Submission to the Deep Geologic Repository Project Joint Review Panel by Gordon Thompson:

"COMMENTS ON OPG's PROPOSAL TO DEVELOP A DEEP GEOLOGIC REPOSITORY FOR RADIOACTIVE WASTE: A NEGLECTED POTENTIAL FOR MALEVOLENT ACTS"

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COMMENTS ON OPG's PROPOSAL TO DEVELOP A DEEP GEOLOGIC REPOSITORY FOR RADIOACTIVE WASTE: A NEGLECTED POTENTIAL FOR MALEVOLENT ACTS

by
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Abstract

Ontario Power Generation (OPG) proposes to construct, operate, and ultimately decommission and abandon a deep geologic repository (DGR) for low- and intermediate-level radioactive waste. The repository would accommodate waste from commercial nuclear reactors that are owned or operated by OPG, and are located at the Bruce, Pickering, and Darlington sites. This report addresses selected issues related to the DGR, in the issue category "malfunctions, accidents, and malevolent acts", with a focus on malevolent acts. OPG has prepared an environmental impact statement (EIS) for the DGR that considers, among other issues, the potential for malevolent acts. This report shows that the EIS has not fully assessed the potential for malevolent acts associated with the DGR, and the impacts of such acts. The report offers recommendations for correcting that deficiency.

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The Institute for Resource and Security Studies (IRSS) is an independent, nonprofit, Massachusetts corporation, founded in 1984. Its objective is to promote sustainable use of natural resources and global human security. In pursuit of that mission, IRSS conducts technical and policy analysis, public education, and field programs. IRSS projects always reflect a concern for practical solutions to resource and security problems.

About the Author

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1. Introduction

Ontario Power Generation (OPG) proposes to construct, operate, and ultimately decommission and abandon a deep geologic repository (DGR) for low- and intermediate-level radioactive waste. The repository would be located in Bruce County, Ontario, and would accommodate waste from commercial nuclear reactors owned or operated by OPG. Those reactors are located at the Bruce, Pickering, and Darlington sites in Ontario.

The federal Minister of the Environment and the President of the Canadian Nuclear Safety Commission (CNSC) have established a Joint Review Panel to conduct an environmental assessment of the proposed DGR. That assessment is governed by the *Canadian Environmental Assessment Act 2012*. The Joint Review Panel has scheduled a public hearing in September 2013 to address issues related to the proposed DGR. This report was prepared as a contribution to public dialogue about the DGR, both in the context of the September 2013 hearing and more generally.

This report addresses selected issues related to the DGR. Absence of discussion of other issues does not imply that those issues are unimportant. The selected issues that are addressed here are in the issue category, "malfunctions, accidents, and malevolent acts". Within that category, this report focuses on malevolent acts. This report shows that OPG has not fully assessed the potential for malevolent acts related to the DGR, and the impacts of such acts. The report offers recommendations for correcting that deficiency.

A major step by OPG in seeking regulatory approval of the DGR was to prepare an environmental impact statement (EIS) for the project. OPG published that EIS in March 2011.[1] At the same time, OPG published a number of Technical Support Documents (TSDs) containing information that supports the EIS. One of those TSDs, prepared for OPG by the contractor AMEC NSS Ltd., addresses malfunctions, accidents, and malevolent acts.[2] The EIS and the TSD prepared by AMEC are used here as definitive sources of information regarding OPG's consideration of malevolent acts pertinent to the DGR.

The term "radiological risk" is used at various points in this report. That term refers to the potential for unplanned exposure of humans to ionizing radiation. Unplanned exposure could arise from malfunctions, accidents, or malevolent acts.

The remainder of this report has six sections. Section 2 summarizes OPG's consideration of malevolent acts in the EIS. Then, Section 3 provides a brief, general review of the potential for malevolent acts in the context of radioactive waste. Informed by that review, Section 4 discusses the risk significance of the expected inventory of radioactive material in the DGR. That discussion, and Section 2, show that OPG has not fully assessed malevolence-related radiological risk associated with the DGR. Section 5 outlines steps needed to correct that deficiency. Conclusions and recommendations are

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[1] OPG, 2011a; OPG, 2011b.
[2] AMEC, 2011.

set forth in Section 6, and a bibliography is provided in Section 7. Documents cited in this report are listed in the bibliography.

Any analyst who discusses malevolence-related radiological risk must be careful to avoid disclosing information that could enhance the probability or impact of a malevolent act. This report provides no such information. The report is suitable for general distribution.

2. OPG's Environmental Impact Statement: Consideration of Malevolent Acts

EIS guidelines

The Canadian government has established guidelines, whose final version is dated January 2009, that OPG was required to follow in preparing its EIS for the proposed DGR. Section 12 of those guidelines specifies the manner in which the EIS must address malfunctions, accidents, and malevolent acts. Specifications in Section 12 include the following statement about malfunctions and accidents:[3]

> "The proponent must describe:
> - Specific malfunction and accident events that have a reasonable probability of occurring during the life of the project, including an explanation of how these events were identified for the purpose of this environmental assessment;
> - Source, quantity, mechanism, rate, form and characteristics of contaminants and other materials (physical, chemical and radiological) likely to be released to the surrounding environment during the postulated malfunctions and accidents and the effect this will have on the environment and health and safety of the nuclear energy worker and the general public; and
> - Any contingency, clean-up or restoration work in the surrounding environment that would be required during, immediately following, or in the longer term following the postulated malfunction and accident scenarios."

Section 12 of the guidelines is cryptic in specifying the treatment of malevolent acts. Its entire statement on this matter is as follows:[4]

> "The EIS must address potential environmental effects that could result from intentional malevolent acts. While intentional malevolent acts are not accidents, the proponent must compare the environmental effects resulting from malevolent acts with the effects identified for accidents and malfunctions involving the DGR."

[3] OPG, 2011b, Appendix A1, Section 12.
[4] OPG, 2011b, Appendix A1, Section 12.

Scope of the EIS regarding malevolent acts

OPG's EIS addresses malfunctions, accidents, and malevolent acts in its Section 8. The portion of that section that examines malevolent acts begins with the statement:[5]

> "Malevolent acts are defined as those events where the initiating event for a malfunction or accident was an intentional attempt to cause damage to the facility. There are four broad categories of potential malevolent acts: threats of violence, sabotage, theft and attack. Threats and theft are not considered in this assessment [emphasis added].
> Malevolent acts are assessed using methods different from those used for conventional malfunctions and accidents. As malevolent acts cannot necessarily be bounded by specified event scenarios, a high level, qualitative assessment of these events is provided in this document.
> The DGR Project is entirely contained within the Bruce nuclear site and will continue to be well protected by the Bruce nuclear site security forces from the start of site preparation and construction through to decommissioning of the facility."

This statement establishes that OPG's EIS considers malevolent acts involving sabotage or attack, but not threats or theft. OPG does not offer a rationale for limiting the scope of the EIS in this manner. The statement also emphasizes that the DGR would be entirely contained within the Bruce nuclear site. It does not follow that adverse impacts arising from the DGR project would be contained within the site. Yet, the EIS assumes that impacts would be contained in this manner.

The Bruce nuclear site contains the Bruce A and Bruce B nuclear generating stations. This site also contains the Western Waste Management Facility (WWMF), which provides an interim storage location for low- and intermediate-level radioactive waste arising at reactors owned or operated by OPG. The DGR would be on land adjacent to the WWMF, and would receive waste only from the WWMF.

Waste forms are currently received at the WWMF from the Bruce A and Bruce B stations, and from the Pickering and Darlington nuclear sites. When received, low-level waste (LLW) may be processed through incineration or compaction to reduce its volume. Low-level waste is then placed into storage at the WWMF. Intermediate-level waste (ILW) is placed directly into storage at the WWMF, without volume reduction. These general practices would continue if the DGR began operating, although the period of interim storage at the WWMF could be brief. Thus, the WWMF would receive several streams of radioactive waste, and would send a single stream to the DGR.

Malevolent acts could affect the several streams of waste going to the WWMF, and the single stream of waste going from the WWMF to the DGR. Relevant types of malevolent act could include theft of waste packages, or attack on a waste shipment. Such acts could

[5] OPG, 2011a, Section 8.4, page 8-25.

occur at any point along each of the various waste streams, which begin with departure from the contributing reactors and end with emplacement in the DGR. Also, these acts could occur during interim storage of waste at the WWMF or the DGR, or after emplacement of waste in the DGR.

OPG's EIS adopts a narrower scope. In considering malevolent acts, the EIS excludes all management of low- and intermediate-level waste prior to departure of waste from the WWMF to the DGR. The EIS does not explicitly describe or seek to justify this limitation of scope, but simply adopts it as an unspoken assumption. Consistent with this unspoken approach, the EIS does not identify any other document that assesses malevolence-related radiological risk during shipment of waste from reactors to the WWMF, or during processing and storage of waste at the WWMF. Thus, the EIS simply ignores these components of risk. This deficiency compounds the failure of the EIS to consider malevolent acts involving threats or theft.

Theft of waste designated for emplacement in the DGR could greatly expand the geographical area that could be adversely affected by malevolent acts. A waste form could be stolen and transported to a place distant from the DGR. Then, the waste form could be employed in various possible ways so as to harm people at the distant place. OPG's EIS ignores this component of risk.

One category of potential malevolent acts consists of threats that may, or may not, be carried out. For example, adversaries might steal a waste package and threaten to explode that package in a city setting unless some condition (e.g., release of a prisoner allied to the adversaries) is met. A range of threat scenarios can be identified, and would be considered in a comprehensive assessment of malevolence-related radiological risk. OPG's EIS ignores this component of risk, and offers no rationale for doing so. Note that a threat could have significant adverse impact – such as economic disruption – even if the threat is not carried out.

Malevolent acts considered in the EIS

Malevolent acts are considered in Section 8.4 of OPG's EIS.[6] They are also considered, in somewhat greater detail, in Section 6 of the TSD prepared by AMEC.[7] The latter source is used here. Highlights of AMEC's findings regarding malevolent acts include:

- "Likely, the most realistic scenario is sabotage or attack by an employee attempting to damage systems or waste packages directly. Potential malevolent acts include deliberately driving a forklift into a package or dropping a package during handling; pushing a package or vehicle into the shaft; and setting waste packages on fire." (Section 6.2.2)
- "A person using an explosive or incendiary device would cause the most damage. As explosives used for construction would be accounted for and removed from

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[6] OPG, 2011a.
[7] AMEC, 2011.

the site before the DGR Project starts operation, this would require the worker to smuggle explosives on-site." (Section 6.2.2)

- "Transfer of ILW from the WWMF to the DGR Project, including any staging at surface prior to emplacement, may present the greatest vulnerability to malevolent acts. This risk can be mitigated through procedures, such as controlling the total amount of radioactivity in transit or queued for emplacement, and use of indoor staging areas to make it more difficult to estimate the total amount of material in queue." (Section 6.2.2)
- "The DGR is about 1.1 km from the nearest Bruce nuclear site boundary, placing it within the range of a remote military-style attack from that boundary; an aircraft crash is also possible." (Section 6.2.2)
- "In general, the radiological consequences of credible malevolent acts are expected to be similar to those of malfunctions and accidents. Scenarios including detonation of explosives have the potential to produce public consequences exceeding those of the bounding accident scenarios, but public consequences would remain significantly below the acute accidental dose criterion of 1 mSv." (Section 6.4)
- "Extreme malevolent acts, such as use of explosives, could cause worker fatalities in the vicinity. More credible malevolent acts, including sabotage of safety systems, are bounded by accident scenarios." (Section 6.4)

Summary

OPG's EIS provides some useful information about malevolence-related radiological risk associated with the proposed DGR. However, the EIS is substantially deficient in its consideration of this risk, in the following respects:

- No consideration of theft
- No consideration of threats
- No consideration of events affecting LLW or ILW prior to its departure from the WWMF to the DGR

3. The Potential for Malevolent Acts in the Context of Radioactive Waste

Governments around the world recognize that radioactive materials generated and used by the nuclear industry could be used by malevolent actors to cause threatened or actual harm.[8] Relevant government agencies often consider this hazard within a broader context using rubrics such as the CBRNE (chemical, biological, radiological, nuclear, and explosives) hazard or the WMD (weapon of mass destruction) hazard.

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[8] Medalia, 2011.

Radiological WMD, RDDs, and REDs

The US Federal Emergency Management Agency (FEMA) has described radiological WMD as follows:[9]

> "Any weapon or device designed to release radiation or radioactivity at a level dangerous to human life without a nuclear explosion. Examples include Radiological Dispersal Device (RDD); Radiation Exposure Device (RED); deliberate radiological contamination of food, water, or consumables; deliberate damage to radioactive material in use, storage or transport or to an associated facility (such as a nuclear power plant)."

Figure 1 shows a crude type of RDD, which many people would describe as a "dirty bomb". The illustrated RDD consists of a pipe bomb placed on a shipping container of radioactive material. That container might be a package of LLW or ILW, designated for emplacement in the DGR. Various other configurations of RDD are possible.

Note that use of an RDD would involve dispersal of radioactive material into the surrounding environment. People in that environment could be exposed to ionizing radiation via external exposure, inhalation, skin contamination, or ingestion of contaminated substances. By contrast, an RED would not disperse radioactive material, but would be hidden in a location such that people nearby would unknowingly experience external exposure.

Potential scale of impact of an RDD incident

The scale of impact of an RDD incident could vary substantially, according to the characteristics of the device, the location of the incident, and other factors. The impact would include health, economic, social, and environmental components. Estimating the direct health component of impact for a particular incident is conceptually straightforward, although subject to a variety of scientific complexities and uncertainties. By contrast, estimating the economic and social components would involve the prediction of human behavior and the assigning of monetary values to human preferences. Findings of this kind are highly sensitive to the assumptions that are made.

Consider, for example, a study – sponsored by Defence Research and Development Canada – to estimate the economic impact of an open-air explosion of an RDD at the CN Tower in Toronto.[10] The assumed release would consist of 37 TBq of Cs-137. The estimated economic impact varies considerably, according to the cleanup standard that is assumed in the analysis. That standard is expressed in terms of the radiation dose rate that would remain after completion of the cleanup. For a cleanup standard of 5 mSv per year, the estimated economic impact would be $28 billion, whereas for a cleanup standard of 0.15 mSv per year the impact would be $250 billion.

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[9] FEMA, 2011/2012.
[10] Cousins and Reichmuth, 2007.

The policy realm

National and international agencies with responsibilities related to nuclear technology take a close interest in the nuclear and radiological aspects of the CBRNE/WMD hazard. One expression of that interest is the agencies' work on "nuclear security" issues. Among those issues is the potential for malevolent acts affecting radioactive waste.

For example, the International Atomic Energy Agency (IAEA) has been concerned for many years about nuclear-security issues. Engagement of IAEA Member States with these issues has tended to increase over time. Thus, in July 2013, IAEA held an international conference on nuclear security, the first such event to be held at ministerial level. The IAEA Director General gave a welcoming speech that included the statement:[11]

> "Much has been achieved in the past decade. Many countries have taken effective measures to prevent theft, sabotage, unauthorized access, illegal transfer, or other malicious acts involving nuclear or other radioactive material. Security has been improved at many facilities containing such material.
> Partly as a result of these efforts, there has not been a terrorist attack involving nuclear or other radioactive material. But this must not lull us into a false sense of security. If a "dirty bomb" is detonated in a major city, or sabotage occurs at a nuclear facility, the consequences could be devastating. The threat of nuclear terrorism is real, and the global nuclear security system needs to be strengthened in order to counter that threat."

During the conference, representatives of 34 Member States adopted a Ministerial Declaration that included the statement:[12]

> "We, Ministers of the Member States of the International Atomic Energy Agency (IAEA), gathered at the International Conference on Nuclear Security: *Enhancing Global Efforts*, convened by the Director General of the IAEA and open to all States, remain concerned about the threat of nuclear and radiological terrorism and of other malicious acts or sabotage related to facilities and activities involving nuclear and other radioactive material."

Given this degree of concern by IAEA and its Member States, one could reasonably expect that the Canadian government would assign a high priority to nuclear-security issues. As a corollary, one could reasonably expect that OPG's EIS for the DGR project would provide a thorough, comprehensive assessment of malevolence-related radiological risk. Unfortunately, as discussed in this report, the EIS does not provide such an assessment.

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[11] IAEA, 2013.
[12] IAEA, 2013.

4. Risk Significance of DGR Radioactive Inventory

Co-60 and Cs-137 as indicators

As a first step toward assessing the malevolence-related radiological risk associated with the DGR project, this report examines the expected radioactive inventory of the DGR. Consistent with the limited scope of this report, the examination focuses on two radionuclides – Co-60 and Cs-137. These isotopes are known to be significant in many radiological-risk contexts, but various other isotopes can also be significant. A comprehensive assessment of risk would examine a range of isotopes.

Co-60 has a half-life of 5.3 years. It decays to Ni-60 in an excited state, which immediately emits two gamma photons of energy 1.17 MeV and 1.33 MeV in succession to reach its stable state. Cs-137 has a half-life of 30 years. In 5% of its decays, it yields stable Ba-137. In 95% of its decays, it yields Ba-137m, a metastable radionuclide that has a half-life of 2.6 minutes and emits a gamma photon of energy 0.66 MeV while decaying to stable Ba-137.

OPG has estimated the radioactive inventory in the DGR during its operation.[13] The resulting data are used here to create Tables 1 and 2, which show the expected inventories of Co-60 and Cs-137 in 2018, for two groups of waste categories. Table 1 covers operational ILW categories, while Table 2 covers reactor refurbishment waste categories. In both tables, volumetric concentrations (Bq/m^3) of Co-60 and Cs-137 are calculated.

Table 3 provides some insight into the radiological risk significance of the data in Tables 1 and 2. In Table 3, the maximum average volumetric concentration of Co-60 and Cs-137 across a DGR waste category is compared to two indicators of risk in the context of the RDD hazard. One indicator is the Quantity of Concern specified by the US Nuclear Regulatory Commission (NRC). The second, related indicator is the threshold amount of Co-60 or Cs-137 needed to contaminate 1 square km of land if dispersed uniformly. These indicators are used here to perform "prima facie" tests of the risk significance of the expected amounts of Co-60 and Cs-137 in the DGR.

One sees from Table 3 that the average volumetric concentration of Co-60 across a DGR waste category could reach 7.4 TBq/m^3. Yet, the NRC Quantity of Concern is only 0.3 TBq, and the threshold amount for land contamination is 0.4 TBq. These two amounts are small fractions of 7.4 TBq, which could be the amount of Co-60 in 1 cubic meter of some waste forms in the DGR. In other words, theft of a small fraction of 1 cubic meter of some waste forms could, in principle, equip a malevolent actor with sufficient Co-60 to create a significant RDD hazard. Of course, the practical feasibility of the theft and the use of the stolen material in an RDD must be assessed, as discussed in Section 5, below.

One also sees from Table 3 that the average volumetric concentration of Cs-137 across a DGR waste category could reach 0.08 TBq/m^3, while the NRC Quantity of Concern for

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[13] OPG, 2010.

Cs-137 is 1 TBq, and the threshold amount for land contamination is 1.6 TBq. Thus, a malevolent actor would need to steal at least 12-20 cubic meters of waste in order to create a significant RDD hazard using Cs-137.

The lower risk posed by Cs-137 in the DGR inventory, compared with Co-60, contrasts with the respective risks posed by these two radionuclides in the context of an operating nuclear power plant. In illustration, Table 4 shows amounts of Cs-137 related to the Chernobyl and Fukushima accidents.

High dose-rate waste forms

Another indicator of malevolence-related radiological risk associated with the DGR project is the radiation dose rate in the vicinity of waste forms. This dose rate is a prima facie indicator of the potential for a waste form to be used in an RED or RDD. Table 5 shows data, compiled by OPG, on high dose-rate ILW received at the WWMF until late 2005. One sees that the WWMF had received almost 1 thousand cubic meters of ILW that exhibited a contact dose rate exceeding 5 Sv/hr. Some waste forms exhibited a dose rate of 700 Sv/hr. It appears that OPG has not provided comparable data for the expected waste inventory in the DGR.

To illustrate the significance of such dose rates for human health, note that the adverse health effects of radiation exposure could include, depending upon whole-body dose:[14]

- >100 Sv: Failure of the central nervous system, with seizures and convulsions, and death within a day
- 10-50 Sv: Failure of the gastro-intestinal tract, extensive internal bleeding, and death within a few days
- 5-10 Sv: Certain death within a few weeks due to failure of bone-marrow cells to make fresh blood cells
- 2.5 Sv: Median lethal dose (LD 50) across a population of adults (death within 30 days)

Summary

In Section 4, this report has identified prima facie evidence that some ILW waste forms being shipped to or emplaced in the DGR could, if stolen, pose a significant RDD or RED hazard.[15] The evidence consists of expected volumetric concentrations of Co-60 and Cs-137 at the DGR, and experience at the WWMF with high dose-rate ILW.

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[14] RCEP, 1976, paragraphs 64-65.

[15] The stolen material could also be used to contaminate food or water supplies.

5. Steps Needed to Fully Assess Malevolence-Related Radiological Risk at the DGR

Preceding sections of this report show that OPG has provided a substantially incomplete assessment of malevolence-related radiological risk associated with the proposed DGR. Section 2 shows that OPG's EIS does not consider substantial components of risk – theft or threats, and events affecting waste prior to its departure from the WWMF to the DGR. Section 4 provides prima facie evidence that these neglected components of risk are significant. The evidence indicates that some ILW waste forms being shipped to or emplaced in the DGR could, if stolen, pose a significant RDD or RED hazard.

Correcting the deficiency in OPG's assessment of malevolence-related radiological risk would require OPG or a qualified contractor to take a sequence of steps including:

- Perform prima facie tests of the risk significance of all relevant radionuclides in the expected DGR inventory, as performed here for Co-60 and Cs-137, considering all potential pathways for human exposure to radiation
- Estimate the inventory and characteristics (dose rate, volume, physical form, etc.) of high dose-rate waste packages destined for the DGR
- For all expected DGR waste packages with prima facie risk significance based on radionuclide content or dose rate, characterize each package according to attributes affecting its susceptibility to attack, sabotage, theft, or use in an RDD or RED – relevant attributes of a package would include size, physical form, and chemical composition
- Develop a range of malevolent-act scenarios involving waste packages which combine prima facie risk significance with comparatively high susceptibility – scenarios would encompass attack, sabotage, theft, threat, and/or use in an RDD or RED, across all waste streams extending from the contributing reactors to emplacement in the DGR
- Estimate adverse impacts of malevolent-act scenarios in terms of health, economic, social, and environmental effects
- Identify and characterize a range of options for reducing malevolence-related radiological risk
- Fully document all investigations specified above – each document should be published but some documents could have limited-circulation appendices containing sensitive information

6. Conclusions and Recommendations

Conclusions

C1. OPG has provided a substantially incomplete assessment of malevolence-related radiological risk associated with the proposed DGR. OPG's EIS does not consider substantial components of risk – theft or threats, and events affecting waste prior to its departure from the WWMF to the DGR.

C2. This report provides prima facie evidence that the components of risk that are neglected by OPG are significant. The evidence indicates that some ILW waste forms being shipped to or emplaced in the DGR could, if stolen, pose a significant RDD or RED hazard.

Recommendations

R1. To correct the deficiency in OPG's assessment of malevolence-related radiological risk, OPG or a qualified contractor should conduct further investigations of risk, involving a sequence of steps as outlined in Section 5 of this report.

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Table 1
OPG Estimate of Radioactive Waste Inventory in the DGR: Operational, Intermediate-Level Waste, in 2018

Waste Category	Net Volume (m^3)	Co-60		Cs-137/Ba-137m	
		Inventory (Bq)	Inventory per Unit Volume (Bq/m^3)	Inventory (Bq)	Inventory per Unit Volume (Bq/m^3)
Moderator IX Resin	1,174	1.7E+13	1.4E+10	3.2E+11	2.7E+08
PHT IX Resin	802	6.9E+11	8.6E+08	6.4E+13	8.0E+10
Misc. IX Resin	1,097	8.4E+12	7.7E+09	2.2E+13	2.0E+10
CAN-DECON Resin	1,427	5.5E+13	3.9E+10	3.2E+12	2.2E+09
IX Columns	299	2.1E+11	7.0E+08	2.0E+13	6.7E+10
Irradiated Core Comp.	23	6.7E+12	2.9E+11		
Filters and Filter Elements	606	1.2E+12	2.0E+09	1.3E+11	2.1E+08
TOTAL	5,428	8.9E+13	1.6E+10	1.1E+14	2.0E+10

Notes:
(a) Data are from Table 2.6 of: OPG, 2010.
(b) Half-lives of Co-60 and Cs-137 are 5.3 years and 30 years, respectively.
(c) OPG has also estimated the inventory of these intermediate-level radioactive waste categories in 2062. (See: OPG, 2010, Table 2.7.) Total net volume would be 9,257 m^3. Total inventory of Co-60 would be 3.5E+12 Bq. Total inventory of Cs-137/Ba-137m would be 9.4E+13 Bq.
(d) OPG has also estimated the inventory of operational, low-level waste in 2018. (See: OPG, 2010, Table 2.4.) Total net volume would be 65,479 m^3. Total inventory of Co-60 would be 2.4E+13 Bq. Total inventory of Cs-137/Ba-137m would be 2.0E+13 Bq.

Table 2
OPG Estimate of Radioactive Waste Inventory in the DGR: Reactor Refurbishment Waste, in 2018

Waste Category	Net Volume (m^3)	Co-60		Cs-137/Ba-137m	
		Inventory (Bq)	Inventory per Unit Volume (Bq/m^3)	Inventory (Bq)	Inventory per Unit Volume (Bq/m^3)
Retube Waste: Pressure Tubes	49	2.3E+14	4.7E+12	2.0E+09	4.1E+07
Retube Waste: End Fittings	600	4.2E+15	7.0E+12	8.8E+01	1.5E-01
Retube Waste: Calandria Tubes	34	1.5E+14	4.4E+12	1.2E+12	3.5E+10
Retube Waste: Calandria Tube Inserts	9	6.7E+13	7.4E+12	1.4E+07	1.6E+06
Steam Generators	8,387	3.5E+12	4.2E+08	5.8E+10	6.9E+06
TOTAL	9,079	4.7E+15	5.2E+11	1.3E+12	1.4E+08

Notes:
(a) Data are from Table 3.2 of: OPG, 2010.
(b) Half-lives of Co-60 and Cs-137 are 5.3 years and 30 years, respectively.
(c) OPG has also estimated the inventory of these reactor refurbishment radioactive waste categories in 2062. (See: OPG, 2010, Table 3.3.) Total net volume would be 11,178 m^3. (No steam-generator waste would be added after 2018.) Total inventory of Co-60 would be 9.0E+14 Bq. Total inventory of Cs-137/Ba-137m would be 5.4E+11 Bq.

Table 3
Some Properties of Co-60 and Cs-137 in the Context of the RDD Hazard

Radionuclide	NRC Quantity of Concern (TBq)	Threshold Amount to Contaminate 1 square km (TBq)	Max. Av. Waste Category Concentration in DGR Inventory (TBq/m^3)
Co-60	0.3	0.4	7.4
Cs-137	1	1.6	0.08

Notes:
(a) Data in columns 2 and 3 and related background information are from: Medalia, 2011, Table A-1.
(b) The Quantity of Concern shown here is a quantity specified by the US Nuclear Regulatory Commission (NRC). This quantity corresponds to a Category 2 source in the IAEA Code of Conduct on the Safety and Security of Radioactive Sources.
(c) The threshold amount of each radionuclide required to contaminate 1 square km of land was calculated by assuming perfect, uniform dispersion across that area, so as to yield a dose of 0.02 Sv to an exposed person over the first year of exposure. This calculation was done at Sandia National Laboratories. The US Environmental Protection Agency (EPA) recommends population relocation if the first-year dose is projected to exceed 0.02 Sv.
(d) Data in column 4 are from Tables 1 and 2 of this report. In those tables, the maximum average volumetric concentration of Co-60 in a waste category is 7.4 TBq/m^3, in the category "Retube Waste: Calandria Tube Inserts". For Cs-137, the maximum average concentration is 0.08 TBq/m^3, in the waste category "PHT IX Resin".

Table 4
Amounts of Cs-137 Related to the Chernobyl and Fukushima Accidents

Category	Amount of Cs-137 (PBq)
Chernobyl release to atmosphere (1986)	85
Fukushima release to atmosphere (2011)	36
Deposition on Japan due to the Fukushima atmospheric release	6.4
Pre-release inventory in reactor cores of Fukushima #1, Units 1-3 (total for 3 cores)	940
Pre-release inventory in spent-fuel pools of Fukushima #1, Units 1-4 (total for 4 pools)	2,200

Notes:
(a) This table shows estimated amounts of Cs-137 from: Stohl et al, 2011. The estimates for release from Fukushima #1 and deposition on Japan might change as new information becomes available.
(b) Stohl et al, 2011, provide the following data and estimates for Fukushima #1, Units 1-4, just prior to the March 2011 accident:

Indicator	Unit 1	Unit 2	Unit 3	Unit 4
Number of fuel assemblies in reactor core	400	548	548	0
Number of fuel assemblies in reactor-adjacent pool	392	615	566	1,535
Cs-137 inventory in reactor core (Bq)	2.40E+17	3.49E+17	3.49E+17	0
Cs-137 inventory in reactor-adjacent pool (Bq)	2.21E+17	4.49E+17	3.96E+17	1.11E+18

(The core capacity of Unit 4 was 548 assemblies. The core of Unit 3 contained some MOX fuel assemblies at the time of the accident.)
(c) 1 PBq = 1.0E+15 Bq = 1,000 TBq

Table 5
High Dose-Rate ILW Received at the WWMF up to December 2005

Contact Dose Rate Range (Sv/hr)	Received Volume (m^3)	Volume Fraction of Each ILW Category in Contact Dose-Rate Range			
		ILW Resin	IX Column	Filter	Misc. ILW
1-5	22	0.1%	3.1%	1.3%	5.7%
>5	985	0.0%	0.2%	0.0%	11.1%
Max. Contact Dose Rate (Sv/hr)		1.6	8	5	700

Notes:
(a) Data are from Table 4.3 of: OPG, 2010.
(b) Misc. ILW included core components.
(c) No LLW was received with dose rates in the ranges shown.
(d) The total volume of ILW received that exhibited a dose rate of 1 Sv/hr or more (i.e., 22+985 = 1,007 m^3) represented 0.37% of the total volume of LLW and ILW received.

Figure 1
A Crude Type of Radiological Dispersal Device (RDD)

Notes:
(a) This illustration is from: FEMA, 2011/2012.
(b) This device employs a pipe bomb with timer, placed on a shipping container of radioactive material.