

# BWR OWNERS' GROUP

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Attention: Mr. Joe Golla (NRC)

Subject: BWROG ECCS Suction Strainers Chemical Effects Strategy Outline

- Reference:
- 1) Summary of August 10 & 11, 2010 Public Meeting with the Boiling Water Reactor Owners' Group (BWROG), September 8, 2010 (ML102360056)
  - 2) BWROG ECCS Suction Strainer Issue Resolution Schedule Update, BWROG-10042, August 31, 2010
  - 3) Summary of October 20, 2010 Public Meeting with the Boiling Water Reactor Owners' Group (BWROG), November 4, 2010 (ML103010393)

The purpose of this letter is to transmit for feedback the Boiling Water Reactors Owners' Group (BWROG) Emergency Core Cooling System (ECCS) Suction Strainers Committee's Chemical Effects Strategy Outline and Flowchart, originally discussed at the August 10, 2010 Public Meeting (summarized in Reference 1). The Strategy Outline and Flowchart was also noted as task 4.1.7, "Submit chemical effect[s] strategy outline and flowchart to NRC," on the level three BWROG program schedule attached to Reference 2. The BWROG requests Nuclear Regulatory Commission (NRC) Staff feedback on the plan described in this Strategy Outline and Flowchart. Written feedback is requested within seven weeks (35 working days) of the NRC Staff's receipt of this letter, an interval which was agreed upon during the October 20, 2010 public meeting (Reference 3). Future tasks depend upon receiving timely feedback from the Staff.

The purpose of the Strategy Outline and Flowchart is to provide the outline for the resolution of potential chemical effects on BWR ECCS strainer operation after a Loss of Coolant Accident (LOCA). A general description of the primary technical approach is included as well as descriptions of the alternative approaches that may be used if required. As part of the investigation into BWR ECCS strainer post-LOCA operation, it is necessary to characterize and quantify the potential dissolved materials and precipitates within the post-LOCA coolant. The output of this task is used for the evaluation of the possible impact on ECCS strainer debris head loss as well as to provide a source term for downstream effects evaluation.

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NRC Staff feedback on the Strategy Outline and Flowchart is important for continuation of tasks under Issue 4, "Chemical Effects," which are listed in Reference 2. Please contact me or Ed Asbury, BWROG Project Manager, at (910) 819-7544, with any questions. Thank you.

Regards,

A handwritten signature in black ink, appearing to read 'F. Schiffley II', with a long horizontal stroke extending to the right.

Frederick P. "Ted" Schiffley, II  
Chairman  
BWR Owners' Group

cc: M. H. Crowthers, BWROG Vice Chairman  
C.J. Nichols, BWROG Program Manager  
BWROG Primary Representatives  
S.L. Scammon, BWROG ECCS Suction Strainers Committee Chairman  
J. Golla, NRC

Commitments: None

Attachments:

1. BWROG ECCS Suction Strainer Chemical Effects Resolution Strategy Plan and Flowchart



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# **BWROG ECCS Suction Strainer Chemical Effects Resolution Strategy Plan and Flowchart**

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BWROG Emergency Core Cooling System Suction Strainers Committee's strategy for resolving ECCS-related concerns over chemical effects after a LOCA

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<p>Document Purpose/Summary:</p> <p>This document describes the overall BWR ECCS Strainer Chemical Effects Resolution Strategy Plan, and provides a flowchart to outline the resolution process.</p> <p><b>SAFETY-RELATED</b></p>		

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## ABSTRACT

During recently completed and ongoing PWR Sump Strainer efforts to address GSI-191, PWR owners performed detailed evaluations and analyses pertaining to material dissolution and chemical precipitation within the post-LOCA coolant and the potential accumulation of precipitates on ECCS suction strainer debris beds. The accumulation of chemical precipitates (“chemical effects”) on ECCS strainer debris beds has the potential to increase ECCS strainer debris head loss and challenge ECCS system functionality, and may form in a BWR post-LOCA coolant environment.

As part of the investigation into BWR ECCS strainer post-LOCA operation, it is necessary to characterize and quantify the potential dissolved materials and precipitates within the post-LOCA coolant. The output of this task is used for the evaluation of the possible impact on ECCS strainer debris head loss as well as to provide a source term for downstream effects evaluation.

The first phase of BWR chemical effect resolution will involve the measurement of material corrosion, dissolution and precipitation in representative fluid chemistry and at representative temperatures. This approach includes single- and mixed-material tests to evaluate possible interactions that may affect dissolution/corrosion as well as to quantify and characterize any precipitates that may form due to dissolved component interactions. A set of correlations will be developed that can be applied to each plant to predict material dissolution and corrosion quantities as well as the types and quantities of potential precipitates that may form in the post-LOCA coolant.

The second phase of BWR chemical effect resolution will consist of measurement of chemical effects on head loss in a vertical test loop using simulated dissolved constituents and a representative debris bed. Chemical precipitates will be allowed to form in-situ to provide a chemical effect head loss profile that will be based on time and temperature of the post-LOCA coolant. Additionally, Phase 2 will include the development of surrogate chemical precipitates to be used for downstream effects analyses. The surrogate precipitates may also be used for alternative approaches to resolving chemical effects, such as large-scale strainer debris and chemical effect head loss testing.

The purpose of this strategy plan is to provide the outline for the resolution of potential chemical effects on BWR ECCS strainer operation after a LOCA. A general description of the primary technical approach is included as well as descriptions of the alternative approaches that may be used if required.

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### LIST OF ABBREVIATIONS/ACRONYMS

AIOOH	Aluminum Oxyhydroxide
BWR	Boiling Water Reactor
BWROG	Boiling Water Reactor Owners' Group
CEF	Chemical Effects Factor
$\Delta P_0$	Measured Head Loss without simulated coolant chemistry
$\Delta P_c$	Measured Head Loss with simulated coolant chemistry
ECCS	Emergency Core Cooling System
EDS	Energy Dispersive X-Ray Spectroscopy
GEH	General Electric Hitachi
GL	Generic Letter
ICET	Integrated Chemical Effects Test
ICP	Inductively Coupled Plasma
IOZ	Inorganic Zinc
LOCA	Loss of Coolant Accident
NAS	Sodium Aluminum Silicate
NaPB	Sodium Pentaborate
NaTB	Sodium Tetraborate
NPSH	Net Positive Suction Head
NRC	Nuclear Regulatory Commission
NUREG	Nuclear Regulatory Guide
PWR	Pressurized Water Reactor
RHR	Residual Heat Removal
RMI	Reflective Metal Insulation
RPV	Reactor Pressure Vessel
SLC	Standby Liquid Control
URG	Utility Resolution Guide
VTL	Vertical Test Loop
XRD	X-Ray Diffraction



## 1 TECHNICAL PHENOMENA

### 1.1 Overview

During a postulated BWR LOCA, insulation, coatings, components and other containment materials can be exposed to jets of water from the pipe break and containment sprays. Exposure of these materials to coolant and spray may lead to material corrosion and dissolution and result in appreciable concentrations of dissolved species in the coolant, including aluminum, silicon, sodium, calcium, iron, and zinc.

The potential impact of chemical effects on BWR ECCS strainer performance has not yet been determined. However, dissolved species can present the following potential issues, which were encountered during the resolution of GL 2004-02 for PWRs:

1. The solubility of a substance in coolant water typically decreases with decreasing temperature. Coolant after a LOCA, whether at a PWR or BWR, experiences high temperatures in the early stages of a LOCA and cools over the post-LOCA mission duration. Materials that dissolved at high temperatures during the early stages of a LOCA may precipitate as the suppression pool cools, such as dissolved aluminum in the form of aluminum oxyhydroxide (AIOOH). These precipitates can accumulate on the ECCS strainer debris bed during post-LOCA recirculation and cause increased debris head loss.
2. Different dissolved species can chemically react to form reaction products that are less soluble than the individual dissolved species. For example, dissolved sodium, silicon, and aluminum can react in a PWR environment to form sodium aluminum silicate, which is less soluble than the reactant ions. These reaction products may then precipitate and accumulate on the strainer debris bed and cause increased head loss.
3. Changes in suppression pool pH can affect the solubility of dissolved species. Materials which dissolve in a particular pH range may precipitate as the pH of the suppression pool changes over time. These precipitates may then accumulate on the strainer debris bed and cause increased head loss. The solubility of aluminum is strongly pH dependent, and AIOOH can precipitate due to a pH reduction.

### 1.2 PWR Experience

The United States Nuclear Regulatory Commission (NRC) and the related PWR nuclear industry jointly developed a test program called the Integrated Chemical Effects Testing (ICET) Program to investigate the chemical reaction products that may develop in a simulated PWR post-LOCA containment sump environment. The primary debris source materials of concern were fiberglass insulation (Al, Si, Ca), metallic aluminum (Al), and calcium silicate insulation (Ca, Si). See Table 1 for more details of dissolved species and

sources. The observed precipitates were either aluminum-based compounds or calcium phosphate (see Section 1.3.4), which depended upon the buffering agent that was used during the individual tests. The ICET investigation provided the first general insight about which containment materials and chemistries could be problematic.

Using the results of the ICET program as a starting point, the PWR industry developed a methodology, via a parametric bench-top material dissolution and precipitate formation test program, to predict release rates of various elemental substances from common materials expected to be present in containment that were shown during ICET testing to produce chemical precipitates [1]. Data was collected via a parametric bench-top material dissolution and precipitate formation test program and empirically correlated to predict precipitate formation as functions of temperature, pH, and concentration. Additionally, a "particulate generator" methodology was developed to produce simulated chemical precipitates that could be added to large-scale strainer head loss tests to determine the chemical effects head loss for PWR strainers.

The methodology developed for the PWR industry included some assumptions that could be regarded as over-conservative, including:

1. All dissolved aluminum (the most problematic dissolved species) was assumed to precipitate and affect head loss.
2. The formation of all chemical precipitates was assumed to occur at the same rate the base constituents (Al, Si, or Ca) were released from their sources. No consideration for precipitation formation kinetics was included in the methodology.
3. All precipitation was assumed to occur at the maximum plant temperature, rather than accounting for the temperature dependent solubility characteristics of the dissolved/potentially-precipitating materials.
4. Precipitate surrogate material was prepared in a concentrated, gelatinous form which caused large increases in head loss in large-scale testing, and while conservative, the surrogate material was not necessarily representative of the expected morphology of formed precipitates after a LOCA.

The BWR chemical effects resolution strategy presented herein takes advantage of lessons-learned from the PWR chemical effect resolution approach and avoids the over-conservatism listed above.

In this document, "dissolution" refers to the process of a solid material dissolving in coolant while "corrosion" refers to the chemical reaction of metallic materials with coolant and species dissolved in the coolant to form corrosion products that are insoluble in the coolant. Corrosion is of particular interest with steel, since steel can corrode in an

aqueous low-pH environment and generate significant corrosion products without resulting in high concentrations of dissolved iron. This corrosion process will continue to occur until the steel has been completely converted to iron oxide, regardless of the dissolved concentration of iron.

### **1.3 Technical Details**

The effect of the chemical corrosion products and environment on strainer head loss depends on multiple factors, including:

#### **1.3.1 Chemistry of Reactor Coolant and Containment Sprays**

Post-LOCA BWR suppression pools experience two distinctly different suppression pool initial chemistry scenarios, depending on whether the plant starts the Standby Liquid Control System (SLCS) during a LOCA [2]. The SLCS injects sodium pentaborate (NaPB) or a mixture of sodium tetraborate (NaTB, Borax) and boric acid solution (which together are equivalent to NaPB) into the reactor pressure vessel (RPV) and ultimately, the suppression pool [3]. The two chemical scenarios will be referred to as “SLC” and “non-SLC” for the remainder of this document. The primary significance of the different SLC injection scenarios in the context of chemical effects is the effect of SLC on coolant pH and buffering capacity, i.e., pH stability.

##### **1.3.1.1 Standby Liquid Control**

The SLC suppression pool chemistry scenario occurs when NaPB dissolved in water is injected as a part of SLCS operation. NaPB is an alkaline ionic compound, when dissolved increases the suppression pool pH to a maximum of ~8.6, depending on the quantity of NaPB injected and the initial conditions of the suppression pool. The range of possible boron concentrations is 0 to ~250 ppm boron, which is approximately an order of magnitude below the average PWR containment sump boron concentration of approximately 3000 ppm boron.

Dissolved NaPB will buffer the suppression pool water, resulting in a pool pH that is more predictable, constant and subject to less variation from dissolving containment materials than in the non-SLC scenario.

##### **1.3.1.2 Non-Standby Liquid Control**

The non-SLC suppression pool chemistry scenario involves “ultrapure” water, which is purified water with low ionic strength and total dissolved solid concentrations generally in the ppb range. The pH of the coolant can range from 4.8 – 8.6 [3], but due to the low ionic strength and lack of any significant buffering capacity, the pH can change readily and significantly as containment materials dissolve, corrode and/or precipitate. The non-SLC suppression pool scenario is very different from that of a PWR, which contains

significant concentrations of dissolved boric acid and alkaline buffer, whether the buffer is sodium hydroxide, trisodium phosphate, or sodium tetraborate.

The effects of material corrosion and dissolution in a BWR suppression pool on strainer debris head loss were not considered in the Utility Resolution Guidance for ECCS Suction Strainer Blockage (URG) [4]. However, more recent material dissolution test data indicates that some containment materials will readily dissolve in an unbuffered pure water environment, and the dissolved materials may potentially re-associate and/or precipitate, accumulate on the strainer, and affect ECCS strainer head loss [5].

### **1.3.2 Temperature Profile of Suppression Pool and Containment Sprays**

The temperature profile describes the temperature of coolant vs. time over the post-LOCA mission time.

#### **1.3.2.1 Containment Spray Temperature**

The rate of material dissolution for materials that are contacted by containment sprays is dependent on the amount of time that the sprays are operating and the temperature of the core spray fluid. The dissolution/corrosion rate may be strongly influenced by temperature, depending on the characteristics of the exposed material.

#### **1.3.2.2 Suppression Pool Temperature**

Species generally tend to be more soluble at elevated temperatures, so the suppression pool temperature profile can affect the amount of chemical precipitation as well as the timing of the precipitation, i.e., some precipitates may not form until the suppression pool has had time to cool well below its maximum temperature.

### **1.3.3 Released Elements and Debris Material Sources**

A table of potential released elements and debris material sources is included as Table 1. This table includes the post-LOCA containment materials that could dissolve in a BWR suppression pool environment.

**Table 1 - Released Elements and Sources [1,6]**

<b>Released Element</b>	<b>Containment Source</b>
Aluminum (Al)	Aluminum reflective metal insulation (RMI), containment components, aluminum silicate insulation, mineral wool, fiberglass, concrete
Calcium (Ca)	Fiberglass, calcium silicate, concrete, mineral wool
Iron (Fe)	Low carbon steel, sludge, galvanized steel, fuel cladding deposits
Sodium (Na)	Fiberglass, calcium silicate
Silicon (Si)	Fiberglass, calcium silicate, concrete, microporous insulation, mineral wool, aluminum silicate insulation, demineralizers
Zinc (Zn)	Galvanized steel, IOZ coatings, fuel cladding deposits

**1.3.4 Known Problematic Precipitates in PWRs**

To evaluate the chemical precipitates that can potentially form in a BWR suppression pool, it is helpful to first understand the characteristics of the three precipitates that were identified as potential sources of increased head loss in PWRs and then consider their formation in the range of possible post-LOCA water chemistries of BWR suppression pools.

**1.3.4.1 Aluminum Oxyhydroxide (AIOOH)**

As aluminum corrodes/dissolves in aqueous solutions at neutral or alkaline pH, dissolved aluminum bonds with hydroxide ions to form  $Al(OH)_4^-$  (aq). In the range of possible water chemistries at a BWR, aluminum corrodes most rapidly at alkaline pH (such as in the SLC injection scenario) and elevated temperatures. These conditions also increase the solubility limit for dissolved aluminum as  $Al(OH)_4^-$  (aq). Due to the relatively large surface area of aluminum RMI in many BWRs, the potential exists that the coolant may become saturated with dissolved aluminum post-LOCA. The locations of the aluminum RMI in BWR plants may need to be reviewed relative to the post-LOCA coolant flow paths to quantify the RMI surface area that may be exposed to the coolant.

If the coolant becomes saturated with dissolved aluminum, it will correspondingly become supersaturated with  $Al(OH)_4^-$  (aq) as it cools, which can precipitate as aluminum oxyhydroxide (AIOOH). This precipitated solid can be amorphous and essentially neutrally buoyant, and can therefore transport and accumulate on ECCS strainer debris beds. Due to the hydrophilic nature of AIOOH leading to the formation of an amorphous gel rather than a purely crystalline morphology, a small amount of AIOOH can result in a large effect on strainer head loss [6]. Since AIOOH forms due to the dissolution of aluminum in water, followed by temperature and/or pH reductions, it is postulated that the chemical environment in a BWR may also be conducive to AIOOH formation.

#### 1.3.4.2 Sodium Aluminum Silicate ( $\text{NaAlSi}_3\text{O}_8$ )

Dissolved aluminum in the presence of sodium and silicon can rapidly react to form sodium aluminum silicate (NAS), also called "low temperature albite" [7]. NAS is mostly insoluble in water, and NAS solubility in water is generally independent of pH. Although NAS is more likely to precipitate than  $\text{AlOOH}$ , it has been observed that NAS formed in a prototypic environment does not necessarily increase head loss significantly, depending on the method of formation, and NAS does not exhibit the strong hydrophilic behavior of  $\text{AlOOH}$  and therefore has less of an effect on head loss [8].

Since PWRs are buffered by compounds containing large amounts of sodium, there is ample sodium available in a post-LOCA PWR sump to form NAS. Although sodium is not necessarily present in BWR cooling water, there is the possibility of sodium leaching from fiberglass and other containment materials, as well being injected as NaPB due to SLC operation. Due to the difference in dissolved sodium availability, NAS may be more readily formed in the SLC scenario in BWRs than in the non-SLC scenario.

#### 1.3.4.3 Calcium Phosphate ( $\text{Ca}_3(\text{PO}_4)_2$ )

Calcium phosphate is formed in PWR sumps from the reaction of dissolved calcium with the dissolved phosphate resulting from the use of trisodium phosphate buffer. Since there are no significant sources of phosphate in a BWR suppression pool, calcium phosphate is not considered a concern for BWRs.

#### 1.3.5 Additional Anticipated Precipitates in BWRs

Due to the amount of exposed zinc (as galvanized steel) in BWR drywells, zinc-based precipitates are a concern, such as zinc hydroxide ( $\text{Zn}(\text{OH})_2$ ) which can form in slightly alkaline environments. Zinc-based precipitates have been shown to cause large head loss increases in a closed loop environment [5]. Iron containing compounds will also be considered, due to existing corrosion products in the suppression pool as well as corrosion of exposed steel during post-LOCA recirculation.

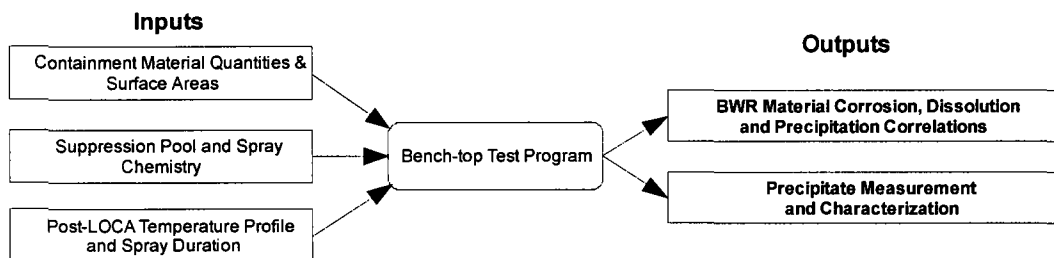
## 2 RESOLUTION STRATEGY

The primary objective of the chemical effects resolution strategy documented herein is to develop a time and temperature based Chemical Effects Factor (CEF) that will be incorporated in the strainer head loss evaluation equations to provide a conservative but appropriate adjustment of ECCS strainer head loss. Where possible, individual BWRs will be grouped by design conditions to avoid plant-specific evaluations. Secondary outputs are predictions of precipitate types and quantities, as well as definitions of usable BWR precipitate surrogates for downstream effects evaluations and alternative strainer head loss approaches.

There are two primary phases of BWR chemical effect resolution:

### 2.1 Phase 1: Material Corrosion, Dissolution and Precipitation

The first phase of the chemical effects evaluation is the determination of the type and amounts of dissolved species that may be released into the suppression pool, based on containment material quantities, exposed surface areas, suppression pool and spray chemistry, post-LOCA temperature profile and spray duration. Additionally, Phase 1 will include measurement and characterization of any resulting precipitates in a bench-top test program.



**Figure 1 - Phase 1: Material Corrosion, Dissolution and Precipitation**

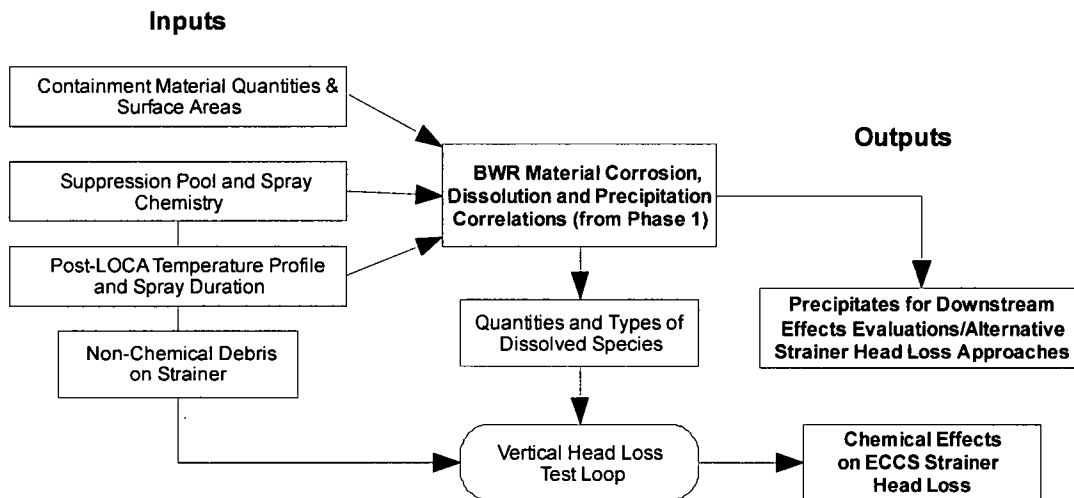
Generic BWR material corrosion, dissolution and precipitation correlations will be developed using both available published information and the results of a bench-top test program that will simulate BWR suppression pool chemistry and materials, similar to the approach taken to evaluate material dissolution for the PWR fleet. The output of Phase 1 will be a set of BWR material corrosion, dissolution and precipitation correlations that can be applied to individual plants to predict the post-LOCA chemical species inventory of the suppression pool as a function of time, temperature, buffer addition and containment reactive materials inventory. Phase 1 will be undertaken through the following steps:

1. Determine bounding suppression pool temperature responses for the postulated LOCA. Determine timing of RHR suppression pool cooling and SLC injection for those plants which may inject SLC.
2. Create an inventory list of containment materials, and their exposure areas and/or quantities that are exposed to coolant flow and containment sprays.
3. Determine which containment materials may corrode and/or dissolve when exposed to coolant or sprays after a LOCA and quantify the resulting concentrations of dissolved species.
4. Characterize and quantify the significant precipitates that can form in a BWR post-LOCA environment.

5. Define or develop empirical material release correlations to facilitate prediction of material corrosion, dissolution and precipitation for plant coolant chemistry types for each individual plant.

## 2.2 Phase 2: Chemical Precipitate Head Loss

The second phase of the BWR chemical effects resolution program is the determination of chemical precipitate head loss and the development of precipitate surrogates to use for downstream effect evaluations and alternative strainer head loss approaches. Phase 2 will use the material corrosion and dissolution correlations from Phase 1 to predict the plant-specific amounts and types of dissolved species in US BWR suppression pools. US BWRs will be categorized based on the results of the correlations and plant details, with the intent of approaching the evaluation of chemical effect head loss generically via the development of a BWR Chemical Effect Head Loss Screening Tool. This Screening Tool aims to reduce the number of plant-specific chemical effect head loss evaluations that will be required by categorizing BWRs based on SLC implementation, debris types and resulting suppression pool chemistry, with the intent of streamlining chemical effects evaluation and reducing the need for plant-specific chemical effect head loss test programs.



**Figure 2 – Phase 2: Chemical Precipitate Head Loss**

After the initial plant-specific correlation application, Phase 2 will approach the resolution of chemical precipitate head loss generically, and plant-specifically as required, through the following steps:

1. Evaluate material dissolution for the fleet of US BWR using the material corrosion and dissolution correlations. Categorize plants according to suppression pool chemistry and dissolved species types and quantities. Possible plant categories



would consider SLC injection, aluminum RMI insulation, and calcium silicate insulation.

2. For each category: Conduct closed-loop head loss tests similar to those used in the development of CR-6224 [9], but with dissolved species to measure the effect of chemical precipitates on head loss, if any, and develop the chemical effects evaluation screening tool for first-pass chemical effects head loss evaluation of individual plants.
3. Apply screening tool to US BWR fleet to determine which plants can address chemical effects with a minor correction factor applied to previous head loss evaluations. Plants that have an outlying post-LOCA debris inventory or post-LOCA coolant chemistry and plants that lack sufficient NPSH margin to incorporate the correction factor may require additional testing or plant-specific characterization of chemical dissolution and precipitation.
4. For those plants that lie outside the ranges defined in the screening tool, conduct plant-specific closed loop chemical effect head loss tests to determine chemical precipitate head loss.
5. Develop chemical precipitate surrogates for evaluation of downstream chemical effects and plant-specific large-scale strainer chemical effect head loss testing.
6. Conduct additional plant-specific tests if required, including large-scale strainer head loss tests with surrogate precipitates, and large-scale "hot tank" chemical effects tests that simulate the suppression pool temperature profile and chemistry and allow for in-situ precipitate formation.

### **3 TECHNICAL APPROACH**

#### **3.1 Phase 1: Material Corrosion, Dissolution and Precipitation Correlation Development**

Material corrosion, dissolution and precipitation correlations are required to predict the amounts and types of dissolved species and precipitation in a post-LOCA BWR suppression pool. They will be derived empirically, based on bench-top material dissolution test data as described below:

- a) Determine problematic containment materials based on existing industry literature and experience and review of BWR design data and material surveys
- b) Obtain material dissolution data from existing industry literature and via analytical material dissolution testing.
  - i) Material dissolution testing will measure dissolution rates for a sample of material over a temperature profile and period of time. The amount of

dissolved material will be determined via inductive coupled plasma spectrometry (ICP) evaluation of the test fluid and material sample weight loss measurement.

- ii) The fluid at the end of each dissolution test will be added to a settling cone and allowed to cool, and any precipitate will be collected via filtration.
  - iii) Quantitative, qualitative and elemental evaluation of precipitates will be used to characterize precipitates and gather additional insight into the materials' dissolution behavior and reactivity.
  - iv) The data set generated by the material dissolution testing will include released material quantities over a range of temperature profiles, and release rates (in terms of mg/m<sup>2</sup>hr) will be calculated from this data. The results of quantification and characterization of observed precipitates will also be included.
- c) Develop empirical material corrosion, dissolution and precipitation correlations from acquired data. Material corrosion, dissolution and precipitate generation correlations will be developed that bound the material corrosion, dissolution and precipitation behavior observed in testing, and will be used to predict post-LOCA material releases and precipitation.
- i) Material corrosion and dissolution correlations will be time and temperature based, and will generate a dissolution/corrosion profile for the accident duration.
  - ii) The precipitation correlations will associate quantities of precipitates with quantities of dissolved materials.
- d) Create easily applied material corrosion, dissolution and precipitation correlation spreadsheet tool using readily available software package (MS Excel).
- e) Determine appropriate synthetic surrogates for dissolved materials based on the solution chemistries observed during the testing conducted in Step 3.1.b. In order to efficiently and controllably conduct head loss tests involving concentrations of dissolved materials, it will be necessary to use synthetic surrogates to simulate dissolved materials.

### **3.1.1 Phase 1: Material Dissolution Test Materials**

The plant sources of dissolved species are included in Table 1 in Section 1.3.3, and the materials to be subjected to dissolution testing are included in Table 2. If additional materials are discovered during Step 3.1.a above that could significantly contribute to the post-LOCA coolant chemistry, they will be added to the test program. Materials identified during Step 3.1.a that do not significantly contribute to the post-LOCA coolant chemistry will be documented along with appropriate justification for their exclusion in the remainder of the BWR chemical effect resolution process.

**Table 2 – Test Materials and Elements Analyzed [1,6]**

<b>Containment Reactive Material</b>	<b>Material Dissolution Test Source</b>	<b>Analyzed Dissolved Elements</b>
Aluminum RMI, aluminum containment components	Metallic aluminum coupons	Al, Fe
Calcium silicate insulation	Calcium silicate insulation samples	Ca, Na, Si
Concrete	Concrete samples	Al, Ca, Si
Fiberglass Insulation (Nukon, Temp-mat, etc)	Fiberglass insulation samples.	Al, Ca, Na, Si
Galvanized Steel, zinc fuel cladding deposits	Galvanized steel coupons	Fe, Zn
Inorganic Zinc Coatings	IOZ filler powder samples	Zn
Microporous insulation	Microporous insulation samples	Si
Mineral Wool	Mineral wool insulation samples	Al, Ca, Si
Steel equipment, iron cladding deposits, structures, containment lining	Steel coupons	Fe

**3.1.2 Phase 1: Material Dissolution Test Conditions**

Test material samples will be weighed prior to being suspended in simulated BWR coolant. The coolant and samples will be subjected to steady state and variable temperature profiles to measure dissolution rate as a function of temperature and concentration. Mixed materials tests will be conducted to measure possible interactions between materials that may affect dissolution or corrosion, such as passivation or activation of metals. During dissolution testing, samples of the test fluid will be removed periodically and analyzed using inductively coupled plasma spectrometry (ICP) to measure the dissolved elemental concentrations and to facilitate development of a time and temperature based model of material dissolution/corrosion. At the conclusion of each test, the material samples will be weighed to determine loss of mass. The test liquid will be placed in a settling cone and allowed to cool, and any observed precipitate will be collected via filtration, dried, weighed and analyzed using XRD or EDS to determine the composition of the precipitate. Based on the composition, surrogate compounds will be determined and will be used in Phase 2 (see Section 2.2). Mixed materials tests will also be used to determine if interactions occur between the dissolved materials and corrosion products, and to determine if mixed material precipitates form in a BWR suppression pool environment.

Material corrosion and dissolution correlations will be developed to model the dissolution and corrosion behavior measured during testing for the two coolant chemistries investigated, SLC and non-SLC. Additionally, precipitate formation correlations will be developed to allow prediction of the types and quantities of precipitates that may be formed for the two coolant chemistries.

The material release and precipitate correlations will be used to develop a material corrosion, dissolution and precipitation spreadsheet tool to provide a conservative method of calculating material release and precipitation types and quantities as a function of material type, quantity, coolant temperature, coolant chemistry and time over the duration of a BWR LOCA.

A material corrosion, dissolution and precipitation test plan will be issued by the BWROG and submitted to the NRC for review and comment prior to the initiation of material dissolution testing.

### **3.2 Phase 2: BWR Chemical Effects Evaluation Screening Tool Development**

The chemical effects screening tool will be used to conduct a first-pass evaluation of each BWR to determine if and what types of chemical precipitates can form in each BWR post-LOCA suppression pool, and to determine if a plant-specific evaluation is required. This tool will reduce the need for plant-specific evaluations and streamline issue resolution for those plants where chemical effects are not significant. Plants that have an outlying post-LOCA debris inventory or post-LOCA coolant chemistry and plants that lack sufficient NPSH margin to incorporate the correction factor may require additional testing or plant-specific characterization of chemical dissolution and precipitation. Phase 2 will include the following steps:

- a) Apply material dissolution correlations to US BWR fleet to predict plant material dissolution for full post-LOCA mission time (released quantities vs. time)
- b) Categorize plants based on suppression pool chemistries, debris beds and dissolved material quantities. Each category will consist of debris, temperature, and chemistry conditions that conservatively bound the plants within the category.
- c) Use closed vertical test loop (VTL) with predicted dissolved material concentrations vs. time and simulated suppression pool chemistry to test each plant category for chemical effect head loss over a representative temperature profile.
- d) Measure head loss across filter/debris bed ( $\Delta P_o$ ) for each category with water (no chemistry) and thermal profile, similar to the approach used as the basis for NUREG/CR-6224 correlation [9].
- e) Measure head loss across filter/debris bed for each category with the respective category suppression pool chemistry and thermal profile, and determine the head

loss ( $\Delta P_c$ ) of the debris bed with chemical precipitation as well as the temperature and timing of the measured head loss increase.

- f) Calculate chemical effects factor (CEF) for each category for incorporation in strainer non-chemical design basis head loss correlations where the CEF is the time-dependent ratio of  $\Delta P_c / \Delta P_o$ .
- g) Develop screening tool spreadsheet using the results from (f), to be used for the first-pass chemical effects evaluation.
- h) Apply the CEF for each category to the plants within each category to calculate the design basis head loss with chemical effects as a function of time for each plant.
- i) Determine which plants can have the chemical effects issue resolved generically and which plants will require plant-specific evaluation. Plant-specific evaluation will be required if application of the CEF results in the strainer head loss exceeding the available NPSH margin.

### 3.2.1 Phase 2: Chemical Precipitate Head Loss Test Conditions

For each test, a vertical test loop (VTL) will be filled with simulated BWR coolant. Deionized water will be used to represent the non-SLC condition and sodium pentaborate-buffered water to represent the SLC condition. A representative debris bed will be formed on a flat perforated plate. Bounding concentrations of predicted dissolved species will be injected into the VTL, and the VTL fluid will then be subjected to a typical suppression pool temperature profile while the head loss across the debris bed is measured. For each debris bed and coolant chemistry, a control test without added dissolved species will be performed. Through this approach, a conservative head loss increase vs. time and temperature profile can be developed for each chemical effects category and integrated with the existing strainer design basis and ECCS NPSH requirements. This vertical closed test loop approach with injected species is consistent with methodology used by the NRC to evaluate chemical effects for PWRs, as documented in NUREG/CR-6913.

### 3.2.2 Phase 2: Chemical Precipitate Surrogates for Downstream Effects

Since chemical precipitates may pass through an ECCS strainer that is not covered with fibrous debris and enter the primary system, it is necessary to consider chemical effects on downstream components and fuel. In order to facilitate downstream effects analysis, the BWR chemical effects program will provide a quantity of chemical precipitate that can pass through the strainer, as well as recipes and procedures for generating surrogate precipitates, similar to what was used in PWR strainer chemical effect head loss testing. The amount of precipitate will be provided as a function of time, and will be based on the material dissolution correlations generated in Phase 1.

### 3.3 Phase 2: Plant-Specific Approaches

Alternative approaches may be required for outlier plants for which chemical effects cannot be resolved using the screening tool. This description of the plant-specific approaches is presented as a general outline only and may change as new information becomes available during the generic dissolution and precipitation testing.

The first alternative approach for outlier plants will be the use of plant-specific, vertical loop chemical effect head loss tests to develop a plant-specific Chemical Effects Factor to be used to modify the plant strainer debris head loss (See Section 3.2). Simulated dissolved species will be added to the VTL over time to represent the gradual dissolution of plant materials. If this approach results in plant strainer head loss that exceeds the available NPSH margin and the chemical effect source term cannot be reduced, large tank testing with a representative plant strainer will be used with representative non-chemical debris and surrogate chemical precipitates, similar to the approach used to validate PWR strainers for chemical effects. Surrogate precipitate will be added in batches to generate a head loss curve for the plant strainer that considers material dissolution as a function of time. Another alternative is the use of a large, heated test tank with simulated BWR suppression pool chemistry with dissolved species and non-chemical debris, and a representative plant strainer.

#### 3.3.1 Phase 2: Plant-Specific Action: Closed Test Loop Approach with In-Situ Precipitate Formation

Plant-specific vertical closed loop chemical effect testing will be identical to the testing described in Section 3.2, but with plant-specific parameters.

- a) Use predicted plant-specific dissolved material concentrations to simulate suppression pool chemistry in closed vertical test loop (VTL) with problematic dissolved species.
- b) Measure head loss across filter/debris bed ( $\Delta P_o$ ) with water (no chemistry) and thermal profile, similar to the approach used as the basis for NUREG/CR-6224 correlation [9].
- c) Measure head loss across filter/debris bed for each category with the respective category suppression pool chemistry and thermal profile and determine head loss ( $\Delta P_c$ ) of the debris bed with chemical precipitation as well as temperature and timing of chemical effects.
- d) Apply time dependent chemical effects factor (CEF) to strainer non-chemical design basis head loss correlations, where CEF is the ratio of  $\Delta P_c / \Delta P_o$ .

### **3.3.2 Phase 2: Plant-Specific Action: Large-Scale Strainer Testing with Surrogate Precipitates**

This approach is included as an alternative to the resolution strategy that can be used for outlier BWR ECCS strainers where the conservative closed test loop approach does not yield a favorable solution or where NPSH margin recovery is desired.

- a) Use predicted plant-specific non-chemical debris and precipitate quantities in large-scale test tank.
- b) Run plant-specific large-scale tests with representative non-chemical debris and chemical species surrogates, using prototypic large-scale strainer test article to measure plant ECCS strainer head loss. Chemical precipitate surrogates will be added in batches to simulate the formation of chemical precipitates in the plant as a function of time.

### **3.3.3 Phase 2: Plant-Specific Action: Large-Scale Strainer Testing with In-Situ Precipitate Formation**

This approach is included as an alternative to the resolution strategy that may be used for outlier BWR ECCS strainers where the closed test loop approach does not yield a favorable solution or where NPSH margin recovery is desired

- a) Use plant-specific predicted non-chemical debris and dissolved material concentrations to simulate suppression pool chemistry in heated large-scale test tank
- b) Run plant-specific large-scale tests with representative non-chemical debris and chemical species surrogates, using prototypic large-scale strainer test article to measure plant ECCS strainer head loss over simulated plant temperature profile

## **4 STRATEGY FLOW DIAGRAMS**

The flow diagram for the development of the Chemical Effects Resolution Screening Tool is included as Figure 3, and the flow diagram for the application of the Screening Tool is included as Figure 4.

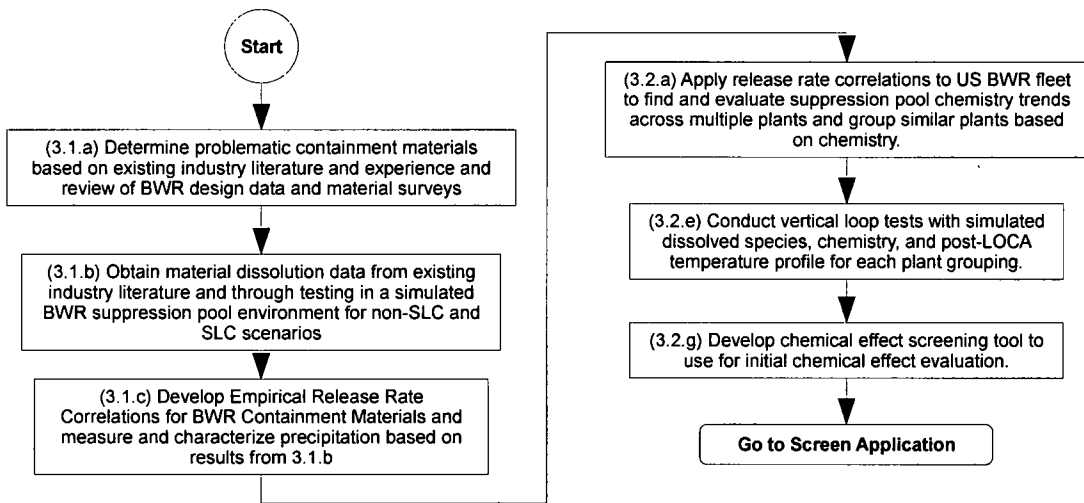


Figure 3 – BWR Chemical Effects Resolution Screening Tool Development Flowchart

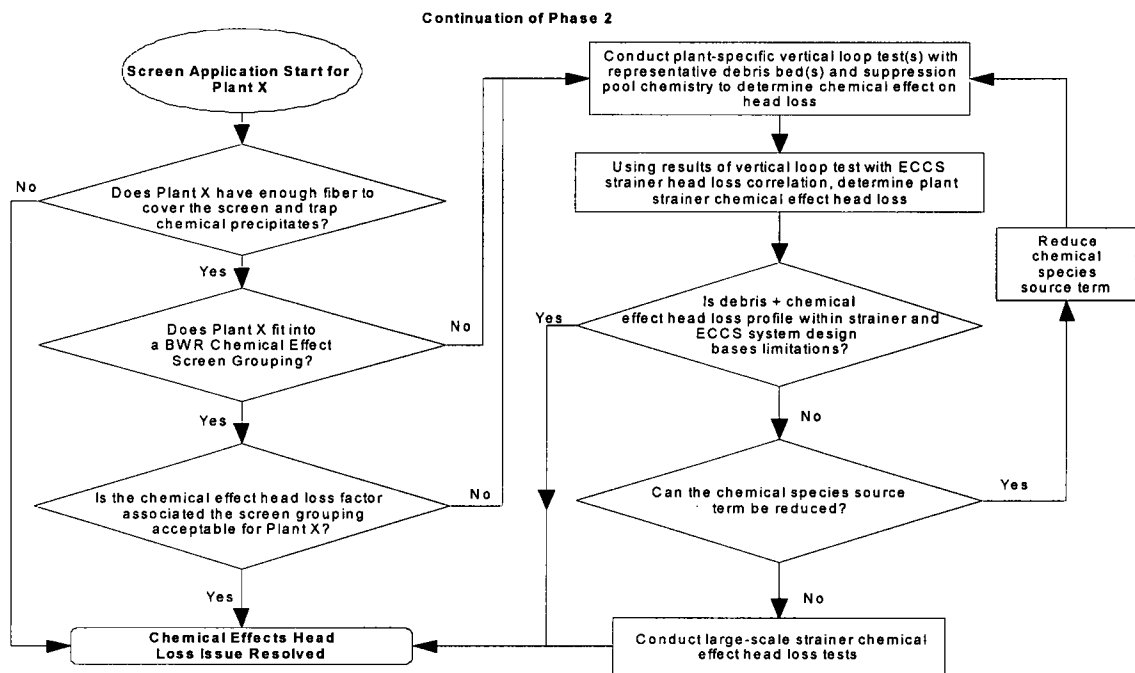


Figure 4 – BWR Chemical Effects Resolution Screening Tool Application Flowchart



## **5 ACTIONS NEEDED TO RESOLVE ISSUE**

This section provides an itemized list of the actions needed to resolve the issue of chemical effects on BWR strainer head loss and to provide a source term for the evaluation of chemical downstream effects.

### **5.1 Material Dissolution and Precipitation Correlation Development**

- 5.1.1 Determine problematic containment materials in US BWR fleet based on existing industry literature and experience and review of BWR design data and material surveys.
- 5.1.2 Develop typical temperature profiles and timing of RHR suppression pool cooling initiation and SLC injection for those plants using SLC injection
- 5.1.3 Obtain material dissolution data from existing industry literature
- 5.1.4 Determine what testing must be performed to supplement existing literature, and write test plan for BWR Material Dissolution Testing
- 5.1.5 Submit material dissolution test plan to NRC for review
- 5.1.6 Address NRC Comments
- 5.1.7 Conduct material dissolution and precipitation testing
- 5.1.8 Develop empirical material dissolution and precipitation correlations from acquired data.
- 5.1.9 Determine appropriate synthetic surrogates for dissolved materials.
- 5.1.10 Develop excel spreadsheets for rapid assessment of chemical releases and precipitation types and quantities
- 5.1.11 Issue BWR Material Dissolution and Precipitation Correlation Report.
- 5.1.12 Submit BWR Material Dissolution and Precipitation Correlation Report to NRC for review.
- 5.1.13 Address NRC comments.

### **5.2 BWR Chemical Effects Evaluation Screening Tool Development and Application**

- 5.2.1 Apply material dissolution correlations to US BWR fleet to predict plant material dissolution for full post-LOCA mission time
- 5.2.2 Categorize plants based on suppression pool chemistries, temperature profiles and dissolved material concentrations
- 5.2.3 Submit screening tool chemical effect head loss test plan to NRC for review
- 5.2.4 Address NRC Comments
- 5.2.5 Use predicted dissolved material concentrations and simulated suppression pool chemistry in closed vertical test loop to test each plant category for chemical effect head loss over a representative temperature profile.
- 5.2.6 Develop surrogate chemical precipitates for downstream effect evaluation and large-scale, plant-specific testing.

- 5.2.7 For each US BWR, provide types and quantities of chemical precipitates for downstream effect evaluations
- 5.2.8 Develop and issue screening tool with criteria and thresholds for the first-pass chemical effects evaluation
- 5.2.9 Develop conservative head loss correction factors for each plant category that can be used with previous strainer head loss predictions
- 5.2.10 Submit BWR Chemical Effects Evaluation Screening Tool to NRC for review.
- 5.2.11 Address NRC comments.
- 5.2.12 Apply screening tool to US BWRs to determine chemical effects on ECCS strainer head loss
- 5.2.13 Determine what testing, if any, must be performed to supplement screening tool application (See Section 5.3), based on suppression pool temperature profiles, chemistries, and acceptability of predicted chemical effects on ECCS strainer head loss.

### **5.3 Plant-specific Chemical Effects Evaluations (As Required)**

Since the plant-specific approaches below follow the generic approaches outlined in Sections 5.1 and 5.2, significant additional information will be available before they are initiated. Therefore, this section is presented only as a general outline and is subject to change. The NRC staff will have the opportunity to review and comment on the plant-specific test methodology prior to the start of testing.

- 5.3.1 Use predicted dissolved material concentrations and simulated suppression pool chemistry in VTL with representative debris bed to measure strainer chemical effect head loss over a representative temperature profile.
- 5.3.2 Use VTL results to develop CEF and modify plant strainer design head loss correlations to account for chemical effects on head loss.
- 5.3.3 Conduct large-scale strainer testing with representative non-chemical debris and surrogate chemical precipitates to determine chemical effects on plant strainer head loss.
- 5.3.4 Conduct large-scale strainer testing with representative non-chemical debris and dissolved chemical concentrations to facilitate in-situ precipitate formation and measurement of chemical effect on strainer head loss.

## **6 FINAL OUTPUTS**

This section provides the documents that will be issued to resolve chemical effects on BWR strainer head loss and to provide a source term for the evaluation of chemical downstream effects.

1. BWR Material Dissolution, Corrosion and Precipitation Test Plan
2. BWR Material Dissolution, Corrosion and Precipitation Test Report
3. BWR Material Dissolution, Corrosion and Precipitation Correlation Report
4. BWR Chemical Effects Screening Vertical Test Loop Test Plan
5. BWR Chemical Effects Screening Vertical Test Loop Test Report
6. BWR Chemical Effects Evaluation Screening Tool
7. BWR Chemical Effects Vertical Test Loop Test Plan and Report (Plant-specific, as required)
8. BWR Chemical Effects Large-Scale Test Plan and Report (Plant-specific, as required)

## 7 REFERENCES

1. NUREG/CR-6914, "Integrated Chemical Effects Test Project: Consolidated Data Report", Los Alamos National Laboratory, December 2006.
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4. NEDO-32686-A, "Utility Resolution Guidance for ECCS Suction Strainer Blockage", October, 1998.
5. NUREG CR-6868, "Small Scale Experiments: Effects of Chemical Reactions on Debris-Bed Head Loss", USNRC, March 2005.
6. NUREG CR-6913, "Chemical Effects Head-Loss Research in Support of Generic Safety Issue 191, Argonne National Laboratory, December 2006
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8. Calvert Cliffs Nuclear Power Plant, Unit Nos. 1 & 2; Docket Nos. 50-317 & 50-318, Supplemental Response to Generic Letter 2004-02, ML093020647.
9. NUREG/CR-6224, "Parametric Study of the Potential for BWR ECCS Strainer Blockage Due to LOCA Generated Debris", Science and Engineering Associates, October 1995.