An Integrated Systems Approach to Performance Assessment of Near Surface Disposal Facilities for Low Level Radioactive Waste Management

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Dissertation

Submitted to the Faculty of the

Graduate School of Vanderbilt University

in partial fulfillment of the requirements

for the degree of

DOCTOR OF PHILOSOPHY

in

Environmental Engineering

May, 2016

Nashville, Tennessee

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To my Mom, Nama, and Papa, for all of your unconditional support,
guidance, encouragement, and love

ACKNOWLEDMENT

This report is partially based on work supported by the U. S. Department of Energy, under Cooperative Agreement Number DE-FC01-06EW07053 entitled 'The Consortium for Risk Evaluation with Stakeholder Participation III' awarded to Vanderbilt University. The opinions, findings, conclusions, or recommendations expressed herein are those of the authors and do not necessarily represent the views of the Department of Energy or Vanderbilt University.

The completion of this research would not have been possible without the very positive support and guidance of my advisor, Dr. Jim Clarke. From the very beginning, your insights, vast experience, enthusiasm, and the personal commitment you have shown through all of the challenges and successes experienced during this dissertation have made me a better researcher, academic, and all around person. Your technical advice and consistent support have been a tremendous gift that will never be forgotten, and I am extremely grateful. I would also like to thank and acknowledge the support and academic excellence of my Dissertation Committee. Thank you, Dr. David Kosson, as a co-chair on my committee, for your technical input and continually supporting my research endeavors. I would like to thank Dr. Steve Krahn, for your many insights, detailed reviews, and invaluable feedback throughout as this research progressed. Thank you Dr. Mike Ryan and Dr. Craig Benson, I am grateful for your encouragement and support, and your input, comments, and suggestions were vital additions to this research.

To all of my family, who have unwaveringly supported me since day one, nobody has been more important to me in the pursuit of this degree. From the bottom of my heart, thank you for all that you've done for me and continue to do on a daily basis. I would like to thank my mom, whose love and support has always been present throughout all of my endeavors. I would also like to thank my grandparents, Nama and Papa, who along with my mom helped shape me into the person I am today and who remain my role models and a constant source of inspiration.

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LIST OF ABBREVIATIONS

AEA	Atomic Energy Act of 1954
AEC	(United States) Atomic Energy Commission
ALARA	As Low As Reasonably Achievable
CA	Composite Analysis
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CFR	Code of Federal Regulations
CH	Contact Handled
COPC	Constituents of Potential Concern
CWA	Clean Water Act
CWR	Complex-Wide Review
DAS	Disposal Authorization Statement
DNFSB	Defense Nuclear Facility Safety Board
DOE	(United States) Department of Energy
DU	Depleted Uranium
EIS	Environmental Impact Statement
EM	Department of Energy Office of Environmental Management
EMWMF	Environmental Management Waste Management Facility (Oak Ridge)
EPA	(United States) Environmental Protection Agency
ERDA	(United States) Energy Research and Development Administration
ET	Engineered Trenches
EVT	Evapotranspiration Cover
FFCA	Federal Facilities Compliance Act
GCL	Geosynthetic Clay
HDPE	High-Density Polyethylene
HLW	High Level Radioactive Waste
IAEA	International Atomic Energy Agency
IC	Institutional Control
ICRP	International Commission on Radiological Protection
IDF	Integrated Disposal Facility (Hanford)
INL	Idaho National Laboratory
ISMS	Integrated Safety Management System
LFRG	Low Level Waste Disposal Facility Federal Review Group
LLW	Low Level Radioactive Waste
NBS	(United States) National Bureau of Standards
NEPA	National Environmental Policy Act
NNSS	Nevada National Security Site
NOAA	(United States) National Oceanic and Atmospheric Administration

NRC	(United States) Nuclear Regulatory Commission
NSDF	Near Surface Disposal Facility
ORR	Oak Ridge Reservation
PA	Performance Assessment
RCRA	Resource Conservation and Recovery Act
RH	Remote Handled
RWMC	Radioactive Waste Management Complex (Idaho)
RWMS	Radioactive Waste Management Site (Area 5)
SA	Special Analysis
SDA	Subsurface Disposal Area
SRNL	Savannah River National Laboratory
SRS	Savannah River Site
TEDE	Total Effective Dose Equivalent
TRU	Transuranic Waste
TSCA	Toxic Substances Control Act
UMTRA	Uranium Mill Tailings Remedial Action
UMTRCA	Uranium Mill Tailings Radiation Control Act
US	United States
WSRC	Westinghouse Savannah River Company

CHAPTER 1

INTRODUCTION

1.1 Motivation

The United States (US) has been producing radioactive waste for over 70 years, beginning with the Manhattan project in 1941 and continuing to the present day (US Department of Energy, 1996a; Gosling, 2010). This waste comes from a number of sources, such as the production of nuclear weapons, production of nuclear power, research on new applications for radioisotopes and their use in medical applications, and from the cleanup of contaminated material (US Department of Energy, 1997a). Over the past decades proper and safe disposal of these diverse waste streams has proven to be a major challenge for the US and the international community. The unique hazards posed by radioactive wastes require that the waste remain isolated for a sufficient period of time, in order to adequately protect the public and environment from harm. The amount of time depends on the quantity and half-life of the radionuclides present.

High-level and high activity radioactive waste (HLW) such as reprocessed nuclear fuel needs to be isolated deep underground for tens of thousands of years in a geologic repository (US Department of Energy, 1997a). Low level radioactive waste (LLW) can be buried closer to the surface, in special engineered disposal facilities, which combine different types of natural and engineered barriers to keep the waste isolated and prevent it from migrating into the surrounding environment (EG&G Idaho, 1994; National Research Council, 2007; Westinghouse Savannah River Company (WSRC), 2008). Typically these facilities need to perform for 1,000 years, a significant challenge considering there is approximately 70 years of experience working with

LLW disposal. Performance of LLW disposal facilities is based upon meeting a set of performance objectives. These objectives are designed to provide an adequate level of protection from the radiological hazards of buried waste by limiting the total amount of disposed waste in each facility.

The hazardous nature of LLW and the 1,000 year period of compliance dictates that a detailed analysis of facility performance be conducted before the start of waste disposal, and updated throughout the operation of the facility. This is accomplished by conducting a [radiological] Performance Assessment (PA), a form of systematic risk analysis used to answer four fundamental questions: " (i) what can happen; (ii) how likely is it to happen; (iii) what are the resulting impacts; (iv) and how these impacts compare to regulatory standards" (Eisenberg et al., 1999; US NRC, 2000). The DOE defines a PA as "an analysis of a radioactive waste disposal facility conducted to demonstrate there is a reasonable expectation that performance objectives…will not be exceeded following closure of the facility" (US Department of Energy, 1999c).

While each PA is different based on the requirement of the regulating agency and the preferences of the authoring organization, there is a logical progression of steps to any PA (Case and Otis, 1988). The first step is to establish the scope of the analysis within the PA and highlight the performance objectives (Shott et al., 1998). The second step is a characterization of all relevant site data (e.g., climate and geology), projected waste inventory, and proposed engineered barrier design. This is followed by the actual analysis of disposal facility performance. Results are used to establish performance-based disposal concentration limits, identity future data needs, and provide a basis for future research to reduce uncertainties in the PA.

Within the analysis of the PA, site engineers and staff must make a number of design decisions for the disposal facility based on the proposed inventory, current best practices, and expert opinion. These engineered disposal facilities incorporate a number of components selected to isolate waste from the environment (Bonaparte et al., 2002; National Research Council, 2007; Westinghouse Savannah River Company (WSRC), 2008). One component is the cover system, placed over the waste and designed to prevent liquids from entering the disposal facility waste zone, the isolated area within the facility containing waste. This is accomplished by resisting the downward flow of moisture or diverting it around the disposal facility (Scanlon et al., 2005). Another component is the liner system. Situated below the waste zone, it acts to prevent waste mobilized in liquid from leaving the disposal facility. Some designs can also remove liquids that collect within the bottom of the waste zone. A third component is the waste form. This represents the type of disposed waste, such as contaminated clothing, equipment, soils, and containers. Depending on the type of waste, the waste form can be disposed of "as is" or be encased in a stabilizing bulk matrix (e.g., waste mixed with grout or vitrified waste). A fourth component is the waste package, the overpack container holding the disposed waste. There are a variety of waste packages: 55-gallon drums, steel canisters, wooden crates, B-25 boxes, and Sealand containers.

The US Department of Energy (DOE) and the US Nuclear Regulatory Commission (NRC) are both in the process of reviewing their respective requirements and guidelines for disposal of LLW (Letourneau, 2010; Abdel-Khalik, 2011). These reviews will take into account advances in understanding of LLW disposal, and issues that have arisen from implementation of the previous set of disposal requirements. The DOE has also been interested in improving consistency in the PA process across the DOE complex, which could lead to an increase in confidence in the PA and disposal facility performance (Letourneau et al., 2009). One area that has been identified in past work relates to the question of when should a DOE disposal facility contain a liner system, and what type of liner should be used (Adams et al., 2009).

This dissertation examines ways to improve the PA process. Lessons learned will be analyzed from historical and current approaches in the DOE and NRC to confirm performance and build confidence in conceptual and mathematical models of disposal facilities. Areas that show potential are the concept of modeling a near surface disposal facility (NSDF) as an integrated system of components, and the use of performance monitoring methodologies to better assess the current and future performance of a disposal facility. Ultimately, the goal of this research is to develop a risk-informed decision-making tool to determine the effects of system components, how they influence each other, and on their combined contribution to LLW NSDF performance.

1.2 Research Objectives

The goal of this research is to demonstrate the development and applicability of an integrated "system of components" framework for analyzing the performance of a NSDF. The specific objectives are:

1) The establishment of a system of components framework for performance evaluation that identifies all components important to performance e.g., waste form, liner, cover, waste specific factors, and site-specific environmental factors.

2) The evaluation of the waste zone for a NSDF, based on past and current practices at DOE disposal sites and the effects of corrosion on the buried waste packages over time.

3) Identification of the effects of changing waste zone parameters on the time to hydraulic failure of buried carbon steel waste packages.

4) Modeling leachate buildup within waste packages and the subsequent release of leachate following hydraulic failure of the waste packages.

5) Modeling of the effects of changing the installation date of an interim engineered cover over a filled section of a NSDF on leachate buildup and release to the environment.

In Chapter 2, the regulation of LLW disposal for the US is discussed in detail. The chapter begins with an extensive history of the DOE, the creation of the Environmental Management (EM) division, and current state of regulations for disposal of DOE LLW. The NRC and its history are then discussed in the context of commercial LLW regulation and disposal. The two different approaches, with their two sets of performance objects, are compared and contrasted. The LLW PA process is then discussed, followed by current efforts to improve consistency in the process through the use of performance confirmation.

Chapter 3 introduces the concept of an integrated "system of components" framework to be used within the PA process. This framework considers a NSDF as a system of three components: the engineered (cover and liner system) component, the waste component (composition, form, and package) and the site-specific environmental component (precipitation, geology, hydrology). The framework establishes that each of these components influences the overall performance of the NSDF, and therefore all three need to be considered when assessing both current and future NSDFs. In order to establish the current state of the practice for DOE LLW disposal, five major DOE disposal sites were compared through investigation of their relevant component parameters.

Chapter 4 focuses on the waste component of a NSDF. The effects on waste packages were evaluated based on changing parameters within the waste zone. Current practice within a NSDF PA is to assume that all waste packages have fully degraded by the end of the 100-year post operational institutional control (IC) period. Within the context of NSDF performance, this assumption means that the fully degraded waste packages would provide no barrier to waste movement within the waste zone. The impacts of changing the degradation parameters and changing the waste package assumption were then assessed using two corrosion cases and four corrosion scenarios. The two corrosion cases, a constant rate of corrosion, and a decreasing rate of corrosion, were chosen to reflect results from historical studies of metals buried in soils. The four corrosion scenarios represented changes in the corrosivity and aeration parameters of the waste zone related to estimated future waste zone conditions. These conditions were based on historical and current operating practices at the DOE Savannah River Site (SRS). The results showed that under certain conditions waste packages remain hydraulically (can hold liquid) intact beyond the 100-year IC period, and some waste packages will be completely filled with liquid from precipitation infiltrating the waste zone through the NSDF engineered cover.

In Chapter 5, the corrosion results from the previous chapter are taken and integrated with a NSDF cover system and environmental conditions modeled off of operating NSDFs at the SRS. Three infiltration situations were established based on past, current, and potential future cover installation practices at SRS. This was done to show the timing effects of installing a cover system on the buildup of liquid within waste packages, and the liquid's subsequent release from the waste packages when the packages hydraulically fail. Results showed that liquid buildup within the waste zone can vary by over 200 percent from past practices to the proposed future practices.

Finally, Chapter 6 provides a summary of the findings for using an integrated system of components framework and the applicability of this framework to future NSDF PAs. The chapter concludes with suggestions for future work to further develop and expand the applicability of the framework.

CHAPTER 2

LITERATURE REVIEW

2.1 History of DOE LLW Regulations

The fundamental problem of how to manage radioactive waste, a man-made and long-lived hazardous waste stream, has been a continuing challenge for the United States (US) government. The arm of the federal government in charge of the nation's nuclear waste legacy is the Department of Energy (DOE). This agency draws its history from the original national defense activities of the Manhattan Project. Following the end of World War II, nuclear activities were put under civilian control and rebranded as the Atomic Energy Commission (AEC) in 1946 (US Department of Energy, 1996a). The new commission had the dual responsibility of continuing to develop the nation's nuclear weapons arsenal and the peaceful implementation of science and technology related to atomic activities. Along with these new goals was the responsibility to safely handle all nuclear waste generated by the government's nuclear activities, both past and future, and manage the waste to adequately protect human health and the environment.

The AEC's authority to manage and dispose of radioactive waste was further expanded in the Atomic Energy Act of 1954 (AEA) Section 161(i). This additional authority granted the agency the power to self-regulate all of its activities regarding nuclear and radioactive material to "protect human health and minimize danger to life or property" (("The Atomic Energy Act of 1954," 1954; US Department of Energy, 1999b)). This was a daunting task, as both substantial quantities and different types of waste were created in the development of nuclear weapons. Initial disposal options during the Manhattan project were limited due to the constraints of time and manpower imposed by the war effort. As well, during this time period the health and environmental hazards of radioactive waste, along with the ability of the waste to move through environmental media, were not well understood. This led scientists to dispose of large quantities of low level radioactive wastes (LLW) in a number of unsatisfactory ways, such as placing LLW mixed with liquids in outdoor lagoons to evaporate or burying the waste in unlined soil trenches (US EPA, 2013).

In the case of liquid high level radioactive waste (HLW), derived from the reprocessing of spent nuclear fuel and contains a mixture of fission products, uranium, plutonium, and actinides, these wastes were stored in large underground metal tanks of up to one million gallons. Complicating matters for HLW, most of these tanks were made of carbon steel, which corrode in the presence of a strong acid. HLW coming from repossessing was dissolved in nitric acid, which required the waste to be neutralized with caustic substances (usually sodium hydroxide) before placement in the tanks. This would later become important to the disposal of LLW because once the tanks are emptied of their liquid HLW fraction, some of the remaining insoluble material, along with the tanks themselves, are currently being considered as potential LLW streams.

2.1.1 Creation of the DOE and Early Regulation

During the early 1970s, the US Congress became concerned with the AEC's dual mandate of promoting nuclear power and regulating safety within the industry. To address this concern, the AEC was separated into two independent organizations under The Energy Reorganization Act of 1974 (42 U.S.C.A. § 5801) (US NRC, 2007). The Energy Research and Development Administration (ERDA) retained the AEC's promotion of atomic energy for civilian and defense purposes, along with the AEA authority to self-regulate waste generated as a result of defense or government activities. The US Nuclear Regulatory Commission (NRC) received broad authority to regulate the civilian nuclear program, including all radioactive wastes generated from civilian activities. A few years later, as a result of the severe oil and energy crisis facing the country, President Carter signed into law The Department of Energy Organization Act of 1977, which created the present-day DOE (P.L. 95-91, 91 Stat. 565). The ERDA, along with a number of other federal agencies and programs, were absorbed into this new agency. With regards to LLW, similar to ERDA, the DOE retained all of the self-regulating authority granted under the AEA.

Also during the 1970s, concerns over radioactive waste began to grow. One of the first efforts to provide legislative remedies to this problem was the Uranium Mill Tailings Radiation Control Act (UMTRCA) of 1978 and the resulting Uranium Mill Tailings Remedial Actions (UMTRAs). This legislation was also one of the first crafted to address a specific radioactive waste stream (Jacobs Engineering Group Inc., 1999). This goal of this act was to remediate the large uranium mill tailings sites left behind from the mining of uranium ore. These sites contained both uranium and all of the associated uranium decay daughter products, such as radium and radon gas. Remediation was accomplished by placing the tailings piles under engineered cover systems to prevent the infiltration of waste mobilizing precipitation while also providing a barrier against the escape of radon gas.

With regards to government (defense) LLW, the next step came during the late 1970s and early 1980s with the enactment of two major pieces of regulation. The first was the Resource Conservation and Recovery Act (RCRA) in 1976, which gave the US Environmental Protection Agency (EPA) the authority to regulate the generation and disposal of hazardous and radioactive wastes from currently operating facilities ("Resource Conservation and Recovery Act," 1976). The second was the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) in 1980. This act was also managed by the EPA and regulated the cleanup of legacy facilities that were no longer in operation but contained sufficient amounts of legacy material hazardous to human health and the environment ("Comprehensive Environmental Response, Compensation, and Liability Act," 1980). However, when RCRA (and also the Clean Water Act of 1977[CWA]) were first promulgated the DOE refused to comply, arguing successfully that because DOE facilities were federal entities they were entitled to the "sovereign immunity" clause of RCRA, and therefore not subject to administrative and civil fines and penalties (Office of Health Safety and Security, 2011).

With the Cold War winding down near the end of the 1980s, the DOE began to shift its resources from the research and production of nuclear weapons to dealing with the radioactive waste that had been produced over the previous four decades. This led to the creation of the Office of Environmental Restoration and Waste Management in 1989, which was soon renamed the Office of Environmental Management (EM). While the DOE had previously lost the ability to regulate commercially generated HLW and LLW with the Department of Energy Organization Act of 1977, it still contained the power to self-regulate waste generated from national defense activities. The management of this waste was covered under DOE Order 5820.2A, Radioactive Waste Management. Issued on September 26th, 1988, the main purpose of this order was "to establish policies, guidelines, and minimum requirements by which the DOE manages its radioactive and mixed waste and contaminated facilities" (US Department of Energy, 1988).

2.1.2 FFCA of 1992 and DNFSB Recommendation 94-2

During the late 1980s and early 1990s, radioactive waste management practices by the DOE were under increasing scrutiny, ultimately leading the state of Ohio to sue the DOE over the department's stance on "sovereign immunity" with regards to the CWA and RCRA. While the

US Supreme Count in DOE VS. OHIO 1992 eventually decided in favor of the DOE, members of Congress believed that the federal government needed to operate under the same rules and regulations as the private sector when it came to pollution (Office of Health Safety and Security, 2011). This lead to the promulgation of the Federal Facilities Compliance Act of 1992 (FFCA), which waived the right of sovereign immunity for all federal facilities under the regulation of RCRA ("The Federal Facilitiy Compliance Act of 1992," 1992). The act also ordered the DOE to enter into negotiated agreements between waste generation sites and the respected states where they were located. Cleanup milestones were established and civil fines and penalties could be levied against the DOE for violation of these agreements.

Within this context, LLW management within the new Office of Environmental Management was challenging from the start. Order 5820.2A was attacked both internally from DOE staff and externally from watchdog groups, who contended that the order was vague and did not provide sufficient guidance for adequate management and disposal of the DOE's LLW. One of the more influential critics was the Defense Nuclear Facility Safety Board (DNFSB), an independent review group established by Congress to provide recommendations on safety across the DOE complex.

In particular the DNFSB had substantial issues with the LLW portion of Order 5820.2A, and in 1994 wrote Recommendation 94-2 to the Secretary of Energy addressing the board's concerns with DOE LLW management practices (DNFSB, 1994). Titled "Conformance with Safety Standards at Department of Energy Low-Level Nuclear Waste and Disposal Sites", the board identified a number of concerns and offered recommendations that it believed were critical to insuring safe disposal of LLW (taken from DOE G 435.1-1 Appendix A) (US Department of Energy, 1999a). The first concern was that the DOE had not kept pace with the evolution of commercial practices for waste disposal, with examples at DOE sites such as "minimal barriers to infiltration and biologic intrusion, no requirements to protect inadvertent human intruders, and operational practices not geared toward maintaining integrity of the waste form and the cover" (DNFSB, 1994; US Department of Energy, 1999a). The second dealt with the requirement in DOE 5820.2A for the creation a PA at each site to show that the disposal facility will meet basic performance objectives similar to those outlined in NRC 10 CFR 61. However, since the order was created there had not been a completion of any PA process. The third issue was that requirements for a PA allowed the application of reference dose criteria to individual disposal facilities, ignored composite effect from interacting adjacent source terms, and excluded doses from legacy waste buried prior to the creation of the order in 1988. A fourth concern was that some burial practices at the time were inadequate and would not meet performance objectives. Along with the likely prospect of one day having to remediate wastes disposed of prior to 1988, the DOE was severely underestimating projections of total LLW volumes.

One main recommendation was that the DOE needed "additional requirements standards, or guidance on LLW Management". This was because there were a number of substantial issues not addressed in 5820.2A, such as how to handle established agreements with States/Tribes/EPA authorities for management and disposal of wastes at sites under provisions of either RCRA or CERCLA. Finally, the other main recommendation was that the "DOE needed to improve its modeling and predictive capability for assessing radionuclide migration, enhancing stability of buried waste forms, deterring intrusion, and inhibiting migration of radionuclides" (US Department of Energy, 1999a).

2.1.3 1996 Complex-Wide Review and DOE Order 435.1

In response to the recommendations of the DNFSB, EM began an extensive revision of Order 5820.2A, and released draft version 5820.2B for DOE and DNFSB comment in May 1995 (US Department of Energy, 1999a). While this version contained a detailed set of deposal requirements, the technical basis behind these requirements and their correlation to guidance within the Order was not clear. Over 1,000 comments from internal DOE and DNFSB reviewers were written when the draft was released for review, with 41 serious safety concerns highlighted by the DNFSB. In light of the inadequate nature of draft 5820.2B, EM decided to scrap the revision process and focus on creating a new order that addressed the many concerns raised by the review staff (US Department of Energy, 1999a; Letourneau et al., 2010).

The first step was a comprehensive review of all LLW management activities within the DOE Complex to locate problems that could have an effect on public and worker safety (Letourneau et al., 2010). Conducted across 36 sites, the 1996 Complex-Wide Review (1996 CWR) provided a baseline assessment of the DOE's LLW disposal activities. The CWR identified 6 major weaknesses with the DOE's current practices, along with a number of site-specific issues. These 6 areas of concern mirrored the recommendations within DNFSB 94-2: there was insufficient forecasting and capacity planning of LLW disposal, ineffective characterization of LLW, continued storage of LLW with a disposal path along with a lack of proper storage conditions for all LLW, there existed quantities of orphaned LLW (no path to disposal), and finally that the PA process does not contain stringent requirements on content and has yet to produce an approved document (US Department of Energy, 1996b).

Using the findings from the CWR and Defense Board recommendations, a new order was completed in the form of DOE Order 435.1, which was issued and implemented in 1999 (with an accompanying Manual (M) 435.1 and Implementation Guide (G) 435.1). Included in this new Order were requirements for the management and disposal of HLW, transuranic waste (TRU), LLW, and the radioactive component of mixed waste (DOE G 435.1 Appendix A). In creating Order 435.1, DOE staff used a process known as the Integrated Safety Management System (ISMS), since it "provided a formal, organized process for planning, performing, assessing, and improving" the DOE's approach to LLW management (Letourneau et al., 2010). There were a number of objectives driving the creation of the final Order (taken from DOE G 435.1-1 Appendix A):

- Incorporation of the recommendations made by the DNFSB (in 94-2 and on 5820.2B) and comments made in response by internal DOE staff;
- Development of a defendable technical basis for requirements and guidance within the Order;
- Development of requirements that are risk-informed and performance-based, as opposed to prescriptive requirements (such as those used under RCRA);
- Adequately address the concerns of stakeholders;
- Other emerging considerations, including a shift closer to external regulation, the adoption of industry consensus standards, and DOE's efforts to delegate more operation authority to field managers.

In operation for over 15 years, Order 435.1 continues to be the main directive governing DOE LLW disposal, and has provided the framework for a number of successful PA, such as the E-

Area LLW disposal facilities at the Savannah River Site (SRS) and the RWMC at Idaho National Labs (INL) (DOE Idaho, 2007; Westinghouse Savannah River Company (WSRC), 2008). EM has recently finished an updated Complex-Wide Review, and is now in the process of revising and updating Order 435.1 (though unlike 5820.2A, this is not planned to be a completely new Order) (Letourneau et al., 2010). EM staff is hoping to address the concept of performance monitoring within the new Order and accompanying guidance. As well, there have been discussions to combine the current Order 435.1 performance objectives and PA process with international standards and methods developed through the International Atomic Energy Agency (IAEA).

2.2 The Nuclear Regulatory Commission Approach to LLW Disposal

In the first few decades after the Manhattan Project, the AEC was responsible for both promoting and regulating the civilian nuclear industry (US Department of Energy, 1997a; US NRC, 2007). Congress acted to change this conflicting dual mandate with The Energy Reorganization Act of 1974, removing the regulating aspect from the AEC's mission and giving this responsibility to the newly created NRC [42 U.S.C.A. § 5801; Public Law 93-438]. As mentioned in section 2.1.1, the NRC received all of the licensing and rule-making authority contained within the AEA of 1954 with regards to the civilian nuclear program (US NRC, 2007).

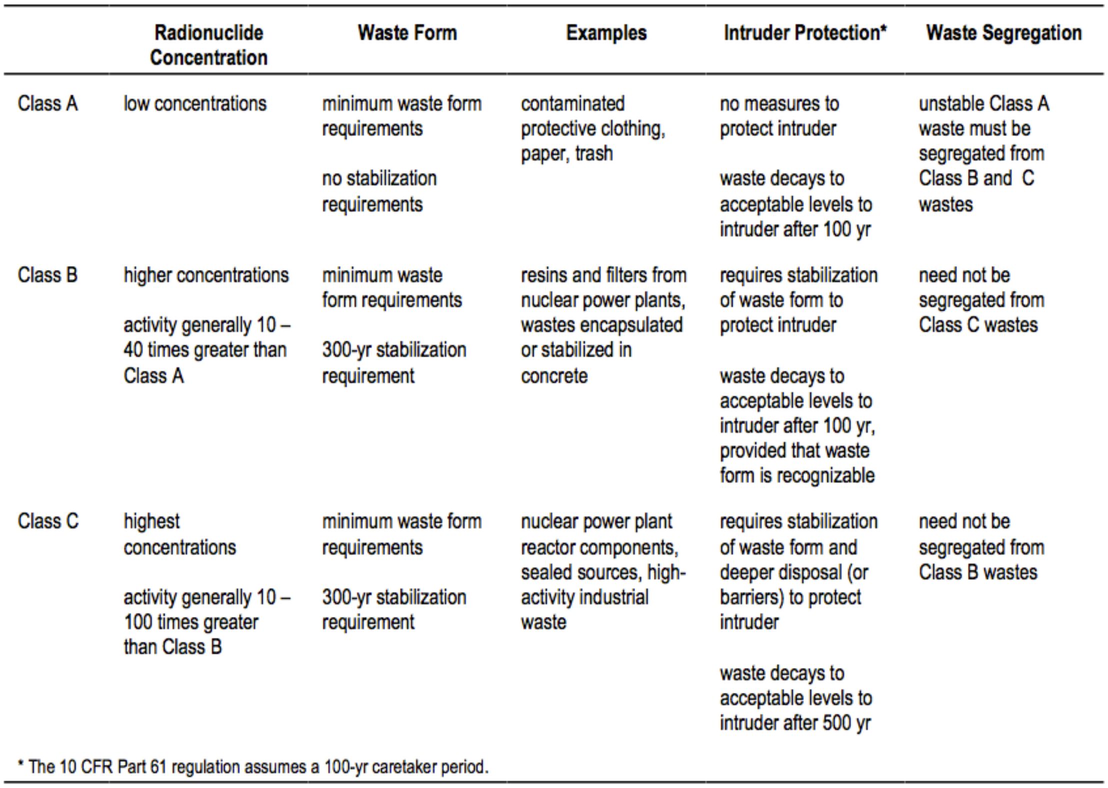
Beginning with the AEC, LLW was regulated using a group of basic and generic regulations. These regulations were included in sections of 10 CFR 20, "Standards for Protection Against Radiation;" 10 CFR 30, "Rules of General Applicability to Domestic Licensing of Byproduct Material;" 10 CFR 40, "Domestic Licensing of Source Material;" and 10 CFR 70, "Domestic Licensing of Special Nuclear Material" (US NRC, 2000; US NRC, 2007). The NRC upon its creation continued to use these regulations as the basis for their operations. They also began a formal rulemaking process to address a number of growing needs and concerns from public and industry stakeholders, along with Congress and local state governments. These concerns developed in part from the failures of early LLW disposal at sites such as Maxey Flats, which were found to have been leaking liquid containing radionuclides into the surrounding environment. Also during this time, there did not exist a defined set of standards (either domestically or abroad) that could be referenced to properly assess whether a LLW disposal facility would provide sufficient protection to the public from disposed waste (US NRC, 2007).

The goals for the new set of regulations were to create a "set of comprehensive standards, technical criteria, and licensing procedures" for the licensing of new commercial LLW disposal sites along with operational and closure requirements for existing sites. A formal National Environmental Policy Act (NEPA) scoping process was initiated in 1978, and four years later the final set of regulations were promulgation in December 1982 as 10 CFR 61, "Licensing Requirements for Land Disposal of Radioactive Waste" [(US NRC, 2007);47 FR 57446)].

The new set of regulations was designed to be applicable to all near surface disposal facilities (NSDF) containing commercial LLW. A detailed discussion of 10 CFR 61 is contained within NUREG 1853, "History and Framework of Commercial Low-Level Radioactive Waste Management in the United States" (US NRC, 2007). Requirements were included on all aspects of LLW disposal, incorporating sections on site selection, facility design, waste form, licensing, site closure, and minimum performance standards during operation and post-closure. Requirements for licensing stressed an integrated systems approach to ensure the facility achieved the relevant performance objectives over its design life. Strong consideration was given to passive engineered waste containment systems (barriers) to adequately protect against release after the institutional control (IC) period of radionuclides with long half-lives.

The idea of the human intruder scenario and protecting the "Inadvertent Intruder" was also introduced for the first time within 10 CFR 61. The concept assumed that disposed waste would be hazardous long after ICs had ended, and that precautions should be taken to provide protection to a future member of the public who might inadvertently come in contact with disposed waste. Flexibility in site design and operation was given to ensure that a NSDF would meet all performance objectives over a wide range of site characteristics (i.e. precipitation, geology/hydrogeology) and waste streams (46 FR 38083). This was done to account for the varying mobility of radionuclides and thus their availability for groundwater/surface water exposure pathways within different environments. Radionuclide mobility can be influenced by the amount of moisture that comes in contact with disposed waste, along with the underlying geomorphology and hydrology of a site.

Site design flexibility was achieved with the creation of a waste classification system, which took into consideration the relative concentrations of short-lived and long-lived radionuclides. Waste can be designated as class A/B/C based on a series of criteria laid out in 10 CFR 61.55 (see figure 2.1 for a detailed explanation of the classification system). Class A waste is the least hazardous and requires the least stringent disposal requirements. Class B waste disposal must meet certain enhanced waste form requirements to guarantee disposal stability. Class C waste must be disposed in a facility that provides additional protection for inadvertent intruders up to 500 years after disposal, along with meeting Class B stability requirements (section 61.52, see below).



	Radionuclide Concentration	Waste Form	Examples	Intruder Protection*	Waste Segregation
Class A	low concentrations	minimum waste form requirements no stabilization requirements	contaminated protective clothing, paper, trash	no measures to protect intruder waste decays to acceptable levels to intruder after 100 yr	unstable Class A waste must be segregated from Class B and C wastes
Class B	higher concentrations activity generally 10 – 40 times greater than Class A	minimum waste form requirements 300-yr stabilization requirement	resins and filters from nuclear power plants, wastes encapsulated or stabilized in concrete	requires stabilization of waste form to protect intruder waste decays to acceptable levels to intruder after 100 yr, provided that waste form is recognizable	need not be segregated from Class C wastes
Class C	highest concentrations activity generally 10 – 100 times greater than Class B	minimum waste form requirements 300-yr stabilization requirement	nuclear power plant reactor components, sealed sources, high-activity industrial waste	requires stabilization of waste form and deeper disposal (or barriers) to protect intruder waste decays to acceptable levels to intruder after 500 yr	need not be segregated from Class B wastes

* The 10 CFR Part 61 regulation assumes a 100-yr caretaker period.

Figure 2.1: Chart reproduced from NUREG-1853 p.4 (US NRC, 2007); information taken from NUREG/BR-0121 (US NRC, 1989).

In order to aid both LLW license applicants and NRC review teams with the implementation of 10 CFR 61, a number of guidance documents (four in particular were significant contributors of guidance) were subsequently developed by NRC staff. The first of these written after the promulgation of 10 CFR 61 was NUREG-1300, “Environmental Standard Review Plan for the Review of a License Application for a Low-Level Radioactive Waste Disposal Facility” ((US NRC, 1987)). This document provided general guidance on license review to applicants and NRC review staff, including relevant information that needed to be incorporated into a LLW disposal application Environmental Impact Statement (EIS). As part of the Low Level Waste Policy Act, each 10 CFR 61 application required the creation of an EIS (US NRC, 2000; US NRC, 2007).

The next document, issued in 1991, was NUREG-1199, “Standard Format and Content of a License Application for a Low-Level Radioactive Waste Disposal Facility”, and details the requirements set forth in 10 CFR 61 for the Licensee in drafting a license application ((US NRC, 1991)). Following this in 1994 was NUREG-1200, “Standard Review Plan for the Review of a License Application for a Low-Level Radioactive Disposal Facility”. This document contains guidance for the NRC review team assigned to a given 10 CFR 61 license application (US NRC, 1994).

The last of the major documents was written in response to the fact that the three previous guidance documents contained general information on license applications but did not contain sufficient guidance relating disposal facility performance to the performance objective in 10 CFR 61.41 (protection of members of the public) (US NRC, 2000). With this in mind, the NRC Performance Assessment Working Group wrote NUREG-1573 (2000), “A Performance Assessment Methodology for Low-Level Radioactive Disposal Facilities” (US NRC, 2000; US NRC, 2007). The document provides in-depth guidance on the creation of a PA for any LLW NSDF application. In addition, a number of regulatory issues that had developed since the promulgation of 10 CFR 61 relating to technical requirements contained within the regulation. The authors of NUREG-1573 also addressed these issues, along with providing advice on modeling approaches used within a PA.

Recently the NRC has been in discussions on ways to update 10 CFR 61 and try to bring some of the PA guidance contained within NUREG-1573 into a formal rulemaking process (Abdel-Khalik, 2011). While no decisions have been made, two issues have been raised from the discussions. The first is what to do about Depleted Uranium (DU), how should it be characterized and how should it be disposed of. The second is an increase in the period of compliance, currently at 10,000 years for the NRC, to 20,000 years to capture the ingrowth of uranium daughter products in DU.

2.3 Comparison of DOE and NRC Approaches to Regulating LLW Disposal Facilities

The basics of regulating LLW disposal are similar between the DOE and the NRC. Many of the concepts and requirements for LLW disposal contained within DOE's regulations were incorporated from parts of 10 CFR 61 ((US Department of Energy, 1999a),(Wilhite, 2001). There are however a number of substantive differences that exist between the two organizations. In comparing the two sets of regulations there are two main areas to consider: performance objectives and PA methodology. This section will discuss each area of regulation from the NRC perspective and then compare that with the relevant requirements contained within DOE Order 435.1.

2.3.1 NSDF Performance Objectives

The performance objectives laid out by the DOE and NRC for LLW disposal facilities are similar between the two agencies, with the DOE including several additional objectives (see Table 2.1). The NRC has five performance objectives contained within 10 CFR 61 (parts 40 through 44), with part 40 outlining general requirements and parts 41-44 discussing specific objectives (US NRC, 1982b). The DOE has a number of corresponding and additional performance objectives within DOE M 435.1, and are contained within Parts IV.P and IV.Q (US Department of Energy, 1999c).

General Requirements (Part 40; NRC) states that "Land disposal facilities must be sited, designed, operated, closed, and controlled after closure so that reasonable assurance exists that exposures to humans are within the limits established in the performance objectives in §§ 61.41 through 61.44" (US NRC, 1982b). The DOE version contained in 435.1 M IV.P (1) is very similar to this, while also including the requirement of disposal site maintenance during the IC period, though this requirement is implied within 10 CFR 61 and NUREG-1573 (Wilhite, 2001).

Next in 10 CFR 61 Part 41, "Protection of the General Population from Releases of Radioactivity", the regulation states that any release of radionuclides from the disposal facility through all pathways (along with environmental media) must not, for a member of the public, exceed a 25 mrem/yr dose to the whole body, a 75 mrem/yr dose to the thyroid, and a 25 mrem/yr dose to any other organ. Protection for a member of the public under Order 435.1 [M 435.1 IV.P (1)(a)] for all pathways (excluding radon) is exactly the same as Part 41, though the terminology was changed to 25 mrem/yr of Total Effective Dose Equivalent (TEDE). This change was done to reflect an update to the original International Commission on Radiological Protection (ICRP)-2 standards used in 10 CFR 61 for establishing dose methodology. Order 435.1 incorporated the updated ICRP-30 standards (ICRP, 1959; ICRP, 1979).

The DOE then includes three additional requirements in Order 435.1, two based on the air pathway and one for the protection of groundwater. The first air requirement states that a dose via the air pathway (excluding radon) to a member of the public shall not exceed 10 mrem/yr TEDE. The second requirement is a limit of 20 pCi/m^2/s average flux for radon at the surface of the disposal facility (or 0.5 pCi/L radon flux at the site boundary). The groundwater requirement is based on the need to ensure that groundwater meets EPA drinking water standards at the point of compliance, located 100 meters (m) downgradient from the edge of a disposal facility. The limit contained in the standards is 4 mrem/yr from man-made beta and gamma emitting radionuclides [M 435.1 IV.P (2)(g)] (U.S.C., 1977; Wilhite, 2001).

Following the performance objective in Part 41 is Part 42, "Protection of Individuals from Inadvertent Intrusion," which states that "Design, operation, and closure of the land disposal facility must ensure protection of any individual inadvertently intruding into the disposal site" once the IC period is over (US NRC, 1982b). The dose limit for an individual is based on the NRC waste classification system and is set at 500 mrem/yr (US NRC, 1982a). The DOE performance objective takes this one step further, requiring a disposal facility to meet a chronic inadvertent intruder exposure scenario of 100 mrem/yr in addition to an acute exposure scenario of 500 mrem/yr (assuming 100 years of IC following site closure) [DOE M 435.1 IV.P (2)(h)] (Wilhite, 2001).

The next performance objective is contained in Part 43, "Protection of Individuals During Operations," which states that radiation protection for all workers and the public during the operation phase of a disposal facility must follow the standards contained in 10 CFR 20, "Standards for Protection Against Radiation" (US NRC, 1982b). The DOE has two sets of regulatory documents that it follows for protection during the operational phase. The first is radiological protection for workers (10 CFR 835, "Occupational Radiation Protection"), while the second is for members of the public and the environment (DOE Order 458.1, "Radiation Protection of the Public and the Environment"). According to a 2001 conference paper by Wilhite, radiological protections for both workers and the public can be assumed to be similar during the operational phase of a disposal facility (Wilhite, 2001).

Table 2.1: Comparison of Relevant DOE and NRC LLW Performance Objectives

NRC				DOE		
Location	**Description**	**Specific Requirement**		**Location**	**Description**	**Specific Requirement**
10 CRF 61.41	Protection of the general population from releases of radioactivity (annual dose limits to a member of the public from all pathways)	-25 mrem to the whole body -75 mrem to the thyroid -25 mrem to any other organ		-M 435.1 IV .P (1)(a) -M 435.1 IV .P (2)(g)	Annual dose limits in TEDE to a representative member of the public	-25 mrem from all pathways (excluding radon) -10 mrem via air pathways (excluding radon) -20 pCi/m^2/s average flux limit for radon at the surface of the disposal facility (or 0.5 pCi/L at site boundary)
No NRC equivalent				-M 435.1 IV.P (2)(b) -M 435.1 IV.P (2)(g) -41 CFR 141	Annual dose limits in groundwater at compliance point (100 meters from site boundary) to a representative member of the public	-4 mrem/yr of beta and gamma emitting radionuclides
10 CRF 61.42	Protection of Individuals from inadvertent Intrusion	-Dose limit of 500 mrem/year		-M 435.1 IV .P (2)(h)	Protection of a hypothetical person assumed to inadvertently intrude for a temporary period after failure of ICs (at 100 years post-closure)	-100 mrem/yr TEDE chronic exposure scenario -500 mrem/yr TEDE acute exposure scenario
10 CFR 61.43	Protection of individuals during operations	-Requirements consistent with 10 CFR 20		-10 CFR 835	Occupational Radiation Protection	-Compatible with 10 CFR 20
				-DOE O 458.1	Radiation Protection of the Public and the Environment	-Compatible with 10 CRF 20

NRC				DOE		
Location	**Description**	**Specific Requirement**		**Location**	**Description**	**Specific Requirement**
10 CFR 61.44	Stability of the disposal site after closure (taken from NUREG-1199)	-“Site Stability is focused on reducing the contact of water with the waste and…will not be a need for active maintenance following closure”		-M 435.1 IV.P (6)(a)	-Stability requirements for site operators	-Ensures that the design and operation of the disposal cell is consistent with procedures and predictions described in the site closure plan
				-M 435.1 IV .Q (1)(b)	-Long-term site stability	-Detail in closure plan how closure will minimize the need for active maintenance following closure
				-M 435.1 IV.P (2)(c)	-PA must include projection of long-term site stability	-“PAs shall address reasonably foreseeable natural processes that might disrupt barriers against release and transport of radioactive material”

The last performance objective laid out in 10 CFR 61 is Part 44, "Stability of the Disposal Site After Closure". A disposal facility is required to have long-term stability throughout its lifespan (operational and post-closure) and to minimize the need for active maintenance once the site is closed (though monitoring is acceptable). For DOE facilities, demonstration of long-term stability is contained within the requirements for the preliminary and final site closure plan, along with the need to minimize active maintenance post-closure. These requirements are located in DOE M 435.1 IV.Q (1)(b) (Wilhite, 2001). Similar to the previous performance objective, 10 CFR 61.44 and the related DOE regulation are shown to be equivalent.

2.3.2 Performance Assessment Methodology

The process of evaluating a potential LLW disposal site using a radiological PA is similar for both the DOE and NRC. Both organizations use an iterative process of site characterization, development of conceptual models followed by mathematical models, analysis using those models, evaluations of parameter sensitivity/uncertainty, and finally an interpretation of the results compared against regulatory performance objectives (Shott et al., 1998; US NRC, 2000). Both require the inclusion of an inadvertent intruder performance scenario (the NRC pioneered this type of performance scenario in the Draft EIS for 10 CFR 61 (US Nuclear Regulatory Comission, 1981; US NRC, 2007)), which simulates a future member of the public inadvertently drilling or disturbing the disposal facility following the end of ICs. They also require that As Low As Reasonably Achievable (ALARA) practices are followed for releases of radionuclides to the environment.

One of the important differences between the two government agencies is the period of compliance: for the DOE it is 1,000 years, while the NRC requires a demonstration of compliance for 10,000 years (20,000 if proposed revisions to 10 CFR 61 proceed). However, the NRC contains a less structured process for issuing and maintaining a disposal license compared to the DOE and their requirement for a "Disposal Authorization Statement" (DAS). In addition to the PA, the DOE requires that a Composite Analysis (CA) (used to demonstrate that all the combined dose from all buried material across an entire site meet the performance objectives), Long Term Maintenance and Surveillance Plan (monitoring plan during the operational phase), and Closure Plan are all created before the DAS is issued. DOE manual 435.1 and the accompanying guidance contain specific instructions on the creation of each document. Maintenance and updates for each document are required throughout the lifespan of the facility. Review and approval of all document versions is conducted by the Low Level Waste Disposal Facility Federal Review Group (LFRG), which contains a mix of DOE headquarters and field staff.

The NRC by contrast contains recommendations within NUREG-1573 for the licensee to monitor the disposal facility and update the Closure Plan if necessary, but leaves wide discretion to the licensee. The DOE goes even further in M 435.1 to require annual assessments of the validity of the conclusions within the PA, with action triggers to force a revision of the PA should assumptions or results change (this is referred to in DOE M 435.1 IV.(P)4 as PA Maintenance).

2.4 Current Efforts to Improving PA Confidence

2.4.1 Performance Evaluation Process

The creation of a PA is not a one-time event, and is not conducted in isolation. Instead, the document can be thought of as growing and evolving over the operational and post-closure life of the facility. The overall process of creating an initial PA and updating it over time is an implementation of the Performance Evaluation Process, and can be broken down into three sections: performance objectives, an initial PA, and performance confirmation.

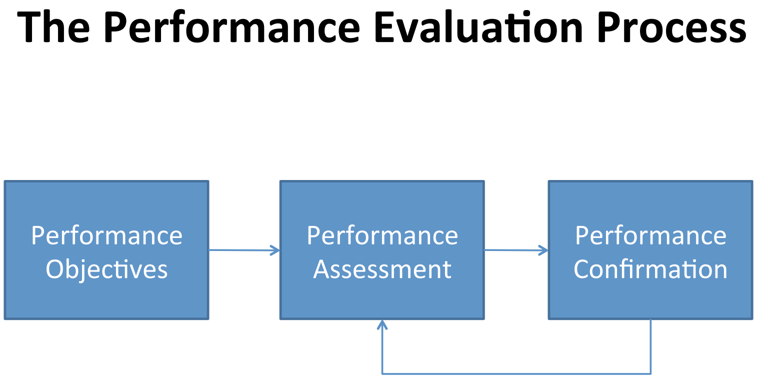


Figure 2.2: Schematic of the Performance Evaluation Process showing the three sections of the process, with feedback loop from performance confirmation to the PA. Taken from a lecture given by Dr. James Clarke, Vanderbilt University (2011).

The first component of the process is the performance objectives, which as discussed in the previous section are a set of objective that any current and future LLW disposal facility must meet in order to ensure the adequate protection of human health and the environment. These objectives are then used as the basis for the design and analysis of the disposal facility performance, which is contained within the PA. For a LLW disposal facility being evaluated, the initial PA is conducted before the construction of the facility. Existing site and waste characterization is combined with estimates and best-guess expert opinions to produce a preliminary evaluation of long-term facility performance for a determined disposal inventory and design. Once operation at the disposal facility has begun however, there needs to be a way to incorporate new knowledge and changes in the assumptions used to produce the original analysis of performance.

This leads into the third component of the performance evaluation process, performance confirmation. Since the lifespan of an operational disposal facility is decades and the post-closure compliance period for the DOE lasts 1,000 years, the performance confirmation step represents a feedback loop to the PA. This helps to confirm the assumptions made in analyzing performance or to update those assumptions as need. Changes in the assumptions can result from changes in inventory, improved knowledge and understanding of waste disposal, changes in site characteristics, or the identification of areas that require further investigation.

The performance confirmation step allows for the PA to be revised to include all new data into the performance analysis of the disposal facility, provide an updated assurance that the performance objectives will continue to be met, or recommend actions to ensure compliance. The following sections discuss how the DOE and NRC each implement an equivalent of the Performance Evaluation Process.

2.4.2 Performance Assessment Maintenance

Under DOE Order 435.1, demonstration that the performance objectives laid out in DOE M 435.1 chapter IV.(P) will be met is accomplished through the analysis conducted within the PA. The role of performance confirmation within 435.1 is carried out through the requirements in M IV (P) 4 and is referred to as “Performance Assessment Maintenance” (Letourneau, 2010). The NRC does not have specific performance confirmation requirements, but rather general requirements for a generic PA within NUREG-1573. Guidance within M IV (P) 4 requires that PA maintenance be conducted to “evaluate changes that could affect the performance, design, and operating basis for the [disposal] facility… and shall include the conduct of research, field studies, and [environmental] monitoring needed to address uncertainties or gaps in existing data”

(US Department of Energy, 1999c). Some specific examples of PA maintenance include the development of novel environmental monitoring techniques (e.g., using aerial satellite imagery to assess the health of a vegetative cover) (Gladden, 2010), field experiments using test beds to better understand the movement of moisture through an engineered cover (Parsons et al., 2010), and field testing of long-term effects on waste packages and barrier components to environmental exposure (Jones et al., 2003).

The DOE sets out three requirements for PA maintenance within chapter IV (4). The first is that a PA must be "reviewed and revised when changes in waste forms or containers, radionuclide inventories, facility design and operations, closure concepts, or the improved understanding of the performance of the waste disposal facility in combination with the features of the site…alter the conclusions or the conceptual model of the existing performance assessment" (IV P [4a]). The second is that the PA is to be evaluated on a yearly basis to ensure that it continues to provides an adequate representation of disposal facility performance while incorporating any new information gathered throughout the past year (IV P [4b]). The third is the preparation of an annual summary to provide information concerning the performance of the facility over the period addressed (US Department of Energy, 1999a; National Security Technologies LLC, 2009; Parsons et al., 2010; Swingle et al., 2010). Along with reporting the inventory of waste disposed to date, environmental monitoring results, and results from any current field studies, the summary discusses whether there is any need to revise or update the PA. Similar to other documents required by 435.1, the annual summaries are written by site technical staff, then reviewed and approved by the LFRG.

One instance of the implementation of PA maintenance is the Z-Area (Saltstone) disposal facility. The initial PA was conducted in 1992 and provided assurances of performance for the disposal of a low-level radioactive aqueous waste stream containing high levels of sodium salts mixed with grout and placed in up to 15 vaults, with adequate protection of groundwater and future inadvertent intruders (Martin Marietta Energy Systems Inc., 1992). With the advent of Order 435.1, the assumptions built into the original PA were reevaluated in a Special Analysis (SA) conducted in 2002. The new requirements of Order 435.1 were taken into account, along with proposed changes in inventory, and changes to the final disposal facility design. The results were to be incorporated into a revision of the existing PA (Cook et al., 2002).

The following year, another study revised the disposal limits of C-14, when it was discovered that C-14 concentrations in Savannah River Tank 41 were higher than estimated and would have exceeded the limit calculated in the 2002 SA (Cook and Kaplan, 2003). Another SA was conducted on Vault Four in 2005, this time to again update the disposal limits based on revisions to the analytical models used to evaluate performance. However, this SA concluded that the conceptual site model of Saltstone nor the conclusions of the PA had been altered, and therefore there was no need to update the PA, superseding the conclusions of the 2002 and 2003 SAs (Cook et al., 2005). Finally, the annual summary for FY 2009 indicated that while disposal vaults one and four were operating under the conceptual models set forth in the 1992 PA and the 2005 SA, a revision of the PA was warranted since future disposal vaults were going to be of a substantially different design than the current vaults (Savannah River Remediation LLC, 2010). The revised PA was then issued in October 2009 (SRR Closure & Waste Disposal Authority, 2009).

CHAPTER 3

COMPARISON OF LLW DISPOSAL FACILITIES AT MAJOR DEPARTMENT OF ENERGY SITES

3.1 Introduction

The United States (US) Department of Energy (DOE) has disposed of millions of cubic meters (m) of low-level radioactive waste (LLW) over the past 70 years. Much of this waste has been placed in near surface disposal facilities (NSDFs), in accordance with DOE's self-regulating authority, as specified in the Atomic Energy Act of 1954 (Letourneau et al., 2010). Beginning in 1988, with the promulgation of DOE Order 5280.2A, each facility that accepted waste after this date was required to demonstrate that radiological performance objectives would be achieved over the lifespan of the facility (US Department of Energy, 1988; US Department of Energy, 1999b; Letourneau et al., 2010). In 1999, this order was replaced with DOE Order 435.1, which emphasized risk-based and performance-based requirements for LLW disposal (US Department of Energy, 1999a).

These requirements include a set of objectives that are designed to restrict concentrations of radioactive materials at a location 100 m downgradient from a disposal facility to a level that is environmentally acceptable. Meeting these performance objectives dictates the type and amount of waste that can be placed within a disposal facility, based on future potential waste releases from that facility and projected doses to representative members of the public (US Department of Energy, 1999c). A required performance assessment (PA) is conducted to demonstrate compliance with the performance objectives for a period of 1,000 years following facility closure. Typically, the disposal site location and waste characteristics are determined prior to designing the engineered portion of the NSDF, and the PA is used to establish the disposal facility waste limits that allow the performance objectives to be met.

This article looks at the concept of a NSDF as a unified system of three components or subsystems. The three subsystems are facility engineering design, waste form/package considerations, and site-specific environmental characteristics. This approach incorporates an analysis of how the subsystems interact and work together within the NSDF system. Since NSDFs all contain these three components, they could be used to provide a basis for an improved approach to facility PA. A system of components framework could be incorporated as part of a future approach to implementing a more standardized PA methodology.

Information was collected for five major LLW disposal facilities from across the DOE complex. This information was used to establish a basis for the current approach to near surface LLW disposal at US federal sites.

3.1.1 Building Confidence in Performance Assessments

Every NSDF operated by the DOE is unique. Waste streams derive from local operations, each site has a distinct climate and geology, and engineered features reflect a mixture of site design preference and regulations. Additional differences arise from the methodology and conceptual models used to conduct the performance analysis within a PA. There are multiple contractors, site technical staff, and regulating offices involved in the PA process, many with their own preferred set of analysis tools (Letourneau et al., 2009). All of this can complicate comparisons of NSDFs and their subsequent PA results.

Along with demonstrating regulatory compliance, providing stakeholder confidence in the analysis and performance of a NSDF is a major goal of all PAs. Historically, methodology and performance results can and have been impacted by a number of factors, including uncertainties present in many assessment input parameters, variability of long-term natural processes, and the durability of engineered components (Letourneau et al., 2009). Long-term performance data on the order of 100s of years is not yet available for NSDFs, and there are no complete long-term natural analogs of NSDFs, so that assumptions with uncertainties must be incorporated into a PA (Rustick et al., 2013).

DOE technical staff have recognized that inconsistencies in PA approaches, such as differences in conceptual models or parameterization, can negatively affect transparency and confidence in the validity of the PA process, and have begun to address this issue (Letourneau et al., 2009). For example, revisions to DOE Order 435.1 are being proposed, and the Risk and Performance Community of Practice has provided a vehicle for increased technical exchanges among stakeholders. Keeping a balance between a more consistent approach to PA methodology, while allowing for genuine differences between sites, is key to avoiding unproductive uniformity. Such a balance also provides a defensible environment for comparison of NSDF design and performance to regulators and stakeholders. The approach discussed in this article is based on a system of components approach that can help to achieve this balance of flexibility and consistency across NSDFs.

The last major comparison of DOE NSDF performance was completed in 1995, to assess the ability of fifteen different DOE sites to safely dispose of a screened list of radionuclides, using either a below ground trench or an above ground tumulus NSDF (Sandia National Laboratories, 1996; Waters and Gruebel, 1996; Waters et al., 1996). Concentrations of radionuclides, at the standard 100 m compliance point from the facility boundary, were examined for subsurface leachate and airborne transport from the facility (source terms). A grouted waste form was used to estimate leaching of radionuclides over time.

This article builds on that study by reporting on the current state of the practice in DOE LLW disposal for five major DOE sites, and provides comparisons of all parameters that would be used for the groundwater transport pathway. To limit the scope for this article, an assumption was made that all radionuclides for a hypothetical site are eventually released to the groundwater, and airborne transport was not investigated at this time.

3.2 An Integrated System Approach

Each DOE facility chosen represents a different set of disposal conditions, is active or in the planning stage, and has a PA that was generated in accordance with DOE Order 435.1. The five selected facilities are:

- the Savannah River E-Area Engineered Trenches (ETs),
- the Hanford Integrated Disposal Facility (IDF),
- the Idaho National Laboratory (INL) Radioactive Waste Management Complex (RWMC),
- the Oak Ridge Environmental Management Waste Management Facility (EMWMF), and
- the Nevada National Security Site (NNSS) Area 5 Disposal Facility.

An effort was made to provide consistent data sets for each facility. Particular care was used to ensure that climate data was readily comparable. Unlike descriptions of waste composition and engineered systems that generally used similar metrics across the DOE complex, there was wide variation in the amount and detail for climate data available directly within the PA. To address this concern, station data from the National Oceanic and Atmospheric Administration (NOAA) was used to provide supplemental climate data to allow direct comparisons across the sites.

3.2.1 The System Components or Subsystems

We modeled a NSDF as an "integrated system" consisting of three components or sub-systems, viz, the engineered facility design, the waste /waste form, and the site-specific environment.

The engineered disposal facility sub-system is comprised of any installed cover and/or liner systems, along with the volume and footprint of the waste zone. Cover systems are used as primary infiltration barriers, incorporating a resistive or evapotranspirative (water balance) approach, and are installed in stages. In many cases, differing components are used before, during, and after the institutional control (IC) period. Typical materials include compacted clay, sand, geomembranes, and geotextiles. Liner systems are used to prevent leachate from leaving the waste zone, and can only be installed before a facility begins accepting waste. Construction materials are similar to those used in cover systems. The footprint area of the disposal facility dictates the potential flux of leachate from the waste zone, and the facility volume affects subsidence potential.

The waste /waste form sub-system is a combination of waste composition, waste form, and waste package. Waste composition defines the specific radionuclide types and amounts within each unit of waste. Waste form comes in many types, ranging from contaminated clothing and filters to machine components and demolition debris. Waste can also be stabilized in a bulk matrix of another material, e.g., a cementitious material, to reduce leaching potential. Waste packages are structures that isolate waste within a defined container, and are used in waste transport, disposal, or both. They can range from cardboard and wooden crates to steel containers and grouted vaults. Not all waste is contained within a package; some is unstabilized (disposed “as is”). Depending on the robustness of the waste package, there can be varying effects on waste zone infiltration, subsidence potential, and radionuclide movement in the waste zone.

The environmental sub-system includes climate and subsurface features. Rain and snowfall events affect infiltration and evapotranspiration on annual and seasonal timescales, and can be related to transport of moisture through the engineered barriers. Precipitation, temperature, and humidity are factors in engineered barrier and waste package degradation over time. Site geology and hydrology control transport of leachate from the disposal facility through the vadose and saturated zones to a point 100 m downgradient within the saturated zone. Chemical distribution coefficients are used to approximate the various sorption processes within site geology to calculate the additional time required for any given radionuclide to reach the 100 m compliance point, compared to natural subsurface recharge and groundwater flow.

3.3 Site Comparison Data

Six comparison categories were developed for the three sub-systems that control NSDF performance: Climate, Hydrogeology, Geochemistry; Facility Dimensions and Cover, Facility Liner; and Waste.

Information for each category is presented in Tables 3.1 through 3.6, followed by a brief introduction of the five sites and additional detail on the hydrogeology, engineered components, and waste parameters for each facility.

Table 3.1: Environmental Parameters - Climate Data

	SRS E-Area		**Oak Ridge**		**Idaho RMWC**		**Hanford IDF**		**NNSS Area 5**	
Avg. Rainfall	1224 mm/yr		1370 mm/yr		214 mm/yr		173 mm/yr		124 mm/yr	
Max. Annual Rainfall	1964	1866 mm	1973	1939 mm	1966	144 mm	1995	313 mm	1998	246 mm
Min. Annual Rainfall	1954	732 mm	2007	910 mm	1963	366 mm	1976	76 mm	1989	29.0 mm
Estimated Infiltration	400 mm/yr		570 mm/yr		10 mm/yr		4.2 mm/yr		0 mm/yr	
Freq. of storm event per 24 hrs.	≥2.5 mm	68/yr	≥2.5 mm	88/yr	≥2.5 mm	26/yr	≥2.5 mm	23/yr	≥2.5 mm	15/yr
	≥13 mm	27/yr	≥13 mm	37/yr	≥13 mm	3/yr	≥13 mm	1/yr	≥13 mm	3/yr
	≥25 mm	12/yr	≥25 mm	14/yr	≥25 mm	0.2/yr	≥25 mm	0.1/yr	≥25 mm	0.8/yr
Largest 24 hr. precip. event	9/3/98	188 mm	8/10/60	189 mm	6/6/95	40 mm	10/2/57	48.5 mm	8/18/83	89 mm
Monthly Avg. Rainfall - Low	Nov.	66 mm	Oct.	76 mm	Jul.	12 mm	Jul.	5 mm	Jun.	4 mm
Monthly Avg. Rainfall - High	Jul.	131 mm	Jul.	134 mm	May	30.5 mm	Dec.	26 mm	Feb.	17 mm
Avg. Snowfall	30.5 mm (Augusta, GA)		260 mm		676 mm		373 mm		50 mm (Desert Rock, NV)	
Max. Monthly Snowfall	Feb. 1973	356 mm	Feb. 1996	305 mm	Dec. 1971	566 mm	Jan. 1950	594 mm	Feb. 1987	152 mm
Avg. Annual Temp.	17.8 °C		14.4 °C		5.7 °C		11.9 °C		15.2 °C	
Max. Daily Temp.	Jul.	41.6° C	Jul.	40.6 °C	Jul.	41 °C	Aug.	45 °C	Jul.	46 °C
Min. Daily Temp.	Jan.	(-) 19.4 °C	Jan.	(-) 27.2 °C	Dec.	(-) 44 °C	Feb.	(-) 31 °C	Dec.	(-) 22.2 °C
Monthly Avg. Winter Temp.	1.7 °C– 12.8 °C		2.8 °C - 9.7 °C		(-) 9 °C - (-) 1 °C		(-) 11.1 °C - 6.9 °C		(-) 5.5 °C - 13 °C	
Monthly Avg. Summer Temp.	26.7 °C– 29.4 °C		19.3 °C - 25 °C		5 °C - 20 °C		17.2 °C - 27.9 °C		16.7 °C - 38.9 °C	
Avg. # of Days Below 0	42		85		212		107		118	
Avg. # of growing days	220		220		88		181		239	
Avg. Relative Humidity	Annual	70%	Annual	71%	Annual	50%	Annual	54%	Annual	~35%
	Monthly	56 - 78%	Monthly	52 - 90%	Monthly	15-89%	Monthly	33 - 80%	Monthly	22 - 50%
Relative Humidity	36 - 97%		47 - 94 %		4 - 100 %		22 - 91%		5 - 100%	
Avg. Annual Evaporation	1450 mm		1285 mm		1090 mm		1350 mm		37200 mm	
Avg. Daily Evaporation	1.5 mm - Jan.	6.8 mm - Jul.	1.2 mm - Dec.	5.5 mm - Jul.	~0 mm - Winter	6.3 mm - July	~0 mm - Jan.	9.7 mm - Jul.	30 mm - Jan.	190 mm - Jul.

Table 3.2: Environmental Parameters - Hydrogeology

	SRS E-Area	Oak Ridge	Idaho RMWC	Hanford IDF	NNSS Area 5
Overview of Near-surface Geology	**Number of defined units in top aquifer zone, mixture of clay and sand**	**Mixed layers of sedimentary rock subjected to faults and upward thrusts**	**Layers of basalt and interbedded sediments**	**Large deposits of sediments, mostly sand and gravel**	**Layer of alluvial fill comprised of volcanic rock mixed with sediments**
Upper Geologic Layering (Vadose Zone)	**Clay Upper Vadose Zone**	Carbonate - dominated rock groups interbedded with sand and silt shale groups	Fractured Basalt	**Hanford Formation -** 116 m	**Alluvial Fill -** 360 - 460 m
			A-B Interbed at 9.1 m	**Upper Gravel Sequence** – 6 m	
	Sand Lower Vadose Zone		**B-C Interbed** at 33.5 m	**Sand Sequence** – 60 m	
			C-D interbed at 73 m	**Lower Gravel Sequence** – 35 m	
Lower Geologic Layering (Saturated Zone)	**Upper Three Runs Aquifer –** 32 m	**Oak Ridge Reservation Aquitards -** Groundwater flow is dominated by fractured flow	**Snake River Aquifer**	**Ringold Formation -** 95 m	**Tuff -** 550 m
	Gordon Confining Unit - 0.6 to 9 m				
	Gordon Aquifer - 23 m				
Surface to Groundwater	7.62 m	~20 m	180 m (9 m of interbed)	98 m	240 m
Soil Dry Bulk Density	2.65 g/cm^3	1.35 g/cm^3	1.9 g/cm^3	1.6 g/cm^3	N/A
Vadose Zone Vol. Moisture Content	0.2	0.305	0.17	0.09	N/A
Groundwater Mixing Depth	10 m	3 m	12 m	5 m	N/A
Groundwater Darcy Velocity	8.1 m/yr	2.9 m/yr	0.75 m/yr	22 m/yr	1.4 m/yr
Saturated Zone Porosity	0.3	0.035	0.06	0.31	N/A
Natural Soil Recharge Rate	270 mm/yr	2000 mm/yr shallow 180 mm/yr deep	70 mm/yr	50 mm/yr	0

Table 3.3: Environmental Parameters - Geochemical Properties

	SRS E-Area		**Oak Ridge**	**Idaho RMWC**	**Hanford IDF**			**NNSS Area 5**
	Radionuclides of Interest and Chemical Sorption Distribution Coefficient in mL/g							
Radionuclide	**Ground Type**							
	Sandy	**Clay**	**General**	**General**	**Sand**	**Gravel Vadose**	**Gravel Saturated**	**General**
Ac	1100	8500	10000	225	350	35	30	10
Am	1100	8500	10000	225	350	35	30	100
Inorganic C	0	0		0.4	20	2	0.5	0
Cl	0	0		0	0			0
Cm	1100	8500		4000	350	35	30	
Co	7	30	1000	10	300	30	200	1
Cs	50	250	10000	500	80	8	200	1
H3, Kr, Rn	0	0	0	0	0	0	0	0
I	0	0.6	0	0	0	0	0.01	0
Nb	0	0		500	80	8	30	
Ni	7	30		100	80	8	30	100
Np	0.6	35	10	23	0.8	0.8	1.5	10
Pa	0.6	35		8	0.8	0.8	1.5	1
Pb	2000	5000		270	100	10	1000	10
Po	2000	5000						
Pu	270	5900	10	2500	200	20	15	100
Ra	5	17		575	10	1	1.4	10
Se	1000	1000		130	4	0.4	0.7	
Sn	2000	5000		130	80	8	30	100
Sr	5	17	100	60	10	1	1.4	1
Tc	0.1	0.2	0	0	0	0	0	0
Th, Zr	900	2000		500	300	30	100	100
U	200	300	10	15.4	10	1	0.6	0
Data Source	Table 10: Kaplan (2006)		Figure 3-13: Solomon (1992)	Table 2-14: DOE Idaho (2007)	Table 4 and 5: Kaplan and Serne (2000)			Table 3-20: Shott et al. (1998)

Table 3.4: Engineered Parameters - Dimensions and Covers

	SRS E-Area	**Oak Ridge**	**Idaho RMWC**	**Hanford IDF**	**NNSS Area 5**
Number of Disposal Cells and Dimensions	4 engineered trenches	6 disposal cells	1 large disposal pit	6 RH waste trenches	28 cells (pits and trenches)
	198 m L x 45.7 m W x 4.9 - 7.6 m D; 100 total acres	44 acres of total land surface	9 m deep, 7.76 total acres	Base - 20 x 200 m; Top - 80 x 260 m; 10 m deep	30 acres of total land surface
Volume	25,175 m^3 per cell	1,682,000 m^3	130,000 m^3	204,000 m^3	572,000 m^3
Operational Cover	1.22 m of soil; Additional interim 610 mm of soil overlain by HDPE membrane	300 mm of clay soil overlain by GCL then 600 mm of vegetative soil	900 mm or greater of soil	1 m thick of soil overlain by plastic sheeting	2.4 m of screened alluvium
Final Cover Layers from Top to Bottom	Topsoil - 152.4 mm	Surface Soil - 1520 mm	Topsoil - 305 mm	Silt Loam with Pea Gravel - 500 mm	4 m monolayer evapo-transpirative cover
	Backfill - 762 mm	Filter Layer - 305 mm	Fine Soil Fill - 1220 mm	Compacted Topsoil - 500 mm	
	Erosion Barrier - 305 mm	Geotextile	Sand - 305 mm	Sand - 150 mm	
	Geotextile Filter Fabric	Biointrusion Layer - 905 mm		Gravel - 150 mm	
	Middle Backfill - 305 mm	Drainage Layer - 305 mm	Gravel Filler - 305 mm	Spray- applied asphalt	
	Geotextile Filter Fabric	Geotextile		Asphaltic Concrete Mixture - 150 mm	
	Drainage Layer - 305 mm	Geomembrane	Cobble Biointrusion - 610 mm	Asphalt Base - 100 mm	
	Geosynthetic Clay	Clay Barrier with Bentonite - 305 mm		Sand - 1 m	
	Backfill - 610 mm	Clay Barrier - 305 mm	Grading Fill - 0 to 3050 mm	Gravel - 1 m	
		Contour Layer - 305 mm		Grading Fill up to 5 m below surface	

Table 3.5: Engineered Parameters - Liners

	SRS E-Area	Oak Ridge	Idaho RMWC	Hanford IDF	NNSS Area 5
Liner Parameters from top to bottom	152.4 mm of granite crusher run overlain by a geotextile filter fabric and compacted soil	Operational Soil - 305 mm	Soil - 600 mm	Crushed Concrete and Soil - 900 mm	Native soil
		Granular layer - 305 mm		Geocomposite Drainage Layer	
		Geomembrane		HDPE Liner	
		Geonet between two geotextiles		Bentonite Clay/Soil Admixture - 500 mm	
		Geomembrane		Geocomposite Drainage Layer	
		Clay - 9150 mm		HDPE Liner	
		Soil Buffer - 3 m		Bentonite Clay/Soil Admixture - 1 m	

Table 3.6: Waste Parameters

	SRS E-Area	Oak Ridge	Idaho RMWC	Hanford IDF	NNSS Area 5
Waste Form	Soil, rubble, wood, debris, concrete, equipment, and job control wastes such as contaminated clothing and plastic sheeting	Demolition debris, contaminated soil/sediments/ sludges with and without a RCRA hazardous waste component, contaminated clothing, trash, and miscellaneous solids	Contaminated clothing, paper, rags, packing material, glassware, tubing, resins, activated metals, beryllium blocks, fuel-like materials, Vycor glass, equipment (i.e. gloveboxes and ventilation ducts), and process wastes	Silicate glass monoliths	Cement-solidified tritium and sludges, sewage sludge with fly ash, laboratory waste, equipment, oil in absorbent, soil, D&D debris, trash, construction wastes, uranium residues, thorium residues
Waste Package	Metal B-25, B-12, and Sealand containers	No standard waste package; material and shape are determined by waste	Wooden and metal boxes, drums, soft-sided reinforced containers, plus specialty containers for non-uniform waste forms	Cylindrical stainless steel (304L) canisters	Steel drums, steel boxes, plywood boxes, cardboard boxes, wood pallets

3.3.1 Savannah River E-Area

The Savannah River Site (SRS) is located in southwestern South Carolina near the cities of Aiken, SC (32 km north), and Augusta, GA (35 km northwest), and separated from Georgia by the Savannah River, with a total site area of close to 777 km^2 (Westinghouse Savannah River Company (WSRC), 2008). E-Area occupies a total of 200 acres, with 100 acres currently in use and 100 acres reserved for future needs. Climate at SRS is characterized as subtropical, with average annual precipitation of 1,224 mm and average annual temperature of 17.8 °C (Kilgo et al., 2005; Phifer et al., 2006; Westinghouse Savannah River Company (WSRC), 2008; Kabela, 2011; NOAA, 2012a; NOAA, 2012b).

The groundwater hydrology underlying SRS consists of several aquifer systems and confining layers (see Figure 3.1). The two aquifer systems of importance to the E-Area are the Upper Three Runs and underlying Gordon aquifer units (Mamatey, 2006; Westinghouse Savannah River Company (WSRC), 2008). The Upper Three Runs Aquifer Unit and can be divided into three hydrostratigraphic zones with a total thickness of 40 m: an upper aquifer zone that includes the vadose zone, an intermittent confining layer called the "Tan Clay Confining Zone", and a lower aquifer zone (Aadland et al., 1995; Denham, 1999; Mamatey, 2006; Westinghouse Savannah River Company (WSRC), 2008). Within the vadose zone there is an upper and lower section, each consisting of clay and sand mixtures, with the upper portion containing a comparatively higher percentage of clay (Phifer et al., 2006; Westinghouse Savannah River Company (WSRC), 2008). For the ETs, the distance from the bottom of the disposal facility to the water table is 7.62 m (Westinghouse Savannah River Company (WSRC), 2008). The "tan clay" zone is intermittent, allowing water in spots to pass freely between the upper and lower aquifer zones. Below the Upper Three Runs is the 0.6 to 9m thick Gordon confining unit and 23 m Gordon Aquifer. At the location of the ETs, contaminant transport from both the Upper Three Runs and Gordon aquifer travels to the Upper Three Runs River. A thick confining layer under the Gordon aquifer coupled with positive upward pressure from the underlying Myers Branch Aquifer prevents groundwater and contaminants from passing to aquifer systems deeper than the Gordon. E-Area geochemistry (element distribution coefficients [K_d]) was examined for 38 generic radionuclides in both sand and clay environments (Kaplan, 2006; Westinghouse Savannah River Company (WSRC), 2008).

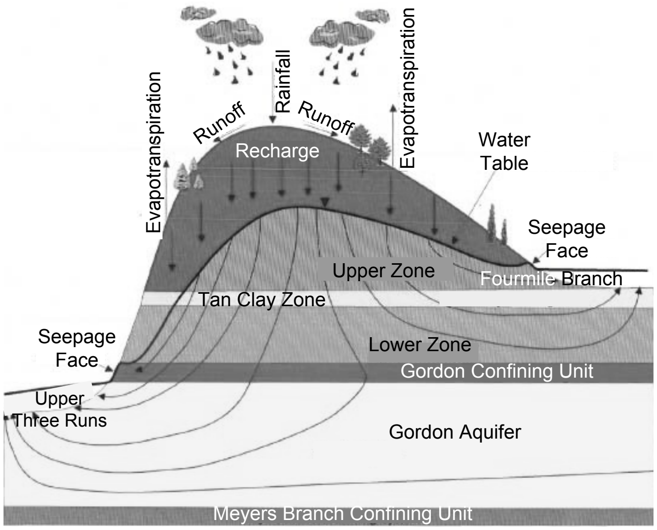


Figure 3.1: Hydrology of General Separations Area (Westinghouse Savannah River Company (WSRC), 2008).

Disposal within E-Area is organized by waste activity, with the ETs accepting a majority of the lowest level waste. An ET is a below-grade disposal cell with sloped sides, 198 m long by 45.7 m wide, ranging in depth from 4.9 to 7.6 m, though ETs may vary a few meters in height and width (Phifer et al., 2006; Westinghouse Savannah River Company (WSRC), 2008). The bottom of each ET contains 150 mm of granite dense grade aggregate (also known as “crusher run”) underlain by a geotextile filter fabric and compacted soil. Two ETs have been completed, with at least two additional ETs under construction (Collard and Hamm, 2012). The base of ET #1 is sloped toward a concrete sump at one end to collect runoff for analysis and prevent water buildup. The base of ET #2 is sloped toward a 610 mm diameter steel pipe that drains into the sump of ET #1 (Jones et al., 2003; Phifer et al., 2006).

Waste forms are made up of soil, rubble, wood, debris, concrete, equipment, and job control wastes such as contaminated clothing and plastic sheeting. The primary type of container (over

77 percent of total containers used) is the B-25 box, a painted and primed steel box constructed out of 12-gauge low-carbon steel with a volume of 2.55 m^3 and capable of holding up to 2,720 kg of LLW (Jones and Li, 2001; Dunn, 2002; Jones et al., 2003). A similar waste package used is the B-12 box, identical in construction but half the volume of a B-25 box; it can hold up to 2,270 kg. In addition, "Sealand" containers (a general term for a standard, multi-modal, corrugated, painted steel box structure) have also been used for disposal (Westinghouse Savannah River Company (WSRC), 2008). Each ET is designed to hold the equivalent of 19,000 B-25 boxes, stacked in rows 4 boxes tall (Phifer et al., 2006; Swingle and Phifer, 2006).

As waste is placed within an ET, an operational cover 1.22 m thick of previously excavated soil is placed over each filled waste section, and compaction occurs as bulldozing equipment passes over the soil cover (Phifer, 2004; Westinghouse Savannah River Company (WSRC), 2008). Once a trench has been completely filled with waste, an interim cover is installed over the operational cover consisting of 610 mm of soil topped with a high-density polyethylene (HDPE) geomembrane or geotextile coated with a water-shedding component. The interim cover system is to be maintained during the 100-year IC period, with a final cover installed at the end of the IC period. The current closure plan is to use a final cover consisting of multiple layers of fill and geosynthetic materials (see Figure 3.2).

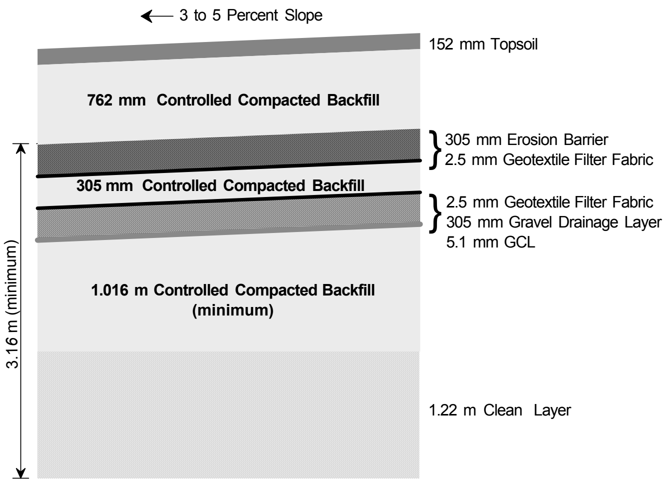


Figure 3.2: Proposed final cover system for the E-Area trenches (Phifer et al., 2006).

3.3.2 Hanford Integrated Disposal Facility

Situated in the south-central part of Washington State along the Columbia River, this site occupies 1,517 km^2 and is located adjacent to the city of Richland and near the cities of Pasco (25 km southeast) and Kennewick (25 km southeast) (Neitzel et al., 2000; Mann et al., 2001; US Census Bureau, 2012). The proposed Immobilized Low-Activity Waste Disposal facility site (also known as the IDF) is found within the 200 East Area. The Hanford climate is characterized as mid-latitude semi-arid, with average annual precipitation of 173 mm and average annual temperature of 11.9 $^{\circ}$C (Farnsworth and Thompson, 1982; Mann et al., 2001; Hoitink et al., 2005; NOAA, 2012a; Hanford Meteorological Station, 2013; NOAA, 2013c).

The geology present at the IDF is comprised of basalt (Columbia River Basalt Group) overlain by the Ringold Formation followed by the Hanford Formation (see Figure 3.3) (Reidel and Horton, 1999; Mann et al., 2001). Within the area of the IDF, the Ringold Formation is 95 m thick and consists of layers of fluvial gravel sediments. The overlying Hanford Formation is up to 116 m thick and contains alternating layers of gravel and sandy sediments (Reidel and Horton, 1999; Mann et al., 2001). Sandy and silty surface sediments form deposits found on the southern part of the IDF site and range in thickness from 3-15 m. The water table historically begins at the boundary of the Ringold and Hanford formations and is the primary pathway for contaminants to reach the Columbia River (Mann et al., 2001). Activities at the Hanford Site have artificially raised the water table to 98 m below the surface (Cole et al., 1997; Mann et al., 2001). The water table is expected to revert to the historical level of 103 m after waste management activities have ended. The geochemistry of the 200 East Area is represented by sand and gravel conditions for the Hanford and Ringold formations (Mann et al., 2001). The "chemically impacted in far-field sand sequence" (pH between 8-11, ionic strength between 0.01 moles per liter [M] and 0.1 M, and low radionuclide activity) and "chemically impacted in far-field gravelly sequence" (same properties as sand sequence with K_ds corrected for gravel) are vadose zone properties for the Hanford Formation. The chemical impaction is a result of glass and concrete leachates from the waste zone contributing to higher ionic strength and pH. "Far-field gravel sequence" (pH of 8, ionic strength between 0.005 M and 0.01 M) represents groundwater zone properties for gravel in the Ringold (Kaplan and Serne, 2000; Mann et al., 2001). It is assumed that the groundwater dilutes all major solutes down to natural background levels (Kaplan and Serne, 2000). K_ds are expected to change with time for the vadose zone, while groundwater K_ds are expected to remain constant.

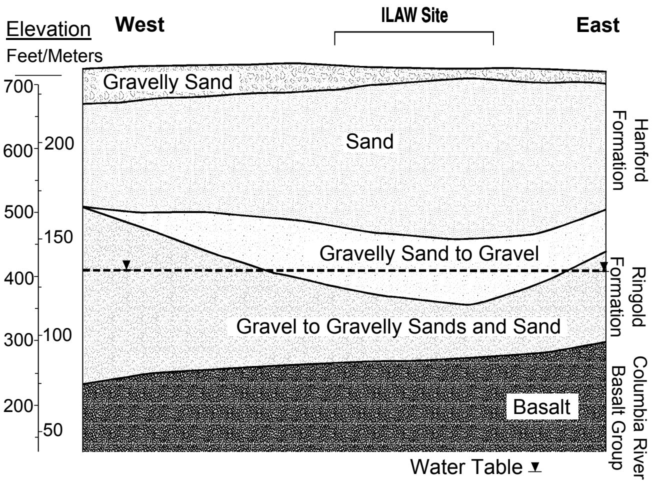


Figure 3.3: West to east cross-section of the IDF disposal site geology (Mann et al., 2001).

Though still in the planning stages, waste estimates for the IDF are 204,000 m^3 of non-radioactive and low-activity tank waste that would fill about 80,000 waste packages placed within six remotely handled (RH) waste trenches (Burbank et al., 2000). Preliminary designs for each disposal trench use a double liner, with a layer of bentonite clay/soil admixture overlain by a geomembrane and a second layer identical in composition placed on top of the first. A leachate detection system is planned between the bottom of the second clay/soil layer and the geomembrane of the first layer, with a leachate collection system above the second geomembrane. A potential operational layer consisting of crushed concrete followed by soil may be placed over the double liner. Proposed trench dimensions are 20 m x 200 m at the base, with 3:1 sloped sides rising 10 m up to the top with dimensions of 80 m x 260 m (Burbank et al., 2000; Mann et al., 2001).

The candidate waste form for the IDF is silicate glass monoliths, with each monolith placed into cylindrical stainless steel (304L) waste package (Mann et al., 2001). The glass would take up approximately 85 percent of the waste package, filling the remaining void space with silicate sand, and welded shut. One plan is to group canisters into a number of small units (cells) and place them in the disposal facility in four layers of cells, with a layer of backfill separating each layer of waste. Waste packages would be RH and placed in the disposal facility by crane.

All waste layers would be covered by up to 1 m thick of soil to limit infiltration, provide a working surface, and shield workers from radiation. Plastic sheeting would also be used to limit infiltration. The proposed final closure plan is to use a modified RCRA Subtitle C multilayer cover to control infiltration and inadvertent intruders (see Figure 3.4) (Fayer et al., 1999; Burbank et al., 2000). This cover would consist of nine layers with a design life of 500 years, with an underlying base layer comprised of grading fill from excavated soil to bring the facility up to 5 m below ground surface, with a two percent slope from center to end.

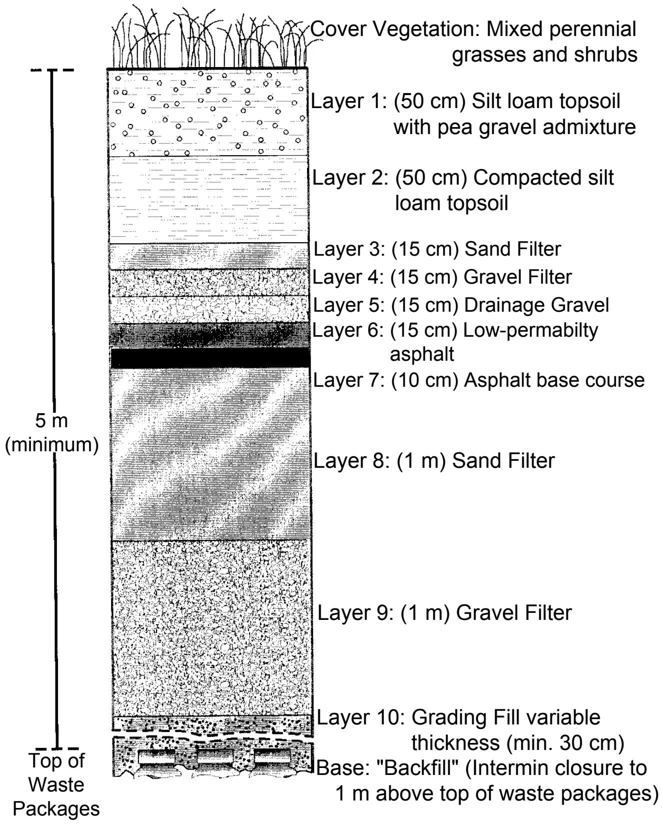


Figure 3.4: Proposed final cover system for the IDF (Burbank et al., 2000).

3.3.3 Idaho Radioactive Waste Management Complex

Positioned on the high desert terrain in Southeastern Idaho, the site occupies 2,305 km^2 and is located near the towns of Arco, ID (11 km west), Blackfoot, ID (37 km southeast), and Idaho Falls, ID (51 km east) (DOE Idaho, 2007; US Census Bureau, 2012). The RWMC is located in the southwestern portion of the site covering an area of 174 acres, with waste management operations occupying 97 acres. The active portion of the facility is named the Subsurface Disposal Area (SDA) and takes up 7.76 acres. Climate at INL is semi-arid sagebrush desert, with average annual precipitation of 214 mm and average annual temperature of 5.7 °C (Clawson et al., 1989; DOE Idaho, 2007; NOAA, 2013a).

The geology of the INL site is a mix of basalt with interbedded layers of sediments (DOE Idaho, 2007). Basalt flows consist of medium to dark vesicular to dense olivine basalt and range from 3-15 m in thickness, while sediment layers vary from well sorted to poorly sorted deposits of gravel, silt, sand, and clay and are found up to 15 m in thickness. Beneath the RWMC there are ten basalt flows and seven sedimentary interbeds, though only seven basalt flows and three interbeds extend across the entire area (see Figure 3.5). The three interbeds are named for the encasing basalt layers, and occur at depths of 9.1 m (A-B interbed), 33.5 m (B-C interbed), and 73 m (C-D interbed). Each interbed is known to have discontinuities, though the C-D bed is the most continuous. The water table begins at 180 m below the surface and is part of the Snake River Plain Aquifer, a sole source aquifer (DOE Idaho, 2007). However, sorption is assumed to occur only within the interbed layers, as the basalt layers contain enough fractures to allow for fast pathways of infiltrating moisture. This reduces the thickness of the vadose zone to 9 m, and K_ds for target radionuclides were calculated for the interbed sections (Adler Flitton et al., 2001; Holdren and Broomfield, 2004; DOE Idaho, 2007). Perched water has also been found above the

B-C and C-D interbeds.

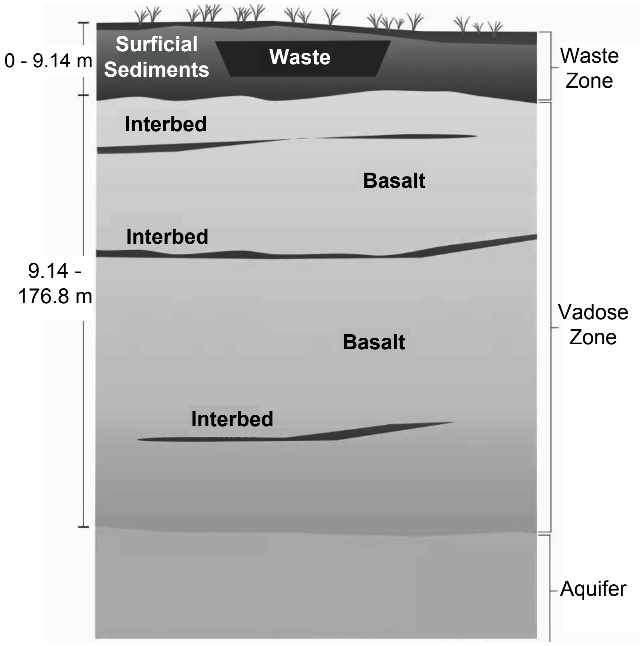


Figure 3.5: Unsaturated lithology underlying the SDA (DOE Idaho, 2007).

Active waste disposal is being carried out within Pits 17-20 of the SDA, one large pit that was blasted down into subsurface basalt (DOE Idaho, 2007). This disposal pit is 9 m deep with 0.6 m of soil at the base. The total area of the pit is 7.76 acres, and is designed to accept a maximum of 130,000 m^3 of waste. The facility accepts both contact-handled (CH) and RH (greater than 500 mrem/hour at 1 m from the waste package surface) waste. CH waste is placed in containers throughout the disposal pit, and RH waste is placed in specialized concrete vaults in the southwest corner of the facility.

Current waste disposal is solely from on-site generation (legacy waste at the RWMC is from across the DOE complex) and is disposed within one of several waste package types. Waste forms include contaminated protective clothing, paper, rags, packing material, glassware, tubing, resins, activated metals, beryllium blocks, fuel-like materials, and Vycor glass (a high temperature and thermal shock resistant glass made by Corning Incorporated), along with contaminated equipment (i.e. gloveboxes and ventilation ducts) and process wastes such as filters cartridges and sludges (DOE Idaho, 2007). Waste packages used are wooden and metal boxes, drums, soft-sided reinforced containers, plus other specialty containers for any non-uniform waste forms. Stacked waste height is controlled by the strength of the waste packages and administrative controls, with a maximum height of 7.3 m.

An interim cover of at least 900 mm of soil is installed over filled disposal portions. Additional soil is placed around concrete vaults to aid in shielding. Four experimental cover designs are being evaluated. These include: a 2 m homogenous soil cover, a 2 m soil cover with a bio-barrier (300 mm of river cobble sandwiched between 100 mm layers of crushed gravel) at a depth of 500 mm below the soil surface, a 2 m soil cover with a bio-barrier at a depth of 1 m below the soil surface, and a RCRA cover (a geomembrane overlain by 600 mm of compacted clay and 1 m of soil) (Anderson and Forman, 2003; DOE Idaho, 2007). The current favored design is the soil with bio-barrier using an evapotranspiration cover (EVT) (see Figure 3.6). The bottom layer is soil with a minimum thickness of 1.8 m to bring the facility up to grade. Above this is a layer of grading fill to create a 3 percent slope over the entire facility area, then overlain by the EVT cover.

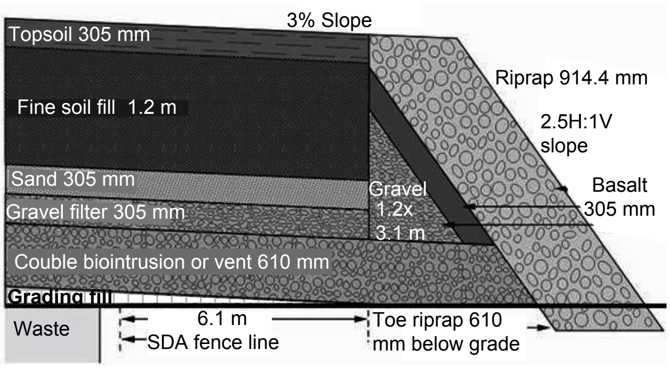


Figure 3.6: Proposed final cover system for the RWMC (DOE Idaho, 2007).

3.3.4 Environmental Management Waste Management Facility at Oak Ridge

Partially located within and adjacent to the city of Oak Ridge in eastern Tennessee and bordered on two sides by the Clinch River, the Oak Ridge Site occupies 140 km^2 of land and is 20 km west-northwest of the city of Knoxville (MMES Inc., 1994; Jacobs EM Team, 1998; US Department of Energy, 2009; US Census Bureau, 2012). The only current operating disposal facility is the EMWMF (US Department of Energy, 1997b). This facility is designed to accept on-site mixed waste, RCRA regulated hazardous waste, and regulated Toxic Substances Control Act (TSCA) wastes (US Department of Energy, 2009). The Oak Ridge climate is humid subtropical or humid continental, with average annual precipitation of 1,370 mm and average annual temperature of 14.4 $^{\circ}C$ (Farnsworth and Thompson, 1982; MMES Inc., 1994; Jacobs EM Team, 1998; Hughes et al., 2012; NOAA, 2012a; NOAA, 2013d).

The site geology is comprised of sedimentary rock layers compressed and folded over one another from historic faults and upward thrusts, resulting in carbonate-dominated rock groups interbedded with predominately clastic (sand and silt) shale groups (see Figure 3.7) (Hatcher et al., 1992; Jacobs EM Team, 1998). There are two types of hydrologic units spread across the site: the Knox aquifer unit, in which groundwater flow is predominately through solution conduits; and the Oak Ridge Reservation (ORR) aquitards, with groundwater flow dominated by fractured flow (Solomon, 1992). Three subsurface sections are present for each unit, a storm flow zone, vadose zone, and groundwater zone. Most groundwater flow occurs laterally in the storm flow zone, with groundwater zone flow decreasing with depth. The vadose zone is highly variable, ranging from nonexistent to a thickness of 50 m, with an average of 20 m. The EMWMF sits in an area of the ORR Aquitard, with depth to groundwater 20 m from the surface or 3 m below the bottom buffer layer of the disposal facility (Benson et al., 2008; US

Department of Energy, 2009). Experimental K_ds were calculated for radionuclides in shale on an order-of-magnitude basis (Solomon, 1992).

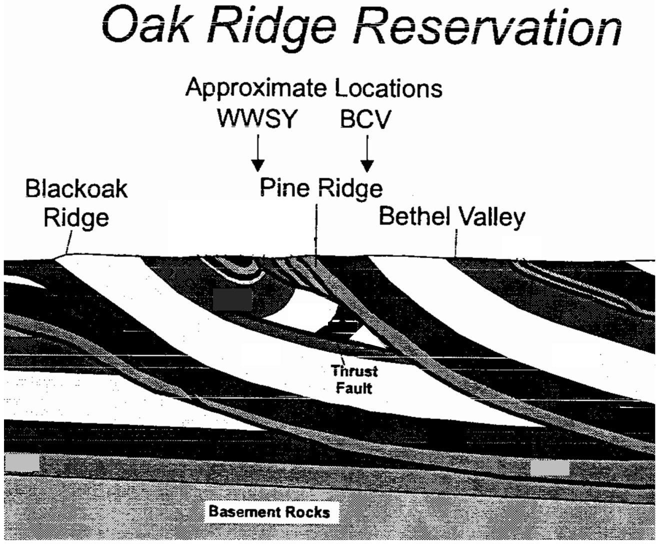


Figure 3.7: ORR generalized geologic cross-section ((Jacobs EM Team, 1998).

The EMWMF has been constructed in phases, with five currently finished disposal cells and a sixth cell in planning stages (Benson et al., 2008; US Department of Energy, 2009). Total land area is expected to exceed 44 acres, with current total disposal volume at 1,300,000 m^3, and an additional 382,000 m^3 of disposal space planned for cell six (Bechtel Jacobs Company LLC, 2001; Benson et al., 2008; US Department of Energy, 2009). Each disposal cell varies in size but is identical in design, with a double composite liner and leachate collection and detection system. The liner system base is a 915 mm layer of clay overlain by a 1.5 mm HDPE geomembrane (Jacobs EM Team, 1998; Benson et al., 2008). The leak detection system rests over the geomembrane consisting of a geonet placed between two non-woven geotextiles and followed by a second 1.5 mm HDPE geomembrane. The leachate collection system is above the second geomembrane and consists of a 305 mm gravel layer sandwiched between two geotextiles and covered with a 305 mm operational soil protective layer. A 3 m buffer layer of clay fill is beneath the liner base (Benson et al., 2008).

The EMWMF receives waste from site environmental remediation, contaminated building demolition debris, and general site operations. Waste forms including demolition debris, contaminated soil, contaminated clothing, trash, contaminated sediments/sludges, and miscellaneous solids (Jacobs EM Team, 1998). There is no standard waste package, and the waste package is determined by waste source and risk.

During the operational phase, an interim cover is placed over completed sections consisting of a minimum 305 mm of clay soil, to reduce infiltration and bring the area up to final grade (Jacobs EM Team, 1998). A water-shedding layer (geosynthetic clay (GCL) or asphalt) is placed over the clay to further limit infiltration, followed by a top 610 mm layer of vegetative soil to reduce erosion. Final cover design for the EMWMF is a 5 m multi-component cover system, and incorporates the interim cover (see Figure 3.8) (Bechtel Jacobs Company LLC, 2001; Benson et al., 2008).

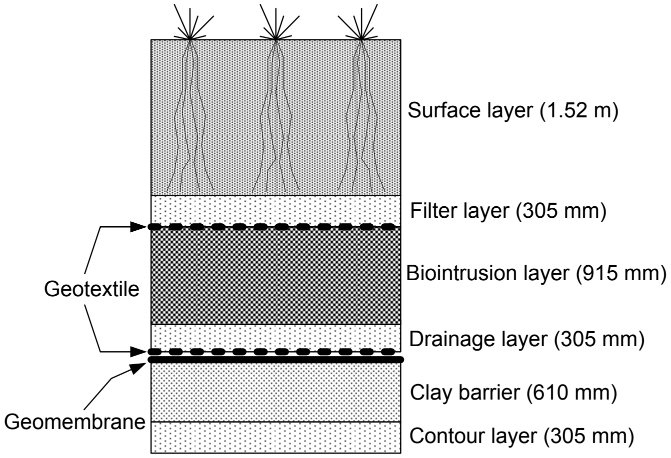


Figure 3.8: Proposed final cover system for the EMWMF (Benson et al., 2008).

3.3.5 Nevada National Security Site Area 5 Radioactive Waste Management Site

Located within the high desert of Southern Nevada, the NNSS occupies over 3,500 km^2 and is found near the communities of Pahrump (80 km southwest) and Indian Springs (42 km southeast) (Shott et al., 1998; Bechtel Nevada, 2006; US Census Bureau, 2012). The Area 5 Radioactive Waste Management Site (RWMS) is located in the southeastern portion of the NNSS within the northern region of the Frenchman Flat formation, an alluvium-filled closed basin containing a dry lake bed (Shott et al., 1998). The site takes up 732 acres, with the RWMS operating on 144 acres. The facility contains legacy on-site disposal, which began in 1961, legacy off-site disposal, which began in 1978, and current disposal from on-site and off-site sources (Bechtel Nevada, 2006). The disposal facility also contains a mixed waste cell allowed under RCRA interim status. The NNSS is situated in a transitional region between the Nevadan and Mojave Desert, with an intermountain desert climate (Shott et al., 1998). Average annual precipitation at Frenchman Flat is 124 mm and average annual temperature is 15.2 °C (Shott et al., 1998; Soule, 2006; NOAA, 2013b).

The Area 5 RWMS and encompassing Frenchman Flat basin are surrounded and underlain by Proterozoic and Paleozoic carbonate sedimentary rocks and Cenozoic volcanic rocks (Shott et al., 1998). Layers of volcanic tuff and infilling alluvium overlie the basement sedimentary rock formations. The surface alluvium layer has an estimated thickness of 360 - 460 m (Reynolds Electrical & Engineering Co., 1994; Snyder et al., 1994). Underlying the alluvium is a layer of interbedded Tertiary ash-fall and ash-flow welded and bedded tuff, with an estimated thickness of over 550 m (see Figure 3.9) (Raytheon Services Nevada, 1991). Distance to the water table is approximately 240 m. A combination of low precipitation coupled with high year-round evaporation rates have resulted in upward groundwater movement within the top 35 m of soil, with no movement of water throughout the remainder of the vadose zone. Distribution coefficients (K_ds) for inventory radionuclides were calculated for alluvium (Shott et al., 1998; Bechtel Nevada, 2006).

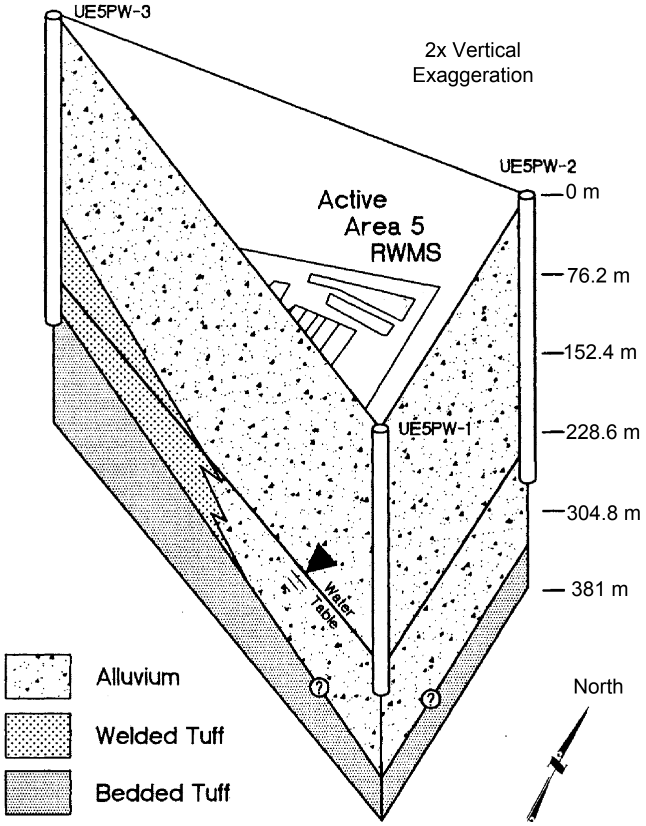


Figure 3.9: Subsurface geology below the RWMS at Area 5 (Shott et al., 1998).

Active waste disposal takes place within 28 pits and trenches dug into the alluvium (Shott et al., 1998; Bechtel Nevada, 2004; Bechtel Nevada, 2006). Each disposal pit ranges in length from 130 – 345 m and from 12 – 61 m in width. Trenches range from 77 – 345 m in length and 12 – 14 m in width (see Figure 3.10). There are two types of pits with varying depth, with a standard pit ranging from 3.1 – 6.7 m for most LLW disposal (trenches have the same depth range), and a deeper version of 7.4 – 9 m for waste that contains quantities of radium-producing isotopes (Bechtel Nevada, 2006). The total disposal area is 30 acres with a combined estimated waste volume of 572,000 m^3. None of the pits or trenches contain an engineered bottom liner, with waste placed on leveled native soil.

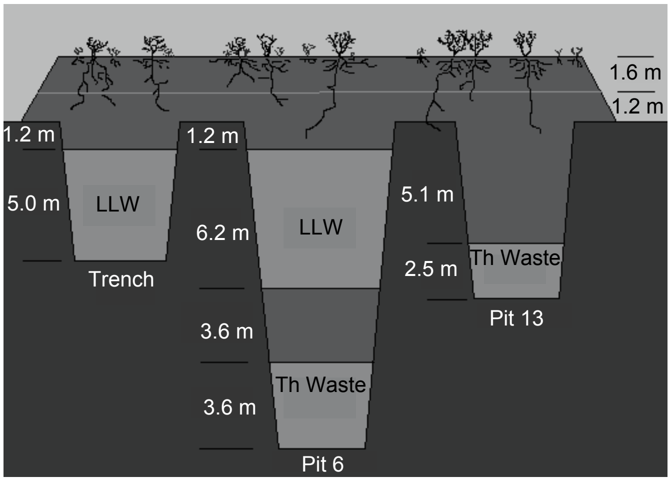


Figure 3.10: Waste zone and proposed final cover system for Area 5 (Bechtel Nevada, 2006).

Waste is accepted from on-site and off-site generators across the country, including large portions of the total waste volume from Rocky Flats, Fernald, and Mound (Shott et al., 1998). The RWMS contains a variety of waste forms, including cement-solidified tritium, cement-solidified sludge, sewage sludge with fly ash, laboratory waste, contaminated equipment, oil in absorbent, contaminated soil, D&D debris, trash, construction wastes, uranium residues, and thorium residues. Waste packages were originally made of plywood and cardboard. At present disposal involves the use of standardized steel boxes with dimensions of 1.2 m x 1.2m x 2.1 m or 0.61 m x 1.2 m x 2.1 m (Shott et al., 1998). Several types of steel drums have also been used. All waste containers are stacked to a height of 1.2 m below the original grade of each disposal pit or trench.

As sections of a pit or trench become filled, a bulldozer pushes native alluvium over the waste in a single lift as an interim cover. The material is scraped of large diameter material over 50 mm so that it fills in void spaces between waste packages. The thickness of the interim cover is approximately 2.4 m, with a final grade of 1.2 m above the surrounding area, and will remain in place during the 100-year IC period (see Figure 3.10). The final cover design calls for a 4 m monolayer EVT planted with natural vegetation (Bechtel Nevada, 2006).

Waste subsidence is expected to take place as waste packages degrade and collapse on voids within waste containers. Most subsidence is expected to take place and be repaired during the IC period, though estimates are that 25 percent of wooden boxes and steel drums and 80 percent of steel boxes will not have degraded by that time, leading to future subsidence (Bechtel Nevada, 2006). However, it is expected that movement of unconsolidated alluvium will fill in any cracks formed from cover subsidence.

3.4 Conclusions

Building stakeholder and regulatory confidence in the performance of a NSDF would be assisted through the use of an assessment methodology across all NSDFs that is standardized when appropriate, but that also reflects necessary variations. The wide variety of environmental properties and waste streams present at each site preclude the use of a uniform engineered barrier design or waste package, such that a flexible approach to analyzing the source term is needed. However, an adaptive process that selects optimal combinations of waste packages and engineered barriers adapted to site/waste specific characteristics in a standardized way across sites would improve the ability to compare various assessments of performance. For areas inherently difficult to compare, such as humid vs. arid sites or leachable vs. stable waste forms, a methodology that recognizes and adapts to these differences in a standardized fashion would also help to build confidence in performance. This article compares and aggregates parameters for five state of the practice DOE NSDFs. A system of components approach could be a useful piece of a future more standardized methodology that is flexible enough to adapt to any combination of disposal facility engineering, waste-specific parameters, and site-specific environmental factors. This would also allow insights into a facility's performance drivers by highlighting the interactions among overall system components.

CHAPTER 4

APPLICATION OF A PROPOSED GENERIC LLW WASTE PACKAGE ANALYSIS WITH CHANGING INFILTRATION IN A HUMID ENVIRONMENT

4.1 Introduction

Disposal of low-level radioactive waste (LLW) is regulated by a set of performance objectives established to ensure protection to human health and the environment from radiological hazards. These limits are typically represented as an activity per unit volume, over a period of time, at a set distance from the disposal facility. For waste generated by the U.S. Department of Energy (DOE) this limit applies 1,000 years after the end of disposal operations at a distance 100 meters (m) downgradient or downwind from the facility (US Department of Energy, 1999c). A near surface disposal facility (NSDF) is a LLW disposal technology designed to handle waste streams for a specific site. A performance assessment (PA) is conducted to establish an allowable inventory, based on specific radionuclides; and to demonstrate facility compliance with the DOE performance objectives using a site conceptual model.

We suggest that a NSDF is best conceptualized as a three-component system. Waste form, waste composition, and waste package represent the *disposal component*; facility bottom and cover layer(s) represent the *engineered facility component*; and site-specific features including precipitation and soil composition represent the *environmental component* (Rustick et al., 2015). The performances of these three components are linked, and this conceptual approach enables the assessment of a NSDF in an integrated manner.

Large uncertainties are present in predicting the processes and events that may occur over a 1,000-year timespan. One common simplifying assumption is that waste packages are fully degraded, or are compromised through mechanical processes, by the end of the DOE standard 100-year institutional control (IC) period. This eliminates a barrier to waste movement within the “waste zone”, defined as the space within the disposal facility where waste is contained. This assumption is considered conservative. However, actual facility performance could be significantly different, compared to assumed performance, if waste packages remained intact up to and beyond the end of ICs, providing an additional level of isolation for the contained waste.

In this article, we describe the development of an analytical approach for a generic NSDF, in a humid environment, that is based on the assumption of an intact waste package for predicted periods of time. Our focus was on the waste constituents that could be available for transport to the surrounding environment (the source term) under this assumption. Our objective was to analyze scenarios that involved different degradation rates for buried waste packages to evaluate effects on facility performance.

4.2 Near Surface Disposal Facilities

Disposal of LLW by the DOE is governed by a set of performance objectives as stated within DOE Order 435.1, under the self-regulating authority given to DOE by Congress in the Atomic Energy Act of 1954, as amended (US Department of Energy, 1999b). These performance objectives are further defined within DOE Manual 435.1 as release limits of radionuclides from a NSDF in terms of an annual dose to a member of the public at the boundary of the facility, taken to be 100 m (US Department of Energy, 1999c). A conceptual model is developed to provide a basis for estimating the release of waste from the NSDF (source term), movement of the waste through the environment (fate and transport), the ways through which a member of the public is exposed to the waste (exposure routes), and the ultimate dose to this individual (Shott et al., 1998; Westinghouse Savannah River Company (WSRC), 2008).

Under the current DOE requirements (US Department of Energy, 1999b), estimation of performance for a disposal facility is conducted for three time periods. The operational phase is the period of active waste disposal. This is followed by a 100-year IC period. The facility is assumed to be actively monitored by site personnel, and all necessary repairs made to the engineered barriers. Following the end of IC, the facility must perform adequately for an additional 900 years under the assumption that no additional repairs or human modifications will be made to the facility.

Since long-term field data do not exist to demonstrate how a facility will behave for periods of 1,000 years, conceptual models are needed to provide the basis for estimation of long-term facility performance. In order to bound the uncertainties of modeling an environmental system over 1,000 years, simplifying assumptions, typically conservative, are employed. As a portion of the source term calculation, many PAs assume that all waste packages within the disposal facility have degraded, to the point of mechanical failure, by the end of the IC period. The result is that all waste constituents of potential concern (COPCs) within the disposal facility are available for transport to environmental receptors prior to the end of ICs (DOE Idaho, 2007; Westinghouse Savannah River Company (WSRC), 2008). The resulting source term includes all remaining waste COPCs within the disposal facility. This approach is believed to be conservative, since the waste packages are no longer available as a barrier to waste transport from the disposal facility; however, such an approach also specifically conflicts with the definition of the IC period, wherein facility performance is monitored and required corrective actions taken. Thus, better estimates of the actual performance of waste forms are called for.

Waste packages were originally made of wood and other readily degradable materials. Most modern waste packages are primed and painted steel boxes (Shott et al., 1998; Westinghouse Savannah River Company (WSRC), 2008). These metal containers are designed for the transportation of material from waste generation areas to disposal in engineered landfills. They are watertight and able to withstand several tons of overburden at the time of disposal (Jones and Li, 2001).

However, once the lid of a container degrades to the point of failure, the overburden material can collapse into the container (Jones and Phifer, 2002). Figure 4.1 demonstrates the progression of waste package failure and cover collapse as part of an engineered facility conceptual model developed by site staff at Savannah River (Jones and Phifer, 2002). This collapse leads to subsidence in the engineered cover of the NSDF, increasing infiltration into the waste zone. Damage to the facility engineered cover is readily fixed during the IC period, but following the end of ICs any new damage would not be addressed. Published reports by DOE staff have identified post-IC subsidence as a major source of concern in meeting performance objectives (Jones and Phifer, 2002; Phifer, 2004; Westinghouse Savannah River Company (WSRC), 2008).

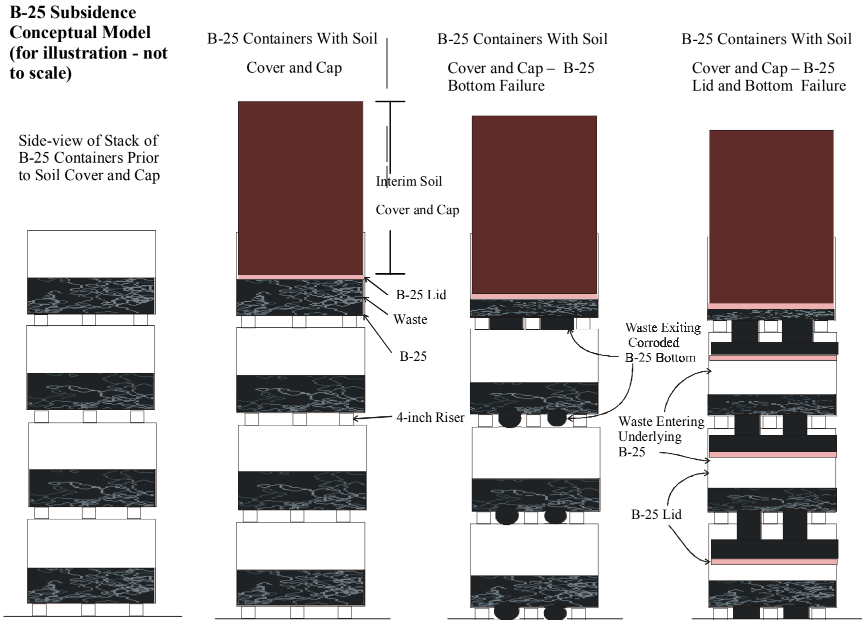


Figure 4.1: Engineered facility subsidence conceptual model constructed by Savannah River staff (Jones and Phifer, 2002).

For the 2008 Savannah River E-Area PA, it was assumed that an unspecified combination of container degradation and a mechanical accelerating agent (e.g., static surcharge, dynamic compaction) at the end of the IC period will cause all remaining intact waste packages to structurally fail and collapse. To compensate for unknown and variable container degradation rates, the accelerating agent will be designed to compact the waste zone to the maximum extent possible. This in turn would eliminate the potential for future subsidence caused by degrading waste packages and remove any remaining void space. This provides the rationale for the "no intact waste package" assumption.

However, the above assumptions are unlikely to provide an accurate representation of waste package corrosion over time and, therefore, actual facility performance would be underestimated. Studies have shown that metal structures buried in soil undergo well-understood, time-variable rates of corrosion depending on the metal and soil type (Romanoff, 1957; Szklarska-Smialowska, 1986; Velázquez et al., 2009). In moist soils, buried iron and steel containers will commonly undergo pitting corrosion. Pits will form on the metal surface and work their way through the metal structure (Mansfeld, 1987; Bradford, 2000). The rate of this type of corrosion can be constant or slowing over time, depending on the soil conditions.

One study, published in 1957 by the U.S. National Bureau of Standards (NBS), was designed to measure corrosion of different metals in a variety of soil types. The study found that corrosion of iron is dependent on soil corrosivity and soil aeration (Romanoff, 1957). Soil corrosivity is based on the characteristics of the soil (e.g. pH levels, Cl^- concentration, soil resistivity) and determines the initial rate of corrosion. Soil aeration is based on the profile of the soil overburden and is related to grain size and depth from ground surface. This determines the change in the corrosion rate over time.

In 1989, additional work was published by Mughabghab and Sullivan, mirroring the NBS study, but specifically looking at carbon steels (Mughabghab and Sullivan, 1989). Their objective was to show that carbon steel behaved similarly to the types of irons studied by the NBS. Mughabghab and Sullivan demonstrated that carbon steels did, in fact, follow corrosion relationships similar to those for wrought iron, one of the metals contained within the NBS study. Both studies showed that in well-aerated soils with high sand content, good drainage, and near the ground surface, the rate of corrosion drops abruptly over time. In poorly aerated soils, containing mostly clays with poor drainage, that are found deeper beneath the ground surface, the corrosion rate slows much less aggressively.

An eight-year study of buried metal boxes at the Savannah River Site (SRS) was conducted from 1993 to 2001 to extrapolate site-specific corrosion over the IC period (Dunn, 2002). Four carbon steel boxes were filled with simulated waste, sealed, and buried in native soil (Figure 4.2). Two of the boxes were stacked boxes under 1.22 m of soil. The other two boxes were buried individually under an additional meter of soil. In 2001, the top box from the stacked group was exhumed for testing, leaving the other three available for future tests. Three important observations were noted: (1) the lid of the top box was collapsed inward, (2) the same box was filled to the top with liquid, and (3) the underlying box also was found to have collected moisture despite remaining sealed. This last observation was discovered when the lid of the underlying box was accidently moved. This study demonstrated that it was possible for liquid to accumulate within an initially sealed waste package over time and also that this liquid could remain in the waste package for an extended period of time.

Figure 4.2: View of SRS B-25 boxes in 1993 prior to burial (Jones and Li, 2001).

The combination of historical literature values for corrosion, and the above Dunn study at SRS, was the basis for the development of our analysis using waste packages that remain intact beyond the operational phase of disposal. While the Dunn study focused on volume of metal loss from each face of the waste package in order to determine how structural integrity would change over time as corrosion progressed, we adapted our analysis to calculate the time taken to corrode through the box. This is important for the potential of a waste package to retain liquid and waste material.

The waste packages and engineered barrier designs were modeled based on disposal practices at the SRS E-Area – to provide real-world supplemental data for the analysis (Phifer et al., 2006; Westinghouse Savannah River Company (WSRC), 2008). SRS was chosen because of its decades of near-surface LLW disposal operations, the availability of numerous published reports and studies on site-specific disposal, and its location in a humid environment.

4.3 Properties of an Engineered Trench

A waste package analysis was created based on the current disposal practices for the Engineered Trenches at SRS (Westinghouse Savannah River Company (WSRC), 2008; Hamm et al., 2013). Each Engineered Trench disposal facility is approximately 198 m long by 46 m wide, with a depth ranging from 4.88 m to 7.62 m (Westinghouse Savannah River Company (WSRC), 2008). Trench sides are sloped at a rate from 1.25:1 to 1.5:1 (horizontal to vertical), and are filled with compacted native soil upon facility closure. The base of each Engineered Trench is compacted native soil overlain by a geotextile filter fabric and a top layer of crushed stone 152 mm thick. The base is also sloped to a sump located at one end.

The standard waste package used in this analysis was a steel box with interior dimensions of 1.17 m by 1.83 m and a height of 1.19 m, yielding a total volume of 2.55 m^3 (Jones and Li, 2001; Dunn, 2002; Jones and Phifer, 2002). This type of box (referred to in DOE as a “B-25”) is not the only type of steel box waste package used at SRS or at other DOE sites, but it is the most common type used in the Engineered Trenches, accounting for approximately 77 percent of waste packages. Each box is constructed of 12-gauge carbon (0.15 percent) hot-rolled, sheet and strip, commercial steel, with a thickness of 2.78 mm (ASTM designation A-569-93) (Dunn, 2002). The box lid is sealed with a rubber gasket to reduce liquid infiltration (Jones and Li, 2001). Three steel 100 mm tall risers are affixed to the bottom of each box to allow for movement and stacking by forklift.

Each box is designed to hold up to 2,722 kg of solid radioactive waste, and can support a uniform load of four fully stacked B-25 boxes, giving a total weight of 1.18 x 10^4 kg. A box can be filled with a mixture of waste forms. However, the waste is not always compacted within the box, and void space can vary between 10 to 90 percent (Jones and Phifer, 2002). The interior and exterior surfaces of the box are coated with a primer 0.051 mm thick. The exterior surfaces are additionally painted with an alkyd enamel coat 0.032 mm thick.

Boxes are stacked four high within an Engineered Trench, with a total height of 5.28 m including risers (see Figure 4.3) (Phifer and Wilhite, 2001). Box stacks are placed next to one another within the disposal facility, preventing any significant outward displacement of individual box walls. At SRS, a layer of soil 1.22 m thick is placed over each full section of Engineered Trench as an operational cover. The soil cover reduces the infiltration rate into the waste zone from natural precipitation to 286 mm/yr. (Hang et al., 2005; Hang et al., 2008).

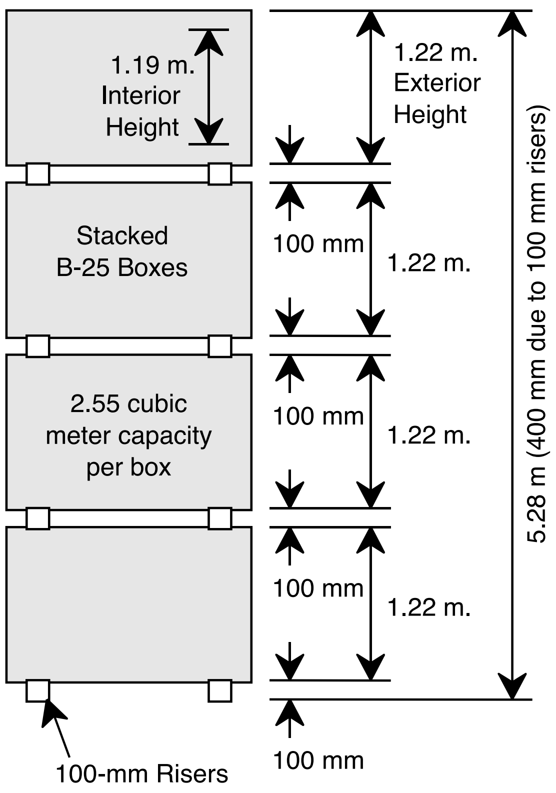


Figure 4.3: Stacked B-25 boxes within a generic disposal facility (Jones and Li, 2001).

Once an Engineered Trench is full, a high-density polyethylene (HDPE) geomembrane is installed over the operational soil cover. The combination soil/geomembrane layers are known as the "interim cover." Infiltration through the interim cover into the disposal cell is estimated to be 10 mm/yr. This value was established in literature, using the HELP computer code, within the 2004 SRS E-Area closure plan (Hang et al., 2005).

For this analysis, we assumed dimensions of 198 m long by 46 m wide by a constant depth of 6.5 m for a hypothetical Engineered Trench. The dimensions for length and width would be for the base of the trench, with no waste placed on the side slopes of the trench. Boxes would be stacked four high with a 1.22 m soil overburden (operational cover). This created a waste zone of approximately 17,000 B-25 boxes. It was assumed that boxes were exposed to natural precipitation rates while each section of the disposal facility was being filled. At SRS, average annual precipitation is 1,220 mm/yr.

The estimated time between start and completion for a recent Engineered Trench at SRS (Trench #3) was 12 years, and this value was selected for the fill rate of our hypothetical Engineered Trench (Hamm et al., 2013). Actual disposal facility fill rates can vary from year to year. For our analysis, an average time period of one year was chosen between emplacement of a waste package and covering the waste with the soil operational cover. This fill rate was based on historical rates for Engineered Trenches #1 and #2 (Westinghouse Savannah River Company (WSRC), 2007; Swingle et al., 2008; Millings et al., 2009; Swingle et al., 2010; Swingle et al., 2011). This divided the modeled disposal facility into 12 equal sized zones, with a fill rate of one zone per year. It was assumed that no significant box infiltration or corrosion would occur before placement of the operational cover. The layers of primer and paint are designed to resist corrosion from precipitation, and there would be no soil cover to depress the lid of the top box.

In the 2002 Dunn study, the uppermost B-25 box was found to be completely filled with liquid after eight years of burial under 1.22 m of compacted native soil (Jones and Li, 2001). In their 2002 report, Jones and Phifer selected an average waste package void space of 50 percent within their conceptual model (Jones and Phifer, 2002), and we assumed this value for our analysis. In addition, the SRS waste acceptance criteria for E-Area trenches requires that waste contain less than one percent free liquid (Westinghouse Savannah River Company (WSRC), 2008), and we assumed that no liquid was present at the time of waste burial. With 50 percent void space, the volume of liquid in a full waste package is 1,280 L, which over an eight-year period produces a fill rate of approximately 160 L/yr. This box would be the equivalent of the top B-25 box under the operational soil cover of an Engineered Trench. For a footprint area of 2.14 m^2 and annual infiltration of 286 mm/yr through compacted native soil, the total volume of infiltration over the area of a B-25 box stack is 610 L/yr.

The underlying box in the Dunn study was estimated to be roughly half filled with liquid despite remaining sealed with an intact lid (only visual inspection was conducted). This resulted in approximately 640 L of total liquid, a fill rate of 80 L/yr, and close to 18 percent of the total annual infiltration minus the amount collected in box one. This is the extent of field data to estimate the infiltration rates into box two of four within an Engineered Trench, and no field data exists for boxes three and four. Currently, there is also no field data that extends beyond eight years, as no date has been set by SRS staff to exhume the remaining boxes. As a best estimate assumption, using the single data point available, boxes three and four would also be estimated to fill with liquid at 18 percent of the remaining available infiltration. For box three of four this would result in a fill rate of 67 L/yr, and for box four of four the resulting fill rate would be 55 L/yr; the remainder of the infiltrating water (L/yr) exits the waste zone.

Within our analysis, some of the waste packages would be buried for up to 11 years under the same depth of soil as the Dunn study. To account for the difference between the available field observation data and the run time of our analysis, it was assumed that the three extra years of infiltration into the waste zone would flow around the top box, which would remain full of liquid. Since there are limited field data, it is difficult to address the uncertainty in estimating the fraction of liquid that would be partitioned between the underlying boxes and liquid that would travel directly to the vadose zone. We chose therefore to assume that for all boxes under the operational cover between years 9 through 11, the overflow from box one becomes available to fill the underlying boxes at the same 18 percent of available liquid as calculated in the previous section. The resulting fill rates are 110 L/yr for box two, 90 L/yr for box three, and 74 L/yr for box four, with the remaining L/yr of infiltrating water exiting the waste zone.

Once the facility is in the IC period, we assumed that the liquid fill rate for all boxes decreases proportional to the reduction in the infiltration rate from 286 mm/yr to 10 mm/yr. Total infiltration per box stack at 10 mm/yr is 21.4 L/yr. For box one this produces a fill rate of 5.6 L/yr, box two 2.8 L/yr, box three 2.3 L/yr, and box four 1.9 L/yr. Once box one is filled with liquid, the fill rate increases for box two to 3.9 L/yr, for box three to 3.2 L/yr, and for box four to 2.6 L/yr based on the resulting proportional increase of available infiltration.

One of the major factors built into this facility analysis is that infiltration is not spatially and temporally constant for all waste packages during the operational disposal phase. The boxes disposed in zone one will experience 11 subsequent years of annual infiltration at 286 mm/yr until the facility is full and the interim cover is installed. By contrast, the boxes disposed in zone 12 will receive infiltration only at the interim cover rate of 10 mm/yr, as the interim cover will be installed directly following the end of waste disposal. The waste sections between zone one and zone 12 will receive proportionally varying amounts of total infiltration.

4.4 Waste Package Degradation

Two corrosion cases were considered for this analysis, a constant corrosion rate and a diminishing corrosion rate. A constant rate of corrosion was used in several SRS studies to support the E-Area PA, including the 2002 Dunn report (Dunn, 2002; Jones and Phifer, 2002; Jones et al., 2003). In addition to the NBS and Mughabghab studies, the aforementioned SRS studies also discuss the possibility of a slowing corrosion rate at Savannah River as an alternative to a constant corrosion rate. Release of waste COPCs dissolved in liquid from each box, to be defined as leachate, was assumed to occur when a pit on the face of a box had fully corroded through, resulting in a hole for liquid to leave the box.

The bottom of the box was chosen as the failure point for all waste packages. This was selected for two reasons; first, it would allow for the greatest amount of leachate to flow from the waste package. Second, the box bottom was observed to have the highest corrosion rate of any side due to abrasions from the forklifts used to transport waste packages (Dunn, 2002; Jones and Phifer, 2002). The tynes of the forklift scrape the protective coatings from the box, disturbing the protective paint layers and exposing the metal underneath (see Figure 4.4).

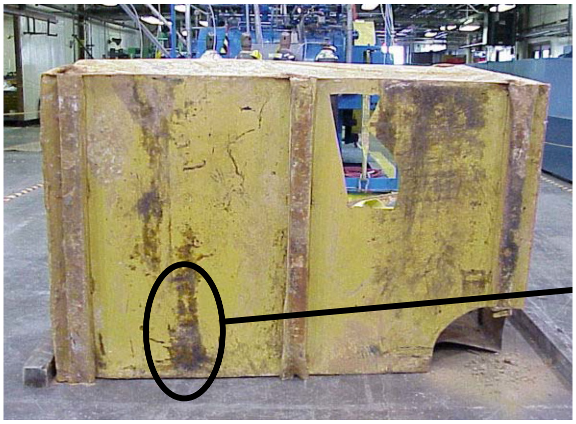


Figure 4.4: Picture of B-25 box bottom exhumed from the 2002 Dunn study. Notice the scrape marks between the risers from forklift transport (Dunn, 2002).

For the base case (constant corrosion), extrapolating from the pit growth observed on the exhumed box from the Dunn study after eight years, SRS staff estimated that corrosion through the box bottom would occur around 42 years from time of burial (Jones and Phifer, 2002). This produces a corrosion rate of 0.066 mm/yr (2.6 mils/yr). This was assuming that site conditions, such as annual infiltration and soil composition, did not change significantly over time.

For the slowing corrosion case, corrosion rates were calculated based on work presented in the NBS report (Romanoff, 1957; Dunn, 2002; Jones and Phifer, 2002). The NBS study derived an equation for rate of corrosion that followed a power law (equation 1) (Romanoff, 1957):

$$h_m = kt^n \quad (1)$$

h_m = maximum pit depth, in mils;
k = site dependent soil corrosivity fitting parameter, in mils/yr;
t = time, in years;
n = soil aeration dependent fitting parameter

Well-aerated soils were found to have lower values of n, and poorly aerated soils higher n values. The NBS, and subsequent study by Mughabghab and Sullivan, showed that k values are based on both the corrosivity and aeration of the soil. Increasing corrosivity leads to higher k values, and better aerated soils have higher k values compared to poorly aerated soils. This method of calculating corrosion rates was also presented as an alternative to a constant corrosion rate within the 2002 Jones and Phifer report.

At SRS, site staff estimated soil conditions to be similar to "very poorly" aerated clay soil with low soil corrosivity. This was reflected in their use of 0.8 for n and 2.6 mils/yr for k in a 2002 report based on the Dunn study for carbon steels (Jones and Phifer, 2002). This compares with a value of 11 mil/yr for k and 0.75 for n for "very poorly" aerated soils reported in Mughabghab and Sullivan (Mughabghab and Sullivan, 1989). The difference in k values was because the soil corrosivity in Mughabghab was relatively high compared to the soil used in the NBS study and measured corrosivity values at SRS. Mughabghab notes that large concentrations of Cl^- and SO_4^{-2} at the sites used in their study likely contributed to the higher soil corrosivity compared to the NBS study. However, the values for n in Mughabghab and SRS are similar, and were expected to be similar, since aeration is independent of soil corrosivity.

4.5 Corrosion Scenarios

Four scenarios were examined for each of the two corrosion cases and are described below (see Table 4.1). For this article, only values for waste packages disposed of in zone one and zone 12 were reported. This was chosen to demonstrate bounding corrosion effects for the 12-year period of disposal. Table 4.2 shows the values for k and n that were used in the analysis.

In all scenarios, it was assumed that during the operational phase, all of the buried waste packages experience conditions characteristic of "good" soil aeration. With one end of the facility open to the external environment, oxygen is able to penetrate between the waste packages and permeate throughout the waste zone. Once the facility is full and sealed with an interim closure cover to start the IC period, ambient air is no longer available to the waste zone. We assumed that the waste zone then transitions to a "very poor" aeration environment.

In the NBS study, "very poor" soil aeration was attributed to clay soils. This is significant, since clay soil types also held moisture against the metal samples in the NBS study, contributing to the rate of corrosion. A justification for our assumption of "very poor" aeration, in addition to oxygen availability, was that available moisture from infiltration would continue to flow through the waste zone during the IC period. The moisture would flow over the surfaces of waste packages while also keeping humidity levels high within the waste zone. This conservatively may create moisture conditions similar to the "very poorly" aerated soils discussed in the NBS study.

In the first scenario, considered the base scenario since it closely follows SRS data, the corrosion fitting parameter k was kept at the measured SRS value of 2.6 mils/yr for both the operational and IC periods. The aeration value n was selected from the NBS study for "good" (0.32) and the

SRS value of 0.8 (for “very poor”). The NBS value was needed since SRS did not consider “good” soil aeration during the operational period in their 2002 report (Jones and Phifer, 2002).

For the second scenario, which is a mix of SRS and NBS findings, the corrosion fitting parameter k was doubled to 5.2 mils/yr for “good” aerated soil and kept at the SRS value of 2.6 mils/yr for “very poor” aerated soil. In the NBS and Mughabghab and Sullivan studies, it was observed that k values for soils with “good” aeration produced values for k that were double or more compared to k values for soils with “very poor” aeration. This scenario was constructed to reflect the observations of the NBS study. The soil aeration values of 0.32 for “good” and 0.8 for “very poor” were kept from the first scenario, since no changes to soil aeration assumptions were made for this scenario.

The third scenario considered a hypothetical environment that was more corrosive than the SRS environment. The change in k values from “good” to “very poor” soil aeration was kept from scenario two, but the k parameter was doubled from 5.2 to 10.4 mils/yr for “good” soil aeration and from 2.6 to 5.2 mils/yr for “very poor” soil aeration. While not at the level of corrosion as the Mughabghab study (36 mils/yr for “good” soils and 11 mils/yr for “very poor” soils), it does represent environments closer to those considered in the NBS study. The values for n remained the same as those in scenario one and two.

The fourth scenario was designed to observe the effects of using a more robust waste package compared to the 12-gauge B-25 box. A wide range of carbon steel boxes are used within the radioactive waste industry and different thickness boxes are readily available commercially (Container Products Corporation, 2016). In this scenario, the thickness of the carbon steel wall for the waste package was changed from 12-gauge (109 mils) to 10-gauge (141 mils) steel.

There is precedent for changing waste package material at SRS, as B-25 box materials were switched in the 1990s from 14-gauge to 12-gauge carbon steel for disposal in the E-Area trenches (Dunn, 2002). Scenario two was used as the basis for this scenario, including keeping the k and n fitting parameters the same as those used in scenario two.

Table 4.1: Corrosion Scenario Descriptions

Scenario #	
1	**Base Case**: SRS values used for all parameters (with the exception of "good" soil aeration, which was not considered by SRS staff)
2	**Mix of SRS and NBS**: SRS k and n values kept for "very poorly" aerated soils; NBS k and n values used for "good" aerated soils. k values for "good" soil aeration were doubled to reflect results of NBS study
3	**Higher Corrosivity**: Corrosivity fitting parameters doubled for "good" and "very poorly" aerated soils to reflect an environment more corrosive to carbon steel; SRS soil was estimated to be on the lower range of soil corrosivity compared to soils from the NBS study.
4	**More Robust Waste Package**: k and n values were kept identical to scenario 2; the waste package wall thickness was increased from 12 to 10 gauge steel to reflect a hypothetical change to waste package procurement (such a change has already occurred once)

Table 4.2: k, n, and Wall Thickness Values Used

	Scenario #							
		1		**2**		**3**		**4**
k good		2.6		5.2		10.4		5.2
k poor		2.6		2.6		5.2		2.6
n good		0.32		0.32		0.32		0.32
n poor		0.8		0.8		0.8		0.8
Wall Thickness in mils		109		109		109		141

Once all four corrosion scenarios were modeled, estimates were calculated for the amount of leachate that would be released following the hydraulic failure of a waste package. Since this article focuses on the waste disposal in the first and last years of the operational phase, only the zone one waste packages will experience two different fill rates, while the zone 12 waste will only experience the IC period fill rates. It was assumed that holes developed in all four waste boxes in a given stack at once, and that all of the leachate contained in the waste packages was immediately released to the vadose zone. This was done to calculate the maximum volume and flux of leachate that could be released from the waste zone for the zone one and zone 12 waste package groups.

4.6 Results

The zone one and zone 12 waste packages for the base and slowing corrosion cases were plotted against each other and can be found in Figures 4.5 through 4.8. Each graph represents one of the four corrosion scenarios. A summary of results from the corrosion scenarios is presented in Table 4.3; specifically the time it took for zone one and zone 12 waste packages to reach hydraulic failure for the two corrosion cases.

Using the data from the four corrosion scenarios, the total amount of liquid within all of the disposed waste packages for a given year was calculated in L and presented in Table 4.4. From a total of 17,000 waste packages per Engineered Trench, it was estimated that each year approximately 1,417 waste packages in 354 stacks are placed in a trench. Liquid flux (L/m^2) for the waste zone was also calculated and reported in Table 4.4.

Figure 4.5: Pit growth in Box Bottom with Savannah River Corrosion Rates

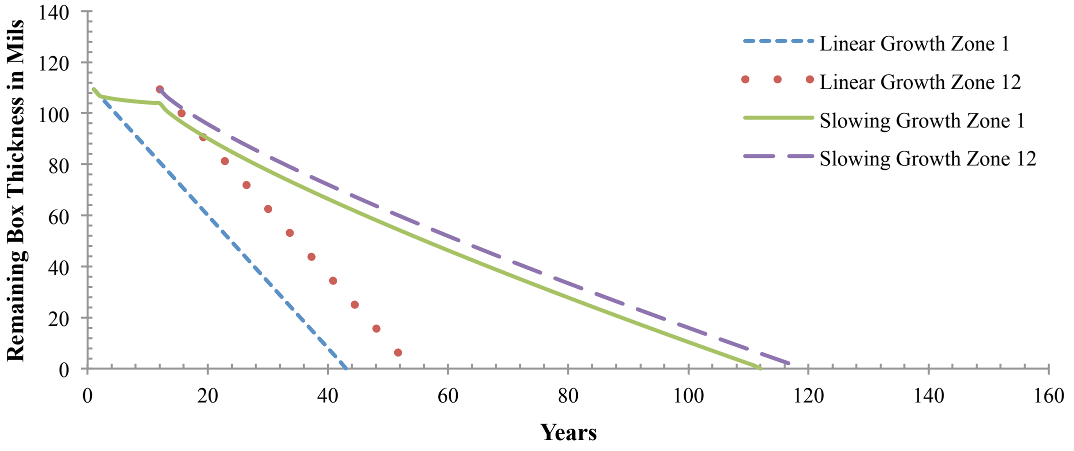


Figure 4.6: Pit Growth in Box Bottom with Corrosion Rates Changed Following Trench Closure

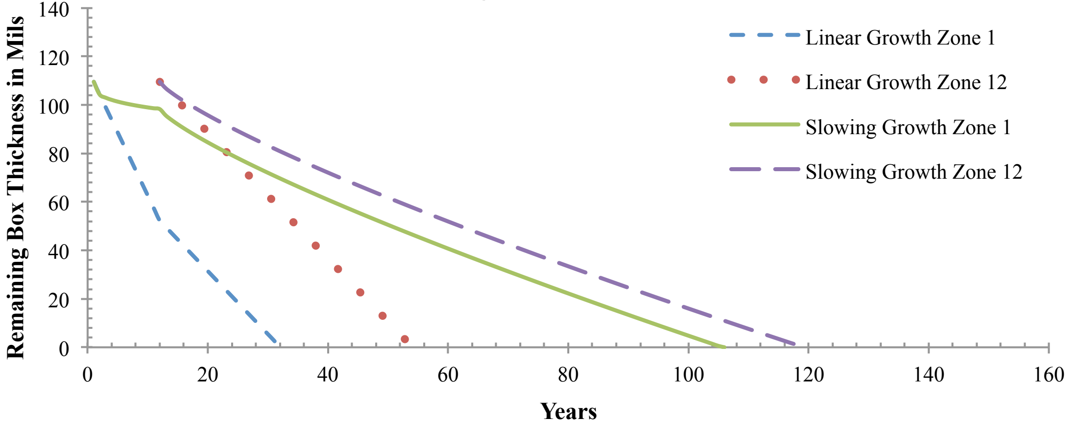


Figure 4.7: Pit Growth in Box Bottom with Corrosion Rates Doubled from Scenario 2

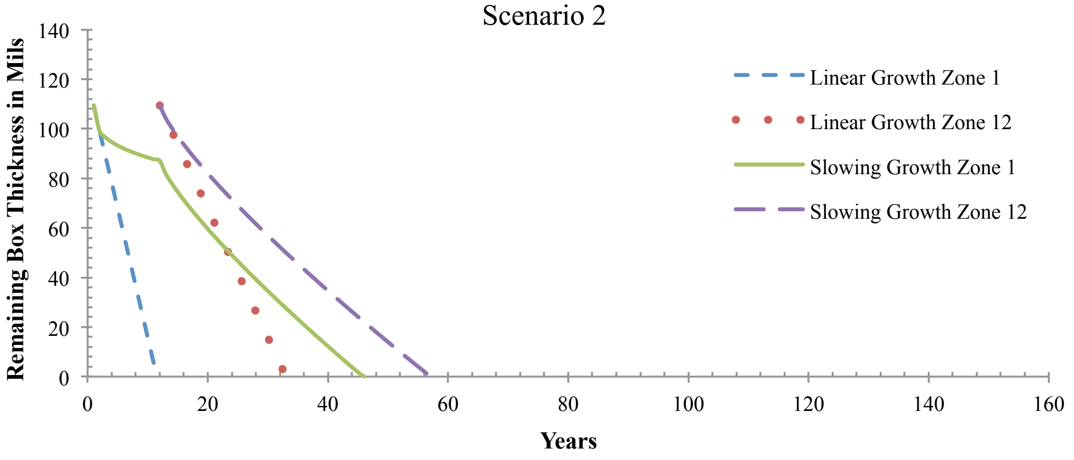


Figure 4.8: Pit Growth in Box Bottom with Scenario 2 Corrosion Rates and 10-gauge Steel Box Walls

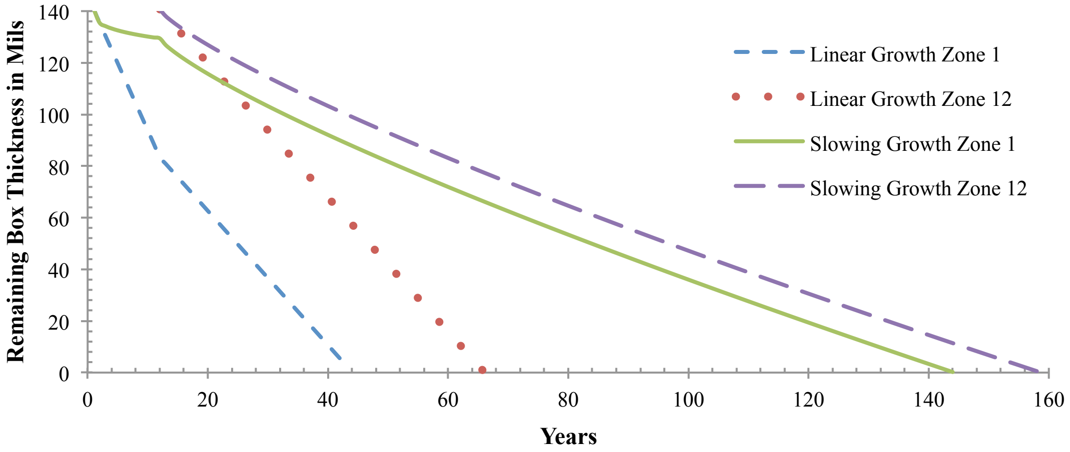


Table 4.3: Time to Hydraulic Failure for Waste Packages under Corrosion Scenarios

			Scenario			
Corrosion Case	**Waste Emplacement Zone**		**1**	**2**	**3**	**4**
			Time in Years			
Constant	1		42	31	11	43
	12		53	53	32	65
Slowing	1		111	105	45	144
	12		118	118	56	158

Table 4.4: Total Waste Zone Liquid Volume and Flux at the Time of Box Hydraulic Failure

Corrosion Case		**Waste Emplacement Zone**		**Scenario**			
				1	**2**	**3**	**4**
Constant	**Total Waste Zone Liquid Volume in L (1417 boxes/zone)**	1		1.42E+06	1.39E+06	1.31E+06	1.43E+06
		12		1.88E+05	1.88E+05	9.37E+04	2.42E+05
	Resulting Liquid Flux [L/m^2]	1		1877	1827	1734	1883
		12		248	248	124	319

Corrosion Case		Waste Emplacement Zone		Scenario			
				1	2	3	4
Slowing	Total Waste Zone Liquid Volume in L (1417 boxes/zone)	1		1.64E+06	1.62E+06	1.43E+06	1.71E+06
		12		4.78E+05	4.78E+05	2.01E+05	6.56E+05
	Resulting Liquid Flux [L/m^2]	1		2160	2140	1890	2258
		12		631	631	265	866

4.7 Discussion

A few initial insights can be made. The spread between the first and last waste package zones are the highest in scenario four at 14 years for the slowing corrosion case, but are equally high at 22 years in scenarios two and four for the constant corrosion case. In scenarios one, two, and four, representing lower corrosivity environments, there is the potential for waste packages to remain leachate-tight beyond 100 years under the slowing corrosion case. Conversely, in a higher corrosivity environment represented by scenario three, some of the early waste packages could develop holes before the installation of the interim cover.

As time progresses during the IC period, the corrosion behavior of the buried waste packages will have impacts on the monitoring and maintenance of the NSDF. If a waste package or group of waste packages begin to fail during this period, the liquid contained within the waste packages will be visible to environmental monitoring as the leachate flows downwards into the vadose zone. At current DOE NSDF sites, two common forms of environmental monitoring are pan lysimeters and vadose zone moisture probes (National Research Council, 2007). Lysimeters collect liquid over a defined area for measurement and sampling, while moisture probes can detect changes in soil pore moisture. Both of these methods would be able to detect an increase in soil liquid from a hydraulically failed waste package. However, an increase in vadose zone leachate could also be mistaken for cover system failure, or vise-versa, for a monitoring method that did not allow for sample removal and radionuclide analysis of leachate. This will influence the selection of monitoring methods, as at least one form of leachate monitoring (e.g., pan lysimeter) must allow for such sampling.

As a related measure, there could be the potential to use estimates of the amount of liquid leaving each waste package as a performance confirmation metric. Through monitoring of the vadose zone directly beneath the disposal facility (or other form of leachate collection), an observed spike in radionuclide concentration could be correlated to the formation of a hole in a waste package. This would help quantify the rate of box corrosion. The use of tracer material specific to box row could increase the resolution of the observations by identifying corrosion rates by the vertical location of the box within the waste zone.

Failure of waste packages after the end of the 100-year IC period, as predicted by most of the slowing corrosion scenarios, presents challenges for the final closure of a NSDF. As mentioned previously, the DOE considers waste zone subsidence as a major failure potential for a NSDF at Savannah River. The proposed remedy for this is some form of mechanical compaction to remove remaining void space within the waste zone before a final facility cover system is installed (Phifer et al., 2006). The presence of leachate in waste packages within a portion or over the entire waste zone could compromise the effectiveness of the mechanical compaction. Leachate could be released in large quantities over a short period of time to the vadose zone. It could also mix with the soil of the interim cover creating a hazard for site workers performing the mechanical compaction.

For existing NSDFs, in order to avoid potential problems from performing mechanical compaction on waste packages that still contain leachate, it may be advisable to delay closing a facility until an acceptable majority of waste packages have hydraulically failed. Assuming this could be done from an administrative standpoint (current rules within DOE Order 435.1 require a facility to be closed after a 100 year IC period), there are several additional benefits from a facility performance standpoint. The additional time will allow for the lids and bottoms of waste packages to more fully corrode before mechanical compaction is applied. Void space remaining within the waste zone, either from no compaction or after incomplete compaction as a result of insufficient corrosion of waste packages, was identified in reports following the 2002 Dunn study and the 2008 E-Area PA as potential causes of engineered cover subsidence following the end of ICs (Jones et al., 2003). Additional time before compaction will also allow for further decay of radionuclides in the leachate of waste packages that had not yet failed.

For future NSDF to better incorporate the concept of a systems approach to waste management, it will be important to consider type, handling, and the corrosion environment for waste packages during the planning phase of the NSDF. Scenario four dealt with choosing a different type of waste package, and demonstrated an over 20-year extension of the hydraulic life of that waste package. This may be advantageous for a waste form that contains a high fraction of short-lived mobile radionuclides that would benefit from extra time in isolation from the surrounding environment. It could also be detrimental if mechanical compaction cannot be delayed beyond the 100 year IC period. Cost is another consideration, as the added steel will increase the price per box. The cost for a 12-gauge B-25 box in 2001 was approximately \$523 (Phifer and Wilhite, 2001). Assuming even a 10 percent premium for the 10-gauge box yields a cost of \$575, and a cost difference between the two boxes over an entire Engineered Trench (17,000 boxes) of $884,000.

Waste package handling, while not specifically addressed by any individual corrosion scenario, would change all scenarios by affecting the box bottom corrosion rate. The current method of using a forklift for transportation damages the box bottom by removing the protection of the primer and paint. A modified forklift with padded tynes would keep the protective coating. Another transport method would be to fit the B-25 box in a sling and lift the box into the waste zone by crane, as has been done in reverse for waste retrieval at Oak Ridge (Turner et al., 2006). Waste packages could also be transported on wooden pallets or suspended in cargo nets similar to waste removal techniques for steel drums at Hanford (DeRosa et al., 2000).

Lengthening the hydraulic lifespan of a waste package may be advantageous if the waste package is in a high corrosion environment similar to scenario three. However, a long lifespan could be detrimental in a low corrosion environment similar to scenario two if it interferes with mechanical compaction. Waste packages could therefore be selected to ensure that all waste packages will fail before the end of ICs. This could mean changing waste package procurement for thinner box bottoms, or designing waste packages with plugs that are designed to degrade under specific conditions. Another option would be to fill in waste package void space with grout or other solid material to prevent infiltrating liquid from mixing with waste. Grouting waste packages would also eliminate subsidence potential. However, the additional weight provided by grout material would necessitate that grouted waste packages be placed under non-grouted waste packages to avoid overloading the underlying boxes, though grouting all waste packages solves this problem.

A hybrid approach could be considered if it was advantageous for certain waste packages to retain leachate and grouting was not an option. This would involve using heavier gauge waste packages for early years of waste disposal and lighter gauge waste packages closer to the end of the operational phase. Since early waste package are subjected to a number of years of infiltration through an operational cover, they would gain more time before hydraulic failure from the thicker steel walls. Later waste packages not subjected to as much infiltration might perform the same as the earlier heavy waste packages while saving on cost from thinner walls.

As a result of a number of simplified assumptions built into our analysis, there are several areas of further study that could have a significant effect on the results provided above. Liquid buildup within waste packages could provide a mechanism for earlier development of holes, as pressure is exerted from accumulated liquid on waste package sections weakened from corrosion pits. In addition to corrosion of waste package walls, the working life of the gasket seals and edge welds of a B-25 box are unknown, and could lead to hydraulic failure before the box bottom over the 100-plus years estimated under several of the corrosion scenarios. Another issue is the presence of microbial activity within the waste package. Depending on a number of factors, including waste compositions, waste package leachate, microbial colonies, and oxygen levels, corrosion could become accelerated within the interior of the waste package in yet unknown ways.

4.8 Conclusion

Our analysis of a general LLW NSDF in a humid environment has shown a wide variation in corrosion rates depending on the assumed type of corrosion and soil conditions. All of the scenarios, under a constant rate of corrosion, developed holes in waste packages during the IC period. However, with a low enough corrosion rate, some waste packages undergoing a slowing corrosion rate could develop holes at times beyond final site closure. On the opposite end, under a high enough corrosion rate some waste packages could develop holes before the installation of an interim cover. Additional study is needed to assess the effects of leachate buildup within waste packages and the presence of microbial activity.

CHAPTER 5

WASTE ZONE LEACHATE BUILDUP AND RELEASE FROM A LLW DISPOSAL FACILITY WITH CHANGING INFILTRATION AND CORROSION PARAMETERS

5.1 Introduction

The United States (US) Department of Energy (DOE) manages the disposal of low-level radioactive waste (LLW) through a set of performance objectives, designed to protect human health and the environment from the hazards of radionuclide exposure (US Department of Energy, 1999b). These performance objectives control the amount of LLW that can be placed within a near surface disposal facility (NSDF). Disposal limits for each radionuclide are defined based on maximum permissible ground and surface water and air radionuclide concentrations at a set distance from the NSDF, along with scenarios in which individuals disturb the buried waste following facility closure. The DOE has determined that all of performance objective must be met for 1,000 years following the end of waste burial operations, and releases from the facility are calculated for meeting performance at a distance 100 meters (m) downgradient or downwind from the facility (US Department of Energy, 1999c). This analysis, in which site conceptual and predictive models are used to demonstrate that a given design of NSDF and proposed inventory will meet all performance objectives, is known as a performance assessment (PA).

In this article, we describe the development of an analytical approach for estimating leachate buildup within waste packages buried in a generic NSDF, in a humid environment. This approach was based on the assumption of an intact waste package for predicted periods of time. Our objective was to analyze different infiltration situations based on the length of a NSDF operational period and the subsequent impacts on facility performance.

5.2 Near Surface Disposal Facilities

We evaluated a NSDF as an integrated system of three components, instead of an engineered facility that is designed and operated independent of waste and surrounding environment as proposed in a previous article by Rustick et al. (Rustick et al., 2015). The basis of this study is that waste form, waste composition, and waste package represent the *disposal component*; facility bottom and cover systems represent the *engineered facility component*; and site-specific environmental features, including precipitation and soil composition, represent the *environmental component* (Rustick et al., 2015). The three components and their respective performance are interrelated, allowing for the assessment of a NSDF to be conducted in an integrated fashion.

Past practice for designing NSDFs at DOE sites and the accompanying PAs typically began with the selection of several cover systems of increasing robustness designed to limit infiltration into the waste zone, defined as the isolating location within the NSDF containing LLW (Phifer, 2004). Each cover system was designed for three distinct time periods of a facility lifespan. The first is the operational period, the period in which parts of the facility are still open and receiving waste. As sections fill, they are covered with a simple cover, such as compacted native soil, to facilitate runoff, provide a working surface for equipment, and reduce infiltration into the waste zone (Hang et al., 2005; Westinghouse Savannah River Company (WSRC), 2008).

Once the facility is filled to capacity, the waste zone is further protected from infiltration by the installation of an interim cover. This is usually installed over the operational cover, is designed to be much less permeable to infiltration, and is constructed from various materials including geomembranes, asphalt, and cement (Cook et al., 2004). The NSDF is then maintained by site staff for a 100-year period that includes the active monitoring and management of the cover system. This period is referred to as the institutional control (IC) period. At the end of the IC, a final cover designed to last for hundreds of years without intervention is installed over the NSDF, and the facility is deemed officially closed. The NSDF must continue to meet performance objectives for an additional 900 years, giving a total of 1,000 years for compliance.

In order to model the subsequent performance of the aforementioned system over 1,000 years, simplifying assumptions are typically employed for the behavior of waste packages in the waste zone over time. Calculations are made of the transport of radionuclides contained in liquid released from the facility, known as leachate, to a potential receptor at the 100 m compliance boundary. As a way to provide an upper bound for the values for leachate released from a NSDF (the facility "source term"), many PAs assume aggressive corrosion of all metal waste packages within a NSDF, so that most waste packages have corroded to the point of collapse by the end of the IC period. The result is that all waste constituents of potential concern (COPCs) within the disposal facility are available for transport to environmental receptors prior to the end of ICs (DOE Idaho, 2007; Westinghouse Savannah River Company (WSRC), 2008).

However, more recent studies have demonstrated the potential for waste packages to not just remain structurally stable but also hydraulically intact for extended periods of time (Rustick et al., 2016). This allows leachate to build up within the waste packages of the waste zone, and could have profound impacts on overall NSDF performance. Thus, better estimates of the actual performance of waste packages are needed to assess the impacts on leachate buildup caused by changes in facility infiltration.

Before analyzing leachate buildup, the process of waste package corrosion needs to be considered. Most modern waste packages used by the DOE are carbon steel boxes. In moist soils, buried iron and steel containers will commonly corrode over time from the formation of pits that grow into the metal surface (Mansfeld, 1987; Bradford, 2000). The US National Bureau of Standards (NBS) published an authoritative study on corrosion of metals in different types of soils in 1957. One finding by the authors was that corrosion of iron was dependent on soil corrosivity and soil aeration (Romanoff, 1957). Soil corrosivity determines the initial rate of corrosion, while aeration properties of the soil determines the change in the corrosion rate over time. Additional work was published by Mughabghab and Sullivan in 1989, confirming the results of the NBS study for carbon steels (Mughabghab and Sullivan, 1989). Both studies showed that the rate of corrosion drops abruptly over time in well-drained and well-aerated soils containing large soil grains and close proximity to the soil surface. Deeper soil layers and those containing higher fractions of clays with poor drainage showed corrosion rates that slowed much less aggressively.

Using an integrated systems approach, we looked at the performance of waste packages in a humid environment under three different infiltration situations: past DOE practices, current DOE disposal methods, and a proposed future disposal practice. Each of these three situations varies the time of installation of the more robust interim cover over the simpler operational cover. The resulting calculated leachate buildup and release at the time of waste package hydraulic failure was then compared for each infiltration situation.

5.3 Analyzing Waste Package Performance

A hypothetical cover and waste package analysis was developed based on the current disposal practices for the Engineered Trenches (ET) at the Savannah River Site (SRS) (Westinghouse Savannah River Company (WSRC), 2008; Hamm et al., 2013). Each ET disposal facility is approximately 198 m long by 46 m wide, with a depth ranging from 4.88 m to 7.62 m (Westinghouse Savannah River Company (WSRC), 2008). For our analysis, we assumed dimensions of 198 m long by 46 m wide by a constant depth of 6.5 m for a hypothetical trench.

A carbon steel box typical of DOE waste packages (termed a “B-25” box) was used for this analysis. Box dimensions were 1.17 m by 1.83 m by a height of 1.19 m, yielding a total volume of 2.55 m^3 (Jones and Li, 2001; Dunn, 2002; Jones and Phifer, 2002). Box walls were 2.78 mm thick (Dunn, 2002). Boxes were stacked four high with a total height of 5.28 m including risers (see Figure 5.1) (Phifer and Wilhite, 2001). Based on the hypothetical trench described above, the resulting waste zone would contain approximately 17,000 B-25 boxes. To provide a year to year comparison of waste disposal across the hypothetical trench, we assumed that disposal of the 17,000 boxes occurred over the span of 12 years, the current estimate for filling an actual ET (Hamm et al., 2013). An equivalent number of waste packages were disposed in each year, resulting in 1,417 waste packages consisting of 354 stacks of four.

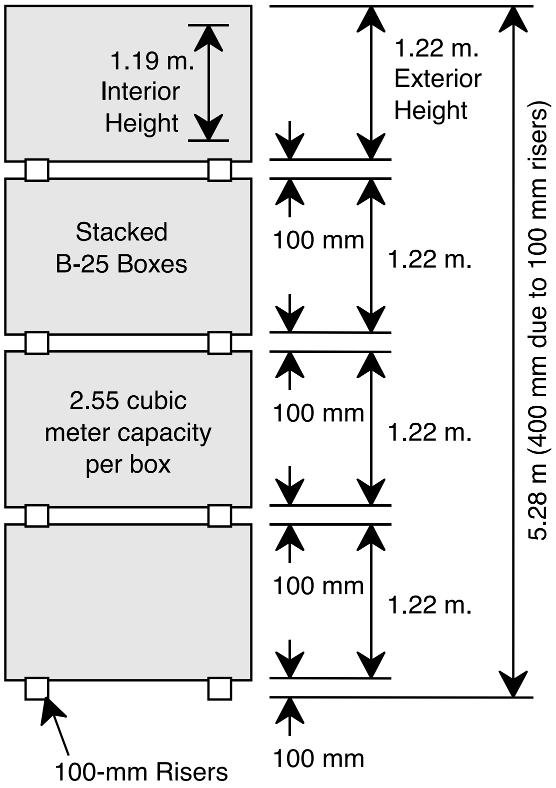


Figure 5.1: Stacked B-25 boxes within a generic disposal facility (Jones and Li, 2001).

To estimate the installation of cover layers, we specified an operational cover consisting of a layer of compacted soil 1.22 m thick that was placed over each section of waste zone, once that section was full. The soil cover was contoured to promote runoff, and reduced the infiltration rate into the waste zone from natural annual precipitation (at SRS this is 1,220 mm/yr) to 286 mm/yr (Hang et al., 2005; Hang et al., 2008). Once the entire trench was considered full, the operational period was deemed to have ended and a high-density polyethylene (HDPE) geomembrane was installed over the operational soil cover. The combination soil/geomembrane layers are known as the "interim cover." Infiltration through the interim cover into the waste zone was estimated to be 10 mm/yr based on literature values developed for the 2004 SRS E-Area closure plan (Hang et al., 2005).

Since void space within waste packages at Savannah River is highly variable (between 10 – 90 percent), we followed the practice of using 50 percent as an average void space, as used by Savannah River staff in their analysis documents (Jones and Phifer, 2002). A waste package with an absolute volume of 2.55 m^3 would then have a maximum potential liquid volume of 1,280 L. Fill rates for stacks of buried B-25 boxes were shown to be variable from an exhumation study conducted in 2002 by Kerry Dunn at Savannah River (Dunn, 2002). Since the Dunn study only contained a stack of two boxes, an extrapolation of the study's findings was required to estimate fill rates for a stack of four boxes.

A footprint area of 2.14 m^2 for one stack of B-25 boxes and annual infiltration of 286 mm/yr through compacted native soil (equivalent to an operational soil cover) results in a total volume of infiltration though that soil of 610 L/yr. Of the 610 L, the Dunn study provided a fill rate of 160 L/yr for box one (the uppermost box) and 80 L/yr for box two, which for box two was close to 18 percent of the total annual infiltration minus the amount of liquid that was collected by box one. Extrapolating from these findings gave a fill rate of 67 L/yr for box three and 55 L/yr for box four. Boxes three and four were also estimated to collect 18 percent of the remaining available infiltration. The remainder of the infiltration liquid was assumed to discharge to the underlying soil.

To estimate changes in fill rates when a waste box became full of liquid, we assumed that overflow from a full box was available to fill all underlying boxes at the same 18 percent of available liquid as estimated within the previous section. The resulting fill rates were 110 L/yr for box two, 90 L/yr for box three, and 74 L/yr for box four. As before, the remaining L/yr of infiltrating water exited the bottom of the waste zone.

Once the operational period had ended at 12 years, we assumed that an interim cover was immediately installed. The liquid fill rate for all boxes subsequently received a proportional reduction related to the decrease from 286 mm/yr to 10 mm/yr for total infiltration. At 10 mm/yr total infiltration over 2.14 m^2 is 21.4 L/yr. For box one this produced a fill rate of 5.6 L/yr, box two 2.8 L/yr, box three 2.3 L/yr, and box four 1.9 L/yr. Once box one was filled with liquid, the fill rate increased for box two to 3.9 L/yr, for box three to 3.2 L/yr, and for box four to 2.6 L/yr based on the resulting proportional increase of available infiltration. If a situation occurred where both box one and two were filled, then the fill rate for box three would rise to 3.9 L/yr and for box four to 3.2 L/yr. Waste package fill rates are summarized in Table 5.1.

Table 5.1: Waste Package Liquid Fill Rates by Time Period

		Fill Rate in L/yr						
		Operational Period				**IC Period**		
Box		**Base Fill Rate**	**Box 1 is Full**	**Box 1 and 2 are Full**		**Base Fill Rate**	**Box 1 is Full**	**Box 1 and 2 are Full**
1		160				5.6		
2		80	110			2.8	3.9	
3		67	90	110		2.3	3.2	3.9
4		55	74	90		1.9	2.6	3.2

5.3.1 Corrosion Scenarios and Infiltration Situations

Two corrosion cases were considered for this analysis, a constant corrosion rate and a diminishing corrosion rate. Release of liquid from each box, to be defined as leachate, was assumed to occur when a pit on the face of a box had fully corroded through, resulting in a hole through which liquid was able to leave the box. The bottom of the box was chosen as the failure point for all waste packages, as this was the box face with the highest corrosion potential as a result from the removal of paint and primer during box transportation, as demonstrated within Dunn (see Figure 5.2) (Dunn, 2002; Jones and Phifer, 2002). All leachate was assumed to flow from the waste package at the time of failure.

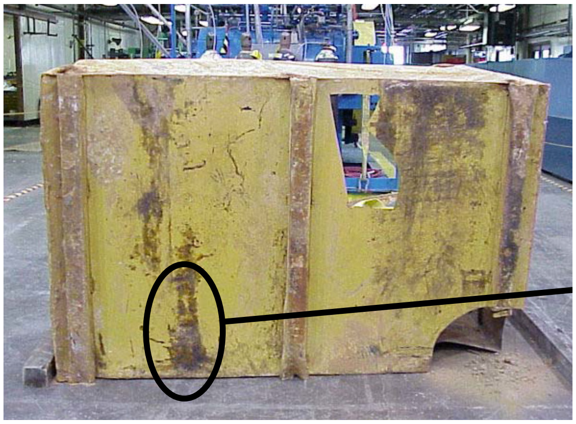


Figure 5.2: Picture of B-25 box bottom exhumed from the 2002 Dunn study. The scrape marks between the risers from forklift transport have removed both paint and primer layers, exposing bare steel (Dunn, 2002).

For the constant corrosion case, a corrosion rate of 0.066 mm/yr (2.6 mils/yr) was used based on extrapolated results from the 2002 Dunn study. Corrosion rates for the diminishing corrosion case (decreasing corrosion rates with time) were calculated based on the NBS report (Romanoff, 1957; Jones and Phifer, 2002). The NBS study developed an equation for rate of corrosion that followed a power law (equation 1) (Romanoff, 1957):

$$h_m = kt^n \quad (1)$$

h_m = maximum pit depth, in mils;
k = site dependent soil corrosivity fitting parameter, in mils/yr;
t = time, in years;
n = soil aeration dependent fitting parameter

Four scenarios were examined for each of the two corrosion cases. The scenarios were set up with two phases, an operational phase, during which the waste zone remained exposed to the atmosphere, and an IC phase during which the waste zone was sealed. In the first scenario, considered to be the base scenario, the corrosion fitting parameter k and aeration parameter n were both kept at the values estimated by SRS staff (Jones and Phifer, 2002). An aeration value n of 0.32 was selected from the NBS study for the operational phase and the SRS value of 0.8 was chosen for the IC period. The second scenario contained a mix of SRS and NBS findings. The third scenario considered a hypothetical environment that was more corrosive than the SRS environment. The fourth scenario was designed to observe the effects of using a more robust waste package compared to the 12-gauge B-25 box. Further explanations of these scenarios and their justifications can be found in Rustick et al. 2016 and Table 5.2 (Rustick et al., 2016). Table 5.3 shows the values for k and n that were used in our analysis.

Table 5.2: Corrosion Scenario Descriptions (Rustick et al., 2016)

Scenario #	
1	**Base Case**: SRS values used for all parameters (with the exception of "good" soil aeration, which was not considered by SRS staff)
2	**Mix of SRS and NBS**: SRS k and n values kept for "very poorly" aerated soils; NBS k and n values used for "good" aerated soils. k values for "good" soil aeration were doubled to reflect results of NBS study
3	**Higher Corrosivity**: Corrosivity fitting parameters doubled for "good" and "very poorly" aerated soils to reflect an environment more corrosive to carbon steel; SRS soil was estimated to be on the lower range of soil corrosivity compared to soils from the NBS study.
4	**More Robust Waste Package**: k and n values were kept identical to scenario 2; the waste package wall thickness was increased from 12 to 10 gauge steel to reflect a hypothetical change to waste package procurement (such a change has already occurred once)

Table 5.3: k, n, and Wall Thickness Values Used (Rustick et al., 2016)

	Scenario #							
		1		**2**		**3**		**4**
k good		2.6		5.2		10.4		5.2
k poor		2.6		2.6		5.2		2.6
n good		0.32		0.32		0.32		0.32

	Scenario #							
		1		2		3		4
n poor		0.8		0.8		0.8		0.8
Wall Thickness in mils		109		109		109		141

Using the data from the four corrosion scenarios for the constant and diminishing corrosion case, three infiltration situations were modeled across all 12 waste zones to provide estimates of the amount of leachate that would be released following the hydraulic failure of each waste zone. It was assumed that holes developed in all four waste boxes in any given waste stack at once, and that all of the leachate contained in the waste packages was immediately available to the vadose zone. The base case infiltration situation modeled current practice at Savannah River, where a NSDF remains open for 12 years before installation of an interim cover (Hamm et al., 2013). The second infiltration situation was based on past practices of a 25-year operational period at Savannah River. In this situation, a NSDF would become full after 12 years but would remain with only an operational soil cover until the entire waste site (multiple NSDFs) was completely full before installation of an interim cover. The third infiltration situation represents a proposed future suggested practice, where a geomembrane or other low permeability cover is placed over a waste zone immediately after that zone is completed. This would limit infiltration into the waste zone to the fill rates present during the IC period (see Table 5.4).

Table 5.4: Infiltration Situations

Situation #	
1	**Current Practice**: The operational period lasts for 12 years, followed by the installation of an interim cover
2	**Past Practice**: The operational period lasts for 25 years, followed by the installation of an interim cover
3	**Proposed Future Suggested Practice**: Installation of a geomembrane (or other low permeability cover method) immediately after waste burial; each zone of waste get interim-style cover fill rates

5.4 Results

The time to hydraulic failure for all waste packages in a given zone of waste was calculated for each corrosion scenario and is presented in Table 5.5.

Table 5.5: Time to Hydraulic Failure for Waste Packages under Corrosion Scenarios

Corrosion Scenario		**1**		**2**		**3**		**4**	
		C	**S**	**C**	**S**	**C**	**S**	**C**	**S**
Waste Emplacement Zone		**Time in Years**							
1		42	111.4	31	104.6	10.5	44.8	43	143.7
2		43	111.6	33	105	12	45.2	45	144.1
3		44	111.8	35	105.5	14	45.5	47	144.6
4		45	112	37	105.9	16	45.9	49	145.1
5		46	112.3	39	106.4	18	46.3	51	145.6
6		47	112.5	41	107	20	46.8	53	146.2
7		48	112.9	43	107.6	22	47.3	55	146.9
8		49	113.2	45	108.3	24	47.9	57	147.7
9		50	1143.7	47	109.2	26	48.6	59	148.6
10		51	114.	49	110.3	28	49.5	61	149.7
11		52	115	51	111.8	30	50.8	63	151.4
12		53	118.2	53	118.2	32	56.1	65	158.2

Using the data from the four corrosion scenarios, three analyses were cacluated for each of the three infiltration situations. Figures 5.3, 5.4, and 5.5 represent the maximum stored leachate potential for each waste zone in L. These figures are not related to years, but instead show the leachate that has built up at the time of hydrualic failiure for each waste zone. Figures 5.6, 5.7, and 5.8 show the leachate released upon hydrualic failure per waste zone, however these figures are represented in releation to the year of zone 1 hydrualic failure. Figues 5.9, 5.10, and 5.11 are also presented in relation to the year of zone 1 hydaulic failure, and show the flux of leachate in L/m^2 from each of the waste zones at their respected time of hydraulic failure.

Figure 5.3: Leachate per Zone: Infiltration Situation 1

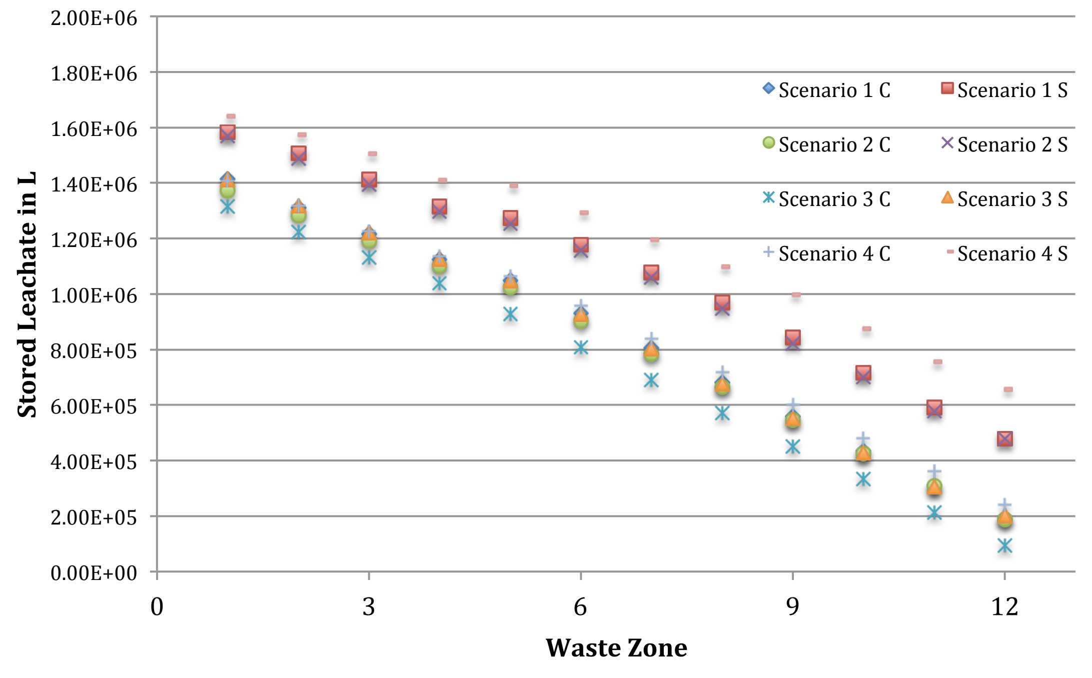


Figure 5.4: Leachate per Zone: Infiltration Situation 2

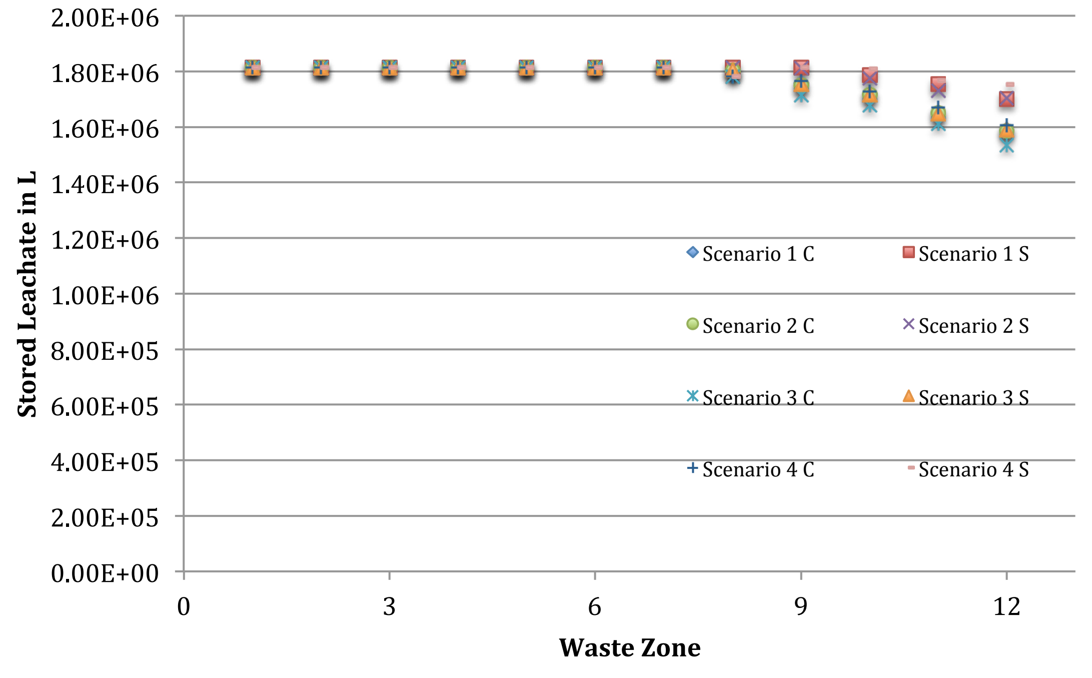


Figure 5.5: Leachate per Zone: Infiltration Situation 3

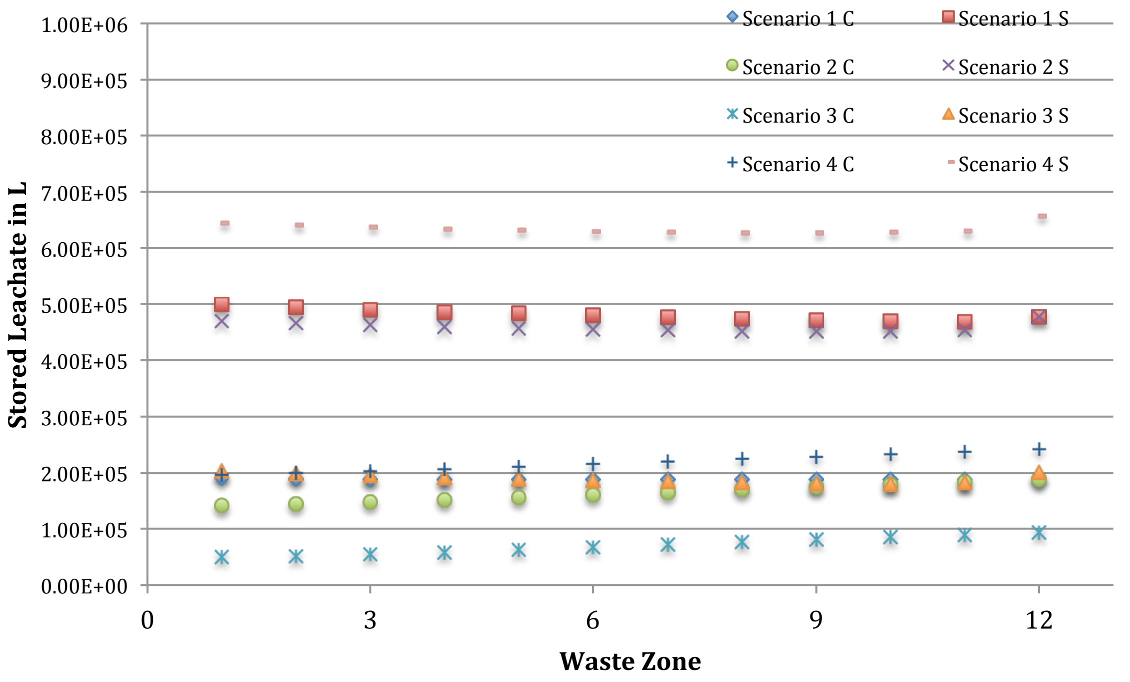


Figure 5.6: Leachate per Year: Infiltration Situation 1

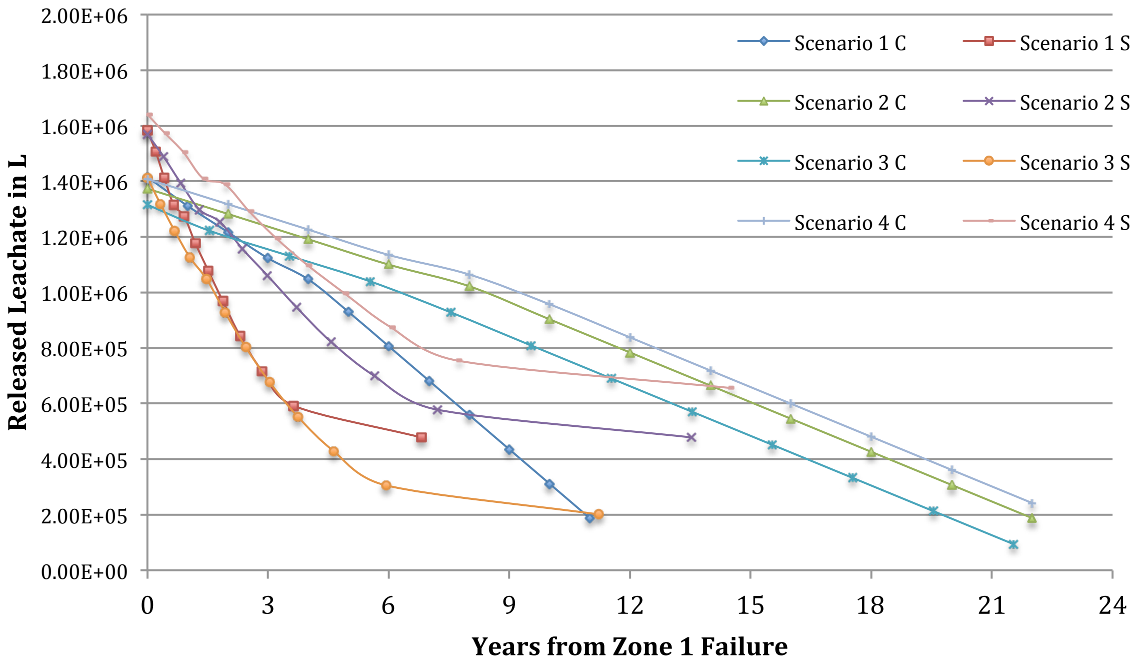


Figure 5.7: Leachate per Year: Infiltration Situation 2

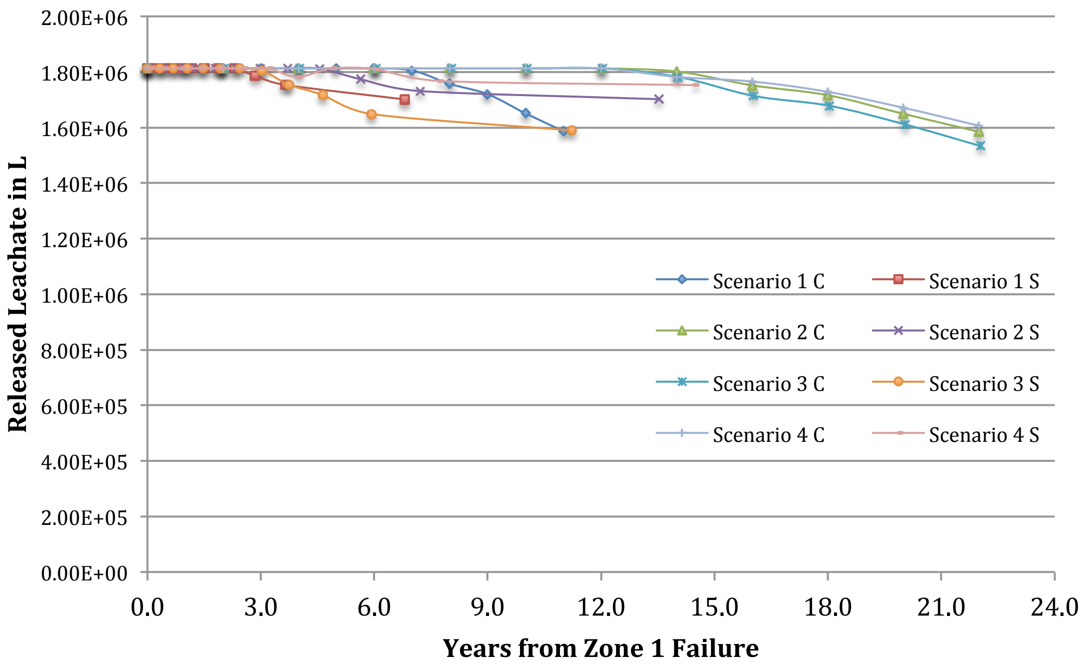


Figure 5.8: Leachate per Year: Infiltration Situation 3

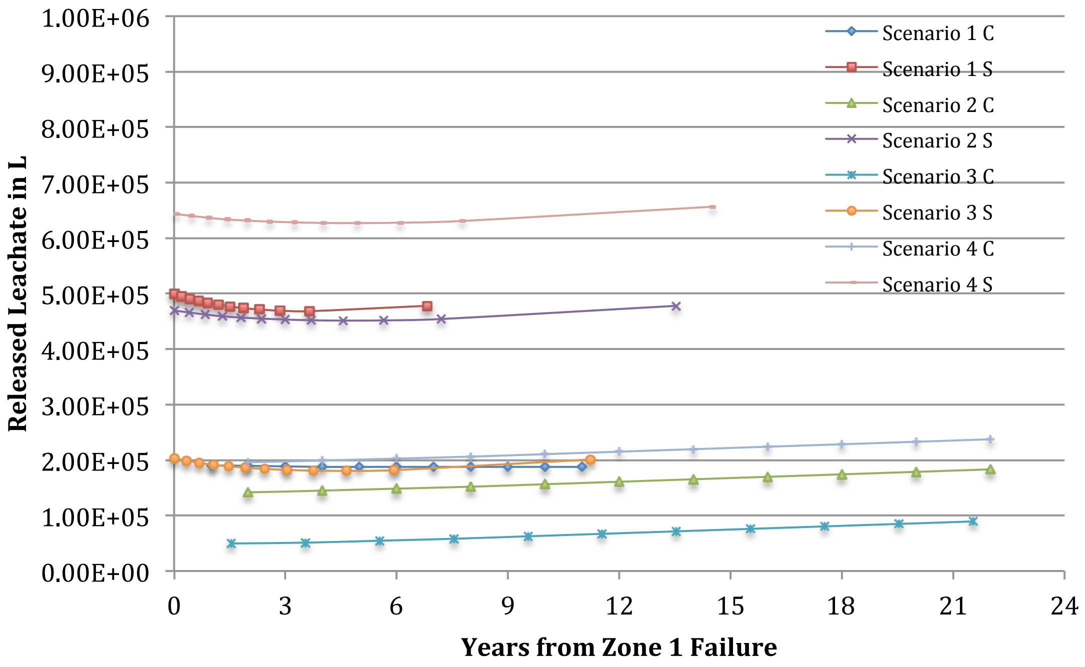


Figure 5.9: Leachate Flux per Year: Infiltration Situation 1

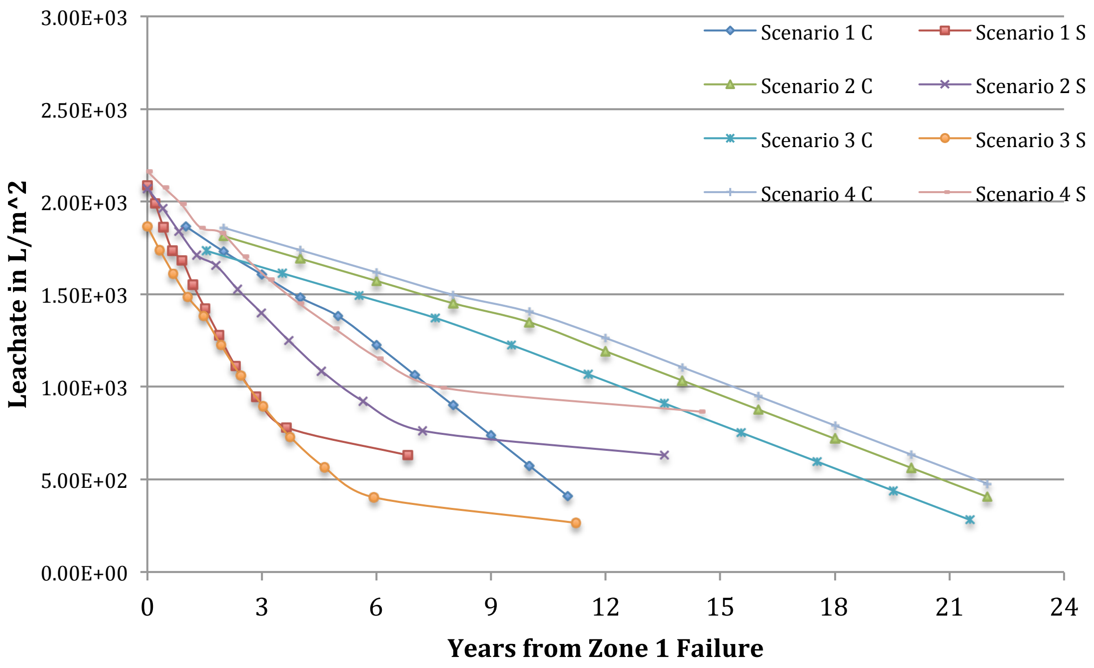


Figure 5.10: Leachate Flux per Year: Infiltration Situation 2

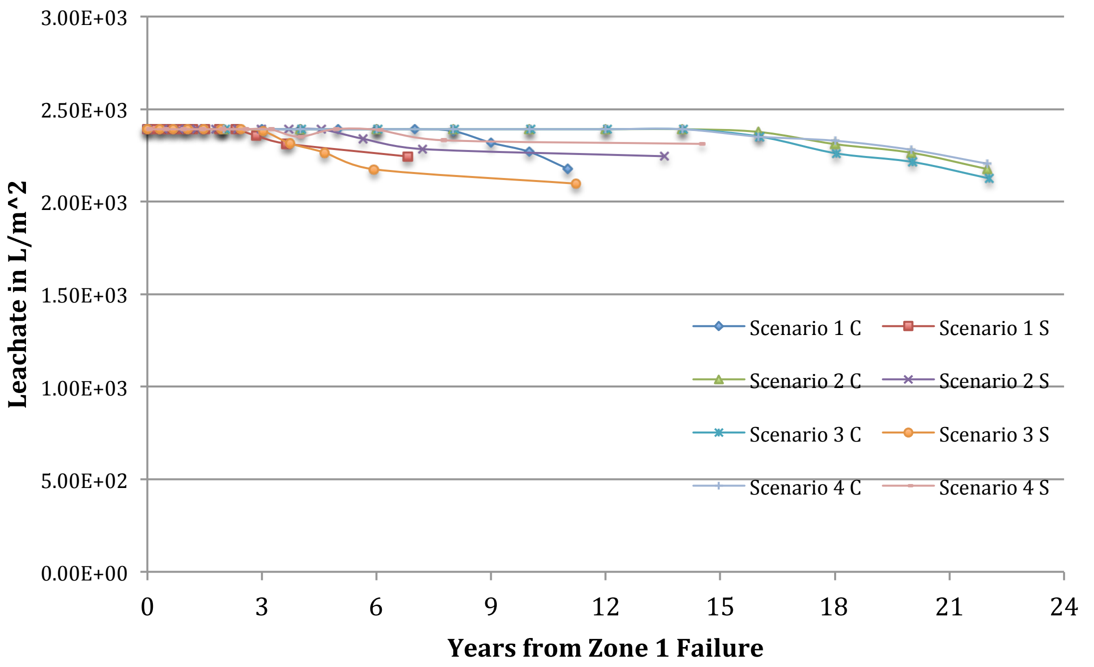
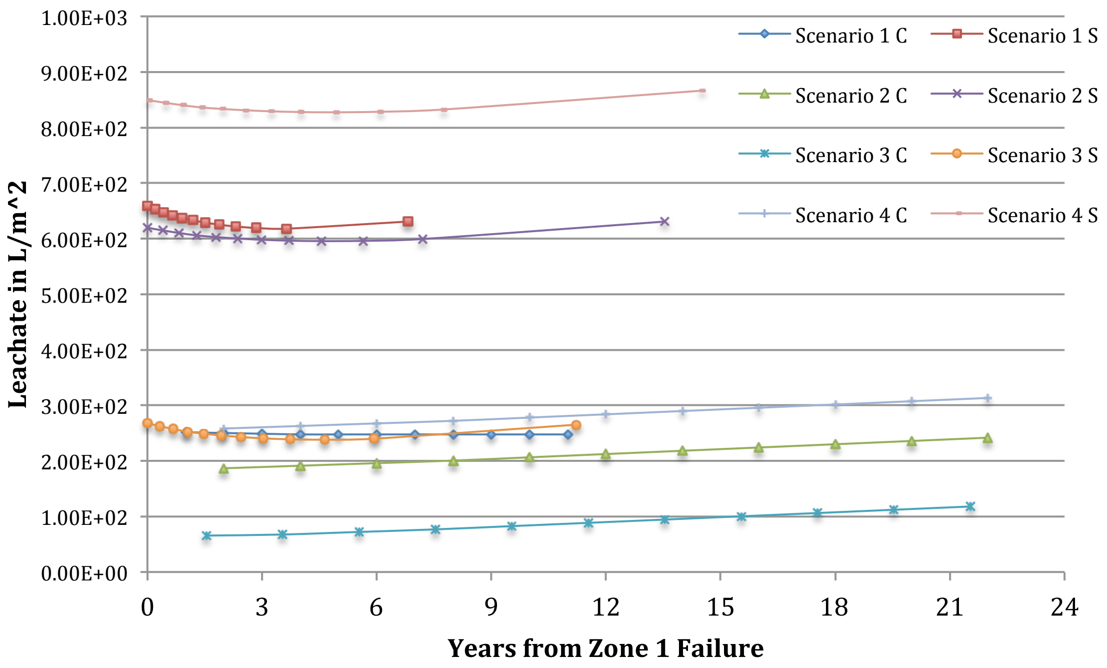


Figure 5.11: Leachate Flux per Year: Infiltration Situation 3



5.5 Discussion

Results from the waste package infiltration analysis revealed several important factors that should be taken into account by site staff at current NSDFs and for any planned NSDFs. By extending the operational period for little over a decade, which is not uncommon when considering delays or changes to waste disposal campaigns in the past (such as at the Idaho RWMC (DOE Idaho, 2013)), a majority of the waste zones become completely filled with liquid. The consequences of such a large amount of leachate remaining within the waste zone of a NSDF have not been studied within DOE PAs and could provide a significant driver for divergence of actual NSDF performance from estimated performance.

When an interim cover is installed directly after placement of waste within the NSDF, our analysis showed that expected leachate buildup and resulting flux was reduced by at least a factor of two from infiltration situation one. There are a wide variety of impermeable covers that have been used across the DOE complex, so that a solution for a given site-specific environment should be readily available (Cook et al., 2004). The main downside to installing such a cover, in addition to cost, would be the loss of a working surface for heavy machinery, as the equipment could potentially damage the interim cover.

The next step in the refinement of the integrated system of components framework is to address some of the inherent uncertainty that has not been considered in this article. In particular, infiltration rates and corrosion rates were presented as single deterministic values, when under real world conditions these values could be expected to vary based on a number of environmental factors. One potential improvement would be to develop probability distributions for steel corrosion rates and annual precipitation. This could be achieved through the use of natural analogs from other industries or studies coupled with a statistical tool such as a Monte Carlo analysis to provide a more complete understanding of potential waste zone conditions.

5.6 Conclusion

Our analysis of a LLW NSDF in a humid environment has shown the effects of different engineered cover designs and installations dates on the accumulation of leachate within the waste zone of the NSDF. The effects of extending the operational period from 12 to 25 years were shown to increase the amount of stored leachate for most waste zones to the maximum potential stored leachate. Installation of an interim cover over buried waste zones immediately, instead of waiting for the entire NSDF to be full, reduced total stored leachate by at least a factor of 2. Going forward, additional study is needed to assess the effects of uncertainty in the corrosion rates of waste packages on leachate releases to the environment.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE STUDY

6.1 Conclusions

The work presented in this dissertation has centered around the merits of using an integrated system of components approach developed to aid the assessment and analysis of the performance of both current and future NSDFs. In chapter 3, each of the five major DOE disposal sites were looked at through the lens of an integrated system of components. The information was presented in a way to provide a broad overview of the current state of disposal practices, and all of the parameters that would be needed to compare each NSDF from a system of component framework. The goal was to show that each site was different and contained different challenges to meeting the required performance objectives, yet all sites could be looked at from a common unified assessment framework.

In chapter 4, one of the three system components, the waste component, was analyzed in detail to assess the effects of corrosion on waste package performance. As a past practice, staff within the DOE did not take into account the barrier effects of individual waste packages. Rather, they assumed that all waste packages failed by the end of the IC period. This assumption causes all of the COPC to be released from the waste packages and be available to the vadose zone as a source term immediately at the end of the IC period. Some recent work by the DOE at Savannah River addressed the performance of waste packages, but their focus was on the structural stability of the waste packages. The study presented in this chapter was focused on the ability of intact waste packages to retain liquid for extended periods of time, with a later release of liquid to the vadose zone. The accompanying analysis showed that under certain corrosion conditions, waste packages could be expected to remain hydraulically intact past the 100-year IC period, potentially causing performance issues upon final closure of the NSDF.

In chapter 5, the analysis conducted within chapter 4 was expanded to include waste package corrosion over the entire waste zone (chapter 4 only considered zone 1 and zone 12 as a bounding analysis). Once a complete corrosion profile of the waste zone was established, a leachate model was created that could show the full extent of leachate to be expected to remain in the waste zone, and could also calculate the subsequent release of leachate from the waste zone due to the hydraulic failure of waste packages under the corrosion scenarios developed for chapter 4. This model was then applied to three different infiltration situations based off of past, current, and proposed future installations of operational and interim cover systems over recently buried waste packages.

Based on the results provided in this thesis, there are several broad conclusions that can be drawn. For currently operating disposal facilities, the amount of time a waste zone sits under an operational cover vs. a more robust interim cover can have a marked increase on the amount of stored leachate within the waste zone. With the assumption of a 25-year operational period, the amount of leachate estimated within the waste zone over current practices was over 200 percent higher. Thus, installing an interim cover over a completed waste zone is recommended as soon as it is possible for all future NSDFs.

For future planned disposal facilities, it would be useful to consider eliminating all future subsidence and leachate potential from corroding steel waste packages by filling the waste packages with grout before disposal. The grout would provide structural stability for the waste zone over hundreds of years, would immobilize disposed waste within a bulk matrix, and would prevent infiltrating liquid from contacting waste within the waste packages. In addition, the high pH environment of the grout means that as waste packages begin to corrode and waste leachates from the waste packages, the grout will cause the dissolved radionuclides in the leachate to precipitate out of solution and further retard their movement to the vadose zone.

Finally, for both current and future disposal facilities, leachate movement through the waste zone and into the vadose zone is a good target for performance monitoring. The composition of the liquid leaving the bottom of the disposal facility could provide a number of indicators on conditions within the facility, such as corrosion rates, leachate generation rates, waste package performance, and engineered cover performance.

6.2 Recommendations for Future Study

The work presented in this dissertation has helped to advance the use of an integrated system of components approach and provide insight into NSDF waste zone conditions that have not previously been considered. The next step is to expand the usefulness of the developed tools and analyses by considering uncertainty in the corrosion rates for the steel waste packages. The environment within the waste zone is subject to many different processes that were simplified for this dissertation. Any number of variables affecting soil corrosivity or aeration could have a profound impact on the presented results. Instead of choosing a single deterministic value for a corrosion rate, it would be useful to consider a distribution of corrosion rates to allow for uncertainty within a waste package analysis. Future work could include the use of statistical analysis, such as Monte Carlo analysis, to help define the uncertainty within the waste zone. This in turn would help to better identify the performance divers within the waste component of the system of components.

REFERENCES

Aadland, R. K., Gellici, J. A. and Thayer, P. A. (1995). Hydrogeologic framework of West-central South Carolina. Columbia, SC: State of South Carolina, Department of Natural Resources.

Abdel-Khalik, S. (2011). Proposed Rulemaking to Introduce a Site-Specific Performance Assessment and Human Intrusion Analysis Requirement to 10 CFR 61. Chairman Gregory B. Jaczko. Washington, DC, Advisory Committee on Reactor Safeguards.

Adams, V., Gupta, D. C. and Smegal, J. S. (2009). "Lessons Learned from Independent Technical Reviews of U.S. Department of Energy Low-Level Radioactive Waste Landfills/Disposal Facilities." Waste Management Symposia 2009, Phoenix, AZ.

Adler Flitton, M. K., Bishop, C. W., Mizia, R. E., Torres, L. L. and Rogers, R. D. (2001). "Long Term Corrosion/Degradation Test Third-Year Results." Idaho Falls, ID: Idaho National Engineering and Environmental Laboratory, Bechtel BWXT Idaho LLC. INEEL/EXT-01-00036, Rev. 0.

Anderson, J. E. and Forman, A. D. (2003). "Evapotranspiration Caps for the Idaho National Engineering and Environmental Laboratory: A Summary of Research and Recommendations." Idaho Falls, ID: Idaho National Engineering and Environmental Laboratory. STOLLER-ESER-56.

Bechtel Jacobs Company LLC (2001). "Attainment Plan for Risk/Toxicity-Based Waste Acceptance Criteria at the Oak Ridge Reservation, Oak Ridge, Tennessee." Oak Ridge, TN: Bechtel Jacobs Company LLC., Oak Ridge Office. DOE/OR/01-1909&D3.

Bechtel Nevada (2004). "Nevada Test Site: 2003 Waste Management Monitoring Report Area 3 and Area 5 Radioactive Waste Management Sites." Las Vegas, NV: Bechtel Nevada, Nevada Site Office. DOE/NV/11718--930.

Bechtel Nevada (2006). "Addendum 2 to the Performance Assessment for the Area 5 Radioactive Waste Management Site at the Nevada Test Site, Nye County, Nevada; Update of Performance Assessment Methods and Results." Las Vegas, Nevada: Bechtel Nevada, Nevada Operations Office. DOE/NV/11718--176-ADD2.

Benson, C. H., Albright, W. H., Ray, D. P. and Smegal, J. (2008). "Review of the Environmental Management Waste Management Facility (EMWMF) at Oak Ridge." Washington, D.C.: US Department of Energy, Environmental Management: Office of Engineering and Technology. ETR-11.

Bonaparte, R., Daniel, D. E. and Koerner, R. M. (2002). "Assessment and Recommendations for Improving the Performance of Waste Containment Systems." Cincinnati, OH: US Environmental Protection Agency. EPA/600/R-02/099.

Bradford, S. A. (2000). Practical Handbook of Corrosion Control in Soils. Edmonton, Canada: CASTI Publishing.

Burbank, D. A., Biyani, R. K. and Janin, L. F. (2000). "Preliminary Closure Plan for the Immobilized Low Activity Waste (ILAW) Disposal Facility." Richland, WA: CH2MHill. RPP-6911, Rev.0.

Case, M. J. and Otis, M. D. (1988). "Guidelines for Radiological Performance Assessment of DOE Low-Level Radioactive Waste Disposal Sites." Washington, DC: US Department of Energy. DOE/LLW-62T.

Clawson, K. L., Start, G. E. and Ricks, N. R. (1989). "Climatography of the Idaho National Engineering Laboratory." Idaho Falls, ID, National Oceanic and Atmospheric Administration. DOE/ID-12118.

Cole, C. R., Wurstner, S. K., Williams, M. D., Thorne, P. D. and Bergeron, M. P. (1997). "Three-dimensional Analysis of Future Groundwater Flow Conditions and Contaminant Plume Transport in the Hanford Site Unconfined Aquifer System: FY 1996 and 1997 Status Report." Richland, WA: Pacific Northwest National Labs. PNNL-11801.

Collard, L. B. and Hamm, L. L. (2012). "Alternative Analysis for Selecting ET #3 Site." Aiken, SC: Savannah River Nuclear Solutions, Savannah River National Laboratory. SRNL-STI-2012-00047, Rev. 0.

Container Products Corporation. (2016). "Welcome to Container Products Corporation." 2016, from http://c-p-c.net/.

Cook, J., Wilhite, E., Hiergesell, R. and Flach, G. (2005). "Special Analysis: Revision of Saltstone Vault 4 Disposal Limits (U)." Aiken, SC: Westinghouse Savannah River Company, Savannah River National Laboratory. WSRC-TR-2005-00074.

Cook, J. R. and Kaplan, D. I. (2003). "Special Analysis: Revised C-14 Disposal Limits for the Saltstone Disposal Facility." Aiken, SC: Westinghouse Savannah River Company, Savannah River Site. WSRC-TR-2003-00417, Rev 0.

Cook, J. R., Kocher, D. C., McDowell-Boyer, L. and Wilhite, E. L. (2002). "Special Analysis: Reevaluation of the Inadvertent Intruder, Groundwater, Air, and Radon Analyses for the Saltsone Disposal Facility." Aiken, SC: Westinghouse Savannah River Company, Savannah River Site. WSRC-TR-2002-00456, Rev. 0.

Cook, J. R., Phifer, M. A., Wilhite, E. L., Young, K. E. and Jones, W. E. (2004). "Closure Plan for the E-Area Low-Level Waste Facility." Aiken, SC: Westinghouse Savannah River Company, Savannah River Site. WSRC-RP-2000-00425, Rev. 4.

Denham, M. E. (1999). "SRS Geology/Hydrogeology Environmental Information Document." Aiken, SC: Westinghouse Savannah River Company, Savannah River Site. WSRC-TR-95-0046.

DeRosa, D. C., Biglin, J. W., Demiter, J. A., Lindberg, S. L. and Pottmeyer, J. A. (2000). "Process Description for the Retrieval of Earth-Covered Transuranic Waste Containers at the Hanford Site." Richland, WA: Fluor Daniel Hanford Inc. HNF-5597, Rev. 0.

DNFSB (1994). "Recommendation 94-2 to the Secretary of Energy pursuant to Atomic Energy Act of 1954, as amended." Washington, DC: Defense Nuclear Facilities Safety Board.

DOE Idaho (2007). "Performance Assessment for the RWMC Active Low-Level Waste Disposal Facility at the Idaho National Laboratory Site." Idaho Falls, ID: DOE Idaho Operations Office, Idaho Operations Office. DOE/NE-ID-11243.

DOE Idaho (2013). "Phase 1 Remedial Design/Remedial Action Work Plan for Operable Unit 7-13/14." Idaho Falls, ID: DOE Idaho Operations Office, Idaho Operations Office. DOE/ID-11389 Rev. 2.

Dunn, K. A. (2002). "B-25 Corrosion Evaluation Summary Report." Aiken, SC: Westinghouse Savannah River Company, Savannah River Site. WSRC-TR-2001-00587.

EG&G Idaho, I. (1994). "Directions in Low-Level Radioactive Waste Management: A Brief History of Commercial Low-Level Radioactive Waste Disposal." Idaho Falls, ID: EG&G Idaho, Inc., Idaho National Engineering Laboratory. DOE/LLW--103-Rev.1.

Eisenberg, N. A., Lee, M. P., McCartin, T. J., et al. (1999). "Development of a Performance Assessment Capability in the Waste Management Programs of the U.S. Nuclear Regulatory Commission." Risk Analysis **19**(5): 847-876.

Farnsworth, R. K. and Thompson, E. S. (1982). "Mean Monthly, Seasonal, and Annual Pan Evaporation for the United States." Washington, DC: National Oceanic and Atmospheric Administration, National Weather Service. NOAA Technical Report NWS 34.

Fayer, M. J., Murphy, E. M., Downs, J. L., et al. (1999). "Recharge Data Package for the Immobilized Low-Activity Waste 2001 Performance Assessment." Richland, WA: Pacific Northwest National Lab. PNNL-13033.

Gladden, J. B. (2010). "Aerial Remote Sensing as a Component of Closure Cap Monitoring." Workshop on Engineered Barrier Performance Related to Low-Level Radioactive Waste, Decommissioning, and Uranium Mill Tailings Facilities, Rockville, MD, US NRC.

Gosling, F. G. (2010). The Manhattan Project: Making the Atomic Bomb. Washington, DC: US Department of Energy.

Hamm, L. L., Smith, F. G., Flach, G. P., Hiergesell, R. A. and Butcher, B. T. (2013). "Unreviewed Disposal Question Evaluation: Waste Disposal in Engineered Trench #3." Aiken, SC: Savannah River Nuclear Solutions, Savannah River National Laboratory. SRNL-STI-2013-00393, Revision 0.

Hanford Meteorological Station. (2013). "Meteorological and Climate Data Summary Products." US Department of Energy, Richland, WA, 2013, from http://www.hanford.gov/page.cfm/MetandClimateDataSummary.

Hang, T., Collard, L. B. and Phifer, M. A. (2005). "Unreviewed Disposal Question Evaluation: Subsidence Study for Non-crushable Containers in Slit Trenches (U)." Aiken, SC: Westinghouse Savannah River Company, Savannah River National Laboratory. WSRC-TR-2005-00104, Revision 0.

Hang, T., Collard, L. B. and Phifer, M. A. (2008). "Subsidence Study for Non-Crushable Containers in Slit Trenches at the Savannah River Cite." Proceedings of the 2008 Spring simulation multiconference, Ottawa, Canada, Society for Computer Simulation International.

Hatcher, R. D. J., Lemiszki, P. J., Dreier, R. B., et al. (1992). "Status Report on the Geology of the Oak Ridge Reservation." Oak Ridge, TN: Oak Ridge National Laboratory, Environmental Sciences Division. ORNL/TM-12074.

Hoitink, D. J., Burk, K. W., Ramsdell, J. V. and Shaw, W. J. (2005). "Hanford Site Climatological Summary 2004 with Historical Data." Richland, WA: Pacific Northwest National Laboratory. PNNL-15160.

Holdren, K. J. and Broomfield, B. J. (2004). "Second Addendum to the Work Plan for the OU 7-13/14 Waste Area Group 7 Comprehensive Remedial Investigation/Feasibility Study." Idaho Falls, ID: US Department of Energy, Idaho Operations Office. DOE/ID-11039.

Hughes, J., Thompson, S., Vasquez, K., McMahon, W. and Coffey, M. (2012). "Oak Ridge Reservation Annual Site Environmental Report for 2011: Appendix B - Climate Overview of the Oak Ridge Area." Oak Ridge, TN: Oak Ridge National Laboratory. DOE/ORO/2418.

ICRP (1959). Report of ICRP Committee II on Permissible Dose for Internal Radiation. ICRP Publication 2. International Commission on Radiological Protection. New York, Pergamon Press.

ICRP (1979). Limits for Intakes of Radionuclides by Workers. ICRP Publicatin 30. International Commission on Radiological Protection. New York, Pergamon Press.

Jacobs EM Team (1998). "Remedial Investigation/Feasibility Study for the Disposal of Oak Ridge Reservation Comprehensive Environmental Response, Compensation, and Liability Act of 1980 Waste." Oak Ridge, TN. DOE/OR/02-1637&D2.

Jacobs Engineering Group Inc. (1999). "Uranium Mill Tailings Remedial Action Surface Project 1979-1999: End-of-Project Report " Albuquerque, NM: Department of Energy,, Environmental Restoration Division. DOe/AL/62350-500.

Jones, W. E. and Li, W. T. (2001). "Long-Term Waste Stabilization Parameter Estimation, Savannah River Site, Aiken, South Caorlina." Aiken, SC: Westinghouse Savannah River Company. WSRC-TR-2001-00323.

Jones, W. E. and Phifer, M. A. (2002). "Corrosion and Potential Subsidence Scenarios for Buried B-25 Waste Containers." Aiken, SC: Westinghouse Savannah River Company, Savannah River Site. WSRC-TR-2002-00354.

Jones, W. E., Wu, T.-T. and Phifer, M. A. (2003). "Structural Analysis for Subsidence of Stacked B-25 Boxes." Aiken, SC: Westinghouse Savannah River Company, Savannah River Technology Center. WSRC-TR-2002-00378.

Kabela, E. D. (2011). "Savannah River Site Annual Meteorology Report for 2010." Aiken, SC: Savannah River Nuclear Solutions, Savannah River National Laboratory. SRNL-RP-2011-01070.

Kaplan, D. I. (2006). "Geochemical Data Package for Performance Assessment Calculations Related to the Savannah River Site (U)." Aiken, SC: Washington Savannah River Company, Savannah River National Laboratory. WSRC-TR-2006-00004 Rev. 0.

Kaplan, D. I. and Serne, R. J. (2000). "Geochemical Data Package for the Hanford Immobilized Low-Activity Tank Waste (ILAW) Performance Assessment." Richland, WA: Pacific Northwest National Laboratory. PNNL-13037, Rev.1.

Kilgo, J. C., Blake, J. I. and Mayer, J. J. (2005). "The Savannah River Site, Past and Present: Industrial Operations and Current Land Use" ." Ecology and Management of a Forested Landscape: Fifty Years on the Savannah River Site. Washington, DC, Island Press.

Letourneau, M. J. (2010). "DOE Overview." Workshop on Engineered Barrier Performance Related to Low-Level Radioactive Waste, Decommissioning, and Uranium Mill Tailings Facilities, Rockville, MD.

Letourneau, M. J., DiSanza, F., Pope, H., Krenzien, S. and Paulsen, H. (2010). "The United States Department of Energy Radioactive Waste Management Order 435.1 Update, The First Step - A Complex Wide Review." Waste Management Symposia, Phoenix, AZ.

Letourneau, M. J., Krahn, S. L., Kosson, D. S., et al. (2009). "Improving Consistency of Performance Assessments in the DOE Complex." Waste Management Symposia, Phoenix, AZ.

Mamatey, A. R. (2006). "Savannah River Site: Environmental Report for 2005." Aiken, SC: Washington Savannah River Company, Savannah River Site. WSRC-TR-2006-00007.

Mann, F. M., Puigh II, R. J., Finfrock, S. H., et al. (2001). "Hanford Immobilized Low-Activity Waste Performance Assessment: 2001 Version." Richland, WA: DOE Office of River Protection. DOE/ORP-2000-24 Rev.0.

Mansfeld, F. (1987). Corrosion mechanisms. New York, NY: M. Dekker.

Martin Marietta Energy Systems Inc. (1992). "Radiological Performance Assessment for the Z-Area Saltstone Disposal Facility." Aiken, SC: Westinghouse Savannah River Company,. WSRC-RP-92-1360 Rev. 0.

Millings, M. R., Butcher, B. T., Crapse, K. P., et al. (2009). "FY 2008 Annual Review E-Area Low-Level Waste Facility Performance Assessment and Composite Analysis." Aiken, SC: Savannah River National Laboratory, Savannah River Site. SRNS-RP-2008-01314 Rev. 0.

MMES Inc. (1994). "Oak Ridge Reservation: Annual Site Environmental Report for 1993." Oak Ridge, TN: US Department of Energy. ES/ESH--47.

Mughabghab, S. F. and Sullivan, T. M. (1989). "Evaluation of the Pitting Corrosion of Carbon Steels and Other Ferrous Metals in Soil Systems." Waste Management **9**(4): 239-251.

National Research Council (2007). Assessment of the Performance of Engineered Waste Containment Barriers. Washington, DC: The National Academies Press.

National Security Technologies LLC (2009). "2008 Annual Summary Report for the Area 3 and Area 5 Radioactive Waste Management Sites at the Nevada Test Site, Nye County, Nevada: Review of the Performance Assessments and Composite Analyses." DOE/NV/25946--691.

Neitzel, D. A., Antonio, E. J., Fosmire, C. J., Fowler, R. A. and Glantz, C. S. (2000). "Hanford Site National Environmental Policy Act (NEPA) Characterization." Richland, WA: Pacific Northwest National Lab. PNNL-6415, Rev. 12.

NOAA. (2012a). "Comparative Climatic Data for the United States through 2012." NOAA, Ashville, NC, from http://ols.nndc.noaa.gov/plolstore/plsql/olstore.prodspecific?prodnum=C00095-PUB-A0001.

NOAA. (2012b). "Summary of Monthly Normals, 1981-2010: Augusta Bush Field Ap, GA " NOAA, Asheville, NC, from http://www.ncdc.noaa.gov/cdo-web/.

NOAA. (2013a). "INL Climate." NOAA INL Weather Center, Idaho Falls, ID, 2013, from http://niwc.noaa.inel.gov/climate.htm?year=2013&month=Jan&site=690.

NOAA. (2013b). "NOWData - NOAA Online Weather Data 1981-2010: Mercury Desert Rock, NV." Las Vegas, NV, 2013, from http://www.nws.noaa.gov/climate/.

NOAA. (2013c). "NOWData - NOAA Online Weather Data 1981-2010: Richland, WA." National Weather Service Forcast Office, Pendleton, OR, 2013, from http://www.nws.noaa.gov/climate/.

NOAA. (2013d). "Oak Ridge Climate Data." Atmospheric Turbulence and Diffusion Division, Oak Ridge, TN, 2013, from http://www.atdd.noaa.gov/?q=node/20.

Office of Health Safety and Security. (2011, August 04, 2011). "Federal Facility Compliance Act." Retrieved September 23rd, 2011, 2011, from http://www.hss.doe.gov/sesa/environment/policy/ffca.html.

Parsons, A. M., McCarthy, J. M., Alder Flitton, K., Ritter, P. D. and Cresap, D. A. (2010). "Annual Performance Assessment and Composite Analysis Review for the Active Low-Level Waste Disposal Facility at the RWMC FY 2009." Idaho Falls, ID: Idaho Cleanup Project, Idaho Cleanup Project. RPT-708 Rev. 0.

Phifer, M. A. (2004). "Preliminary E-Area Trench Closure Cap Closure Sequence, Infiltration, and Waste Thickness (U)." Aiken, SC: Westinghouse Savannah River Company. WSRC-TR-2004-00119.

Phifer, M. A., Millings, M. R. and Flach, G. P. (2006). "Hydraulic Property Data Package for the E-Area and Z-Area Vadose Zone Soils, Cementitious Materials, and Waste Zones." Aiken, SC: Washington Savannah River Company. WSRC-STI-2006-00198, Rev. 0.

Phifer, M. A. and Wilhite, E. L. (2001). "Waste Subsidence Potential Verses Supercompaction." Aiken, SC: Westinghouse Savannah River Company, Savannah River Site. WSRC-RP-2001-00613.

Raytheon Services Nevada (1991). "Compiled and Interpreted Geological Cross Sections for Frenchman Flat for Integrated Site Assessment and Characterization (ISAAC) of Area 5 - Nevada Test Site." Las Vegas, NV: Raytheon Services Nevada, Environmetnal Operations Department.

Reidel, S. P. and Horton, D. G. (1999). "Geologic Data Package for 2001 Immobilized Low-Activity Waste Performance Assessment." Richland, WA: Pacific Northwest National Lab. PNNL-12257 Rev. 1.

Reynolds Electrical & Engineering Co. (1994). "Site Characterization and Monitoring Data from Area 5 Pilot Wells." Las Vegas, NV: Reynolds Electrical & Engineering Co., Environmental Restoration & Technology Development. DOE/NV/11432-74 UC721.

Romanoff, M. (1957). Underground Corrosion. Washington, DC: Government Printing Office.

Rustick, J. H., Kosson, D. S., Krahn, S. L. and Clarke, J. H. (2013). "Building Confidence in LLW Performance Assessments." Waste Management Symposia, Phoenix, AZ.

Rustick, J. H., Kosson, D. S., Krahn, S. L., et al. (2015). "Comparison of LLW Disposal Facilities at Major Department of Energy Sites." Remediation Journal **26**(1): 69-91.

Rustick, J. H., Kosson, D. S., Krahn, S. L., Ryan, M. T. and Clarke, J. H. (2016). "Application of a Proposed Generic LLW Waste Package Analysis with Changing Infiltration in a Humid Environment - IN REVIEW." Remediation Journal **26**(2).

Sandia National Laboratories (1996). "Performance Evaluation of the Technical Capabilities of DOE Sites for Disposal of Mixed Low-Level Waste: Executive Summary." Albuquerque, NM: Sandia National Laboratories, Office of Waste Management. SAND96-0721/1 - US-2020.

Savannah River Remediation LLC (2010). "FY2009 Annual Review: Saltstone Disposal Facility (Z-Area) Performance Assessment." Aiken, SC: Savannah River Remediation LLC, Closure and Waste Disposal Authority. SRR-CWDA-2009-00036.

Scanlon, B. R., Reedy, R. C., Keese, K. E. and Dwyer, S. F. (2005). "Evaluation of Evapotranspirative Covers for Waste Containment in Arid and Semiarid Regions in the Southwestern USA." Vadose Zone Journal **4**(1): 55-71.

Shott, G. J., Barker, L. E., Rawlinson, S. E., Sully, M. J. and Moore, B. A. (1998). "Performance Assessment for the Area 5 Radioactive Waste Management Site at the Nevada Test Site, Nye County, Nevada (Rev. 2.1)." Las Vegas, NV: Bechtel Nevada. DOE/NV/11718-176, UC-721.

Snyder, K. E., Gustafson, D. L., Miller, J. J. and Rawlinson, S. E. (1994). "Geological Components of Site Characterization and Performance Assessment for a Radioactive Waste Management Facility at the Nevada Test Site." Waste Management 1994, Tuscon, AZ.

Solomon, D. K. (1992). "Status Report: A Hydrologic Framework for the Oak Ridge Reservation." Oak Ridge, TN: MMES. ORNL/TM-12026.

Soule, D. A. (2006). "Climatology of the Nevada Test Site." Las Vegas, NV: NOAA, Special Operations and Research Division. SORD Technical Memorandum SORD 2006-03.

SRR Closure & Waste Disposal Authority (2009). "Performance Assessment for the Saltstone Disposal Facility at the Savannah River Site." Aiken, SC: Savannah River Remediation LLC, SRR Closure & Waste Disposal Authority. SRR-CWDA-2009-00017 Revision 0.

Swingle, R. F., Butcher, B. T., Crapse, K. P., Millings, K. R. and Sink, D. F. (2011). "FY 2010 Annual Review E-Area Low-Level Waste Facility Performance Assessment and Composite

Analysis." Aiken, SC: Savannah River National Laboratory, Savannah River Site. SRNS-STI-2011-00024 Rev. 0.

Swingle, R. F., Butcher, B. T., Crapse, K. P., et al. (2010). "FY 2009 Annual Review: E-Area Low-Level Waste Facility Performance Assessment and Composite Analysis." Aiken, SC: Savannah River National Laboratory, Savannah River Site. SRNS-RP-2009-01369 Revision 0.

Swingle, R. F. and Phifer, M. A. (2006). "Unreviewed Disposal Question Evaluation: Increased Disposal Volume in Slit and Engineered Trenches." Aiken, SC: Westinghouse Savannah River Company. WSRC-TR-2006-00186, Rev. 0.

Swingle, R. F., Sink, D. F., Millings, K. R. and Crapse, K. P. (2008). "FY 2007 Annual Review E-Area Low-Level Waste Facility Performance Assessment and Composite Analysis." Aiken, SC: Washington Savannah River Company, Savannah River Site. WSRC-RP-2008-00228 Rev. 0.

Szklarska-Smialowska, Z. (1986). Pitting corrosion of metals. Houston, TX: National Association of Corrosion Engineers.

Turner, D. W., Bolling, D. H. and Johnson, M. A. (2006). "Retrieval of buried transuranic waste at Oak Ridge National Laboratory." Waste Management Symposia, Tucson, AZ.

U.S.C. (1977). National Primary Drinking Water Regulations. 40 CFR. US Environmental Protection Agency. Washington, DC. **141**.

US Census Bureau. (2012). "American FactFinder fact sheet." New York, NY, 2012, from http://factfinder2.census.gov/faces/nav/jsf/pages/index.xhtml.

US Congress (1954). "The Atomic Energy Act of 1954." USA: 42 U.S.C., 2011 et seq., 68 Stat. 919, 83-703. 83rd United States Congress, August 30, 1954.

US Congress (1980). "Comprehensive Environmental Response, Compensation, and Liability Act." USA: 42 U.S.C., 9601 et seq., 94 Stat. 2767, 96-510. 96th United States Congress, December 11, 1980.

US Congress (1992). "The Federal Facilitiy Compliance Act of 1992." USA, 102-386. 102nd Congress, Oct. 6, 1992.

US Congress (1976). "Resource Conservation and Recovery Act." USA: 42 U.S.C., 94-580. 96th United States Congress.

US Department of Energy (1988). Radioactive Waste Management. DOE Order 5820.2A. US Department of Energy. Washington, DC. **DOE Order 5820.2A**.

US Department of Energy (1996a). Closing the Circle on the Splitting of the Atom. Washington, DC: US Department of Energy.

US Department of Energy (1996b). "Final Report Complex-Wide Review of DOE's Low-Level Waste Management ES&H Vulnerabilities." Washington, DC, Office of Environmental Management. DOE/EM-0280.

US Department of Energy (1997a). Linking Legacies: Connecting the Cold War Nuclear Weapons Production Processes to Their Environmental Consequences. Washington, DC: US Department of Energy,.

US Department of Energy (1997b). "Performance Assessment for Continuing and Future Operations at Solid Waste Storage Area 6." Oak Ridge, TN: US Department of Energy. ORNL--6783/R1-Vol.1.

US Department of Energy (1999a). An Implementation Guide for Use with DOE M 435.1-1. DOE G 435.1-1. Department of Energy. Washington, DC. **DOE G 435.1-1**.

US Department of Energy (1999b). Radioactive Waste Management. DOE Order 435.1-1. US Department of Energy. Washington, DC, US Department of Energy. **DOE O 435.1**.

US Department of Energy (1999c). Radioactive Waste Management Manual. DOE M 435.1-1. US Department of Energy. Washington, DC, US Department of Energy. **DOE M 435.1-1**.

US Department of Energy (2009). "Explanation of Significant Differences for the Record of Decision for the Disposal of Oak Ridge Reservation Comprehensive Environmental Response, Compensation, and Liability Act of 1980 Waste, Oak Ridge, Tennessee." Oak Ridge, TN: US Department of Energy, Oak Ridge Office. DOE/OR/01-2426&D1.

US EPA (2013). "Hanfod Site 300 Area: Record of Decision for 300-FF-2 and 300-FF-5, and Record of Decision Amendment for 300-FF-1." Richland, WA: US Department of Energy, Richland Operation Office.

US NRC (1982a). "Final Environmental Impact Statement on 10 CFR 61, "Licensing Requirements for Land Disposal of Radioactive Waste"." Washington, DC: US Nuclear Regulatory Commission, Office of Nuclear Material Safety and Safeguards. NUREG-0945.

US NRC (1982b). Licensing Requirements for Land Disposal of Radioactive Waste. 10 CFR. Nuclear Regulatory Comission. U.S. Code of Federal Regulations. **61**.

US NRC (1987). "Environmental Standard Review Plan for the Review of a License Application for a Low-Level Radioactive Waste Disposal Facility." Washington, DC: US Nuclear Regulatory Commission, Office of Nuclear Material Safety and Safeguards. NUREG-1300 rev.0.

US NRC (1989). "Regulating the Disposal of Low-Level Radioactive Waste: A Guide to the Nuclear Regulatory Commission's 10 CFR Part 61." Washington, DC: US Nuclear Regulatory Commission, Office of Nuclear Material Safety and Safeguards. NUREG/BR-0121.

US NRC (1991). "Standard Format and Content of a License Application for a Low-Level Radioactive Waste Disposal Facility." Washington, DC: US Nuclear Regulatory Commission, Office of Nuclear Material Safety and Safeguards. NUREG-1199 rev.2.

US NRC (1994). "Standard Review Plan for the Review of a License Application for a Low-Level Radioactive Waste Disposal Facility." Washington, DC: US Nuclear Regulatory Commission, Office of Nuclear Material Safety and Safeguards. NUREG-1200 rev.3.

US NRC (2000). "A Performance Assessment Methodology for Low-Level Radioactive Waste Disposal Facilities." Washington, DC: US Nuclear Regulatory Commission, Office of Nuclear Material Safety and Safeguards. NUREG-1573.

US NRC (2007). "History and Framework of Commercial Low-Level Radioactive Waste Management in the United States." Washington, DC: US Nuclear Regulatory Commission, Advisory Committee on Nuclear Waste. NUREG-1853.

US Nuclear Regulatory Comission (1981). "Draft Environmental Impact Statement on 10 CFR Part 61, "Licensing Requirements for Land Disposal of Radioactive Waste"." Washington, DC, U. N. R. Comission. NUREG-0782.

Velázquez, J., Caleyo, F., Valor, A. and Hallen, J. (2009). "Predictive Model for Pitting Corrosion in Buried Oil and Gas Pipelines." Corrosion **65**(5): 332-342.

Waters, R. D. and Gruebel, M. M. (1996). "Performance Evaluation of the Technical Capabiities of DOE Sites for Disposal of Mixed Low-Level Waste: Site Evaluations." Albuquerque, NM: Sandia National Laboratories, Office of Waste Management. SAND96-0721/3 - UC-2020.

Waters, R. D., Gruebel, M. M., Hospelhorn, M. B., et al. (1996). "Performance Evaluation of the Technical Capabilities of DOE Sites for Disposal of Mixed Low-Level Waste: Technical Basis and Discussion of Results." Albuquerque, NM: Sandia National Laboratories, Office of Waste Management. SAND96-0721/2 - UC-2020.

Westinghouse Savannah River Company (WSRC) (2007). "FY2006 Annual Review E-Area Low-Level Waste Facility Performance Assessment and Composite Analysis." Aiken, SC: Westinghouse Savannah River Company, Savannah River Site. M&O-WMAP-2007-00020.

Westinghouse Savannah River Company (WSRC) (2008). "E-Area Low Level Waste Facility DOE 435.1 Performance Assessment." Aiken, SC: Washington Savannah River Company, Savannah River Site. WSRC-STI-2007-00306.

Wilhite, E. L. (2001). "Comparison of LLW Disposal Performance Objectives 10 CFR 61 and DOE 435.1." Aiken, SC: Westinghouse Savannah River Company. WSRC-RP-2001-00341.