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ABSTRACT

This report evaluates the durability of WAXFIX when used for in situ grouting of transuranic and low-level mixed wastes, typical of those buried in the Subsurface Disposal Area (SDA), a radioactive landfill at the Radioactive Waste Management Complex, part of the Idaho National Engineering and Environmental Laboratory (INEEL). In situ grouting at the SDA can be used to produce one or more of three potential applications: contaminant immobilization, cap and overlying material support, or retrieval enhancement. Durability is important to immobilization of contaminants and support of a cap, but is not an issue for retrieval enhancement since the material does not remain in situ for a long time. WAXFIX can immobilize contaminants by coating and permeating waste material and by restricting the access of water to contaminants and waste. WAXFIX can also provide structural support by eliminating voids and forming monoliths to prevent subsidence.

The durability of WAXFIX, a paraffin wax-based grout, was evaluated using an extensive literature search, previous tests of in situ grouting at the INEEL, and information available from tests currently being conducted at the INEEL. Where data on WAXFIX were not available, data on paraffin were used. This evaluation includes a review of behavior developed using standard test procedures applicable to grouts (e.g., contaminant leaching and compressive strength), as well as behavior under possible harsh Subsurface Disposal Area conditions that could affect the long-term stability of WAXFIX grout. Results will be used to support the feasibility study for Waste Area Group 7, Operable Unit 7-13/14. The existing data and estimations of biodegradation and radiolysis rates for WAXFIX/paraffin do not indicate any immediate problems with the use of WAXFIX for grouting in the SDA. Reducing the uncertainties in the currently available data and rate estimations would require additional modeling and experimental work.

EXECUTIVE SUMMARY

The purpose of this report is to evaluate the durability of WAXFIX when used for in situ grouting of transuranic and low-level mixed wastes, typical of those buried in the Subsurface Disposal Area (SDA), a radioactive landfill at the Radioactive Waste Management Complex, part of the Idaho National Engineering and Environmental Laboratory (INEEL). In situ grouting at the SDA can be used to produce one or more of these three potential applications: contaminant immobilization, cap and overlying material support, or retrieval enhancement. Durability is important to immobilization of contaminants and support of a cap, but is not an issue for retrieval enhancement since the material does not remain in situ for a long time. WAXFIX can immobilize contaminants by coating and permeating waste material and by restricting the access of water to contaminants and waste. WAXFIX can also provide structural support by eliminating voids and forming monoliths to prevent subsidence.

WAXFIX, a paraffin wax-based grout, has several desirable characteristics for use at the INEEL that include the following:

- Low permeability to water, which reduces the likelihood of contaminant transport
- Substantial penetration into voids that may exist in the soil/waste matrix, enhancing long-term stabilization of waste
- Inert chemistry that is not likely to accelerate degradation
- Reduction of the generation of dust and particulates that could spread contamination, should waste retrieval eventually be desired.

Information on WAXFIX was identified using an extensive literature search, previous tests of in situ grouting at the INEEL, and information available from tests currently being conducted at the INEEL. These results were reviewed and an evaluation of the expected performance of WAXFIX was made based on current and projected grouting plans for the SDA. This evaluation includes a review of behavior developed using standard test procedures applicable to grouts (e.g., contaminant leaching and compressive strength), as well as the behavior for possible harsh SDA conditions that could affect the long-term stability of WAXFIX grout, including biodegradation and radiolysis. Results will be used to support the feasibility study for Waste Area Group 7, Operable Unit 7-13/14. The following conclusions are based on the findings of the literature search and results assessment:

- Although compressive strength values for WAXFIX/waste mixtures are significantly less than cement-based grouts, all values were above the minimum 0.41 MPa (60 psi) required by the Nuclear Regulatory Commission, except those with a 30% organic waste loading.
- Hydraulic conductivity values were about an order of magnitude less than some cement-based grouts, demonstrating the impermeability of WAXFIX grout to water.
- WAXFIX did not experience rapid reactions with an oxidizer (e.g., sodium nitrate) for the full range of temperatures tested (up to 350°C).
- WAXFIX would not be classified as an oxidizer, based on testing to the U.S. Department of Transportation standards.

- WAXFIX specimens maintained their integrity, but lost about 50% of their compressive strength when exposed to a strong base solution (pH 12.5) for a 90-day period. Chemical forms and compositions in the SDA are sufficiently different that a similar degree of degradation is not expected.

- Exposing WAXFIX to a solvent (i.e., deionized water saturated with trichloroethylene) caused weight loss, an increase in volume, and a 55% reduction in compressive strength. WAXFIX would be expected to have a similar response to carbon tetrachloride. However, degradation within a waste/grout monolith formed by WAXFIX in the SDA would be localized because the Rocky Flats organic sludge containing TCE, carbon tetrachloride, trichloroethane, and tetrachloroethylene comprises only a small portion of the total waste.

- Accelerated leach tests show that WAXFIX is effective in preventing leaching of chromium and lead. Toxicity characteristic leaching procedure leach tests indicate that WAXFIX alone is not effective in preventing mercury leaching. Adding a material with a high affinity for mercury to the grout (about 2 wt% of sodium sulfide) reduced mercury leaching to below current limits.

- Degradation of a paraffin-based grout by microorganisms in the SDA is possible and perhaps likely, but the rate of degradation will be at a slower rate than found in the literature reviewed. The rate of biodegradation for two paraffin monoliths, based on grouting beryllium blocks, was estimated using literature data for a well mixed aqueous system inoculated with microorganisms from a land farm for oil-contaminated soil. The calculations showed that 1,500 to 5,200 years would be required to consume the monoliths. The outer 0.46 m (18 in.) layer of each monolith, which represents the minimum expected distance to the beryllium block, was calculated to require 1,000 to 3,600 years to be consumed.

- Conservative radioactive doses for WAXFIX were calculated for the “hottest” (i.e., highest-activity) Advanced Test Reactor beryllium block in the SDA. These results indicate that WAXFIX would not reach a level of radiation damage for many hundreds of years.

- Calculation of radiation induced hydrogen generation in WAXFIX indicated that grout physical performance should not be reduced beyond the effect of radiation dose.

During the review of this document, an issue was raised on the possibility that proprietary ingredients or additives in WAXFIX could cause additional or accelerated corrosion of the beryllium blocks. Although this issue does not affect the durability of WAXFIX, it could influence whether WAXFIX is acceptable for grouting beryllium. Based on information from the patent owned by the manufacturer of WAXFIX, the proprietary ingredients in WAXFIX 25 do not contain any of the ions that accelerate beryllium corrosion and that WAXFIX 25 is “specifically designed to eliminate the potential for ionic transport by eliminating any continuous aqueous phase in the waste and its surroundings.”

Recommendations on testing that can improve understanding of WAXFIX durability are provided.

CONTENTS

FIGURES

TABLES

ACRONYMS

ASTM	American Society for Testing and Materials
ATR	Advanced Test Reactor
CFL	cumulative fraction leached
CFR	Code of Federal Regulations
DOT	Department of Transportation
EPA	Environmental Protection Agency
FS	Feasibility Study
ICP	Idaho Completion Project
INEEL	Idaho National Engineering and Environmental Laboratory
NRC	Nuclear Regulatory Commission
ORIGEN2	Oak Ridge Isotope GENeration and Depletion Code Version 2
OU	operable unit
RI/FS	remedial investigation and feasibility study
RWMC	Radioactive Waste Management Complex
SDA	Subsurface Disposal Area
TCE	trichlorethylene
TCLP	toxicity characteristic leaching procedure
TD	thermally desorbed
TRU	transuranic
WAG	waste area group

Evaluation of the Durability of WAXFIX for Subsurface Applications

1. INTRODUCTION

This report presents an evaluation of currently available data about the physical and chemical characteristics of WAXFIX, a paraffin wax-based grouting material, to understand better its expected performance when injected in situ in buried radioactive waste. This in situ injection is expected to increase the long-term stability of waste buried in the Subsurface Disposal Area (SDA), a radioactive landfill that is part of the Radioactive Waste Management Complex (RWMC) at the Idaho National Engineering and Environmental Laboratory (INEEL). In situ injection of WAXFIX grout creates solid monoliths that reduce infiltration of moisture into soil and waste and provide added support to reduce the potential for subsidence of overlying material.

In situ jet grouting has been identified as a method of stabilizing waste in the SDA (Holdren and Broomfield 2003). Tests of jet grouting carried out at the INEEL have indicated that WAXFIX has several qualities that are necessary for jet grouting in the SDA. However, WAXFIX has not been widely used and additional information is needed about the performance, durability, and long-term behavior of WAXFIX under SDA conditions to ensure its performance as required.

This report combines information from tests of in situ jet grouting at the INEEL over a previous 9-year period, available information from tests now being carried out, and an extensive literature search to evaluate the performance of WAXFIX under specific conditions at the SDA.

1.1 Purpose

The purpose of this report is to evaluate the durability of WAXFIX when used as a grout for transuranic (TRU) and low-level mixed wastes, typical of those in the SDA. This report presents an evaluation of information from a broad range of literature to better understand better the expected performance of WAXFIX at the SDA. Results from this work will support risk assessment, preremedial design studies, and a better understanding of expected grout behavior for the feasibility study (FS) for Waste Area Group (WAG) 7, Operable Unit (OU) 7-13/14.[a] The plan describing the requirements for the remedial investigation and feasibility study (RI/FS) is in the *Second Revision to the Scope of Work for the OU 7-13/14 Waste Group 7 Comprehensive Remedial Investigation Feasibility Study* (Holdren and Broomfield 2003).

1.2 Overview

Field-monitoring data and modeling of contaminant fate and transport suggest that release and migration of mobile, long-lived fission and activation products pose the most immediate health risk from the SDA (Holdren et al. 2002). Grouting is one of several potential remedial alternatives for the SDA and WAXFIX is one of the grout materials under consideration.

Grouting at the SDA can be used to produce one or more of these three potential applications: contaminant immobilization, cap and overlying material support, or retrieval enhancement. Durability is

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a. The Federal Facility Agreement and Consent Order lists 10 WAGs for the INEEL. Each WAG is subdivided into OUs. The RWMC is identified as WAG 7 and originally contained 14 OUs. Operable Unit 7-13 (TRU pits and trenches RI/FS) and OU 7-14 (WAG 7 comprehensive RI/FS) were ultimately combined into the OU 7-13/14 comprehensive RI/FS for WAG 7.

important to immobilization of contaminants and support of a cap, but is not an issue for retrieval enhancement since the material does not remain in situ for a long time.

Grouting can immobilize contaminants through micro encapsulation, macro encapsulation of contaminants, chemical binding of contaminants, exclusion of water from contaminants, or a combination of the four. WAXFIX grout combines micro encapsulation of contaminants, macro encapsulation of contaminants and exclusion of water from contaminants. WAXFIX coats and permeates many typical waste materials including paper, wood, cloth, and soil. When waste materials are finely divided and easily wetted by WAXFIX, such as the case for finely divided soil, the immobilization occurs through micro encapsulation. During the jet grouting process, larger particulates (such as chunks of soil or sludge) mix with the WAXFIX to microencapsulate the waste. The third way WAXFIX immobilizes contaminants is by restricting the access of water to the contaminants; WAXFIX has a low porosity and a low hydraulic conductivity, properties that work together to exclude water from materials coated with WAXFIX. The long-term durability of WAXFIX is very important to its performance as a material for immobilization of contaminants, since many of the contaminants of concern in the SDA have long half-lives.

Structural support of the cap is important to its overall performance. Grouting waste within the SDA can eliminate voids, which will prevent later subsidence and damage. Grouting can also be used to provide structural support pillars that support the cap independent of the waste. Grouting to eliminate voids will result in a series of monoliths being formed within the SDA. The strength of the grouted monolith only needs to be enough to support the soil and cap directly above the grouted region. The purpose of the monoliths is to prevent subsidence; the monoliths are not the primary support for the cap. The durability of the grouted material is important mainly in terms of immobilization. Grouting to provide structural support places stricter requirements on the physical properties and durability of the grout. The compressive strength of the grouted column must be sufficient to support the local regions of the overlying material and cap. The design may require that no credit is taken for the support from the surrounding wastes. The structural properties of the grout must be specified so that even after placement in a wide variety of wastes, the properties are sufficient to support the cap. The long-term durability of grouts used for pillars is very important, since most of the waste is not treated with grout and may not have sufficient strength to support the cap. WAXFIX is not a high-strength grout and would not be suitable for use as a support pillar. WAXFIX is not a crystalline material and can deform under stress, but does have sufficient strength to be used to fill voids and form monoliths. WAXFIX is able to permeate paper, cloth, wood, and soil, filling micro and macro voids.

Durability is not an issue for grouting for retrieval of waste; however, WAXFIX was originally considered as a grout that could simplify retrieval of waste. The ability of WAXFIX to permeate and coat many materials made it a good candidate for a contamination control technique. The relatively low compressive strength along with its low friability make it a good candidate for waste excavation activities.

Composition of the waste is important to the performance of the grout. Contaminants in the SDA include hazardous chemicals (both organic and inorganic), remote-handled fission and activation products, and TRU radionuclides. The waste is buried in pits, trenches, and soil vaults. Waste placed in the SDA is in diverse forms, including metal drums, wood and cardboard boxes, soft-side boxes, bags, and large objects. Some of the waste was stacked and some was dumped at random. Similar surrogate test materials were jet grouted in a cold (i.e., nonradioactive) test pit (Loomis, Zdinak, and Bishop 1996). Examination of these surrogate wastes revealed that WAXFIX penetrated even small void areas and soaked into all materials that were permeable, such as paper and wood. Testing of in situ jet grouting at the INEEL (Loomis, Zdinak, and Jessmore 1998; Loomis et al. 2002) has demonstrated the following desirable characteristics of WAXFIX grout for use at the SDA:

- Substantial penetration into voids in the soil/waste matrix, reducing the potential for subsidence of overlying material

- Low water permeability, reducing the likelihood of contaminant transport

- Inert chemistry that is unlikely to accelerate degradation (e.g., corrosion) of waste materials

- Reduction of dust and particulates to control the spread of contamination, if waste retrieval eventually should be desired (waste retrieval after grouting is not currently being considered).

This report documents the long-term durability aspects of WAXFIX grout with respect to immobilizing contaminants within the waste and structurally supporting a cap through elimination of voids.

1.3 Scope

This report summarizes a wide range of information about WAXFIX derived from (1) testing sponsored by the INEEL (both in the past and continuing today), and (2) information from an extensive literature search to aid in understanding expected WAXFIX grout performance for the areas that will influence usefulness or durability. The major criteria addressed in this evaluation are the grout's physical properties, physical stability, hydraulic conductivity, chemical stability, biodegradability, and radiation susceptibility. An assessment is included of the behavior of WAXFIX for standard test procedures applicable to grouts (e.g., leaching) as well as expected behavior under harsh environmental conditions at the SDA that could affect long-term stability of this grout material. If information about WAXFIX specifically was not available, the performance of paraffin wax, the primary component in WAXFIX, was used.

1.4 Brief History and Description of the Idaho National Engineering and Environmental Laboratory

The INEEL, originally established in 1949 as the National Reactor Testing Station, is a Department of Energy-managed facility that has historically been devoted to energy research and related activities. The INEEL is located in southeastern Idaho and occupies 2,305 km^2 (890 mi^2) in the northeastern region of the Snake River Plain. Regionally, the INEEL is nearest to the cities of Idaho Falls and Pocatello and to U.S. Interstate Highways I-15 and I-86. The INEEL Site extends nearly 63 km (39 mi) from north to south, is about 58 km (36 mi) wide in its broadest southern portion, and occupies parts of five southeast Idaho counties. Public highways (i.e., U.S. 20 and 26 and Idaho 22, 28, and 33) within the INEEL boundary and the Experimental Breeder Reactor I, which is a national historic landmark, are accessible without restriction (Zitnik et al. 2002). See Figure 1 for the location of the INEEL and the major facilities.

The RWMC, located in the southwestern quadrant of the INEEL, encompasses a total of 72 ha (177 acres) and is divided into three separate areas by function: the SDA, the Transuranic Storage Area, and the Administration and Operations Area. The original landfill, established in 1952, covered 5.2 ha (13 acres) and was used for shallow land disposal of solid radioactive waste. In 1958, the landfill was expanded to 35.6 ha (88 acres). Relocating the security fence in 1988 to outside the dike surrounding the landfill established the current size of the SDA as 39 ha (97 acres). The Transuranic Storage Area was added to the RWMC in 1970. Located adjacent to the east side of the SDA, the Transuranic Storage Area encompasses 23 ha (58 acres) and is used to store, prepare, and ship retrievable TRU waste to the Waste

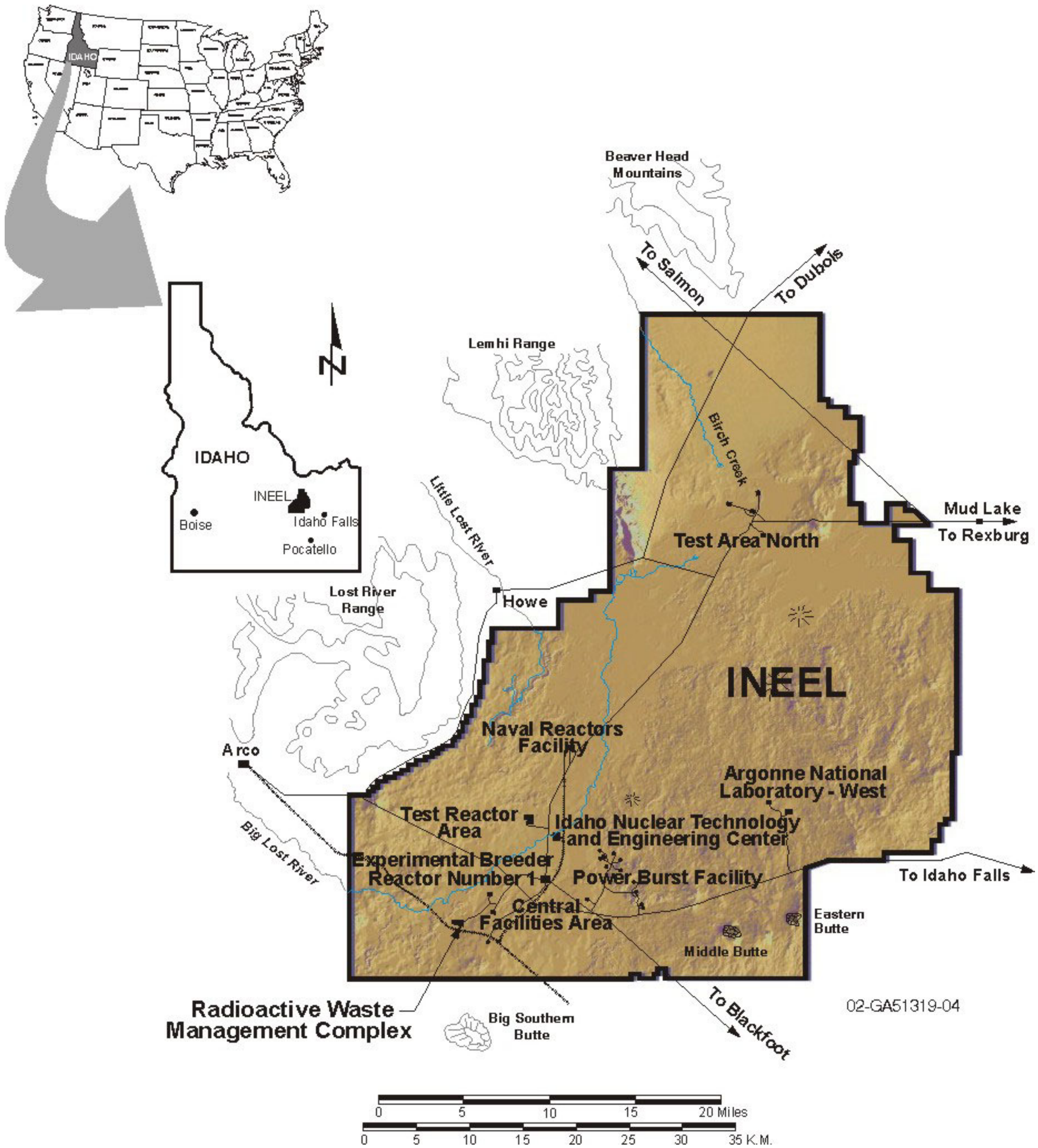

Figure 1. Map of the Idaho National Engineering and Environmental Laboratory showing the location of the Radioactive Waste Management Complex and other major facilities.

Isolation Pilot Plant. The 9-ha (22-acre) Administration and Operations Area at the RWMC includes administrative offices, maintenance buildings, equipment storage, and miscellaneous support facilities (Zitnik et al. 2002). See Figure 2 for a map of RWMC showing the location of the SDA.

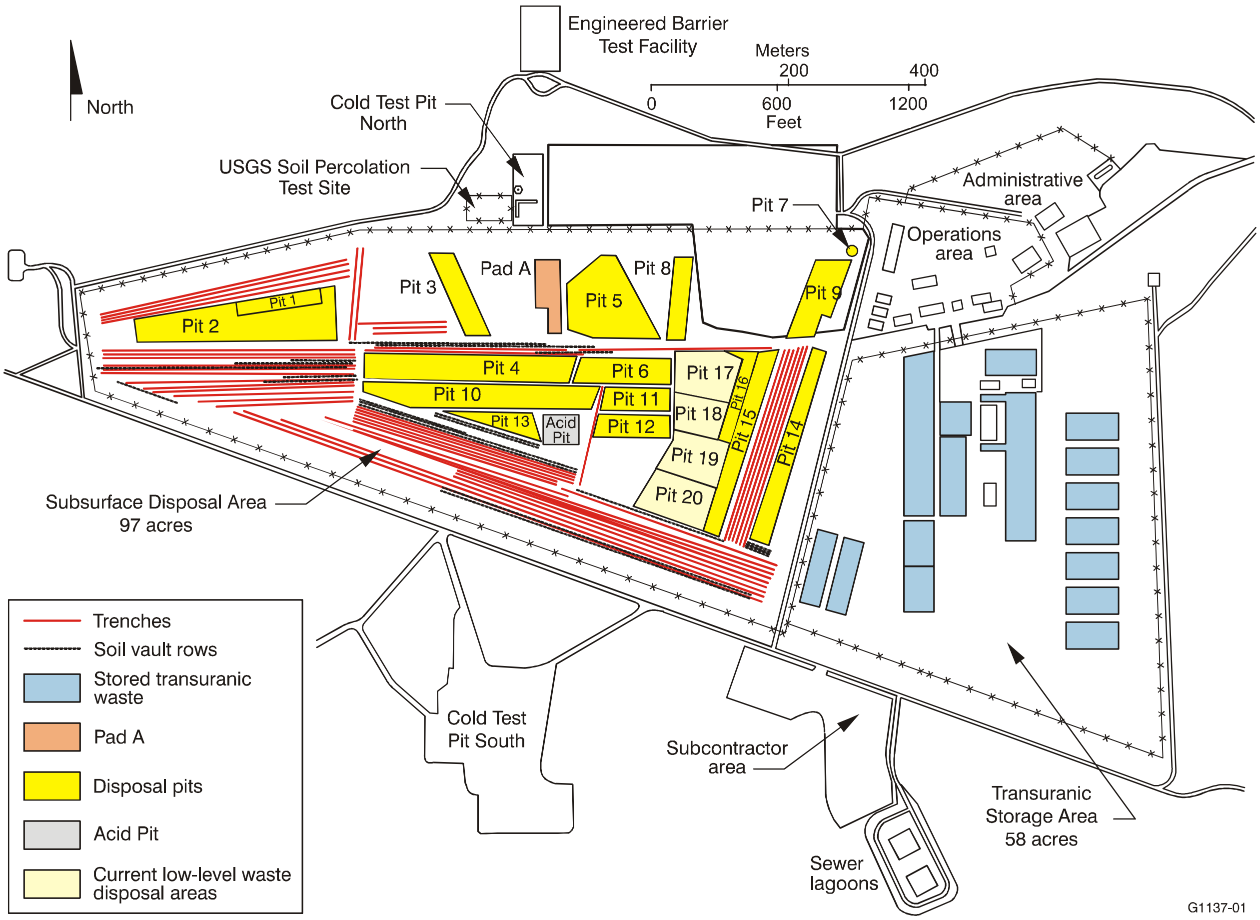

Figure 2. Diagram showing the Radioactive Waste Management Complex.

Underlying the RWMC at an approximate depth of 177 m (580 ft), the crescent-shaped Snake River Plain aquifer flows generally from the northeast to the southwest. The aquifer is bounded on the north and south by the edge of the Snake River Plain, on the west by surface discharge into the Snake River near Twin Falls, Idaho, and on the northeast by the Yellowstone basin. The aquifer consists of a series of water-saturated basalt layers and sediment.

The surface of the SDA is a semiarid, sagebrush desert. The undisturbed surficial sediments at the RWMC range in thickness from 0.6 to 7.0 m (2 to 23 ft). The subsurface below these shallow surficial sediments is characterized by alternating layers of fractured basalt and sedimentary interbeds. The regional subsurface consists mostly of these layered basalt flows with a few comparatively thin layers of sedimentary deposits, called interbeds. The interbeds tend to retard infiltration to the aquifer and are important features in assessing the fate and transport of contaminants. However, there will be little remaining stratigraphic layering in the soil used to bury waste containers. Infiltration of water occurs episodically from rain, flood, and snowmelt (Zitnik et al. 2002).

These geophysical and meteorological conditions at the SDA are important background in understanding the tests that WAXFIX has undergone and continues to undergo, and the results of those tests.

1.5 Brief Summary of Past Field Demonstrations

Testing at the INEEL over a 9-year period developed jet grouting equipment and techniques, and provided important information on its effectiveness as an option for long-term stabilization of fission and activation products in the SDA (Loomis et al. 2002). The jet grouting process begins by driving a drill stem, with nozzles mounted near the bottom, to the full depth to be treated (at the SDA this is approximately 20 ft). The drill stem is then rotated as grout is injected at 400 bar (6,000 psi) through the nozzles. The drill stem is withdrawn in predetermined increments, forming a column of soil/grout mixture. Depending on the expected void volume of the region to be grouted, the time interval for each step of the drill stem extraction can be adjusted (longer steps equal more grout placed). The high pressure of the grout aids in the mixing of the grout and subsurface material. The grouted columns are approximately 24 in. in diameter. A monolith is formed by jet grouting a series of holes on a triangular pitch with a spacing of approximately 20 in. When the columns solidify, they form a solid monolith that substantially reduces the likelihood of contaminant migration.

In a previous field test at a simulated waste (drums, boxes, debris) pit, WAXFIX was jet grouted and a small monolith (approximately 6 ft × 6 ft × 6 ft) was formed with 15 injection points. The WAXFIX was injected at a temperature of 140°F (60°C) and an average of 81 gal was injected in each hole. The pit remained above 120°F (49°C), the melting point of WAXFIX, for at least 3 days. The pit was allowed to cool to ambient temperatures and was then destructively analyzed. Examination of the pit contents showed that the WAXFIX permeated the soil, wood, paper, and cardboard in the test pit. The WAXFIX that was injected into a drum of simulated organic sludge, contained in the test pit, showed good mixing and produced a thick mixture that could stand alone. No void spaces were detected in the soil and debris. Figures 3 through 10 show the result of grouting simulated wastes with WAXFIX (blue dye added in test to help visualize WAXFIX). Figures 3 through 10 show the excavation of monoliths and monolith debris created in simulated TRU waste pits by jet grouting paraffin. One picture (Figure 10) of an aluminum can containing WAXFIX suggests that WAXFIX can pull away from the sides if a metal container holds the WAXFIX (–Loomis, Zdinak, and Bishop 1997). It is not clear where the can was located in the demonstration pit. If a piece of metal is imbedded in the WAXFIX, or if the surface of the metal is rough, then the shrinkage of the WAXFIX may not cause separation from the metal. Based on experience gained in making cylinders for testing with WAXFIX and various amounts of soil, the shrinkage decreases with the amount of soil in the WAXFIX. This is similar to the behavior observed in cement when sand and aggregate are added.

1.6 Document Organization

The following briefly describes the remaining sections in this report:

- Section 2 describes the requirements for grout used at the INEEL, including the findings of previous tests at the INEEL, and lists the characteristics for evaluating WAXFIX.
- Section 3 provides detailed information describing WAXFIX performance and relates this performance to the expected conditions in the SDA.
- Section 4 summarizes the conclusions developed for the durability of WAXFIX for conditions expected in the SDA.

Figure 3. Detail of excavation wall of a pit grouted with paraffin (WAXFIX) (Photo 96-587-3-15).

Figure 4. Detail of paper from a pit grouted with paraffin (WAXFIX) (Photo 96-584-2-5).

Figure 5. Paraffin (WAXFIX) pit detail at 12 in. from the east face (Photo 96-587-3-15), Figure 72 (Loomis, Zdinak, and Bishop 1997).

Figure 6. Paraffin (WAXFIX) pit 18 in. from the east face (Photo 96-587-3-17), Figure 74, (Loomis, Zdinak, and Bishop 1997).

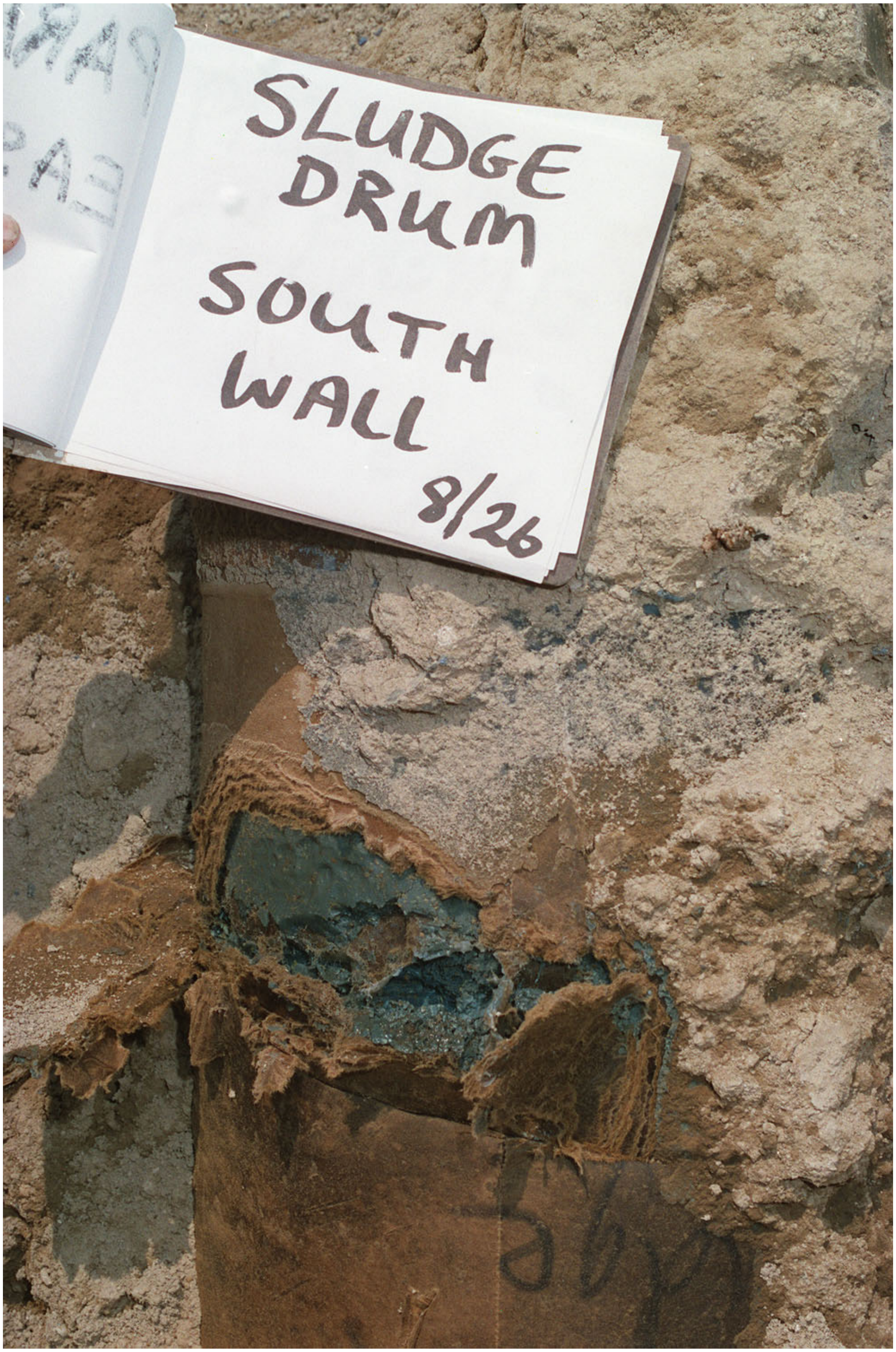

Figure 7. Drum of canola oil (simulated organic sludge) in south wall of paraffin (WAXFIX) pit (Photo 96-584-2-11), Figure 77 (Loomis, Zdinak, and Bishop 1997).

Figure 8. Detail of canola oil (simulated organic sludge) mixed with paraffin (WAXFIX) (Photo 96-584-1-10).

Figure 9. Sample of wood encased in paraffin (WAXFIX) (Photo 96-584-1-6) Figure 80 (Loomis, Zdinak, and Bishop 1997).

Figure 10. Sample of metal encased in paraffin (WAXFIX) (Photo 96-584-2-18) Figure 79 (Loomis, Zdinak, and Bishop 1997).

- Section 5 describes the approaches that could be used if uncertainty reduction is desired.
- Section 6 contains the references used throughout this report.
- Appendix A provides physical property information for a wide range of paraffin hydrocarbons.
- Appendix B describes calculations conducted to estimate the amount of radiation absorbed by grout that could surround an Advanced Test Reactor (ATR) irradiated beryllium component buried in the SDA and presents the results from these calculations.
- Appendix C describes calculations performed to estimate the rate of biodegradation of WAXFIX when placed below ground level in the SDA.

2. WAXFIX PERFORMANCE CHARACTERISTICS

WAXFIX is composed primarily of paraffins in the C_{18} – C_{25} range with a small amount of proprietary additives, designed to enhance its handling properties as a grout. The exact composition of the proprietary additives is not known, but the patent held by the manufacturer of WAXFIX indicates they include emulsifiers and wetting agents such as fluoraliphatic polymeric esters, oleic acid, alkanolamine and nonyl phenol ethoxylate (Patent). Grout material must remain effective for long periods of time, perhaps hundreds of years, to properly stabilize buried waste. The grout may need to immobilize contaminants, provide support for a cap overlying the waste, or reduce the infiltration of water into the waste. The effectiveness in terms of long-term performance and durability of the grout will depend on its physical characteristics and its ability to withstand harsh chemical, biological, and radiation conditions. The general characteristics of WAXFIX grout that will affect its performance include:

- Physical properties – accurate physical property information can (1) define the range of conditions (such as temperatures and pressures) over which this grout can meet expectations, and (2) provide accurate parameters to use in calculations and modeling. Physical properties are important to all three potential applications of grout at the SDA: immobilization, structural support, and retrieval..

- Physical stability – the compressive strength of the material is important since the material is expected at least to withstand the weight, and possibly provide additional support, to prevent subsidence of the overlying material. The Nuclear Regulatory Commission (NRC) specifies that the grout compressive strength be 60 psi or greater to support overlying materials (NRC 1991). Physical stability is important to all three potential applications of grout at the SDA: immobilization, structural support, and retrieval.

- Hydraulic conductivity – the grout's ability to conduct water is a good indicator of its permeability to water and can strongly influence the grout's physical stability. Hydraulic conductivity is important to the application of grout for immobilization at the SDA.

- Chemical stability – there must be an understanding of the reaction rates of WAXFIX with strong bases and acids and chemicals that can cause rapid oxidization since many different chemicals are in the SDA. Leach rates with a variety of contaminants must also be understood to ensure the grout is effective in meeting regulations. Chemical stability is important to the application of grout for immobilization and structural support at the SDA.

- Biodegradability – important parameters in understanding biodegradation include (1) the numbers and types of microorganisms that may attack the grout, (2) the conditions that must exist for these microorganisms to metabolize the grout and grow, especially over time, and (3) the resistance of the grout to these organisms over time. Biodegradability is important to the application of grout for immobilization and structural support at the SDA.

- Radiation susceptibility – grout materials must be able to withstand high levels of radiation and not sustain damage that will compromise the performance of the grout. The possibility of hydrogen generation from paraffin-based grout could also be important if large quantities of the gas are formed and cannot easily diffuse from the waste matrix. Radiation susceptibility is important to the application of grout for immobilization and structural support at the SDA.

The costs of WAXFIX grout were also estimated so decisionmakers can compare this grout with others being considered.

The authors performed an extensive literature search to obtain information on WAXFIX. These results were reviewed and compared and an evaluation made of the expected performance of WAXFIX based on current and projected SDA conditions. Studies were identified that included experimental work to provide needed performance characteristics for WAXFIX (Milian et al. 1997; Heiser and Fuhrmann 1997). Results from these studies are compared with more recent results to aid in evaluating possible performance. Since much of the information obtained from the literature search is very detailed, these details have been summarized to provide a concise description of the applicability of the results in expected SDA use.

When information on WAXFIX specifically is incomplete, information on the general performance of paraffin wax is used, since it is the primary component of this grout.

3. INFORMATION AVAILABLE ON WAXFIX PERFORMANCE

WAXFIX is the brand name of a grouting material composed primarily of paraffin wax, plus proprietary additives. The paraffin molecules in WAXFIX have an estimated range of carbon atoms from C_{18} to C_{25}. Paraffins are mineral oil (i.e., petroleum) products, consisting principally of the organic family of heavy hydrocarbons called alkanes, with the chemical formula C_nH_{n+2}. For this report, paraffin refers to the higher carbon number n-alkanes, those that are solid at room temperature and are commonly known as wax. Paraffin wax generally is composed of long chain n-alkanes with the number of carbon atoms in a range of ≥ 18 and ≤ 40.

The following sections address the general WAXFIX characteristics listed in Section 2.

3.1 Physical Properties

The physical properties of WAXFIX are important to all three potential applications of grout, immobilization, structural support, and retrieval. Jet grouting is the likely method of placement for all three potential applications of grout at the SDA. A brief description of the physical properties of WAXFIX that could be important to jet grouting is provided to aid in the understanding and analysis of successful jet grouting. The most important physical properties are primarily density and viscosity. Thermal properties are also included because heat capacity and thermal conductivity will influence solidification time and the general behavior of the grout in the vicinity of heat sinks, such as metal forms. This information is particularly useful if calculations on the behavior of the grout are necessary for understanding behavior during or shortly after jet grouting.

Specific information on WAXFIX properties is relatively limited. Information on the physical properties of paraffin as a surrogate for WAXFIX is provided to supplement existing specific information. Appendix A provides a set of properties for a range of n-alkanes, each having a uniform chain length. Solid paraffin waxes, those with carbon numbers greater than 18, are included. Table A-1 illustrates the effect of carbon chain length on several physical properties and is a resource in finding important physical characteristics. A typical composition for general use paraffin wax is also described in Appendix A.

3.1.1 Density

The material safety data sheet for WAXFIX states that the density of a typical solid WAXFIX grout is between 0.8 and 0.9 g/cm^3 (Milian et al. 1997). Experimental measurements of density were performed for a WAXFIX grout composed of 100 g WAXFIX 125 and 12 g WAXFIX 12, which is considered to be a typical blend that could be used in the SDA. The measured solid grout density for this composition is 0.88 g/cm^3 (Heiser and Fuhrmann 1997). The liquid density is 0.77 g/cm^3 for this same WAXFIX grout composition (Milian et al. 1997). Although the reference does not provide details, it appears that these measurements were taken at room temperature. Paraffin wax results indicate that the temperature dependence of density for paraffin wax with about the same density as WAXFIX is in the range of -0.002 g/cm^3/°C for temperatures around 20°C.

3.1.2 Viscosity

The viscosity of WAXFIX grout (a combination of WAXFIX 12 and WAXFIX 125) was measured to be 5 ± 1 cP at 65°C (149°F) (Milian et al. 1997). For the individual components, the viscosity of WAXFIX 12 is about 1,000 cP at 20°C (68°F) and the viscosity of WAXFIX 125 is 4 to 5 cP at 70°C (158°F). A typical commercial paraffin wax viscosity is in the range of about 5 to 7 cP at 70°C (158°F) (Milian et al. 1997).

3.1.3 Specific Heat

Information on the specific heat of WAXFIX was not found. A rule-of-thumb value of 2.1 kJ/kg-K is generally used for the specific heat of C_{20} to C_{40} alkanes, both in the solid and liquid state (Freund et al. 1982). This value is approximate because the specific heat varies with temperature, molecular weight, and the crystal structure if a solid. Studies of paraffin wax indicate the specific heat of solid paraffin wax is in the range of 2.16 to 2.95 kJ/kg-K, and the specific heat of the liquid is reported in the range of 2.16 to 2.51 kJ/kg-K (Haji-Sheikh, Eftekhar, and Lou 1982). (See Appendix A for the sensitivity to molecular weight of relatively pure n-alkanes.)

3.1.4 Melting Point and Latent Heat of Fusion

The melting point and latent heat of fusion vary substantially with the molecular weight and crystalline structure of the solid. Thermal testing on WAXFIX 125 (Milian et al. 1997) indicates that the melting point is about 58°C (136°F). Appendix A shows typical values for n-paraffins with a wide range of molecular weights. Typically the melting points for paraffin wax range from 47 to 65°C (117 to 149°F). Depending on the molecular composition of the commercial paraffin wax used in WAXFIX and the proportion of proprietary ingredients in the mixture, the melting point of WAXFIX should be in the range of 55 to 60°C (131 to 140°F). The latent heat of fusion for WAXFIX was not found, but based on paraffin will be in the range of 230 to 260 kJ/kg.

3.1.5 Thermal Conductivity

The thermal conductivity of both solid and liquid paraffin wax is generally reported as the same value, in the range 0.24 to 0.21 W/m-C. Thermal conductivity of solid wax becomes very sensitive to temperature and can drop by up to 30% as the melting temperature is approached (Haji-Sheikh, Eftekhar, and Lou 1982).

3.1.6 Volume Contraction During Cooling

Paraffin wax contracts significantly as it cools from the liquid state to the solid state. There are three components that contribute to volume contraction during cooling: contraction as a liquid, contraction during solidification, and contraction as a solid. Experimental results for a temperature range of 5.56°C (10°F) above the melting point to 27.8°C (50°F) below the melting point show the total volume contraction ranged from 14.1 to 11.4 vol% (Freund et al. 1982). Volume contraction correlated to some extent with wax melting temperature. Based on its melting point, the WAXFIX volume contraction during solidification would be expected to be larger than the midpoint of this range. Data from testing with WAXFIX are consistent with this and suggest a 12% shrinkage (Heiser and Fuhrmann 1997, Milian et al. 1997). Liquid paraffin waxes were found to contract at about the same rate during cooling, 0.072 ± 0.008 vol% per degrees C. Volume contraction following solidification was assumed to be identical to the liquid value. This allows calculation of volume contraction during solidification, which ranged from 9.3 to 11.7 vol% for the test methods used. In the SDA, most of the WAXFIX would be mixed with soil and other materials, which would reduce the effective shrinkage in the same way as aggregate does for cement in concrete. Destructive evaluation of 6 × 6 × 6-ft monoliths formed by jet grouting WAXFIX in simulated buried waste did not reveal any voids (Loomis 1997).

3.1.7 Self Healing

Although there is no specific information on WAXFIX self healing, the crystalline structure of paraffin wax can result in "self healing" qualities if cracks form because of excessive physical or thermal stress or shock. This behavior would tend to reduce infiltration of water if the paraffin based grout was damaged through natural phenomena (e.g., earthquake) or accident conditions. Specific information on the degree of self healing for given environmental conditions was not found in the literature.

3.2 Physical Stability

As mentioned earlier, WAXFIX is not a candidate for providing physical support to a cap via columns. WAXFIX is a candidate for placement as a monolith for structural support, immobilization, or retrieval. Monoliths formed during jet grouting will provide support for the material overlying the grouted waste. Loading from the normal 1 to 2 m of overburden at the SDA is generally insufficient to make this support a major factor in the performance of surface material. However, support from the grout monoliths becomes increasingly important when a cap is constructed over the grouted waste to restrict moisture penetration. If the monoliths do not provide adequate support for all areas of the cap, localized subsidence may cause ponding of water on the cap surface that could cause permeable pathways to develop through the cap to the grouted waste.

3.2.1 Compressive Strength

Understanding the unconfined compressive strength of jet-grouted soil or waste is important for calculating the future performance of the grouted areas under the overlying materials. Compressive strength values also provide a basis for assessing changes in the integrity of the grouted material, using results from tests on the effects of physical or chemical attack on grouted material. WAXFIX compressive strength results are provided from both recent and continuing Idaho Completion Project (ICP) preremedial design testing, which is currently being performed, and from previous testing by Brookhaven National Laboratory. Compressive strength is also an important consideration for retrieval; materials with very high compressive strengths may make retrieval more complicated.

3.2.1.1 Idaho Completion Project-Sponsored Waxfix Grout Tests. Unconfined compressive strength of WAXFIX has been tested for soil and waste loadings that cover the range of conditions expected in the SDA. These tests were conducted as part of ICP preremedial design testing. WAXFIX compressive strength test results are presented for:

- No waste loading (i.e., neat grout)
- Grout and soil mixtures
- Grout and simulated organic sludge mixtures
- Grout and nitrate salt mixtures
- Grout and mixtures of in situ thermally desorbed (TD) organic sludge.

The objective of the tests outlined above (Yancey et al. 2003) is to determine whether materials similar to those that will be mixed with WAXFIX during jet grouting at the SDA will have an adverse effect on the grout's compressive strength. Test results for WAXFIX test samples without other materials blended in (i.e., neat grout) are not presented separately, but are presented with the other results so that easy comparisons can be made of the effect of soil and waste.

WAXFIX 125B was used in the following ICP-sponsored testing. Initial tests covered a range of temperatures to examine any variation of the compressive strength of paraffin wax with temperature. These results indicated there is a relatively strong influence of temperature on the compressive strength for several types of paraffin. Since the influence of temperature was not entirely consistent among the different types of paraffin, the ICP tests were made at typical SDA temperatures to ensure the results are directly applicable. Historical data for the SDA indicates the subsurface soil temperatures varied from 7 to 10°C. Consequently, all compressive strength testing for WAXFIX was performed at 8°C. WAXFIX compressive strength testing was performed using American Society for Testing and Materials (ASTM) D-695, "Standard Test Method for Compressive Strength of Rigid Plastics." A brief description of the test results is found in the following sections.

3.2.1.1.1 WAXFIX/Soil Mixtures—WAXFIX grout and INEEL soil (sieved to 50 mesh) were mixed at loadings of 40, 50, 60, 70, and 80 wt% and were poured into cylindrical samples and allowed to cure. Results from the compressive strength tests are presented in Table 1 and are presented graphically in Figure 11. The results show that, with the exception of the 50 wt% soil loading, mixing WAXFIX with soil increased the grout's compressive strength. The highest measured compressive strength was observed at the 70 wt% soil loading. At 80 wt% loading, the wax was not able to mix with all of the soil, leaving only a partial test sample monolith; therefore, testing above this soil loading was not practical.

Table 1. WAXFIX compressive strength data for neat grout and grout/soil mixtures (soil loadings are in weight percent).

Sample	Neat Grout (psi)	40% Soil (psi)	50% Soil (psi)	60% Soil (psi)	70% Soil (psi)	80% Soil (psi)
0	276.10	349.89	227.54	302.88	628.27	367.24
a	294.79	440.55	205.75	315.00	696.00	354.88
b	303.94	403.08	198.11	355.64	790.48	292.28
c	323.91	366.16	204.06	366.55	658.80	270.19
d	295.57	299.69	225.45	391.14	584.39	357.63
Average	298.86	371.87	212.18	346.24	671.59	328.44
Standard deviation	15.49	47.78	11.98	32.78	69.82	39.39

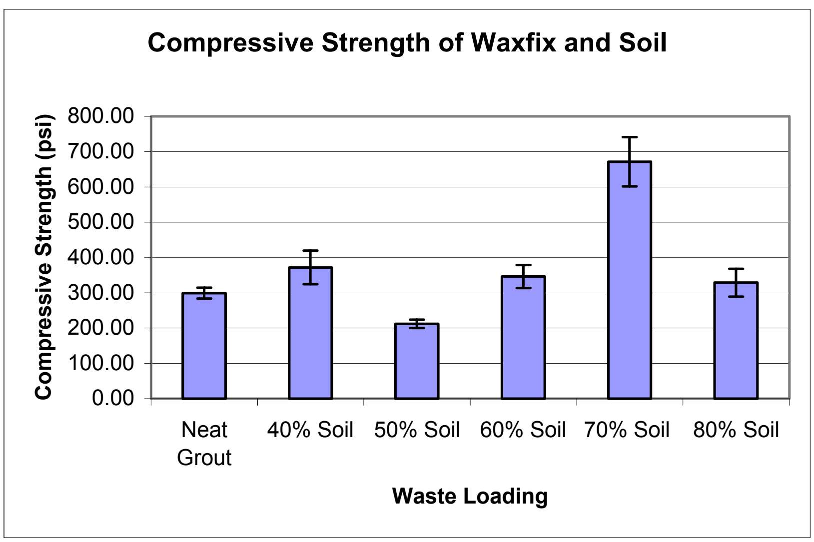

Figure 11. Compressive strength of WAXFIX and soil for neat grout and various soil loadings.

Previous jet grouting tests at full scale with cold simulated waste indicate (Loomis, Zdinak, and Bishop 1996) that WAXFIX grout penetrates very well. However, there is no way to ensure that mixing with soil will always be close to 70 wt%. As a result, a conservative compressive strength value to use in calculations would be the neat grout value. This would ignore the low value at 50 wt%, but it appears that this value only applies over a restricted range of soil loadings. All compressive strength values for the soil loadings tested were above the minimum 0.41 MPa (60 psi) the Nuclear Regulatory Commission (NRC) requires in its Technical Position on Waste Form (NRC 1991).

3.2.1.1.2 WAXFIX/Simulated Organic Sludge Mixtures—Organic sludge in the TRU pits and trenches at the SDA represents a small percentage of the waste pit volume. However, there are zones where drums of organic sludge could make up the majority of the waste. A previous study (Loomis, Zdinak, and Bishop 1996) shows that jet grouting of highly organic materials can degrade grout curing and monolith stability. However, certain grouts will form cohesive monoliths when used to jet grout isolated drums of organic material.

For the ICP-sponsored tests, WAXFIX grout was mixed with simulated Rocky Flats Plant waste. The simulated waste uses an organic formulation based on general knowledge of the typical composition of waste shipped to the INEEL from the Rocky Flats Plant. The simulated waste consists of trichlorethylene (TCE), tetrachloroethylene, carbon tetrachloride, and trichloroethane as volatile organics mixed with absorbers and Texaco Regal Motor Oil in the quantities shown in Table 2. This mixture of volatile organics, oil, and absorbers exhibits a grease-like consistency. WAXFIX grout was mixed with quantities of 5, 7, 10, 12, and 30 wt% simulated organic sludge. The resulting material was tested for compressive strength.

Table 2. Material proportions for the organic sludge mixture.

Ingredient	Quantity
Calcium silicate	4,120 g
Oil Dri	620 g
Carbon tetrachloride	2,680 mL
Tetrachloroethylene	740 mL
Trichloroethylene	740 mL
Trichloroethane	1,030 mL
Texaco Regal Oil, R&O 68	5,130 mL

Table 3 and Figure 12 present the results from the compressive strength tests. These results show that simulated organic sludge in quantities of 5 wt% and greater significantly decrease the compressive strength of the WAXFIX grout. For loadings of 5 and 12 wt%, the compressive strength is reduced by about 60%, while for the 30 wt% loading the decrease in compressive strength is about 85%. With the exception of the samples with 30% organic waste loading, the organic waste compressive strength values were above the minimum 0.41 MPa (60 psi) required by the NRC Technical Position on Waste Form (NRC 1991) to provide adequate support to overlying material.

Table 3. Compressive strength of WAXFIX and organic sludge for neat grout and various organic sludge loadings (organic waste loadings are in weight percent).

Sample	Neat Grout (psi)	5% (psi)	7% (psi)	10% (psi)	12% (psi)	30% (psi)
0	276.10	131.18	139.62	124.59	105.27	47.87
a	294.79	124.79	120.63	66.48	104.85	53.65
b	303.94	135.87	107.22	132.36	128.71	31.58
c	323.91	102.85	130.38	110.03	113.44	45.14
d	295.57	121.36	122.00	126.69	120.18	47.79
Average	298.86	123.21	123.97	112.03	114.49	45.21
Standard deviation	15.49	11.35	10.78	23.94	9.10	7.36

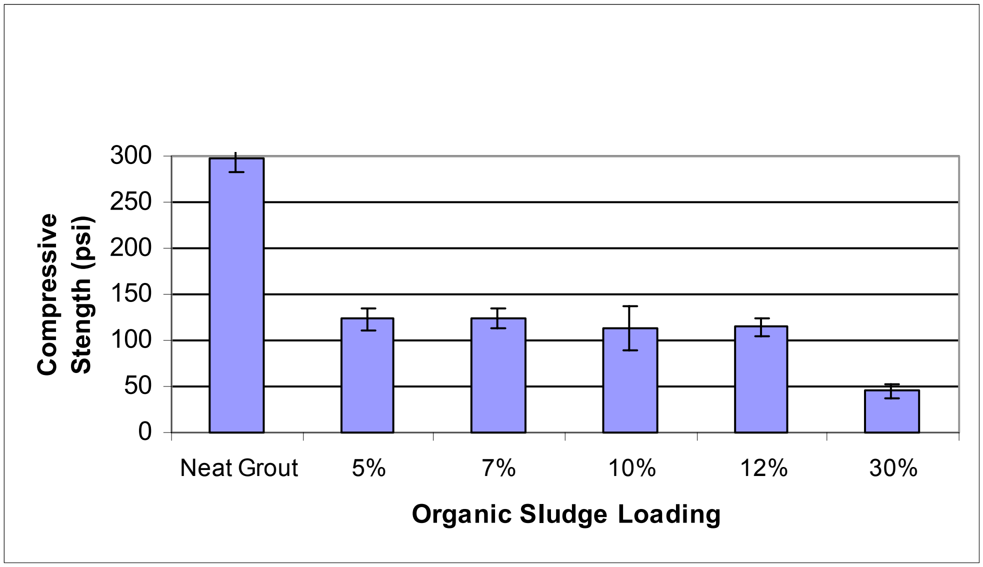

Figure 12. Compressive strength of WAXFIX and organic sludge for neat grout and various organic sludge loadings (organic waste loadings are in weight percent).

3.2.1.1.3 WAXFIX/Nitrate Salt Mixture—Salts in general can be difficult to mix uniformly with wax-based materials, possibly compromising the required mechanical properties since concentrations of salt may degrade compressive strength. Granular nitrate salts (roughly 33% potassium nitrate and 67% sodium nitrate) were blended to represent Rocky Flats Plant evaporation pond salts found in TRU pits and trenches at the SDA. WAXFIX grout was mixed with the nitrate salts at loadings of 40, 50, and 60 wt%. Table 4 and Figure 13 present the data from compressive strength testing.

Table 4. Compressive strength of WAXFIX and nitrate salt for neat grout and various nitrate salt loadings (nitrate salt loadings are in weight percent).

Sample	Neat Grout (psi)	40% Nitrate Salt (psi)	50% Nitrate Salt (psi)	60% Nitrate Salt (psi)
0	276.10	171.44	183.74	243.76
a	294.79	220.27	188.38	178.66
b	303.94	222.25	185.26	202.39
c	323.91	227.91	181.59	172.86
d	295.57	231.33	186.34	164.74
Average	298.86	214.64	185.06	192.48
Standard deviation	15.49	21.96	2.30	28.54

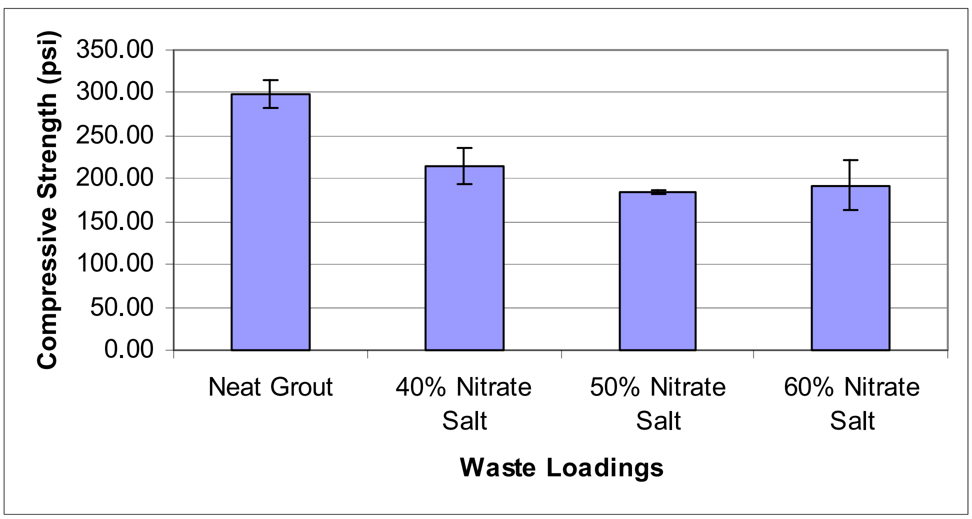

Figure 13. Compressive strength of WAXFIX and nitrate salt for neat grout and various nitrate salt loadings (nitrate salt loadings are in weight percent).

Calculations are being conducted to assess the influence of compressive strength on the potential for subsidence. The nitrate salt loading decreased the compressive strength by about 30% (see Figure 13). This decrease was relatively constant over the range of nitrate salt concentrations tested. The compressive strength values for all nitrate salt waste loadings were above the minimum 0.41 MPa (60 psi) required by the NRC Technical Position on Waste Form (NRC 1991) to provide adequate support to the overlying material.

3.2.1.1.4 WAXFIX/Thermally desorbed-Treated Organic Sludge Mixture—
The thermal desorption process was expected to make the waste and WAXFIX more compatible, thus increasing the maximum waste loading over that obtained for organic sludge. WAXFIX grout was mixed with TD-treated organic sludge at nitrate loadings of 30, 40, 50, and 60 wt%. Table 5 presents the compressive strength data for these tests. Figure 14 also graphically represents this data.

Table 5. Compressive strength of WAXFIX and thermally desorbed waste for neat grout and various thermally desorbed waste loadings (waste loadings are in weight percent).

Sample	Neat Grout (psi)	30% Waste (psi)	40% Waste (psi)	50% Waste (psi)	60% Waste (psi)
0	276.10	269.32	240.04	226.91	226.79
a	294.79	262.64	247.80	234.09	239.96
b	303.94	132.87	263.12	228.68	238.65
c	323.91	185.98	193.86	227.35	269.58
d	295.57	169.99	238.09	244.66	241.57
Average	298.86	204.16	236.58	232.34	243.31
Standard deviation	15.49	53.38	23.11	6.67	14.13

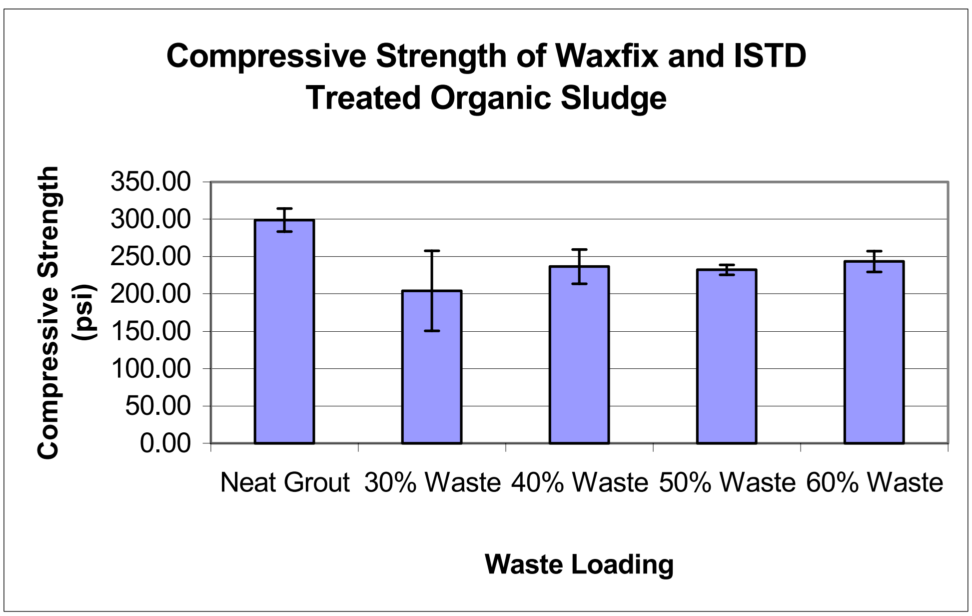

Figure 14. Compressive strength of WAXFIX and thermally desorbed waste for neat grout and various thermally desorbed waste loadings (waste loadings are in weight percent).

Loading the grout with TD-treated organic sludge decreased the compressive strength by about 20% for waste loadings between 40 and 60%. This decrease was relatively constant over this range and is significantly less than the 60 to 85% decrease in WAXFIX/waste compressive strengths observed for loadings with untreated organic sludge. Since the decrease in compressive strength is not large, it may not be sufficient to significantly reduce overburden support. The compressive strength values for all

TD-treated organic sludge loading were above the minimum 0.41 MPa (60 psi) required by the NRC Technical Position on Waste Form (NRC 1991).

3.2.1.2 WAXFIX Grout (Including Sodium Sulfide) and Acid Pit Soil Tests.

Dual purpose test specimens were prepared using SDA Acid Pit soils spiked with mercury and mixed with two forms of WAXFIX grout (Milian et al. 1997). The initial use of these specimens was for compressive strength testing. After the compressive strength tests were completed, the size of the specimens was reduced to meet requirements for toxicity characteristic leaching procedure (TCLP) tests.

For the compressive strength and leach testing, WAXFIX comprised a mixture of 100 g WAXFIX 125 and 12 g WAXFIX 12. Sodium sulfide was added to half of the grout to investigate its capability to stabilize mercury during leaching tests. The amount of sodium sulfide mixed in the WAXFIX was set at 2 wt% of the soil mass that was to be added. Contaminants in the soil from the Acid Pit included metals, radionuclides, organics, and nonmetal inorganics. The initial soil samples contained some mercury, but it was less than the average for Acid Pit soil. Therefore, additional mercury was added to the soil samples to reach an average concentration of 927 ppm.

About half of the grout was mixed with soil to obtain a ratio of 33 wt% WAXFIX grout and 67 wt% soil. The average density of the test mixture was 1.38 g/cm^3. Specimens were compression tested using ASTM D-695 (1996). Table 6 presents the results of these compression tests.

Table 6. Compressive strength results from WAXFIX/soil and soil with an additive.

Grout Mixture	Test ID	Load (lb)	Compressive Strength (psi)	Compressive Strength (MPa)
WAXFIX/soil[a]	1-1	260	130	0.9
	1-2	290	150	1.0
	1-3	300	150	1.1
	Average	280	140	1.0
	Standard deviation	17	9	0.1
WAXFIX/soil with sodium sulfide[b]	6-1	240	120	0.8
	6-2	320	160	1.1
	6-3	300	150	1.0
	Average	290	140	1.0
	Standard deviation	34	17	0.1

a. 33 wt% WAXFIX, 67 wt% soil

b. 33 wt% WAXFIX, 67 wt% soil with sodium sulfide

Results from Table 6 indicate that compressive strength is not affected by the addition of sodium sulfide to the WAXFIX grout. This leaves open an option to use WAXFIX and sodium sulfide mixtures if the results from the TCLP leach tests show that mercury leaching is reduced to acceptable levels. The compressive strength values for all Acid Pit soil sample waste loading were above the minimum 0.41 MPa (60 psi) required by the NRC Technical Position on Waste Form (NRC 1991).

3.2.1.3 WAXFIX Grout with Soil and Simulated Waste Tests.

Mixtures of WAXFIX grout, simulated waste, and soil formed specimens for a variety of grout performance tests (Milian et al. 1997). Before selecting mixture ratios for simulated waste and WAXFIX, compatibility and formulation of the individual components of the simulated waste, canola oil, sodium nitrate, and soil were studied. The canola oil, which was about 10 wt% of the simulated waste, was relatively immiscible with the wax. When a cylindrical specimen of WAXFIX and canola oil was prepared, some of the oil separated from the cylinder and some was encapsulated in a central cavity of the cylinder after it had cooled. Sodium nitrate was also difficult to mix homogeneously with WAXFIX; it tended to settle to the bottom of the samples before wax solidification. This same settling behavior was observed in the tests for ICP. Addition of soil to the WAXFIX resulted in a thickened mixture that could suspend the sodium nitrate.

Optimized mixtures of WAXFIX and soil were also tested. The maximum amount of soil mixed with the WAXFIX was 86.9 wt%. Tests at various soil loadings indicated an optimal mixture, in terms of good homogeneity and soil suspension in the grout, was between 65 to 70 wt% soil. Soil and grout mixtures with the soil above about 70 wt% resulted in a combination that was very difficult to pour while mixtures with the soil below about 65 wt% allowed settling of the soil causing inhomogeneous combinations. Based on these results, a standard formulation of 33 wt% WAXFIX and 67 wt% soil or simulated waste was used for all performance and durability test specimens. Table 7 summarizes the formulation for the grout and for the waste mixture. The grout/INEEL soil mixture average density was measured to be 1.36 ± 0.01 g/cm^3, and the grout/simulated waste average density was measured to be 1.45 ± 0.02 g/cm^3.

Table 7. WAXFIX grout and waste form formulation.

Component	Weight Percent
Grout	*33*
WAXFIX 125	89.3
WAXFIX 12	10.7
Waste Stream	*67*
INEEL soil	70
Sodium nitrate	20
Canola oil	10

Unconfined compressive strength tests were performed for WAXFIX and INEEL soil, and for WAXFIX and simulated waste mixtures. These tests were conducted in accordance with ASTM D-695M, “Compressive Strength of Rigid Plastics (Metric),” because the specimens may exhibit nonrigid, plastic characteristics, resulting in specimen failure without brittle fracture. The test (ASTM D-695M [1986]) was modified slightly to include compressive strength measurements at 10% deformation, or at the compressive yield point, whichever occurred first.

Results from the unconfined compressive strength tests are shown in Table 8. Five replicates were performed for both the soil and the simulated waste. All specimens failed before the 10% deformation, and all grout and INEEL soil specimens were higher than their grout and simulated waste counterparts. The results indicate that all measured compressive strength values were above the minimum 0.41 MPa (60 psi) required by NRC in the NRC Technical Position on Waste Form (NRC 1991) to provide adequate support to the overlying material.

Table 8. Results from unconfined compressive strength tests for WAXFIX and soil and waste mixtures.

Grout Mixture	Compressive Strength (psi)	Compressive Strength (MPa)
WAXFIX Soil[a]	263 ± 22.1	1.8 ± 0.2
WAXFIX Waste[b]	106 ± 3.7	0.73 ± 0.03

a. 33 wt% WAXFIX and 67 wt% soil

b. 33 wt% WAXFIX and 67 wt% simulated waste

3.2.1.4 Summary of WAXFIX Compressive Strength Tests. The WAXFIX and simulated waste compressive strength values reported in the literature are significantly less than those measured in the most recent ICP tests. These differences appear to be caused by a difference in the temperature of the specimens when they were tested. Compressive strength results presented in the literature are based on specimens that are assumed to be tested at room temperature (since the temperature is not generally specified). Specimens from the most recent ICP-sponsored tests were held at 9°C during testing, a much lower temperature. Limited testing with paraffin wax samples over a range of temperatures show compressive strength value differences of about the same size as those observed for the ICP and literature tests. Typical compressive strength test results for paraffin in the literature revealed a strong variation depending on the amount of oil in the paraffin. Paraffin with very low oil content (e.g., 1 wt%) had a compressive strength of about 1.15 MPa, and the value for paraffin with a higher oil content (e.g., 11.4 wt%) was about 0.85 MPa (Freund et al. 1982).

Based on both ICP and literature results, the compressive strength of WAXFIX is observed to be much lower than cement-based grouts. The highest WAXFIX compressive strength is about 4.62 MPa (670 psi) when loaded with soil or waste, and cement-based grouts have values in the range of 10.34 to 13.79 MPa (1,500 to 2,000 psi). However, the compressive strength values for all but one specimen tested (i.e., a specimen loaded with 30% organics) were above the minimum 0.41 MPa (60 psi) the NRC requires in their Technical Position on Waste Form (NRC 1991).

3.3 Hydraulic Conductivity

An important performance characteristic for grout as an immobilization agent is the rate at which water will penetrate the grout-waste mixture. Hydraulic conductivity is an indicator of the ability of the grout to encapsulate the mixture of soil and waste and prevent percolated water from moving through this mixture. Small hydraulic conductivity values indicate a high resistance to the penetration of water, a highly desirable characteristic because water could percolate from outside a waste containing area.

Results for the hydraulic conductivity of WAXFIX were obtained from two separate sources. Although there are differences between the two sources in the hydraulic conductivity values given, both are very low and the differences probably result from measurement techniques that are near their lower limit of measurement accuracy.

3.3.1 Idaho Completion Project-Sponsored Hydraulic Conductivity Tests

WAXFIX was tested for hydraulic conductivity of soil and waste loadings covering the range of conditions expected in the SDA. These tests were part of ICP preremedial design testing. WAXFIX grout hydraulic conductivity test results are presented for:

- No waste loading (i.e., neat grout)
- Grout and soil mixtures
- Grout and simulated organic sludge mixtures
- Grout and nitrate salt mixtures
- Grout and mixtures of TD organic sludge.

The objective of these tests (Yancey et al. 2003) is to establish a base hydraulic conductivity for WAXFIX grout with no waste loading and then determine whether the waste loadings will have an adverse effect on the hydraulic conductivity. The hydraulic conductivity tests were performed using the falling head method according to ASTM D-5084, “Standard Test Method for Measurement of Hydraulic Conductivity of Saturated Porous Material Using a Flexible Wall Permeameter” (ASTM 1990). Head measurements were taken over 12 days. The hydraulic conductivity results are accurate to about 10^{-8} cm/sec, based on the accuracy of the measurements taken during the test. Three replicate tests were performed for the neat grout and for each grout and waste mixture. Table 9 provides results from these tests.

Table 9. Hydraulic conductivity for combinations of WAXFIX and different types of wastes.

Grout/Waste Type	Waste Loading (Weight %)[a]	Hydraulic Conductivity (cm/sec)	Standard Deviation (cm/sec)
Neat grout	0	1.21 E-09	2.09 E-09
Grout and soil	70	6.43 E-08	2.99 E-08
Grout and organic sludge	10	Nondetect[b]	—
Grout and nitrate salt sludge	60	1.04 E-07	2.68 E-08
Grout and thermally desorbed organic sludge	60	1.18 E-08	2.05 E-08

a. The waste loadings for each waste type were selected based on the results of compressive strength testing and represent an expected maximum loading for that waste type in WAXFIX.

b. Below detection limit; no change in water level was observed during the test

3.3.2 WAXFIX Grout With Soil and Simulated Waste Tests

The hydraulic conductivity of WAXFIX with INEEL soil and WAXFIX with simulated waste (Milian et al. 1997) was measured using the constant head method according to ASTM Method D-5084 (1990) A pressure differential across the test specimen of 210 kPa (30 psi) was established from the end containing water to the end that was initially dry. The pressure difference was maintained for about 24 hours and the inflow and outflow of water was measured.

Hydraulic conductivity was tested for the mixture of WAXFIX with soil and for WAXFIX with simulated waste. The hydraulic conductivity measurement limits for these tests were 2.0×10^{-11} cm/sec. Results from the tests indicated the hydraulic conductivity was less than the measurement limit. Consequently, the hydraulic conductivity was reported as less than 2.0×10^{-11} cm/sec for both WAXFIX with soil and WAXFIX with simulated waste. Each waste type was tested only once because of the proximity of the results to the lower measurement limit.

The hydraulic conductivity value reported by Milian et al. (1997) is about three orders of magnitude less than some cement-based grouts and the ICP results are about one order of magnitude less. The higher hydraulic conductivity values from the ICP tests (roughly two orders of magnitude) are attributed to differences in the reported measurement accuracy (10^{-11} for tests from Milian et al versus 10^{-8} for the ICP tests) and possibly to differences in the method of measuring hydraulic conductivity (the constant head method versus the falling head method). Both the Milian and the ICP hydraulic conductivity results are substantially less than the hydraulic conductivity of SDA soils, which is reported to range from 6.94×10^{-4} to 1.1×10^{-8} cm/s, with an arithmetic mean hydraulic conductivity of 1.52×10^{-4} cm/s (McCarthy and McElroy 1995).

3.4 Chemical Stability

Understanding the overall chemical stability of WAXFIX is important to the potential applications of structural support and immobilization of contaminants. A number of different types of chemicals are buried in the SDA (Holdren et al. 2002). It is desirable for WAXFIX to have low reaction rates with strong bases and acids and chemicals that can cause rapid oxidation. Leach rates with a variety of contaminants must also be understood to ensure the grout is effective in minimizing the spread of contaminants and in meeting regulations.

3.4.1 Potential for Rapid Reaction with Nitrates

Strong oxidizers have the potential to react rapidly with organic wax materials. This section discusses two different types of tests that assessed reaction rates of sodium nitrate with WAXFIX and paraffin wax: thermal analysis and the Department of Transportation (DOT) oxidizer test. Results of these tests are important because some of the areas to be grouted may contain nitrate salts.

3.4.1.1 Thermal Analysis: Differential Scanning Calorimetry. Tests of combinations of WAXFIX with sodium nitrate used differential scanning calorimetry to assess the extent of the chemical interactions and characterize the thermal stability of these chemicals (Milian et al. 1997). With heat flux differential scanning calorimetry, the WAXFIX and sodium nitrate were heated slowly in a furnace with a uniform temperature distribution. The temperatures of the two materials were monitored. Measurement sensitivity was very high because temperature fluctuations in the furnace and changes in convection were small. Therefore, any temperature difference is proportional to the heat absorbed or generated by the sample. All tests were conducted in accordance with ASTM Method E-537, “Assessing the Thermal Stability of Chemicals by Methods of Differential Thermal Analysis,” (Milian et al. 1997). Tests were conducted with a mixture of grout (i.e., 10.7 wt% WAXFIX 25 and 89.3 wt% WAXFIX 125) and sodium nitrate at WAXFIX-to-sodium nitrate ratios of 25:75, 50:50, and 75:25 (by weight).

The test results indicated that WAXFIX 12 had only minor endothermic reactions with sodium nitrate up to 350°C (since heat is being added, large endothermic reactions could indicate rapid reaction rates between WAXFIX and sodium nitrate). WAXFIX 125, basically a paraffin wax, showed two endothermic reactions. There was a small peak at about 38°C, which is typical of a change in crystalline structure in paraffin, and a larger peak at about 58°C. The larger peak is presumed to be the melting point of the wax, and falls within the typical melting point range of paraffin wax (47 to 65°C). The WAXFIX thermogram showed no other reactions occurring after about 58°C. A large endothermic peak was observed at about 300°C, the melting point of sodium nitrate. The large and smaller peaks in the thermograms for all mixture ratios were reviewed and the conclusion was reached that no major extraneous reactions appear to be occurring between the WAXFIX grout and the sodium nitrate up to a temperature of 350°C.

3.4.1.2 Department of Transportation Oxidizer Test. Since the potential for a rapid reaction is present if nitrates are involved in an accidental fire during storage or shipping, the objective of these tests was determining whether sodium nitrate encapsulated in paraffin would be classified as a DOT oxidizer. The tests were "designed to measure the potential for a solid substance to increase the burning intensity of a combustible substance when the two are thoroughly mixed" (Milian et al. 1997).

The recommended test procedure for quantifying hazards associated with solid oxidizing materials is identified in 49 CFR 173, "Shippers–General Requirements for Shipments and Packaging." The definition of an oxidizer is found in 49 CFR 173.127, "Class 5, Division 5.1—Definition and assignment of packing groups." The procedure is found in Appendix F of 49 CFR 173.127. Test materials were prepared in the following compositions:

- Refined paraffin wax cut and sieved to a particle size less than 2 mm and mixed with sodium nitrate in a mass ratio of 1 to 1
- Sodium nitrate salt encapsulated in refined paraffin wax in a 1 to 1 mass ratio
- Sodium nitrate salt encapsulated in refined paraffin wax in a 1 to 1 mass ratio, but cut to a sieve mesh size less than 9.5 mm following solidification
- 100% sodium nitrate salt.

A combustible material, wood sawdust, was added to each test material in mass ratios of 1 to 1 and 4 to 1. All tests were conducted according to the previously-indicated DOT test procedures.

Results in Table 10 indicate the nitrate salt encapsulated in paraffin wax, either as one large piece or sieved to less than 9.5 mm, burned significantly slower and less violently than the sodium nitrate without wax. Similarly, the nitrate salt mixed with chopped paraffin wax resulted in much slower burn times. Based on these results, sodium nitrate solidified in solid paraffin wax or mixed with paraffin wax is not classified as an oxidizer based on the recommended DOT tests.

Table 10. Results from the Department of Transportation oxidizer tests.

Combustion Time for Test Materials		
	1 to 1 Mass Ratio Test Mixture	4 to 1 Mass Ratio Test Mixture
Material Composition (weight %)	Burn Time (seconds)	Burn Time (seconds)
50% Chopped wax (less than 2 mm)/50% $NaNO_3$	161[a]	188[a]
Encapsulation: 50% Wax/50% $NaNO_3$	131[a]	819[a]
Encapsulation: 50% Wax/50% $NaNO_3$ and sieve to less than 9.5 mm	628[b]	525[b]
100% $NaNO_3$	37[b]	25[b]

a. Mean of two replicates
b. Based on one replicate

3.4.2 Chemical Stability: Resistance to Chemical Attack

Understanding the resistance of WAXFIX to attack by different types of chemicals is important because there is a wide range of chemical waste materials in the SDA. Chemical resistance tests used mixtures of both WAXFIX grout and INEEL soil and WAXFIX grout and simulated waste (Milian et al. 1997). A standard formulation of 33 wt% WAXFIX and 67 wt% soil or simulated waste was used for all test specimens. Table 7, initially discussed in Section 3.2.1.3, summarizes the formulation for the grout and for the waste mixture. Chemical resistance tests using these mixtures include the base resistance tests, solvent resistance tests, and accelerated leach tests (with lead and chromium added).

Results from leach testing of paraffin-containing concentrations of boric acid and simulated contaminants are also presented. These test results are from the Korean radioactive waste program as part of their studies of disposing of nuclear reactor waste. The test results provide insight on leaching mechanisms that may apply to leaching of salts in the SDA.

3.4.2.1 Base Resistance. Base resistance tests of WAXFIX and simulated waste specimens (with the composition shown in Table 7) were conducted by immersing them for 90 days in 3 L of aqueous, sodium hydroxide solution with a pH of 12.5. The pH value was selected based on the Environmental Protection Agency's (EPA's) characteristic corrosive for hazardous waste. Specimens were removed at 30-day intervals and subjected to compressive strength testing using ASTM D-695M (1985).

Visual inspection revealed that after 30 days of immersion, the surface was discolored and there were many surface deformations resulting from material precipitation. Deformations ranged in diameter from fractions of a millimeter to 5 mm. At each stage of the full immersion period, there were several other indications the WAXFIX and waste specimens were deteriorating. The volume of the specimens increased by up to 3% and the mass decreased by about 2%. The sodium hydroxide solution (pH 12.5) needed to be replaced three times over the test period due to declining pH levels, suggesting reactions that decrease some acidic components in the specimen. The base solution was a murky amber color at test completion, resulting from dissolution/leaching losses.

The specimens maintained their physical integrity (i.e., form) over the full test period, but the compressive strength after 30 days had decreased by about 47% (see Table 11 in the following section). At 60 days, the compressive strength decrease was measured to be 52% and the 90-day decrease was 51%. These results indicate the majority of the strength decrease takes place in the initial 30 days and there is little additional decrease up to 90 days. The strong base solution resulted in compressive strength values that were less than required by causes the compressive strength to be reduced below the minimum in the NRC Technical Position on Waste Form (NRC 1991). Although the decrease in compressive strength is significant, it is highly unlikely the SDA will contain liquids with a pH value this high. There may be some instances where cement or other materials with a high pH come in contact with WAXFIX, but it is doubtful that degradation would be as rapid or would affect areas large enough to cause widespread reduction of compressive strength.

3.4.2.2 Solvent Resistance. Specimens of WAXFIX and simulated waste (with the composition shown in Table 7) were immersed in deionized water saturated with TCE at room temperature for 30, 60, and 90 days. TCE was chosen as the media for volatile organic compound solvent testing because it is a dominant contaminant found at many Department of Energy sites. The WAXFIX and simulated waste specimens were immersed in the same container as a cement-based grout for these tests. Inspections and compressive strength tests used ASTM D-695M (1985) at each sampling interval.

Over the 90-day solvent immersion period, the WAXFIX/simulated waste samples lost weight and increased in volume. After 90 days, specimen degradation was indicated by a mass loss of 1.2% and a volume increase (swelling) of 4%. Compressive strength results are shown in Table 11. After 30 days, compressive strength decreased about 42%. At 60 and 90 days, the compressive strength had decreased by about 52 and 55%, respectively. Given that carbon tetrachloride and trichloroethylene have Hildebrand solubility parameters that are close (18.0 and 18.7 δ(SI) respectively (solar2) or 8.6 and 9.2 $\delta(\text{cal-cm}^{-3})^{0.5}$ (CRC 1980) respectively), paraffin submerged in carbon tetrachloride is expected to result in approximately the same amount of swelling (and compressive strength decrease) as observed with TCE. However, the Rocky Flats organic sludge containing TCE, carbon tetrachloride, trichloroethane, and perchloroethelene comprise only a small portion of the total waste in the SDA, indicating any degradation within a waste/grout monolith formed by WAXFIX would be localized.

Table 11. Compressive strength results from base resistance and solvent resistance testing.

	Compressive Strength, MPa (psi)[a] [Baseline Compressive Strength = 0.73 MPa (105.9 psi)]		
Tests	30 Days	60 Days	90 Days
Base Resistance	0.39 ± 0.03 (56.6 ± 4.3)	0.35 ± 0.06 (50.8 ± 8.7)	0.36 ± 0.07 (52.2 ± 10.2)
Solvent Resistance	0.42 ± 0.05 (60.9 ± 7.2)	0.35 ± 0.05[c] (50.8 ± 7.2)	0.33 ± 0.05[b] (47.9 ± 7.2)

a. Results based on 5 replicates and 2 sigma errors.
b. Results based on 4 replicates and 2 sigma errors
c. Data taken from Heiser and Milian (1994)

3.4.2.3 Leach Resistance. If water percolates through the waste, leaching of contaminants from the grout and waste matrix could transport contaminants outside the boundary of the waste field. Leach tests have been designed to evaluate the capability of grout to immobilize the contaminants. Several studies on various aspects of leaching for various contaminants with WAXFIX and paraffin materials were identified in the literature. A brief description of these studies on accelerated leach testing, testing using the standard TCLP, and paraffin grout leach testing of highly concentrated waste is included in the following sections. Additional leach testing of WAXFIX is planned (Yancey et al. 2003), but the results are not yet available and therefore not included in this document.

3.4.2.3.1 Accelerated Leach—Accelerated leach tests (Milian et al. 1997) of WAXFIX were conducted in accordance with ASTM C-1308, "Accelerated Leach Test for Diffusive Releases from Solidified Waste and Computer Program to Model Diffusive, Fractional Leaching from Cylindrical Waste Forms." Leaching was accelerated by testing with the leaching solutions at temperatures higher than they would be in the field (i.e., at room temperature, which is about 7°C higher than expected temperatures in the lower portions of the SDA). A higher temperature was not advisable because of the relatively low melting temperature of WAXFIX.

Accelerated leach test specimens were prepared with contaminant-spiked soil. Lead (II) nitrate [$Pb(NO_3)_2$] and chromium (III) nitrate [$Cr(NO_3) \bullet 9H_2O$] were added to distilled water and blended with INEEL soil. After drying and grinding, this spiked soil was used in the simulated waste. Table 7, initially discussed in Section 3.2.1.3, provides the weight percentages of the spiked soil in the simulated waste mixture and for formulation of the grout. A standard formulation of 33 wt% WAXFIX and 67 wt% simulated waste was used for all test specimens. Based on calculations, sufficient lead and chromium were added to the soil to produce a final concentration of 1,000 ppm for each of these metals in the simulated waste.

A pretest determined that a representative WAXFIX and simulated grout specimen using 300 mL of leachate was appropriate for the tests. Thirteen leachate changes were made over an 11-day period, two the first day and then one each day for the remainder of the test. About 125 mL of sample was collected for analysis at the end of each time interval. Leachates were analyzed using inductively coupled plasma spectroscopy for both lead and chromium metal concentrations. After the 11-day accelerated test, no leaching was detected for either chromium or lead (i.e., both were below the instrument detection limits: chromium less than 0.04 μg/mL; lead less than 0.14 μg/mL). These results indicate that WAXFIX is effective in preventing leaching of chromium and lead for the conditions tested.

3.4.2.3.2 Toxicity Characteristic Leaching Procedure**—**TCLP was used for testing a mixture of WAXFIX and soil, and a mixture of WAXFIX and soil plus an additive (Heiser and Fuhrmann 1997). These tests used samples prepared from the remnants of monoliths from the compressive strength tests of Acid Pit soil. Acid Pit soil was selected for the TCLP test contaminant carrier because it was considered to be typical of INEEL soils that may be grouted. Mercury was chosen as the contaminant for the TCLP testing. Typical Acid Pit soil samples selected for testing were assayed and found to have relatively low mercury concentrations. To bring the mercury content of these soil samples up to a level known to exist in some INEEL soils, mercury chloride ($HgCl_2$) was added to distilled water, which was then mixed with the soil. After mixing and air-drying to remove the excess water initially mixed with the $HgCl_2$, the average mercury concentration was 927 ppm, based on three small samples with measured concentrations of 878 ppm, 1,004 ppm, and 898 ppm.

To examine methods for minimizing mercury leaching from the soil, additional tests were conducted on grout mixed with an additive that would retard mercury migration. Nine potential additives were initially tested for their capability to retain mercury. Three were selected for additional testing and TCLP leach tests were performed on small soil samples with 1 wt% of each of the selected additives. Sodium sulfide ($Na_2S \bullet 9H_2O$) proved most effective in retaining mercury and was selected as the additive for the grout.

The specimens for TCLP testing were taken from the remains of the monoliths prepared for the compressive strength tests of Acid Pit soil. The WAXFIX comprised a mixture of 100 g WAXFIX 125 and 12 g WAXFIX 12. This WAXFIX mixture had a measured density of 0.88 g/cm^3. For half the samples prepared, 2 wt% (based on the soil weight) of sodium sulfide was mixed with the WAXFIX. The WAXFIX was blended with the mercury-spiked soil at a ratio of 33 wt% WAXFIX and 67 wt% soil.

The size of the test specimens used in the compressive strength tests was reduced so that all pieces were smaller than the required 1 cm at their narrowest dimension. A series of sieves were used to size the particles for the required 100 g TCLP testing sample. For the WAXFIX testing, all particles were less than 9.5 cm and greater than 4.5 cm. The procedures used for TCLP analyses for mercury were EPA SW846 Method 1311, "Toxicity Characteristic Leaching Procedure" (EPA 1992) and EPA SW846 Method 7470, "Mercury In Liquid Waste (Manual Cold-Vapor Technique" (EPA 1994). These procedures were used for tests of WAXFIX and soil and WAXFIX plus sodium sulfide/soil samples.

The TCLP leach test results show that the WAXFIX and soil samples did not pass the TCLP leach testing (see Table 12). The concentration of mercury in the leachate was significantly higher than the current mercury TCLP limits. For the WAXFIX and soil plus sodium sulfide mixture, the concentration of leached mercury was about half the current TCLP limit of 25 ppb. For chunks of a mixture grout with contaminants, these results indicate that WAXFIX alone is not effective to prevent leaching of mercury. Adding a material with a high affinity for mercury, such as sodium sulfide, to the grout is effective in reducing the amount of mercury leached to levels that are below the TCLP limit.

Table 12. Toxicity characteristic leaching procedure leachate concentrations for WAXFIX and WAXFIX with a mercury-retaining additive.

Sample	Grout	TCLP Hg Limit (ppb)	Leachate Hg Concentration (ppb)
1-1	WAXFIX	25	630
1-2	WAXFIX	25	630
6-1	WAXFIX + sodium sulfide	25	11.6
6-2	WAXFIX + sodium sulfide	25	14.6

***3.4.2.3.3 Paraffin Grout Leach Tests for Highly Concentrated Waste*—**Tests performed in Korea with paraffin and high waste loadings could provide an enhanced understanding of the leach mechanisms that may be applicable for certain waste types formed during grouting in the SDA (Kim, Kim, and Chung 2001; Kim, Kim, and Chung 2002).

Low-level liquid borate wastes (e.g., boric acid, waste material, and radionuclides) are produced during operation of Korean nuclear power plants. A concentrate waste drying system was developed that concentrated the waste through evaporation. Following concentration, this system mixed the remaining waste material with paraffin wax with the goal of stabilizing the waste and immobilizing the radionuclides. The resulting waste forms were intended for long-term storage in a waste repository. Although these wastes are not considered to be typical of SDA grouted wastes, results from these tests may provide insight into leaching mechanisms when WAXFIX is used with materials that are difficult to encapsulate and are highly soluble.

A series of scoping tests optimized the loadings (i.e., proportions of waste to paraffin) that would produce a stable and acceptable waste form. The results of the scoping tests indicate that a mixing ratio of 78 wt% boric acid and 22 wt% paraffin produced a waste form that was stable (Kim et al. 2000). The results indicated that a mixture with a borate acid loading of greater than 85 wt% produced a waste that was too thick to flow and efficiently produce the waste forms; a borate acid loading of less than 75 wt% resulted in stratification of the waste within the paraffin waste form. A ratio of 78:22 borate concentrate to paraffin was selected for further testing, including TCLP leach tests.

Leach test samples were prepared with a 78:22 mixture ratio, using boric acid to simulate the concentrated reactor waste. Contaminants similar to those expected in the waste were added to the boric acid in the form of cobalt (II) chloride hexahydrate ($CoCl_2 \bullet 6H_2O$), strontium chloride hexahydrate ($SrCl_2 \bullet 6H_2O$), and cesium chloride (CsCl) (Kim et al. 2000). The American National Standards Institute/American Nuclear Society (ANSI/ANS 16.1 1986) leaching standard procedure was used to evaluate the leaching behavior of these waste forms. This procedure uses demineralized water as the leachant and is conducted at a temperature of 22.5 ± 5°C. The leachant was sampled and replaced at 2-, 7-, and 24-hour intervals from test initiation, then at 24-hour intervals for 4 days, and finally at intervals of 14, 28, and 43 days to extend the entire testing period to 90 days. The concentrations of cobalt, strontium, and cesium in the leachate were measured using inductively coupled plasma-mass spectroscopy. The concentration of boric acid in the leachate was measured by titration.

Results from the leach tests reveal that the cumulative fraction leached (CFL) for boric acid, cobalt, strontium, and cesium in the first 4 days was about 15 to 17%. Over the entire 90 days, the CFL was about 66% for boric acid, 70% for cobalt, 69% for strontium, and 67% for cesium. The results taken at each time interval of the test consistently show that the CFL for the spiked contaminants—cobalt, strontium, and cesium—were only slightly higher than the boric acid, even though the solubilities of these simulants were 7 to 14 times higher than that of boric acid. The boric acid, which forms a large portion of the waste form, appears to be easily dissolved from the waste form surface, and the leaching behavior of the contaminants is strongly influenced by the dissolution rate of the boric acid.

The cylindrical leach test specimens were sectioned and a uniform region of leaching (i.e., a reacted layer of equal thickness) was obvious over all surfaces (top, bottom, and sides). The fractional volume of the reacted layer corresponded directly with the CFL for the boric acid (66%). The dissolution kinetics of the paraffin waste form appear to be most strongly influenced by diffusion because the CFL values have a linear relationship to the square root of time. These observations indicate the dissolution reaction begins at the surface, and a dissolution front moves uniformly inward, leaving a reacted paraffin layer behind. Leaching rates for boric acid and the contaminants are reduced as the dissolution progresses and the reacted layer depth increases. A shrinking core model was developed based on diffusion-controlled dissolution kinetics, and the analytical results were in reasonable agreement with the test results.

Compressive strength tests were performed for both unleached and leached test specimens. These tests were conducted according to ASTM C39, "Compressive Strength of Cylindrical Concrete Specimens." The specimens that were not leached had an average compressive strength of 4.49 MPa (666 psi). The compressive strength of the leached specimens was reduced to 1.6 MPa (232 psi). Leaching of boric acid and contaminants from the paraffin-waste mixture significantly reduced the structural integrity of the cylindrical test monolith.

Although acid concentrations in the SDA will not be high enough for these results to apply directly, insights on the kinetics of diffusion could have application. For example, leach rates for nitrate salts in WAXFIX may be affected by similar diffusion behavior where the salt crystals are in contact with each other and leaching may occur in small pathways through a honeycombed wax shell. Leach tests that are currently being conducted using typical INEEL soils and contaminants will provide important insights on expected leach behavior in the SDA and can be compared to the Korean leaching mechanisms.

3.5 Biodegradability

Biodegradability is important to the potential grout applications of immobilization and structural support. No data were found specifically for the biodegradability of WAXFIX, so data for paraffin, the principal ingredient of WAXFIX, were used.

While microbial degradation of hydrocarbons has been studied the past 80 years, recently, many studies have examined the biodegradation of hydrocarbons in soil and aqueous environments. Some of this work was driven by interest in the effect of oil spills on the environment and in developing methods to remediate oil spills. Another major area of interest is the maintenance of oil wells. Longer chain paraffins contained in crude oil often deposit on pipe walls and the equipment within well bores, compromising the production of the well. Biodegradation of paraffin is being explored as an option for removing material from the well. No specific studies were found of the biodegradation of chunks or blocks of paraffin in arid or humid soils, as would be more representative of paraffin in a waste stabilization application at the SDA.

Hydrocarbons biodegrade in the environment through bacteria, fungi, molds, and yeasts; however, the first two classes of organisms account for most of the degradation (Ponsford 1966). Most microorganisms that metabolize paraffin are aerobic (some are anaerobic) (Ponsford 1966; Leahy and Colwell 1990; Bishop and Woodward 1990). Biodegradation has been demonstrated in a variety of environments including soil, aquatic systems, leaf litter, and well bores (Ponsford 1966; Leahy and Colwell 1990; Kuyukina et al. 2003; Davie, Winter, and Varoney 1995; Bishop and Woodward 1990; Blenkinsopp et al. 1992; Rosenberg 1991; American Petroleum Institute 2004). Microorganisms that degrade hydrocarbons have been shown to account for 6 to 82% of all soil fungi and 0.13 to 50% of soil bacteria (Leahy and Colwell 1990). At least 22 genera of bacteria and 31 genera of fungi are capable of hydrocarbon degradation in soil (Leahy and Colwell 1990).

Table 13 is a partial list of genera for a wide range of bacteria, filamentous fungi, and yeasts that can metabolize most aliphatic hydrocarbons, including the solid paraffin waxes (Watkinson and Morgan 1990). The solid nature of wax and its low solubility in water should make it difficult for microorganisms to attack. However, the microorganisms have developed a variety of adaptations that allow them to use hydrocarbons in gas (except for methane, which does not biodegrade), liquid, and solid substrates. Generally, the shorter chain compounds (i.e., less than C_{10}) are microbially degraded first; then the longer chain (i.e., greater than C_{10}) compounds are attacked (Soriano and Pereira 2002). Oxidizers of lower molecular weight (i.e., C_{10} to C_{12}) paraffins generally grow more rapidly than those for higher molecular weight paraffins (Rosenberg 1991).

Table 13. Partial list of genera that can metabolize most aliphatic hydrocarbons.

Bacteria	Yeasts	Filamentous Fungi
Acetobacter	Candida	Aspergillus
Acinetobacter	Cryptococcus	Cladosporium
Actinomyces	Debaryomyces	Corollaspora
Alcaligenes	Hansenula	Dendryphiella
Bacillus	Pichia	Gliocladium
Beneckea	Rhodotorula	Lulworthia
Corynebacterium	Sporobolomyces	Penicillium
Flavobacterium	Torulopsis	Varicospora
Mycobacterium	Trichosporon	
Nocardia		
Pseudomonas		
Rhodococcus		
Xanthomonas		

Most of the bacteria and fungi that degrade hydrocarbons prefer a near neutral pH (Leahy and Colwell 1990); however, biodegradation has been observed in well bores with a pH of 4 to 9 (Ferguson et al. 1996). The optimum temperature is 20 to 40°C, although degradation has been observed in temperatures ranging from –2 to 132°C (Ferguson et al. 1996; Leahy and Colwell 1990; Brown 1987). Soil water contents of 30 to 90% saturation support degradation of oil sludge (Leahy and Colwell 1990).

Many microorganisms can use hydrocarbons as a sole source of carbon (Ponsford 1966). To degrade, sufficient quantities of hydrocarbons, oxygen, nitrogen, phosphorous, sulfur, metals, and trace compounds must also be available (Leahy and Colwell 1990; Brown 1987; Rosenberg 1991). About 150 mg of nitrogen and 30 mg of phosphorous are required for the conversion of 1 g of hydrocarbon into cell material (Rosenberg 1991). Oxygen has been identified as the rate-limiting step for biological degradation of hydrocarbons in soil (Leahy and Colwell 1990). Surface area for cell attachment or emulsification of hydrocarbon is also an important determiner of the rate of hydrocarbon degradation (Leahy and Colwell 1990). Microbial degradation is facilitated by high surface-to-volume ratios (Ponsford 1966; Leahy and Colwell 1990; Brown 1987). For longer alkanes (greater than or equal to C_{12}) with low solubilities (less than 0.01 mg/liter), the rate of degradation is faster than the rate of dissolution (Leahy and Colwell 1990).

Generally, hydrocarbon biodegradation occurs very slowly under anaerobic conditions (Leahy and Colwell 1990; Blenkinsopp et al. 1992). Microorganisms require nitrate as an electron donor when grown on hydrocarbons under anaerobic conditions (Rosenberg 1991). The ecological significance of this pathway is thought to be small; however, more work needs to be performed in this area to understand the pathways involved in anaerobic degradation (Leahy and Colwell 1990). Well bore environments are generally anaerobic (Blenkinsopp et al. 1992). Bacteria have been observed reducing the amount of solidified paraffin present in well bores (Ferguson et al. 1996; Bishop and Woodward 1990). There is some discussion as to whether the removal of paraffin is because of degradation of paraffin or emulsification of paraffin (Ferguson et al. 1996; Bishop and Woodward 1990; Blenkinsopp et al. 1992). Hydrocarbon-degrading bacteria are known to produce biosurfactants when using hydrocarbons as a carbon source; this is one of the mechanisms by which the cells can increase the available surface area of the hydrocarbon.

It is clear that paraffin can be biodegraded by several organisms under the proper conditions. Moisture, neutral pH, relatively warm temperatures (i.e., 20 to 40°C), the presence of oxygen, nitrogen, and phosphorous, and high surface-to-volume ratios favor the biodegradation of paraffin. At the SDA, some of these conditions could be met in the waste seam where the paraffin would be placed. The waste is located about 1 m below the surface (it will be 1–3 m deeper once the cap is installed) and forms a layer 1–5 m thick. The temperature in the soil at 2 m below the surface fluctuates between 4 and 15°C over a year; at 6 m below the surface, the temperature fluctuates between 8 and 10°C over a year (Pittman 1989). The water in the soil near the surface generally varies with the season, but remains within a narrower range from about 2.5 to 6 m. Near the surface, the water volume varies from about 12 to 34%, and at lower levels varies from 18 to 24 vol% (the range of one measurement location was from 26 to 32 vol%). This level of moisture at all elevations is sufficient to support growth of paraffin-degrading microorganisms.

The rate of biodegradation of a paraffin monolith was calculated using rate data from the American Petroleum Institute's Robust Summary (American Petroleum Institute 2004). This calculation, described in Appendix C, provides an order of magnitude bounding estimate on the rate of biodegradation of paraffin. The biodegradation rates used come from well-mixed, aqueous, shake-flask experiments using mineral media at 20°C and a microbial inoculum from a land farming facility for oil contaminated soil. Data was also available for similar experiments using a microbial inoculum from domestic activated sludge. The size of the monoliths used in the estimate are based on the projected minimum monoliths for grouting the beryllium blocks in the soil vaults and trenches in the SDA (EDF-4397). These monoliths would also be representative if WAXFIX columns were used to support a cap, and would degrade faster than the large body of wax needed to grout a large area of waste. The following assumptions were used in the estimation of the rate of paraffin biodegradation in the SDA:

- Surface area of the monolith remains constant with time

- Monolith is 100% paraffin
- Biodegradation rate of paraffin is not limited by the availability of oxygen or other nutrients
- Other compounds present in WAXFIX do not affect the rate of biodegradation of paraffin
- Metabolism products from biodegradation do not affect the rate of biodegradation
- No other conditions or process in the subsurface affect the rate of biodegradation.

Calculated results using the data from the land farming facility were chosen because they were believed to be more representative of the conditions at the SDA. These results estimate an area-based biodegradation rate that ranges from 0.0818 to 0.285 kg/m^2/year. Two monoliths sizes were considered based on the location of the beryllium block:

- cylindrical monolith
  - 2.5 m in diameter
  - 5 m in height
  - initial surface area of 49.09 m^2
  - initial mass of 21,599 kg
  - thickness of outer layer is 0.46 m (18 in.)
- block monolith
  - 2 m in width and 3m in length
  - 5 m in height
  - initial surface area of 62 m^2
  - initial mass of 26,400 kg
  - thickness of outer layer is 0.46 m (18 in.)

For the cylindrical monolith, the calculated rate of mass loss is 4 to 14 kg per year. At this rate it will take 1,500 to 5,400 years for microorganisms to consume the monolith. For the block monolith, the calculated rate of mass loss is 5 to 18 kg per year; microorganisms will take 1,500 to 5,200 years to consume the monolith. The outer 0.46 m (18 in.) layer of each monolith, which represents the minimum expected distance to the beryllium block, was calculated to require 1,000 to 3,600 years to be consumed.

The pH of the soils at the SDA is slightly alkaline, generally a pH of about 8 (Mincher et al. 2003), and is within the range of conditions for growth of paraffin-degrading microorganisms. The temperature of the soil varies with the season and with depth. The temperature of the soil surrounding the waste will generally range from 7 to 15°C, which is below the optimum temperature for paraffin degradation, but within the range of viability for use of paraffin by the microorganisms. This suggests the degradation rate of paraffin in the SDA would be slower than that observed in the calculations and articles referenced above. The soil gases measured at the SDA generally indicate aerobic conditions (Rightmire and Lewis 1987) and would support paraffin degradation; however, the rate of degradation might be limited by the rate of oxygen diffusion to the surface of the paraffin. The soils at the SDA are generally low in nitrogen (0.01 wt% [Mincher et al. 2004]) and phosphate (0.01 to 0.16 wt% [Mincher et al. 2004; Dechert, McDaniel, and Falen 1994]), two elements required for growth of paraffin-degrading microorganisms. The nitrate salt sludge waste deposited at the SDA is a potential source of nitrogen, but it represents a very small portion of the total volume of the SDA wastes. In the waste seam, the paraffin would form a monolith and would have a low surface-to-volume ratio. During the grouting process, some soil would be intimately mixed with the paraffin, but this would effectively isolate the soil from other compounds required for degradation.

Overall, degradation of paraffin by microorganisms in the SDA is possible and even likely, but the rate of degradation will be slower than the referenced studies, which were under well-mixed, high surface area-to-volume ratio, and well-oxygenated conditions (Soriano and Pereira 2002; Brown 1987; Kuyukina et al. 2003; Davie, Winter, and Varoney 1995; Blenkinsopp et al. 1992; American Petroleum Institute 2002; Marino 1998). As mentioned before, paraffin is the primary but not the only ingredient of WAXFIX (United States Patent). The composition of the proprietary additives in WAXFIX is not known and these additives could influence (reduce or enhance) the biodegradability of WAXFIX in the SDA. Identifying the chemical composition of the proprietary additives in WAXFIX would establish their potential for affecting the biodegradability of paraffin. The mixing of WAXFIX with SDA wastes including soil, nitrate salts, and organic compounds could also affect the biodegradation rate.

One way to address the uncertainties associated with extrapolating previous biodegradation test results for paraffin, is to conduct laboratory tests of paraffin and WAXFIX in soil from the SDA under conditions appropriate to the SDA. Experiments using blocks of WAXFIX/paraffin, alone and mixed with soil/waste, buried in soil and monitored for 6 months to 3 years would provide some useful data on the biodegradation of paraffin/WAXFIX under conditions more similar to the SDA than those currently available in the literature. (Note: This recommendation may not be compatible with the timeframe for use of WAXFIX and may need to be considered as input after the fact to assess future lifetime.) However, the initial order of magnitude estimate of the rate of biodegradation, using a rate from conditions more favorable than those at the SDA, indicates that a paraffin monolith would last more than 1,000 years.

3.6 Radiation Susceptibility

Hydrocarbon chemical reactions caused by high-energy radiation are generally complex. When paraffin is irradiated, the radiation imparts energy to molecules in the straight hydrocarbon chain. This increase in energy can cause the chain to be cleaved, generally leaving a relatively short chain molecule and a long chain molecule. Some of these chains can then react (crosslink) with unbroken molecules to form branched chains. The resulting reaction mixture produced during irradiation contains a broad range of gaseous, liquid, and solid products with molecular weights that are both lower and higher than the original hydrocarbon (Chapiro 1962; Mahmood and Mousa 1972). Each of the intermediate reaction products may react with the radiation in slightly different ways, depending on the phase and structure of the molecule. Experimental results have provided some general rules for the effects of radiation on hydrocarbons, including paraffins. First, hydrogen is always present in the gas phase with lower molecular weight hydrocarbons, such as methane. Second, heavier reaction products, the so-called “polymers” (i.e., many with crosslinking between hydrocarbon chains), accumulate in the liquid phase. And third, free carbon has never been observed in these processes (Chapiro 1962).

Following is a brief discussion of possible radiation exposure rates for WAXFIX grout and a review of the possible effects of radiation on the structure of paraffin wax and on the radiation-induced hydrogen generation. No specific information of irradiation tests using WAXFIX was found.

3.6.1 Potential Radiation Exposure of WAXFIX Grout

If selected for use, WAXFIX grout will be exposed to various levels of radiation as it comes in contact with the different types of radioactive waste buried in the SDA. WAXFIX was initially a candidate for grouting relatively large areas of the SDA where the average concentration of radionuclides is not high, but where localized concentrations of waste may have relatively high radioactive content. WAXFIX is currently the choice for grouting irradiated beryllium components that are buried in soil vaults and trenches at the SDA. Determining the WAXFIX radiation dose will be key in evaluating the potential for significant radiation damage to its crystalline structure and estimating the amount of hydrogen gas that will be generated. This section develops a worst-case estimate of the radiation dose that can be used to provide a rough order of magnitude estimate of radiation damage and hydrogen generation.

Between 1970 and 1993, beryllium components were buried as low-level radioactive waste after being irradiated during testing in the ATR, the Materials Test Reactor, or the Engineering Test Reactor. Compared to some of the waste buried in the SDA, the irradiated beryllium components are compact in size and shape and have experienced high levels of irradiation that initially resulted in high levels of radioactive nuclides. These components were selected as a likely worst case for irradiation of the WAXFIX grout based on their compact nature and potential for relatively high, localized radiation doses.

Understanding the dose to the grout requires current information on the amount and types of radiation being released, which depends on the initial irradiation levels, the radionuclides initially produced, and the time elapsed since the irradiation ended. A search for information on the current fluence rate at the surface of the beryllium components was not successful. The most recent characterization of the radioactive contents of these components (Mullen et al. 2003) provided information up to the 2001 timeframe. Calculations in that characterization were reported to be accurate within about a factor of two of measured values for an ATR beryllium block currently in the ATR canal.

To provide a worst-case estimate of the radiation dose to the grout, an ATR beryllium block that was buried in the SDA in 1993 was selected as the radiation source. This block had the most recent irradiation history (it was removed from the reactor in 1986) and was the most highly irradiated of the blocks buried at that time. Estimating the current radioactive isotope inventory for this block required extending calculations made previously (Mullen et al. 2003) with the Oak Ridge Isotope GENeration and Depletion Code Version 2 (ORIGEN2) (Croff 1980) model. Calculations were extended to provide radioisotope inventories for July 1, 2004 and July 1, 2014. Results from the ORIGEN2 calculations were used as the radiation source term for calculations to estimate how much radiation enters and is absorbed by the grout.

Calculations to estimate the surface fluence rate and exposure rate for the ATR beryllium block were made using the MicroShield computer code (Grove Engineering 2003). MicroShield is designed to analyze shielding and estimate exposure from gamma radiation. It includes the effects of self-shielding and can simulate multiple materials. Simplifications in the modeling of the block were necessary because the ATR beryllium block has a very complicated surface and cross-sectional shape, and it has multiple holes within its geometry (see Figure 15). The block has a height of 129.54 cm (51 in.). The beryllium block was simulated in the code as a solid rectangle with an identical height, but with a length (40.15 cm [15.8 in.]) and width (26.04 cm [10.3 in.]) chosen to approximate the actual blocks cross-sectional dimensions. A description of the model and the rationale for selecting the dimensions is discussed in Appendix B. The density of the material for the model comprising the solid rectangle was adjusted to provide a total mass that was identical to the actual mass of the block. This model was intended to provide an estimate of the gamma radiation near the surface of a bare block. (The MicroShield code was not designed to provide a surface radiation flux, so a 1.27 cm air gap had to be modeled to obtain the desired fluxes.)

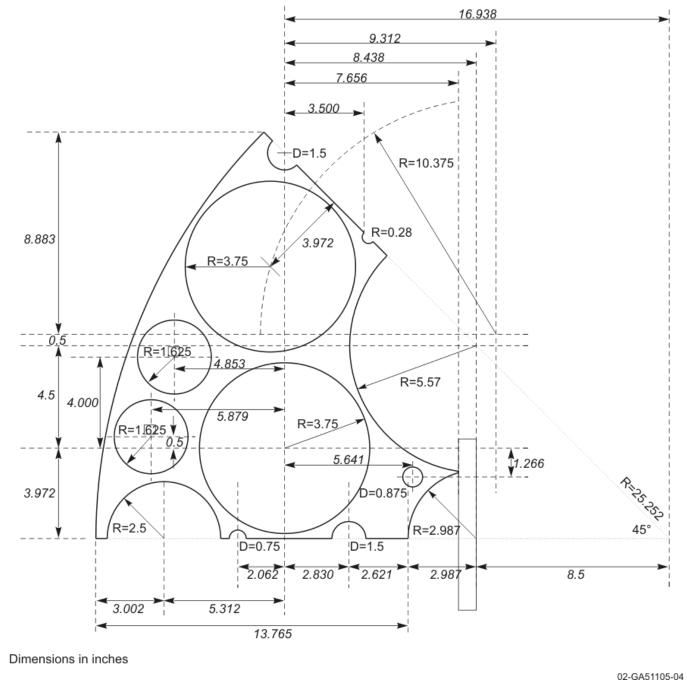

Figure 15. Cross-section diagram of an Advanced Test Reactor beryllium block.

A rectangular beryllium block with 2 ft of paraffin wax on its outer surface was also modeled by simulating a layer of pure paraffin adjacent to the beryllium surface of the initial beryllium block model. Two feet was chosen as a likely thickness for the WAXFIX as it is jet grouted adjacent to the block. Soil and waste were not included in the model because of a lack of information on the radiation absorption characteristics of the dirt/paraffin mixture. The intent of this model was to calculate radiation fluxes near the surface of the wax that could be subtracted from the bare block fluxes to estimate how much radiation was absorbed in the wax.

Four calculations were made, a bare beryllium block and a beryllium block with wax for the year 2004 and for the year 2014. Preliminary calculations indicated there was not a substantial difference (i.e., only about 8%) between the surface fluences on the centerline of the front (length) and sides (width) of the rectangle. As a result, radiation fluences were calculated at six positions on the front surface of the block as shown by the dots in Figure 16 for the bare block and in Figure 17 for the block with 2 ft of paraffin wax. Table 14 provides the calculated fluence rates in MeV per square centimeter per second and the exposure rates in mRem per hour.

The energy exiting the surface of the block was calculated assuming the fluence rates were the same on the fronts and sides of the rectangle and roughly integrating the fluence rates over the area of the modeled block (the top and bottom areas were not included). The integration was performed for the surface of the bare block and the surface of the wax, and the two were subtracted to calculate the energy absorbed by the wax. Based on the integration for July 1, 2004, the rate of energy absorption in the wax was 9.30×10^{19} MeV per year. A rough check of this value was performed by assuming the hot spot (i.e., middle center) value was applicable to the entire surface, giving an absorbed energy in the wax of 12.18×10^{19} MeV per year. Integrating to include edge effects only reduced the energy absorbed by about 30%, and may not be conservative since the integration method was simple and was only based on six points. Details on the calculation of these numbers are provided in Appendix B.

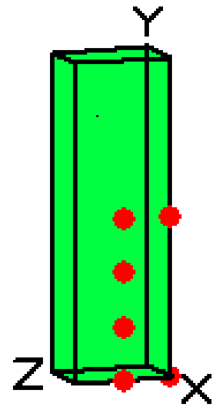

Figure 16. MicroShield bare rectangular model of an Advanced Test Reactor beryllium block showing calculated fluence positions.

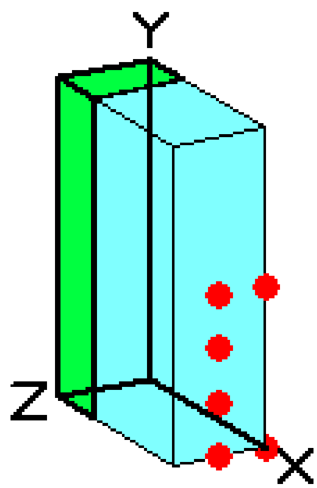

Figure 17. MicroShield rectangular model of an Advanced Test Reactor beryllium block with wax showing calculated fluence positions.

The fluence rate values in 2004 were compared to those calculated for 2014. The ratio of the 2014 values to the 2004 values is 0.278. Assuming that Co-60 is the only contributor to the fluence (half life 5.274 years), this ratio would be 0.269. Comparing these ratios shows that Co-60 is the primary contributor to the beryllium block fluence rate over the next 10 years. Understanding this dominance of the source term by Co-60 is important in estimating the energy deposited in the wax for the long term.

The values for the exposure rates presented in Table 14, with the calculated energy absorbed in the wax, will be used in the following sections to provide insight on potential radiation damage to the wax and an estimate of the hydrogen that could be generated in the wax.

Table 14. Summary of MicroShield calculated fluence rates and exposure rates for the six positions on the Advanced Test Reactor beryllium block, both with and without wax.

Position on Surface	2004 No Wax MeV/cm^2 –sec (R/hr)	2004 with Wax MeV/cm^2 –sec (R/hr)	2014 No Wax MeV/cm^2 –sec (R/hr)	2014 with Wax MeV/cm^2 –sec (R/hr)
Middle Center	2.29×10^8 (400)	0.35×10^7 (6.1)	0.64×10^8 (112)	0.10×10^7 (1.7)
Middle 2nd Down	2.25×10^8 (394)	0.33×10^7 (5.8)	0.62×10^8 (110)	0.09×10^7 (1.6)
Middle 3rd Down	2.08×10^8 (364)	0.28×10^7 (4.9)	0.58×10^8 (102)	0.08×10^7 (1.3)
Middle Bottom	1.20×10^8 (210)	0.20×10^7 (3.4)	0.33×10^8 (59)	0.05×10^7 (0.9)
Edge Center	1.51×10^8 (265)	0.30×10^7 (5.3)	0.42×10^8 (74)	0.08×10^7 (1.5)
Edge Bottom	0.81×10^8 (141)	0.17×10^7 (3.0)	0.22×10^8 (39)	0.05×10^7 (0.8)

3.6.2 Radiation Effects on Paraffin Structure

In many materials, radiation will change the crystal lattice and deteriorate the lattice order. These changes to the crystal structure can lead to a decrease in the structural performance of the material. Changes in the thermal characteristics of the material may also occur. Investigating the effects of radiation on the structure of long chain n-alkane carbon compounds, including paraffin wax, is a very narrow field, but some studies have been conducted as part of more extensive radiation studies on a broader range of hydrocarbons.

Paraffins were found to respond to radiation in a way that is clearly different from the behavior of many other materials, including many hydrocarbons. Experimental studies have been conducted on several n-paraffins ranging from tricosane ($C_{23}H_{48}$) to tetracontane ($C_{40}H_{82}$) (Ungar 1980). The results reveal a discrete difference in the way radiation affects the crystal lattice in n-paraffins when compared to other hydrocarbons. For example, radiation causes deterioration of crystal lattice order in polyethylene, changing the crystal lattice (Ungar 1980; Ungar, Grubb, and Keller 1980). Even though radiation causes substantial crosslinking of molecules in both materials (Ungar 1980; Mahmood and Mousa 1972), the effects on the paraffin structure are much different. The basic crystal structure of irradiated n-paraffins remains almost free of defects, but the amount of crystalline material decreases. This material coexists with the radiation-damaged material, which is amorphous and has characteristics typical of a liquid. The amorphous material contains most of the crosslinked hydrocarbon molecules, and the crystalline structure contains most of the molecules that are not crosslinked but may have a shorter carbon chain length. The proportion of this liquid phase increases with increasing radiation dose and with increasing temperature (i.e., more molecules are dissolved into the liquid phase at higher temperatures).

The gradual increase in amorphous material with increased radiation levels or with increased exposure time is expected to slowly degrade the structural capabilities of paraffin; however, no measurements have been made to quantify the extent of degradation on the material's mechanical properties. A limiting dose that would have a negligible effect on plastics is reported as about 10^7 Rad, and a dose that generally results in major damage is about 10^9 Rad (CRC Handbook 1983). These results would include both damage to the crystal structure and the effect of gas phase (e.g., hydrogen and methane) in the hydrocarbon material.

A conservative estimate of the dose to WAXFIX surrounding an ATR beryllium block can be made using the highest exposure rate in Table 14. Using the Co-60 half life, it is estimated that over the 10-year period between 2004 and 2014, the WAXFIX would get a dose of 1.95×10^7 R. This is just beginning to approach material damage for a plastic. The limiting dose for paraffin would be expected to be higher than the values quoted for plastic, based on differences in the effect of radiation on plastic crystalline structure versus paraffin structure. If all of the fluence was assumed to be from Co-60, the total dose possible for an infinite time would be about 2.67×10^7 R. Longer-lived radionuclides would continue to provide low levels of radiation for long periods of time, but the WAXFIX would not reach levels of radiation that would cause substantial damage (i.e., 10^9 R or more) for a very long time, likely many hundreds of years or longer.

Another means of considering possible damage is to examine the number of paraffin molecules crosslinked through radiation and is also possible through the limited irradiation information available. Radiation studies (Miller, Lawton, and Balwit 1956) with n-octacosane ($C_{28}H_{58}$), a paraffin with a melting point of about 61°C (Timmermans 1956) and a radiation source with 800 kV peak electrons were conducted to investigate the generation of radiation products. Results from these studies indicate the number of n-octacosane molecules that were damaged by the radiation and that formed longer chain, crosslinked molecules was 1.6×10^{12} molecules per gram of octacosane per Roentgens (R). Using the dose from assuming an infinite time value and only Co-60, the number of molecules crosslinked in a gram of octacosane would be 2.27×10^{19}. The number of molecules in a gram would be 1.53×10^{21}, so about 3% of the molecules would be crosslinked. This is not considered to be a substantial portion of the molecules and should not be detrimental to the material properties of the paraffin.

3.6.3 Hydrogen Generation Resulting from Radiation

Radiation effects on long-chain paraffins indicate a preferred cleavage near the chain ends, particularly at the third and fourth C-C bonds (Chapiro 1962). This cleavage pattern results in a large and a small radical; the shorter eventually forming a saturated, volatile hydrocarbon and the longer remaining to crosslink with another large radical. Further cleavages can then occur in the small, short chain paraffins to produce shorter chain products, including hydrogen. As an example, a small sample of octacosane was irradiated to a dose of 64.6 Mega-roentgen (Miller, Lawton, and Balwit 1956). A mass spectrometric analysis of the gas involved indicated 91.0 mole-percent (M%) hydrogen, and 7.2 M% volatile alkanes, including 0.5 M% methane, 2.1 M% ethane, 1.3 M% butane, 1.1 M% hexane, and 0.6 M% octane.

Understanding the yields of hydrogen and other volatile hydrocarbons generated by irradiation of WAXFIX grout may be important in situations where the exposure will be long-term. The symbol G is used for expressing radiation-induced chemical yields. For a given irradiated system, G is defined as the absolute chemical yield, expressed as the number of individual chemical events occurring per 100 eV of absorbed energy. Most of the studies for determining hydrogen generation rates were conducted in the absence of oxygen because oxygen combines with the hydrogen, making the results difficult to interpret.

Data on radiation-induced chemical yields for general, commercial-grade paraffin wax was not found. However, data from studies on refined, primarily single-chain-length paraffin were obtained for the following carbon numbers: 20 (eicosane), 21 (heneicosane), 23 (tricosane), 24 (tetracosane), and 28 (octacosane). Initial studies were performed on octacosane (Miller, Lawton, and Balwit 1956) with high energy electrons (i.e., 800 kV), a total dose of 64.6 Mega-roentgen, and at temperatures between 25 and 50°C. Results from this study indicate that G_{H2} was equal to 4.3. This value assumed the energy absorbed per roentgen in octacosane was the same as air, 84 ergs/g. Later work (Chapiro 1962) found that the assumed energy absorbed value was too low for paraffin and the correct amount of energy absorbed per roentgen should be 96 ergs/g, lowering the G_{H2} value to 3.8. As a result, exposure of this particular paraffin to radiation is expected to yield 3.8 hydrogen atoms for every 100 eV of radiation energy absorbed. This study also indicated that 0.05 methane atoms would be generated from every 100 eV of energy absorbed.

Irradiation of the remaining paraffins (Seguchi et al. 1985) was performed using Cobalt-60 as a source of gamma radiation. A dose rate of 1 Mrad/h (10 kGy/h) was used with gas generation rates taken at 100, 200, 300, and 400 Mrad. Irradiations were conduced at -77°C, room temperature, and 55°C. G_{H2} values taken under these conditions are presented in Table 15 and range from 2.14 to 3.28. The influence of increasing hydrogen generation rates with increasing temperature can be seen from these results. The highest temperature G_{H2} values are slightly smaller than those discussed previously for octacosane.

Table 15. G value of hydrogen (G_{H2}) from irradiation of several paraffins.

Irradiation Temperature	-77°C	Room Temperature	55°C
$C_{20}H_{42}$	2.14	2.26	3.32
$C_{21}H_{44}$	2.16	2.38	3.22
$C_{23}H_{48}$	2.25	2.45	3.28
$C_{24}H_{50}$	2.16	2.52	3.22

The paraffin G values for hydrogen were compared to G values for other hydrocarbons to assess whether the values are reasonable for a broad range of paraffins. n-Hexadecane is a paraffin with a carbon number of 16 and is a liquid at room temperature. The G value for n-hexadecane is reported as 4.8 hydrogen molecules per 100 eV (Dewhurst 1957). A G value for linear hydrocarbons that is independent of chain length is reported as 4.3 ± 0.3 hydrogen molecules per 100 eV by Chapiro (1962). Polyethylene is a more complex hydrocarbon molecule and has a reported G value of 3.1 hydrogen molecules per 100 eV (Chang and LaVerne 1999). There are many more examples, but the relative agreement of these sources shows that the values reported are sufficiently close to be considered applicable to WAXFIX.

A rough estimate of the hydrogen generated in a 2-ft slab of paraffin surrounding the ATR beryllium block was calculated. The initial value for energy absorbed by the wax was selected as the Microshield-calculated fluences integrated over the surface of the block (see the discussion in Section 3.6.1). This value of 9.30×10^{19} MeV may not be conservative, but the degree of nonconservatism is not large because it is only about 30% lower than the value calculated by integrating the highest (hot spot) fluence over the block. A G value of 3.8 molecules of hydrogen per 100 eV was used, which is on the high end of the range of G values for paraffin. Decay of the initial fluence was accounted for in the calculations assuming the source is decaying with the half-life of Co-60 (a reasonable assumption as discussed in Section 3.6.1 and Appendix B). Based on this input, the calculated amount of hydrogen that would be generated over the first year in 2 ft of pure paraffin surrounding the beryllium block would be about 5.5 moles or about 123.3 L. This compares with a rough estimate of about 2,400 L of wax surrounding the block. Using the same methodology, the amount of hydrogen generated during the first 10 years (July 1 2004 to July 1 2014) is calculated to be about 32.7 moles. These values are considered to be conservative for a number of reasons.

The assumption of pure paraffin surrounding the beryllium block is not realistic, as the grout will be well mixed with the soil. The proportions will depend on how tightly the soil is packed and whether there are remaining voids that the WAXFIX can fill. Voids surrounding the beryllium blocks have been estimated to range from 33 to 50% (EDF-4397). As a minimum, mixing with the soil would reduce the number of wax molecules available for irradiation by about 33%, which would reduce the hydrogen generated by about the same proportion. Generated hydrogen will diffuse through the wax, and water and oxides of carbon may accumulate in the gas phase while peroxides and their degradation products (i.e., carbonyl and carboxyl groups) may form in the condensed state (Chapiro 1962). In addition, hydrogen may recombine with some of the molecules in the grout given the long period of time over which they are generated. Hydrides can also form with metals that are present near the beryllium block, including the metal cage. None of these effects have been accounted for in the reported hydrogen generation values.

To more accurately calculate the amount of hydrogen present in the grout would require a relatively sophisticated series of calculations. A less conservative calculation of fluence rates would be needed, as wells as a more sophisticated examination of the distribution of generated hydrogen in the wax. An estimate of the amount of wax mixed with the soil in the vicinity of a beryllium component would be needed. Chemical kinetics code calculations could then be made to estimate the rates of recombination of hydrogen with the hydrocarbon molecules, with any oxygen present, and with other materials within the grout monolith. A diffusion calculation would also be needed to calculate the hydrogen leaving the grout monolith. A value for the diffusion coefficient of hydrogen through paraffin was not found, but the diffusion coefficient for hydrogen through high-density polyethylene was calculated to be 2.2×10^{-6} cm^2/second (Chang and LaVerne 1999). This could be used as a “ballpark” value.

Results from the hydrogen generation calculations intentionally used assumptions to provide a conservative estimate of hydrogen radiolysis. Even with these conservatisms, the volumes of hydrogen calculated are not large when compared to the estimated volume of grout that would be surrounding the beryllium blocks. Consequently the effect of the hydrogen would not adversely affect the capability to limit infiltration of water to the beryllium surface. In addition, the hydrogen should not adversely affect grout physical structure based on the discussion of the effect of radiation dose, in Section 3.6.2.

3.7 Rough Estimate of WAXFIX Grout Costs

A rough estimate of the cost of the WAXFIX was made based on a previous estimate of the volume required to grout the beryllium blocks in the SDA. About 105,000 gal of grout were estimated to be needed (EDF-4397). Based on a cost of $8 per gallon quoted by Carter Technologies Company, the cost of WAXFIX grout would be $840,000 just for the material. The cost of performing the jet grouting would be significantly more.

4. SUMMARY AND CONCLUSIONS

Information on WAXFIX was identified using an extensive literature search, previous tests of in situ grouting at the INEEL, and information available from tests currently being conducted at the INEEL. These results were reviewed and an evaluation of the expected performance of WAXFIX was made based on current and projected grouting plans for the SDA. This evaluation includes a review of behavior developed using standard test procedures applicable to grouts (e.g., contaminant leaching and compressive strength), as well as the behavior for possible harsh SDA conditions that could affect the long-term stability of WAXFIX grout. Results will be used to support the FS for WAG 7, OU 7-13/14. The following conclusions are based on the findings of the literature search and results assessment:

Physical Properties

- Although specific information on WAXFIX physical properties is somewhat limited, using selected properties from paraffin wax provides sufficient detail that it can be concluded that WAXFIX is suitable for use in jet grouting.

Physical Stability

- Based on compressive strength tests conducted for the ICP preremedial design testing, the maximum compressive strength of WAXFIX/soil mixtures is about 4.62 MPa (670 psi) with a 70% soil loading. For comparison, this value is a factor of three to four less than cement-based grouts. When loaded with organic wastes in the range of 5 to 30%, the WAXFIX compressive strength was reduced by more than 80% from the maximum and by more than 60% from the neat grout value of 2.06 MPa (298.9 psi). Other waste types (i.e., nitrate salts and TD-treated organic sludge) experienced decreases in compressive strength of about 30% and 20%, respectively, when compared to neat grout. With the exception of the 30% organic waste loading, all measured compressive strength values were above the minimum 0.41 MPa (60 psi) the NRC specifies for all solidification agents (NRC 1991).

Hydraulic Conductivity

- Hydraulic conductivity is an indicator of the permeability of WAXFIX grout. The hydraulic conductivity for tests conducted by Milian was measured to be less than 2.0×10^{-11} cm/sec for a mixture of WAXFIX and soil and for a mixture of WAXFIX and simulated waste. For the ICP tests, the hydraulic conductivity ranged from 1.21×10^{-9} to 1.04×10^{-7}. The minimum value is about an order of magnitude less that some cement-based grouts, demonstrating the impermeability of WAXFIX grout to water.

Chemical Stability

- The potential for rapid reactions between WAXFIX and an oxidizer (e.g., sodium nitrate) was evaluated. It was concluded that there does not appear to be any major extraneous reactions occurring between WAXFIX grout and the sodium nitrate up to a temperature of 350°C (well above the 7 to 15°C expected in the SDA).

- Tests on the potential for WAXFIX to become hazardous if involved in an accidental fire indicate that when sodium nitrate is solidified in solid paraffin wax or mixed with paraffin wax, the rate of burning is much slower than with sodium nitrate alone. As a result, WAXFIX would not be classified as an oxidizer by the DOT.

- When WAXFIX is exposed for a 90-day period to a strong base (i.e., a sodium hydroxide solution with a pH of 12.5), the test specimen maintained its integrity, but the compressive strength was decreased by 51%. The results indicate the majority of the strength decrease takes place in the initial 30 days and there is little additional decrease up to 90 days. Although the decrease in compressive strength is significant considering the relatively low compressive strength of unaffected WAXFIX, the chemical forms and compositions in the SDA are sufficiently different from the tests that this degree of degradation is not expected.

- Exposing WAXFIX to a solvent (i.e., deionized water saturated with trichloroethylene) caused weight loss, an increase in volume, and a 55% reduction in compressive strength. WAXFIX would be expected to have a similar response to carbon tetrachloride. However, the Rocky Flats organic sludge containing TCE, carbon tetrachloride, trichloroethane, and perchloroethylene comprise only a small portion of the total waste in the SDA indicating any degradation within a waste/grout monolith formed by WAXFIX would be localized.

- Accelerated leach test results reveal that WAXFIX is effective in preventing leaching of chromium and lead. TCLP leach tests indicate that WAXFIX alone is not effective in preventing mercury leaching. Additional TCLP tests showed that a reduction in the amount of mercury leached (at levels below the TCLP limit) could be achieved by adding a material with a high affinity for mercury (i.e., about 2 wt% of sodium sulfide) to the grout.

- A series of leaching studies conducted in Korea can help understand the leaching process for mixtures of WAXFIX and salts. The Korean tests indicate that waste with high levels of boric acid and contaminants encapsulated in paraffin experienced high rates of contaminant leaching. These results indicate that because the boric acid was a high percentage of the waste and could be leached, it allowed the other contaminants to also be diffused out of the paraffin at about the same rate. Paraffin remaining after the contaminants were leached formed a labyrinth that controlled further diffusion. Insights on the kinetics of diffusion from these tests could have application to SDA waste. For example, leach rates for nitrate salts in WAXFIX may be affected by similar diffusion patterns, where the salt crystals are in contact with each other and leaching may occur in small pathways leaving a honeycombed wax shell.

- Leach tests that are currently being conducted (Yancey et al. 2003) using typical INEEL soils and contaminants will provide important insights on expected leach behavior of WAXFIX in the SDA.

Biodegradability

- There are a broad range of microorganisms that can metabolize paraffin. Conditions for metabolization cover a wide range of temperatures, chemical conditions, and moisture levels. These conditions overlap SDA conditions, indicating degradation of a paraffin-based grout by microorganisms in the SDA is possible and even likely, but the rate of degradation will be slower than those sited in the literature because the tests were conducted under well mixed and oxygenated conditions. In addition, WAXFIX contains compounds other than paraffin and the mixing of WAXFIX with the waste forms in the SDA could also influence (reduce or enhance) the biodegradability of WAXFIX. The rate of biodegradation for two paraffin monoliths, sized for application to beryllium blocks, was estimated using literature data for a well mixed aqueous system inoculated with microorganisms from a land farm for oil contaminated soil. The calculations showed that 1,500 to 5,200 years would be required to consume the monoliths. The outer 0.46 m (18 in.) layer of each monolith, which represents the minimum expected distance to the beryllium block, was calculated to require 1,000 to 3,600 years to be consumed. To more accurately predict the timing for WAXFIX biodegradation in the SDA, additional work, possibly including identifying the chemical composition of the proprietary additives and experimentation, will be necessary.

Radiation Susceptibility

- Radiation damage to the crystalline structure of paraffin is not as substantial as damage to other hydrocarbon-based materials, such as plastics. Although a dose level for damage to paraffin was not found in the literature, damaging doses in plastics can be initiated but are minor at 10^7 Rad and become more severe at 10^9 Rad. Conservative doses in the SDA were calculated for the highest activity ATR beryllium block that may be grouted. The calculations indicate that Co-60 dominates the source term in the next decade and its domination is probable for decades into the future. Based on these calculations, WAXFIX probably would not reach a level of radiation damage for many hundreds of years.

- Radiation-induced hydrogen production in a refined paraffin was measured to be about 3.8 hydrogen molecules for every 100 eV of radiation absorbed by the paraffin. A conservative calculation was made to estimate the amount of hydrogen produced from the most highly activated beryllium block in the SDA. About 5.5 moles of hydrogen would be generated in a year, beginning July 1, 2004. The total hydrogen production during 10 years (i.e., 2004 to 2014) of about 32.7 moles. These values are conservative because they assume 100% WAXFIX, which could be reduced by as much as 50 – 67% due to mixing with the soil (void volume in soil is 33–50%). This calculation did not predict the fate and transport of hydrogen resulting from diffusion through the grout and combination with other chemical compounds. Grout physical performance should not be reduced beyond the previous discussion of the effect of radiation dose.

During the review of this document, an issue was raised on the possibility that proprietary ingredients or additives in WAXFIX could cause additional or accelerated corrosion of the beryllium blocks. Although this issue does not affect the durability of WAXFIX, it could influence whether WAXFIX is acceptable for grouting beryllium.

Corrosion studies indicate that halogen and chalogen ions and others, including sulfate and nitrate, accelerate beryllium corrosion (Floyd and Lowe 1979, Webster and Landon 1979). This information was sent to Carter Technologies Company, the company that manufactures WAXFIX grout, to determine if their proprietary ingredients contained any of the ions that are identified as accelerating corrosion. Their reply was that the proprietary ingredients in WAXFIX 25 do not contain any of the ions that accelerate beryllium corrosion and that WAXFIX 25 is “specifically designed to eliminate the potential for ionic transport by eliminating any continuous aqueous phase in the waste and its surroundings”.

A direct confirmation of the inert character of WAXFIX would require testing. These tests are not recommended based on the information from Carter Technologies Company and the fact that there are no plans at the INEEL to add other ingredients to the grout.

5. APPROACHES TO REDUCE UNCERTAINTY

Results and conclusions presented in Section 4 describe some uncertainties relative to long-term performance of WAXFIX under the full range of SDA conditions. Measures to reduce uncertainty are discussed in the following:

1. The radiolysis results can be refined through more detailed calculations. These calculations would require: (1) detailed analysis of radiation absorbed in the wax and soil mixture, (2) use of a reactive chemistry code to calculate reactions of hydrogen with chemicals in soil, waste, or other materials (air bubbles, trapped moisture, etc.), and (3) use of a diffusion code to examine the extent of movement of hydrogen in the soil and WAXFIX mixture.

2. Data forthcoming from current hydrogen generation tests using finely divided alpha particles mixed with WAXFIX (Yancey et al. 2003) should be assessed to determine if an appreciable amount of hydrogen is generated. If necessary, additional experiments and modeling could be performed to refine hydrogen generation values using different alpha-emitting materials with a wider distribution of particle sizes. Alpha-emitting materials can self-shield, so a given mass of smaller particles will release more alpha to WAXFIX than an equivalent mass of larger particles. The particles being used in the ongoing tests are at the smaller end of the size distribution expected to present in the SDA, and therefore the results of the ongoing tests are expected to result in a higher hydrogen generation rate than would be observed on average in the SDA.

3. If WAXFIX grout is considered for use where beta-emitting materials are finely divided and can mix well with grout, the effect of beta particles on hydrogen generation should be evaluated. (Note-beryllium blocks are not finely divided materials.)

4. Calculations to examine the potential for jet-grouted WAXFIX to support overlaying material can be performed to assess compressive strength and capability to support overlying material.

5. Leach testing is currently being conducted with waste surrogates that are typical of those found in the SDA (Yancey et al. 2003). Results from these tests will be evaluated for those contaminants that are of concern.

6. The rate of biodegradation of WAXFIX in the SDA was assessed using existing data from the literature. In general, these data were developed under conditions significantly different than expected in the SDA. Degradation rates extrapolated from these data are likely to overstate the degradation rate that would occur when exposed to actual SDA conditions. In addition, proprietary additives in WAXFIX could influence (reduce or enhance) biodegradability of WAXFIX in the SDA. Mixing of WAXFIX with SDA wastes including soil, nitrate salts, and organic compounds also could affect the biodegradation rate. However, experimentally determining less conservative biodegradation time would require several years of study.

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Appendix A

Physical Properties of n-Alkanes

Appendix A

Physical Properties of n-Alkanes

The properties of solid paraffin wax will vary, depending on the numbers of different n-alkane chains that comprise the wax. The density, melting point, and heat of fusion of individual n-alkanes increase with the number of carbon atoms. Table A-1 (Suwono and Mansorri 1994) summarizes some important n-alkane physical properties as a function of the number of carbon atoms in the chain. Paraffin wax, with a predominance of one chain, must be refined from the paraffin generally available and is more expensive than a less refined product. Although analysis of the distribution of n-alkane chain lengths has not been performed for WAXFIX, it is likely that it will be similar to many of the commercially available paraffin waxes.

Paraffin wax is generally considered to be a mixture of n-alkane chains ranging from C_{21} to C_{40} Figure A-1 shows a typical distribution of carbon atoms for a commercially available paraffin wax (Haji-Sheikh, Eftekhar, and Lou 1982). Some commercial paraffins also contain some branched alkanes and Monocycloalkanes, but usually in weight percents around 2 to 3 (for relatively high-grade commercial paraffins) (Freund et al. 1982).

Table A-1. Thermodynamic properties of n-alkanes.

n-Alkanes	No. of C Atoms	Mole Weight	Melting Point (K)	Latent Heat of Fusion (kJ/kg)	Density at 20°C (kg/m^3)	Specific Heat: Solid (J/mol.K) at 298 K	Specific Heat: Liquid (J/mol.K) at 353 K	Boiling Point (K)
Methane	1	16	90.68	58	0.658 (g)	—	—	116.6
Ethane	2	30	90.38	95	0.124 (g)	—	—	184.6
Propane	3	44	85.47	80	1.834 (g)	—	—	231.1
Butane	4	58	134.79	105	2.455 (g)	—	—	272.7
Pentane	5	72	143.45	117	621 (1)	—	167.2	309.0
Hexane	6	86	177.83	152	655 (1)	—	195.4	341.9
Heptane	7	100	182.55	141	649 (1)	—	225.0	371.6
Octane	8	114	216.37	181	699 (1)	—	254.2	398.8
Nonane	9	128	219.65	170	714 (1)	—	284.5	424.0
Decane	10	142	243.50	202	726 (1)	—	314.5	447.3
Undecane	11	156	247.55	177	737 (1)	—	345.0	469.1
Dodecane	12	170	263.55	216	745 (1)	—	376.0	489.5
Tridecane	13	184	267.75	196	753 (1)	—	406.9	508.6
Tetradecane	14	198	278.95	227	759 (1)	—	438.5	526.7
Pentadecane	15	212	283.05	207	765 (1)	—	470.0	543.8
Hexadecane	16	226	291.25	236	770 (1)	—	501.5	560.0
Heptadecane	17	240	295.05	214	775 (s)	—	534.3	575.2
Octadecane	18	254	301.25	244	779 (s)	485.4	564.4	589.5
Nonadecane	19	268	305.15	222	782 (s)	514.6a	618[a]	603.1
Eicosane	20	282	309.75	248	785 (s)	544.3	658[a]	617.0

Table A-1. (continued).

n-Alkanes	No. of C Atoms	Mole Weight	Melting Point (K)	Latent Heat of Fusion (kJ/kg)	Density at 20°C (kg/m^3)	Specific Heat: Solid (J/mol.K) at 298 K	Specific Heat: Liquid (J/mol.K) at 353 K	Boiling Point (K)
Heneicosane	21	296	313.35	213	788 (s)	570.7[a]	698[a]	629.7
Docosane	22	310	317.15	252	791 (s)	598.1[a]	739.0	641.8
Tricosane	23	324	320.65	234	793 (s)	625.0[a]	772.0	653.4
Tetracosane	24	338	323.75	255	796 (s)	651.4[a]	805.0	664.5
Pentacosane	25	352	326.65	238	798 (s)	670.4[a]	815.9	675.1
Hexacosane	26	366	329.45	250	800 (s)	677.8	870.0	685.4
Heptacosane	27	380	331.95	235	802 (s)	728.1[a]	928[a]	695.3
Octacosane	28	394	334.35	254	803 (s)	752.8[a]	937.0	704.8
Nonacosane	29	408	336.35	239	805 (s)	777.2[a]	1001[a]	714.0
Triacontane	30	422	338.55	252	806 (s)	801.2[a]	1037[a]	722.9
Hentriacontane	31	436	341.05	242	808 (s)	824.5[a]	1073[a]	731.2
Dotriacontane	32	450	342.85	266	809 (s)	867.4	1095	740.2
Tritriacontane	33	464	344.55	256	810 (s)	871.0[a]	1113	748.2
Tetratriacontane	34	478	346.25	268	811 (s)	887.4	1149	755.2
Pentatriacontane	35	492	347.85	257	812 (s)	916.0	1210[a]	763.2
Hexatriacontane	36	506	349.35	269	814 (s)	937.5[a]	1206	770.2
Heptatriacontane	37	520	350.85	259	815 (s)	959.1[a]	1276[a]	777.2
Octatriacontane	38	534	352.15	271	815 (s)	980.4[a]	1305[a]	784.2
Nonatriacontane	39	548	353.45	271[a]	816 (s)	1001[a]	1341[a]	791.2
Tetracontane	40	562	354.65	272	817 (s)	1022[a]	1411	795.2
Dotetracontane	42	590	357.32	273	817 (s)	1062[a]	1435	804.2
Tritetracontane	43	604	358.65	273[a]	819[a] (s)	1085[a]	1465[a]	813.2

Table A-1. (continued).

n-Alkanes	No. of C Atoms	Mole Weight	Melting Point (K)	Latent Heat of Fusion (kJ/kg)	Density at 20°C (kg/m^3)	Specific Heat: Solid (J/mol.K) at 298 K	Specific Heat: Liquid (J/mol.K) at 353 K	Boiling Point (K)
Tetrateracontane	44	618	359.55	274	820[a] (s)	1102[a]	1495[a]	818.2
Hextetracontane	46	646	361.45	276	822[a] (s)	1140[a]	1553[a]	829.2
Octatetracontane	48	674	363.45	276	823 (s)	1177	1595	838.2
Pentacontane	50	702	365.15	276	825[a] (s)	1213[a]	1665[a]	848.2
Hexacontane	60	842	372.15	279	831[a] (s)	1380[a]	1916[a]	888.2
Heptacontane	70	982	378.65	281[a]	836[a] (s)	1526[a]	2131[a]	919.2
Hectane	100	1402	388.40	285[a]	846[a] (s)	1869a	2598[a]	935.2

a. Estimated values—experimental data not available.

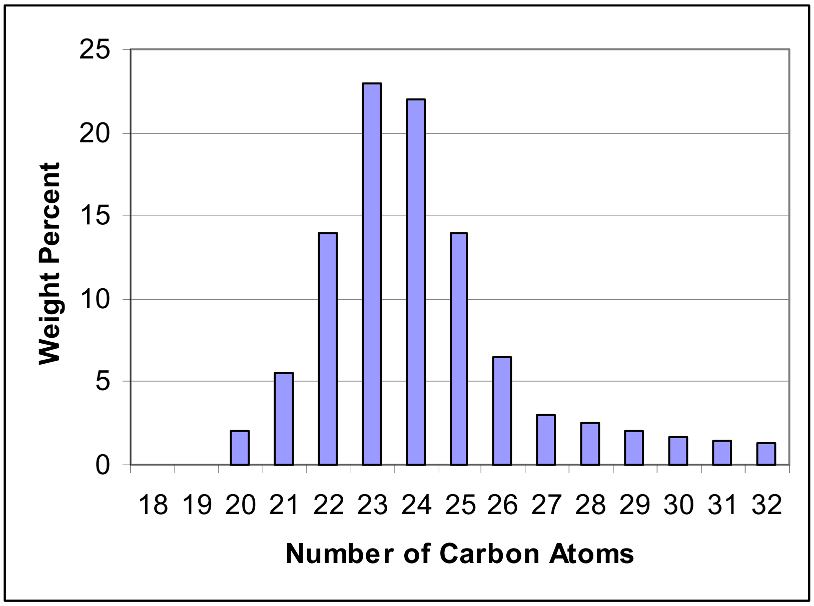

Figure A-1. Weight percent of various n-alkane chain length molecules in commercially available paraffin wax.

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Appendix B

Calculation of the Radiation Energy Deposited in Paraffin Wax Surrounding an Advanced Test Reactor Beryllium Block

Appendix B

Calculation of the Radiation Energy Deposited in Paraffin Wax Surrounding an Advanced Test Reactor Beryllium Block

WAXFIX is currently the choice for grouting irradiated beryllium components that are buried in soil vaults and trenches at the SDA. Determining the WAXFIX radiation dose will be key in evaluating the potential for significant radiation damage to its crystalline structure and estimating the amount of hydrogen gas that will be generated. This appendix provides details on the development of a worst-case estimate of the radiation dose that can be used to provide a rough order of magnitude estimate of radiation damage and hydrogen generation.

Beryllium components were irradiated during testing in the Advanced Test Reactor (ATR), the Materials Test Reactor, and the Engineering Test Reactor. These components were buried as low-level radioactive waste in the SDA between 1970 and 1993. These components were selected as a likely worst case for irradiation of WAXFIX grout based on their compact nature and potential for relatively high, localized radiation doses. A search for information on the current fluence rate at the surface of the beryllium components was not successful. The most recent characterization of the radioactive contents of these components (Mullen et al. 2003) provided information up to the 2001 timeframe. Calculations in this characterization were reported to be accurate within about a factor of two measured values for an ATR beryllium block currently in the ATR canal.

To calculate a worst-case estimate of the radiation dose to the grout, an ATR beryllium block that was buried in the SDA in 1993 was selected. This block had the most recent irradiation history (it was removed from the reactor in 1986) and was the most highly irradiated of the blocks buried at that time. The ATR beryllium block has a very complicated cross-sectional shape with a surface area that is complex. There are multiple holes of varying size within its geometry, as shown in Figure B-1. The dimensions of the block (in inches) are shown on this figure. The block has a height of 129.54 cm (51 in.).

Estimating the current radioactive isotope inventory for this block required extending calculations previously made (Mullen et al. 2003) with the ORIGEN2 (Croff 1980) model. These calculations were extended to provide radioisotope inventories for July 1, 2004 and July 1, 2014.

The MicroShield computer code (Grove Engineering 2003) Version 6.02 (6.02-00061) was selected to calculate the surface fluence rates and the exposure rates. MicroShield is designed to analyze shielding and estimate exposure from gamma radiation. It includes the effects of self shielding and can simulate multiple materials. Both the isotopes represented in the ORIGEN2 calculation and the geometry and material comprising the block indicate that gamma radiation will dominate the source term to the wax.

Simplifications in the modeling of the block were necessary because of the complex cross-section shape. There are several standard options in MicroShield for modeling objects. Of the standard shapes available in the code, a rectangular, parallel-piped shape was selected because it seemed to best approximate the general shape of the block. The size of the model was derived by reviewing the dimensions of the actual block, then estimating the length and width for a corresponding volume. The width of the block was estimated by first selecting an inside radius of 38.1 cm (15 in.), where the amount of material inside this radius was similar to that missing outside the radius (excluding holes). Subtracting

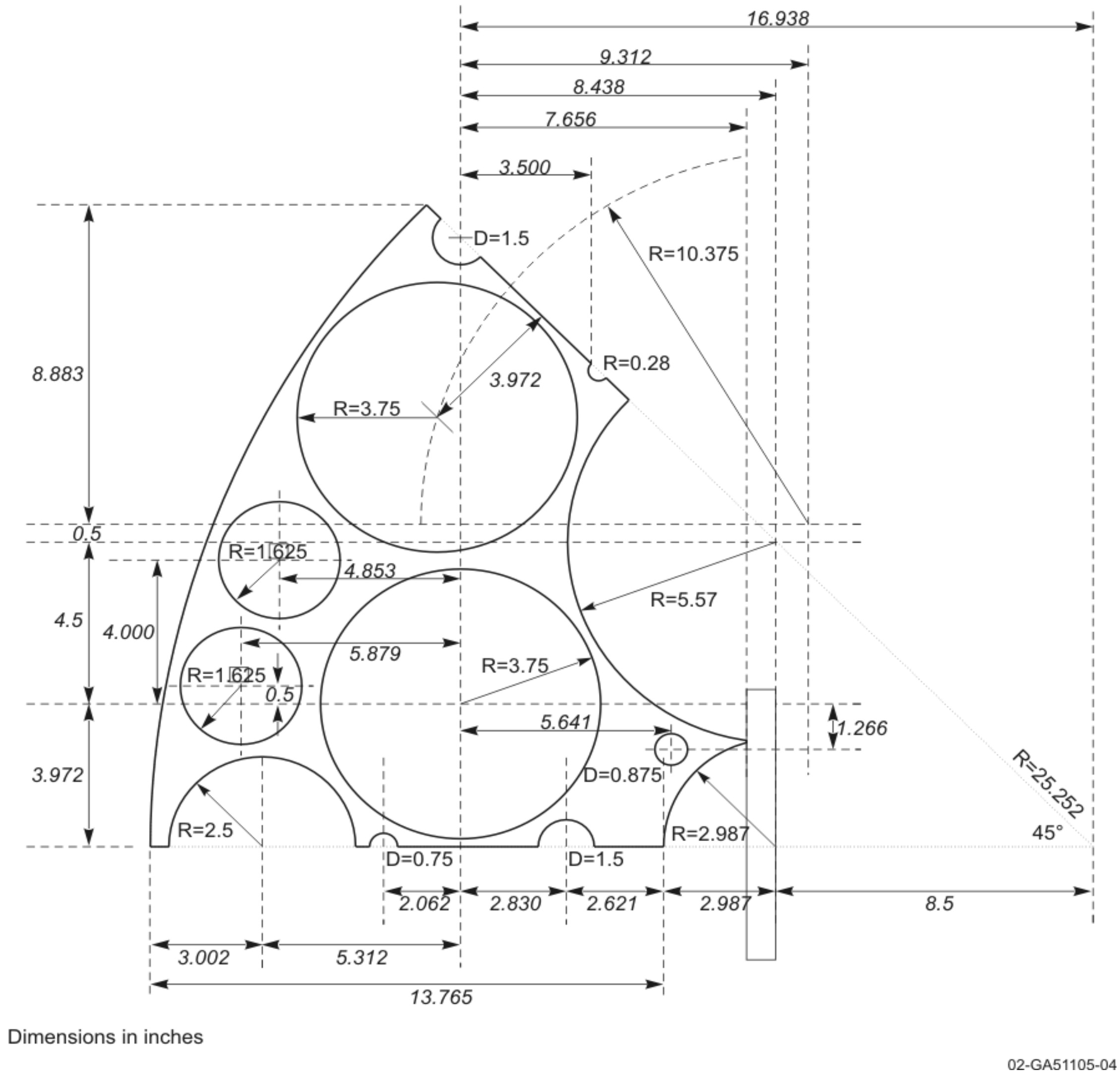


Figure B-1. Cross-section view of an Advanced Test Reactor beryllium reflector block.

the selected inside radius from the block outside radius provided a width of 26.04 cm (10.25 in.). The length was derived from the arc at the midpoint of the modeled region width. Specifically, the width midpoint of 51.12 cm (20.13 in.) yields an arc of 40.15 cm (15.81 in.), which was used as the modeled length. The modeled block height was made equal to actual block height of 129.5 cm (51 in.). The mass of beryllium in the ATR block is known, and the density of the model was adjusted to simulate that mass.

The rectangular MicroShield model was configured to provide an estimate of the radiation fluence rate at the surface of a bare block. Since MicroShield was not designed to provide a surface radiation fluence, a 1.27-cm (0.5-in.) air gap was included to approximate the desired results. Figure B-2 shows the points selected for output from the model: four along the block centerline beginning at the center of the block and ending at the bottom edge. Two additional points were specified at the center edge and bottom edge of the block to provide information on the expected decrease in fluence at the block edge.

A beryllium block with paraffin wax on its outer surface was also simulated. The bare block model was used with a 2-ft layer of pure paraffin adjacent to the beryllium surface. Figure B-3 shows the output points for this model are on the outside of the wax and correspond in location to the bare block model.

The 2-ft layer was chosen since it is expected to be typical of WAXFIX grout thickness. Soil and waste were not included in the modeled paraffin slab because of a lack of information on the exact composition and the radiation absorption characteristics of the dirt/paraffin mixture. This model was intended to estimate the gamma radiation near the surface of the wax (an identical 1.27-cm [0.5-in.] air gap had to be included). The intent of this model was to provide radiation fluxes near the surface of the wax that could be subtracted from the bare block fluxes to estimate how much radiation was absorbed in the wax. In these calculations, the wax was assumed to be in the form of $C_{28}H_{58}$.

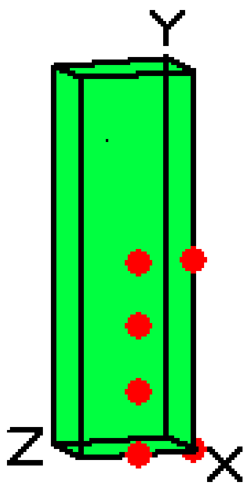


Figure B-2. Bare beryllium block model.

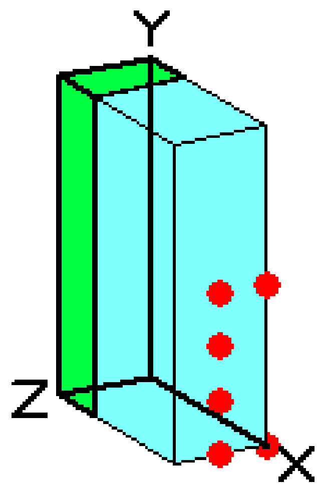


Figure B-3. Beryllium block model with 2 ft of pure paraffin wax.

Initial calculations were made for the length and the width of the rectangular model. The results showed there was only an 8% difference between the fluxes for identical positions on the block. To simplify the remainder of the analysis, all calculations were performed for the length, which had the higher values. To provide input for the calculations, a total of four MicroShield calculations were made, a bare beryllium block and a beryllium block with wax for the year 2004 and for the year 2014. Table B-1 summarizes the calculated fluence rate in MeV per square centimeter per second and the exposure rate in milliroentgen/hr from the two models. Table B-2 describes the MicroShield calculation model for the bare rectangular model of the beryllium block for July 1, 2004, summarizes the ORIGEN2 input for the source term at this time, and provides the MicroShield calculated results for the six output locations on the block. Table B-3 describes this same bare rectangular model, the ORIGEN2 input for July 1, 2014, and the calculated results. Since ORIGEN2 source terms for the calculations with wax are identical to those without wax, these results are not included in the remaining tables. Table B-4 describes the calculation model for the rectangular model with 2 ft of pure paraffin wax on one surface and the results on July 1, 2004 for the for the six output locations. Table B-5 provides similar information for the calculation with wax on July 1, 2014.

Table B-1. Calculated results from the MicroShield models for the Advanced Test Reactor beryllium block with and without paraffin wax.

Position on Surface	2004 No Wax MeV/cm^2 –sec (R/hr)	2004 With Wax MeV/cm^2 –sec (R/hr)	2014 No Wax MeV/cm^2 –sec (R/hr)	2014 With Wax MeV/cm^2 –sec (R/hr)
Middle Center	2.29×10^8 (400)	0.35×10^7 (6.1)	0.64×10^8 (112)	0.10×10^7 (1.7)
Middle 2nd Down	2.25×10^8 (394)	0.33×10^7 (5.8)	0.62×10^8 (110)	0.09×10^7 (1.6)
Middle 3rd Down	2.08×10^8 (364)	0.28×10^7 (4.9)	0.58×10^8 (102)	0.08×10^7 (1.3)
Middle Bottom	1.20×10^8 (210)	0.20×10^7 (3.4)	0.33×10^8 (59)	0.05×10^7 (0.9)
Edge Center	1.51×10^8 (265)	0.30×10^7 (5.3)	0.42×10^8 (74)	0.08×10^7 (1.5)
Edge Bottom	0.81×10^8 (141)	0.17×10^7 (3.0)	0.22×10^8 (39)	0.05×10^7 (0.8)

The fluence leaving the surface of the block was calculated by roughly integrating the fluence rates over the areas of the rectangle block sides (ignoring the top and bottom of the block). Since only six points exist, this integration is rough. To simplify the calculations, the following steps were performed:

- The fluence rates for the first three positions along the centerline were assumed to be equal to the middle center (There is very little difference in fluence rates between middle center, middle 2nd down, middle 3rd down). The with-wax fluence rate was subtracted from the no-wax value to get an approximation of the fluence rate deposited in the wax.

- The fluence rate at the edge (i.e., edge center) was assumed to be constant for positions corresponding to the middle 2nd and 3rd positions. The with-wax value fluence rate was subtracted from the no-wax value to get an approximation of the fluence rate deposited in the wax.

- The block was divided into three areas along the height of the block corresponding to the midpoints between the four output positions shown on Figures B-2 and B-3. Each area would have a height of 1/6 the height of the block (129.5 cm/6 = 21.59 cm).

- The distribution of the fluence rates from the center to the edge was assumed to be triangular, and the fluence rates were integrated based on subtracted fluence rates at the center, the subtracted fluence rates at the edge, and the area under this triangular distribution. The result was multiplied by 2 to account for assuming symmetry above and below the center. This simplified integration will underestimate the energy leaving this area since the edge affects are not as pronounced as the integration assumes, based on the relative small change in the values of the fluence along the vertical centerline.

- The fluence rates for the area at the bottom third (and top third) of the block were integrated by subtracting the with-wax from the no-wax fluence rates, averaging the four fluence rates (one at each corner of the area, middle center, edge center, middle bottom, and edge bottom) and multiplying the average by the area for 1/3 of the block (1/6 at the bottom and 1/6 at the top of the block). This integration is likely not conservative because the edge effects are not strong enough to produce a triangular distribution.

The value obtained for integrated energy absorbed by the wax was 9.30×10^{19} MeV per year for July 1, 2004. A rough check was performed by assuming the hot spot value was applicable to the entire surface of the block, giving an absorbed energy in the wax of 12.18×10^{19} MeV per year at this same time. Integrating the flux reduced the energy absorbed by about 30%, and may not be conservative since the integration was simple, was only based on six points, and likely overestimated the effects of the edge.

The fluence rate values from 2004 were compared to those calculated for 2014. The ratio of the 2014 values to the 2004 values is 0.278. Assuming that Co-60 is the only contributor to the fluence (half life 5.274 years), this ratio would be 0.269. Comparing these ratios shows that Co-60 is the primary contributor to the beryllium block fluence rate over the next 10 years. This knowledge allows an approximate calculation of the total amount of energy deposited in the wax over a period of time. The equation for the reduction of source term, assuming a Co-60 half-life (i.e., 5.27 years) is given by:

$$A/Ao = \exp [-(0.693 \bullet t / 5.27)]$$

Where t is the time expired. Integrating this equation in time produces the following result:

$$A = Ao \{ - 5.27 \bullet \exp [-(0.693 \bullet t / 5.27)] / 0.693 \}$$

Integrating over 1 year (i.e., t = 1) gives a multiplier of 0.937 and integrating over 10 years gives 5.57. If the time frame is chosen to be very long, the maximum value this multiplier can attain is 7.61. These values can be used along with the fluence rate in MeV per year to estimate the energy absorbed in the wax for the expected timeframe.

REFERENCES

Croff, A. G., 1980, *ORIGEN2—A Revised and Updated Version of the Oak Ridge Generation and Depletion Code*, ORNL-5G21, Oak Ridge National Laboratory, Oak Ridge, Tennessee.

MicroShield, Version 6, Rockville, Maryland: Grove Engineering, 2003.

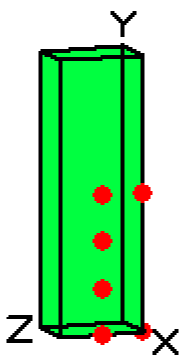
Mullen, Carlen K., Glen R. Longhurst, Michael L. Carboneau, and James W. Sterbentz, 2003, *Beryllium Waste Transuranic Inventory in the Subusrface Disposal Area, Operable Unit 7-13/14*, INEEL/EXT-01-01678, Rev. 2, Idaho National Engineering and Environmental Laboratory, March 2003.

Table B-2. Model Input and Output for the Bare Advanced Test Reactor Beryllium Block on July 1, 2004

Page	:1
DOS File	:ERW2004.MS6
Run Date	: March 12, 2004
Run Time	: 10:19:43 AM
Duration	: 00:02:46

File Ref	:
Date	:
By	:
Checked	:

Case Title: ERW2004
Description: 2004; rectangular vol; wide exposure; 1x ci source
Geometry: 13 - Rectangular Volume



Source Dimensions:

Length	26.04 cm	(10.3 in)
Width	40.15 cm	(1 ft 3.8 in)
Height	129.54 cm	(4 ft 3.0 in)

Dose Points

A	X	Y	Z
# 1	27.31 cm	64.77 cm	20.075 cm
Center Top	10.8 in	2 ft 1.5 in	7.9 in
# 2	27.31 cm	43.18 cm	20.075 cm
Center 2nd	10.8 in	1 ft 5.0 in	7.9 in
# 3	27.31 cm	21.59 cm	20.075 cm
Center 3rd	10.8 in	8.5 in	7.9 in
# 4	27.31 cm	0 cm	20.075 cm
Center Bottom	10.8 in	0.0 in	7.9 in
# 5	27.31 cm	64.77 cm	0 cm
Side Top	10.8 in	2 ft 1.5 in	0.0 in
# 6	27.31 cm	0 cm	0 cm
Side Bottom	10.8 in	0.0 in	0.0 in

Shields

Shield N	Dimension	Material	Density
Source	1.35e+05 cm³	Be	0.60118
Air Gap		Air	0.00122

ORIGEN2 Source Input : Grouping Method - Standard Indices
Number of Groups : 25
Lower Energy Cutoff : 0.015
Photons < 0.015 : Included
Library : Grove

Nuclide	curies	becquerels	µCi/cm³	Bq/cm³
Ac-225	1.5440e-008	5.7128e+002	1.1400e-007	4.2181e-003
Ac-227	1.6170e-008	5.9829e+002	1.1939e-007	4.4175e-003
Ac-228	2.8420e-009	1.0515e+002	2.0984e-008	7.7642e-004
Ag-108	3.7250e-003	1.3783e+008	2.7504e-002	1.0176e+003
Ag-108m	4.1860e-002	1.5488e+009	3.0908e-001	1.1436e+004
Ag-109m	4.9460e-006	1.8300e+005	3.6519e-005	1.3512e+000
Ag-110	1.7624e-010	6.5209e+000	1.3013e-009	4.8148e-005
Ag-110m	1.3252e-008	4.9032e+002	9.7848e-008	3.6204e-003
Am-241	1.7530e-002	6.4861e+008	1.2943e-001	4.7891e+003
Am-242	2.8830e-005	1.0667e+006	2.1287e-004	7.8762e+000
Am-242m	2.8970e-005	1.0719e+006	2.1390e-004	7.9144e+000
Am-243	1.6520e-003	6.1124e+007	1.2198e-002	4.5132e+002
Am-245	1.2410e-015	4.5917e-005	9.1631e-015	3.3903e-010
Am-246	1.3960e-014	5.1652e-004	1.0308e-013	3.8138e-009
Ar-39	1.2580e-002	4.6546e+008	9.2886e-002	3.4368e+003
At-217	1.5440e-008	5.7128e+002	1.1400e-007	4.2181e-003
Ba-133	1.2820e-003	4.7434e+007	9.4658e-003	3.5023e+002
Ba-137m	1.6641e+000	6.1572e+010	1.2287e+001	4.5462e+005
Be-10	3.1450e-001	1.1637e+010	2.3221e+000	8.5920e+004
Bi-208	8.0174e-015	2.9664e-004	5.9197e-014	2.1903e-009
Bi-210	1.2770e-011	4.7249e-001	9.4289e-011	3.4887e-006
Bi-211	1.6200e-008	5.9940e+002	1.1961e-007	4.4257e-003
Bi-212	2.1900e-005	8.1030e+005	1.6170e-004	5.9830e+000
Bi-213	1.5440e-008	5.7128e+002	1.1400e-007	4.2181e-003
Bi-214	6.4770e-012	2.3965e-001	4.7824e-011	1.7695e-006
Bk-249	8.5560e-011	3.1657e+000	6.3174e-010	2.3374e-005
Bk-250	1.9840e-014	7.3408e-004	1.4649e-013	5.4202e-009
C-14	2.4930e+000	9.2241e+010	1.8407e+001	6.8107e+005
Ca-41	3.5400e-003	1.3098e+008	2.6138e-002	9.6711e+002
Ca-45	1.0330e-012	3.8221e-002	7.6273e-012	2.8221e-007
Cd-109	4.9460e-006	1.8300e+005	3.6519e-005	1.3512e+000
Cd-113m	7.7510e-004	2.8679e+007	5.7230e-003	2.1175e+002
Ce-139	9.8780e-019	3.6549e-008	7.2935e-018	2.6986e-013
Ce-144	5.5920e-007	2.0690e+004	4.1289e-006	1.5277e-001
Cf-249	4.9990e-007	1.8496e+004	3.6911e-006	1.3657e-001
Cf-250	2.8600e-006	1.0582e+005	2.1117e-005	7.8134e-001
Cf-251	4.4920e-008	1.6620e+003	3.3167e-007	1.2272e-002
Cf-252	7.3460e-007	2.7180e+004	5.4240e-006	2.0069e-001
Cl-36	1.9570e-002	7.2409e+008	1.4450e-001	5.3464e+003
Cm-242	2.3890e-005	8.8393e+005	1.7639e-004	6.5266e+000
Cm-243	1.7990e-004	6.6563e+006	1.3283e-003	4.9148e+001
Cm-244	8.0330e-001	2.9722e+010	5.9313e+000	2.1946e+005
Cm-245	8.6800e-005	3.2116e+006	6.4090e-004	2.3713e+001
Cm-246	3.1750e-004	1.1748e+007	2.3443e-003	8.6739e+001
Cm-247	2.5220e-009	9.3314e+001	1.8621e-008	6.8900e-004

Nuclide	curies	becquerels	µCi/cm³	Bq/cm³
Cm-248	4.4910e-008	1.6617e+003	3.3160e-007	1.2269e-002
Cm-250	5.5830e-014	2.0657e-003	4.1223e-013	1.5252e-008
Co-58	6.2580e-029	2.3155e-018	4.6207e-028	1.7096e-023
Co-60	2.5000e+001	9.2500e+011	1.8459e+002	6.8299e+006
Cs-134	3.7379e-002	1.3830e+009	2.7599e-001	1.0212e+004
Cs-135	2.2511e-005	8.3291e+005	1.6621e-004	6.1499e+000
Cs-137	1.7596e+000	6.5105e+010	1.2992e+001	4.8071e+005
Es-254	1.2010e-014	4.4437e-004	8.8677e-014	3.2811e-009
Eu-152	9.0650e-005	3.3541e+006	6.6933e-004	2.4765e+001
Eu-154	1.6501e-001	6.1054e+009	1.2184e+000	4.5080e+004
Eu-155	3.7830e-002	1.3997e+009	2.7932e-001	1.0335e+004
Fe-55	6.1250e-001	2.2663e+010	4.5225e+000	1.6733e+005
Fr-221	1.5440e-008	5.7128e+002	1.1400e-007	4.2181e-003
Fr-223	2.2310e-010	8.2547e+000	1.6473e-009	6.0950e-005
Gd-152	1.6120e-017	5.9644e-007	1.1902e-016	4.4039e-012
Gd-153	8.5380e-012	3.1591e-001	6.3041e-011	2.3325e-006
H-3	2.0960e+004	7.7552e+014	1.5476e+005	5.7261e+009
Ho-166m	5.7977e-003	2.1451e+008	4.2808e-002	1.5839e+003
I-125	3.9720e-035	1.4696e-024	2.9328e-034	1.0851e-029
I-129	2.2007e-006	8.1426e+004	1.6249e-005	6.0122e-001
In-113m	8.9650e-020	3.3171e-009	6.6194e-019	2.4492e-014
In-115	2.9484e-016	1.0909e-005	2.1770e-015	8.0549e-011
Ir-192	6.2330e-006	2.3062e+005	4.6022e-005	1.7028e+000
Ir-194	3.8510e-005	1.4249e+006	2.8434e-004	1.0521e+001
K-40	1.4580e-007	5.3946e+003	1.0765e-006	3.9832e-002
K-42	2.7670e-008	1.0238e+003	2.0430e-007	7.5593e-003
Kr-81	1.7350e-003	6.4195e+007	1.2811e-002	4.7399e+002
Kr-85	3.0891e+000	1.1430e+011	2.2809e+001	8.4392e+005
Lu-177	1.7080e-016	6.3196e-006	1.2611e-015	4.6662e-011
Lu-177m	7.4260e-016	2.7476e-005	5.4831e-015	2.0287e-010
Mn-54	2.8830e-006	1.0667e+005	2.1287e-005	7.8762e-001
Mo-93	1.2060e-004	4.4622e+006	8.9047e-004	3.2947e+001
Nb-93m	2.1729e-005	8.0397e+005	1.6044e-004	5.9362e+000
Nb-94	4.9500e-003	1.8315e+008	3.6549e-002	1.3523e+003
Nb-95	4.6194e-031	1.7092e-020	3.4108e-030	1.2620e-025
Nb-95m	1.5440e-033	5.7128e-023	1.1400e-032	4.2181e-028
Ni-59	3.1190e-002	1.1540e+009	2.3030e-001	8.5209e+003
Ni-63	6.8960e+000	2.5515e+011	5.0917e+001	1.8839e+006
Np-235	4.4640e-015	1.6517e-004	3.2960e-014	1.2195e-009
Np-236	6.1040e-013	2.2585e-002	4.5070e-012	1.6676e-007
Np-237	2.5420e-007	9.4054e+003	1.8769e-006	6.9446e-002
Np-238	1.4490e-007	5.3613e+003	1.0699e-006	3.9586e-002
Np-239	1.6520e-003	6.1124e+007	1.2198e-002	4.5132e+002
Np-240m	3.9780e-010	1.4719e+001	2.9372e-009	1.0868e-004
Os-185	1.0280e-029	3.8036e-019	7.5904e-029	2.8084e-024
P-32	9.4540e-009	3.4980e+002	6.9805e-008	2.5828e-003
Pa-231	3.2970e-008	1.2199e+003	2.4344e-007	9.0072e-003
Pa-233	2.5420e-007	9.4054e+003	1.8769e-006	6.9446e-002
Pa-234	6.6910e-010	2.4757e+001	4.9404e-009	1.8279e-004
Pa-234m	5.1470e-007	1.9044e+004	3.8004e-006	1.4061e-001
Pb-205	3.5350e-009	1.3080e+002	2.6101e-008	9.6574e-004
Pb-209	1.5440e-008	5.7128e+002	1.1400e-007	4.2181e-003

Nuclide	curies	becquerels	µCi/cm³	Bq/cm³
Pb-210	1.2760e-011	4.7212e-001	9.4215e-011	3.4860e-006
Pb-211	1.6200e-008	5.9940e+002	1.1961e-007	4.4257e-003
Pb-212	2.1900e-005	8.1030e+005	1.6170e-004	5.9830e+000
Pb-214	6.4770e-012	2.3965e-001	4.7824e-011	1.7695e-006
Pd-107	7.2030e-006	2.6651e+005	5.3184e-005	1.9678e+000
Pm-145	2.4520e-004	9.0724e+006	1.8105e-003	6.6987e+001
Pm-146	5.7940e-006	2.1438e+005	4.2781e-005	1.5829e+000
Pm-147	1.2442e-002	4.6035e+008	9.1867e-002	3.3991e+003
Po-210	1.2790e-011	4.7323e-001	9.4437e-011	3.4942e-006
Po-211	4.5350e-011	1.6780e+000	3.3485e-010	1.2389e-005
Po-212	1.4030e-005	5.1911e+005	1.0359e-004	3.8329e+000
Po-213	1.5100e-008	5.5870e+002	1.1149e-007	4.1252e-003
Po-214	6.4760e-012	2.3961e-001	4.7816e-011	1.7692e-006
Po-215	1.6200e-008	5.9940e+002	1.1961e-007	4.4257e-003
Po-216	2.1900e-005	8.1030e+005	1.6170e-004	5.9830e+000
Po-218	6.4790e-012	2.3972e-001	4.7839e-011	1.7700e-006
Pr-144	5.5920e-007	2.0690e+004	4.1289e-006	1.5277e-001
Pr-144m	6.7110e-009	2.4831e+002	4.9552e-008	1.8334e-003
Pt-193	3.8030e-002	1.4071e+009	2.8080e-001	1.0390e+004
Pu-236	2.5310e-009	9.3647e+001	1.8688e-008	6.9145e-004
Pu-238	8.9250e-003	3.3023e+008	6.5899e-002	2.4383e+003
Pu-239	1.9100e-003	7.0670e+007	1.4103e-002	5.2180e+002
Pu-240	5.4390e-003	2.0124e+008	4.0160e-002	1.4859e+003
Pu-241	3.5870e-001	1.3272e+010	2.6485e+000	9.7995e+004
Pu-242	1.0720e-004	3.9664e+006	7.9152e-004	2.9286e+001
Pu-243	2.5220e-009	9.3314e+001	1.8621e-008	6.8900e-004
Pu-244	3.9830e-010	1.4737e+001	2.9409e-009	1.0881e-004
Pu-246	1.3960e-014	5.1652e-004	1.0308e-013	3.8138e-009
Ra-223	1.6200e-008	5.9940e+002	1.1961e-007	4.4257e-003
Ra-224	2.1900e-005	8.1030e+005	1.6170e-004	5.9830e+000
Ra-225	1.5440e-008	5.7128e+002	1.1400e-007	4.2181e-003
Ra-226	6.4790e-012	2.3972e-001	4.7839e-011	1.7700e-006
Ra-228	2.8420e-009	1.0515e+002	2.0984e-008	7.7642e-004
Rb-87	1.5925e-008	5.8923e+002	1.1758e-007	4.3506e-003
Re-187	2.7120e-008	1.0034e+003	2.0024e-007	7.4090e-003
Re-188	2.8820e-030	1.0663e-019	2.1280e-029	7.8735e-025
Rh-106	2.8830e-005	1.0667e+006	2.1287e-004	7.8762e+000
Rn-219	1.6200e-008	5.9940e+002	1.1961e-007	4.4257e-003
Rn-220	2.1900e-005	8.1030e+005	1.6170e-004	5.9830e+000
Rn-222	6.4790e-012	2.3972e-001	4.7839e-011	1.7700e-006
Ru-106	2.8830e-005	1.0667e+006	2.1287e-004	7.8762e+000
S-35	1.3020e-022	4.8174e-012	9.6135e-022	3.5570e-017
Sb-124	1.6230e-034	6.0051e-024	1.1984e-033	4.4339e-029
Sb-125	3.4250e-003	1.2673e+008	2.5289e-002	9.3569e+002
Sb-126	3.0310e-006	1.1215e+005	2.2380e-005	8.2805e-001
Sb-126m	2.1650e-005	8.0105e+005	1.5986e-004	5.9147e+000
Sc-46	2.1510e-023	7.9587e-013	1.5882e-022	5.8764e-018
Se-75	6.7050e-018	2.4809e-007	4.9507e-017	1.8318e-012
Se-79	6.3716e-005	2.3575e+006	4.7045e-004	1.7407e+001
Si-32	9.4530e-009	3.4976e+002	6.9797e-008	2.5825e-003
Sm-147	1.2153e-010	4.4966e+000	8.9733e-010	3.3201e-005
Sm-151	7.5000e-003	2.7750e+008	5.5377e-002	2.0490e+003

Nuclide	curies	becquerels	µCi/cm³	Bq/cm³
Sn-113	8.9500e-020	3.3115e-009	6.6083e-019	2.4451e-014
Sn-119m	1.6030e-009	5.9311e+001	1.1836e-008	4.3793e-004
Sn-123	7.0050e-018	2.5919e-007	5.1722e-017	1.9137e-012
Sn-126	2.1650e-005	8.0105e+005	1.5986e-004	5.9147e+000
Sr-85	1.8870e-033	6.9819e-023	1.3933e-032	5.1552e-028
Sr-90	5.0500e-001	1.8685e+010	3.7287e+000	1.3796e+005
Ta-182	1.7420e-009	6.4454e+001	1.2862e-008	4.7590e-004
Tb-157	9.8590e-005	3.6478e+006	7.2795e-004	2.6934e+001
Tb-160	1.0734e-027	3.9716e-017	7.9256e-027	2.9325e-022
Tc-97	3.0910e-007	1.1437e+004	2.2823e-006	8.4444e-002
Tc-97m	3.4400e-027	1.2728e-016	2.5400e-026	9.3979e-022
Tc-98	2.0910e-010	7.7367e+000	1.5439e-009	5.7125e-005
Tc-99	2.6249e-004	9.7121e+006	1.9381e-003	7.1711e+001
Te-121	2.1880e-016	8.0956e-006	1.6155e-015	5.9775e-011
Te-121m	2.1970e-016	8.1289e-006	1.6222e-015	6.0021e-011
Te-123	5.3179e-013	1.9676e-002	3.9265e-012	1.4528e-007
Te-123m	2.4475e-017	9.0558e-007	1.8071e-016	6.6864e-012
Te-125m	8.3550e-004	3.0914e+007	6.1690e-003	2.2825e+002
Te-127	2.5255e-019	9.3444e-009	1.8647e-018	6.8995e-014
Te-127m	2.5764e-019	9.5327e-009	1.9023e-018	7.0386e-014
Th-227	1.5980e-008	5.9126e+002	1.1799e-007	4.3656e-003
Th-228	2.1860e-005	8.0882e+005	1.6141e-004	5.9720e+000
Th-229	1.5440e-008	5.7128e+002	1.1400e-007	4.2181e-003
Th-230	9.0610e-010	3.3526e+001	6.6903e-009	2.4754e-004
Th-231	1.9770e-010	7.3149e+000	1.4597e-009	5.4010e-005
Th-232	3.0210e-009	1.1178e+002	2.2306e-008	8.2532e-004
Th-234	5.1470e-007	1.9044e+004	3.8004e-006	1.4061e-001
Tl-204	4.3970e-001	1.6269e+010	3.2466e+000	1.2012e+005
Tl-207	1.6150e-008	5.9755e+002	1.1925e-007	4.4121e-003
Tl-208	7.8680e-006	2.9112e+005	5.8094e-005	2.1495e+000
Tl-209	3.3340e-010	1.2336e+001	2.4617e-009	9.1083e-005
Tm-170	6.1130e-016	2.2618e-005	4.5136e-015	1.6700e-010
Tm-171	6.9230e-004	2.5615e+007	5.1117e-003	1.8913e+002
U-232	2.1290e-005	7.8773e+005	1.5720e-004	5.8163e+000
U-233	6.8790e-006	2.5452e+005	5.0792e-005	1.8793e+000
U-234	2.5860e-006	9.5682e+004	1.9094e-005	7.0648e-001
U-235	1.9770e-010	7.3149e+000	1.4597e-009	5.4010e-005
U-236	1.0900e-007	4.0330e+003	8.0482e-007	2.9778e-002
U-237	8.8010e-006	3.2564e+005	6.4983e-005	2.4044e+000
U-238	5.1470e-007	1.9044e+004	3.8004e-006	1.4061e-001
U-240	3.9780e-010	1.4719e+001	2.9372e-009	1.0868e-004
W-181	1.0840e-017	4.0108e-007	8.0038e-017	2.9614e-012
W-185	2.4820e-026	9.1834e-016	1.8326e-025	6.7807e-021
W-188	2.8530e-030	1.0556e-019	2.1065e-029	7.7942e-025
Y-90	5.0510e-001	1.8689e+010	3.7295e+000	1.3799e+005
Y-91	1.1123e-034	4.1155e-024	8.2128e-034	3.0387e-029
Zn-65	1.6570e-008	6.1309e+002	1.2235e-007	4.5268e-003
Zr-93	3.3313e-005	1.2326e+006	2.4597e-004	9.1009e+000
Zr-95	2.0806e-031	7.6982e-021	1.5362e-030	5.6841e-026

Buildup : The material reference is - Source

Integration Parameters

X Direction	30
Y Direction	40
Z Direction	40

Results - Dose Point # 1, Middle Center - (27.31,64.77,20.075) cm

Energy MeV	Activity Photons/sec	Fluence Rate MeV/cm²/sec No Buildup	Fluence Rate MeV/cm²/sec With Buildup	Exposure Rate mR/hr No Buildup	Exposure Rate mR/hr With Buildup
0.015	2.631e+06	8.046e-01	1.949e+00	6.901e-02	1.672e-01
0.02	1.019e+09	5.455e+02	2.074e+03	1.889e+01	7.185e+01
0.03	3.805e+09	3.619e+03	2.549e+04	3.587e+01	2.527e+02
0.04	2.374e+09	3.193e+03	3.211e+04	1.412e+01	1.420e+02
0.05	4.650e+08	8.101e+02	9.533e+03	2.158e+00	2.540e+01
0.06	3.479e+08	7.473e+02	8.948e+03	1.484e+00	1.777e+01
0.08	7.993e+08	2.394e+03	2.448e+04	3.788e+00	3.873e+01
0.1	2.812e+09	1.094e+04	8.992e+04	1.674e+01	1.376e+02
0.15	1.361e+06	8.589e+00	4.237e+01	1.414e-02	6.978e-02
0.2	6.003e+08	5.375e+03	2.107e+04	9.487e+00	3.718e+01
0.3	1.031e+08	1.518e+03	4.137e+03	2.880e+00	7.848e+00
0.4	1.540e+09	3.239e+04	7.732e+04	6.311e+01	1.507e+02
0.5	5.734e+08	1.589e+04	3.122e+04	3.120e+01	6.127e+01
0.6	5.921e+10	2.057e+06	3.721e+06	4.015e+03	7.262e+03
0.8	5.746e+09	2.847e+05	4.645e+05	5.415e+02	8.835e+02
1.0	9.269e+11	6.042e+07	8.974e+07	1.114e+05	1.654e+05
1.5	9.274e+11	9.910e+07	1.345e+08	1.667e+05	2.262e+05
2.0	1.767e+03	2.668e-01	3.494e-01	4.126e-04	5.403e-04
3.0	2.905e+05	7.080e+01	8.631e+01	9.606e-02	1.171e-01
Totals	1.934e+12	1.619e+08	2.287e+08	2.829e+05	4.007e+05

Results - Dose Point # 2, Middle 2nd Down - (27.31,43.18,20.075) cm

Energy MeV	Activity Photons/sec	Fluence Rate MeV/cm²/sec No Buildup	Fluence Rate MeV/cm²/sec With Buildup	Exposure Rate mR/hr No Buildup	Exposure Rate mR/hr With Buildup
0.015	2.631e+06	8.036e-01	1.946e+00	6.893e-02	1.669e-01
0.02	1.019e+09	5.446e+02	2.064e+03	1.886e+01	7.149e+01
0.03	3.805e+09	3.611e+03	2.515e+04	3.579e+01	2.493e+02
0.04	2.374e+09	3.185e+03	3.147e+04	1.409e+01	1.392e+02
0.05	4.650e+08	8.079e+02	9.306e+03	2.152e+00	2.479e+01
0.06	3.479e+08	7.451e+02	8.712e+03	1.480e+00	1.730e+01
0.08	7.993e+08	2.386e+03	2.377e+04	3.776e+00	3.762e+01
0.1	2.812e+09	1.090e+04	8.732e+04	1.668e+01	1.336e+02
0.15	1.361e+06	8.554e+00	4.122e+01	1.409e-02	6.788e-02
0.2	6.003e+08	5.350e+03	2.053e+04	9.443e+00	3.624e+01
0.3	1.031e+08	1.510e+03	4.045e+03	2.864e+00	7.673e+00
0.4	1.540e+09	3.218e+04	7.576e+04	6.270e+01	1.476e+02
0.5	5.734e+08	1.578e+04	3.062e+04	3.098e+01	6.009e+01
0.6	5.921e+10	2.041e+06	3.652e+06	3.983e+03	7.129e+03
0.8	5.746e+09	2.822e+05	4.564e+05	5.368e+02	8.680e+02
1.0	9.269e+11	5.984e+07	8.823e+07	1.103e+05	1.626e+05

Energy MeV	Activity Photons/sec	Fluence Rate MeV/cm²/sec No Buildup	Fluence Rate MeV/cm²/sec With Buildup	Exposure Rate mR/hr No Buildup	Exposure Rate mR/hr With Buildup
1.5	9.274e+11	9.801e+07	1.322e+08	1.649e+05	2.225e+05
2.0	1.767e+03	2.636e-01	3.436e-01	4.076e-04	5.314e-04
3.0	2.905e+05	6.987e+01	8.490e+01	9.479e-02	1.152e-01
Totals	1.934e+12	1.603e+08	2.249e+08	2.799e+05	3.941e+05

Results - Dose Point # 3, Middle 3rd Down - (27.31,21.59,20.075) cm

Energy MeV	Activity Photons/sec	Fluence Rate MeV/cm²/sec No Buildup	Fluence Rate MeV/cm²/sec With Buildup	Exposure Rate mR/hr No Buildup	Exposure Rate mR/hr With Buildup
0.015	2.631e+06	7.936e-01	1.903e+00	6.807e-02	1.632e-01
0.02	1.019e+09	5.346e+02	1.967e+03	1.852e+01	6.814e+01
0.03	3.805e+09	3.526e+03	2.308e+04	3.495e+01	2.287e+02
0.04	2.374e+09	3.104e+03	2.828e+04	1.373e+01	1.251e+02
0.05	4.650e+08	7.861e+02	8.269e+03	2.094e+00	2.203e+01
0.06	3.479e+08	7.243e+02	7.698e+03	1.439e+00	1.529e+01
0.08	7.993e+08	2.315e+03	2.094e+04	3.664e+00	3.313e+01
0.1	2.812e+09	1.056e+04	7.701e+04	1.616e+01	1.178e+02
0.15	1.361e+06	8.255e+00	3.669e+01	1.359e-02	6.042e-02
0.2	6.003e+08	5.148e+03	1.840e+04	9.086e+00	3.247e+01
0.3	1.031e+08	1.446e+03	3.663e+03	2.743e+00	6.948e+00
0.4	1.540e+09	3.070e+04	6.896e+04	5.982e+01	1.344e+02
0.5	5.734e+08	1.501e+04	2.804e+04	2.947e+01	5.504e+01
0.6	5.921e+10	1.937e+06	3.353e+06	3.780e+03	6.545e+03
0.8	5.746e+09	2.668e+05	4.199e+05	5.075e+02	7.987e+02
1.0	9.269e+11	5.641e+07	8.137e+07	1.040e+05	1.500e+05
1.5	9.274e+11	9.192e+07	1.221e+08	1.547e+05	2.053e+05
2.0	1.767e+03	2.465e-01	3.169e-01	3.811e-04	4.901e-04
3.0	2.905e+05	6.508e+01	7.834e+01	8.829e-02	1.063e-01
Totals	1.934e+12	1.506e+08	2.075e+08	2.631e+05	3.635e+05

Results - Dose Point # 4, Middle Bottom - (27.31,0,20.075) cm

Energy MeV	Activity Photons/sec	Fluence Rate MeV/cm²/sec No Buildup	Fluence Rate MeV/cm²/sec With Buildup	Exposure Rate mR/hr No Buildup	Exposure Rate mR/hr With Buildup
0.015	2.631e+06	4.029e-01	9.766e-01	3.456e-02	8.377e-02
0.02	1.019e+09	2.733e+02	1.041e+03	9.465e+00	3.606e+01
0.03	3.805e+09	1.814e+03	1.289e+04	1.798e+01	1.277e+02
0.04	2.374e+09	1.601e+03	1.638e+04	7.079e+00	7.246e+01
0.05	4.650e+08	4.061e+02	4.907e+03	1.082e+00	1.307e+01
0.06	3.479e+08	3.746e+02	4.640e+03	7.441e-01	9.217e+00
0.08	7.993e+08	1.200e+03	1.282e+04	1.900e+00	2.029e+01
0.1	2.812e+09	5.487e+03	4.735e+04	8.394e+00	7.244e+01
0.15	1.361e+06	4.310e+00	2.241e+01	7.097e-03	3.691e-02
0.2	6.003e+08	2.699e+03	1.114e+04	4.763e+00	1.966e+01
0.3	1.031e+08	7.633e+02	2.179e+03	1.448e+00	4.134e+00
0.4	1.540e+09	1.630e+04	4.055e+04	3.176e+01	7.901e+01
0.5	5.734e+08	8.008e+03	1.639e+04	1.572e+01	3.218e+01
0.6	5.921e+10	1.037e+06	1.951e+06	2.025e+03	3.807e+03

Energy MeV	Activity Photons/sec	Fluence Rate MeV/cm²/sec No Buildup	Fluence Rate MeV/cm²/sec With Buildup	Exposure Rate mR/hr No Buildup	Exposure Rate mR/hr With Buildup
0.8	5.746e+09	1.439e+05	2.430e+05	2.737e+02	4.621e+02
1.0	9.269e+11	3.060e+07	4.695e+07	5.641e+04	8.654e+04
1.5	9.274e+11	5.042e+07	7.030e+07	8.483e+04	1.183e+05
2.0	1.767e+03	1.363e-01	1.828e-01	2.107e-04	2.826e-04
3.0	2.905e+05	3.638e+01	4.526e+01	4.935e-02	6.140e-02
Totals	1.934e+12	8.225e+07	1.196e+08	1.436e+05	2.096e+05

Results - Dose Point # 5, Edge Center - (27.31,64.77,0) cm

Energy MeV	Activity Photons/sec	Fluence Rate MeV/cm²/sec No Buildup	Fluence Rate MeV/cm²/sec With Buildup	Exposure Rate mR/hr No Buildup	Exposure Rate mR/hr With Buildup
0.015	2.631e+06	4.188e-01	1.043e+00	3.592e-02	8.950e-02
0.02	1.019e+09	2.890e+02	1.195e+03	1.001e+01	4.140e+01
0.03	3.805e+09	1.948e+03	1.638e+04	1.931e+01	1.623e+02
0.04	2.374e+09	1.730e+03	2.195e+04	7.650e+00	9.708e+01
0.05	4.650e+08	4.406e+02	6.760e+03	1.174e+00	1.801e+01
0.06	3.479e+08	4.078e+02	6.483e+03	8.100e-01	1.288e+01
0.08	7.993e+08	1.314e+03	1.807e+04	2.079e+00	2.860e+01
0.1	2.812e+09	6.034e+03	6.661e+04	9.232e+00	1.019e+02
0.15	1.361e+06	4.790e+00	3.093e+01	7.889e-03	5.093e-02
0.2	6.003e+08	3.026e+03	1.515e+04	5.342e+00	2.674e+01
0.3	1.031e+08	8.681e+02	2.891e+03	1.647e+00	5.485e+00
0.4	1.540e+09	1.874e+04	5.305e+04	3.651e+01	1.034e+02
0.5	5.734e+08	9.287e+03	2.117e+04	1.823e+01	4.155e+01
0.6	5.921e+10	1.212e+06	2.502e+06	2.365e+03	4.884e+03
0.8	5.746e+09	1.700e+05	3.097e+05	3.233e+02	5.890e+02
1.0	9.269e+11	3.645e+07	5.949e+07	6.719e+04	1.097e+05
1.5	9.274e+11	6.093e+07	8.885e+07	1.025e+05	1.495e+05
2.0	1.767e+03	1.661e-01	2.313e-01	2.569e-04	3.576e-04
3.0	2.905e+05	4.483e+01	5.718e+01	6.082e-02	7.758e-02
Totals	1.934e+12	9.881e+07	1.514e+08	1.725e+05	2.653e+05

Results - Dose Point # 6, Edge Bottom - (27.31,0,0) cm

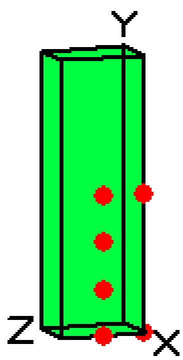
Energy MeV	Activity Photons/sec	Fluence Rate MeV/cm²/sec No Buildup	Fluence Rate MeV/cm²/sec With Buildup	Exposure Rate mR/hr No Buildup	Exposure Rate mR/hr With Buildup
0.015	2.631e+06	2.100e-01	5.235e-01	1.801e-02	4.491e-02
0.02	1.019e+09	1.450e+02	6.010e+02	5.022e+00	2.082e+01
0.03	3.805e+09	9.777e+02	8.313e+03	9.690e+00	8.239e+01
0.04	2.374e+09	8.685e+02	1.127e+04	3.841e+00	4.983e+01
0.05	4.650e+08	2.213e+02	3.505e+03	5.894e-01	9.337e+00
0.06	3.479e+08	2.048e+02	3.390e+03	4.068e-01	6.733e+00
0.08	7.993e+08	6.600e+02	9.561e+03	1.044e+00	1.513e+01
0.1	2.812e+09	3.032e+03	3.546e+04	4.639e+00	5.426e+01
0.15	1.361e+06	2.409e+00	1.658e+01	3.967e-03	2.731e-02
0.2	6.003e+08	1.523e+03	8.129e+03	2.689e+00	1.435e+01
0.3	1.031e+08	4.376e+02	1.547e+03	8.302e-01	2.935e+00
0.4	1.540e+09	9.464e+03	2.827e+04	1.844e+01	5.508e+01

Energy MeV	Activity Photons/sec	Fluence Rate MeV/cm²/sec No Buildup	Fluence Rate MeV/cm²/sec With Buildup	Exposure Rate mR/hr No Buildup	Exposure Rate mR/hr With Buildup
0.5	5.734e+08	4.698e+03	1.131e+04	9.221e+00	2.220e+01
0.6	5.921e+10	6.139e+05	1.335e+06	1.198e+03	2.605e+03
0.8	5.746e+09	8.640e+04	1.648e+05	1.643e+02	3.134e+02
1.0	9.269e+11	1.858e+07	3.167e+07	3.425e+04	5.838e+04
1.5	9.274e+11	3.126e+07	4.728e+07	5.259e+04	7.955e+04
2.0	1.767e+03	8.569e-02	1.231e-01	1.325e-04	1.904e-04
3.0	2.905e+05	2.331e+01	3.055e+01	3.163e-02	4.145e-02
Totals	1.934e+12	5.056e+07	8.057e+07	8.826e+04	1.412e+05

Table B-3. Model Input and Output for the Bare Advanced Test Reactor Beryllium Block on July 1, 2014

Page	:1		File Ref	:
DOS File	:ERW2014.MS6		Date	:
Run Date	: March 12, 2004		By	:
Run Time	: 10:22:35 AM		Checked	:
Duration	: 00:02:49			

Case Title: ERW2014
Description: 2014; rectangular vol; wide exposure; 1x ci source
Geometry: 13 - Rectangular Volume



Source Dimensions:

Length	26.04 cm	(10.3 in)
Width	40.15 cm	(1 ft 3.8 in)
Height	129.54 cm	(4 ft 3.0 in)

Dose Points

A	X	Y	Z
# 1	27.31 cm	64.77 cm	20.075 cm
Middle Center	10.8 in	2 ft 1.5 in	7.9 in
# 2	27.31 cm	43.18 cm	20.075 cm
Middle 2nd Down	10.8 in	1 ft 5.0 in	7.9 in
# 3	27.31 cm	21.59 cm	20.075 cm
Middle 3rd Down	10.8 in	8.5 in	7.9 in
# 4	27.31 cm	0 cm	20.075 cm
Middle Bottom	10.8 in	0.0 in	7.9 in
# 5	27.31 cm	64.77 cm	0 cm
Edge Center	10.8 in	2 ft 1.5 in	0.0 in
# 6	27.31 cm	0 cm	0 cm
Edge Bottom	10.8 in	0.0 in	0.0 in

Shields

Shield N	Dimension	Material	Density
Source	1.35e+05 cm^3	Be	0.60118
Air Gap		Air	0.00122

ORIGEN2 Source Input : Grouping Method - Standard Indices
Number of Groups : 25
Lower Energy Cutoff : 0.015
Photons < 0.015 : Included
Library : Grove

Nuclide	curies	becquerels	µCi/cm³	Bq/cm³
Ac-225	2.1920e-008	8.1104e+002	1.6185e-007	5.9884e-003
Ac-227	2.0750e-008	7.6775e+002	1.5321e-007	5.6688e-003
Ac-228	2.9580e-009	1.0945e+002	2.1841e-008	8.0811e-004
Ag-108	3.5280e-003	1.3054e+008	2.6049e-002	9.6383e+002
Ag-108m	3.9630e-002	1.4663e+009	2.9261e-001	1.0827e+004
Ag-109m	2.1140e-008	7.8218e+002	1.5609e-007	5.7753e-003
Ag-110	7.0238e-015	2.5988e-004	5.1861e-014	1.9189e-009
Ag-110m	5.2806e-013	1.9538e-002	3.8990e-012	1.4426e-007
Am-241	2.1780e-002	8.0586e+008	1.6082e-001	5.9502e+003
Am-242	2.7540e-005	1.0190e+006	2.0335e-004	7.5238e+000
Am-242m	2.7680e-005	1.0242e+006	2.0438e-004	7.5620e+000
Am-243	1.6510e-003	6.1087e+007	1.2190e-002	4.5104e+002
Am-245	4.5550e-019	1.6854e-008	3.3632e-018	1.2444e-013
Am-246	1.3950e-014	5.1615e-004	1.0300e-013	3.8111e-009
Ar-39	1.2260e-002	4.5362e+008	9.0523e-002	3.3494e+003
At-217	2.1920e-008	8.1104e+002	1.6185e-007	5.9884e-003
Ba-133	6.7230e-004	2.4875e+007	4.9640e-003	1.8367e+002
Ba-137m	1.3214e+000	4.8892e+010	9.7567e+000	3.6100e+005
Be-10	3.1450e-001	1.1637e+010	2.3221e+000	8.5920e+004
Bi-208	8.0174e-015	2.9664e-004	5.9197e-014	2.1903e-009
Bi-210	1.1680e-011	4.3216e-001	8.6241e-011	3.1909e-006
Bi-211	2.0770e-008	7.6849e+002	1.5336e-007	5.6742e-003
Bi-212	1.9870e-005	7.3519e+005	1.4671e-004	5.4284e+000
Bi-213	2.1920e-008	8.1104e+002	1.6185e-007	5.9884e-003
Bi-214	1.0880e-011	4.0256e-001	8.0334e-011	2.9724e-006
Bk-249	3.1410e-014	1.1622e-003	2.3192e-013	8.5810e-009
Bk-250	7.8150e-015	2.8916e-004	5.7703e-014	2.1350e-009
C-14	2.4900e+000	9.2130e+010	1.8385e+001	6.8025e+005
Ca-41	3.5400e-003	1.3098e+008	2.6138e-002	9.6711e+002
Ca-45	1.8540e-019	6.8598e-009	1.3689e-018	5.0650e-014
Cd-109	2.1140e-008	7.8218e+002	1.5609e-007	5.7753e-003
Cd-113m	4.8200e-004	1.7834e+007	3.5589e-003	1.3168e+002
Ce-139	1.0140e-026	3.7518e-016	7.4870e-026	2.7702e-021
Ce-144	7.5880e-011	2.8076e+000	5.6027e-010	2.0730e-005
Cf-249	4.9010e-007	1.8134e+004	3.6187e-006	1.3389e-001
Cf-250	1.6840e-006	6.2308e+004	1.2434e-005	4.6006e-001
Cf-251	4.4580e-008	1.6495e+003	3.2916e-007	1.2179e-002
Cf-252	5.3100e-008	1.9647e+003	3.9207e-007	1.4507e-002
Cl-36	1.9570e-002	7.2409e+008	1.4450e-001	5.3464e+003
Cm-242	2.2780e-005	8.4286e+005	1.6820e-004	6.2234e+000
Cm-243	1.4110e-004	5.2207e+006	1.0418e-003	3.8548e+001
Cm-244	5.4780e-001	2.0269e+010	4.0447e+000	1.4966e+005
Cm-245	8.6730e-005	3.2090e+006	6.4038e-004	2.3694e+001
Cm-246	3.1700e-004	1.1729e+007	2.3406e-003	8.6603e+001
Cm-247	2.5220e-009	9.3314e+001	1.8621e-008	6.8900e-004
Cm-248	4.4920e-008	1.6620e+003	3.3167e-007	1.2272e-002

Nuclide	curies	becquerels	µCi/cm³	Bq/cm³
Cm-250	5.5810e-014	2.0650e-003	4.1208e-013	1.5247e-008
Co-58	1.5247e-008			
Co-60	6.7120e+000	2.4834e+011	4.9559e+001	1.8337e+006
Cs-134	1.2969e-003	4.7985e+007	9.5758e-003	3.5431e+002
Cs-135	2.2511e-005	8.3291e+005	1.6621e-004	6.1499e+000
Cs-137	1.3967e+000	5.1678e+010	1.0313e+001	3.8157e+005
Es-254	1.2360e-018	4.5732e-008	9.1262e-018	3.3767e-013
Eu-152	5.4460e-005	2.0150e+006	4.0211e-004	1.4878e+001
Eu-154	7.3710e-002	2.7273e+009	5.4425e-001	2.0137e+004
Eu-155	9.3510e-003	3.4599e+008	6.9044e-002	2.5546e+003
Fe-55	4.2600e-002	1.5762e+009	3.1454e-001	1.1638e+004
Fr-221	2.1920e-008	8.1104e+002	1.6185e-007	5.9884e-003
Fr-223	2.8630e-010	1.0593e+001	2.1139e-009	7.8215e-005
Gd-152	1.7394e-017	6.4358e-007	1.2843e-016	4.7519e-012
Gd-153	2.4480e-016	9.0576e-006	1.8075e-015	6.6878e-011
H-3	1.1960e+004	4.4252e+014	8.8308e+004	3.2674e+009
Ho-166m	5.7647e-003	2.1329e+008	4.2564e-002	1.5749e+003
I-125	1.5749e+003			
I-129	2.2007e-006	8.1426e+004	1.6249e-005	6.0122e-001
In-113m	2.5180e-029	9.3166e-019	1.8592e-028	6.8790e-024
In-115	2.9484e-016	1.0909e-005	2.1770e-015	8.0549e-011
Ir-192	6.0560e-006	2.2407e+005	4.4715e-005	1.6545e+000
Ir-194	1.2130e-005	4.4881e+005	8.9563e-005	3.3138e+000
K-40	1.4580e-007	5.3946e+003	1.0765e-006	3.9832e-002
K-42	2.2430e-008	8.2991e+002	1.6561e-007	6.1277e-003
Kr-81	1.7350e-003	6.4195e+007	1.2811e-002	4.7399e+002
Kr-85	1.6188e+000	5.9896e+010	1.1953e+001	4.4225e+005
Lu-177	1.3800e-023	5.1060e-013	1.0189e-022	3.7701e-018
Lu-177m	6.0000e-023	2.2200e-012	4.4302e-022	1.6392e-017
Mn-54	8.7480e-010	3.2368e+001	6.4592e-009	2.3899e-004
Mo-93	1.2030e-004	4.4511e+006	8.8825e-004	3.2865e+001
Nb-93m	2.5684e-005	9.5031e+005	1.8964e-004	7.0167e+000
Nb-94	4.9490e-003	1.8311e+008	3.6542e-002	1.3520e+003
Nb-95	1.3520e+003			
Nb-95m	1.3520e+003			
Ni-59	3.1190e-002	1.1540e+009	2.3030e-001	8.5209e+003
Ni-63	6.3960e+000	2.3665e+011	4.7226e+001	1.7473e+006
Np-235	7.4750e-018	2.7658e-007	5.5193e-017	2.0421e-012
Np-236	6.1030e-013	2.2581e-002	4.5062e-012	1.6673e-007
Np-237	3.1850e-007	1.1785e+004	2.3517e-006	8.7012e-002
Np-238	1.3840e-007	5.1208e+003	1.0219e-006	3.7810e-002
Np-239	1.6510e-003	6.1087e+007	1.2190e-002	4.5104e+002
Np-240m	3.9780e-010	1.4719e+001	2.9372e-009	1.0868e-004
Os-185	1.0868e-004			
P-32	9.3530e-009	3.4606e+002	6.9059e-008	2.5552e-003
Pa-231	3.2960e-008	1.2195e+003	2.4336e-007	9.0045e-003
Pa-233	3.1850e-007	1.1785e+004	2.3517e-006	8.7012e-002
Pa-234	6.6910e-010	2.4757e+001	4.9404e-009	1.8279e-004
Pa-234m	5.1470e-007	1.9044e+004	3.8004e-006	1.4061e-001
Pb-205	3.5350e-009	1.3080e+002	2.6101e-008	9.6574e-004
Pb-209	2.1920e-008	8.1104e+002	1.6185e-007	5.9884e-003
Pb-210	1.1670e-011	4.3179e-001	8.6167e-011	3.1882e-006

Nuclide	curies	becquerels	µCi/cm³	Bq/cm³
Pb-211	2.0770e-008	7.6849e+002	1.5336e-007	5.6742e-003
Pb-212	1.9870e-005	7.3519e+005	1.4671e-004	5.4284e+000
Pb-214	1.0880e-011	4.0256e-001	8.0334e-011	2.9724e-006
Pd-107	7.2030e-006	2.6651e+005	5.3184e-005	1.9678e+000
Pm-145	1.6580e-004	6.1346e+006	1.2242e-003	4.5296e+001
Pm-146	1.6430e-006	6.0791e+004	1.2131e-005	4.4886e-001
Pm-147	8.8621e-004	3.2790e+007	6.5434e-003	2.4211e+002
Po-210	1.1680e-011	4.3216e-001	8.6241e-011	3.1909e-006
Po-211	5.8160e-011	2.1519e+000	4.2943e-010	1.5889e-005
Po-212	1.2730e-005	4.7101e+005	9.3994e-005	3.4778e+000
Po-213	2.1440e-008	7.9328e+002	1.5830e-007	5.8573e-003
Po-214	1.0880e-011	4.0256e-001	8.0334e-011	2.9724e-006
Po-215	2.0770e-008	7.6849e+002	1.5336e-007	5.6742e-003
Po-216	1.9870e-005	7.3519e+005	1.4671e-004	5.4284e+000
Po-218	1.0890e-011	4.0293e-001	8.0408e-011	2.9751e-006
Pr-144	7.5880e-011	2.8076e+000	5.6027e-010	2.0730e-005
Pr-144m	9.1060e-013	3.3692e-002	6.7235e-012	2.4877e-007
Pt-193	3.7510e-002	1.3879e+009	2.7696e-001	1.0248e+004
Pu-236	2.2270e-010	8.2399e+000	1.6443e-009	6.0840e-005
Pu-238	8.2490e-003	3.0521e+008	6.0908e-002	2.2536e+003
Pu-239	1.9100e-003	7.0670e+007	1.4103e-002	5.2180e+002
Pu-240	6.1400e-003	2.2718e+008	4.5335e-002	1.6774e+003
Pu-241	2.2170e-001	8.2029e+009	1.6369e+000	6.0567e+004
Pu-242	1.0720e-004	3.9664e+006	7.9152e-004	2.9286e+001
Pu-243	2.5220e-009	9.3314e+001	1.8621e-008	6.8900e-004
Pu-244	3.9830e-010	1.4737e+001	2.9409e-009	1.0881e-004
Pu-246	1.3950e-014	5.1615e-004	1.0300e-013	3.8111e-009
Ra-223	2.0770e-008	7.6849e+002	1.5336e-007	5.6742e-003
Ra-224	1.9870e-005	7.3519e+005	1.4671e-004	5.4284e+000
Ra-225	2.1920e-008	8.1104e+002	1.6185e-007	5.9884e-003
Ra-226	1.0890e-011	4.0293e-001	8.0408e-011	2.9751e-006
Ra-228	2.9570e-009	1.0941e+002	2.1833e-008	8.0783e-004
Rb-87	1.5925e-008	5.8923e+002	1.1758e-007	4.3506e-003
Re-187	2.7120e-008	1.0034e+003	2.0024e-007	7.4090e-003
Re-188	7.4090e-003			
Rh-106	2.9780e-008	1.1019e+003	2.1988e-007	8.1357e-003
Rn-219	2.0770e-008	7.6849e+002	1.5336e-007	5.6742e-003
Rn-220	1.9870e-005	7.3519e+005	1.4671e-004	5.4284e+000
Rn-222	1.0890e-011	4.0293e-001	8.0408e-011	2.9751e-006
Ru-106	2.9780e-008	1.1019e+003	2.1988e-007	8.1357e-003
S-35	4.1890e-035	1.5499e-024	3.0930e-034	1.1444e-029
Sb-124	1.1444e-029			
Sb-125	2.8050e-004	1.0379e+007	2.0711e-003	7.6631e+001
Sb-126	3.0310e-006	1.1215e+005	2.2380e-005	8.2805e-001
Sb-126m	2.1650e-005	8.0105e+005	1.5986e-004	5.9147e+000
Sc-46	1.6340e-036	6.0458e-026	1.2065e-035	4.4640e-031
Se-75	4.4580e-027	1.6495e-016	3.2916e-026	1.2179e-021
Se-79	6.3705e-005	2.3571e+006	4.7037e-004	1.7404e+001
Si-32	9.3530e-009	3.4606e+002	6.9059e-008	2.5552e-003
Sm-147	1.2181e-010	4.5070e+000	8.9940e-010	3.3278e-005
Sm-151	6.9450e-003	2.5697e+008	5.1279e-002	1.8973e+003
Sn-113	2.5170e-029	9.3129e-019	1.8585e-028	6.8763e-024

Nuclide	curies	becquerels	µCi/cm³	Bq/cm³
Sn-119m	5.2261e-014	1.9337e-003	3.8588e-013	1.4277e-008
Sn-123	2.1588e-026	7.9876e-016	1.5940e-025	5.8977e-021
Sn-126	2.1650e-005	8.0105e+005	1.5986e-004	5.9147e+000
Sr-85	5.9147e+000			
Sr-90	3.9800e-001	1.4726e+010	2.9387e+000	1.0873e+005
Ta-182	1.7420e-009	6.4454e+001	1.2862e-008	4.7590e-004
Tb-157	9.4140e-005	3.4832e+006	6.9509e-004	2.5718e+001
Tb-160	2.5718e+001			
Tc-97	3.0910e-007	1.1437e+004	2.2823e-006	8.4444e-002
Tc-97m	2.0340e-039	7.5258e-029	1.5018e-038	5.5568e-034
Tc-98	2.0910e-010	7.7367e+000	1.5439e-009	5.7125e-005
Tc-99	2.6249e-004	9.7121e+006	1.9381e-003	7.1711e+001
Te-121	1.5980e-023	5.9126e-013	1.1799e-022	4.3656e-018
Te-121m	1.6050e-023	5.9385e-013	1.1851e-022	4.3848e-018
Te-123	5.3179e-013	1.9676e-002	3.9265e-012	1.4528e-007
Te-123m	1.5943e-026	5.8989e-016	1.1772e-025	4.3555e-021
Te-125m	6.8440e-005	2.5323e+006	5.0534e-004	1.8697e+001
Te-127	2.0732e-029	7.6708e-019	1.5308e-028	5.6639e-024
Te-127m	2.1165e-029	7.8311e-019	1.5627e-028	5.7822e-024
Th-227	2.0490e-008	7.5813e+002	1.5129e-007	5.5977e-003
Th-228	1.9870e-005	7.3519e+005	1.4671e-004	5.4284e+000
Th-229	2.1920e-008	8.1104e+002	1.6185e-007	5.9884e-003
Th-230	1.1500e-009	4.2550e+001	8.4912e-009	3.1417e-004
Th-231	2.1650e-010	8.0105e+000	1.5986e-009	5.9147e-005
Th-232	3.0210e-009	1.1178e+002	2.2306e-008	8.2532e-004
Th-234	5.1470e-007	1.9044e+004	3.8004e-006	1.4061e-001
Tl-204	7.0980e-002	2.6263e+009	5.2409e-001	1.9391e+004
Tl-207	2.0720e-008	7.6664e+002	1.5299e-007	5.6606e-003
Tl-208	7.1390e-006	2.6414e+005	5.2712e-005	1.9503e+000
Tl-209	4.7340e-010	1.7516e+001	3.4954e-009	1.2933e-004
Tm-170	1.7250e-024	6.3825e-014	1.2737e-023	4.7126e-019
Tm-171	1.8730e-005	6.9301e+005	1.3830e-004	5.1169e+000
U-232	1.9330e-005	7.1521e+005	1.4273e-004	5.2808e+000
U-233	6.8790e-006	2.5452e+005	5.0792e-005	1.8793e+000
U-234	2.8290e-006	1.0467e+005	2.0888e-005	7.7287e-001
U-235	2.1650e-010	8.0105e+000	1.5986e-009	5.9147e-005
U-236	1.1070e-007	4.0959e+003	8.1737e-007	3.0243e-002
U-237	5.4390e-006	2.0124e+005	4.0160e-005	1.4859e+000
U-238	5.1470e-007	1.9044e+004	3.8004e-006	1.4061e-001
U-240	3.9780e-010	1.4719e+001	2.9372e-009	1.0868e-004
W-181	9.1850e-027	3.3985e-016	6.7819e-026	2.5093e-021
W-185	2.5093e-021			
W-188	2.5093e-021			
Y-90	3.9810e-001	1.4730e+010	2.9394e+000	1.0876e+005
Y-91	1.0876e+005			
Zn-65	5.1430e-013	1.9029e-002	3.7974e-012	1.4050e-007
Zr-93	3.3313e-005	1.2326e+006	2.4597e-004	9.1009e+000
Zr-95	9.1009e+000			

Buildup : The material reference is - Source
Integration Parameters

X Direction	30
Y Direction	40
Z Direction	40

Results - Dose Point # 1, Middle Center - (27.31,64.77,20.075) cm

Energy MeV	Activity Photons/sec	Fluence Rate MeV/cm²/sec No Buildup	Fluence Rate MeV/cm²/sec With Buildup	Exposure Rate mR/hr No Buildup	Exposure Rate mR/hr With Buildup
0.015	2.639e+06	8.070e-01	1.955e+00	6.922e-02	1.677e-01
0.02	9.643e+08	5.163e+02	1.964e+03	1.789e+01	6.802e+01
0.03	2.939e+09	2.795e+03	1.969e+04	2.770e+01	1.952e+02
0.04	1.308e+09	1.759e+03	1.768e+04	7.779e+00	7.821e+01
0.05	2.270e+08	3.955e+02	4.654e+03	1.054e+00	1.240e+01
0.06	3.300e+08	7.089e+02	8.489e+03	1.408e+00	1.686e+01
0.08	3.160e+08	9.463e+02	9.676e+03	1.498e+00	1.531e+01
0.1	1.226e+09	4.768e+03	3.919e+04	7.295e+00	5.996e+01
0.15	9.234e+05	5.828e+00	2.875e+01	9.596e-03	4.734e-02
0.2	3.594e+08	3.218e+03	1.261e+04	5.679e+00	2.226e+01
0.3	9.537e+07	1.405e+03	3.828e+03	2.665e+00	7.262e+00
0.4	1.390e+09	2.922e+04	6.976e+04	5.694e+01	1.359e+02
0.5	2.980e+08	8.259e+03	1.622e+04	1.621e+01	3.184e+01
0.6	4.568e+10	1.587e+06	2.870e+06	3.097e+03	5.603e+03
0.8	3.095e+09	1.534e+05	2.502e+05	2.917e+02	4.759e+02
1.0	2.492e+11	1.624e+07	2.413e+07	2.994e+04	4.447e+04
1.5	2.494e+11	2.665e+07	3.616e+07	4.484e+04	6.084e+04
2.0	1.458e+03	2.201e-01	2.883e-01	3.404e-04	4.458e-04
3.0	2.636e+05	6.424e+01	7.832e+01	8.716e-02	1.063e-01
Totals	5.568e+11	4.469e+07	6.361e+07	7.832e+04	1.120e+05

Results - Dose Point # 2, Middle 2nd Down - (27.31,43.18,20.075) cm

Energy MeV	Activity Photons/sec	Fluence Rate MeV/cm²/sec No Buildup	Fluence Rate MeV/cm²/sec With Buildup	Exposure Rate mR/hr No Buildup	Exposure Rate mR/hr With Buildup
0.015	2.639e+06	8.060e-01	1.952e+00	6.913e-02	1.674e-01
0.02	9.643e+08	5.155e+02	1.954e+03	1.786e+01	6.768e+01
0.03	2.939e+09	2.789e+03	1.943e+04	2.764e+01	1.926e+02
0.04	1.308e+09	1.754e+03	1.733e+04	7.759e+00	7.667e+01
0.05	2.270e+08	3.944e+02	4.543e+03	1.051e+00	1.210e+01
0.06	3.300e+08	7.068e+02	8.264e+03	1.404e+00	1.642e+01
0.08	3.160e+08	9.433e+02	9.398e+03	1.493e+00	1.487e+01
0.1	1.226e+09	4.752e+03	3.806e+04	7.270e+00	5.823e+01
0.15	9.234e+05	5.804e+00	2.797e+01	9.557e-03	4.606e-02
0.2	3.594e+08	3.203e+03	1.229e+04	5.653e+00	2.169e+01
0.3	9.537e+07	1.397e+03	3.743e+03	2.650e+00	7.100e+00

Energy MeV	Activity Photons/sec	Fluence Rate MeV/cm²/sec No Buildup	Fluence Rate MeV/cm²/sec With Buildup	Exposure Rate mR/hr No Buildup	Exposure Rate mR/hr With Buildup
0.4	1.390e+09	2.903e+04	6.836e+04	5.657e+01	1.332e+02
0.5	2.980e+08	8.200e+03	1.591e+04	1.610e+01	3.122e+01
0.6	4.568e+10	1.574e+06	2.818e+06	3.073e+03	5.500e+03
0.8	3.095e+09	1.520e+05	2.458e+05	2.892e+02	4.676e+02
1.0	2.492e+11	1.609e+07	2.372e+07	2.966e+04	4.372e+04
1.5	2.494e+11	2.636e+07	3.557e+07	4.435e+04	5.984e+04
2.0	1.458e+03	2.175e-01	2.835e-01	3.363e-04	4.385e-04
3.0	2.636e+05	6.339e+01	7.703e+01	8.601e-02	1.045e-01
Totals	5.568e+11	4.423e+07	6.255e+07	7.751e+04	1.102e+05

Results - Dose Point # 3, Middle 3rd Down - (27.31,21.59,20.075) cm

Energy MeV	Activity Photons/sec	Fluence Rate MeV/cm²/sec No Buildup	Fluence Rate MeV/cm²/sec With Buildup	Exposure Rate mR/hr No Buildup	Exposure Rate mR/hr With Buildup
0.015	2.639e+06	7.960e-01	1.909e+00	6.827e-02	1.637e-01
0.02	9.643e+08	5.060e+02	1.862e+03	1.753e+01	6.450e+01
0.03	2.939e+09	2.724e+03	1.783e+04	2.699e+01	1.767e+02
0.04	1.308e+09	1.709e+03	1.558e+04	7.561e+00	6.889e+01
0.05	2.270e+08	3.838e+02	4.037e+03	1.022e+00	1.075e+01
0.06	3.300e+08	6.871e+02	7.302e+03	1.365e+00	1.450e+01
0.08	3.160e+08	9.152e+02	8.276e+03	1.448e+00	1.310e+01
0.1	1.226e+09	4.603e+03	3.357e+04	7.041e+00	5.135e+01
0.15	9.234e+05	5.601e+00	2.490e+01	9.224e-03	4.100e-02
0.2	3.594e+08	3.082e+03	1.101e+04	5.439e+00	1.944e+01
0.3	9.537e+07	1.338e+03	3.389e+03	2.538e+00	6.429e+00
0.4	1.390e+09	2.770e+04	6.222e+04	5.397e+01	1.212e+02
0.5	2.980e+08	7.800e+03	1.457e+04	1.531e+01	2.860e+01
0.6	4.568e+10	1.494e+06	2.587e+06	2.916e+03	5.049e+03
0.8	3.095e+09	1.437e+05	2.262e+05	2.734e+02	4.302e+02
1.0	2.492e+11	1.516e+07	2.187e+07	2.795e+04	4.032e+04
1.5	2.494e+11	2.472e+07	3.282e+07	4.159e+04	5.522e+04
2.0	1.458e+03	2.034e-01	2.615e-01	3.145e-04	4.044e-04
3.0	2.636e+05	5.905e+01	7.108e+01	8.011e-02	9.643e-02
Totals	5.568e+11	4.158e+07	5.769e+07	7.288e+04	1.016e+05

Results - Dose Point # 4, Middle Bottom - (27.31,0,20.075) cm

Energy MeV	Activity Photons/sec	Fluence Rate MeV/cm²/sec No Buildup	Fluence Rate MeV/cm²/sec With Buildup	Exposure Rate mR/hr No Buildup	Exposure Rate mR/hr With Buildup
0.015	2.639e+06	4.041e-01	9.795e-01	3.466e-02	8.402e-02
0.02	9.643e+08	2.587e+02	9.855e+02	8.960e+00	3.414e+01
0.03	2.939e+09	1.401e+03	9.955e+03	1.388e+01	9.866e+01
0.04	1.308e+09	8.816e+02	9.024e+03	3.899e+00	3.991e+01
0.05	2.270e+08	1.983e+02	2.396e+03	5.282e-01	6.383e+00
0.06	3.300e+08	3.554e+02	4.402e+03	7.059e-01	8.743e+00
0.08	3.160e+08	4.745e+02	5.068e+03	7.509e-01	8.020e+00

Energy MeV	Activity Photons/sec	Fluence Rate MeV/cm²/sec No Buildup	Fluence Rate MeV/cm²/sec With Buildup	Exposure Rate mR/hr No Buildup	Exposure Rate mR/hr With Buildup
0.1	1.226e+09	2.391e+03	2.064e+04	3.659e+00	3.158e+01
0.15	9.234e+05	2.924e+00	1.521e+01	4.816e-03	2.504e-02
0.2	3.594e+08	1.616e+03	6.669e+03	2.852e+00	1.177e+01
0.3	9.537e+07	7.062e+02	2.016e+03	1.340e+00	3.825e+00
0.4	1.390e+09	1.471e+04	3.659e+04	2.865e+01	7.129e+01
0.5	2.980e+08	4.161e+03	8.518e+03	8.168e+00	1.672e+01
0.6	4.568e+10	8.004e+05	1.505e+06	1.562e+03	2.937e+03
0.8	3.095e+09	7.753e+04	1.309e+05	1.475e+02	2.489e+02
1.0	2.492e+11	8.227e+06	1.262e+07	1.517e+04	2.326e+04
1.5	2.494e+11	1.356e+07	1.891e+07	2.281e+04	3.181e+04
2.0	1.458e+03	1.124e-01	1.508e-01	1.739e-04	2.332e-04
3.0	2.636e+05	3.301e+01	4.106e+01	4.478e-02	5.571e-02
Totals	5.568e+11	2.269e+07	3.327e+07	3.976e+04	5.859e+04

Results - Dose Point # 5, Edge Center - (27.31,64.77,0) cm

Energy MeV	Activity Photons/sec	Fluence Rate MeV/cm²/sec No Buildup	Fluence Rate MeV/cm²/sec With Buildup	Exposure Rate mR/hr No Buildup	Exposure Rate mR/hr With Buildup
0.015	2.639e+06	4.200e-01	1.047e+00	3.603e-02	8.977e-02
0.02	9.643e+08	2.736e+02	1.131e+03	9.476e+00	3.919e+01
0.03	2.939e+09	1.505e+03	1.265e+04	1.491e+01	1.254e+02
0.04	1.308e+09	9.527e+02	1.209e+04	4.214e+00	5.347e+01
0.05	2.270e+08	2.151e+02	3.300e+03	5.731e-01	8.792e+00
0.06	3.300e+08	3.868e+02	6.150e+03	7.684e-01	1.222e+01
0.08	3.160e+08	5.194e+02	7.145e+03	8.219e-01	1.131e+01
0.1	1.226e+09	2.630e+03	2.903e+04	4.024e+00	4.441e+01
0.15	9.234e+05	3.250e+00	2.099e+01	5.353e-03	3.456e-02
0.2	3.594e+08	1.812e+03	9.070e+03	3.198e+00	1.601e+01
0.3	9.537e+07	8.032e+02	2.675e+03	1.524e+00	5.075e+00
0.4	1.390e+09	1.691e+04	4.786e+04	3.294e+01	9.326e+01
0.5	2.980e+08	4.825e+03	1.100e+04	9.472e+00	2.159e+01
0.6	4.568e+10	9.348e+05	1.930e+06	1.825e+03	3.768e+03
0.8	3.095e+09	9.157e+04	1.668e+05	1.742e+02	3.173e+02
1.0	2.492e+11	9.800e+06	1.599e+07	1.806e+04	2.948e+04
1.5	2.494e+11	1.639e+07	2.390e+07	2.757e+04	4.020e+04
2.0	1.458e+03	1.371e-01	1.908e-01	2.120e-04	2.951e-04
3.0	2.636e+05	4.067e+01	5.188e+01	5.518e-02	7.039e-02
Totals	5.568e+11	2.724e+07	4.213e+07	4.771e+04	7.420e+04

Results - Dose Point # 6, Edge Bottom - (27.31,0,0) cm

Energy MeV	Activity Photons/sec	Fluence Rate MeV/cm²/sec No Buildup	Fluence Rate MeV/cm²/sec With Buildup	Exposure Rate mR/hr No Buildup	Exposure Rate mR/hr With Buildup
0.015	2.639e+06	2.106e-01	5.251e-01	1.806e-02	4.504e-02
0.02	9.643e+08	1.372e+02	5.689e+02	4.754e+00	1.971e+01
0.03	2.939e+09	7.552e+02	6.421e+03	7.484e+00	6.363e+01
0.04	1.308e+09	4.783e+02	6.206e+03	2.116e+00	2.745e+01
0.05	2.270e+08	1.080e+02	1.711e+03	2.878e-01	4.558e+00
0.06	3.300e+08	1.943e+02	3.216e+03	3.859e-01	6.387e+00

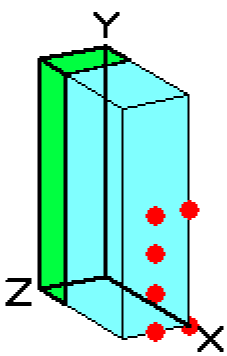
Energy MeV	Activity Photons/sec	Fluence Rate MeV/cm²/sec No Buildup	Fluence Rate MeV/cm²/sec With Buildup	Exposure Rate mR/hr No Buildup	Exposure Rate mR/hr With Buildup
0.08	3.160e+08	2.609e+02	3.779e+03	4.129e-01	5.981e+00
0.1	1.226e+09	1.322e+03	1.546e+04	2.022e+00	2.365e+01
0.15	9.234e+05	1.635e+00	1.125e+01	2.692e-03	1.853e-02
0.2	3.594e+08	9.120e+02	4.867e+03	1.610e+00	8.589e+00
0.3	9.537e+07	4.049e+02	1.432e+03	7.681e-01	2.716e+00
0.4	1.390e+09	8.538e+03	2.551e+04	1.664e+01	4.970e+01
0.5	2.980e+08	2.441e+03	5.876e+03	4.791e+00	1.153e+01
0.6	4.568e+10	4.736e+05	1.030e+06	9.245e+02	2.010e+03
0.8	3.095e+09	4.654e+04	8.876e+04	8.852e+01	1.688e+02
1.0	2.492e+11	4.995e+06	8.514e+06	9.208e+03	1.569e+04
1.5	2.494e+11	8.406e+06	1.272e+07	1.414e+04	2.139e+04
2.0	1.458e+03	7.071e-02	1.016e-01	1.093e-04	1.571e-04
3.0	2.636e+05	2.115e+01	2.772e+01	2.870e-02	3.761e-02
Totals	5.568e+11	1.394e+07	2.242e+07	2.441e+04	3.949e+04

Table B-4. Model Input and Output for the Advanced Test Reactor Beryllium Block With Paraffin Wax on July 1, 2004

Page	:1
DOS File	:ERWW2004.MS6
Run Date	: March 12, 2004
Run Time	: 9:54:58 AM
Duration	: 00:02:53

File Ref	:
Date	:
By	:
Checked	:

Case Title: ERWW2004
Description: 2004; rectangular vol; wide exposure; 1x ci source; w/ wax
Geometry: 13 - Rectangular Volume



Source Dimensions:

Length	26.04 cm	(10.3 in)
Width	40.15 cm	(1 ft 3.8 in)
Height	129.54 cm	(4 ft 3.0 in)

Dose Points

A	X	Y	Z
# 1	88.27 cm	64.77 cm	20.075 cm
Middle Center	2 ft 10.8 in	2 ft 1.5 in	7.9 in
# 2	88.27 cm	43.18 cm	20.075 cm
Middle 2nd Down	2 ft 10.8 in	1 ft 5.0 in	7.9 in
# 3	88.27 cm	21.59 cm	20.075 cm
Middle 3rd Down	2 ft 10.8 in	8.5 in	7.9 in
# 4	88.27 cm	0 cm	20.075 cm
Middle Bottom	2 ft 10.8 in	0.0 in	7.9 in
# 5	88.27 cm	64.77 cm	0 cm
Edge Center	2 ft 10.8 in	2 ft 1.5 in	0.0 in
# 6	88.27 cm	0 cm	0 cm
Edge Bottom	2 ft 10.8 in	0.0 in	0.0 in

Shields

Shield N	Dimension	Material	Density
Source	1.35e+05 cm³	Be	0.60118
Shield 1	60.96 cm	WAX	0.88
Air Gap		Air	0.00122

Buildup : The material reference is - Shield 1
Integration Parameters

X Direction	30
Y Direction	40
Z Direction	40

Results - Dose Point # 1, Middle Center - (88.27,64.77,20.075) cm

Energy MeV	Activity Photons/sec	Fluence Rate MeV/cm²/sec No Buildup	Fluence Rate MeV/cm²/sec With Buildup	Exposure Rate mR/hr No Buildup	Exposure Rate mR/hr With Buildup
0.015	2.631e+06	1.494e-18	1.248e-17	1.281e-19	1.070e-18
0.02	1.019e+09	1.084e-08	3.471e-07	3.755e-10	1.202e-08
0.03	3.805e+09	2.133e-04	4.424e-02	2.114e-06	4.384e-04
0.04	2.374e+09	1.445e-03	1.214e+00	6.391e-06	5.368e-03
0.05	4.650e+08	8.829e-04	1.540e+00	2.352e-06	4.102e-03
0.06	3.479e+08	1.395e-03	3.406e+00	2.771e-06	6.765e-03
0.08	7.993e+08	9.135e-03	2.411e+01	1.446e-05	3.816e-02
0.1	2.812e+09	7.087e-02	1.484e+02	1.084e-04	2.271e-01
0.15	1.361e+06	1.494e-04	1.508e-01	2.461e-07	2.484e-04
0.2	6.003e+08	1.953e-01	8.861e+01	3.447e-04	1.564e-01
0.3	1.031e+08	1.552e-01	2.458e+01	2.943e-04	4.663e-02
0.4	1.540e+09	6.767e+00	5.235e+02	1.319e-02	1.020e+00
0.5	5.734e+08	5.677e+00	2.609e+02	1.114e-02	5.122e-01
0.6	5.921e+10	1.123e+03	3.474e+04	2.191e+00	6.781e+01
0.8	5.746e+09	2.932e+02	5.133e+03	5.576e-01	9.764e+00
1.0	9.269e+11	9.920e+04	1.172e+06	1.829e+02	2.161e+03
1.5	9.274e+11	3.521e+05	2.286e+06	5.924e+02	3.845e+03
2.0	1.767e+03	1.534e-03	7.089e-03	2.372e-06	1.096e-05
3.0	2.905e+05	7.286e-01	2.278e+00	9.885e-04	3.090e-03
Totals	1.934e+12	4.528e+05	3.499e+06	7.781e+02	6.086e+03

Results - Dose Point # 2, Middle 2nd Down - (88.27,43.18,20.075) cm

Energy MeV	Activity Photons/sec	Fluence Rate MeV/cm²/sec No Buildup	Fluence Rate MeV/cm²/sec With Buildup	Exposure Rate mR/hr No Buildup	Exposure Rate mR/hr With Buildup
0.015	2.631e+06	1.494e-18	1.248e-17	1.281e-19	1.070e-18
0.02	1.019e+09	1.082e-08	3.462e-07	3.747e-10	1.199e-08
0.03	3.805e+09	2.113e-04	4.367e-02	2.094e-06	4.328e-04
0.04	2.374e+09	1.426e-03	1.189e+00	6.306e-06	5.259e-03
0.05	4.650e+08	8.692e-04	1.501e+00	2.315e-06	3.998e-03
0.06	3.479e+08	1.371e-03	3.309e+00	2.724e-06	6.573e-03
0.08	7.993e+08	8.957e-03	2.333e+01	1.417e-05	3.692e-02
0.1	2.812e+09	6.936e-02	1.432e+02	1.061e-04	2.191e-01
0.15	1.361e+06	1.456e-04	1.449e-01	2.398e-07	2.386e-04
0.2	6.003e+08	1.897e-01	8.492e+01	3.349e-04	1.499e-01
0.3	1.031e+08	1.500e-01	2.348e+01	2.846e-04	4.455e-02
0.4	1.540e+09	6.519e+00	4.994e+02	1.270e-02	9.730e-01
0.5	5.734e+08	5.455e+00	2.486e+02	1.071e-02	4.879e-01
0.6	5.921e+10	1.076e+03	3.307e+04	2.101e+00	6.455e+01
0.8	5.746e+09	2.803e+02	4.881e+03	5.332e-01	9.285e+00
1.0	9.269e+11	9.467e+04	1.114e+06	1.745e+02	2.054e+03
1.5	9.274e+11	3.353e+05	2.172e+06	5.641e+02	3.655e+03
2.0	1.767e+03	1.459e-03	6.740e-03	2.256e-06	1.042e-05
3.0	2.905e+05	6.932e-01	2.168e+00	9.404e-04	2.942e-03
Totals	1.934e+12	4.313e+05	3.325e+06	7.413e+02	5.784e+03

Results - Dose Point # 3, Middle 3rd Down - (88.27,21.59,20.075) cm

Energy MeV	Activity Photons/sec	Fluence Rate MeV/cm²/sec No Buildup	Fluence Rate MeV/cm²/sec With Buildup	Exposure Rate mR/hr No Buildup	Exposure Rate mR/hr With Buildup
0.015	2.631e+06	1.457e-18	1.216e-17	1.249e-19	1.043e-18
0.02	1.019e+09	1.011e-08	3.218e-07	3.500e-10	1.115e-08
0.03	3.805e+09	1.892e-04	3.861e-02	1.875e-06	3.826e-04
0.04	2.374e+09	1.259e-03	1.030e+00	5.569e-06	4.555e-03
0.05	4.650e+08	7.626e-04	1.287e+00	2.031e-06	3.429e-03
0.06	3.479e+08	1.198e-03	2.821e+00	2.380e-06	5.603e-03
0.08	7.993e+08	7.782e-03	1.975e+01	1.231e-05	3.125e-02
0.1	2.812e+09	6.000e-02	1.207e+02	9.180e-05	1.847e-01
0.15	1.361e+06	1.250e-04	1.215e-01	2.058e-07	2.000e-04
0.2	6.003e+08	1.619e-01	7.104e+01	2.857e-04	1.254e-01
0.3	1.031e+08	1.270e-01	1.959e+01	2.409e-04	3.716e-02
0.4	1.540e+09	5.493e+00	4.164e+02	1.070e-02	8.112e-01
0.5	5.734e+08	4.582e+00	2.072e+02	8.994e-03	4.067e-01
0.6	5.921e+10	9.025e+02	2.758e+04	1.761e+00	5.383e+01
0.8	5.746e+09	2.345e+02	4.076e+03	4.460e-01	7.752e+00
1.0	9.269e+11	7.914e+04	9.318e+05	1.459e+02	1.717e+03
1.5	9.274e+11	2.806e+05	1.825e+06	4.720e+02	3.071e+03
2.0	1.767e+03	1.224e-03	5.688e-03	1.893e-06	8.796e-06
3.0	2.905e+05	5.847e-01	1.843e+00	7.933e-04	2.501e-03
Totals	1.934e+12	3.609e+05	2.789e+06	6.202e+02	4.852e+03

Results - Dose Point # 4, Middle Bottom - (88.27,0,20.075) cm

Energy MeV	Activity Photons/sec	Fluence Rate MeV/cm²/sec No Buildup	Fluence Rate MeV/cm²/sec With Buildup	Exposure Rate mR/hr No Buildup	Exposure Rate mR/hr With Buildup
0.015	2.631e+06	7.470e-19	6.240e-18	6.407e-20	5.352e-19
0.02	1.019e+09	5.420e-09	1.735e-07	1.878e-10	6.011e-09
0.03	3.805e+09	1.067e-04	2.216e-02	1.058e-06	2.196e-04
0.04	2.374e+09	7.240e-04	6.099e-01	3.202e-06	2.697e-03
0.05	4.650e+08	4.427e-04	7.760e-01	1.179e-06	2.067e-03
0.06	3.479e+08	7.000e-04	1.721e+00	1.390e-06	3.419e-03
0.08	7.993e+08	4.589e-03	1.224e+01	7.262e-06	1.937e-02
0.1	2.812e+09	3.565e-02	7.563e+01	5.453e-05	1.157e-01
0.15	1.361e+06	7.538e-05	7.748e-02	1.241e-07	1.276e-04
0.2	6.003e+08	9.883e-02	4.579e+01	1.744e-04	8.081e-02
0.3	1.031e+08	7.905e-02	1.284e+01	1.499e-04	2.436e-02
0.4	1.540e+09	3.470e+00	2.761e+02	6.762e-03	5.379e-01
0.5	5.734e+08	2.930e+00	1.388e+02	5.751e-03	2.724e-01
0.6	5.921e+10	5.831e+02	1.862e+04	1.138e+00	3.634e+01
0.8	5.746e+09	1.541e+02	2.790e+03	2.931e-01	5.308e+00
1.0	9.269e+11	5.272e+04	6.456e+05	9.719e+01	1.190e+03
1.5	9.274e+11	1.918e+05	1.292e+06	3.227e+02	2.174e+03
2.0	1.767e+03	8.523e-04	4.092e-03	1.318e-06	6.329e-06
3.0	2.905e+05	4.177e-01	1.356e+00	5.667e-04	1.839e-03
Totals	1.934e+12	2.453e+05	1.960e+06	4.213e+02	3.407e+03

Results - Dose Point # 5, Edge Center - (88.27,64.77,0) cm

Energy MeV	Activity Photons/sec	Fluence Rate MeV/cm²/sec No Buildup	Fluence Rate MeV/cm²/sec With Buildup	Exposure Rate mR/hr No Buildup	Exposure Rate mR/hr With Buildup
0.015	2.631e+06	8.014e-19	6.706e-18	6.873e-20	5.752e-19
0.02	1.019e+09	6.460e-09	2.093e-07	2.238e-10	7.250e-09
0.03	3.805e+09	1.408e-04	3.015e-02	1.395e-06	2.988e-04
0.04	2.374e+09	9.880e-04	8.718e-01	4.369e-06	3.856e-03
0.05	4.650e+08	6.137e-04	1.137e+00	1.635e-06	3.029e-03
0.06	3.479e+08	9.803e-04	2.560e+00	1.947e-06	5.085e-03
0.08	7.993e+08	6.516e-03	1.852e+01	1.031e-05	2.931e-02
0.1	2.812e+09	5.115e-02	1.156e+02	7.826e-05	1.769e-01
0.15	1.361e+06	1.103e-04	1.202e-01	1.817e-07	1.979e-04
0.2	6.003e+08	1.468e-01	7.145e+01	2.591e-04	1.261e-01
0.3	1.031e+08	1.197e-01	2.019e+01	2.271e-04	3.829e-02
0.4	1.540e+09	5.321e+00	4.349e+02	1.037e-02	8.474e-01
0.5	5.734e+08	4.528e+00	2.188e+02	8.889e-03	4.295e-01
0.6	5.921e+10	9.060e+02	2.934e+04	1.768e+00	5.727e+01
0.8	5.746e+09	2.408e+02	4.388e+03	4.581e-01	8.346e+00
1.0	9.269e+11	8.259e+04	1.011e+06	1.522e+02	1.864e+03
1.5	9.274e+11	2.999e+05	2.002e+06	5.045e+02	3.368e+03
2.0	1.767e+03	1.325e-03	6.274e-03	2.049e-06	9.701e-06
3.0	2.905e+05	6.407e-01	2.041e+00	8.692e-04	2.769e-03
Totals	1.934e+12	3.836e+05	3.048e+06	6.590e+02	5.300e+03

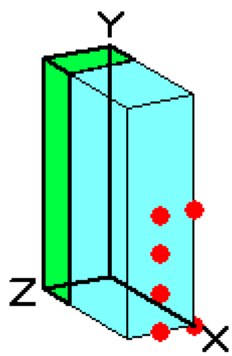
Results - Dose Point # 6, Edge Bottom - (88.27,0,0) cm

Energy MeV	Activity Photons/sec	Fluence Rate MeV/cm²/sec No Buildup	Fluence Rate MeV/cm²/sec With Buildup	Exposure Rate mR/hr No Buildup	Exposure Rate mR/hr With Buildup
0.015	2.631e+06	4.007e-19	3.353e-18	3.437e-20	2.876e-19
0.02	1.019e+09	3.230e-09	1.047e-07	1.119e-10	3.625e-09
0.03	3.805e+09	7.048e-05	1.510e-02	6.985e-07	1.497e-04
0.04	2.374e+09	4.951e-04	4.382e-01	2.190e-06	1.938e-03
0.05	4.650e+08	3.078e-04	5.735e-01	8.200e-07	1.528e-03
0.06	3.479e+08	4.920e-04	1.295e+00	9.773e-07	2.572e-03
0.08	7.993e+08	3.275e-03	9.411e+00	5.183e-06	1.489e-02
0.1	2.812e+09	2.574e-02	5.898e+01	3.938e-05	9.023e-02
0.15	1.361e+06	5.570e-05	6.183e-02	9.173e-08	1.018e-04
0.2	6.003e+08	7.437e-02	3.698e+01	1.313e-04	6.527e-02
0.3	1.031e+08	6.108e-02	1.057e+01	1.159e-04	2.004e-02
0.4	1.540e+09	2.733e+00	2.299e+02	5.326e-03	4.480e-01
0.5	5.734e+08	2.342e+00	1.167e+02	4.597e-03	2.290e-01
0.6	5.921e+10	4.717e+02	1.577e+04	9.207e-01	3.078e+01
0.8	5.746e+09	1.270e+02	2.394e+03	2.415e-01	4.553e+00
1.0	9.269e+11	4.405e+04	5.592e+05	8.120e+01	1.031e+03
1.5	9.274e+11	1.640e+05	1.138e+06	2.760e+02	1.914e+03
2.0	1.767e+03	7.401e-04	3.642e-03	1.144e-06	5.631e-06
3.0	2.905e+05	3.695e-01	1.223e+00	5.013e-04	1.659e-03
Totals	1.934e+12	2.087e+05	1.715e+06	3.584e+02	2.981e+03

Table B-5. Model Input and Output for the Advanced Test Reactor Beryllium Block With Paraffin Wax on July 1, 2014

Page	:1		File Ref	:
DOS File	:ERWW2014.MS6		Date	:
Run Date	: March 12, 2004		By	:
Run Time	: 10:00:37 AM		Checked	:
Duration	: 00:02:56			

Case Title: ERWW2014
Description: 2014; rectangular vol; wide exposure; 1x ci source: w/ wax
Geometry: 13 - Rectangular Volume



Source Dimensions:

Length	26.04 cm	(10.3 in)
Width	40.15 cm	(1 ft 3.8 in)
Height	129.54 cm	(4 ft 3.0 in)

Dose Points

A	X	Y	Z
# 1	88.27 cm	64.77 cm	20.075 cm
Middle Center	2 ft 10.8 in	2 ft 1.5 in	7.9 in
# 2	88.27 cm	43.18 cm	20.075 cm
Middle 2nd Down	2 ft 10.8 in	1 ft 5.0 in	7.9 in
# 3	88.27 cm	21.59 cm	20.075 cm
Middle 3rd Down	2 ft 10.8 in	8.5 in	7.9 in
# 4	88.27 cm	0 cm	20.075 cm
Middle Bottom	2 ft 10.8 in	0.0 in	7.9 in
# 5	88.27 cm	64.77 cm	0 cm
Edge Center	2 ft 10.8 in	2 ft 1.5 in	0.0 in
# 6	88.27 cm	0 cm	0 cm
Edge Bottom	2 ft 10.8 in	0.0 in	0.0 in

Shields

Shield N	Dimension	Material	Density
Source	1.35e+05 cm³	Be	0.60118
Shield 1	60.96 cm	WAX	0.88
Air Gap		Air	0.00122

Buildup : The material reference is - Shield 1

Integration Parameters

X Direction	30
Y Direction	40
Z Direction	40

Results - Dose Point # 1, Middle Center - (88.27,64.77,20.075) cm

Energy MeV	Activity Photons/sec	Fluence Rate MeV/cm²/sec No Buildup	Fluence Rate MeV/cm²/sec With Buildup	Exposure Rate mR/hr No Buildup	Exposure Rate mR/hr With Buildup
0.015	2.639e+06	1.498e-18	1.252e-17	1.285e-19	1.074e-18
0.02	9.643e+08	1.026e-08	3.285e-07	3.554e-10	1.138e-08
0.03	2.939e+09	1.647e-04	3.417e-02	1.633e-06	3.386e-04
0.04	1.308e+09	7.959e-04	6.686e-01	3.520e-06	2.957e-03
0.05	2.270e+08	4.311e-04	7.517e-01	1.148e-06	2.002e-03
0.06	3.300e+08	1.323e-03	3.231e+00	2.629e-06	6.418e-03
0.08	3.160e+08	3.611e-03	9.532e+00	5.714e-06	1.508e-02
0.1	1.226e+09	3.089e-02	6.470e+01	4.726e-05	9.898e-02
0.15	9.234e+05	1.014e-04	1.023e-01	1.670e-07	1.685e-04
0.2	3.594e+08	1.169e-01	5.305e+01	2.063e-04	9.362e-02
0.3	9.537e+07	1.436e-01	2.274e+01	2.724e-04	4.314e-02
0.4	1.390e+09	6.106e+00	4.724e+02	1.190e-02	9.204e-01
0.5	2.980e+08	2.950e+00	1.356e+02	5.790e-03	2.661e-01
0.6	4.568e+10	8.661e+02	2.680e+04	1.691e+00	5.231e+01
0.8	3.095e+09	1.579e+02	2.765e+03	3.004e-01	5.260e+00
1.0	2.492e+11	2.667e+04	3.151e+05	4.916e+01	5.809e+02
1.5	2.494e+11	9.470e+04	6.146e+05	1.593e+02	1.034e+03
2.0	1.458e+03	1.265e-03	5.849e-03	1.957e-06	9.045e-06
3.0	2.636e+05	6.611e-01	2.067e+00	8.969e-04	2.804e-03
Totals	5.568e+11	1.224e+05	9.601e+05	2.105e+02	1.674e+03

Results - Dose Point # 2, Middle 2nd Down - (88.27,43.18,20.075) cm

Energy MeV	Activity Photons/sec	Fluence Rate MeV/cm²/sec No Buildup	Fluence Rate MeV/cm²/sec With Buildup	Exposure Rate mR/hr No Buildup	Exposure Rate mR/hr With Buildup
0.015	2.639e+06	1.498e-18	1.252e-17	1.285e-19	1.074e-18
0.02	9.643e+08	1.024e-08	3.277e-07	3.547e-10	1.135e-08
0.03	2.939e+09	1.632e-04	3.373e-02	1.618e-06	3.343e-04
0.04	1.308e+09	7.854e-04	6.549e-01	3.473e-06	2.897e-03
0.05	2.270e+08	4.244e-04	7.328e-01	1.130e-06	1.952e-03
0.06	3.300e+08	1.301e-03	3.139e+00	2.584e-06	6.236e-03
0.08	3.160e+08	3.541e-03	9.222e+00	5.603e-06	1.459e-02
0.1	1.226e+09	3.023e-02	6.242e+01	4.625e-05	9.550e-02
0.15	9.234e+05	9.882e-05	9.831e-02	1.627e-07	1.619e-04
0.2	3.594e+08	1.136e-01	5.084e+01	2.005e-04	8.973e-02
0.3	9.537e+07	1.388e-01	2.173e+01	2.633e-04	4.122e-02
0.4	1.390e+09	5.882e+00	4.506e+02	1.146e-02	8.779e-01
0.5	2.980e+08	2.834e+00	1.292e+02	5.563e-03	2.535e-01
0.6	4.568e+10	8.305e+02	2.551e+04	1.621e+00	4.980e+01
0.8	3.095e+09	1.510e+02	2.629e+03	2.872e-01	5.001e+00
1.0	2.492e+11	2.545e+04	2.995e+05	4.692e+01	5.521e+02
1.5	2.494e+11	9.017e+04	5.842e+05	1.517e+02	9.828e+02
2.0	1.458e+03	1.204e-03	5.561e-03	1.862e-06	8.600e-06
3.0	2.636e+05	6.290e-01	1.967e+00	8.533e-04	2.669e-03
Totals	5.568e+11	1.166e+05	9.125e+05	2.005e+02	1.591e+03

Results - Dose Point # 3, Middle 3rd Down - (88.27,21.59,20.075) cm

Energy MeV	Activity Photons/sec	Fluence Rate MeV/cm²/sec No Buildup	Fluence Rate MeV/cm²/sec With Buildup	Exposure Rate mR/hr No Buildup	Exposure Rate mR/hr With Buildup
0.015	2.639e+06	1.461e-18	1.220e-17	1.253e-19	1.046e-18
0.02	9.643e+08	9.566e-09	3.046e-07	3.313e-10	1.055e-08
0.03	2.939e+09	1.461e-04	2.982e-02	1.448e-06	2.955e-04
0.04	1.308e+09	6.935e-04	5.673e-01	3.067e-06	2.509e-03
0.05	2.270e+08	3.723e-04	6.284e-01	9.918e-07	1.674e-03
0.06	3.300e+08	1.137e-03	2.676e+00	2.257e-06	5.315e-03
0.08	3.160e+08	3.076e-03	7.807e+00	4.868e-06	1.235e-02
0.1	1.226e+09	2.615e-02	5.263e+01	4.001e-05	8.051e-02
0.15	9.234e+05	8.481e-05	8.242e-02	1.397e-07	1.357e-04
0.2	3.594e+08	9.691e-02	4.253e+01	1.710e-04	7.506e-02
0.3	9.537e+07	1.175e-01	1.813e+01	2.229e-04	3.438e-02
0.4	1.390e+09	4.956e+00	3.756e+02	9.657e-03	7.319e-01
0.5	2.980e+08	2.381e+00	1.077e+02	4.673e-03	2.113e-01
0.6	4.568e+10	6.962e+02	2.127e+04	1.359e+00	4.153e+01
0.8	3.095e+09	1.263e+02	2.195e+03	2.403e-01	4.176e+00
1.0	2.492e+11	2.128e+04	2.505e+05	3.922e+01	4.617e+02
1.5	2.494e+11	7.545e+04	4.908e+05	1.269e+02	8.258e+02
2.0	1.458e+03	1.010e-03	4.693e-03	1.562e-06	7.258e-06
3.0	2.636e+05	5.305e-01	1.672e+00	7.198e-04	2.269e-03
Totals	5.568e+11	9.756e+04	7.654e+05	1.678e+02	1.334e+03

Results - Dose Point # 4, Middle Bottom - (88.27,0,20.075) cm

Energy MeV	Activity Photons/sec	Fluence Rate MeV/cm²/sec No Buildup	Fluence Rate MeV/cm²/sec With Buildup	Exposure Rate mR/hr No Buildup	Exposure Rate mR/hr With Buildup
0.015	2.639e+06	7.492e-19	6.259e-18	6.426e-20	5.368e-19
0.02	9.643e+08	5.131e-09	1.643e-07	1.777e-10	5.690e-09
0.03	2.939e+09	8.244e-05	1.712e-02	8.171e-07	1.696e-04
0.04	1.308e+09	3.988e-04	3.359e-01	1.764e-06	1.486e-03
0.05	2.270e+08	2.162e-04	3.789e-01	5.758e-07	1.009e-03
0.06	3.300e+08	6.641e-04	1.633e+00	1.319e-06	3.243e-03
0.08	3.160e+08	1.814e-03	4.839e+00	2.871e-06	7.657e-03
0.1	1.226e+09	1.554e-02	3.296e+01	2.377e-05	5.043e-02
0.15	9.234e+05	5.114e-05	5.258e-02	8.422e-08	8.658e-05
0.2	3.594e+08	5.917e-02	2.741e+01	1.044e-04	4.838e-02
0.3	9.537e+07	7.314e-02	1.188e+01	1.387e-04	2.254e-02
0.4	1.390e+09	3.131e+00	2.491e+02	6.101e-03	4.853e-01
0.5	2.980e+08	1.522e+00	7.210e+01	2.988e-03	1.415e-01
0.6	4.568e+10	4.498e+02	1.436e+04	8.780e-01	2.803e+01
0.8	3.095e+09	8.301e+01	1.503e+03	1.579e-01	2.859e+00
1.0	2.492e+11	1.417e+04	1.736e+05	2.613e+01	3.199e+02
1.5	2.494e+11	5.158e+04	3.475e+05	8.678e+01	5.847e+02
2.0	1.458e+03	7.033e-04	3.377e-03	1.088e-06	5.222e-06
3.0	2.636e+05	3.790e-01	1.230e+00	5.142e-04	1.669e-03
Totals	5.568e+11	6.629e+04	5.374e+05	1.140e+02	9.363e+02

Results - Dose Point # 5, Edge Center - (88.27,64.77,0) cm

Energy MeV	Activity Photons/sec	Fluence Rate MeV/cm²/sec No Buildup	Fluence Rate MeV/cm²/sec With Buildup	Exposure Rate mR/hr No Buildup	Exposure Rate mR/hr With Buildup
0.015	2.639e+06	8.038e-19	6.726e-18	6.894e-20	5.769e-19
0.02	9.643e+08	6.115e-09	1.981e-07	2.118e-10	6.863e-09
0.03	2.939e+09	1.088e-04	2.329e-02	1.078e-06	2.308e-04
0.04	1.308e+09	5.442e-04	4.802e-01	2.407e-06	2.124e-03
0.05	2.270e+08	2.996e-04	5.552e-01	7.982e-07	1.479e-03
0.06	3.300e+08	9.300e-04	2.429e+00	1.847e-06	4.824e-03
0.08	3.160e+08	2.576e-03	7.323e+00	4.076e-06	1.159e-02
0.1	1.226e+09	2.230e-02	5.040e+01	3.411e-05	7.711e-02
0.15	9.234e+05	7.487e-05	8.155e-02	1.233e-07	1.343e-04
0.2	3.594e+08	8.789e-02	4.278e+01	1.551e-04	7.550e-02
0.3	9.537e+07	1.108e-01	1.868e+01	2.101e-04	3.543e-02
0.4	1.390e+09	4.801e+00	3.924e+02	9.354e-03	7.646e-01
0.5	2.980e+08	2.353e+00	1.137e+02	4.619e-03	2.232e-01
0.6	4.568e+10	6.990e+02	2.263e+04	1.364e+00	4.418e+01
0.8	3.095e+09	1.297e+02	2.363e+03	2.468e-01	4.496e+00
1.0	2.492e+11	2.220e+04	2.719e+05	4.093e+01	5.012e+02
1.5	2.494e+11	8.064e+04	5.384e+05	1.357e+02	9.059e+02
2.0	1.458e+03	1.093e-03	5.177e-03	1.691e-06	8.005e-06
3.0	2.636e+05	5.813e-01	1.852e+00	7.887e-04	2.513e-03
Totals	5.568e+11	1.037e+05	8.359e+05	1.782e+02	1.457e+03

Results - Dose Point # 6, Edge Bottom - (88.27,0,0) cm

Energy MeV	Activity Photons/sec	Fluence Rate MeV/cm²/sec No Buildup	Fluence Rate MeV/cm²/sec With Buildup	Exposure Rate mR/hr No Buildup	Exposure Rate mR/hr With Buildup
0.015	2.639e+06	4.019e-19	3.363e-18	3.447e-20	2.885e-19
0.02	9.643e+08	3.058e-09	9.907e-08	1.059e-10	3.432e-09
0.03	2.939e+09	5.443e-05	1.167e-02	5.395e-07	1.156e-04
0.04	1.308e+09	2.727e-04	2.414e-01	1.206e-06	1.067e-03
0.05	2.270e+08	1.503e-04	2.800e-01	4.004e-07	7.458e-04
0.06	3.300e+08	4.668e-04	1.228e+00	9.272e-07	2.440e-03
0.08	3.160e+08	1.295e-03	3.720e+00	2.049e-06	5.887e-03
0.1	1.226e+09	1.122e-02	2.571e+01	1.716e-05	3.933e-02
0.15	9.234e+05	3.780e-05	4.195e-02	6.224e-08	6.908e-05
0.2	3.594e+08	4.452e-02	2.214e+01	7.858e-05	3.908e-02
0.3	9.537e+07	5.651e-02	9.777e+00	1.072e-04	1.855e-02
0.4	1.390e+09	2.466e+00	2.074e+02	4.805e-03	4.042e-01
0.5	2.980e+08	1.217e+00	6.063e+01	2.389e-03	1.190e-01
0.6	4.568e+10	3.639e+02	1.217e+04	7.103e-01	2.375e+01
0.8	3.095e+09	6.840e+01	1.289e+03	1.301e-01	2.453e+00
1.0	2.492e+11	1.184e+04	1.503e+05	2.183e+01	2.771e+02
1.5	2.494e+11	4.412e+04	3.059e+05	7.423e+01	5.147e+02
2.0	1.458e+03	6.107e-04	3.005e-03	9.443e-07	4.647e-06
3.0	2.636e+05	3.353e-01	1.109e+00	4.549e-04	1.505e-03
Totals	5.568e+11	5.640e+04	4.701e+05	9.690e+01	8.187e+02

Appendix C

Estimation of Rate of Biodegradation of Paraffin Monoliths

Appendix C

Estimation of Rate of Biodegradation of Paraffin Monoliths

Monolith Dimensions

Dimensions from EDF-4397, pp 29-31
Density of 0.88 g/cm3 from Heiser and Fuhrmann (1997)

Dimension	Unit	Block	Cylinder
Height	m	5	5
Depth	m	2	
Diameter	m		2.5
Width	m	3	
Surface Area	m^2	62	49.09
Volume	m^3	30	24.54
Density of Paraffin	kg/m^3	880	880
Mass of Paraffin Monolith	kg	26,400	21,599
Outside layer thickness	m	0.46	0.46
Mass of Paraffin in Outside .46 m of Monolith	kg	18,335	14,559

Rates from Literature

The paraffin for these experiments was deposited on 13-mm-diameter glass fiber filters, the entire filter was placed in the flask

Surface area from filter, assume both sides of 13-mm-diameter filter provide area of paraffin accessible to microbes

System is well mixed, shake flasks, aqueous, mineral media

Some data was available on overall rate, but no surface area data was available, this data is included for completeness

Source	Temp. (°C)	Initial Mass (kg)	% Degraded	Surface Area (m^2)	Time (year)	Rate ($kg/m^2/yr$)	Rate (kg/yr)	Microbe Source
Robust Summary pp 9-11	20	2.00E-05	87.0	2.65E-04	2.30E-01	2.85E-01	7.56E-05	oil contaminated soil from land-farming project
Robust Summary pp 11-12	20	2.00E-05	21.0	2.65E-04	7.67E-02	2.06E-01	5.48E-05	oil contaminated soil from land-farming project
Robust Summary pp 9-10	20	2.00E-05	25.0	2.65E-04	2.30E-01	8.18E-02	2.17E-05	oil contaminated soil from land-farming project
Robust Summary pp 14-15	25	1.18E-05	55.0	no data available	8.49E-02		7.64E-05	domestic sewage sludge
Robust Summary pp 14-15	25	1.18E-05	98.5	no data available	3.75E-01		3.10E-05	domestic sewage sludge
Robust Summary pp 15-16	25	1.18E-05	27.0	no data available	8.49E-02		3.75E-05	domestic sewage sludge
Robust Summary pp 15-16	25	1.18E-05	67.2	no data available	3.75E-01		2.11E-05	domestic sewage sludge
Robust Summary pp 16-17	22	3.70E-05	39.6	2.65E-04	7.67E-02	7.19E-01	1.91E-04	domestic activated sludge

Estimated Duration of Monoliths

Using blocks and cylinders from monolith dimensions
Assume microbes present in soil closer to Subsurface Disposal Area conditions than microbes in domestic activated sludge (line 31)
Using rate from line 28 for maximum
Using rate from line 30 for minimum
Assume the rate is not limited by oxygen or any other nutrient
Assume no other process (radiolysis, solvent swelling, etc.) affect rate of paraffin biodegradation
Assume no inhibition from metabolism by-products
Assume monolith is pure paraffin (WAXFIX contains other ingredients, no soil)

	Max Rate (kg/yr)	Min Rate (kg/yr)	Monolith Min Duration (yr)	Monolith Max Duration (yr)	Outer .46m of Monolith Min Duration (yr)	Outer .46m of Monolith Max Duration (yr)
Cylinder - Paraffin Removal for one year (kg)	1.40E+01	4.02E-00	1545	5376	1041	3624
Cylinder - Paraffin Removal for one year %	6.47E-02	1.86E-02				
Block - Paraffin Removal for one year (kg)	1.77E+01	5.07E-00	1495	5203	1038	3613
Block - Paraffin Removal for one year%	6.69E-02	1.92E-02				

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