

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

**Non-Proprietary Version**

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## **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°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°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.



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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	v
List of Figures	vi
List of Acronyms	ix
1.0 INTRODUCTION	1
2.0 OBJECTIVE	3
3.0 EXPERIMENTAL MATERIALS AND METHODS	4
3.1 Chemical Test Apparatus Functional Description	4
3.1.1 Recirculation Test Apparatus	5
3.1.2 Autoclave Test Apparatus	7
3.2 Chemical Tank Assembly and Circulation Details	9
3.2.1 Recirculation Test Apparatus	9
3.2.1.1 Materials	9
3.2.1.2 Tank Sizing	10
3.2.1.3 Coupon Racks	15
3.2.1.4 Tank Insulation	16
3.2.1.5 Tank Heaters	16
3.2.1.6 Pump Selection	16
3.2.1.7 Others	17
3.2.2 Autoclave Test	18
3.2.2.1 Materials	18
3.2.2.2 Tank Sizing	19
3.2.2.3 Coupon Rack	21
3.2.2.4 Tank Insulation	23
3.2.2.5 Tank Heaters	23
3.2.2.6 Others	23
3.3 Experimental Plan and Test Matrix	24
3.3.1 Physical Parameters	24
3.3.2 Chemical Parameters	27
3.3.3 Test Materials	29
3.4 Test Procedure and Methods	31
3.4.1 Test Operation	31
3.4.1.1 Recirculation Test	31
3.4.1.2 Autoclave Tests	32
3.4.2 Test Termination Criteria	33
3.4.3 Examination of Test Samples	33
3.4.3.1 Test coupon Examination	33
3.4.3.2 Fiberglass Sample Examination	33
3.4.3.3 Precipitate/Sediment Examination	33
3.4.3.4 Fluid Sample Examination	33
3.5 QA Program	35
4.0 EXPERIMENTAL RESULTS	36
4.1 Recirculation Test Results	36
4.1.1 Test Operation and Sequence	36
4.1.1.1 Description	36
4.1.1.2 Process Control	36
4.1.2 Metallic and Concrete Coupons	37
4.1.2.1 Coupon Racks	37

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4.1.2.2	Coupon Photographs	40
4.1.2.3	Weight Measurements	44
4.1.2.4	Deposition Analysis	45
4.1.3	NUKON Fiberglass Samples	46
4.1.4	Concrete Particles Sample	48
4.1.5	Solution Chemistry	49
4.1.5.1	Chemical concentration	49
4.1.5.2	Turbidity	53
4.1.5.3	Total Suspended Solids	54
4.1.5.4	pH	54
4.1.5.5	Viscosity	55
4.1.6	Precipitated Solids	56
4.2	Autoclave Test Results	58
4.2.1	Test Operation and Sequence	58
4.2.1.1	Description	58
4.2.1.2	Process Control	58
4.2.2	Metallic and Concrete Coupons	60
4.2.2.1	Coupon Racks	60
4.2.2.2	Coupon Photographs	61
4.2.2.3	Weight Measurements	63
4.2.2.4	Deposition analysis	63
4.2.3	NUKON Fiberglass Samples	64
4.2.4	Concrete Samples	65
4.2.5	Solution Chemistry	65
4.2.5.1	Chemical concentration	65
4.2.5.2	pH	67
4.2.5.3	Viscosity	67
4.2.6	Precipitated Solids	68
4.3	Summary of Test Results	69
5.0	CONCLUSIONS	70
6.0	REFERENCES	71
Appendix A Chemical Effects Test Data		A-1

## **List of Tables**

Table 3.3-1	Physical Parameters of US-APWR and Chemical Effect Tests	24
Table 3.3-2	Chemistry condition for US-APWR	27
Table 3.3-3a	Chemistry condition for Recirculation test	28
Table 3.3-3b	Chemistry condition for Autoclave test	28
Table 3.3-4	Sump debris sources for US-APWR and tests	29
Table 3.3-5	Quantity of chemical debris coupons for tests	30
Table 4.1-1	Observation Results of Coupon Surface after Test	42
Table 4.1-2	Average Weight for Each Coupon in Recirculation Test	44
Table 4.1-3	Elemental Composition of Deposition on Coupon Surface(EDS Analysis)	45
Table 4.1-4	Elemental Composition of NUKON Fiberglass before test and of Deposition on the Fiberglass after Test ( EDS Analysis )	47
Table 4.1-5	Elemental composition of powdery concrete ( EDS Analysis )	48
Table 4.1-6	The amount of sediments in a test tank	57
Table 4.1-7	Elemental Composition of Precipitated Solids in Test Tank ( EDS Analysis )	57
Table 4.2-1	Observation Results of Coupon Surface after test	61
Table 4.2-2	Average Weight for Each Coupon in Autoclave Test of Standard Condition(A-5)	63
Table 4.2-3	Elemental Composition of Deposition on Coupon Surface (EDS Analysis)	63
Table 4.2-4	Elemental Composition of deposition on NUKON™ Fiberglass after Test	64
Table 4.2-5	Viscosity	67
Table 4.2-6	Elemental Composition of Precipitated Solid in Test Tank (EDS Analysis)	68
Table A.1.1-1	Chemical Concentration for 0 – 10 days in Recirculation Test Solution	A-2
Table A.1.1-2	Chemical Concentration for 11 – 20 days in Recirculation Test Solution	A-3
Table A.1.1-3	Chemical Concentration for 21 – 30 days in Recirculation Test Solution	A-4
Table A.1.2-1	Chemical Concentration for Standard condition (A-5) in Autoclave Test Solution	A-5
Table A.1.2-2	Chemical Concentration for Alkaline condition (A-6) in Autoclave Test Solution	A-6
Table A.1.2-3	Chemical Concentration for Acidic condition (A-8) in Autoclave Test Solution	A-7

## **List of Figures**

Figure 3.1-1	Photo of Recirculation Test apparatus	5
Figure 3.1-2	Outline of Recirculation Test apparatus	6
Figure 3.1-3	Photo of Autoclave Test apparatus	7
Figure 3.1-4	Outline of Autoclave Test apparatus	8
Figure 3.2-1	External view of Recirculation Apparatus	10
Figure 3.2-2	The feed water headers, heaters, thermocouples inside the bottom of test tank	11
Figure 3.2-3	The angle for supporting coupon racks in test tank	11
Figure 3.2-4	One of spray nozzles on top corner of test tank	12
Figure 3.2-5	The cover lid of test tank showing window( right) and access hatch(left)	12
Figure 3.2-6	Side view of test tank.	13
Figure 3.2-7	Top view for bottom of test tank.	14
Figure 3.2-8	Photo of coupon rack	15
Figure 3.2-9	Photo of coupon rack with coupons	15
Figure 3.2-10	Circulation pump	16
Figure 3.2-11	View of two Autoclave Test Apparatus	19
Figure 3.2-12	Drawing of autoclave test vessel	19
Figure 3.2-13	Interior aspect of test tank	20
Figure 3.2-14	Interior aspect of test tank with coupon rack	20
Figure 3.2-15	Coupon rack with test coupons	21
Figure 3.2-16	Drawing of coupon rack	22
Figure 3.3-1	Recirculation Sump Water Temperature Profile	25
Figure 3.3-2	Post-LOCA sump water temperature profile(estimated) and autoclave test liquid temperature profile	26
Figure 4.1-1	The Position of Metal and Concrete Coupons in Each Coupon Racks	38
Figure 4.1-2	The Position of the Coupon Racks in a Test Tank: View from Control Box Side of the Tank	39
Figure 4.1-3	The NUKON Fiber Glass Holder Made of Stainless Steel Mesh with Sample on Coupon Rack #1	40
Figure 4.1-4	Coupon Racks #2,#3,#4 in Test Tank	41
Figure 4.1-5	Coupon Racks #5,#6,#7 in Test Tank	41
Figure 4.1-6	Coupon Racks #2,#3,#4 After Test	42
Figure 4.1-7	Coupons before and after Recirculation Test	43
Figure 4.1-8	SEM Image of NUKON Fiberglass before Test	46
Figure 4.1-9	SEM image of NUKON fiberglass after Recirculation Test	46
Figure 4.1-10	SEM image for before test of Powdery Concrete Samples	48
Figure 4.1-11	Aluminum concentration in Recirculation test	49
Figure 4.1-12	Calcium concentration in Recirculation test	50
Figure 4.1-13	Copper concentration in Recirculation test	50
Figure 4.1-14	Iron concentration in Recirculation test	51
Figure 4.1-15	Nickel concentration in Recirculation test	51
Figure 4.1-16	Silicon concentration in Recirculation test	52
Figure 4.1-17	Magnesium concentration in Recirculation test	52
Figure 4.1-18	Zinc concentration in Recirculation test	53
Figure 4.1-19	Turbidity in Recirculation test	53

Figure 4.1-20	Total Suspended Solids in Recirculation test	54
Figure 4.1-21	pH in Recirculation test	54
Figure 4.1-22	Viscosity in Recirculation test	55
Figure 4.1-23	Internal View of Test Tank after test	56
Figure 4.1-24	Precipitated Solids in Test Tank after test	56
Figure 4.1-25	SEM image of Precipitated Solids on Test Tank Screen after recirculation test	57
Figure 4.2-1	Operating Temperature of Standard condition(A-2)test	58
Figure 4.2-2	Operating Temperature of Standard condition(A-5)test	58
Figure 4.2-3	Operating Temperature of Acidic condition(A-7,A-8)test	59
Figure 4.2-4	Operating Temperature of Alkaline condition(A-3,A-6)test	59
Figure 4.2-5	Arrangement of test coupon	60
Figure 4.2-6	Galvanized steel (left) , Aluminum(right) of Standard condition	62
Figure 4.2-7	Carbon Steel(left),Copper(right) of Standard condition	62
Figure 4.2-8	Concrete of Standard condition	62
Figure 4.2-9	SEM image of Fiber glass for a Standard condition	64
Figure 4.2-10	Aluminum( left ) and Calcium ( right ) concentration	65
Figure 4.2-11	Copper( left ) and Iron( right ) concentration	66
Figure 4.2-12	Nickel( left ) and Silicon( right ) concentration	66
Figure 4.2-13	Magnesium( left ) and Zinc( right ) concentration	66
Figure 4.2-14	pH	67
Figure 4.2-15	SEM image of deposit on the Coupon rack(left), Inside surface of Autoclave(right) for a Standard condition	68
Figure A.2.1-1	EDS Spectrum of deposition on Galvanized Steel in recirculation test	A-8
Figure A.2.1-2	EDS Spectrum of deposition on Aluminum in recirculation test	A-8
Figure A.2.1-3	EDS Spectrum of deposition on Concrete in recirculation test	A-9
Figure A.2.1-4	EDS Spectrum of deposition on Carbon Steel in recirculation test	A-9
Figure A.2.1-5	EDS Spectrum of deposition on Copper in recirculation test	A-10
Figure A.2.1-6	EDS Spectrum of NUKON before test	A-10
Figure A.2.1-7	EDS Spectrum of deposition on NUKON in recirculation test	A-11
Figure A.2.1-8	EDS Spectrum of Concrete Particles before test	A-11
Figure A.2.1-9	EDS Spectrum of deposition on Tank Screen in Recirculation Test	A-12
Figure A.2.1-10	EDS Spectrum of deposition on Coupon Rack in Recirculation Test	A-12
Figure A.2.2-1	EDS Spectrum of deposition on Galvanized Steel in Autoclave test (Standard condition, A-5)	A-13
Figure A.2.2-2	EDS Spectrum of deposition on Aluminum in Autoclave test (Standard condition, A-5)	A-13
Figure A.2.2-3	EDS Spectrum of deposition on Concrete in Autoclave test (Standard condition, A-5)	A-14
Figure A.2.2-4	EDS Spectrum of deposition on Carbon Steel in Autoclave test (Standard condition, A-5)	A-14
Figure A.2.2-5	EDS Spectrum of deposition on Copper in Autoclave test (Standard condition, A-5)	A-15

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Figure A.2.2-6	EDS Spectrum of deposition on NUKON in Autoclave test (Standard condition, A-5)	A-15
Figure A.2.2-7	EDS Spectrum of deposition on Coupon Rack in Autoclave Test (Standard condition, A-5)	A-16
Figure A.2.2-8	EDS Spectrum of deposition on Tank Surface in Autoclave Test (Standard condition, A-5)	A-16

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## **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 <sub>3</sub> O <sub>8</sub>	Sodium Aluminum Silicate
NaOH	Sodium Hydroxide
NaTB	Sodium Tetra Borate, decahydrates    Na <sub>2</sub> B <sub>4</sub> O <sub>7</sub> · 10H <sub>2</sub> O
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

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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 planned (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.

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### **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:

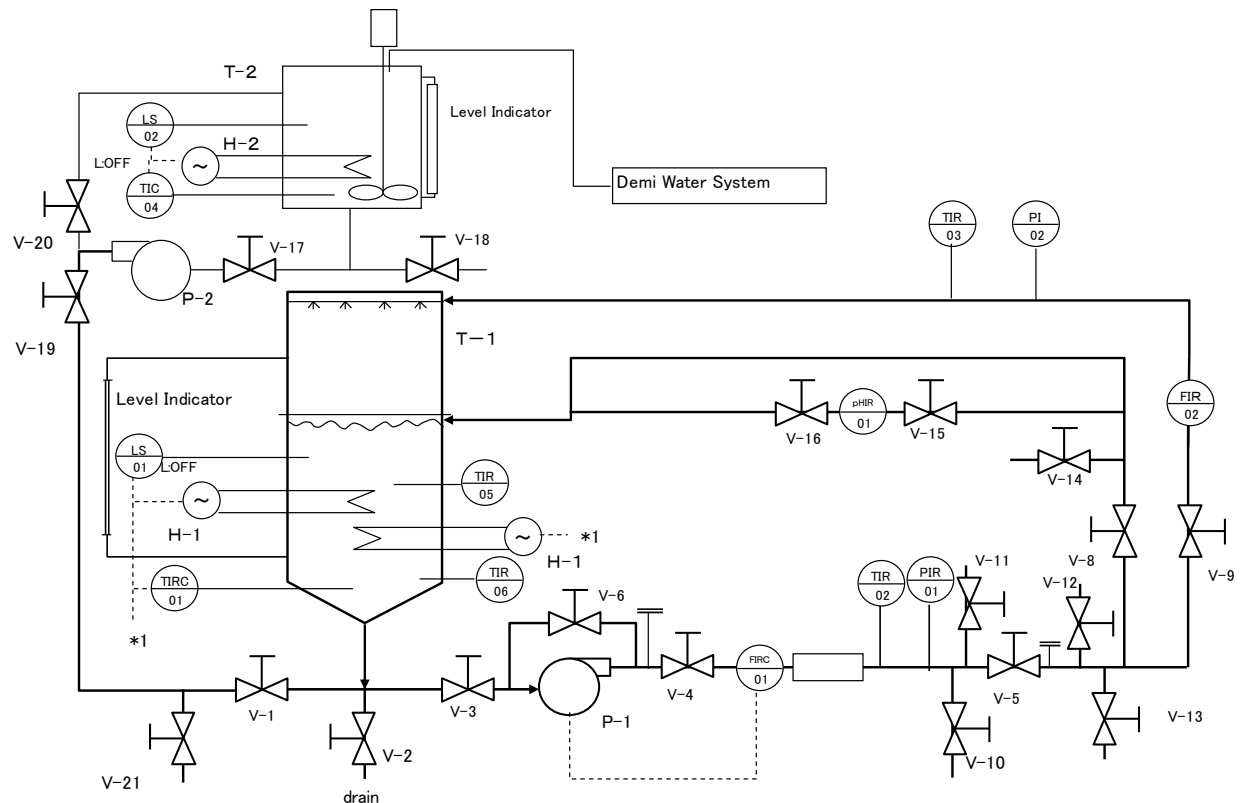
The test loop consists of a test tank, a preparation tank, a recirculation pump, flow meters, several isolation valves, and pipes that connect the major components.

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	V-1	Test Water Feed Valve
T-2	Preparation Tank	V-2	Test Water Drain Valve
P-1	Circulation Pump	V-3	Circulating Line Stop Valve
P-2	Feed Pump	V-4	Circulating Pump discharge valve
H-1	Test Tank Heater	V-5	Circulating flow meter outlet valve
H-2	Preparation Tank Heater	V-6	Bypass Line valve
FIRC-01	Circulation Flow Indicator/Recorder/Controller	V-7	not applicable
FIR-02	Spray Flow Indicator/Recorder	V-8	Circulating Line Stop Valve
pHIR-01	pH Indicator/Recorder	V-9	Spray line valve
TIRC-01	Tank temperature Indicator/Recorder/controller	V-10	Sampling Valve 1
TIR-02	Circulating Water Indicator/Recorder	V-11	Filter line valve 1
TIR-03	Spray Water Temp Indicator/Recorder	V-12	Filter line valve 2
TIC-04	Preparation Tank Temperature Indicator/Controller	V-13	spare valve 1
TIR-05	Tank temperature Indicator/Recorder	V-14	spare valve 2
TIR-06	Tank temperature Indicator/Recorder	V-15	pH meter inlet valve
PIR-01	Circulating line Pressure Indicator/Recorder	V-16	pH meter outlet valve
PI-02	Spray Pressure Indicator/Recorder	V-17	Test Tank Outlet Valve
LS-01	Test Tank Level Switch	V-18	Test Tank Drain Valve
LS-02	Preparation Tank Level Switch	V-19	Feed Pump Outlet Valve
		V-20	Preparation Tank Circulating 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:

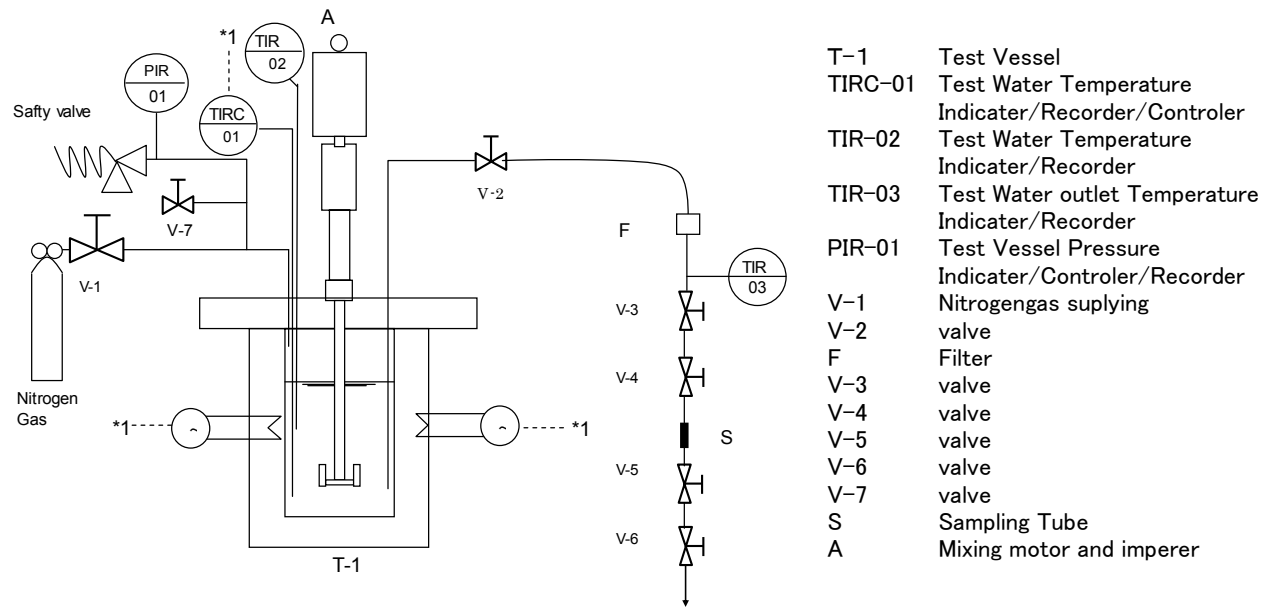
Autoclave test apparatus consists of a test vessel, a sampling tube, several isolation valves, and pipes that connect the major components.

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 ( $>212^{\circ}\text{F}$ ) 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  $284^{\circ}\text{F}$ .
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**



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



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## 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.

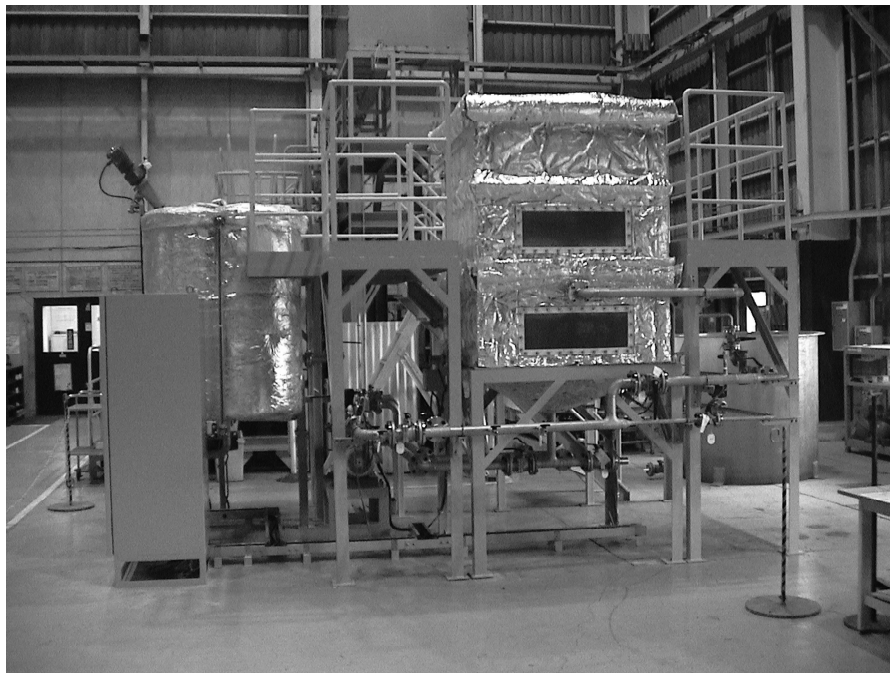
The lower half of test tank accommodates the mesh cassette that fills insulation material of 0.057ft<sup>3</sup> and the test solution of 264 gallons, one coupon rack.

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.

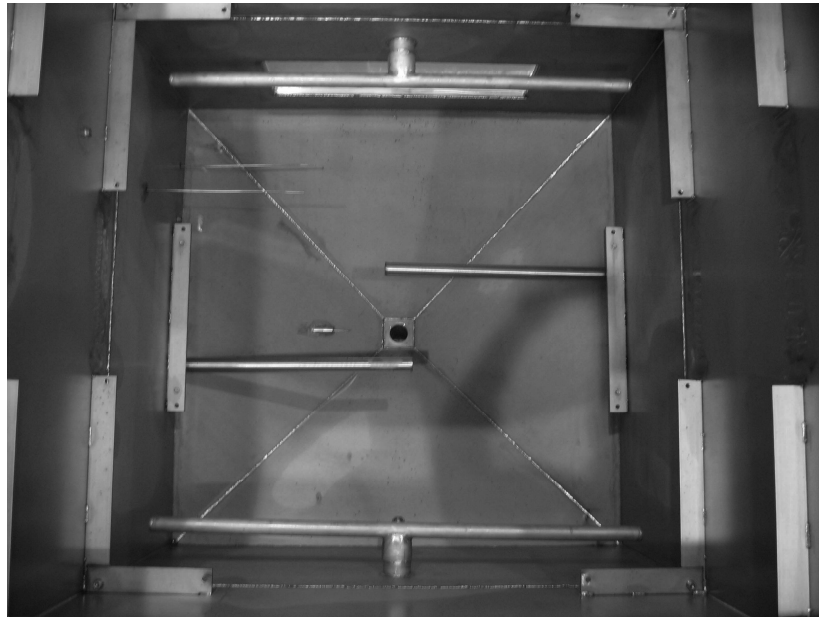
The test tank is nominally 4 feet × 4feet and 6.6 feet in height.

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**



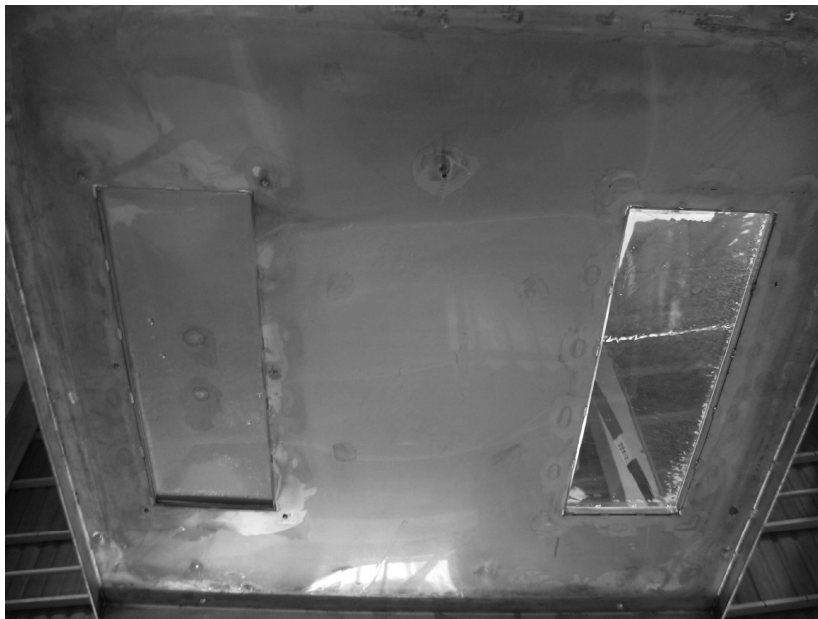
**Figure 3.2-2 The feed water headers, heaters, thermocouples inside the bottom of test tank**



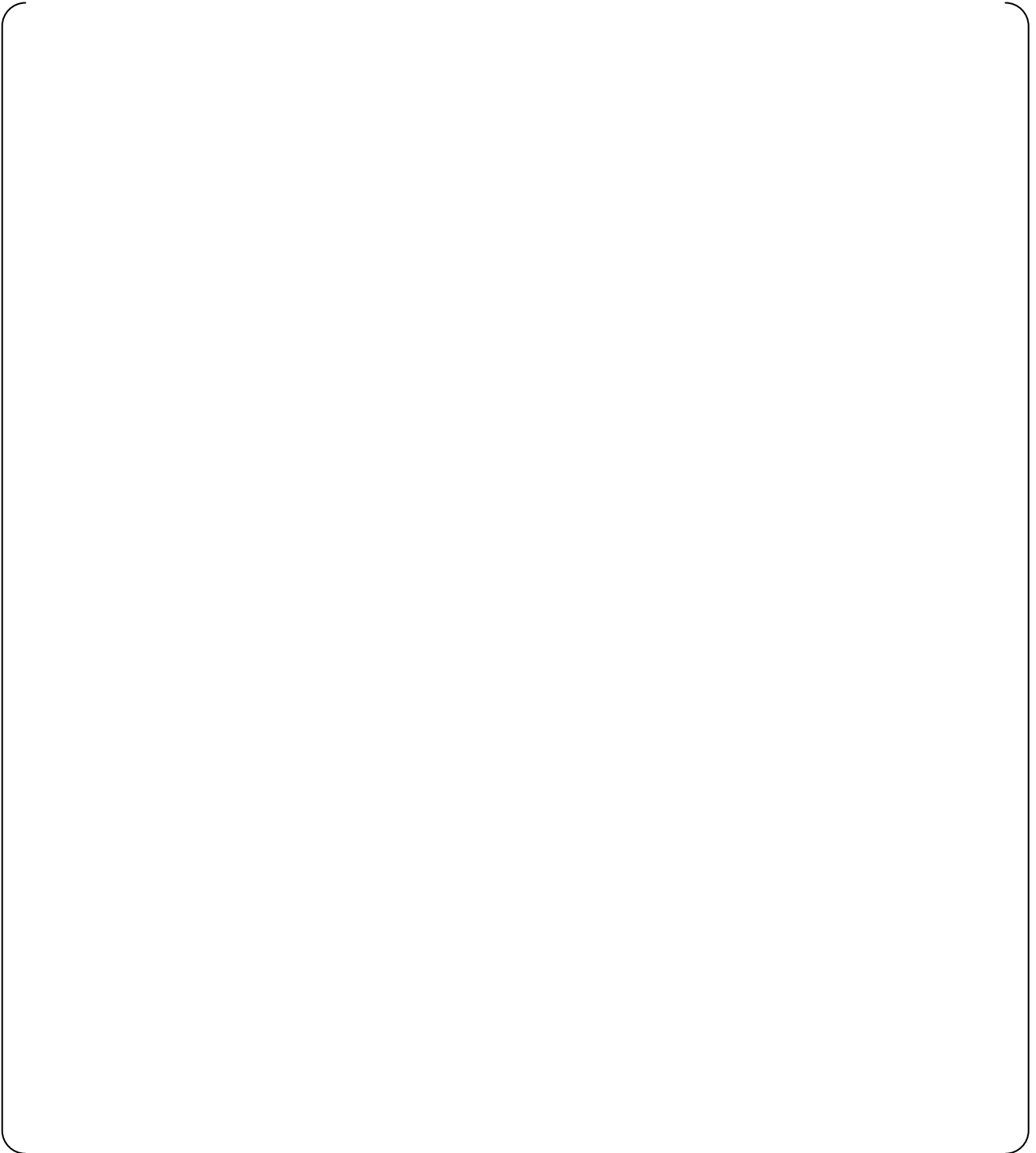
**Figure 3.2-3 The angle for supporting coupon racks in test tank**



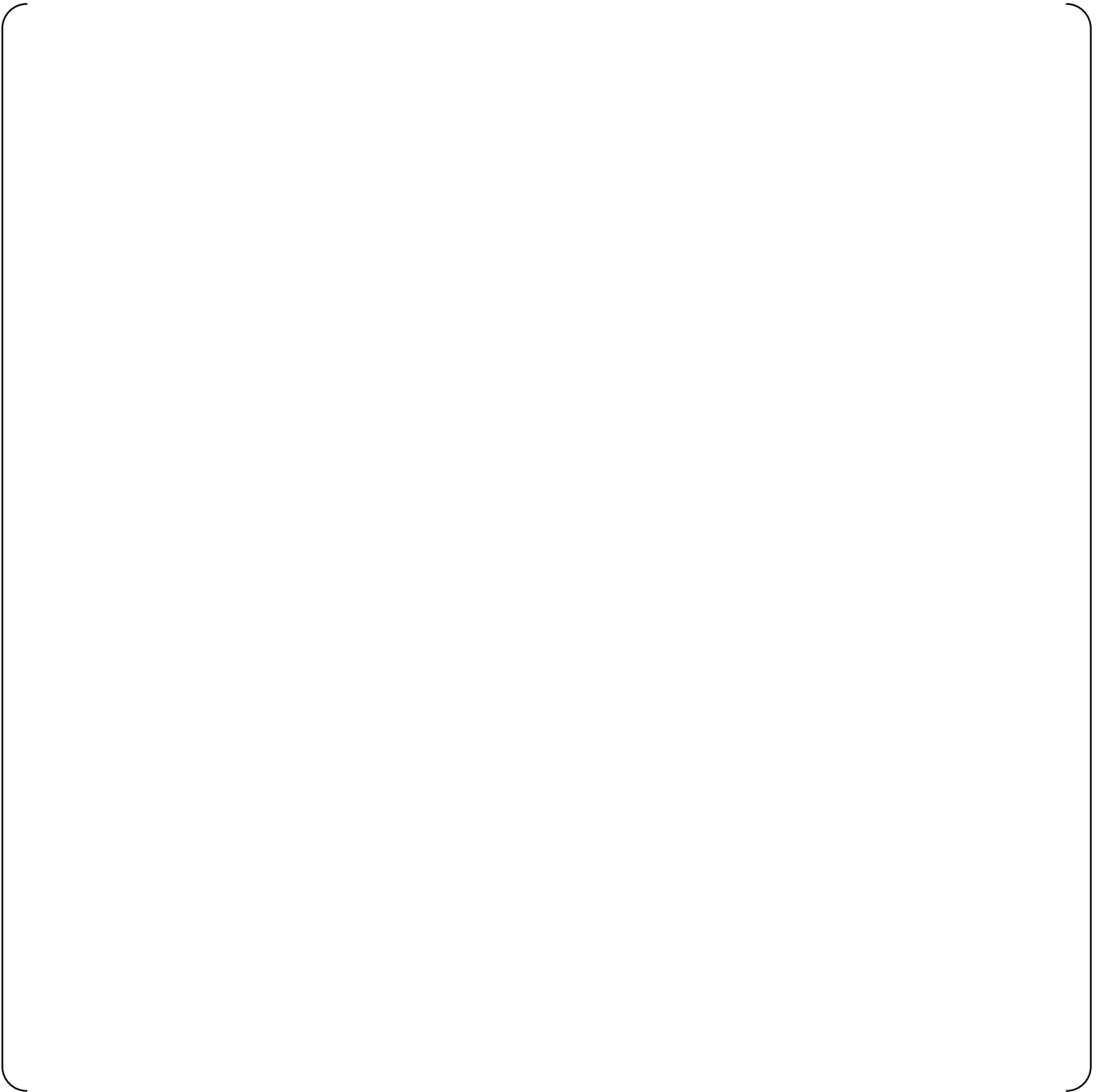
**Figure 3.2-4 One of spray nozzles on top corner of test tank**



**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.**