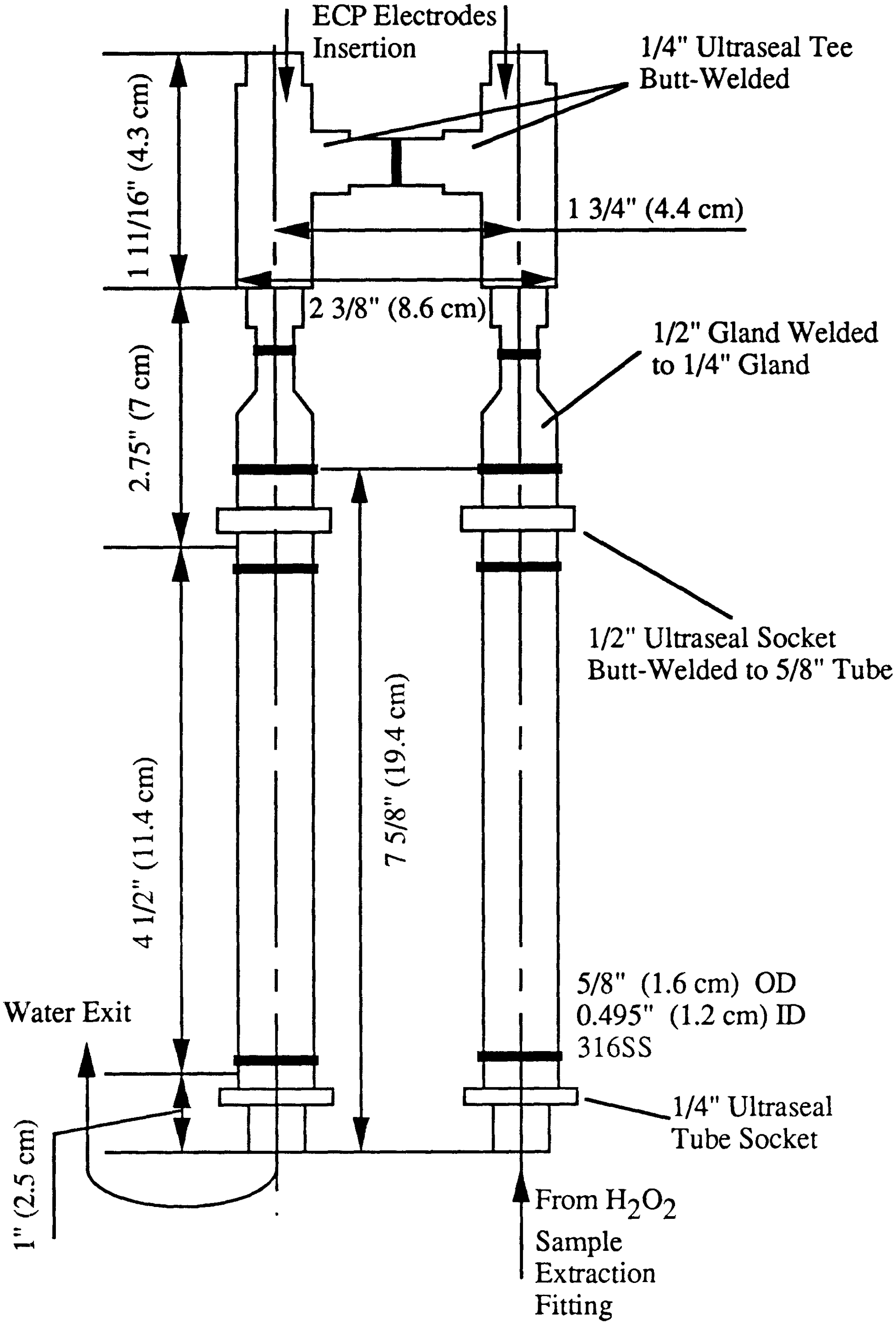


Figure 2-9. In-Thimble ECP Electrode Plenum

2.4 NITROGEN-16 MEASUREMENT SYSTEM

The N-16 measurement system is designed to measure N-16 gamma activity in the water and steam return lines. It has the same features as before, except that NaI detectors were not widely used in this campaign. They were employed mostly to normalize new data against the data obtained in the past. Two Ge detectors were installed to measure the gamma spectra from both the steam and water lines. A computer was connected to the MCA to save data for future analysis. Specifications of the new detectors are summarized in G-1.

2.4.1 Nitrogen-16 Detectors

As mentioned above, the two NaI detectors were replaced by Ge detectors. One of the reasons for this upgrade was to permit measurement of C-15, since one of the C-15 peaks lies in the vicinity of the 5.5 MeV peak of N-16. Employing Ge detectors allows determination of the effect of C-15 on the accuracy of N-16 measurements, and also to help understand the results of previous campaigns in greater detail.

2.4.2 N-16 Data Acquisition System

In order to provide for thorough analysis of N-16 data, an IBM computer was hooked up to the MCA. This permitted recording all data on disc for retention, later interpretation, and archiving.

2.5 ECP MEASUREMENT SYSTEM

The electrochemical corrosion potential (ECP) of a metal is the electrical potential between the metal and a reference electrode. In the BCCL, the ECP measurements are conducted using two types of electrodes under different loop conditions including chemical addition.

2.5.1 Description of Reference ECP Sensors

Two types of reference ECP sensors were employed during the BCCL 1993/94 Campaign: 1) internal silver/silver-chloride (Ag/AgCl) sensors provided by Toshiba and 2) external silver/silver-chloride (Ag/AgCl) sensors with 0.1N KCl electrolyte solution fabricated at MIT. The two Toshiba sensors were placed in the ECP plenum (shown in Figure 2-11) located 0.1 meters above the steam separator plenum. The external Ag/AgCl sensors were located in an autoclave on the water line approximately 2.7 m beyond the thimble exit.

The Toshiba sensors are a standard design fabricated for use in BWR pressure vessels as in-core and recirculation line ECP monitoring devices. They are a self-contained unit with the Ag/AgCl electrode housed within a stainless steel body and use a sapphire plug as the semi-porous membrane allowing ionic contact with the water (see Figure 2-11). Because the corrosion current is so small, the current-carrying wire (1/8" MI cable) must be judiciously insulated from the outside stainless steel shell and this is done by a ceramic to metal braze developed for this technology. Because of the limited space for feedthroughs on the thimble lid, the MI cable was junctioned with copper wire in the 12" pod section in a manner similar to that used in the 1992 BCCL Campaign (H-1). ECP measurements made by the Toshiba Ag/AgCl reference sensors are corrected to the standard hydrogen electrode (SHE) scale by the following correlation,

$$E_{\mathrm{IntAg\,/\,AgCl}} = E_{\mathrm{meas}} + 642.9 - 1.645 \times (T)\text{ , mV SHE} \qquad (2\text{-}1)$$

where T is the temperature in degrees Celsius.

The design of the second type, the external reference sensor, was developed by Peter Andresen at GE Research Laboratory in Schenectady and has been used in previous work at MIT (A-1, H-1). Figure 2-10 {from H. Mansoux's S.M. thesis (M-1)} shows

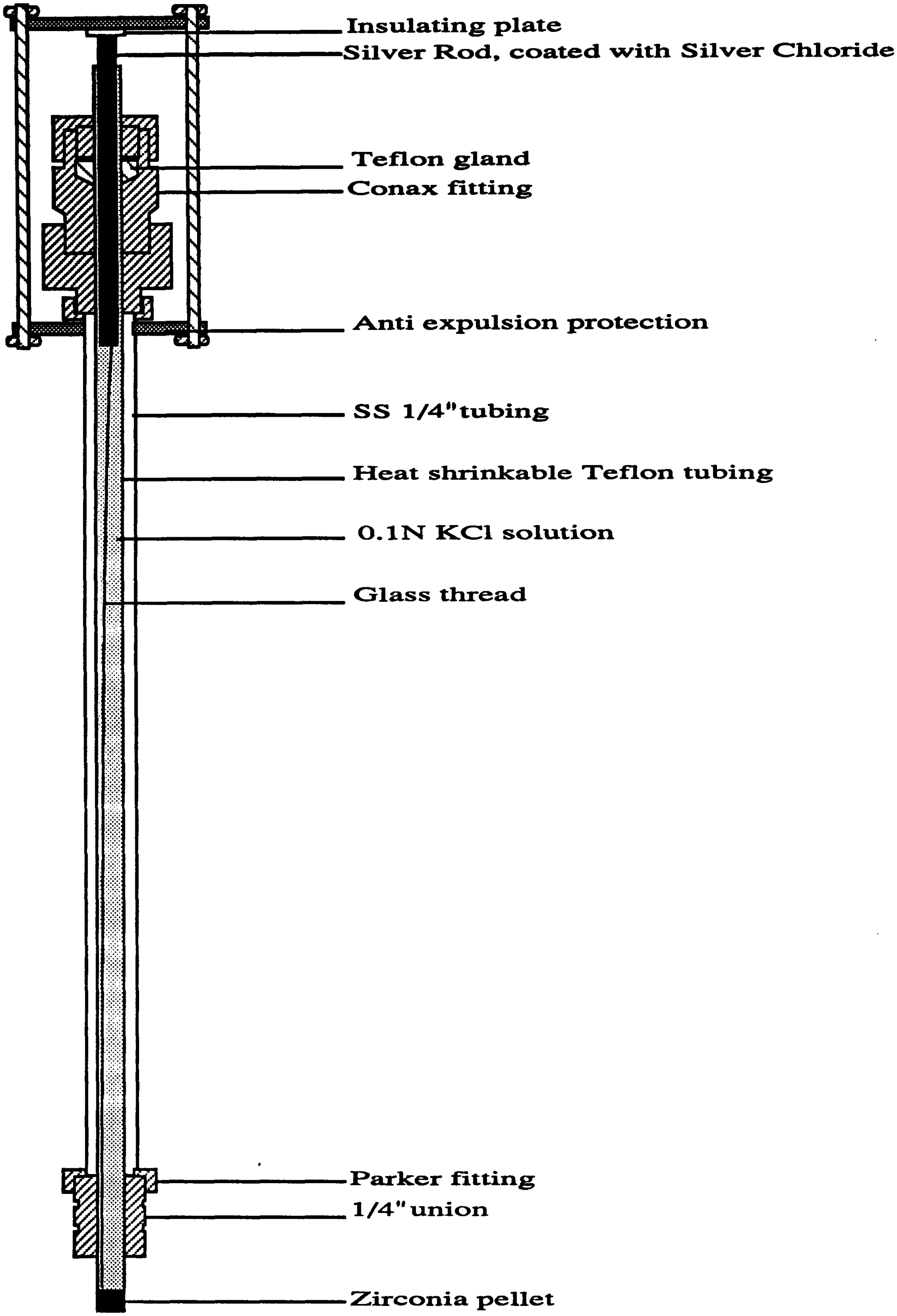


Figure 2-10. Schematic of External Ag/AgCl Reference Electrode

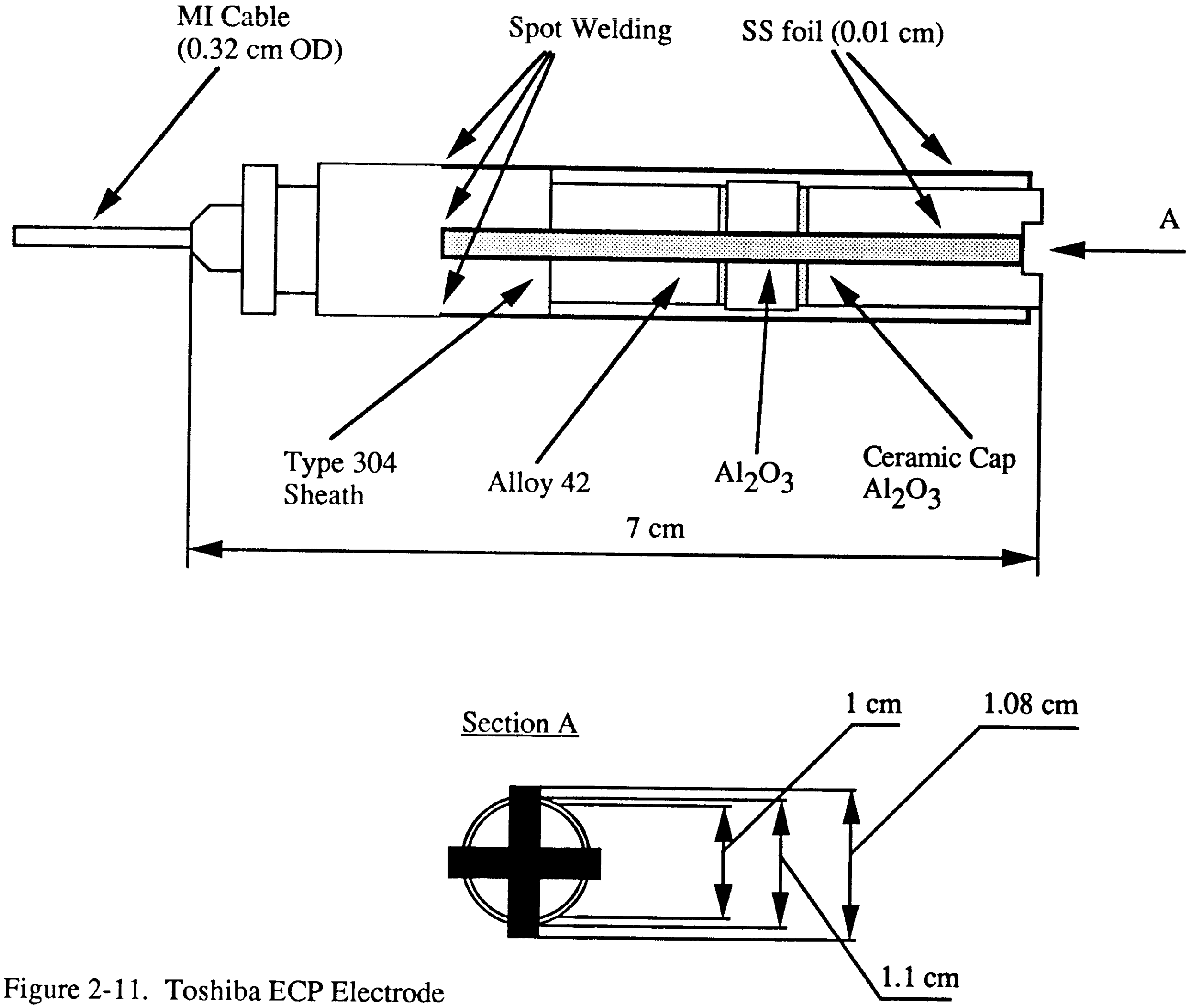


Figure 2-11. Toshiba ECP Electrode

the basic design which consists of a zirconia plug as the semi-porous ionic conducting path, a Teflon heat shrink tube (which houses the Ag/AgCl electrode, the KCl fill solution and the zirconia plug forming a pressure boundary with the environment of interest) and the Conax® fitting which provides the pressure seal against the environment while ensuring an insulated wire for the current path. The electrochemical potential measured against a 0.1N KCl filled external Ag/AgCl sensor is corrected to SHE by the expression below (M-1),

$$E_{extAg/AgCl} = E_{meas} + 286.6 - 1.003 \times (T-25) + 1.745 \times 10^{-4} \times (T-25)^2 - 3.030 \times 10^{-6} \times (T-25)^3, \text{ mV SHE} \tag{2-2}$$

where T is the temperature in degrees Celsius. During the out-of-pile tests, all external sensors produced meaningless results due to leakage of the fill solution out the top fitting (a Conax® with a Teflon® gland). This problem was eliminated by heat shrinking the tube where it seals on the silver rod to make a snugger fit around the silver rod, thereby reducing the likelihood of a leak. Details of fabricating these external reference sensors are specified in Appendix G.

2.5.2 Water Return Line Autoclave

The water return line autoclave was redesigned to simplify its maintenance and operability. It is shown in Figure 2-12. The autoclave was fabricated from four 1/2" Ultraseal® tees and a union gland similar to the original design, but ports for sensor employment were changed to face in the same direction and a drip-tray was installed. Two pairs of two tees welded together formed the body of the autoclave, thus minimizing the length, but maintaining flexibility. Compared to the design for previous campaigns the parallel port design for sensor employment improved the maintainability in the event of a leak which mandated valving out the autoclave, and the drip-tray localized possible leaks in case fittings loosened up during the rapid temperature changes experienced during cooldown.

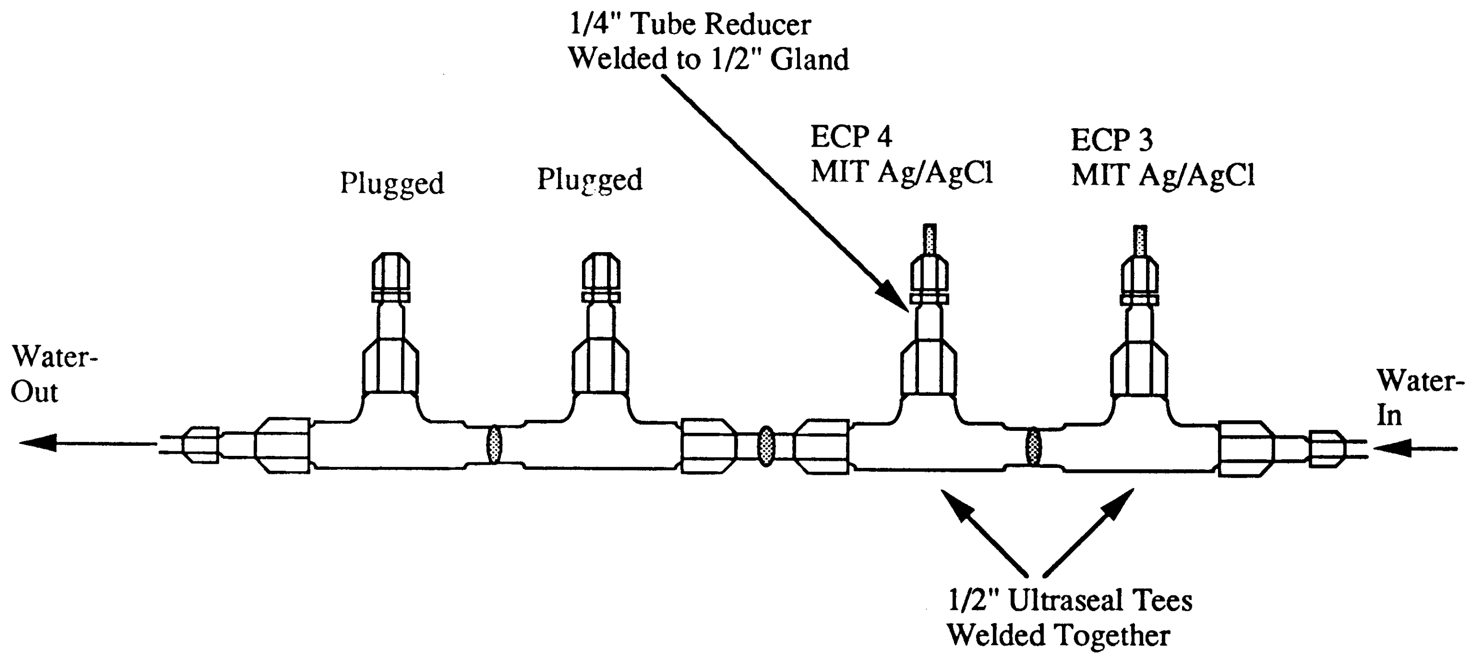


Figure 2-12. Water Return Line Autoclave

2.5.3 Data Acquisition System

Signals from the ECP electrodes, both in thimble and autoclave, are read by a HP 3457 A Digital Voltmeter and recorded directly on the BCCL DA system which was installed on the reactor front mezzanine. (In the 1992 Campaign the ECP signals were recorded by a Hewlett-Packard computer and printed out every two minutes.) The ECP signals were also displayed on the computer screen, so that ECP behavior and trends could be observed in real time.

2.6 STEAM AND WATER EFFLUENT SAMPLING SYSTEM

The system was not changed since the 1992 Campaign. It consists of a sample cooler and water and steam sampling lines. The chiller bath was moved from the reactor top to the back mezzanine to reduce personnel dose, and the bath volume was increased to enhance cooling potential. Design of the system can be found in the previous reports.

2.7 LEVEL CONTROL SYSTEM

The level control system is necessary to maintain the level in the steam separator plenum in order to monitor stable boiling conditions and avoid water carryover in the steam line. A detailed description of the system is given in previous reports (see Table 2.2). This system was not changed significantly; only minor engineering changes were implemented to increase system reliability. The level monitoring range is shown in Figure 2-8.

2.7.1 Float

New floats were manufactured from quartz tubing of 8.0/6.9 mm OD/ID. After manufacture, the floats were tested at 1200 psi and 550°F for 8 hours and at 1500 psi at room temperature for 24 hours. Those floats that withstood the tests were considered qualified for use in this campaign. However, after one month of loop operation (when the thimble was already in the core tank of the MITR) the float failed, so the thimble was taken out of the reactor, and the internals were taken out of the thimble to install a new float and continue the run. Appendix H describes in detail the fabrication of this key component, including changes implemented to make them more robust following the most recent failure incident.

2.7.2 Coils

Issues regarding the durability of the aluminum wire used for the coils have already been addressed in a previous thesis (H-1). In the present campaign the aluminum wire on the upper coil broke. As a result, the steam-water level in the outlet plenum was monitored and maintained in the lower part of the plenum using the lower coil only, i.e. at 40% of full height instead of the originally planned 50%. Changes to remedy this problem in future runs are recommended in Chapter 7.

2.7.3 Electronics

The electronics used to monitor the level in the outlet plenum remained the same as in the past. However a filter was introduced to smooth the signal from the coil, and the high frequency level oscillations formerly seen on the computer screen were eliminated.

2.8 HYDROGEN PEROXIDE SAMPLING SYSTEM

The purpose of this system is to allow sampling from the water return line for hydrogen peroxide analysis. The system consists of a peroxide sample cooler, a forced cooling heat exchanger, mixed injection cooling system, a sample line and tap.

The hydrogen peroxide sample cooler underwent further modifications during preparations for the 1993/94 BCCL Campaign. One of the major changes in the design was relocation of the sampling line. In the 1992 Campaign the water exit line left the steam separator plenum from the bottom (towards the in-core section), one potential factor leading to relatively high measured H_2O_2 concentrations. During this campaign the steam plenum was redesigned, so that the water line exits the separator from the top, thereby avoiding high neutron and gamma doses. The peroxide sampler is located where the water line leaves the steam plenum.

Figure 2-13 shows the configuration of the new peroxide sampler. A 3/16" fitting is welded to the water line right after the water leaves the steam plenum. In this fitting the sample water is mixed together with the cooling water (so that the mixed temperature drops below the ~400°F-threshold above which significant peroxide decomposition occurs) and goes to the tube-in-tube heat exchanger for further cooling. Two thermocouples are provided to measure the temperature of the cooling water before mixing, and the mixed temperature. Dimensions of the sampler are given in the same figure. Design of the mixed cooling injection system and sample tap is discussed in (H-1) in detail.

2.9 CONTROL/POWER/DATA ACQUISITION (DA) SYSTEMS

The BCCL control system allows monitoring of thermocouple readings, level in the steam separator plenum, thimble humidity, pressure, and the power level of the in-core heater. During this campaign, the ECP electrodes were also hooked up to the DA system computer. All these data were recorded on the computer hard disc. A detailed description of the control system and alarm signals can be found in Ref. (H-1). The current BCCL campaign also featured the recirculation mode of operation, and, therefore, new auxiliary copper heater and recirculation pump controls were provided; they were

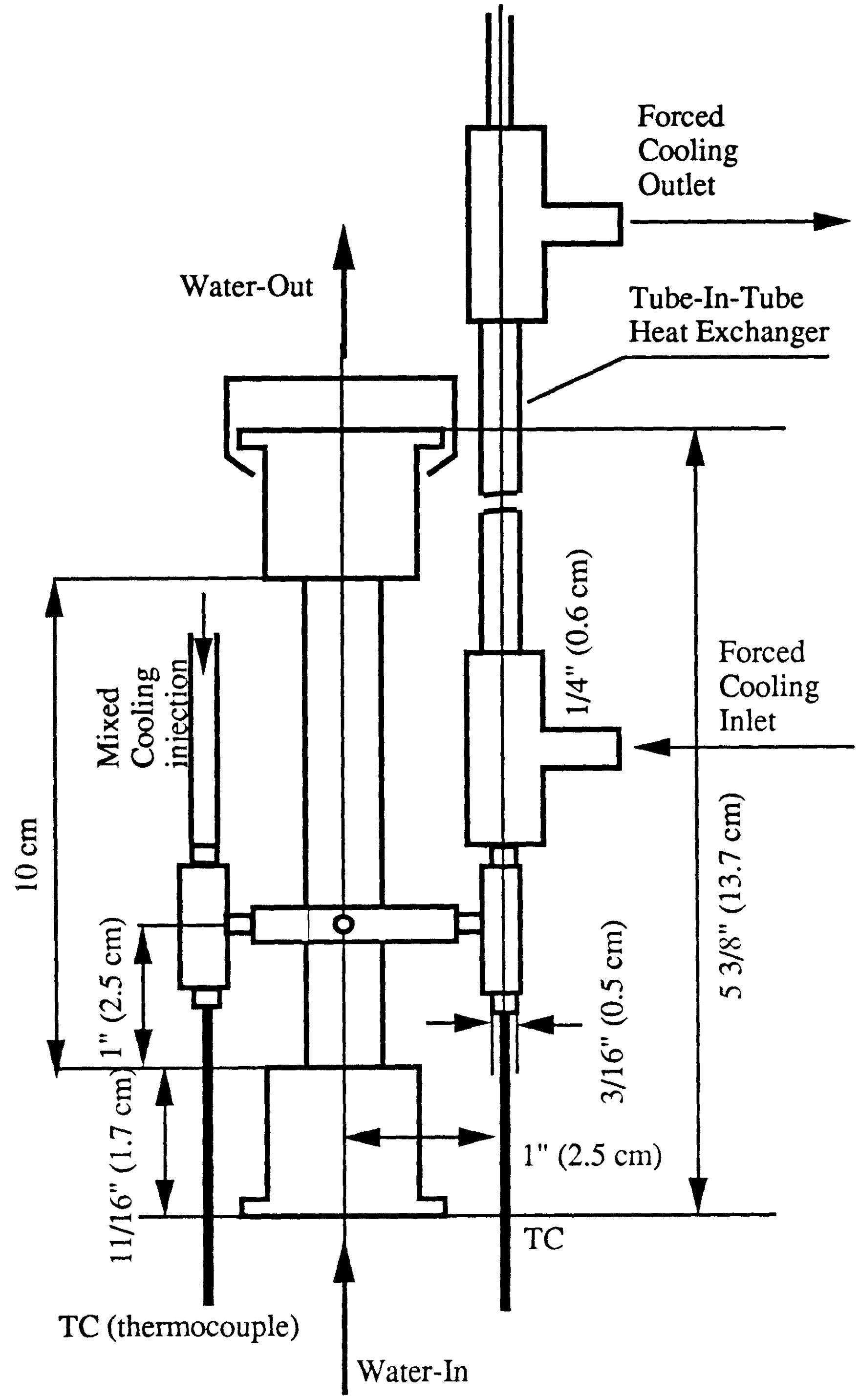


Figure 2-13. Hydrogen Peroxide Sample Cooler

placed on the reactor front mezzanine. A venturi flowmeter was installed on the reactor top downstream of the recirculation pump to measure recirculation flow rate. The signal from the venturi flowmeter was sent to a pressure drop monitor. Another signal was sent from the steam orifice to determine the flow rate through the steam line to calculate steam quality. A revised list of data acquisition and control signals is compiled in Table 2.3 and 2.4.

2.10 CHAPTER SUMMARY

As discussed in this Chapter, the BCCL consists of the following systems: out-of-pile system, thimble and internals, N-16 and ECP measurement systems, steam and water effluent sampling system, level control system, hydrogen peroxide sampling system, and control/power/data acquisition system. These systems have been described in great detail in (O-1), (R-1), (H-1), and previously cited EPRI Report (E-1); in the present write-up attention was given mostly to recent loop modifications.

Table 2.3. List of Data Acquisition Signals

#	DA SIGNAL	SIGNAL DESCRIPTION
1	CORE-IN	Coolant temperature at the in-core section inlet
2	CORE-OUT	Coolant temperature at the in-core section outlet
3	SAMPLE BLK	Temperature of the mixed cooling injection measured prior to mixing with the sample stream
4	RHX-TUBE-IN	Coolant temperature at the tube-inlet of the regenerative heat exchanger
5	RHX-TUBE-OUT	Coolant temperature at the tube-outlet of the regenerative heat exchanger
6	RHX-SHL-IN	Coolant temperature at the shell-inlet of the regenerative heat exchanger
7	RHX-SHL-OUT	Coolant temperature at the shell-outlet of the regenerative heat exchanger
8	LEVEL-DET	Water level in the steam plenum
9	DELTA-P	Pressure drop across venturi or steam orifice
10	WATER-COND	Water conductivity
11	WATER-PH	Water pH
12	PRESSURE	Loop pressure
13	POWER	In-core section heater power
14	OXYGEN	Oxygen concentration
15	HYDROGEN	Hydrogen concentration
16	ECP1	Toshiba in-thimble ECP sensor
17	ECP2	Toshiba in-thimble ECP sensor
18	ECP3	Ag/AgCl MIT ECP sensor in autoclave
19	ECP4	Ag/AgCl MIT ECP sensor in autoclave

Table 2.4. List of Control Signals

CONTROL SIGNAL	NOMINAL VALUE	ALARM
In-core section lead bath high temperature	415°C (780°F)	427°C (800°F)
Low BCCL pressure	7.0 MPa	3.55 MPa
Low water level in the charging tank	55 L	30 L
High thimble humidity	5%	40%
Low thimble pressure	12 psig	10 psig
Low in-core section heater current	5 KW	0.5 KW
Low water level in out-of-pile test tank	4.58 m (15 ft)	3.66 m (12 ft)
Regenerative heat exchanger tube outlet high temperature during experimental run	277°C (530°F)	288°C (550°F)
Feedwater heater outlet temperature	260°C (500°F)	288°C (550°F)
Auxiliary (Copper) heater outlet temperature	282°C 540°F)	288°C (550°F)
Charging tank inlet high temperature	28°C (82°F)	43°C (110°F)

CHAPTER 3 EXPERIMENT PROCEDURES

3.1 INTRODUCTION

The BCCL experiment procedures did not undergo significant changes since the 1992 Campaign. The loop was operated at hot standby, hot single phase, and boiling in the once-through and recirculation modes. Primary data included the oxygen and hydrogen concentrations in the charging tank, mixed-return line and water sample line. N-16 activity was measured in the steam and water lines with Ge detectors. In several runs NaI detectors were used to obtain results for the 1993/94 Campaign comparable with those recorded in the past. Hydrogen peroxide was measured in the loop water letdown line, in the charging tank, and the mixed return. Electrochemical corrosion potential (ECP) was measured in the in-thimble ECP plenum and the external autoclave. Water conductivity was measured by using an in-line conductivity meter. Data were gathered both on-line and in batch samples. Several samples were taken for ICP analysis.

All actions performed by the loop operators were recorded, as in the past, in the BCCL Run Log on the back-mezzanine Mac computer, the IBM-386 data acquisition (DA) computer located on the front mezzanine, and on the log sheets. For more details refer to (H-1). The Hewlett Packard computer previously used for processing ECP signals was eliminated in this campaign, and the signals were sent directly to the front mezzanine DA computer, and trends displayed on the monitor. As before, the cover gas in the charging system was varied to simulate both NWC and HWC conditions.

To permit operation in the recirculation mode, the BCCL featured new components, as described in the previous chapter. A typical recirculation run will be presented later in this chapter. A list of standard operating parameters for the BCCL is given in Table 3.1.

Table 3.1. Standard Operating Parameters for the BCCL

PARAMETER	HOT SINGLE PHASE	BOILING
Coolant Flow Rate (Once-Through)	1500 cc/min	1500 cc/min
Coolant Flow Rate (Recirculation)	900 cc/min	750-1000 cc/min
Feedwater Flow Rate (Recirculation Mode Only)	200 cc/min	80-150 cc/min
Loop Pressure	7.0 MPa (1000 psi)	7.0 MPa (1000 psi)
Core Inlet Temperature	233°C (450°F)	280°C (535°F)
Core Outlet Temperature	275°C (530°F)	290°C (555°F)
In-Core Lead Bath Temperature	360°C (680°F)	415°C (780°F)
Reactor Power	4.5 MW	4.5 MW
Outlet Plenum Water Level	100%	40%
Steam Exit Quality (Once-Through Mode)	0%	10%
Steam Exit Quality (Recirculation Mode)	0%	15%
In-Core Heater Power	3.5 KW	5.0 KW
Feedwater Heater Outlet Temperature	221°C (430°F)	263°C (505°F)
Feedwater Heater Current	10 A	20 A
Auxiliary (Copper) Heater Current	10A	20 A

3.2 LOOP OPERATION

Three operation regimes in the once-through mode of operation-standby, hot single phase, and boiling-have already been discussed in detail in previous reports (R-1) and (H-1). The only significant change for this campaign was the use of an auxiliary

(Copper) heater. This heater was incorporated for the recirculation mode runs to keep core inlet temperature in the desirable range. For the once-through runs the heater was either turned off or operated to decrease the thermal load on the feedwater heater, thus sharing thermal power with it. Since a detailed description of once-through procedures can be found in previous theses (O-1, R-1, H-1), the discussion which follows deals only with operation in the recirculation mode. It should be noted here, that for the recirculation runs, the regenerative heat exchanger was disconnected on the shell side, so that the return flow bypassed directly to the non-regenerative heat exchanger. In this case, feedwater temperature can be varied within a wider range to permit safe (i.e. non-cavitating) operation of the recirculation pump.

3.2.1 Standby

The standby regime was used when the loop was left overnight with the MIT reactor at power. The loop remained at operating pressure, but reduced temperatures, to serve three purposes: to maintain the loop below saturation, to shorten time for heatup to boiling conditions the next day, and to prevent accumulation of hydrogen peroxide in the loop and charging tank while the reactor is running. To comply with these purposes the core outlet temperature was chosen to be higher than 400°F, and in most cases it was maintained as high as 450-480°F. In the standby mode, the in-core heater and feedwater heater powers were reduced, and the auxiliary Copper Heater was turned off. The recirculation pump and the feedwater pump remained running.

3.2.2 Hot Single Phase

This mode of operation was used in cases when loop parameters had to be below saturation for a short period of time, and a fast return to boiling anticipated. These conditions were established, for example, during lunch breaks or foreseen reactor power reductions. Hot single phase did not differ much from standby, except that the core outlet temperature setpoint was fixed at about 530°F instead of 450°F. To achieve this goal, in-core heater and feedwater heater power were increased relative to that employed in standby, and the Copper Heater was turned on.

3.2.3 Boiling

Boiling is achieved by increasing the power of all available heaters in such a way that the core outlet temperature reaches saturation temperature (at a fixed pressure, normally 1000 psi, set by the LEWA® charging pump and back pressure regulator on the pump cabinet). One of the major concerns during operation was to keep the recirculation pump inlet temperature well below saturation. Failure to meet this condition can cause pump cavitation and subsequent loss of flow rate, which would necessitate a reactor scram to prevent overheating the aluminum block of the in-core section due to gamma heat, and pump damage.

There are two flows coming to the circulation pump inlet: recirculation and feedwater. Recirculation water temperature is less than saturation due to heat losses in the tubing which extracts plenum water from the in-pile thimble. The feedwater (only 10-15% of the loop flow rate) is heated up by the feedwater heater to approximately 500°F, and hence the recirculation pump can be protected from cavitation when the recirculation water is mixed with the relatively cold feedwater. The temperature difference between the core inlet and pump inlet flow is compensated for by the Copper Heater. Steam quality is controlled by adjusting the LEWA® pump charging rate and the electric heaters. The level in the steam separator plenum can be controlled either by varying the power of the available heaters (primarily, the in-core heater) or with the needle valve in the steam line. The details of adjusting plenum level while in the recirculation mode do not differ from those for the once-through mode, and one can find them in the previous reports already cited. It should be noted, however, that the system is more stable in the recirculation mode than in the once-through mode. The need to adjust power is reduced from around once per minute to approximately once per three to four minutes.

Steam quality for the recirculation mode of operation can be calculated after having measured loop flow rate and feedwater rate, since during stable conditions (when the level in the steam plenum is constant) the steam flow rate is equal to the feedwater flow rate. Loop core inlet flow rate is measured using a venturi flowmeter (see Figure 2-2), which was calibrated during the once-through runs, and the feedwater flow rate is measured by the rotameter located on the pump cabinet. The ratio of the feedwater-to-core-inlet mass flow rates gives steam quality. Two other methods-an energy balance across the in-core section and an energy balance across the regenerative heat exchanger-discussed earlier (H-1) were not used during the current campaign, one reason being that an energy balance across the regenerative heat exchanger could not be employed, since this heat exchanger was disconnected on the shell side. The steam orifice was calibrated during the once-through runs, and the orifice calibration curve was used to verify the steam flow rate measured by the return water rotameter.

Adjustments of the in-core heater controller to control level in the steam plenum were made as in the once-through mode. The level can be monitored on the DA computer screen over the range 0-50% (cannot be higher than 50% due to the aforementioned failure of the upper coil of the level detector), and during the experimental campaign it was maintained within 35-45% to avoid significant carryover and carryunder, and to produce data comparable with those obtained in the previous years.

3.3 SAMPLING

A number of sample points for coolant water chemical analysis were provided to measure oxygen, hydrogen, hydrogen peroxide, and conductivity of the water, steam, return lines, and charging tank water. Locations of the available sample points are shown in Figure 2-2 and Figure 3-1.

3.3.1 Hydrogen Peroxide Sample Tap

The hydrogen peroxide sample tap provides cooled batch samples of water phase BCCL coolant from a sampling point downstream of the steam separator plenum. A detailed description of the peroxide tap and sample cooler is given in the previous chapter. Sample flow drawn from the water line is mixed with the cooling water to decrease the temperature below the point where thermal decomposition of H_2O_2 is significant (approximately 370°F). Further cooling down to ~200°F is provided in the tube-in-tube heat exchanger.

The procedure for drawing a sample did not change since the last campaign. First, the peroxide sample tap cutout valve is slightly opened to allow flow to go through the 1/16" sample line. Then, the coolant injection pump was turned on. When the loop water conductivity was not high due to chemical injection, KNO_3 solution was injected to permit calculation of the sample dilution factor. The value of the dilution factor can be calculated as follows:

$$K = C_{KNO_3} / (C_{KNO_3} - C_{sample}) \qquad (3\text{-}1)$$

where C_{KNO_3} is the conductivity of the KNO_3 solution and C_{sample} is the conductivity of the sample flow.

When a chemical having high conductivity was injected in the feedwater, pure DI water was pumped to the peroxide sampler. Batch samples of 30 ml were drawn over a period of approximately 2-5 minutes. Once the sample was drawn, it was analyzed using colorimetric H_2O_2 ampoules from CheMetrics® Inc. and a Hach® DR/2000 colorimeter, and occasionally checked using the more accurate Luminol method following the procedure described in Appendix F.

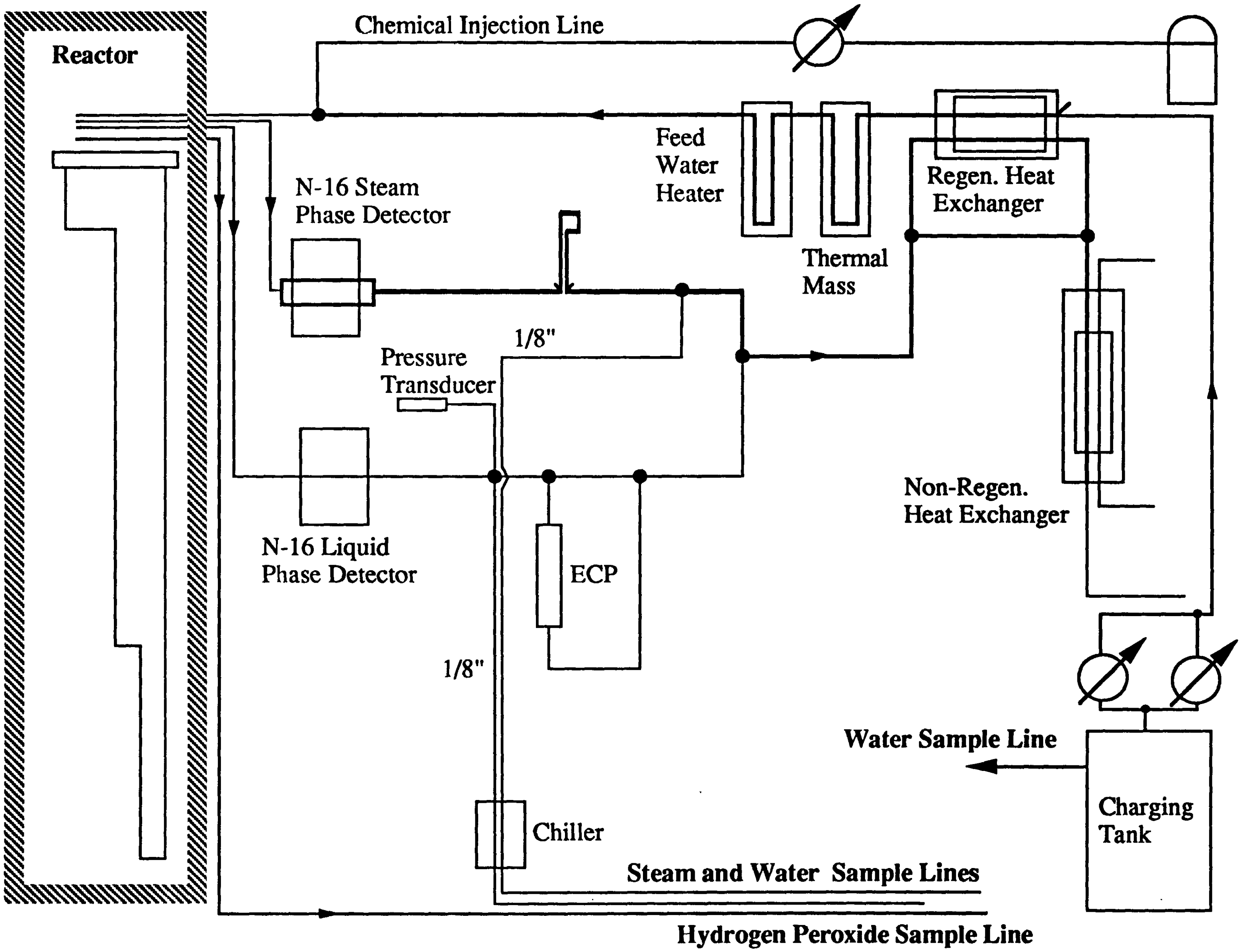


Figure 3-1. BCCL Sample Lines Configuration

3.3.2 Steam and Water Sample Lines

The continuous drains, as mentioned in (H-1), serve as taps for dissolved oxygen measurements in the water letdown line, for carryover and carryunder tests, pH, conductivity and resistivity measurements. A schematic of the water and steam sampling system is described in Chapter 2.

Before drawing samples, the refrigeration unit is turned on to cool the chiller bath to ~4°C. This cools down the sample to approximately room temperature. The three-way cutout valve is opened, and the pressure reducing valve is adjusted to allow a minimal flow rate that does not cause severe loop flow rate perturbations. All details of the measurement procedures can be found in previous reports.

3.3.3 Dissolved Oxygen and Hydrogen Sampling System

Dissolved oxygen and hydrogen were measured in the charging tank, return line, and loop water sample lines (see Figure 2-2 and Figure 3-1 for sample points) using sensors made by Orbisphere® Laboratories. A HYDRAN® 202 N meter was also used to measure higher hydrogen concentrations in the charging tank and return line. Since Orbisphere® sensors require a flow rate of the order of 50-200 ml/min, the entire return stream (condensed vapor) in the recirculation mode of operation was directed through the sensors. When the loop was running in the once-through mode, only a small fraction of the combined water plus condensate return stream went through the sensors. To monitor the flow rate through the sensors, a flowmeter was employed in the line.

The sensors were periodically switched from the return line to the charging tank and back, and every operation was registered in the BCCL Run Log. Signals from this sample system, were sent to the front mezzanine DA system.

A low flow oxygen sensor was also installed in the loop water sample line. Under hot single phase operation, prior to bringing the loop to boiling, the oxygen level in the charging tank was set depending on the program plan for the experiment.

3.3.4 Charging Tank Sample Tap

The charging tank sample tap shown in Figure 2-2 was used for measurement of hydrogen peroxide and for collecting batch samples to be analyzed by ICP or NAA (neutron activation analysis) techniques. This system did not undergo any changes since the last BCCL campaign, and it is described in previous reports (see Table 2.2).

3.4 N-16 MEASUREMENT

N-16 is measured in the water and steam lines. Space for two detectors is provided in the lead shield which was utilized in the past. In the 1993/94 Campaign, two Ge detectors were added to the measurement system to distinguish N-16 peaks from those of C-15, and to compare results of this and past campaigns. Signals from the detectors were sent to a Canberra® Series 20 MCA. As before, energy peaks, net counting area, and the peak heights were recorded on a logsheet. At the same time a PC computer was hooked up to the MCA, so that the measured spectra were recorded on the computer for future analysis.

Since employing Ge detectors on both lines allowed visualization and separation of all N-16 and C-15 peaks, the energy span of interest was chosen to be narrower than when a NaI detector is used; a range equal to 20 channels was used (corresponding to ~67 KeV): 10 channels on each side of a peak (instead of the 250 channels used with the NaI detectors in 1992). Measurements of peak height and net area were performed in the vicinity of the 5.1 MeV, 5.6 MeV, and 6.1 MeV N-16 peaks and the 4.3 MeV, 4.8 MeV, and 5.3 MeV C-15 peaks. A representative spectrum is shown in Figure 3-2.

Counting time for both the steam and the water lines was increased from one minute, which was the case in the past, to five minutes. With the new system, dead time was reduced from 20-22% to 16-18% for water, and from 25-30% to 3-4% for steam.

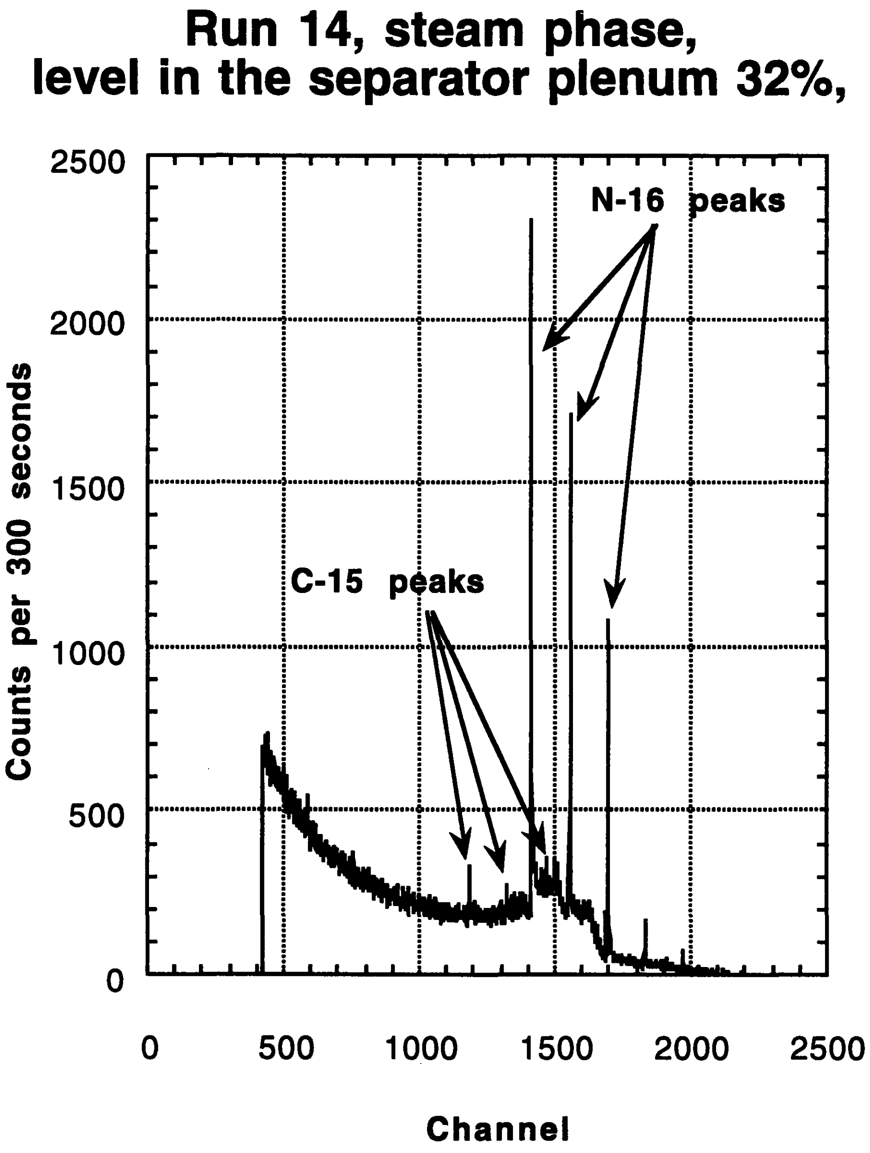


Figure 3-2. Representative Steam Line Spectrum

Several tests were carried out to show that the counting system was accurately corrected for dead time in the range of interest.

3.5 CHEMICAL ADDITION

The chemical injection system, as shown in Figure 2-4 and described in Chapter 2, remained the same as during the 1992 Campaign with the only change being the installation of a new chemical injection PulsaFeeder® pump in place of a Milton Roy® pump. The chemical injection solution was injected into the feedwater prior to where it enters the MITR core tank. Bottles which contained an additive were purged with helium cover gas prior to and during use.

The procedures for running the chemical injection system in the once-through mode were not changed since the 1992 Campaign, however chemical injection under recirculation was much more complicated from an operating standpoint. The recirculation mode of operation required very flexible operation of the system, since the concentration of the additive in the loop water in this mode changes with time as the ratio of letdown to recirculation flow rate varies. Varying the injection flow rate can be achieved by varying pump frequency, pump piston stroke, or running the pump with constant frequency and stroke in a "pulse" mode turning it on and off depending on how fast the concentration of the chemical additive in the loop approached the desired value. All methods were tried during recirculation runs. Additive concentration was monitored using water conductivity measurements.

Hydrogen (under HWC) was introduced into the loop water through the cover gas system, design and operation of which remained unchanged since 1992.

3.6 ECP MEASUREMENT

Measurement and recording of ECP did not involve any special operational procedure, since the ECP signals were directly transferred to the loop DA system. The only essential operation required valving the ECP autoclave in before the beginning of the run. When the experiment was over and the loop was left overnight, the autoclave was valved out. This procedure was dictated by the possibility of a fast cooldown at night if reactor power has to be lowered. During a fast cooldown, the ECP electrode seals might loosen enough to develop a leakage path. This happened once during this campaign, with the loss of several liters of coolant.

3.7 TYPICAL RECIRCULATION RUN DESCRIPTION

A description of typical BCCL once-through mode operations is given in previous reports (O-1), (R-1), and (H-1). During the last campaign the loop was operated in both modes: once-through and recirculation. The only difference in operations under the once-through mode, in comparison with past years, arose from the concurrent availability of the features supporting recirculation mode operation. These were the auxiliary copper heater, the recirculation pump, the venturi flowmeter, and the recirculation line with corresponding cutout valves. In once-through operation, the recirculation pump (together with the venturi and recirculation line) were valved out, and the copper heater was turned on to redistribute thermal power between this heater and the feedwater heater. Since these modernizations did not change once-through loop operation in any significant way, only a recirculation mode run description will be presented below.

The run itself starts with checking H_2O_2 in the loop water and charging tank. High peroxide concentration may arise from running the loop overnight with core outlet temperature below 400°F. If this occurs, then by increasing the power of one of the available heaters, core outlet temperature is increased to 450°F to decompose peroxide in the system. Normally, after leaving the loop at hot standby overnight, no peroxide (i.e.<10 ppb) was found. Oxygen and hydrogen concentration in the charging tank should also correspond to NWC conditions (e.g. see Table 6.1), and the level of H_2 in the tank can also be controlled by adding O_2. When the loop is switched from once-through to the recirculation mode of operation, all pumps are off, and the reactor is shutdown. The cutoff valve on the return water line is closed, and the valve on the recirculation line is opened (see Figure 3-3). The line with the recirculation pump has to be valved in, and the regenerative heat exchanger is isolated from the shell side, so the steam flow bypasses this heat exchanger. Table 3.2 lists the valves' status for the recirculation and once-through modes of operation.

Table 3.2. Status of the Loop Valves for Different Modes of BCCL Operation

MODE OF OPERATION	VALVE #	STATUS
Recirculation	1, 3, 5	Closed
Recirculation	2, 4, 6,7	Opened
Once-through	1, 3, 5	Opened
Once-through	2, 4, 6,7	Closed

See Figure 3-3 for valve identities.

After all adjustments are done, the recirculation pump is turned on. Its frequency of operation is set to 75 Hz, which corresponds to the maximum achievable loop flow rate-0.9 LPM. Then the LEWA® charging pump is turned on, and the flowmeter on the LEWA® suction line used to monitor feedwater flow rate. Once both pumps are running, the loop pressure is set by adjusting the back-pressure regulator on the return line and the flow rate of the LEWA® pump. Once 900 cc/min maximum loop flow rate is achieved,

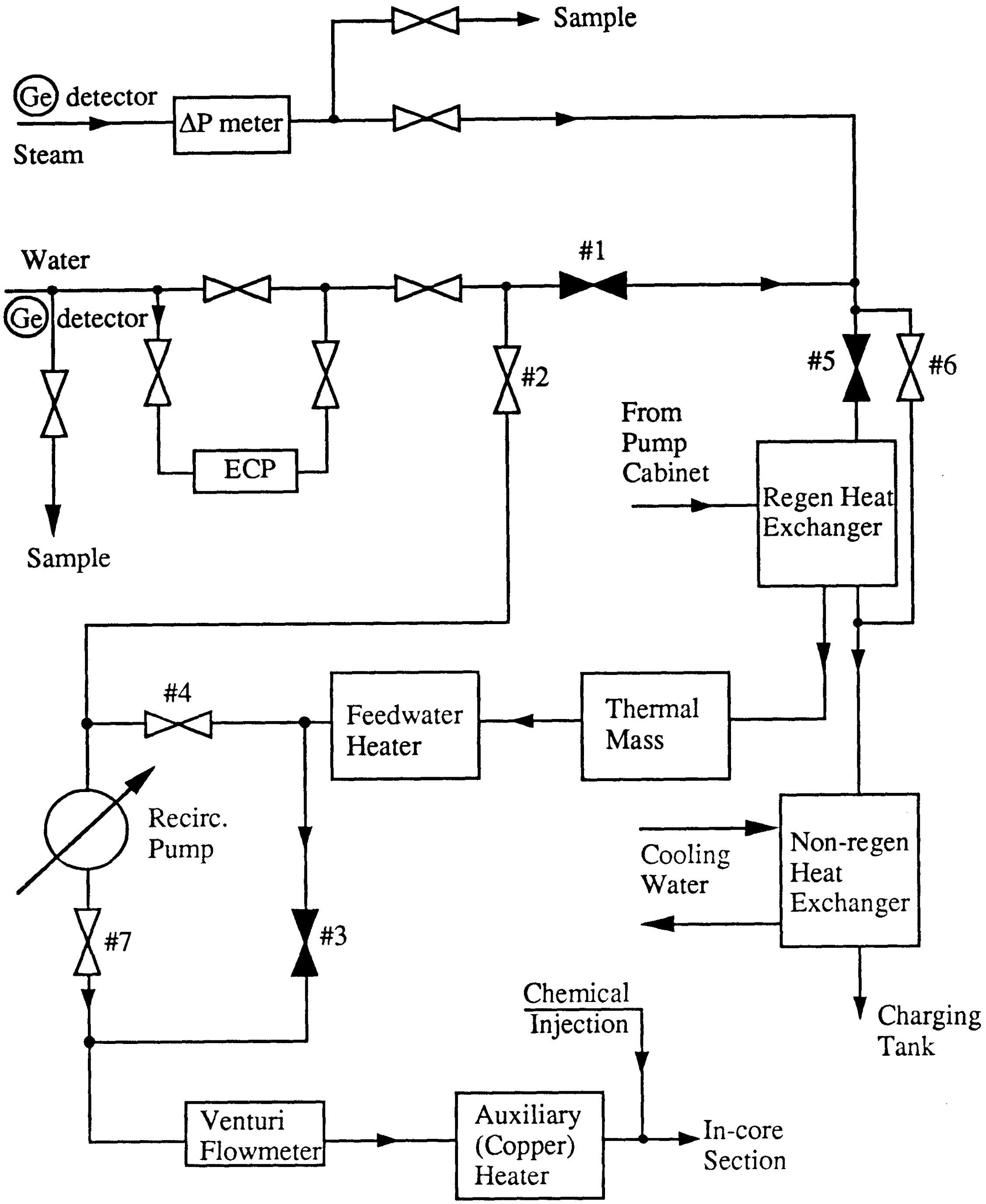


Figure 3-3. Locations of the Cutoff Valves for Switching the BCCL from Recirculation Mode of Operation to Once-Through

the feedwater flow rate is set to be 120-140 cc/min. Under stable conditions, feedwater and return water flow rates are equal.

The next step is heating up the loop to hot single phase conditions by increasing the thermal power of the loop heaters. Before bringing the loop to boiling conditions, hot single phase baseline measurements are conducted. Oxygen can be added to the charging tank water to closer simulate BWR conditions. After the baseline measurements are completed, the power of the heaters is further increased. Boiling operation starts when the core outlet temperature achieves saturation (555°F) at 1000 psi. Then the level detector coils are energized and their nominal voltage (5.04 V) applied. As soon as phase separation is established in the steam plenum and the level falls to 50%, (upper detection limit) the level can be monitored on the DA computer screen. Further adjustments of the level in the plenum can be done by changing in-core heater power or by closing down (opening up) the needle valve on the steam return line. Stable boiling is defined as when the feedwater flow rate and the flow rate of the condensed steam are equal. Core inlet temperature is adjusted by varying the copper heater or feedwater heater powers. Cavitation is avoided by limiting the recirculation pump inlet coolant temperature, which is achieved by lowering feedwater outlet coolant temperature to 505°F and maintaining the feedwater flow rate >100 cc/min. When the level in the steam plenum stabilizes within the 35-45% range, boiling baseline data are taken. Measurements are H_2O_2 in the loop, O_2 and H_2 in the return and charging tank, O_2, conductivity and pH in the loop water, N-16 in the steam and water lines, ECP in the external autoclave and ECP in the in-thimble plenum.

Chemical addition under the recirculation mode differs from that under once-through operation due to accumulation of the injected additive in the coolant. Therefore, approaching equilibrium is a gradual process depending on the ratio of the chemical additive flow rate to the flow rate at which water samples are drawn. Measuring loop flow rate and injection flow rate, as in the case of the once-through mode, does not give any information on the additive concentration. The only on-line method used to determine and control concentration during the campaign is measurement of the conductivity of the chemical in the injection bottle and loop coolant.

After the conductivity of the concentrated chemical solution (typically in the range 20-250 μS/cm) is measured and its concentration in the loop determined, then the targeted coolant conductivity is calculated as the ratio of the targeted concentration to the concentration in the injected solution multiplied by the conductivity of the chemical additive.

$$\mu_{target}=\mu_{add}x(C_{target}/C_{inj}) \tag{3-2}$$

where μ_{target} is the targeted coolant conductivity, μ_{add} is the conductivity of the chemical additive, C_{target} is the targeted concentration, and C_{inj} is the concentration of the injected solution. Note that all conductivities considerably exceed those of untreated loop coolant (~1.0 μS/cm), hence no correction for "background" is required.

Having connected the helium line to the injection bottle and purged helium through the solution for more than 1 hour, the chemical injection pump is then turned on. Its flow rate is ~10 cc/min-a factor of 100 less than the loop flow rate. The water sample line is then opened, so that the conductivity and pH of the loop water can be measured. When the additive concentration is close enough to the target value, the chemical injection pump is either turned off or its flow rate reduced. In fact, due to flow rate oscillations (loop flow rate, chemical injection flow rate, water sample flow rate) the concentration never reaches true "equilibrium", but changes slowly (10-20% in 10 minutes). In this period of time data are taken again.

After the data are taken, chemical injection is ended, and heaters reduced in power to bring the loop back to hot standby conditions. The chemical injection line is flushed with DI water, and the loop, with the single phase regime established, is flushed overnight to permit the cleanup system to remove any remaining traces of additives. A list of the BCCL Operation Procedures is given in Table 3.3.

Table 3.3. BCCL Operation Procedures

1. Check H_2O_2 in the loop water and charging tank. If H_2O_2 in the loop is high, then increase power of the available heaters so that the core-outlet temperature exceeds 450°F.

2. Check O_2 and H_2 concentrations in the charging tank. O_2 should correspond to NWC conditions. If O_2 in the charging tank is high then the run should be postponed until the O_2 goes down while the charging tank water is purged with helium, or a small amount of H_2 can be purged through the charging tank water.

3. Check status of the cutoff valves to make sure that the loop is operated in the recirculation mode. Open ECP electrodes' autoclave.

4. Turn on the recirculation pump. Its frequency should be about 70-75 Hz.

5. Turn on the LEWA® charging pump. Feedwater flow rate is set to be ~130 cc/min.

6. Turn on all available loop heaters. Heat up the loop to hot single phase conditions.

7. Conduct baseline measurements.

8. Increase heaters' power to bring the loop to boiling conditions. Core outlet temperature should achieve ~555°F at 1000 psi.

9. Energize coils of the level detector. Set voltage equal to 5.04 V.

10. Adjust level in the steam plenum by varying power of the in-core section. Steam flow rate at a stable level in the plenum can be changed by opening (closing) the needle valve on the steam line.

11. Take boiling baseline data.

12. Measure conductivity of the chemical injection solution prior to starting chemical injection.

13. Determine target conductivity of the loop water when chemical injection will proceed.

14. Purge chemical injection solution with helium for more than an hour before injection begins. Start chemical injection.
15. Open loop water sample line.
16. Adjust additive concentration in the loop water. This can be done either by changing chemical injection pump flow rate or by cycling it off and on at a constant flow rate.
17. Take data when stable additive concentration is achieved.
18. Stop chemical injection. Turn off chemical injection pump.
19 Reduce power of all the heaters.
20. Turn off level detector.
21. Flush the loop and chemical injection line with DI water.
22. Leave the loop overnight in hot standby.

3.8 CHAPTER SUMMARY

As described in this chapter, the loop can be operated in hot standby, hot single phase and boiling modes. A description of the recirculation mode is given in detail. During hot single phase and boiling conditions, data are collected, including N-16 activity , radiolytic species concentrations and electrochemical corrosion potential. All operating procedures are recorded in the Run Log, and selected parameters are also manually recorded in the Log sheets. Under the recirculation mode of operation, as well as under the once-through mode, characterization runs are conducted and chemical compounds are added. The results of the experiments are presented in the following chapters.

CHAPTER 4 OUT-OF-PILE TESTS

4.1 INTRODUCTION

The introduction of the new components into the loop for the 1993/94 Campaign made it necessary to conduct several tests prior to installation of the BCCL facility inside the MITR core tank. In particular, reliable operation of the new in-core section, the steam separator plenum, and the peroxide sampler had to be verified before the internals were exposed to irradiation in the reactor core.

Before the out-of-pile tests commenced, the new in-core section was thermally cycled in a furnace in a temperature over a range from 32°F to 800°F. After every thermal cycle the internal surface of the in-core section was carefully examined. No cracks or other visible deterioration were found on the surface, except a slight bow (several degrees) over the upper quarter of its height. This phenomenon could be caused by temperature gradients along the furnace height, and by non uniform heatup of the in-core section. The in-core section was then inserted inside the elliptical section of the simulated lower thimble, so that these components were heated up and cooled down together. This was done to verify that bending of the in-core section will not affect facility maintenance when it may be necessary to pull internals out of the thimble.

The new steam separator plenum was also tested before installation inside the thimble, to check whether its increased length and modifications of the tubing inside it enhance steam separation performance to the extent desired.

The new hydrogen peroxide sampler performance was also experimentally proved, and the sampler calibrated before it was installed inside the in-reactor thimble.

Finally, the pump cabinet and charging tank systems were mounted on the reactor back mezzanine, and their reliable operation as a whole system was demonstrated.

4.2 OUT-OF-PILE LOOP DESIGN

The out-of-pile test loop comprised an out-of-pile fluid system, internals not enclosed inside a thimble during the test, the ECP measurement system, steam and water effluent sample system, level control system, and hydrogen peroxide sampling system. All these systems were connected to the loop DA/POWER/CONTROL systems. During the out-of-pile runs, most of the elements were installed inside the MITR containment at the locations reserved for them for the rest of the campaign. The in-pile fluid system, in-core section, steam separator plenum, ECP plenum, and peroxide sampler were mounted on the reactor top. A special frame was erected there to support the internals while the out-of-pile run was carried out. The in-thimble configuration and all dimensions of the elements were preserved. To simulate in-core gamma heat, the new copper heater, designed and manufactured mostly in support of the recirculation run, was connected to the loop. It compensated for thermal losses in the region from the feedwater heater down to the in-core section, and also helped avoid excessive thermal load on the other loop heaters. To reduce heat losses, the internals mounted on the frame were thermally insulated. The design of the out-of-pile test loop is shown in Figure 4-1.

4.3 EXPERIMENTS

The out-of-pile tests continued from mid-October till the end of November. Eleven experiments were completed, and summary run descriptions are presented in Table 4.1.

During the first run the level detector was calibrated. A new quartz float containing an iron wire was inserted inside the level arm and positioned first at the 0% and then at the 100% locations. Signals from the two level detector coils were sent to the

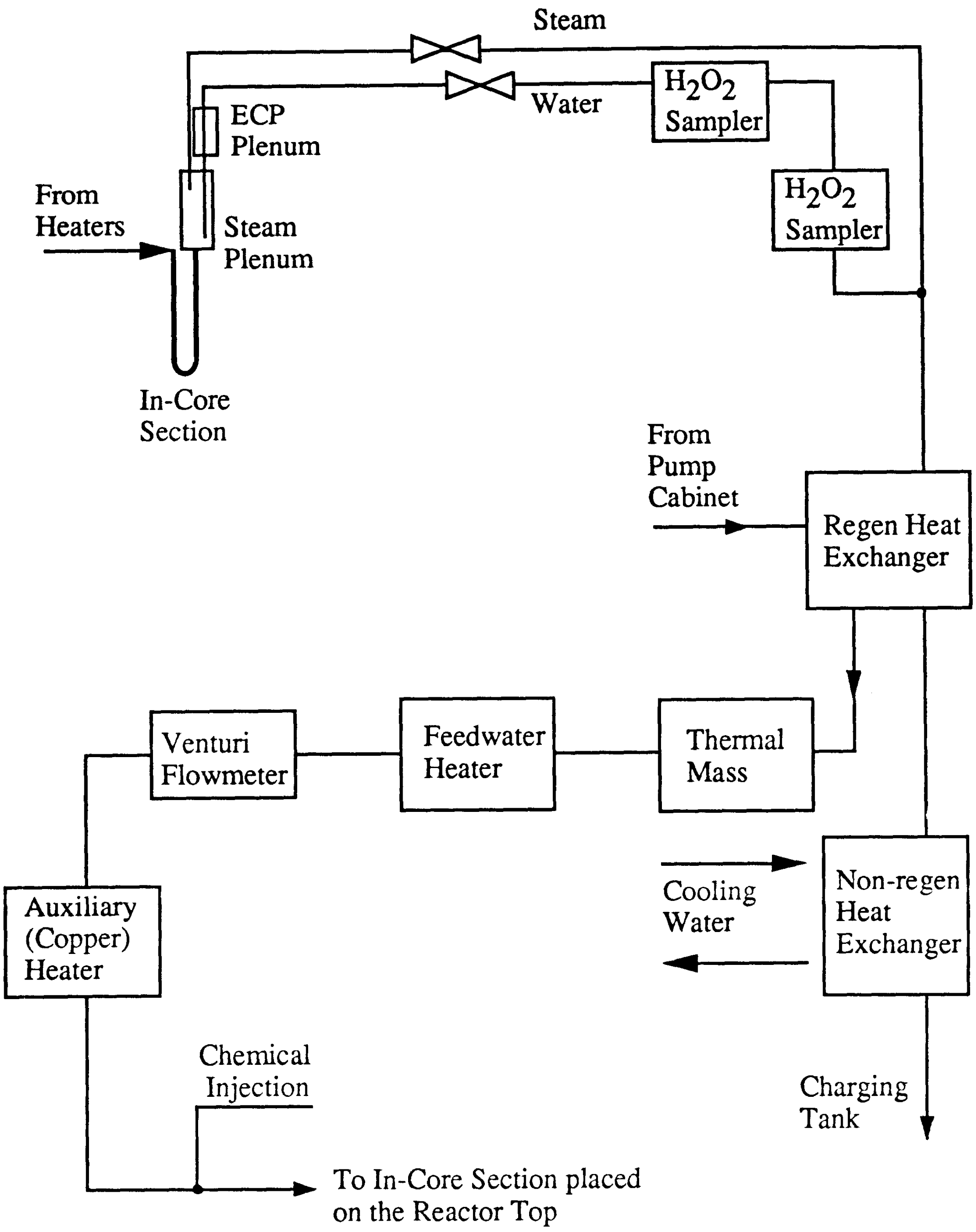


Figure 4-1. Setup for the Out-of-Pile Tests

Table 4.1. Summary Out-of-Pile and In-Pile Shakedown Run Descriptions

RUN #	OUT-OF-PILE RUN DESCRIPTIONS
1*	Float calibration. To calibrate steam orifice, the water line was closed, so the entire flow was directed through the steam line. Level in the steam separator not achieved although saturation point reached. Auxiliary (Copper) heater tripped because of saturation and critical heat fluxes. Float stuck at 100% position inside the level arm.
2*	All water drained from the loop, and the float moved down to 0% level. Problem with the stuck float attributed to thermal hydraulics. Both steam and water lines were then opened. Loop brought to boiling and desirable level within 0-100% range can be achieved.
3*	Shakedown run. It is found that the level can be controlled reliably.
4*	Auxiliary (Copper) heater is set to work in automatic mode to keep level in the steam plenum constant.
5*	By the time of the beginning of this run, loop had been over 200 hours at hot standby to acquire prefilming as required by the sponsors. H_2O_2 sampler calibration-KNO_3 injection into the loop. Float remains at 0% level while non boiling and is later found to have broken.
6*	H_2O_2 sampler calibration-H_2O_2 injection into the loop (130 ppm in the chemical injection bottle, 1.3 ppm in the loop).
7*	Problem with the float-0% level in the plenum at hot standby solved. This float had a crack and was filled with loop water. It was replaced by a new one.
8*	H_2O_2 sampler calibration. H_2O_2 injected (75.5 ppm in the bottle, 755 ppb in the loop).
9*	H_2O_2 sampler calibration at lower loop flow rate (0.8-0.9 LPM). Chemical injection pump works very reliably.
10*	In-core section is connected to the out-of-pile test loop. Second Toshiba electrode is inserted inside the ECP plenum. Steam orifice and venturi flowmeters are emptied and rezeroed. In-core section is tested, and level in the steam plenum is very stable.

11*	Run # 10 is repeated with the in-core section placed inside an elliptical section. This test showed that after heating and cooling down, the in-core section can be pulled out easily (in case internals have to be pulled out of the thimble due to unforeseen circumstances) . Carryover test conducted. KNO_3 injected into the loop (~1000 µS/cm conductivity in the loop). Results show very low carryover (less than 0.1%).

RUN #	IN-PILE SHAKEDOWN RUN DESCRIPTIONS
12*	Shakedown test. During the test the upper coil of the level detector failed, so level can be detected only within 0-50%. Problems occurred with a seal on helium line. Helium is leaking out with very high flow rate. Loop is cooled down.
13*	Problem with helium leak was found: a fitting was leaking. Torr seal applied to eliminate the leakage.
14*	Loop brought to boiling after problems with leaking fitting and level coil fixed.
15*	Loop is at boiling conditions. Level within 0-50% range measured reliably.

* This symbol designates out-of-pile and in-pile shakedown runs.

electronics module where the signals were transformed and calibrated. After float calibration, the loop was prepared for steam orifice calibration. For this purpose the water line valve was completely closed, so the entire flow would go through the steam line. In this case a signal from the steam orifice flowmeter corresponds to the loop flow rate precisely measured with a rotameter on the pump cabinet. However, after the water line was closed, reliable steam-water separation in the outlet plenum was not achieved, and the level could not be observed, since the float stuck at the 100% location. At the same time, once slightly superheated steam was generated, the thermal load on the auxiliary (copper) heater exceeded the critical value, and the heater tripped.

In order to determine why the float stuck at the 100% location in the level arm, the whole loop was completely drained. The float returned to the bottom of the level arm, and it was therefore concluded that there was a problem with loop thermal hydraulics. Once the water valve was opened, a level in the plenum was easily achieved. The third and fourth out-of-pile runs successfully demonstrated that level control is reliable, and can be automatically controlled using the copper heater.

The next five runs were associated with the new peroxide sampler calibration. Before calibration began, the loop had been at hot conditions over 200 hours. The prefilming was a requirement, since some of the titanium components making up the loop were replaced with stainless steel. However, the first calibration run was interrupted due to the fact that the level detector showed 0% level at hot standby. The loop was cooled down and drained, the level arm was disassembled, and it was found that the float was broken. One of a number of possible causes was damage during the previous loop drain and subsequent refilling, when the float went down and up with high speed and hit against the level arm enclosure. A minor crack, as a result of this process, could not withstand the high loop pressure (1000 psi). The broken float was replaced with a new one, and new procedures limiting the speed of loop drainage and filling, as well as pressurization, were established.

The peroxide sampler was calibrated when peroxide of known concentration was injected into the loop. The first two experiments were performed at full loop flow rate and different peroxide concentrations. The third experiment was done at reduced loop flow rate. Two samplers were installed on the reactor top and were connected together with SS tubing. The downstream sampler was calibrated, while the upstream one was used for peroxide injection. The results of the experiments are shown in Table 4.2 and discussed in Section 4.4. Sampler calibration was finished after the chemical injection pump stability had been determined. The goal of this experiment was to prove that pump

Table 4.2. Peroxide Sampler Calibration Results

#	Mixed Temperature	Sample Temperature	Loop Temperature	Sample Time	Measured Peroxide
	(°F)			(min:sec)	(ppb)
Loop flow rate 1500 cc/min					
1	89	302	537	3:00	470
2	89	280	537	3:40	365
3	92	375	537	1:35	520
4	93	385	537	1:28	520
5	92	343	537	2:19	545
6	92	340	537	2:17	585
7	90	309	543	3:20	412
8	89	301	544	3:20	480
9	94	426	544	2:00	630
10	94	426	544	2:00	655
11	92	295	538	3:25	235
12	93	334	540	1:40	170
13	89	301	539	3:20	230
14	89	287	539	4:00	205
15	89	237	539	5:50	175
Loop flow rate 900 cc/min					
16	90	339	512	2:00	465
17	91	330	517	2:05	580
18	95	384	518	1:30	560
19	94	380	521	1:30	585
20	95	375	526	1:33	540

Table 4.2 (continued)

#	Average Conduct.	Dilution Factor	Corrected Peroxide	Thermal Decomp. Ratio	Injected Peroxide	Sampler Thermal Decomp. Ratio
	(μS/cm)		(ppb)		(ppb)	
Loop flow rate 1500 cc/min						
1	67.9	1.92	901	2.10	1500	1.67
2	73.2	2.06	753	2.35	1500	1.99
3	52.5	1.59	825	1.57	1500	1.82
4	48.7	1.52	791	1.52	1500	1.90
5	58.3	1.70	925	1.77	1500	1.62
6	58.6	1.70	996	1.79	1500	1.51
7	67.0	1.89	780	2.07	1500	1.92
8	69.1	1.95	935	2.15	1500	1.60
9	36.9	1.35	851	1.36	1500	1.76
10	36.4	1.34	881	1.36	1500	1.70
11	61.5	1.76	415	2.20	755	1.82
12	55.2	1.64	278	1.85	755	2.71
13	61.1	1.76	404	2.12	755	1.87
14	64.3	1.83	375	2.27	755	2.02
15	76.1	2.15	377	3.03	755	2.00
Loop flow rate 900 cc/min						
16	26.9	1.58	735	1.69	1330	1.81
17	25.9	1.64	952	1.78	1330	1.40
18	29.4	1.45	810	1.46	1330	1.64
19	28.3	1.50	879	1.49	1330	1.51
20	27.5	1.55	835	1.54	1330	1.59

Notes:

Dilution Factor-ratio determined as **142/(142-μ_{av})**, where **142** μS/cm is conductivity of mixed cooling injection, and μ_{av} is average (during extraction period) measured conductivity of a sample

Thermal Decomposition Ratio-ratio determined as $(T_{loop}-T_{mix})/(T_{loop}-T_{sample})$, where T_{loop} is measured core-outlet temperature, T_{mix} is temperature of the mixed cooling injection, and T_{sample} is temperature of the extracted sample

Sampler Thermal Decomposition Ratio-ratio determined as C_{inj}/C_{corr}, where C_{inj} is concentration of the injected peroxide, and C_{corr} is concentration of the corrected peroxide calculated as measured peroxide concentration multiplied by Dilution Factor

pulsations during the operation do not cause oscillations of measured peroxide level. For this purpose KNO_3 solution of known conductivity (2550 μS/cm) was injected into the loop. No cooled injection was added during the experiment, and conductivity of the drawn sample was measured. The test demonstrated that pump operation cannot affect H_2O_2 measurement since its working frequency is much higher than the response time of the conductivity meter.

During the remaining out-of-pile experiments, the second Toshiba electrode was installed inside the ECP plenum. The steam orifice and venturi flowmeter were emptied and rezeroed for subsequent calibration. Before completion of the test, the new in-core section was connected to the internals, and its successful operation was demonstrated in both manual and automatic modes. In order to confirm maintainability of the section it was placed inside an elliptical section simulating the lower part of the in-pile thimble. After the experiment has completed, the in-core section could be easily pulled out, which satisfied this goal.

The last experiment was a steam carryover test. KNO_3 solution of known conductivity was injected into the loop, and the conductivity of steam and water was measured using the water and steam sample lines. Results of the test are shown in Table 4.3 and discussed in the following section. Results of the carryover test conducted during the in-pile recirculation mode of operation are discussed in Chapter 5.

Table 4.3. Out-of-Pile Carryover Test Results

TIME	CONDUCTIVITY (μS/cm)		
	WATER LINE	STEAM LINE	RETURN
17:14	1130		
17:15			1020
17:18			1060
17:30		1.5	
17:40			995
17:45	1180		
17:57		1.0	

A discussion of the carryover test results is given in Appendix D.

4.4 RESULTS

The results of the out-of-pile tests are presented in Tables 4.2 and 4.3. The peroxide sampler thermal decomposition factor-(the measure of the sampler effectiveness)-was determined. This parameter is the fraction of hydrogen peroxide decomposed while flowing inside the sampler before mixing with the cooling flow. The measured sampler thermal decomposition ratio data showed no significant dependence upon loop flow rate or concentration of peroxide dissolved in the loop water. Hence this ratio was taken to be 0.55±15% (i.e. 1/1.8, 1.8 being the average sampler thermal decomposition ratio calculated based upon data from Table 4.2) for the duration of the present campaign. Therefore, after H_2O_2 in a sample is directly measured by the CheMetrics® colorimetric method, its real content in the loop is determined by multiplication of this number by the coolant dilution factor and dividing by the thermal decomposition ratio. The first correction is the ratio between the loop water extracted for the peroxide measurement and the cooled injection water measured using conductivity as discussed in (H-1); the second one entirely depends on sampler design and remains constant.

The data in Table 4.3 demonstrate that the water carryover into the steam phase is very small-a factor of ten better than in earlier BCCL campaigns-and comparable to that in commercial BWRs, which supports the decisions made in developing the new steam plenum design.

4.5 CHAPTER SUMMARY

Out-of-pile tests were conducted to check loop operability and reliability before loop internals were installed in the reactor core. The tests demonstrated that the loop is stable during operation, and the new internals components behave in accordance with design goals. The new peroxide sampler was calibrated, and its thermal decomposition factor was determined. A carryover test demonstrated effective performance of the new steam separator, i.e. very low carryover. After installation in the MITR Core tank, several further installation checks were carried out before the reactor was brought to power. These are also listed in Table 4.1 as shakedown runs.

CHAPTER 5 IN-PILE RECIRCULATION MODE RESULTS

5.1 INTRODUCTION

The recirculation mode in-pile runs followed the once-through shakedown tests and the first ten once-through baseline runs. As mentioned in Chapter 6, the float was replaced after its failure, and the loop was fully tested again in the once-through mode to prove its operability. The once-through mode of operation was preferred for this check, since no appreciable experience with running the loop with recirculation had been accumulated by that time. Overall, 18 recirculation runs (## 11-28) were performed during this Campaign, although some were either repeated several times or in some instances not completed due to equipment or other problems, such as the requirements of other reactor projects, and delays due to severe weather conditions, when the reactor had to reduce power or shut down. Table 5.1 summarizes the in-pile recirculation runs. The recirculation mode of operation in the 1993/94 Campaign was unique in the sense that it had not been used routinely in the past, but was the final goal of all previous experiments. Descriptions and analyses of the results are summarized in the following sections.

5.2 RESULTS

Before taking baseline data in the recirculation mode, several shakedown runs were carried out. Although the feasibility of recirculation mode operation had been proved at the end of the 1992 campaign, it was still somewhat questionable whether last years results could be reproduced. The shakedown test showed excellent loop controllability, very stable and effective separation in the steam plenum, as indicated by the level detector system, and very slow level changes in response to heat input transients or flow perturbations.

Table 5.1 Recirculation Mode of Operation, Summary of Experimental Results under NWC (Normal Water Chemistry)

Run #	Additive or Baseline	Loop flow rate (LPM)	Feed-water flow rate (cc/min)	O_2 in the loop (ppb)	O_2 in the Ch. Tank (ppb)	H_2 in the Ch. Tank (ppb)	Additive Conc. (M)	N-16 Effect	pH	H_2O_2 in the loop water (ppb)	ECP 1 mV SHE	ECP 3 mV SHE
12	Baseline	0.9	80	<400	N/A	N/A	N/A***	None	N/M	35	227	-3
15	Baseline	0.9	135	360	7	5	N/A	None*	5.29	95	322	6
16	H_2O_2	0.9	120	450	120	27	10^{-5}	None	N/A	0	230	N/M
17	KOH	0.9	130	250	90	19	$7x10^{-5}$	None	8.7	0	18	7
19	KOH	0.9	130	600	70	18	$2x10^{-5}$	None	8	180	185	N/M
22	O_2	0.8	150	360	500	0	N/A	N/M**	7	80	N/M	N/M
24	O_2	0.9	150	230 330	500 5000	20 25	N/A	N/M	6.9	~0	291 274	N/M
25	O_2	0.9	150	570	10,000	~0	N/A	N/M	6.7	0	279	N/M
27	Na_2SO_3	0.8	130	250	3,000	N/M	$2.1x10^{-5}$	None	6.7	80	242	N/M
28	LiOH	0.75	145	250	2,000	N/M	$3.6x10^{-5}$	up 90%	10	0	116	N/M

Table 5.1 (continued)

Notes:

For all once-through mode runs loop flow rate remained ~1.4 LPM, and steam quality was ~10%.

* Ratio of steam/water counts during baseline measurements was 0.45 (the corresponding ratio for the once-through mode of operation under NWC was 0.42)

** N/M-not measured

***N/A- not available

ECP 1-Toshiba in-thimble ECP sensor

ECP 3-Ag/AgCl MIT ECP sensor located in the return water autoclave

Additive or Baseline - chemical additive injection or taking baseline data

O_2 in the loop - oxygen concentration in the water sample line (average over a period of ~30 min after steady state has been achieved)

O_2 in the Ch.Tank - oxygen concentration in the charging tank water (average over a period of ~30 min after steady state has been achieved)

H_2 in the Ch.Tank - hydrogen concentration in the charging tank water (average over a period of ~30 min after steady state has been achieved)

Additive Conc - concentration of chemical additive in loop water (average over a period of ~20 min after steady state has been achieved)

N-16 Effect - effect of chemical addition on N-16 in steam phase relative to NWC baseline (average over a period of ~30 min after steady state has been achieved)

H_2O_2 in the loop - hydrogen peroxide concentration in the loop water (average over a period of ~30 min after steady state has been achieved)

Loop flow rate - coolant flow rate through the in-core section

Feedwater flow rate - flow rate delivered by the charging pump

After the target level of 40% of the level monitoring range was achieved, it was maintained within 40±5%. Loop flow rate entirely depended on the frequency of the recirculation pump. Since the only way to measure loop flow rate reliably was to use a venturi tube, this flowmeter had to be calibrated over the range of loop operating parameters. For this purpose the venturi flowmeter was calibrated when the loop was working in the once-through mode. This allowed measurement of flow rate with the flowmeter mounted on the pump cabinet, and to match its reading with the signal from the calibrated flowmeter. The venturi calibration curve is presented in Figures 5-1 and 5-2. When the maximum allowable frequency of the recirculation pump had been achieved during the recirculation shakedown, it was found that the maximum pump flow rate was 1000 cc/min. The steam orifice was also calibrated during the following runs (see Figures 5-1 and 5-3).

During the first run (#11) recirculation feasibility was proved, level in the 0-50% range was achieved, and two N-16 spectra from the steam line were collected using the Ge detectors. However the experiment was not continued due to the very high H_2 concentration in the charging tank. The reason for this unpredictably high H_2 content was not found, and the loop was left overnight in cold standby to see whether H_2O_2 produced during this period scavenged excess hydrogen. This decision turned out to be correct, since no H_2O_2 and little H_2 were measured in the charging tank the following morning. First recirculation mode baseline data were taken under these conditions. It was found that the oxygen concentration in the water sample line was less than 400 ppb after parameters reached equilibrium. The future target oxygen content in the sample line was discussed with the sponsors, and several baseline measurements under different O_2 concentrations in the sample water were conducted.

Since drawing steam line samples decreases the flow rate measured by the rotameter on the pump cabinet, calibration of the steam orifice became the first order of priority to determine steam quality thereafter. The orifice calibration was done with all

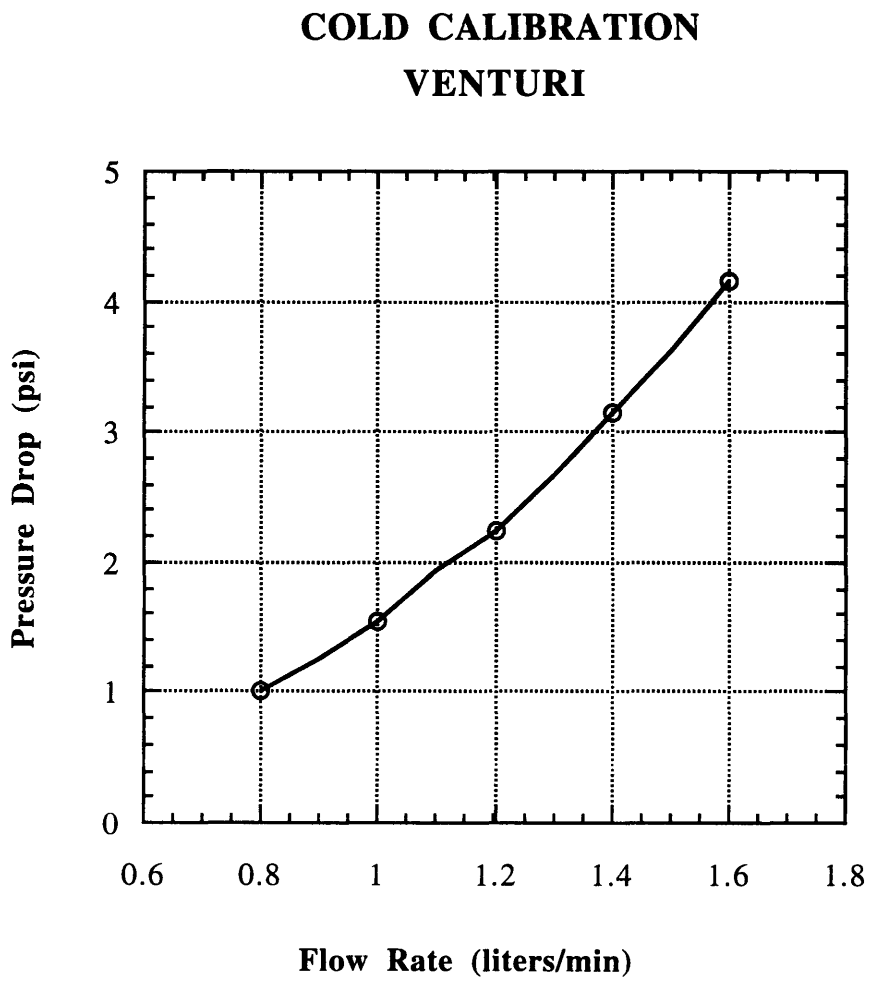
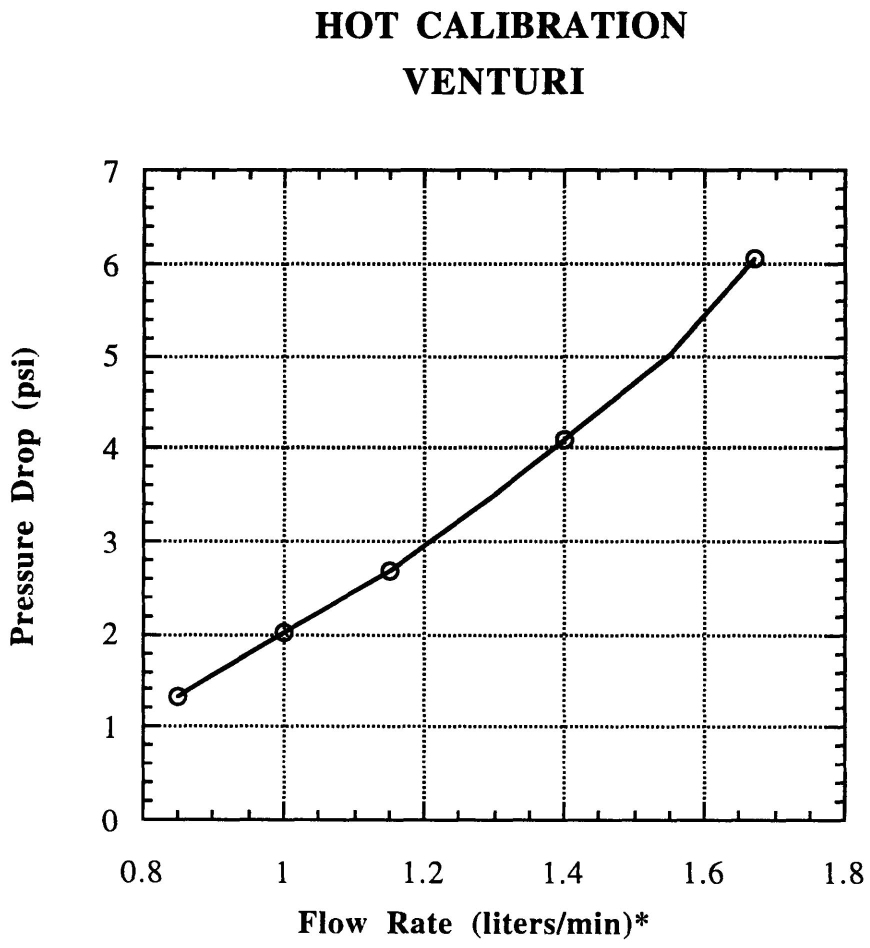


Figure 5-1. Venturi Calibration under Cold Conditions {77°F (25°C)}



*liters/min of water at 25°C

Figure 5-2. Venturi Calibration under Hot Conditions {532°F (278°C)}

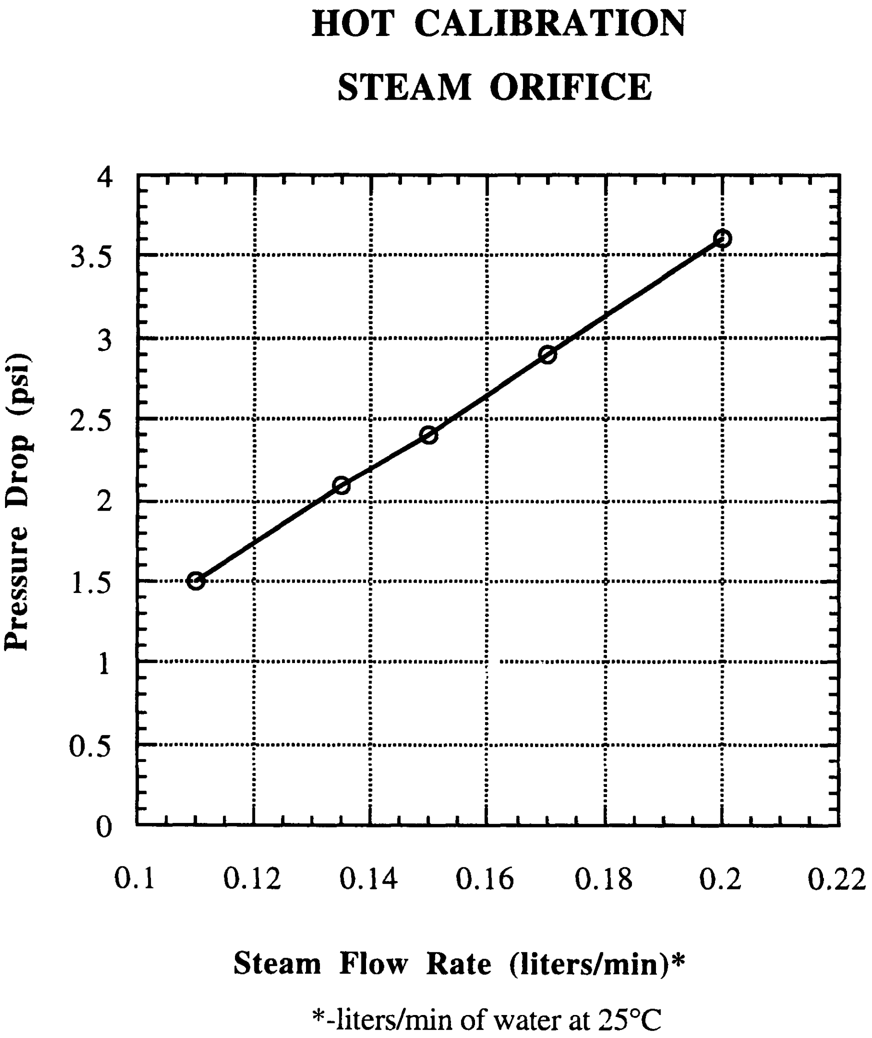


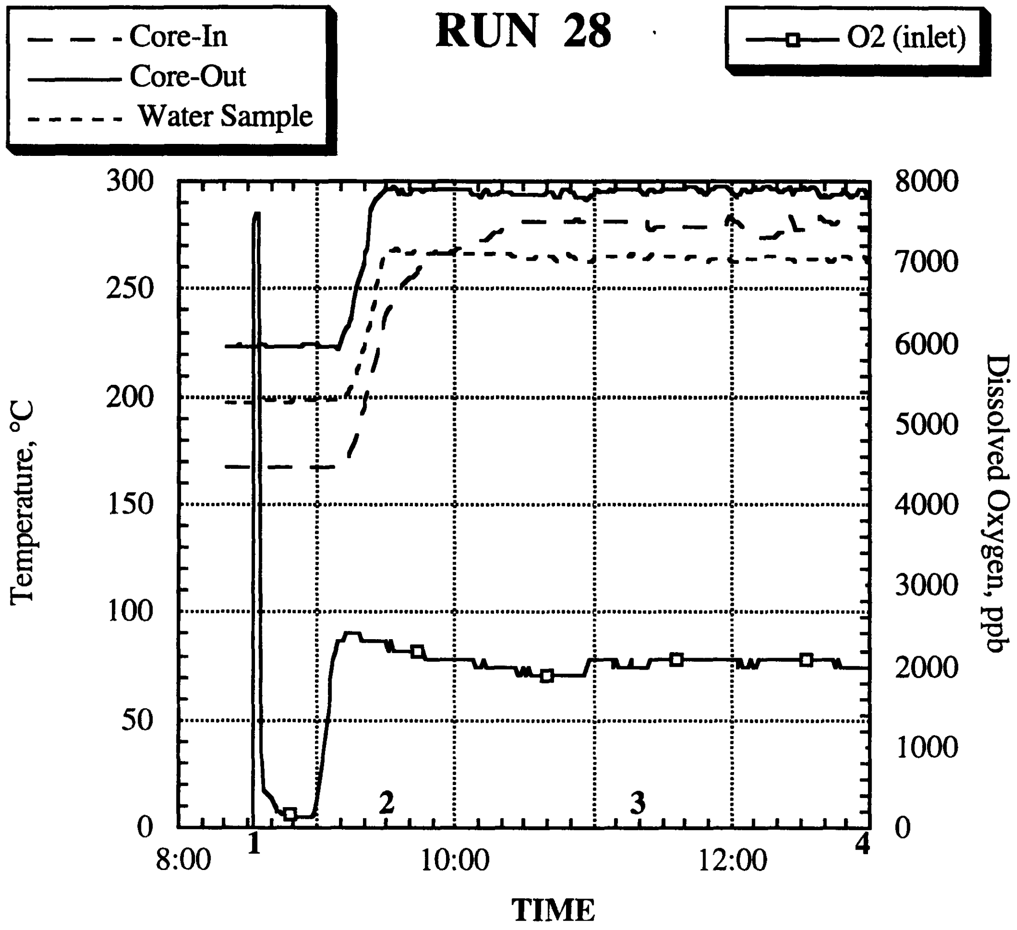
Figure 5-3. Steam Orifice Calibration: 1000 psi (7 MPa), 555°F (290°C)

sample lines closed and level in the steam plenum maintained constant at ~40%. Feedwater flow rate was changed in steps by 50 cc/min, and in-core heater power was changed correspondingly to keep the level at 40%. When the return flowmeter and inlet (prior to feedwater pump) flowmeter readings became the same, it was taken as an indication that the loop was at steady state.

One more experiment to obtain baseline data was suggested by Hitachi. For this run the oxygen concentration in the loop was varied by purging H_2 through the deionized water in the chemical injection bottle while maintaining NWC, and then adding this hydrogen-saturated water to the loop. It was found that O_2 in the loop stabilized at 360 ppb and did not change after the H_2 concentration in the bottle was raised. Measured H_2O_2 in the water sample line was below 100 ppb.

Following baseline experiments, chemical additive injection began. The first additive was H_2O_2 to examine the effect of its injection on the peroxide balance in the loop; however no H_2O_2 (i.e.<10 ppb) was detected in the water effluent sample line. During the rest of the recirculation mode part of the campaign the effect of injection of O_2, KOH, LiOH, and Na_2SO_3 was investigated and the results are presented below. A typical recirculation mode NWC run history is shown in Figures 5-4 to 5-6.

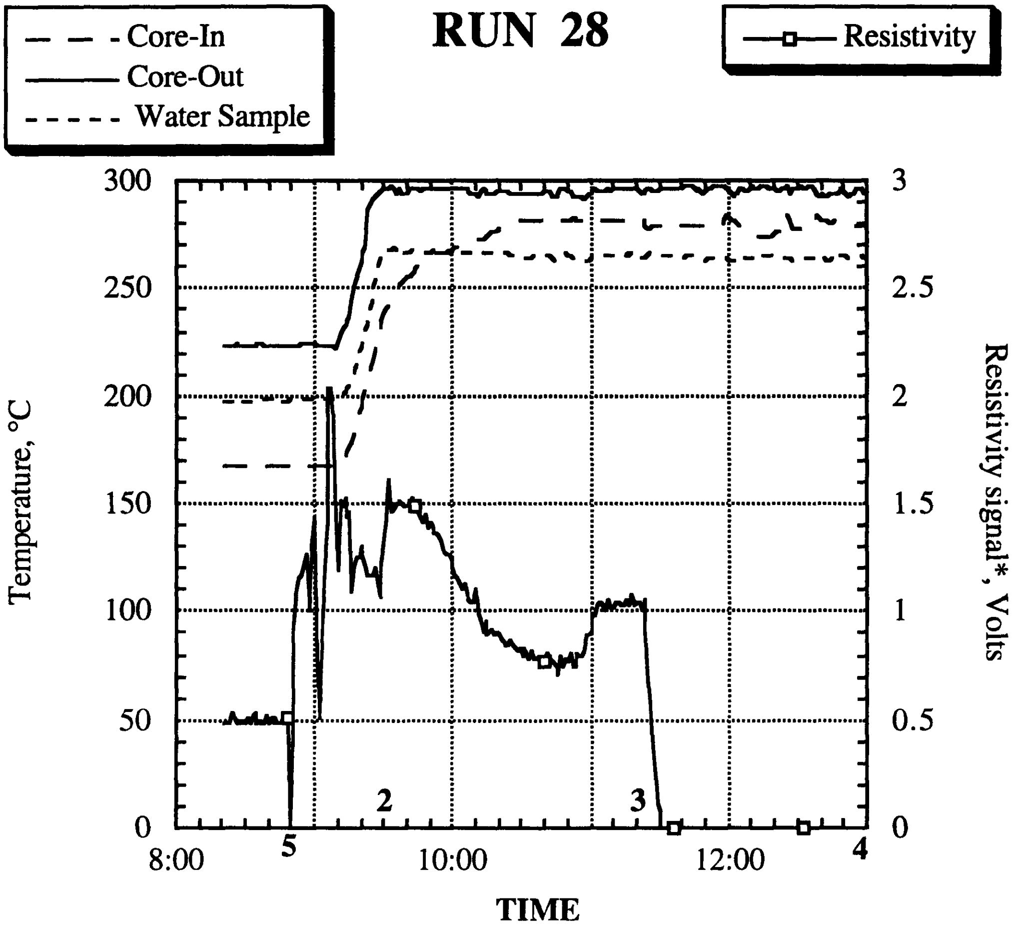
The first KOH injection run was different from all those in the past in the sense that the concentration of a chemical injected into the loop could not be directly determined on the basis of charging pump and chemical injection pump flow rates. Since in the recirculation mode, the additive concentration in the loop depends on many parameters, including chemical volatility, the ratio of recirculation rate to feedwater flow rate and the ratio of the chemical injection flow rate to the water sample extraction rate, it changes with time and should be measured by some other means rather than those used during once-through operation. One of the methods utilized in this campaign (as described in Chapter 3 of this work) was measurement of the conductivity of the loop sample water and the conductivity of the additive solution in the chemical injection



Notes:

1. Filling Charging Tank with DI Water
2. Started Boiling
3. Started LiOH Injection
4. Finished LiOH Injection, Went to Hot Standby

Figure 5-4. Run 28 Oxygen Concentration in the Recirculation Water

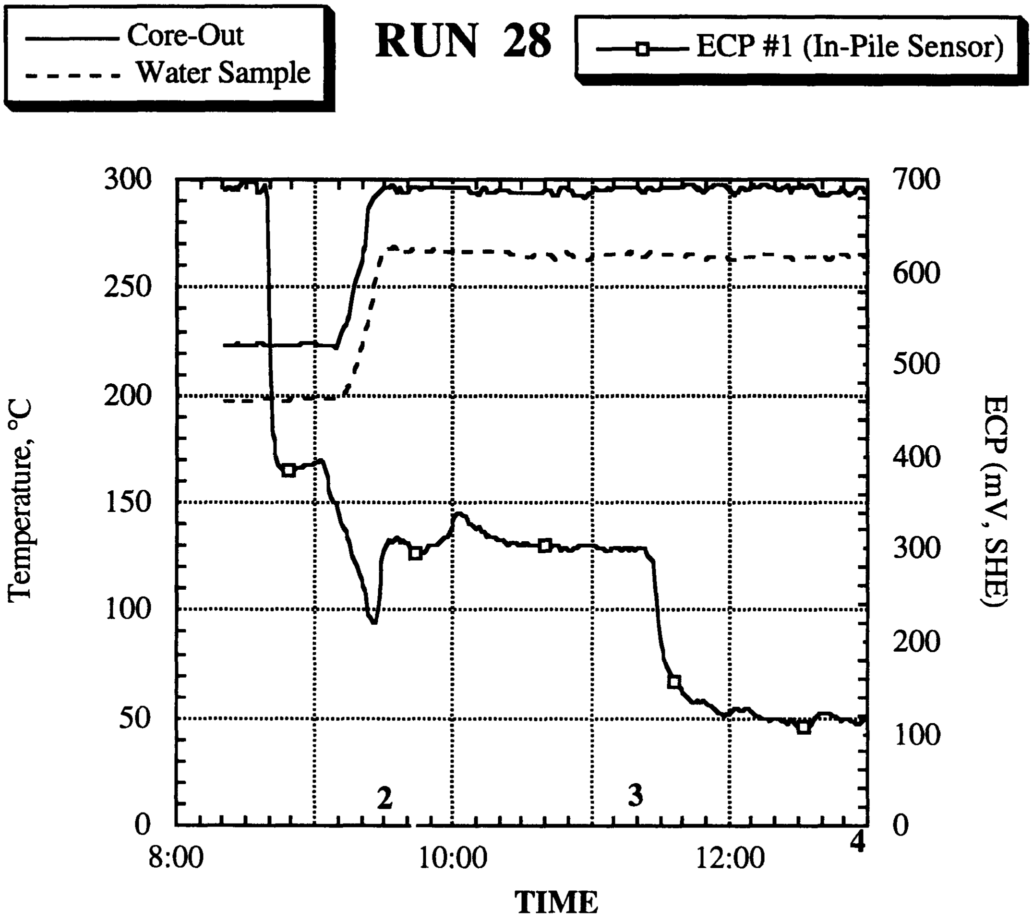


Notes:

1. Filling Charging Tank with DI Water
2. Started Boiling
3. Started LiOH Injection
4. Finished LiOH Injection, Went to Hot Standby
5. Turned on Conductivity Meter

* - This signal had never been calibrated, and it showed only relative value

Figure 5-5. Run 28 Recirculation Water Resistivity



Notes:

1. Filling Charging Tank with DI Water
2. Started Boiling
3. Started LiOH Injection
4. Finished LiOH Injection, Went to Hot Standby

Figure 5-6. Run 28 ECP

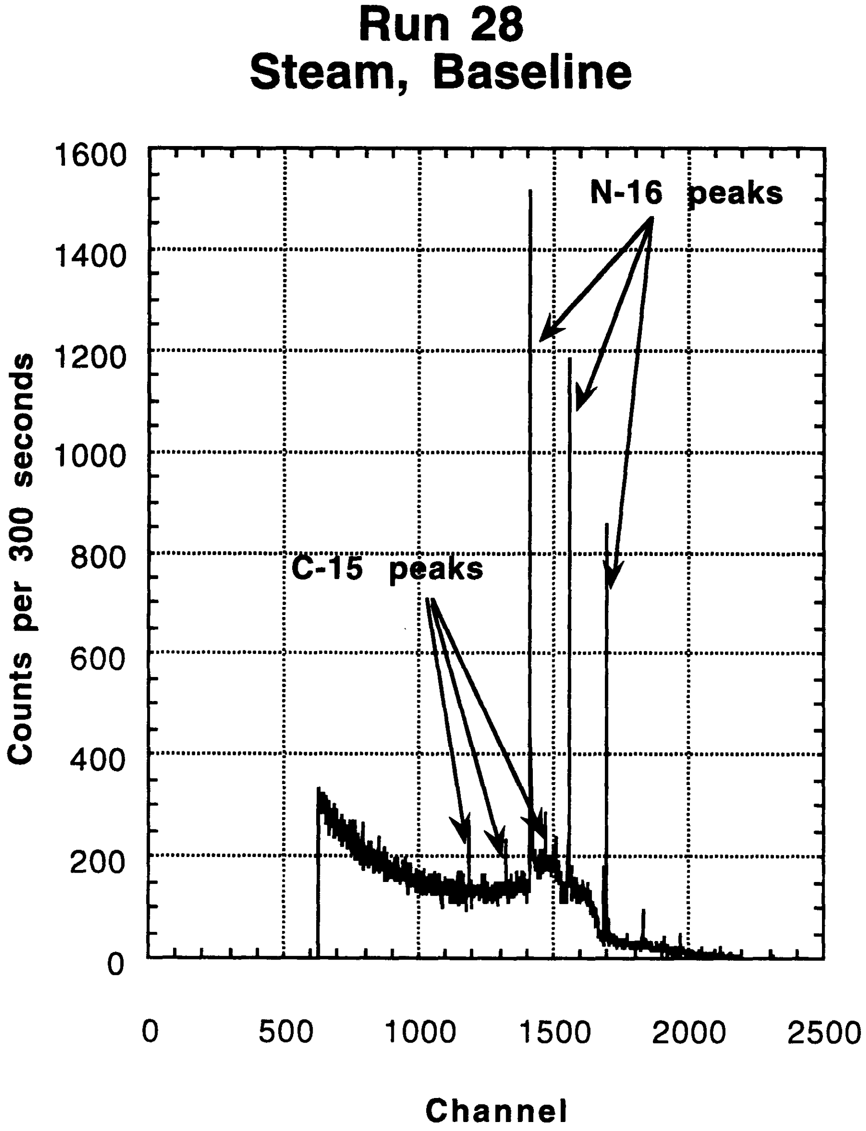
bottle. Due to lack of experience with injection under recirculation, several attempts had to be made to get stable additive concentration in the loop by varying chemical injection pump frequency, piston stroke, and the time intervals when the pump is on or off. The very first KOH injection run (#17) was a shakedown during which all operational issues were resolved. Run #18 could not be conducted because of the loss of pressure in one of the helium bottles on the reactor back mezzanine. Helium pressure loss caused an increase in the oxygen level of the feedwater, and the experiment was postponed until the next day, when O_2 in the charging tank returned to the value corresponding to NWC conditions. The relatively high oxygen concentration subsequently measured in the sample water during the run is explained by the fact that the O_2 sensors were fouled and required refurbishment. Runs 20 and 21 were not completed due to the difference in values of measured oxygen in the return line and loop water sample line at hot standby which should have eventually equal readings. Both O_2 sensors were then refurbished and the experiments resumed.

The next three runs were conducted under different O_2 concentrations in the charging tank, with the oxygen varied from 500 ppb to 5000 ppb. During these runs, the ratio of recirculation flow rate to feedwater (steam plus water letdown) rate was ~4.5-5. The results presented in Table 5.1 show that O_2 content in the feedwater does not affect peroxide in the loop or N-16 carryover. As expected, H_2 in the feedwater was less than 25 ppb (stoichiometrically equivalent to 200 ppb O_2); the amount of H_2O_2 in the loop was found to be less than 100 ppb (stoichiometrically equivalent to 47 ppb O_2). The oxygen concentration in the loop also did not show any dependence on O_2 in the charging tank. As shown in Table 5.1, at 10,000 ppb O_2 in the feedwater, the O_2 in the water sample line was measured to be 570 ppb.

One of the experiments conducted during recirculation mode operation was a carryover test based on the measurement of waterborne activity. This test was performed with the following loop parameters: loop flow rate 900 cc/min, feedwater flow rate 130 cc/min, level in the steam separator plenum 40%. The results of this test are presented in Appendix D, where it is shown that the carryover was found to be 0.02%, which is less than the target value of 0.1%, and in good agreement with the out-of-pile carryover test results also presented in Appendix D.

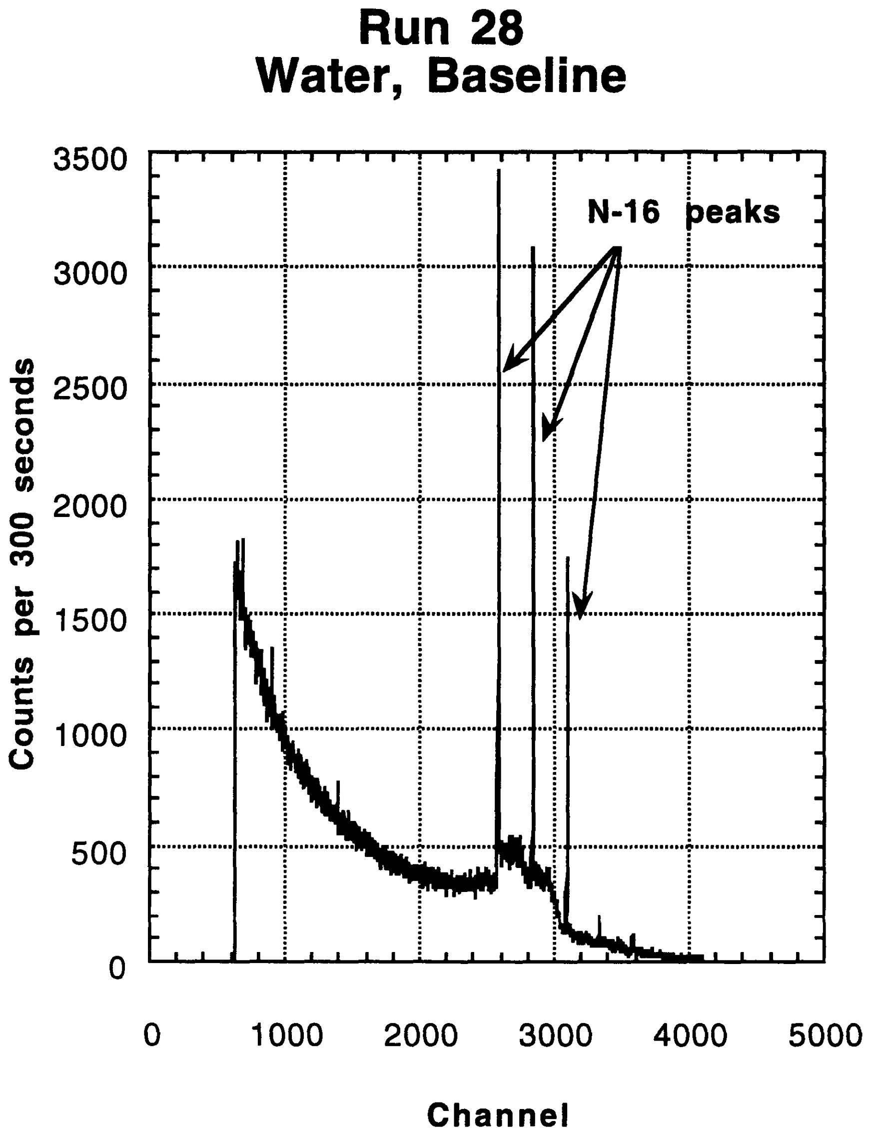
The last two runs during recirculation involved injection of Na_2SO_3 (run #27) and LiOH (run # 28). In both cases, the loop flow rate was reduced below 800 cc/min (see Table 5.1), and the O_2 level in the charging tank remained over 2 ppm. LiOH was injected to get two different concentrations in the loop: first 3.6×10^{-5}M, and then it was brought to a higher level with loop $pH_{20°C}$ equal to 10. In the former case, N-16 in the vapor phase increased by 30%, in the latter by 90%. Na_2SO_3 did not change N-16 activity in the vapor phase.

Concern has been expressed regarding the influence of C-15 on the measurement of N-16 in the steam phase. Since the half-life of C-15 is shorter than that for N-16 (2.45 seconds versus 7.13 seconds), the C-15 is not a problem in an actual BWR: N-16 in the vapor phase is dominant. However, if C-15 activity represents a significant part of the overall vapor phase gamma level, then the effect of chemical addition on N-16 might not be distinguishable. To minimize C-15 influence, the energy band used to measure gamma activity in the steam phase was shifted upward from 4.5-7.5 MeV to 5.5-7.5 MeV. The use of Ge detectors for both the vapor and liquid lines virtually eliminates all uncertainties with respect to C-15 measurement because of their excellent resolution. During the N-16 measurements in the recirculation mode the detector dead-time did not increase beyond the level of 20%. Discussion of the effects of carryover and carryunder on N-16 in steam is given in Appendices D and E; App. J discusses C-15 interference. Characteristic gamma spectra for the LiOH injection run (#28) are shown in Figures 5-7 to 5-10. It is seen that the three C-15 peaks can be distinguished from those of N-16. This figure also demonstrates that for the steam line, the C-15 effect on the integral N-16 spectrum is insignificant (less than 10%, based on total area under the photopeaks



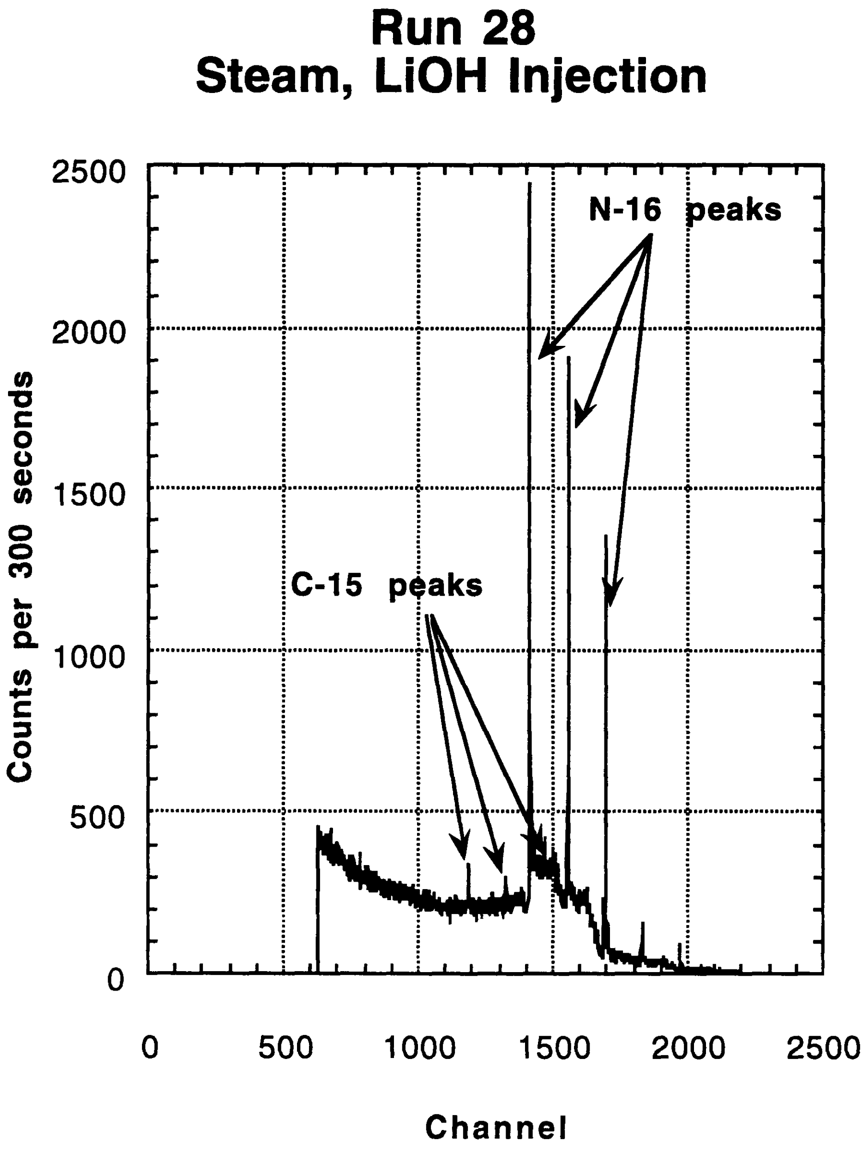
PEAKS	PEAK ENERGY (MeV)		
N-16	5.1	5.6	6.1
C-15	4.3	4.8	5.3

Figure 5-7. Run 28 Steam Baseline Spectrum



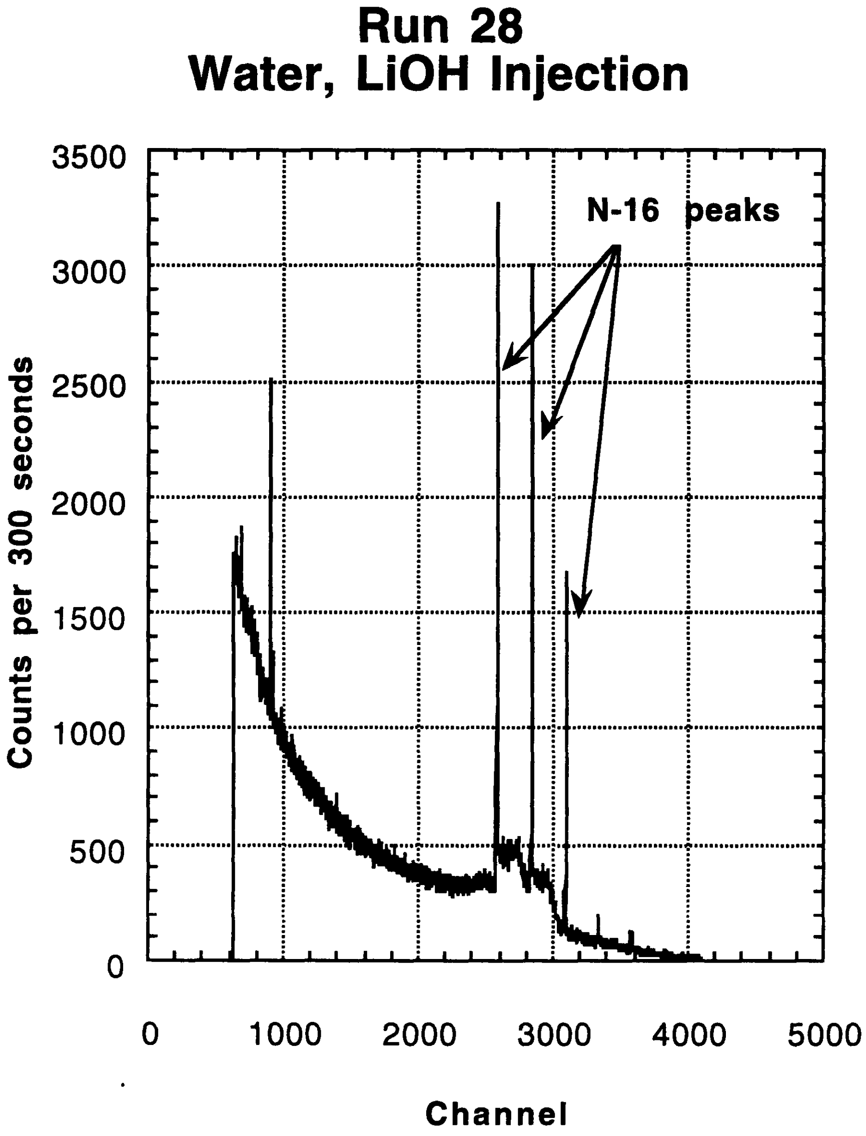
PEAKS	PEAK ENERGY (MeV)		
N-16	5.1	5.6	6.1
C-15	4.3	4.8	5.3

Figure 5-8. Run 28 Water Baseline Spectrum



PEAKS	PEAK ENERGY (MeV)		
N-16	5.1	5.6	6.1
C-15	4.3	4.8	5.3

Figure 5-9. Run 28 Steam Spectrum During Chemical Injection (3.6×10^{-5} M LiOH)



PEAKS	PEAK ENERGY (MeV)		
N-16	5.1	5.6	6.1
C-15	4.3	4.8	5.3

Figure 5-10. Run 28 Water Spectrum During Chemical Injection (3.6x10^{-5} M LiOH)

for each species) and cannot mask the influence of the chemical additives on the N-16. Using isolated photopeaks, which is possible with Ge detectors, virtually complete separation of N-16 and C-15 is achievable. Data supporting the conclusions regarding the low influence of the C-15 peaks on N-16 measurements are given in Appendix J of this thesis.

When comparing the in-thimble ECP with the out-of-thimble ECP, it is important to remember that the in-thimble ECP sensor's resistance was lower than the recommended value. It's resistance typically read ~60 KΩ, whereas the minimum resistance of an ECP reference electrode is suggested to be 100 KΩ, and can be as high as 1 MΩ. Because of the low resistance of the in-thimble Toshiba sensor, the observed difference between the in-thimble and out-of-thimble ECP is most likely due to improper functioning of the sensor, rather than some difference in water chemistry or other environmental conditions. In spite of the suspect performance of the reference sensor, its data are included, since it trended with the out-of-pile ECP; and the in-thimble ECP in the BCCL, being analogous to the upper plenum or downcomer region in an operating BWR, is important for in-vessel corrosion considerations. Also note that for 1993, the in-thimble sensor was in a single phase liquid, whereas in prior loop runs the GE electrode was in the two phase separator plenum.

5.3 CHAPTER SUMMARY

Overall, ten runs were conducted in the recirculation mode of operation under normal water chemistry. A recirculation baseline was established. Loop chemistry under different concentrations of oxygen in the feedwater was investigated. Injection of LiOH, especially at very high concentrations (loop $pH_{20^\circ C}=10$), gave results opposite to that expected: namely, N-16 carryover increased. LiOH was the only additive which affected N-16 in the steam phase. The experiments were conducted with reduced flow rate (and increased residence time) compared to the once-through mode operation experiments. Only moderate amounts of H_2O_2 (80 to 180 ppb) were measured in the loop regardless of what chemicals were injected. Employing Ge detectors on both the steam and water lines eliminated questions associated with the influence of C-15 on N-16 measurements. The data on C-15 activity also confirmed that the integrated N-16 spectra obtained in the past BCCL campaigns using NaI detectors were not significantly affected by C-15.

CHAPTER 6 IN-PILE ONCE-THROUGH MODE RESULTS

6.1 INTRODUCTION

As already noted previously, the 1993/94 Campaign proceeded in several stages, and not in the order discussed in this report. Hence we return here to the subject of initial startup, despite having already discussed recirculation mode operation in the preceding chapter.

After the out-of-pile test was completed, the internals were dismantled and transferred from the reactor top to the assembly laboratory, where they were finally tested before installation inside the BCCL thimble.

The final test included an internals bench top assembly, fit test, and pressurization. After the internals were assembled, they were placed inside an acrylic tube which had the same internal diameter as the BCCL thimble. This fit test showed that the existing thimble, used in the 1992 Campaign, can easily enclose all new components. After the fit test completion, the internals and in-core section were pressure tested under 1200 psi for a 24 hour period to confirm leak tightness.

All elements assembled in the assembly laboratory were placed inside the thimble in the reactor disassembly area and then pressurized again. After the thimble installation in the MITR core tank, loop shakedown experiments started.

Several incidents occurred during shakedown. The major one was loss of the upper coil of the level detector. Detector electronics was reconfigured to be able to monitor level in the steam plenum within the 0-50% range. This limitation did not adversely affect the subsequent experiment, although it caused complications with loop operation and reduced the flexibility of getting to a stable level fast. After the problems with the upper coil were overcome, a severe leak in the thimble helium line occurred. This was fixed employing torr seal. All following shakedown runs were conducted in a once-through mode of operation under normal water chemistry. Level control was very stable regardless of reactor power, and the maximum temperature inside the in-core section (heater block temperature) did not exceed 780°F at nominal loop and reactor operating parameters.

During the loop shakedown the NWC baseline was established. This was done for two purposes. The first was to characterize the new loop, because a significant part of the loop components was now made of stainless steel rather than the previous metal of choice, titanium. The second goal was to establish a reference point for comparison with data obtained under hydrogen water chemistry (HWC). Continuation of the once-through runs was unexpectedly interrupted by failure of the level float. The loop was shut down, and the thimble was taken out of the core and placed inside the disassembly area. The internals were easily pulled out of the thimble, and a new float was installed. The new float was made of the same batch of quartz as successfully used for the 1991 Campaign, and before installation it was pressure (1500 psi) and temperature (560°F) tested (see Section 6.2 and Appendix H for a more detailed discussion of float technology).

After these problems were fixed, it was decided to run the loop in the recirculation mode. A description of these experiments and results were presented in the previous chapter. When the recirculation runs were finished, the loop was switched back to the once-through mode and operated under NWC and HWC conditions till the end of the 1993/94 Campaign. Operation in the once-through mode and results are discussed in this chapter. Results of the experiments under NWC are presented in Table 6.1.

6.2 NWC RESULTS

As already mentioned in the previous section, a series of shakedown runs were performed to establish a baseline under NWC conditions. Loop characterization was conducted at hot single phase and boiling conditions, and at nominal (1500 cc/min) and

Table 6.1. Once-Through Mode of Operation, Summary of Experimental Results under NWC (Normal Water Chemistry)

Run #	Chemical Additive	O_2 in the loop (ppb)	O_2 in the Ch.Tank (ppb)	H_2 in the Ch.Tank (ppb)	Additive Conc. (M)	N-16 Effect (Steam)	pH	H_2O_2 in the loop (ppb)	ECP 1 mV, SHE	ECP 3 mV, SHE	ECP 4 mV, SHE
31	Baseline	200 230 280 600	200 500 1000 5000	4 4 2 0	N/A***	None*	7.5	180 285 315 315	325 313 308 283	115 170 91 124	N/M**
32	$VOSO_4$	100-200	200	5	$1.2x10^{-5}$ and 10^{-4}	Down by 2.5	4.3	60	343 434	118 208	N/M
40	MoO_3	180	200	5	10^{-5}	None	5.1	600	364	119	113
41	V_2O_5	160	200	5	10^{-5}	None	5.7	815	340	82	74
42	$Zn(OH)_2$	160	200	5	$6.1x10^{-5}$	Up by 20%	5.9	750	336	24	-30
43	$ZnMoO_4$	140	200	5	10^{-4}	Up by 15%	6	1270	342	22	10
44	Na_2SnO_4	155	200	5	10-4	Up by 15%	9.3	1220	159	-116	-147
	K_2WO_4	155	200	5	10-4	None	9.3	1220	212	44	-15
	C_2H_2	250	200	40	N/A	Up by 5.5	4.8	2380	473	203	175
45	K_2MoO_4	250	850	32	10^{-4}	None	6	490	216	-6	-50
	$PdNO_3$	200	850	23	$2x10^{-4}$	Up by 100%	3.3	N/M	625	503	466

Table 6.1 (continued)

Notes:

For all once-through mode runs loop flow rate remained ~1.4 LPM, and steam quality was ~10%.

* Ratio of steam/water counts during baseline measurements was 0.42 (corresponding ratio for the recirculation mode of operation under NWC was 0.45)

** N/M-not measured

***N/A- not available

ECP 1-Toshiba in-thimble ECP sensor

ECP 3 and ECP 4-Ag/AgCl MIT ECP sensors located in the return water autoclave

Chemical Additive - chemical additive injection

O_2 in the loop - oxygen concentration in the water sample line (average over a period of ~30 min after steady state has been achieved)

O_2 in the Ch.Tank - oxygen concentration in the charging tank water (average over a period of ~30 min after steady state has been achieved)

H_2 in the Ch.Tank - hydrogen concentration in the charging tank water (average over a period of ~30 min after steady state has been achieved)

Additive Conc - concentration of chemical additive in loop water (average over a period of ~20 min after steady state has been achieved)

N-16 Effect - effect of chemical addition on N-16 in steam phase relative to NWC baseline (average over a period of ~30 min after steady state has been achieved)

H_2O_2 in the loop - hydrogen peroxide concentration in the loop water (average over a period of ~30 min after steady state has been achieved) reduced (900 cc/min) flow rates. H_2O_2 data were taken to compare with those obtained during the past BCCL Campaigns. Once phase separation in the steam plenum was achieved, a number of N-16 measurements were taken using both NaI and Ge detectors. N-16 spectra were measured at hot single phase, boiling onset, and at boiling conditions during which a 40% level was maintained in the steam plenum. Then background was measured, first for the steam line, and then for the water line. To get a background reading on the steam line, a valve on this line was closed, so that the entire flow was directed through the water line. Background for the water line was measured in analogous manner. The background measurement results demonstrated that the influence of the gamma level from the water line on the steam phase gamma measurements and vice versa is insignificant.

After completion of N-16 measurements a new carryover test was conducted. However, as noted in the introduction, during this run the float failed. As a result, the experiment was interrupted, so the thimble had to be transferred to the reactor disassembly area, and a new float was fabricated and substituted for the broken one.

The new float was made in the Laboratory from an original batch of quartz (1991 BCCL Campaign). The float was tested at 1500 psi and 560°F for 24 hours and then inserted in the level arm. New BCCL runs resumed in January, 1994. The first run (#9) was a shakedown to check loop operability and to take baseline data. During the next run (#10) KOH was injected under NWC conditions. N-16 data were taken at hot single phase and boiling. In view of the priority of the recirculation mode of operation, it was decided to switch to the recirculation mode after run # 10 was finished (see results in Chapter 5). Once-through operation was resumed in March.

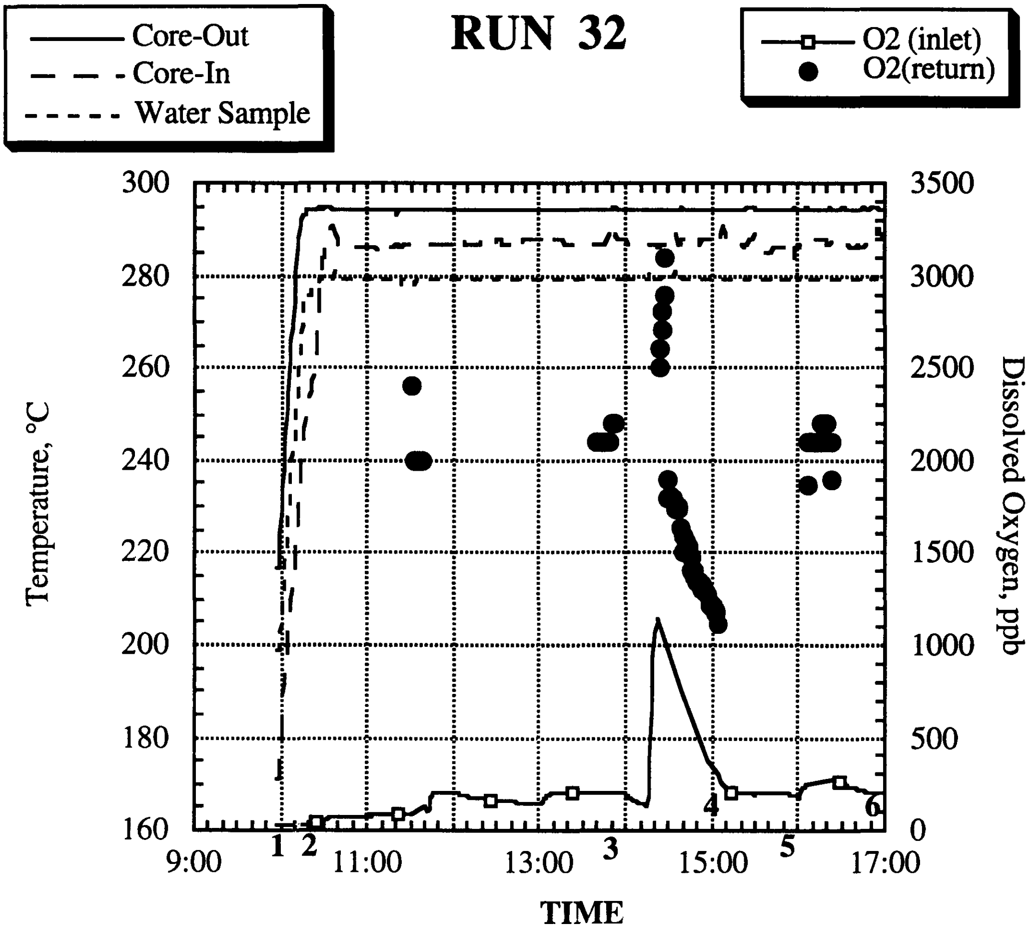
In order to more closely simulate BWR water chemistry, the O_2 concentration in the charging tank water was varied between 200-5000 ppb to evaluate the effect of the oxygen content in the feedwater on the oxygen in the loop. Feedwater oxygen was varied stepwise, and as seen in Table 6.1, the O_2 concentration in the loop changed very slowly and exhibited only a small dependence on the feedwater oxygen. Only after exceeding 1 ppm in the feedwater, did the loop oxygen level begin to rise, albeit gradually. It is also worth to mention here, that the baseline data were obtained with very high H_2O_2 concentration (~470 ppb) in the charging tank water. This was due to the relatively low maximum loop temperature (less than 400°F) when the loop was kept on hot standby overnight. The decomposition capacity of the ultra-violet tube in the cleanup system was not enough to destroy all the peroxide generated in the loop. Thus when the experiment commenced, 470 ppb of peroxide was measured in the charging tank. It also can be seen from Table 6.1, that the H_2O_2 level in the loop is leveling off as the O_2 in the charging tank increases. The most important results of the NWC once-through mode baseline test can be summarized as:

1. Oxygen level in the feedwater was maintained at 200 ppb.
2. Hydrogen level in the feedwater did not exceed 5 ppb, much less than stoichiometric (i.e. 40 ppb O_2).
3. Oxygen content in the loop was about 200 ppb and was not a strong function of oxygen in the feedwater.
4. Hydrogen peroxide concentration in the loop water did not exceed 200 ppb while 200 ppb of oxygen was maintained in the feedwater. These peroxide data are strongly opposed to those obtained in the past BCCL Campaigns, when 1200 ppb was measured in the samples extracted from plenum effluent water. The result of the current Campaign (~200 ppb) is closer to the computer calculations, ~300 ppb, see (H-2). These values of H_2O_2 may be explained by 1) the fact that the steam separator water outlet line was redesigned to increase its distance from the reactor core and thereby reduce its gamma dose, 2) stainless steel was employed as tubing material rather than titanium or 3) in-core gamma dose is ~60% higher due to the removal of lead from the heater bath.

All following runs under NWC in the once-through mode were conducted with chemical addition to evaluate the effect on N-16 activity in the steam phase and the magnitude of the electrochemical corrosion potential measured in- and out-of-pile. During every run, baseline measurements preceded chemical injection, so the values of H_2O_2, N-16, O_2 in the loop water, and ECP obtained during injection could be compared with the baseline. After injection was completed the chemical injection line was flushed with deionized water, and addition of new chemical started only after all parameters, O_2, H_2, H_2O_2, N-16, returned to their baseline values. A typical NWC run history is shown in Figures 6-1 and 6-2.

It was found that six additives had measurable effect on N-16, namely, $VOSO_4$, C_2H_2, K_2MoO_4, $Zn(OH)_2$, $ZnMoO_4$, and $PdNO_3$. $VOSO_4$ was the only additive which significantly suppressed N-16, while the other chemicals either did not change N-16 level in the steam phase or caused it to increase. Adding $VOSO_4$ to the loop (10^{-4} M) decreased N-16 by a factor of 2.5. During the 1992 BCCL Campaign the same effect was observed, although N-16 decreased by only 15%. When the $VOSO_4$ concentration in the loop was reduced to 1.2×10^{-5} M, the steam gamma dose decreased by some 20%. N-16 spectra for $VOSO_4$ injection run (#32) are shown in Figures 6-3 to 6-8.

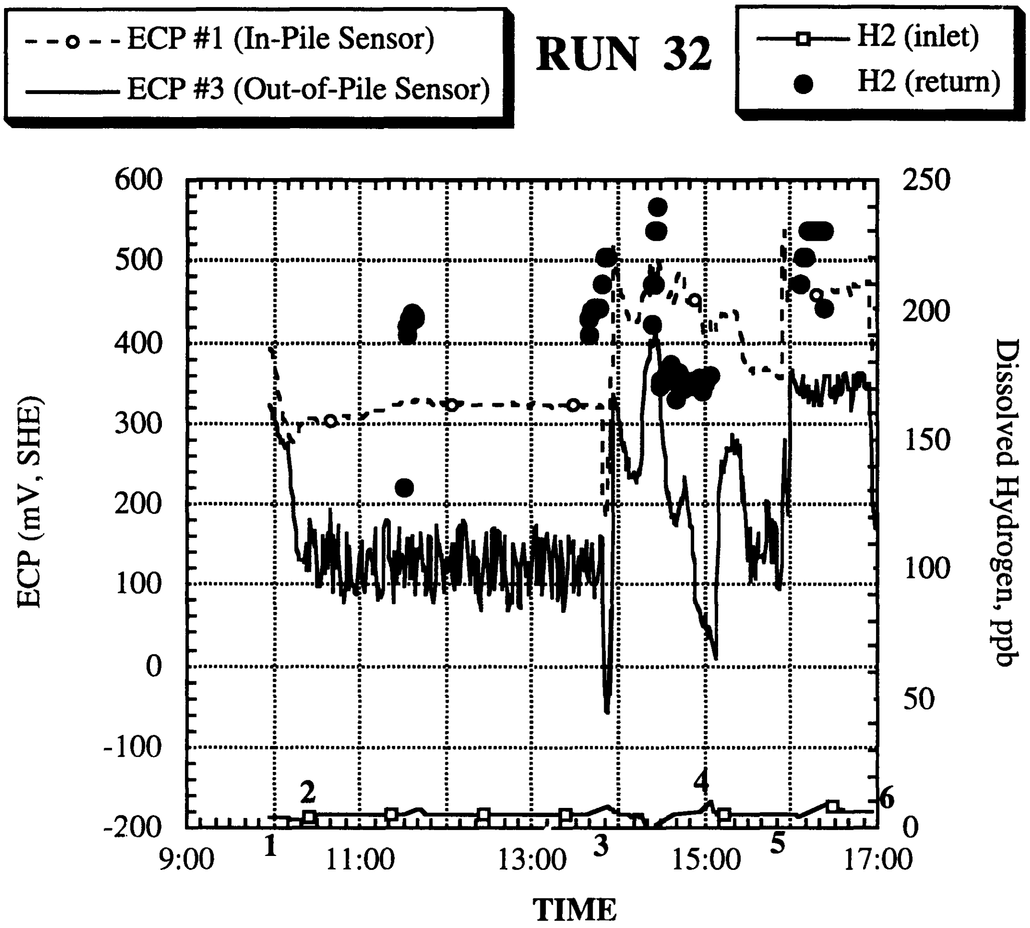
Injection of K_2MoO_4 in this Campaign increased N-16 by 15%, whereas in 1992 the steam line gamma dose decreased by 30%. C_2H_2 had the same effect on the N-16 as if the loop was operated under hydrogen water chemistry: the gamma level in the steam phase increased by a factor of 5.5. This behavior was analogous to the results of previous campaigns, when other organic compounds were injected. A relatively high concentration of hydrogen (which is not typical of NWC) in the charging tank during the next day's run was observed due most probably to flushing out of some residual C_2H_2 from the chemical injection leg. Oxygen was added to the tank water to suppress H_2. Although O_2 and H_2 concentrations in the feedwater did not exactly match baseline conditions, the loop water O_2 remained within the baseline range (200-250 ppb). In the



Notes:

1. Valved in Out-of-Pile ECP Sensor
2. Started Boiling
3. Started VOSO4 Injection (10^{-4} M)
4. Finished VOSO4 Injection
5. Started VOSO4 Injection (1.2×10^{-5} M)
6. Finished VOSO4 Injection

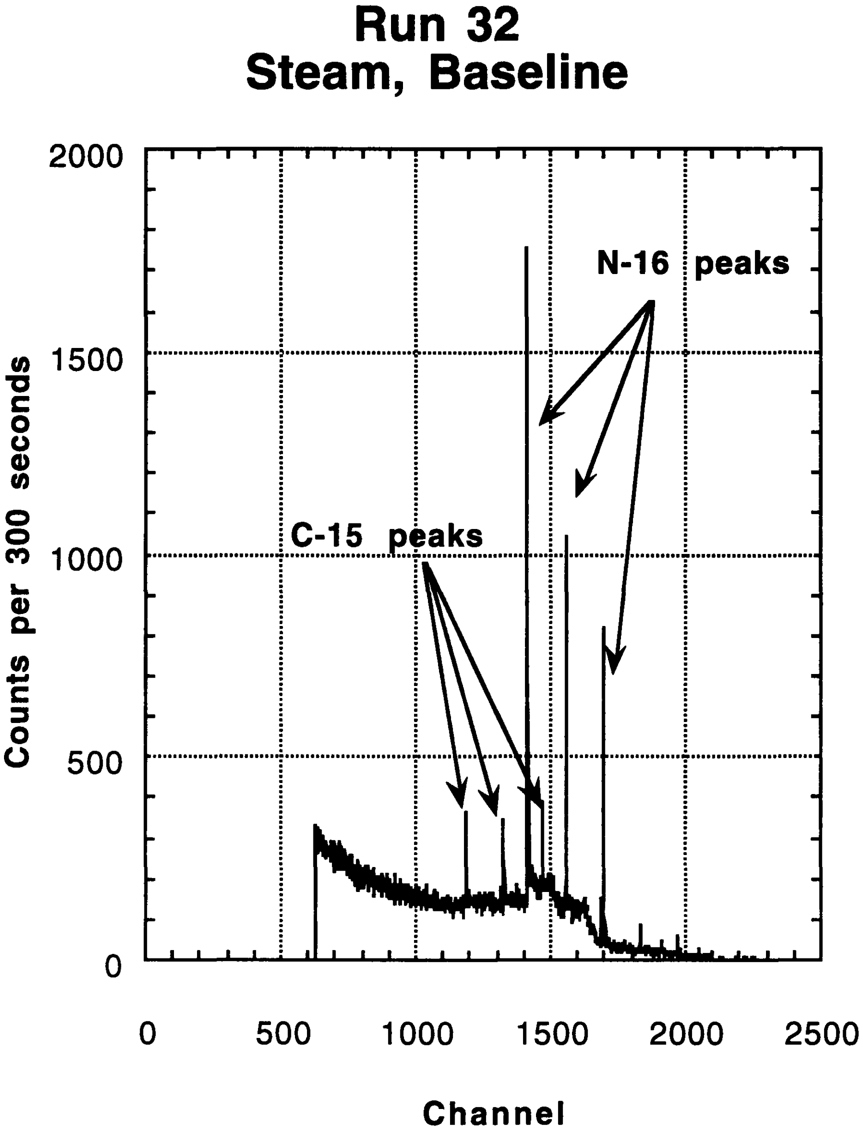
Figure 6-1. Run 32 Oxygen Concentration



Notes:

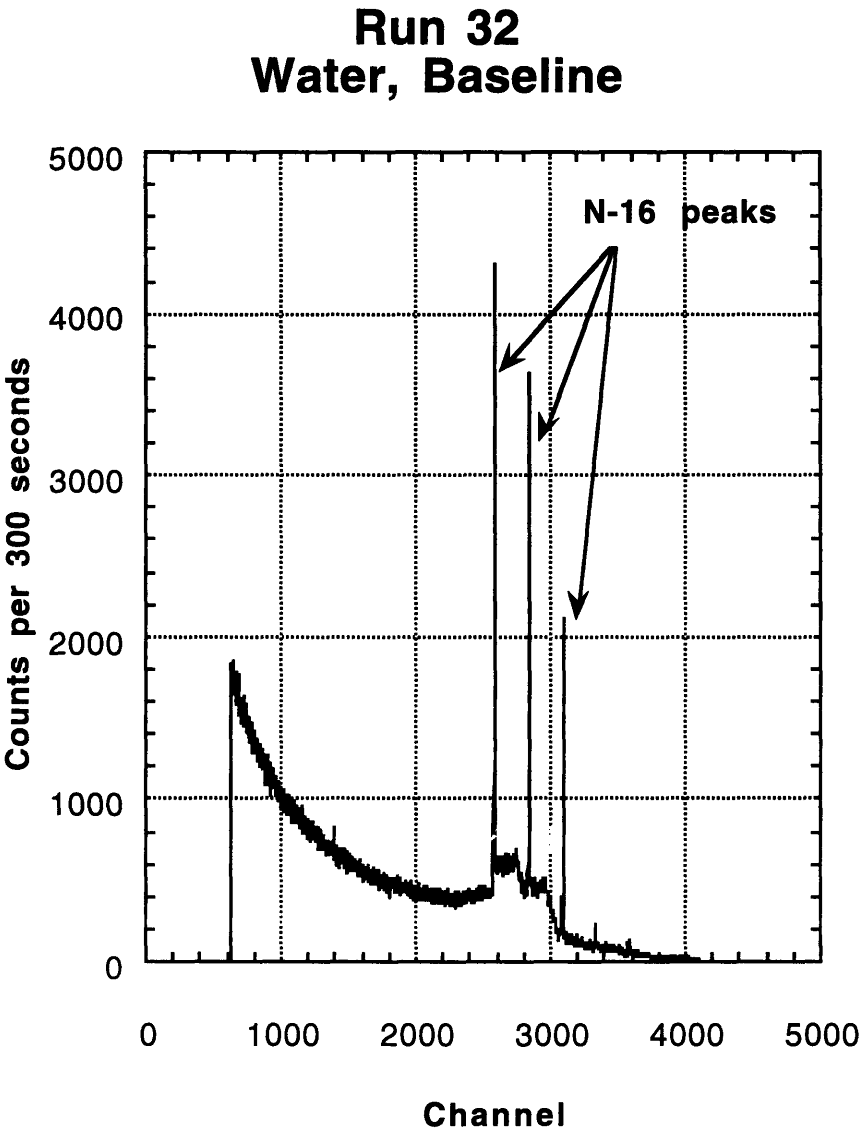
1. Valved in Out-of-Pile ECP Sensor
2. Started Boiling
3. Started VOSO4 Injection (10^{-4} M)
4. Finished VOSO4 Injection
5. Started VOSO4 Injection (1.2×10^{-5} M)
6. Finished VOSO4 Injection

Figure 6-2. Run 32 Hydrogen Concentration and ECP



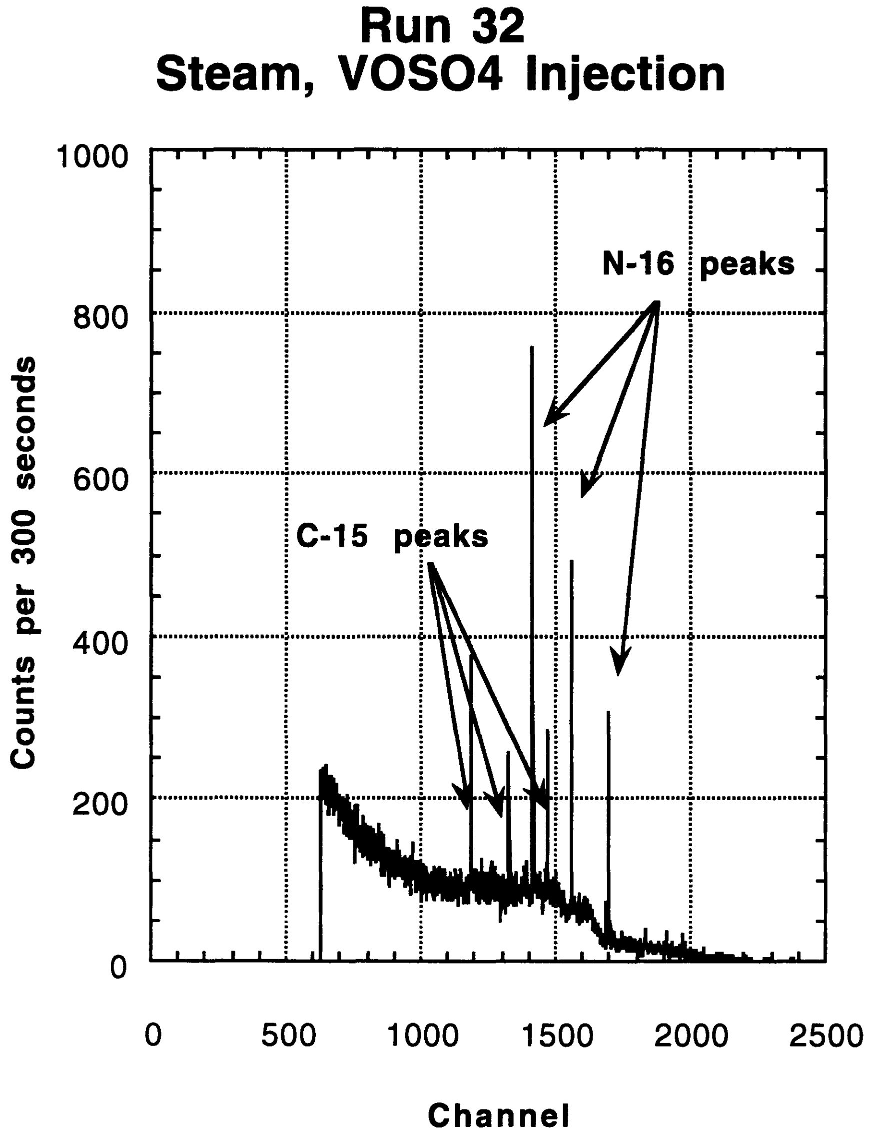
PEAKS	PEAK ENERGY (MeV)		
N-16	5.1	5.6	6.1
C-15	4.3	4.8	5.3

Figure 6-3. Run 32 Steam Baseline Spectrum



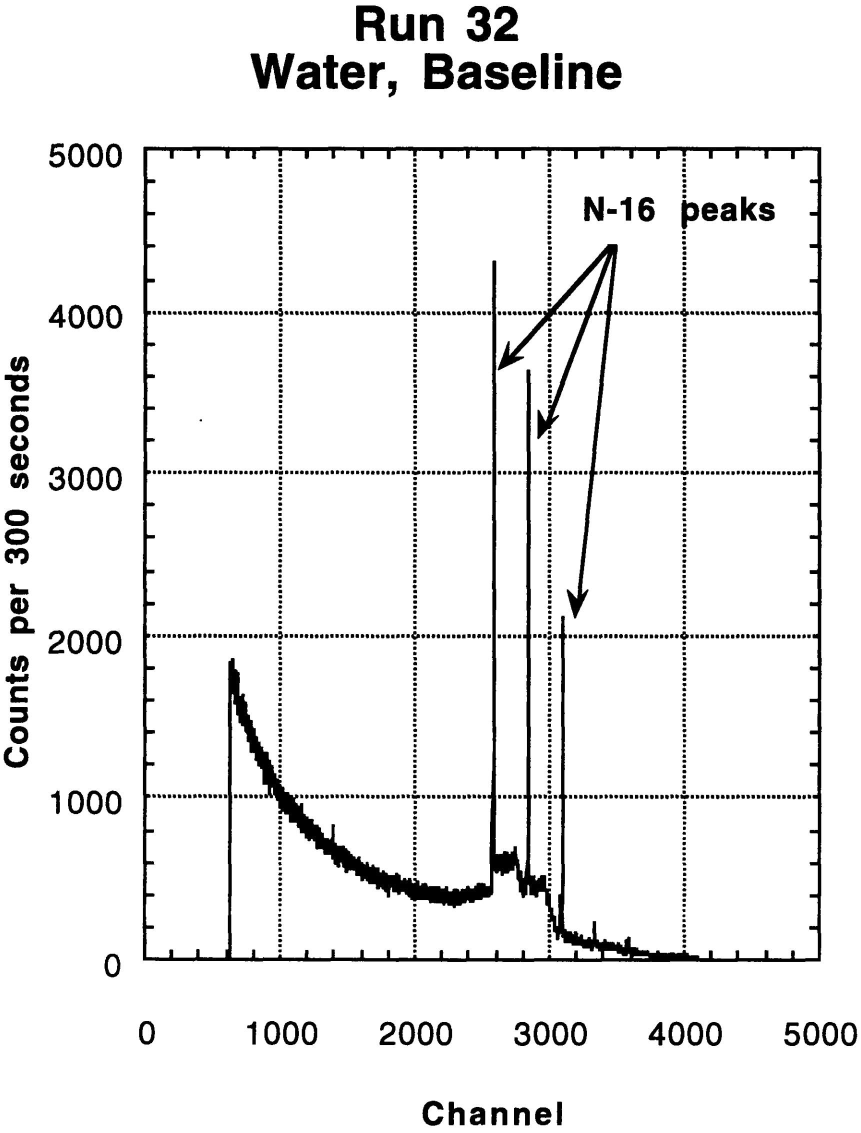
PEAKS	PEAK ENERGY (MeV)		
N-16	5.1	5.6	6.1
C-15	4.3	4.8	5.3

Figure 6-4. Run 32 Water Baseline Spectrum



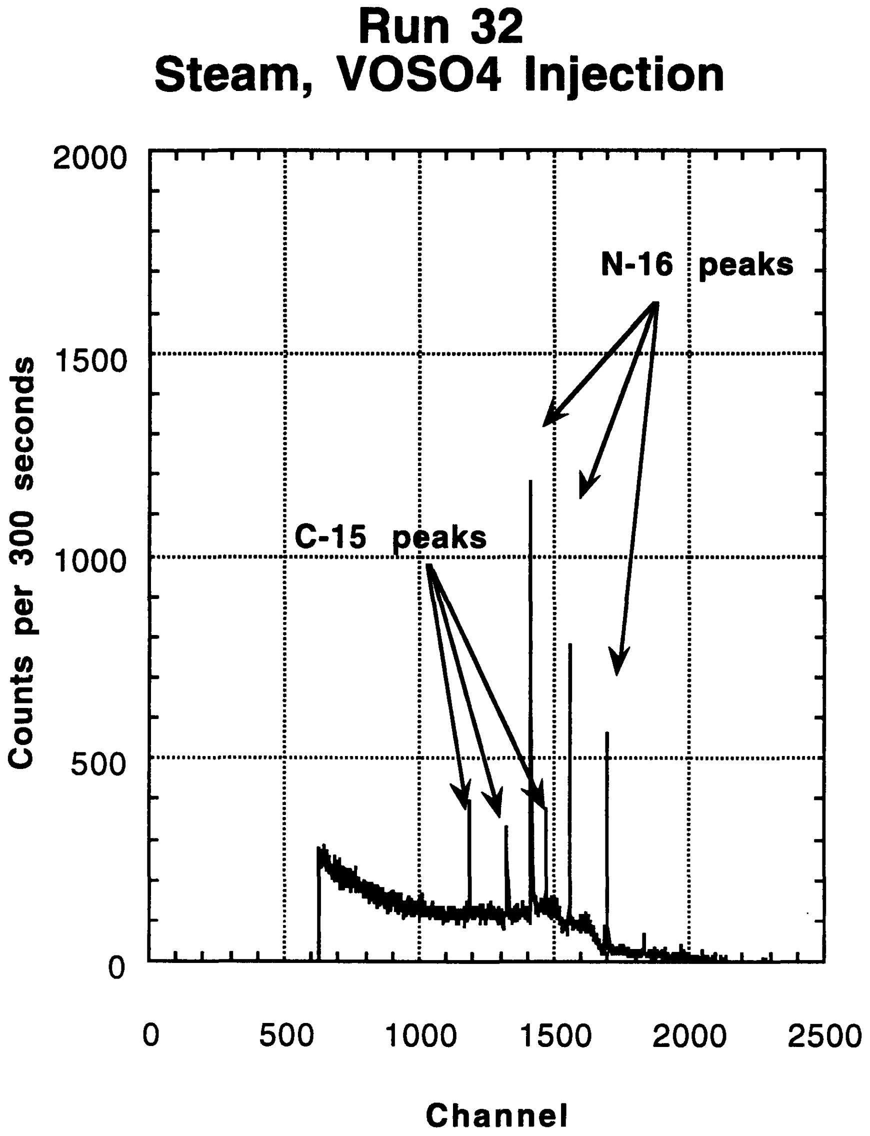
PEAKS	PEAK ENERGY (MeV)		
N-16	5.1	5.6	6.1
C-15	4.3	4.8	5.3

Figure 6-5. Run 32 Steam Spectrum During Chemical Injection (10^{-4} M VOSO4)



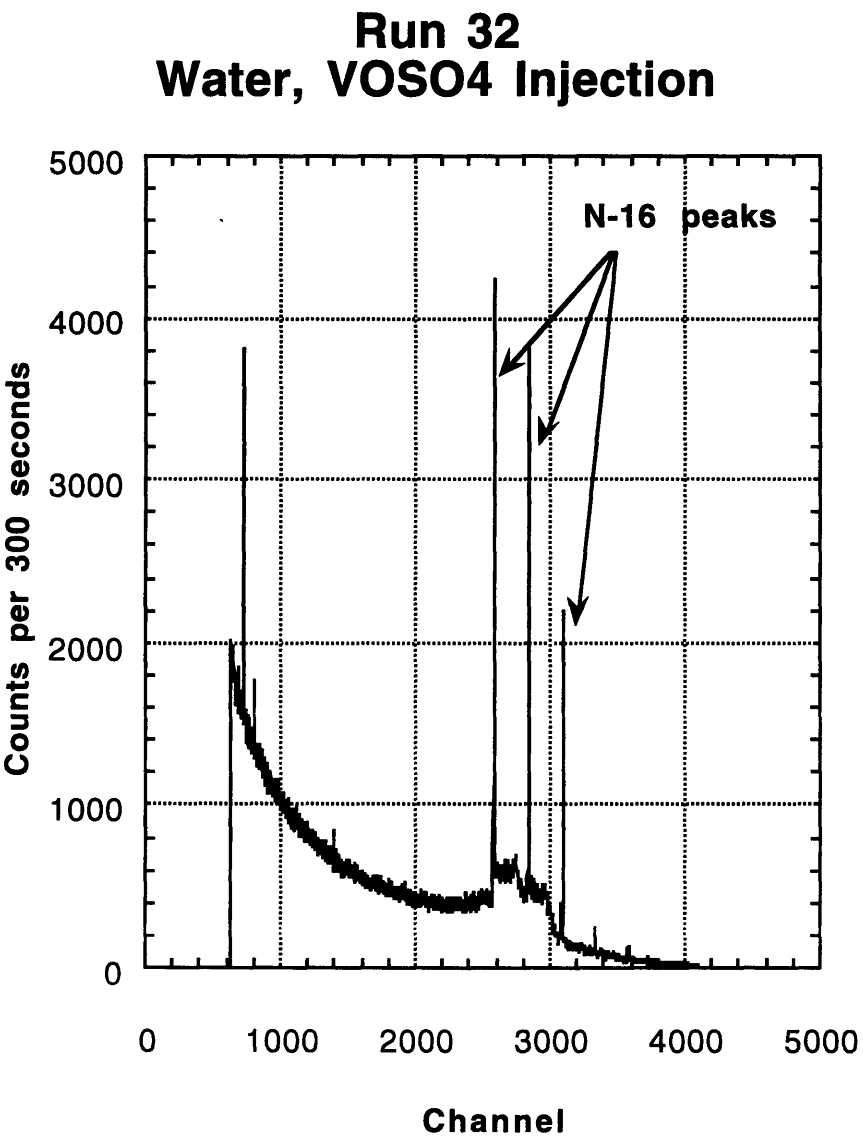
PEAKS	PEAK ENERGY (MeV)		
N-16	5.1	5.6	6.1
C-15	4.3	4.8	5.3

Figure 6-6. Run 32 Water Spectrum During Chemical Injection (10^{-4} M VOSO4)



PEAKS	PEAK ENERGY (MeV)		
N-16	5.1	5.6	6.1
C-15	4.3	4.8	5.3

Figure 6-7. Run 32 Steam Spectrum During Chemical Injection (1.2×10^{-5} M $VOSO_4$)



PEAKS	PEAK ENERGY (MeV)		
N-16	5.1	5.6	6.1
C-15	4.3	4.8	5.3

Figure 6-8. Run 32 Water Spectrum During Chemical Injection (1.2×10^{-5} M $VOSO_4$)

last experiment conducted during NWC, injection of $PdNO_3$ increased the N-16 level by 100%.

A number of auxiliary tests were also done under NWC. These were a carryover test, an ozone test, and determination of the ionic form of N-16. For the carryover test the nonvolatile soluble compound K_2WO_4 was added to the loop, and the activity of W-187 was measured in the steam phase. The very low activity of W-187 in the vapor demonstrated low carryover (less than 0.1%), which confirmed the earlier out-of-pile carryover measurement results (see Appendix D for details).

The ionic form of N-16 was measured in samples both from the steam and water lines. A schematic of this experiment is shown in Figure 6-9. A set of ion exchange columns (anion and cation) was connected to the steam and water sample lines. Five shutoff valves directed flow to the columns. A Ge detector was used to measure the gamma activity of the effluent from each of the columns in turn. This detector was installed on the back mezzanine inside lead shielding to cut down on the high background from the loop piping. The experiment showed that N-16 is in cation form for steam and anion form for water (see Tables 6.2, 6.3 and 6.4). Note that in Tables 6.2 and 6.3 the data are for the water after passing through the indicated column. The results are consistent with the expectation that N-16 volatilizes into steam as NH_3, and is present in water as NO_3^-. Although variations in flow rate prevent quantitative comparison of the anion+cation to non-resin results, sufficient verifiable matchups were observed to suggest the absence of inert (i.e. non-ionic) forms of N-16.

Tables examining the potential influence of C-15 on N-16 measurements for a typical once-through run under normal water chemistry are given in Appendix J.

Table 6.2. N-16 Ionic Form Experimental Data

CONDITION	**N-16 PEAKS: HEIGHT /AREA**		
	5.1 MeV	**5.6 MeV**	**6.1 MeV**
STEAM			
Anion Resin	508/1764	449/1772	293/1451
Anion Resin	457/1814	466/1551	281/1433
Cation Resin	205/759	190/654	107/566
Cation Resin	210/732	211/821	122/636
Background	182/648	167/560	100/488
Background	187/722	169/598	97/543
WATER			
Background	270/1126	246/1041	166/725
Cation Resin	710/2881	738/2694	421/2119
Cation Resin	963/3747	1036/3693	577/2926
Anion Resin	296/973	244/889	169/811
Anion Resin	263/914	246/888	143/740
Background	200/601	235/731	112/583

Note: results are for H_2O which has passed through the indicated column

Table 6.3. N-16 Ionic Form Experimental Data (averaged)

CONDITION	**N-16 PEAKS: HEIGHT /AREA**		
	5.1 MeV	**5.6 MeV**	**6.1 MeV**
STEAM			
Anion Resin	483/1789	458/1662	287/1442
Cation Resin	207/745	200/737	114/601
Background	184/685	168/579	98/515
WATER			
Anion Resin	280/944	245/888	156/776
Cation Resin	837/3314	887/3193	500/2522
Background	235/864	240/886	139/654

Table 6.4. N-16 Ionic Form Experiment Results

	N-16 PEAKS: HEIGHT* /AREA*			**% of Total**
CONDITION	**5.1 MeV**	**5.6 MeV**	**6.1 MeV**	**Peak Area**
		STEAM		
Cationic (thru Anion Resin)	299/1104	290/1083	189/927	**90**
Anionic (thru Cation Resin)	23/60	32/158	16/86	**10**
		WATER		
Cationic (thru Anion Resin)	45/80	5/2	27/122	**4**
Anionic (thru Cation Resin)	602/2450	6472307	361/1868	**96**

* Background subtracted

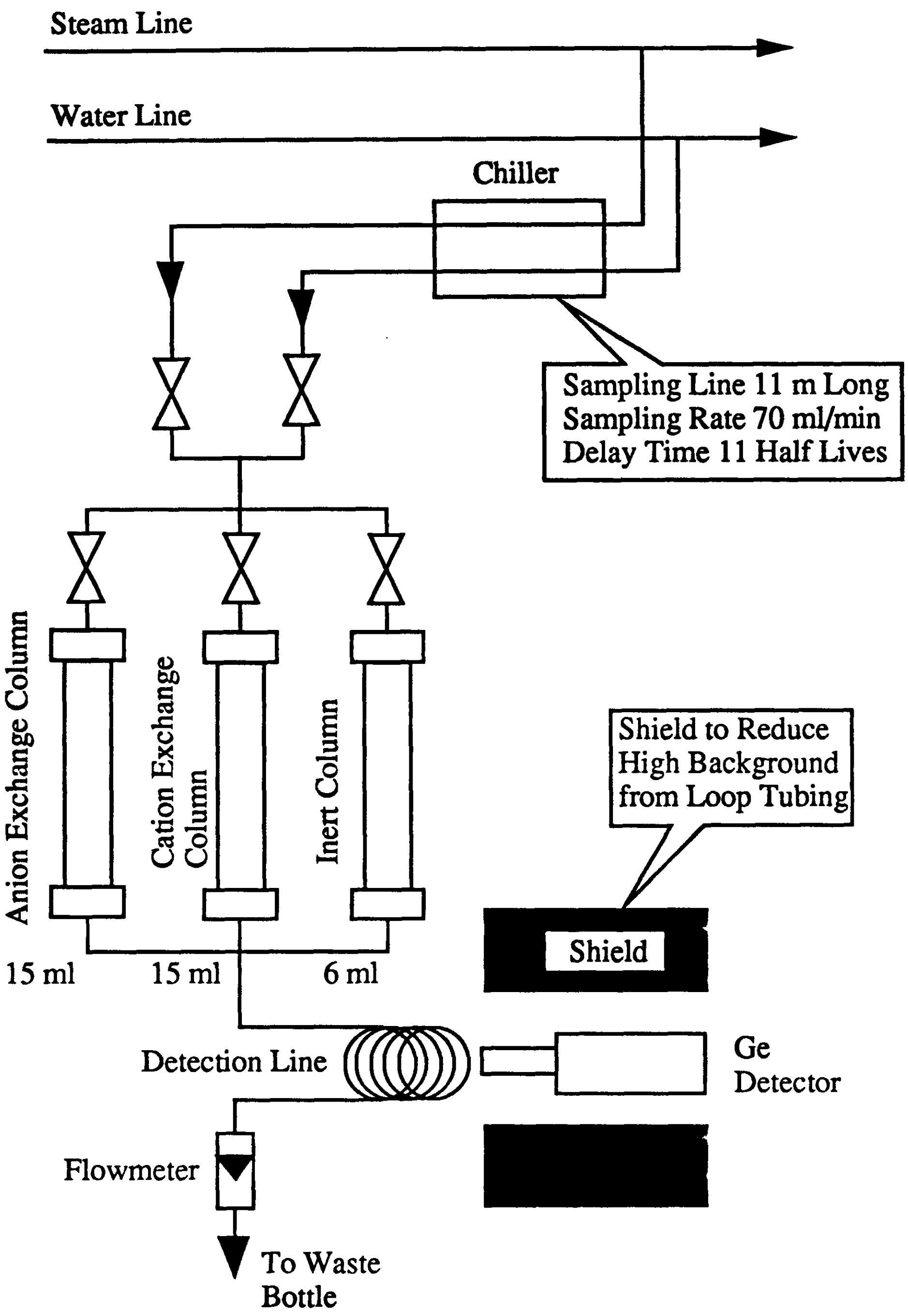


Figure 6-9. Experimental Setup for Determination of the Chemical Form of N-16

6.3 HWC RESULTS

A brief summary of the experiments under hydrogen water chemistry is presented in Table 6.6. As in the NWC case, first the HWC baseline was established. For all experiments discussed in this section the baseline remained unchanged, i.e. less than 10 ppb of O_2 in the feedwater and loop water, 445±25 ppb of H_2 in the feedwater, and less than 1 ppb H_2O_2 in the loop. Peroxide concentration was measured with the Luminol method which is especially precise at very low H_2O_2 concentrations. A comparison between NWC and HWC baseline data for this and the 1992 BCCL Campaign is given in Table 6.5. A typical HWC run history is shown in Figures 6-10 and 6-11.

Table 6.5. Comparison Between Once-Through Mode Baseline Data for 1992 and 1993/94 Campaigns

CAMPAIGN	H_2O_2 in the loop* (ppb)	O_2 in feedwater (ppb)	H_2 in feedwater (ppb)	O_2 in the loop (ppb)
1992 NWC	1155	202	18	N/M**
1993/94 NWC	200	200	5	200
1992 HWC	560	0	966	N/M
1993/94 HWC	0	<10	420	<10

*-Peroxide sample line

**N/M-not measured

Table 6.6 shows that there was no peroxide found in the water sample line under HWC. This result is in agreement with computer code predictions (C-1) and the suppressed electrochemical corrosion potential, and resolves concerns arising from the high H_2O_2 concentrations measured in the loop during the previous BCCL Campaigns.

Table 6.6. Once-Through Mode of Operation, Summary of Experimental Results under HWC (Hydrogen Water Chemistry)

Run #	Chemical Additive	O_2 in the loop (ppb)	O_2 in the Ch.Tank (ppb)	H_2 in the Ch.Tank (ppb)	Additive Conc. (M)	N-16 Effect (Steam)	pH	H_2O_2 in the loop (ppb)	ECP 1 mV, SHE	ECP 3 mV, SHE
	Baseline	2	2	420	N/A*	None**	7.1	0	150	-575
33	KNO_2	8	2	420	10^{-4}	None	8.1	0	392	-520
34	MoO_2	<8	<10	420	10^{-5}	Down by 10%	5.1	0	495	-466
35	V_2O_5	2	<10	420	$<10^{-6}$	None	6.1	0	283	-532
36	$ZnMoO_4$	2	<10	420	$<2x10^{-7}$	None	6.4	0	227	-548
37	$Zn(OH)_2$	<1	<10	420	$6.1x10^{-8}$	None	6.7	0	216	-572
38	KNO_2	9	<10	470	10^{-4}	Down by 25%	8.3	0	358	-513
39	K_2MoO_4	3	<10	470	10^{-4}	Down by 35%	6.6	0	370	-671

Table 6.6 (continued)

Notes:

For all once-through mode runs loop flow rate remained ~1.4 LPM, and steam quality was ~10%.

* N/A- not available

** Ratio of steam/water counts during baseline measurements was ~0.9 (corresponding ratio for NWC once-through mode of operation was 0.42 and for the recirculation mode of operation under NWC it was 0.45)

ECP 1-Toshiba in-thimble ECP sensor

ECP 3-Ag/AgCl MIT ECP sensors located in the return water autoclave

Chemical Additive - chemical additive injection in loop feedwater

O_2 in the loop - oxygen concentration in the water sample line (average over a period of ~30 min after steady state has been achieved)

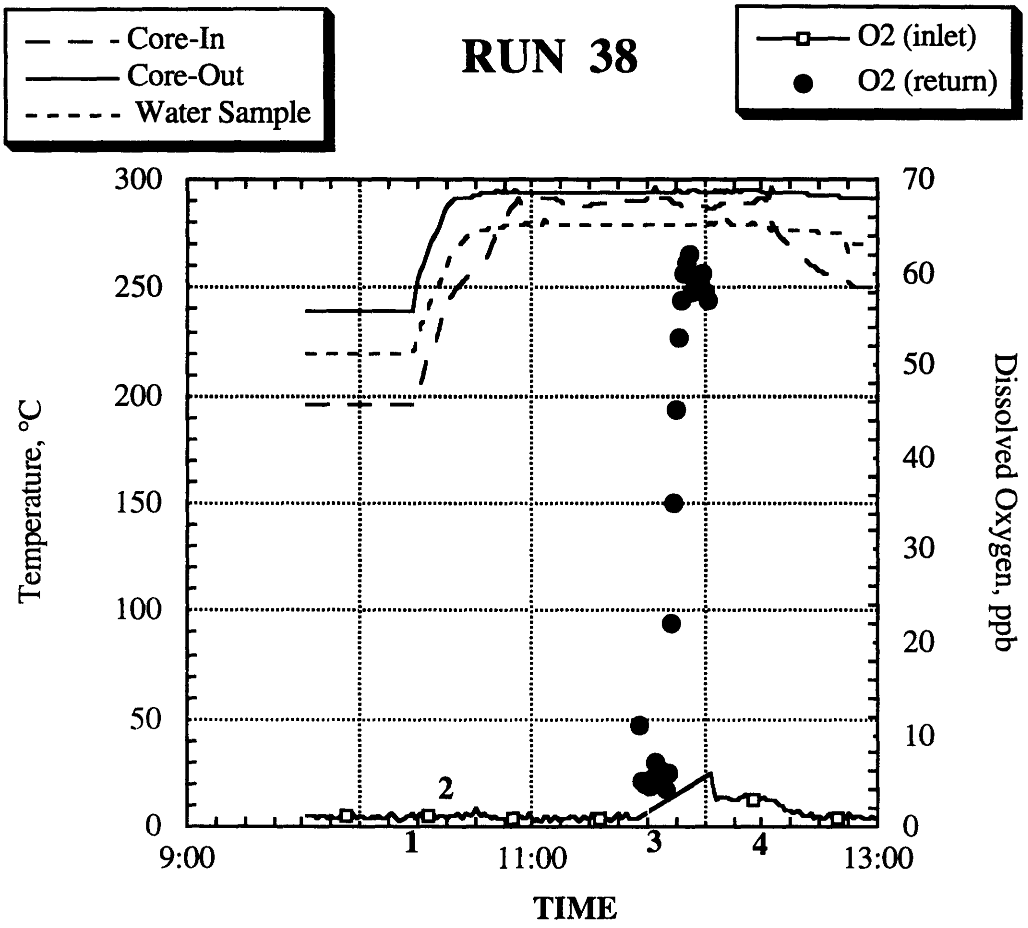
O_2 in the Ch.Tank - oxygen concentration in the charging tank water (average over a period of ~30 min after steady state has been achieved)

H_2 in the Ch.Tank - hydrogen concentration in the charging tank water (average over a period of ~30 min after steady state has been achieved)

Additive Conc - concentration of chemical additive in loop water (average over a period of ~20 min after steady state has been achieved)

N-16 Effect - effect of chemical addition on N-16 in steam phase relative to HWC baseline (average over a period of ~30 min after steady state has been achieved)

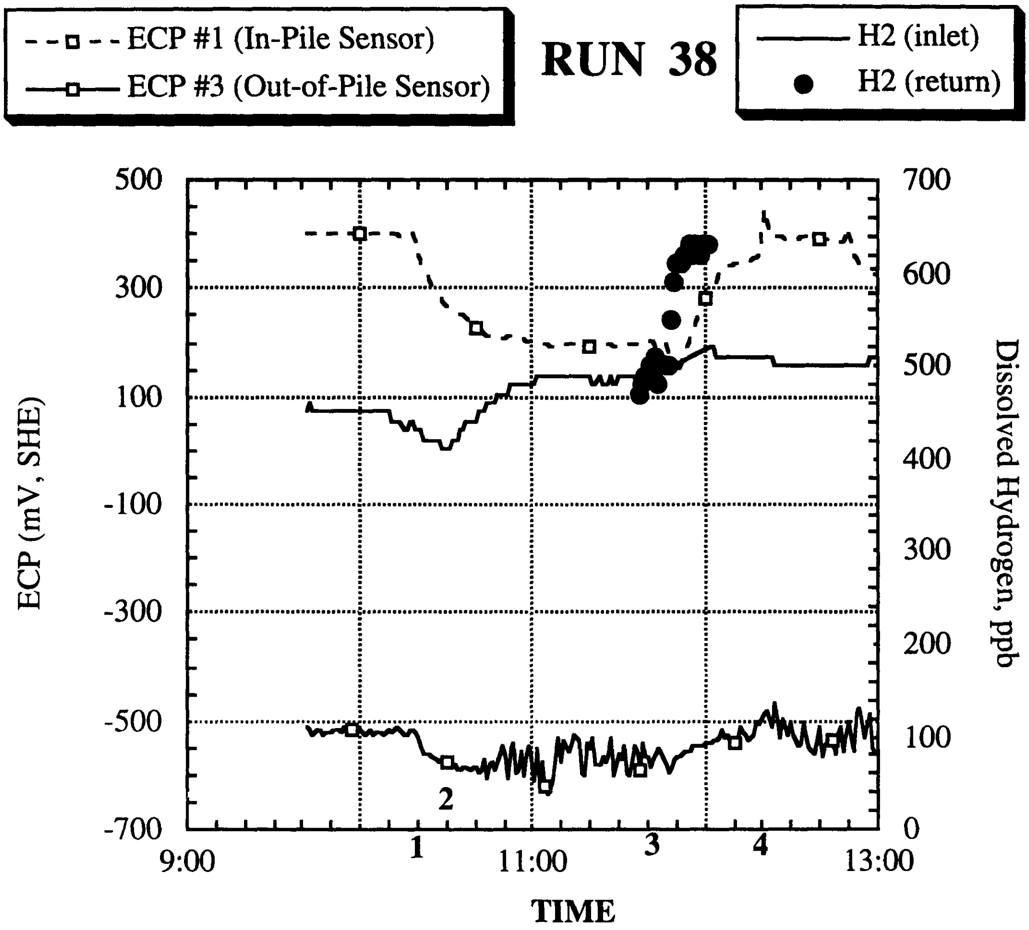
H_2O_2 in the loop - hydrogen peroxide concentration in the loop water (average over a period of ~30 min after steady state has been achieved)



Notes:

1. Started Heatup
2. Started Boiling
3. Started KNO_2 Injection
4. Finished KNO_2 Injection, Went to Hot Standby

Figure 6-10. Run 38 Oxygen Concentration



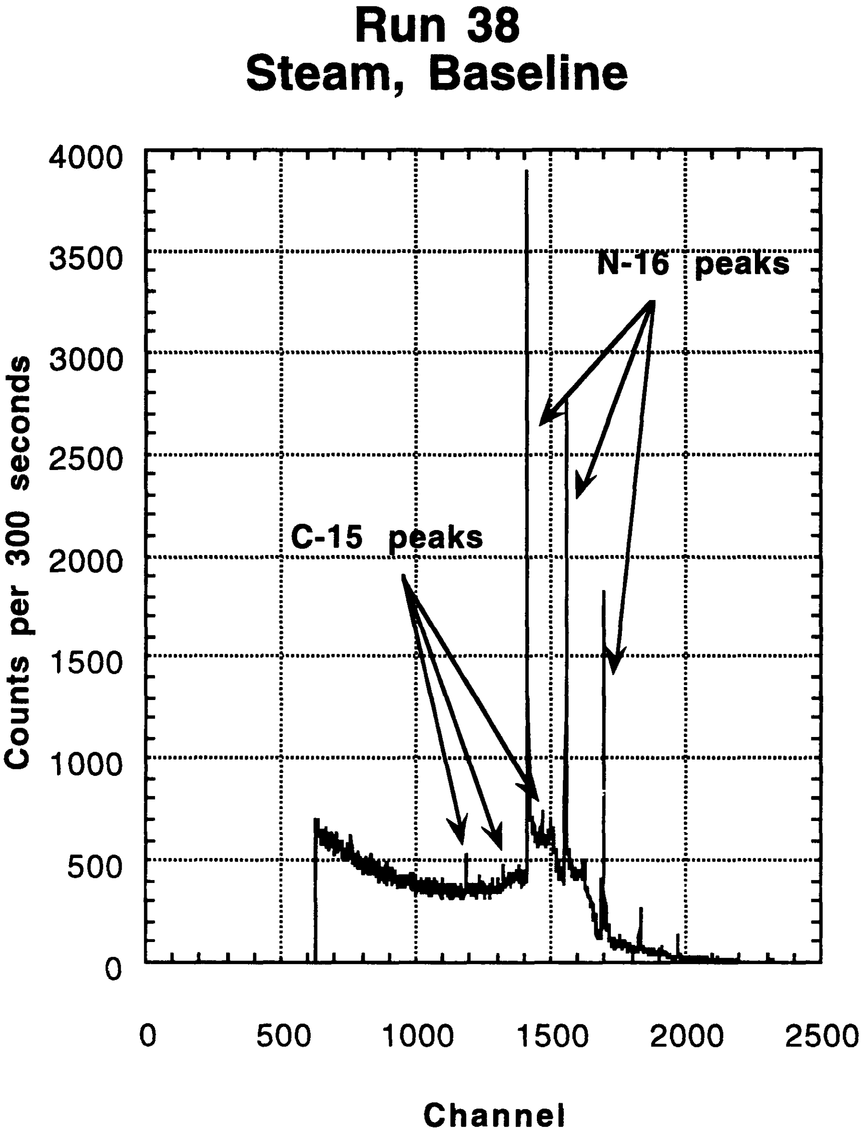
Notes:

1. Started Heatup
2. Started Boiling
3. Started KNO_2 Injection
4. Finished KNO_2 Injection, Went to Hot Standby

Figure 6-11. Hydrogen Concentration and ECP

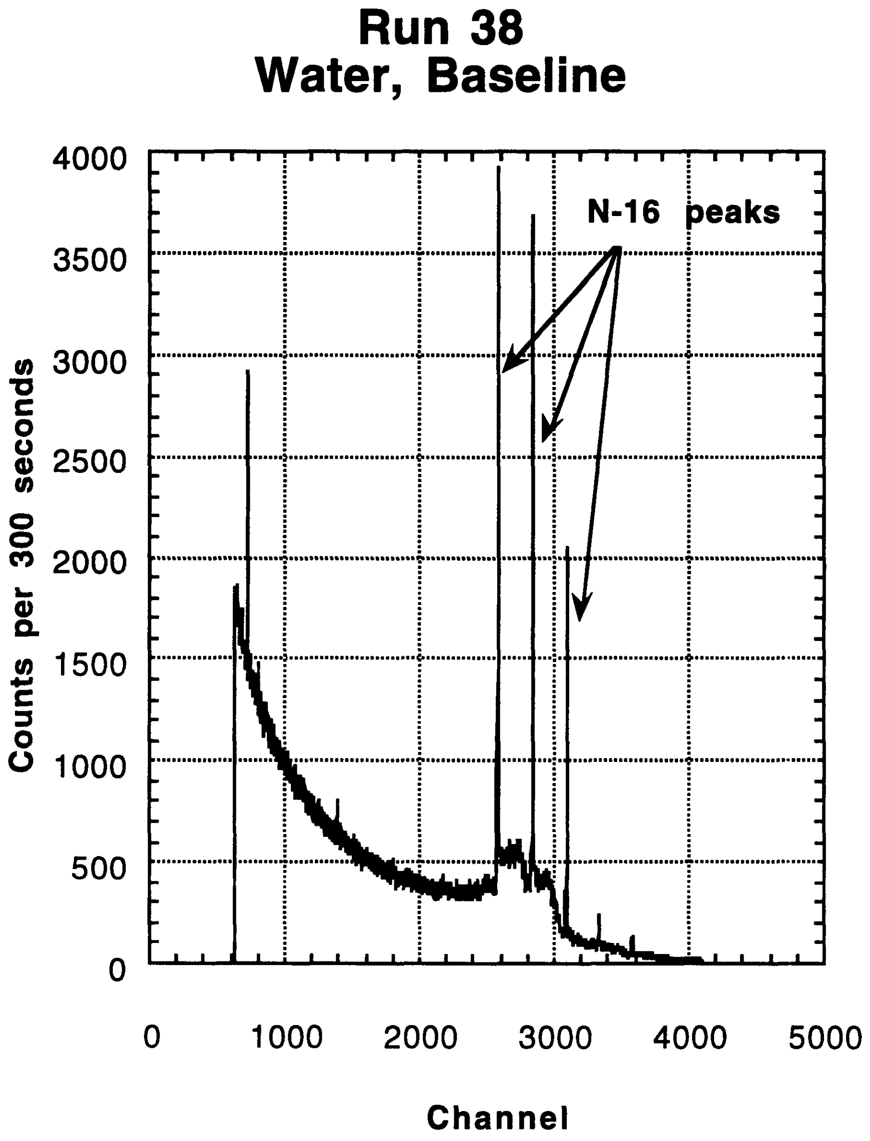
After the loop characterization under HWC was completed, several chemical compounds were added to the loop. Some were among those injected under NWC. All additives, except $ZnMoO_4$ and $Zn(OH)_2$, reduced N-16 carryover to the steam phase. KNO_2 as well as K_2MoO_4 (10^{-4} M) reduced N-16 by 30% compared to the HWC baseline, although chemical injection concentrations of the order of 10^{-5} M were not enough to reduce gamma activity. N-16 spectra for the KNO_2 injection run (#38) are shown in Figures 6-12 to 6-15. K_2MoO_4 exhibited the same effect as in the past campaign, except that N-16 reduction was not so pronounced in 1993/94 (35% instead of 50%). A possible explanation is the fact that the hydrogen water chemistry was established with lower hydrogen content in the feedwater (420 ppb in the 1993/94 Campaign against 966 in 1992). MoO_3 and V_2O_5 decreased the steam line dose by 20% and 15% respectively under HWC, whereas they did not show any effect on N-16 carryover to the vapor under NWC conditions.

Tables demonstrating the potential influence of C-15 on N-16 measurements for a typical once-through run under hydrogen water chemistry are given in Appendix J. The maximum contribution of C-15 will not exceed 10% if integral counts were used to measure N-16.



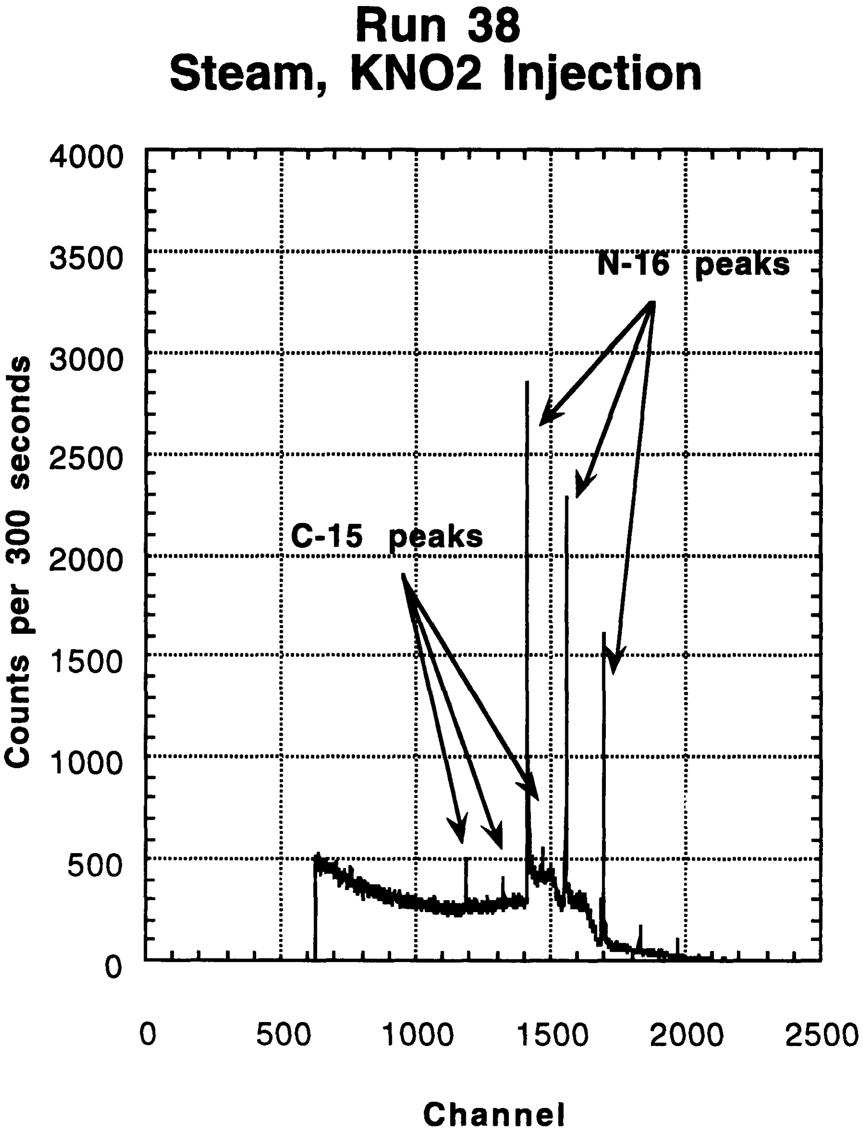
PEAKS	PEAK ENERGY (MeV)		
N-16	5.1	5.6	6.1
C-15	4.3	4.8	5.3

Figure 6-12. Run 38 Steam Baseline Spectrum



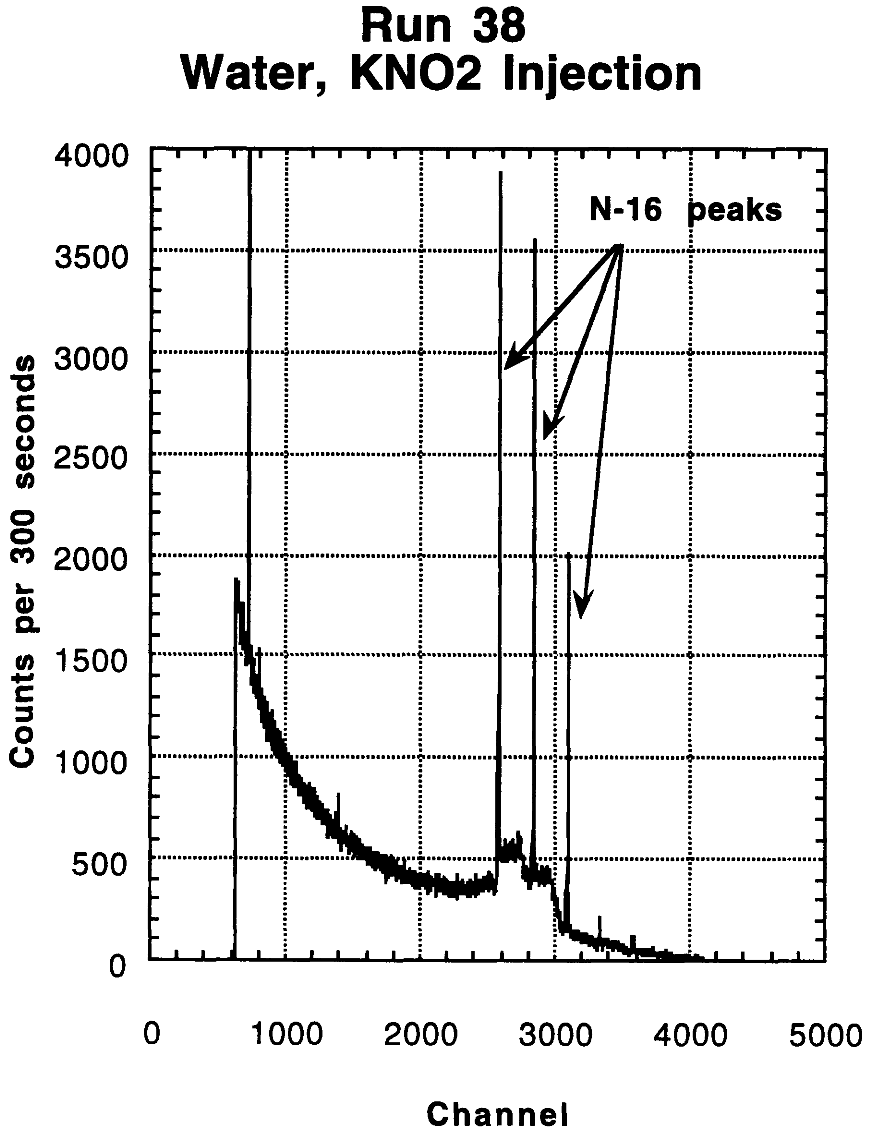
PEAKS	PEAK ENERGY (MeV)		
N-16	5.1	5.6	6.1
C-15	4.3	4.8	5.3

Figure 6-13. Run 38 Water Baseline Spectrum



PEAKS	PEAK ENERGY (MeV)		
N-16	5.1	5.6	6.1
C-15	4.3	4.8	5.3

Figure 6-14. Run 38 Steam Spectrum During Chemical Injection (10^{-4} M KNO_2)



PEAKS	PEAK ENERGY (MeV)		
N-16	5.1	5.6	6.1
C-15	4.3	4.8	5.3

Figure 6-15. Run 38 Water Spectrum During Chemical Injection (10^{-4} M KNO_2)

6.4 CHAPTER SUMMARY

Results of the in-pile once-through mode operation experiments are presented and discussed in this chapter. A comparison is given between NWC and HWC data as well as between the results of this campaign and the previous 1992 Campaign. During these runs a new baseline data set was established. A number of chemical additives were injected to see the effect on N-16 carryover. It was found that $VOSO_4$-the only additive among all injected under NWC-reduced the N-16 level in the vapor phase by a factor of 2.5. Addition of $Zn(OH)_2$, $ZnMoO_4$, K_2MoO_4, C_2H_2, and $PdNO_3$ caused N-16 activity in the steam to increase. All additives injected under HWC, except KNO_2 and compounds containing Zn, reduced N-16. The N-16 dose reduction and ECP suppression while adding K_2MoO_4 confirms the results of the past BCCL Campaigns, albeit dose reduction was not as significant. Hydrogen peroxide concentration during all HWC runs was measured to be zero (i.e. less than 1 ppb with the Luminol method), which strongly suggests that similar suppression will take place in full scale BWR units.

CHAPTER 7 SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

7.1 INTRODUCTION

A detailed description of those BCCL components which were changed before the 1993/94 Campaign, as well as experimental procedures and results under NWC and HWC conditions while the loop was operated in its once-through mode, and under NWC conditions during the recirculation mode of operation, has been given in the preceding chapters of this report. Figure 1-2 shows the key features of the loop in its recirculation mode, and Table 2.1 summarizes the principal modifications compared to earlier designs. In this Chapter a general review of results of the 1993/94 Campaign and conclusions will be considered. Future changes and modifications suggested for the BCCL are discussed in the last section of this chapter.

In summary, the following principal results have been achieved in BCCL runs to date, with special emphasis on the 1993/94 Campaign:

1. Significant reduction in N-16 carryover by adding benign chemicals at reasonable concentrations has not been achieved; and all organics create conditions similar to HWC (but with higher water conductivity).
2. Anion inhibitors, such as molybdate, show a beneficial suppression of ECP (by ~100 mV) under both NWC and HWC; but for the short tests employed only at higher-than-preferred concentrations (~10^{-4} M).
3. The upgraded BCCL configuration now generates radiolysis products (H_2, O_2, H_2O_2) in better agreement with computer code predictions; but in general measured yields are about twice those predicted.
4. Recirculation mode operation is more stable than once-through; and all loop components and subsystems, including those modified or added prior to the

1993/94 Campaign, performed well, with the exception of the level float/coil units and the in-pile electrodes.

5 A new in-core section was designed and employed for the 1993/94 Campaign to allow loop operation at lower flow rates. In recirculation mode operation, the pressure drop across the recirculation loop did not allow achievement of the nominal (i.e. same as once-through) flow rate (1.5 LPM) because of insufficient pump capacity, hence a lower flow rate (0.9 LPM) was employed. The new in-core section design also avoided employing a titanium can, which has experienced cracking and warping problems in the last PCCL and BCCL runs (same design was used for both projects).

7.2 FINDINGS RELEVANT TO BWR OPERATION

7.2.1 Radiolysis Chemistry and ECP

7.2.1.1 Once-Through Mode of Operation

The BCCL was operated in the once-through mode during all campaigns. For the campaigns with the titanium loop (1990-1992), the experimental results were consistent, so only 1992 results are discussed as representative of past baseline data. The measurements and code predictions for the 1993-94 stainless steel loop are presented and discussed later in this section. For the selected results for 1992 and 1993 examined here, the total mass flowrate was ~25 g/s, but the quality was ~15% for 1992 and ~10% for 1993.

NWC Baseline

During normal water chemistry conditions for boiling, the feedwater oxygen concentration was 200 ppb and the hydrogen concentration was 18 ppb and 5 ppb, respectively for 1992 and 1993. Hot single phase data for 1992 is also presented and can serve as a benchmark of the radiolysis G-values and reaction set rate constants, since the complicating influence of boiling is eliminated. Table 7.1 shows the results for the NWC baseline conditions.

Table 7.1. Comparison Between 1992 and 1993 Experimental Data and Predicted Results for Once-Through Boiling and Non-Boiling Cases under NWC (loop flow rate was 25 g/s)

Condition	Chemistry		O_2 inlet [ppb]	H_2 inlet [ppb]	H_2O_2 sample [ppb]	O_2 return [ppb]	H_2 return [ppb]	ECP OOP[b] [mV,SHE]
Boiling x=15%	NWC 1992	measured	202±104	18±6	1155±417	1048±225	165±23	-160±60
		computed	202[a]	18[a]	252	752	84	16
		computed	202[a]	5	292	910	90	29
Boiling x=10%	NWC 1993	measured	200±25	5±5	180±20	1868±300	197±16	325±50
		computed	200[a]	5[a]	194	630	56	7
						O_2 water[c]	H_2 water	ECP OOP
		measured				200	NM	115±30
		computed				217 (126)	9	7
Single phase x<0	NWC 1992	measured	150±37	5±1	272±79	359±59	41±11	-65±80
		computed	150[a]	5[a]	153	175	7	-9

[a] Initial condition, set equal to experimental value.

[b] ECP is predicted according to Lin's correlation (EPRI NP-6732) using total oxidant; out-of-pile refers to MIT electrodes in ex-thimble autoclave.

[c] Measured concentration of O_2 in H_2O is total oxidant (O_2 + 8/17 H_2O_2). Predicted concentration is total oxidant (with oxygen concentration alone shown in parentheses).

For the 1992 titanium rig, the two outstanding data results are the high measured hydrogen peroxide compared to the predicted value (1155 ppb measured compared with 252 ppb predicted for boiling and 272 ppb measured to 153 ppb predicted for single phase) and the correspondingly "low" measured ECP (-160 mV, SHE boiling and -65 mV, SHE single phase). This apparent inconsistency between high measured peroxide and low ECP has been observed at an independent lab (A1), and suggests the need for further research on the influence of hydrogen peroxide in BWR systems. In addition, for single phase operation it can be observed that the computed concentrations of peroxide and dissolved gases in the mixed return stream are ~2 times lower than the measured values. Although the very high measured peroxide concentrations were not reproduced with the 1993 stainless steel loop, the general trend of code predictions underestimating measured dissolved gas concentrations in the mixed return stream was also observed.

This suggests that the G-values and chemistry set may need some adjustment to increase the net radiolysis of the water.

HWC Baseline

Guidelines for hydrogen water chemistry conditions for 1992 and 1993 boiling were different, hence the feedwater concentrations were different (996 ppb H_2 and 480 ppb H_2 for 1992 and 1993, respectively with 0 ppb O_2 for both years. For 1992, feedwater hydrogen was adjusted to give a 5-fold increase of N-16 steam phase activity compared to NWC conditions. This was deemed an appropriate similitude condition for studying the effect of chemical additives and applying BCCL results to a BWR plant. In 1993, a more liberal criterion for similitude was defined as when the water letdown O_2 concentration was suppressed below 10 ppb. As for NWC baseline, single phase data under HWC for the 1992 campaign are also shown (see Table 7.2).

Table 7.2. Comparison Between 1992 and 1993 Experimental Data and Predicted Results for Once-Through Boiling and Non-Boiling Cases under HWC (loop flow rate was 25 g/s)

Condition	Chemistry		O_2 inlet [ppb]	H_2 inlet [ppb]	H_2O_2 sample [ppb]	O_2 return [ppb]	H_2 return [ppb]	ECP OOP[b] [mV,SHE]
Boiling x=15%	HWC 1992	measured	0±5	966±38	560±557	0±5	896±45	-530±25
		computed	0[a]	966[a]	3.7	1.6	991	-322
Boiling x=10%	HWC 1993	measured	0±5	480±20	0±5	0±5	482±25	240±60
		computed	0[a]	480[a]	6	2.6	531	-301
						O_2 water[c]	H_2 water	ECP OOP
		measured				2±5	NM	-570±25
		computed				2.7 (~0.1)	82	-301
Single phase	HWC 1992	measured	0±5	419±224	410±224	0±5	407±4	-450±40
		computed	0[a]	419[a]	0.29	0.13	457	-388

[a] Initial condition, set equal to experimental value.

[b] ECP is predicted according to Lin's correlation (EPRI NP-6732) using total oxidant; out-of-pile refers to MIT electrodes in ex-thimble autoclave.

[c] Measured concentration of O_2 in H_2O is total oxidant (O_2 + 8/17 H_2O_2). Predicted concentration is total oxidant (with oxygen concentration alone shown in parentheses).

The trends for HWC once-through operation parallel those for NWC once-through operation, but the contrast between computed and measured H_2O_2 is even greater. Hydrogen peroxide concentrations predicted by RADICAL are 0-6 ppb, whereas measured concentrations in the 1992 BCCL are ~500 ppb for both single phase and boiling conditions. Again the high peroxide concentrations are accompanied by low ECP (-500 mV, SHE), much lower than expected with these peroxide concentrations. The mixed return dissolved gas concentrations are less interesting under HWC since the hydrogen and oxygen concentrations remain almost the same as the inlet concentrations. Still, it is interesting to note that for all cases, the computed hydrogen exceeds the experimental value. Nevertheless, the most interesting point of discussion is the discrepancy between the measured and predicted hydrogen peroxide concentrations for the 1992 results, whereas there is good agreement between measured and computed values for the 1993 tests: as expected H_2 almost totally suppresses both O_2 and H_2O_2.

7.2.1.2 Recirculation Mode of Operation

NWC Baseline

Recirculation mode operation of the BCCL was briefly demonstrated during the 1992 campaign, but no chemistry parameters were recorded since it was only a proof-of-principle test. In 1993-94, recirculation-mode was a substantial part of the campaign and the data are presented in Table 7.3. Feedwater concentrations were 200 ppb O_2 and 20 ppb H_2. The results for H_2O_2 are quite different from the once-through case, where calculations and measurements were in good agreement. For recirculation operation, the predicted peroxide concentration is ~2 times the measured concentration. Again, the letdown dissolved gas concentrations trend similarly to once-through results, with the measurements exceeding predictions. During recirculation, there are separate measurements for the water and steam lines which show that the condensed vapor phase concentrations are more poorly predicted (less by a factor of 4-5) than the liquid phase concentrations (underestimated by a factor of 1.5-2). This suggests that stripping of gas from solution in the BCCL may be more efficient than that employed in the computational model.

Table 7.3. Comparison Between 1993 Experimental Data and Predicted Results for Recirculation Boiling Case under NWC (loop flow rate was 15 g/s)

Condition	Chemistry		O_2 feedwtr [ppb]	H_2 feedwtr [ppb]	H_2O_2 sample [ppb]	O_2 water [ppb]	H_2 water [ppb]	ECP OOP [mV,SHE]
Boiling	NWC	measured	200±25	20±5	95±40	270±45	27±5	4±25
x=15%	1993	computed	200^a	20^a	168	193 (114)	13	-30
						O_2 steam	H_2 steam	
		measured				16500±500	2200±300	
		computed				3530	474	

[a] Initial condition, set equal to experimental value.

[b] ECP is predicted according to Lin's correlation (EPRI NP-6732) using total oxidant; out-of-pile refers to MIT electrodes in ex-thimble autoclave.

[c] Measured concentration of O_2 in H_2O is total oxidant (O_2 + 8/17 H_2O_2). Predicted concentration is total oxidant (with oxygen concentration alone shown in parentheses).

Measurements and predictions for the 1993 BCCL compare fairly well for once-through NWC and HWC and for recirculation NWC conditions. Results for the mixed return line and the individual liquid and steam letdown lines indicate that radiolysis code predictions underestimate the dissolved gas concentrations. The measurement results for the 1992 BCCL differ most significantly from the 1993 rig in the concentration of hydrogen peroxide measured in the loop. 1992 data shows that peroxide is ~1000 ppb during boiling NWC and ~500 ppb during boiling and single phase HWC whereas 1993 data indicate peroxide is ~ 100-200 ppb during once-through and recirculation NWC, and 0 ppb under HWC. These measured concentrations for 1992 are 3-5 times greater than the predicted ones and seem unrealistically high in light of the relatively low measured ECPs and the 1993 data.

7.2.2 N-16 Carryover

A detailed discussion of N-16 carryover has been given in a previous thesis (H-1). In this chapter only a summary of the effect of the C-15 on N-16 measurements in the vapor phase will be considered prior to reviewing the measured N-16 enhancement factors. Appendix J goes into this in considerable detail.

Two Ge detectors were employed in the 1993/94 BCCL Campaign to both eliminate and to determine the effect of C-15 on the accuracy of N-16 measurements. These detectors allowed separation of N-16 from C-15 photopeaks, and hence also determination of the percentage of integral counts attributed to C-15 activity. It was found that C-15 contributes up to 20-25% of the vapor phase activity during baseline operation, and up to 30% during chemical injection when an additive tends to suppress N-16 activity in steam. Run #32 can serve as an extreme example. In this case $VOSO_4$ injection reduces N-16 by a factor of 2, and C-15 contributes up to 31% of measured total photopeak gamma activity in the range 4.3-6.1 MeV. Including Compton counts would considerably reduce this percentage. Under HWC conditions (see Run #38) the potential effect of C-15 on N-16 measurements is not significant (less than 10%), and may be neglected. Note that all enhancement factors for the 1993/94 Campaign were measured using resolved N-16 photopeak data and are thus free of any C-15 contribution. In Appendix J additional information is presented to justify the credibility of the pre-1993 integral NaI enhancement factor measurements.

7.3 EFFECT OF CHEMICAL ADDITIVES

Table 7.4 summarizes experimental results of adding different chemicals to the loop and their effect on the N-16 in the vapor phase. This table accumulates data on all preceding, and the last, BCCL Campaigns.

Table 7.4. Summary of 1991, 1992, 1993/94 N-16 Carryover Studies

ADDITIVES	**VAPOR PHASE N-16 ENHANCEMENT FACTOR**
1991 (NWC)	
NH_4OH, C_2H_5OH, H_2	5.7, 5.0, 4.5
CO, CH_4, NH_3OHCl, $C_6H_6SO_3Na$	4.2, 4.1, 3.8, 3.7
NO, $N(CH_3)_3HCl$, KNO_2	2.7, 2.7, 2.5
K_2CrO_4, O_2, $PdCl_2$, K_2CO_3, $KMnO_4$	1.5, 1.4, 1.3, 1.2, 1.2
H_2O_2, KOH, CO_2, N_2O, N_2, HNO_3	1.0
HCL	0.8
1991 (HWC)	
H_2O_2, KOH	1.2, 1.1
KNO_2	0.67
1992 (NWC)	
$(NH_2)_2CO$, N_2H_4, $O(CH_2)_2NH(CH_2)_2$	9.3, 7.8, 6.1
$(CH_3)_3COH$, $(CH_3)_2CO$, $HCHO$	6.0, 5.5, 5.4
C_6H_5OH, $CuCl_2$, CH_3OH, C_2H_5OH	5.3, 5.2, 5.1, 5.0
$ZnSO_4$, $FeSO_4$, $HCOOH$	4.8, 3.0, 1.8
K_2CrO_4, K_2MoO_4, $LiOH$, $VOSO_4$	1.7, 1.3, 1.2, 0.9
1992 (HWC)	
$ZnSO_4$, $FeSO_4$, $CuCl_2$	2.8, 1.1, 0.6
K_2MoO_4, K_2CrO_4,	0.54, 0.45

Table 7.4. Summary of 1991, 1992, 1993/94 N-16 Carryover Studies (continued)

ADDITIVES	**VAPOR PHASE N-16 ENHANCEMENT FACTOR**
1993/94 (NWC) Once-Through Mode	
C_2H_2, $PdNO_3$, $Zn(OH)_2$	5.5, 2.0, 1.2
$ZnMoO_4$, K_2MoO_4	1.15
MoO_3, V_2O_5, Na_2SnO_4, K_2WO_4	1.0
$VOSO_4$	0.4
1993/94 (HWC) Once-Through Mode	
V_2O_5, $ZnMoO_4$, $Zn(OH)_2$	1.0
MoO_3, KNO_2, K_2MoO_4	0.9, 0.75, 0.65
1993/94 (NWC) Recirculation Mode	
LiOH	1.9
Na_2SO_3, H_2O_2, O_2, KOH	1.0

Notes:

N-16 Enhancement Factor: ratio of N-16 activity in steam to that in liquid divided by the same ratio for baseline

HWC values are related to HWC baseline (i.e. H_2 addition)

A number of chemicals were added to the loop water when the BCCL 1993/94 was operated in its once-through and recirculation modes. One purpose of the injections was to verify results of the previous campaigns when the loop was made of titanium instead of stainless steel. At the same time, since new detectors were employed, significant attention was given to accuracy of the N-16 measurements during chemical addition.

The results of the last Campaign demonstrate that LiOH injection into the loop (recirculation mode of operation) increased N-16 gamma dose in the vapor phase by 80% (an increase was also demonstrated during the 1992 Campaign). This measurement resolved an issue raised during the very first, 1990 BCCL Campaign where it was suggested that LiOH suppressed gamma dose by ~40%. For the once-through operation mode under NWC, $VOSO_4$ injection reduced N-16 dose in the vapor by a factor of 2. This was the only 1993 additive that decreased gamma dose in steam . It was also once again found that adding organic compound (here acetylene, C_2H_2) causes the same effect as HWC conditions. HWC experimental results showed that KNO_2 decreased N-16 activity in steam by 30%; the same as found during the 1991 Campaign. Zinc containing compounds did not display any effect on N-16 carryover for either NWC or HWC runs. K_2MoO_4 led to a small steam dose decrease under HWC in both the 1992 and 1993/94 Campaigns.

7.4 EFFECT OF C-15 ON N-16 MEASUREMENTS

Based on an investigation of C-15 effects on the 1993-1994 data as well as comparisons to 1992/1991 data as described in Appendix J, it has been concluded that C-15 had no adverse affects on the results presented in past years and, if anything, C-15 seems to follow N-16 behavior.

7.5 FUTURE FACILITY APPLICATIONS AND CHANGES IN DESIGN

Several loop modifications should be implemented for future BCCL runs. Suggested changes in design and experimental applications include:

1. Longer runs to test anion inhibitors such as molybdate and stannate, coordinated with out-of-pile autoclave tests of solubility and ECP suppression capability.
2. Improvements in float durability and level coil reliability.
3. Better in-thimble ECP electrode measurements, and means for easier replacement during runs.
4. Develop a new in-pile section, based on Sensor project experience, for in-core ECP measurements.
5. Design an automatic loop control system capable of keeping level in the steam separator plenum constant to permit longer BCCL runs.
6. Reduce hydraulic resistance of the recirculation line to achieve nominal flow rate (1.5 LPM) during recirculation mode operation.

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APPENDIX A BRIEF SUMMARY OF RUNS

Table A.1. Brief Summary of Runs

RUN #	IN-PILE RUN DESCRIPTION
1	Loop shakedown run after installation inside the MITR. H_2O_2 measured while reactor was at 4.5 MWt and at zero power. Loop at hot standby throughout.
2	Taking H_2O_2 data. Loop is at hot standby, NWC, once-through.
3	Taking H_2O_2 data.
4	Taking baseline data when hot single phase and boiling conditions. Loop flow rate reduced to 0.9 LPM. O_2 level in the charging tank is 2.8 ppm-result of no He purging overnight. Small amount of H_2 was injected to suppress O_2 and bring it back to 2 ppb.
5	Establishing a baseline under NWC once-through mode and reduced flow rate (0.9 LPM). Loop pressure increased to 1040 psi to maintain single phase conditions at high temperature (555°F).
7	Once-through shakedown test. Taking N-16 data. Auxiliary copper heater plumbed in to compensate for heat losses from the feedwater heater to the in-core section.
8	Carryover test. Taking N-16 data for the steam and water lines using NaI detectors at hot single phase, and for boiling with 99% and 40% level in the steam plenum.. Background measured while the steam line is valved out. Then the same measurements were performed for the water line. Plenum level gauge breaks, requiring shutdown for repairs.
9	First run in 1994. Loop operated in once-through mode under NWC. Taking baseline data at hot single phase and boiling conditions.
10	KOH injection under NWC in once-through mode. N-16 data taken at hot single phase, boiling at 40% level in the steam plenum, at 35% level during KOH injection, at 30% level after KOH injection is finished.
11	First recirculation mode shakedown run. Level in the steam plenum is reliably controlled within the range 0-50%. Loop flow rate is ~1.0 LPM, feedwater flow rate is 0.1 LPM. Very high H_2 level measured in the charging tank water. BCCL is left at cold standby overnight so that the H_2O_2 generated during the night will consume extra H_2.

12	Taking baseline data. No H_2O_2 measured in the charging tank water. Stable boiling achieved. H_2O_2 and N-16 (steam line) data taken.
13	Steam orifice calibration. LEWA® charging pump flow rate is changed in steps from 50 cc/min to 200 cc/min. Level in the steam plenum is kept constant (40%) by changing heater power.
14	Run not carried out because reactor was forced to shut down due to city of Cambridge water main burst emergency.
15	Changing O_2 concentration in the loop water by varying H_2 content in the chemical injection bottle. DI water saturated with H_2 injected into the loop. Loop O_2 stabilized at 360 ppb, and does not depend on increased H_2 content in the bottle.
16	Injection of H_2O_2 and steam orifice calibration. Feedwater flow rate changed in steps from 0.11 to 0.2 LPM. Injection of H_2O_2 did not change loop H_2O_2.
17	KOH injection shakedown (first chemical injected in the recirculation mode of operation). KOH concentration in the letdown line determined using a conductimeter. To achieve desirable KOH level in the loop, the chemical injection flow rate varied (piston stroke or pump frequency).
18	New KOH injection test not conducted because of high O_2 level in the charging tank water due to the loss of helium pressure in the charging tank during the previous night.
19	KOH injection test.
20	Measure H_2 in the letdown line at reduced loop flow rate-0.7 LPM. O_2 concentration in the charging tank is ~500 ppb to more closer match BWR conditions. Experiment ended early because of the different readings of the two O_2 Orbisphere® sensors hooked up to the letdown line. Both sensors removed for refurbishment.
21	Run # 20 repeated, but not completed because the low O_2 Orbisphere® sensor borrowed from the "Sensor" project also needed refurbishment.
22	Repeat Run # 20. Both O_2 sensors refurbished. Loop water conductivity went up (probably, because of some conductivity injection during H_2O_2 measurements). Ge detectors show very high background, so N-16 data not taken. H_2 not measured in the letdown line.

23	Check out influence of C-15 on the N-16 spectra. The experiment was not successful due to problems with the Ortek® Ge detector.
24	H_2 sensor transferred from the charging tank to the letdown line. H_2 concentration measured. O_2 concentration in the charging tank varied from 500 ppb to 5,000 ppb.
25	Taking data changing O_2 content in the charging tank: from 2 to 10 ppm.
26	LiOH injection. Useful data not collected due to uncertainties with the loop conductivity measurements. New test will be conducted during Run # 28
27	Na_2SO_3 injection. H_2O_2 and N-16 data taken.
28	Second LiOH injection test (Run # 26 repeated). During this run loop pH increased to 10. H_2O_2 and N-16 data taken.
29	First once-through mode shakedown run. Loop switched from the recirculation to once-through mode. The shakedown was not performed because reactor had to decrease power down to 250 KW due to the "Silicon" project.
30	Second once-through shakedown run. Stable level in the steam plenum not achieved due to problems with loop control. All other loop systems operated smoothly.
31	Establishing NWC baseline. High concentration of H_2O_2 in the charging tank (up to 470 ppb) attributed to relatively low (400°F) core-outlet temperature at hot standby. O_2 concentration in the charging tank varied in steps: 200, 500, 1000, 5000 ppb.
32	$VOSO_4$ injection under NWC. N-16 decreased by a factor of 2.
33	KNO_2 injection under HWC after HWC baseline has been established.
34	MoO_3 injection under HWC. N-16 decreased by ~20%.
35	V_2O_5 injection under HWC. N-16 decreased by ~15%.
36	$ZnMoO_4$ injection under HWC.
37	$Zn(OH)_2$ injection under HWC.

38	KNO_2 injection under HWC. N-16 decreased by 30%.
39	K_2MoO_4 injection under HWC. N-16 decreased by 30% while K_2MoO_4 in the loop water was ~10^{-4} M. When its concentration in the loop decreased by a factor of 10 no effect on N-16 observed. NaI detectors temporarily connected to the N-16 measurement system. The goal of this test was to compare N-16 spectra taken with the new Ge detectors and NaI detectors used during the previous BCCL Campaigns.
40	MoO_3 injection under NWC. Reactor operated at 4.0 MWt due to failure of one of the cooling tower fans. N-16 spectra taken using both the Ge and NaI detectors.
41	V_2O_5 injection under NWC.
42	$Zn(OH)_2$ injection under NWC.
43	$ZnMoO_4$ injection under NWC.
44	Na_2SnO_4 injection under NWC. K_2WO_4 injected for carryover measurements. Zero ozone (O_3) concentration measured in the letdown line. C_2H_2 injected. N-16 increased by a factor of 5.5.
45	K_2MoO_4 and $PdNO_3$ injection under NWC. Charging tank chemistry is different from baseline due to some contamination in the chemical injection line after C_2H_2 injection. Charging tank cannot be cleaned thoroughly. N-16 increased by 60% due to $PdNO_3$.

APPENDIX B EFFLUENT RESIDENCE TIMES FOR BCCL 1992 AND 1993/ 1994 DESIGNS

Table B.1. Residence Times for BCCL 1992 and 1993/94 Designs

Description	I.D. (cm)	Length 92 (cm)	Length 93 (cm)	Time 92 (s)	Time 93 (s)	Time 93 Recirc (s)
WATER						
Zy core exit to tee	0.67	40.1	40.1	0.149	0.149	0.248
Tube to plenum	0.48	61.0	57.5	0.097	0.092	0.153
Separator plenum	3.35	22	19	4.6	8.47	14.12
Separator plenum to ECP plenum	0.48	60.0	99.8	0.38	0.63	1.05
ECP plenum	0.61	0	32	0	0.32	0.53
ECP plenum to N-16 plenum	0.48	384.6	320.4	2.43	2.03	3.38
Total				7.66	11.69	19.48
STEAM						
Zy core exit to tee	0.67	40.1	40.1	0.149	0.149	0.248
Tube to plenum	0.48	61.0	57.5	0.097	0.092	0.153
Separator plenum	3.35	30	63	1.28	4.23	7.05
Separator plenum to N-16	0.48	332.5	320.6	0.58	0.57	0.95
Total				**2.11**	**5.04**	**8.40**

As seen from this table, the residence time (delay prior to counting) for the steam during the 1993/94 Campaign is a factor of 2.5 larger than that for the previous campaigns. Higher residence time results in a larger effect on C-15 decay.

Assumptions for residence time calculations

1) Nominal mass flow rate of 25 g/s for 1992 and 1993 once-through and 15 g/s for 1993 in recirculation mode. Note that other than for the different flowrates, the residence times for 1993 once-through and recirculation modes would be identical.
2) Quality is 15%.
3) For two-phase sections, the Homogenous Equilibrium Model was applied to determine the velocity and density of the steam-water mixture.
4) Instantaneous separation in the separator plenum is assumed. Void-free water level is assumed to be measured by the plenum level gauge at 50% during the 1992 Campaign and 40% during the 1993/94 Campaign.
5) After separation, the water and steam densities are given by saturation values.

APPENDIX C PHASE SEPARATION IN BCCL EXIT PLENUM

Concerns have been raised concerning the potential lack of sufficiently good phase separation in the BCCL loop. If there is inadequate separation in the MIT BCCL steam separator plenum, then the subsequent carryover and carryunder would unduly influence measurements of N-16 enhancement.

This appendix will address data and analysis showing that phase separation is achieved in the BCCL plenum; Appendices D and E (carryover and carryunder) discuss specific measurements of carryover and carryunder which quantify this finding.

1. BCCL Operational Experience.

Under what is known to be hot single phase conditions (230°C core inlet and 280°C core outlet) at 7.1 MPa (1030 psig,) a distinct sequence of events indicates that separation occurs as boiling conditions are approached and then achieved at a controlled 15% quality at 280°C core inlet and 291°C core outlet.

(a) at hot single phase (HSP) - level indication is constant at 100% and temperature at the RHX shell inlet is constant.

(b) during transition - oscillations occur in the level indication, steam orifice ΔP and the RHX shell inlet temperature (this behavior lasts about one minute followed by a decrease in level at a constant rate.)

(c) boiling - level indicates constant 50% (or other desired level,) the temperatures are 280°C inlet and 291°C outlet, which corresponds to 7.6 MPa at saturation. Since the pressure readout on the water line reads 7.1 MPa (1030 psig,) there is a 0.5 MPa pressure drop from the core outlet to the reactor top. The steam orifice ΔP stabilizes and reads without oscillation.

If there were no phase separation, i.e. very high carryover, then one would expect to observe the same periodic oscillations that occur during the transition under stable boiling conditions.

2. Temperature reading in the water exit line (ECP autoclave on the reactor top) is well below saturation and therefore the fluid is subcooled. The temperature reading typically reads 275 - 280°C while the pressure is 7.1 MPa (7.0 MPa at the lowest, with T_{sat} = 285.9°C.)

3. N-16 consistency with full separation.

Table C.1. Conditions and Parameters during the N-16 Measurements (1992 Campaign)

Chemistry	Condition	Integral NaI Counts (*1000/min) WATER	Integral NaI Counts (*1000/min) STEAM	DEAD TIME (%)	RUN#
NWC	HSP	482	>1000*	58/-	25
	Boiling	402	146	51/34**	25
HWC	HSP	507	>1000*	60/-***	22
	Boiling	351	503	46/62	22
NWC	HSP	468	>1000*	58/-	24
	Boiling	395	145	50/32	24
HWC	HSP	454	>1000*	57/-	21
	Boiling	343	578	45/69	21

Notes:

NWC: Normal water chemistry
HWC: Hydrogen water chemistry
HSP: Hot single phase
* Too much activity to count reliably
** 51/34 means 51% dead time for water and 34% dead time for steam
*** 60/- means 60% dead time for water and no steam in the loop

wtr: water line
stm: steam line

The above table shows trends which support separation. First there is reasonable reproducibility in HSP between runs in NWC (480 ± 20.) Next, the water line counts for NWC and HWC in HSP are also consistent and similar. The addition of hydrogen does not increase the total N-16 production but only its chemical form so that a greater fraction goes to the steam phase. During NWC boiling, the fraction of the N-16 counts in the water line decreases to 80-85% of the HSP condition, while under HWC it decreases to 70-75%, as one would expect in view of the N-16 increase in the steam line. The steam line values between NWC and HWC increase by 3.5-4 times. These values are consistent in all NWC and HWC runs. If there were no significant separation, there is no explanation for the steam line to decrease in count rate by a factor of almost 10 in NWC (Boiling vs. HSP - consistent with the higher density of liquid: 20 X vapor, counteracted to some extent by a reduced transit time) while the water line remains at 85% of its original value. Also, since HWC only changes the chemical form of N-16, one would not see the large increase in the steam line compared to NWC without a significant increase in the water line as well if there were two phases in both lines, i.e. the ratio of counts in the steam line to those in the water line changes under HWC and it would not if there was no separation.

APPENDIX D CARRYOVER

Several modernizations aimed at carryover minimization which were implemented during preparation for the 1993-1994 Campaign proved to be worthwhile. The out-of-pile as well as in-pile experiments have demonstrated extremely low carryover.

MODERNIZATIONS TO REDUCE POTENTIAL CARRYOVER:

1. Impingement cone welded to the steam extraction tube.
2. Increased length of the steam separator plenum by 30 cm.
3. Decreased number of slits on the steam extraction tube from six to four.

OUT OF PILE CARRYOVER TEST

Out-of-pile results (1993-1994 campaign) show that carryover is insignificant. Here, carryover is defined as the ratio of the mass of water carried over to that of dry steam. The results are shown below:

LOOP CONDITIONS:

Pressure	1020 psi
Level in the plenum	50%
Loop flowrate	1500 cc/min
Mode of operation	Once-through
Chem. injection rate	20 cc/min
Steam quality	10.7 %

17:00 Baseline data was taken. At the beginning of the experiment the conductivity of the water and condensed steam was measured to be 2.8 µS/cm, return flow conductivity was 2.0 µS/cm. This data was remeasured at the end of the experiment (18:20) to obtain the following baseline conductivity values:

Water line	1.6 µS/cm
Steam line	0.7 µS/cm
Return	1.1 µS/cm

17:07 Started KNO_3 injection. Chem. injection rate was 20 cc/min. Measured conductivity was (in µS/cm):

Table D.1. Out-of-Pile Carryover Test Results

TIME	CONDUCTIVITY (µS/cm)		
	WATER LINE	STEAM LINE	RETURN
17:14	1130		
17:15			1020
17:18			1060
17:30		1.5	
17:40			995
17:45	1180		
17:57		1.0	

18:00 Chem. injection was completed. Carryover can be calculated according to the equation:

$$F=(Cs-Cso)/(Cw-Cwo)$$

where Cs=conductivity of condensed steam measured during chem. injection,

Cso=background conductivity of condensed steam,

Cw, Cwo=like quantities for water sample.

CARRYOVER CALCULATION:

1. F= (1.5-0.7)/(1130-1.6)*100%=0.071< **0.1%**
2. F= (1.0-0.7)/(1180-1.6)*100%=0.025< **0.1%**

IN-PILE CARRYOVER TEST DURING RECIRCULATION MODE

LOOP CONDITIONS:

Recirculation mode, flow rate= 0.9 LPM, steam level in the separator plenum= 40%

KOH injection of ~10^{-5} M during boiling. Steam and water samples. K-42 activity was the intended measured activity.

The water sample was counted for 300 seconds using Ge detectors and the following activities of interest were recorded.

Table D.2. Water Sample Activities Results

Isotope	Peak E (KeV)	Net area (counts)
K-42	1524	1590 ± 2.6%
W-187	479	39621 ± 0.8%
W-187	685	39248 ± 0.6%
Na-24	1369	403 ± 05.8%
Na-24	2754	239 ± 6.5%
Ar-41	1293	0

The steam sample was counted for 3 hours (10800 seconds) with the following results:

Table D.3. Steam Sample Activities Results

Isotope	**Peak E (KeV)**	**Net area (counts)**
K-42	1524	0
W-187	479	146 ± 71.7%
W-187	685	271 ± 14.6%
Na-24	1369	0
Na-24	2754	5 ± 53%
Ar-41	1293	439 ± 6.3%

Since no K-42 showed up in the steam line, W-187, and one Na-24 peak will be used.

For peak 685 KeV carryover is: $271*300/(10800*39248)=1.9*10^{-4}$=**0.019%**

For peak 479 KeV carryover is: $146*300/(10800*39621)=1.0*10^{-4}$=**0.01%**

For peak 2754 KeV carryover is: $5*300/(10800*239)=5.8*10^{-4}$=**0.06%**

For K-42 there would be in the steam sample, for **0.02%** carryover:

$0.0002*1590*10800/300=11.5$ counts in peak, which is near the detection limit.

Thus it is confirmed that carryover is < **0.1%** and most likely around **0.02%**

APPENDIX E CARRYUNDER

During the 1992 campaign, a low flow O_2 Orbisphere was used on the water drain sample line. In conjunction with the Orbisphere O_2 reading on the condensed, mixed steam and water return line, this data allows carryunder to be estimated.

Given:	mixed return O_2 :	1048 ± 225 ppb
	water line O_2 :	50 ± 18 ppb
	quality :	~15 %

Using this data, we can determine the carryunder fraction. Two cases will be analyzed, an upper bound assuming all the O_2 transfers to the gas phase with no carryover and therefore any O_2 in the water line is due to steam carryunder, and, a realistic calculation assuming vapor/liquid phase equilibrium and Henry's Law (H/P ~ 200 for BCCL conditions, i.e. 7 MPa, 290°C).

Definition of variables:

H = Henry's Law constant: 50.62×10^{-4} mol(kg H_2O)/ atm for O_2

C = carryunder ratio = mass of steam carried under per unit mass of water

S = measured steam mass flow rate

W = measured water mass flow rate (includes condensed carryunder)

O_s = mass fraction of O_2 in the steam line = TBD

O_w = mass fraction of O_2 in the water line = 50 ppb

O_{s+w} = mass fraction of O_2 measured in mixed return line = 1048 ppb

P = system pressure = 7.0 MPa

p = partial pressure of O_2 in vapor phase

x = quality = 0.15

Henry's law $p = HO_w$

hence $O_s = (p/P) = (H/P)O_w = 200\ O_w$

and the oxygen concentration in the steam line can be estimated by a mass balance:

$O_{s+w}\ (S + W) = O_s\ S + O_wW$

$1048\ (S + W) = O_s\ S + 50W$

$(O_s - 1048)\ S = 998W$

$O_s = 1048 + 998\ (W/S)$

$O_s = 1048 + 998\ (0.85/0.15) = 6703$ ppb

Let carryunder, C = mass ratio of steam to true water

U = mass flow rate of steam in the liquid phase

$C = U\ /(W\text{-}U)$

$= 1\ /(W/U\text{-}1) = [1/O_w\ /\ 1/O_s\ \text{-}1]^{-1}$

$= O_w\ /(O_s\text{-}O_w)$

a) Now for the bounding case: assume that all the oxygen in the water line is due to carryunder (i.e. assume that Henry's Law constant is infinite).

$C = O_w\ /(O_s\text{-}O_w\ ) = (50\ \text{ppb})\ /\ (6703\ \text{ppb} - 50\ \text{ppb}) = 0.75\ \%$

0.75 wt % steam in water is an upper bound for carryunder

b) Due to solubility, there would be some fraction total oxygen remaining in the water phase even without carryunder. Assuming Henry's Law is valid we have

$O_w = O_s\ /\ 200 = 34$ ppb due to solubility.

And the oxygen due to carryunder is the difference between total oxygen measured and oxygen due to solubility

50 - 34 = 16 ppb due to carryunder

Hence the carryunder ratio is then

$C = 16\ /\ (6703\text{-}16) \times 100\% = 0.24\ \%$

so we can say that ~16 ppb out of the 50 ppb O_2 in the water line are due to carryunder. Hence, while carryunder is quite small, it still represents a large contributor to the gas content in water.

APPENDIX F LUMINOL METHOD FOR H_2O_2 (H-2)

The procedure discussed in the following paragraphs was employed from time to time to check H_2O_2 concentrations measured using the colorimetric method and to determine very low concentrations in the range 1-10 ppb.

1. Setup

The system is set up as shown in Figure F-1. The black box is made of a piece of wood and painted black. There is a 1/2" opening at the top of the reaction cell, which is used for changing test tubes and sample injection. A cap (a piece of black rubber) covered this opening during counting. The PMT is fixed in place during this series of tests.

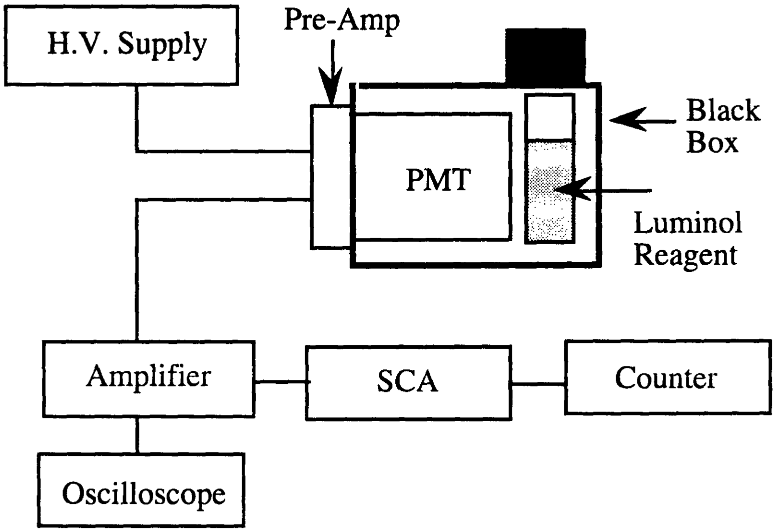

Figure F-1. Setup of Luminometer

2. Luminol Reagent Preparation

The concentrations of luminol and Cu^{++} (used as a catalyst) are 2×10^{-4} M and 2×10^{-5} M, respectively, and the pH is 12.8. It is reported that this condition gives the best response of the chemiluminescence system for hydrogen peroxide measurement (K-1).

It is found that the solution produces red precipitation instantaneously when an intermediate solution (luminol: 2×10^{-2} M, Cu^{++}: 2×10^{-3} M) is made. If the reagent is instead made in one-step (which leads to uncertainty from weighing the trace amounts of chemicals needed), a small amount of black precipitate is produced several hours after the solution is made.

In the present runs four liters of reagent were made, using 0.146 g of luminol, 0.011 g of $CuCl_2$ and 10.41 g of NaOH. This reagent has been used in the following experiments.

3. Sample Preparation and Calibration

Hydrogen peroxide samples were prepared fresh. A "standard" hydrogen peroxide sample (~ 1 ppm) was prepared first and its concentration was then measured using colorimetry. Other samples were prepared by diluting the "standard" solution. Sample concentrations were also measured using colorimetry, if their concentrations were still in the detectable range (> 10 ppb). The concentration of the sample determined by colorimetry was within ±20% error for that calculated from dilution.

Samples of lower hydrogen peroxide concentrations (< 10 ppb) were prepared by diluting a 10 ppb solution, which was determined using colorimetry, since 10 ppb is the lowest detection limit of the CheMetrics 5543 hydrogen peroxide reagent. Low concentration hydrogen peroxide samples may cause significant uncertainty for the experiment since they are unstable in the environment.

4. Experiment Procedure

10 mm x 75 mm borosilicate test tubes were used for the reaction cells. 2 cc of the reagent was used for each measurement. 1.5 cc of the hydrogen peroxide sample was injected into the reaction cell using a plastic syringe with a 2" needle.

The lower level discriminator (LLD) was set at 0.3 V and the upper level discriminator (ULD) at 10 V. Since no calibration has been done for the SCA to detect blue light (~ 420 nm), the LLD and ULD were determined to discriminate most of the background and detect most of the light from chemiluminescence reactions. Further information on background measurement will be given in section 5 of this appendix.

Room light was turned off and only a small flashlight was left on when removing the cap and changing the test tubes. Then the flashlight was turned off for the sample injection. The counter was started before the sample injection since it was found that the counting rate rapidly reaches its maximum when the sample is injected. The manner of sample injection determines the rate of sample/reagent mixing, which may be the major source of uncertainty in this experiment. The cap must be in place when the room light is turned on again.

A time range of 10 minutes was set for every sample chemiluminescence counting session, which was determined through the observation that most of the chemical reaction occurs during this time range for hydrogen peroxide samples on the order of tens of ppb.

5. Experiment Results

Tests have been performed for hydrogen peroxide samples ranging from 0.5 ppb to 1.2 ppm, which covered the range of hydrogen peroxide production of interest. The results were satisfactory and showed the feasibility of the luminol method.

For high concentration hydrogen peroxide samples (from 10 ppb to 1.2 ppm), colorimetry was used to determine the concentrations. Figure F-2 shows the experiment results for high concentration hydrogen peroxide samples. The test was repeated at least twice for each sample and the data shown on the graph are the average counts for each sample. The error ranged from 1% up to 5 %; the lower the concentration, the higher the error.

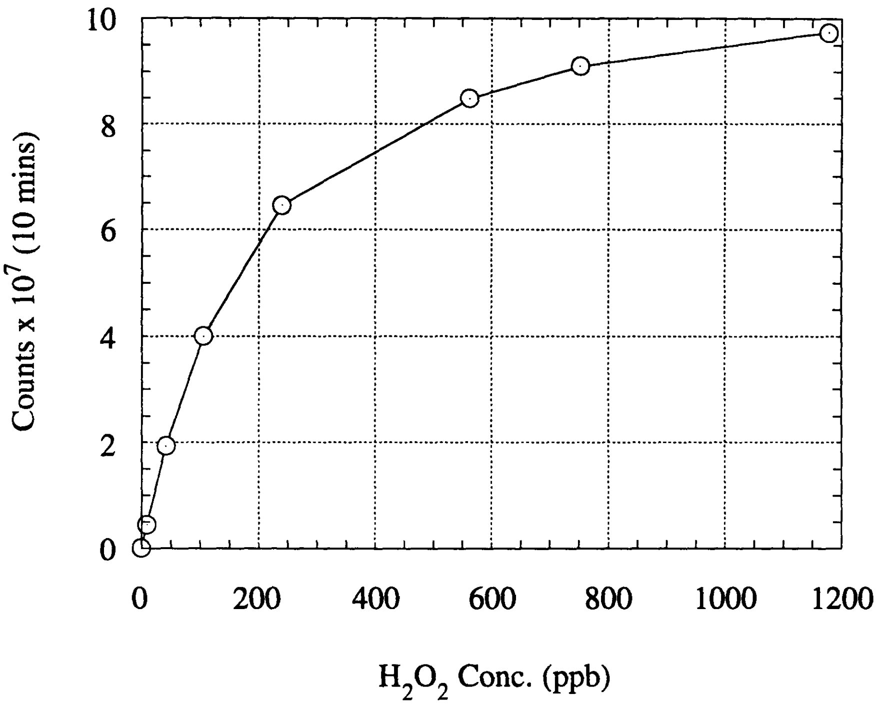

Figure F-2. Luminol Method Test for High Concentration H_2O_2 Samples

(H_2O_2 Concentrations are Determined Using Colorimetry)

Figure F-3 shows the experiment results for low concentration (< 10 ppb) hydrogen peroxide samples. Since the concentrations exceeded the detection limit of colorimetry, only the 10 ppb sample concentration was determined by colorimetry, other samples were then made by diluting this "standard" sample solution. Errors of the counting ranged from 3% to 10%, which seemed to be independent of the sample concentration. Major uncertainties for the low hydrogen peroxide concentration tests were from the dilution procedure, background hydrogen peroxide concentration in the DI water, and the decomposition of low concentration hydrogen peroxide, which seemed faster than expected.

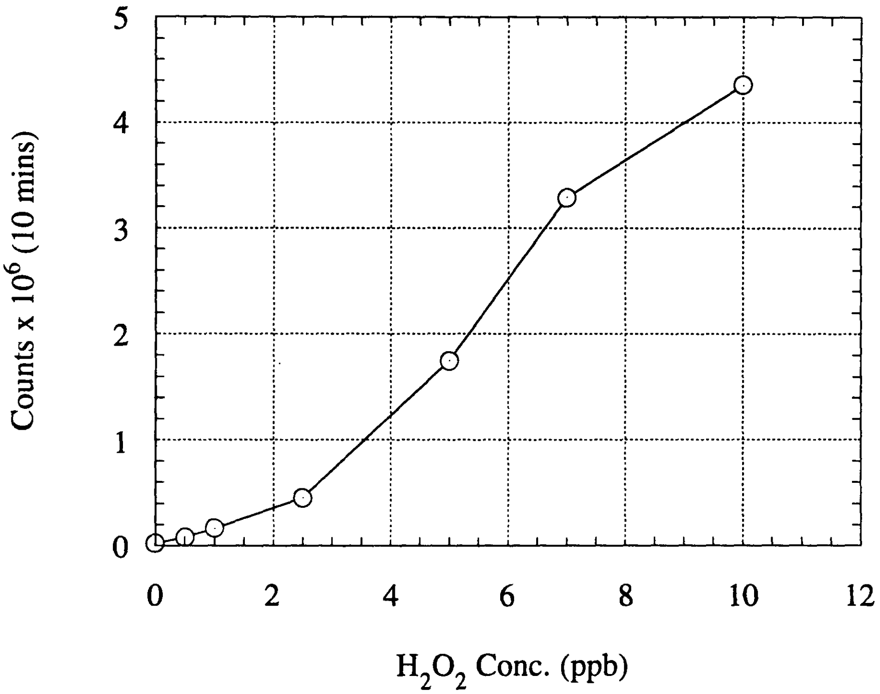

Figure F-3. Luminol Method Test for Low Concentration H_2O_2 Samples (Samples are Prepared by Diluting 10 ppb H_2O_2 Solution)

Tests have also been done for background light emission. There were approximately 10 counts/min of background contributed by light leakage and the dark current of the PMT. An extra ~2 counts/min was attributed to the luminescence from the borosilicate glass (J-1), which was negligible in this case. A test also showed that luminol emitted light without adding hydrogen peroxide, as shown in Figure F-4.

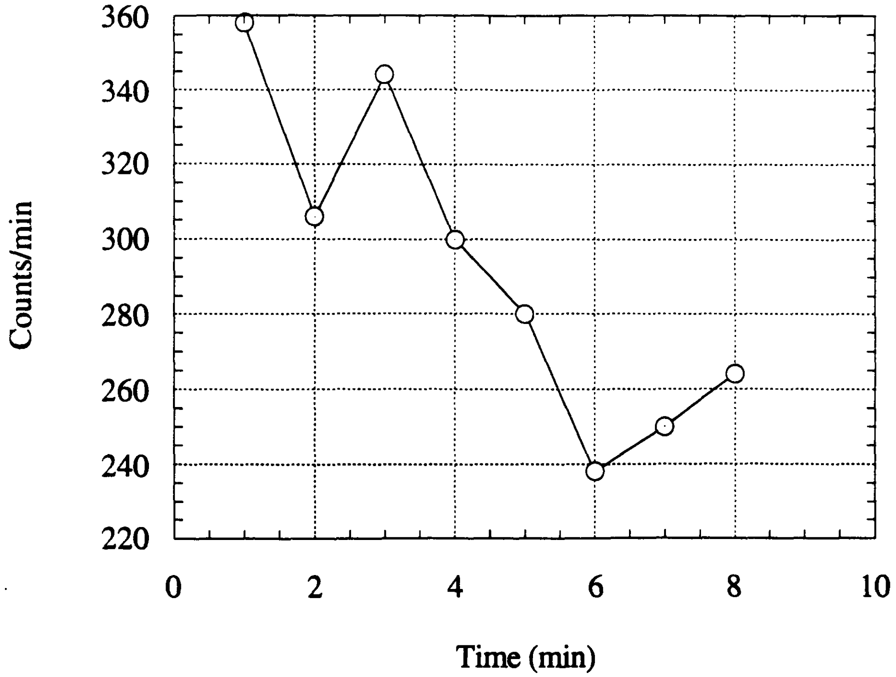

Figure F-4. Background Counts Due to Luminol (3.5 cc Luminol)

DI water was also tested using the luminol method. The trend of decreasing counting rates (which is also observed for hydrogen peroxide sample tests) shows there is a trace amount of hydrogen peroxide (or perhaps ozone) in the DI water.

The amount of hydrogen peroxide in DI water can be calculated by interpolating between counts for a 0.5 ppb hydrogen peroxide sample and counts for pure luminol reagent.

Total counts for 0.5 ppb sample over 10 minutes : 81188

Total counts for DI water sample over 10 minutes: 20796

counts per minute for pure luminol : ~ 360

$$0.5 \text{ ppb} \times \frac{20796-3600}{81188-3600} = 0.11 \text{ ppb of hydrogen peroxide in DI water}$$

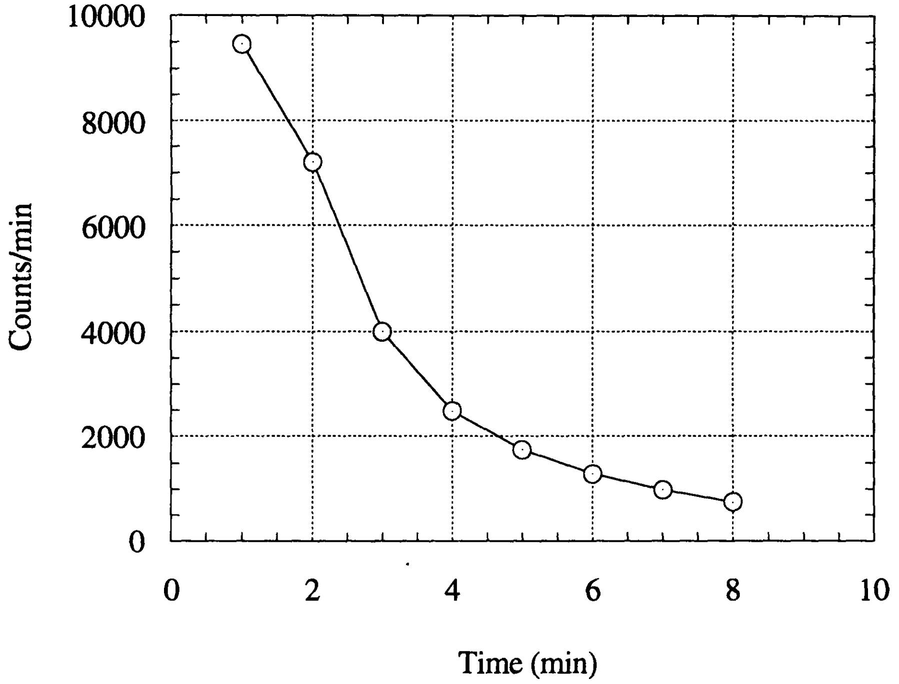

Figure F-5. Background Counts Due to DI Water and Luminol (1.5 cc DI Water + 2 cc Luminol)

APPENDIX G DETAILS OF EXTERNAL REFERENCE ECP SENSOR FABRICATION

G.1 ASSEMBLY INSTRUCTIONS

The design for the external Ag/AgCl reference ECP sensors fabricated at MIT is based on guidelines suggested by Peter Andresen at GE Research and Development Center in Schenectady (A-1, D-1). Due to the importance of the ECP measurements and the difficulties experienced in making reliable and functional sensors, detailed instructions (based on procedures employed at MIT) for assembling these external reference ECP sensors are presented in this appendix.

A general description of the sensor is in section 2.5.1, but for proper fabrication it is important to understand the operating conditions for the sensor. This type of electrode operates at a system pressure of 7.1 MPa (1200 psig) and temperature of 280°C although its voltage generating reference electrode portion is maintained at room temperature (25°C). The critical component is the pressure boundary which is located within the Conax® fitting where the Teflon® gland seals against the PTFE tube and chloridized silver rod (see Figure 2.10). A common failure mode for these reference sensors is electrolyte solution extrusion through this pressure boundary, hence the emphasis in fabrication procedures was to mitigate this leakage path. Table G.1 lists the components and equipment necessary for fabrication (a suppliers list can be found in ref. M-1) and a "cookbook style" list of assembly instructions follows:

1. Form the Ag/AgCl couple. Plate the Ag rod at a current density of 2 mA/cm^2 for 1 hour in 0.1N HCL at room temperature.

2. Form Teflon® housing. Cut length sufficient to extend from the autoclave housing to beyond the Conax® fitting, thus ensuring an insulated current path. Place the zirconia plug in the Teflon® tubing, slightly showing. Heat tubing from top of zirconia until it gets clear. Be careful to keep temperature gradient small enough so that the zirconia does not crack.

3. Insert a 1/8" SS rod ~10 cm into the top end of the Teflon® housing and pre shrink the Teflon® tubing so that it makes a snug fit. Be careful not to stick them together.

4. Soak the glass string in 0.1N KCl solution.

5. Wash the silver rod in 0.1N KCl solution.

6. Draw ~10 cc of 0.1N KCl solution into the syringe and boil for ~30 seconds to de-oxygenate. A heat gun can be used if sufficient caution is taken to induce <u>uniform</u> heating around the syringe's perimeter (this reduces the risk of cracking).

7. Slide the Teflon® gland around the Teflon® tubing; then place the de-oxygenated KCl solution in the Teflon® sleeve and carefully remove any bubbles entrained in KCl solution (this can be accomplished by tapping the sleeve's sides).

8. Lay glass thread in the Teflon tubing so that it touches the zirconia plug, but make sure there is enough slack to extend out to the top.

9. Slide Ag/AgCl rod into the Teflon tubing. Be careful that the glass thread is in contact with the rod, but does not extend too far between the rod and the sleeve (see Figure 2.8). This could prevent a good pressure seal. Slide the Teflon® gland up over the PTFE sleeve and Ag/AgCl rod to the point where it sits in the Conax® fitting.

Table G.1. Components and Equipment for Fabricating External Ag/AgCl Reference ECP Sensors

Components:

- 10 cm Silver rod of 3.2 mm diameter(Aldrich chemical company),
- 1/4" stainless steel tubing, about 20 cm,
- 1/4" Parker compression fittings
- Conax fittings (Conax corp.),
- size 14 shrink fit Teflon tubing (Alpha Wire Corporation, Mac Master Carr), length to fit the other parts and allow the tip of the electrode to be in the circulating water, not in a stagnant path,
- zirconia plug
- glass thread,
- 0.1N KCl solution,
- rulon cap,
- Al plates,

- 1/8" threaded rods and nuts.

Equipment:

- DC current source (0-50V, 0-500 mA),
- 0.1 N HCL solution,
- saturated KCl solution,
- Pt wire (cathode),
- heat gun,
- glass syringe with needle (lab supply),
- Calomel reference electrode,
- voltmeter (impedance ~10^{11}-10^{12} Ω)
- wire insulation resistance ~1 MΩ

10. Place the Conax® fitting around the electrode, with the seal gland in the pre-shrunk region and tighten finger-tight.

11. Connect the Conax® fitting and PTFE housing to the compression fitting and metal tubing. After these fittings are tight, then torque down on the Conax® fitting to seal the electrode. It is important to not over-tighten, since an excessively high torque can deform the Teflon® gland and the rod, and will not necessarily improve the seal.

12. Fasten the anti-expulsion protection unit in place.

In summary, these assembly instructions, based on procedures given by P. Andresen, consist of the specific methods and techniques employed at MIT in fabricating external silver/silver-chloride reference ECP sensors suitable for measurements in high temperature and pressure systems. For further information the interested reader should consult the references A-1, D-1, or M-1.

G.2 OPERATION AND MEASUREMENT GUIDELINES

If properly made, the external silver/silver-chloride reference ECP sensors can be successfully used for ECP measurements in high temperature (280°C) and high pressure (7.5 MPa) environments for long continuous periods (upwards of 8 weeks). Since the continuous operation period may include temperature and/or pressure transients it is important to periodically monitor the performance of the sensor against a known standard. In addition, a number of guidelines, if followed, will increase the life expectancy and protect the integrity of the signal measurement of these sensors. These operation and measurement guidelines are discussed in this subsection.

A key feature of the external reference electrode is that the electrochemical reaction occurs at room temperature while the system measured is at BWR operating temperature and pressure; hence, it is vital that the silver rod be maintained at room temperature. This is accomplished in the BCCL by distancing the chloridized silver rod from the semi-porous interface by about ~20 cm. To reduce convective heat transport to the electrode reaction surface, Danielson (D-1) commonly bends the electrode down so that the silver rod is lower than the zirconia tip. This extra precaution has been successfully used on another MIT in-core materials test loop (M-1).

Periodic monitoring of the Ag/AgCl reference electrode's equilibrium potential can be made by measurement against a standard Calomel (Hg_2Cl_2) electrode in a saturated KCl electrolyte. At room temperature, the reading should stabilize at +43 mV, SHE, within a 24 hour soaking period. This provides a convenient check at room temperature, but does not guarantee good operation at high temperature (the calomel reference electrode does not work above ~80°C). It is suggested that high temperature measurement against other silver/silver-chloride sensors be performed at regular intervals (although less frequently than the room temperature test).

Prior to installing an external reference electrode on the BCCL, it was pressure-tested at room temperature. Furthermore, and to the extent possible, all planned temperature and pressure transients should be slow enough (1-5 °C/min) so that the electrode's electrolyte will equilibrate with the system coolant with a minimal loss of electrolyte. These safeguards will mitigate the loss of electrolyte which is a weakness of all reference electrodes, not only the subject external silver/silver chloride reference sensors. Since a reference sensor that has lost electrolyte can still transmit a current, it is especially important to perform periodic inspections and monitor the calibration as outlined in the paragraph above.

Finally, some guidelines for ensuring the integrity of the voltage measured and recorded are discussed. All ECP measurements in the BCCL have been made against ground. When electrodes are measured against ground, the current flows to the nearest metal, then flows up the metal to the ground clamp. For this reason, the measured potential is against an electrode's "line-of sight" metal surroundings; thus potential measurements against ground in the ECP plenum and in the water return line autoclave represent a measurement against stainless steel (O-2). Because of the very tiny currents transmitted by the ECP measurement devices, careful attention must be paid to the signal carrying wires to avoid excessive noise in the signal.

For this purpose, the electrical leads are shielded everywhere possible and the lines and junction boxes are grounded at one physical point; if two points were used, a "ground loop" would result. Any magnetic field (such as from an electric motor or from another signal line) passing through a ground loop will generate a potential of several tens to hundreds of millivolts in the line, swamping the electrode signal. Since several of the measurements are made against ground (i.e. against the stainless steel ECP plenum or water line autoclave), the ground signal line is shielded by a separately grounded overbraid that does not carry a signal-- otherwise high noise levels would result (O-2).

APPENDIX H FLOAT MANUFACTURING

Before BCCL runs commenced, a number of new floats were manufactured. Since the float is a crucial component for the BCCL, significant attention was given to manufacturing a robust float capable of withstanding operation at elevated pressures and high temperatures while the loop is running in steady state mode or while it experiences transients.

It was decided that the new float would be made by a company specializing in glass and quartz work. For this purpose ten quartz tubes {6.9/8.0 mm ID/OD, 23 cm length} were ordered from Quartz Plus and subsequently sent to VitriForms for manufacturing. The design of the new float was not changed from the past campaigns and consisted of a quartz tube closed on both ends with an iron wire inside it. Several small standoffs to permit the float to slide inside the level detector arm without sticking to the arm walls were provided at the top and the bottom of the float.

However, float tests demonstrated that only half of the manufactured floats were able to withstand nominal operating conditions. The failure mode observed was cracking through or adjacent to the standoffs. It is likely that the VitriForms technique of applying relatively large standoffs was responsible for the high failure rate.

During the BCCL run the newly manufactured float broke after two weeks of operation at nominal working parameters, and in-pile experiments were delayed while the float was replaced. The broken float was taken out of the thimble and carefully examined. A crack had developed near one of the standoffs resulting in water in-leakage.

As a result of the unsatisfactory performance of VitriForms floats, it was decided that new floats should be manufactured at the Nuclear Reactor Laboratory, using procedures that had resulted in satisfactory floats for earlier campaigns.

New floats were made from an older batch of quartz (used in the 1991 BCCL Campaign). Dimensions of the quartz tubes were the same as above mentioned, and the iron wire (24 gage) 16" long and bent double once was prepared for insertion into the tube.

Given below is a list of operations used for manufacturing the floats:

1. Take a quartz tube, measure its ID and OD, and carefully examine the outer surface. Reject out-of-specification, heavily scratched or cracked tubes.
2. Treat the tube surface with acetone and methanol. All subsequent operations are performed using gloves to protect the float surface.
3. Use a methane/oxygen torch to melt one of the tube ends shut. Spin the tube around its long axis to allow uniform heat distribution. Continue the process until the tube edges are fully collapsed to the center and have adhered to each other.
4. Put four to five 1 mm high standoff bumps onto the tube surface 1-2 cm from the sealed end of the tube. For this purpose use a 2-3 mm OD quartz rod. First, the tube surface has to be heated up using the torch. During the heatup process the tube has to be rotated (as in #3) to avoid damage due to overheating. As soon as the surface is ready, the quartz rod has to be heated up rapidly to melting and applied to the tube surface. Some pressure should be exerted on the rod to provide good contact with the float surface. Repeat this process at the other end of the tube allowing 2-3 cm extra length at the unsealed end, since the tube length is reduced during sealing.
5. Insert the iron wire into the tube.
6. Repeat the sealing process as in item #3. However, in this case care should be taken not to prolong the melting process because the iron wire inside the tube is also heated up, and released gases can prevent adhesion of the edges.
8. After the float is manufactured the standoffs on both ends are ground using water lubricated 600 grit paper to allow the float to slide into the level detector arm.

APPENDIX I LAY-UP PROTOCOL FOR THE BCCL RIG

The most recent campaign of the BCCL was completed on April 1, 1994 and the rig was removed from the reactor on April 4, 1994. Since many items of the loop can be reused in future campaigns (i.e. which may occur after current personnel are no longer with the lab), it is important to specify the location and condition of the facility components in sufficient detail that a researcher unfamiliar with the rig can find necessary items. The rig will be discussed in four sections: 1) internals (items within the thimble), 2) ex-core tubing and valves (e.g. feedwater, recirculation, water and steam letdown, and sample lines), 3) charging system and 4) chemistry analysis instrumentation (e.g. dissolved gas sensors, hydrogen peroxide equipment, ECP sensors and N-16 detectors)

INTERNALS

The internals, still encased within the aluminum thimble, have been placed in the spent fuel pool for temporary storage. No removal from the thimble has been attempted, so it is assumed all components are in the same working condition as when the loop was removed from the MITR-II. All water in tubing is drained, and tubing is dried with helium and capped. Highlights of important components follows.

In-core heater: Working order. The extent of deformation of the aluminum casting is unknown since removal was not attempted. No spare heater.

Level Detector: Upper coil is shorted. Lower coil works. Two new coils (received ~2/94) are stored in the locked cabinet in the main lab.

ECP Sensors: Two Toshiba Internal Ag/AgCl Reference ECP Sensors are in-place, but neither appears to be in working order.

Hydrogen Peroxide Sampler: Working order. Spare sampler is stored in the locked cabinet in the main lab. Needs one end of 1/16" tee drilled out.

Thermocouples: Core-in, core-out, lead bath, H_2O_2 cooled injection, H_2O_2 mixed sample working order. Single-ended type (2 48", 1 120", 3 80"), and double-ended TCs are stored in the locked cabinet in the main lab.

EX-CORE TUBING AND VALVES

All tubing located on the reactor top has been placed in one large plastic bag and stored on the Operations equipment racks located on the back mezzanine. The tubing and accompanying valves, disconnected at compression fitting unions, have been marked with permanent marker and left in large sections to facilitate reassembly. Although the valves are rated to high temperature-high pressure, we have observed that after long layover the shutoff types tend to leak. There are 4 Whitey® shutoff valves and 3 Whitey® needle valves (ECP autoclave). One needle valve showed slight leakage when closing at high temperature.

All tubing from the Charging system to the reactor top is still in place. There are just the feedwater and return lines which are marked. It should be noted that all this tubing is CP-2 titanium and should be in good condition to re-use.

The chemical injection and sample lines from the back mezzanine to the reactor top stairs are still in place, but out of the way. Since they pose no hazard nor do they interfere with another project, it is suggested that they remain there until further demand or need dictates otherwise. Before shutting down the BCCL 93/94 runs, all lines were flushed with nitric acid (10^{-4} M) followed by de-ionized water for approximately 20 and 40 minutes, respectively, and then they were subsequently dried with helium.

CHARGING SYSTEM

The charging system is still in operable condition and remains on the back mezzanine. The status of main items is outlined below.

LEWA® charging pump: Working order with pulsation dampener plumbed in (set point ~500 psig). Used for recirculation runs (maximum flow rate of 250 ml/min).

CAT® pump (charging): Working order and air tight. Two spare CAT® pumps are on the back mezzanine, but both need to be rebuilt with new seals, since evidence indicates that they are not airtight.

Feedwater Heater: 2 of 3 heating sticks work. A spare heater with 3 operable sticks is stored in the assembly lab.

Micro® pump (cleanup): Working order. To maintain system cleanliness, it can be run independently of other systems.

Ion-exchange columns: 3 columns on the return line and 2 on the cleanup line. It is suggested to change out resins before the next campaign. The return line columns are all hi-purity mixed-bed resins and the cleanup line has one hi-purity and one ultra hi-purity resin. In addition, there are 3 (0.2 μm) final filters with 1/4" NPT fittings that should also be replaced. There are no spare parts in the loop lab's stocks.

CHEMISTRY ANALYSIS INSTRUMENTATION

The chemistry analysis instrumentation is on hand and working, but can not be placed in temporary storage since it is used on other projects (e.g. PCCL, IASCC, and Sensor). An inventory and likely places to find such equipment is listed below.

Dissolved gas sensors: Orbisphere® brand sensors include one normal flow rate (50-250 ml/min) O_2 sensor [BCCL charging system] and one low flow rate (10-250 ml/min depending on the membrane) O_2 sensor [BCCL water sample line], one normal flow rate (50-250 ml/min) H_2 sensor [BCCL charging system, but belongs to Sensor Project]. There is also a HYDRAN® H_2 sensor [PCCL charging system] that operates with a nominal flow rate of 200±50 ml/min, but perhaps as low as 50 ml/min.

Hydrogen Peroxide Equipment: The HACH® DR2000 spectrophotometer is in good working condition and stored in the ICP lab. Approximately 5 boxes (30 ea.) of CheMetrics® 5543 Vacu-vials are stored under the table on the back mezzanine; the Vacu-vials have no expiration date according to CheMetrics®. The Luminol chemical equipment is stored in the back mezzanine cabinet.

ECP Reference Sensors: The "in-pile" Toshiba reference sensors are still installed in the internal rig's ECP plenum. Out-of-pile sensors do not last indefinitely and will need to be remade when the time comes. Directions are filed in the main lab cabinet and additional suggestions can be found in appendices of H. Mansoux's, and this thesis.

N-16 Detectors: 2" and 3" NaI crystals and PM tubes are stored on the back mezzanine cabinet. A portable ORTEK® Ge detector was acquired from Hitachi during BCCL 93/94. This detector, as well as the Canberra® detector, is temporarily stored on the back mezzanine. All detectors are in working order.

APPENDIX J EFFECT OF C-15 ON N-16 MEASUREMENTS

The question has been raised as to the potential influence of C-15 activity on N-16 measurements in previous campaigns. In the current campaign two HpGe detectors were used to measure N-16 and discriminate C-15. This also gave the possibility to carefully measure the effects of chemical additives on both N-16 and C-15. While the residence times in an actual plant are large enough to ignore the C-15 contribution to external exposure in the steam lines, the residence times in the loop for all BCCL campaigns have been sufficiently low (see Appendix B) that C-15 is present at the N-16 monitor point for the steam line.

The use of NaI detectors in the past gave a relatively poor resolution of peaks, so that a net area encompassing the entire spectrum of N-16 peaks (and consequently C-15 as well), including N-16 Compton contributions, was used for comparison. The reported N-16 enhancement factors for all runs were determined by first calculating the ratio of the N-16 steam net area to the N-16 water net area. This steam to water ratio is calculated for baseline conditions and then for injection conditions. The ratio of these ratios, injection ratio / baseline ratio, is the enhancement factor. For the past campaigns, the enhancement factor included the contribution of C-15 in the ratios. In this campaign, due to the use of the Ge detectors, the resolved N-16 photopeak data is available. There is, therefore, good confidence in the most recent enhancement factors.

The data can also be used to determine what effect including C-15 would have had in this year's campaign as well as extrapolating what effect it might have had on previous campaigns. First, the potential effect of C-15 on this years runs was determined. Three different runs were selected.

Run 28:	A recirculation run where LiOH was injected (Tables J.1.1-J.1.3) (Typical recirculation run)
Run 32:	A once-through run where $VOSO_4$ was injected (Tables J.2.1-J.2.3) (Worse case of C-15 contribution, NWC)
Run 38:	A once-through run where KNO_2 was injected (Tables J.3.1-J.3.3) (Typical run under HWC)

Table J.1.1 gives the net photopeak areas for N-16 and C-15 for the baseline and injection conditions of run 28, the recirculation run.

Table J.1.1. Areas under Photopeaks of N-16 and C-15 for Steam and Water Phases During Baseline and LiOH Injection, $3.6\text{x}10^{-5}$ M (Run 28 Recirc.)

PEAKS	**NET AREA (Counts per 300 seconds)**			**Total Area**
N-16	**5.1 MeV**	**5.6 MeV**	**6.1 MeV**	**N-16**
STEAM				
Baseline	3632	2590	1947	8169
Injection	6858	4554	3549	14961
WATER				
Baseline	13630	11972	9600	35202
Injection	12120	12312	9323	33755
C-15	**4.3 MeV**	**4.8 MeV**	**5.3 MeV**	**C-15**
STEAM				
Baseline	287	209	187	683
Injection	422	251	291	964

Table J.1.2 gives the total photopeak areas, both including C-15 and excluding C-15, used for determining the enhancement factors.

Table J.1.2. Determination of the Effect of C-15 on N-16 Measurements During Baseline and LiOH Injection, 3.6×10^{-5} M (Run 28 Recirc.)

PARAMETER	VALUE
TOTAL PHOTOPEAK AREAS	
Steam Baseline N-16	8169
Steam Baseline C-15	683
Total	8852
Steam Injection N-16	14961
Steam Injection C-15	964
Total	15925
Water Baseline N-16	35202
Water Injection N-16	33755

Table J.1.3 shows the calculated enhancement factors both including C-15 and excluding C-15. Also shown is the % contribution of C-15 to the total net area used. It is important to note, that unlike in previous campaigns where the entire area between discrimination settings, including the N-16 dominated Compton area and the 7.1 MeV photopeak and its 6.6 MeV escape peak, only the sum of the three largest N-16 peaks (6.1 MeV, 5.6 MeV and 5.1 MeV) was used for the N-16 area. This comparison is therefore deemed very conservative: i.e. the contribution of C-15 is overestimated. It can be seen that for this campaign, under recirculation, the inclusion of C-15 does not greatly affect the reported results, since the calculated enhancement factors including C-15 are less than 2% different from those excluding C-15.

Table J.1.3. Enhancement Factors for Run 28 (Recirc.) Including and Excluding C-15

PARAMETER	VALUE
Steam Baseline (no C-15) Water Baseline	8169/35202 =0.232
Steam Baseline (with C-15) Water Baseline	8852/35202 =0.251
Steam Injection (no C-15) Water Injection	14961/33755 =0.443
Steam Injection (with C-15) Water Injection	15925/33755 =0.472
Enhancement Factor (no C-15)	0.443/0.232 =**1.91**
Enhancement Factor (with C-15)	0.472/0.251 =**1.88**
Difference in Enhancement Factors	**1.6%**
% C-15 OF TOTAL PHOTOPEAK AREA	
Baseline	683/8852 =0.077 (**7.7%**)
Injection	964/15925 =0.061 (**6.1%**)

The same calculations were made for the two once-through conditions under HWC and NWC. The calculations for run 32 (once-through NWC $VOSO_4$) and run 38 (once-through HWC KNO_2) are shown in Tables J.2.1-J.2.3 and Tables J.3.1-J.3.3 respectively. Note that run 32 was selected based on its high (20 - 30% C-15 contribution-Table J.2.3) to give an upper boundary of the C-15 effect on enhancement factors.

Table J.2.1. Areas under Photopeaks of N-16 and C-15 for Steam and Water Phases During Baseline and $VOSO_4$ Injection, 10^{-4} M (Run 32)

PEAKS	**NET AREA (Counts per 300 seconds)**			**Total Area**
N-16	**5.1 MeV**	**5.6 MeV**	**6.1 MeV**	**N-16**
STEAM				
Baseline	3111	2258	1820	7189
Injection	1177	1173	743	3093
WATER				
Baseline	16381	15261	12011	43653
Injection	17291	15881	12823	45995
C-15	**4.3 MeV**	**4.8 MeV**	**5.3 MeV**	**C-15**
STEAM				
Baseline	611	755	533	1899
Injection	578	340	460	1378

Table J.2.2. Determination of the Effect of C-15 on N-16 Measurements During Baseline and $VOSO_4$ Injection, 10^{-4} M (Run 32)

PARAMETER	**VALUE**
TOTAL PHOTOPEAK AREAS	
Steam Baseline N-16	7189
Steam Baseline C-15	1899
Total	9088
Steam Injection N-16	3093
Steam Injection C-15	1378
Total	4471
Water Baseline N-16	43653
Water Injection N-16	45995

Table J.2.3. Enhancement Factors for Run 32 Including and Excluding C-15

PARAMETER	**VALUE**
Steam Baseline (no C-15) Water Baseline	7189/43653 =0.165
Steam Baseline (with C-15) Water Baseline	9089/43653 =0.208
Steam Injection (no C-15) Water Injection	3093/45995 =0.067
Steam Injection (with C-15) Water Injection	4471/45995 =0.097
Enhancement Factor (no C-15)	0.067/0.165 =**0.406**
Enhancement Factor (with C-15)	0.097/0.208 =**0.466**
Difference in Enhancement Factors	**14.8%**
% C-15 OF TOTAL PHOTOPEAK AREA	
Baseline	1899/9088 =0.21 (**21%**)
Injection	1378/4471 =0.31 (**31%**)

Table J.3.1. Areas under Photopeaks of N-16 and C-15 for Steam and Water Phases During Baseline and KNO_2 Injection, 10^{-4} M (Run 38)

PEAKS	**NET AREA (Counts per 300 seconds)**			**Total Area**
N-16	**5.1 MeV**	**5.6 MeV**	**6.1 MeV**	**N-16**
STEAM				
Baseline	11902	8043	3994	23939
Injection	8483	5901	3588	17972
WATER				
Baseline	15090	14473	11312	40875
Injection	15580	13977	10966	40523
C-15	**4.3 MeV**	**4.8 MeV**	**5.3 MeV**	**C-15**
STEAM				
Baseline	423	158	367	948
Injection	506	163	594	1263

Table J.3.2. Determination of the Effect of C-15 on N-16 Measurements During Baseline and KNO_2 Injection, 10^{-4} M (Run 38)

PARAMETER	VALUE
TOTAL PHOTOPEAK AREAS	
Steam Baseline N-16	23939
Steam Baseline C-15	948
Total	24887
Steam Injection N-16	17972
Steam Injection C-15	1263
Total	19235
Water Baseline N-16	40875
Water Injection N-16	40523

Table J.3.3. Enhancement Factors for Run 38 Including and Excluding C-15

PARAMETER	VALUE
$\frac{\text{Steam Baseline (no C-15)}}{\text{Water Baseline}}$	23939/40875 =0.586
$\frac{\text{Steam Baseline (with C-15)}}{\text{Water Baseline}}$	24887/40875 =0.609
$\frac{\text{Steam Injection (no C-15)}}{\text{Water Injection}}$	17972/40523 =0.444
$\frac{\text{Steam Injection (with C-15)}}{\text{Water Injection}}$	19235/40523 =0.475
Enhancement Factor (no C-15)	0.444/0.586 =**0.758**
Enhancement Factor (with C-15)	0.475/0.608 =**0.780**
Difference in Enhancement Factors	**2.9%**
% C-15 OF TOTAL PHOTOPEAK AREA	
Baseline	948/24887 =0.038 (**3.8%**)
Injection	1263/19235 =0.066 (**6.6%**)

The enhancement factors are in very good agreement for all three conditions. Run 32 is of particular interest because even though C-15 contributed 20 to 30% of the total area, the enhancement factors were not affected significantly. It appears that C-15 carryover behaves similarly to N-16.

The next comparison is that of similar runs from previous campaigns and the present one. K_2MoO_4 was injected in the once-through mode under both NWC and HWC conditions in the 1994 Campaign. It was also added in the 1992 Campaign under both NWC and HWC conditions. The enhancement factors for both run 39 (HWC K_2MoO_4) and run 45 (NWC K_2MoO_4) are calculated below in Tables J.4.1-J.5.3 including and excluding C-15, and are then compared with the 1992 results which included C-15.

Table J.4.1. Areas under Photopeaks of N-16 and C-15 for Steam and Water Phases During Baseline and K_2MoO_4 Injection, 10^{-4} M (Run 39, HWC)

PEAKS	**NET AREA (Counts per 300 seconds)**			**Total Area**
N-16	**5.1 MeV**	**5.6 MeV**	**6.1 MeV**	**N-16**
STEAM				
Baseline	11799	8443	4108	24350
Injection	8006	5574	3498	17078
WATER				
Baseline	14619	13142	10680	38441
Injection	15303	14714	11584	41601
C-15	**4.3 MeV**	**4.8 MeV**	**5.3 MeV**	**C-15**
STEAM				
Baseline	439	773	767	1979
Injection	510	314	684	1508

Table J.4.2. Determination of the Effect of C-15 on N-16 Measurements During Baseline and K_2MoO_4 Injection, 10^{-4} M (Run 39)

PARAMETER	VALUE
TOTAL PHOTOPEAK AREAS	
Steam Baseline N-16	24350
Steam Baseline C-15	1979
Total	26329
Steam Injection N-16	17078
Steam Injection C-15	1508
Total	18586
Water Baseline N-16	38441
Water Injection N-16	41601

Table J.4.3. Enhancement Factors for Run 39 Including and Excluding C-15

PARAMETER	VALUE
$\frac{\text{Steam Baseline (no C-15)}}{\text{Water Baseline}}$	24350/38441 =0.633
$\frac{\text{Steam Baseline (with C-15)}}{\text{Water Baseline}}$	26329/38441 =0.685
$\frac{\text{Steam Injection (no C-15)}}{\text{Water Injection}}$	17078/41601 =0.410
$\frac{\text{Steam Injection (with C-15)}}{\text{Water Injection}}$	18586/41601 =0.447
Enhancement Factor (no C-15)	0.410/0.633 =**0.648**
Enhancement Factor (with C-15)	0.447/0.685 =**0.652**
Difference in Enhancement Factors	**0.6%**
% C-15 OF TOTAL PHOTOPEAK AREA	
Baseline	1979/26329 =0.075 (**7.5%**)
Injection	1508/18585 =0.081 (**8.1%**)

Table J.5.1. Areas under Photopeaks of N-16 and C-15 for Steam and Water Phases During Baseline and K_2MoO_4 Injection, 10^{-4} M (Run 45, NWC)

PEAKS	**NET AREA (Counts per 300 seconds)**			**Total Area**
N-16	**5.1 MeV**	**5.6 MeV**	**6.1 MeV**	**N-16**
STEAM				
Baseline	3512	3258	2602	9372
Injection	3969	3955	3064	10988
WATER				
Baseline	16265	15099	12656	44020
Injection	16384	15161	12725	44270
C-15	**4.3 MeV**	**4.8 MeV**	**5.3 MeV**	**C-15**
STEAM				
Baseline	449	593	643	1685
Injection	544	532	648	1724

Table J.5.2. Determination of the Effect of C-15 on N-16 Measurements During Baseline and K_2MoO_4 Injection, 10^{-4} M (Run 45, NWC)

PARAMETER	**VALUE**
TOTAL PHOTOPEAK AREAS	
Steam Baseline N-16	9372
Steam Baseline C-15	1685
Total	11057
Steam Injection N-16	10988
Steam Injection C-15	1724
Total	12712
Water Baseline N-16	44020
Water Injection N-16	44270

Table J.5.3. Enhancement Factors for Run 45 Including and Excluding C-15

PARAMETER	VALUE
$\frac{\text{Steam Baseline (no C-15)}}{\text{Water Baseline}}$	9372/44020 =0.213
$\frac{\text{Steam Baseline (with C-15)}}{\text{Water Baseline}}$	11057/44020 =0.251
$\frac{\text{Steam Injection (no C-15)}}{\text{Water Injection}}$	10988/44270 =0.248
$\frac{\text{Steam Injection (with C-15)}}{\text{Water Injection}}$	12712/44270 =0.287
Enhancement Factor (no C-15)	0.248/0.213 =**1.164**
Enhancement Factor (with C-15)	0.287/0.251 =**1.143**
Difference in Enhancement Factors	**1.8%**
% C-15 OF TOTAL PHOTOPEAK AREA	
Baseline	1685/11057 =0.152 (**15%**)
Injection	1724/12712 =0.136 (**14%**)

Comparing the above enhancement factor (EF) results with the 1992 campaign:

NWC K_2MoO_4 1992, EF = **1.3** (from Table 7.4)

NWC K_2MoO_4 1993, EF = **1.2** (with C-15) and **1.1** (without C-15)

HWC K_2MoO_4 1992, EF = **0.54** (from Table 7.4)

HWC K_2MoO_4 1993, EF = **0.652** (with C-15) and **0.648** (without C-15)

Considering run-to-run differences, it is apparent that C-15 has not significantly affected the 1992 results. From Table 7.4, the following comparison of 1991 results (which include C-15) with the 1993 results (which exclude C-15) also are in very good agreement;

HWC KNO_2 1991, EF = **0.67** (from Table 7.4, with C-15)

HWC KNO_2 1993, EF = **0.70** (without C-15)

The next comparison is between 1993 and 1992 results with and without C-15 and correcting for the changes in holdup time between the core exit and detection points. The relocation of the peroxide sampler, the addition of the ECP plenum, and the enlargement of the steam separator plenum for the 1993 campaign have all contributed to lengthening the core exit residence time. In the recirculation mode, the flow rate is 40% lower, also adding to the residence time from the core exit to the detection point.

Table J.6. Half Life and Residence Times of Interest

	Half Life $T_{1/2}$, s	ln 2 / $T_{1/2}$ λ, s^{-1}		Residence Time (s) from core exit to detection system		
				92 Campaign	93/94 Camp. (OT)	93/94 Camp. (Recirc)
N-16	7.13	0.0972	Steam	2.11	5.04	8.40
C-15	2.45	0.02829	Water	7.66	11.69	1948
				Time Enhancement Factor *		
Steam			N-16	1.23	1.63	2.26
			C-15	1.82	4.16	10.76
Water			N-16	2.11	3.12	6.64

* Decay time correction to core exit from the detection point for each campaign.

	Residence Time Correction Ratios*			
	$\frac{\text{C-15(93)}}{\text{C-15(92)}}$	$\frac{\text{C-15(93 recirc)}}{\text{C-15(92)}}$	$\frac{\text{N-16(93)}}{\text{N-16(92)}}$	$\frac{\text{N-16(93 recirc)}}{\text{N-16(92)}}$
Steam	2.29	5.91	1.33	1.84
Water			1.48	3.15

*Factor by which activity would be increased if the 1993 loop had the same residence time from the core exit to the detection point as the 1992 loop.

Table J.7. Residence Time Correction Effects on Enhancement Factors

PARAMETER	VALUE
RUN 28	
Steam Baseline (no C-15) Water Baseline	0.232x1.84/3.15 =0.136
Steam Baseline (with C-15) Water Baseline	(8169x1.84+683x5.91)/(35202x3.15) =0.172
Steam Injection (no C-15) Water Injection	0.443x1.84/3.15 =0.259
Steam Injection (with C-15) Water Injection	(14961x1.84+964x5.91)/(33755x3.15) =0.312
Enhancement Factor (no C-15)	0.259/0.136 = **1.90**
Enhancement Factor (with C-15)	0.312/0.172 = **1.81**
Difference in Enhancement Factor	**5.0%**
RUN 32	
Steam Baseline (no C-15) Water Baseline	0.165x1.33/1.48 =0.148
Steam Baseline (with C-15) Water Baseline	(7189x1.33+1899x2.29)/(43653x1.48) =0.215
Steam Injection (no C-15) Water Injection	0.067x1.33/1.48 =0.060
Steam Injection (with C-15) Water Injection	(3093x1.33+1378x2.29)/(45995x1.48) =0.107
Enhancemert Factor (no C-15)	0.060/0.148 = **0.406**
Enhancement Factor (with C-15)	0.107/0.215 = **0.498**
Difference in Enhancement Factor	**23%**
RUN 38	
Steam Baseline (no C-15) Water Baseline	0.586x1.33/1.48 =0.527
Steam Baseline (with C-15) Water Baseline	(23939x1.33+948x2.29)/(40875x1.48) =0.562
Steam Injection (no C-15) Water Injection	0.444x1.33/1.48 =0.399
Steam Injection (with C-15) Water Injection	(17972x1.33+1263x2.29)/(40523x1.48) =0.447
Enhancement Factor (no C-15)	0.399/0.527 = **0.757**
Enhancement Factor (with C-15)	0.447/.562 = **0.795**
Difference in Enhancement Factor	**5%**

RUN 39	
$\frac{\text{Steam Baseline (no C-15)}}{\text{Water Baseline}}$	0.633x1.33/1.48 =0.569
$\frac{\text{Steam Baseline (with C-15)}}{\text{Water Baseline}}$	(24350x1.33+1979x2.29)/(38441x1.48) =0.649
$\frac{\text{Steam Injection (no C-15)}}{\text{Water Injection}}$	0.410x1.33/1.48 =0.368
$\frac{\text{Steam Injection (with C-15)}}{\text{Water Injection}}$	(17078x1.33+1508x2.29)/(41601x1.48) =0.425
Enhancement Factor (no C-15)	0.368/0.569 = **0.647**
Enhancement Factor (with C-15)	0.425/0.649 = **0.655**
Difference in Enhancement Factor	**1.2%**
RUN 45	
$\frac{\text{Steam Baseline (no C-15)}}{\text{Water Baseline}}$	0.213x1.33/1.48 =0.191
$\frac{\text{Steam Baseline (with C-15)}}{\text{Water Baseline}}$	(9372x1.33+1685x2.29)/(44020x1.48) =0.251
$\frac{\text{Steam Injection (no C-15)}}{\text{Water Injection}}$	0.248x1.33/1.48 =0.222
$\frac{\text{Steam Injection (with C-15)}}{\text{Water Injection}}$	(10988x1.33+1724x2.29)/(44270x1.48) =0.283
Enhancement Factor (no C-15)	0.222/0.191 = **1.16**
Enhancement Factor (with C-15)	0.283/0.251 = **1.13**
Difference in Enhancement Factor	**2.7%**

As can be easily seen, the effect on the calculated enhancement factors when decay corrected to 1992 residence times was at worst 23%, but in general about 5% or less. For example, in run 45 the steam to water ratios were recalculated using decay corrected N-16 and C-15 values to account for the holdup time differences between 1992 and 1993. The enhancement factors were again calculated, both including C-15, which had a larger multiplier due to a shorter half-life than N-16, and therefore a potentially greater affect, and excluding C-15. The calculated enhancement factor excluding C-15 was 1.16. Including C-15 in the calculation gave an enhancement factor of 1.13. The difference, 2.7% is unimportant. It can be concluded that the change in residence time from core exit to the N-16 detection point did not adversely change the comparison of

1993 (no C-15) enhancement factors to 1991 and 1992 (C-15 included) enhancement factors.

The 1990-1992 campaigns used NaI detectors to measure N-16. Consequently, the measurements consisted of the total MCA channel area over the energy range encompassing about 4.0 MeV to 7.2 MeV. This area included the same three N-16 peaks used for the 1993 run as well as the 7.1 MeV peak and its first escape peak. The three C-15 peaks were also included in this area. The Compton contribution, which added significantly to the integral counts, was almost exclusively from N-16.

The 1993 campaign did not consider the Compton contribution to the N-16 areas because of the resolution of the Ge detectors. For comparison, the worst case (highest C-15) NWC once-through run (Run 32) will be analyzed including the Compton contribution. The Compton contribution is taken to be the background area (i.e. excluding only the six N-16 and C-15 peaks) all of which is credited to N-16 in this simplistic analysis.

The Compton areas are displayed along with peak areas in Table J.8.

Table J.8. Compton Background under N-16 and C-15 Peaks

Condition	Activity	Peak Area Total	Compton Total	Total Area
Injection	N-16 water	45995	256465	302460
	N-16 steam	3093	43804	46897
	C-15 steam	1378	-	-
Baseline	N-16 water	43653	259517	303170
	N-16 steam	7189	78099	85288
	C-15 steam	1899	-	-

The enhancement factor (EF) excluding all C-15 and Compton is equal to 0.406 as shown in Table J.7. Table J.9 shows the comparative EFs when considering Compton background.

Table J.9. Enhancement Factors Including Background

Condition	Enhancement Factor (EF)
EF using N-16 peaks only	0.406
EF using N-16 and C-15 peaks	0.498
EF excluding C-15 but including Compton	0.551
EF including C-15 and Compton	0.555

The total C-15 contribution as per Table J.7 during injection is 31%, but including Compton (all credited to N-16) would only be 0.4%. For the baseline condition, the contribution was 21% and if Compton is included it would be 0.6%. Compton background contributes 259517 / 303170 = 86% of the counts in the water phase and 78099 / 85288 = 92% in the steam line. Note that in the simulated NaI situation (including Compton, with and without C-15) the difference between including C-15 and excluding C-15 was only 0.7%, which is statistically insignificant. Thus, while the integral EF value of 0.555 exceeds the peak-only value of 0.406, factors other than C-15 are probably responsible.

It is obvious that the Ge detectors provide a much clearer picture of the effects the chemicals have on N-16 distribution than NaI detectors. This appendix considered the effect C-15 has on the interpretation of N-16 carryover data if integral count rates are used. The above analysis suggests that C-15 should have only a small effect on the reported EFs even when considering residence time differences in the runs made in earlier campaigns. All chemicals tested in the 1993 campaign which had been tested under similar conditions in previous campaigns show similar EFs. It is therefore a reasonable conclusion based on the data in this appendix that the EF results obtained using NaI detectors in previous campaigns is valid.