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Scoping Study of Moisture Carryover in Boiling Water Reactors

2010 TECHNICAL REPORT

Scoping Study of Moisture Carryover in Boiling Water Reactors

1021185

Final Report, December 2010

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ACKNOWLEDGMENTS

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This report describes research sponsored by EPRI.

This publication is a corporate document that should be cited in the literature in the following manner:

Scoping Study of Moisture Carryover in Boiling Water Reactors. EPRI, Palo Alto, CA: 2010. 1021185.

ABSTRACT

Several BWRs have recently experienced higher than expected shutdown dose rates in steam-affected components/areas. The dose rate increases appear to be associated with increases in reactor water Co-60 activity and moisture carryover (MCO), particularly in the latter portions of the operating cycle. In addition to mechanical carryover, it has been suggested that volatile impurities such as hydrochloric acid may be transported with the BWR steam and concentrate in condensate on surfaces, such as the low pressure turbine, and accelerate corrosion.

The objective of this scoping study is to collect data and experience and to clearly identify the issues related to MCO and the increased transport of activity and chemical impurities to balance of plant systems. The project team completed the following tasks to support this work.

- Assembled a database of BWR design and operating characteristics.
- Assessed plant procedures for measuring moisture carryover.
- Collected moisture carryover data and related plant operational conditions.
- Collected data on steam component dose rates and corrosion product activity levels on BOP components and condensate cleanup systems.

Keywords
Activity transport
BWR
Hydrochloric acid
Moisture carryover
Steam cycle
Steam transport
Volatility

REPORT SUMMARY

Several boiling water reactors (BWRs) have recently experienced higher than expected shutdown dose rates in steam-affected components/areas. This report documents the results of a scoping study to identify issues related to moisture carryover (MCO) and areas for future work.

Background

The shutdown dose rate increases observed in some BWRs appear to be associated with increases in reactor water Co-60 activity and MCO, particularly in the latter portions of the operating cycle. General trends in the BWR industry indicate that a number of changes could be contributing to these increases. These include core design and operation, power uprate, first applications or reapplications of NMCA or OLNC, changing to two-year fuel cycles, reducing feedwater iron input through filtration and/or component replacement and other operational changes. In addition to mechanical carryover, it has been suggested that volatile impurities such as hydrochloric acid (HCl) may be transported with the BWR steam and concentrate in condensate on surfaces, such as the low pressure turbine, and accelerate corrosion. It was suggested that this type of corrosion risk should be considered in future chemistry guidelines.

Objective

To collect data and experience to clearly identify the issues related to MCO and the increased transport of activity and chemical impurities to balance of plant systems.

Approach

The project team assembled a database of BWR design and operating characteristics to support the identification of design or operating conditions that may relate to MCO and volatile impurity transport. They also assessed plant procedures for measuring moisture carryover and collected MCO data along with related plant operational conditions. The report also documents data on steam component dose rates and corrosion product activity levels on balance of plant (BOP) components and condensate cleanup systems that may have been related to MCO. The project team evaluated the data for correlations between moisture carryover, corrosion product activity transport to the steam system, and dose rates on steam system components and condensate cleanup resins. They assessed impurity transport in steam by volatile impurities and those carried by entrained moisture, and BWR steam purity relative to standards established for fossil drum boilers operating at the same pressure.

Results

The cause of increased moisture carryover at plants that do not have failed steam dryers is increased loading on the steam separators, due either to increased steam velocities with power uprate, or very low quality steam from peripheral bundles following the change to a low leakage

core design. Moisture carryover tends to increase at the end of the cycle, when core flow is maximized to maintain power output. Several plants have experienced increases in shutdown radiation fields from steam system components, which correlate to an increase in the transport of radioactive corrosion products (Co-60) to the steam cycle as a consequence of elevated reactor water activity and increased MCO.

The transport of the corrosive impurity HCl in BWR steam was assessed. The concentration in steam is very low for BWRs that operate within the BWR Water Chemistry Guidelines with moisture carryover <0.1%. A very high concentration of reactor water chloride in combination with a very high MCO would be required to approach the steam purity limit of 2 ppb for fossil drum boilers operating at 1000 psia.

Since the BWR produces saturated steam, there is no phase transition zone in the high pressure turbine for concentrated solutions or turbine deposits to form. For non-reheat steam cycles, the low pressure turbines similarly will not be affected. BWRs with steam reheat may have the potential to form moisture concentrated in impurities in the phase transition zone. However, for BWRs operating within the BWR Water Chemistry Guidelines with moisture carryover <0.2% and moisture separation efficiency >99% in the moisture separator reheater (MSR) the concentrations will be a few tens of ppt.

EPRI Perspective

This report gathers recent industry data on MCO and corrosion product activity transport to the steam cycle, and documents evaluations performed at a number of plants that have identified the causes of increased moisture carryover and increased radiation fields. The information provides a basis for evaluating approaches to reduce radiation dose and chemistry impacts in further work to be supported by the Nuclear Program, potentially including BWRVIP, Fuel Reliability Program, Chemistry and Radiation Management. The project team recommends future work to include evaluating the steam transport of sodium and the sulfate anions and zinc and its potential effects. They also suggest applying EPRI expertise for impurity transport, turbine deposition and corrosion, and steam purity limits on the fossil side to BWR steam chemistry and potential turbine impacts and conducting a survey to document instances of deposition and corrosion in BWR turbines that may have been related to corrosive impurities in steam.

Keywords

Activity transport
BWR
Hydrochloric acid
Moisture carryover
Steam cycle
Steam transport
Volatility

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1
INTRODUCTION AND BACKGROUND

Problem Statement

Recently several BWRs have experienced higher than expected shutdown dose rates in steam-affected components/areas. The dose rate increases appear to be associated with increases in MCO (moisture carryover), particularly in the latter portions of the operating cycle. General trends in the BWR industry indicate that a number of changes could be contributing to these dose rate increases such as core design and operation, power uprate, first applications or reapplications of NMCA or OLNC, changing to two-year fuel cycles, reducing feedwater iron input through filtration and/or component replacement, and other operational changes. Some of the recent industry experience is summarized as follows:

- Exelon has been working with Global Nuclear Fuels (GNF) to determine the root cause of increased steam-affected area dose rates in Limerick Generating Station's spring 2009 refueling outage for Unit 2. The evaluation highlighted a ~3X increase in MCO for the last three months of the cycle, compared to prior cycles. Given that reactor water radioisotopes, most significantly Co-60, tend to increase at end of cycle, the increased MCO is likely a significant factor in the increased steam area dose rates.

- Peach Bottom 3 also had an event after its first OLNC application, where there was relatively high MCO and higher than expected contamination levels in the main steam piping in the turbine area.

- Vermont Yankee, Pilgrim and LaSalle have reported dose increases in the balance of plant steam-affected areas.

- Hatch has reported IGSCC indications on a Low Pressure Turbine rotor, which may be related to the transport of chemical impurities with increased MCO.

GE SIL No. 644 [1] was issued in response to BWR steam dryer cracking found at plants that were operating under OLTP (original licensed thermal power) or EPU (extended power uprate) conditions. Monitoring for MCO is recommended in BWRVIP-190: BWR Water Chemistry Guidelines – 2008 Revision [2] and in GE Nuclear Energy SIL (Service Information Letter) 644, Revision [2], for assessing the performance of the steam dryer. It is noted that MCO may be impacted by factors other than steam dryer cracking, including reactor power level, core flow and power distributions, localized hot spots, core inlet sub-cooling (related to final feedwater temperature) and reactor water level. MCO has been observed to increase when steam flow is increased toward the center of the core, core inlet sub-cooling decreases (feedwater temperature

increases), reactor level increases (due to degraded separator performance) or changes in core power distribution are associated with an increased radial peaking factor.

BWRVIP-190 and GE SIL No. 644 discuss MCO monitoring approaches for plants with cascaded heater drains and those with forward-pumped drains (FPD). Quantification of MCO is normally based on gamma isotopic analysis of liquid samples drawn from the reactor coolant and either the condensate pump discharge (for plants with cascaded drains) or the high pressure heater drains (for plants with FPD). The isotope normally used to quantify MCO is Na-24. Per GE SIL No. 644, sampling approaches should be used that are capable of quantifying Na-24 in the condensed steam rather than using "less than" values if MCO exceeds 0.025%. Care must be taken to avoid overestimating the Na-24 concentration as a result of interference from I-135, if present.

BWRVIP-190 reports that 57% of BWRs surveyed measure MCO at least monthly. Data collected under the EPRI BWR Chemistry Monitoring and Assessment program show that normal MCO varies with BWR type, with older designs (BWR-2, BWR-3) having higher MCO than newer designs (BWR 4 – 6).

In addition to mechanical carryover, it has been suggested that volatile impurities such as HCl may be transported with the BWR steam and concentrate in condensate on surfaces, such as the low pressure turbine, and accelerate corrosion [3]. The likelihood of this potential corrosion mechanism depends on the availability of a significant source of volatile compounds in the reactor feedwater and the chemistry of the reactor coolant that may drive the dissociation of such species, causing them to become non-volatile. It was suggested that this type of corrosion risk should be considered in future chemistry guidelines [3].

Objectives of Study

Prepare a Scoping Study to document BWR plant design characteristics, core design changes, MCO results, chemistry data, plant experience, trends and issues related to MCO. Document issues related to increased MCO as a basis for evaluating approaches to reduce radiation dose and chemistry impacts in further work to be supported by the Nuclear Program, potentially including BWRVIP, Fuel Reliability Program, Chemistry and Radiation Management.

Results

Industry operating experience was reviewed to priority plants for this study. The following plants, which have experienced elevated MCO or problems believed to be related to MCO were identified and solicited for information:

- Quad Cities Units 1 and 2
- Forsmark Units 1, 2 and 3
- Hatch Units 1 and 2
- LaSalle Units 1 and 2

- Limerick Units 1 and 2
- Peach Bottom Units 2 and 3
- Pilgrim
- Vermont Yankee

Plant design characteristics and typical chemistry data were obtained and tabulated. Operating experience with MCO, corrosion product transport to the steam system, and steam system dose rates was obtained and evaluated. Plant practices for measuring MCO were reviewed, and best practice guidance for sampling for MCO is provided.

An evaluation of the potential for corrosive impurities to be transported to the steam cycle was performed, focusing on hydrogen chloride, which is a highly aggressive impurity that also has significant steam volatility.

Evaluations

Analyses were performed at a number of plants that have experienced elevated MCO to understand the causes and to identify corrective actions. In the absence of mechanical failure of the steam dryer, the root cause of increased MCO is over-loading of the original equipment steam separators, either with lower quality steam or excessive steam velocity. This increased the moisture loading on the steam dryer, resulting in greater pass-through of moisture to the steam leaving the RPV.

The steam separators are mounted on the RPV shroud head a short distance above the core, and distributed uniformly over the cross-sectional area of the core. The core is orificed to distribute inlet water over the fuel bundles, but power distribution is not uniform. Consequently, lower power bundles discharge steam with lower quality than high power bundles, and high power bundles discharge a steam/water mixture with a higher velocity than low power bundles. Since the distance from the core discharge to the steam separator inlets is short, there is little opportunity for the steam and water loadings to be equalized to the separators. The original equipment steam separators were likely designed to accommodate a range of steam qualities and velocities, based on the original license thermal power and the core loading strategies of the time.

The primary causes of increased MCO are as follows:

1. Increase in rated power, which increases the amount of steam generated for the same core flow (increasing steam quality but also increasing velocity)

2. Low leakage core designs, which reduce power output on the periphery and increase power in the center. This reduces the steam quality from the peripheral bundles, putting a high moisture loading on the peripheral steam separators, and increases steam velocity to the central separators.

Higher core flow rates, which reduce steam quality, may also produce noticeable increases in MCO, since the steam separators and dryers must remove a greater quantity of water from the steam. Core is adjusted between rod sequence exchanges to maintain full power, resulting in periods when core flow is near maximum. At the end of the cycle, core flow is maximized to maximize power output during the remaining weeks of full power operating and during coastdown. Hence, MCO tends to be elevated at the end of the cycle relative to the beginning and middle of the cycle.

Options for limiting MCO during operation are limited. Core flow can be reduced, but at the expense of power production. At plants that both increase core flow and reduce feedwater temperature at the end of cycle to maintain full power, there is some benefit to reducing feedwater temperature first, to delay increasing core flow and to minimize the time spent at maximum core flow.

There may be some potential to design core loading to reduce the difference in core power between the center and the periphery, but the effects on fuel economics are likely to be significant.

Mechanical design options include changing the fuel orificing to reduce flow to the peripheral bundles and upgrading the steam separators. The Forsmark units have installed uprated steam separators to reduce MCO.

A combination of high reactor water Co-60 activity and high MCO can result in the transport of sufficient activity to increase radiation levels in areas where activity can be deposited. Some stations have correlated increases in steam-side radiation levels with curies of Co-60 transported with steam over a cycle. However, other plants with similar combinations of high reactor water activity and high MCO have not seen suffered increased radiation levels. This may be related to the design of the steam cycle or to the form of Co-60 in reactor water. Further study may be warranted.

There is a large body of literature on the transport of boiler impurities to steam and subsequent corrosion damage, much of it generated by ORNL and funded by the EPRI Fossil Division. This work formed the bases for steam purity limits for fossil boilers. Although transport conditions for PWR steam generators and BWRs were considered in this work, no steam purity limits were derived for BWRs from it. For this report, the potential for one of these impurities, hydrogen chloride, to be transported to the turbines and other steam cycle components, resulting in corrosion damage, was evaluated. Volatile chloride transport to main steam is low for normal BWR conditions. With 4.25 ppb chloride in reactor water (equivalent to 5 ppb at the steam/water interface), the equilibrium concentration in steam due volatility is ~0.3 ppt. With 0.2% MCO, the total concentration in steam (volatile plus entrained moisture) is ~10 ppt.

Since the BWR produces saturated steam, the high pressure turbine is wetted throughout and there is no deposition of highly soluble materials such as chloride. For plants with moisture separation between the high pressure and low pressure turbines, but no reheat, the low pressure turbines are also wetted throughout. Therefore, corrosive impurity transport with steam is not a significant risk to non-reheat BWR steam cycles.

For BWR cycles with reheat, after moisture removal steam is superheated by about 150°F to increase thermal efficiency and reduce water formation in the low pressure turbines. Entrained water from the moisture separator will be evaporated, releasing volatile impurities (or highly concentrated droplets) to the steam entering the low pressure turbines. At some point in the turbine, moisture will again form as work is extracted from the steam. The location of the start of moisture formation in a turbine fed superheated steam is known as the Phase Transition Zone (PTZ). The "early condensate" or the first condensate to form from the steam will be concentrated in impurities. The literature indicates concentration factors in the range of 5 to 100. Corrosion from steam-born impurities has been observed in the vicinity of the Phase Transition Zone.

For the example above, with 10 ppt chloride in steam from the RPV, the quantity of chloride entering the low pressure turbine will depend on the inlet steam flow, the moisture content upstream of the moisture separator reheater (MSR), and the MS efficiency. Assuming typical values of 70% steam to the low pressure turbines (after moisture removal), 15% moisture in the steam entering the MS, and a MS efficiency of 99%, the concentration of chloride in the steam entering the low pressure turbine would be ~0.12 ppt. Assuming a concentration factor of 100 in early condensate, the concentration would be 12 ppt.

Although higher concentrations would be predicted with lower MS efficiencies, higher MCO and higher reactor water concentrations, the range of concentrations is well below acceptable levels for fossil drum units at 1050 psia (<0.45 ppm chloride in boiler water). Therefore, turbine corrosion does not appear to be of significant concern for BWRs with reheat cycles operating within the BWR Water Chemistry Guidelines.

Future Work

Collect and evaluate operating experience and perform evaluations to understand the relationships among the magnitude and forms (soluble or insoluble) of reactor water Co-60 activity, MCO, plant design or operation and the buildup of radiation fields in steam-bearing equipment and on condensate cleanup system filters and resins. Identify methods to minimize radiation field buildup even when MCO and/or reactor water Co-60 activity are high.

Perform evaluations similar to those for fossil units on impurity transport in BWR steam cycles. Confirm that existing BWR Water Chemistry Guidelines are adequate to minimize corrosive impurity transport to the steam cycle, or develop further guidelines on reactor water quality or steam purity as appropriate.

In conjunction with the EPRI Fuel Division, quantify the relationships among core power distribution, steam/core flow ratio and MCO. Provide recommendations for fuel loading or core operation that would reduce MCO without significantly affecting fuel economics.

2
BWR DESIGN AND OPERATING CHARACTERISTICS

BWR Design and Operation Characterization

Moisture carryover (MCO) is a measure of the portion of liquid phase water in the steam-water mixture leaving the BWR reactor vessel. The steam separators and dryers in the reactor vessel are designed to efficiently remove liquid from the steam-water mixture exiting the reactor core. MCO can be used to monitor the performance of the steam dryer under operating conditions. The dryer design specification for many General Electric BWRs is 0.1% MCO at original licensed power. This value is also a monitoring guideline in GE SIL 644. [1]

Moisture carryover is a design characteristic of a nuclear reactor which has taken on greater emphasis since cracks in the reactor steam dryer were discovered at Quad Cities Units 1 and 2 and Dresden Units 2 and 3. GE issued SIL No. 644 on August 21, 2002 and SIL No. 644, Supplement 1 on September 5, 2003 documenting their concerns and recommendations for monitoring steam dryer performance. Nuclear plants began measuring MCO regularly to monitor the steam dryer during plant operation.

The onset of MCO monitoring led to concerns when MCO would increase unexpectedly or exceed the 0.1% level mentioned in the GE SIL. The priority plants contacted for this study have each had issues known to the industry that appeared to be MCO related. The priority plants are: Dresden Units 2 and 3, Quad Cities Units 1 and 2, Forsmark Units 1, 2 and 3, Hatch Units 1 and 2, LaSalle Units 1 and 2, Limerick Units 1 and 2, Peach Bottom Units 2 and 3, Pilgrim and Vermont Yankee.

Since 2002, steam dryer cracking and flow-induced vibration damage on components and supports for the main steam and feedwater lines have been observed at Quad Cities and Dresden following extended power uprates (EPUs). Modifications have since been made at Quad Cities Units 1 and 2 and Dresden Units 2 and 3 to the steam dryers.

Peach Bottom Units 2 and 3 and Limerick Units 1 and 2, have observed spikes in MCO. Pilgrim, Vermont Yankee and LaSalle have reported dose increases in the balance of plant steam affected areas. Forsmark Units 1, 2 and 3, have experienced elevated moisture carryover and have since made modifications to their steam separators and dryers. Hatch has reported IGSCC (intergranular stress corrosion cracking) indications on a low pressure turbine rotor, which may be related to the transport of chemical impurities with increased MCO.

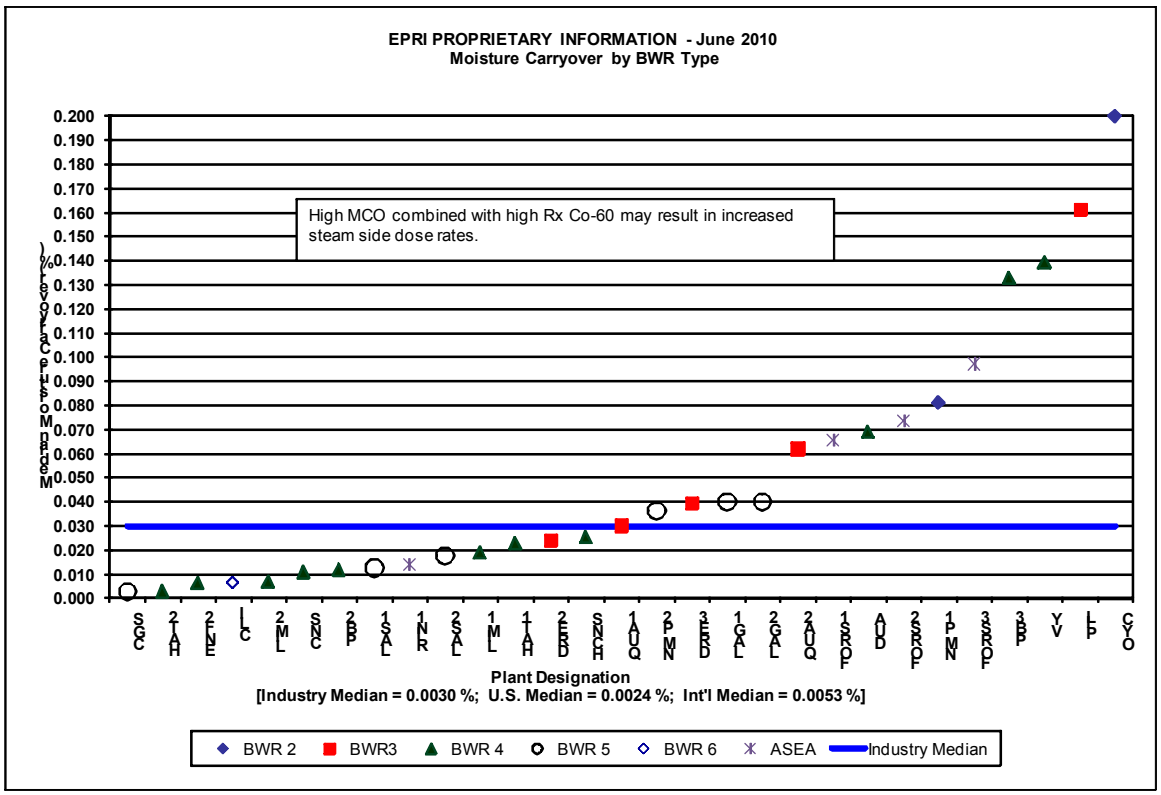


Figure 2-1
2009 Median Moisture Carryover by BWR Type

Moisture carryover is highest at BWRs 2 and 3. Improvements in steam dryer efficiencies and differences in core and vessel design have resulted in generally lower % MCO in later model BWRs. A BWR 2, Oyster Creek has the highest median MCO value. The Vermont Yankee steam dryer is a BWR 3 type. The Quad Cities and Dresden Plants steam dryers have been modified.

BWR NSSS and BOP Design Information

NSSS and BOP design information for the priority plants is shown in Table 2-1. The Forsmark units are ASEA-Atom BWRs and the other priority plants are GE BWRs.

Table 2-1
Plant Design Characteristics

General Design Information					
Station	**Dresden**	**Forsmark 1 & 2**	**Forsmark 3**	**Hatch**	**LaSalle**
Utility	Exelon Corp - Nuclear	Vattenfall	Vattenfall	Southern Nuclear	Exelon Corp - Nuclear
BWR Model Number/ Containment	GE - BWR 3/Type 4g (Mark I)	ABB-Atom BWR 69	ABB-Atom BWR 75	GE - BWR 4/Type 4g (Mark I)	GE - BWR 5/Type 4g (Mark I)
Power Rating (MWe)/ (MWth)	912/2957	1010/2928	1190/3300	910/2804	1189/3489
Power Uprate	17%, 430 MWth (12/01 Unit 2, 11/02 Unit3)	to 108% (1985-1986 Unit 1, 1985 Unit 2)	1989 to 109%	5% (122 MWth)(8/95); 8% (205 MWth)(1/99 Unit1, 11/98 Unit 2); 1.4% (41 MWth)(2/05 Unit 1, 4/05 Unit 2)	5% (166 MWth)(2001 Unit 1, 11/00 Unit2)
Drains Path (Cascaded or FPD)	Cascaded	Cascaded	FPD	Cascaded	FPD
Reheat (Yes/No)	No	Yes	Yes	Yes	Yes
Station	**Limerick**	**Peach Bottom**	**Pilgrim**	**Quad Cities**	**Vermont Yankee**
Utility	Exelon Corp - Nuclear	Exelon Corp - Nuclear	Entergy Nuclear Northeast	Exelon Corp - Nuclear	Entergy Nuclear Northeast
BWR Model Number/ Containment	GE - BWR 4/Type 5g (Mark II)	GE - BWR 4/Type 4g (Mark I)	GE - BWR 3/Type 4g (Mark I)	GE - BWR 3/Type 4g (Mark I)	GE - BWR 4/Type 4g (Mark I)
Power Rating (MWe)/ (MWth)	1250/3458	1164/3514	687/2028	912/2957	648 est/1912
Power Uprate	5% (165 MWth)(1/96 Unit 1, 2/95 Unit 2)	5% (165 MWth)(10/94 Unit 2, 7/95 Unit 3); 1.6% MUR (65 MWth)(11/04 Unit 2, 10/03 Unit 3)	1.5% (30 MWth)(6/03)	17.8% (446 MWth) (12/02 Unit 1)(3/02 Unit 2)	20% (319 MWth)(5/06), BWR3-style dryer reinforced prior to uprate.
Drains Path (Cascaded or FPD)	Cascaded	Cascaded	Cascaded	Cascaded	Cascaded

Reheat (Yes/No)	No	No	No	No	No
Condensate/Feedwater System					
Station	**Dresden**	**Forsmark 1 & 2**	**Forsmark 3**	**Hatch**	**LaSalle**
Main Condenser Cooling Water Source	Kankakee river			Altamaha River	Lake/River
Condensate Purification System (DB/FD/Filter+DB)	Filter + Deep Bed (current)	F/D	F/D	F/D	F+DB
Total Condensate Flow (lb/hr)	1.12E+07	7.40E+06	8.09E+06	1.22E+07	9.98E+06
Total Feedwater Flow (lb/hr)	1.12E+07	1.16E+07	1.42E+07	1.15E+07	1.50E+07
Station	**Limerick**	**Peach Bottom**	**Pilgrim**	**Quad Cities**	**Vermont Yankee**
Main Condenser Cooling Water Source	River	Susquehanna River	Atlantic Ocean	Mississippi River	Connecticut River
Condensate Purification System (DB/FD/Filter+DB)	Filter + DB	F/D	D/B	F/D	F/D
Total Condensate Flow (lb/hr)	1.503E+07	1.40E+07	7.95E+06	1.13E+07	7.72E+06
Total Feedwater Flow (lb/hr)	1.503E+07	1.40E+07	7.95E+06	1.13E+07	7.72E+06
Reactor Water Cleanup System					
Station	**Dresden**	**Forsmark 1 & 2**	**Forsmark 3**	**Hatch**	**LaSalle**
RWCU Purification Type	DB	DB	DB	F/D	F/D
Normal Flow (% of Feedwater Flow)	2.6	1.7	1.7	1	0.9
Maximum Flow (% of Feedwater Flow)	2.8	2.7	2.8	1	0.9
Station	**Limerick**	**Peach Bottom**	**Pilgrim**	**Quad Cities**	**Vermont Yankee**
RWCU Purification Type	F/D	F/D	F/D	F/D	F/D

Normal Flow (% of Feedwater Flow)	1.1	1.07	1	1.74	0.8
Maximum Flow (% of Feedwater Flow)	1.1	1.2	1.5	2	0.8
Chemistry Regime					
Station	**Dresden**	**Forsmark 1 & 2**	**Forsmark 3**	**Hatch**	**LaSalle**
Hydrogen Water Chemistry	yes	no	no	yes	yes
Zinc Injection (NZO, DZO, or None)	DZO	none	none	DZO	DZO
NMCA	yes	no	no	yes	yes
LTNC	no	no	no	no	yes (Unit 2)
OLNC	No	no	no	no	no
Iron Addition to Feedwater	No	no	no	no	no
Station	**Limerick**	**Peach Bottom**	**Pilgrim**	**Quad Cities**	**Vermont Yankee**
Hydrogen Water Chemistry	Yes	yes	yes	yes	yes
Zinc Injection (NZO, DZO, or None)	DZO	DZO	DZO	DZO	DZO
NMCA	Yes	yes	yes	yes	yes
LTNC	No	no	no	yes	no
OLNC	no	yes (Unit 3)	no	no	no
Iron Addition to Feedwater	yes	no	no	no	no

Figure 2-2 shows the major components of the steam system of boiling water reactors. The reactor provides saturated steam with a small amount of moisture carryover to a high pressure turbine, which extracts work from the steam. The steam pressure and temperature decrease and water condenses out of the steam, such that the discharge steam contains ~15% moisture. The high pressure turbine operates "wet" throughout. The high pressure turbine exhaust steam passes through moisture separators (MS), which remove most of the water (>99% for newer designs) from the steam going to the low pressure turbines. At some plants, the steam is reheated to above the saturation temperature (superheated) to improve thermal efficiency. At plants with moisture separator reheaters (MSRs), the inlet stages of the low pressure turbine operate "dry" until the pressure and temperature are reduced to saturation, at which moisture begins to form. The location where moisture begins to wet the turbine is the Phase Transition Zone (PTZ). The initial condensate will be concentrated in whatever impurities may have been carried over from the MSR. At plants without reheat, the entire low pressure turbine operates wet, so there is no PTZ. Exhaust steam with entrained moisture from the low pressure turbines is condensed and collected in the hotwell.

Although not shown on Figure 2-2, for all plants the condensate and feedwater are heated to near reactor coolant temperature (e.g. ~400°F) prior to entering the reactor. Main steam and extraction steam from the high pressure turbine is condensed in the high pressure feedwater heaters, and main steam is also used for reheat in plants with MSRs. Lower temperature feedwater heaters are heated by extraction steam from the low pressure turbines. There are two common system designs for handling condensate from the feedwater heaters and MS(R) drains.

Forward Pumped Drains (FPD): The condensed steam from the high pressure feedwater heaters, the moisture separator drains, and condensed steam from the MSR if present are collected and pumped into the feedwater flow at a point where the temperatures of the two streams are about the same. All of this flow came from steam drawn upstream of the MS or MSR. The condensed steam from the low pressure feedwater heaters is cascaded back through lower temperature heaters to the condenser. About 70% of the steam from the reactor is collected in the condenser.

Cascaded Drains: The condensed steam from all the feedwater heaters, the moisture separator drains, and condensed steam from the reheater if present cascade back through the lower temperature heaters to the condenser. All the steam from the reactor is collected in the condenser.

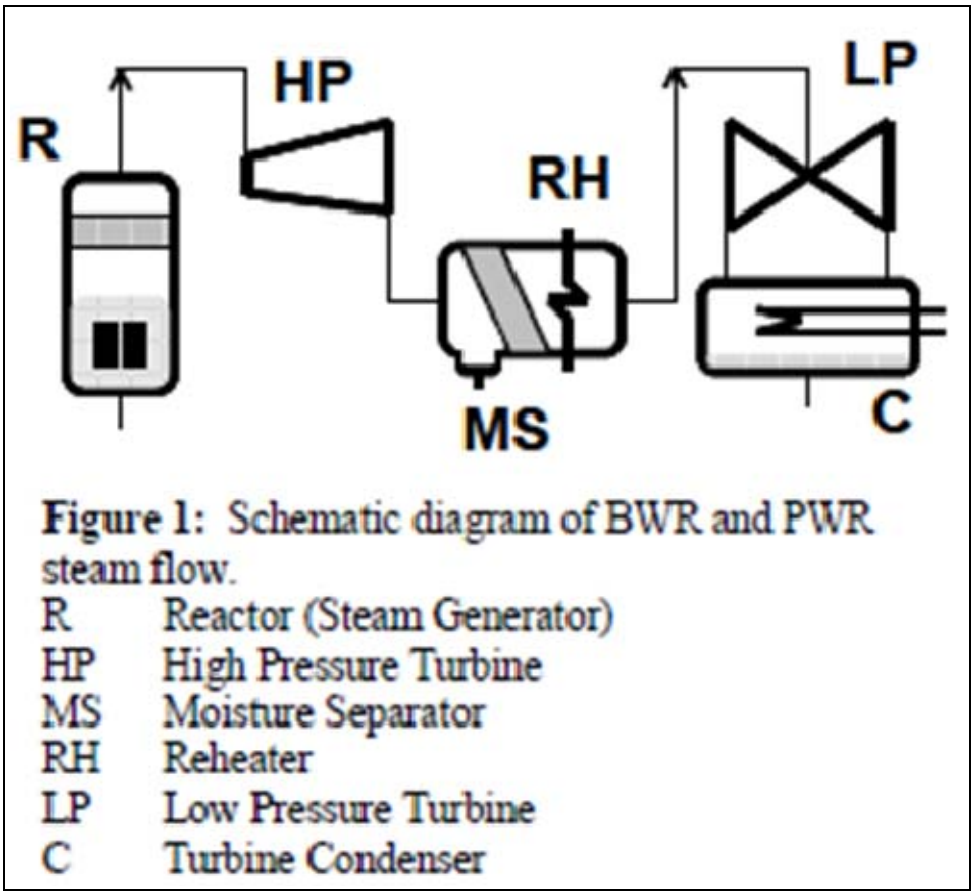


Figure 2-2
BWR Steam Flow Schematic Diagram

LaSalle Units 1 and 2 and Forsmark Unit 3, have forward pumped drains (FPD). In the FPD plants, low volatility species and trace contaminants carried over with moisture in the steam would be pumped to the final feedwater without passing through the condensate treatment system. Since the moisture separator removal efficiency is very high (>99% for newer designs), the fraction of non-volatile steam contaminants that migrate downstream to the low pressure turbines is very small. Moisture carryover for the FPD plants is calculated based on measurements of contaminants or tracers in the forward pumped drains.

LaSalle Units 1 and 2, Forsmark Units 1, 2 and 3 and Hatch Units 1 and 2, have moisture separator reheaters (MSRs). As the steam is superheated, contaminants in residual moisture would be concentrated as the liquid evaporated. Depending on the species, the contaminants would either volatilize, form particles, or form concentrated liquid droplets. The volatile species with low distribution factors between steam and water, such as HCl, would form concentrated solutions when moisture begins to form near the Phase Transition Zone (PTZ), potentially setting up locally corrosive conditions.

The reactor water cleanup (RWCU) system removes contaminants from the reactor water. Systems with higher capacity (% of feedwater flow) can be more efficient at removing contaminants that could be carried over with the steam.

Chemistry Regimes, Power History, Fuel Strategy

The power uprate history for each of the priority plants is included in Table 2-1. Power uprates have a profound effect on moisture carryover. The MCO increase at Vermont Yankee after an extended power uprate of 20% in May 2006 is shown in Figure 2-3.

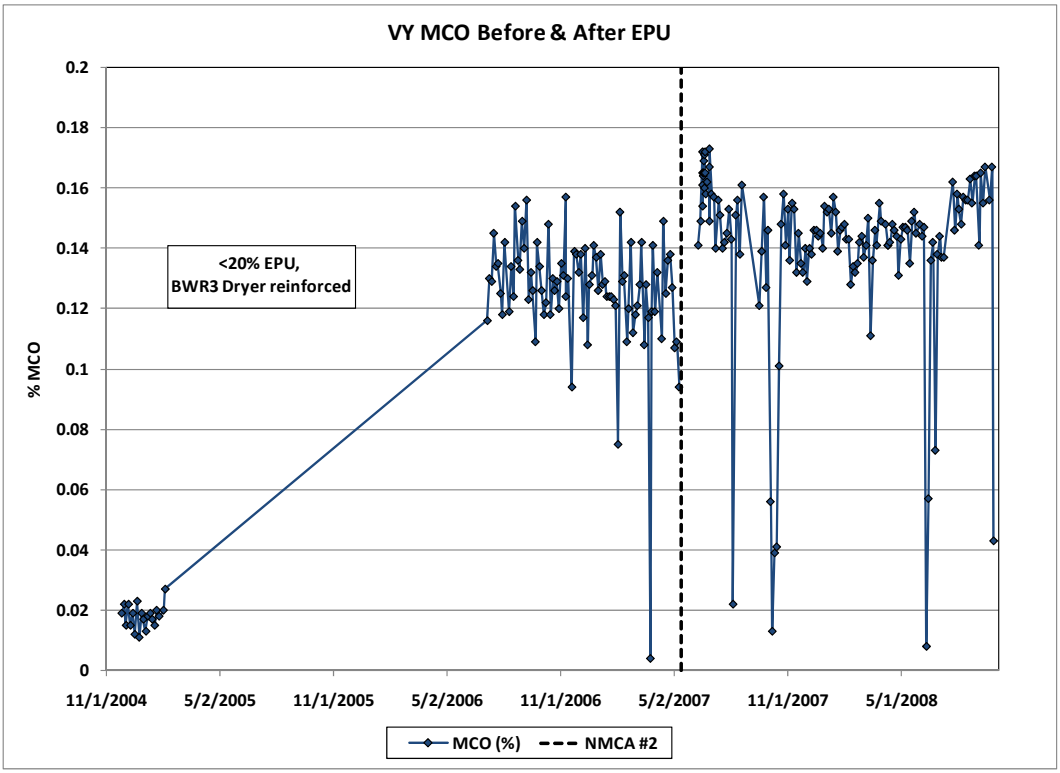


Figure 2-3
Moisture Carryover before and after EPU at Vermont Yankee

Figure 2-3 also shows an MCO increase after a noble metals reapplication (NMCA) in May 2007. The chemistry regime of all of the priority plants is shown in Table 2-1. All of the priority plants add noble metals, zinc and hydrogen, except for the Forsmark plants. The Forsmark plants do not add any chemicals to the reactor.

Moisture carryover has been observed to increase when steam flow is increased toward the center of the core. Core inlet sub-cooling decreases (feedwater temperature increases), reactor level increases (due to degraded separator performance) or changes in core power distribution are associated with an increased radial peaking factor. Figure 2-4 shows MCO increase with core flow increase at Peach Bottom Unit 3. An end of cycle strategy to control core flow until the MCO increase will have the least affect on steam side dose and cobalt transport is employed at Peach Bottom Unit 3.

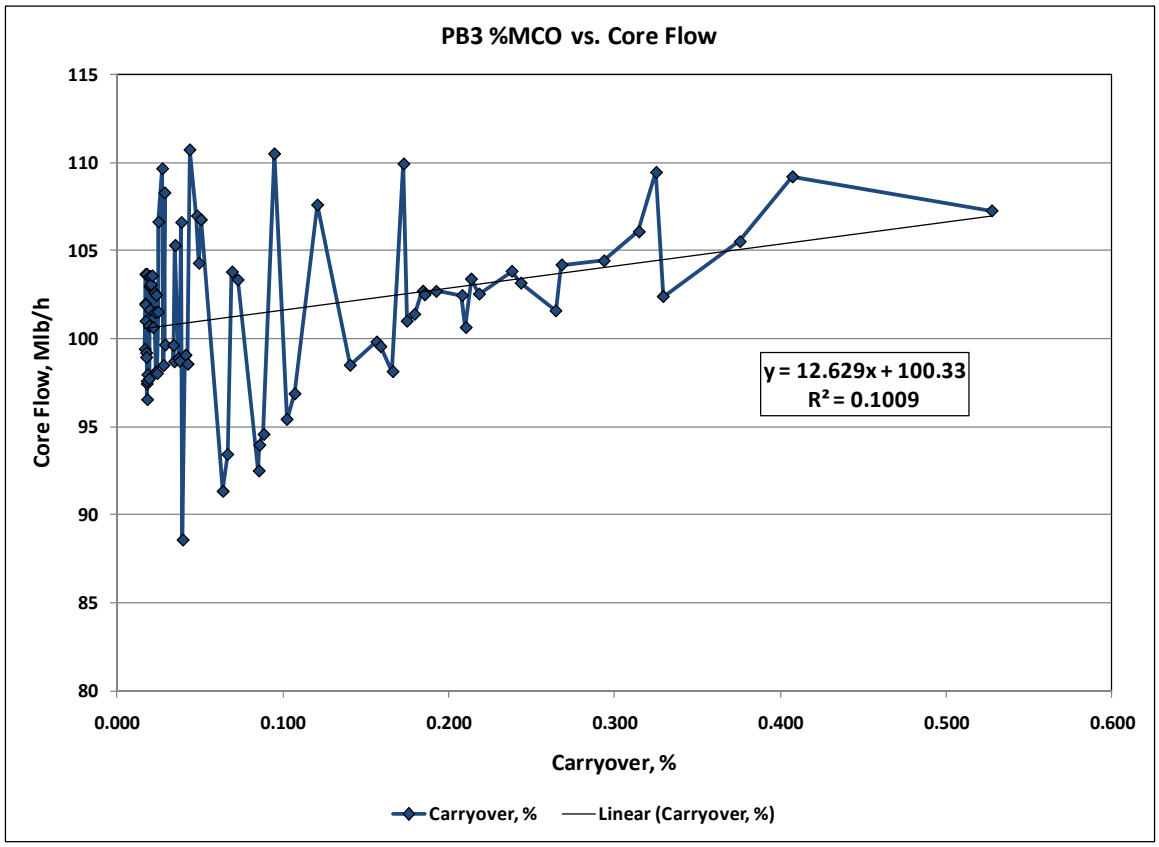


Figure 2-4
Peach Bottom 3 Moisture Carryover and Core Flow

Figure 2-5 shows Pilgrim MCO spiking. Pilgrim applied noble metals prior to cycle 17 for the first time. The graph shows Pilgrim MCO spiking as a hydrogen water chemistry plant and it continues after adding noble metals. Note the spike from a rod pattern change.

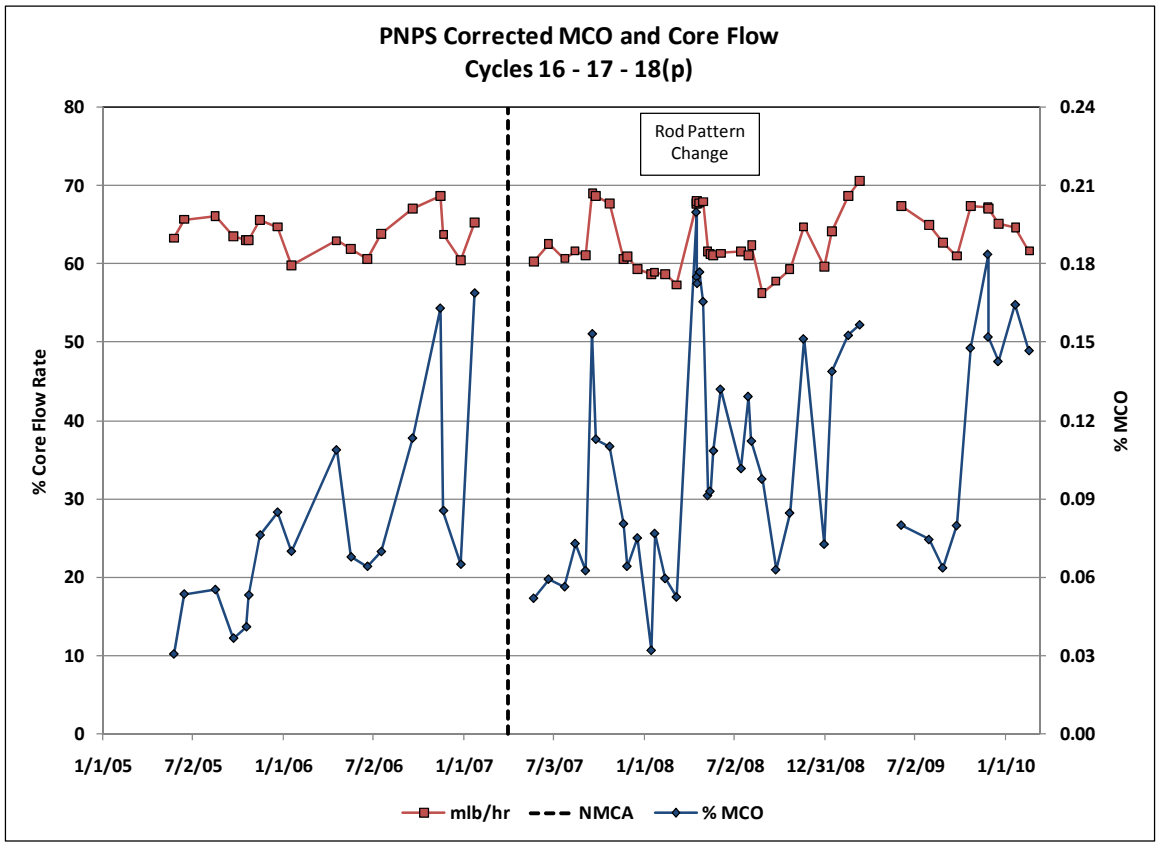


Figure 2-5
Pilgrim Moisture Carryover (corrected for 1-R)

3
OPERATING DATA

MCO Data and Plant Operational Conditions

Information was collected from all of the priority plants and a few others. Data included moisture carryover and chemistry data from all of the priority plants. The data received varied from detailed operational and fuel data to only MCO and chemistry data.

Pilgrim submitted operational data including reactor power, core flow, control rod drive flow, feedwater flow, main steam flow, recirculation flow, reactor water cleanup system flow, reactor water level, reactor water temperature and pressure and main steam line radiation monitor data from roughly the same time as their MCO measurements for comparison purposes. The station also submitted detailed fuel data from the same time period. Core average relative power from 19 locations and core average radial power distribution from 7 rings of fuel bundles. Pilgrim also submitted the Na-24 activity data from the hotwell and reactor water used to calculate the MCO data.

Peach Bottom submitted detailed data from Units 2 and 3 from the same time period. Condensate demineralizer inlet Na-24 and reactor water Na-24 used to calculate MCO, along with reactor power, core flow, feedwater flow, recirculation flow, reactor water level and reactor pressure. Fuel data was submitted for the same time period for comparison, including axial peak node data and radial power from 8 rings of fuel bundles. Peach Bottom also submitted calculated Co-60 transported to the steam side of the plant with moisture carryover during the course of a cycle.

Data from Limerick Units 1 and 2 was similar to that submitted by Peach Bottom and included reactor power, core flow, reactor level, feedwater flow and the radial peaking factor for ring 8 of the fuel bundles. Co-60 transported to the steam side of the plant with moisture carryover during a cycle was also calculated.

Forsmark submitted a large amount of data from Units 1, 2 and 3. Included with the MCO data was operational data, including reactor power, core flow, feedwater flow and reactor level. Forsmark submitted detailed historical information on the Units 1, 2 and 3 steam separators and dryers and modifications that were made to them, along with MCO data before and after.

LaSalle Units 1 and 2 submitted Na-24 data from the heater drain, the condensate polisher inlet and reactor water, along with reactor power and core flow data. LaSalle performed an iodine carryover study in which I-131 and I-133 activities were measured at the heater drain, the

condensate polisher inlet and reactor water sample points, and compared with the % MCO calculated from the Na-24 activities at the same sample points.

Hatch Units 1 and 2 reported steam quality, where steam quality = 100% - (MCO). Hatch measures Na-24 activity at the main steam line and reactor water, and calculates a % moisture carryover that is subtracted from 100% to obtain steam quality. Hatch also submitted reactor power and historical hotwell Na-24 data.

Vermont Yankee is one of the few plants that still operate with 18-month cycles. Since the extended power uprate of 20% in May 2006 (see Figure 2-2), Vermont Yankee has operated consistently with one of the highest % MCO. The Vermont Yankee Type 3 steam dryer was reinforced prior to the power uprate, and the % MCO data is consistently high throughout the 18-month cycle. Their data does not show the % MCO spiking some other plants have seen.

The Fermi 2 plant has a consistently low % MCO; the 2009 median value was 0.0065%. The station provided operational data for the same time period as MCO, which can be used as a control for the study of the priority plants. Data provided included reactor power, reactor level, reactor pressure, core flow, control rod drive flow, final feedwater temperature, feedwater flow, main steam line flow and the flow for each steam line.

In 2000 to 2004, Quad Cities Units 1 and 2 and Dresden Units 2 and 3, following extended power uprates, had indications of higher moisture carryover. All four plants are BWR 3 design. These plants discovered cracks in the steam dryers and did the necessary repairs. Recent Quad Cities and Dresden MCO data were reviewed for this study.

Moisture carryover data from Oyster Creek, Nine Mile Point 1, Hope Creek and Duane Arnold nuclear power plants were also reviewed.

Plant Chemistry Data

Chemistry data from each of the priority plants was reviewed to look for contaminants that could be carried over with the moisture or affect moisture carryover in some manner. Activation products, primarily Co-60, Co-58, Zn-65 and Mn-54, and fission products, primarily iodines, have been found on the steam side at several plants. Iodine activity carryover is primarily due to volatility, with ~2% carryover under normal water chemistry and up to ~8% carryover with Moderate HWC. Steam carryover of radioactive corrosion products is favored by elevated % MCO values and elevated concentrations in reactor water.

Co-60 is the major isotope found on the secondary side causing the greatest dose increase. Plants that have reported large increases in steam side dose during a refuel outage, for example: Pilgrim, Vermont Yankee, Peach Bottom and Limerick, have found the largest contributor to the dose increase was an increase in Co-60 activity on the steam side of the plant. For this reason, Peach Bottom Units 2 and 3 and Limerick Units 1 and 2 calculate the cumulative curies of Co-60 transported to the steam system during a cycle. The calculation uses the reactor water Co-60 activity, feedwater flow, hours of plant operation and the % MCO. Figure 3-1 shows curies of

Co-60 transported to the steam side of the plant and the number of days into the cycle for several cycles of operation at Limerick 1 and Limerick 2.

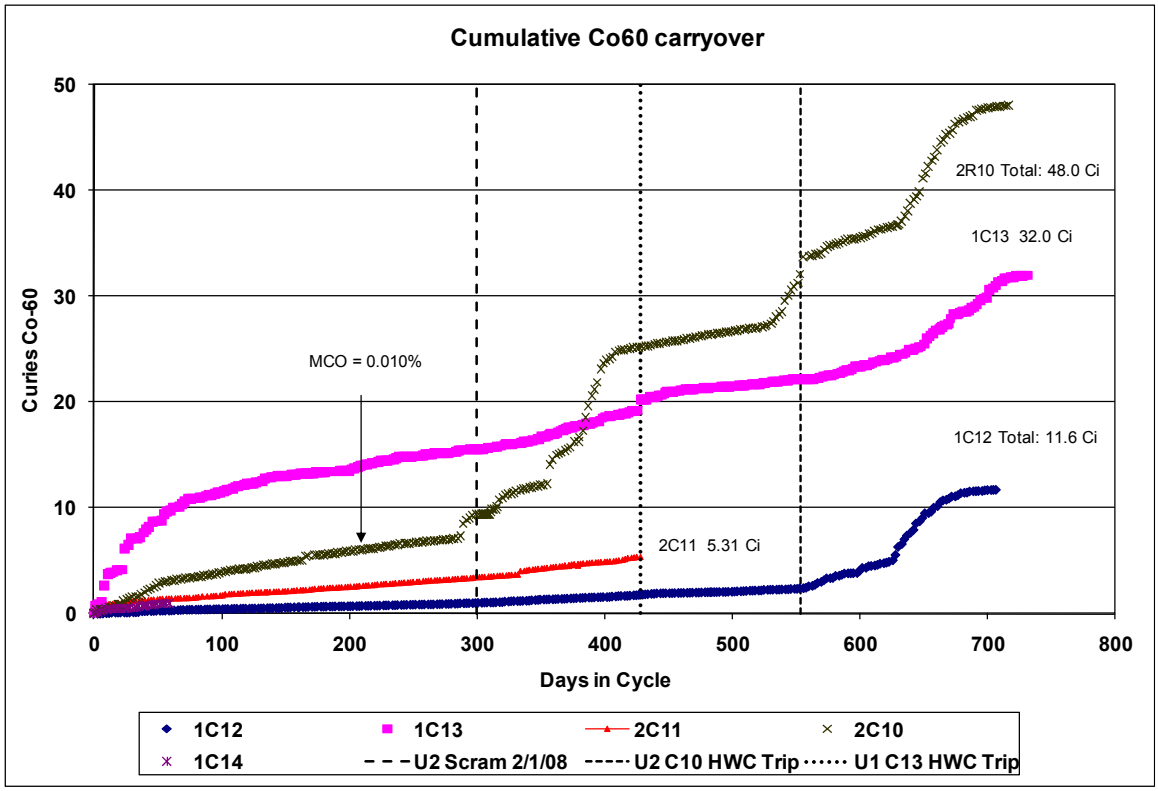


Figure 3-1
Co-60 Transport vs. Cycle Days at Limerick 1 and 2

2009 median values for selected chemistry parameters for the priority plants are shown in Table 3-1. A rough calculation of cumulative Co-60 transport to the steam side of the plant during 2009 could be made using the median Co-60 total, the median % MCO, the feedwater flow (see Table 2-1) and the number of hours of operation during 2009.

As shown in Table 3-1, reactor water anion concentrations are very small. Condenser tube leaks result in an increase in input of anions to the reactor. The size and duration of the leak and the effectiveness of the condensate polishing system will influence the concentration of anions and cations from the condenser cooling water that reach the reactor water. Moisture carryover will cause a small percentage of the increased reactor water anion concentration to be carried over with the steam, where it could be corrosive on the steam side of the plant. Corrosive impurity transport in steam is discussed in detail in Section 5.

Table 3-1
2009 Chemistry Parameter Median Values for Selected Plants

Reactor Water									
Plant	**DRE2**	**DRE3**	**FORS1**	**FORS2**	**FORS3**	**HAT1**	**HAT2**	**LAS1**	**LAS2**
Conductivity (µS/cm)	0.1060	0.0760	0.0900	0.1018	0.0887	0.1010	0.1200	0.1440	0.1450
Chloride (ppb)	0.30	0.30	0.10	0.10	0.10	0.11	0.23	0.30	0.27
Sulfate (ppb)	0.53	0.81	0.39	0.24	0.40	0.72	0.74	0.32	0.45
Silica (ppb)	39.5	20.3	255.0	220.0	86.0	37.0	67.5	131.0	186.2
Zn Total (ppb)	12.20	7.04	0.04	0.11	0.02	10.60	10.21	15.06	16.36
Co-60 Total (µCi/ml)	1.02E-04	1.41E-04	2.79E-04	1.80E-04	1.71E-04	1.03E-04	6.15E-05	2.93E-04	3.69E-04
Moisture Carry Over (%)	0.0240	0.0395	0.0655	0.0735	0.0970	0.0230	0.0030	0.0125	0.0175
Plant	**LIM1**	**LIM2**	**PB2**	**PB3**	**PIL**	**QUA1**	**QUA2**	**VY**	
Conductivity (µS/cm)	0.1100	0.1300	0.1140	0.1150	0.0790	0.1440	0.1490	0.1030	
Chloride (ppb)	0.31	0.31	0.30	0.30	0.28	0.25	0.65	0.41	
Sulfate (ppb)	0.48	0.43	0.79	0.81	0.69	0.50	0.85	0.65	
Silica (ppb)	45.0	47.0	176.0	116.0	34.0	55.0	47.0	64.0	
Zn Total (ppb)	17.48	18.75	15.47	11.99	5.66	16.87	17.20	9.78	
Co-60 Total (µCi/ml)	1.74E-04	3.65E-04	2.21E-04	2.14E-04	2.09E-04	2.22E-04	1.65E-04	1.08E-04	

Moisture Carry Over (%)	0.0190	0.0070	0.0120	0.1330	0.1610	0.0300	0.0620	0.1394	
Feedwater									
Plant	**DRE2**	**DRE3**	**FORS1**	**FORS2**	**FORS3**	**HAT1**	**HAT2**	**LAS1**	**LAS2**
Dissolved Oxygen (ppb)	55.300	40.32	32.00	56.50		37.00	42.00	38.49	85.41
Fe Total (ppb)	0.040	0.441	0.010	0.008	0.345	0.140	0.240	0.060	0.810
Cr Total (ppb)			0.010	0.006	0.051	0.020	0.020		
Ni Total (ppb)	0.018	0.038	0.092	0.075	0.046	0.100	0.020	0.020	0.020
Cu Total (ppb)	0.020	0.008	0.001	0.001	0.002	0.040	0.018	0.040	0.030
Zn Total (ppb)	0.485	0.338	0.002	0.003	0.001	0.410	0.390	0.390	0.570
Plant	**LIM1**	**LIM2**	**PB2**	**PB3**	**PIL**	**QUA1**	**QUA2**	**VY**	
Dissolved Oxygen (ppb)	40.00	38.40	60	73.00	56.90	47.20	46.800	41.00	
Fe Total (ppb)	0.317	0.224	0.386	0.728	2.016	0.278	0.397	0.271	
Cr Total (ppb)	0.075	0.024	0.022	0.004					
Ni Total (ppb)	0.032	0.035	0.018	0.017	0.049	0.018	0.013		
Cu Total (ppb)	0.004	0.007	0.003	0.004	0.034	0.029	0.014	0.163	
Zn Total (ppb)	0.393	0.487	0.636	0.535	0.550	0.564	0.646	0.323	
Hotwell									
Plant	**DRE2**	**DRE3**	**FORS1**	**FORS2**	**FORS3**	**HAT1**	**HAT2**	**LAS1**	**LAS2**
Conductivity (µS/cm)	0.0560	0.0560	0.0418	0.0442	0.0553	0.0560	0.0560	0.0580	0.0590
Fe Total (ppb)	28.138		12.910	13.275	6.834	15.740	14.200	14.320	19.005

Cu Total (ppb)			0.049		0.014	0.029	0.032	0.300	0.320
Co Total (ppb)			0.004	0.002	0.003				
Plant	**LIM1**	**LIM2**	**PB2**	**PB3**	**PIL**	**QUA1**	**QUA2**	**VY**	
Conductivity (µS/cm)	0.0640	0.0600	0.0560	0.0550	0.0560	0.0580	0.058	0.0580	
Fe Total (ppb)	11.668	14.844	11.210	13.500	9.044	27.405	23.450	8.937	
Cu Total (ppb)	1.890	2.109	0.018	0.047				2.354	
Co Total (ppb)								0.020	
Calculated Parameters									
Plant	**DRE2**	**DRE3**	**FORS1**	**FORS2**	**FORS3**	**HAT1**	**HAT2**	**LAS1**	**LAS2**
Rx Zn total/FW Zn total	25.1	20.8				25.9	26.2	38.6	28.7
Rx Co60 sol/Rx Zn sol (µCi/ml/ppb)	5.12E-06	1.14E-05				1.00E-05	7.07E-06	1.15E-05	1.56E-05
Plant	**LIM1**	**LIM2**	**PB2**	**PB3**	**PIL**	**QUA1**	**QUA2**	**VY**	
Rx Zn total/FW Zn total	44.5	38.5	24.3	22.4	10.3	29.9	26.6	30.3	
Rx Co60 sol/Rx Zn sol (µCi/ml/ppb)	5.40E-06	1.40E-05	1.39E-05	1.57E-05	2.25E-05	8.95E-06	6.63E-06	8.11E-06	

The data in Table 3-1 were examined to determine any correlation of MCO with the selected chemistry parameters. Very little correlation was seen in most cases. A weak correlation of moisture carryover with feedwater iron is shown in Figure 3-2. Data used in the correlation are from U.S. BWRs, which all operate under reducing reactor water chemistry. Further study would be needed to explore the relationship between feedwater iron and MCO.

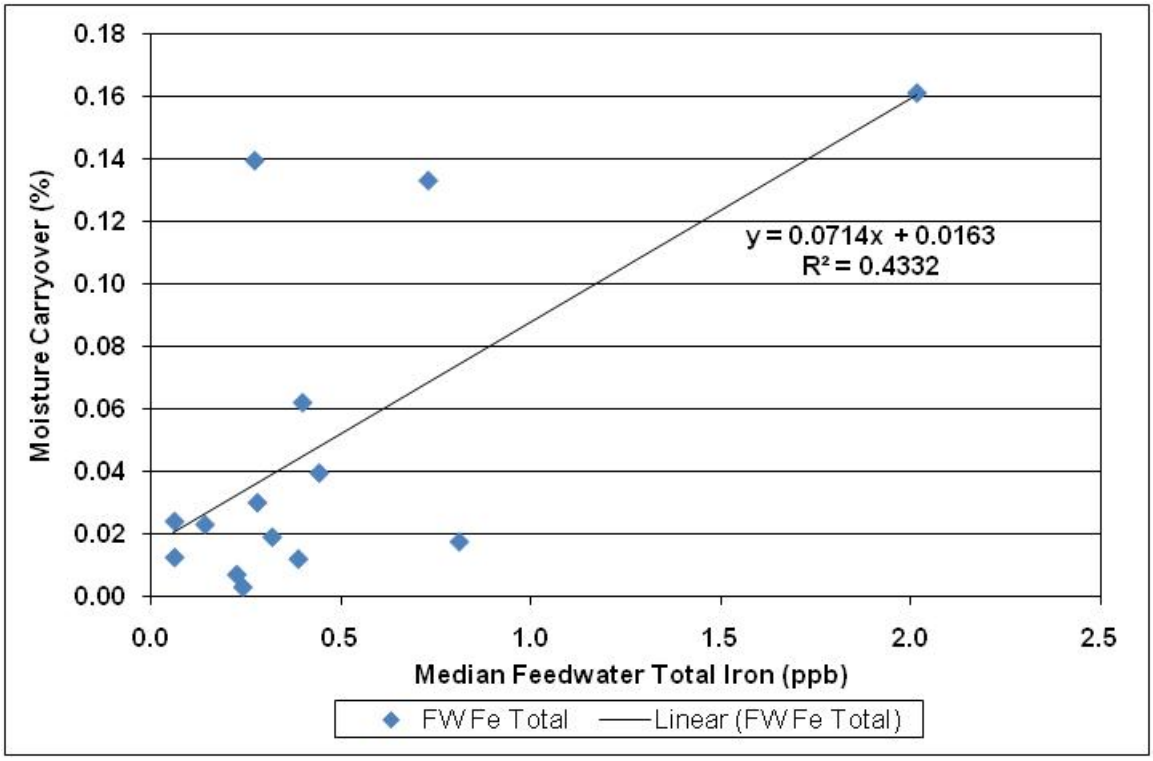


Figure 3-2
U.S. Priority Plants Median Moisture Carryover vs. Feedwater Iron

Moisture Carryover Analysis Procedures

Plant methods for MCO sampling and analysis from Dresden, Forsmark, Hatch, LaSalle, Limerick, Peach Bottom, Perry, Pilgrim, Quad Cities, River Bend and Vermont Yankee were reviewed. In many cases MCO sampling and analysis is only part of a larger procedure. All of the plants use Na-24 activity in the reactor water to compare with Na-24 activity on the steam side of the plant.

The sampling and analysis methods were compared to other BWRs and verified to be correct for the drains configuration of the plant. Forsmark Unit 3, LaSalle Units 1 and 2 and River Bend, have forward pumped drains. All four plants sample the condensate demineralizer inlet and ratio that with samples representative of the forward pumped drains. Forsmark Unit 3 samples from the high and low pressure drains. LaSalle Units 1 and 2 sample the heater drain. River Bend samples from the third point feedwater heater.

All of the priority plants with cascaded drains sample from a point in the condensate system upstream of the condensate treatment system except Hatch Units 1 and 2. The Hatch plants sample from the main steam lines.

4
SHUTDOWN DATA

Outage Radiation Surveys/Gamma Scans of Steam Affected Areas

Outage radiation survey and some gamma scan information were received from Dresden Unit 3, Forsmark Units 1, 2 and 3, LaSalle Units 1 and 2, Limerick Units 1 and 2, Pilgrim and Vermont Yankee. Forsmark submitted the average main steam line dose for every outage since 1993 at Units 1, 2 and 3. The average moisture carryover for each cycle since 1992 at Units 1, 2, and 3 was calculated and graphed with the average main steam line dose for the following refuel outage (RFO), see Figure 4-1. It shows good correlation between MCO and outage dose.

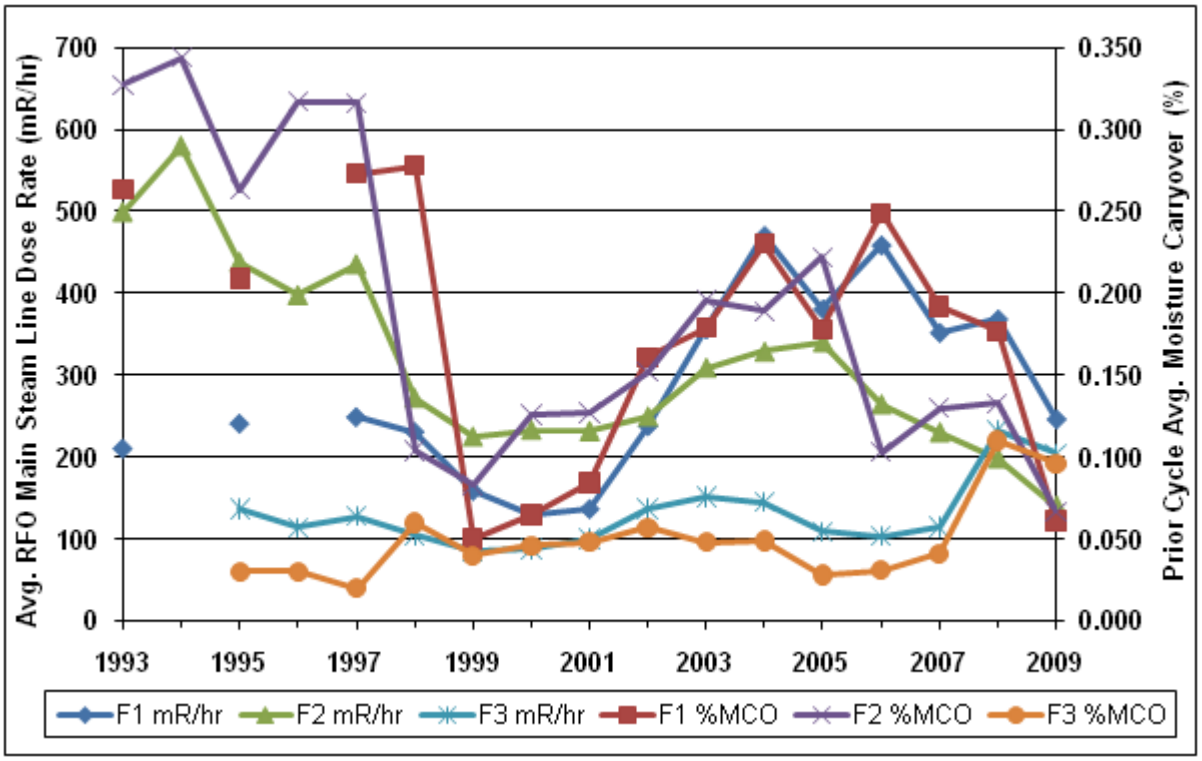


Figure 4-1
Average RFO Main Steam Line Dose vs. Average Moisture Carryover in the Preceding Cycle at Forsmark 1, 2 and 3

Vermont Yankee experienced an unexpected dose rate increase on the steam side of the plant following shutdown for refuel outage (RFO) 27, after a cycle at elevated moisture carryover. The observations are summarized in Table 4-1. Vermont Yankee reapplied noble metals prior to

the beginning of the cycle preceding RFO 27. When Vermont Yankee shut down for RFO 28 in April 2010, the dose rates on the steam side were less than the RFO 27 levels.

Table 4-1
Vermont Yankee RFO 27 (October 2008) Dose Increase Observations

	RFO 26	RFO 27
Main Steam Line Dose (mR/hr)	10 – 20	As high as 75
Heater Bay General Work Area Dose (mR/hr)	<1 – 8	10 – 20
Condenser Contamination (dpm/100 cm^2)	<1000 – 2000	As high as 40,000
Condensate Demineralizer Element Replacement Dose		20x previous
Average BRAC (mR/hr)	176	105
Outage Activity affecting Reactor Water Chemistry	NMCA	

When Pilgrim shut down for refuel outage 17 in April 2009, secondary side dose rates and contamination levels had increased approximately 4.5 times. The increase pertained to all secondary side components that come in contact with the steam, including steam lines, turbine, and condenser. Smears taken from the condensers and feedwater heaters were analyzed for radioactive species. Activated corrosion products that are present in reactor water, including Co-60, Co-58, Mn-54, Zn-65 and Fe-59, were found on the smears. These nuclides are normally not seen on the steam side of the plant.

During the preceding cycle, cycle 17, moisture carryover increased by a factor of 2. Prior to the beginning of cycle 17, Pilgrim applied noble metals for the first time. The activity in reactor water increased 5 to 8 times after noble metals were applied. Another factor was a reactor scram with a crud burst on 12/19/08, which contributed a steam release of reactor water activation products to the secondary side of the plant.

Limerick Unit 2 experienced high steam side dose rates following shutdown for refuel outage 10 (2R10) in February 2009. The low pressure turbine effective dose rate was 0.07 mR/hr, about 60% higher than at Limerick Unit 1 at refuel outage 13 in March 2010 (Table 4-2) . Moisture carryover spiked above 0.1% during the cycle. Figure 4-2 shows the cycle 10 MCO along with the calculated curies of Co-60 transported to the steam side of the plant.

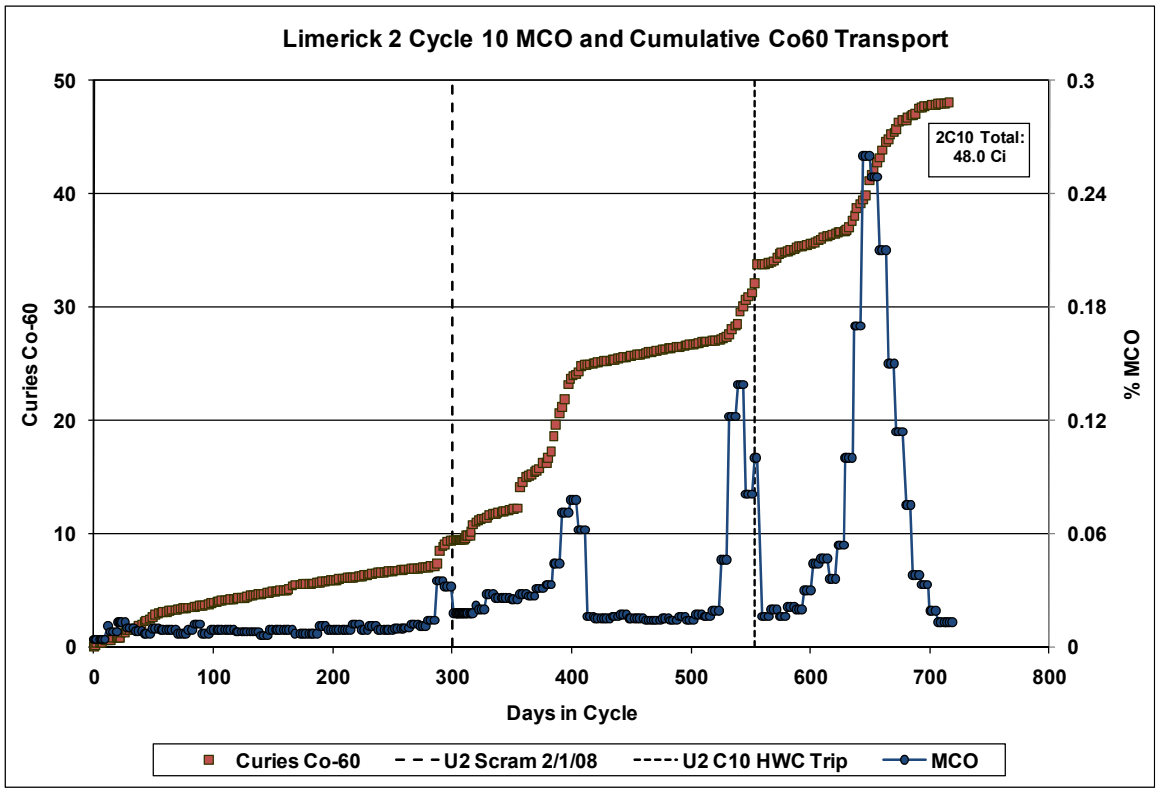


Figure 4-2
Limerick 2 Cycle 10 Moisture Carryover and Cumulative Co-60 Transport

When Limerick Unit 1 was shut down for refuel outage 13 (1R13) in March of 2010, results were similar to those for Unit 2. The Limerick 1 MCO had spiked to greater than 0.1% during cycle 13, and the low pressure turbine effective dose rate on shutdown was unusually high, 0.04 mR/hr. Limerick 1 calculated the cumulative curies of Co-60 carried over with the steam for cycle 13, see Figure 4-3, and compared Unit 1 to Unit2, see Table 4-2. The ratio of the effective dose rate on the low pressure turbine to the total curies of Co-60 transported was the same for both Units 1 and 2. Based on this comparison, the dose on the steam side of the plant was primarily due to the Co-60 carried over with the steam.

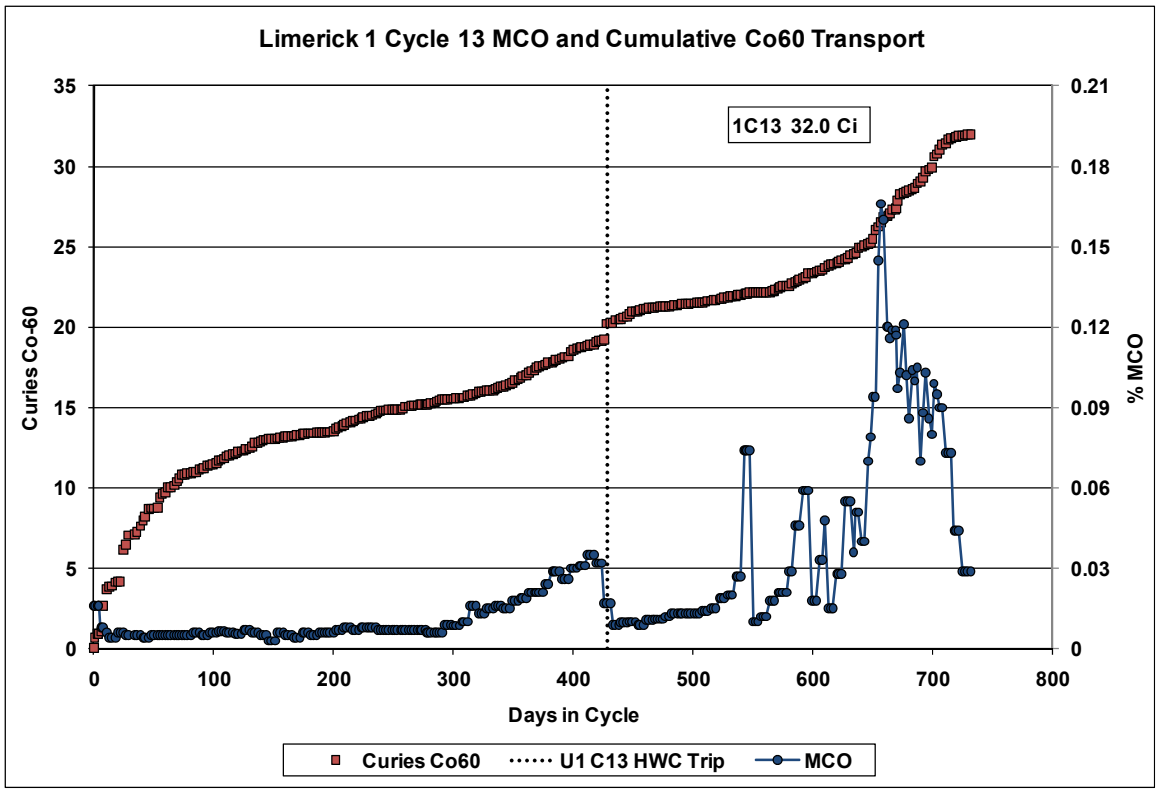


Figure 4-3
Limerick 1 Cycle 13 Moisture Carryover and Cumulative Co-60 Transport

Table 4-2
Limerick 1 and 2 Outage Dose Comparison

Outage	1R13	2R10	U1/U2
Co-60 Transport during Operating Cycle (Ci)	32.0	52.6	0.61
LP Turbine Effective Dose Rate (mR/hr)	0.044	0.071	0.61
LP Turbine Effective Dose Rate/Co-60 Transport (mR/hr/Ci)	1.37E-3	1.36E-3	1.01
Drywell Effective Dose Rate (mR/hr)	4.0	5.8	0.69

LaSalle Unit 2 shut down for refuel outage 12 (L2R12) in February 2009. General area dose rates on the steam side of the plant were elevated compared to historical data. Moisture carryover had been high during the preceding cycle. During vessel "flood up", reactor coolant entered the main steam line piping. The piping was flushed afterwards. The majority of the out of core piping, that had seen reactor coolant or suppression pool water, had elevated dose rates. Gamma scanning of the piping was performed to determine whether the activity on the steam side was due to reactor coolant before the outage (from moisture carryover) or reactor coolant during the outage (from "flood up"). The observations from L2R12 are summarized in Table 4-3. The steam dryer was inspected during the refueling outage and no major defects were identified.

Table 4-3
LaSalle 2 RFO 12 (February 2009) Observations

	Dose Rates (mR/hr)
Low Pressure Turbine (exterior perimeter)	<1
Main Condenser (22A Heater inside condenser	2-3

Main Steam Line Gamma Scan Data (Corrected)

Target	Dose Rate (mR/hr)	Activity ($\mu Ci/cm^2$)		
		Co-60	Mn-54	Zn-65
A MSL	21	0.8	0.1	0.03
B MSL	19	0.51	0.06	0.03
C MSL	8	0.19	0.04	ND
D MSL	21.5	0.68	0.07	0.02

Main Steam Line Co-60/Mn-54 Ratio

Steam Line	Gamma Scan Co-64/Mn-54	Steady State Median Co-60/Mn-54			L2R12 Shutdown Median Co-60/Mn-54		
		Soluble	Insoluble	Total	Soluble	Insoluble	Total
A MSL	7.72						
B MSL	6.33						
C MSL	4.36						
D MSL	9.87						
Median	8.02	13.22	7.71	10.55	4	7.37	6.87

Main Steam Line Co-60/Zn-65 Ratio

Steam Line	Gamma Scan Co-60/Zn-65	Steady State Median Co-60/Zn-65			L2R12 Shutdown Median Co-60/Zn-65		
		Soluble	Insoluble	Total	Soluble	Insoluble	Total
A MSL	26.5						
B MSL	16.93						
C MSL	ND						
D MSL	34.05						
Median	26.5	1.92	11.9	2.72	2.95	18.63	12.74

"A' Condenser Hood Manway Cover Qualitative Data								
Target	**Dose (mR/hr)**	**Percent of Identified Activity**						
		Co-60	**Mn-54**	**Zn-65**	**I-131**	**Ba-140**	**La-140**	**Ce-141**
A Hood	0.5	60.8	5.4	ND	2.3	15.4	15.4	0.8
Steam Line to High Pressure Turbine, 26" Insulated, Empty (Corrected)								
Target	**Dose (mR/hr)**	**Activity (μCi/cm^2)**						
		Co-60	**Mn-54**					
A Hood	0.5	0.035	0.016					

Table 4-3 Notes
ND = not detected

LaSalle Unit 1 was shut down for refuel outage 13 (L1R13) in February 2010, after a cycle with elevated moisture carryover. The station was concerned about dose on the steam side because of the elevated MCO and how that would be affected by the fuel defect the plant operated with during the cycle. LaSalle had gamma scanning performed on the high pressure turbine hood to see how much of the activity was due to the reactor coolant and how much due to the fuel defect. LaSalle's refuel outage observations are summarized in Table 4-4.

Table 4-4
LaSalle 1 RFO 13 (February 2010) Observations

	Dose Rate (mR/hr)
Low Pressure Turbine exterior perimeter	<1
Main Condenser A Hood	0.5 – 1.5
Hotwell	20 - 50
High Pressure Turbine Hood Gamma Scan Data	
Species	**Percentage of Activity**
Mn-54	7.5
Co-58	0.2
Co-60 (average)	62.9
Zn-65	17
Ru-103 (average)	2.8
Ru-106	2
I-131	2
La-140 (average)	1.4
Ce-141	4.1

Dresden Unit 3 shut down for refuel outage 19 (D3R19) in November 2006, after a cycle of high MCO values. Dose rates on the steam side of the plant increased significantly. Steam side dose observations are summarized in Table 4-5.

Table 4-5
Dresden 3 RFO 19 (November 2006) Elevated Steam Side Dose Rates

	D3R19 Values	Comments
Low Pressure Turbine Dose Rates (mR/hr)	3 – 4	Doubled from 1 -2 mR/hr
Main Condenser (mR/hr)	1 – 3	Doubled from 0.5 – 1
Condensate Demineralizers		Limited work scope; no increase noted
Drywell Steam Relief Valve Work General Area Dose Rates (mR/hr)	70 (steam lines empty)	Increased from 30
Drywell ISI Main Steam Line Nozzle Dose Rates (mR/hr)	500 – 700	Increased from 150 -200

Dose Rate Measurements on Condensate Cleanup Resins

The condensate cleanup system is an area where low dose rates are expected, but that could see higher dose rates due to activity transport with moisture carryover. Pilgrim and Vermont Yankee reported unexpected dose rate increases on the condensate cleanup system that were later linked to elevated steam side dose rates observed in refuel outage 17 for Pilgrim and refuel outage 27 for Vermont Yankee.

Pilgrim saw an approximate four times increase in resin activity in January 2009, during cycle 17. When Pilgrim was shutdown for refuel outage 17 in April 2009, secondary side dose rates and contamination levels had increased approximately 4.5 times. On 1/14/09, the 'F' condensate demineralizer resin dose rate was ~1200 mR/hr, compared to prior dose rates in the range of 200 to 300 mR/hr. Similar increases were seen with 'E' and 'D' condensate demineralizer resins. These resin beds were in service at the time of the plant scram with the associated crud burst on 12/19/08. The scram was probably the major cause of the elevated dose rates on the condensate system, with higher moisture carryover a contributing cause [4].

Vermont Yankee found dose rates 10 to 20 times higher than expected when 'A' and 'C' condensate demineralizer filter elements were replaced in November 2007. Then dose rates were approximately 20 times normal when two additional condensate demineralizer, 'D' and 'E', had filter elements replaced in the spring of 2008. The dose increase was attributed to poor backwashing of the condensate demineralizer filter elements. In an analysis of the causes of unexpectedly high shutdown dose rates for refuel outage 27, Vermont Yankee identified the condensate demineralizer dose rate increases as precursors to the shutdown dose rate increase [5].

Turbine Inspection Observations

Refuel outage turbine inspection results could show the affects of an extended period of operation at elevated moisture carryover. Inspection indications could be caused by contaminants carried over with the steam, causing corrosion of metal surfaces. However, no abnormal results were reported, except for Hatch Unit 2.

Hatch Unit 2 discovered intergranular stress corrosion cracking (IGSCC) indications on one of the low pressure turbine rotors. Hatch Unit 2 has not experienced increased moisture carryover. The root cause evaluation identified improper layup and storage as the most probable cause.

5
EVALUATIONS

Moisture Carryover and Volatile Impurity Transport

Introduction

The steam separators and dryers in the reactor vessel are designed to efficiently remove liquid from the steam-water mixture exiting the reactor. Moisture carryover (MCO) is used to measure the percentage of liquid water exiting the reactor vessel with the steam and can be used to monitor the performance of the steam dryer under operating conditions. Contaminants in reactor water will partition between the water and steam based on their volatility. Na-24 is the nuclide used to monitor MCO because of its minimum volatility. Contaminants like silica and iodine are partially volatile; they will carryover in larger proportion in the steam. MCO is used to monitor the percentage of the minimally volatile components, such as cobalt and other corrosion products, which are carried over with the steam. The major contributors to steam side dose are the activated corrosion products carried over with the steam, primarily Co-60.

Volatile impurities carried over with the steam include H_2, O_2, N_2, CO_2, Kr and Xe. Although there are radioactive species associated with these gases, only a small amount partitions with the liquid phase and most are short-lived and not a concern after shutdown. H-3 will be in both the steam and the liquid phase. Partially volatile contaminants, such as NH_3, H_3BO_3, SiO_2 and I_2, will carryover at a greater percentage than the minimally volatile contaminants and radioactive products, such as radioiodines, will be detected in the moisture separator drains and the hotwell.

Some other contaminants with low volatility, such as HCl and NaOH, may become volatile in the reheat region of the moisture separator. They could be corrosive to the low pressure turbine. This is the subject of Svoboda's report "Steam Turbine Chemistry in Light Water Reactor Plants" [3]. Corrosive impurity transport is discussed in detail in Section 5.

The dryer design specification for many General Electric BWRs is 0.1 weight % MCO at original licensed power. This value is also a monitoring guideline in GE SIL 644 [1]. A moisture carryover value greater than 0.1 % at the original licensed power level can be an indicator of steam dryer damage. However, operating parameters should be checked for any indication of dryer problems before drawing any conclusions. Moisture carryover may be impacted by reactor power, core flow and power distributions, localized "hot spots", core inlet sub-cooling (which is related to final feedwater temperature), and reactor water level. Changes in reactor power, such as a power uprate, should result in a new evaluation of baseline MCO. An operating limit greater than 0.1% may be found to be appropriate. The trending of % MCO at operating power is a better indicator for potential problems than a relatively constant value of 0.1%.

Moisture Carryover Measurement

The theory and standard practices for MCO measurement are presented in Appendix A [6].

Moisture Carryover Sampling Points and Frequencies

In BWRs with cascaded drains, condensed steam from all turbine drains, moisture separators and reheaters (if present) and feedwater heaters is returned to the condenser hotwell. In BWRs with forward pumped drains, condensed steam from the high pressure turbine drains, moisture separators and reheaters (if present) and feedwater heaters receiving main steam or steam from high pressure turbine extractions is collected and pumped forward into the feedwater flow. Condensed steam from the low pressure turbine drains and feedwater heaters receiving steam from low pressure turbine extractions is cascaded back to the condenser hot well, as seen in Figure 5-1.

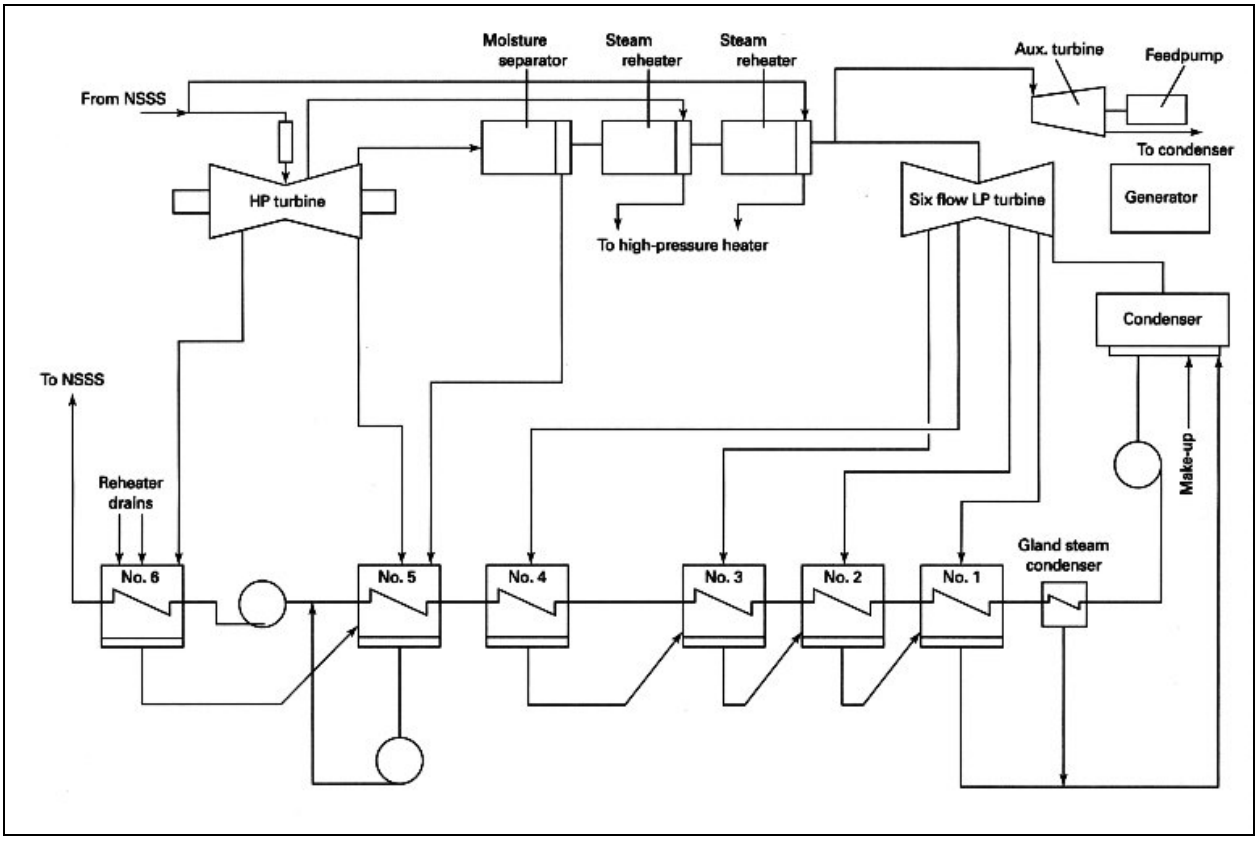


Figure 5-1
BWR Forward Pumped Drain Cycle Schematic Diagram

- All plants sample reactor water to determine the concentration of Na-24 in the entrained moisture.

- To monitor % MCO, the cascaded drains plant would measure Na-24 in the condensate upstream of the condensate cleanup system (condensate pump discharge or common cleanup inlet).
- Forward pumped drains BWRs could sample the moisture separator drains, the forward pumped drains or the final feedwater. The Na-24 activity would be highest in the moisture separator drains, lower in the forward pumped drains, and lowest in final feedwater.
- For both plants, an alternative that is discouraged would be to sample main steam directly.

BWR moisture carryover sampling locations and frequencies are shown in Table 5-1.

Table 5-1
BWR Moisture Carryover Sample Location(s) and Frequency

Plant	Drains	MCO Sampling Point Location(s) (Note 1)	Normal Sampling Frequency
Browns Ferry 1	Cascaded	CDI	monthly
Browns Ferry 2	Cascaded	CDI	monthly
Browns Ferry 3	Cascaded	CDI	monthly
Cofrentes	FPD	Main Steam	2/month
Columbia	Cascaded	CPD	weekly
Cooper	Cascaded	CDI	weekly
Dresden 2	Cascaded	CPD	weekly
Dresden 3	Cascaded	CPD	weekly
Duane Arnold	Cascaded	Hotwell	weekly
FitzPatrick	Cascaded	CDI	monthly
Forsmark 1	Cascaded	CDI	monthly
Forsmark 2	Cascaded	CDI	monthly
Forsmark 3	FPD	CDI, High & Low Pressure Turbine Drains	monthly
Hatch 1	Cascaded	Main Steam	weekly
Hatch 2	Cascaded	Main Steam	weekly
LaSalle 1	FPD	CDI, Heater Drain	monthly
LaSalle 2	FPD	CDI, Heater Drain	monthly
Limerick 1	Cascaded	Condensate Filter Inlet	weekly
Limerick 2	Cascaded	Condensate Filter Inlet	weekly
Nine Mile Point 1	Cascaded	CDI	monthly
Nine Mile Point 2	FPD	Heater Drain Line A	monthly

Plant	Drains	MCO Sampling Point Location(s) (Note 1)	Normal Sampling Frequency
Peach Bottom 2	Cascaded	CDI	weekly
Peach Bottom 3	Cascaded	CDI	weekly
Pilgrim	Cascaded	CDI	monthly
Quad Cities 1	Cascaded	CPD	weekly
Quad Cities 2	Cascaded	CPD	weekly
Ringhals 1	Cascaded	CDI	biweekly
River Bend	FPD	CDI/3rd point heat exchanger	monthly
Susquehanna 1	Cascaded	CDI	weekly
Susquehanna 2	Cascaded	CDI	weekly
Vermont Yankee	Cascaded	CPD	2/week

Table 5-1 Notes
CDI = Condensate Demineralizer Inlet
CPD = Condensate Pump Discharge

Moisture Carryover Sampling Points and Frequencies

Appendix A provides formulas for calculating %MCO based on the steam cycle design and the sample points used. This section discusses inputs for the calculations.

- Inputs

  Na-24 activity at water/steam interface in reactor pressure vessel

  Na-24 activity in condensed steam

- Use of R-Factor

  The activity or impurity concentration in entrained reactor water will be higher than in the reactor water sample because 15% to 20% of the core flow is converted to steam. The measured activity or concentration should be increased to provide an estimate of the average activity or concentration at the steam/water interface, as shown below [6, 7].

  $A_{S/W} = A_{RW} / (1 - R)$ *where* $R = F_{STM}/F_{CORE}$

  $A_{S/W}$ *– Activity at water/steam interface*

  $A_{R/W}$ *– Activity of reactor water sample*

  F_{STM} *– Steam flow rate*

  F_{CORE} *– Core Flow Rate*

- General Equation for MCO

  The calculation of MCO is based on a mass or activity balance for the tracer used to measure MCO. The rate of moisture leaving the reactor is equal to the steam flow rate times the fraction of moisture in the steam times the concentration of tracer in the water at the steam water interface. Steam condensate is sampled at a location where the rate of tracer transport (condensate flow times condensate activity) is equal to the tracer transport rate in steam.

  $$A_{S/W} \times \%MCO/100 \times F_{STM} = A_{CND} \times F_{CND}$$

  $$\%MCO = 100 \times A_{CND}/A_{S/W} \times F_{CND}/F_{STM}$$

  A_{CND} – *Activity in condensed steam (e.g. MS, CDI or FPD)*

  F_{CND} – *Flow rate of sampled stream*

  Figure 5-2 shows the effect of correcting the measured reactor water activity for steam production on the calculated moisture carryover.

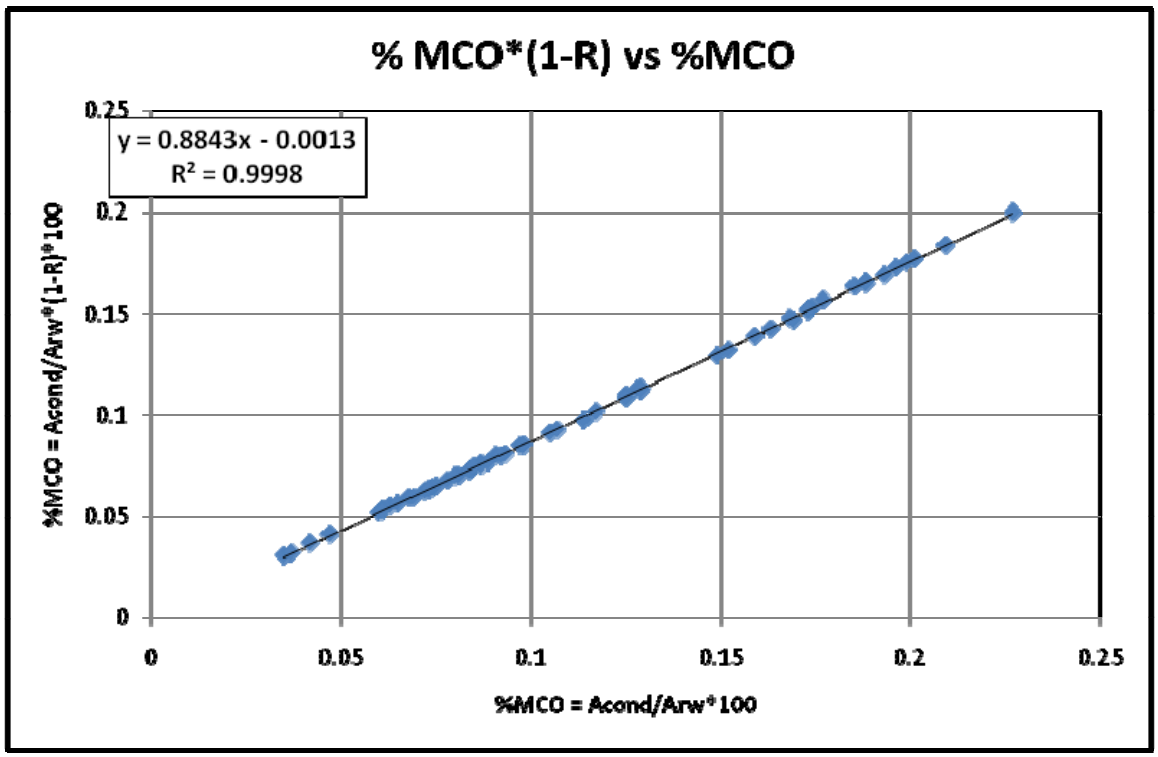


Figure 5-2
Effect of R Factor on MCO Calculation

- Equations for Specific Sample Points are provided in Appendix A.
- Use of LLDs

The isotope normally used to quantify MCO is Na-24. Per GE SIL No. 644, sampling approaches should be used that are capable of quantifying Na-24 in the condensed steam rather than using "less than" values if MCO exceeds 0.025%.

- Interferences

  Secondary gamma line from I-135, if failed fuel is present, interferes with the Na-24 gamma causing an overestimation. An Entergy BWR shutdown the plant to examine the steam dryer based on this overestimation of Na-24 in the condensate system and the %MCO calculation that resulted.

  Use of poor quality cation filter papers for collecting soluble Na-24, leads to an underestimation of Na-24. Toray cation filter papers have been found to be best for soluble Na-24 collection.

Correlations of Moisture Carryover Trends with Plant Characteristics

Philippsburg Experience

The Philippsburg MCO Experience is described in the paper "Increase of Steam Moisture in the BWR-Facility KKP-1" [8]. KKP 1 is a 900 MW BWR from Germany (KWU). The station experienced increased MCO and shutdown radiation after shifting to a low leakage core design. The power and quality were higher at the center of the core and lower at the periphery. This resulted in degraded steam separator performance. Performance results are shown in Figures 5-3 through 5-6.

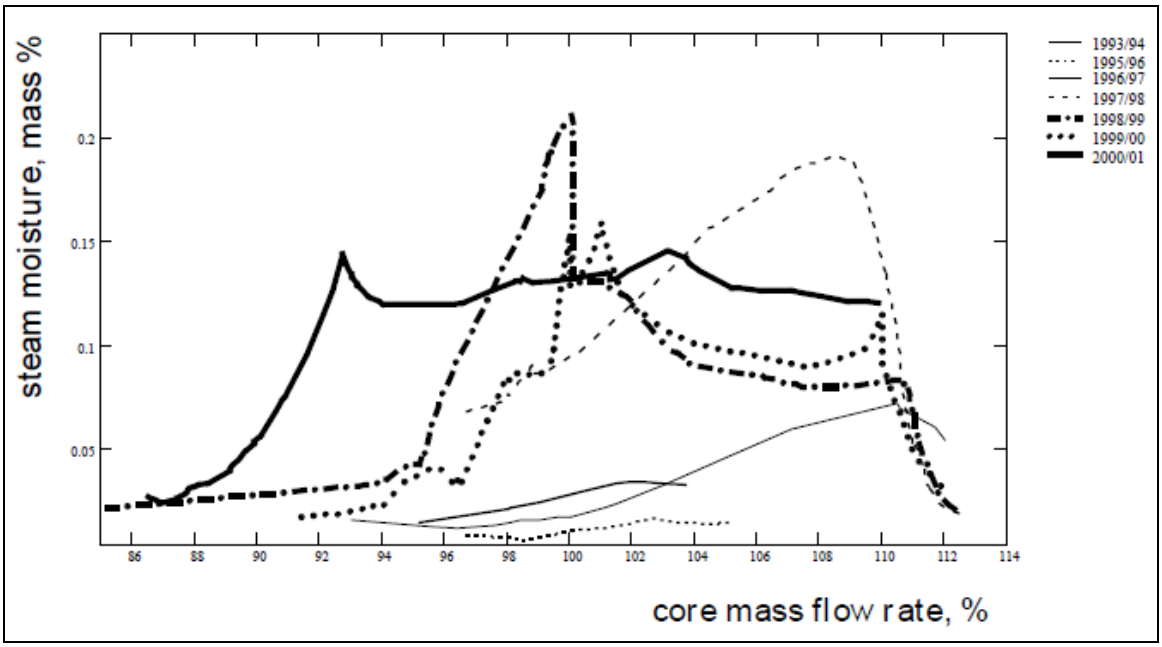


Figure 5-3
Moisture Carryover vs. Core Flow [8]

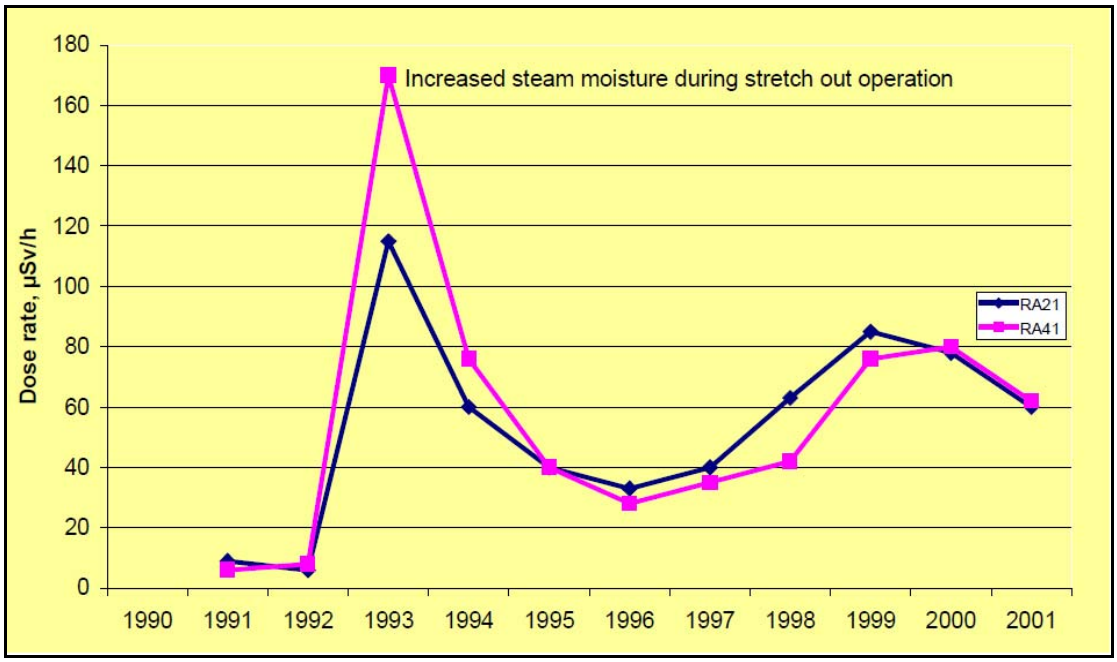


Figure 5-4
Dose Rate at Turbine Bypass System [8]

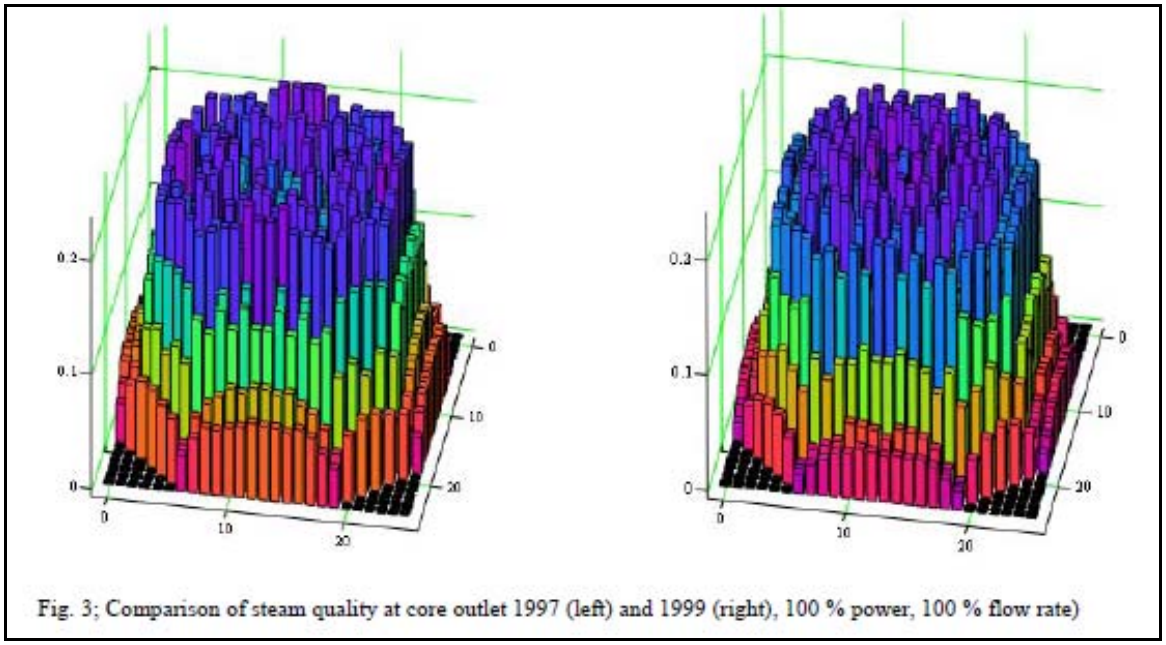


Figure 5-5
Changes in Steam Quality Distribution [8]

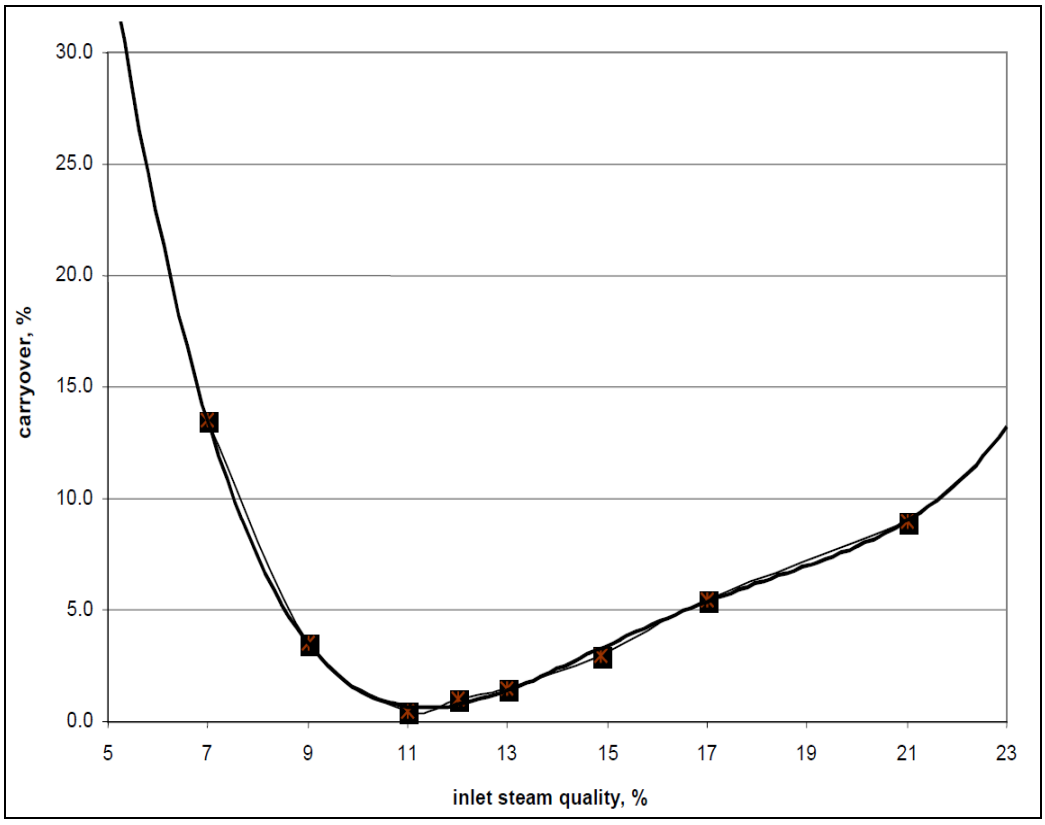


Figure 5-6
Separator Efficiency vs. Inlet Steam Quality [8]

The steam dryers were designed for <10% carryover from the Steam Separators. With the low leakage core the inlet steam quality at the periphery of the core was 8% or less. From Figure 5-6, this steam quality leads to approximately 10% carryover. KKP-1 began spectral shift operation, operation at 80% core flow before stretch out, in 2000. This had the desired effect of reducing moisture carry over and reducing dose, as can be seen in Figures 5-3 and 5-4.

Forsmark Experience

Forsmark Units 1 and 2 (F1/F2) are ABB Atom BWR 69 of 2928 MWt. Each has 125 steam separators, 25 groups of 5, of the ABB VU8fas design. 16 groups were replaced in 1991/1992 and 9 groups in 1997. A schematic of the steam separators can be seen in Figure 5-7. The affect that these changes had on MCO can be seen in Figure 5-8 (F1=10332, F2=20332, F3=30332). These changes resulted in MCO in the 0.1- 0.3% range. The original design steam dryers were 32 single pocket P8-vanes. New steam dryers of the Peerless P8X-vanes double pocket design were installed at Forsmark Unit 2 in October 2009 along with 170 AS01 steam separators. This will allow the plant to operate at full load (3253 MWt, 120%) and provide outlet moisture content less than 0.05%. These changes are scheduled for 2011 at Forsmark Unit 1.

Forsmark Unit 3 (F3) is an ABB Atom BWR 75 of 3300 MWt. F3 has 33 groups of 5 steam separators and the steam dryer original design has 32 double pocket vanes.

Baffles installed on the steam dryer in 2007 to reduce steam line vibrations, caused the MCO to increase from 0.05 to 0.11%, as seen in Figure 5-8.

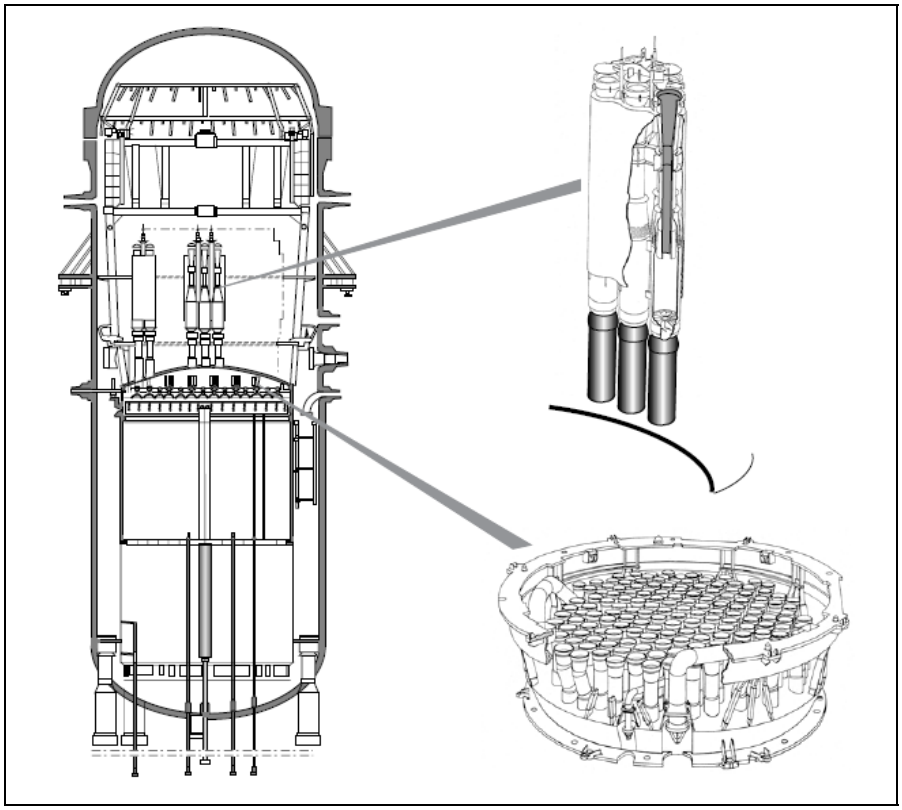


Figure 5-7
Forsmark 1 and 2 Steam Separator Schematic Diagrams

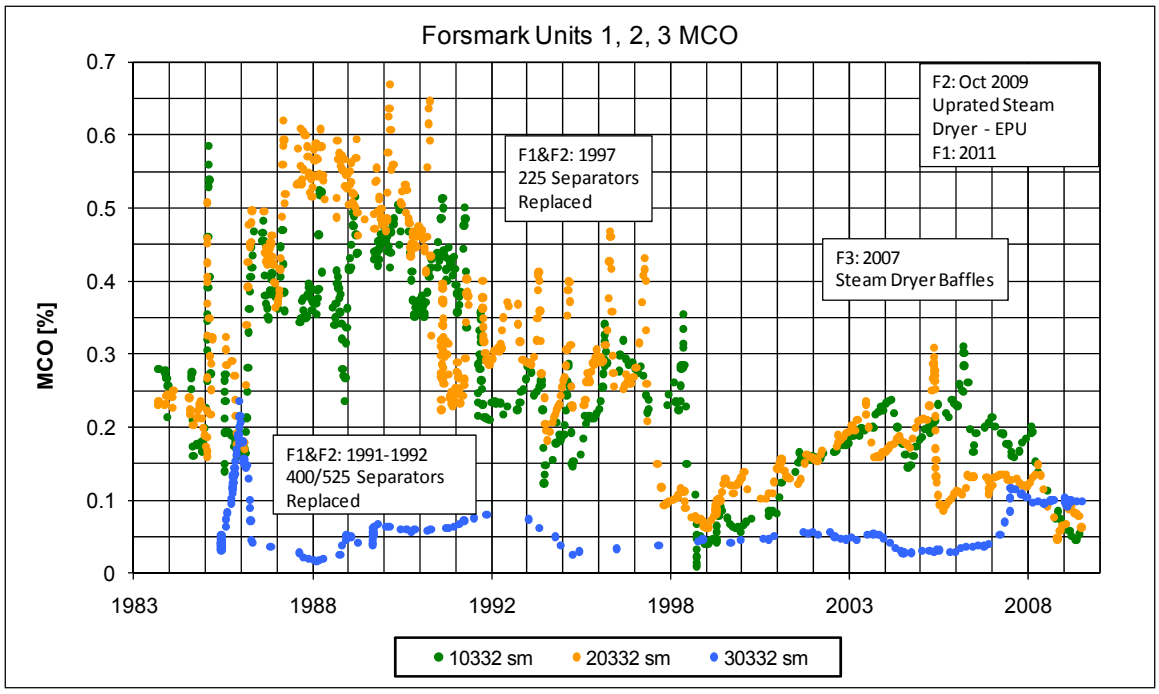


Figure 5-8
Forsmark 1, 2 and 3 Moisture Carryover Trends

Peach Bottom 3 Experience

Peach Bottom Unit 3 is a BWR4. The total dose for refuel outage 16 (RFO 16) exceeded the planned goal by 70 person-REM. Station's Root Cause noted an increase in steam side dose rates and contamination levels as contributing cause. Online noble chemistry (OLNC) was performed in cycle 16, a few months prior to refuel outage 16 (RFO 16), causing elevated Co-60. This was during a period of increasing MCO. Peach Bottom 3 end of cycle core flow increases contribute to an MCO increase, see Figure 5-9. The end of cycle core fuel design with a high peak at the top of the core will contribute to the increased MCO, due to overloading the outer ring of the Reactor Steam Dryer. Figure 5-10 shows the outer ring, Ring 8, as the power goes down, when it becomes overloaded, compared to the %MCO.

Peach Bottom experienced high MCO again in Cycle 17. OLNC was performed again in cycle 17. %MCO values were higher in cycle 17 than cycle 16, but the method of analysis was changed to a more efficient cation filter, resulting in increased %MCO values. Core flow increased toward the end of the cycle influencing the MCO values, as shown in Figure 5-11.

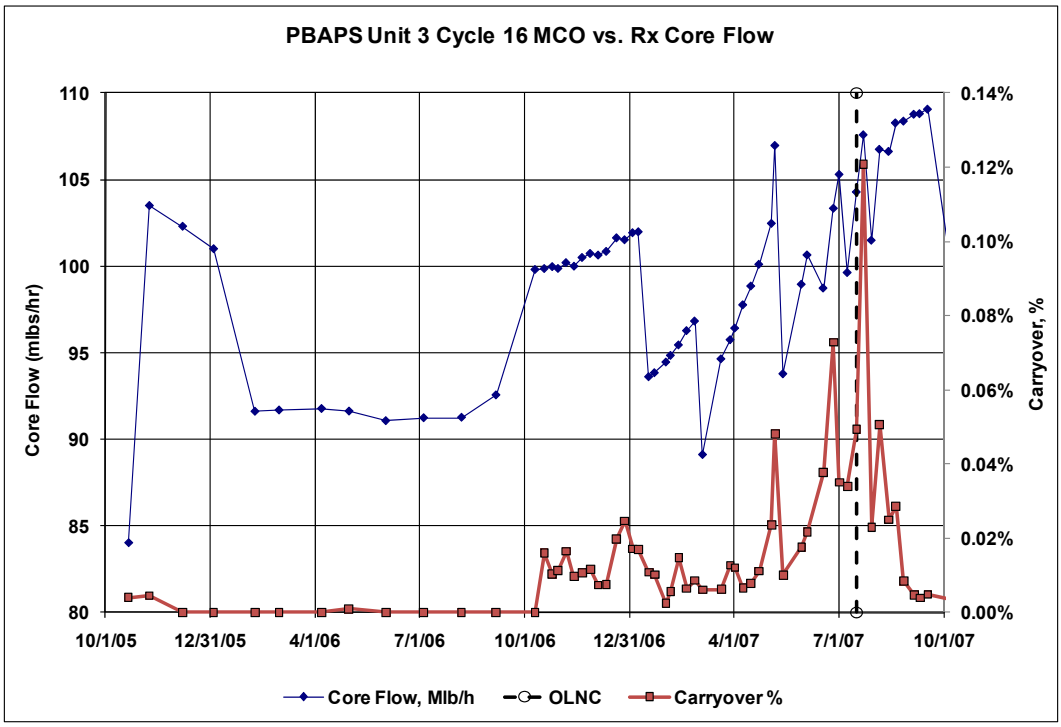


Figure 5-9
Peach Bottom 3 Cycle 16 Core Flow and Moisture Carryover

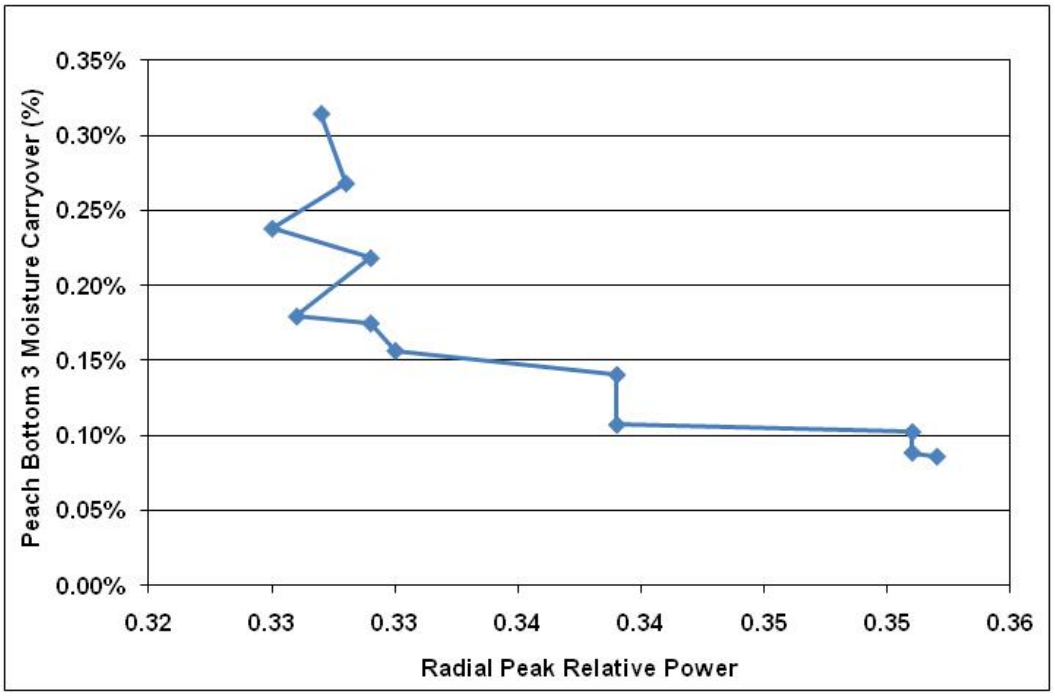


Figure 5-10
Peach Bottom 3 Moisture Carryover vs. Ring 8 Radial Power

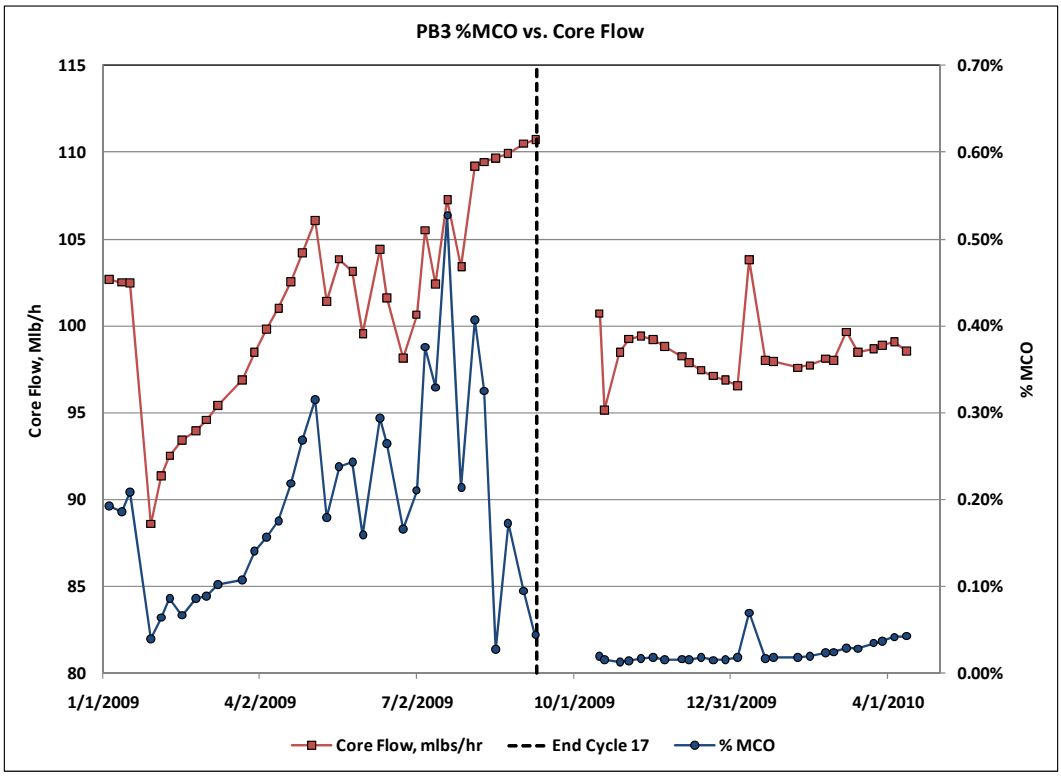


Figure 5-11
Peach Bottom 3 Core Flow and Moisture Carryover

Peach Bottom 2 Experience

Peach Bottom Unit 2 had a similar experience to Unit 3. Peach Bottom 2 has the same BWR 4 steam dryer and the same core design as Unit 3. Figure 5-12 shows how the moisture carryover is influenced by the core flow. At Peach Bottom Unit 2, as Ring 8 power trends down MCO increases, similar to what was observed at Unit 3, see Figure 5-13.

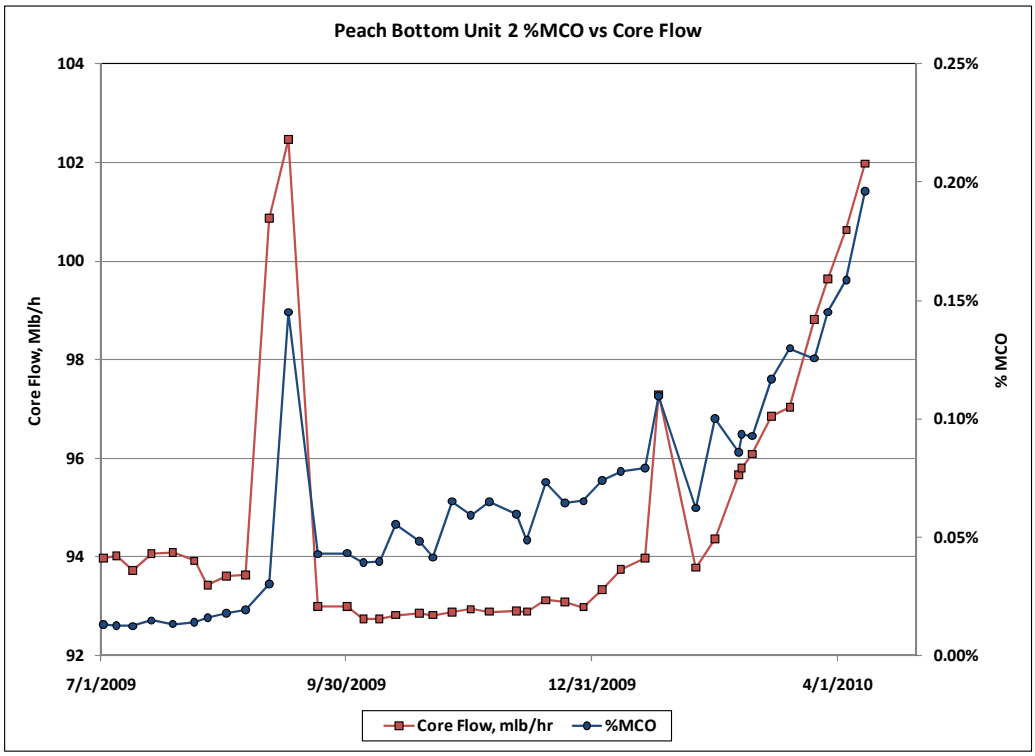


Figure 5-12
Peach Bottom 2 Core Flow and Moisture Carryover

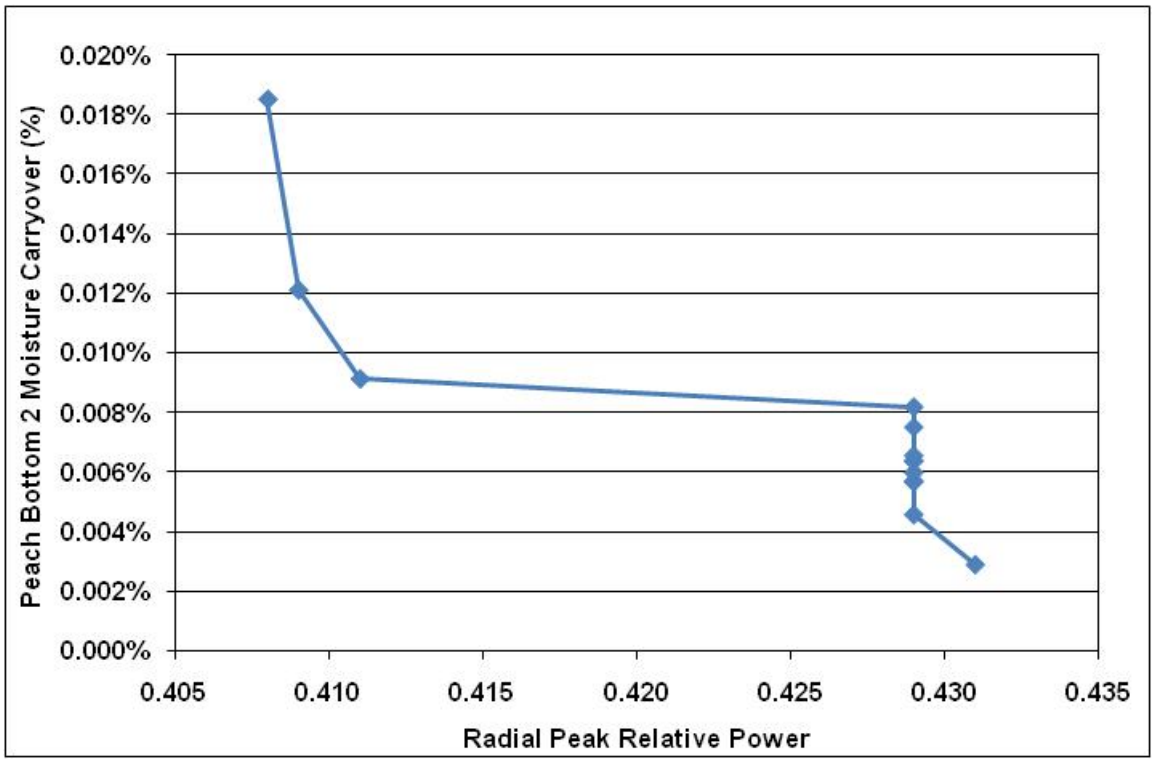


Figure 5-13
Peach Bottom 2 Moisture Carryover vs. Ring 8 Radial Power

Pilgrim Experience

Pilgrim (PNPS) is a BWR 3 design. Pilgrim experienced higher than expected steam side dose rates after shutdown for refuel after cycle 17. High dose rates were seen on condensate demineralizer beds during the cycle, but after the reactor scram with crud burst on 12/19/08 [4].

Initial classic noble metals were applied prior to the cycle yielding higher Co-60 levels in the reactor water. Figure 5-14 shows the Pilgrim MCO for cycle 17. Figure 5-15 shows the correlation between MCO and core flow over cycles 16, 17 and part of 18. Figure 5-16 shows the Pilgrim core radial rings of fuel bundles. Figure 5-17 shows the relative radial power of each ring. Figure 5-18 shows the correlation between MCO and Ring 2 power. Figure 5-19 shows the downward correlation between Ring 7, the outer ring, and MCO, similar to what was seen at the Peach Bottom plants. Figure 5-20 shows power variation at different locations in the core. Figure 5-21 shows the MCO correlation with power at location N00-loc24. The MCO increase is attributed to low steam flow and high moisture loading on peripheral steam separators. The design of the peripheral bundle flow orifices allows too much flow for bundle power.

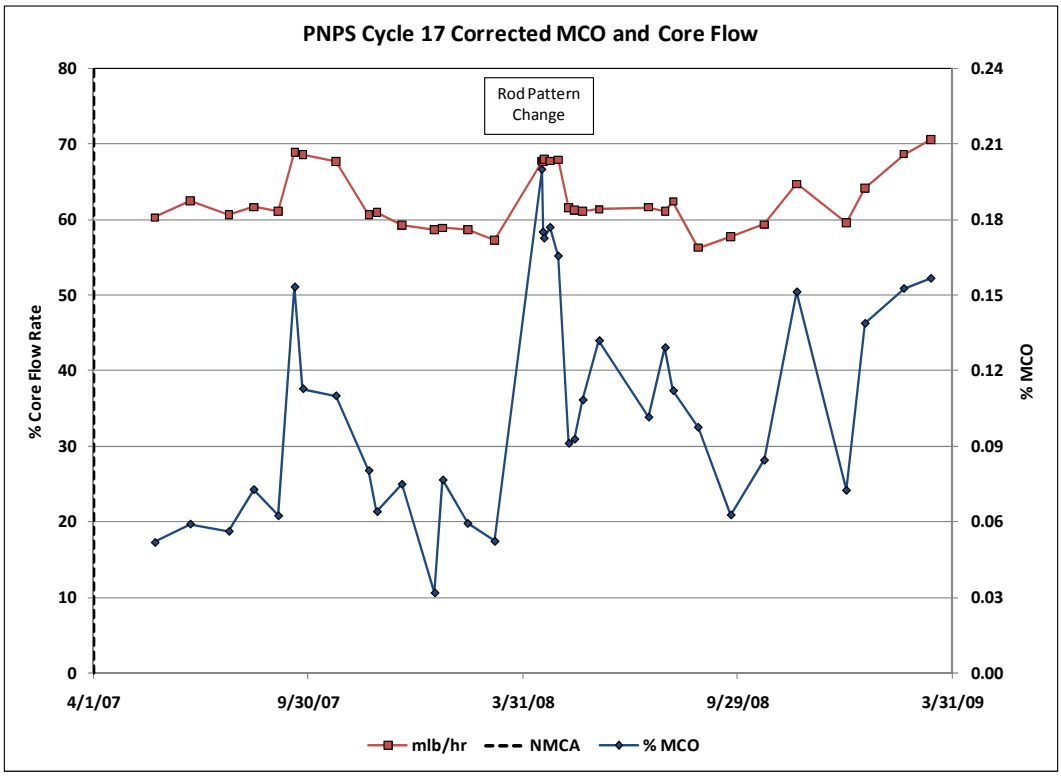


Figure 5-14
Pilgrim Cycle 17 Moisture Carryover (corrected for 1-R)

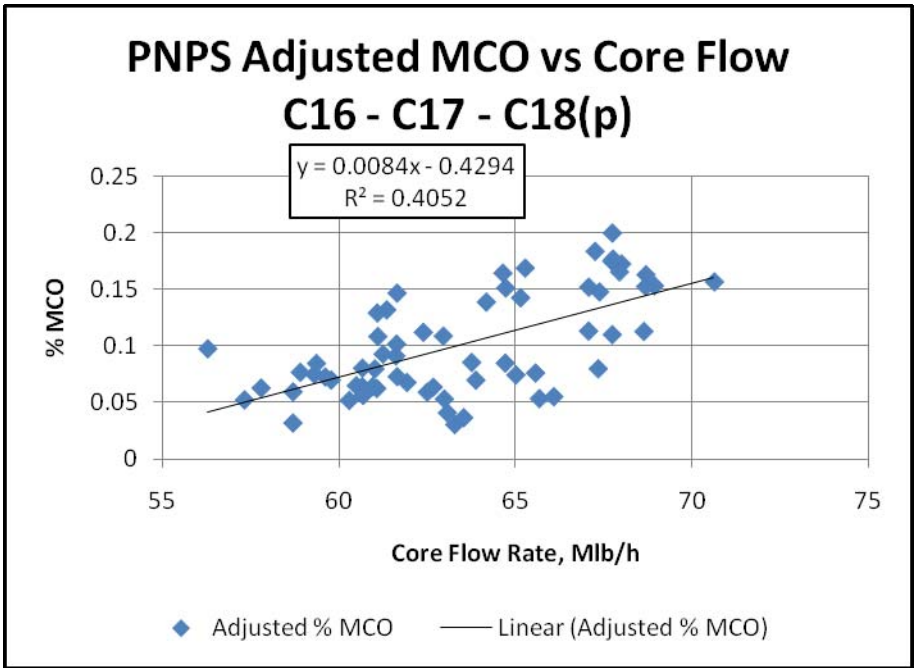


Figure 5-15
Pilgrim Moisture Carryover vs. Core Flow

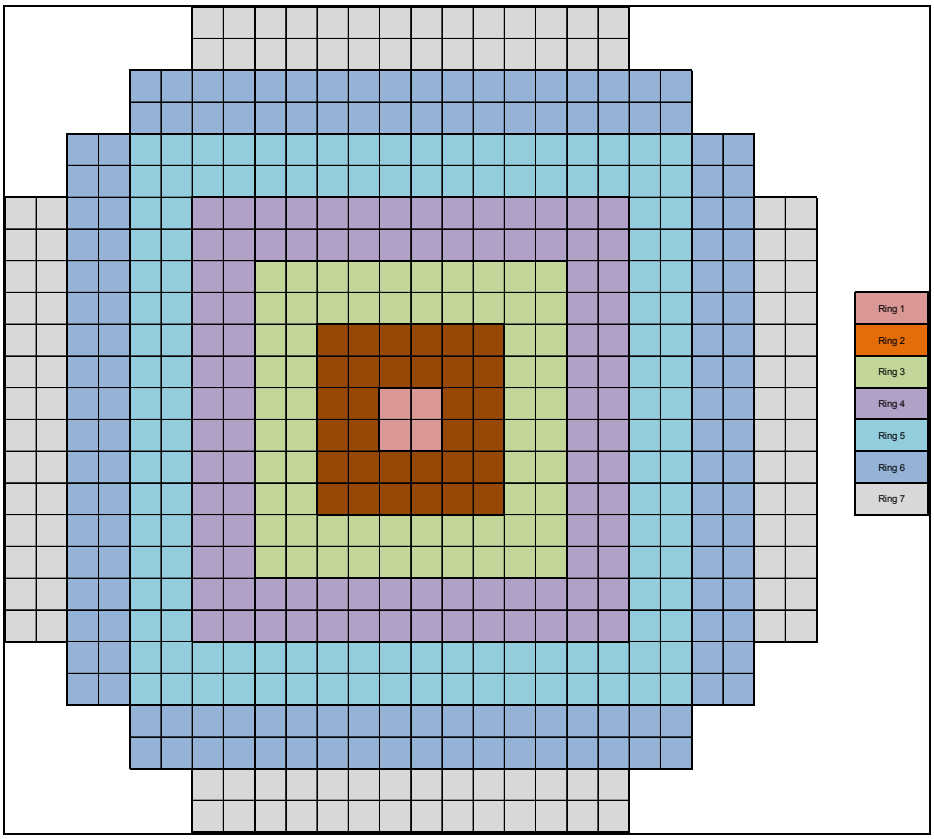


Figure 5-16
Pilgrim Core Radial Rings

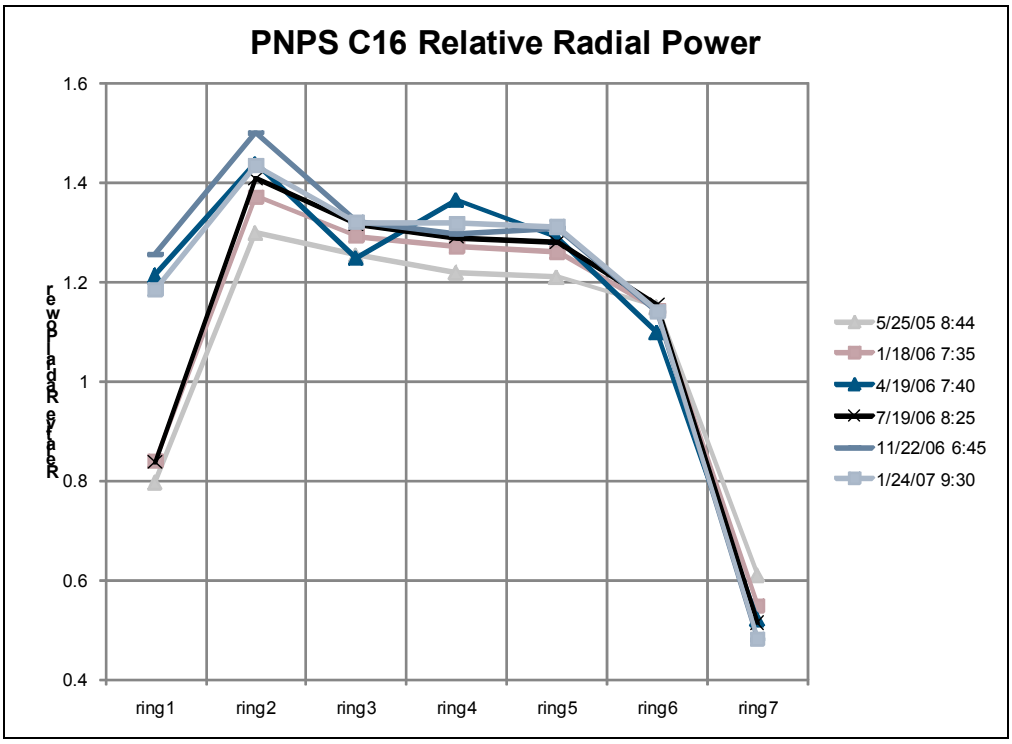


Figure 5-17
Pilgrim Relative Radial Power

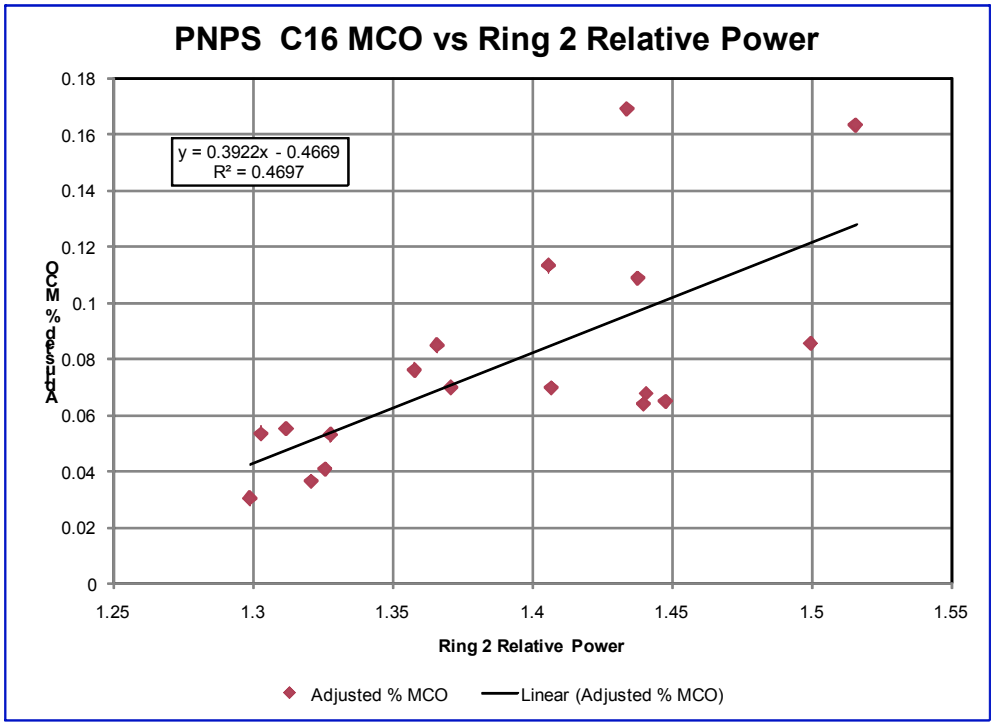


Figure 5-18
Pilgrim Moisture Carryover vs. Ring 2 Relative Power

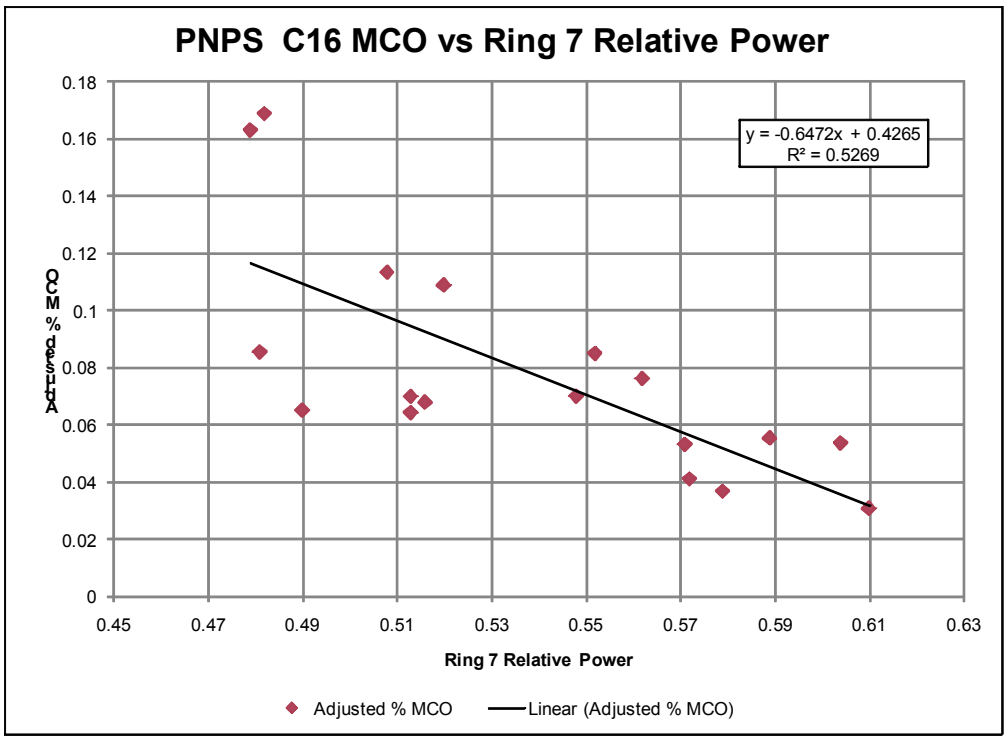


Figure 5-19
Pilgrim Moisture Carryover vs. Ring 7 Relative Power

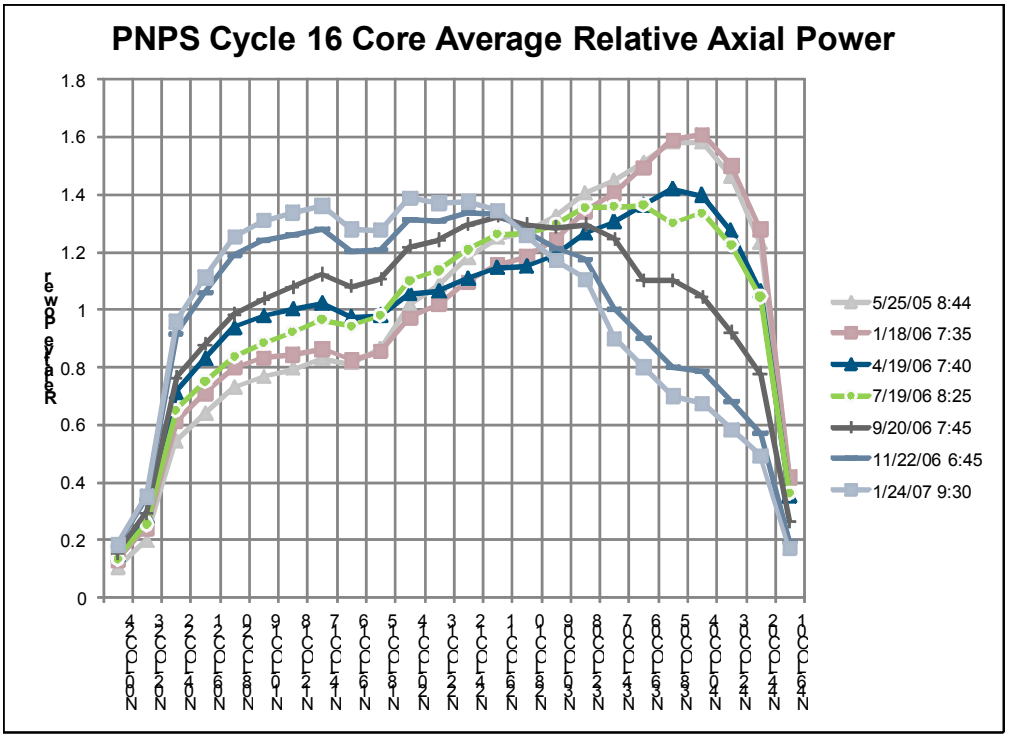


Figure 5-20
Pilgrim Relative Axial Power

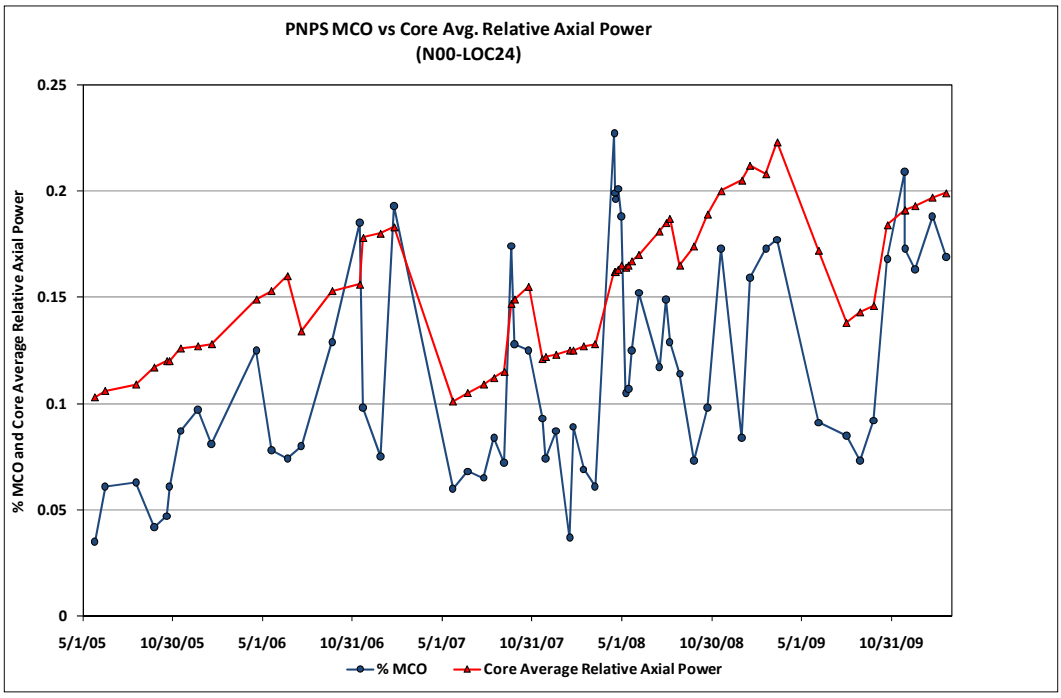


Figure 5-21
Pilgrim Moisture Carryover and Core Average Relative Axial Power (Location N00-LOC24)

Vermont Yankee Experience

Vermont Yankee (VY) is a BWR 4 design plant with a BWR3 design steam dryer. Vermont Yankee is one of the few BWRs still on 18 month cycles. The steam dryer was reinforced prior to a 20% power uprate in May 2006. This caused a large increase in %MCO as shown in Figure 5-22. Vermont Yankee observed higher than expected steam side dose rates after Cycle 26, in October of 2008. Noble metals (NMCA) was reapplied prior to Cycle 26, leading to higher Co-60 levels during the cycle and higher MCO values, as seen in Figure 5-22. There was a crud burst during Cycle 26, due to reactor water cleanup system problems [5]. Figure 5-23 shows the %MCO trend downward in Cycle 27 after being elevated due to NMCA in Cycle 26. Vermont Yankee does not experience large upward spikes in the MCO trend, as do Peach Bottom Units 2 and 3 and Pilgrim. The MCO is relatively constant at a high MCO value.

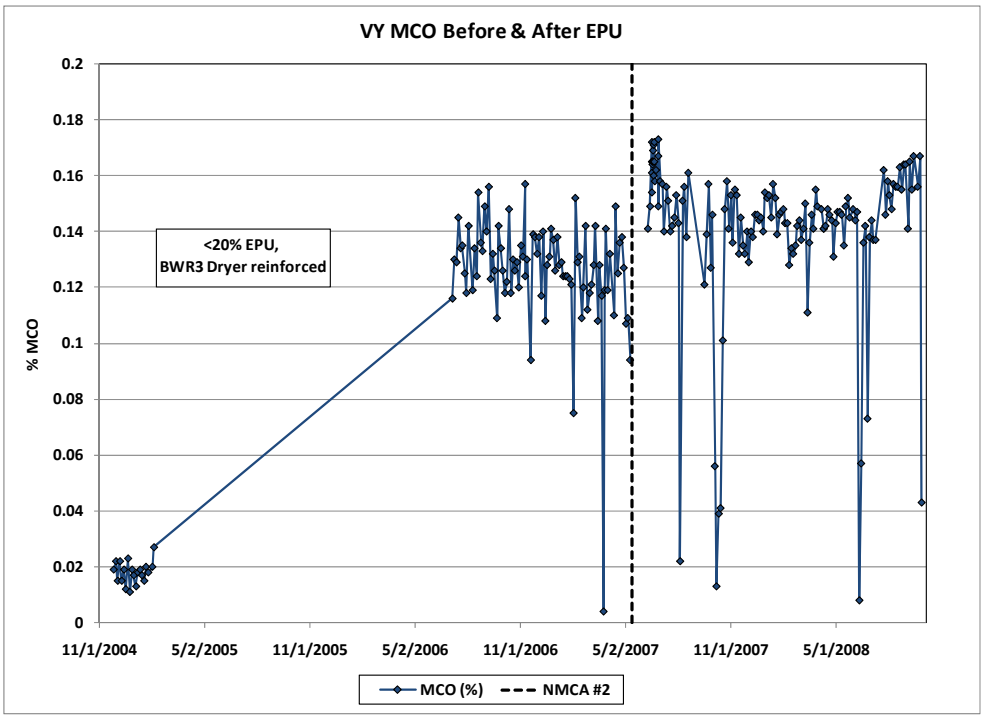


Figure 5-22
Vermont Yankee Moisture Carryover Trend

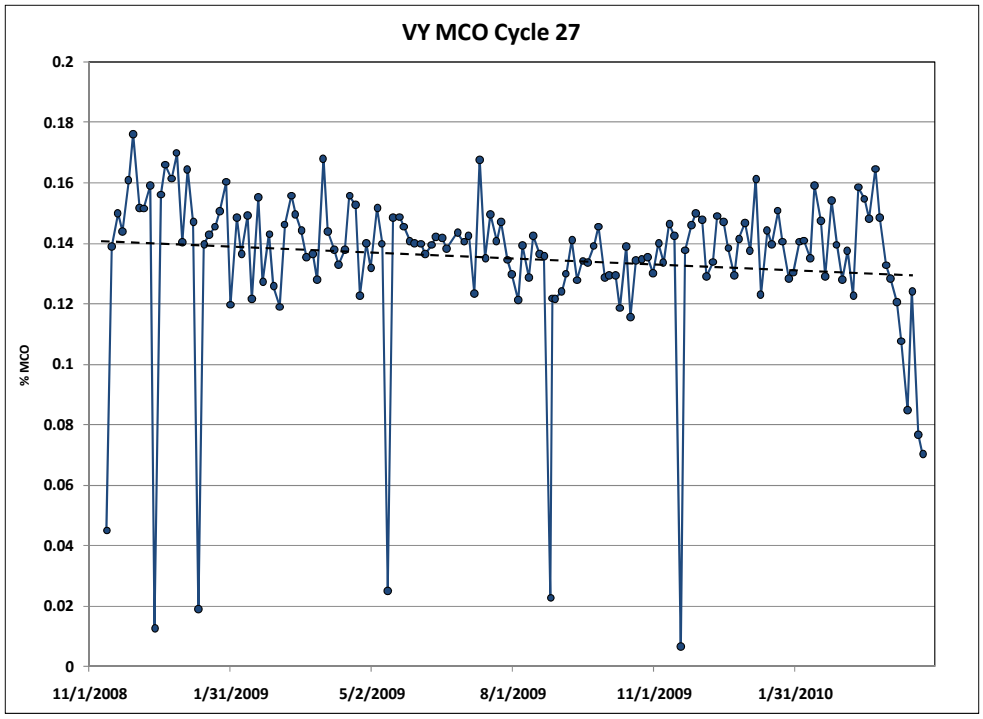


Figure 5-23
Vermont Yankee Cycle 27 Moisture Carryover Trend

Limerick 1 and 2 Experience

Limerick Units 1 and 2 are a BWR 4 design with a similar core design as Peach Bottom Units 2 and 3. As core flow increases at the end of the cycle, MCO increases; as can be seen for Unit 2 cycle 10 and Unit 1 cycle 13 in Figure 5-24. The end of cycle core fuel design, with a high peak at the top of the core, will contribute to the increased MCO, due to overloading the outer ring of the Reactor Steam Dryer.

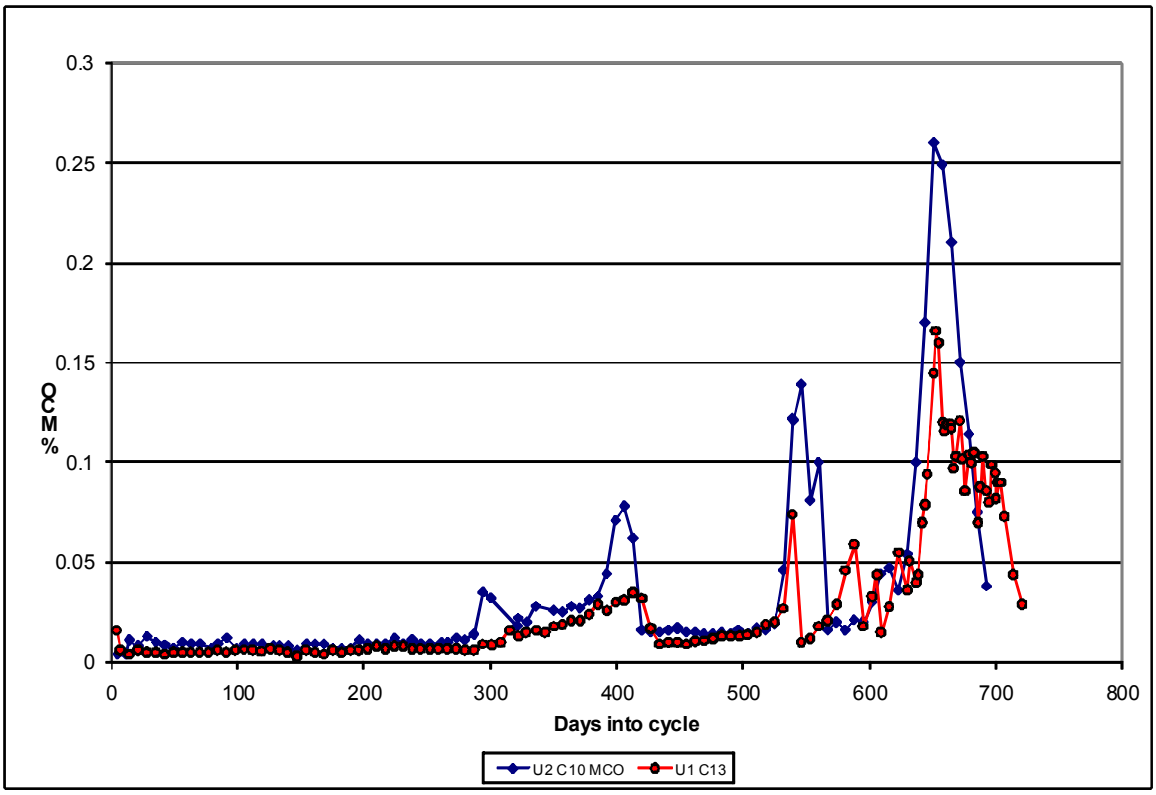


Figure 5-24
Limerick 1 and 2 Moisture Carryover Trends

Factors that Affect Moisture Carryover

Industry data show that MCO is higher at BWR 2 and BWR 3 design plants. There have been improvements in separator/dryer efficiencies and differences in core and vessel designs for BWR 4, 5, and 6 designs.

MCO typically increases towards the end of the cycle. Increasing core flow reduces core exit quality. Lower quality increases liquid loading on steam separators and dryers.

Exelon's Evaluation of MCO Excursions at Quad Cities, Dresden, Peach Bottom and Limerick, presents the contributing factors to increased moisture carryover at each plant [9]. These factors are listed below.

- Dresden and Quad Cities
  Breakthrough in areas of high power in core interior locations
  Radial Power Peaking
  Channeling through Steam Separators

- Limerick Unit 1 Cycle 10 (elevated end of cycle MCO)
  Unique core power distribution due to channel bow issues with 5 inoperable rods at various core locations.

- Limerick Unit 2 RFO 10 high steam side dose rates
  Elevated moisture carryover
  Elevated reactor coolant Co-60 for several cycles led to an increased inventory of Co-60 available to be transported

- Limerick and Peach Bottom common factors
  Increased core flow
  End of cycle operation with high axial flux profile and low power bundles in outer portion of core

Impact of Increased Moisture Carryover [9]

Impacts of moisture carryover include:

- Increased dose on the steam side of the plant. This is primarily due to Co-60 loading in the reactor water. The source of Co-60 is Co-59 from Stellite™ and/or certain steel components, jet pump wedge wear and crud in control rod drive mechanisms or on fuel. The effect on the steam side of the plant is a function of the amount and timing of carryover.

- Possible degradation of downstream secondary components (e.g. turbine blades, orifices, etc.). This would be a function of the amount of carryover and whether it is long term or short term.

Mitigating Moisture Carryover [9]

Short and long term mitigating actions are listed below.

Short Term Mitigating Actions

- Revise core operating strategies

- Rod pattern changes (less aggressive operation)

- End of cycle operations (final feedwater temperature reduction before increased core flow)

- Reduce core flow (power penalty)

Long Term Mitigating Actions

- Core design change
- Add bundles (de-tune the core)
- Re-design orifices for low leakage core designs
- Vessel internals design change
- Replace steam dryers and/or separators
- Source term reduction
- Nuclear fuels group should work with vendors to develop an MCO prediction model to be used in core design to adjust design and/or operating strategy for acceptable MCO to minimize dose and production impact.

Corrosion Product Transport with MCO

Co-60 Transport Calculations

Rate Equation:

$Ci\ Co^{60}/h = 454 \times C_{rw}/(1\text{-}R) \times f_{mco} \times F_{stm}$

C_{rw} = Reactor Water Co^{60} Activity, µCi/g

F_{stm} = Steam (or Feedwater) Flow Rate, Mlb/h

f_{mco} = Mass Fraction Moisture Carryover, %MCO/100

$R = F_{stm}/F_{cf}$, Steam (or Feedwater)/Core Flow Ratio

Unit Conversion, 454 g/lb

General Equation for MCO:

$f_{mco} = A_{cnd}/A_{rw} \times (1 - R) \times F_{cnd}/F_{stm}$

Substituting for f_{mco} to eliminate (1-R):

$Ci\ Co^{60}/h = 454 \times C_{rw} \times A_{stm}/A_{rw} \times F_{cnd}$

Recall: F_{cnd} = Flow Rate at MCO sample point

BWR Monitoring Practices

Peach Bottom Units 2 and 3 and Limerick Units 1 and 2 calculate Co-60 transported to the steam system during the operating cycle. Figure 5-25 shows the reactor water Co-60, the %MCO and the curies of Co-60 transported over the course of a cycle at Peach Bottom Unit 2. Limerick

Units 1 and 2 cumulative Co-60, transported during Unit 2 cycles 10 and 11, and Unit 1 cycles 12, 13 and 14, shown in Figure 5-26.

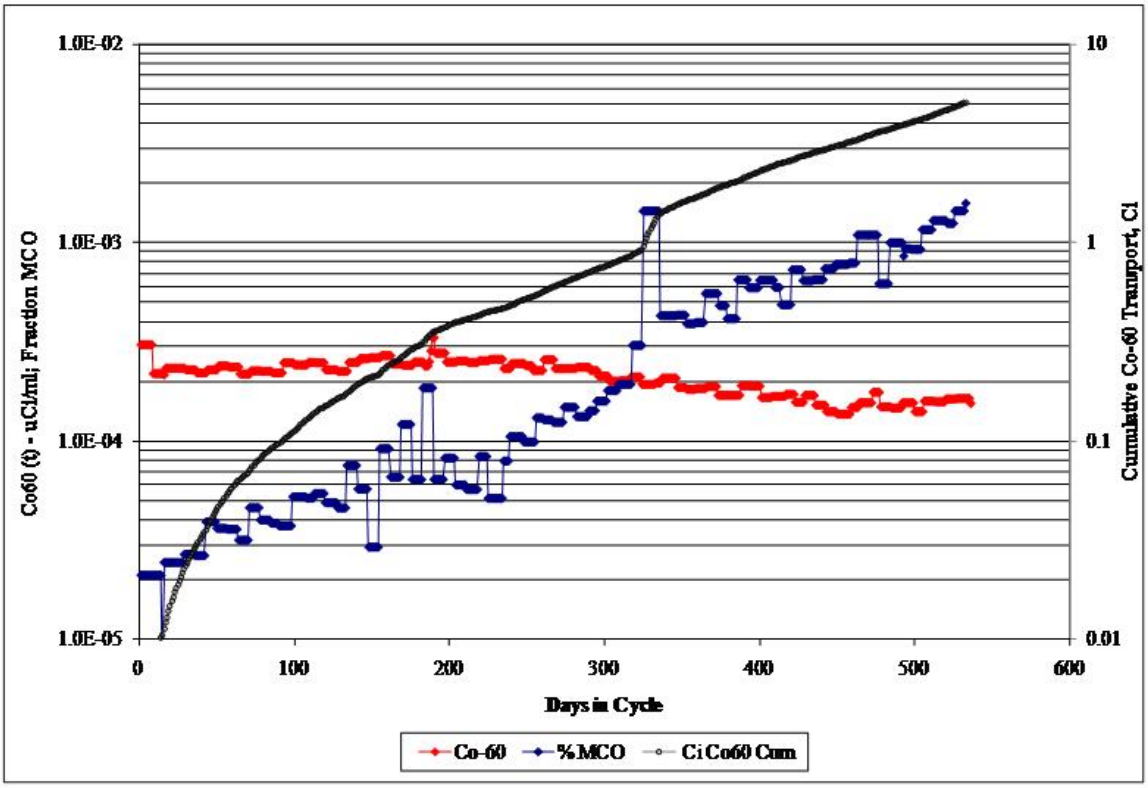


Figure 5-25
Peach Bottom 2 Co-60 Transport and MCO

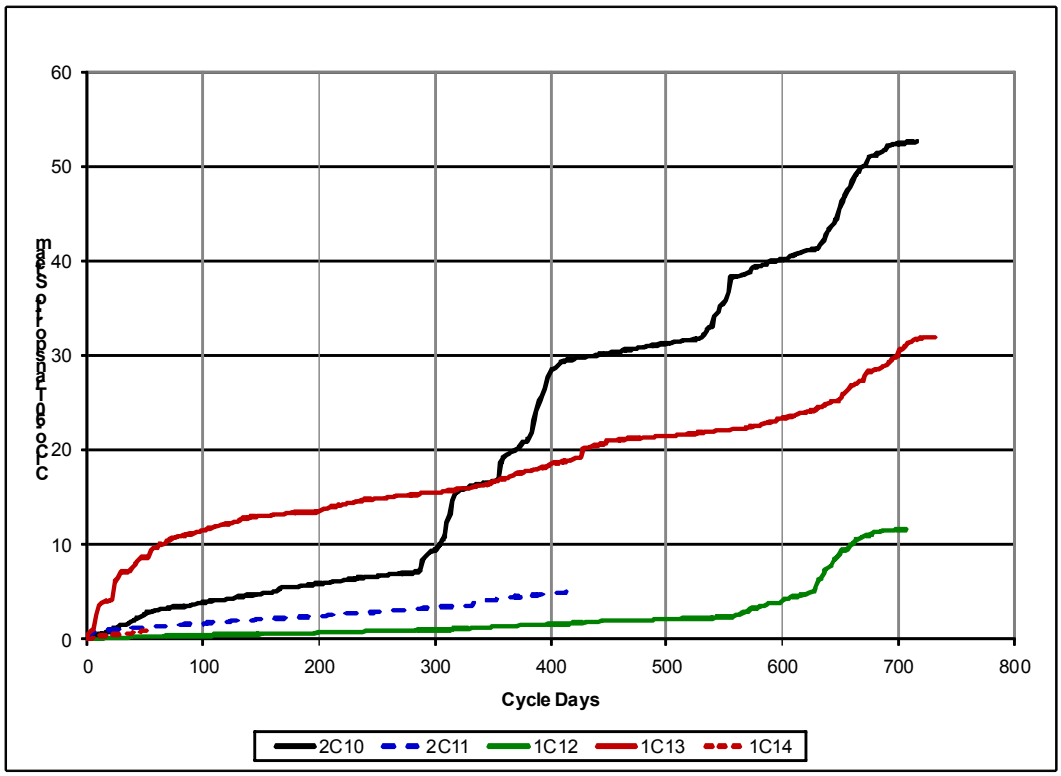


Figure 5-26
Limerick Co-60 Transport

Correlations

Limerick developed the relationship between cobalt transported and dose, shown in Table 4-2, after high MCO and cobalt transport cycles, Cycle 10 at Unit 2 and Cycle 13 at Unit1, shown in Figure 5-26. These plants can use the calculated Co-60 transported during a cycle to predict what the effective dose rate at the low pressure turbine will be the following refuel outage.

Factors that Cause Increased Corrosion Product Transport

Some of the factors that may result in increased corrosion product transport are listed below:

- Timing of noble metal applications
- Elevated MCO
- Crud restructuring and release
- Increased reactor water Co-60 activity
- BWR 2, BWR 3 plant design
- Increasing core flow toward end of cycle

Mitigating Corrosion Product Transport

Short Term Mitigating Actions

- Reduce reactor water Co-60
- Maximize reactor water cleanup Co-60 removal
- Avoid crud restructuring near end of cycle
- Timing of classic and online noble metals applications
- Revise core operating strategies
- Reduce core flow (power penalty)

Long Term Mitigating Actions

- Reduce reactor water Co-60
- Cobalt source term reduction:
- Replace components or minimize component degradation
- New jet pump wedge design
- Main turbine buckets
- Valve seats
- Original equipment control blades
- Remove crud/vacuum control rod drive mechanisms
- Fuel bundle ultrasonic cleaning
- Install reactor water cleanup deep beds

Install permanent or temporary shielding as necessary

Corrosive Impurity Transport

Corrosion due to Corrosive Impurities in Steam

Reactor steam can contain impurities both in entrained water droplets (moisture carryover) and as steam soluble species. Of concern are corrosive volatile impurities such as molecular hydrogen chloride, sodium hydroxide and sulfuric acid and its salts. These compounds are not 100% ionized at reactor temperature, and the associated compounds are soluble in steam. It has

been postulated that the volatile transport of corrosive impurities, particularly HCl, may be significant in BWRs.

The potential for corrosion arises when steam is superheated (heated to increase the temperature above the saturation temperature for the pressure). As water is evaporated, the impurities in liquid droplets increase in concentration until either:

- Impurities volatilize to the steam;
- Impurities precipitate as particulate solids transported by the steam;
- Impurities concentrate until the boiling temperature of the droplet increases to equal the superheat temperature (characteristic of highly soluble compounds with low volatility, such as NaOH).

As work is extracted from superheated steam in the turbines, pressure and temperature decrease until the steam is saturated and moisture forms. Moisture begins to form in the Phase Transition Zone in the turbine (from before the saturation line to about 4-5% moisture). The low volatility impurities will partition to the liquid phase, and since the initial volume of liquid is small, the concentration of impurities in the first condensate will be high. Estimates of the concentration factor (first condensate to superheated steam) range from <10 to >100 [10, 11]. If the initial steam purity were low, the concentration of corrosive impurities in the first condensate could be high enough to cause corrosion in the Phase Transition Zone.

Another mechanism for steam impurities to concentrate would be the expansion of moist steam through a regulating valve for a low pressure use such as for turbine gland sealing [3]. During expansion, the steam moisture decreases until the steam is superheated. Impurities will be concentrated in the residual liquid until dryout occurs. The concentrated impurities may cause corrosion in the dryout zone, which may be within the gland seal.

Since the BWR generates saturated steam, there is no phase transition zone in the high pressure turbine portion of the steam cycle. For plants with moisture separation but no reheat, there is no phase transition zone in the low pressure turbines. Only plants with moisture separation and reheat (which produces superheated steam) will have phase transition zones in the low pressure turbines. The potential for corrosion in these turbines will be related to the concentration of impurities in the superheated steam leaving the moisture separator/reheater.

The following sections will evaluate volatile carryover of corrosive impurities, focusing on HCl, and compare volatile transport to moisture carryover. The concentration of impurity in steam leaving the moisture separator/reheater will be shown to be related to the sum of volatile and moisture carryover.

Volatile Transport

Although compounds such as hydrogen chloride, sulfuric acid and sodium hydroxide are highly ionized, a very small fraction of the total quantity present in solution is associated as molecular species, and these species are volatile. The molal dissociation constant for the association reaction is defined as follows [12].

$$H^+ + Cl^- \rightleftharpoons HCl$$

$$K_A = m_{HCl} * \gamma_{HCl}/(m_{H+} * \gamma_{H+} * m_{Cl-} * \gamma_{Cl-}) = m_{HCl} * \gamma_{HCl}/(m_{H+} * m_{Cl-} * \gamma^2_{\pm})$$

K_A – Equilibrium constant for association of HCl

m – molality (mole/kg)

γ – Activity coefficients

$\gamma^2_{\pm}$ – mean stoichiometric activity coefficient for H^+ and Cl^-, = $\gamma_{H+} * \gamma_{Cl-}$

For dilute solutions (m < 10-4 or <3550 ppb chloride if HCl), the activity coefficients approach 1, as shown in Figure 5-27. The above equation can be simplified to:

$$K_A = m_{HCl}/(m_{H+} * m_{Cl-})$$

At 25°C the K_A for HCl is very small (6.5E-7) but not zero [13]. K_A increases with temperature, resulting in an increase in volatility. For HCl at 288°C, K_A increases to ~8.8 [14]. However, for a 5 ppb chloride solution the percentage of total chloride associated as HCl is still very small, ~0.002%. Figure 5-28 shows the association constants for HCl as a function of total chloride concentration.

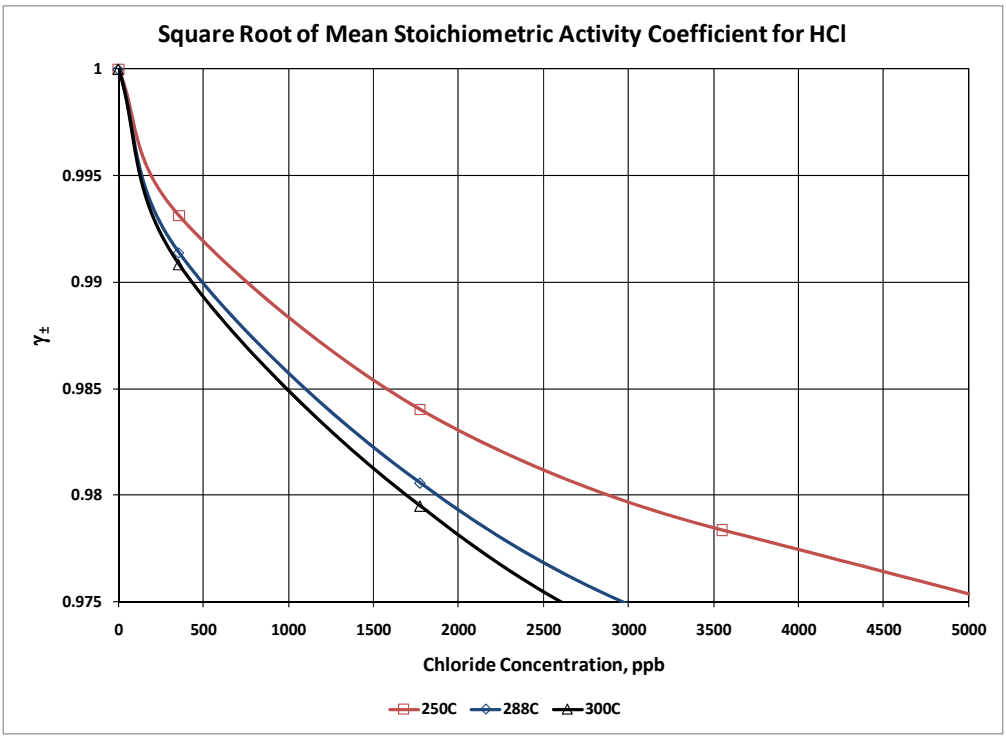


Figure 5-27
HCl Activity Coefficient vs. Concentration

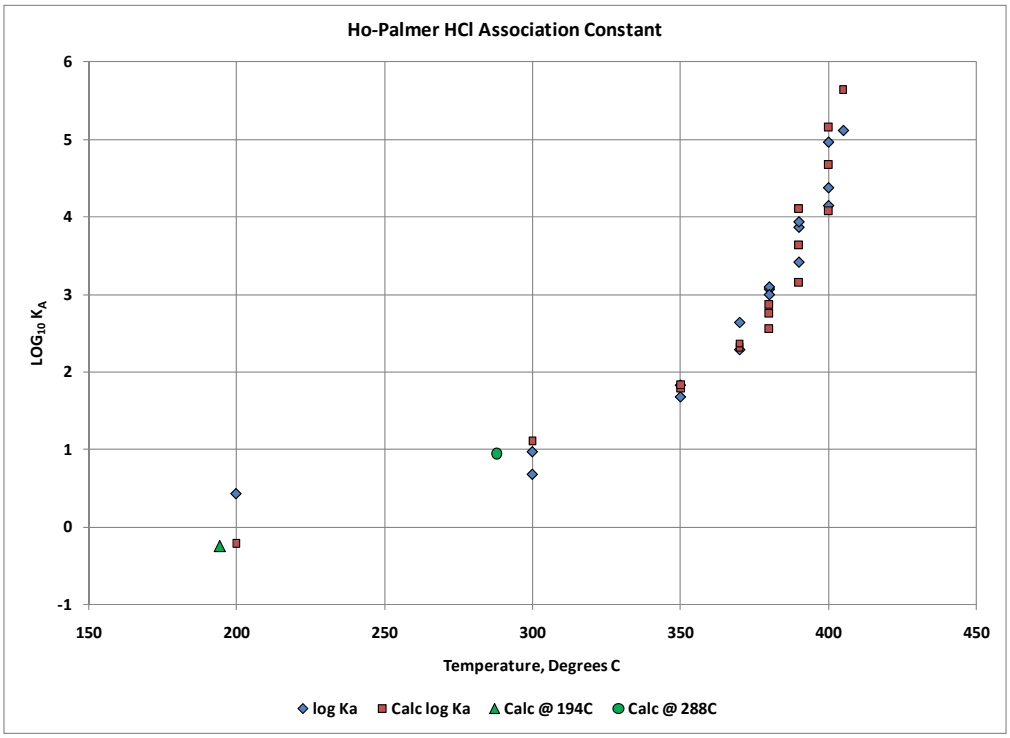


Figure 5-28
Association Constant for HCl vs. Temperature [14]

The volatility of molecular species is indicated by a distribution coefficient, K_D, which is the ratio of the concentration of molecular species in the steam to the product of the concentrations of species that react to form the molecule in the liquid phase. The association constant, K_A, is included in the K_D, so that the extent of ionization of the compound in the liquid phase does not need to be determined [12]. For dilute solutions where the activity coefficients can be assumed to be equal to one, and where the contribution of H^+ from water ionization is significant, the equation for K_D for HCl is shown below. Figure 5-29 shows values of K_D as a function of temperature for a number of species [15].

$$H^+_{liquid} + Cl^-_{liquid} \rightleftharpoons HCl_{steam}$$

$$\mathbf{K_D = K_V * K_A = m_v[HCl]/(m_l[H^+] * m_l[Cl^-]}$$

K_D – molal liquid-vapor distribution coefficient

K_V – molal volatility, associated species = $m_v[HCl]/m_l[HCl]$

K_A – molal association coefficient

m_l – molality liquid phase

m_v – molality vapor phase

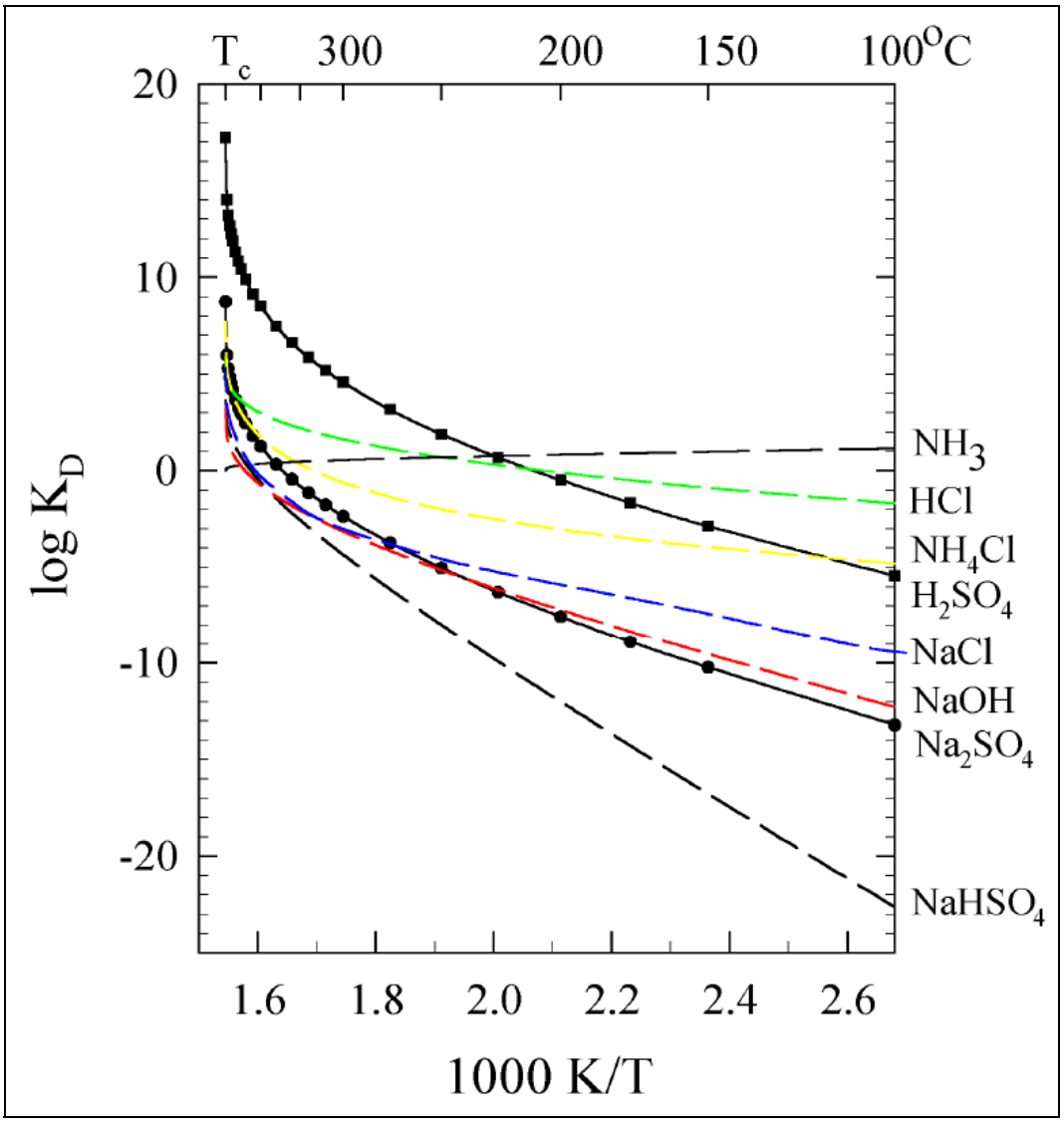


Figure 5-29
Logarithms of Partitioning Constants [15]

Although the values for K_D in Figure 5-29 appear to be high, for highly ionized materials such as HCl or NaOH the concentrations of molecular species in the liquid phase and in the steam are a small fraction of the total concentration in the liquid. Also, when the acid or base are neutralized, the extent of ionization increases, which further reduces the concentration of associated acid or basic species in the liquid phase (although the associated salt species may also be present). Figure 5-30 shows the concentrations of molecular HCl in the liquid phase and HCl in the steam phase as a function of total chloride concentration for HCl alone and for NaCl. Although molecular HCl is highly volatile (the steam concentration is higher than the liquid phase concentration), the liquid phase concentration of HCl is only a very small fraction of the total chloride concentration. At 100 ppb reactor water chloride, the concentration of molecular HCl in the liquid phase is 3.6 ppt, with 10 ppt (0.01% of reactor water) in the steam.

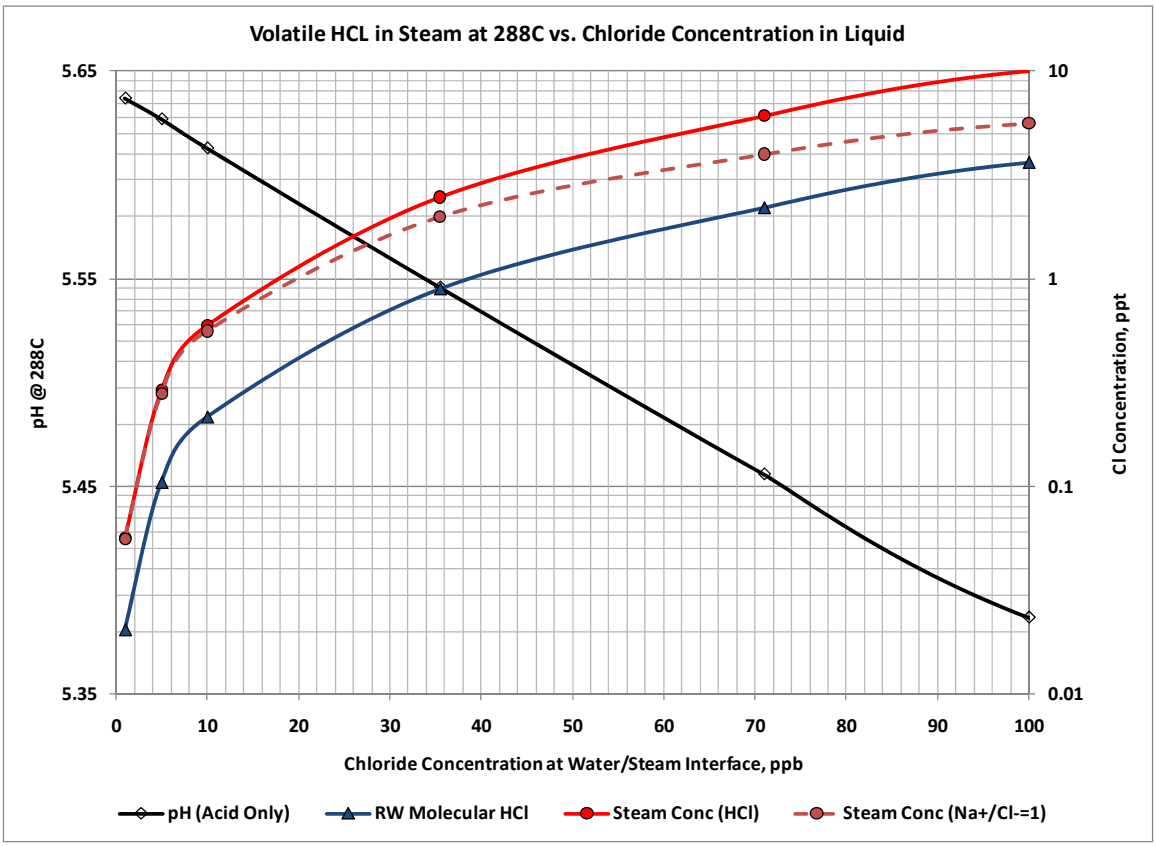


Figure 5-30
Molecular HCl Concentrations in Steam

In Reference 3, it was postulated that the volatile chloride concentration in steam would equal the chloride concentration in feedwater, resulting in significant transport of chloride to steam as HCl. However, the chloride concentration in BWR reactor water can be quite accurately predicted by assuming removal only by the reactor water cleanup (RWCU) system. This implies that the loss rate of chloride to steam is well below the loss rate to RWCU, which is nominally ~1% of the feedwater flow rate at many BWRs. Figure 5-30 implies that the loss rate of volatile chloride to steam will be very small, ≤ 1% of the RWCU removal rate.

Figure 5-31 shows the volatility of HCl at the saturation temperature for 200 psia steam, which is about the pressure of the high pressure turbine exhaust. The volatility is lower at the reduced temperature. However, as discussed later, for reheat plants chloride will also be present in the superheated steam from moisture carryover from the separator section of the MSR.

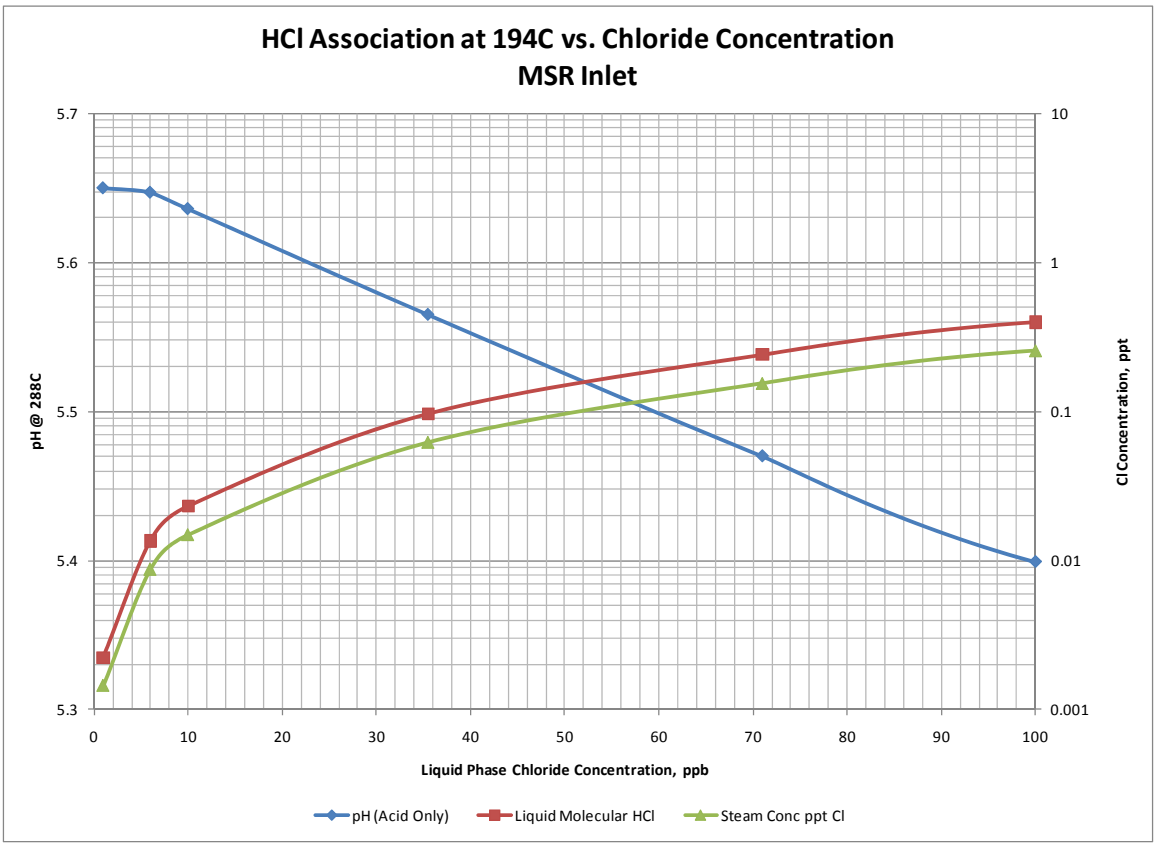


Figure 5-31
Volatility of HCl at MSR Inlet

Total Transport to Steam

Corrosive impurities can be transport to the steam cycle as volatile impurities or as dissolved materials in entrained water (moisture carryover). This section provides an estimate of the total concentration of chloride in steam as a function of %MCO. For the volatile component, it was assumed that on HCl was present in reactor water (e.g. there was no sodium or zinc to neutralize the acidity). This assumption produces a higher concentration of volatile HCL than would be expected from alkaline reactor water. It was also assumed that R, the ratio of feedwater to core flow, was 0.15, a nominal value for BWRs. The reactor water concentrations were increased by the factor of 1/(1-R) to estimate the concentration at the steam water interface for both volatility and transport with moisture carryover. Figure 5-31 shows the total chloride in steam as a function of %MCO. For BWRs operating well within the BWR Chemistry Guidelines with <0.1% MCO, the chloride concentration in steam leaving the RPV is ≤ 1 ppt.

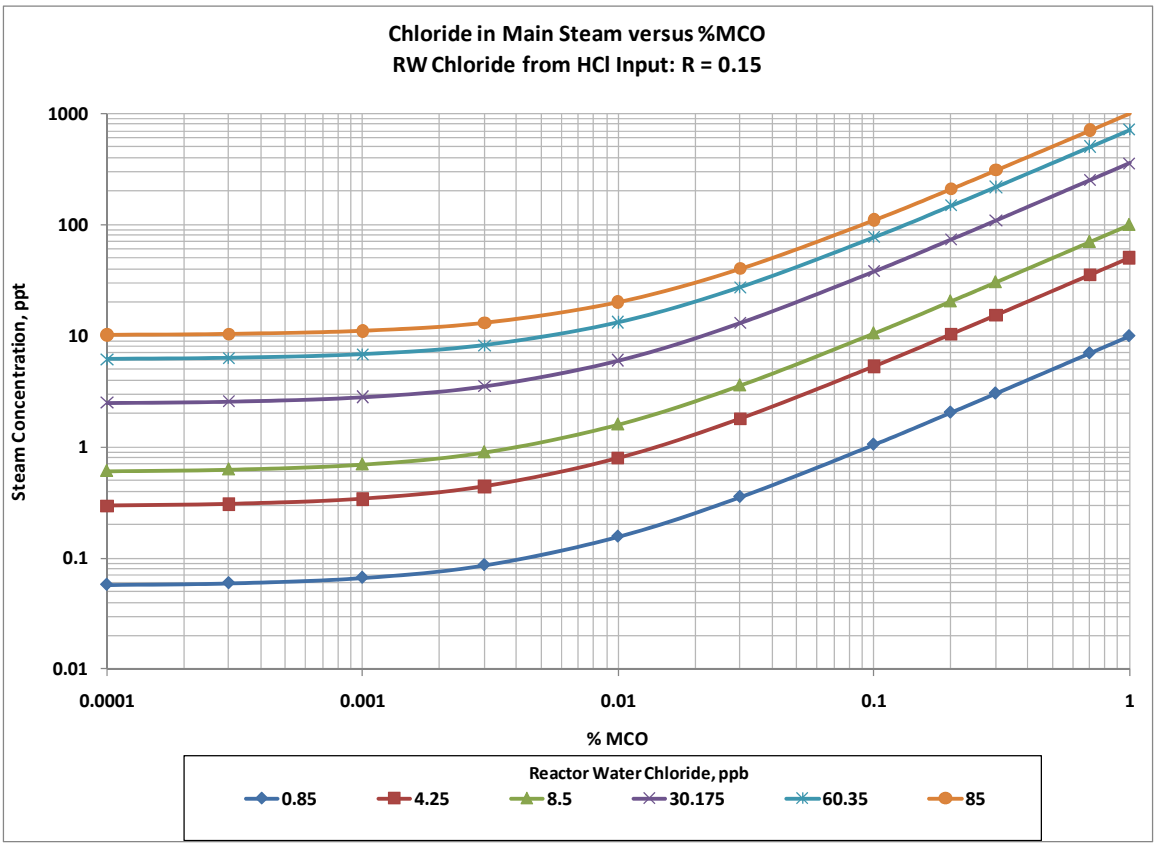


Figure 5-32
Chloride in Steam vs. Moisture Carryover

Figure 5-32 shows the ratio of feedwater to steam concentration for the cases analyzed above. As %MCO increases to the point of becoming equivalent to RWCU in removing impurities, the concentration of impurity in feedwater needs to increase to maintain the same reactor water concentration. The ratio of feedwater to steam concentration decreases to ~2 as the %MCO increases to 1%. For BWRs operation with moisture carryover >0.01%, moisture carryover is the predominant source of corrosive impurity input to the steam cycle.

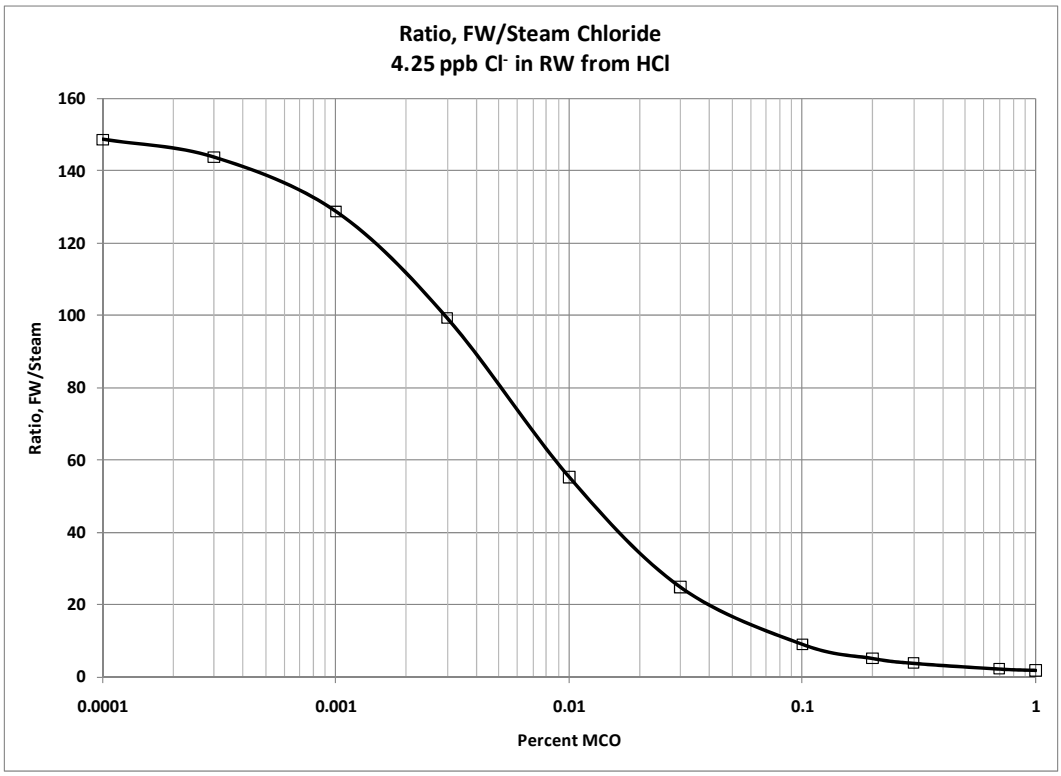


Figure 5-33
Feedwater/Steam Chloride Ratio vs. Moisture Carryover (RWCU flow = 1% of feedwater flow, R = 0.15)

Transport from the Moisture Separator Reheater

The low pressure turbines typically receive ~70% of the steam generated by the reactor. The steam entering the MSR may contain from 10% to 15% moisture. The moisture separator removal efficiency can vary with plant design and changes in loading due to power uprates, but modern designs are capable of >99% removal of moisture prior to reheat. The total concentration of impurity in the steam to the reheat section will be the sum of the volatile concentration plus that present in moisture carryover. For HCl, as the residual moisture is evaporated in the reheat section, all of this will dissolve into the superheated steam.

As shown in Figure 5-32, the total chloride concentration in the steam at a BWR operating with <5 ppb reactor water chloride and <0.2% MCO will be ≤10 ppt (97% in entrained moisture). Assuming 15% moisture, the total flow entering the MSR will be 80.5% of the reactor steaming rate. The liquid phase concentration will be ~77 ppt (10 ppt x 80.5/10.5). Figure 5-31 indicates that the volatile concentration of chloride will be negligible in the steam/liquid mixture. Assuming 99% moisture removal efficiency, the concentration of chloride in the steam entering the reheat section will be ~0.12 ppt (77 ppt x 10.5 x 0.01/70). This will be the concentration of volatile chloride in the superheated steam entering the low pressure turbines.

As discussed above, the first condensate to form in the phase transition zone of the low pressure turbines will be high in impurity concentration, since steam impurities will preferentially partition to the water phase. Assuming a concentration factor of 100, the first condensate chloride concentration would be ~12 ppt.

For steam-soluble constituents with low volatility to steam from the liquid phase, the equation for estimating the impurity concentration in steam entering the low pressure turbines is as follows.

$$\mathbf{C_{MSR\text{-}OUT} = C_{RX\text{-}STM} * (2 - Q_{MSR\text{-}IN}/100) * (1 - E/100)}$$

$C_{MSR\text{-}OUT}$ – Impurity concentration in steam at the MSR outlet

$C_{RX\text{-}STM}$ – Reactor steam total impurity concentrations (volatile plus MCO)

$Q_{MSR\text{-}IN}$ – Quality of steam entering MSR, %

E – MSR moisture separation stage removal efficiency, %

Operating Experience

Hatch Unit 2 has reported intergranular stress corrosion cracking (IGSCC) indications on a low pressure turbine rotor. An evaluation was conducted to assess whether the transport of chemical impurities in steam may have been a factor in the corrosion. Hatch Units 1 and 2 have reheat in the moisture separator [16]. However, Hatch Unit 2 has not experienced elevated moisture carryover in reactor steam. The root cause evaluation identified improper layup and storage as the most probable cause.

Conclusions and Recommendations

Based on a review of the transport properties of HCl, which has relatively high volatility from the liquid phase at reactor operating temperature and pressure, the concentration of steam-soluble impurities in reactor steam is expected to be insignificant when reactor water chemistry is within BWR water chemistry guidelines.

Moisture carryover in reactor steam will be the primary mode of impurity transport to the steam cycle at levels >0.01% MCO. Moisture carryover becomes a significant mode for removing impurities from reactor water at levels >0.1% at a BWR with a nominal 1% RWCU system. At 1% MCO the rate of impurity transport to steam is approximately equal to the rate of RWCU removal at a BWR with a 1% RWCU system.

Since the BWR generates saturated steam, the high pressure turbine and all the high pressure steam loads (feedwater heating, reheater steam) operate wet. Liquid phase impurity concentrations will be well below that in reactor water, and highly water soluble impurities will not be concentrated to precipitation.

For BWRs with moisture separation without reheat, the low pressure turbines and extractions will also operate wet. Liquid phase impurity concentrations will be very low because most of the liquid carrying impurities will be removed by the moisture separator.

For BWRs with moisture separation and reheat, there will be a phase transition zone within the low pressure turbines, with the potential to form deposits and concentrated solutions of impurities in that region. The concentration of impurities in the steam entering the low pressure turbine is a function of the reactor steam purity (primarily the MCO when >0.01%) and the removal efficiency of the moisture separating section of the MSR. For BWRs operating within the BWR Water Chemistry Guidelines and with moisture carryover to reactor steam <0.2%, the concentration of impurities in the liquid in the phase transition zone may be on the order of tens of ppt, depending on local concentration factors.

For all BWRs, there is the potential for dryout to occur when moist high pressure steam is expanded without extracting work (e.g. reducing pressure through a control valve to provide low pressure sealing steam). Impurities in the steam may concentrate or deposit in the dryout zone. Reference 3 provides one instance of corrosion in the gland seal of a high pressure turbine in a foreign BWR plant attributed to impurity concentration in the dryout zone. It is not known whether this is occurring at U.S. BWRs.

EPRI research indicates that the steam limits (2 ppb of Na, Cl and SO_4) for All-Volatile Treatment and Oxygenated Treatment in fossil boilers should result in markedly reduced levels of deposition in turbines in the phase transition zone [17]. For drum boilers operating at 1000 psia, the maximum concentrations of sodium, chloride and sulfate in the boiler water consistent with the steam limits are 2.5 ppm for sodium and sulfate, and 2.4 ppm for chloride. For BWRs operating within the BWR Water Chemistry Guidelines, the reactor water concentrations of chloride and sulfate are well below the Action Level 1 of 5 ppb, and the sodium concentration is well below 45 ppb, the limit imposed by the Action Level 1 of 0.3 μS/cm. Therefore, the steam purity for BWRs operating within the BWR Water Chemistry Guidelines is expected to be well below the fossil drum boiler criterion of ≤2 ppb. Deposition and corrosion in the phase transition zone of the low pressure turbines of BWRs operating with reheat are not expected.

Recommendations

- This report focused on HCl as an indicator of the potential for corrosive impurities to be transported to the steam cycle. Although it is believed that the conclusions for HCl are generally applicable to other corrosive impurities in the BWR, specific evaluations of the transport of sodium and the sulfate anions from neutral to slightly basic reactor coolant should be considered.

- Zinc is present in BWR reactor water and may be transported to the steam cycle with moisture carryover. The potential for the deposition of zinc compounds in the reheater and in the phase transition zone of BWR steam cycles that have reheat should be considered for evaluation.

- The fossil boiler side of EPRI has funded extensive research by Oak Ridge National Laboratory (ORNL) into the volatility of various chemical compounds, to support

understanding transport processes in the steam cycle. Personnel with this knowledge and experience should be asked to review the conditions for BWRs operating at ~1000 psia, with and without steam reheat, to identify potential issues and to provide recommendations.

- It is recommended that a survey be conducted of U.S. and foreign BWRs to identify occurrences of turbine deposition or corrosion that may have been related to steam impurities. These occurrences should be evaluated against the plant chemistry and operating conditions (main steam MCO, moisture separation efficiency in the MSR) to identify the conditions that cause problems. This survey could form a basis for establishing steam purity limits for BWRs.

6
CONCLUSIONS

Moisture Carryover Monitoring

A review of industry practices identified the following practices that are less than ideal:

- Most plants do not correct the measured reactor water Na-24 activity for steam generation to obtain the activity at the steam-water interface. The correction factor is obtained by dividing the measured Na-24 activity by (1-R), where R is the ratio of feedwater flow to core flow.
- A few plants are directly sampling main steam to determine the Na-24 activity in condensate. Main steam sampling is discouraged because the sample is likely to be unrepresentative.
- Some FPD plants may be sampling both the forward pumped drains and the condensate cleanup inlet. The Na-24 activity in the hotwell at an FPD plant should be minimal, unless reactor water cleanup letdown is being sent to the hotwell. Moisture carryover will be overestimated if the LLD for Na-24 is applied to the condensate measurement.

Causes of Increased Moisture Carryover

Excluding steam dryer failures, increases in moisture carryover are due to decreased performance of the moisture separators, which increases the moisture loading on the steam dryers and consequently increases moisture in the steam. The steam separators are not equally loaded because the quality of steam exiting the fuel channels varies across the cross-sectional area of the core. Moisture carryover is acceptable as long as the number of heavily loaded separators is small enough that the overall moisture loading on the dryer is acceptable.

Excessive moisture carryover has been attributed to the following factors:

- Power uprates, which increase velocities through the separators.
- Significantly reduced quality of the steam produced by peripheral bundles due to the implementation of low leakage core designs. The steam quality is reduced because there is less steam generation in the bundle, while bundle flow is not proportionally reduced. As steam quality is reduced, water loading on the steam separators is increased.
- Increases in core flow rate, which reduce the core exit quality because more water must be removed per unit volume of steam.

- Core power configurations that significantly increase localized power generation. Steam separators above the high power region will experience higher steam velocities, which may reduce separator efficiency.

Moisture Carryover Mitigation

Options for near-term reduction in moisture carryover are limited and require some reduction in power generation. Plants with high moisture carryover have taken the following mitigating actions:

- For plants that increase core flow rate and reduce feedwater temperature at the end of the cycle to maximize power generation, implementing feedwater temperature reduction before maximizing core flow reduces the operating time on high core flow. Since moisture carryover tends to increase with core flow, this reduces the time with high moisture carryover at the end of the cycle.
- Plants that have reached upper limits on moisture carryover have reduced core flow (i.e., reduced power) to maintain the moisture carryover limit.

Design changes that can be considered to reduce moisture carryover include the following:

- Replacement of the steam separators with a design having higher performance or that can tolerate a greater range of steam quality. The Forsmark plants upgraded moisture separators as part of power uprate.
- Justification of a reduction in the normal reactor water level, which will reduce the depth that the separators are submerged and potentially increase performance.
- Fuel bundle loading and operation that increases power in the peripheral bundles, with some sacrifice in fuel economics.
- Reducing bundle flow in the peripheral bundles to increase discharge quality, which would require design changes to the core flow orifices.

Corrosion Product Transport

Increases in corrosion product transport to the steam cycle are due to a combination of elevated corrosion product activity in reactor coolant and increased moisture carryover. The following mitigating actions can be considered:

- Scheduling activities likely to increase reactor water corrosion product activity (such as OLNC application) early in the cycle, during periods when moisture carryover is low.
- To the extent possible, operating the RWCU system to maintain a removal factor for corrosion product activity >10 in order to reduce reactor water activity.

- Implementing cobalt reduction strategies which, over the long term, are expected to reduce reactor water corrosion product activity.

Corrosive Impurity Transport

Based on a review of hydrogen chloride transport, corrosive impurity transport is not expected to be a significant issue for BWRs except under highly abnormal conditions. BWR non-reheat steam cycles do not have phase transition zones in the turbines at which deposits or concentrated solutions of corrosive impurities can form. BWRs operating within the BWR Water Chemistry Guidelines maintain the concentration of corrosive impurities two to three orders of magnitude below that considered acceptable for steam purity in fossil boilers operating at the same steam pressure. For cycles with reheat, a combination of highly degraded reactor water quality and high moisture carryover would be needed to transport significant quantities of corrosive impurities to the steam cycle.

7
RECOMMENDATIONS FOR FUTURE WORK

1. Core Loading and Operation

   Evaluate fuel loading designs and core operating practices that may reduce moisture carryover with minimal impact on fuel economics.

2. Reactor Normal Water Level (NWL) Reduction

   Evaluate the feasibility of reducing the normal reactor water level and the potential benefit on steam separator performance and reduced moisture carryover.

3. Reduced Flow in Peripheral Bundles

   For plants that have implemented low leakage core loading, evaluate the feasibility of reducing flow to the peripheral bundles by modifying the fuel orifice design.

4. Corrosive Impurity Transport

   a. Evaluate the transport of sodium hydroxide and salts of sulfuric acid to the BWR steam cycle.

   b. Evaluate the transport of zinc and the potential impacts of zinc compounds on turbine deposits and corrosion.

   c. Conduct a survey of deposition and corrosion in BWR turbines and evaluate whether impurity transport was a factor.

   d. Perform an evaluation of steam purity requirements for BWRs using EPRI expertise with impurity transport and turbine issues in fossil boilers.

8
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A
MEASUREMENT OF BWR MOISTURE CARRYOVER (NWT 808)

NWT 808, Measurement of BWR Moisture Carryover [5] is presented in its entirety in this appendix.

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NWT 808
August 24, 2010

MEASUREMENT OF BWR MOISTURE CARRYOVER

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SECTION 1
INTRODUCTION

Quantification of moisture carryover (MCO) from the BWR reactor vessel has recently received increased industry attention because of steam dryer performance issues, particularly following power uprates [1, 2]. MCO normally is being quantified based on measurements of Na-24 in the reactor water and condensate at plants with fully cascaded heater drains and in the reactor water and heater drains at plants with forward pumped heater drains.

NWT has employed chemical and radiochemical tracers for a variety of purposes in light water reactors. For example, Na-24 and potassium have been used to quantify moisture carryover (MCO) from PWR steam generators. Na-24 and potassium have also been used to calibrate feedwater flow instrumentation, to quantify turbine moisture separator removal efficiencies, to calibrate blowdown flow instrumentation at PWRs and to quantify feedwater heater leakage. The most extensive use of Na-24 has been during thermal performance testing where the tracer is used to quantify flow rate and steam quality in multiple process streams in the power generating cycle.

In these cases, injection of the tracer into a process stream has been required. For moisture carryover measurements in BWRs, this is generally not necessary since numerous possible tracers are present in the reactor water. However, only a select number are of use relative to quantifying moisture carryover. The most commonly used nuclide is Na-24 since it is highly soluble in the liquid phase, has minimum volatility and is readily quantifiable by gamma spectrometry.

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In Section 2, approaches to quantifying MCO from the BWR reactor pressure vessel are reviewed. In Section 3, these approaches are summarized and recommendations are provided.

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SECTION 2
METHODOLOGY

2.1 Background

Moisture carryover (MCO) is defined as the ratio of activity concentration of tracer in the steam, A_S, to the activity concentration in the water at the steam/water interface, $A_{S/W}$.

$$MCO = \frac{A_S}{A_{S/W}}$$

Since BWRs do not have sample taps near the steam/water interface, the reactor water concentration, A_{RW}, is used to estimate $A_{S/W}$ based on the core circulation ratio, R, or the average steam quality at the core exit. R is defined as the ratio of the mass flow rate of steam, W_{Steam}, at the core exit to the total core flow rate, W_{Core}.

$$R = \frac{W_{Steam}}{W_{Core}} = \frac{X}{100}$$

and

$$A_{S/W} = \frac{A_{RW}}{1 - R}$$

where

X	=	Average Steam Quality at the exit of the core, %
A_{RW}	=	Reactor water concentration
$A_{S/W}$	=	Liquid phase concentration at steam/water interface
R	=	Ratio of steam flow rate to total core flow rate
W_{Steam}	=	Steam or feedwater flow rate
W_{Core}	=	Total core flow rate

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Note that a fundamental assumption in developing the activity transport relations in two phase regions is that the ratio of the tracer concentration in the steam phase to that in the liquid phase is very low. This ratio is commonly referred to as the vapor to liquid distribution coefficient. For NaCl, the ratio is approximately 2E-6 at the reactor pressure and <1E-7 at the MSR pressure. Examples of MCO calculations are given below.

2.2.1 Feedwater Basis

Assuming that the turbine moisture separator efficiency is ~100%, all of the steam borne Na-24 will be routed to the feedwater via the forward pumped high pressure heater drains and the feedwater concentration will equal the steam concentration. As a result, the percent MCO can be calculated as follows:

$$\%MCO = \frac{A_S}{A_{S/W}} \cdot 100$$

and

$$A_S = A_{FW}$$

Therefore,

$$\%\,MCO = \frac{100 \cdot A_{FW}}{A_{S/W}}$$

where

A_{FW} = Decay corrected feedwater activity concentration, µCi/g
$A_{S/W}$ = Steam water interface concentration, µCi/g

and

$$A_{S/W} = \frac{A_{RW}}{1 - R}$$

Activity transport to the condenser by leakage from the RWCU system or as a result of less than 100% turbine moisture separator moisture removal efficiency could increase the feedwater tracer concentration if the demineralizer efficiency is not high. However, Na-24 decay across the demineralizer is expected to be very high due to isotopic exchange and leakage will be minimal. The above relations can be corrected to reflect estimated moisture separator efficiency. However, more accurate MCO values can be determined based on the RW and HD or RW and MSD concentration and flow rate data.

2.2.2 High Pressure Heater Drain (HPHD) Basis

Values of MCO can also be developed from the forward pumped heater drain and steam generator liquid/steam interface concentrations as a function of MSR moisture separator removal efficiency. In this case, total activity transport by the heater drains can be expressed as follows:

$$W_{HD}A_{HD} = (W_S - W_{MSRI})\,A_S + (W_{MSRI})(A_S)\left(\frac{\varepsilon}{100}\right)$$

where

W_{MSRI} = Total flow rate at MSR Inlet, lbs/h

W_S = Total steam flow rate from reactor vessel, lbs/h

A_S = Decay corrected steam concentration, μCi/g

ε = MSR moisture separator removal efficiency, % (Measured or estimated value based on heat balance)

The steam concentration calculated from the above relation is used to calculate MCO, i.e.:

$$\%MCO = \frac{\dfrac{100 \cdot W_{HD} \cdot A_{HD}}{W_S - W_{MSRI} + W_{MSRI} \cdot \left(\dfrac{\varepsilon}{100}\right)}}{A_{S/W}}$$

where

$$A_{S/W} = \frac{A_{RW}}{1 - R}$$

The effect of an error in moisture separator efficiency on the calculated value of MCO based on the heater drain approach is generally small but can be estimated using the same relation.

2.2.3 Moisture Separator Drain (MSD) Basis

Values of MCO also can be developed from the MSD and vessel liquid/steam interface concentrations. Tracer transport by the moisture separator drains can be expressed as follows:

$$W_{MSD} \cdot A_{MSD} = W_{MSRI} \cdot A_S \left(\frac{\varepsilon}{100}\right)$$

where

A_{MSD} = Moisture separator drain decay corrected activity concentration, µCi/g

W_{MSD} = Moisture separator drain flow rate, lbs/h

ε = Moisture separator removal efficiency, % (based on heat balance)

The steam concentration calculated from the above relation is then used to calculate MCO by dividing by the reactor vessel liquid/steam interface concentration:

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$$\%MCO = \frac{\dfrac{100\, W_{MSD} \cdot A_{MSD}}{W_{MSRI}\left(\dfrac{\varepsilon}{100}\right)}}{A_{S/W}}$$

and

$$A_{S/W} = \frac{A_{RW}}{1 - R}$$

2.3 Calculation of Moisture Carryover for Cascaded Heater Drain Plants

At plants with all drains cascaded to the condenser, reliance is generally placed on measurements of reactor water and condensate tracer concentrations. At such plants, all of the tracer leaving the pressure vessel will be transported to the condenser. Fortunately, the half life of Na-24 is long compared to the transport times so delay time effects do not impact on the measurement. Moisture carryover is calculated as follows:

$$\%MCO = \frac{A_S}{A_{S/W}} \cdot 100$$

where

$$A_S = A_{CN}$$

Therefore,

$$\%\,MCO = \frac{100 \cdot A_{CN}}{A_{S/W}}$$

where

A_{CN} = Decay corrected condensate activity concentration, µCi/g
$A_{S/W}$ = Steam water interface concentration, µCi/g

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and

$$A_{S/W} = \frac{A_{RW}}{1 - R}$$

MCO can also be calculated from turbine moisture separator drain and high pressure heater drain concentrations (See Section 3.3).

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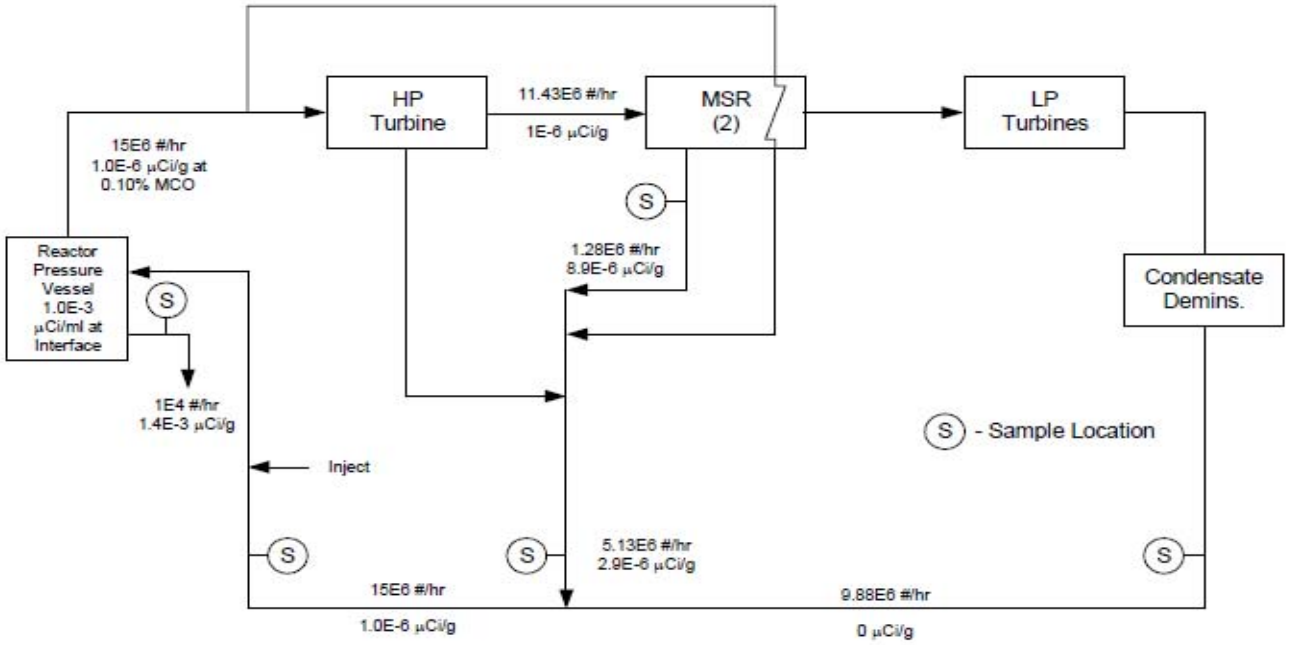


Figure 2-1 Turbine Cycle Mass Flow and Projected Activity Balance at 0.10% MCO at a Plant with Forward Pumped Heater Drains and 100% Turbine Moisture Separator Efficiency

SECTION 3
SUMMARY

3.1 General Considerations

Na-24 is normally used as a tracer to quantify moisture carryover in BWRs. In evaluating approaches to performing such measurements or the data obtained during such measurements, the following should be noted:

- At plants with forward pumped heater drains, it is not possible to employ measurements in the condensate to calculate moisture carryover since most of the tracer is routed directly to the feedwater through the forward pumped drains. Measurement of concentrations in the forward pumped heater drains, turbine moisture separator drains or feedwater are required. The tracer concentration in the moisture separator drains will be significantly greater than that in the forward pumped drains which will be significantly greater than that in the feedwater (Reference Figure 2-1). Thus, accuracy of the MCO measurement can be increased if calculations are based on the reactor water and moisture separator drain or heater drain measurements.
- Attempts to employ measurements of tracer concentrations in the steam are discouraged due to the high probability that the steam line samples will be biased high in concentration due to the preferential removal of moisture from the sample probe or tap or biased low due to preferential removal of steam.
- Na-24 concentrations (particularly in the feedwater, heater drain, moisture separator drain and condensate samples) can be overestimated as a result of an interference from the 6.57 hour half life I-135 peak at 1367.9 keV (0.606% abundance). Including the 1367.9 keV I-135 peak in the multichannel analyzer library can help avoid this misidentification. The possible interference is of particular concern if the plant is operating with a significant fuel failure. Since Na-24 has a 15.0 hour half life and major peaks (100% abundance) at 1368.5 keV and 2754.1 keV, misinterpretation can be avoided by validation of the Na-24 concentration using the 2754.1 keV peak or checking the rate of decay of the activity producing the ~1368 keV peak.
- All Na-24 concentration data should be decay corrected to the same time.

Equations for calculating MCO at BWRs are summarized below.

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3.2 Forward Pumped Heater Drain Plants

Moisture carryover at plants with forward pumped heater drains can be calculated from the relations below. The approach based on the moisture separator drains is expected to yield the highest accuracy followed by the approach using the high pressure heater drain samples and finally the feedwater approach.

Feedwater Basis

$$\%MCO = \frac{100 \cdot A_{FW}}{A_{S/W}} \qquad \text{Eq. 3.1}$$

Heater Drain Basis

$$\%MCO = \frac{\dfrac{100 \cdot W_{HD} \cdot A_{HD}}{W_S - W_{MSRI} + W_{MSRI} \cdot \left(\dfrac{\varepsilon}{100}\right)}}{A_{S/W}} \qquad \text{Eq. 3.2}$$

Moisture Separator Drain Basis

$$\%MCO = \frac{\dfrac{100\, W_{MSD} \cdot A_{MSD}}{W_{MSRI}\left(\dfrac{\varepsilon}{100}\right)}}{A_{S/W}} \qquad \text{Eq. 3.3}$$

where

$$A_{S/W} = \frac{A_{RW}}{1-R}$$

where

A_{FW} = Decay corrected feedwater activity concentration, µCi/g
$A_{S/W}$ = Decay corrected steam water interface concentration, µCi/g
W_{HD} = Forward pumped heater drain flowrate, lbs/h
A_{HD} = Decay corrected forward pumped heater drain activity concentration, µCi/g
W_S = Total steam flow rate from reactor vessel, lbs/h

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W_{MSRI} = Total flow rate at MSR Inlet, lbs/h
ε = Moisture separator removal efficiency, % (based on heat balance)
W_{MSD} = Decay corrected moisture separator drain flow rate, lbs/h
A_{MSD} = Decay corrected moisture separator drain concentration, µCi/g
A_{RW} = Decay corrected reactor water concentration, µCi/g
R = Ratio of steam flow rate to total core flow rate

3.3 Cascaded Heater Drain Plants

At plants with all heater drains cascaded to the condenser, reliance generally is placed on reactor water and condensate Na-24 concentrations. However, if measurements of the Na-24 concentration in the turbine moisture separator drains or a drain from a heater at a lower pressure than that into which the moisture separator drains are routed, increased accuracy can be achieved. Note that MCO values determined from condensate tracer measurements can be biased high if leakage from the RWCU to the condenser is occurring. However, the bias generally will be minimal, e.g., <0.01% at a leakage of 1 gpm. Moisture carryover at plants with cascaded heater drains can be calculated from the relations below.

Condensate Basis (Only plants with all drains cascaded)

$$\%\,MCO = \frac{100 \cdot A_{CN}}{A_{S/W}} \qquad \text{Eq. 3.4}$$

where

A_{CN} = Decay corrected condensate concentration, µCi/g
$A_{S/W}$ = Reactor vessel steam/water interface concentration, µCi/g

and

$$A_{S/W} = \frac{A_{RW}}{1 - R}$$

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Moisture Separator Drains

Refer to Equation 3.3.

Heater Drain Basis

Relations similar to Equation 3.2 can be developed for plant specific cycle configurations and sample point locations.

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