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# Decision Analysis Methodology for Assessing ALARA Collective Radiation Doses and Risks

## Clive DU PA Model v1.4

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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 R313-25-9 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 R313-25-9 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 R313-25-9 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 process is 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, 2000a, 2015). 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 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 US'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 ALARA concept can be thought of as a cost-benefit trade-off that requires an evaluation of human health risk and the costs of achieving those risks. In the context of the Clive DU PA, calculations that would be needed to support a more complete ALARA analysis are performed for collective doses germane to the receptor populations described in *Dose Assessment* (Appendix 11). That is the costs of the population doses are calculated based on the modeled doses and the cost per person rem specified in the relevant NRC and DOE guidance.

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, 2000a, and 2015. 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, 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.

# 3.0 Development of Current ALARA Cost per Person-Rem Estimates

## 3.1 History

The decision analysis context for radioactive waste disposal is essentially a benefit-cost analysis, within which the dose costs associated with different options for the placement of waste are ideally evaluated. In practice, 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 concept of assigning a monetary value to radiation dose in regulatory decision-making arose in 1974 during a hearing for a rulemaking addressing routine effluent releases from nuclear power reactors. The subsequent rule was Title 10 of the Code of Federal Regulations (10 CFR), Part 50, "Domestic Licensing of Production and Utilization Facilities," Appendix I, "Numerical Guides for Design Objectives and Limiting Conditions for Operation To Meet the Criterion 'As Low As Is Reasonably Achievable' for Radioactive Material in Light-Water-Cooled Nuclear Power Reactor Effluents." In adopting design criteria for limiting routine effluent releases from power plants, NRC promoted the use of a cost-benefit test (NRC, 1975a):

> "Such a cost-benefit analysis requires that both the costs and the benefits from the reduction in dose levels to the population be expressed in commensurate units, and it seems sound that these units be units of money. Accordingly, to accomplish the cost-benefit balancing, it is necessary that the worth of a decrease of a person-rem be assigned monetary values."

NRC stated that "the record, in our view, does not provide an adequate basis to choose a specific dollar value for the worth of decreasing the population dose by a man-rem." Published studies that were reviewed provided values ranging from $10 to $980 per person-rem. NRC concluded that "there is no consensus in this record or otherwise regarding the proper value for the worth of a man-rem," and "we also recognize that selection of such values is difficult since it involves, in

addition to actuarial considerations that are commonly reduced to financial terms, aesthetic, moral, and human values that are difficult to quantify" (NRC, 1975a). The final outcome was a decision to adopt the value of $1,000 per person-rem as an interim measure (NRC, 1975a).

Two executive orders (EO) issued in 1977 (EO 11821 and EO 11949) encouraged Federal agencies to perform value-impact (now called cost-benefit or benefit-cost) evaluations of proposed regulatory requirements to demonstrate adequate justification for new requirements. The NRC adopted this type of evaluation and issued their "Value-Impact Analysis Guidelines" (NRC, 1977). This document referred to the techniques and detailed consequence analyses used in the "Reactor Safety Study: An Assessment of Accident Risks in U.S. Commercial Nuclear Power Plants (WASH-1400)," and recommended that the person-rem avoided as a result of proposed changes should be multiplied by $1,000 per person-rem in order to place the benefit in the same units as the costs (NRC, 1975b). Also in 1977, Congress added Section 210 to the Energy Reorganization Act of 1974, directing the NRC to develop a plan for the identification and analysis of unresolved safety issues relating to nuclear reactors. In response, the NRC developed a program for the prioritization and resolution of unresolved safety issues and generic issues. In 1982, the NRC issued guidance relating to the assignment of priorities with the publication of "A Prioritization of Generic Safety Issues," NUREG-0933 (NRC, 1982). NUREG-0933 used $1,000 per person-rem value in setting the priority of unresolved safety issues and more generic issues. Issues identified as high priority were then subject to resolution employing a more detailed cost-benefit analysis that also applied the $1,000 per person-rem value.

In February 1981, EO 12291 was issued, which directed executive agencies to prepare a regulatory impact analysis for all major rules and stated that regulatory actions should be based on adequate information concerning the need for and consequences of any proposed actions. EO 12291 directed that actions were not to be undertaken unless they resulted in a net positive benefit to society. As an independent agency, the NRC was not required to comply with EO 12291. NRC, however, noted that its established regulatory review procedures included an evaluation of proposed and existing rules in a manner consistent with the regulatory impact analysis provisions of EO 12291. NRC determined that clarifying and formalizing the existing NRC cost-benefit procedures for the analysis of regulatory actions would advance the purposes of regulatory decision-making.

In January 1983, the NRC published NUREG/BR-0058, "Regulatory Analysis Guidelines of the US Nuclear Regulatory Commission", followed in December 1983 by publication of NUREG/CR-3568, "A Handbook for Value-Impact Assessment" (NRC, 1983a and 1983b, respectively). These documents were issued to formalize NRC's policies and procedures for analyzing the costs and benefits of proposed regulatory actions. The $1,000 per person-rem figure was not mentioned in the first revision of the Guidelines issued in May 1984, however, NUREG/CR-3568 recommended that a range of values should be used, one of which should be the $1,000 per person-rem value. As NUREG/CR-3568 provides implementation guidance for performing regulatory analyses, it became standard practice of the NRC staff to apply this guidance whenever a quantitative regulatory analysis or cost-benefit analysis was performed.

In 1983, NRC issued an interim Policy Statement on Safety Goals for the Operation of Nuclear Power Plants for use during a two-year trial period (NRC, 1983c). In this statement, NRC adopted qualitative and quantitative design goals for limiting individual and societal risks from

severe accidents. Also in this policy statement, NRC stated the benefit of an incremental reduction of societal mortality risks should be compared with the associated costs on the basis of $1,000 per person-rem averted as one consideration in decisions on safety improvements. The value proposed was in 1983 dollars and was to be modified to reflect general inflation in the future. As a result of comments on this interim policy statement, the $1,000 per person-rem value was deleted in the Final Policy Statement on Safety Goals when published in August 1986 (NRC, 1986).

In 1985, the NRC staff revisited the $1,000 per person-rem valuation and its use in regulatory analyses of nuclear power plant improvements designed to enhance safety. Although the monetary value of averted person-rem of radiation exposure up to that time referred only to averted health effects (such as averted latent cancer fatalities), the use of $1,000 per person-rem was evaluated and defined at that time as a surrogate for all averted offsite losses, such as health and property. The basis for this determination is documented in a memorandum from the NRC Executive Director for Operations dated October 23, 1985 (NRC, 1985).

In 1995, the NRC revisited the $1,000 per person-rem value again and issued "Reassessment of NRC's Dollar per Person-Rem Conversion Factor Policy," NUREG-1530 (NRC, 1995a). This report updated the dollar per person-rem conversion factor to $2,000 per person-rem. The $2,000 per person-rem conversion factor served only as a dollar proxy for the health effects associated with a person-rem of dose. Offsite property damage costs were no longer included within the $2,000 per person-rem value. Separate estimates of the offsite costs were now necessary to account for impacts beyond human health impacts. The dollar per person-rem estimate was derived from a value of a statistical life (VSL; see below) of $3 million in 1995 dollars, multiplied by a risk coefficient for stochastic health effects (see below) of $7.3 \times 10^{-4}$ per person-rem rounded to the nearest thousand. The VSL amount was derived using a willingness-to-pay (WTP) method that reflected median values estimated in numerous studies. This process was similar to the approaches used by other Federal agencies responsible for public health and safety (NRC, 1995a). The risk coefficient for stochastic health effects as a result of radiation exposure was taken from the International Commission on Radiation Protection (ICRP) Publication No. 60 (ICRP, 1991). This risk coefficient includes both mortality (e.g., fatal cancers) and morbidity (e.g., nonfatal cancers and hereditary effects).

In July 2000, the NRC issued revision 3 to the "Regulatory Analysis Guidelines of the US Nuclear Regulatory Commission" (NRC, 2000b), and in September 2004, the NRC issued revision 4 (NRC, 2004). This revision reflects economic evaluation guidance provided in Office of Management and Budget's (OMB) Circular A-4, published in September 2003 (OMB, 2003).

In 2010, as discussed in "Consideration of Economic Consequences within the US Nuclear Regulatory Commission's Regulatory Framework," NRC staff recommended updating numerous guidance documents, including NUREG-1530 (NRC, 2012). This was approved in 2013. NRC has routinely used the $2,000 per person-rem value from the original revision of NUREG-1530 and, on a case-by-case basis, used other dollar per person-rem values to understand the sensitivity of this parameter on the resulting cost and benefit estimates.

Application of discount rates, which assume that present individuals and populations assign less "worth" to future benefits, risks, and costs, has been inconsistent and controversial in radioactive waste regulation. Typically, economists apply discount rates for short-term decisions, as there is

ample experimental evidence to support this. However, discounting for the extreme time horizons associated with radioactive waste disposal has not been fully evaluated. If even small (e.g., 3%, which is a typical lower bound currently employed by OMB in their economic analyses) discount rates are applied to the problem of radioactive waste disposal, the "value" of future lives reduces to essentially zero in a few hundred years. It is unclear, without conducting extensive surveys and research, whether stakeholders truly believe that peoples' lives a few hundred years from now are essentially worthless. NRC, in its latest (2015) guidance, does not mention discount rates, likely because application of such would be highly controversial. The assumption made for the Clive DU PA model is that the discount rate is zero, thus assigning as much worth to future populations as to the present population. This is likely a highly conservative assumption.

## 3.2 Estimating Value of a Statistical Life

The dollar per person-rem conversion factor for health effects is calculated as the product of the value of a statistical life (VSL) and the risk coefficient for stochastic radiation effects.

The VSL (and therefore the associated dollar per person-rem conversion factor) corresponds to society's willingness-to-pay (WTP) for small reductions in a particular mortality risk. VSL is not a measurement or valuation of a human life. OMB Circular A-4 states (OMB, 2003):

> "Some describe the monetized value of small changes in fatality risk as the "value of statistical life" (VSL) or, less precisely, the "value of a life." The latter phrase can be misleading because it suggests erroneously that the monetization exercise tries to place a "value" on individual lives. You should make clear that these terms refer to the measurement of willingness to pay for reductions in only small risks of premature death. They have no application to an identifiable individual or to very large reductions in individual risks. They do not suggest that any individual's life can be expressed in monetary terms. Their sole purpose is to help describe better the likely benefits of a regulatory action. Confusion about the term "statistical life" is also widespread. This term refers to the sum of risk reductions expected in a population. For example, if the annual risk of death is reduced by one in a million for each of two million people, that is said to represent two "statistical lives" extended per year (2 million people x 1/1,000,000 = 2). If the annual risk of death is reduced by one in 10 million for each of 20 million people, that also represents two statistical lives extended."

VSL is estimated using revealed- or stated-preference methods, or meta-analysis. These methods can include statistical analysis of markets, wage statistics, surveys, and the like. NRC (2015) provides further explanation. NRC chose to align its current VSL recommendations with those of other Federal agencies. NRC's current best estimate of $9.0 million is derived from the average of the US Department of Transportation's (DOT's) estimate of $9.3 million and the US Environmental Protection Agency's (EPA's) estimate of $8.7 million (in 2014 dollars). For the purpose of sensitivity analysis, NRC adopted low and high median VSLs from other agencies that have published ranges, per below:

| Agency | Low | High |
|---|---|---|
| DOT | $5.3 million | $13.2 million |
| DHS | $6.8 million | $10.8 million |
| OMB | $1.3 million | $13.3 million |
| *Median* | *$5.3 million* | *$13.2 million* |

## 3.3 Risk Coefficient Estimates

For the purposes of the Clive DU PA model, although 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.

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 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.

For the purposes of ALARA, it is assumed that the LNT hypothesis is valid, despite the likely conservatism of doing so. For NRC's radiation risk coefficient, NRC's previous dollar per person-rem conversion factor was based upon the recommendations in the International Commission on Radiological Protection (ICRP) Publication 60, published in 1991 (ICRP, 1991). For doses to a population, the ICRP recommendation is a risk coefficient value of $7.3 \times 10^{-4}$ per rem. This coefficient accounts for the probability of occurrence of a harmful health effect plus a judgment of the severity of the effect. The coefficient includes allowances for fatal and nonfatal cancers and for severe hereditary effects. The nonfatal cancers and hereditary effects are translated into loss-of-life measures based upon an assumed relationship between quality of life and loss of life. Thus, the VSL is theoretically applicable across all contributors to the total health risk coefficient.

In the subsequent ICRP Publication Number 103, (ICRP, 2007), the ICRP total risk coefficient decreased by about 20 percent, from $7.3 \times 10^{-4}$ per rem to $5.7 \times 10^{-4}$ per rem. ICRP states that this change was due primarily to improved methods in the calculation of heritable risks, as well as advances in understanding of the mutational process. Also, the ICRP calculated its values differently in ICRP 103 compared to ICRP 60. ICRP 103 states:

> "It is important to note that the detriment-adjusted nominal risk coefficient for cancer estimated here has been computed in a different manner from that of Publication 60. The present estimate is based upon lethality/life-impairment-weighted data on cancer incidence with adjustment for relative life lost, whereas in publication 60 detriment was based upon fatal cancer risk weighted for non-fatal cancer, relative life lost for fatal cancers and life impairment for non-fatal cancer. In this respect it is also notable that the detriment-unadjusted nominal risk coefficient for fatal cancer in the whole population that may be projected from the cancer incidence-based data of Table A.4.1a is around 4% per Sv [per 100 rem] as compared with the Publication 60 value of 5% per Sv [per 100 rem]. The corresponding value using cancer mortality-based models is essentially unchanged at around 5% per Sv [per 100 rem]."

As discussed above, WTP approaches are meant for application to small reductions in only mortality risk. ICRP Publication No. 60 and ICRP Publication No. 103 combine both morbidity

and mortality into their risk coefficient numbers (ICRP, 1991, 2007). In contrast, EPA uses a mortality-only risk coefficient with a value of $5.8 \times 10^{-4}$ per rem (EPA, 2011). Using EPA's value would align the cancer risk coefficient with the underlying definition of WTP, and the value is slightly greater than the ICRP risk coefficient. The US National Academies of Sciences estimated the total risk for all classes of genetic diseases to be about 3,000-4,700 cases per million first-generation progeny per gray of low dose rate low-LET radiation (NAS, 2006). This numerical estimate ($0.4 \times 10^{-4}$ per rem) is defined relative to the "genetically significant dose" (i.e., the combined dose received by both parents prior to conception). Thus, the EPA value may be adjusted to account for heritable effects (i.e., adding $5.8 \times 10^{-4}$ per rem and $0.4 \times 10^{-4}$ per rem, to result in $6.2 \times 10^{-4}$ per rem). However, changing the risk coefficient from total detriment to a mortality/heritable effects coefficient may still not adequately consider the full range of consequences associated with public radiation exposure. This EPA adjusted factor ($6.2 \times 10^{-4}$ per rem) may thus underestimate an appropriate risk coefficient because it is not weighted to include cancer incidence data weighted for lethality and life impairment. Thus, by not accounting for cancer morbidity, the benefits of a proposed action (e.g., medical costs averted, value of lost production, etc.) may be underestimated by as much as another 20 percent.

NRC (2015) regardless chose to use the ICRP 103 value of $5.7 \times 10^{-4}$ per rem for use in dollar per person-rem estimates with the understanding this coefficient may underestimate US population risk. The reason provided was consistency with their other regulatory programs. The final dollar per person-rem estimate calculated using either the EPA or ICRP values is not substantially different, due to the relatively large value of the VSL multiplier. Thus, as a practical matter in estimation of dollars per person-rem, the ICRP and EPA values are similar.

## 3.4 Current NRC Recommendations

Per above, draft NRC (2015) guidance currently recommends use of a VSL of $9.0 million, and the ICRP 103 risk coefficient of $5.7 \times 10^{-4}$ per rem. The dollar conversion factor as a result of multiplying these values is therefore equal to a rounded $5,100 in per person-rem in 2014 dollars. NRC also recommends a low value of $3,000 per person-rem and $7,500 for a high value, based upon variation in VSL estimates across agencies (NRC chose to use one risk coefficient for unclear reasons, but perhaps because the risk coefficients would have to vary considerably in order to make a difference in final estimates). NRC states that this value is to be used for "routine effluent releases, accidental releases, 10 CFR Part 20 "as low as is reasonably achievable" (ALARA) programs, regulatory analyses, backfit analyses, and environmental analyses". NRC suggests using the recommended best estimate of $5,100 per person-rem, and use of the low and high estimates in sensitivity analysis.

NRC (2015) notes that the dollar per person-rem conversion factor is for stochastic effects only, and is not to be applied to deterministic effects (e.g., organ failure as a result of high radiation doses). It should also not be applied to any individual dose that could result in an early fatality. These omissions are consistent with NRC's view that the monetizing of mortality effects as it relates to the value of any single individual's life is not appropriate. Rather, the use of dollars per person-rem is as an estimate of the value of small reductions in the probability of total detriment for a given population.

DOE guidance (DOE, 1997) 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".

As estimated collective doses from the Clive DU PA are much less than 100 person-rem per year. Consequently, the semi-quantitative approach using the NRC (2015) value of $5,100 per person-rem is applied here.

## 3.5 Approach for the Clive ALARA Analysis

For the Clive DU PA model Version 1.2, the individual doses and the population doses are small, justifying a semi-quantitative analysis. Consequently, current the NRC value of $5,100 per person rem per year is used in the ALARA analysis, assuming a zero discount rate. This is a highly conservative approach when applied to a 10,000-year time frame, considering the potential exponential effects of discounting. However, it is considered sufficient considering the low individual and population doses, and hence low dose-based costs, which are estimated by the Clive DU PA model.

Version 1.4 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 1.0 of the Clive DU PA model, the cap design and erosion model for Version 1.4 are very different than for the Version 1.0 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 1.4 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.

# 4.0 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 including 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 uncertain 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. For Version 1.4 of the Clive DU PA model only one set of conditions is evaluated, hence the comparison is between the consequences of disposing of the DU waste versus not disposing of the waste.

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 decision alternatives). The idea is to 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.

# 5.0 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 Clive DU PA model evaluates dose for the three types of receptors evaluated – ranchers, hunters and OHV enthusiasts. For the current, Version 1.4, model the DU waste is buried below grade, and the cover is an evapo-transpiration design. The ALARA analysis evaluates the per person rem costs of disposal of the DU waste. The results can be compared to those provided in Version 1.0 of the model, but Version 1.0 includes DU waste disposal above grade, a rip-rap cover, and other changes to the conceptual and probabilistic model. Given the changes, a direct comparison of the Version 1.0 and Version 1.4 models is not appropriate. The ALARA analysis for Version 1.4 of the model involves a cost analysis for the population risks (doses) associated with the disposal of the DU waste.

The goal is to estimate the dose-related costs for Version 1.4 of the Clive DU PA model; that is, assuming all DU waste is disposed below grade. As noted above, a discount rate 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 decision to not use a discount factor in the approach to ALARA estimation. A further consideration is the low population dose estimates.

As noted in the introduction, specific performance objectives for land disposal of radioactive waste are set forth in Utah Administrative Code (UAC) Rule R313-25-9 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 perhaps 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. However, for the current ALARA analysis a simple approach was taken: A

per person rem cost of $5,100 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’ decision alternative with regard to long-term disposal of DU. The decision evaluated for Version 1.4 of the Clive DU PA model essentially is whether to dispose of the DU waste below grade, or to not dispose of the waste. 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 the 'best' decision was defined in terms of overall benefit-cost in the context of the costs involved in reducing 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 must comply with the performance objectives.

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