Strategic Plans for Primary and Secondary Water Chemistry Programs

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1 Background

In the late 1990s, the U.S. Nuclear Regulatory Commission (NRC) began putting considerable pressure on U.S. nuclear utilities to resolve their concerns regarding steam generator (SG) integrity. In response, the nuclear industry responded to the NRC by making several commitments via the Nuclear Energy Institute (NEI). In these commitments the industry agreed to certain voluntary initiatives for managing SG integrity and liability, which included the development and maintenance of a strategic water chemistry plan (SWCP).

The U.S. nuclear power industry established a framework for increasing the reliability of steam generators by adopting NEI 97-06, Steam Generator Program Guidelines (NEI document #6, 1997). The issue of NEI 97-06 includes the following requirements regarding secondary water chemistry:

- "Each licensee shall have procedures for monitoring and controlling secondary-side water chemistry to inhibit secondary-side corrosion-induced degradation in accordance with the EPRI PWR Secondary Side Water Chemistry Guidelines." [Fruzzetti, 2009]

NEI 03-08 "outlines the policy and practices that the industry commits to follow in managing materials aging issues", indicating that "each licensee will endorse, support and meet the intent of NEI 03-08" and further stating that it "commits each nuclear utility to adopt the responsibilities and processes described in this document." [Fruzzetti, 2009]

With respect to these Guidelines, the scope of NEI 03-08 includes "PWR steam generators" and "chemistry/corrosion control programs". The NEI document states that "as deliverables or guidelines are developed, action should be classified as to relative level of importance." In this regard, these Guidelines identify mandatory, shall and recommended elements. Mandatory elements are those that are important to secondary system component integrity, including steam generator tube integrity, and should not be deviated from by any utility. Steam generator tube integrity is defined as meeting the performance criteria as specified in NEI 97-06 (generally tube burst pressure under different accident conditions). Shall elements are those that are considered important to secondary system component reliability. It is recognized that shall elements may be subject to legitimate deviations due to plant differences and/or special situations. Recommended elements are those that are considered good or best practices that utilities should try to implement when practical. [Fruzzetti, 2009]

The mandatory, shall and recommended elements in these Guidelines are identified in Chapter 8 of the Guidelines [Fruzzetti, 2009]. To be in compliance with NEI 03-08 and NEI 97-06, utilities must meet the mandatory and shall elements in these Guidelines or provide a technical justification for any deviations for the shall requirements. There are no deviations allowed for mandatory requirements, that is, the requirement to have a strategic water chemistry plan for the primary and secondary systems. Any deviation to a shall element must be handled in accordance with the guidance in the current revision of the Steam Generator Management Program (SGMP) Administrative Procedures.

So far, this document has mentioned only secondary-side water chemistry guidelines, but similar requirements given for the primary water chemistry program. These will be addressed in Section 2.1.

2 Primary Water Chemistry Strategic Plan

2.1 Introduction to Optimizing the Primary SWCP

Providing a framework for plant chemistry personnel to develop an optimized primary chemistry program considering plant design, materials of construction, fuel design and cycle length, corrosion degradation history, regulatory commitments, fuel vendor warranty requirements, etc. is described in this section. Utilities should develop documentation to define a Strategic Water Chemistry Plan (SWCP). The development and maintenance of the Strategic Water Chemistry Plan is a mandatory requirement, and the only mandatory requirement, according to NEI 03-08 and NEI 97-06. [Fruzzetti, 2007]

Documenting the water chemistry plan recognizes that nuclear power plants must consider a variety of issues in developing a primary water chemistry program and these issues must be dealt with on a plant specific basis. [Note: A plant specific requirement, such as pH, is EPRI's point of view and is not necessarily compatible with the opinions of other ANT experts.] Optimization of the primary water chemistry program is the process of developing a program which reflects the technical bases of the impurities and limits. The SWCP should not, in any way, contradict the plant technical specifications but is meant to expand and clarify them. The chemistry control guidance should be optimized relative to approaches for insuring primary system pressure boundary and fuel cladding integrity and minimizing radiation fields. [Fruzzetti, 2007]

In addition to providing the technical bases for the primary water chemistry program, the Strategic Water Chemistry Plan shall: [Fruzzetti, 2007]

- Provide continuity of programmatic decisions to assist personnel understand why certain parameters or limits have been adopted, and
- Provide for periodic reviews, such as end-of-cycle reports, of technical bases to determine required program changes. End of cycle reports are not required but is generally a good practice. Some plants have even gone so far as to put these end of cycle reports into the SWCP.

Both NEI 03-08 and NEI 97-06 commit the industry to adopting the requirements of the EPRI *Guidelines* to ensure pressure boundary integrity and fuel cladding integrity. These requirements are identified as "mandatory" and "shall" parameters in these Guidelines (again, not to supersede technical specifications). However, not all the primary water chemistry parameters discussed in the EPRI *Guidelines* impact the pressure boundary or fuel cladding integrity. The parameters that have an effect on pressure boundary or fuel cladding integrity includes adopting site-specific chemistry limits within the appropriate bounds, including setting action levels. For example, Chemistry personnel could adopt a 50 ppb chloride limit as a station action level value, if a site-specific evaluation suggests that operation above this limit indicates possible ion exchanger deterioration. Chemistry personnel must document such decisions and include a brief description of the bases for the decision in their Strategic Water Chemistry Plan.

For those parameters that do not affect pressure boundary integrity or fuel cladding integrity, chemistry personnel have additional optimization flexibility. For example, RCS silica concentration limits must "balance" the possible effects on fuel deposits and the costs of clean-up. Silica has been identified as an important parameter by fuel vendors. This value can be adjusted in the optimization process based on the utility evaluation of risks of elevated silica operation and the costs of pre-start-up clean-up. Although in many cases the fuel vendor is the entity that supplies the silica limit rather than a utility or plant evaluation. Likewise, plants injecting zinc may have fuel vendor requirements that should be considered. Such an optimization philosophy can be implemented for all parameters that do not have a direct pressure boundary integrity or fuel cladding integrity impact.

The results of the optimization process should be incorporated into a station chemistry program that is approved for implementation by plant management (in the U.S., this is a plant manager or site vice president). The "Strategic Water Chemistry Plan" should be a living document that is reviewed periodically, such as the end-of-cycle or when a revised EPRI guideline is issued, and compared against plant experience and research data to determine if modifications are warranted.

2.2 Objective of the Plan

The purposes of the primary water chemistry control program [Fruzzetti, 2007] are to:

- Ensure primary system pressure boundary integrity,
- Ensure fuel cladding integrity and achievement of design fuel performance, and
- Minimize out-of-core radiation fields.

These goals can be competing. For example, raising the primary pH_T may be of benefit for reducing out of core radiation levels but this may not be possible because fuel vendor limit values may be exceeded. In this case, a balance must the determined. The best chemistry control approach for accomplishing one of these goals may not be the best approach for another. Therefore, chemistry programs may reflect a compromise based on station-specific or utility priorities. The highest priorities will always be the water chemistry approaches that ensure pressure boundary integrity and fuel cladding integrity.

The parameters that affect pressure boundary integrity or fuel cladding integrity are generally designated control parameters, that is, parameters whose limits should not be exceeded for lengthy periods of time. They have associated action level values and/or hold limits, monitoring frequencies, and corrective actions. These identified parameters limits are considered "shall" requirements as well as their action levels. A lower priority for the primary water chemistry program is radiation field control.

2.3 Parameters Impacting the Pressure Boundary or Fuel Cladding Integrity

Action level limits and monitoring frequencies for parameters having an established impact on primary system pressure boundary or fuel cladding integrity should be specified. Chemistry personnel may adopt specific values within predefined ranges without technical justification because the ranges identified are consistent with the appropriate technical bases. Chemistry personnel may also adopt values either action level values, hold values or monitoring frequencies, outside the specified ranges if justified by a formal technical evaluation. Deviations to "shall" requirements shall be handled in accordance with the guidance of the Steam Generator Management Program (SGMP) Administrative Procedures. This evaluation must be documented and approved by station management in the Primary SWCP. Utilities may also adopt action levels which are less conservative, but each is considered a deviation to a "shall" requirement and shall be handled in accordance with the SGMP Administrative Procedures. The impact on primary system pressure boundary or fuel cladding integrity should be specified.

Chemistry personnel should not adopt specific values within these predefined ranges without technical justification because the ranges identified are consistent within established technical bases. Chemistry personnel may also adopt values if justified by a formal technical evaluation. Deviations to "shall" requirements shall be handled in accordance with the guidance in the SGMP Administrative Procedures. This evaluation must be documented and approved by station management in the "Primary Strategic Water Chemistry Plan." [Fruzzetti, 2007]

3 Secondary Water Chemistry Strategic Plan

The primary and the secondary strategic water chemistry plans required for U.S. plants are similar. Both are required by the previously referenced NEI documents and the approach is outlined in the EPRI primary and secondary water chemistry guidelines. Both plans are required to be periodically reviewed and updated according to the water chemistry guidelines and other documents, such as fuel vendors or NSSS manuals, as appropriate. In particular, the secondary strategic plan should be reviewed by a variety of plant personnel including the chemistry manager, SG engineer, and the Operations manager.

In general, the secondary plan tends to be more complicated than the primary plan owing to the diversity of construction materials, temperature and pressures, of the different components.

It can be, and has been, argued that some elements in the secondary (and primary) strategic water chemistry plan are more related to reliability than SG integrity. This debate will not be resolved in this document.

3.1 Introduction to the Plan

According to EPRI, owing to the wide range of conditions and materials of construction in the secondary system, no single optimum water chemistry program's parameters can be specified for similar PWRs. **Note: this position is not taken by several ANT chemistry experts.** As noted earlier, the plan governing the optimization of the water chemistry program requires development and maintenance. The Plan should consider factors such as steam generator and Balance of Plant (BOP) component design, operating history and use of condensate and/or blowdown demineralizers. The overall objective of the optimization is to maximize the total avoided costs from corrosion and other performance related issues while minimizing operating costs. The approach presented considers the relative risks/benefits of various chemistry programs on a component-by-component basis.

EPRI argues that the relative importance of individual components should be evaluated based on utility and plant specific considerations. This is based on the assumption that trade-offs exist whereby optimization of the water chemistry program for one component (e.g., steam generators) could negatively impact costs of operating other components (e.g., demineralizers).

According to EPRI the development of a cost/benefit analysis for secondary chemistry is difficult for several reasons. [Fruzzetti, 2009]

1. The long-term benefits of water chemistry cannot be easily quantified, although the value of minimizing corrosion is well understood. Lower steam generator sodium levels are expected to result in reduced steam generator corrosion. Although the potential cost savings cannot be accurately determined, the expense of reducing sodium often can be quantified (e.g., improved condensate polisher regeneration, etc.). In cases where the cost can be quantified but the benefit can be assessed only qualitatively, optimization consists of pursuing the minimum cost water chemistry program which provides the greatest expected benefit (e.g., lowest sodium levels).
2. Sometimes, both the costs and benefits can be quantified. If several amines can be used for pH control in the secondary system, the costs associated with the amine program can be determined with the aid of secondary side software models, such as EPRI ChemWorks™ or the EPRI/EDF "CIRCE – PWR Secondary Water Chemistry Optimization Tool." Both model the chemistry around the secondary system, the corrosion product transport to the steam generators and resultant steam generator fouling. The value of the benefits can be assumed as a first approximation to be proportional to the feedwater iron concentration achievable with a given amine program. The optimum amine program then would be the lowest cost program which achieved a target iron value. The target iron value would be determined on a more qualitative basis. For plants using condensate and/or blowdown demineralizers, the use of alternate amines could also increase contaminant levels in the system when demineralizers are allowed to remain in service beyond the amine break. Optimization of the amine program must also, at least, qualitatively assess the cost of contaminants in the system. This could be

achieved by establishing an upper contaminant limit in the system and determining the minimum cost amine program which achieves both the contaminant and iron targets.

3. The trade-offs are illustrated for the optimization of the pH control program. Optimization for one component or portion of the system can lead to less than optimum conditions in other parts of the system. Therefore, an overall systems approach must be taken in developing the SWCP. To do this effectively, a ranking system should be provided. The ranking system attempts to put the qualitative factors on a firmer basis. The system considers the merits of the secondary water chemistry initiatives. Each utility must evaluate the merits of each initiative relative to plant design specific design features, materials of construction, etc. Ultimately, a utility must decide where it sees its greatest risks and potential rewards.

3.2 Key Elements of a Strategic Water Chemistry Plan

The items in the list below are recommendations for elements of the SWCP: [Fruzzetti, 2009]

- Statement of the objectives of the Plan
- Key plant design parameters, chemistry milestones and significant plant transients
- Evaluation of technical issues, including risk/susceptibility/performance
- Evaluation of chemistry control strategies
- Deviations from identified mandatory, shall, or recommended elements
- References (such as NSSS documents, EdF, Siemens, Westinghouse, B&W, EPRI, etc.)

3.3 Objectives of the Strategic Water Chemistry Plan

The objectives of the plan may be plant specific depending upon the utility and should be aligned with corporate goals. Examples of such objectives could be:

- Implement water chemistry programs considering the relative risk and expected benefits of different chemistry control approaches
- Maximize total avoided costs from material degradation and other performance related issues while minimizing operating costs
- Optimize water chemistry programs balancing plant design and operating considerations along with materials issues
- Align decisions that affect chemistry (and thus systems and components) with overall corporate goals
- Improve the understanding and cooperation of chemistry related materials management issues by communicating and coordinating chemistry program actions with other departments such Engineering, Fuels, Operations, SG Engineer, Low Level Radwaste Processing, Radiation Protection, etc.

3.4 Key Plant Design Parameters, Chemistry Milestones and Significant Plant Transients

Similar to the Primary plan, the secondary plan should include a listing of key system materials, plant design parameters and a history of key milestones/events, including past secondary chemistry programs. This may most easily be expressed in a table format. Table 3-1 is a generic example of documenting key design and operating parameters. Table 3-4 presents a generic example of documenting plant milestones and events. Table 3-2 and Table 3-3 are from an actual U.S. four-loop PWR plant.

Table 3-1: Example of Key Design and Operating Parameters

Parameter	Value	Parameter	Value
Rated Power (MW_t)		SG Tube Expansion Method	
Initial Criticality		Steam Pressure, full load, psia	
Commercial Operation		Steam Temperature, full load, °F	
Current Fuel Cycle	Cycle X	Primary Side, T-hot, °F	
EFPYs @ EOC X-1		Primary Side, T-cold, °F	
Number of SGs		Main Condenser Tubesheet / Tube Material	
Number of SG tubes / % plugged		Main Condenser Tubesheet Coating Material	
SG Manufacturer / Model		LP FW Heater Tubing Material	
SG Tube Material		HP FW Heater Tubing Material	
Total Surface Area of SG Tubes, Primary Side, ft^2		Reheater Tubing Materials (MSR)	
SG Support Plate Material		Type of Cooling Water	
SG Tube Support Configuration		Condensate Purification Method	
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4 Important Points

- Strategic Water Chemistry Plans for primary and secondary systems are a mandatory requirement (that is, none are allowed) of NEI 97-06 and NEI 03-08. This is a U.S. nuclear industry commitment. NEI (Nuclear Energy Institute) is the U.S. nuclear industry's regulatory interface with the Nuclear Regulatory Commission (NRC). The "shall" and "recommended" elements of the plan are given in the EPRI primary and secondary water chemistry guidelines.
- The guidelines are required to be reviewed and updated, if needed, periodically (end of cycle) or after a revision to the EPRI guidelines. The water chemistry guidelines per procedure must be reviewed every two years to determine if a revision is appropriate. If a revision is not issued, then the guidelines are reviewed annually until a revision is published.
- The EPRI water chemistry guidelines are controlled by the Steam Generator Management Program (SGMP) administrative procedures. The SGMP is managed by EPRI but is funded outside the EPRI base budget. All nuclear utilities are required to be members of the SGMP.
- "Shall" elements require a documented justification if any deviations are taken.
- Some people argue that some of the elements in the primary and secondary guidelines do not directly relate to steam generator reliability such as the primary suspended solids and organics. This may be true, since in the U.S. it is common to approach programs (especially for utilities) such as these very conservatively rather than have separate programs for those elements that affect SG integrity and those that affect SG performance.
- Despite the additional work, in general, the SWCP have provided a benefit to the overall water chemistry programs in the U.S. by focusing the plants to include all important system parameters with respect to the steam generator, primary system and fuel cladding integrity. They also instruct plant Chemistry and/or Utility personnel to document these plans in a retrievable format.

References

Fruzzetti, K., *EPRI Pressurized Water Reactor Primary Chemistry Guidelines, Revision 6*, December 2007

Fruzzetti, K., *EPRI Pressurized Secondary Water Chemistry Guidelines, Revision 7*, February 2009

Rochester, D.P., *Duke Energy Nuclear Generation Division (NGD) System Chemistry Manual (SCM), SCM-12, Revision 7, Appendix A, "Catawba Primary Chemistry Optimization Plan"*, June 2007

Rochester, D.P., *Duke Energy Nuclear Generation Division (NGD) System Chemistry Manual (SCM), SCM-8, Revision 11, Appendix A, "Catawba Secondary Chemistry Optimization Plan"*, May 2005

List of Abbreviations

3-MPA	3-methoxypropylamine
BOC	Beginning of cycle
BWI	Babcock & Wilcox International (Canada)
°C	Centigrade (Celsius) degrees
DE	Duke Energy
DMA	Dimethylamine
EFPY	Effective full power years
EOC	End of cycle
EPRI	Electric Power Research Institute
°F	Fahrenheit degrees
FRA	Framatome
HP	High Pressure
LP	Low Pressure
MOX	Mixed oxide fuel
MRP	EPRI Materials Reliability Program
MSR	Moisture separator reheater
MWt	Megawatts thermal
NEI	Nuclear Energy Institute
NGD	Nuclear Generation Division (Duke Energy)
NH4Cl	Ammonium chloride
NRC	Nuclear Regulatory Commission
PWR	Pressurized Water Reactor
PWSCC	Primary water stress corrosion cracking
psia	Pounds per square inch, absolute (pressure)
R	Reliability
RO	Reverse osmosis
S	Susceptibility
SCC	Stress corrosion cracking
SCM	System Chemistry Manual
SG	Steam Generator
SGMP	Steam Generator Management Program
SS	Stainless steel
SWCP	Strategic Water Chemistry Plan
T_{ave}	Average temperature
UST	Upper surge tank (secondary)
X	Cycle number

Unit conversion

TEMPERATURE		
°C + 273.15 = K		°C × 1.8 + 32 = °F
T(K)	T(°C)	T(°F)
273	**0**	32
289	16	61
298	25	77
373	**100**	212
473	**200**	392
573	**300**	572
633	360	680
673	**400**	752
773	**500**	932
783	510	950
793	520	968
823	550	1022
833	560	1040
873	**600**	1112
878	605	1121
893	620	1148
923	650	1202
973	**700**	1292
1023	750	1382
1053	780	1436
1073	**800**	1472
1136	863	1585
1143	870	1598
1173	**900**	1652
1273	**1000**	1832
1343	1070	1958
1478	1204	**2200**

Radioactivity	
1 Sv	= 100 Rem
1 Ci	= 3.7×10^{10} Bq = 37 GBq
1 Bq	= 1 s^{-1}

MASS	
kg	lbs
0.454	**1**
1	2.20

DISTANCE	
x (µm)	x (mils)
0.6	0.02
1	0.04
5	0.20
10	0.39
20	0.79
25	0.98
25.4	**1.00**
100	3.94

PRESSURE		
bar	MPa	psi
1	0.1	14
10	**1**	142
70	7	995
70.4	7.04	**1000**
100	10	1421
130	13	1847
155	15.5	2203
704	70.4	**10000**
1000	100	14211

STRESS INTENSITY FACTOR	
MPa√m	ksi√inch
0.91	**1**
1	1.10