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Determining the Effects of Radiation on Aging Concrete of Nuclear Reactors

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ABSTRACT

The U.S. Department of Energy Office of Environmental Management (DOE-EM) is in charge of the Decontamination and Decommissioning (D&D) of nuclear facilities around the DOE Complex. Some of these facilities will be completely dismantled, while others will be partially dismantled and the remaining structure will be stabilized with cementitious materials. The latter is a process known as In-Situ Decommissioning (ISD). The ISD decision process requires a detailed understanding of the existing facility conditions, and its operational history. Coupled with system information, material properties, and their impacts/changes resulting from operational conditions is needed. Understanding the facility's technical envelope, ranging from system conditions to material properties and characteristics, provides the basis for pursuing nuclear facility ISD. This report investigated the properties of existing aging concrete structures exposed to radiation. This study addressed the Savannah River Site (SRS) nuclear reactors in particular. At the end of this study, it was found that the levels of radiation experienced by the reactors at SRS are not completely deleterious to the concrete structure. The study also showed that the most common effect of radiation on concrete at a nuclear facility was the loss of compressive strength.

EXECUTIVE SUMMARY

This research work has been supported by the DOE/FIU Science & Technology Workforce Initiative, an innovative program developed by the US Department of Energy's Environmental Management (DOE-EM) and Florida International University's Applied Research Center (FIU-ARC). During the summer of 2009, DOE Fellow (Cristian Acevedo) spent 10 weeks doing a summer internship at Savannah River National Laboratory, located in Aiken, South Carolina, under the supervision and guidance of Mr. Michael Serrato.

The U.S. Department of Energy Office of Environmental Management (DOE-EM) is in the process of Decontamination and Decommissioning (D&D) of nuclear reactors, chemical separation plants, and other nuclear production facilities that are no longer in service. The D&D process involves several approaches such as decontamination and reuse, complete dismantlement, and partial dismantlement and entombment (e.g., In-situ Decommissioning [ISD]) of these facilities. A detailed understanding of the existing conditions, materials properties and characteristics, and operational history of these facilities is important to carry out the D&D process successfully. This information will help estimate the durability of the nuclear facility and its continued performance.

Understanding the properties of concrete in NRs is crucial for the physical integrity of ISD. The objective of this report was to investigate the properties of aging concrete in nuclear reactors (NRs) exposed to radiation. This report addressed the Savannah River Site (SRS) NRs and factors such as the types of concrete used in the reactor facilities, the radiation levels and doses the concrete was subjected to, dose estimates accumulated over the service period of the reactor, and the effects of these radiation doses on concrete. Since information on the SRS reactors is limited, a cursory comparison was made with commercial reactors (CR) since more studies were conducted regarding their deterioration. This comparison was used to set parameters and understand the environmental conditions (e.g., temperature and irradiation) in the SRS reactors. The areas of most concern were the reactor vessel concrete containment structures or biological shield (BS) and the basins. Using these set of parameters, rough estimates were generated to project the levels of radiation the BS was exposed to.

The levels of radiation found in the SRS reactors were below the threshold values (i.e., orders of $\sim 10^{25}$ neutrons/cm^2 for neutrons and $\sim 10^{10}$ rads for gamma-rays) known to cause severe damage in the concrete. In the basins, the radiation is so low (i.e., orders of ~ 75 -134 rad/hr) that it has insignificant effects on the concrete. The only common sign of irradiation-induced deterioration expected to be found on the BS concrete in reactors was the loss of compressive strength. Nonetheless, this loss of compressive strength is not significant enough to cause loss in the soundness of the concrete structure of the BS.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1. INTRODUCTION

The U.S. Department of Energy (DOE) focuses on managing the nuclear waste generated at the different nuclear complexes used for the production of nuclear weapons; this involves the Decontamination and Decommissioning (D&D) of nuclear facilities (i.e., nuclear reactors, chemical separation processing plants, etc.). These nuclear facilities are aging and their life cycle durability is questionable. Nevertheless, performing D&D is quite a complex task as careful measures need to be taken for personnel protection due to the high levels of radiation in those facilities. The D&D program involves several approaches such as decontamination and reuse, complete dismantlement, and partial dismantlement and entombment (e.g., In-situ Decommissioning [ISD]) of these nuclear facilities. Therefore, it is crucial to understand the properties of the structure of the nuclear facility after being exposed to many deteriorating factors (e.g., environmental, irradiation, chemical attack, corrosion of steel, etc.). This information will help estimate the durability of the nuclear facility and its continued performance.

Nuclear facilities have proven to be one of the biggest challenges in terms of environmental cleanup for engineers at different DOE sites. Among these facilities, the most prioritized targets for D&D are the nuclear reactors (NRs) and the chemical separation processing plants or canyons. The structure's components, such as concrete and steel, of these facilities have deteriorated over the years due to freezing and thawing, chemical attack, chemical reactions of aggregates, high temperatures and irradiation (Naus, 1987).

Many studies have been conducted over the years on the deterioration of concrete in NRs; nonetheless, it is not very clear what the effects are as the concrete ages over time after being exposed to radiation. The objective of this report is to investigate the properties of aging concrete in NRs exposed to radiation. In particular, this report addresses the Savannah River Site (SRS) nuclear reactors.

2. METHODOLOGY

A literature study was conducted to investigate the properties of concrete in the SRS NRs exposed to radiation. The first part of this study analyzed the irradiation levels and types of concrete in SRS NRs. Due to the lack of information regarding the SRS NRs, comparisons were made with other types of reactors in order to investigate and estimate the irradiation levels experienced by the concrete as well as the components or types of concrete present in the reactors. The second part of this study investigated the irradiation levels that damage concrete and its relation to the SRS NRs irradiation levels.

3. REACTOR ANALYSIS

3.1 Irradiation levels

3.1.1 Reactor Vessel

The areas of main concern in NRs are the containment structure (biological shield (BS)) of the reactor vessel (RV) and the basins. At these locations, the contamination levels are high coming from alpha and beta particles, gamma-rays and neutrons (fast and slow); which originate from the decay of different isotopes and fission of atoms (in the BS). Table 1 shows a list of the most common elements found in NRs that emit the mentioned types of radiation. Among these types of radiation, gamma-rays and neutron irradiation are of concern because of their strong penetrating properties. As it can be seen from Table 1 most of the isotopes decay as gamma-rays. Similarly, there are also those who decay through spontaneous fission, which is where the fast and slow neutron radiation originates—these take place inside the BS due to its proximity to the RV.

Table 1 Common Sources of Radiation at Nuclear Reactors for the Production of Nuclear Weapons

Source of Radiation (Isotope)	Type of Radiation Emitted/Decay Mode	Half-Life
Strontium-90	Beta	28 years
Cesium-137	Beta/Gamma	30 years
Cobalt-60	Beta/Gamma	5 years
Tritium	Beta	12 years
Uranium-235	Alpha/Spontaneous Fission	703800000 years
Uranium-238	Alpha/Spontaneous Fission	4468000000 years
Plutonium-239	Alpha	87.74 years
Plutonium-240	Spontaneous Fission/ Alpha	6537 years
Plutonium-242	Spontaneous Fission/Alpha	376300 years

From “Reactor Concepts Manual,” Radiation sources at nuclear plants, by U.S. Nuclear Regulatory Commission (NRC) Technical Training Center, “Handbook of Health and Physics and Radiological Health (3rd ed.),” by Shleien, Slaback Jr., L. A., & Birky, B., K. (1998); “Special Nuclear Material,” by U.S. Nuclear Regulatory Commission. (2007); “Plutonium: The first 50 years, Unite States plutonium production, acquisition, and utilization from 1944 through 1994,” by U.S. Department of Energy.

Currently, the majority of the studies in existence regarding the deterioration of aging concrete by radiation in NRs pertain mainly to light water reactors (LWRs), pressurized heavy water-moderated reactors (PHWR or Canadian Deuterium Uranium (CANDU) reactors) and Graphite Reactors (GRs).

The types of NRs found at SRS are known as heavy water-moderated reactors (HWRs). One major difference between these reactors and LWRs is the type of moderator used to control the speed of neutrons. According to the Canadian Nuclear Association (CNA) (2008) and other HWR related papers, HWRs use heavy water as a moderator and coolant while the LWRs use light water (ordinary water) instead; in addition, heavy water absorbs less neutrons allowing the usage of natural uranium instead of enrich uranium (CNA, 2008). Although the CANDU reactors also use heavy water as a moderator and coolant, their design configuration is not the same as that of the reactors at SRS; nevertheless, their concept (using natural uranium by moderating with heavy water) is still the same. Thus, this was used as a basis to compare PHWRs to the HWRs. Both were assumed to have similar environments.

The HWRs built at SRS were designed to operate at less than 500 MW thermal, but they were later increased to 2500 MW from 1955 to 1965 in order to increase production (U.S. Department of Energy). Using Table 2, it was possible to classify the type of environment inside the SRS reactors using the CANDU reactors as a scale. Based on information depicted on the table, it can be deduced that the temperature in the reactor core ranged from ~260°C to ~315°C. Meanwhile, for the two types of LWRs, that is the boiling water reactor (BWR) and the pressurized water reactor (PWR), the temperatures ranges were from ~288°C to ~360°C (Busby et al. 2008). Taking the latter values into account, it can be seen that the PHWRs and the LWRs have a very close temperature range.

In Table 2, note *b* provides the irradiation levels present at a PHWR. The latter was used to compare the irradiation levels of LWRs shown in Table 3—1 Sv ~ 100 rads for gamma rays. As it can be seen from both tables, the range of fast neutrons found in the PHWRs and the PWRs at the 60 year operating period is roughly close. The values for the PHWRs are from inside the tube sheets or Calandria tubes (see Figure 1), thus once they go out the reactor vessel they are expected to be attenuated by the metal enclosing the tube sheets to approximately the same values of the PWRs. In addition, despite the difference in years and reactor type the values do not seem to differ—Table 3 presents values estimated in 1977 for LWRs while Table 2 presents values estimated in 2001 for PHWRs. Figure 2 shows the design of the HWR vessel which can be seen to resemble the PHWR or Calandria vessel.

Table 2 Characteristics of PHWRs with Different Thermal Output (MWt)

PHWR (CANDU)	Thermal Output (MWt)	Gross Electrical Output (MW(e))	Net Electrical Output (MW(e))	Operating Temperature (RIH) (°C)	Operating Temperature (ROH) (°C)
MZFR	200	57	50	251	280
Pickering A	1742	540	508	249	293
Pickering B	1744	540	508	249	293
Atucha 1	1179	367	345	265	299
Atucha 2	2160	744.7	693	279.9	312.3
Bruce A[a]	2551	791	740	265	305
Darlington	2949	936	881	267	310
CANDU 9[b]	2720	940	875	279	318

Note.

[a] Using the values from the Bruce A PHWR it was estimated that a NR at SRS (2500 MWt) would produce approx. 775.2 MW(e).

[b] CANDU 9 is a newly improved design of the current PHWR, it has a 90% capacity factor and a designed life of 60 years. The irradiation parameter inside the tube sheet of the calandria (reactor core) at the end of its life design is estimated to be 1.3 x 10^{21} neutrons/cm^2 for fast neutrons (E>1.0 MeV). Note that the irradiation parameter is less at the outside of the reactor core due to the attenuation by the inside components (primarily steel). None has been constructed as of yet.

From "Heavy water reactors: Status and projected development. Tech. Rep. No. 407,"International Atomic Energy Agengy. (2002); "Assessment and management of ageing of major nuclear power plant components important to safety: CANDU reactor Assemblies," by International Atomic Energy Agency. (2001). Retrieved July 30, 2009, from http://www-pub.iaea.org/MTCD/publications/PDF/te_1197_prn.pdf

Table 3 Estimated Irradiation Levels at the Outside Boundary of a RPV for Several Operating Periods

	BWR*			PWR*		
	40 Year (32 EFPY[a])	60 Year (60 EFPY)	80 Year (64 EFPY)	40 Year (32 EFPY)	60 Year (60 EFPY)	80 Year (64 EFPY)
Neutron Fluence (n/cm^2)						
Slow (E < 1.0 MeV)	3.7×10^{18}	5.6×10^{18}	7.5×10^{18}	2.0×10^{19}	3.0×10^{19}	4.0×10^{19}
Fast (E > 1.0 MeV)	5.1×10^{17}	7.7×10^{17}	1.0×10^{18}	1.0×10^{18}	1.5×10^{18}	2.0×10^{18}
Gamma Total Inegrated Dose (rads)	1.6×10^{10}	2.4×10^{10}	3.2×10^{10}	4.7×10^{9}	7.0×10^{9}	9.3×10^{9}

Note. * 1000 MW(e) plant with 80% capacity factor.
[a]EFPY = effective full-power years.
From: Copyright © 1977. Electric Power Research Institute EPRI NP-152, “PWR and BWR Radiation Environment for Radiation Damage Studies. Reprinted with permission.
Adapted from “Report on aging of nuclear power plant reinforced concrete structures,” by Naus, D. J., Oland, C. B., Ellingwood, B. R. (1996). NUREG/CR—6424, ORNL/TM—13148. Retrieved July 29, 2009, from http://www.osti.gov/bridge/product.biblio.jsp?query_id=0&page=0&osti_id=219361

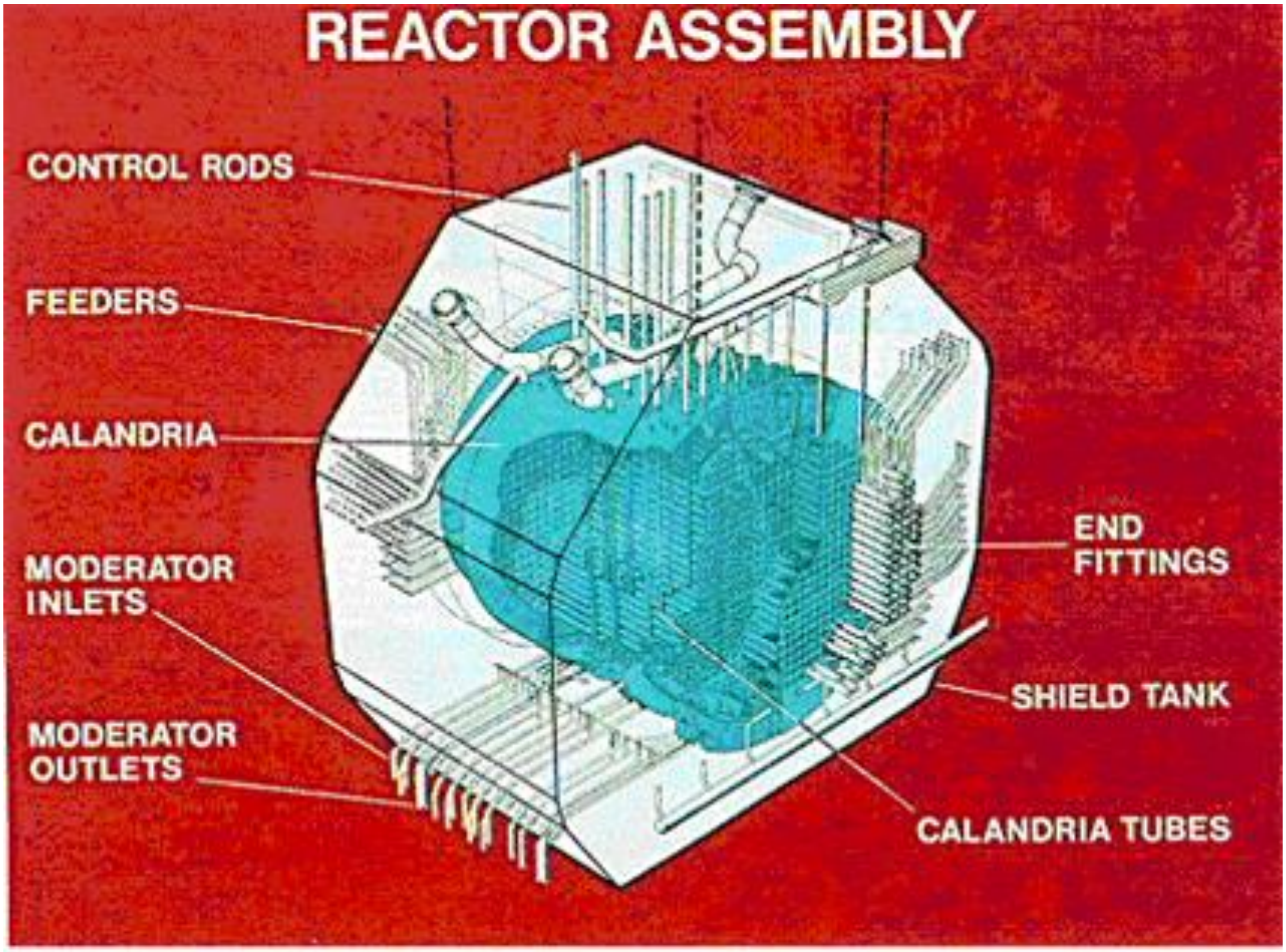

Figure 1 Calandria Vessel (PHWR Vessel)

From "Nuclear technology at work," by Canadian Nuclear Association (2008). Retrieved July 30, 2009. from http://www.cna.ca/curriculum/cna_nuc_tech/candu-eng.asp?bc=The Candu Reactor&pid=The Candu Reactor

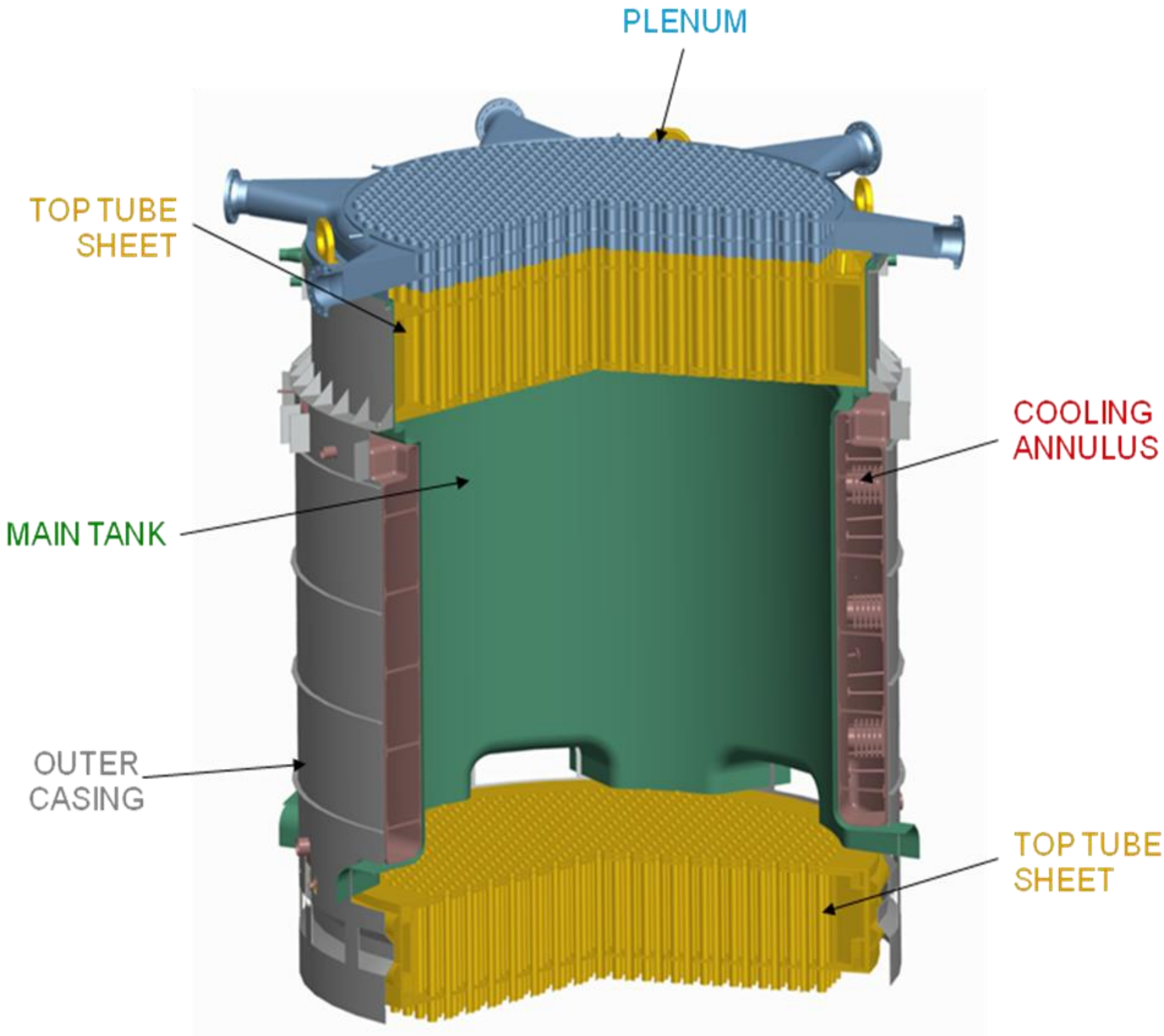

Figure 2 SRS HWR Vessel

From “General Reactor Figures at SRS,” by Serrato, M. (2009). SRNL-STI-2009-00584

From the information presented above, it can be seen that the environments among these different types of reactors are similar.

3.1.2 Basins

Contrasting the BS, the basins in the NRs of SRS are contaminated with different doses of radiation. Unlike the BS, more studies have been published regarding the basins located in SRS reactors. As mentioned before, the irradiation levels of the basin are lower than those of the experienced by the BS. For instance, the R-Disassembly Basin at SRS contains radiation levels of < 100mR/hr (1 R ~ 1 rad) in the Vertical Tube Storage (VTS) with hot spots of 75 R/hr and 134 R/hr in the Dry Cave Section (DCS) and Machine Basin (MB) areas, respectively (Pickett, 2000). At the same time, there is water in the basin which is contaminated with ~1.8 curies of Cesium-137 and Tritium concentrations of 38 x 10^{3} pCi/ mL (Pickett, 1998). These radiation values are not of the same magnitude of the ones the BS was exposed to (refer to Table 3—previously shown—for comparisons).

3.2 Concrete components

3.2.1 Biological Shield

The BS of the RV is where the most contamination is found at a nuclear reactor. The BS consists of the primary reactor shield (PS) and the secondary reactor shield (SS), where the PS encloses the RV and the SS surrounds the latter including the main coolant loop (Davis, 1972). The PS was usually built of concrete with a thickness varying between three feet to six feet (Davis, 1972; Boswell et al., 1964). Meanwhile, the SS was four to five feet thick (Davis, 1972).

According to studies conducted at the Oak Ridge National Laboratory (ORNL) GR, the PS was built using barite (to increase the concrete density and lower wall thickness), haymite (to increase concrete mix water content), water, bituminous coatings, and Portland cement (Blosser, 1958). As it is known, GRs were one of the first reactors built for the production of nuclear weapons; therefore, they served as a reference for the construction of the HWRs found at SRS. It is clear that the use of high-density or heavyweight concrete for the PS was a common practice due to its high resistance to radiation. Based on U.S. Patent No. 2,726,339 (1955), knowledge of the usage of high-density concrete as well as metal aggregates was known before the construction of the NRs at SRS. Furthermore, the usage of Type II Portland cement was very common in the construction of the BS (Davis, 1972). Admixtures (e.g., Plastiment and Intrusion Aid) were also used to enhance the flow of the dense concrete (Rockwell III, 1956). For the construction of the SS, ordinary concrete was used (Davis, 1972). The following standards contain a complete description of the mixtures used for concrete in the BS: ASTM C 33/C 33M-08, ASTM C 150/C 150M-09, ASTM C 638-92 (see references for ASTM description).

Based on the information above, it was assumed that the construction of the BS in NRs at SRS involved some if not all of the components presented above. In fact, according to Davis (1972) the construction of the PS in the N-Reactor at Hanford (Richland, Washington) was made out of several concretes, mortars, and grouts. Thus, not just one specified mixed was used. However, one of the main components that the PS in NRs at SRS is bound to have is barite. The construction of NRs was based on a budget and most of the time local aggregates were used as they were cheaper. Since SRS is located in South Carolina (SC), the closest sources of high-density aggregates were Tennessee and Georgia with barite (Searls, 2000). At the same time, gravel is abundant in SC and could have been used for the construction of the SS in the HWRs of the SRS.

Furthermore, the SRS NRs were not only shield with concrete. Water was also used as a thermal shield. This shield can be seen in Figure 3 which shows the cross section of the SRS NR reactor vessel.

3.2.2 Basins

Unlike the BS, the basins in the NRs at SRS were made of reinforced concrete with a varying thickness of 2.5 to 7 feet (Duncan et al., 2008). Epoxy coatings were also used to protect the reinforced concrete in the basin. According to Duncan et al. (2008), Amercoat 33 (vinyl paint) was one type of coating used to prevent its direct contact of the concrete with the basin water.

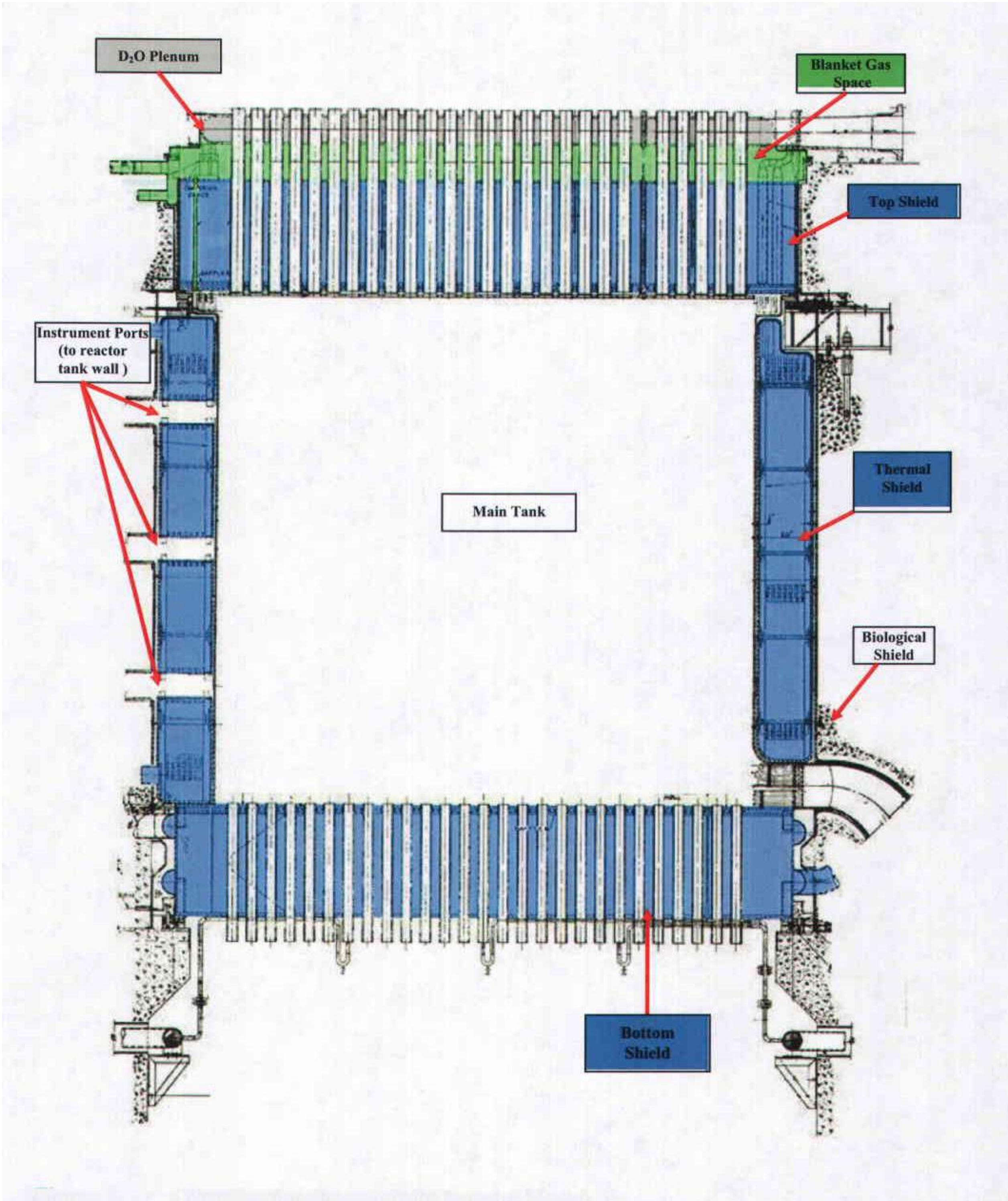

Figure 3 SRS HWR Vessel Cross Section

From "General Reactor Figures at SRS," by Serrato, M. (2009). SRNL-STI-2009-00584

4. LITERATURE STUDY OF CONCRETE BEHAVIOR UNDER IRRADIATION

Hilsdorf et al. argued that critical neutron and gamma irradiation levels causing concrete deterioration are in the order of 1 x 10^{25} neutrons/m^2 (1x 10^{21} neutrons/cm^2) and 10^{10} rad, respectively, resulting in the cracking of concrete (ACI 349.3R-02). Similarly, Morinaga argued that fast neutrons of the order of ~5 x 10^{19} neutrons/cm^2 causes expansion of aggregates and shrinkage of cement paste (Ichikawa & Kimura, 2007).These irradiation levels have been used as reference in many studies involving the irradiation of concrete but are nowhere near the values endured by a NR. Nevertheless, discrepancies exist as to whether the concrete is really affected in NRs by radiation at all (Clifton, 1991).

Several studies conducted explain that major deterioration of concrete occurs after being exposed to high doses of radiation. Granata and Montagnint (1972) reported that at neutron fluxes of the order 10^9 neutrons/cm^2 (at temperatures of 130°C) had minimal effects on Portland 730 and limestone aggregate (standard mortar) and Portland 730 cement and barite aggregate (BHT mortar); the gamma dose equivalent used during the experiment was measured to be 10^{11} roentgens (1roentgen ~ 1 rad). However, upon increasing the temperatures to 280°C—commonly found in HWRs—and neutron integrated flux up to 10^{20} neutrons/cm^2 the concrete samples were heavily damaged. Elleuch, Dubois, and Rappeneau (1972) conducted similar experiments using serpentine granulate and aluminous cement paste while maintaining a temperature of 200°C. The density was 2.51 g/cm^3, which was lower than that used in other high density concretes, especially that of barite. The samples were exposed to doses of 1.2 x 10^{19} n/cm^2 to 1.2 x 10^{20} n/cm^2 fast flux, resulting in dehydration of the cement paste and decreasing bending strength by 50% (Elleuch, Dubois, & Rappeneau, 1972). It was concluded that fluxes ranging from 2 x 10^{19} to 10^{20} neutrons/cm^2 damage concrete; nevertheless, the effects are noticed after irradiation doses of 3 x 10^{19} neutron/cm^2 with the expansion of the material, shrinking of the cement paste, and micro-cracking (Elleuch, Dubois, & Rappeneau, 1972).

One of the most common concerns in the study of the effects of radiation in concrete involves discerning between temperature- and radiation- related deterioration. To date, it has been difficult to determine whether the deterioration of BS in NRs comes from the radiation itself or the high temperatures in the RV. Yevick argued that temperatures of 150°F (~66°C) are the threshold in which the hydrated-water molecule bond begins breaking (El-Sayed Abdo & Amin, 2001). Based on a report studying the effects of temperature on heavyweight concrete, temperatures of 100°C starts decreasing the strength of the concrete; furthermore, if the temperature increases beyond 500°C the strength drops sharply (Sakr & EL-Hakim, 2005). Sakr and EL-Hakim (2005) also noted that magnetite and SF have high residual compressive strength after high temperature exposures. It can be seen from the information presented above that high temperatures are very detrimental to concrete. Referring back to Table 2, it can be seen that the temperatures at the SRS reactors were not as high as described by the studies of Sakr and EL-Hakin. However, the concrete in the BS suffered from the breaking of the hydrated-water molecule and decrease in strength as depicted above. Meanwhile, El-Sayed Abdo and Amin (2001) conducted a study that dealt with the temperatures caused by slow (thermal) neutrons of the order of 10^9 neutrons/cm^2 and their effects on concrete; it was found that the heat generation by thermal neutrons occurs in the first layer of the concrete (10 – 50cm) with values of 0.2 mW/ cm^3 (rise of 1.7°C) and 6.6E-3 mW/ cm^3 (rise of 0.125 °C), respectively. As denoted by the latter, the heat generated by the thermal neutrons is quite insignificant in comparison to the temperature generated by the RV as a whole.

As mentioned above, telling the difference between the effects of temperature and radiation in concrete is not relatively easy to discern when both are acting at the same time. Most of the studies presented on this paper have irradiated the concrete in the presence of temperatures ranging from 100°C to 280°C. In an effort to differentiate between the two, Lowinska-Kluge and Piszora (2008) evaluated the effects of radiation in different cement pastes without taking temperature into account. The experiment involved four different types of cement, i.e., one being ordinary, one containing fly ash (FA), another silica fume (SF), and the last was granulated (GA), irradiated with a Cobalt-60 source. The irradiation doses varied from 0 to 1409 MGy (1.409 x 10^{12}rads—values are converted to rads to compare to dose rates found at NRs). As it can be seen once again, the values used were higher than those estimated to be present in a NR (see Table 3). The results obtained by Lowinska-Klurge and Piszora (2008) showed that Portland cement samples were completely destroyed at irradiation levels of 836 MGy (8.36 x 10^{11}rads). Meanwhile the cement samples containing FA, SF, and GA showed progressive decomposition. The beginning signs of deterioration were at 130 MGy (1.3 x 10^{11}rads) in Portland cement, 290 MGy (2.90 x 10^{11}rads) in SF and FA cements, and 466 MGy (4.66 x 10^{11}rads) in GA cement; showing decomposition of the cement matrix, hydrates, clincker phase relicts, separation of chemically bonded water, and pseudomorphoses and densification (Lowinska-Klurge & Piszora, 2008). Most of the studies presented above, have irradiated the concrete with high doses of radiation. However, it needs to be understood that this values are at or above the published values for concrete damage. Suggestions have been made to keep a limited flux of 1 x 10^{17} neutrons/cm^2 dosage during the life-time of the NR to prevent the deterioration by irradiation (ACI 349.3R-02). Sha, V. N. and Hookhan (1998) argued that these high radiation values are not experienced by the BS of the LWRs, resulting in no detrimental effects.

Another important study was conducted by Ichikawa and Kimura. Although radiation-induced alkali-silica reactions (ASRs) do not take place during the lifetime of the NR as long as ASR-tolerant aggregates are used; according to them, lower doses of radiation (e.g., 1 x 10^8 rads and 1 x 10^{16}neutrons/cm^2) induce ASRs of aggregates containing silica-rich aggregates, such as plagioclase, as one of the major minerals. Nonetheless, the ASRs do not affect the soundness of the concrete structure (Ichikawa & Kimura, 2007). In addition, Swamy points out that it is unlikely that structures will collapse due to ASRs (Clifton, 1991).

Most of the studies about the deterioration of concrete due to radiation assume full power phase of the reactor. According to Stacho et al., radiation energies emitted by the RV are of up to 2 MeV for downtime phase and up to 10 MeV for full power phase. This means that the irradiation on the concrete is five times less when the reactor is not operating. Fillmore (2004) argues that the effects of low doses of radiation, i.e., <10^{10} neutron/cm^2 or 10^{10} rad gamma dose, over a period of 50 years are negligible. Several studies have shown that the deterioration of concrete at NRs involves chemical attack, leaching, irradiation, temperature, cement-aggregate reactions, fatigue, freezing and thawing, abrasion and erosion, etc. (see ASTM 349.3R-02; Naus et al., 1996).Taking this information into account, it can be concluded that overtime the major cause of deterioration for the concrete is not attributed to radiation alone. For instance, Basyigit et al. (2006) argues that freezing and thawing affects the attenuation properties of high-density concrete such as barite. This in turn makes the concrete vulnerable to radiation, and the irradiation makes the concrete vulnerable to the other types of deterioration. In other words, radiation and the other types of deterioration factors help one another deteriorate concrete over time at NRs, but with the effects of irradiation being insignificant.

One important study relating to irradiation of concrete was conducted at the ORNL GR. As mentioned before, the GRs served as a reference for the construction of the NRs at SRS. Blosser et al. (1958) investigated the properties of the PS used for the GR after being exposed to radiation for 12 years. The shield at this reactor was made out typical aggregates used for shielding, that is, barites-haydite concrete, ordinary concrete, and bituminous coating (see Blosser et al. 1958 for schematic and measurements). Their findings showed that radiation had no change on the chemical properties and density of the concrete used; nonetheless, the compressive strength was decreased by ~ 40% on the first layer (closest to the RV) made out of one foot of ordinary concrete. Similarly, another study conducted relating the Temelin PWR (in Czech Republic) yield a 10% decrease in the compressive strength of the concrete, the porosity was reported to have decreased by one-half, along with calcite formation, and signs of brittleness (Vodak et al., 2005). In this study, the concrete was exposed to irradiation levels of 5×10^5 Gy (5×10^7 rads)—57 years of normal operation; clearly, more than the operation of the SRS reactors (see Table 4 for SRS reactor operation time period). The concrete components used were siliceous gravel and CEM I 42,5R Mokra (see reference for composition).

Table 4 SRS Reactor Operation Period

Name	Start-Up Date	Shut-Down Date
R-Reactor	December 1953	June 1964
P-Reactor	February 1954	August 1988
K-Reactor	October 1954	Standby July 1992
L-Reactor	July 1954	June 1988
C-Reactor	March 1955	June 1985

Note. The operation time of these reactors were less than 40 years. From “Plutonium: The first 50 years, United States plutonium production, acquisition, and utilization from 1944 through 1994,” by U.S. Department of Energy. Retrieved July 30, 2009, from http://www.fas.org/sgp/othergov/doe/pu50y.html#ZZ0

5. DISCUSSION

The operation time of NRs plays a major role in the deterioration of concrete by radiation. The longer the operation time is the more radiation the concrete is subjected to. The literature study presented shows that the levels of radiation within the lifetime of the SRS NRs were lower than threshold values depicted earlier. As it was shown in Table 4, the operation time of the SRS NRs did not reach the 40 year mark.

The BS of the SRS NRs was made of various radiation resistant concretes or high density concrete (e.g., barites, haymite, etc.); thus, having better resistance to radiation deterioration than ordinary concrete as seen in the study conducted at the ORNL GR. Most of the studies presented above show different kinds of concrete mixtures irradiated at or beyond threshold values, having significant impact on concrete, especially ordinary concrete. Nonetheless, these irradiation values were not present in the lifetime of the SRS NRs.

The degradation of the reinforced concrete present at the basins of the SRS NRs can be attributed to other deterioration factors other than radiation. According to Pickett (2000), significant amounts of calcium and magnesium were found to be present in the basin water. Leaching of the concrete is a possible reason discussed by Pickett (2000). Water has been in the basin for years and it seems to have had penetrated the coating of the concrete causing this leaching. Furthermore, various kinds of debris are present in the basin water; with time its presence seems to have damaged the concrete coating allowing direct contact of the concrete with the water. Duncan et al. (2008) pointed out that the only visible signs of deterioration found at the basins are cracks do to shrinkage of the cement paste and water migration through the wall—they argued that the degradation is insignificant to the concrete. Meanwhile, there is no evidence that the concrete present at the basins have been affected by radiation. According to Vodak et al. (2005), calcite is a by-product of irradiation in concrete; nonetheless, a high dose of radiation (i.e., irradiation levels of 5×10^7 rads) is needed for a significant reaction. Still, this is not the case at the basins since the radiation levels are low and therefore not significant enough to cause major damage on the concrete structure as mentioned earlier.

6. CONCLUSION

A comprehensive study of the effects of radiation in concrete of NRs found at SRS was conducted. The study aimed at investigating the deterioration of concrete caused by radiation in the NRs found at SRS. Due to the lack of information available about these reactors, parameters were created to have a general idea of the environments the concrete was exposed to. These parameters were designed to provide an understanding of the conditions the BS (especially the PS) was exposed to at these reactors; due to its proximity to the RV, the BS is the only concrete structure in the NR that is highly affected by gamma-rays and neutron irradiation. By comparing the HWRs in SRS with the CRs (LWRs and PHWRs), an understanding of the temperature and irradiation levels was acquired. This understanding was used to relate the many studies done regarding aging of CRs to the HWRs at SRS.

It can be seen that the irradiation values shown were estimated within the operation time frame of most of the SRS reactors. Similarly, the levels calculated in recent years are close to these values. From this information it can be concluded that the levels of radiation are within the same range despite the reactor type. With the help of these parameters and the information presented, it can be deduced that the NRs at SRS were mostly affected by radiation deterioration during operation years; however, this deterioration did not have major effects on the properties of the concrete since the radiation levels were below the thresholds. Moreover, the operation time of the NRs did not exceed 40 years. This means that the BS was not irradiated long enough to suffer any significant damage.

From the information presented in this paper, it can be concluded that the effects of radiation in the concrete of the BS are not detrimental since the radiation doses interacting are below the threshold values (i.e., orders of ~10^{25} neutrons/cm^2 for neutrons and ~10^{10} rads for gamma-rays). Based on different studies presented, radiation values at or beyond these threshold values can damage the concrete severely, causing expansion of aggregates, shrinking of cement paste, brittleness, micro-cracking, dehydration of cement paste, and decrease in bending strength. Nonetheless, the irradiation levels found in many of these studies are beyond those found in a NR.

One common sign of deterioration that was noticed to occur within the lifetime of a NR involved the loss of compressive strength of the concrete. As proven by the studies of Blosser (1958), compressive strength of the PS in the ORNL-GR was decreased within the first layers (i.e., within one foot of ordinary concrete). Meanwhile, Vodak et al. (2005) conducted a more recent study with also concluding that the compressive strength of concrete is decreased by irradiation.

The basins were also taken into account in this study as there are significant levels of gamma-rays radiation in them, but not as strong as the levels found in the BS. Based on the information presented above, it was concluded that the levels of radiation present at the basins have insignificant effects on the reinforced concrete.

In conclusion, concrete found in the HWRs at SRS is not significantly affected by the irradiation levels coming from the RV or the basins.

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