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Decision Analysis Methodology for Assessing ALARA Collective Radiation Doses and Risks

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1.0 Introduction

The safe storage and disposal of depleted uranium (DU) waste is essential for mitigating releases of radioactive materials and reducing exposures to humans and the environment. Currently, a radioactive waste facility located in Clive, Utah (the "Clive facility") operated by the company Energy*Solutions* Inc. is being considered to receive and store DU waste that has been declared surplus from radiological facilities across the nation. The Clive facility has been tasked with disposing of the DU waste in a manner that protects humans from future radiological releases.

To assess whether the proposed Clive facility location and containment technologies are suitable for protection of human health, specific performance objectives for land disposal of radioactive waste set forth in Utah Administrative Code (UAC) Rule R313-25-8 and Title 10 of the Code of Federal Regulations (CFR) Part 61 (10 CFR 61) Subpart C, promulgated by the Nuclear Regulatory Commission (NRC), must be met. In order to support the required radiological performance assessment (PA), a detailed computer model has been developed to evaluate the doses to human receptors that would result from the disposal of DU and associated radioactive compounds (collectively termed "DU waste"), and conversely to determine how much DU waste can be safely disposed at the Clive facility.

The Neptune and Company, Inc. (Neptune) white paper *Dose Assessment* (Appendix 11) details the methods for estimating radiation doses to future human receptors associated with DU waste and its decay products. Both the NRC and UAC Rule R313-25-8 specify clear performance goals of 25 mrem/yr for individual members of the public (MOP) and 500 mrem/yr for inadvertent human intruders (IHI) within a 10,000-year compliance period. These goals are the result of a complex balance of risk and feasibility, and are not specifically addressed here because they are (at present and in a practical sense) inflexible and non-negotiable.

However, the CFR (Section 61.42) and UAC Rule R313-25-8 also define a second decision rule that pertains to populations as well as individuals. The CFR regulation states "reasonable effort should be made to maintain releases of radioactivity in effluents to the general environment as low as is reasonably achievable" (or ALARA). Ionizing radiation protection limits have been utilized since the 1920s, but the concept of keeping radiation doses as low as practicable or achievable was an outgrowth of worker safety in the nuclear weapons development industry (Hendee and Edwards, 1987). The ALARA concept can be applied to either individuals or populations. In the context of the Clive DU PA, ALARA is applied to collective doses germane to the receptor populations described in *Dose Assessment* (Appendix 11).

The ALARA process is also described in DOE regulations and associated guidance documents such as 10 CFR Part 834 and DOE 5400.5 ALARA (10 CFR 834; DOE 1993, 1997), in NRC regulations (10 CFR 20.1003, 10 CFR 61.42), and in other NRC documents (NRC, 1995, 2000). The definitions in each case are very similar; indicating that exposures should be controlled so that releases of radioactive material to the environment are as low as is reasonable taking into account social, technical, economic, practical, and public policy considerations. It is also noted that ALARA is not a dose limit, but rather a process which has the objective of attaining doses as far below the applicable limit of this part as is reasonably achievable.

The ALARA concept was first described in publication in ICRP (1973), following similar concepts that date back to ICRP publications at least as early as 1959 (ICRP, 1959). Updates have been provided by the ICRP in both 1977 (ICRP, 1977), and more recently in 2006 (ICRP, 2006). In this latest report, the ICRP focuses more on expanding the optimization process. This includes evaluating different relatively homogeneous population groups, stakeholder involvement in addressing receptor scenarios, site-specific evaluation of exposure, intergenerational equity, and many other aspects. The ICRP report provides a comprehensive list of factors that should be considered for optimization. However, the ICRP stops short of describing a methodology for implementation, even suggesting that full quantification of all relevant factors is not possible. However, with modern decision analysis methods this need not be the case (e.g., Keeney, 1992; Gregory et al., 2012). The Office of Management and Budget (OMB, 1992) also provides a road map for applying a decision analysis approach to policy analysis that could be adapted to PA. Another obstacle that is recognized in ICRP, 2006, is that lack of regulatory support for such an approach. However, the ALARA principle exists in both DOE and NRC regulations and guidance, decision analysis methods exist to implement the intended optimization, and there appears to be some traction now with both DOE and NRC regarding decision analysis methods for optimization, or ALARA.

In terms of the ALARA analysis performed for the Clive DU PA, it does not achieve all that the ICRP calls for. This is primarily because the regulatory support for doing so does not clearly exist. However, as ICRP has made clear, this is an approach that will help focus decision-making on finding optimal solutions. To implement this approach to ALARA a paradigm shift is needed in the industry, starting with the regulators, so that the focus is on optimal use of the Country's limited disposal resources as opposed to somewhat arbitrary compliance decisions. ICRP (2006) recognizes this same need. For the current PA the approach has included evaluation of specific relatively homogeneous receptor groups, and has included a metric for evaluating potential costs for the simulated doses. It has not engaged many of the other recommendations of the ICRP.

The words "reasonably" and "achievable" in ALARA are not precise. The two words imply some degree of consideration of tradeoffs, but no clear definition is published. Assuming that there are trade-offs, then this implies that an analysis should be performed that explicitly evaluates the trade-offs and how different disposal options, designs, or sites may differentially satisfy the objectives and resource constraints (e.g., a decision or economic analysis). Yet, at present, there is limited specific guidance on how to apply ALARA principles to the PA process.

The probabilistic Clive DU PA model is designed to estimate individual annual doses to hypothetical individuals in future populations that may be exposed to radionuclide releases from the Clive facility. The model is also able to aggregate individual doses into estimates of collective and cumulative population dose, on an annual basis as well as over the 10,000 year period of performance. Additionally, the model is able to evaluate non-radiological toxicity; e.g. associated with uranium. The remainder of this discussion will focus upon the concepts of population dose/risk and ALARA, and how these can be integrated into a Bayesian decision analysis (DA) for application to the Clive facility.

2.0 ALARA

The ALARA concept, as germane to radiation protection for both individual and population (collective) levels, was described as follows by the ICRP in 1977 (ICRP, 1977):

> "Most decisions about human activities are based on an implicit form of balancing of costs and benefits leading to the conclusion that the conduct of a chosen practice is 'worthwhile.' Less generally, it is also recognized that the conduct of the chosen practice should be adjusted to maximize the benefit to the individual or to society. In radiation protection, it is becoming possible to formalize these broad decision-making procedures."

The ICRP (1977) basically recommended a system of radiation protection that included the following principles:

- No practice shall be adopted unless its introduction produces a positive net benefit – *justification of the practice*.
- All exposures shall be kept as low as reasonably achievable, economic and social factors being taken into account – *optimization of radiation protection*.
- The dose equivalent to individuals shall not exceed the limits recommended for the appropriate circumstances by the Commission – *the limits of individual dose assessment*.

In other words, ICRP defined radiation protection in the context of decision analysis, at least in terms of the first two principles, considering health, economic, and social objectives; and invoked the concept of net benefit. The third principle can, instead, be interpreted as a compliance objective, so that the decision analysis can only be performed for decision options that first comply with regulatory performance objectives.

The ALARA process is also described in DOE regulations and associated guidance documents such as 10 CFR Part 834 and DOE 5400.5 ALARA (10 CFR 834; DOE 1993, 1997), and in various NRC documents such as NRC, 1995, 2000. The definitions in each case are very similar; indicating that exposures should be controlled so that releases of radioactive material to the environment are as low as is reasonable taking into account social, technical, economic, practical, and public policy considerations. 10 CFR 834 further describes the ALARA process as a “logical procedure for evaluating alternative operations, processes, and other measures, for reducing exposures to radiation and emissions of radioactive material into the environment, taking into account societal, environmental, technological, economic, practical and public policy considerations to make a judgment concerning the optimum level of public health protection". Although 10 CFR 834 is not aimed specifically at disposal of radioactive waste, the basic goals are protection of the public from DOE activities, of which radioactive waste disposal is one such activity.

NRC also provides guidance on application of the principle of ALARA. For example, although the context is different, 10 CFR Part 20 provides guidance that suggests – "Reasonably achievable" is judged by considering the state of technology and the economics of improvements in relation to all the benefits from these improvements (NRC Regulatory Guide 8.8, Revision 3, 2008). NRC also notes that "...a comprehensive consideration of risks and benefits will include risks from non-radiological hazards".

The overall implication of the various Agency regulations and guidance documents regarding ALARA is that many factors should be taken into account when considering the potential benefits of different options for disposal of radioactive waste. In order to implement ALARA in a logical system, and so that economic factors are taken into consideration, a decision analysis is implied. Decision analysis is the appropriate mechanism for evaluating and optimizing disposal, closure and long term monitoring and maintenance of a radioactive waste disposal system. Decision options for disposal at Clive might include engineering options and waste placement. More generally, if decision analysis is applied, then a much wider range of options can be factored into the decision model, such as transportation of waste, risk to workers, and effect on the environment. However, for the Clive DU PA, the focus is on understanding the dose-based costs associated with different options for waste disposal within the current proposed configuration of the Federal DU Cell.

The decision analysis in this context is essentially a benefit-cost analysis, within which the dose costs associated with different options for the placement of waste are evaluated. For each option, the PA model predicts doses to the array of receptors, and the consequences of those doses are assessed as part of an overall cost model, which also includes the costs of disposal of waste for each option. The goal is to find the best option, which is the option that provides the greatest overall benefit. The consequences of risk can be measured through a simplification that is available in ALARA guidance, including NRC 1995, which provides the basis for, and history of, assigning a dollar value to person-rem as a measure of radiation dose. Prior to the NRC guidance, a single value of $1,000 per person-rem was recommended, with the accompanying assumption that a discount rate would not be applied. The history of the selection of this value is described in NRC, 1995, and further references to prior documents. In 1995, NRC instead promoted the idea of using $2,000 per person-rem as the relevant value, subject to present worth considerations. This appears to be an overt attempt by the NRC to allow an economic decision analysis to be performed, allowing for a discount factor to be used in the assessment of ALARA. This is made clearer in NRC, 2000, which provides examples and formulas for how to implement ALARA, which include discount factors of 7% for the first 100 years, and 3% thereafter. These are steep discounting rates that result in small costs comparatively at 100 years into the future. DOE guidance also suggests that a range of $1,000 to $6,000 could be considered

(DOE, 1997), but that the $2,000 value is sufficient for most purposes. The allowable range presented by DOE, however, could be used to describe uncertainty over the appropriate value.

The DOE guidance (DOE, 1997) also suggests that:

> "In general, if the maximum individual dose is less than 1 mrem in a year and collective dose is less than 100 person-rem in a year, only a qualitative or semi-quantitative ALARA assessment can be justified. However, if individual doses are significant, say 10s of mrem in a year, or collective dose exceeds 100 person-rem in a year, quantitative ALARA analyses are recommended".

For the Clive DU PA model Version 1.2, the individual doses and the population doses are very small, justifying a semi-quantitative analysis. Consequently, the original value of $1,000 per person rem per year is used without discounting. This is a conservative approach when applied to a 10,000-year time frame, considering the effects of the 7% and subsequent 3% discounting suggested by the NRC. However, it is considered sufficient considering the very low individual and population doses, and hence dose-based costs, which are realized from the Clive DU PA model.

Version 1.2 of the Clive DU PA model evaluates doses to several site-specific receptor groups for the disposal option that all the DU waste is disposed below grade. Although comparisons are made with the results from Version 1 of the PA model, the cap design and erosion model for Version 1.2 are very different than for the Version 1 model. Direct comparison of waste disposal options is, hence, confounded by the different engineered systems. Consequently, the focus of the ALARA analysis for the Version 1.2 model is simply to evaluate the dose costs associated with disposal of DU waste below grade, including the evapo-transpiration cover and a revised erosion model. The dose-based costs are projected to support at ALARA analysis for the disposal of DU at the Clive site. Prior to describing the specific application, a more generic discussion of decision analysis is provided.

3.0 Decision Analysis

A generic process for decision analysis has been described in many references, and includes the following basic steps (cf., Berry, 1995, Clemen, 1996):

1. State a problem
2. Identify objectives (and measures of those objectives – i.e., attributes or criteria)
3. Identify decision alternatives or options
4. Gather relevant information, decompose and model the problem (structure, uncertainty, preferences)
5. Choose the 'best' alternative (the option that maximizes the overall benefit)
6. Conduct uncertainty analysis, sensitivity analysis and value of information analysis to determine if the decision should be made, or if more data/information should be collected to reduce uncertainty and, hence, increase confidence in the decision
7. Go back if more data/information are collected

This framework is iterative and flexible; e.g., sensitivity analysis can also be performed before choosing alternatives. Value-of-information analysis can be performed to help determine where further data collection will be most informative. In the case of ALARA as described in Section 2, the only disposal and design options that can be considered are those that first demonstrate compliance. If no options are identified that comply after the first pass through the decision analysis, then it might be necessary to redefine the options, or the problem. In this sense, the decision analysis process is constrained.

Generally, in a decision analysis, there are many considerations for successful applications ranging from identifying the decision makers and stakeholders, the objectives of interest for all parties involved in the decision making process, their preference structures (which attributes of the decision problem do they prefer), characterization of uncertainty in the model, and measures of the probable consequences of the different decision options. The spatial and temporal constraints on the decision are also important.

There are many technical approaches that have been used to provide some form of numerical decision support for a wide variety of decision problems (cf., Kiker et al, 2005, Linkov et al, 2009), however, only one is commonly recognized as rational and logical: Bayesian statistical decision theory, although other names have been used. The main components of Bayesian decision analysis include probability distributions that are used to capture what is known and uncertainty about the underlying process, and specification of cost and value functions to capture the costs of each decision option that is being considered.

For an ALARA analysis of a PA, implementation of a Bayesian decision analysis requires development of a PA model for different options (e.g., different disposal options, closure options). This includes specification of probability distributions for each input parameter in the PA model so that both the best estimate and its uncertainty is accounted for, subsequent estimation of population doses from the model, and characterization of the costs of implementing each option. The cost-benefit trade-off is performed by comparing options for the risks to human health (as measured through dose), and the costs of each option considered.

In general, Bayesian decision analysis is a powerful means of facilitating decisions under uncertainty. Decision analysis models, developed properly, are transparent and easy to use, even for complex decisions. Decision analysis is also amenable to sensitivity and value-of-information analyses, which can be used to inform decision makers regarding uncertainty in the decision. That is, if the uncertainty is low enough, then confidence is high enough, and a decision can be made. However, if greater confidence is needed, then further data collection is indicated, and this is informed by the sensitivity analysis and a value of information analysis (i.e., which variables are most uncertain and have the most influence on ranking of alternatives). The idea is the reduce uncertainty cost-effectively. At some point the cost of collecting more data outweighs the benefit from the reduction in uncertainty. Then the best decision option should be selected.

4.0 Scope of ALARA Decision Analysis for the Clive Depleted Uranium Performance Assessment

Decision analysis in the context of ALARA has been simplified for application to the Clive DU PA. There is one primary objective, which is to maximize human health in the context of disposal of the DU waste. The attribute of interest is radiation dose to the receptors, which is measured in terms of millirem in a year. Note that groundwater concentrations are also of concern, but a simplification similar to the dose costs per person rem are not available for groundwater, hence, an ALARA assessment for the groundwater pathway is not evaluated for the current Clive DU PA model. However, it is noted that groundwater at Clive is not considered potable because it is more saline than seawater. The cost consequences to human health are, consequently, negligible or non-existent.

The main focus of Version 1.2 of the Clive DU PA model is disposal of the DU waste below grade. The ALARA analysis focuses on this one scenario. Version 1.2 also includes changes to the cap design (evapotranspiration cap), the erosion model (to address the change in cap design), and changes in the input tortuosity distributions. Consequently, an ALARA analysis is also performed for Version 1 of the model with the waste placed below grade in that model. Version 1 of the model included a riprap design for the cover system and a different erosion model. The ALARA analyses allow comparison of the performance of the two models and, hence, of the two cover systems.

The different models resulted in different dose estimates for the three types of receptors evaluated – ranchers, hunters and OHV enthusiasts. The comparative results are consistent with expectations. That is, the evapotranspiration (ET) cover allows less infiltration of water through the system. Consequently, groundwater concentrations are smaller for the ET cover design than for the riprap cover design. However, doses are slightly greater for the ET cover design because more radon can migrate through the system.

The remainder of Section 4.0 describes how ALARA decision analysis was implemented for the evaluation of disposal options for Version 1.2 of the model.

Assuming the cost of disposal is the same for each configuration (which might not be the case, but is a simplifying assumption that is made for this purpose), then the differentiating factor is the cost associated with the radiation risk – i.e., the dose costs. The PA model is constructed to present both doses to hypothetical individuals and to the populations of those individuals, as described in *Dose Assessment* (Appendix 11).

The goal is to estimate the dose-related costs for both V1.2 and V1 of the model; that is, assuming all DU waste is disposed below grade. As noted above, a discount factor could be applied to the analysis. However, DU has a characteristic that is different than most forms of radioactive waste; i.e., its decay dynamics result in higher radioactivity (and therefore dose) of the waste over time, as opposed to lower radioactivity associated with many other types of radionuclide decay. This perhaps has implications for whether to include a discounting factor for future benefits, risks, and costs. Intergenerational issues are also considered in the approach taken.

As noted in the introduction, specific performance objectives for land disposal of radioactive waste are set forth in Utah Administrative Code (UAC) Rule R313-25-8 and Title 10 of the Code of Federal Regulations (CFR) Part 61 (10 CFR 61) Subpart C, promulgated by the Nuclear Regulatory Commission (NRC). These require a quantitative individual dose assessment over the next 10,000 years. In effect, a decision is intended for all possible receptors over the course of the next 10,000 years, and dose-based decisions are not made beyond that point. From the perspective of an economic analysis this corresponds to a zero discount rate for the next 10,000 years followed by a zero value thereafter, at least from the perspective of dose. This also means that decisions are made for possible receptors 10,000 years from now, apparently obviating the need for any further decision making. An alternative is to couple a decision analysis approach that includes discounting coupled with a financial plan to address continued evaluation of the disposal system. There are other arguments for considering shorter compliance periods, such as the reasonableness of evaluating dose far into the future, and the uncertainty that should increase with time.

Despite the potential benefits of including a discount rate in an ALARA analysis (coupled with financial planning and a rolling window for continued evaluation), for this current ALARA analysis a simple approach was taken as an initial screen. That is, a per person rem cost of $1,000 was assigned, and zero discounting was assumed for the next 10,000 years.

The overall decision scenario can be stated as in terms of the ‘best’ alternatives with regard to long-term disposal of DU. As a first application, the decision analysis focused on the “best” alternatives for achieving ALARA with respect to future population doses/risks at the Clive facility. The decision analysis was confined to the disposal site itself, and did not address other potentially important life-cycle issues such as interim storage, transportation, etc. However, note that the decision analysis framework could be easily expanded to address these other issues. For this decision analysis 'best' was defined in terms of overall benefit-cost in the context of the cost to reduce risk, the cost consequences of the risk, and the uncertainty associated with choosing the best option. That is, the decision problem was framed as a benefit-cost problem, but constrained by the requirement that each decision option considered (ET cover and rip rap cover, both with waste disposed below grade) must comply with the performance objectives.

5.0 Dose Assessment

For present purposes, as regulatory agencies have adopted and applied clear dose limits for individuals, evaluation of ALARA is restricted to collective doses and risks. This is appropriate in the context of design and siting of radioactive waste facilities; as it is likely, if any substantial future risks occur, that health concerns will be at a population level. Further, it is assumed that facility workers will be protected under existing health and safety regulations and guidance, and not evaluated as part of ALARA. In a complete decision analysis, however, many other factors could be considered, including health and safety of workers, transportation, etc.

Applying formal decision analysis to ALARA implies evaluation of the trade-off between risk reduction and the costs associated with the actions that can be taken to reduce risk and the benefits of the risk reduction. Risk in a PA is assessed through radiation dose, which is, perhaps, one of the most uncertain aspects of a PA.

Ionizing radiation protection limits have changed over time as more information regarding the negative biological effects of radiation has become available (especially after World War II). Concurrently, therapeutic and diagnostic (i.e., beneficial) uses of radiation have increased dramatically, and nuclear fission is an important source of power in most of the developed world. Thus, a tradeoff is immediately apparent; radiation can be both harmful and helpful, with the balance depending upon the dose and the context.

An additional consideration are the biological endpoints of concern. Radiation in high doses kills cells (so-called 'deterministic' effects), which can be harmful or beneficial to the receptor of the doses (e.g., in the latter case, radiation is used to kill cancer cells). The effects of low doses of radiation are more uncertain. There is ample evidence that ionizing radiation can damage DNA and enhance cell proliferation in doses below those that kill cells, and thus can potentially cause cancer (so-called 'stochastic' effects).

However, it is uncertain at what low doses carcinogenicity becomes a concern (also, note that different tissues have different susceptibility to the effects of ionizing radiation). For many years, there has been a presumption in radiation protection, based upon statistical analysis of animal and human data, that ionizing radiation has a linear dose-response curve at low doses and that there essentially is no threshold of effect; i.e. any dose of radiation can result in an increased probability of cancer (this is termed the linear no-threshold, or LNT, hypothesis). This is not borne out by all experimental and clinical observation. Additionally, the fact that radiation is associated with a large number of natural sources, ranging from sunlight to radon, and the fact that multiple highly-efficient molecular and cellular defense and repair mechanisms exist, must be considered (Scott 2008). Regardless, this LNT hypothesis is the basis for most regulatory standards today. Consequently, if a PA uses the LNT approach to develop dose estimates, then the ALARA analysis essentially assumes no carcinogenic threshold of radiation carcinogenesis.

A threshold of dose effect model is, arguably, more realistic than the LNT model, and could be used to estimate dose and in the ensuing ALARA analysis. If ALARA is applied in the case of a threshold or “target” concentration, then the threshold would be treated as a limit on the amount of risk reduction that can be achieved by a particular management alternative. Proper evaluation of uncertainty associated with the LNT hypothesis would be a large task in itself, but the influence of a LNT assumption could still be evaluated within the decision analysis framework.

A different sort of threshold exists with regard to natural background levels of radiation. The doses that the public receives from all environmental sources (e.g., local geology, extraterrestrial, etc.) can be quite variable. For example, people who live at a location in the US with high levels of uranium compounds in the local soil and rocks may have a much higher level of annual exposure (due to radon) than people who live at sea level with little uranium compound content of the soil and rocks (http://www.epa.gov/radon/zonemap.html). Similarly, individuals who reside at higher elevations are exposed to higher levels of cosmic radiation that individuals residing at sea level. From an ALARA perspective, it might be reasonable to consider that the *incremental* population dose is of interest as well as the magnitude of the incremental dose relative to dose from natural background radiation.

Uranium and many other metals are also associated with non-radiological toxicity; e.g. kidney or liver damage. In such cases, toxicology has developed concepts such as the reference dose and benchmark dose to account for the clear thresholds of effect that are associated with non-carcinogenic toxicity (Filipsson et al., 2003). In these cases the threshold can be viewed as a target, below which health effects are not of substantial concern.

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