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Assessment of the Environmental Impacts of Decontamination and Decommissioning Activities for Research Reactors at the Brookhaven National Laboratory

Bernd Franke

Regine Vogt

Standing for Truth About Radiation, Inc.

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Prepared by

Bernd Franke and Regine Vogt
ifeu-Institut für Energie- und Umweltforschung Heidelberg GmbH
Institute for Energy and Environmental Research, Heidelberg
Wilckensstr. 3, 69120 Heidelberg, Germany

under contract with STAR Foundation, East Hampton, NY, U.S.A.

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1 Introduction

Brookhaven National Laboratory (BNL) has three closed reactors: (1) the Brookhaven Graphite Research Reactor (BGRR), a graphite, gas cooled reactor shut-down in 1969; (2) the High-Flux Beam Reactor (HFBR), a heavy water 40 MW_{th} used to perform neutron experiments, and (3) the Brookhaven Medical Research Reactor (BMRR), a small medical research reactor (5 MW_{th} modified, water cooled "tank-type reactor". Figure 1 provides an overview of the locations of the three reactors at the site of the laboratory.

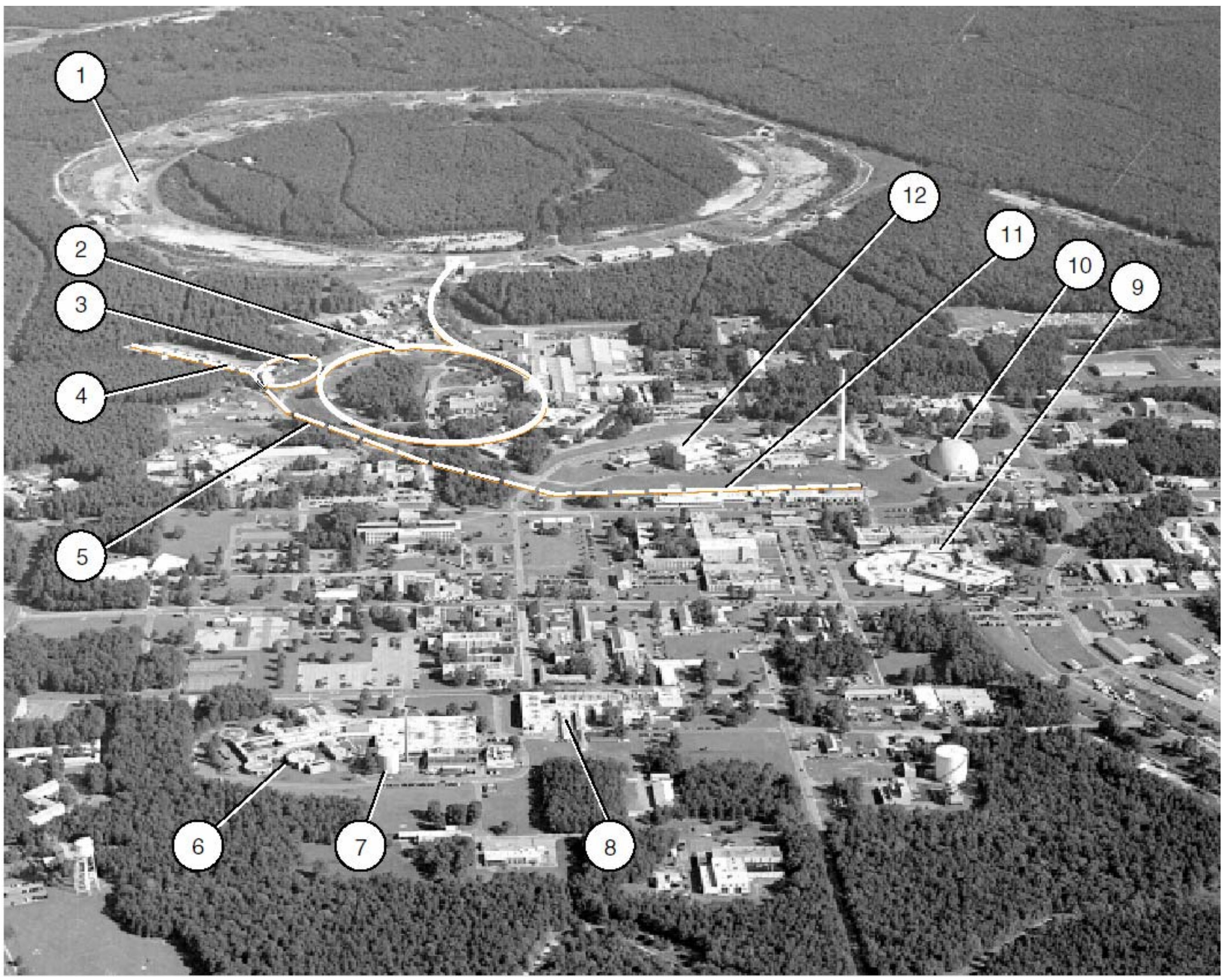

Figure 1 Brookhaven National Laboratory Site with major facilities. The three reactor sites are merked as follows: (7) Brookhaven Medical Research Reactor (BMRR), (10) High Flux Beam Reactor (HFBR), and (12) Brookhaven Graphite Research Reactor (BGRR) (Source: BNL, 2000)

It is the overall goal of the project to determine the environmental impacts of decontamination and decommissioning activities for research reactors at the Brookhaven National Laboratory, STAR Foundation from East Hampton, NY contracted with the Institute for Energy and Environmental Research based in Heidelberg, Germany (IFEU) to provide a detailed technical analysis in collaboration with the Institute for Resource and Security Studies (IRSS) in Cambridge, Massachusetts. A focal point was the comparative assessment of various alternatives (i.e. current status, entombment and various types of decommissioning). Whereas efforts by IRSS centered on engineering questions, IFEU focused on public health impacts.

To date, there has been little public discussion by the Laboratory and the DOE about the ultimate disposition of the reactors and the relative risks associated with disposition options. To the best of our knowledge, no technical assessment of the environmental, safety and health risks associated with reactor disposition options at the Laboratory has been done.

The ultimate disposition of the three reactors remains an open question. The Department of Energy has budgeted a total of $150.9 million for “Decontamination and Decommissioning Actions” with planned completion dates 8/31/2005 presumably for the graphite and medical research reactors, and 9/30/2008 for the High Flux Beam Reactor. Current funding for reactor D&D and the Laboratory is very limited and the short time for the completion of D&D projects at BNL in the FY 2002 Budget Request, suggest that DOE may be implicitly pursuing a policy of indefinite entombment of the BNL reactors. Currently, DOE is removing ancillary equipment (ducts etc) from the reactors, but no activities relative to addressing the reactor vessel and heavily contaminated internal piping and equipment have been undertaken.

The Department of Energy is responsible for 67 reactors, which for the most part are now closed. The preponderance of closed DOE reactors, were constructed and operated for research purposes and are similar in size as those at Brookhaven National Laboratory. A grant from the MTA Fund would enable, for the first time, an independent technical assessment that would to identify and compare the risks associated with the options for the ultimate disposition of research reactors at the Laboratory. Funding from the MTA Fund would allow citizens to assess DOE’s efforts to address the fate of BNL reactors, in a manner that has the potential as a template approach for other DOE sites with similar problems and issues.

2 Study Objectives

The three defunct reactors at the Brookhaven National Laboratory contain large concentrations of radioactive materials and, may, perhaps be single largest inventory of such on Long Island. This problem is significant because the BNL reactors are in a highly populated area above a sole source drinking water supply. As such, the risks of leakage from these reactors into the island's aquifer, and handling radioactive reactor components and wastes associated with reactor decontamination and decommissioning could be quite significant. However, DOE and the Laboratory have yet to provide salient details or analyses regarding this important issue.

The specific objective of the project is to begin to address the environmental, safety and health risks associated with the disposition of the three-closed BNL reactors. Reactor disposition clearly is a major element of the DOE's environmental restoration and waste management program for the Laboratory. However, this important issue is missing from public discussion and from the DOE's overall environmental cleanup plan for the BNL site. Thus, we propose to perform a critical review of environmental, safety and health issues and activities pertaining to the disposition of three closed research reactors at BNL. The review will address technical issues related to: (1) the potential for contamination of the environment (air, land, water) by radioactive and otherwise hazardous material, in the short and long term; (2) options for disposition of the reactors over the long term; (3) health and safety of workers involved in reactor disposition; and (4) human risk assessment.

The study assesses reactor disposition options – ranging from in-place entombment to complete dismantlement and removal. In doing so, it two basic issues are adressed:

- Potential releases of hazardous materials from the BNL reactors; and
- Public health risks.

Accordingly, the study tasks are defined as follows

Potential Releases

- The potential (in terms of probability and magnitude) for release of hazardous material from reactor facilities (including transportation) through incidents and accidents and chronic leakage from slow degradation of confinement;
- Administrative and regulatory oversight by DOE and other agencies that is relevant to the above mentioned issues; and
- Identification of reactor disposition options and relevant technical issues considered or not by the DOE and other parties.

Public Health Risks

- The potential for migration and uptake in the environment and human exposures to hazardous releases from the BNL reactors from accidents and chronic leakage;
- A life-cycle analysis and risk assessment of doses and subsequent public health risks from hazardous materials associated with the BNL reactors;
- Development of ranking criteria for public health impacts.

3 Radionuclide Inventory

The three defunct reactors at the Brookhaven National Laboratory contain large amounts of radioactive materials. The inventory for the Brookhaven Graphite Research Reactor (BGRR) and the High Flux Beam Reactor (HFBR) are shown in Table 1 and Table 2. No information is available with respect to the radionuclide inventory of the Brookhaven Medical Research Reactor (BMRR).

Table 1 Estimated Radionuclide Inventories at Brookhaven Graphite Research Reactor (BGRR), as complied by IRSS (2003)

Radio-nuclide	Half-Life (yr)	Building 702 Inventory (Ci)			Balance of Plant (Ci)	
		Graphite Pile	Control Rods	Radiation Shield	Removed	Residual
H-3	1.23E+01	3.40E+03			1.16E-02	3.22E-02
C-14	5.72E+03	1.05E+03			1.67E-04	5.59E-03
Fe-55	2.70E+00	3.14E-02			1.17E-06	2.04E-05
Co-60	5.27E+00	1.25E+01	3.32E-01		3.06E-03	8.13E-03
Ni-63	1.00E+02	9.73E+01			2.53E-03	8.41E-02
Sr-90	2.88E+01	4.21E-01			4.22E-01	2.97E+00
Y-90	7.31E-03	4.21E-01			4.22E-01	2.97E+00
Tc-99	2.14E+05	4.96E-03			1.25E-04	1.23E-03
I-129	1.57E+07	5.13E-03			3.08E-05	4.07E-04
Cs-137	3.02E+01	1.26E+00	1.75E-03		8.13E-01	1.03E+01
Eu-152	1.30E+01	3.95E-02	8.57E-04		4.68E-04	5.49E-03
Eu-154	8.50E+00	5.66E+00	1.80E-03		2.38E-04	2.66E-03
Eu-155	4.90E+00	3.55E-01	1.14E-02		5.51E-05	3.04E-06
Ra-226	1.60E+03	6.88E-03			5.90E-01	3.67E-03
Th-232	1.41E+10	2.07E-03			5.57E-03	6.55E-05
U-233	1.59E+05				1.08E-01	
U-234	2.45E+05	7.16E-03			5.85E-04	9.54E-04
U-235	7.04E+08	6.93E-04			2.59E-05	3.89E-05
U-238	4.47E+09	6.07E-04			2.75E+00	9.06E-04
Np-237	2.14E+06				1.00E-04	
Pu-238	8.77E+01	4.81E-02			1.58E-04	1.78E-03
Pu-239	2.44E+04	7.61E-02			7.12E-03	1.09E-01
Pu-240	6.57E+03				7.12E-03	
Pu-241	1.44E+01	1.09E-01			9.32E-03	1.56E-01
Am-241	4.33E+02	1.66E-01	2.53E-02		2.41E-02	2.57E-02
Cm-244	1.81E+01				6.93E-09	
Cf-252	2.64E+00				1.93E-02	

Table 2 Estimated Radionuclide Inventories at High Flux Beam Reactor (HFBR)

Radio-nuclide	Half-Life (yr)	Estimated Radionuclide Inventories (Ci)					
		Control Rods & Transition Plate (stainless steel)	**Reactor Vessel & Internals** (aluminum)	**Thermal Shield** (steel and lead)	**Radiation Shield** (steel and concrete)	**H-6 Beam Plug**	**Balance-of-Plant "Material at Risk"**
H-3	1.23E+01						2.91E+03
C-14	5.72E+03						
Fe-55	2.70E+00	4.10E+04		<7.20E+05	3.60E+02		<1.00E+00
Co-60	5.27E+00	2.00E+04				2.10E+01	<1.00E+00
Ni-63	1.00E+02	8.19E+03					<1.00E+00
Sr-90	2.88E+01						
Y-90	7.31E-03						
Tc-99	2.14E+05						
I-129	1.57E+07						
Cs-137	3.02E+01						
Eu-152	1.30E+01						
Eu-154	8.50E+00	2.32E+02					
Eu-155	4.90E+00	1.42E+01					
Ra-226	1.60E+03						
Th-232	1.41E+10						
U-233	1.59E+05						
U-234	2.45E+05						
U-235	7.04E+08						
U-238	4.47E+09						
Np-237	2.14E+06						
Pu-238	8.77E+01						
Pu-239	2.44E+04						
Pu-240	6.57E+03						
Pu-241	1.44E+01						
Am-241	4.33E+02						
Cm-244	1.81E+01						
Cf-252	2.64E+00						

If the radionuclide inventory of the BGRR of 4,600 curies is taken at face value, it indicates that the greatest fraction for many radionuclides is contained in the graphite pile. In order to provide a measure of the magnitude of the magnitude of radioactive materials still present in the BGRR, the inventory was compared to that of the 177 Hanford high-level waste tanks, using data published by the U.S. Department of Energy (DOE, 2003). Figure 2 presents the Hanford tank inventory data in the form of cumulative frequency distribution. The radionuclide inventory of Hanford tanks ranges from 30 curies to 22 million curies. About 18 or 10% of the Hanford tanks have a radionuclide inventory of less than the BGRR (4,600 curies); inversely, 159 or 90% of the Hanford tanks have a greater radionuclide inventory. A proper comparison has to account for the differences in radiotoxicity. For this, the radiotoxicity BGRR inventory was compared to that of 3 tanks: the one with the lowest activity (T-202), one with an activity slightly higher than BGRR (T-104) and the tank with the highest inventory (AZ-101). The RESRAD computer model was used for this purpose; the inventory of radionuclides that are modelled in RESRAD is shown in Table 3.

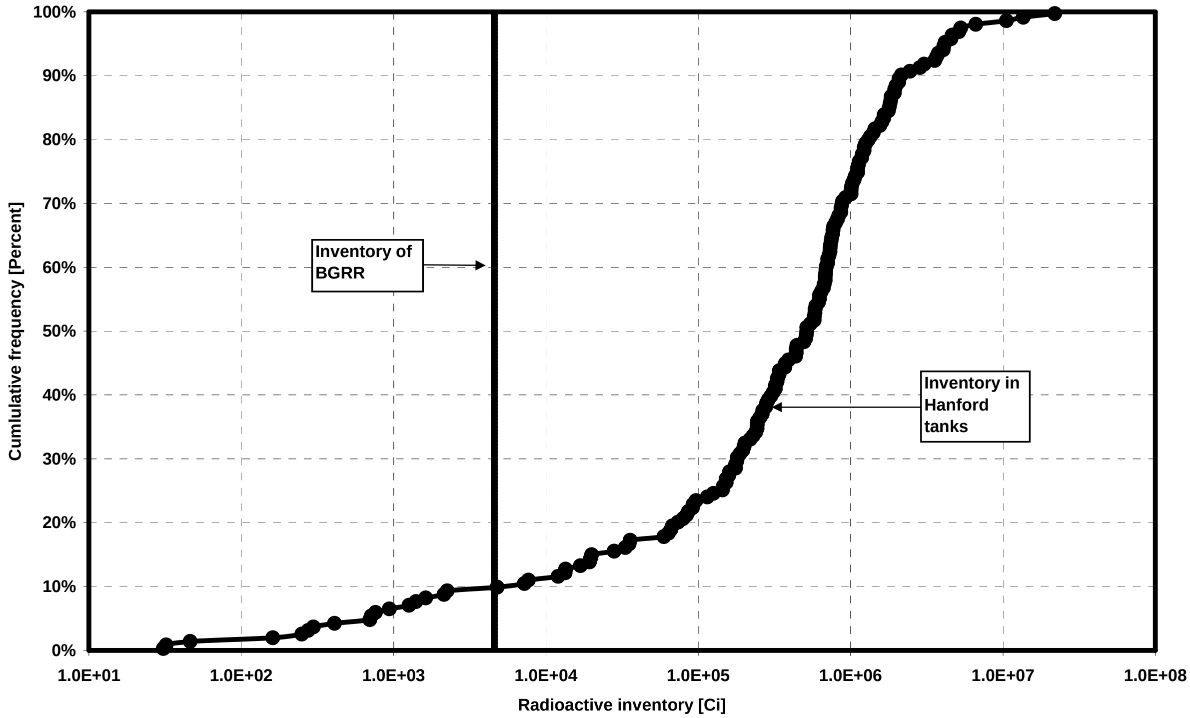

Figure 2 Radionuclide inventory of BGRR compared to that of 177 Hanford tanks

Table 3 Radionuclide inventory of BGRR and of selected Hanford tanks for which RESRAD calculations were performed

Nuclide	BGRR	T-202	T-104	AZ-101
Am-241	2.2E-01	2.1E-01	2.1E-01	2.6E+04
C-14	1.1E+03	1.0E-04	6.9E-02	6.7E+00
Co-60	1.3E+01	1.3E-05	9.4E-03	1.2E+03
Cs-137	1.2E+01	2.6E+00	2.6E+02	6.0E+06
Eu-152	4.6E-02	7.3E-05	2.1E-02	4.0E+02
Eu-154	5.6E+00	2.9E-04	2.7E+00	1.4E+04
Eu-155	3.7E-01	3.6E-03	1.8E+00	1.8E+04
H-3	3.4E+03	2.2E-04	3.4E-01	5.9E+01
I-129	5.5E-03	1.3E-06	1.4E-03	3.9E-01
Ni-63	9.7E+01	2.5E-03	2.6E+00	3.0E+03
Pu-238	5.0E-02	1.3E-01	2.6E+00	1.3E+02
Pu-239	1.9E-01	1.9E+01	1.9E+02	1.2E+03
Pu-241	2.7E-01	4.0E+00	9.1E+01	1.0E+04
Ra-226	1.1E-02	4.7E-09	4.7E-09	7.0E-04
Sr-90	3.4E+00	2.3E-01	3.4E+03	4.6E+06
Tc-99	6.2E-03	7.0E-04	9.7E-01	1.3E+03
Th-232	2.1E-03	2.7E-14	3.1E-11	8.1E-03
U-234	8.1E-03	3.4E-03	6.3E-01	7.9E-01
U-238	1.5E-03	3.4E-03	4.6E-01	5.5E-01
Total	**4.6E+03**	**2.6E+01**	**3.9E+03**	**1.1E+07**

4 Hazard potential of BGRR vs. Hanford tanks

The hazard potential of the radionuclide inventory was determined using RESRAD 6.21 computer model with the default configuration. The model predicts doses for a reference individual as a result of contaminated soil. In other words: the calculations are based on the scenario that the radionuclide inventory of the selected Hanford tanks and the BGRR would be present in soil and exposed to the element. The probability of releases and the means of transport are beyond the scope of this report, the calculation allows the evaluate the relative toxicity of the various radionuclides taking into account the magnitude of the activity, differences in their half-lives, environmental bahavior and distribution in the human body.

The calculations were performed using the default data set provided in version 6.21 for the radionuclide inventory listed in Table 3. The resulting radiation doses were normalized to those calculated for the BGRR in year 1 and presented in summary form in Figure 3.

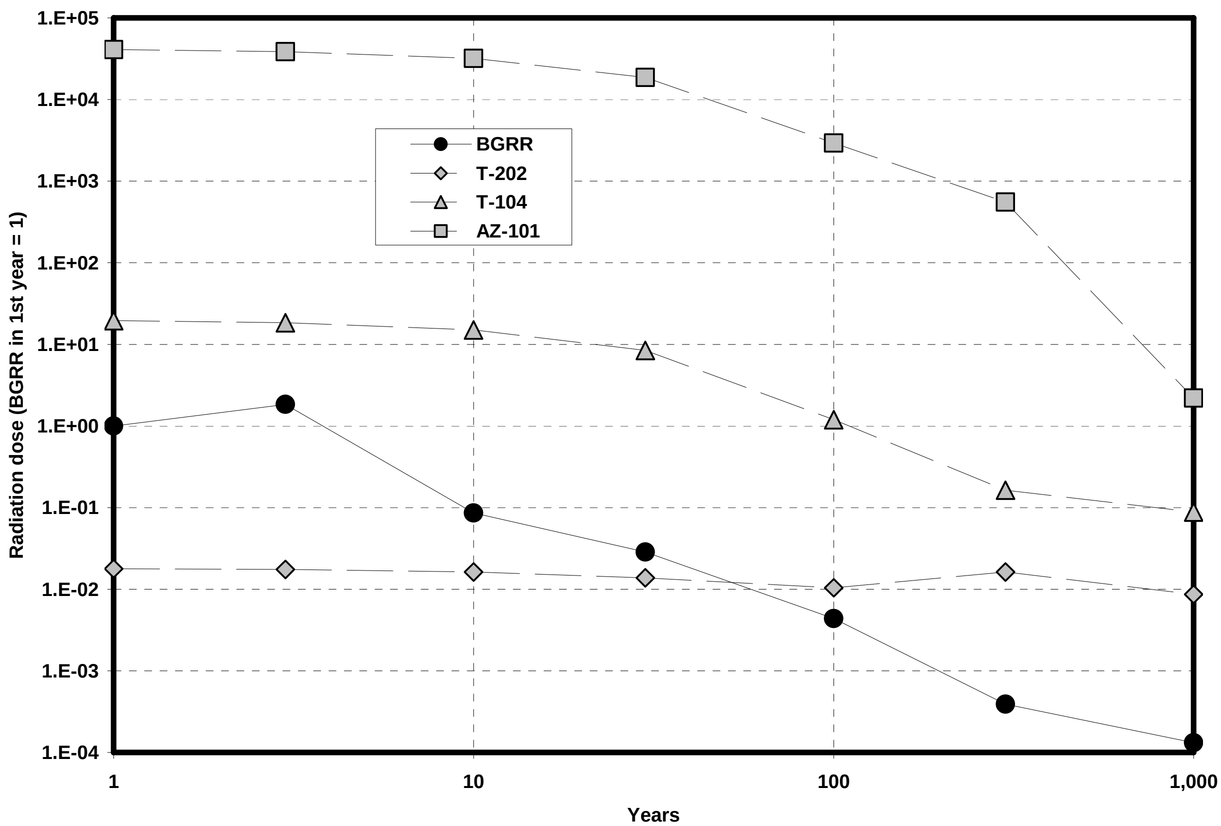

Figure 3 Relative radiotoxicity of radionuclide inventory of BGRR and of the three Hanford tanks T-202, T-104 and AZ-101 over time (RESRAD radiation dose for BGRR inventory in year one = 1)

Based on the results, the hazard potential of the BGRR inventory within the next 10 years is about a factor of 10 higher than that of tank T-202 at Hanford and about a a factor of 10 to 100 lower than that of tank T-104. After about 50 years, the hazard potential of the BGRR inventory is lower than that of tank T-202. The radiotoxicity of the inventory of tank AZ-101, the Hanford tank with the highest inventory, is about five to six orders of magnitude higher than that of BGRR. The contribution of the various exposure pathways to total dose is summarized in Tables 4 and 5 using year 10 as an example. The major radionuclides of concern in the case of BGRR are cobalt-60 and cesium-137, the major exposure pathway is external radiation, whereas it the ingestion pathways dominate the impacts of impacts of the Hanford tanks.

Table 4 Contribution of environmental pathways to the hazard potential as calculated with RESRAD default scenario (year 10)

Pathway	BGRR	T.202	T-104	AZ-101
Ground	76.3%	27.8%	3.2%	32.5%
Inhalation	0.0%	3.8%	0.0%	0.0%
Plant	16.6%	50.0%	76.4%	51.3%
Meat	5.0%	4.0%	15.5%	12.3%
Milk	1.7%	1.0%	4.6%	3.7%
Soil	0.1%	13.4%	0.2%	0.1%
Water	0.2%	0.0%	0.0%	0.0%
Fish	0.0%	0.0%	0.0%	0.0%
Total	**100.0%**	**100.0%**	**100.0%**	**100.0%**

Table 5 Contribution of radionuclides to the hazard potential calculated as with RESRAD default scenario (year 10)

Nuclide	BGRR	T-202	T-104	AZ-101
Am-241	0.1%	0.6%	0.0%	0.0%
C-14	0.0%	0.0%	0.0%	0.0%
Co-60	40.3%	0.0%	0.0%	0.0%
Cs-137	27.7%	33.1%	3.5%	38.6%
Eu-152	0.1%	0.0%	0.0%	0.0%
Eu-154	14.0%	0.0%	0.0%	0.1%
Eu-155	0.0%	0.0%	0.0%	0.0%
H-3	0.0%	0.0%	0.0%	0.0%
I-129	0.3%	0.0%	0.0%	0.0%
Ni-63	0.6%	0.0%	0.0%	0.0%
Pu-238	0.0%	0.3%	0.0%	0.0%
Pu-239	0.1%	59.5%	0.6%	0.0%
Ra-226	0.0%	0.3%	0.0%	0.0%
Pu-241	0.0%	0.0%	0.0%	0.0%
Sr-90	16.7%	6.0%	95.8%	61.2%
Tc-99	0.0%	0.0%	0.0%	0.0%
Th-232	0.0%	0.0%	0.0%	0.0%
U-234	0.0%	0.0%	0.0%	0.0%
U-238	0.0%	0.0%	0.0%	0.0%
Total	**100.0%**	**100.0%**	**100.0%**	**100.0%**

There are charcteristic differences in the type of radionuclides that contribute to the total dose:

- in the case of BGRR, it is cobalt-60, cesium-137 and europium-154
- for Hanford tanks it is strontium-90, cesium-137 and plutonium-239

The calculations suggest that the hazard potential of BGRR is comparable with that of some Hanford high-level waste tanks.

5 Preliminary Remediation Goals

In the case of decontamination and decommissioning projects, preliminary remediation goals (PRGs) are used to identifying initial cleanup goals at a site. In this role, PRGs provide long-term targets to use during the analysis of different remedial alternatives. They are not de facto cleanup standards, however, they could be used to establish final cleanup levels for a site after a proper evaluation takes place.

5.1 PRGs in the Brookhaven Graphite Research Reactor (BGRR) Decommissioning Project

The preliminary radionuclide PRGs for the BGRR are summarized in Table 6. PRGs have already been developed for several operable units (OUs) at Brookhaven National Laboratory (BNL). In the "Removal Action Alternatives Study" (RAA-Study) (BNL, 2000), only preliminary soil remediation goals for radionuclides are listed (Table 2-10, page 2-37). These PRGs have not by then been approved for BGRR decommissioning activities.

Table 6 Radionuclide Preliminary Soil Remediation Goals

Radionuclide	Soil Cleanup PRG - Residential Land Use (pCi/g)	Half Life (yrs)
Carbon-14	31	5,730
Cobalt-60	1300 (1100) [(c)]	5.3
Nickel-63	290,000	100
Strontium-90	15 [(b)]	28.5
Technetium-99	44	210,000
Iodine-129	2.4	16,000,000
Cesium-137	23 [(b)]	30.2
Samarium-151	1,000,000	93
Europium-152	49	13.3
Europium-154	170	8.8
Europium-155	150,000	4.8
Radium-226	5 [(a)]	1,600
Thorium-232	5	14,000,000,000
Uranium-234	9	250,000
Uranium-235	9	700,000,000
Uranium-238	9	4,400,000,000
Plutonium-238	66 (65) [(c)]	87.7
Plutonium-239	40	24,000
Plutonium-240	40	6,550
Americium-241	40 (39) [(c)]	432.6

Source: RAA-Study (BNL, 2000) ("consolidated from pile fan sump SAP (BNL, 1999a)
Values in brackets given in pile fan sump removal (BNL, 2001), Attachment 9, Table 1
(a) Cleanup goals for Ra-226 are based on DOE Order 5400.5 (DOE, 1993)
(b) Cleanup goals for Cs-137 and Sr-90 are also listed in OUI ROD (BNL, 1999b)
(c) values in brackets are listed in (BSA, 2000)

The listed soil cleanup PRGs are similar to those summarized in the "BGRR Sampling and Analysis Program for the Cleanup Verification of Soil and Disposal of Debris from the Removal of the Pile Fan Sump, Piping and Above-Ground Ducts" (BNL, 1999a and BSA, 2000). As stated in the RAA-Study with reference to the "Record of Decision (ROD) for Operable Unit I (OUI) and Radiologically Contaminated Soils" (BNL, 1999b), the cleanup goal for radionuclides is based on a total dose limit of 15 mrem per year above background. Soil PRGs are calculated using the Department of Energy (DOE) Residual Radioactive Material Guidelines (RESRAD) computer code or are based on regulatory documents. The chosen land use option is residential. 50 years of institutional control were assumed when running the RESRAD code.

As mentioned before, the listed values have not been approved for the BGRR Decommissioning Project. Whether a final set of Derived Concentration Guideline Levels (DCGLs) has been determined is unknown. The RAA-Study mentions that DCGLs may reflect the listed preliminary dose-based goals, they may be risk-based (pending results of additional characterization or full risk analysis), or they may be a combination of both dose-based preliminary goals and risk-based goals.

The available documentation does neither contain a rationale for the radioncuclides for which PRGs are calculated and for which not, and further does not provide details regarding the specific parameters selected for the RESRAD calculations.

5.2 PRGs by the Environmental Protection Agency (EPA)

The most recent set of preliminary remediation goals (PRGs) was provided by the USEPA in 2002 (USEPA, 2002). The values represent risk-based concentration levels that were derived from standardized equations combining exposure information assumptions with toxicity data. They are considered by the EPA to be protective for humans (including sensitive groups) over a lifetime. They do not address non-human health endpoints such as ecological impacts.

The Toxics Integration Branch (TIB) of EPA's Office of Emergency and Remedial Response, Hazardous Site Evaluation Division has developed PRG's for Superfund and/or a CERCLA[1] sites based on the "Risk Assessment Guidance for Superfund (RAGS): Volume I - Human Health Evaluation Manual (Part B, Development of risk-based preliminary Remediation Goals)".

Risk-based PRGs generally are modified based on site-specific data gathered during the remedial investigation/feasibility study (RI/FS). The above mentioned guidance does not discuss the risk management decisions that are necessary at a Superfund/CERCLA site (e.g., selection of final remediation goals). The potential users of Part B are persons involved in the remedy selection and implementation process, including risk assessors, risk assessment reviewers, remedial project managers, and other decision-makers.

Risk-based PRGs are concentration levels that correspond to a specific cancer risk level of 10^{-6} (or one in one million) or a hazard quiotient HQ/HI[2] for a given substance. They are generally

[1] **C**omprehensive **E**nvironmental **R**esponse, **C**ompensation, and **L**iability **A**ct

[2] HQ = Hazard Quotient - the ratio of a single substance exposure level over a specified time period to a reference dose for that substance derived from a similar exposure period.
HI = Hazard Index - the sum of two or more hazard quotients for multiple substances and/or multiple exposure pathways.

selected when applicable or relevant and appropriate requirements (ARARs) are not available. The PRGs considered in the following are generic, that is, they are calculated without site-specific information. Nevertheless, EPA also provides the possibility to re-calculate PRGs with site-specific data. Table 7 summarizes risk-based PRGs for those radionuclides discussed in the RAA-Study. The PRGs for for agricultural soil are more stringent given that the risk potential due to ingestion of food grown on the soil is considered.

Table 7 Risk-based Radionuclide Preliminary Soil Remediation Goals

Radionuclide	Soil Cleanup PRG Residential Land Use (pCi/g)	Soil Cleanup PRG Agricultural Land Use (pCi/g)
Carbon-14	4.56E-01	5.63E-05
Cobalt-60	3.61E-02	9.02E-04
Nickel-63	9.48E+01	1.03E+00
Strontium-90	3.31E-01	1.93E-03
Technetium-99	2.50E-01	5.60E-03
Iodine-129	5.96E-01	2.80E-05
Cesium-137	3.88E+00	1.23E-03
Samarium-151	4.65E+02	2.42E+02
Europium-152	4.16E-02	3.76E-02
Europium-154	4.99E-02	4.72E-02
Europium-155	3.80E+00	3.74E+00
Radium-226	1.93E-01	6.77E-04
Thorium-232	3.10E+00	9.42E-03
Uranium-234	4.01E+00	1.88E-03
Uranium-235	2.05E-01	1.88E-03
Uranium-238	4.46E+00	2.07E-03
Plutonium-238	2.97E+00	7.31E-03
Plutonium-239	2.59E+00	6.09E-03
Plutonium-240	2.60E+00	6.10E-03
Americium-241	1.87E+00	1.32E-01

Source: EPA, http://epa-prgs.ornl.gov/radionuclides

5.3 Clearance values of the German Order on Radiation Protection

Table 8 provides a summary the radionuclide clearance values of the German Order on Radiation Protection (StrSchV, 2001). The regulation addresses various practices: unrestricted clearance for solids and liquids, clearance for construction waste and earth more than 1,000 Mg/yr[3], and clearance for disposal of solids and liquids (except construction waste and earth more than 1,000 Mg/yr). The clearance values were calculated based on the dose limit of 10 µSv per year (= 1 mrem/yr) that was established in the European Directive EURATOM 96/29 (EU, 1996).

[3] Mg = Megagrams = 10^6 grams = one metric ton

Table 8 Clearance Values of the German Order on Radiation Protection

Radionuclide	Unrestricted Clearance	Clearance for disposal	
	Solids, liquids except in column 3 (pCi/g)	Construction waste, earth more than 1,000 Mg/yr (pCi/g)	Solids, liquids except column 3 (pCi/g)
(*column 1)*	*(column 2)*	*(column 3)*	*(column 4)*
Carbon-14	2.16E+03	2.70E+02	5.41E+04
Cobalt-60	2.70E+00	2.40+E00	1.08E+02
Nickel-63	8.11E+03	8.11+E03	8.11E+04
Strontium-90	5.40E+01	4.10E+01	5.40E+01
Technetium-99	2.70E+00	3.80E+01	2.70E+02
Iodine-129	1.10E+01	3.20E+00	1.10E+01
Cesium-137	1.40E+01	1.10E+01	2.70E+02
Samarium-151	1.35E+04	1.35E+04	1.35E+05
Europium-152	5.40E+00	5.40E+00	2.16E+02
Europium-154	5.40E+00	4.90E+00	1.89E+02
Europium-155	8.11E+02	2.19E+02	2.70E+03
Radium-226	8.00E-01	8.00E-01	2.70E+00
Thorium-232	8.00E-01	8.00E-01	2.70E+01
Uranium-234	1.40E+01	1.00E+01	2.43E+02
Uranium-235	1.40E+01	9.00E+00	8.10E+01
Uranium-238	1.60E+01	1.20E+01	2.70E+02
Plutonium-238	1.10E+00	2.20E+00	2.70E+01
Plutonium-239	1.10E+00	2.10E+00	2.70E+01
Plutonium-240	1.10E+00	2.10E+00	2.70E+01
Americium-241	1.40E+00	1.40E+00	2.70E+01

Source: StrSchV Germany, values in Bq/g converted into pCi/g (1 pCi = 0.037 Bq)

5.4 Comparison of the different PRGs

The comparison of the PRGs and/or clearance values in Tables 6 to 8 illustrates wide differences. The soil cleanup PRGs of the BGRR D&D project are less stringent for all of the listed radionuclides compared to to the risk-based PRGs that were established by the EPA, the, no matter whether residential or agricultural land use is taken into account. These differences are mainly due to two reasons: (1) risk levels and/or maximum annual doses and (b) scenarios and parameters. The PRGs of the BGRR D&D project are based on a total dose limit of 15 mrem per year above background. The risk-based PRGs of the EPA correspond to a specific cancer risk level of 10^{-6} and the German clearance values are calculated based on a maximum annual dose of 1 mrem/yr.

Of the three, the most stringent one is the cancer risk level of 10^{-6} set by the EPA. Taking the cancer morbidity rate for low dose rates of $7.6x10^{-7}$ per mrem of whole body exposure (= committed effective dose equivalent, CEDE) (EPA, 1994), a 50 year exposure to ~ 0.2 mrem/yr CEDE results in a lifetime risk of 10^{-5}. Consequently, 50 years of 15 mrem/yr CEDE is equivalent to an incremental lifetime cancer risk of ~ $6x10^{-4}$ or ~ 1 : 1,800. Hence, the risk that is equivalent to the dose limit for the BNL cleanup significantly exceeds the widely accepted risk level of 1 : 10,000.

It is prudent to use a low risk level to account for uncertainties in the characterization of contaminated areas and associated risks and in order to be consistent with cleanup risk targets used elsewhere in the US. The risk level is compatible with the "de minimis" dose limit of 1 mrem/yr CEDE that is used as a target dose for clearance of radioactive materials in international regulations (IAEA, 2002), (EU, 1996). This is because a limit for the maximum annual dose of 1 mrem/yr will result in the average dose over lifetime years to be much smaller than 1 mrem/yr, likely in the range of 0.2 mrem/yr. While the target risk is a reasonable, we recommend appending this by limiting the maximum annual dose to 1 mrem/yr CEDE.

Apart from the selected dose limit, the exact value of the PRG depends on the exposure scenarios and parameters used in the calculation. In order to facilitate the comparison, the PRGs and clearance values are normalized to a dose limit of 1 mrem/yr. The ratios between the soil cleanup PRGs of the BGRR D&D project and the other discussed PRGs are shown in Figues 4 to 8.

Because the RAA Study assumed a time period of 50 years for institutional control, the radionculides are sorted according to their decay rate in the graphs. Figure 4 illustrates that BGRR PRGs for radionuclides with half lives less than 50 years are less stringent than the risk-based PRGs of the EPA for residential use (except for Cs-137 and Sr-90 which are of special concern in the BGRR D&D project).

This aspect is less visible for the ratio of BGRR PRGs to risk-based PRGs of the EPA for agricultural land use (see Figure 5) for which no dependency on the half life can be recognized. However, all of the ratios are well above the value of one, hence the dose-adjusted BGRR PRGs are generally less stringent than the EPA values, mostly by a factor of 10 to 100. In the case of cobalt-60, nickel-63 and carbon-14, dose adjusted BGRR PRGs are four to five magnitudes less stringent as the EPA values.

The comparison of dose adjusted BGRR PRGs and German values for unrestricted clearance is shown in Figure 6, the comparison of dose adjusted BGRR PRGs and German values for for construction waste and earth is shown in Figure 7, and the comparison of dose adjusted BGRR PRGs and German values for waste disposal waste is shown in Figure 8. The dose adjusted BGRR PRGs are between a factor of 10 smaller and a factor of 10 greater than the German values for unrestricted clearance and construction waste/earth; while the BGRR PRGs values are significantly smaller than the German values for clearance for waste disposal.

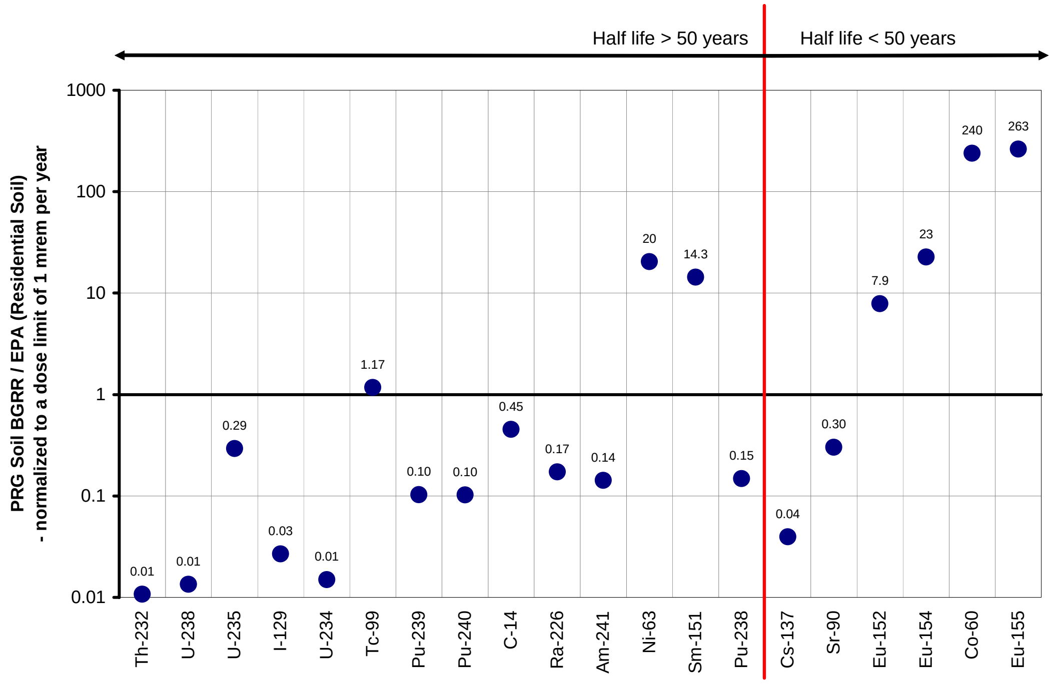

Figure 4 Ratio of the soil cleanup PRGs of the BGRR and the risk-based PRGs of the EPA (residential land use)

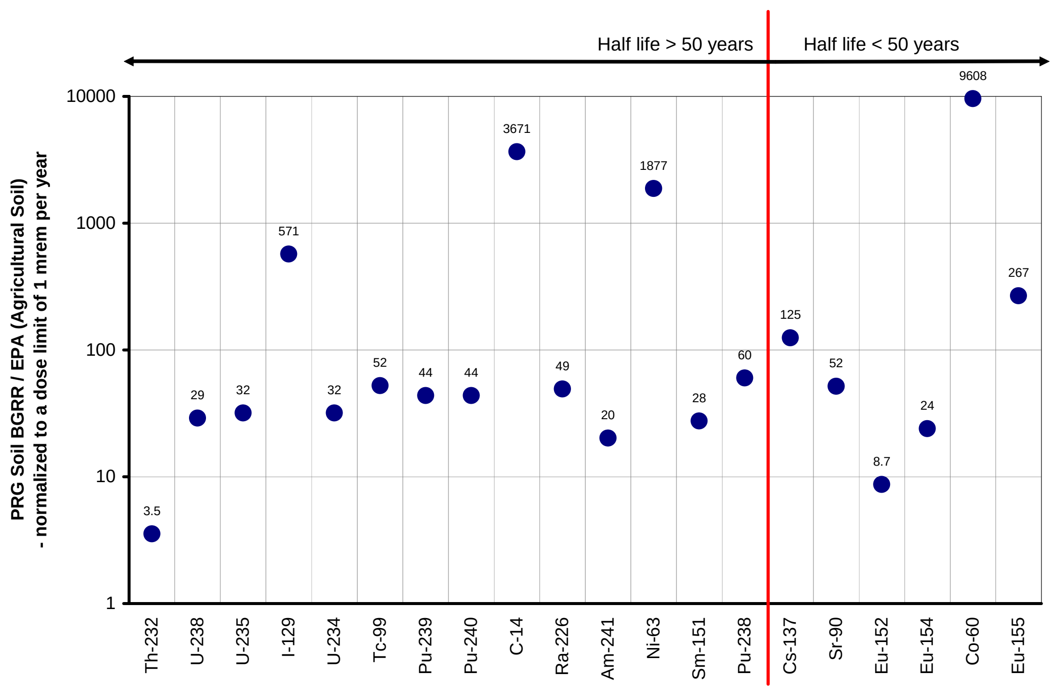

Figure 5 Ratio of the soil cleanup PRGs of the BGRR and the risk-based PRGs of the EPA (agricultural land use)

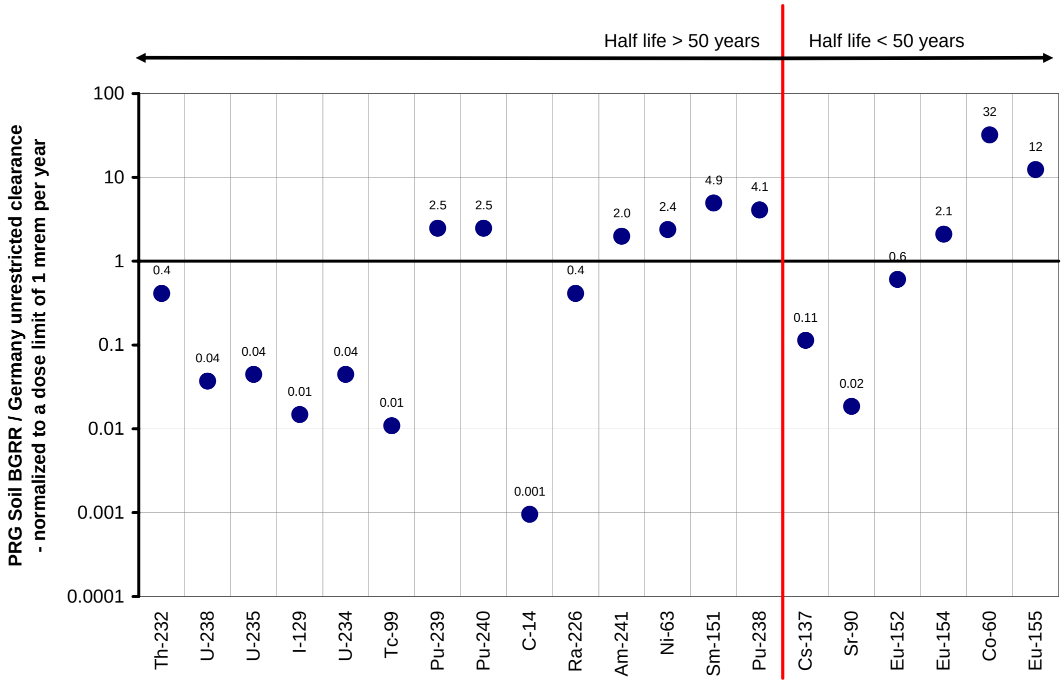

Figure 6 Ratio of the soil cleanup PRGs of the BGRR and the unrestricted clearance values for solids and liquids of the German order on Radiation Protection

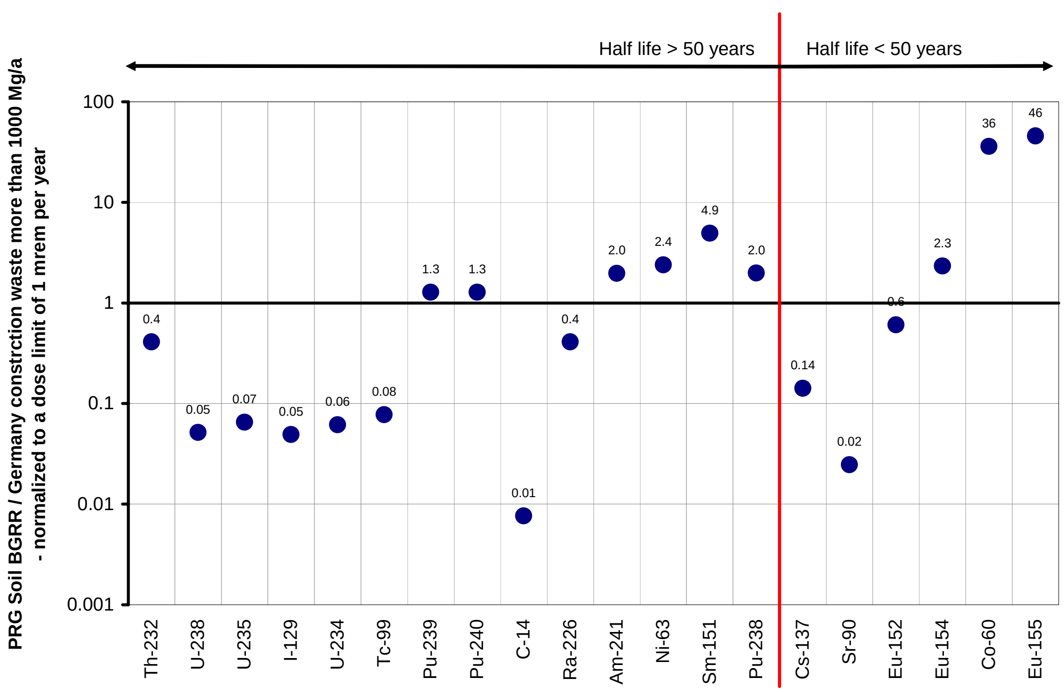

Figure 7 Ratio of the soil cleanup PRGs of the BGRR and the unrestricted clearance values for construction waste and earth more than 1,000 Mg/yr of the German order on Radiation Protection

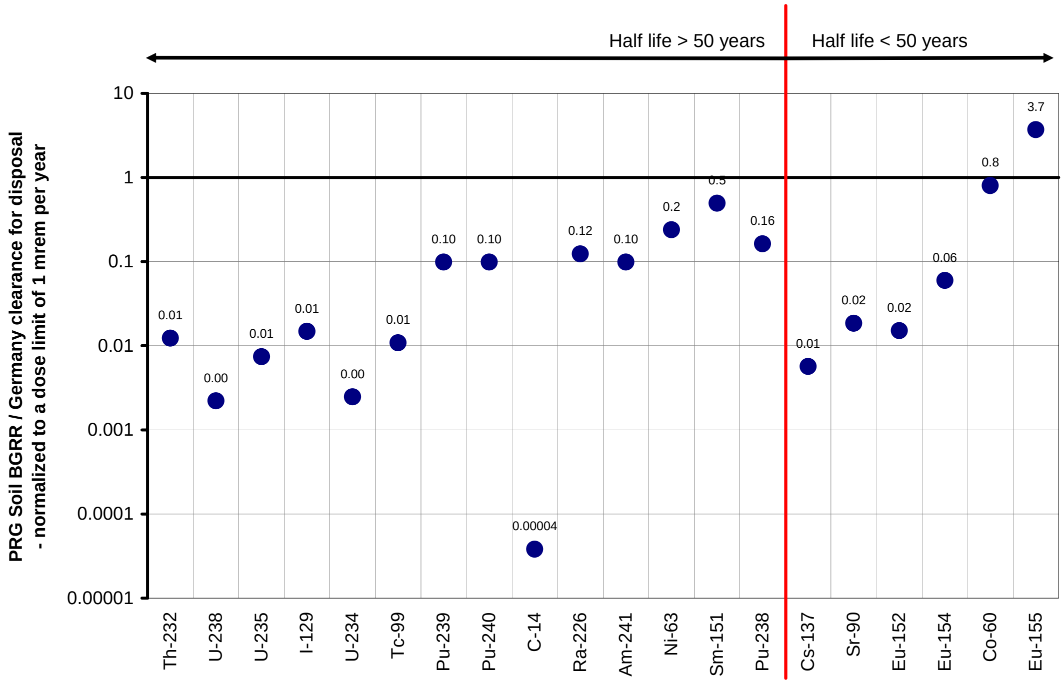

Figure 8 Ratio of the soil cleanup PRGs of the BGRR and the clearance values for disposal of solids and liquids (except construction waste and soil disposal of more than 1,000 Mg/yr) of the German order on Radiation Protection

Table 9 Comparison of Preliminary Remediation Goals (PRG) for selected radionuclides

Type of PRG	Reference	C-14	Co-60	Sr-90	Cs-137	Eu-154	Pu-239
BGRR (2000)	15 mrem/yr	31	1,300	15	23	170	40
BGRR (2000)	1 mrem/yr	2.1	87	1	1.5	11	2.7
EPA (2003) residential soil	10^{-6} cancer risk	0.46	0.036	0.33	3.9	0.05	2.6
EPA (2003) agricultral soil	10^{-6} cancer risk	0.000056	0.0009	0.0019	0.0012	0.047	0.00061
EPA (2003) residential soil	10^{-5} cancer risk *)	4.6	0.36	3.3	39	0.5	26
EPA (2003) agricultral soil	10^{-5} cancer risk *)	0.00056	0.009	0.019	0.012	0.47	0.0061
German regulation for unrestricted clearance (2001)	1 mrem/yr	2,100	2.7	54	13	5.4	1.1

**) A 50 year exposure to 0.2 mrem/yr is associated with a cancer risk of ~10^{-5}. The limit of 1 mrem/yr in the maximum year likely results in an average dose over 50 years of around 0.2 mrem/yr; hence the reference of a 10^{-5} cancer risk and a maximum annual dose of 1 mrem are comparable.*

Table 9 summarizes the findings for selected important radionuclides. The comparison of the PRGs suggests allows the following conclusions:

- In absolute numbers, the BGRR PRGs are far less stringent than the most recent EPA PRGs. For plutonium-239 for example, the BGRR PRG of 40 pCi/g compares to 0.0061 pCi/g for the agricultural soil scenario, a difference by a factor of 6,600.
- Even if one adjusts the PRGs to the same dose limit, the BGRR PRGs are less stringent than EPA's PRGs for agricultural soil scenario by up to a factor 9,600 (in the case of cobalt-60).
- There is no internal consistency in the relative magnitude of the various PRGs if adjusted them to the same dose level. In other words: there is no simple reason for the difference.
- Given the fact that the PRG level is crucial in determining the amount and the fate of material or soil from the BGRR and the other reactors, a careful analysis and documentation of PRGs should preceed any further D&D activity at BNL.

Such analysis should focus on the following issues and select stakeholder inout in these:

- List of radionuclides to be considered
- Risk level
- Translation into dose rate level
- Usage scenarios
- Choice of parameters
- Treatment of uncertainties

6 Review of Life-cycle Impacts of D&D Options

The BGRR Removal Action Alternatives Study (BNL, 2000) acknowledges in Table D-3, p. D-13 that lifecycle impacts need to be considered. Chapter 2.4.5 defines that the regulations that need to be considered (TBCs) “consist of non-enforceable advisories, criteria, or guidance developed by federal, state, or local agencies that may be useful in developing CERCLA remedies" (ibid. p. 2-32). A further review identifies the order that needs to be addressed in this context as the pertinent regulation is DOE Order 430.1A “Life Cycle Asset Management” (USDOE, 1998) that defines the following objectives:

“The Department of Energy (DOE), in partnership with its contractors, shall plan, acquire, operate, maintain, and dispose of physical assets as valuable national resources. The management of physical assets from acquisition through operations and disposition shall be integrated and seamless process linking the various life cycle phases. Stewardship of these physical assets shall be accomplished in a safe and cost-effective manner to meet the DOE mission, and to ensure protection of workers, the public, and the environment. This shall incorporate industry standards, a graded approach, and performance objectives.”

Such in-depth review cannot be seen in light of the methodology outlined in chapter 3.2. The documents reviewed do not provide a complete picture of the indirect environmental costs and environmental benefits of D&D impacts.

Consequently, a detailed life-cycle assessment would be necessary for the following options:

- No Action (Surveillance and Maintenance)
- Decontaminate and Leave in Place
- Isolate, Seal or Enclose and Leave in Place
- Remove and Disposal in Permitted Waste Disposal Facility without Clearance of of Contaminated Material
- Remove and Disposal in Permitted Waste Disposal Facility with Clearance of Contaminated Material

The method of Life Cycle Assessment (LCA) is the first and only ecological evaluation instrument developed by an international scientific export group (Technical Committee ISO/TC 207 "Environmental Management" in collaboration with the Technical Board of CEN/CS). And it is the first method that has been standardized in its main features (ISO EN DIN 14040ff). Using the LCA method in compliance with the requirements of the Standard minimizes the risk of an incorrect application. Nevertheless, also LCA-based results need not to be clear-cut. Therefore, like with other ecological evaluation instruments understandings need to be found (boundary conditions and system boundaries) and presented in a transparent way. Thus the final interpretation of the results usually stamped by subjective valuation is traceable and easy to classify.

The main modifications for the special context of evaluating waste disposal routes in comparison to the usual steps within the LCA are shown in Figure 9.

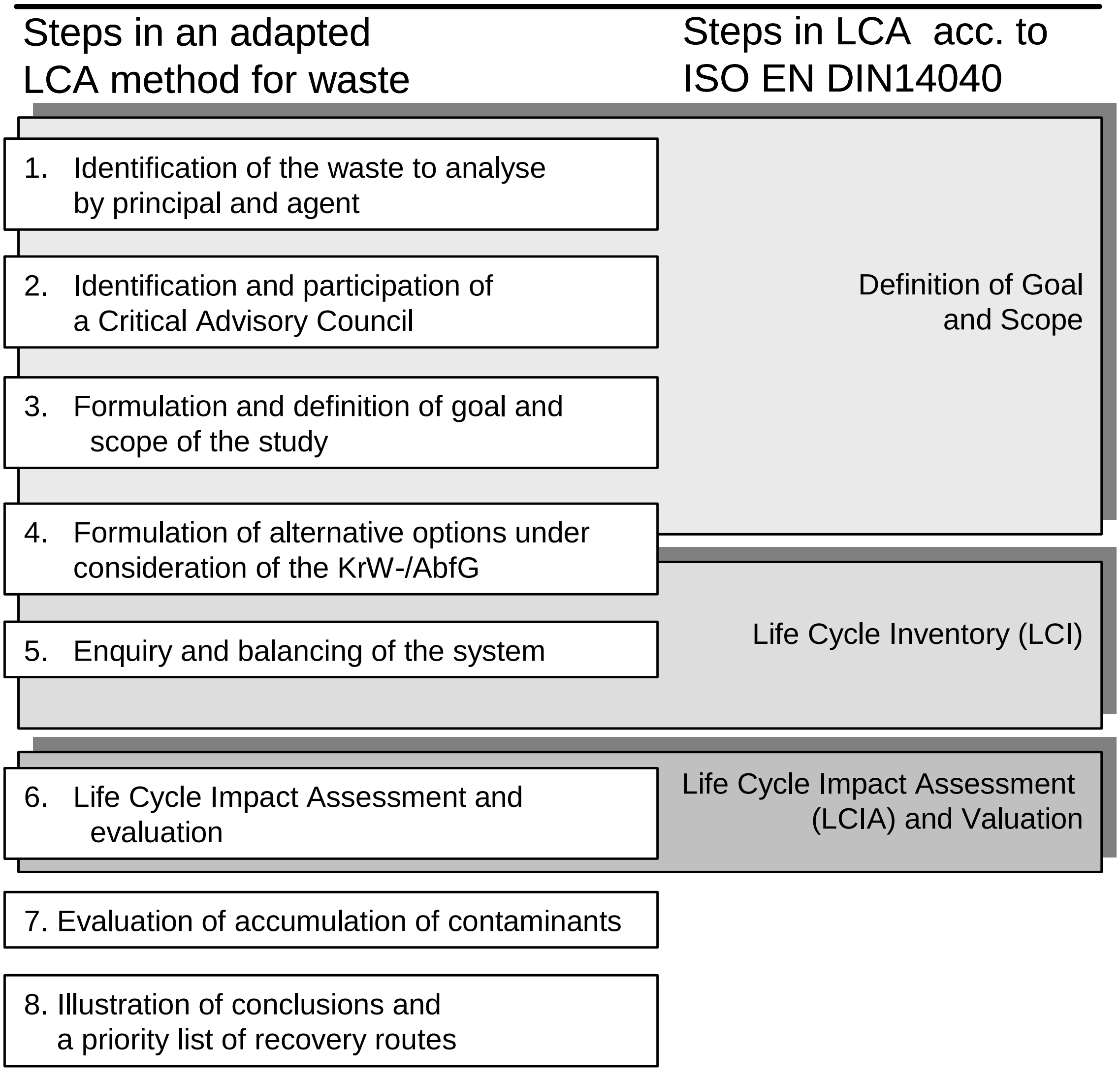

Figure 9 Procedure of the LCA method for waste management

The definition of the goal is only possible in the specific context of a project. As an example the goal in a D&D project might be the comparison of all reasonable alternatives to define the alternative most compatible with the environment. Generally, the scope of a study covers the path of the waste from its generation to its disposal. In the case of a D&D project emissions and affords for the possible removal itself should be included as well. Subsequently, all main processes like collection and transport, conditioning, treatment, final disposal or application and collateral processes (e.g. energy supply, auxiliaries production) are calculated.

Depending on the recycling or disposal options each recovery route may have a different outcome. For instance, removal material with low or non contamination might be reused substituting primary construction material. It is mandatory to consider the primary production processes substituted in order to keep the environmental impacts of the different recycling options comparable. The primary processes substituted will be referred to as equivalent processes.

Hence the environmental analysis is not limited to the performance of recycling plants, but extends to the environmental impacts of the entire recycling system of specific wastes from the source of generation to its possible application as a secondary material (Figure 10).

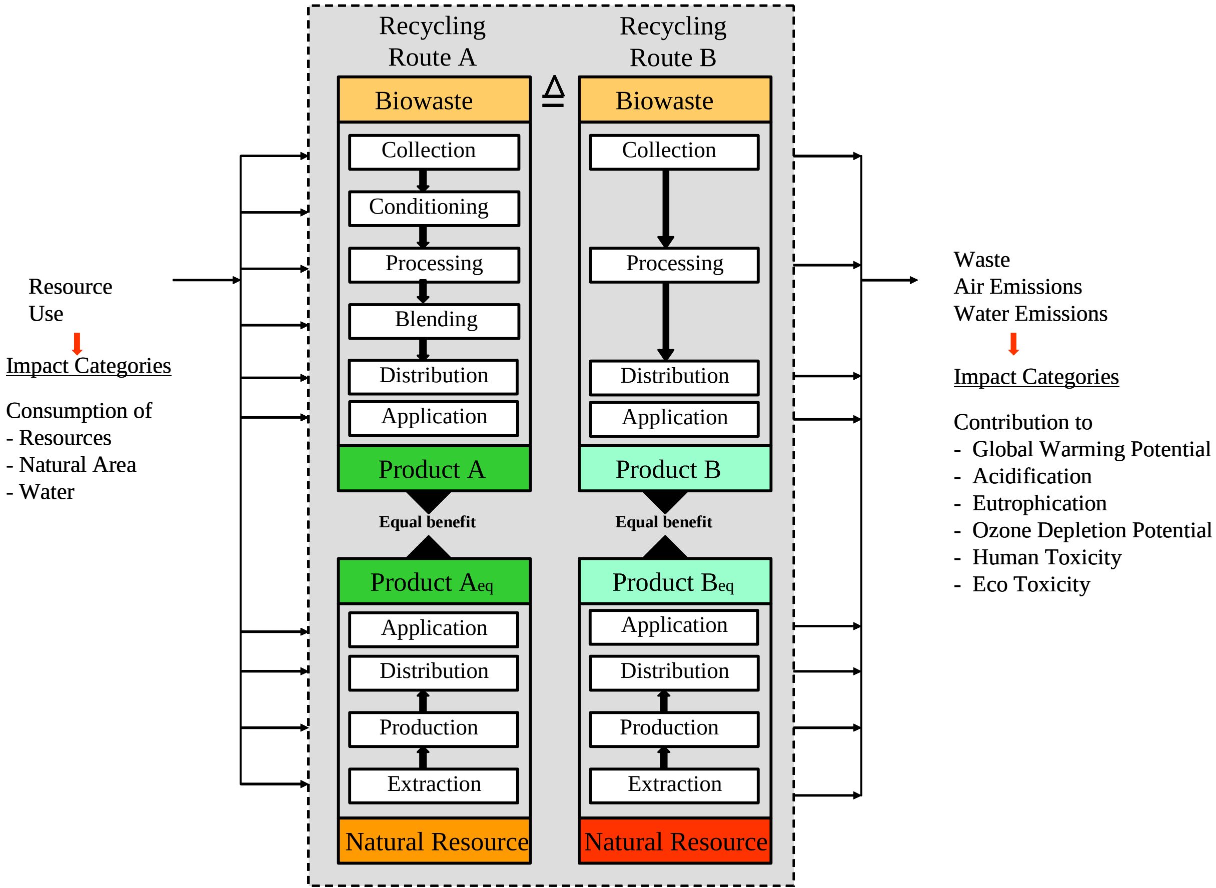

Figure 10 Method for comparative evaluation of recycling systems for waste

Usually, the environmental effects from the generation of the waste itself are not considered in the life cycle assessment of wastes, because the wastes are not produced on purpose. Therefore, we find quite often the situation that the environmental impacts from the equivalent processes have a very high influence on the results of the ecological valuation, especially when high quality products are substituted. That is to say, waste management systems undertaking high efforts in waste treatment aiming on a high value for recycling in good production, may come out as the better option from an ecological point of view, due to the saving of harmful effects on the production of goods.

7 Conclusions and Recommendations

From this review of BNL D&D projects, the main conclusions and recommendations can be summarized as follows:

- The **radionuclide inventory** of the BGRR of 4,300 curies is comparable with that of some Hanford high-level waste tanks: about 18 or 10% of the Hanford tanks have a radionuclide inventory of less than the BGRR. Even if the radiotoxicity and environmental transport of the different radionuclides are considered using the RESRAD computer model, the **hazard potential** of BGRR is comparable with that of Hanford tanks with a small inventory.

  Recommendation*: *The long-term hazard potential of the BGRR should be adequately addressed in order to provide appropriate protection against the hazards it poses with respect to human health and the environment.

- The **preliminary remediation goals** (PRGs) that were selected for BGRR D&D are far less stringent than the most recent EPA PRGs. For plutonium-239 for example, the BGRR PRG of 40 pCi/g compares to 0.0061 pCi/g for the agricultural soil scenario, a difference by a factor of 6,600. Even if one adjusts the PRGs to the same dose limit, the BGRR PRGs are less stringent than EPA's PRGs for agricultural soil scenario by up to a factor 9,600 (in the case of cobalt-60). A detailed comparison between a range of PRGs showed no internal consistency in the relative magnitude of the various PRGs even if they adjusted them to the same dose level.

  Recommendation: Given the fact that the PRG level is crucial in determining the amount and the fate of material or soil from the BGRR and the other reactors, a careful analysis and documentation of PRGs should preceed any further D&D activity at BNL.

- Despite the 1998 DOE Order 430.1A "Life Cycle Asset Management" there has been no systematic evaluation of **life-cycle impacts** of the D&D activities at BNL.

  Recommendation: A careful study of the life-cycle impacts of D&D activities at BNL should be carried out addressing the principles described in chapter 6.

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