# US-APWR
# Sump Debris
# Chemical Effects Test Results

**Non-Proprietary Version**

**May 2012**

# Revision History

| Revision | Page | Description |
|---|---|---|
| 0 | All | Original issued |
| | iii | Typos (omitted word (Apparatus)) |
| | iv | Typos (capitalization (Concentration))<br>Typos (capitalization (Analysis))<br>Typos (added word (Particles)) |
| | vi | The titles for Figures 3.3-1 and 2 were changed. |
| | 21 | Typos (capitalization for the title of section 3.2.2.3 (Coupon Rack)) |
| | 23 | Typos (corrected chapter number) |
| | 24 | The table 3.3-1 was revised. |
| | 25 | Figure 3.3-1 and the description of the figure were revised.<br>The title of Figure 3.3-1 was revised. |
| | 26 | Figure 3.3-2 and the description of the figure were revised.<br>The title of Figure3.3-2 was revised.<br>The description on recirculation flow rate was revised. |
| | 27 | The description on chemistry parameters was revised.<br>Recirculation sump water volume (min.) in table 3.3-2 was changed from 1244 $m^3$ to 1218$m^3$.<br>The system unit of “RCS water volume (min.)” is changed from pound mass (lbm) to gallon. |
| | 28 | Corrected the title of Table 3.3-3b from “tests” to “test”.<br>The 1st note for Table 3.3-3b was revised. |
| | 29 | The description on test materials was revised.<br>Table 3.3-4 was revised.<br>The description on the recirculation sump water volume (min.) in Note 1 was revised.<br>Note 5 was added. |
| | 30 | The description on Table 3.3-4 was revised.<br>Table 3.3-5 was revised.<br>Note 1 and Note 2 for Table 3.3-5 were revised. |
| | 47 | Typos (correct the table number of Table 4.1-4) |
| | 48 | Typos (capitalization for the title of section 4.1.4 (Concrete Particles Sample)) |
| | 61 | Typos (capitalization for the title of section 4.2.2.2 (Photographs)) |
| | 65 | Typos (capitalization for the title of section 4.2.4 (Concrete Particles Sample)) |
| | 71 | Reference 5 is added. |

Mitsubishi Heavy Industries, Ltd.
16-5, Konan 2-chome, Minato-ku
Tokyo 108-8215 Japan

# Abstract

The containment system of the US-APWR is designed to accommodate the energy release following a postulated accident. The containment system also permits the recirculation of reactor coolant, the containment spray system (CSS) water and emergency core cooling system (ECCS) water to the decay heat removal (DHR) heat exchangers. Water collected in the recirculation sump from the reactor coolant system, the safety injection system, and the containment spray system is recirculated through the reactor core to remove residual heat. The recirculation sump contains strainers to protect the downstream components that are in the reactor coolant, containment spray, and ECCS flow paths from the effects of debris that could be transported to the recirculation sump. During operation of the ECCS, debris in the recirculating fluid that passes through the recirculation sump strainers may affect long-term core cooling when recirculating coolant from the recirculation sump.
The PWR post-LOCA (loss-of-coolant accident) environment creates several challenges to containment materials and debris sources based on temperature, chemical reactions, and effects from sprayed and pooled water. The combination of spray chemicals, insulation, corroding metals, and submerged materials creates a potential condition for the formation of chemical substances that may impede the flow of water through the recirculation sump strainers or affect downstream components in the emergency core cooling or reactor coolant systems.
The Integrated Chemical Effects Test (ICET) Project represented a joint effort by the United States (U.S.) Nuclear Regulatory Commission (NRC) and the nuclear utility industry to simulate the post-LOCA chemical environment present inside a containment structure and to monitor the chemical system for an extended period of time to identify the presence, composition, and physical characteristics of chemical products that may form. The ICET test series was conducted by Los Alamos National Laboratory (LANL) at the University of New Mexico (UNM). The results of the ICET testing are published NUREG/CR-6914.

The US-APWR is a low fiber plant that uses sodium tetraborate as a buffer and based on a review of the results presented for ICET Test#5 is expected to have minimal corrosion and reaction products. However, in order to further understand the plant specific interactions between the containment materials and post-LOCA debris with the recirculation sump fluid chemistry, MHI has elected to perform an ICET experiment for the US-APWR.

The integrated chemical effects tests conducted in the program attempted to simulate the chemical environment present inside the US-APWR containment recirculation water after a loss-of-coolant-accident. Autoclave tests as parts of the testing were performed to simulate the temperature transient of early LOCA phase, and to further understand the sensitivity related to the recirculation sump fluid chemistry. The recirculation test was conducted for 30 days at a constant temperature of 149$^{o}$F. The chemical environment within the tank included boric acid, lithium hydroxide, and sodium tetraborate was added to the test. The autoclave test water temperature was similarly operated with a time-temperature profile representative of the US-APWR post-LOCA operation for the first 100 hours until such time the temperature falls to 149$^{o}$F.

The objective for the chemical effect experiment is to obtain experimental data under simulated plant conditions on the corrosion products that may form in a post-LOCA environment.

This data will then be used to determine compositions, characterize properties, and quantify masses of chemical reaction products that may develop in the recirculation sump under a representative post-LOCA environment. The tests on this report were performed in Takasago Research and Development Center.

# Table of Contents

# List of Tables

# List of Figures

# List of Acronyms

| | |
|---|---|
| AAS | Atomic Absorption Spectroscopy |
| Al | Aluminum |
| APWR | Advanced Pressurized Water Reactor |
| Ca | Calcium |
| CPVC | Chlorinated Poly Vinyl |
| CSS | Containment Spray System |
| DHR | Decay Heat Removal |
| ECCS | Emergency Core Cooling System |
| GL | Generic Letter |
| GSI | Generic Safety Issue |
| ICET | Integrated Chemical Effects Testing |
| ICP | Inductively Coupled Plasma |
| ICP-AES | Inductively Coupled Plasma-Atomic Emission Spectroscopy |
| LANL | Los Alamos National Laboratory |
| LBLOCA | Large Break Loss of Coolant Accident |
| LOCA | Loss of Coolant Accident |
| $NaAlSi_3O_8$ | Sodium Aluminum Silicate |
| NaOH | Sodium Hydroxide |
| NaTB | Sodium Tetra Borate, decahydrates $Na_2B_4O_7 \cdot 10H_2O$ |
| NEI | Nuclear Energy Institute |
| MHI | Mitsubishi Heavy Industries, Ltd. |
| NRC | Nuclear Regulatory Commission |
| PWR | Pressurized Water Reactor |
| PWROG | Pressurized Water Reactor Owners Group |
| RCS | Reactor Coolant System |
| RMI | Reflective Metal Insulation |
| RWSP | Refueling Water Storage Pit |
| SEM/EDS | Scanning Electron Microscopy/Energy Dispersive Spectrometer |
| Si | Silicon |
| UNM | University of New Mexico |
| ZOI | Zone of Influence |

## 1.0 INTRODUCTION

Generic Letter (GL) 2004-02 (Ref. 1) required PWRs to perform evaluations of the emergency core cooling system (ECCS) and the containment spray recirculation functions. These evaluations are to include the potential for debris blockage at the recirculation sump screens and flow restrictions within the ECCS recirculation flow path downstream of the recirculation sump screen, including potential blockage at fuel assembly inlet debris screens. Other potential flow restrictions are the fuel assembly inlet debris screens and the spacer grids within the fuel assemblies. Debris blockage at such flow restrictions has the potential to impede or prevent the recirculation of coolant to the reactor core, potentially leading to inadequate long-term core cooling.

The containment system of the US-APWR is designed to accommodate the energy release following a postulated accident. The containment system also permits the recirculation of reactor coolant, the containment spray system (CSS) water and emergency core cooling system (ECCS) water to the decay heat removal (DHR) heat exchangers. Water collected in the recirculation sump from the reactor coolant system, the safety injection system, and the containment spray system is recirculated through the reactor core to remove residual heat. The recirculation sump contains strainers to protect the downstream components that are in the reactor coolant, containment spray, and ECCS flow paths from the effects of debris that could be transported to the recirculation sump. During operation of the ECCS, debris in the recirculating fluid that passes through the sump strainers may affect long-term core cooling when recirculating coolant from the recirculation sump.

The acceptance criteria for the performance of a nuclear reactor core following a LOCA are found in Section 50.46 of Title 10 of the Code of Federal Regulations (10 CFR). The acceptance criterion dealing with the long-term cooling phase of the accident recovery is as follows:

“Long-term cooling: After any calculated successful initial operation of the ECCS, the calculated core temperature shall be maintained at an acceptably low value and decay heat shall be removed for the extended period of time required by the long-lived radioactivity remaining in the core. “

NEI-04-07 (Ref. 2) and the Staff Safety Evaluation on this document provide an acceptable method for licensees to evaluate the post-LOCA debris sources and their impact on specifically recirculation sump performance and providing adequate assurance of maintaining long term core cooling. The NEI-04-07 document provides limited guidance on three supplemental topical areas: 1) strainer head loss testing, 2) chemical effects and 3) downstream effects due to the immaturity of these issues at the time of the NEI-04-07 issuance. Largely these remaining issues have been resolved by industry and the NRC has issued GL Supplemental Review Guidance for approved methods. However, the issue of chemical effects and the impact on downstream components, more importantly the impact on fuel, has not been fully resolved at this time.

The PWR post-LOCA environment creates several challenges to containment materials and debris sources based on temperature, chemical reactions, and effects from sprayed and pooled water. The combination of spray chemicals, insulation, corroding metals, and submerged materials creates a potential condition for the formation of chemical substances that may impede the flow of water through the recirculation sump strainers or affect

downstream components in the emergency core cooling or reactor coolant systems.

The Integrated Chemical Effects Test (ICET) Project represented a joint effort by the United States (U.S.) Nuclear Regulatory Commission (NRC) and the nuclear utility industry to simulate the post loss of coolant accident (LOCA) chemical environment present inside a containment structure and to monitor the chemical system for an extended period of time to identify the presence, composition, and physical characteristics of chemical products that may form. The ICET test series was conducted by Los Alamos National Laboratory (LANL) at the University of New Mexico (UNM). The results of the ICET testing are published NUREG/CR-6914 (Ref. 3).

The US-APWR is a low fiber plant that uses sodium tetraborate as a buffer and based on a review of the results presented for ICET Test#5 is expected to have minimal corrosion and reaction products. However, in order to further understand the plant specific interactions between the containment materials and post-LOCA debris with the recirculation sump fluid chemistry, MHI has planed (Ref. 4) and performed an ICET experiment for the US-APWR. The tests on this report were performed in Takasago Research and Development Center.

## 2.0 OBJECTIVE

The objective for the chemical effect test is to obtain experimental data under simulated plant conditions on the corrosion products that may form in a post-LOCA environment.

This data will then be used to determine compositions, characterize properties, and quantify masses of chemical reaction products that may develop in the containment under a representative post-LOCA environment.

The test results will be used
- to determine composition, properties, and amount of chemical reaction products that may impact on debris head losses on the strainers..
- to determine inputs for the downstream chemical effects evaluation to confirm their minimal impact on long term cooling.

## 3.0 EXPERIMENTAL MATERIALS AND METHODS

This section is summarized the functional description of test apparatus which are used for long term recirculation test and short term autoclave tests, the test plan, test matrix, test procedure and analytic methods to provide context for the test results.

### 3.1 Chemical Test Apparatus Functional Description

The test apparatus was designed to meet the functional requirements of Ref.4.
Two types of chemical effect tests were performed to obtain experimental data under simulated plant conditions in corrosion products that may form in a post-LOCA environment.

Chemical effect tests were conducted by recirculation test for long term and autoclave tests for short term post-LOCA.

(Recirculation test)
Recirculation test simulated 30days long term duration post-LOCA.
(Autoclave tests)
Autoclave tests simulated 100 hours short term duration post-LOCA that has temperature transient period.

### 3.1.1 Recirculation test apparatus

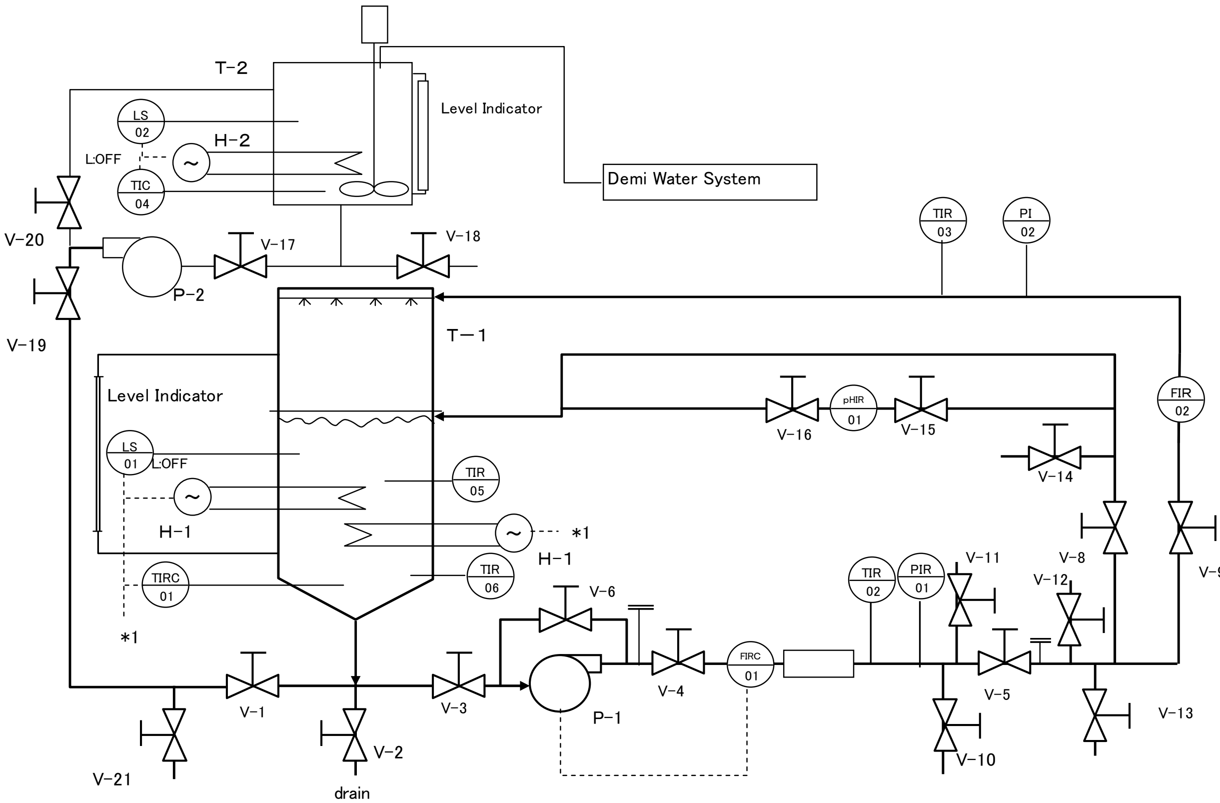
The recirculation test apparatus is designed to meet the functional requirements of this test plan (Ref.4). Specifically, the functional aspects of the recirculation test apparatus are as follows:

The test loop consists of a test tank, a preparation tank, a recirculation pump, flow meters, several isolation valves, and pipes that connect the major components.

Photo of recirculation test apparatus is shown in Figure 3.1-1 and outline of the test apparatus is shown in Figure 3.1 -2.

1. The central component of the system is the test tank. The test apparatus is designed to prevent solids from settling in the test piping.
2. The system includes a pre-mixing tank to ensure the solution chemistry is adequately established prior to introduction into the preparation tank.
3. The test tank includes both a pool and atmospheric environment as expected in a post-LOCA containment.
4. The test tank is controlled at the required test temperature of 149 °F.
5. The test tank has provisions for spray representative of that in the containment.
6. Piping and related isolation valves are provided such that a section of piping could be isolated without interrupting a test.
7. The pump discharge line is split into two branches: one branch directing flow to the spray header in the tank and the other branch returning flow (recirculation) to the liquid pool. Each branch is provided with an isolation valve and a flow measurement.
8. The main pump flow rate is controlled at the pump discharge to establish target flow rate in both the spray and pool region. The flow is controlled manually by the discharge control valve.
9. The test tank accommodates racks of sample coupons subject to spray.
10. The fluid volumes and sample surface areas are based on scaling considerations that relate the test conditions to actual plant conditions.
11. Provisions will be made for these racks to be visually inspected through polycarbonate windows.

**Figure 3.1-1 Photo of Recirculation Test apparatus**




| | |
|---|---|
| T-1 | Test Tank |
| T-2 | Preparation Tank |
| P-1 | Circulation Pump |
| P-2 | Feed Pump |
| H-1 | Test Tank Heater |
| H-2 | Preparation Tank Heater |
| FIRC-01 | Circulation Flow Indicator/Recoder/Controler |
| FIR-02 | Spray Flow Indicater/Recorder |
| pHIR-01 | pH Indicater/Recorder |
| TIRC-01 | Tank temperature Indicater/Recorder/controler |
| TIR-02 | Circurating Water Indicator/Recorder |
| TIR-03 | Spray Water Temp Indicater/Recorder |
| TIC-04 | Preparation Tank Temperature Indicater/Contoroler |
| TIR-05 | Tank temperature Indicater/Recorder |
| TIR-06 | Tank temperature Indicater/Recorder |
| PIR-01 | Circurating line Pressure Indicator/Recorder |
| PI-02 | Spray Pressure Indicator/Recorder |
| LS-01 | Test Tank Level Switch |
| LS-02 | Preparation Tank Level Switch |

| | |
|---|---|
| V-1 | Test Water Feed Valve |
| V-2 | Test Water Drain Valve |
| V-3 | Circurating LineStop Valve |
| V-4 | Circurating Pump discharge valve |
| V-5 | Circurating flow meter outlet valve |
| V-6 | Bypass Line valve |
| V-7 | not applicable |
| V-8 | Circurating LineStop Valve |
| V-9 | Spray line valve |
| V-10 | Sampling Valve 1 |
| V-11 | Filter line valve 1 |
| V-12 | Filter line valve 2 |
| V-13 | spare valve 1 |
| V-14 | spare valve 2 |
| V-15 | pH meter inlet valve |
| V-16 | pH meter outlet valve |
| V-17 | Test Tank Outlet Valve |
| V-18 | Test Tank Drain Valve |
| V-19 | Feed Pump Outlet Valve |
| V-20 | Preparation Tank Circurating Valve |
| V-21 | Drain valve |

**Figure 3.1-2 Outline of Recirculation Test apparatus**

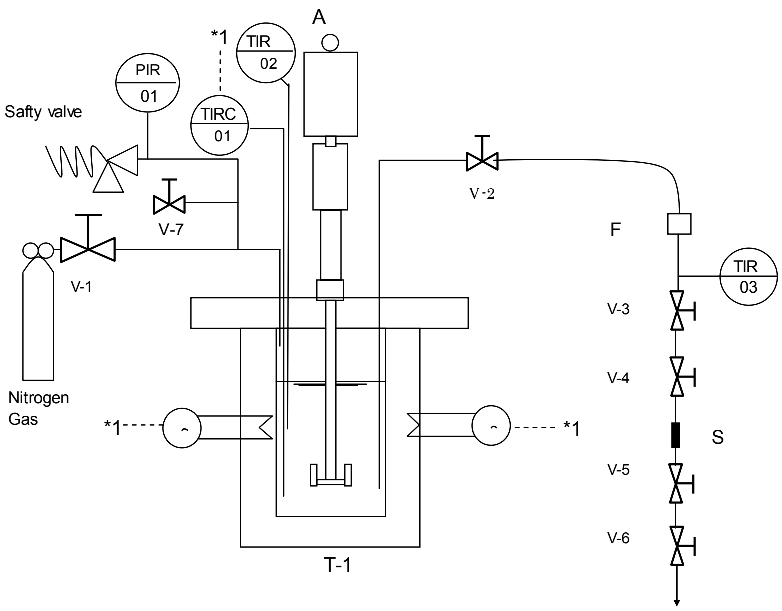
### 3.1.2 Autoclave test apparatus

The autoclave test apparatus is designed to meet the functional requirements of this test plan (Ref.4). Specifically, the functional aspects of the autoclave test apparatus are as follows:

Autoclave test apparatus consists of a test vessel, a sampling tube, several isolation valves, and pipes that connect the major components.
Photo of autoclave test apparatus is shown in Figure 3.1-3 and outline of the test apparatus is shown in Figure 3.1-4.

1. The autoclave test apparatus is designed to meet the functional requirements of the test parameters during the short term high temperature (>212 °F) transient period.
2. The main component of the system is a stainless steel autoclave vessel. The test vessel has 10 liters of inner volume with agitator of solution.
3. The test vessel maintains a liquid environment, as would be expected in a post-LOCA containment vessel.
4. The test vessel controls the liquid temperature at the range of 120 to 284 °F.
5. The autoclave has no provision for spray. The test coupons will be submerged to conservatively represent the spray conditions.
6. The liquid volume and sample surface areas are based on scaling considerations that relate the test conditions to actual plant conditions.


**Figure 3.1-3 Photo of Autoclave Test apparatus**




| | |
|---|---|
| T−1 | Test Vessel |
| TIRC−01 | Test Water Temperature Indicater/Recorder/Controler |
| TIR−02 | Test Water Temperature Indicater/Recorder |
| TIR−03 | Test Water outlet Temperature Indicater/Recorder |
| PIR−01 | Test Vessel Pressure Indicater/Controler/Recorder |
| V−1 | Nitrogengas suplying |
| V−2 | valve |
| F | Filter |
| V−3 | valve |
| V−4 | valve |
| V−5 | valve |
| V−6 | valve |
| V−7 | valve |
| S | Sampling Tube |
| A | Mixing motor and imperer |

**Figure 3.1-4 Outline of Autoclave Test apparatus**

## 3.2 Chemical Tank Assembly and Circulation Details

### 3.2.1 Recirculation Test Apparatus

#### 3.2.1.1 Materials

Components of the test tank and piping, etc. were designed by the material that were chemically endured at range of pH 7.0-8.0 of the mixed liquid for pure water, boric acid, lithium hydroxide (LiOH), and hydrochloric acid (HCl) and the temperature of 149 °F .

The test tank material was Stainless Steel type 304(SUS304), and the observation window was made of polycarbonate with Goretex gasket.

The lower portion of test tank was made of SUS304 of 1/4 in. in thickness, and reinforced by the angle steel of two inches in width ×1/4in. in thickness.
The upper portion of test tank was made of SUS304 of 1/6 in. in thickness, and reinforced by the angle steel of two inch in width ×1/5 in. in thickness.
The cover lid of test tank was made of SUS304 of 1/13 in., and reinforced by the angle steel of two inches in width ×1/5 in. in thickness.
The observation made of the polycarbonate window of 1/1.6 in. in thickness was set up in the cap of the lower portion of the tank, the upper portion of the tank, and the cover lid of tank as observation windows.

SUS304 was used to prevent corrosion chemically from the material in the circulation pipeline. To prevent corrosion and elution of material, equipment touching test solution were made by SUS304, which were piping, pump touching liquid, test tank, preparation tank and agitator in preparation tank.

#### 3.2.1.2 Tank Sizing

The test tank was designed by volume of 264 gallons for chemical test solution and as the distance under the coupon rack was between 4-5 inches on the top of test water level.
The lower half of test tank accommodates the mesh cassette that fills insulation material of 0.057ft$^3$ and the test solution of 264 gallons, one coupon rack.
The upper portion of the test tank is enabled for six coupon racks (coupons up to 53 pieces are set up respectively) to be set up.

The test tank is nominally 4 feet × 4feet and 6.6 feet in height.

The photograph of the recirculation test apparatus, feed water headers, heaters, thermocouples inside the bottom of test tank, the angle for supporting coupon racks, spray nozzle, showing window, access hatch of the cover lid of test tank are shown from Figure 3.2-1 - Figure 3.2-5.
The test tank drawings with size are shown in Figure 3.2-6 and Figure 3.2-7.

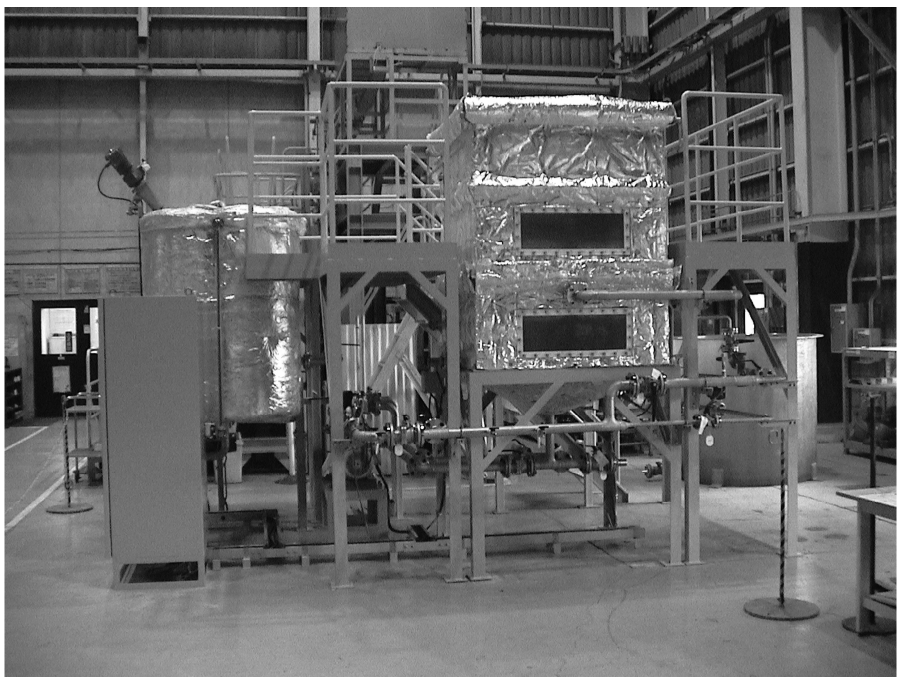


**Figure 3.2-1 External view of Recirculation Apparatus**

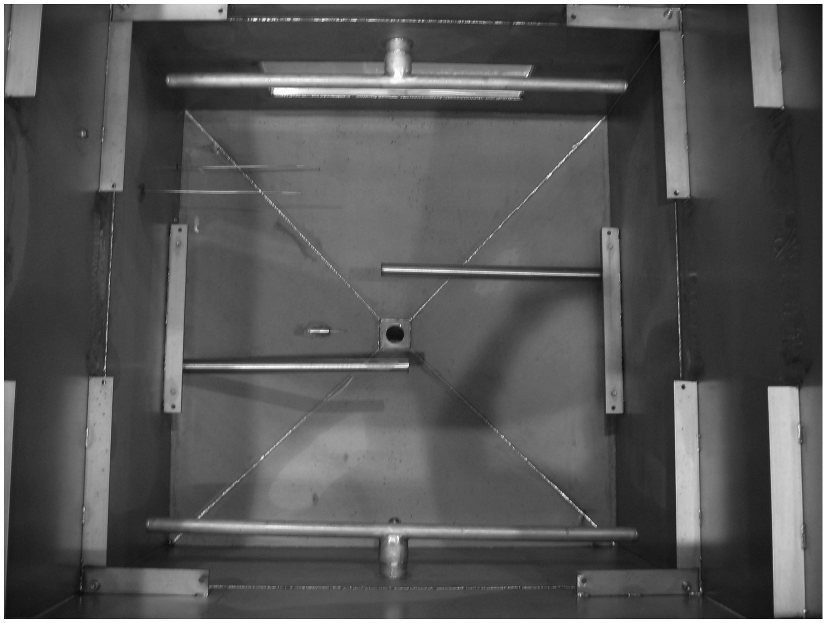


**Figure 3.2-2 The feed water headers, heaters, thermocouples inside the bottom of test tank**

**Figure 3.2-3 The angle for supporting coupon racks in test tank**

**Figure 3.2-4 One of spray nozzles on top corner of test tank**

**Figure 3.2-5 The cover lid of test tank showing window( right) and access hatch(left)**

**Figure 3.2-6 Side view of test tank. Dimensions are in inches.**

**Figure3.2-7 Top view for bottom of test tank. Dimensions are in inches.**