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DOSE REDUCTION BENEFITS OF ZINC INJECTION INTO THE PRIMARY COOLING SYSTEM OF A PRESSURIZED WATER REACTOR

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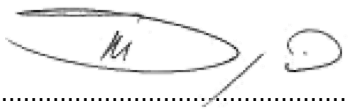
Degree of Master of Science

A research report submitted to the Faculty of Science, University of the Witwatersrand, in fulfilment of the requirements for the degree of Master of Science.

Johannesburg 2018

CANDIDATE'S DECLARATION

I, Martin Anthony Saaymans, declare that this research report is my own, unaided work. It is being submitted for the Degree of Master of Science at the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination at any other University. Information obtained was done while in the employ of Eskom, Koeberg Nuclear Power Station.



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SIGNATURE OF CANDIDATE

Signed in Melkbosstrand, Cape Town on this 26th day of February 2018.

ABSTRACT

Koeberg Nuclear Power Station has set itself the objective of achieving world top quartile performance in terms of dose to workers. Achieving this goal requires implementation of a number of dose reduction initiatives. One such initiative is the continuous injection of depleted zinc acetate into the primary cooling system of the plant as a means of cobalt reduction, the principal contributor to out-of-core radiation fields.

The purpose of this research report is to investigate the measure of success in reducing the radiation dose that nuclear plants world-wide have achieved through zinc injection, and how Koeberg measures up to international results.

The investigation method included an extensive literature study on international experiences and results of other cobalt reduction methods, the benefits of zinc injection, as well as the potential negative impact it may have on major plant components. The report also presents the results of Koeberg's zinc monitoring programme while comparing it to international trends.

A recommendation is made for a more coordinated monitoring programme at Koeberg in order to obtain maximum benefits in the long term. Notwithstanding, the research has led to the conclusion that Koeberg is achieving the desired results compared to industry performances for plants that are in the same phase of their respective zinc injection programmes.

DEDICATION

To my wife,

Natalie Saaymans;

Thank you for your unwavering support.

ACKNOWLEDGEMENTS

The task of writing this research report over many months has provided me with excitement, pleasure, and frustration in equal weight. It had a big impact on my personal and intellectual growth. I would not have been able to reach this goal without the support of my family, friends, colleagues, and lecturers.

I want to start by thanking my family and in particular my wife, for her unwavering support during this period. I am forever grateful for her unselfish care of the family in times I was not able to do so.

In addition, I want to express my gratitude towards my supervisors, Professor Ivo Petr and Professor James Larkin for their guidance and encouragement. To my colleagues at Koeberg who shared with me their expertise and knowledge, thank you.

Thank you all very much!

Martin Saaymans

Melkbosstrand, 26 February 2018

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NOMENCLATURE

DEFINITIONS

Term	Definition
Depleted zinc oxide (DZO)	A zinc oxide depleted in the zinc isotope with the atomic mass 64, and used as a corrosion inhibitor in nuclear pressurized water reactors. The depletion of ^{64}Zn is necessary, because this isotope is transformed into ^{65}Zn by neutron capture. ^{65}Zn, with a half-life of 244.26 days, emits gamma radiation with 1.115 MeV (EPRI, 2010). ^{64}Zn has a natural abundance of 48.6%, but in DZO, it is reduced below 1%.
Electro-polishing	An electrolytic process to remove microscopic irregularities from metal surfaces, thereby reducing its surface area in order to minimise the deposition of foreign material on such surfaces.
EPRI	Electric Power Research Institute (EPRI) is a non-profit organization funded by the electric utility industry, founded in 1972 with its headquarters in Palo Alto, California. EPRI is primarily a US-based organization, but receives international participation. EPRI's research covers different aspects of electric power generation, delivery, and its use.
Stellite	Any of several alloys containing cobalt, chromium, carbon, tungsten, and molybdenum. It is characteristically very hard and wear-resistant, and is used in castings or hard surface coatings.

ABBREVIATIONS

Abbreviation	Definition
ALARA	As Low As Reasonably Achievable
BWR	Boiling Water Reactor
CIPS	Crud-Induced Power Shift
CILC	Crud-Induced Localised Corrosion
CRUD	Chalk River Unidentified Deposits
CZE	Cumulative Zink Exposure
EDF	Électricité de France (French Electricity Utility)
EPRI	Electric Power Research Institute
PWR	Pressurised Water Reactor
PWSCC	Primary Water Stress Corrosion Cracking
RCP	Reactor Coolant Pump
RCS	Reactor Coolant System
RCV	Chemical and Volume Control System
SG	Steam Generator
SGR	Steam Generator Replacement
SRMC	Standard Radiation Field Monitoring and Characterization
SRMP	Standard Radiation Field Monitoring Programme
WOG	Westinghouse Owners Group

1 INTRODUCTION

Optimisation is a key principle of radiation protection and it implies that all practical and cost-effective steps be taken to reduce the risk of radiation, i.e. in this case specifically, the dose to workers. By applying this principle, Koeberg Nuclear Power Station has set itself the objective of achieving world top quartile performance in terms of dose to workers. Achieving this goal in the short to medium term requires implementation of a number of dose reduction initiatives. One such initiative is the continuous injection of depleted zinc acetate into the primary cooling system of the plant as a means of cobalt reduction. It has been determined that ^{60}Co is the principal contributor to out-of-core radiation fields.

The focus of this report is to illustrate the measure of success in reducing the radiation dose that nuclear plants world-wide have achieved by zinc injection, and how Koeberg measures up to international best practice. As Koeberg is in the first few cycles of zinc injection, the results will be presented in comparison with the trends experienced internationally for the same duration of zinc injection.

Zinc injection is carried out to reduce the dose rate and to mitigate the initiation of primary water stress corrosion cracking (PWSCC). Zinc is also injected to kerb the generation of corrosion products and to minimize the deposition of crud on fuel surfaces. Crud—an acronym for Chalk River Unidentified Deposits named after the Canadian plant where it was first observed—is an accumulation of corrosion products containing radioactive nuclear species and is produced during the normal operation of a nuclear plant. Eighty-five per cent of nuclear power plants implementing a zinc injection programme report the reduction in dose rates as their primary objective. Secondary objectives include PWSCC mitigation and crud mitigation (EPRI, 2006).

Zinc injection, as a dose reduction tool, works as follows. Spinel, a hard, glassy substance of oxides, which incorporates radioactive fission products such as ^{58}Co and ^{60}Co as well as corrosion products such as Fe and Ni, over time build up in layers on the steel internals of the primary system. By injecting a more stable, non-radioactive metal ion namely depleted zinc into the primary system coolant, the zinc is incorporated in the layers of spinel and displaces the radioactive cobalt, nickel, and iron corrosion products. The demineralisers would then remove the radioactive cobalt from the primary system, thereby reducing the overall radioactivity in the system (Eskom, 2007). The reduction in the radioactivity leads to reduction in the ambient dose rates in the vicinity, and therefore potentially reducing the whole-body dose to workers performing work on or close to the primary system.

2 ACTIVATION PRODUCTS

According to the Nuclear Energy Agency (NEA, 2014), the three main types of radioactivity that contribute to radiation fields at PWRs such as Koeberg are:

- fission products, such as ^{137}Cs;
- primary coolant activation products, such as ^{16}N; and
- neutron-activated corrosion products, such as ^{58}Co.

Plant dose rates around the reactor coolant system (RCS) during normal power operation are determined mainly by ^{16}N. It has no impact on worker dose when work is carried out during refuelling outages due to its short half-life, namely 7.13 seconds.

The principal contributors to the occupational dose are activated corrosion products of which the sources are:

- out-of-core corrosion products, mainly steam generator corrosion products; and
- fuel assembly and/or material corrosion products (reactor internals and others).

Corrosion products undergo a series of complex processes to become activated and reach out-of-core surfaces of the RCS. Corrosion products released from material surfaces are transported by the primary coolant and become exposed to the neutron flux in the reactor core. The fraction of activated corrosion products that is not removed by the reactor chemical and volume control system (RCV) is deposited on ex-core surfaces of the RCS. It is these longer-lived radionuclides captured on the ex-core surfaces, which create the radiation fields that necessitate control of exposure to workers.

The main radionuclides in activated corrosion products are listed in Table 2.1. The data for ^{58}Co and ^{60}Co are highlighted (NEA, 2014).

Table 2.1: Radionuclides resulting from activation of corrosion products

Radio-nuclide	Half Life	Activation Reaction	Principal Source
^{110m}Ag	249.76 days	^{109}Ag (n,γ) ^{110m}Ag	Silver-indium-cadmium control rod wear, Helicoflex™ seals
^{58}Co	70.86 days	^{58}Ni (n,p) ^{58}Co	Nickel alloys – corrosion of SG tubes is the principal source of ^{58}Ni
^{60}Co	5.271 years	^{59}Co (n,γ)^{60}Co	Stellite™ and cobalt bearing components
^{51}Cr	27.7 days	^{50}Cr (n,γ) ^{51}Cr	Stainless steel and nickel based alloy
^{64}Cu	12.7 hours	^{63}Cu (n,γ) ^{64}Cu	17-4 PH Steel
^{55}Fe	2.737 years	^{54}Fe (n,γ) ^{55}Fe	Stainless steel and nickel based alloy

Radio-nuclide	Half Life	Activation Reaction	Principal Source
^{59}Fe	44.5 days	^{58}Fe (n,γ) ^{59}Fe	Stainless steel and nickel based alloy
^{181}Hf	42.39 days	^{180}Hf (n,γ) ^{181}Hf	Fuel cladding impurities
^{54}Mn	312.1 days	^{54}Fe (n,p) ^{54}Mn	Stainless steel and nickel based alloy
^{56}Mn	2.58 hours	^{55}Mn (n,γ) ^{56}Mn	Stainless steel and nickel based alloy
^{95}Nb	34.99 days	^{95}Zr decay	Fuel cladding
^{59}Ni	1.01E05 years	^{58}Ni (n,γ) ^{59}Ni	Stainless steel and nickel based alloy
^{122}Sb	2.724 days	^{121}Sb (n,γ) ^{122}Sb	Secondary start-up source
^{124}Sb	60.20 days	^{123}Sb (n, γ) ^{124}Sb	Secondary start-up source, RCP bearings, impurities
^{125}Sb	2.758 years	^{125}Sn decay; ^{124}Sb (n,γ) ^{125}Sb	Fuel cladding impurities and neutron capture by ^{124}Sb
^{99}Tc	2.111E5 years	^{98}Mo (n,γ) $^{99}Mo/^{99}Tc$	Stainless steel, tramp impurities, and fission
^{187}W	23.72 hours	^{186}W (n,γ) ^{187}W	Stainless steel, carbides, and welding artefacts
^{65}Zn	244.06 days	^{64}Zn (n,γ) ^{65}Zn	Natural zinc injection
^{95}Zr	64.03 days	^{94}Zr (n,γ) ^{95}Zr	Fuel cladding

Radiation fields in a nuclear plant can be controlled by limiting the corrosion of materials and the concentration of corrosion products in the RCS. With the view on minimizing plant radiation and worker dose, it is therefore important to consider the resistance to corrosion of the various alloys found in RCS components. Notwithstanding RCS material characteristics, the optimum control of primary coolant chemistry (mainly by means of pH adjustment, hydrogen control, and zinc injection) is essential to limit corrosion (Eskom, 2015).

3 COBALT SOURCE REDUCTION INITIATIVES

Several methods other than the addition of zinc are available to reduce cobalt content in the primary coolant system.

As stated previously, ^{58}Co and ^{60}Co generally are the two major isotopes that contribute to shutdown dose rates. Although concentrations of these species may be similar on piping surfaces, the contribution of ^{60}Co to shutdown dose rates can be significantly greater due to the energetics of its decay reactions (Eskom, 2015). ^{60}Co produces two gamma rays with energies of 1.17 MeV and 1.33 MeV and has a significantly longer half-life than ^{58}Co as illustrated in Table 2.1. The major source of ^{58}Ni (precursor to ^{58}Co) is known to be in the steam generator tubing, whereas the sources of ^{59}Co (precursor to ^{60}Co) are more distributed and varied, and estimates of its relative source strengths have varied over the years.

The major sources of ^{60}Co in the primary system have been identified through extensive studies. Reductions in the cobalt content in the primary system, the steam generator tubing, replacement of Stellite with non-cobalt alloys, and the minimization of cobalt concentrations in replacement material are pursued whenever possible in order to reduce the ^{59}Co source term (EPRI, 2006). Internationally applied methods for the reduction of cobalt are discussed below.

3.1 Preconditioning Surfaces

Preconditioning of the surfaces of replacement components can significantly reduce recontamination rates, as well as reduce the rate of cobalt release. The tendency of passive oxides to adhere to the internal surfaces of primary coolant system components is affected by the nature of such surfaces. These oxides readily accommodate activated corrosion products, mainly ^{60}Co, ^{58}Co, and ^{65}Zn that are responsible for occupational radiation exposure. Surface roughness, surface chemistry, and even surface residual stresses play a role in determining the amount of activity pick-up. It was recognised in the past that electro-polishing might lower activity pick-up simply by reducing the total surface area in contact with the primary coolant (Eskom, 2015).

3.2 Primary System Clean-Up Operation

The chemical and volume control systems of PWRs effectively removes both soluble and particulate contaminants and radioactivity. Recent experiences from the industry have claimed significant improvements in overall radiological performance, such as the reduction of forced oxidation peaks and radiation fields due to increased efficiency in the removal of these products by the chemical and volume control system. Virtually 100% of soluble activity can be removed, and while the maximum removal of insoluble activity is desirable, the impact on radiation due to insoluble activity is generally limited to local deposition and airborne contamination issues during maintenance activities.

Industry experience suggests that the use of filtration and ion exchange mechanisms has proven to be marginally effective in reducing the concentration of activity available for deposition in primary systems. The low flow rate and vessel media capacities for the vast majority of installed clean-up systems in PWR applications had proven to be less than adequate for the volume of liquid requiring treatment. This leads to increased time required to process one full system volume completely; however, as a minimum, the available capacity should be optimised through careful research and application of available media types and configurations. Recent advances in both filtration and ion exchange media have improved the overall effectiveness of these systems (Eskom, 2015).

3.3 Cobalt Reduction in Component Alloys

Due to the long-lived ^{60}Co isotope being a key contributor to shutdown dose rates, eliminating its sole precursor isotope (^{59}Co) is one of the most effective approaches for reducing shutdown radiation fields. Cobalt is found as an impurity in the structural alloys used in the primary system of light water reactors. Cobalt is also a major constituent of wear-resistant hard-facing alloys—such as Stellite—that are used to provide wear and corrosion resistance properties to critical components such as valves and control rod drive mechanisms.

Significant levels of impurities are present in materials manufactured by metal fabricators using conventional smelting practices; therefore, specifying the limits of cobalt content is vital when procuring replacement plant components that come into contact with the primary fluid. Ideally, cobalt impurity levels should be less than 500 mg/kg in stainless steels and less than 200 mg/kg in nickel-based alloys for all nuclear replacement components (Eskom, 2015). There is little cobalt present in the zirconium-based Zircaloy alloys used for fuel rod cladding and in some fuel spacer grids, with the cobalt content of Zircaloy typically less than 50 mg/kg. The nickel-based Alloy 690 tubing used in replacement SGs can be readily supplied with an average cobalt content of less than 150 mg/kg and a maximum value of 200 mg/kg.

3.4 Reducing Cobalt originating from Maintenance Activities

According to Eskom (Eskom, 2015), valve maintenance activities can generate significant amounts of debris containing cobalt. This debris results mainly from seat repair activities such as lapping and cutting and can result in significant radiation fields. Much of the debris can be controlled by close attention to barrier types and their application, clean-up techniques and tools, and the quality of close-out inspections. The potential for cobalt introduction may be reduced by using of non-cobalt-containing seat replacements, whole-valve replacements, or by using flanged valves that can be removed and repaired elsewhere.

3.5 Reduction of Cobalt Source Term

The major source of ^{58}Ni, the precursor to ^{58}Co, is known to be contained in the steam generator tubing. The sources of ^{59}Co are more variedly distributed, and the estimates of relative source amounts have fluctuated over the years. Sources of ^{60}Co in the PWR primary system have been studied extensively over the years and the major sources have been identified. Reductions in the cobalt content of the steam generator tubing, the replacement of Stellite with non-cobalt alloys, and the minimization of cobalt concentrations in the replacement material are pursued whenever possible to reduce the ^{59}Co source term (Eskom, 2015). The replacement of steam generators and valves containing Stellite are further discussed below.

3.5.1 Steam generator replacement

The surface area of a typical PWR in contact with the primary coolant consists of approximately 25% fuel cladding, 65% SG tubing, and about 10% stainless steel (EPRI, 2002). An SG, as illustrated in Figure 3.1, is therefore a large potential source of corrosion products.

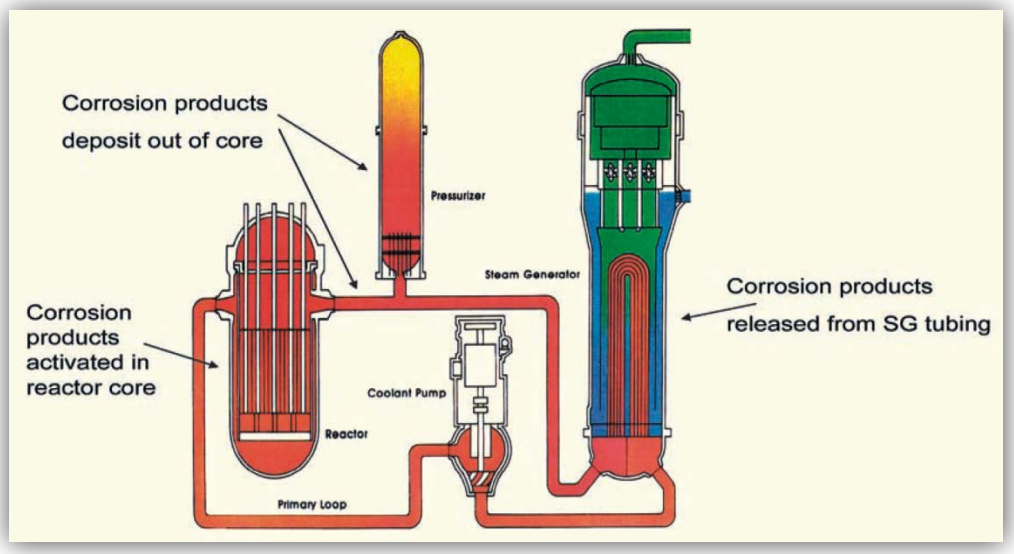


Figure 3.1: Typical RCS layout

SG tubes are made of either Inconel Alloy 600, 690, or 800. The corrosion and release rates of Fe, Ni, Cr, Co, and other elements from the SG tubes have a major effect on the subsequent formation of activated corrosion products. Nickel (Ni) is the main element; approximately 72 per cent weight in Inconel 600, the alloy used in the current Koeberg SGs, and approximately 59 per cent by mass in Inconel 690 in the replacement SGs (EPRI, 2002). The total tube surface area and Ni content therefore represent the principal source for ^{58}Ni that can be activated to ^{58}Co (refer to Table 2.1).

The high chromium content in Alloy 690 (about 29% Cr, 59% Ni, and 10% Fe) is intended to combat corrosion (Dacquait, 2010). Nuclear plants that have replaced Alloy 600 tubes with Alloy 690 observe a reduction in corrosion and corrosion release rates over time. Laboratory data indicate as much as a three-fold reduction in corrosion for Alloy 690 tubing compared to Alloy 600 tubing. Alloy 690TT and its compatible weld metals have also been introduced to eliminate a generic problem encountered in Alloy 600 and its weld metals, i.e. primary water stress corrosion cracking (PWSCC).

Notwithstanding the material characteristics, manufacturing methods also influence corrosion behaviour of SGs. The manufacturing of Alloy 690 tubes has improved significantly since the initial SGR projects, which reportedly have led to improved corrosion product behaviour and subsequent release of corrosion products. The corrosion resistance of the material can be improved by means of processes such as electro-polishing. Electro-polishing reduces the total surface area in contact with the primary coolant and results in a significant reduction of activity uptake and dose rates (NEA, 2014). Electro-polishing is included in the manufacturing of the Koeberg's replacement of the SGs. International operational experience shows that nuclear power plants that have electro-polished steam generator channel heads and use Alloy 690 tubing have generally lower dose rates than those that do not use these improvements (Eskom, 2015).

It is concluded that the design improvements mentioned above and the improvements in the manufacturing methods of replacement SGs will contribute to lower plant dose rates and consequently the dose to workers when compared to the existing SGs.

3.5.2 Replacement of valves containing Stellite

The replacement of valves containing Stellite with non-Stellite containing valves, may also contribute to dose reduction. By implementing a Stellite reduction programme, which includes the phasing out of valves containing Stellite, will contribute to the reduction of cobalt sources.

4 ZINC ADDITION

4.1 General Theory

A layer of spinel oxide, a hard glassy mineral, builds up over time on the steel internals of the primary system of a nuclear plant. This layer contains radioactive fission products of ^{58}Co and ^{60}Co as well as other corrosion products e.g. Fe and Ni.

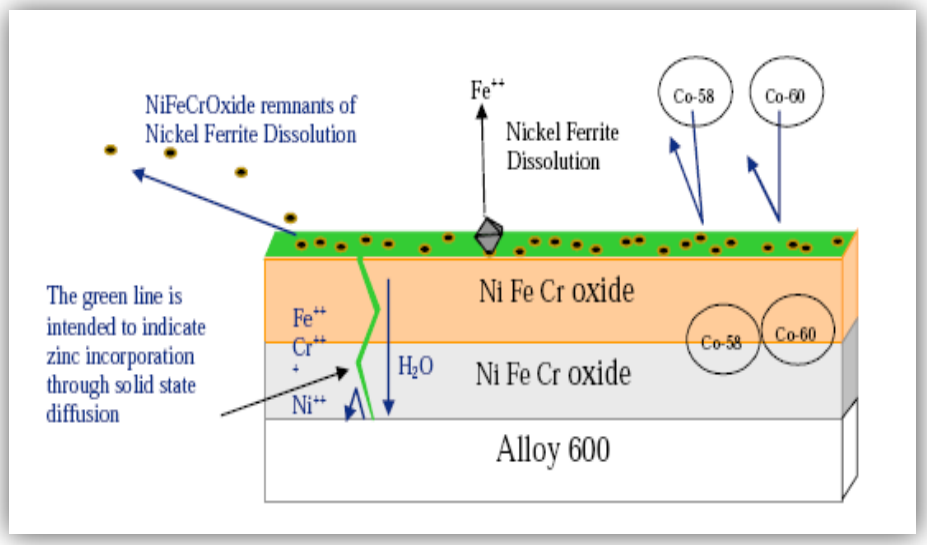


Figure 4.1: Zinc contained in the spinel oxide layer

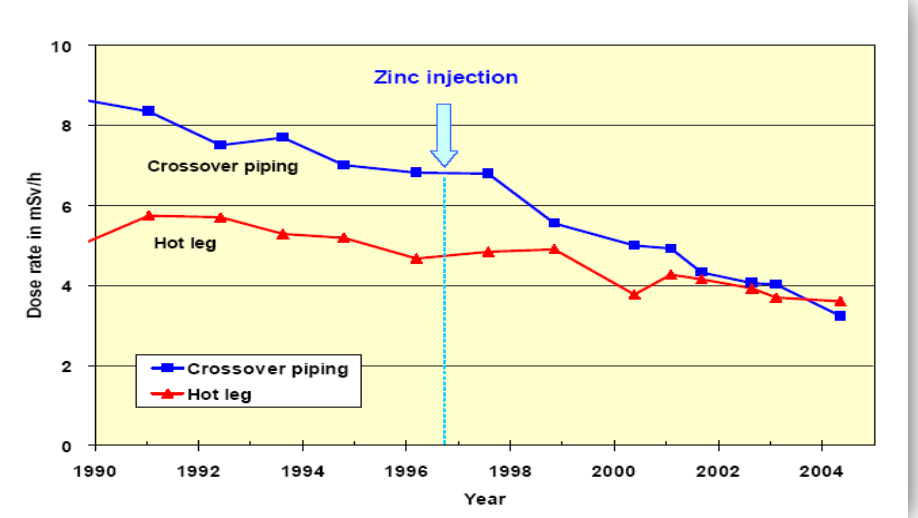
By injecting the primary system water with a more stable, non-radioactive metal ion such as depleted zinc, the zinc becomes incorporated in the spinel layers and displaces the radioactive cobalt, nickel, and iron corrosion products. The demineralisers would then remove the radioactive cobalt in the primary system, thereby reducing the radioactivity in the system (Eskom, 2007). The reduction of the radioactivity leads to the reduction of ambient dose rates, which in turn potentially reduces the whole-body dose to workers performing work on or close to the primary system.

Depleted zinc differs from the naturally occurring zinc in that its ^{64}Zn isotope is depleted so that it consists almost entirely of ^{66}Zn, ^{67}Zn, ^{68}Zn, and ^{70}Zn isotopes. Depleted zinc contains more than 99% of these heavier isotopes and less than 1% of ^{64}Zn, whereas natural zinc contains 48% of ^{64}Zn. The light isotope ^{64}Zn readily absorbs a neutron when in a neutron field, and in so doing, it becomes radioactive ^{65}Zn. On the other hand, the heavier isotopes remain radiologically unaffected in a neutron field and are thus effective as a non-radioactive substitute to displace radioactive products such as ^{58}Co and ^{60}Co (EPRI, 2006).

Data provided by EPRI from the mid-nineties and the data collected from PWRs that have injected depleted zinc indicate an annual dose reduction by 10-20% for the first fuel cycle after initial zinc injection and up to 50% for the subsequent cycles (EPRI, 2006). A cycle

is generally defined as a period between two scheduled refuelling outages. For Koeberg, this cycle may last between 14 and 18 months.

Such a reduction of dose implies a significant ambient dose rate reduction for the primary system equipment, which still needs to be converted to a reduction of dose to the plant worker. Figure 4.2 illustrates an example of reduced dose rates at Biblis B after zinc injection. It must be noted that some PWRs have not achieved significant reduction in dose rates.



Source: (EPRI, 2006)

Figure 4.2: Example of dose rates at Biblis B before and after zinc injection

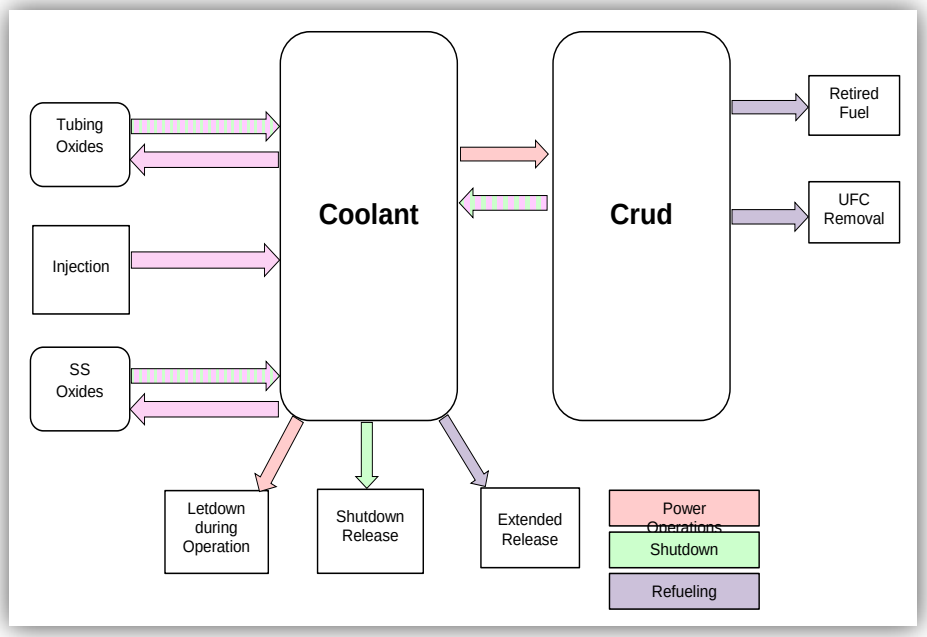
4.1.1 Distribution of zinc within the primary system

Once injected into the primary system, zinc can be distributed to many locations by several mechanisms. Figure 4.3 illustrates the main locations and mechanisms (EPRI, 2012 b). These locations include the coolant, oxide deposits on component surfaces, and the fuel.

Zinc removal from the system is done through the following mechanisms:

- letdown purification during operation by the chemical and volume control system;
- letdown purification during shutdown (i.e. forced oxidation);
- extended releases (i.e. continued clean-up of the coolant during the outage);
- retiring/removing fuel i.e. spent fuel;
- major component replacement;
- ultrasonic fuel cleaning; and

- chemical decontamination.



Source: (EPRI, 2012 a)

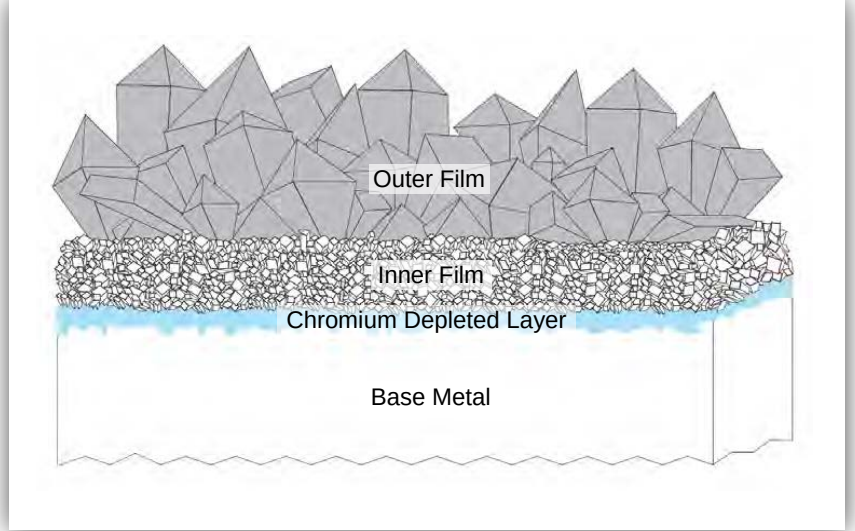
Figure 4.3: Migration of zinc within the primary system

4.1.2 Initial state of metal surfaces

Considerable work has been done to characterize the corrosion films that are formed on stainless steels and nickel alloys, as well as on construction materials that are wetted by the primary coolant. Conceptually, the stainless steel and nickel alloy surfaces may be understood to include the following four layers:

- an underlying base metal, with a relatively uniform chemical composition;
- a chromium depleted layer, which is still in a metallic form;
- an inner corrosion film, enriched in chromium; and
- an outer corrosion film, typically having a spinel structure.

Figure 4.4 shows the surface film with four distinct layers from spectroscopy results of an Alloy 600 stream generator tube removed from Farley Unit 2 before the initial application of zinc (EPRI, 2012 b).



Source: (EPRI, 2012 b)

Figure 4.4: Schematic of the corrosion film formed on stainless steel or nickel alloys in primary water

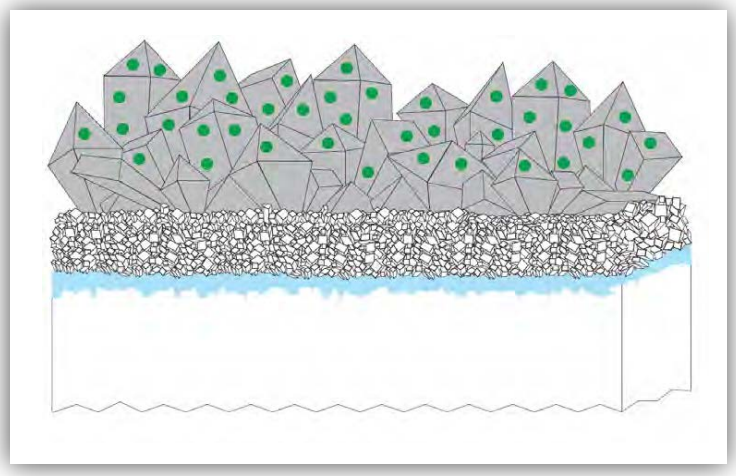
4.1.3 Time scales of interest

The effects of zinc application can be observed at various times after the introduction of zinc. For discussion of a general theory of how zinc interacts with primary system materials, it is convenient to divide the plant response into short-, medium-, and long-term responses (EPRI, 2012 b). General descriptions of the relevant periods follow.

4.1.4 Short-term response

In the very short term, zinc is initially adsorbed onto primary system surfaces. Simplistic calculations imply that, in the absence of the bulk incorporation into surface films, the system surfaces would typically be saturated within 1-3 days.

There is a significant body of evidence that indicates a short-term primary coolant radio cobalt response to zinc injection. In a recent review (Gary, G, 2010), approximately 50% of assessed plants showed a certain increase of radio cobalt activity in the coolant following zinc injection. These results have been confirmed by comparison of the pre- and post-zinc periods within the first cycle of zinc addition as well as by comparison of non-zinc cycles with the first cycle of addition. In some cases, other transients in zinc injection—not just during the initial start of zinc injection—demonstrated a clear correlation with radio cobalt coolant activity. The time scale of the response to zinc in many of these cases (a few days to some weeks) indicates that this radio cobalt response is due to the short-term incorporation (including adsorption) into the outermost surface films illustrated in Figure 4.5.

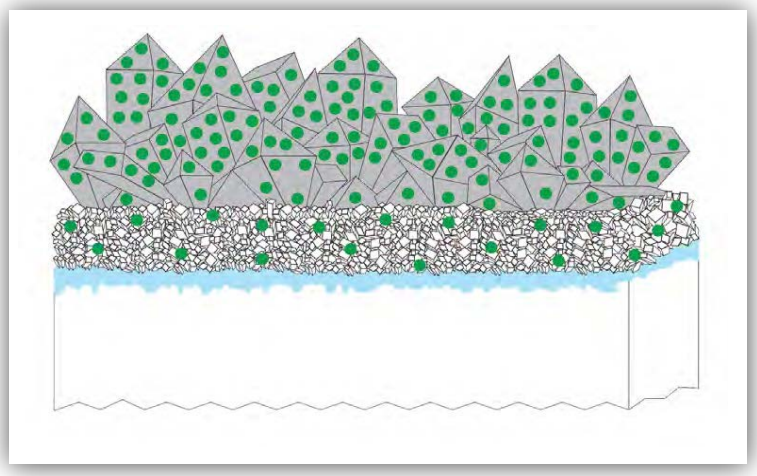


Source: (EPRI, 2012 b)

Figure 4.5: Schematic of the corrosion film with short-term zinc incorporation

4.1.5 Medium-term response

In the medium term, zinc slowly diffuses into the surface films of primary system components. Figure 4.6 shows a schematic of zinc incorporation in the medium term (EPRI, 2012 b). The concentration of zinc in the regions closest to the coolant is the highest, although not significantly higher than in the short term. The zinc concentration decreases deeper into the surface film. Using classical diffusion models, the concentration profile can be predicted, with finite zinc concentrations predicted throughout the film thickness. However, in practice, the concentration of zinc deep into the film may be too low to be detected.

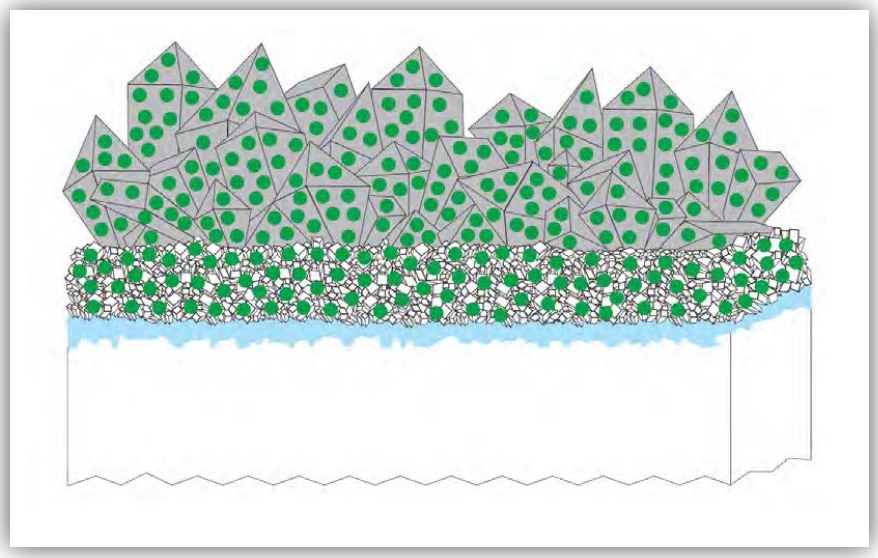


Source: (EPRI, 2012 b)

Figure 4.6: Schematic of the corrosion film with medium-term zinc incorporation

4.1.6 Long-term response

The concentration of zinc throughout the primary system surface films is expected to reach equilibrium in the long term. Once this equilibrium status is achieved, the surface film concentration will be influenced by the average zinc concentration in the coolant. Figure 4.7 schematically illustrates this condition where the zinc concentration is uniform throughout the corrosion film. It is possible that concentration differences may occur where different layers display varying affinity of the zinc. (i.e. the chemical potential of zinc will be uniform even though the concentration may not be).



Source: (EPRI, 2012 b)

Figure 4.7: Schematic of the corrosion film with long-term zinc incorporation

4.2 Coolant Chemistry Requirements

According to Westinghouse, a nuclear fuel supplier, it is essential that zinc concentration of the reactor coolant is consistent with the fuel risk evaluation. To this end, analysis of the reactor coolant for zinc concentration is required to ensure the proper control of the target zinc concentration (Westinghouse, 2012). It is expected that a plant will maintain a weighted monthly (30 day) average zinc concentration that is less than or equal to the target value, which is established by the cycle-specific CIPS/CILC assessment. The monthly average applies once zinc is detectable in the coolant, with measurements weighted by time. The operating range around the target is ± 5 ppb.

Limits are placed on the nickel concentration in the coolant in order to ensure that there is not a significant amount of corrosion products circulating in the core, while limits on the coolant silica concentration reduce the risk for zinc silicate precipitation on fuel surfaces.

The concentrations of nickel and silica are required to be determined prior to initiating zinc injection in a given cycle. The acceptable initial concentration of nickel shall be less

than or equal to 6 ppb total nickel (soluble plus particulate). This level of nickel is considered low enough to pose low risk for significant crud accumulation on the nuclear fuel, based on estimates. The silica concentration shall be less than or equal to 1000 ppb silica for a high-duty plant and less than or equal to 2000 ppb silica for a low-duty plant. Nickel and silica values are evaluated to be acceptable if measured in two consecutive samples that are taken 24 hours apart. Confirmatory sampling and zinc injection may begin once criticality has been achieved.

After zinc injection has been initiated, nickel sampling shall be performed once per week for the first month of zinc injection in each cycle and approximately once every other week thereafter. It is considered best practice to continue to sample for nickel at least once per week throughout the cycle. If, after zinc injection is initiated, analyses over a two-week period indicate that nickel concentrations are greater than 6 ppb, a flux map of the core shall be taken to determine whether indications of CIPS are evident (refer to §4.5). If multiple samples are taken during the two-week period, it is acceptable to determine the average concentration of the samples to compare against the 6 ppb nickel limit. If indication of CIPS is evident, the results of the coolant analyses and flux map information shall be discussed with the fuel supplier to determine future actions, which may include temporary termination of zinc addition (Westinghouse, 2012).

4.3 Zinc Injection Strategy

Reports from Westinghouse (Westinghouse, 2012), indicates that the maximum zinc concentration used in PWRs has approached 40 ppb in some of the initial low boiling duty cycles at Farley and Diablo Canyon. Both plants have reduced the zinc concentration in recent cycles to the 15-25 ppb zinc range.

As higher boiling duty plants have implemented zinc addition, the initial recommended concentrations have been lowered to minimize concerns with additional crud deposition on fuel. Characteristically, the high boiling duty cores have started with a target concentration of 5-10 ppb zinc in the initial cycle. Several cores have now started with a target concentration of 5 ppb zinc and then increased the target to 10 ppb zinc when approaching the end of the first zinc cycle after the absence of CIPS was verified and all fuel performance concerns were resolved.

For the initial application or first cycle of zinc addition, Westinghouse recommends initiating zinc addition after completion of the first half of an operating cycle. This reduces the risk for further increases in early-cycle corrosion product concentrations when it may already be elevated following the refuelling outage. It also allows verification that the core is not already experiencing CIPS since the most severe cases of CIPS generally begin well before completion of the first half of the cycle.

For the subsequent cycles, Westinghouse (Westinghouse, 2012) recommends restarting zinc injection near the beginning of the cycle after criticality has been achieved (a

“start/continue” or “continue” strategy). This is recommended to avoid destabilizing the existing RCS corrosion films by varying between zinc and non-zinc chemistry. Plants that have added zinc in one cycle and stopped zinc addition in the next cycle (a “start/stop/start” or “pause” strategy) typically still see measurable zinc concentrations in the RCS even though no zinc is being injected. This would appear to be an indication that zinc is being released from the RCS corrosion films and may indicate that corrosion films are being destabilized. This could lead to additional corrosion product release and further concerns about fuel crud deposition.

The recommendation for the “continue” strategy originally came out of root cause evaluations that were performed after Vogtle Unit 1 had experienced CIPS during its second zinc cycle. Unit 1 had paused zinc addition at the beginning of the second zinc cycle before restarting zinc about five months into the cycle. Since the Vogtle experience, other higher boiling duty plants, such as the Byron and Braidwood units, have used partial cycles of zinc addition in subsequent zinc cycles without experiencing CIPS. Nonetheless, Westinghouse generally recommends that zinc injection be continued once it has been started; however, if sufficient oxide conditioning is not achieved during the first zinc cycle, then restarting zinc addition should be delayed until halfway through the next cycle. Westinghouse currently defines an effective first zinc cycle as either ≥ 1 kg net zinc uptake or ≥ 10 ppb-months zinc exposure.

4.4 Zinc Impact on PWR Crud

Zinc injection potentially has significant benefits with respect to radiation field control and PWSCC mitigation; however, there are risks with respect to nuclear fuel. A concern associated with adding zinc to PWR coolant is the possibility of zinc oxide or zinc silicate depositing within the crud on the fuel cladding. Such deposition could decrease heat transfer through porous crud, potentially increasing fuel cladding corrosion. This would be likely if the boiling concentration process within the crud causes the zinc concentration to exceed the solubility limit of either zinc oxide or zinc silicate (EPRI, 2012 b).

In most of the fuel examinations conducted to date, zinc addition has had an effect on the distribution, composition, and microstructure of the deposits.

Zinc has the following general effects on crud observed on PWR fuel:

- **Distribution**: Crud deposits are observed axially along the entire length of the assembly, including non-heated surfaces (e.g. grids). While deposits may form on the lower spans during the cycle at non-zinc units, little, if any material is observed at these locations during refuelling outages.
- **Microstructure**: The crud is composed of very small particles with diameters in the nanometre range. Under high magnification the particles have ill-defined crystalline faces. This contrasts with non-zinc crud where particles have

typically diameters 100 times larger and have sharp and defined crystalline faces. Exceptions have been noted where acicular needles—Nickel oxide (NiO), Bonaccordite (Ni_2FeBO_5), and sub-micron nickel metal particles—have been observed. In rare examples where porosity measurements have been possible, no evidence of crud densification was observed. There are some indications (Vogtle samples) that indicate that these microstructural changes depend on the extent of the zinc exposure (EPRI, 2012 b).

- **Composition**: The zinc fraction of the crud analysed at most of the plants thus far has ranged between 2 and 11 wt. % for both feed and twice-burned assemblies. These amounts are considerably below the zinc fractions measured in BWR crud, but warrant attention as crud is monitored from progressively higher duty units. In plants that have not injected zinc, elevated nickel and chromium fractions are commonly observed only in thick crud (e.g. > 25 µm) from high-duty cores. To date, significant carbon concentrations in zinc crud have been measured at Diablo Canyon Unit 1 Cycle 11, Crystal River Unit 3 Cycle 16, and Three Mile Island Unit 1 Cycle 17 (EPRI, 2012 b).



Source: (EPRI, 2012 b)

Figure 4.8: Normal Crud



Source: (EPRI, 2012 b)

Figure 4.9: Zinc Crud

Results documented in Koeberg engineering reports indicate that the crud deposit on its fuel does not have adverse effects on safety (Greeff, 2017).

4.5 Zinc Impact on PWR Crud-Induced Power Shift (CIPS)

Boron is used in the operation of nuclear plants. When boron concentrates in the crud in the upper section of a PWR core, a situation known as crud-induced power shift (CIPS) is created. Boron causes a reduction in neutron flux. In order to maintain the power stable, the flux shifts downward in the core, resulting in a more negative axial offset than designed.

The culmination of three conditions, namely sub-cooled nucleate boiling at the clad surface, corrosion product deposition in the boiling regions, and boron incorporation into these deposits, is necessary for CIPS to manifest.

According to EPRI (EPRI, 2012 b), CIPS has been found in at least 20 US PWRs in 49 operating cycles as of mid-2011 and it is typically associated with high-temperature units with high-duty cores. It has been noted in these cycles that crud deposits have been higher on the fuel operating at the highest relative powers, which is typically the feed fuel in U.S. plants. The crud from cores with significant sub-cooled boiling tends to be rich with nickel.

Of the 39 US PWRs injecting zinc and their corresponding 134 cycles, there have been 3 PWRs and 5 cycles where CIPS has been measured. It must be noted that CIPS had been measured in previous non-zinc injection cycles at these units. It is therefore unclear if zinc injection played a role in the observed CIPS during the zinc cycles.

To date, there has been no indication of CIPS at Koeberg according to the senior physicist, Innes Greeff from the Reactor Fuel Engineering department at Koeberg (Greeff, 2017).

4.6 The Impact of Zinc on Steam Generators

A review of field experience regarding the effects of zinc injection on PWSCC in steam generator tubes was previously completed (Gary, G, 2010). This review evaluated the effects of zinc injection on detected rates of PWSCC initiation and growth in steam generator tubes using data from Diablo Canyon and several other PWRs with similar steam generators. The factor of improvement in the reduction of PWSCC initiation ranged from about 2 to about 20 based on a Weibull analysis of steam generator non-destructive examination (NDE) data. Zinc also showed benefit in reducing PWSCC crack growth rates of steam generator tubes, with a reduction in crack growth rate from 17% to 60% (EPRI, 2012 b).

There have been no reports related to problems with steam generators associated with the use of zinc. The effects of zinc on the oxide films on the inner diameters of the steam generator tubes have not been deleterious, e.g. have not increased activity levels or abrasiveness in a noticeable manner, nor otherwise interfered with performance of eddy current testing (EPRI, 2012 b).

With regard to shutdown dose rates, the general trend subsequent to the use of zinc has been a steady decrease, with the extent of the decrease being larger as zinc concentration and zinc exposure increase. However, there have been some exceptions for units using 5 ppb zinc, where dose rates have not decreased in the third and fourth cycles of zinc use. Operating experience in the minimizing of shutdown dose rates indicates that there may be significant advantage in the introduction of a zinc application programme one or even more cycles prior to steam generator replacement, especially when accompanied by other initiatives such as the electropolishing of channel heads.

4.7 The Impact of Zinc on Reactor Coolant Pump

While various studies and field experience have shown that zinc was either beneficial or benign with respect to most PWR RCS materials, additional evaluation was required to verify the acceptability of zinc with specific primary system materials such as the reactor coolant pump (RCP) seals and valve hard-facing—a standard term for a wear-resistant weld overlay (Eskom, 2015). RCP seal materials (including alumina and silicon nitride) were not included in the early zinc material qualification testing; however, the current understanding of the seal degradation mechanism is that deposition of corrosion products on the seals rather than dissolution or corrosion of seal materials is responsible for degraded seal performance. Zinc has retrograde solubility characteristics—the solubility decreases with increasing solution temperature. With this characteristic, together with a low zinc concentration in the RCS, no deposition of zinc compounds on the RCP seals or other RCP internal components is expected.

A post-zinc addition evaluation of the reactor coolant system was conducted at Farley Unit 2 to determine whether zinc was responsible for any negative material effects. The following parameters were monitored prior to and during operation with zinc during Cycle 10 at Farley Unit 2 to study the effect of zinc on RCP performance:

- # 1 seal leak-off flow rate.
- Seal leak-off temperature.
- Seal injection flow rate.
- Volume control tank temperature.
- RCP bearing temperature.
- RCP shaft and frame vibration.

The # 1 seal leak-off flow rate decreased but operated within specifications for all three RCPs at Farley Unit 2 during Cycle 10; it was concluded that zinc did not significantly contribute to the decrease. An observed decrease in seal injection water temperature and increase in # 2 seal leak rate resulting from wear and scratches on the # 2 seal face were the major factors that contributed to the observed decrease in seal leak-off flow. In § 8 of (Azevedo, 2008), it is stated that subsequent to Farley Unit 2 Cycle 10, no further incidents of unusual RCP seal leak-off characteristics have been reported concurrent with the use of zinc. No unusual readings were reported on the other monitored parameters.

A study of eight RCP seal sets, reported to have operating anomalies, was performed through a sponsorship programme by a Westinghouse Owners Group (WOG) with the objective of improving RCP seal performance. The results of this study showed that there is no direct evidence from any plant showing an adverse impact of zinc addition on RCP seals. There is neither plant experience nor laboratory data to suggest that the addition of zinc has an adverse impact on RCP seals (EPRI, 2012 b).

5 INDUSTRY ZINC INJECTION

5.1 Background

Zinc injection into the reactor coolant system has been successfully performed at approximately 70 pressurized water reactors worldwide since the mid-1990s (Haas, C; Perkins, D, n.d.).

At nuclear power plants, radiation fields in the proximity of plant primary and secondary components influence worker dose acquired during on-line and outage work activities. Reducing radiation fields is one aspect that can contribute to lower operational and maintenance costs at plants. For instance, the need for moving less shielding required for maintenance work to be performed will lower the cost of the task.

Electric Power Research Institute (EPRI) developed the Standard Radiation Field Monitoring and Characterization (SRMC) programme, previously known as Standard Radiation Field Monitoring Programme (SRMP) and which now combines the radiation field data from all types of reactors to assess and lower the radiation fields, and therefore, optimise radiation field control.

The SRMC programme, sponsored by EPRI, was first instituted in 1978 as part of a more general programme with the major emphasis on improving plant reliability and availability while observing radiation fields (EPRI, 2016). The objectives of this programme have not changed since its inception in 1978 and include:

- the provision of a meaningful, consistent, and systematic approach to monitoring the radiation fields and the provision of a basis for projecting the trend of those fields;
- the provision of a meaningful, consistent, and systematic approach to monitoring the radiation fields and the provision of a basis for projecting the trend of those fields;
- the monitoring of certain plant parameters that affect or may affect observed radiation fields; and
- the use of information from this programme to identify plant design features, material selection, and operational techniques that present opportunities for radiation field control.

Zinc was initially added to US PWR reactor coolant systems in an effort to reduce the rate of PWSCC. These initial plants also experienced significant reductions in shutdown radiation fields. This result is consistent with the stabilizing effect of zinc on oxide films, its displacement of cobalt ions from these films, and the reduction of further cobalt incorporation into the films (refer to § 4.1). It is also consistent with the experience in

Europe, where lower concentrations of zinc were added for the purpose of radiation field reduction starting in 1996 with Biblis (EPRI, 2006).

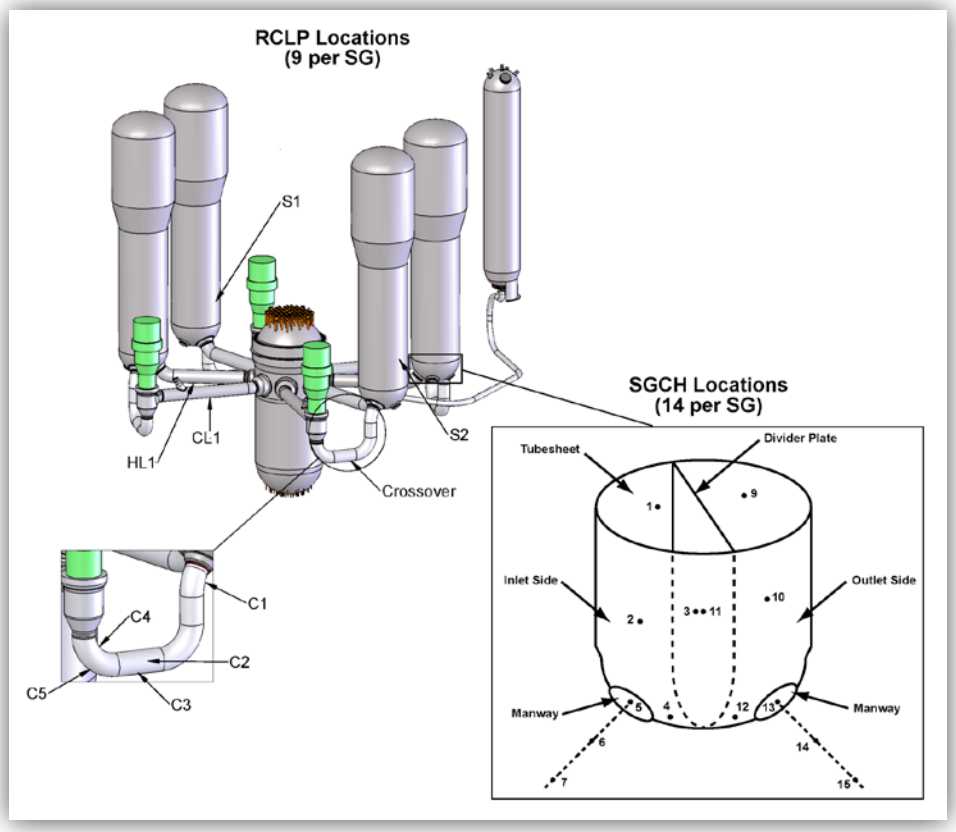
After the initial use of zinc at Farley Unit 2 in 1994, zinc has been used at more PWRs, thereby increasing the total cumulative zinc exposure in terms of ppb-months. This has allowed the development of fitted curves of dose rate reduction versus zinc exposure to be developed based on industry experience. These curves are shown in § 5.5.

The effects on shutdown radiation fields are somewhat different for plants using natural zinc versus depleted zinc. Naturally occurring zinc consists of 48.6% ^{64}Zn, 27.9% ^{66}Zn, 4.1% ^{67}Zn, 18.8% ^{68}Zn, and 0.6% ^{70}Zn. In the presence of a neutron flux, ^{64}Zn can absorb a neutron to become ^{65}Zn, which is radioactive with a 243.8-day half-life. Therefore, plants adding natural zinc experience a smaller radiation dose benefit because of the production of ^{65}Zn (EPRI, 2006).

Another factor that needs to be considered when evaluating industry data is that plants with Alloy 800 steam generator tubes may respond differently than units with nickel-based alloy tubes, i.e. with Alloy 600 or Alloy 690 tubes. Alloy 800 has much less nickel and more iron than Alloy 600 (as in the case of Koeberg) and 690, which could affect corrosion product release rates and the behaviour of ^{58}Co, and thus affect shutdown radiation fields. For this reason, plants should base their predictions of the likely effect of using zinc on experience of other plants with the same Alloy steam generators to ensure a more representative comparison. .

5.2 Measurement Method

Since the first applications of zinc addition to nuclear plants (Farley Unit 2 and Diablo Canyon Unit 1) were being considered, the technique to measure the effect on plant dose rate changes was evaluated. A requirement from EPRI (EPRI, 2006) was that the tests should not add substantially to plant operations. It was therefore decided to use the measurement locations of the Standard Radiation Field Monitoring Programme (SRMP) as a benchmark because it was developed to provide a consistent basis for measuring dose rates at the same locations. Furthermore, there were some earlier SRMP data from the plants to use as a basis and other plants had been using the same locations. The SRMP locations are indicated by markers placed on the RCS piping and outside the SG tube bundle, and in locations inside the SG channel head that could be plotted on survey maps. Figure 5.1 illustrates the measurement locations for a Westinghouse plant design, as in the case of Koeberg.



Source: (EPRI, 2012 b)

Figure 5.1: Westinghouse design plants – SRMC survey point locations

5.3 Factors affecting Dose Rates

The standard health physics survey instruments in use at the plant were to be used to collect the data. Data from survey instruments are subject to several types of errors, e.g. the inherent error associated with the instrument and errors associated with persons making the measurements such as failure to take the measurement at the same location, incorrect positioning of the survey instrument, and incorrect reading of the instrument indicator. Other variables, such as water levels and activity concentrations in components, lead shielding, the time lapsed after plant shutdown, and crud traps close to measurement locations, may also result in variations. If known, these factors should be considered when evaluating data. The effect of the variations in the individual measurements may be reduced by using average dose rates. For four-loop plants, the RCS piping average was calculated by averaging (i) the average of the 20 cross-over locations, (ii) the average of the four hot-leg locations, and (iii) the average of the four cold-leg locations. The SG tube bundle was represented by the average of the eight hot- and cold-leg locations, and the SG channel head was represented by the average of the eight hot- and cold-leg centre locations. The numbers in a three-loop plant such as Koeberg would be ¾ that of a four-loop plant.

As stated previously, plant dose rates can also vary depending on the use of depleted versus natural zinc and/or the concentration of zinc in the RCS. Depleted zinc eliminates the influence of ^{65}Zn on dose rates and a higher zinc concentration increases the zinc exposure (the product of the coolant zinc concentration and the duration of zinc injection) which typically leads to decreased dose rates.

Additional factors that could affect the dose rates at the end of a zinc cycle include:

- fuel cladding and/or neutron source leaks resulting in additional activities in the coolant and deposits;
- changes in operational and shutdown chemistry evolutions that have an impact on dose rates; and
- replacement of steam generator with Alloy 690 tubing.

Occurrence of these events could obscure the effect of zinc addition (EPRI, 2006).

5.4 Evaluation of the Effectiveness of Zinc

The effectiveness of zinc addition was evaluated by computing the ratio of the average dose rates at the three locations noted in Figure 5.1 in the previous cycle without zinc addition, to the average dose rates at the same locations in the cycles after zinc addition. By applying this technique, variations in the data should be minimized since comparisons are made to data in the same numerical range. It should be noted that the effectiveness of zinc addition on plant dose rates at the SRMP locations was considered in evaluations and not necessarily the effect on dose rates in other parts of the plants (EPRI, 2006).

Another method to evaluate the effectiveness of zinc addition is the effective dose rate, which is defined as the ratio of the dose (mSv) to personnel accumulated during the operation divided by the man-hours required to perform the operation. Accordingly, if the dose rate outside the SG tube bundle has decreased due to zinc addition, it is expected that the dose for sludge lancing within the SG in the zinc addition outage would be less compared to that before zinc addition. This would be the case assuming that the same equipment and technique were used, the workers were positioned at the same locations, and no equipment failures occurred for both outages. However, these conditions may not always exist (EPRI, 2006).

Effective dose rate data are available from the health physics radiation work permit records. Since the total time to perform the job is used, differences in the technique or equipment failures would tend to be normalized; however, other items that affect the dose rate such as local shielding would not be accounted for in this technique, nor would failure of persons to log in under the correct radiation work permit be noted (EPRI, 2006).

5.5 Industry Trends

According to EPRI (EPRI, 2012 b), most PWRs that are operating on zinc chemistry have implemented zinc for its attributed benefits in radiation field reduction. A measure of zinc injection effectiveness is the observed dose rates relative to the primary system's cumulative zinc exposure (CZE). The total exposure to zinc, i.e. the cumulative amount of zinc injected expressed in ppb-month, continues to provide a meaningful correlation between zinc injection and achieved dose rate reduction.

Assessing the impact of zinc injection on dose rates is challenged by the wide variety of zinc injection regimes and the different maturity levels of the zinc injection programmes. Reference (EPRI, 2016) provides equations that correlate zinc exposures to the expected dose reduction based on observed plant data. These equations were solved for CZE needed to achieve dose rate reductions up to 20%, between 20 and 50%, between 50 and 65% and greater than 65%. These CZE ranges (refer to Table 5.1) provide the basis for the 5-tier plant zinc classification scheme, namely non-zinc plants, initiating plants, building up plants, mature plants, and saturated plants. Note that the CZE needed to achieve the tiers are different for RCS loop piping and SG channel head locations. Plant observations indicate that the steam generator radiation fields are about twice as quickly influenced by zinc than RCS loop piping, as expressed in the CZE needed to achieve the various levels of maturity.

Table 5.1: Zinc – Dose rate reduction classification scheme

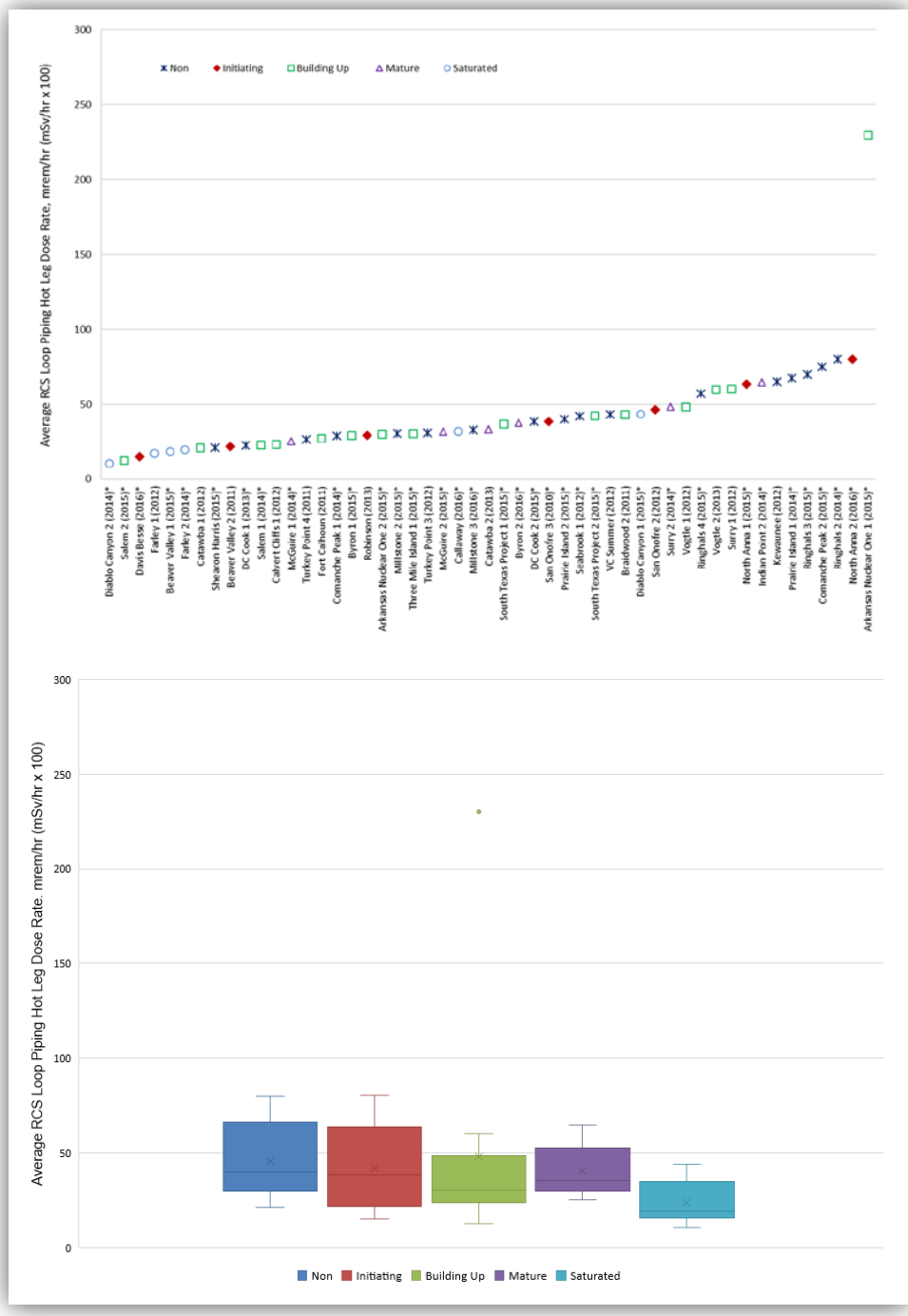
	Cumulative Zinc Exposure, ppb-month				
	Non	**Initiating**	**Building Up**	**Mature**	**Saturated**
RCS Loop Piping	0	< 170	170 – 620	620 – 1300	> 1300
Number of RCS Loop Data Points	17 – 21	7	13 – 15	6	6
SG Channel Head	0	< 80	80 – 310	310 – 650	> 650
Number of SG Channel Head Data Points	21	6	8	8	10

For plants that practise zinc addition programmes but who have not reported their latest cumulative zinc exposure data, the exposure data from the previous cycle was used as an estimate for the zinc exposure for the current cycle. In Figure 5.2 to Figure 5.9, the radiation field data are plotted according to the zinc classification as outlined in Table 5.1 based on provided plant zinc exposure data as summarized in Appendix 1 and Appendix 2. The plants that reported recent data are identified by an asterisk following the plant name. Figure 5.2 to Figure 5.6 also contain a benchmarking plot that shows the dose rates classified according to zinc maturity level for each individual plant at the RCS loop

and SG channel head locations along with a box plot of the same dataset in which the data are binned by the zinc exposure classification (EPRI, 2016).

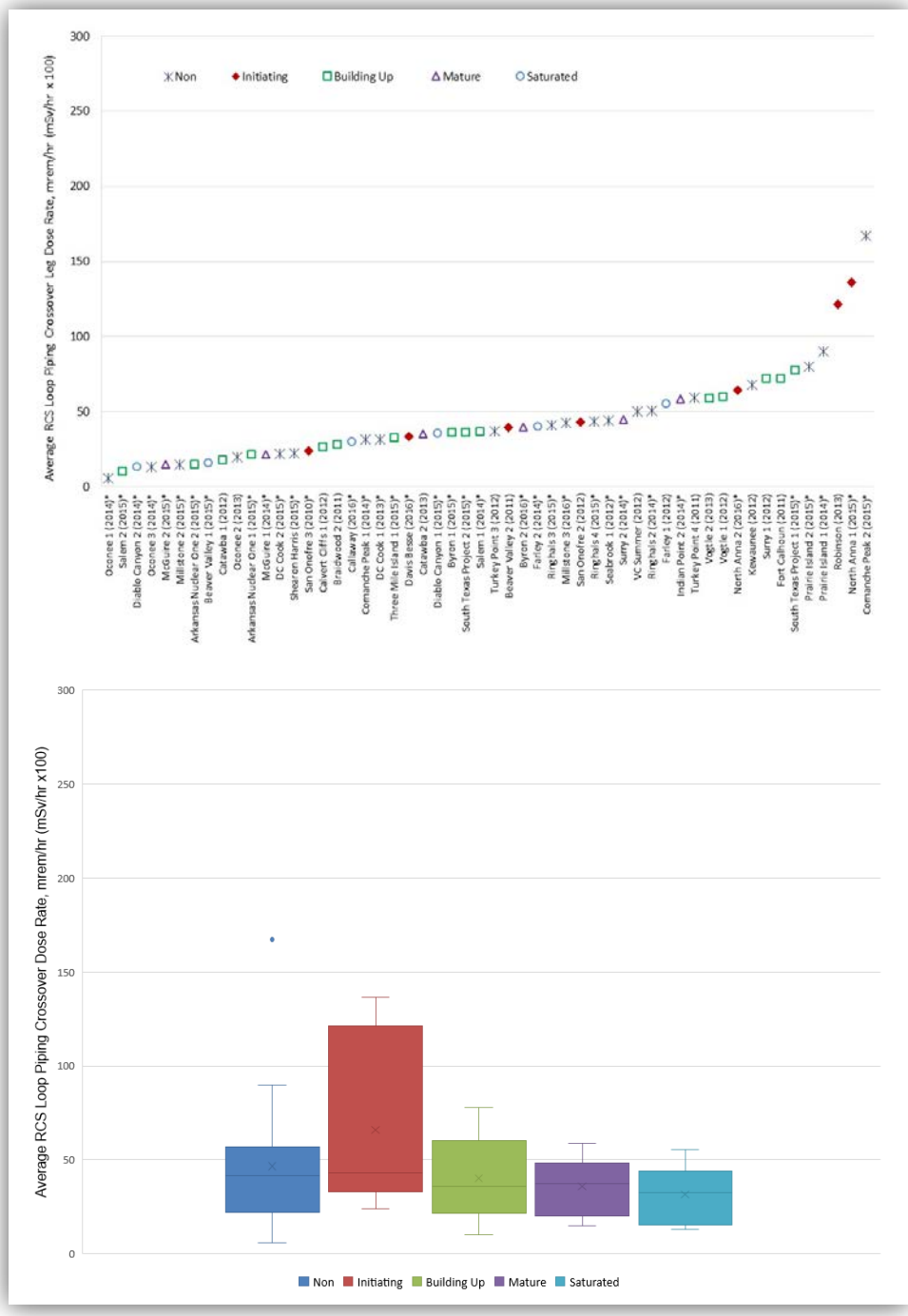
The data reported to EPRI illustrate the nuclear industry's determined efforts to lower radiation fields and the consequent reduced dose rates. While the tendency to compare the dose rates of non-zinc-injecting plants to zinc-injecting plants is tempting, such comparison does not consider plant specific variables. Such comparison cannot adequately substitute for the comparison of dose rates prior to and after the start of zinc injection. A critical observation in the box plots is the higher and outlying dose rates for plants in the initiating category. It was to be expected that plants in the initiating category show a higher dose rate due to their pre-injection dose rate probably being higher than during the now initiating period.

A general observation is that the RCS loop piping dose rates decrease after the initiating category, as expected, with increasing zinc exposure. The higher dose rate points in the mature category for the RCS cold leg loop piping may warrant more investigation to ascertain what operational variables may have caused them. Being only one of several influences on the generation and control of radiation fields, the effects of zinc exposure may to some extent be blurred by other aspects of plant operation e.g. plant transients.



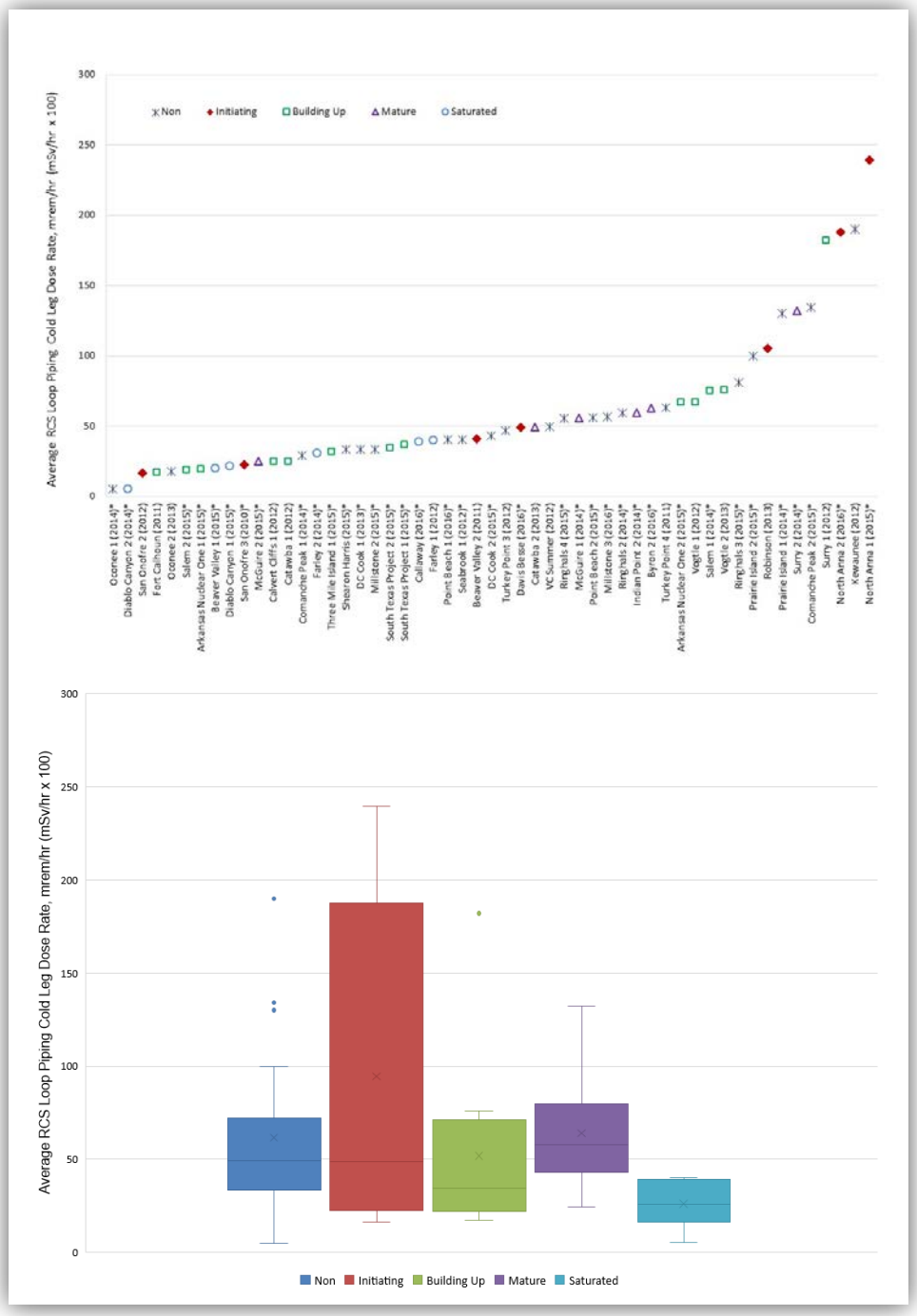
Source: (EPRI, 2016)

Figure 5.2: Average RCS hot leg loop piping dose rates



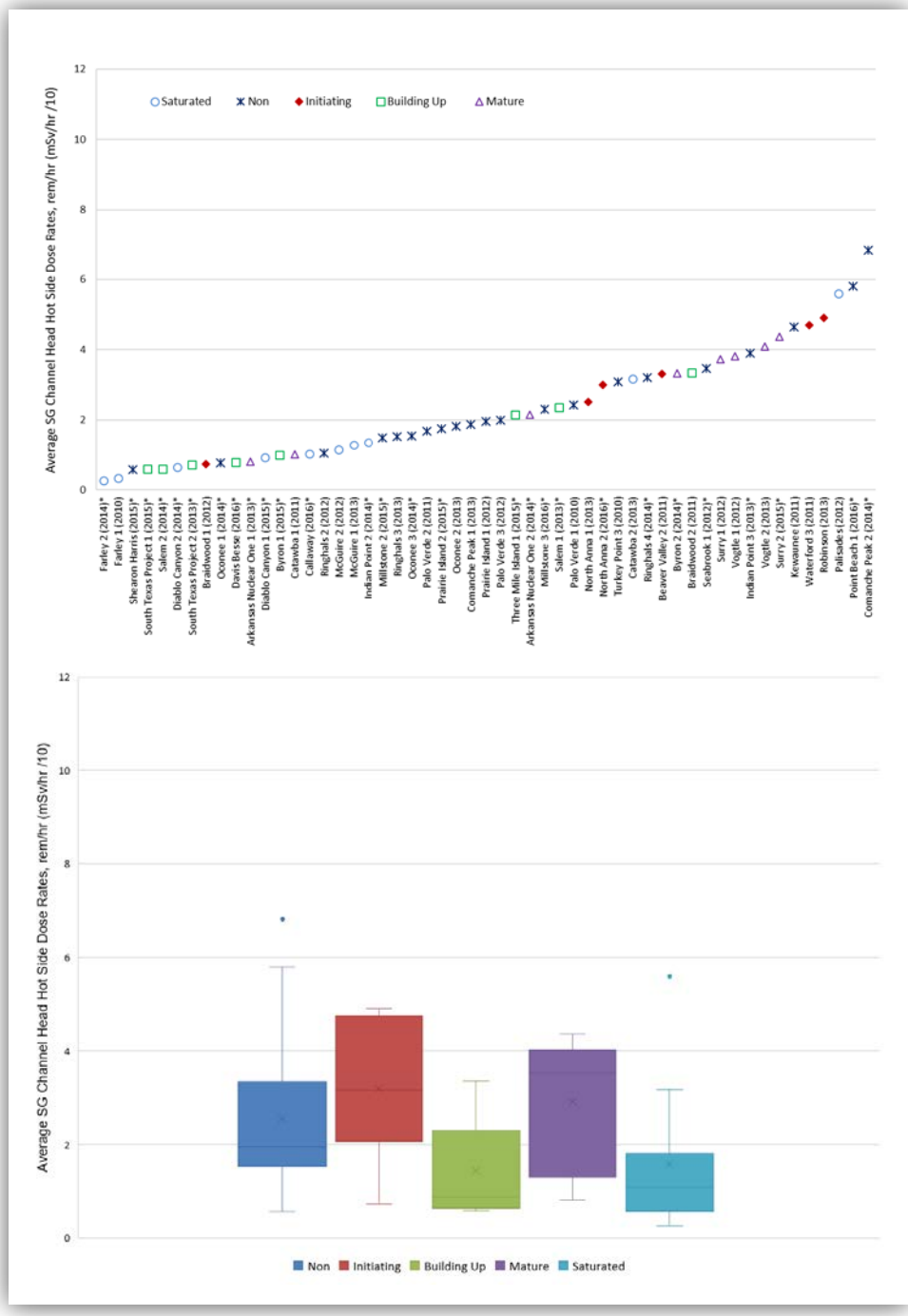
Source: (EPRI, 2016)

Figure 5.3: Average RCS crossover leg loop piping dose rates



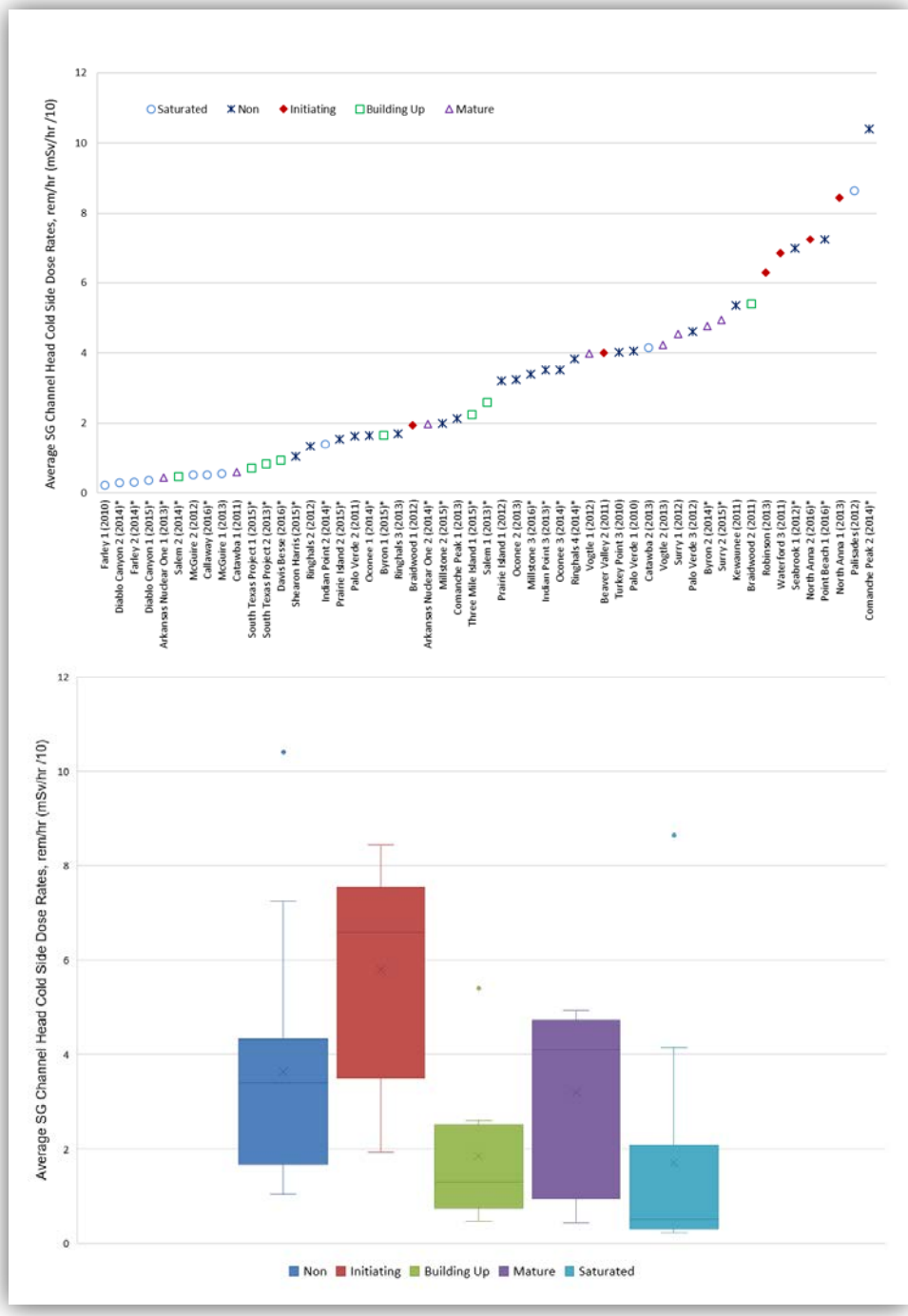
Source: (EPRI, 2016)

Figure 5.4: Average RCS cold leg loop piping dose rates



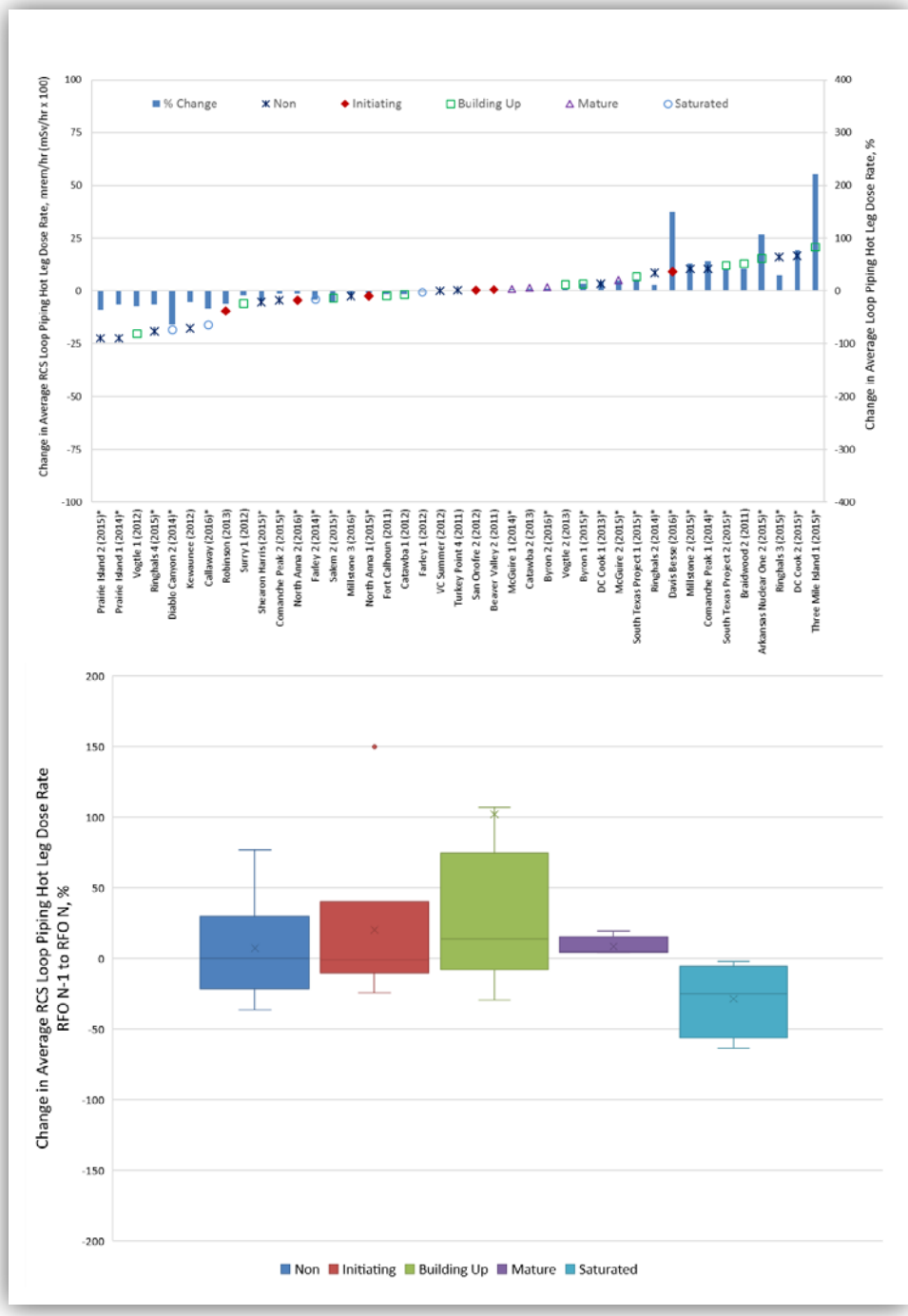
Source: (EPRI, 2016)

Figure 5.5: Average SG channel head hot side dose rates



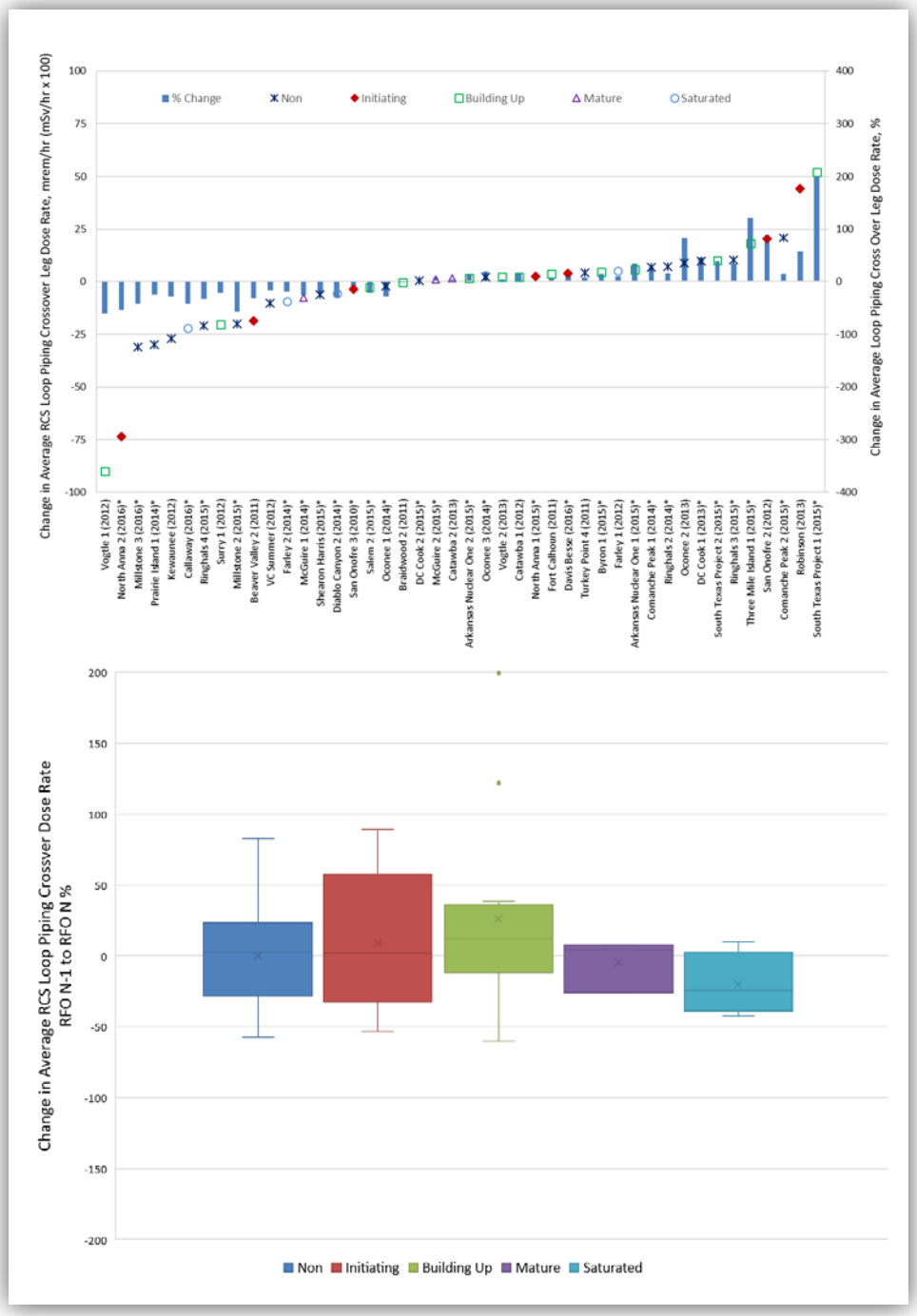
Source: (EPRI, 2016)

Figure 5.6: Average SG channel head cold side dose rates



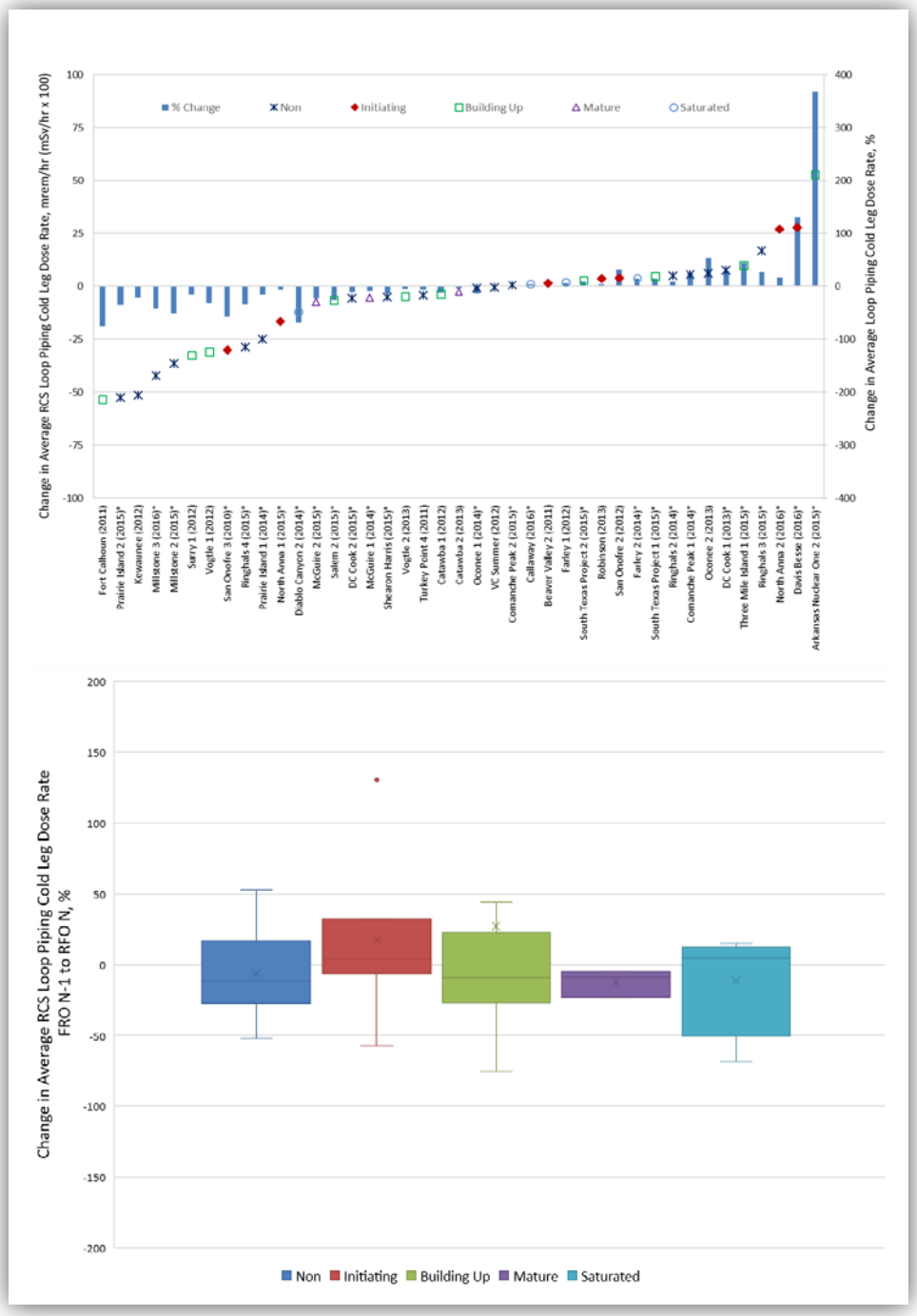
Source: (EPRI, 2016)

Figure 5.7: Change in average RCS hot leg loop piping dose rate, absolute and in percentage



Source: (EPRI, 2016)

Figure 5.8: Change in average RCS crossover leg loop piping dose rate, absolute and in percentage



Source: (EPRI, 2016)

Figure 5.9: Change in average RCS cold leg loop piping dose rate, absolute and in percentage

5.6 Summarising Observations

In Figure 5.7 to Figure 5.9, the radiation field data are plotted according to the zinc classification as outlined in Table 5.1 and demonstrate the success of the industry's concerted efforts to lower radiation fields (EPRI, 2016).

The following observations are noteworthy:

- Plants that decided to perform zinc injection have typically experienced higher than average radiation fields. The plants that do not inject zinc tend to have experienced lower radiation fields. Hence, it is not surprising that the dose rates of plants in the initiating and building up zinc exposure category tend to be higher than the dose rates observed in plants that do not inject zinc.
- In general, dose rates decreased as expected with increasing zinc exposure. Plants operating at the mature and saturated zinc exposure category levels observed the largest and most consistent benefits.
- Anomalous observations should be analysed to ascertain whether conditions potentially averse to the benefits of zinc injection were present.

6 KOEBERG ZINC INJECTION

Since 2014 / 2015 (cycles 121 / 221), depleted zinc acetate has been added to the reactor coolant to reduce out-of-core radiation fields and to mitigate the initiation of primary water stress corrosion cracking. Since the implementation, results were monitored and recorded by means of the existing standard radiation field monitoring programme (SRMP) at Koeberg. This was done in line with the guidance provided by EPRI (EPRI, 2016).

At the commencement of the research project, the SRMP was already initiated. The monitoring was being performed by trained and authorised personnel as it was conducted in high dose-rate locations. The collation and analysis of previous and new data was performed by the author and all conclusions and recommendations were made by the author.

This chapter firstly discusses the Koeberg zinc injection design to provide insights into modification to the relevant plant systems and the operation of the zinc injection equipment. It also describes the initial and operational zinc injection requirements.

Due to the inherent risks of zinc injection to the plant's chemistry and RCS equipment as discussed in the previous chapters, it is vital to monitor the plant chemistry. Therefore, the chemical monitoring requirements will also be briefly elaborated upon.

Lastly, this chapter aims to specify the details of the incorporation of zinc monitoring into the SRMP and to evaluate both the compliance and the initial results thereof. The results

are summarised and further discussed in relation to the summaries made by EPRI on the industry trends in the previous chapters.

6.1 Koeberg's Zinc Injection Modification Design

The modification to the relevant plant systems is relatively simple and inexpensive. It introduces an injection mechanism that forms part of the reactor chemical and volume control system. It injects small volumes of a low concentration depleted zinc acetate solution into the primary coolant water charging line, situated between the RCV volume control tank and the suction header for the three RCV pumps. A low-capacity, positive displacement pump taking suction from a small tank controls the volume of solution injected. The system does not involve any control loops and control is performed manually (Eskom, 2007).

As previously discussed, zinc is incorporated into the layers of spinel oxide of existing components and pipe work, and displaces the radioactive cobalt products in conjunction with nickel and iron corrosion products. These displaced ions are absorbed by the RCV demineralisers. The zinc that is injected will also be continuously extracted in the RCV demineralisers; therefore, the zinc injection system is constantly online and dosing takes place throughout the duration of the cycle.

Each unit at Koeberg has its own independent zinc injection installation. The installation consists of a 25-litre lockable polyethylene container, which is calibrated and closed but not sealed. It provides a negative suction head to the small, positive displacement pump. The tank does not have an agitator as the depleted zinc acetate, $Zn(CH_3COO)_2.2H_2O$ in solution, is soluble up to 430 g per litre water at 20°C. Furthermore, the solution is stable for several months, which is far shorter than the dwell time of the solution in the tank. The tank is closed in order to prevent the ingress of foreign materials. Refer to Figure 6.1 and Figure 6.2 below, illustrating Koeberg's zinc injection installation.

The pump has a built-in suction reservoir and ultrasonic level control in order to stop the pump in the advent that it may run dry. The pump is extremely accurate in the range of doses required.



Figure 6.1: Koeberg's zinc injection unit (closed)

During the incubation period of zinc injection (approximately 3 weeks), the pump was set to discharge 95 ml/h of a 10 g Zn/kg water solution, up until such time as chemistry measurements yielded a 5 ppb zinc concentration in the primary coolant. The pump discharge was then reset to a flow rate of 68 ml/h of a 1 g Zn/kg water solution. The justification of the chosen zinc solution flow rates and concentrations is discussed below.

Zinc oxide is insoluble in water, whereas zinc acetate is highly soluble. The aqueous solubility of zinc acetate is quoted as 311 g per litre in water at a temperature of 20°C and a pressure of 1 atm, and as 666 g per litre in water close to its boiling point under atmospheric pressure. The material safety data sheet (MSDS) supplied by the manufacturer indicates the solubility to be 430 g per litre water at 20°C. There is therefore no risk of precipitation of zinc acetate and consequent damage to the RCP pump seals.



Figure 6.2: Koeberg's zinc injection unit (open)

This is significant as the amount of zinc that could be injected into the primary system during incubation was capped by the concentration—minus a safety factor—at which there existed a risk that the zinc may precipitate and damage the RCP seals. This is, however, not a concern as discussed above. That said though, during incubation, zinc acetate was still being injected into the system in small quantities (a maximum concentration of 70 ppb in the primary coolant immediately downstream of the injection point). The reasons for injecting small quantities of zinc during incubation, when equilibrium could be reached quicker by injecting larger quantities, were as follows:

- Injecting at extremely low concentration and low flow rate takes longer (about three weeks) for the system to completely absorb the zinc into the oxide layer and reach equilibrium than it would if a greater concentration flow rate were injected. This is advantageous in that it does not result in an immediate crud burst and radiological release. Instead, radiological release is gradual. This is beneficial to plant operational protocol and the health of plant workers.
- A higher incubation injection concentration and flow rate would require an impractically high monitoring frequency, which would require more Chemistry department resources.
- The concentration of zinc is manually controlled. Upon reaching a concentration of 5 ppb, injection is shifted from incubation injection to steady-state injection, (steady-state injection simply injects the same quantity that is removed in the demineralisers, in order to keep the primary coolant concentration constant). Should the concentration continue to increase, zinc injection is terminated at 40 ppb. By performing incubation injection at low concentrations and monitoring the concentration, it minimises the risk of the target concentration being

overshot. This is important for fuel integrity because, at such low concentrations, zinc injection has no bearing upon the fuel cladding (IAEA, 2003).

When the spinel oxide lattice is saturated with zinc, the zinc will accumulate in the primary water and will be removed by the demineralisers. At steady state with 5 ppb zinc in the RCS coolant, the zinc injection pump only has to replace the zinc acetate that is removed from the system by the demineralisers. According to the calculations in the Koeberg design document, this amounts to 1.6 g Zn/day, which the pump will replace at 68 ml/h and a concentration of 1 g Zn/kg water (Eskom, 2007).

6.2 Koeberg Zinc Chemical Monitoring Programme

All the technical specification control parameters are listed in Koeberg's Chemistry Operating Technical Specifications document with limit values, action levels, and surveillance frequencies. The document also contains the actions to be taken when a parameter limit value is exceeded. The diagnostic parameters with limit values, target values, and analysis frequencies are listed in Table 6.1 (Eskom, 2016).

Table 6.1: Guidelines for Koeberg's zinc injection

Condition	Recommended Action
Weighted monthly average [Zn] above allowable band.	Reduce zinc injection rate or terminate if necessary. Increase sampling frequency for Zn, Ni, ^{58}Co, and ^{60}Co. If average of Zn samples over 2 days >60 ppb, notify the fuel manufacturer for re-evaluation. Re-start injection when limits are met.
Average [Ni] over 2-week period > 6 ppb.	Notify the fuel manufacturer, take a flux map of the core, and evaluate for local indications of CIPS.
Average of monthly SiO_2 samples >2000 ppb.	Terminate zinc injection, notify Westinghouse to determine whether additional actions required.
Planned power changes	Terminate zinc injection if [Zn] exceeds allowable band. Increase sampling frequency for Zn, Ni, ^{58}Co, and ^{60}Co. Re-start injection when limits are met.
Mid-cycle shutdown	Terminate zinc injection 1 day prior. Increase sampling frequency for Zn, Ni, ^{58}Co, and ^{60}Co. Re-start injection when limits are met.
Unscheduled trip	Terminate zinc injection as soon as possible after trip. Increase sampling frequency for Zn, Ni, ^{58}Co, and ^{60}Co. Re-start injection when limits are met.
Stretch-out	Terminate zinc injection if [Zn] exceeds allowable band.
Refuelling shutdown	For the initial cycles, terminate zinc injection 2 days prior. This time can be reduced as plant experience is gained. Sample for Zn, Ni, ^{58}Co, and ^{60}Co throughout shutdown operations with sufficient frequency to characterise the corrosion product and Zn return behaviour.
Leaking fuel	Decision to proceed with Zn injection should follow a

Condition	Recommended Action
	detailed chemistry review.

6.3 Koeberg SRMP

In line with EPRI guidance, the existing SRMP is used for the monitoring of zinc and the associated changes in the concentration of ^{58}Co and ^{60}Co. In accordance with Table 5.1, Koeberg can be classified under “initiating” plants due to the short duration (30 months) since the start of zinc injection. Comparisons between Koeberg and industry trends, is therefore based on observations made for other “initiating” plants.

The zinc monitoring programme for Koeberg includes the following:

- Isotopic analysis of samples taken from the reactor coolant system by the Chemistry department. This monitoring is formally stipulated in procedures and is performed daily by authorised personnel; refer to § 6.3.1 and (Eskom, 2016).
- Isotopic analysis at SRMP points 12 hours after reactor shutdown by Radiation Protection department. This monitoring is not formalised; however, it has been performed at the end of each zinc injection cycle to date; refer to § 6.3.2.
- Dose rate measurements at SRMP points 12 hours after reactor shutdown by Radiation Protection department. This monitoring is formalised in (Eskom, 2011) as it has been since before the commencement of zinc injection. This offers a good basis for comparison between dose rates before and after zinc injection; refer to § 6.3.3.
- Dose rate measurements at specified locations in the auxiliary rooms to the reactor building by Radiation Protection department. This monitoring is not formalised and only some measurements have been taken; refer to § 6.3.4.

It was noted during the research that Koeberg is not actively transmitting its operational experience to EPRI and therefore not contributing to the industry trending performed by EPRI. This is mainly due to additional burden on resources. Koeberg does however make use of the operational experience provided by EPRI and other industry experts such as Westinghouse and EDF.

6.3.1 Isotopic Analysis of Reactor Coolant System

Instrument	Canberra Inspector 1000 (NaI detector) (refer to Appendix 5)
Location	RCS sampling points
Method	Daily samples are taken from the RCV system and gamma spectrometry/isotopic analysis is performed to derive the measurements of isotopes including Co and Zn.
Results	Refer to Figure 6.3 and Figure 6.4 below (Warren, Sandra, 2016).
Discussion	Based on the observations made from the illustrations in the figures

	below, it can be concluded that zinc injection has a direct impact on the ^{58}Co activity. The ^{60}Co measurements are not illustrated, but it has produced a similar trend as ^{58}Co. This is in line with the theory of zinc injection, whereby these isotopes have been replaced by the depleted zinc in the spinal layers. As an initiating plant, it is expected that a decrease be observed after three to four cycles. It is also observed that the zinc measurements are controlled within the prescribed range around 5 ppb. It is recommended that the monitoring continue in order to control zinc addition and experience the benefits of reduced dose rates and the limitation of PWSCC.

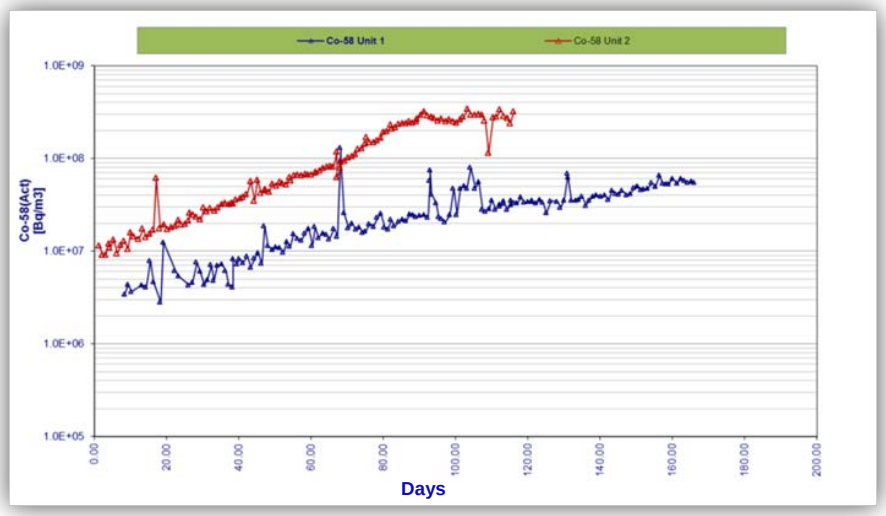


Figure 6.3: Dependence of ^{58}Co concentration on increased Zn (Koeberg Unit 1 and Unit 2)

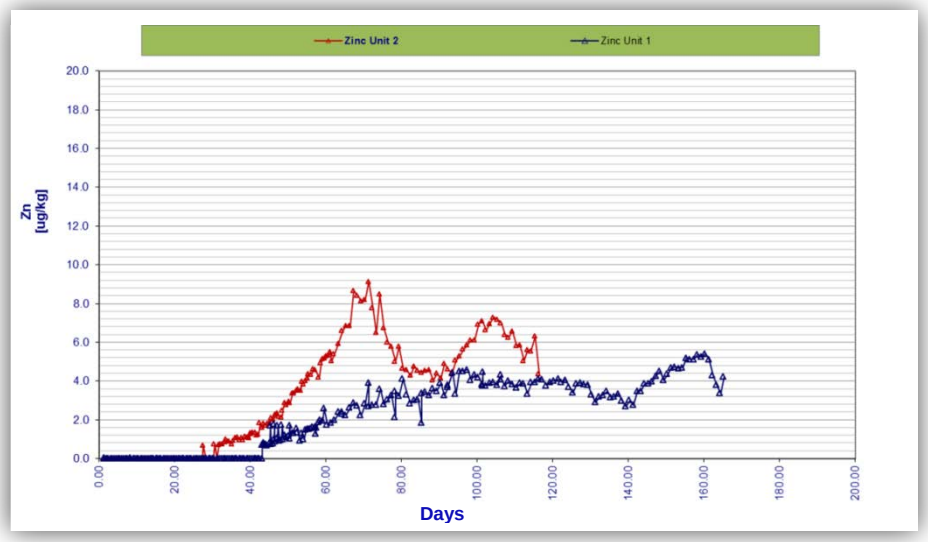


Figure 6.4: Zn measurements since initial injection (Koeberg Unit 1 and Unit 2)

6.3.2 Isotopic Analysis – SRMP Points

Instrument	Canberra Inspector 1000 (refer to Appendix 5)
Location	SRMP points (refer to Appendix 4)
Method	A gamma spectrum was obtained from the reference points on the RCS piping using the Canberra Inspector 1000. Genie analysis package from ISOCS was used to analyse the results since the Inspector 1000 is unable to show the spectra or identify the nuclei. The detector was placed directly on the pipe or lagging as indicated in Figure 6.5 for 120 seconds. Note that the measurements were performed by authorised staff due to the radiation exposure risk.
Results	Measurements of ^{58}Co and ^{60}Co have been taken for zinc cycles of Unit 1 (120, 121, and 122) and Unit 2 (220 and 221). The ratio between ^{58}Co and ^{60}Co has been calculated with the aim of assessing if Zn has an impact on these isotopes. However, the data available is limited; only two data measurements are available for some points. The number of readable samples decreased from one Outage to the other. This could imply there is a decrease in the number of ^{58}Co and ^{60}Co with time. Due to the quality of the collected data, no data will be illustrated in this report.
Discussion	It was observed that no correlation exists between the available data for the measured cycles and this makes it difficult to make a meaningful conclusion. It is recommended that the data collection be formalised into the SRMP. This will ensure improved data collection for future cycles, which will allow for better trending and meaningful information. It is also recommended that training be provided to more staff on the use of the equipment. This will mitigate the risk of inconsistent technique between different staff members.



Figure 6.5: Measurement at Point 1 using Inspector 1000

6.3.3 Dose Rate Measurements – SRMP Points

Instrument	Thermo Ion Chamber (refer to Appendix 7) /Teletector (refer to Appendix 6)
Location	SRMP points (refer to Appendix 4)
Method	Dose rate measurements are taken 12 hours after shutdown at the SRMP points. These points are all taken on contact with the lagging. If lagging is removed, the survey is taken 15 cm away from pipe. Note that the measurements were performed by authorised staff due to the radiation exposure risk.
Results	The average dose rates are calculated for the hot leg (HL), cold leg (CL), and the cross-over leg (CO) of all three steam generators. Refer to Figure 6.6 for the average dose rates for the respective outages for Unit 1, before and after zinc injection i.e. outage 117 until 122. Refer to Figure 6.7 for the average dose rates for the respective outages for Unit 2, before and after zinc injection i.e. outage 217 until 221. A dose rate index is also calculated by averaging the data recorded for all the SG piping points; refer to Figure 6.8 and Figure 6.9 for Unit 1 and Unit 2 respectively. This index is useful as it allows for trending the average dose.

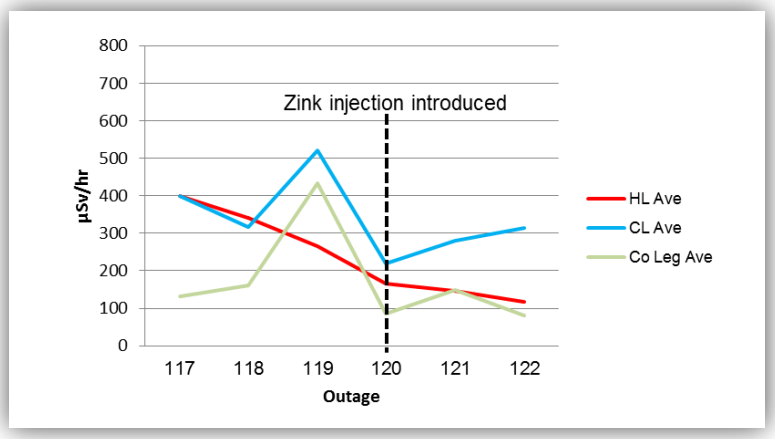


Figure 6.6: Unit 1 Average SG piping dose rates (12 hours after shutdown)

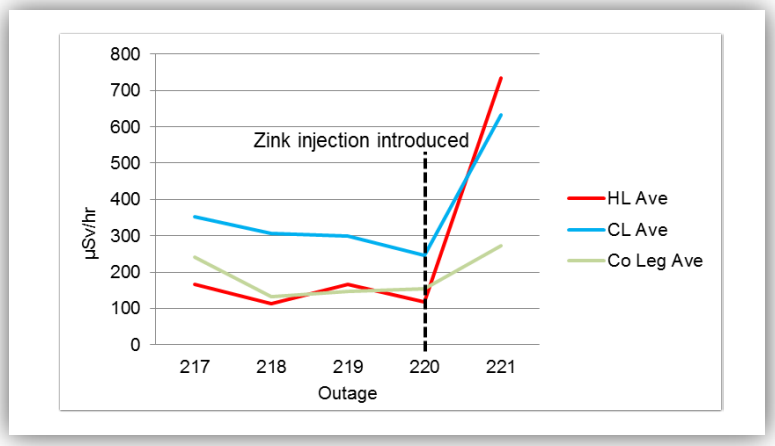


Figure 6.7:Unit 2 Average SG piping dose rates (12 hours after shutdown)

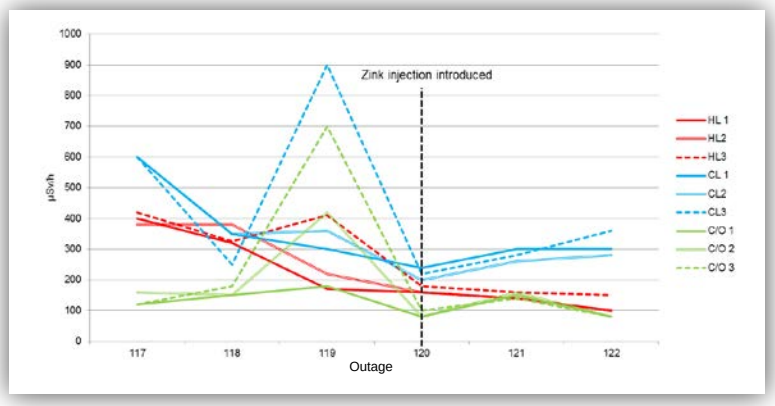


Figure 6.8: Unit 1 Dose rate index comparison (12 to 16 hours after shutdown)

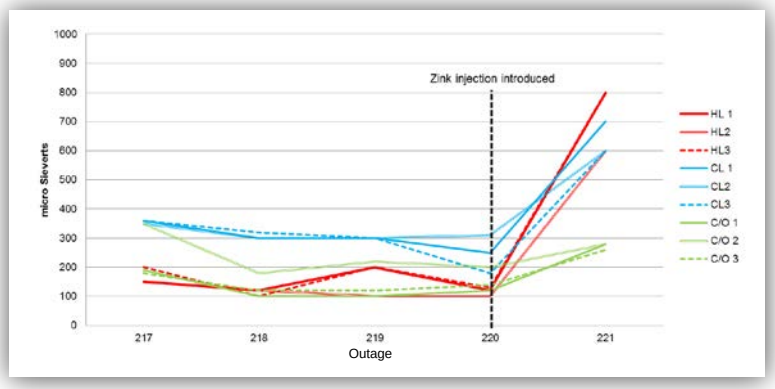


Figure 6.9: Unit 2 Dose rate index comparison (12 to 16 hours after shutdown)

Discussion	It is observed that Unit 1 and Unit 2 experienced initial increases in dose rates as expected. Unit 1 experienced a reduction in the dose rate index after its second cycle, i.e. the end of Outage 122. This is encouraging; however, it is premature to make any conclusions, as the data pertain to two cycles only. It would be of interest to evaluate the results of Unit 2 at the end of its second cycle. It is recommended that monitoring continue in order to assess long-term results.

6.3.4 Dose Rate Measurement – Auxiliary Rooms

Instrument	Teletector (refer to Appendix 6).
Location	• RCV letdown line (rooms N213 and N223) • Penetration 255 (rooms W218 and W258) • Centre of heat exchanger (rooms N215 and N225)
Method	Monthly contact dose rate measurements are taken with the same instrument to ensure consistency and to limit inaccuracies introduced through different instruments. Note that the measurements were performed by authorised staff due to the radiation exposure risk.
Results	Refer to graphs illustrated in Figure 6.10, Figure 6.11, Figure 6.12, Figure 6.13, Figure 6.14, and Figure 6.15; based on data listed in Appendix 3.
Discussion	A general observation is made of the average increase in dose rates since zinc injection commenced. This is in line with the theory whereby it is expected that there will be an increase in dose rate due to the increased Co and other corrosion product displaced by the depleted Zn from the spinal layers of the RCS. It must be noted that some data was not available and interpolated data was calculated to establish a complete trend. It is observed that not all data for the respective rooms displayed the same trends. Possible factors that may have influenced the trends include the following: • errors associated with survey instruments; • different survey instruments used; • surveys performed at not the exact locations as previously; • worker practices that differs from one worker to another; and • other operational activities that could result in temporary elevation of dose rates. It is recommended that the monitoring be formally incorporated into the SRMP. This could include standard operating procedures that will address the factors listed above.

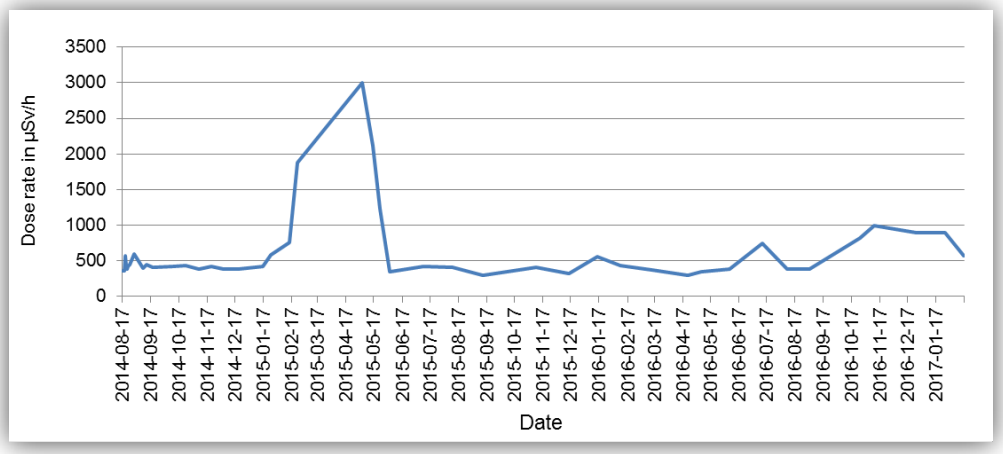


Figure 6.10: Unit 1, Room N213
RCV letdown line, CT

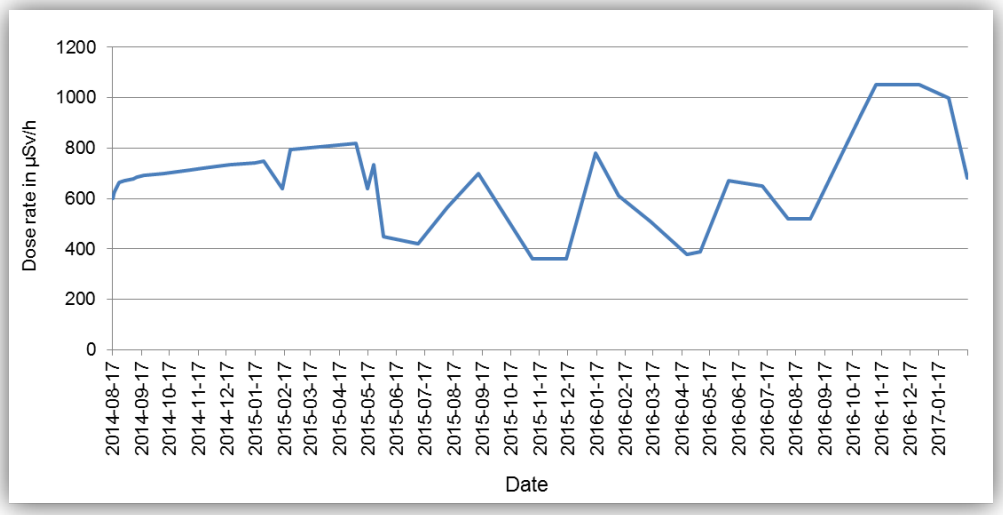


Figure 6.11: Unit 2, Room N223
RCV letdown line, CT

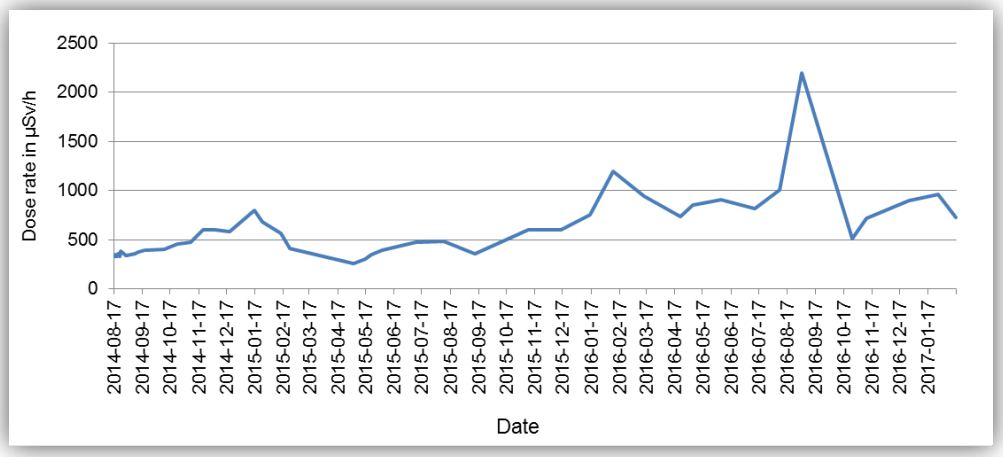


Figure 6.12: Unit 1, Room W218
Penetration 255 (pipe bend as pipe exits containment), CT

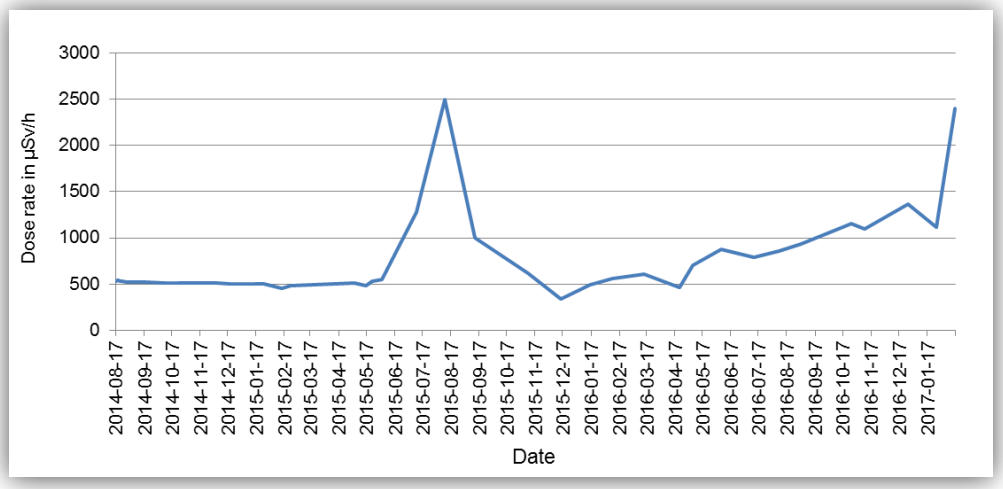


Figure 6.13: Unit 2, Room W258
Penetration 255 (pipe bend as pipe exits containment), CT

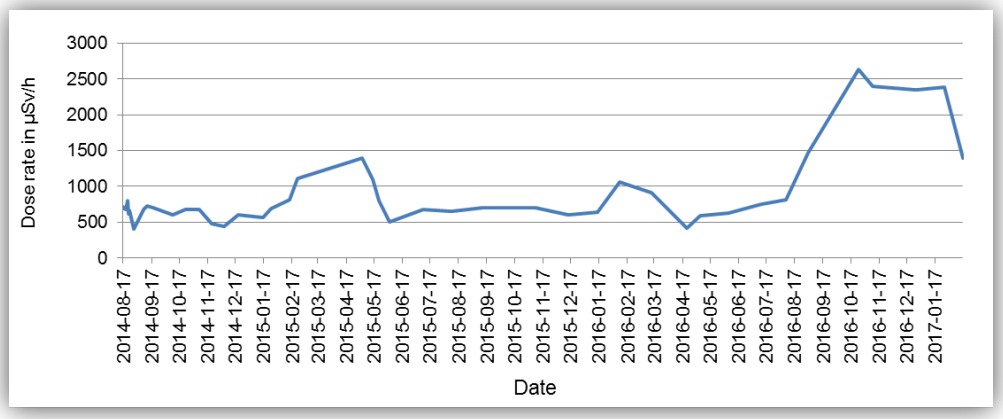


Figure 6.14: Unit 1, Room N215,
Centre of RCV 002 RF Heat Exchanger, CT

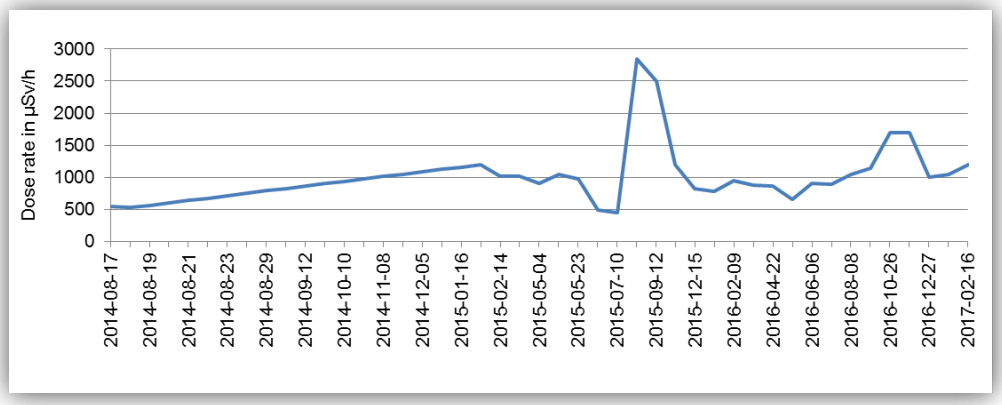


Figure 6.15: Unit 2, Rom N225,
Centre of RCV 002 RF Heat Exchanger, CT

6.4 Summarising Observations

Koeberg has developed a chemistry monitoring programme that is being strictly adhered to. It provides important information that assists in managing plant chemistry and the impact this has on major RCS equipment.

Koeberg's zinc modification programme has been implemented successfully in 2014 and is continuing to operate effectively.

Isotopic analysis and dose rate assessments results are showing positive indications that zinc injection at Koeberg is following the industry trends for plants that are in the initiating phase. Continued disciplined monitoring will allow for better trending and comparison with other plants that are in more advanced phases.

Although zinc monitoring is performed by a number of departments, not all monitoring form part of Koeberg's SRMP. It is recommended that this anomaly be addressed and that accountability for the programme be centralised.

It is further recommended to include the training of more staff on specialised equipment such as the Inspector 1000, and the associated techniques. It is also recommended that Koeberg becomes an active participant in EPRI's zinc monitoring initiative.

7 CONCLUDING CHAPTER

Koeberg Nuclear Power Station has set itself the objective of achieving world top quartile performance in terms of dose to workers. Achieving this goal requires implementation of a number of dose reduction initiatives. One such initiative is the continuous injection of depleted zinc acetate into the primary cooling system of the plant as a means of cobalt reduction, the principal contributor to out-of-core radiation fields.

Sources of ^{60}Co in the primary system of a PWR have been studied extensively over the years, and the major sources have been ascertained. Reductions in the cobalt content in the primary system, the steam generator tubing, replacement of Stellite with non-cobalt alloys, and the minimization of cobalt concentrations in replacement material are pursued whenever possible in order to reduce the ^{59}Co source term.

The use of zinc to minimize cobalt in the primary system is based on the theory outlined in § 4.3. Spinel oxide layers, a hard, glassy mineral, build up over time on the steel internals of the primary system of a nuclear plant. This layer incorporates the radioactive fission products of ^{58}Co and ^{60}Co as well as other corrosion products such as Fe and Ni. By injecting the primary system water with a more stable, non-radioactive metal ion such as depleted zinc, the zinc is incorporated in the spinel layers and displaces the radioactive cobalt, nickel, and iron corrosion products. The demineralisers would then remove the radioactive cobalt in the primary system, thereby reducing the radioactivity in the system. The reduction in the radioactivity leads to the reduction of the ambient dose rates and therefore potentially reducing the whole-body dose to workers performing work on or close to the primary system.

The injection of zinc requires a specific programme based on the characteristics of the plant. Guidance from international bodies such as EPRI and Westinghouse is available to set up a zinc injection monitoring programme. Operational experience is available on the impact of zinc on major RCS components e.g. fuel, steam generators, and primary pumps. Results from studies and experience acquired conclude that zinc injection does not pose a significant risk to these components.

Industry trending results have concluded that zinc injection is an effective initiative for dose rate reduction on most plants of similar design. Although not all plants have experienced the same level of success, some plants have achieved a dose rate reduction of 50 per cent over a longer term. Not only does it represent a huge cost saving, but also means a significant improvement in safety and specifically the protection of workers by the reduction of occupational radiation exposure.

Koeberg is in the initiating phase of its zinc injection initiative; however, early results compare favourably with those of similar plants in the same phase. Recommendations made by the author, in support of achieving future benefits similar to the rest of the industry include:

1. The formalisation of all the zinc monitoring into the existing SRMP;
2. Training of staff on the required monitoring techniques and equipment; and
3. Participation in international zinc monitoring initiatives such as the EPRI programme for this purpose.

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APPENDIX 1

RCS LOOP PIPING CUMULATIVE ZINC EXPOSURE BY PLANT (2010 – CURRENT)**

Plant Name	Cycle End Date	Standard Outage ID	Cumulative Zinc Exposure	Zinc Classification
Arkansas Nuclear One 1	2015-01-25	EOC 25	170 < CZE < 620*	Building up
Arkansas Nuclear One 2	2015-09-20	EOC 24	170 < CZE < 620*	Building up
Beaver Valley 1	2015-04-25	EOC 23	> 2031	Saturated
Beaver Valley 2	2011-03-07	EOC 15	16	Initiating
Braidwood 2	2011-04-17	EOC 15	219	Building up
Byron 1	2015-09-14	EOC 20	170 < CZE < 620*	Building up
Byron 2	2016-04-18	EOC 19	620 < CZE < 1300*	Mature
Callaway	2016-04-02	EOC 21	> 1300*	Saturated
Calvert Cliffs 1	2012-02-05	EOC 20	390	Building up
Catawba 1	2012-11-25	EOC 20	521	Building up
Catawba 2	2013-09-14	EOC 19	730	Mature
Comanche Peak 1	2014-10-04	EOC 17	No zinc injection	Non
Comanche Peak 2	2015-10-03	EOC 15	No zinc injection	Non
Davis Besse	2016-03-26	EOC 19	88 < CZE < 170*	Initiating
DC Cook 1	2013-03-27	EOC 24	No zinc injection	Non
DC Cook 2	2015-03-25	EOC 21	No zinc injection	Non
Diablo Canyon 1	2015-10-04	EOC 19	> 2455*	Saturated
Diablo Canyon 2	2014-10-05	EOC 18	> 2099*	Saturated
Farley 1	2012-04-15	EOC 24	> 2018*	Saturated
Farley 2	2014-10-15	EOC 23	> 2567*	Saturated
Fort Calhoun	2011-04-10	EOC 26	411	Building up
Indian Point 2	2014-02-25	EOC 21	837 < CZE < 1300*	Mature
Kewaunee	2012-04-06	EOC 31	No zinc injection	Non
McGuire 1	2014-09-13	EOC 23	943	Mature
McGuire 2	2015-09-12	EOC 23	917 < CZE < 1300*	Mature
Millstone 2	2015-10-03	EOC 23	No zinc injection	Non
Millstone 3	2016-04-09	EOC 17	No zinc injection	Non
North Anna 1	2015-03-08	EOC 24	< 170*	Initiating
North Anna 2	2016-03-06	EOC 24	< 170*	Initiating
Oconee 1	2014-11-30	EOC 28	No zinc injection	Non
Oconee 2	2013-10-12	EOC 26	No zinc injection	Non
Oconee 3	2014-04-15	EOC 27	No zinc injection	Non
Point Beach 1	2016-03-12	EOC 36	No zinc injection	Non

APPENDIX 1

RCS LOOP PIPING CUMULATIVE ZINC EXPOSURE BY PLANT (2010 – CURRENT)**

Plant Name	Cycle End Date	Standard Outage ID	Cumulative Zinc Exposure	Zinc Classification
Point Beach 2	2015-10-03	EOC 34	No zinc injection	Non
Prairie Island 1	2014-10-08	EOC 28	No zinc injection	Non
Prairie Island 2	2015-10-17	EOC 28	No zinc injection	Non
Ringhals 2	2014-08-16	EOC 37	No zinc injection	Non
Ringhals 3	2015-05-20	EOC 32	No zinc injection	Non
Ringhals 4	2015-08-12	EOC 32	No zinc injection	Non
Robinson	2013-09-14	EOC 28	< 1701	Initiating
Salem 1	2014-10-19	EOC 23	304 < CZE < 620*	Building up
Salem 2	2015-10-22	EOC 21	216 < CZE < 620*	Building up
San Onofre 2	2012-01-09	EOC 16	118	Initiating
San Onofre 3	2010-10-10	EOC 16	90	Initiating
Seabrook 1	2012-11-01	EOC 16	No zinc injection	Non
Shearon Harris	2015-04-02	EOC 19	No zinc injection	Non
South Texas Project 1	2015-10-17	EOC 19	251 < CZE < 620*	Building up
South Texas Project 2	2015-03-28	EOC 17	170 < CZE < 620*	Building up
Surry 1	2012-05-06	EOC 24	335	Building up
Surry 2	2014-04-20	EOC 25	641	Mature
Three Mile Island 1	2015-10-30	EOC 20	450 < CZE < 620*	Building up
Turkey Point 3	2012-02-26	EOC 26	No zinc injection	Non
Turkey Point 4	2011-03-21	EOC 25	No zinc injection	Non
VC Summer	2012-10-13	EOC 20	No zinc injection	Non
Vogtle 1	2012-09-16	EOC 17	400 < CZE < 620*	Building up
Vogtle 2	2013-03-10	EOC 16	586	Building up

** Exact exposure unknown, but expected to be within the provided range based on previous cycle information.*

*** Source:* (EPRI, 2016)

APPENDIX 2

SG CHANNEL HEAD CUMULATIVE ZINC EXPOSURE BY PLANT (2010 – CURRENT)**

Plant Name	Cycle End Date	Standard Outage ID	Cumulative Zinc Exposure	Zinc Classification
Arkansas Nuclear One 1	2013-03-24	EOC 24	310 < CZE < 650*	Mature
Arkansas Nuclear One 2	2014-04-27	EOC 23	310 < CZE < 650*	Mature
Beaver Valley 2	2011-03-07	EOC 15	16	Initiating
Braidwood 1	2012-04-16	EOC 16	9	Initiating
Braidwood 2	2011-04-17	EOC 15	219	Building up
Byron 1	2015-09-14	EOC 20	80 < CZE < 310*	Building up
Byron 2	2014-09-29	EOC 18	511	Mature
Callaway	2016-04-02	EOC 21	> 1300*	Saturated
Catawba 1	2011-04-23	EOC 19	333	Mature
Catawba 2	2013-09-14	EOC 19	730	Saturated
Comanche Peak 1	2013-03-30	EOC 16	No zinc injection	Non
Comanche Peak 2	2014-03-29	EOC 14	No zinc injection	Non
Davis Besse	2016-03-26	EOC 19	88 < CZE < 310*	Building up
Diablo Canyon 1	2015-10-04	EOC 19	> 2455*	Saturated
Diablo Canyon 2	2014-10-05	EOC 18	> 2099*	Saturated
Farley 1	2010-10-11	EOC 23	2018	Saturated
Farley 2	2014-10-15	EOC 23	> 2567*	Saturated
Indian Point 2	2014-02-25	EOC 21	> 837*	Saturated
Indian Point 3	2013-03-04	EOC 17	No zinc injection	Non
Kewaunee	2011-02-26	EOC 30	No zinc injection	Non
McGuire 1	2013-03-16	EOC 22	730	Saturated
McGuire 2	2012-09-15	EOC 21	761	Saturated
Millstone 2	2015-10-03	EOC 23	No zinc injection	Non
Millstone 3	2016-04-09	EOC 17	No zinc injection	Non
North Anna 1	2013-09-08	EOC 23	14	Initiating
North Anna 2	2016-03-06	EOC 24	< 80*	Initiating
Oconee 1	2014-11-03	EOC 28	No zinc injection	Non
Oconee 2	2013-10-12	EOC 26	No zinc injection	Non
Oconee 3	2014-04-15	EOC 27	No zinc injection	Non
Palisades	2012-04-08	EOC 22	1515	Saturated
Palo Verde 1	2010-04-03	EOC 15	No zinc injection	Non
Palo Verde 2	2011-04-02	EOC 16	No zinc injection	Non
Palo Verde 3	2012-03-17	EOC 16	No zinc injection	Non

APPENDIX 2

SG CHANNEL HEAD CUMULATIVE ZINC EXPOSURE BY PLANT (2010 – CURRENT)**

Plant Name	Cycle End Date	Standard Outage ID	Cumulative Zinc Exposure	Zinc Classification
Point Beach 1	2016-03-12	EOC 36	No zinc injection	Non
Prairie Island 1	2012-10-23	EOC 27	No zinc injection	Non
Prairie Island 2	2015-10-17	EOC 28	No zinc injection	Non
Ringhals 2	2012-09-15	EOC 35	No zinc injection	Non
Ringhals 3	2013-08-10	EOC 30	No zinc injection	Non
Ringhals 4	2014-08-60	EOC 31	No zinc injection	Non
Robinson	2013-09-14	EOC 28	< 80*	Initiating
Salem 1	2013-04-14	EOC 22	304	Building up
Salem 2	2014-04-13	EOC 20	216	Building up
Seabrook 1	2012-11-01	EOC 16	No zinc injection	Non
Shearon Harris	2015-04-02	EOC 19	No zinc injection	Non
South Texas Project 1	2015-10-17	EOC 19	80 < CZE < 310*	Building up
South Texas Project 2	2013-11-16	EOC 16	167	Building up
Surry 1	2012-05-06	EOC 24	335	Mature
Surry 2	2015-10-19	EOC 26	641	Mature
Three Mile Island 1	2015-10-30	EOC 20	80 < CZE < 310*	Building up
Turkey Point 3	2010-09-25	EOC 24	No zinc injection	Non
Vogtle 1	2012-09-16	EOC 17	310 < CZE < 650*	Mature
Vogtle 2	2013-03-10	EOC 16	586	Mature
Waterford 3	2011-04-05	EOC 17	< 170*	Initiating

** Exact exposure unknown, but expected to be within the provided range based on previous cycle information*

*** Source:* (EPRI, 2016)

APPENDIX 3

SURVEY FOR ZINC INJECTION MONITORING

			Survey Points[1]					
			RCV Letdown line CT		Penetration 255 (pipe bend as pipe exits containment) CT		Centre of RCV 002 RF Heat Exchanger CT	
#	Date	Time	N213	N223	W218	W258	N215 (Top middle)	N225 (Bottom middle)
1	2014-08-17	08:00	355[2]	600	330	530	710	555
2	2014-08-18	08:20	360	620	345	540	690	530
3	2014-08-19	11:00	360	627[3]	330	538	700	567
4	2014-08-20	13:36	570	634	330	536	680	604
5	2014-08-21	11:53	430	642	360	533	740	642
6	2014-08-22	11:07	380	649	360	531	800	679
7	2014-08-23	10:04	427	656	334	529	620	716
8	2014-08-24	11:38	448	663	380	527	660	753
9	2014-08-29	12:49	600	671	340	524	400	791
10	2014-09-08	10:15	400	678	360	522	680	828
11	2014-09-12	07:54	441	685	374	520	720	865
12	2014-09-19	08:10	410	692	395	518	700	902
13	2014-10-10	10:00	420	699	400	516	600	939
14	2014-10-24	07:30	440	707	452	513	680	977
15	2014-11-08	12:45	380	714	470	511	680	1014
16	2014-11-21	10:15	420	721	600	509	480	1051
17	2014-12-05	08:20	380	728	600	507	440	1088
18	2014-12-20	13:00	380	736	580	504	600	1126
19	2015-01-16	13:20	420	743	800	502	560	1163
20	2015-01-25	14:00	587	750	683	500	685	1200
21	2015-02-14	11:00	753	638	566	452	810	1020
22	2015-02-23	18:00	1877	796	413	481	1105	1020
23	2015-05-04	11:55	3000	820	260	510	1400	910
24	2015-05-16	09:15	2115	640	303	480	1100	1050
25	2015-05-23	09:30	1230	735	347	530	800	980
26	2015-06-03	08:15	345	450	390	550	500	490
27	2015-07-10	03:30	420	420	470	1280	670	450
28	2015-08-10	12:00	405	566	486	2500	645	2840
29	2015-09-12	13:00	300	700	360	1000	700	2500
30	2015-11-09	18:35	405	360	600	615	700	1200
31	2015-12-15	10:00	320	360	600	340	605	825
32	2016-01-15	09:20	560	780	750	490	640	780
33	2016-02-09	09:00	430	610	1200	560	1060	950
34	2016-03-14	14:00	370	510	940	605	910	880
35	2016-04-22	00:00	300	380	740	460	420	870

APPENDIX 3

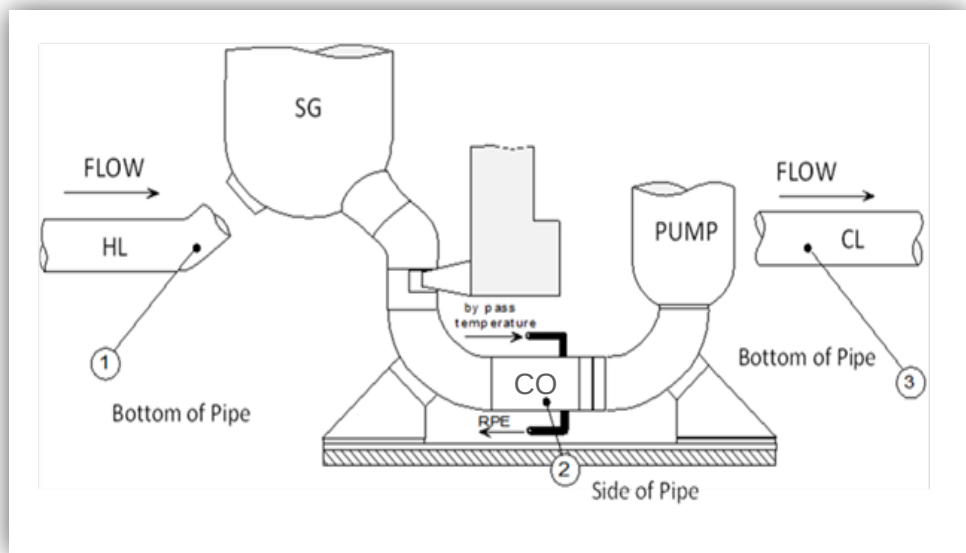
SURVEY FOR ZINC INJECTION MONITORING

			Survey Points[(1)]					
			RCV Letdown line CT		Penetration 255 (pipe bend as pipe exits containment) CT		Centre of RCV 002 RF Heat Exchanger CT	
#	Date	Time	N213	N223	W218	W258	N215 (Top middle)	N225 (Bottom middle)
36	2016-05-06	09:15	350	390	850	700	590	660
37	2016-06-06	14:10	390	670	910	880	630	903
38	2016-07-12	02:10	750	650	820	785	750	900
39	2016-08-08	16:25:00	380	520	1010	860	810	1040
40	2016-09-01	03:00:00	380	520	2200	930	1470	1150
41	2016-10-26	22:00:00	820	940	510	1150	2630	1700
42	2016-11-10	12:15:00	1000	1050	720	1100	2400	1700
43	2016-12-27	03:45:00	900	1050	900	1360	2350	1000
44	2017-01-27	10:00:00	900	1000	960	1120	2380	1040
45	2017-02-16	00:25:00	565	680	725	2400	1400	1200

***NOTE**:*
1) Readings obtained using a Teletector (refer to Appendix 6).
2) Dose rate in µSv/h.
3) Grey data: Interpolated.

APPENDIX 4

KOEBERG's SRMP MEASUREMENT POINTS



APPENDIX 5

CANBERRA INSPECTOR 1000 DIGITAL HAND-HELD MULTICHANNEL ANALYZER



APPENDIX 5

CANBERRA INSPECTOR 1000 DIGITAL HAND-HELD MULTICHANNEL ANALYZER

InSpector 1000 Digital Hand-Held Multichannel Analyzer

Specifications

INPUTS
- DC POWER/CHARGER – 12 V, 2 A dc output; universal ac/dc adapter input with IEC 320 power connector.

OUTPUTS
- USB DEVICE – USB device interface for connection to host computer for spectrum upload and library/efficiency download.

DETECTORS
- GM TUBE – Internal Geiger-Mueller tube for high dose/count rate measurements. Operates in CANBERRA's unique time-to-count mode.
- NaI PROBES – External NaI(Tl) detector with integrated preamplifier and programmable HVPS. Sensitivity referenced to ^{137}Cs.
  - IPRON-1: 1.5" x 1.5"; 6000 cps/mrem/h ±3.5%.
  - IPROS-2: Stabilized 2" x 2" NaI probe*; 13 000 cps/mrem/h ±3.5%.
  - IPROS-3: Stabilized 3" x 3"; 32 000 cps/mrem/h ±3.5%.
  - IPROL-1: Stabilized 1.5" x 1.5" LaBr probe 8000 cps/mrem/h ±3.5%.
- PULSE SHAPE – Tail pulse from detector preamplifier, positive or negative polarity.
- AMPLITUDE – 0.16 V to 1.6 V, full scale output.
- NEUTRON PROBE – External detector; moderated ^{3}He tube (8 cm active length – 2 atm); intrinsic neutron sensitivity ≈1%, using an unmoderated ^{252}Cf fast neutron source; weight: 1.36 kg (3 lb).

DISPLAY
- TYPE – 9 cm (3.5 in.) backlit color LCD and touch panel.
- RESOLUTION – 320 x 240 pixels.

INDICATOR
- CHARGE INDICATOR – Yellow LED on keypad.

AUDIO
- AUDIBLE ANNUNCIATOR – Indicates touch screen selection.
- AUDIBLE COUNT RATE INDICATOR – Off or one beep for every 100, 1000 or 10 000 counts; user selectable.
- AUDIBLE ALARM/WARNING INDICATOR – Alarms/warnings using tones; user configurable.

COUNT/DOSE RATE DISPLAY
- DOSE RATE BARGRAPH FULL SCALE – 0.1, 1.0, 10, 100, 1000, 10 000, Auto; user selectable.
- DOSE RATE UNITS – µR/h, mR/h, R/h; µSv/h, mSv/h; µrem/h, mrem/h, rem/h; user selectable.

PERFORMANCE
- ENERGY RANGE –
  - For 1.5, 2 and 3 in. NaI detectors – 50 keV to 3 MeV.
  - For GM detector – 30 keV to 1.4 MeV.
  - For 1.5 in. LaBr detector – 30 keV to 3 MeV.
- INTEGRAL – 0.1% over top 99% of conversion range.
- THROUGHPUT – >50 kcps.
- INPUT COUNT RATE – >500 kcps total, if not limited by detector/probe.
- LIVE TIME CORRECTION – Live Time Correction (LTC) of spectral data.
- PRESETS – Live time preset: 1 – 1 000 000 s; Real time preset: 1 – 1 000 000 s.
- SPECTRAL DATA STORAGE – More than 512 spectra of 1024 channels each (CAM file format).
- CHANNEL STORAGE – 32 bits.
- NUCLIDE IDENTIFICATION ENERGY TOLERANCE WINDOW – ±4%.
- MINIMUM DOSE RATE EQUIVALENT H*(10) – 10 nSv/h.
- MAXIMUM DOSE RATE EQUIVALENT H*(10) – 100 mSv/h.
- TOTAL (cumulative) DOSE EQUIVALENT H*(10) RANGE – 100 nSv to 1 Sv.
- DOSE UPDATE RATE – 3–10 s; user selectable.

BATTERY
- TYPE – Two-cell rechargeable Li-ion battery.
- CAPACITY – 2.2 AH.
- OPERATING TIME – Approximately 9 hours while acquiring with battery at full charge (frequent use of backlight reduces battery life).
- CHARGE TIME – Approximately 3 hours.

EXTERNAL POWER
- DC POWER/CHARGER – 12 V dc output, 2 A universal ac/dc adapter input with IEC 320 power connector.

PHYSICAL
- SIZE – InSpector alone: 19.0 x 16.5 x 6.4 cm (7.5 x 6.5 x 2.5 in.); with an IPRON-N probe: 25.4 x 24.1 x 14.0 cm (10 x 9.5 x 5.5 in.).
- WEIGHT – With batteries and an IPROS-2 probe: <2.4 kg (5 lb 3 oz); with batteries, and both an IPROS-2 probe and an IPRON-N probe: 3.5 kg (7 lb 11.5 oz).

ENVIRONMENTAL
- OPERATING TEMPERATURE – Range: –10 to +50 °C, ambient.
- HUMIDITY – Up to 80%, non-condensing. Meets the environmental conditions specified by EN 61010, Installation Category I, Pollution Degree 2.
- SHOCK – Shock proof design (not including the detector). Can withstand a drop from 1 m onto concrete.
- PROTECTION RATING – Meets IP 54 specifications (complete dust and splash/low pressure spray protection).
- DIRECTIVES – Meets all relevant EU safety, RFI and EMI directives (CE compliance).

*Stabilized Scintillation Detector. U.S. Patent Numbers 7,005,646 B1 and 7,049,598.

APPENDIX 5

CANBERRA INSPECTOR 1000 DIGITAL HAND-HELD MULTICHANNEL ANALYZER

InSpector 1000 Digital Hand-Held Multichannel Analyzer

ORDERING INFORMATION

IN1KN-1 – InSpector 1000 and IPRON-1 1.5" x 1.5" NaI Intelligent Probe.

IN1KS-3 – InSpector 1000 and IPROS-3 3" x 3" NaI Stabilized Intelligent Probe.

IN1KS-2 – InSpector 1000 and IPROS-2 2.0" x 2.0" NaI Stabilized Intelligent Probe.

IN1KL-1 – InSpector 1000 and IPROL-1 1.5" x 1.5" LaBr Stabilized Intelligent Probe.

- All include cables, charger, padded soft case, Model S504 Genie 2000 InSpector Basic Spectroscopy Software, utility software and a set of manuals.

IN1KN-1N – InSpector 1000 with IPRON-1 1.5" x 1.5" NaI Intelligent Probe, and Neutron Probe.

IN1KS-2N – InSpector 1000 with IPROS-2 2.0" x 2.0" NaI Stabilized Intelligent Probe, and Neutron Probe.

IN1KL-1N – InSpector 1000 with IPROL-1 1.5" x 1.5" LaBr Stabilized Intelligent Probe and Neutron Probe.

- All equipped with gamma probe, moderated ^{3}He probe, cables, charger, padded soft case, Model S504 Genie 2000 InSpector Basic Spectroscopy Software, utility software and set of manuals.

PROBES ONLY

IPRON-1 – 1.5" x 1.5" NaI Intelligent Probe.

IPROS-3 – 3" x 3" NaI Stabilized Intelligent Probe.

IPROS-2 – 2" x 2" NaI Stabilized Intelligent Probe.

IPROL-1 – 1.5" x 1.5" LaBr Stabilized Intelligent Probe.

- Included in the probe's housing are the PMT, the HVPS, the preamplifier and the communication interface.

IPRON-N – InSpector 1000 Neutron Probe (Moderated ^{3}He Tube).

- Included in the probe's housing are the ^{3}He tube, the HVPS and the communication board. The associated InSpector 1000 must have V1.1 or greater software installed. Backward compatible with existing InSpector 1000's.

ACCESSORIES

IN1KCAR – InSpector 1000 Car Adapter/Charger.

IN1KHCA – Hard Case for the InSpector 1000 Digital Hand-Held MCA.

IPRONC – Short Probe Cable (8 in.) for the InSpector 1000.

IPRONL – 20 ft Probe Cable for the InSpector 1000.

IN1KBAT – Battery Pack for the InSpector 1000 Digital Hand-Held MCA.

ISXCLNA2 – ISOCS/LabSOCS™ Characterization for 2" x 2" NaI Detectors.

- For characterization of InSpector 1000 IPRON-2 detectors.
- Accuracy estimated at 15–25%, 1 standard deviation.
- Requires S573 ISOCS or S574 LabSOCS calibration software.

ISXCLNA3 – ISOCS/LabSOCS Characterization for 3" x 3" NaI Detectors.

- For characterization of InSpector 1000 IPRON-3 detectors.
- Accuracy estimated at 10–20%, 1 standard deviation.
- Requires S573 ISOCS or S574 LabSOCS calibration software.

ISXCLNS2 – ISOCS/LabSOCS characterization for 2" x 2" NaI Stabilized Detectors.

- For characterization of InSpector 1000 IPROS-2 probe.
- Accuracy estimated at 15-25%, 1 standard deviation.
- Requires S573 ISOCS or S574 LabSOCS calibration software.

ISXCLLA1 – ISOCS/LabSOCS characterization for 1.5" x 1.5" LaBr Stabilized Detectors.

- For characterization of InSpector 1000 IPROL-1 probe.
- Accuracy estimated at 15-25%, 1 standard deviation.
- Requires S573 ISOCS or S574 LabSOCS calibration software.

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APPENDIX 6

TELETECTOR 6112M DOSE RATE METER



APPENDIX 6

TELETECTOR 6112M DOSE RATE METER

SPECIFICATIONS

Low range detector (energy compensated)	beta gamma end window tube ZP1400 or equivalent, effective length 40 mm, sensitivity approx. 5800 pulses per µSv
High range detector (energy compensated)	gamma tube ZP1300 or equivalent, effective length 8 mm, sensitivity approx. 100 pulses per µSv
Detector selection	automatically with hysteresis: > 10 mSv/h: goes to high range < 7 mSv/h: returns to low range manual selection of detector for radiological check provided
Measuring quantity	6112M: Js (R), Hx (Sv), Ka (Gy) 6112M/H: H*(10) (Sv)
Dose rate range	analogue: ZP1400: 0.1 µSv/h to 10 mSv/h, ZP1300: 7 mSv/h to 10 Sv/h, digital: 0.01 µSv/h to 10 Sv/h
Instrumental background	< 20 nSv/h (low range tube)
Linearity of dose rate measurement	±8% (calibration with Cs-137)
Dose range	10 nSv to 10 Sv (beyond 10 Sv up to 100 Sv flashing)
Energy range and angular range for photon radiation	6112M: 65 keV to 1.3 MeV (response within ±30% referred to Cs-137) ±45° (respon se within ±20% referred to response in preferential direction of 0° at the same energy) 6112M/H: 45 keV to 1.3 MeV and ±45° (at any energy and direction within these ranges, response is within ±40% referred to response at Cs-137 at 0°)
Detection of beta radiation	through end window tube ZP1400 behind the face of the tube housing (see photo on the front page). The protective cap must be removed. The beta rejection factor of the protective cap is in the order of 100.
Beta window	tube window: 2 - 3 mg/cm², protective foil: 6 mg/cm², sensitive area: approx. 60 mm²
Relative response to beta dose rate H'(0.07, 0°)	without protective cap: Pm-147 (E ~ 60 keV): 3.5%, Kr-85 (E ~ 240 keV): 4.4%, Sr-90/Y-90 (E ~ 800 keV): 22%
Display	fully graphic LCD (128 x 128 pixels) transflective, LED back-light
Range selection	automatically
Dose rate warning	acoustically and visually
Overload	dose rates above the full range (10 Sv/h) are indicated as over-range up to dose rates of 100 Sv/h; after overload the Teletector is still functioning
Detection of single pulses	acoustically, speaker may be replaced for decontamination
Speaker loudness level	> 90 dB(A) in a 30 cm distance
Climatic conditions	temperature range: -20°C to +60°C humidity range: 0 to 95% within the specified temperature range; change of response ±6%
Storage temperature	-40°C to +85°C
Atmospheric pressure	nominal range: 60 to 130 kPa (600 to 1300 mbar)
Geotropism	none (no change of response as a result of gravitational effects)
Teletector housing	aluminium die-cast
Telescope	stainless steel
Protection class	IP 67 according to DIN 40050 *if telescope completely retracted and protective cap applied*
Supply voltage range and power supply	4.0 to 7.0 Volt four C cells (LR14, AM2)
Battery life	approximately 100 hours with alkaline batteries (without illumination and speaker)
Dimensions	length: 970 mm (telescope retracted), 4170 mm (telescope extended), width 130 mm, max. height approx. 90 mm
Weight	2.7 kg (without batteries), 3.0 kg (including batteries)
CE compatible according to	EN 50 082-2:1995, EN 55 011:1998, ENV 50 140:1993, EN 61 000-4-2:1995

LAURUS SYSTEMS

LAURUS Systems, Inc. - Ph: 410-465-5558 - Fax: 410-465-5257 - www.LaurusSystems.com

APPENDIX 7

SmartION DATA LOGGING ION CHAMBER

Product Specifications

The SmartION is an advanced microcomputer-based instrument for the measurement of Gamma, Beta and X-ray radiation. It provides functions previously not available in meters of this type, including data logging, alarm, remote calibration and security features. Operation is simple, reliable and maintenance-free, and the instrument is housed in a robust case.

Mini SmartION Series

Data Logging Ion Chamber





- Sensitive ion chamber
- Electrometer with minimal leakage and drift
- Measurement in µSv h^{-1}, µGy $^{-1}$ and mR $^{-1}$
- Data logging by random or pre-ordered routes
- Audible alarm preset
- Large character LCD digital and analog display
- Local/ remote calibration and interlocks
- Handle-mounted function keys facilitate one-handed operation
- Tested against the requirements of standard IEC 60846
- Complies with SDI communication protocol

The instrument's ion chamber has a capacity of 450 cm³. Measurement in mixed beta/gamma fields is simplified by the moveable beta shield, which is 550 mg cm^{-2} plastic. The Ambient Dose Equivalent [Sv $^{-1}$] version is corrected for a response of H' (0.07) from 10 keV with the shield open and H*(10) from 22 keV with it shut. The 7 mg cm^{-2} window density permits accurate measurement of beta dose rates in the energy (Emax) range of 150 keV to 2.5 MeV. The chamber is vented to the air volume within the instrument and thence to atmosphere.

The electrometer is based upon a low-leakage MOSFET operational amplifier. Special guard-ring techniques and packaging pin-out keep offset leakage to a minimum. Careful matching and circuit design minimize zero drift with temperature. Zero adjustment is established by microcomputer control: pressing the Zero button engages a precision digital servo loop adjustment.

There are three SmartION models: the basic version is the 2100; the 2120 has an integrating dose facility; the 2140 has in integrated barcode reader. Each of these models is available to measure the quantities ambient dose equivalent rate (Sv), air kerma (Gy) and exposure (R). In each case the ion chamber is configured at the time of manufacture.

Dose rate data from random surveys can be stored in up to 400 storage locations. Ordered location surveys are organized by downloading 4-character locations before issue from a PC file (ASCII) through a serial cable which is supplied with the PC software option. The memory inside SmartION is non-volatile through switch-off, as is the internal clock.

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APPENDIX 7

SmartION DATA LOGGING ION CHAMBER

System Specifications

A dose rate alarm is provided which may be set from 10% of the lowest range, through 6.5 decades to 100% of the highest range. The dose rate is displayed in characters 1 cm (0.4") high on a custom-made liquid crystal display, with the appropriate units and location code, if any. The wide simulated analogue scale has 50 segments clearly indicating dose rate trends. Status indications show battery condition, ion chamber bias and beta shield position.

The wipe-clean membrane keys offer easy access to the wide-range of functions, some can be locked-out using the PC remote interface to protect calibration and alarm settings, route codes and backlight timer from unauthorized tampering.

Local calibration is provided for use with beta sources. Up-Down keys obviate an insecure screwdriver adjustment, while an RS232 link to a remote PC allows the monitor to be safely tested with high dose rate gamma radiation sources. The supervised PC link also enables the calibration to lock out of operator interface, adjust or lock the alarm, clock adjustment, a battery-saving time-out and access to certain engineering adjustments.

The energy-conscious design uses two 'D' size alkaline cells, with chamber bias and clock back-up using very long-life Lithium cells. The case is molded in hard-wearing wipe-clean ABS/polycarbonate with easy external access to a separate battery compartment.

If the expected dose rate is greater than the current displayed range, the user can set the meter on the required range to reduce the autoranging time. Any of the five ranges can be selected. This feature is useful in situations where the range-changing delay could be hazardous, e.g. where high intensity, collimated beams are encountered.

The Mini SmartION 2120 model includes two integrating (dose) ranges: 0 to 50 µSv and 0 to 500 µSv. This version is suitable for measuring radiation from linear accelerators and pulsed x-ray systems. In addition, the Mini SmartION 2140 model has an integral bar-code reader. By placing bar-code placards at analysis points, the dose-rate encountered can automatically be registered in memory against the actual location. Software can be provided for interfacing to Windows™ based dosimetry and plant management systems.

Characteristics

Ion Chamber vented to atmosphere.
Walls of resin bonded paper:
250 mg cm^{-2}, windows of aluminized polyester with a total density of 7 mg cm^{-2}. Collecting potential 45 V.

Measurement quantity and units:
Three versions of each of 2100, 2120 and 2140 denoted by the suffix S/G/R:

S	$H^*(10)$ and $H'(0.07)$	Sv
G	Air Kerma	Gy
R	Exposure	R

Range of measurement: Dose Rate: 0 to 500 mSv h^{-1} (0 to 50 R/h) in 5 autoranges:
- 0 to 50 µSv h^{-1} (0 to 5 mR/h)
- 0 to 500 µSv h^{-1} (0 to 50 mR/h)
- 0 to 5 mSv h^{-1} (0 to 500 mR/h)
- 0 to 50 mSv h^{-1} (0 to 5 R/h)
- 0 to 500 mSv h^{-1} (0 to 50 R/h)

Integrated Dose (2120 only):
- 0 to 50 µSv (0 to 5 mR)
- 0 to 500 µSv (0 to 50 mR)

2120 Only, integrating: Effect of Dose rate on aggregated dose accuracy: -3% @ 2 mSvh^{-1} (200 mR/h), -10% @ 200 mSv h^{-1} (20 R/h), -20% @ 500 mSv h^{-1} (50 R/h)

Effective range: 1 µSv h^{-1} to 500 mSv h^{-1} (100 µR/h to 50 R/h)

Relative intrinsic error: ±15%
(to conventionally true value):

Linearity: ±15% (reference radiation ^{137}Cs)

Statistical fluctuations:
- 2.9 µSv h^{-1} (0.29 mR/h) 4.5%
- 40 µSv h^{-1} (4.0 mR/h) 1%

Response time:

- 0 to 45 µSv h^{-1} (0 to 4.5 mR/h)	6 s
- 0 to 450 µSv h^{-1} (0 to 45 mR/h)	6 s
- 0 to 450 mSv h^{-1} (0 to 45 R/h)	1 s

Energy dependence:

	Closed ($H^*(10)$)	Open $H'(0.07)$
5.9	-	0.79
16	1.08	1.00
33	1.04	0.99
65 (^{241}Am)	0.9	0.82
248	0.98	0.83
1250 (^{60}Co)	0.98	-

$H'(0.07)$ beta response:
^{90}Sr/^{90}Y Emax 2.27 MeV 1.01
^{204}Tl Emax 0.77 MeV 0.62
^{147}Pm Emax 0.23 MeV 0.82

Overload: Recovery from 12 Sv h^{-1} (1200 R/h) to background levels < 3 mins.

Geotropism: ±5% for 90° change in meter orientation

Warm-up time: 1 minute

Ambient temperature range: -10 to 50 °C (14 to 122 °F)

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