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ISOE INFORMATION SHEET

North American Technical Center
Information System on Occupational Exposure

NATC Analysis of Teledosimetry Data from Multiple PWR Unit Outage CRUD Bursts

NATC ISOE Information Sheet No. 2010-14

The NATC ISOE Information Sheet No. 2010-14 provides a technical analysis of teledosimetry results from three PWR shutdown CRUD Bursts using electronic dosimeters in the same locations at the Letdown Lines, RHR Heat Exchangers (contact dose rates) and RHR Pumps. Results of the study show a significant reduction in colloids (Co-60) over 3 sequential outages. The NATC Analysis was performed on a PWR unit employing specialty resins and engineering solution from Los Alamos National Laboratory and an engineering firm.

Outage results were reported at the 2010 North American ISOE ALARA Symposium in Ft. Lauderdale, Fl. The PWR Unit achieved a US refueling outage dose record for a 4 Loop US Ice Condenser PWR of 34 person.rem (340 person.mSv). Westinghouse PWR Ice condensers have very small containment buildings which attracted attention of several RPMs. Benchmarking site visits from Duke Power, Beaver Valley and Exelon Fleet have resulted in additional US PWR units to closely evaluate and/or implement similar engineered solution for Co-60 removal. Cook followed the lead of Summer and Turkey Point who had started the engineered solution over 10 years previously. (Cook is on its 8th year of use.)

Next Refueling Outage:
The outage dose goal for Cook Unit 2 in October 2010 is 27 person.rem (270 person.mSv). Cook RP personnel participated in many European and Asian ISOE benchmarking visits and ISOE Symposia which favorably helped the ALARA staff and Site Managers achieve this success. The international cooperation on ISOE benchmarking site visits and ISOE symposia paid high technical dividends to referenced nuclear utility.

Acknowledgements:
The comparison study was prepared by Anastasios Deligiannis, NATC Graduate Engineeing student. He has a Mechnical Engineering Degree from Athens, Greece and a MS degree from the University of Illinois. He is currently working on his PhD degree at Idaho State under the NATC ISOE research studies programs.

Faculty Research Advisors include Dr. Barclay Jones, Professor of Nuclear Engineering. With 40 years of research on CRUD on nuclear fuel cladding and fossil plant boilers (EPRI sponsored) and Dr. James Stubbins, Head, Department of Nuclear, Plasma & Radiological Engineering, University of Illinois. Dr. Stubbins is a materials expert conducting original industry research on Inconel 690.

COMPARATIVE ANALYSIS OF SOURCE TERM REMOVAL AT COOK NUCLEAR PLANT

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Abstract:

Research was conducted on the effectiveness of colloid mitigation at the Cook Nuclear Plant located in Bridgman, Michigan. Specialty resin was employed to remove Cobalt-60 CRUD and other contaminates from the primary coolant piping and fuel cladding. Cook is a two unit Ice Condenser Pressurized Water Reactor (Westinghouse). Unit 1 has completed 22 cycles and refueling outages and Unit 2 has completed 18 cycles and refueling outages.

Specialty resin was utilitized during the Unit 2 shutdown chemistry protocol to capture and remove Co-60 from the reactor coolant. A CRUD burst was achieved during the first 48 hours of shutdown with the addition of peroxide to achieve significant CRUD removal from the coolant. The study monitored the dose rates on selected in-plant primary loop piping to provide a comprehensive database of the dose rate changes during the shutdown and Crud burst regimes. The database collected represents one of the largest data analysis undertaken for multiple PWR unit outages.

Technical comparisons are made of the cycle 16, 17 and 18 telemetry data to demonstrate the improvements in source term removal. Significant source term improvement was observed during the Unit 2, Cycle 18 refueling outage due to successive uses for the specialty resin after full core replacement after 6 cycles, major high source term piping removal in lower containment (RTD bypass line removal) and use of specialty resin on unit startup to remove nickel.

Results demonstrate how Cook Unit 2 achieved the lowest record refueling outage dose of 34 person.rem for 4 loop, Westinghouse PWR Ice Condenser. The similar PWR outage dose is in the range of 70-90 person.rem.

The study provides recommendations for future analysis to better understand the radiochemistry phenomena that are working together to achieve this significant reduction in refueling outage doses.

TABLE OF CONTENTS

LIST OF FIGURES

CHAPTER 1: INTRODUCTION

Nuclear plants are constructed to high engineering standards, operated by highly trained and USNRC licensed operators and independently assessed by government regulatory authorities and industry organizations. The mandate of error-free performance is essential for safety, efficiency and public acceptance of nuclear plant technology.

Throughout the world, occupational exposures at nuclear power plants have steadily decreased since the early 1990s. Regulatory pressures, technological advances, improved plant designs and operational procedures, As Low As Reasonably Achievable (ALARA) culture and information exchange have contributed to this downward trend.

The objective of this research is to examine the effectiveness of source term removal via colloid mitigation at the Cook Nuclear Plant. The goal of any source term reduction campaign is to reduce occupational doses to ALARA. Developing specific source term reduction strategies tailored to address a plant's unique design, system operation limitations and metallurgical characteristics are critical to reduce the production, activation and transport of radioactive species responsible for in-plant radiation fields. Finally, sharing the information from each plant's source term reduction successes and lessons learned is an important good industry practice to achieve continuous improvement as each plant and for the US fleet of BWRs and PWRs.

The Cook Nuclear Plant planned a refueling outage for Unit 2 at the end of the Unit's eighteenth fuel cycle (U2C18), which commenced on March 25, 2009, and was completed on May 01, 2009 (38 days). Specialty resin was utilized during the Unit 2 shutdown chemistry protocol to capture and remove the source term from the reactor coolant. During this outage, telemetry data including real-time dose rates, at specific locations of the power plant, were collected. In this thesis, the pump starts/stops dose rates data were analyzed and compared with chemistry data and the operational events. The study provided conclusions on the effectiveness of the source term removal practices that were being implemented at Cook Nuclear Plant during cycle 18 and the previous 6 cycles.

In the study, real-time dose rates data from the two previous Unit 2 outages (U2C16 and U2C17) were compared to the U2C18 data. This comparison documented scientific results that show the effectiveness of the ongoing ALARA initiates at the Cook Units.

Chapter 2 provides the background information, which is needed for the understanding of the later chapters of the thesis. Chapter 3 discusses the data collection methodology and the technical specifications of the specialty resin that was employed. Data analysis results are provided in Chapter 4. Chapter 4 also discusses the comparison of the data from the three referred outages. Conclusions, summary and future research areas are presented in Chapter 5. In Appendix A, chemical analysis of reactor CRUD smears is given. A sample of the raw data collected and used can be found in Appendix

B. In Appendix C, the Electric Power Research Institute (EPRI) PWR standard radiation measurements are provided. EPRI provides specific instructions on how measurements are taken and recorded one week after unit shutdown. The standard locations on the steam generators are repeated during each outage at most PWRs. Finally, all the raw data of the dose rates are given in Appendix D, which are given in the supplementary appendix file named Deligiannis_thesis_data.zip.

CHAPTER 2: BACKGROUND INFORMATION

2.1 Cook Nuclear Plant

The Cook Nuclear Plant is located in the state of Michigan on 2.63×10^6 m^2 (650 acres) of property along the southeastern shoreline of Lake Michigan. The site consists of two, Westinghouse four-loop pressurized water reactors with ice condenser containments. Reactor Unit 1 is rated at 1016 MWe (3304 MWt) and Unit 2 is rated at 1077 MWe (3468 MWt). Unit 1 and Unit 2 commercial operation began in August 1975 and July 1978, respectively (U.S. NRC 2005).

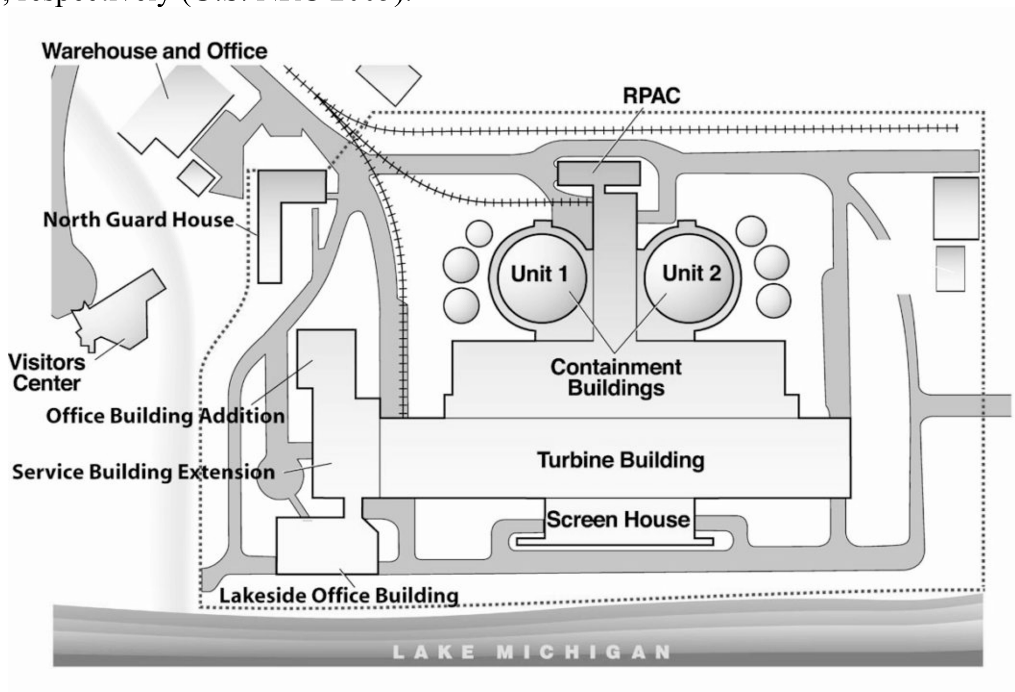


Figure 1: Map of Cook Nuclear Plant

A cross section of the containment of this type of PWRs can be seen in Figure 2.

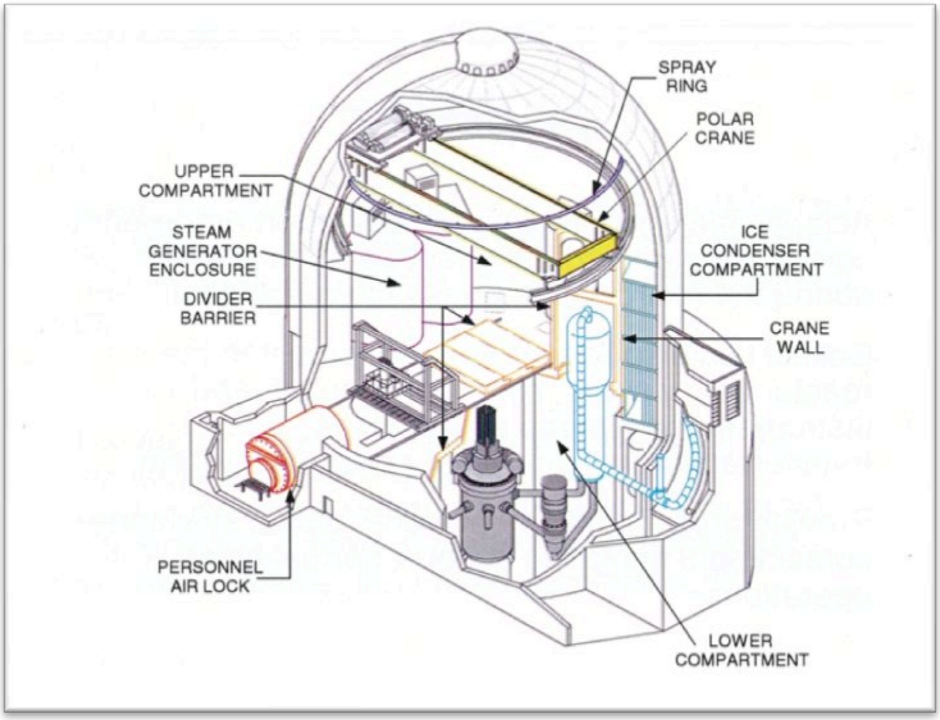


Figure 2: Cross section of a Westinghouse PWR, ice condenser

Unit 1 has completed 22 cycles and refueling outages and Unit 2 has completed 18 cycles and refueling outages.

2.2 Refuel outage

US commercial nuclear power plants are generally base load units. They are being operated continuously on the grid generating electricity unless there are unexpected component repair. The normal PWR operating cycle is 18 months before a shutdown is required to rotate and change the fuel assemblies. That means that the unit will undergo a shutdown and cool down process in preparation for core alterations and plant maintenance. By changing, we mean that a number of fuel assemblies will be removed and new assemblies inserted into the core. Also, the remaining fuel assemblies will be rotated in the core in a way to optimize fuel burnup when the plant is returned to power. During the outage, there are many maintenance activities that are being scheduled concurrent with reactor vessel refueling. Those include the maintenance of many components of the power plant systems as well as inspections and even corrective actions on other components too.

2.3 Source term

In a nuclear power plant, the main sources of occupational exposures are from activation products (e.g. Co-58, Co-60, Mn-54, Cr-51) arising from the structural material of the nuclear reactor. The activation products constitute what is called the source term. In order to develop appropriate exposure reduction measures for these sources, it is important to understand their characteristics. Source term characterization includes the radionuclides and their energies, the amount of radioactivity present and its spatial distribution, the dose rate distribution etc. Equipment employed to characterize the source term must be calibrated and staged for use in planned and forced outages. The simulation of the dose rate distribution based on historic measured or estimated values is also useful for work optimization during pre-job mockup training exercises.

2.4 CRUD

CRUD is an acronym for "Chalk River Unidentified Deposit". In the early years of nuclear reactor prototype development and testing, it was observed that unanticipated deposits were forming on nuclear fuel during reactor operation at the Chalk River reactor in Ontario, Canada. Not knowing its origin or composition, it was initially referred to as the "Chalk River Unidentified Deposit" - CRUD. It is known now, that the Chalk River deposit consisted of corrosion products from system materials. As it turned out, corrosion products in the reactor system preferentially deposit on fuel surfaces due to their high temperatures. The early industry coined the acronym CRUD and is now common to refer to any highly radioactive corrosion product inventory (typically fuel deposits) as CRUD. It follows that CRUD is typically a mixture of system metals and metal oxides that have become (neutron) activated to a radioactive species. CRUD is therefore a mixture of iron, nickel, chrome and other trace elements along with their corresponding activated forms (Co-58, Co-60, Fe-55, Fe-59, Cr-51 etc.) [6].

In practice, if at any given time a liter of the coolant is taken as a sample, and passed through filters, insoluble material remaining on the filter will typically be referred to as CRUD.

Cook technical staff recognized the need to characterize the chemical composition and chemical forms of contemporary primary system CRUD samples. Kinetrics was provided with a sample of CRUD from the Cook steam generator bowl. The experimental results in Kinetrics Laboratory analysis report is provided in appendix A.

During power operation, ongoing general corrosion of system materials (metal alloys containing primarily iron, nickel, chrome, zirconium, cobalt and other trace metals) result in the slow release of metals and metal oxides into the circulating coolant. Much of this inventory becomes deposited on fuel cladding surfaces as a result of the high nuclear fuel operating temperature. Neutron activation of these metals and metal oxides results in the production of a highly radioactive core deposit inventory. A portion of this inventory leaves the fuel surface and re-deposits on system surfaces. This process over time results in radiation fields in areas that are accessed by plant workers during maintenance activities. A small fraction of the remaining core activated corrosion product inventory is re-solubilized during the shutdown [5].

Plant chemists and health physicists develop chemistry shutdown protocols, to maintain in-plant doses ALARA. They control the timing of this CRUD burst during unit shutdowns such that extra personnel exposures do not occur. Extra time is taken in refuel outage schedules to allow for the controlled cleanup (removal) of this highly radioactive material.

2.5 Cobalt in PWRs

After the first few full-power years, Co-60 becomes the dominant isotope of concern. The source of Co-60 is neutron activation within the reactor core of the stable isotope Co-59 present as an impurity in the range of 0.002 to 0.2 percent in stainless steel, zircalloy, and inconel materials employed in the fabrication of components in the reactor coolant systems (RCS). In addition, component surfaces subjected to wear are typically hardfaced with cobalt-based alloys, which are composed of approximately 60 percent Co-59. Wear and corrosion of these surfaces and corrosion of RCS components release cobalt and other corrosion products into the coolant. Redeposition on and erosion from the nuclear fuel surfaces, results in the release of the activated isotope, Co-60, back to the coolant with subsequent deposition on the primary coolant piping, valves and pumps [13].

Evaluation of Co-60 sources depends on the identification of the major Co-59 contributors. Factors that can contribute to the uncertainty in this identification are the relative areas and cobalt corrosion release rates of the RCS components and wear rates of hardfaced surfaces.One of the most important factors governing the input of cobalt into a plant is the corrosion release of the material and the chemical constituents of the material, specifically cobalt, under reactor operating pressure, temperature and flow. The amount of cobalt input into the primary system of a plant due to wear of high cobalt alloys (stellite) can be another significant factor affecting the total cobalt input into the system.

Plant components containing a significant amount of stellite include:

- Primary coolant system valves
- Fuel assemblies
- Main coolant pumps
- Control rod drive mechanisms
- Reactor vessel internals

2.6 CRUD burst

A "CRUD burst" is again an industry term used to describe the release and transport of a previously stationary corrosion product inventory in a fluid system. Typically it refers to the release of activated corrosion product inventories from fuel assembly surfaces. A "CRUD burst" manifests itself in increased reactor coolant activity and high dose rates. The phrase is typically used during shutdowns to describe a process of intentionally forcing the release of core corrosion products (by chemical means) at a set time in the outage schedule. This is achieved through hydrogen peroxide additions (8-10 litres) to the RCS which create oxidizing conditions and dramatically increases the solubility of corrosion product deposits. Every effort is made to control the timing of the release such that all station workers are aware of the event and personnel exposure controls are in place. The process would occur naturally when the reactor coolant system is opened to atmosphere during refueling activities when dissolved oxygen from air reaches the core deposit surfaces. For this reason the release is chemically induced prior to refueling activities with hydrogen peroxide additions when the radiological controls are in place and the reactor coolant system cleanup can be most effective [7].

Plant chemists and health physicists carefully control the CRUD burst event such that there is no detrimental impact on the current outage and potentially can be useful in reducing future dose rates. A forced oxidation (technical term for refueling CRUD burst) is used as a tool to potentially reduce corrosion product inventories that have the potential to contribute to ex-core corrosion film dose rates in the future. A good industry practice of the plant chemistry organization, is to achieve a shutdown chemistry protocol that minimizes particulate inventories and maximize the coolant solubility of the corrosion product inventory. The overall objective is to remove it from the reactor coolant system. Particulate inventories have the tendency to "plate out" due to their zeta potential and become unavailable to removal via the letdown purification system. They park in areas of system piping (CRUD traps) that become "hot spots" (high dose rate locations) and personnel radiation hazards. This being the case, chemistry personnel should be watchful of the conditions that reduce corrosion product solubility and increase particulate populations. The forced oxidation (CRUD burst) presents itself as an opportunity to reduce activated corrosion product inventories before they are incorporated in ex-core corrosion films where they contribute to radworker dose [5].

2.7 Water chemistry control

Water chemistry is an important factor to achieve chemistry regimes that favour continued reduction in source terms, including the prevention of CRUD adherence on the surface of devices and piping. This involves an optimization of chemical conditions during power operation, as well as during transients, start-up and shutdown.

Of major importance is the pH of the water, since higher pH operation can bring about exposure reduction effects. The pH is controlled by adding lithium as a pH adjuster. Note that boron concentration is high at the beginning of the cycle, so the applicability of high lithium operation has been investigated as a means to pH optimization through the entire operational cycle. Also, application of enriched B-10 as a chemical shim control material has been studied with respect to decreasing boron concentration in reactor water [10].

The optimization of dissolved hydrogen concentration in the water is also important. Hydrogen is added to the primary coolant to prevent stress corrosion cracking (SCC) due to dissolved oxygen by inhibiting oxygen generation arising from radiolysis of the primary coolant. The chemical composition of CRUD is also considered controllable through appropriate control of the dissolved hydrogen concentration.

The control of iron concentration in reactor feed water is important from the perspective of reactor fuel integrity. It is also important from the perspective of exposure reduction and efforts to reduce iron concentration have included: the injection of oxygen to prevent the corrosion of the feed water system piping; the installation of condensate pre-filters to remove the iron contained in the condensate; and the improvement of the condensate demineraliser resin. The presence of elemental iron in the RCS is an expected and normal condition in any light water reactor. The slow corrosion of the reactor components and piping contribute to this small inventory of iron. The chemical and volume control system, residual heat removal, and emergency cooling systems will also contribute to this inventory during the course of a fuel cycle. The iron present in the reactor coolant system during normal operating pressure and temperature is deposited on the hot fuel rods and is incorporated into the CRUD layer that is formed on the fuel rod. This CRUD layer contains many other elements including iron, nickel, calcium, magnesium, and various radioisotopes such as Cr-51, Co-58, and Co-60 [5].

When the temperature of the reactor coolant system is lowered to less than 205°C some of the iron located in the CRUD layer will become soluble and move throughout the system. When the iron becomes soluble it also breaks down the structure of the CRUD layer and allows other species, which may be insoluble and of a particulate form, to be released into the coolant. These particulate species include the Cr-51, Co-58, Co-60, and insoluble material containing iron and nickel. As this material is circulated throughout the RCS it has a tendency to plate out on the relatively cooler surfaces of the RCS piping and the steam generator tube sheets, bowls, and tubes. If the RCS temperature is raised again to normal operating temperatures, which could occur during a mid cycle outage, the iron will rapidly plate out. This can lead to higher than expected contamination levels in the steam generators if maintenance is performed shortly after an event of this type. During a normal refueling shutdown the temperature continues to decrease rapidly through the range of concern and the amount of material deposited on RCS surfaces is minimized [6].

2.8 Reactor Coolant Cleanup System

A major objective of the plant Radiation Protection (RP) program is to effectively capture and remove cobalt in order to ensure occupational exposures are ALARA. The PWR reactor coolant cleanup system is designed to capture and remove cobalt from the primary coolant.

The basic options for liquid cleanup are: filtration, evaporation, ion exchange, reverse osmosis and holdup. All but the last one are widely used in the nuclear industry because if properly used they can concentrate large inventories of radioactive nuclides. They can concentrate high levels of radionuclide in the balance-of-plant. The Cook Nuclear Plant, effectively uses the ion exchange reactor coolant cleanup to achieve cobalt removal.

Demineralizers ("ion-exchangers") are used in liquid radwaste systems to remove dissolved ionic impurities from the liquid streams. The beds of resin beads or resin powder also act as rather efficient filters, but their unique characteristic is their ability to undergo ion-exchange to trap dissolved ionic impurities.

Ion-exchange resins (sometimes called "demineralizer resins") are generally small beads (16-50 mesh, 0.3-1.2 mm) of a permeable polymeric ("resin") material with the property of having a large number of ion-exchange points. Each of these exchange points can give up a loosely held ion in exchange for one offering itself from solution, dependent on equilibrium preferences [7].

There are two types of ion-exchange resins; anion resins and cation resins. Their names indicate the types of ions with which they can affect an exchange.

Fresh cation exchange resins begin their life with H+ ions added to their exchange points. Exposed to a solution of cations, they will exchange these H+ ions for the cations in solution in the following order of ascending preference: Na+, K+, Rb+, Cs+, Ba+, Mg++, Ca++, Sr++, Ba++, Fe++, Co++, Ni++, Cu++, Zn++. These preference express themselves in the form of equilibria of the concentrations of various cations on the resin versus their concentrations in solution. The value and order of affinities will vary between various specific resins [7].

Fresh anion exchange resins begin their life with OH- ions loosely bound at their exchange points. Their exchange affinities, in rising preference, are roughly; fluoride, iodate, bicarbonate, chloride, nitrite, nitrate, bisulfate, iodide. Ion-exchange resins are generally utilized in what is called a "deep bed" configuration. A deep-bed demineralizer is a tank in which the treated stream is passed through from 3 ft to 8 ft of ion exchange resin beads. These systems are normally operated at 50-110 gpm.

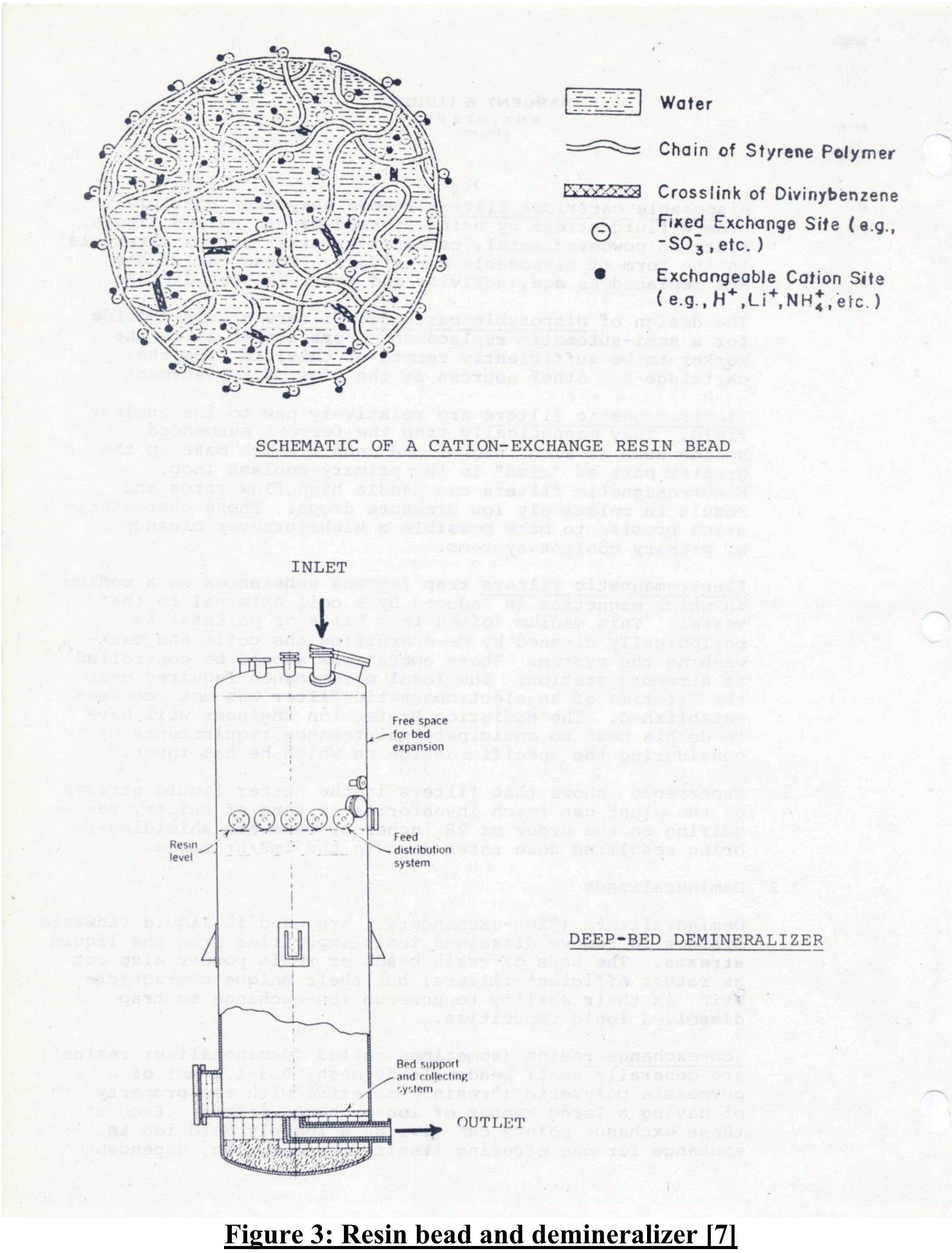


Figure 3: Resin bead and demineralizer [7]

Such a tank can contain all cation-exchange resins, all anion-exchange resins, or a mixture of the two (a mixed-bed demineralizer). During operation, deep-bed demineralizers are monitored for backpressure buildup and ionic breakthrough. (Backpressure indicates the accumulation of particulates which block flow in the filter. Ionic breakthrough indicates that the resin's exchange points are exhausted and that ionic impurities are now passing through). When predefined criteria of backpressure or breakthrough are exceeded, the resin beads can be either sliced from the demineralizer tank and discarded or they can be regenerated.

One further characteristic of ion-exchange resins which may be significant to the Radiation Protection Engineer is their temperature sensitivity which at times requires the placement of a heat exchanger upstream of a demineralizer. This heat exchanger will be a significant CRUD trap due to CRUD builds up on its large surface area of piping.

Experience shows that a single deep-bed demineralizer can concentrate a radioactive inventory to hundreds of curies and require on the order of 3 ft of concrete shielding to lower dose rates to the 1 mR/hr range.

2.9 Typical sequence of refuel outage events

The refuel outage shutdown and startup sequence can be almost infinitely expanded to encompass the intricate detail that is actually followed. In this section, a very condensed version of the process will be presented [6]:

- The plant begins a decrease in power [typically from full power (100%)] at a given rate perhaps 10%/hour.
- The reactor is tripped and the plant enters Mode 3 of plant operation. Reactor coolant system's temperature typically > 300 ^{o}C
- Initial containment building radiological surveys are performed.
- Initial operation department containment building walk-downs are preformed for initial reactor building conditions.
- Boration of the reactor coolant system is begun.
- Initial actions to create acid coolant conditions are performed.
- Dissolved hydrogen removal is begun if not already initiated during power operation.
- Reactor coolant cooldown is commenced.
- When temperature and pressure conditions allow, residual heat removal system is placed in service. (Typically < 175^{o}C)

- Reactor coolant system cooldown continues to < 95^{o}C.
- Preparations for reactor coolant oxidation (CRUD burst) are made.
- Coolant oxidation is performed and reactor coolant system cleanup is commenced.
- Coolant cleanup continues until endpoint concentrations are achieved.
- Partial RX cavity flooding is initiated. Reactor head is removed. Upper reactor internals are removed.
- Reactor cavity flooding is completed.
- Refueling is begun.

CHAPTER 3: EXPERIMENTAL SECTION

3.1 Telemetry with Electronic Dosimeters

US nuclear plants employee remote monitoring systems to provide a stronger radiological control barrier to avoid unplanned exposures to workers. The systems were installed in the 1990's and continually upgraded to meet in-plant radiological control needs. Remote monitoring systems are generally owned by the Radiation Protection Department and are composed of pan & tilt cameras, communication headsets and wireless electronic dosimeters (telemetry). Multiple in-plant work crews can be radiologically monitored from the central remote monitoring control panel by one trained RP technician. The system can be an effective ALARA tool because the workers are continuously monitored on a real time basis and can be coached to keep their doses ALARA.

At the Cook Nuclear Plant, an extensive Telemetry system is used during outages including Electronic Dosimeters (EDs). MGP DMC 2000 S Personnel Electronic Dosimeters with transmitters are used as the remote area monitors. The DMC 2000s are placed at the specified locations and connected to a Dosimeter Data Collection Unit (DDC-16) using the Data interface module (clamshell). One DDC-16 is located on the 609' elevation of the Auxiliary building and another inside containment. The Cook station has two radiological access control points. One is from the Turbine Building. The second from the dedicated access control building called the Radiation Protection Access Control (RPAC) Building. Both DDC-16 units send their signals to the RPAC monitoring station on fiber optical cable. The results are viewed and trended at the RPAC location. The telemetry ED data is also available for many Cook departments via the local network.

The electronic dosimeters were reporting a value of dose rate to the DDC every minute, but in order to be easier to plot and see the trend, the average 10-minute value was used.

The Cook Radiation Protection and Chemistry programs have developed a reproducible shutdown telemetry ED network that provides valuable radiological source term information to plant health physicists during reactor shutdown, CRUD Burst and outage duration. The telemetry ED network is important to monitor radiological parameters during the outage but also to compare the current outage dose rates at pre-selected locations with prior outage dose rates.

Auxiliary Building monitors were installed/set-up prior to the beginning of the Hydrogen Peroxide addition. The Monitoring locations were selected based on historical information and have proven to be areas reaching the highest radiation levels. These locations include:

1. Letdown Heat Exchanger
2. East Residual Heat Remover (RHR) Heat Exchanger (contact)
3. East RHR Heat Exchanger Room (general area)
4. West RHR Heat Exchanger (contact)
5. West RHR Heat Exchanger Room (general area)
6. Reactor Coolant Filter (contact)
7. East RHR Heat Exchanger Pump (contact)
8. East RHR Heat Exchanger Pump Room (general area)
9. West RHR Heat Exchanger Pump (contact)
10. West RHR Heat Exchanger Pump Room (general area)

EDs are located to provide both contact and general area dose rates. The contact EDs are approximately 1 cm from a given component. The general area EDs are positioned 30 centimeters away from the component. Contact and general area dose rates measurement terminology are used universally in the nuclear industry for RP survey instrument measurements.

The purpose of remote monitoring for U2C18 was to provide remote monitoring of work groups in lower and upper containment. Communications devices and remote equipment were used primarily for evolutions such as entries into the regeneration heat exchanger room, RCP Seal work, reactor cavity work and lower containment work.

In U2C16, new equipment was procured to enhance the ability to monitor workers dose remotely while observing work from the control monitor station in the RPAC. The new equipment installs quicker, provides full coverage of lower containment and the Aux Building, and is less expensive than the earlier system. A reduction on radiation protection technicians dose has been documented as well as radworker dose.

The following schematic diagrams document the positions of these EDs in the field. The data from all EDs was collected and saved, in order to create the charts that will be given in the next chapter. The raw data collected is provided in Appendix D.

In each of the next diagrams, the number that accompanies it mentions the elevation of the specific location from sea level.

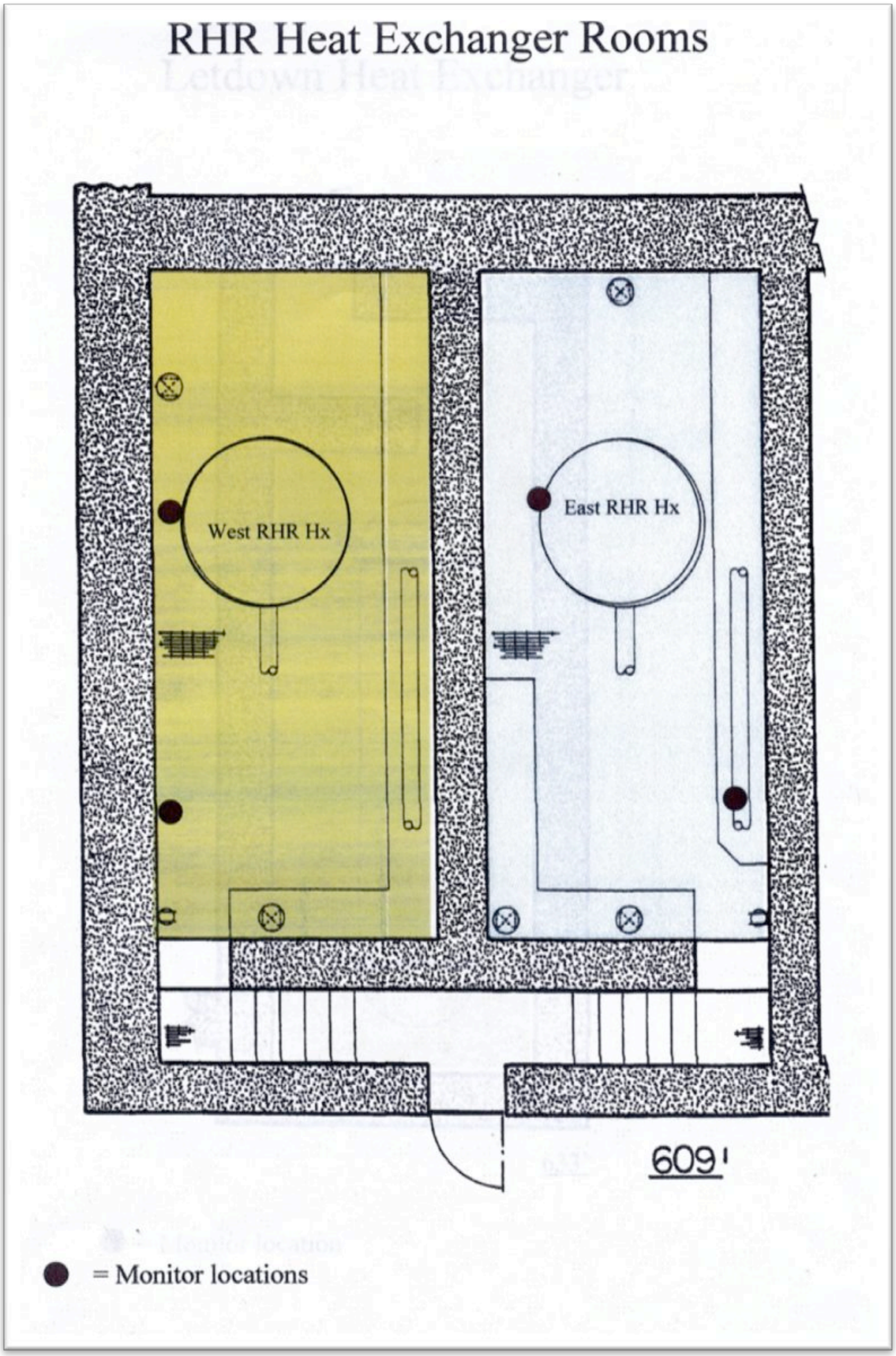


Figure 4: Locations of EDs in the RHR Heat exchanger rooms [8]

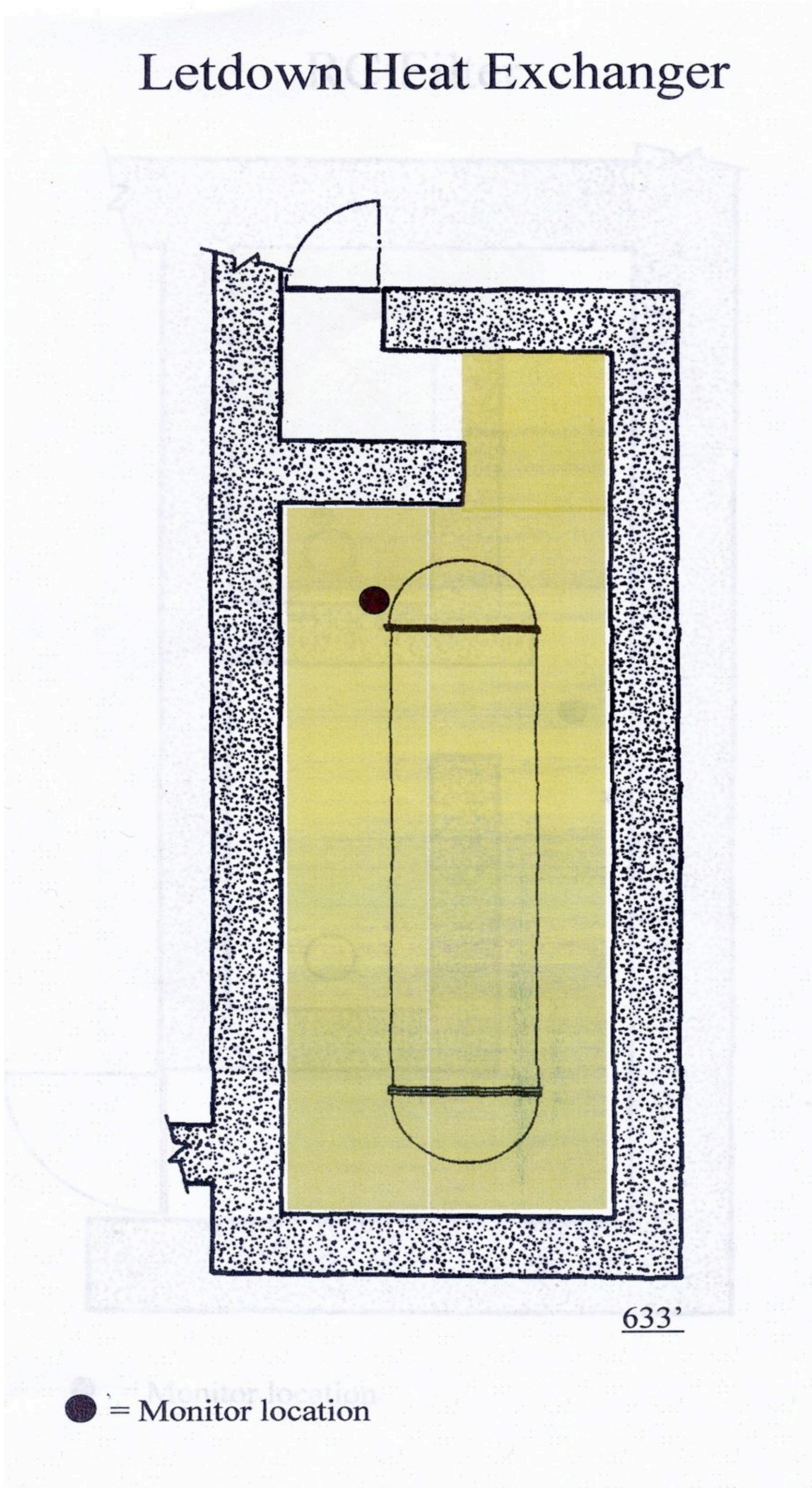
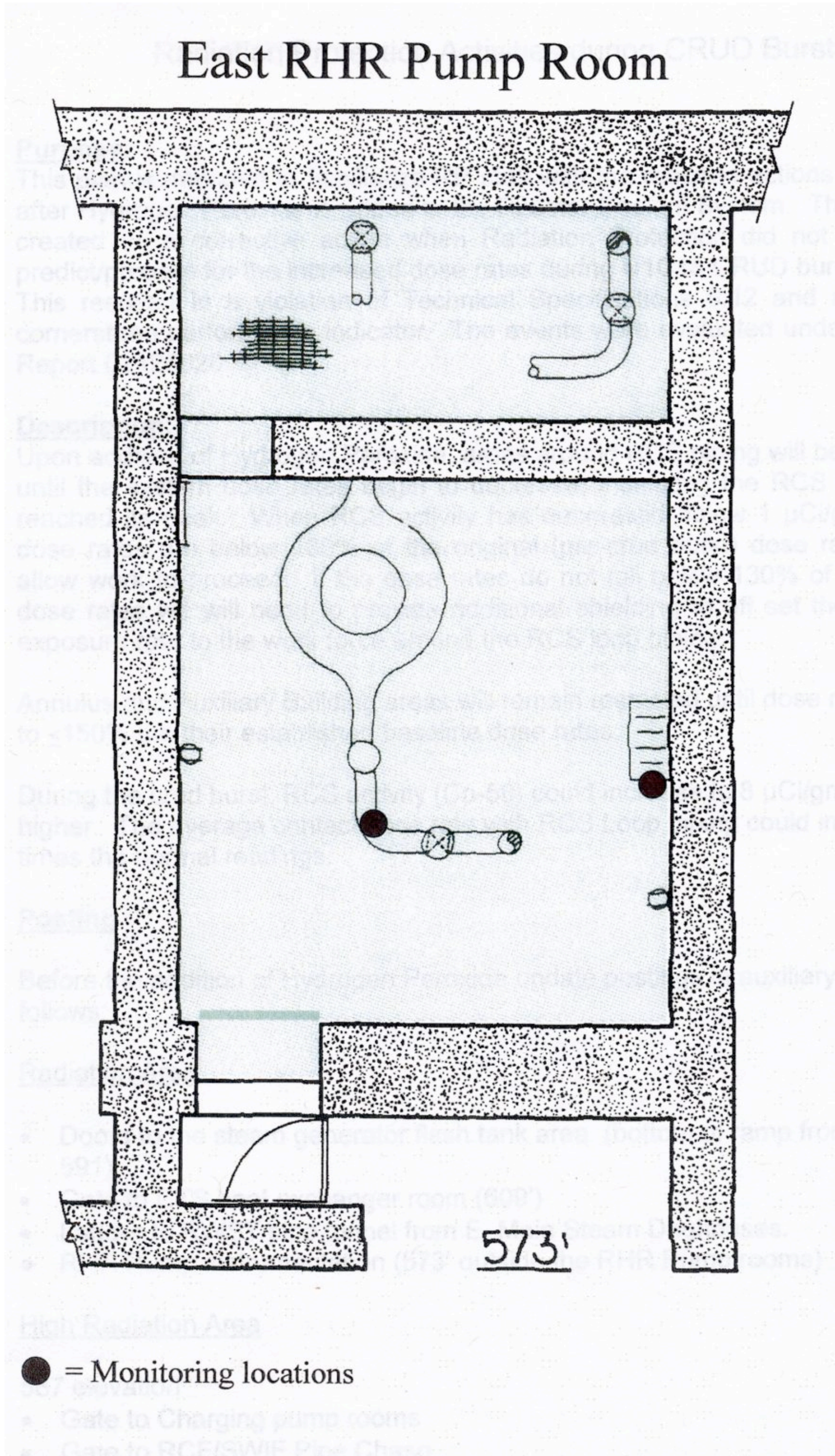


Figure 5: Locations of EDs in the Letdown Heat Exchanger [8]



<u>Figure 6: Locations of EDs in the East RHR pump room [8]</u>

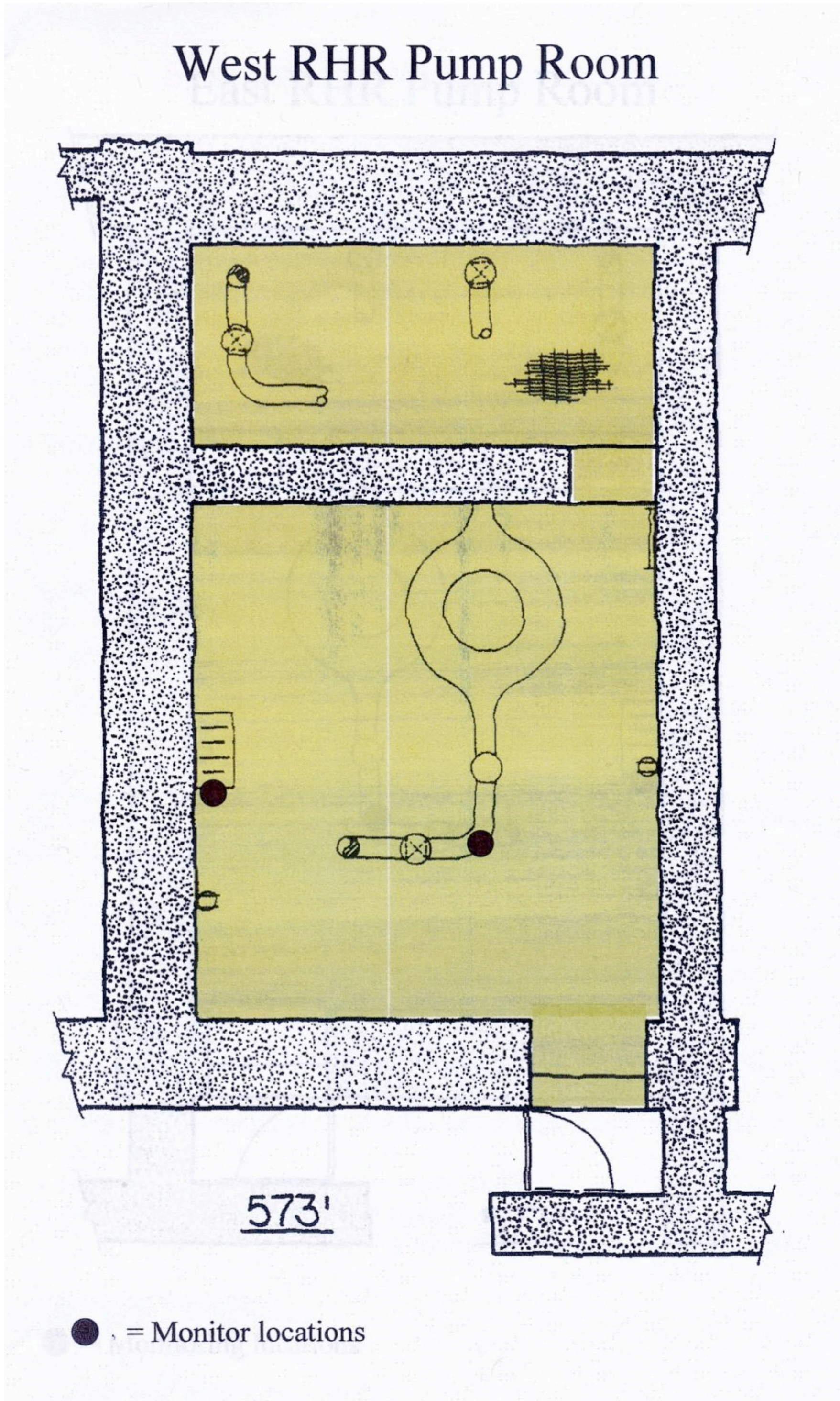


Figure 7: Locations of EDs in the West RHR pump room [8]

3.2 PRC-01 Media Resin

Corrosion product inventory molecular diameters, vary greatly during a shutdown depending upon the system temperature, particle metallurgy (oxide species), coolant chemistry (oxidizing / reducing) pH etc. Inventory that is susceptible to dissolution during a shutdown, does so as a function of coolant chemistry (temperature, pH, ECP) and will display an ongoing particle diameter change. The spectrum of particle diameters will shift lower as the dissolution process continues to place the inventory into solution. Additionally, some species do not undergo dissolution in typical coolant chemistry and they remain insoluble throughout the shutdown process.

There are particles that are smaller than the current collection or measurement techniques indicate. A typical mechanical filtration for filter demineralizer performance is >1 microns particle size, while the insoluble threshold is 0.45 μm. Specifically, Cobalt-60 particles/colloids are insoluble and much smaller than 1 μm, and <0.01 μm. Also, plant data (for 0.45 μm) has indicated 30-40% insoluble Cobalt-60 for a typical refuel outage [6].

The PRC Media technology (used in the PRC-01 Media Resin), has enabled nano-polymers to be attached to the surface of conventional resin. In that way, it can remove particles with diameter <0.01 μm and has the unique property of removing the ultra small diameter particulates and colloidal inventory that contributes to the overall source term inventory [7].

The PRC-01 specialty resin, is being put as a layer on top of the other resin (~1/3 of it). At this point, we should note that the benefits of the specialty resin are optimized when specific system controls are applied. These controls include both system operation and coolant chemistry adjustment.

CHAPTER 4: DATA RESULTS ANALYSIS

In this chapter, the ED data collected during the outage are provided. The significance and importance of the data is analyzed. Several charts from ED data, chemical data as well as comparison with previous outages of Cook Nuclear Plant will be provided. The goal is to analyze the trend in the charted data collected during U2C18, and to correlate the data with the historical prior outage shutdowns. Nuclear plants give great emphasis for learning from the analysis of events. Hence, a key objective of the study is to identify the differences between this outage and the two previous Unit 2 outages.

4.1 ED data results from U2C18 outage

As it was mentioned in the previous chapter, all the EDs were reporting dose value rates and the average 10-minute values were selected in order to graphically show the trends. The results of the data analysis for U2C18 are provided and explained. Note that the time scale is of 3-4 days in duration.

In the next figures, the abbreviation HX of the figures stands for Heat Exchanger.

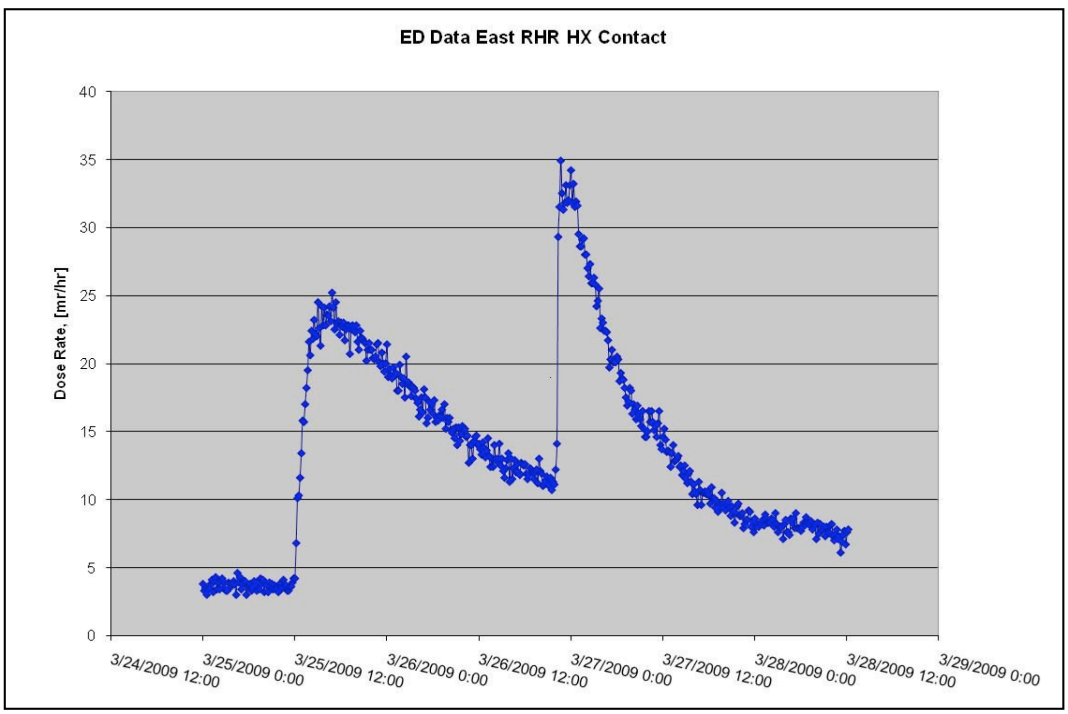


Figure 8: ED results for the East RHR HX Contact

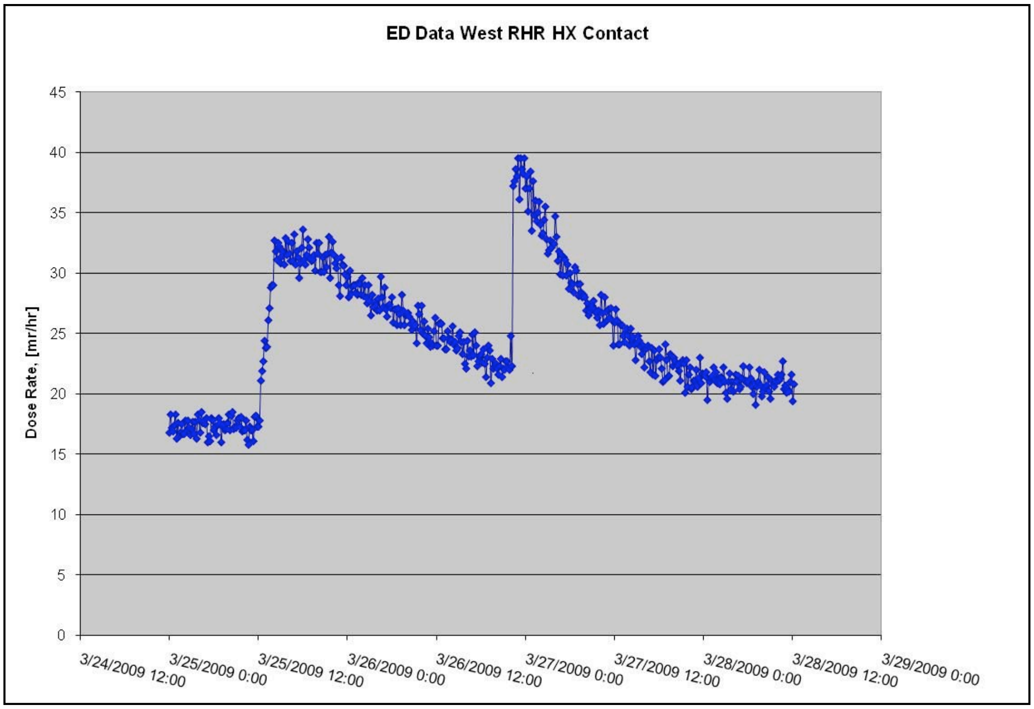


Figure 9: ED results for the West RHR HX Contact

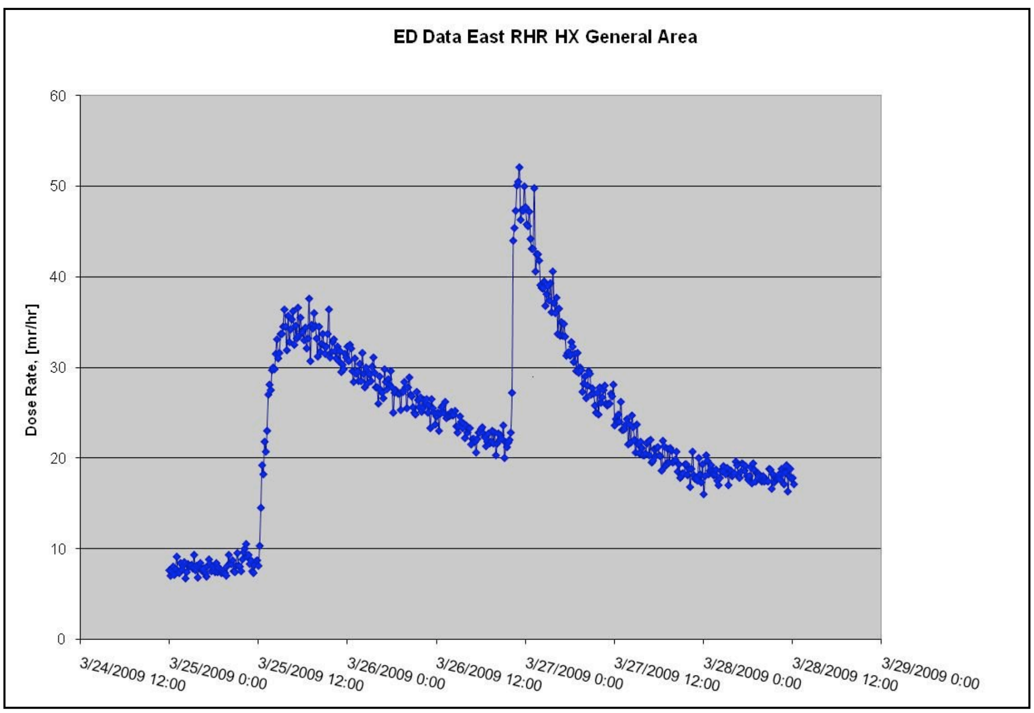


Figure 10: ED results for the East RHR HX General Area

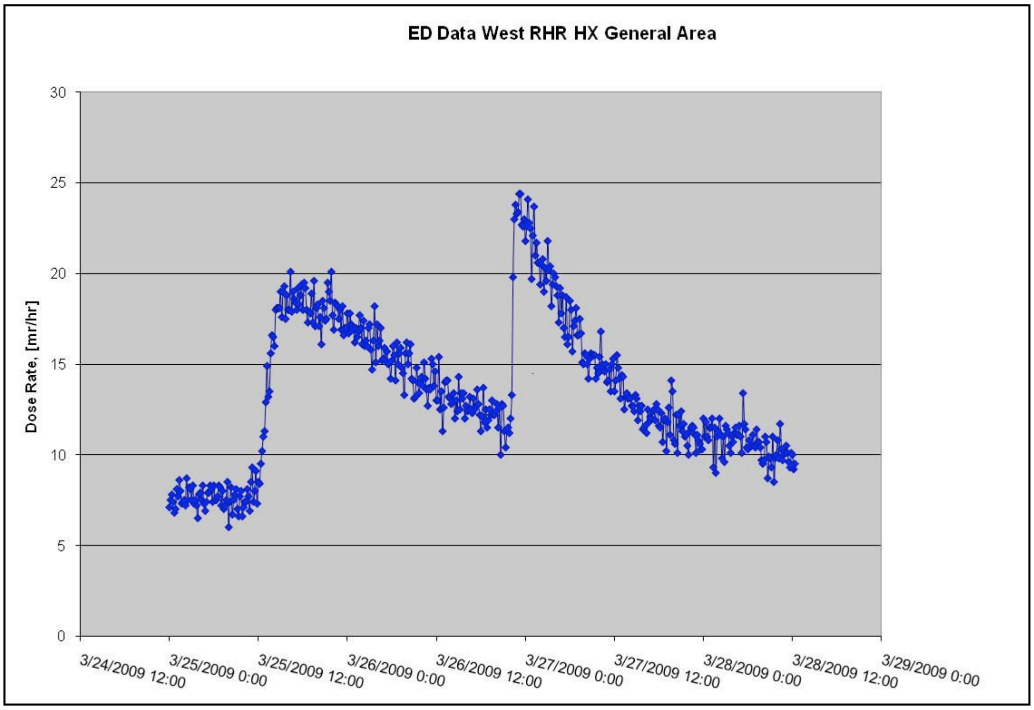


Figure 11: ED results for the West RHR HX General Area

The above graphs of the dose rates depict the telemetry ED dose rates measured at reproducible locations during the U2C18 shutdown. The dose rates of the general area EDs are lower than the contact EDs dose rates.

In subsequent CRUD bursts, only the east RHR pump was used while the west RHR pump is on standby. The graph shows the differences in the dose rates between the two RHR pumps. The east RHR has significantly higher dose rates than the west. Due to a telemetry system setup error, the serial numbers that were accredited to the EDs reporting the dose rate values of the East RHR HX room were mixed-up. The graph that is supposedly showing the contact dose rates is in fact showing the general area values.

The RHR system, as we've seen in Chapter 2, is only brought into service when specific temperature and pressure requirements are met. Thus, the flat line of dose rates that can be seen in the beginning (for the first few days according to the time scale till it was brought into service), is when the RHR is not in service.

The "double hump" that is seen in the graphs is a somewhat atypical result trend. Usually, there is only one CRUD burst peak, which corresponds to the forced oxidation using peroxide. In U2C18, this wasn't the case. An investigation found the reason was, during the degassing phase (removing hydrogen from the core), the concentration of hydrogen in the core reached lower values than expected. Subsequently, the RHR was brought into service, oxygen was introduce into the primary loops. This led to more concentrated oxidizing conditions which led to Co-58 becoming soluble and being released into the RCS. There wasn't enough hydrogen to "neutralize" the oxygen that got into the core and thus there was an earlier peak.

Approximately 48 hrs were then allowed in order to have clean-up before the addition of the peroxide.

The addition of hydrogen peroxide induced the CRUD burst: the subsequent second peak on the graphs. This happened right after the peroxide addition which was on 22:50 pm on March 26, 2009. The trend observed afterwards demonstrates decreasing dose rates over time. The post CRUD burst clean-up was achieved by letting the RHR pumps run and the specialty resin effectively removed a significant fraction of the source term.

Additional ED dose data collected are shown in the following figures. It should be mentioned that all data collected and analyzed was possible due to the cooperation of many different departments of the nuclear plant at Cook. The refuel outage of any power plant is a team effort.

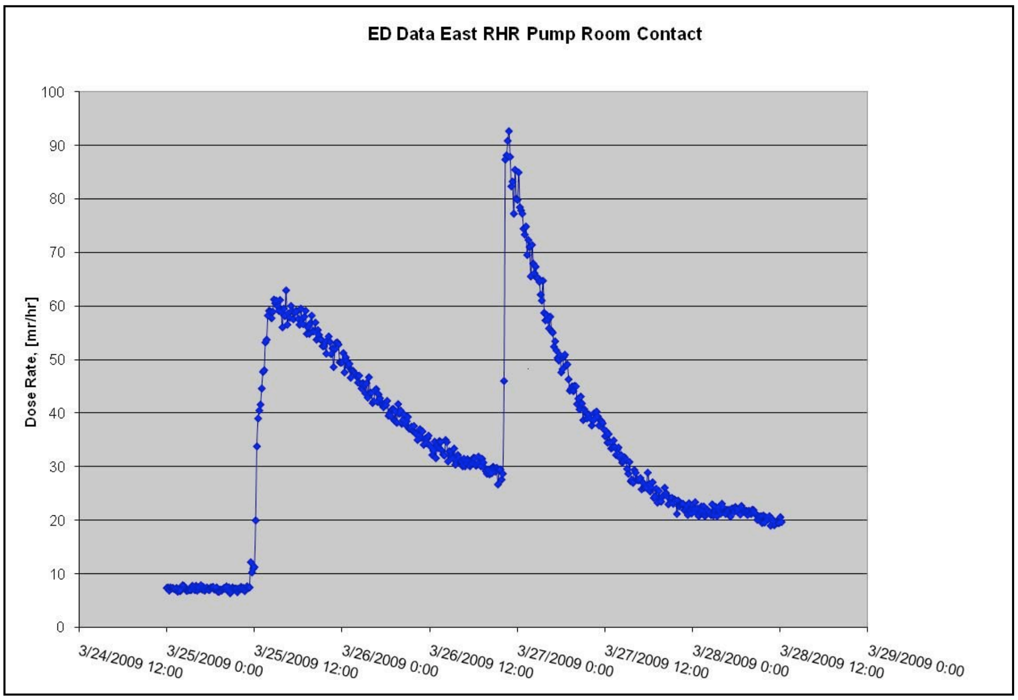


Figure 12: ED results for the East RHR Pump Room Contact

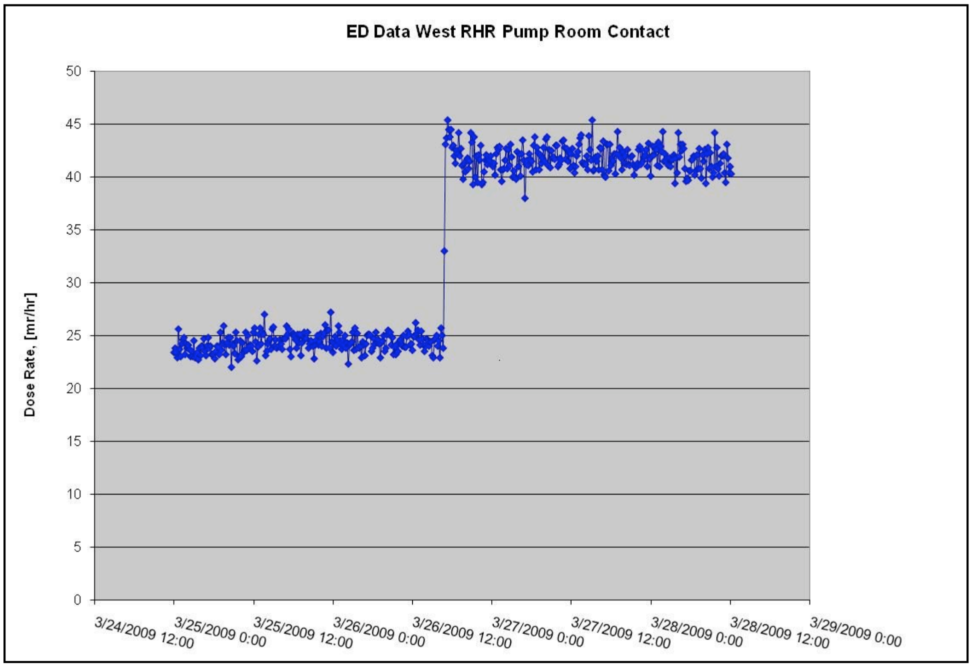


Figure 13: ED results for the West RHR Pump Room Contact

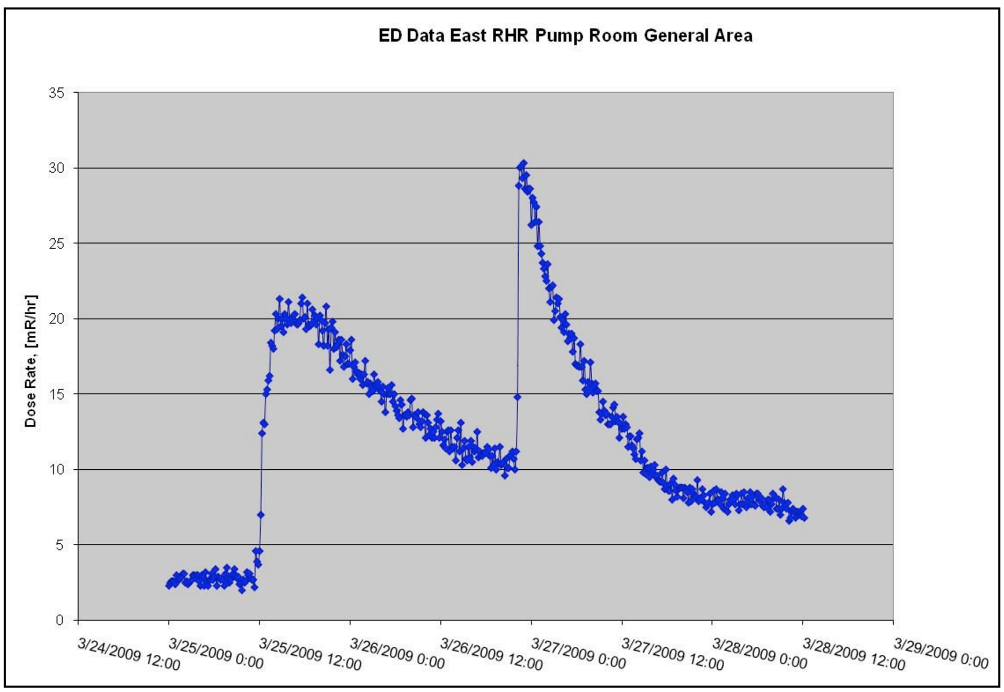


Figure 14: ED results for the East RHR Pump Room General Area

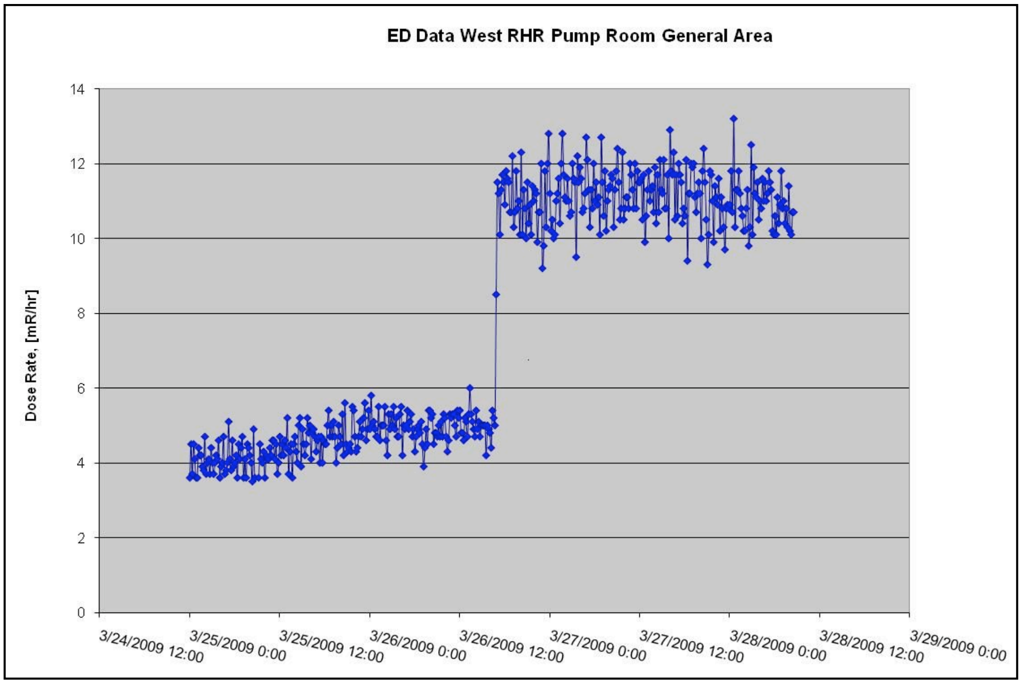


Figure 15: ED results for the West RHR Pump Room General Area

As was mentioned previously, there was only the East RHR pump in use for the clean-up. Hence, there was no significant increase in the dose rate on the West RHR pump (either contact or general area).

Since the previous four graphs are from the pump rooms, it can be noted in the graphs depicting the data from the East RHR pump, the dose rates are significantly higher than the ones observed in the heat exchanger room.

Also, it can be noted that the dose rates in the general area EDs are lower than the dose rates for the contact EDs.

Of major importance are the data from the letdown heat exchanger, since a clear picture of the good practices that were taken in this outage can be drawn from them; something that will be demonstrated when the ED results of this outage with the data from the previous two Unit 2 outages are compared.

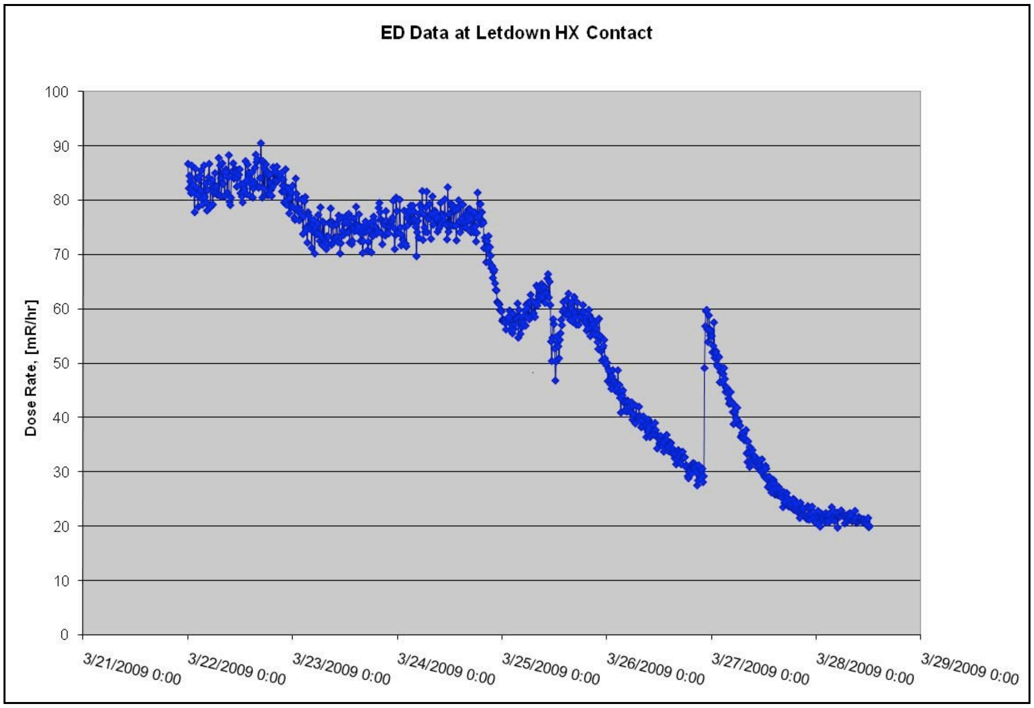


Figure 16: ED results for the Letdown HX Contact

First thing to notice in Figure 16, is that the time scale is different than the one used in the previous figures. In the case of the east and west RHR, as it has been said earlier, they weren't brought into service until certain requirements were met. Thus, before that point, only baseline dose rate can be seen.

Examination of the ED data from the above graph, shows a different trend than the data of the RHR systems. Initially, there are decreasing plateaus; from 3/22 to roughly 3/23 and then from 3/23 to roughly 3/25, during the stage of the reactor power decrease. The dose rates that are depicted in the graph are due to short lived fission products, whose concentration is dependable on time after reactor shutdown. During the shutdown stage, power decreases gradually. The dose rates also decrease gradually as the production of the short lived fission products is decreased.

Eventually, the reactor shutdown is completed and there is a rapidly decreasing trend as observed on the night of March 24, 2009. At that time, according to the series of events in the Unit 2 outage, there was initiation of acid coolant conditions. The acid conditions in the coolant eventually begin to dissolve the depositions and radioactive species which were released in the coolant. This explains the increase of the dose rate after the reactor shutdown.

The temperature and the pressure at this point are so that the RHR system can be brought into service. Its initiation is easily seen from the abrupt decrease of the dose rate at 11 am on March 25, 2009. It was seen earlier, that the initiation of the RHR system, led to unexpected peak due to oxygen entering the core and primary loop. This is the reason why there was an increasing dose rate after the abrupt decrease with the initiation of the RHR system.

The decreasing trend for some hours is the pre-CRUD clean-up, which led eventually to the addition of the hydrogen peroxide and the planned CRUD burst. The peak that can be clearly seen is the effect of the addition of the peroxide (CRUD burst). Afterwards, there is the section of post-CRUD burst clean-up.

4.2 Cobalt chemistry data and charts

First, as was already mentioned in Chapter 2, cobalt is the primary element of importance and it is of major importance in in-plant dose fields to accurately calculate the amount of cobalt that is removed, as well as which isotope of cobalt it is; an important step in source term removal is isotope characterization. Note that the ratio between Co-58 and Co-60 can indicate where the cobalt is coming from (fuel cladding or deposition on pipes). The units in the CRUD burst peak following, are shown in μCi/g. That is radioactivity per gram of insoluble material (CRUD) deposited on the filters of a liter sample of the coolant during the CRUD burst.

Key chemistry data from U2C18 outage:
Total Co-58 & 60 removed: 767.8 Ci
CRUD burst peak: 0.855 μCi/g
CRUD Busrt Estimate: 0.87 μCi/g
Total Ni removed: 1003 grams
Clean up time: 39.5 hours

The next graph shows the amount of curies of cobalt that were successfully removed during U2C18 outage. At this point it should be mentioned that the graph is providing with integrated activities of cobalt, thus the total amount observed from each isotope at any given time.

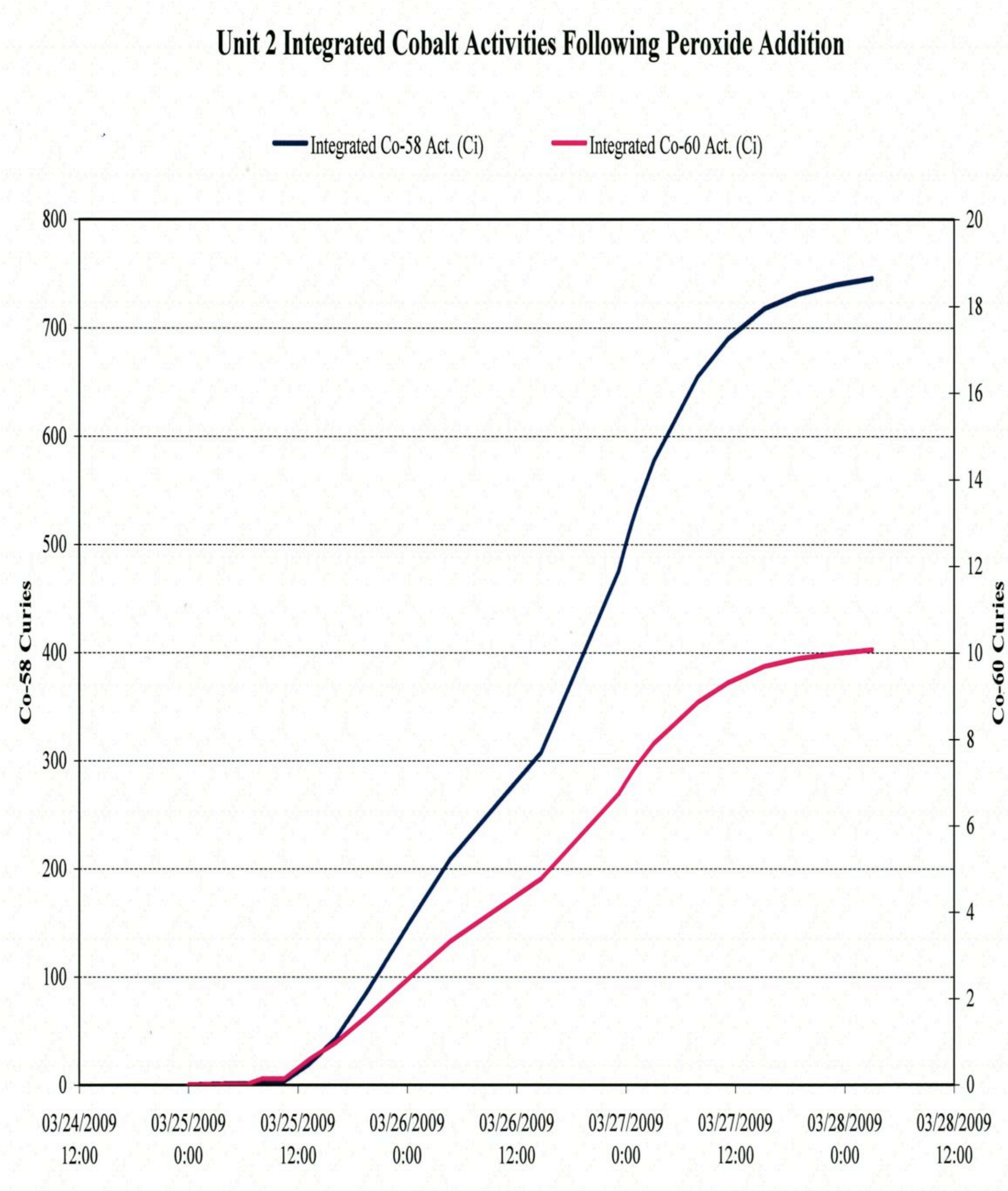


Figure 17: Cobalt activity after peroxide addition

It is noticeable that as soon as the East pump starts for the pre-CRUD burst clean-up, an increase in the cobalt activity is observed. This was discussed earlier with oxygen going into the core and leading to oxidation of the depositions. Also, the major peak was observed after the addition of peroxide (CRUD burst), which is again expected and leads to a successful source term removal.

Due to outage critical path schedule pressures, it is desirable to minimize the cleanup time. The next graph shows the hard gamma activity (in units of μCi/g) as a function of time, after the hydrogen peroxide addition. In the same graph the value limits in order for some tasks during the outage to be allowed are given.

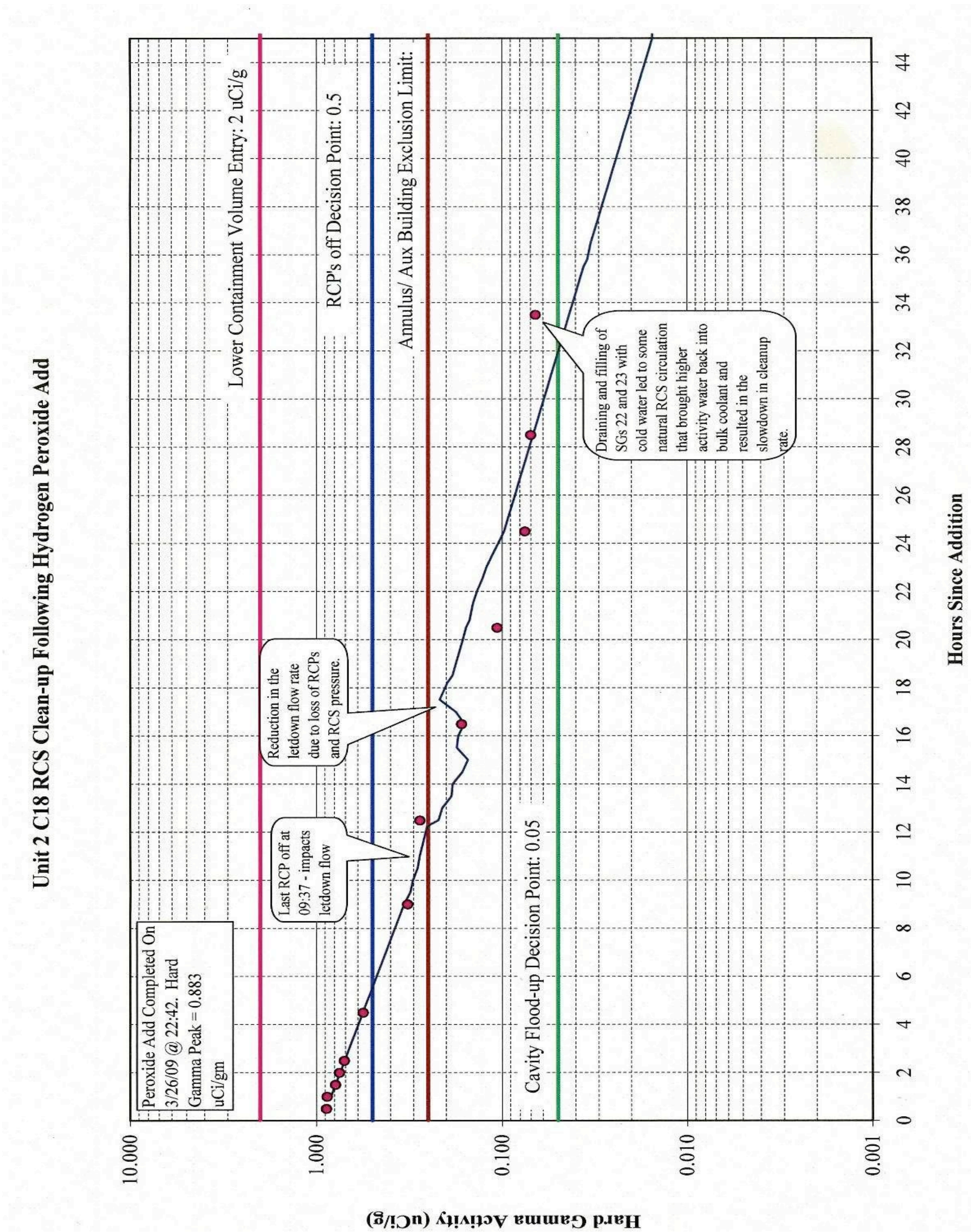
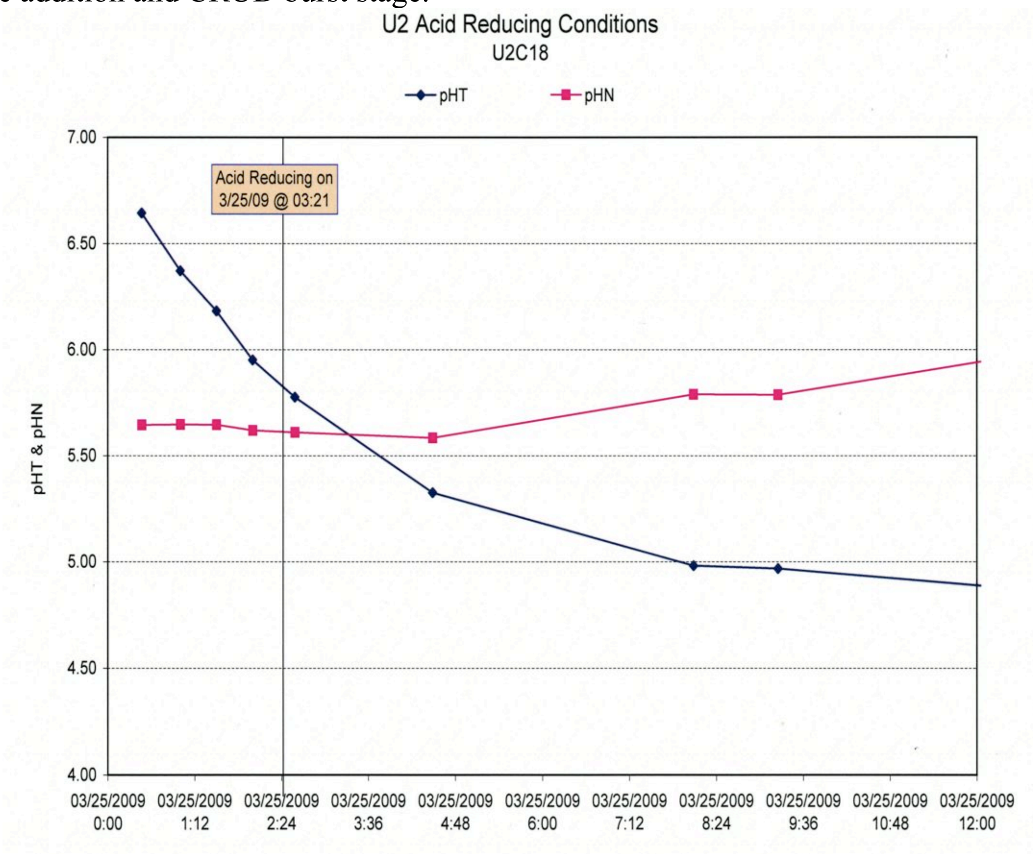


Figure 18: Clean-up following hydrogen peroxide

Something that needs to be mentioned is the really small time that was needed in order for the cobalt activity to be in the low level that was required: less than 40 hours.

4.3 pH change chemistry data

As was mentioned earlier, the pH of the primary water feed is important for the CRUD burst. The changes of the pH must be well planned and timely enforced to be able to ensure a successful CRUD burst. The graph below shows the changes of the pH that were made during the acid reducing stage of the outage. This is prior to hydrogen peroxide addition and CRUD burst stage.



<u>**Figure 19: Trend of pH changes during the acid reducing conditions**</u>

4.4 Comparison with previous outages of Cook Power Plant Unit 2

Telemetry data from previous outages can be helpful when being compared with the data from successive outages. Specifically, data from the previous two outages of the Unit 2 were available.

In order to be able to compare those three outages, five key-time points during an outage were selected. Then, specific ED positions were chosen and their values of dose rates for the aforementioned time points were recorded for each outage. To be precise, the east and west RHR pump room (contact) and the letdown heat exchanger contact were selected. Using these points, the changes among the different outages can be seen.

The five time points that were selected were:

1. initial dose rate (shutdown of unit),
2. pre-CRUD burst (acid reducing stage),
3. CRUD burst,
4. 12 hours after CRUD burst and
5. 24 hours after CRUD burst.

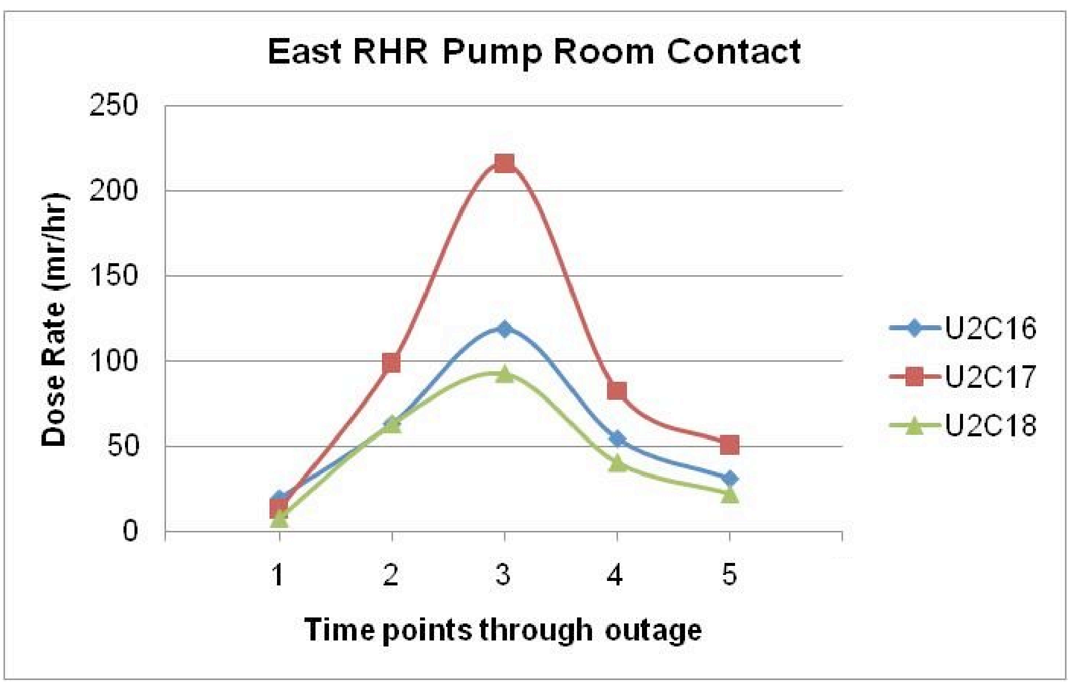


Figure 20: Comparison of ED data of the East RHR Pump Room Contact through different outages

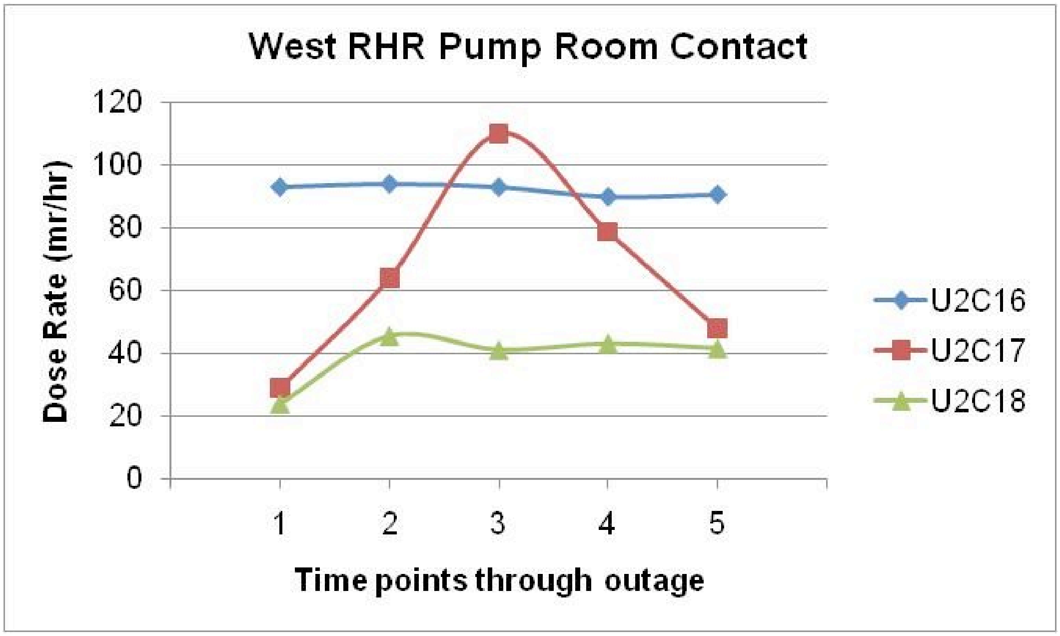


Figure 21: Comparison of ED data of the East RHR Pump Room Contact through different outages

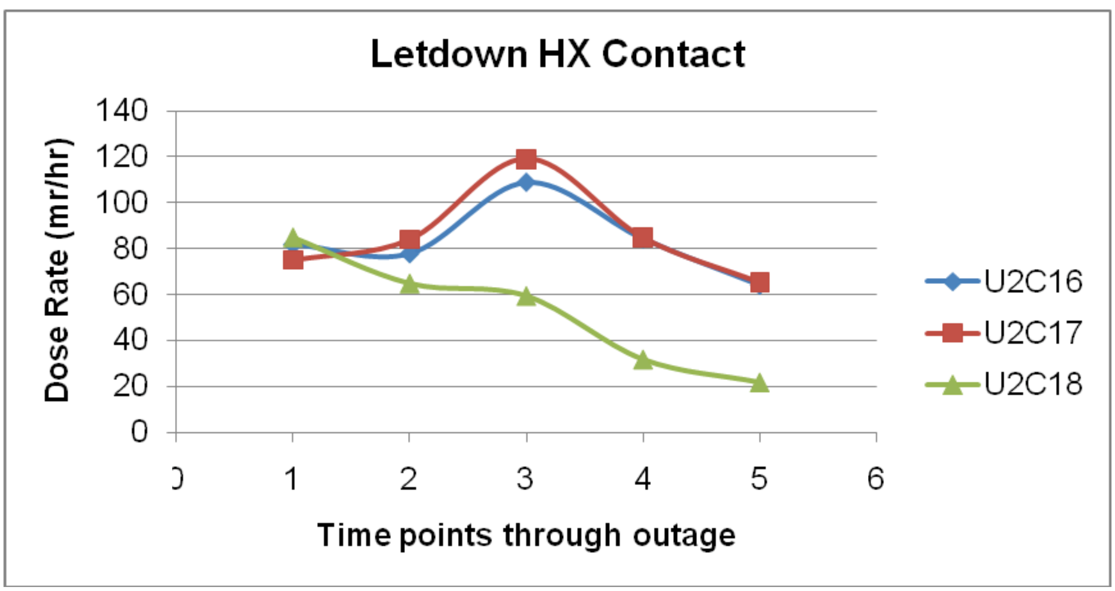


Figure 22: Comparison of ED data of the Letdown HX Contact through different outages

Immediately it can be seen, that U2C17 has the highest dose rates during the outage for most positions. That can be attributed to the fact, that during that outage the degassing process was not long enough and time was lost. This may have led to higher dose rates as opposed to U2C16.

In Figure 20, the same trend of the dose rates through all time points are noted. It is of importance to see, that the U2C18 clearly has the lowest dose rate through all time points selected. Accordingly, the total outage dose of 34 person-rem was the lowest ever achieved at Cook refueling outages.

In Figure 21, it is important to notice that both in U2C16 and U2C18, the west RHR system was not used, and that's why there almost flat lines can be seen in their dose rates. Though, once again, the dose rate recorded in U2C18 was significantly less than the one on U2C16. In U2C17, both east and west RHR systems were used, since there were adjustments in the refueling outage schedule.

Before proceeding to the analysis of Figure 22, it must be mentioned that the five time points that were selected, may not be adequate to represent actual dose trend at the letdown trend line. This practice was followed in order to be able to do a qualitative analysis.

In Figure 22, a fundamental difference is presented between the two previous outages and the U2C18. While in the previous outages the trend of the dose rates are similar to the ones noticed in the east RHR pump room contact. In the U2C18, dose rates are much less. The trend also seems to be decreasing (even though the resolution was not the most appropriate for this specific location).

In order to be able to analyze this difference, a study was conducted to look into what has changed among the U2C16, U2C17 and the U2C18.

The RDT bypass lines were installed in Westinghouse reactors to provide a coolant temperature SCRAM indicator. The lines were small in diameter (~2 inches). Over years of operation, the lines became a "CRUD trap". Hence, the RTD lines increased dose rates due to the CRUD deposition in the small diameter piping and lower containment dose rates were elevated.

Cook Nuclear Plant, invested $32 million in removing the RTD bypass lines from both Units. U2C18 was the first refuel outage after their removal. Hence, it was the first time that the results of that investment could be measured.

As can be understood, one of the main reasons that contributed to the low dose rates in U2C18, was the removal of those lines.To be able to show that graphically, the chart below of the dose rates at the Unit 2 steam generators are given in Figure 23.

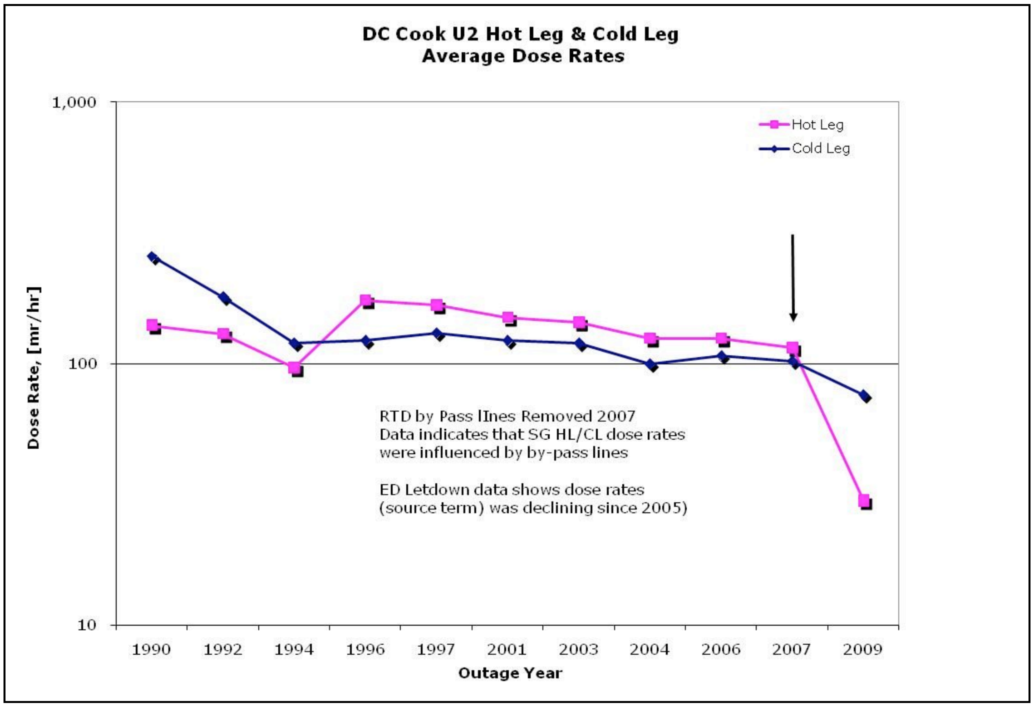


Figure 23: Average dose rates of steam generators of unit 2

In this figure, we can see the average dose rates over the years at the specific locations. It can be said that after 1996, a decreasing trend is noticed. But what is remarkable, is the sudden decrease of dose rates as soon as the by-pass lines were removed. Hence, the effect of the specialty resin on Co-60 removal had been masked by the high ambient dose contributed from the RTD bypass lines.

CHAPTER 5: CONCLUSIONS AND FUTURE RECOMMENDATIONS

U2C18 commenced on March 25, 2009, and was completed on May 01, 2009 (38 days). The original outage dose estimate for U2C18 was 43.235 person-Rem and the outage dose goal of 40 Rem was based on several activities and on previous cycle dose rates. U2C18 dose estimates were compared against historical performance. The original dose goal was revised downward on April 7, 2009 to 34 Rem due to worker engagement, strong shutdown chemistry, coupled with the use of specialty resin in the Chemical Volume Control System (CVCS) demineralizer cleanup system has resulted in a lowering trend in our source term.

5.1 Dose Budget Analysis

The initial outage dose estimate of 43.235 person-Rem was based on proposed outage activities. The goal was subsequently reduced on April 7, 2009 to 39.266 Rem dose estimate and 34 Rem outage dose goal by the ALARA Committee, achieving this would set a new site record for Cook Nuclear Plant. The goal was then readjusted to 36.650 Rem. The final dose for U2C18 was 34.840 person-Rem (TLD dosimeter), a new Cook Unit 2 and loop 4 Ice Condenser outage dose record. The U2C18 outage finished 3.032 person-Rem under the original dose goal and was better than the previous Unit 2 (U2C16) best dose at 49.208 person-Rem. It should be noted that pre and post outage dose was not included in the total for U2C18.

The following factors ultimately had a positive effect on the occupational dose received for U2C18:

- Ongoing commitment to shutdown and startup chemistry optimization consistent with the use of specialty resins
- Positive step change in radworker practices and worker engagement
- The new ALARA dose reduction incentive program
- The use of remote monitoring
- Reduced work time in the Restricted Area

5.2 ALARA Committee activities

The ALARA Committee met on four occasions during U2C18 to provide management oversight of the following topics:

- CRUD burst cleanup results
- Dose budget status review and adjustment
- Personnel contamination event (PEP) reviews
- Review of the analysis of dose rate data

5.3 Dose reduction and engineering controls

Pre-outage planning efforts focused on repeating the source term reduction successes of past outages. The combination of providing time in the outage schedule to de-lithiate early in the cooldown, solubilize core deposits, degassing the RCS, maintaining corrosion product solubility, and the use of PRC-01 resin, worked synergistically to produce a successful reactor shutdown. There were no adverse impacts on the outage schedule or personnel exposures.
Shutdown Chemistry successes included:

- No spent reactor coolant filters were generated during the RCS cleanup/cooldown
- RCS cleanup, following the hydrogen peroxide addition, was completed ahead of schedule, without loss of critical path time
- Lower than projected general area dose rates were experienced in lower containment.
- The reactor cavity water clarity was considered as good as or better than any past outages

Total Co-58 & 60 removed: 767.8 Ci
CRUD burst peak: 0.855 μCi/g
Total Ni removed: 1003 grams
Clean up time: 39.5 hours
Nominal Letdown flowrate: 155 gpm

5.4 PRC-01 Media Performance: Observations and Results

PRC-01 media was used during the planned CRUD burst for the second time during U2C16. The purpose of the PRC-01 technology is to remove and mitigate deposition mechanisms of source term in the primary coolant during the CRUD burst and subsequent cleanup via filtration and ion exchange. Source term can be directly correlated to the amount of CRUD deposition in the core and its support systems.

Based on industry experience at VC Summer and other US PWRs, PRC-01 technology has been demonstrated to be effective in removing colloidal Co-58 and Co-60 from the primary coolant. This is the key technological difference between PRC-01 and all other conventional mixed bed ion exchange resins and macroporous conventional resins.

PRC-01 media has been easily integrated into existing plant reactor cleanup system at Cook and 21 other US PWR reactors. The science of this product combines the applied chemical engineering knowledge of colloid formation and transport in reactor systems with the selective extraction.

No steam generator work was scheduled during the outage, so channel head dose rates were not available. However, water clarity in the reactor cavity was observed to be excellent.

5.5 Remote monitoring

The remote monitoring room (located in the RPAC building) is equipped with two remote monitoring consoles. Each monitoring console is equipped with video, audio and telemetry (remote dose monitoring). Each console had four video monitor, two PC monitors (for telemetry info), camera controls, and audio equipment controls.
During U2C16, the Cook remote monitoring system was expanded and an RP technician was stationed in the remote monitoring room to provide RP coverage of lower containment work. All personnel entering lower containment, and most who entered upper, were equipped with a transmitting (telemetry) electronic dosimeter (ED). This provided for the dose and area dose rate monitoring for all personnel were being monitored remotely (at several locations outside containment – including the RMR). There were no ED dose alarms during the entire U2C16 refueling outage. The remote monitoring room was also utilized for supervisory oversight.

The use of remote monitoring for U2C18 was to provide visual oversight of work groups in lower and upper containment. Communications devices and remote equipment were used primarily for evolutions such as entries into the regeneration heat exchanger room, RCP seal work and reactor cavity work.

In U2C16, new equipment was purchased that gave the ability to monitor workers dose remotely while observing work from monitors in the RPAC. The new equipment installs quicker, provides full coverage of lower containment and the aux Building, and is less expensive than the former system. This has a favorable impact on radiation protection as well as worker dose.

The manufacture of the ED transmitters (MGP Instruments) recently produced a new model of transmitter (WRM-2) that greatly improves the signal transmission.
Radiation levels in the auxiliary and containment buildings were remotely monitored using MGP DMC 2000s personnel electronic dosimeters (EDs). Approximately 20 EDs were located in strategic areas. Monitoring locations were chosen using dose rate information from past outages and CRUD burst data. The EDs were configured as remote area monitors and connected to the RP temporary remote monitoring system. This temporary system was then connected to the plant's local area network (LAN). Radiation levels were able to be viewed and plotted from the computers throughout the site using new remote monitoring software (RADS).

The use of nontraditional RP help from the Information Technologies (IT) group was extremely beneficial to the remote monitoring program. These individuals aided in increasing the reliability of the temporary system and simplified data trending.

5.6 Refuel outage highlights

Cycle 18, Unit 2 Refueling outage achieved a high water mark for the Cook ALARA Committee and site employees in the success of the multi-cycle effort of removal the Co-60 source term from plan piping systems. Many planned activities over the past 7 years came together during the Unit 2 refueling outage to achieve a site and 4-loop Westinghouse Ice Condenser ALARA outage dose record. The important activities included:

- Early mechanical degassing on Tuesday one day before reactor shutdown got the hydrogen out
- CRUD burst achieved within 48 hours of unit shutdown
- Use of PRC-01 specialty resin for the 4th cycle shutdown
- Use of PRC-01 specialty resin during the start up Unit 2 at the beginning of cycle 18 remove nickel (which is the element responsible for the Co once it gets activated)
- Attention to lessons learned from earlier source term challenges, e.g. rapid reactor coolant temperature reduction from 175-120 ºC to prelude the release of iron oxides, chromium and cobalt from the fuel assembly cladding.

- Accurate prediction of CRUD burst peak activity concentration.
- Full turnover of all fuel assemblies over 3 prior cycles. All new fuel assemblies will have the benefit of the specialty resin.

5.7 Discussion of Source Term Removal:

- CRUD Burst results:

  The importance of Cobalt-60 removal (not reduction) to reduce outage dose has been a key focus of the Cook ALARA Program. Use of Specialty Resin (PRC-01) to mitigate colloids achieved satisfactory results for the Unit 2 refueling outage. The CRUD Burst Peak was 0.883 μCi/g. In-plant dose rates are equal to or lower than Cycle 17 refueling outage dose rates in most in-plant areas. Reactor cavity water clarity was very good according to fuel handling personnel. Dose rates on the refueling bridge were very low. Personnel contamination was low (4 Percons for the outage so far vs. a goal of less than 30). It is yet to be determined if the reactor cavity drain down and decon also showed improvements from prior outages.

- Cobalt Removal from Plant Piping vs. Fuel Cladding:

  Plants need to monitor the Co-60 to Co-58 ratio over time to to assess the progress in reducing the ^{60}Co impact on current and future dose rates. The magnitude may not be as important (because of differences in materials from unit to unit) as the historic decrease/increase of the ratio. The U2C18 ratio was 1:70 (nickel to ^{58}Co) which may indicate a diminishing ^{60}Co plant piping inventory.

- Fuel Assembly Rotation

  Unit 2 Cycle 18 represented the first time that the entire nuclear core (all fuel assemblies) were returned to service following a shutdown with the specialty resin in use. For the specialty resin to work most efficiently it ~~is~~ appears necessary to complete 3 cycles to achieve a full replacement of fuel assemblies before the full benefit of specialty resin is realized.

- Electronic Dosimetry Telemetry Results:

  The results of 11 electronic dosimeters located on the RHR pumps, RHR heat exchangers and letdown lines indicated a 65% reduction in dose rate on plant piping after the CRUD Burst. A chart comparing the changes in dose rates at the electronic dosimeter locations during the operation of the E RHR pump (introduction of oxygenated water) and peroxide addition is attached. The reduction in electronic dosimeter dose rates (mR/hr) tracked well with the cleanup of the primary coolant with the PRC-01 resin (uCi/g).

- Dose Reduction in Lower Containment Due to RTD Bypass Line Removal:

  The removal of the Unit 2 RTD Bypass Lines in Cycle 17 has significantly reduced the dose rate for many work activities in lower containment. The Reactor Water Coolant Pump Seal Replacement jobs have clearly benefited from the reduced dose rate.

- Future Cook Source Term Removal Plans:

  Cook is also changing to elevated lithium program to increase the pH to 7.2 on Unit 1 Cycle 22 and 7.3 in Unit 2 Cycle 18 with a maximum lithium concentration of 6.0 ppm. It has been found at other US PWRs that lower pH values contribute to undesirable corrosion product movement in the primary coolant.

- Benchmarking with Other Specialty Result PWRs

  Cook ALARA staff has maintained close contact with other specialty resin PWRs. The Unit 2 shutdown chemistry and telemetry data results were closely compared to V.C. Summer results with favor similarities noted. Contact with sister ice condensers clearly demonstrate that Cook Unit 2 has achieved significantly more than Co-60 removal than sister Units. The Institute of Nuclear Power Operations awarded an INPO 1 rating to the Cook site in August 2009 including an industry strength for the source term removal accomplishments.

5.8 Recommendations for future work

This research is the first step of comparative analyses that can be performed. Namely, future work can include comparison of source term removal during outage in the same kind of PWRs (Cook Nuclear Plant for example is an ice condenser pressurized water reactor), comparison of more than three consecutive refuel outages (in this research data were not available for further comparison) or even expand it to more than source term removal comparison.

Future analysis can bring insight to better understand the radiochemistry phenomena that are working together to achieve significant reduction in refueling outage doses.

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APPENDIX A

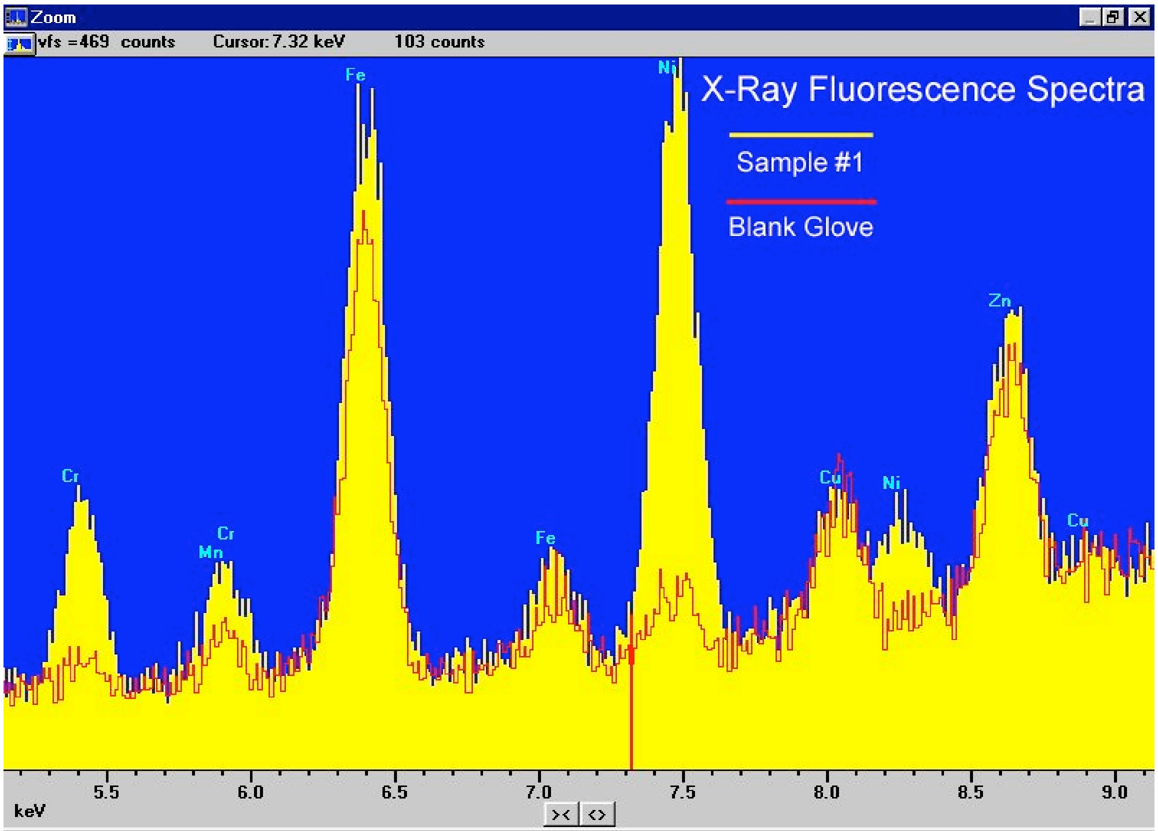

Figure A-1: Comparison of XRF spectra of 1st sample of CRUD smear and blank

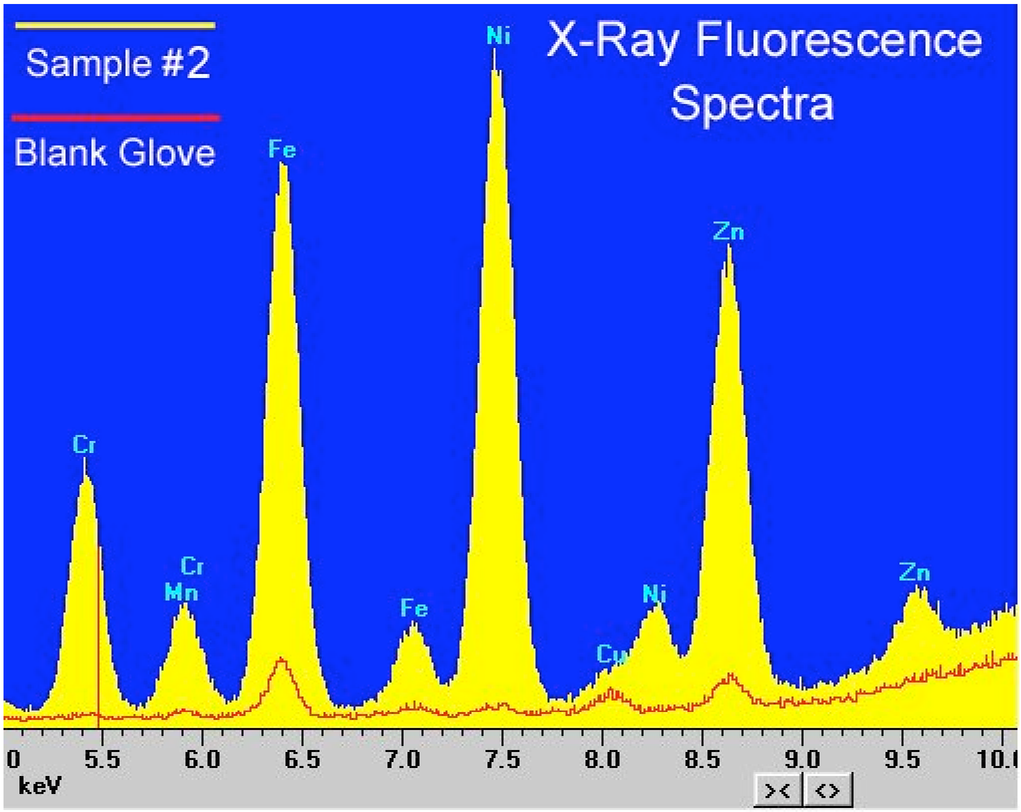

Figure A-2: Comparison of XRF spectra of 2nd sample of CRUD smear and blank

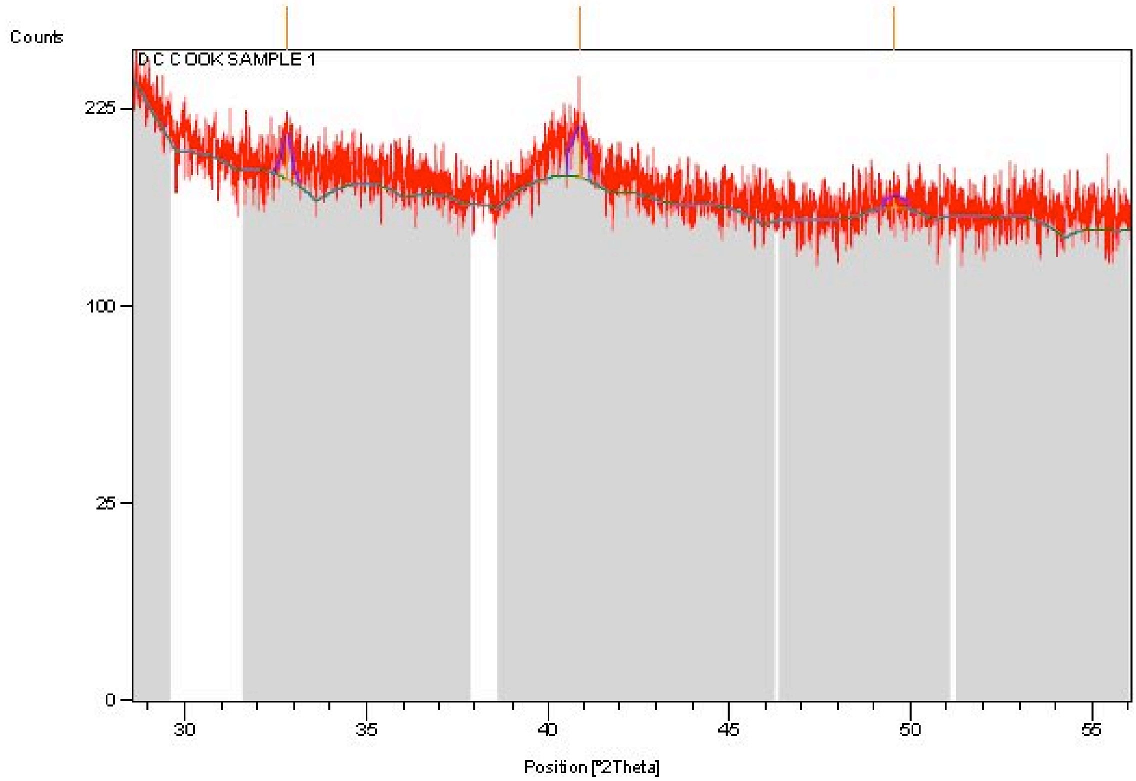

Figure A-3: X-Ray diffraction pattern of 1st sample

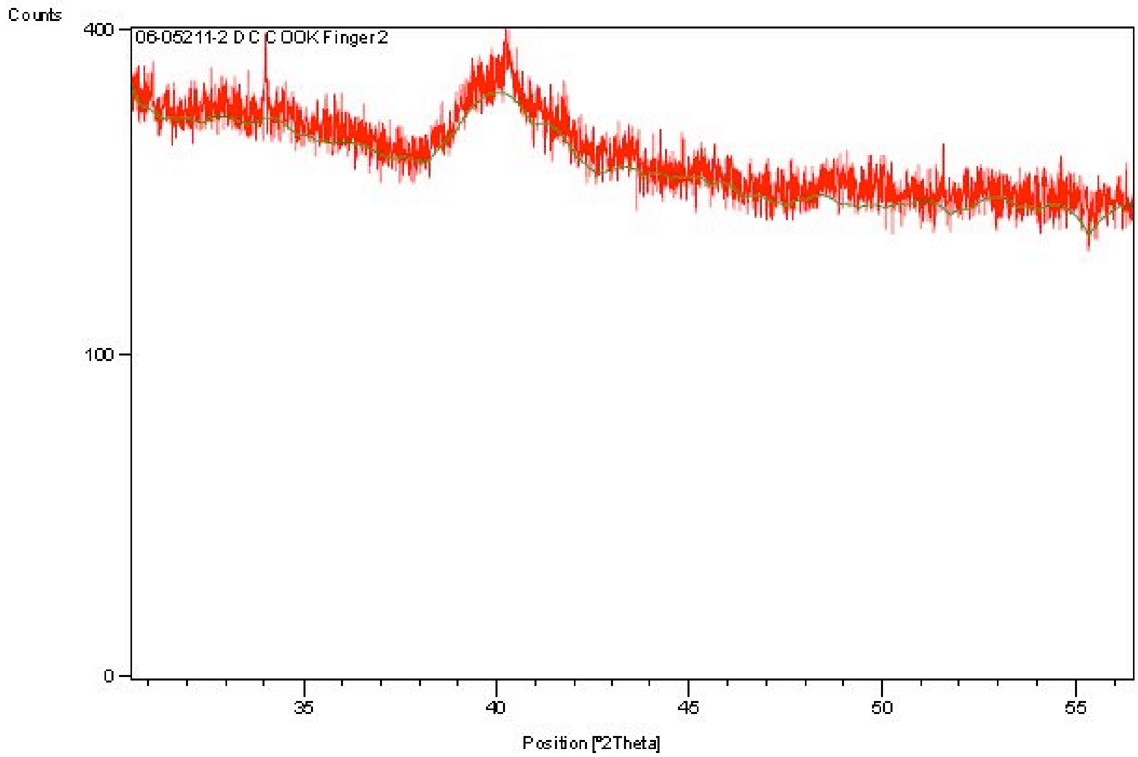

Figure A-4: X-Ray diffraction pattern of 2nd sample

Table A-1: Results of metal analyses in Cook Nuclear Plant steam generator CRUD sample 1 and 2

Analyte	Sample 1	Sample 2
Co	0.7	0.1
Cr	25.1	16.7
Cu	0.6	0.3
Fe	51.7	52.3
Mn	0.1	0.5
Mo	0.1	0.1
Ni	17.2	18.9
Sn	0.2	0.1
Zr	2.9	2.2
Zn	1.4	8.8

APPENDIX B

Table B-1: Excerpt of the raw ED dose rate data.

ED ID Number	Time	Dose rate (mr/hr)	ED Location
241033	3/24/2009 4:10	75.1	CB 633 Letdown HX Rm
241033	3/24/2009 4:20	69.7	CB 633 Letdown HX Rm
241033	3/24/2009 4:30	74.1	CB 633 Letdown HX Rm
241033	3/24/2009 4:40	76.2	CB 633 Letdown HX Rm
241033	3/24/2009 4:50	73.1	CB 633 Letdown HX Rm
241033	3/24/2009 5:00	77.4	CB 633 Letdown HX Rm
241033	3/24/2009 5:10	79.2	CB 633 Letdown HX Rm
241033	3/24/2009 5:20	77.8	CB 633 Letdown HX Rm
241033	3/24/2009 5:30	78.6	CB 633 Letdown HX Rm
241033	3/24/2009 5:40	81.7	CB 633 Letdown HX Rm
241033	3/24/2009 5:50	72.7	CB 633 Letdown HX Rm
241033	3/24/2009 6:00	77.4	CB 633 Letdown HX Rm
241033	3/24/2009 6:10	75	CB 633 Letdown HX Rm
241033	3/24/2009 6:20	74.2	CB 633 Letdown HX Rm
241033	3/24/2009 6:30	78.7	CB 633 Letdown HX Rm
241033	3/24/2009 6:40	81.6	CB 633 Letdown HX Rm
241033	3/24/2009 6:50	74.1	CB 633 Letdown HX Rm
241033	3/24/2009 7:00	76.7	CB 633 Letdown HX Rm
241033	3/24/2009 7:10	76.6	CB 633 Letdown HX Rm
241033	3/24/2009 7:20	79.3	CB 633 Letdown HX Rm
241033	3/24/2009 7:30	77.5	CB 633 Letdown HX Rm
241033	3/24/2009 7:40	72.9	CB 633 Letdown HX Rm
241033	3/24/2009 7:50	77.5	CB 633 Letdown HX Rm
241033	3/24/2009 8:00	80.7	CB 633 Letdown HX Rm
241033	3/24/2009 8:10	75.5	CB 633 Letdown HX Rm
241033	3/24/2009 8:20	76.8	CB 633 Letdown HX Rm
241033	3/24/2009 8:30	78.1	CB 633 Letdown HX Rm
241033	3/24/2009 8:40	77.7	CB 633 Letdown HX Rm

APPENDIX C

Table C-1: ED data for the EPRI points at the hot leg of the system

Year	Cycle	Loop1 HL1	Loop2 HL1	Loop3 HL1	Loop4 HL1	Avg	% Change	Overall % Change RFOs with PRC
1990	**U2C8**	160	100	150	150	140		
1992	**U2C9**	120	140	130	130	130	**-7%**	
1994	**U2C10**	130	90	65	100	96	**-26%**	
1996	**U2C11**	150	200	150	200	175	**82%**	
1997	**U2C12**	160	190	160	160	168	**-4%**	
2001	**U2C13**	180	150	120	150	150	**-10%**	
2003	**U2C14**	150	150	125	150	144	**-4%**	
2004	**U2C15**	120	140	120	120	125	**-13%**	
2006	**U2C16**	150	150	100	100	125	**0%**	
2007	**U2C17**	140	100	100	120	115	**-8%**	
2009	**U2C18**	35	30	25	30	30	**-74%**	**-76%**

Table C-2: ED data for the EPRI points at the cold leg of the system

Year	Cycle	Loop1 CL1	Loop2 CL1	Loop3 CL1	Loop4 CL1	AVG	% Change	Overall % Change RFOs with PRC
1990	**U2C8**	200	130	450	250	258		
1992	**U2C9**	180	160	130	250	180	-30%	
1994	**U2C10**	120	100	100	160	120	-33%	
1996	**U2C11**	100	120	90	180	123	2%	
1997	**U2C12**	120	130	85	190	131	7%	
2001	**U2C13**	120	120	100	150	123	-7%	
2003	**U2C14**	150	100	80	150	120	-2%	
2004	**U2C15**	160	80	60	100	100	-17%	
2006	**U2C16**	100	100	80	150	108	8%	
2007	**U2C17**	80	100	80	150	103	-5%	
2009	**U2C18**	70	85	80	70	76	-26%	**-24%**

APPENDIX D

Located in supplementary appendix file named Deligiannis_thesis_data.zip.

VITA

Anastasios Deligiannis was born in Athens, Greece on the 25^{th} of January, 1984. He attended the National Technical University of Athens in the fall of 2001. In the spring of 2007, Mr. Deligiannis received his Ptychion in Mechanical Engineering. Upon completion, he was accepted in the graduate program of the Nuclear Engineering department of the University of Illinois at Urbana-Champaign in August 2007. He continued his studies there, where he was a researcher for the North American Technical Center investigating source term removal studies.