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NWMO BACKGROUND PAPERS
1. GUIDING CONCEPTS

1-5 RISK AND UNCERTAINTY IN NUCLEAR WASTE MANAGEMENT

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NWMO Background Papers

NWMO has commissioned a series of background papers which present concepts and contextual information about the state of our knowledge on important topics related to the management of radioactive waste. The intent of these background papers is to provide input to defining possible approaches for the long-term management of used nuclear fuel and to contribute to an informed dialogue with the public and other stakeholders. The papers currently available are posted on NWMO's web site. Additional papers may be commissioned.

The topics of the background papers can be classified under the following broad headings:

1. **Guiding Concepts –** describe key concepts which can help guide an informed dialogue with the public and other stakeholders on the topic of radioactive waste management. They include perspectives on risk, security, the precautionary approach, adaptive management, traditional knowledge and sustainable development.
2. **Social and Ethical Dimensions** - provide perspectives on the social and ethical dimensions of radioactive waste management. They include background papers prepared for roundtable discussions.
3. **Health and Safety –** provide information on the status of relevant research, technologies, standards and procedures to reduce radiation and security risk associated with radioactive waste management.
4. **Science and Environment –** provide information on the current status of relevant research on ecosystem processes and environmental management issues. They include descriptions of the current efforts, as well as the status of research into our understanding of the biosphere and geosphere.
5. **Economic Factors** - provide insight into the economic factors and financial requirements for the long-term management of used nuclear fuel.
6. **Technical Methods** - provide general descriptions of the three methods for the long-term management of used nuclear fuel as defined in the NFWA, as well as other possible methods and related system requirements.
7. **Institutions and Governance** - outline the current relevant legal, administrative and institutional requirements that may be applicable to the long-term management of spent nuclear fuel in Canada, including legislation, regulations, guidelines, protocols, directives, policies and procedures of various jurisdictions.

Risk and Uncertainty in Nuclear Waste Management

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1. Introduction

Risks and uncertainties associated with nuclear-waste management are massive. The best waste-related scientific data cover only several decades (US DOE 1998, 2000, 2001; IAEA 2002), yet the waste and spent fuel will remain lethal, causing cancers and mutations for at least a million years, according to the US National Academy of Sciences (NRC 1995; see Kohnlein and Nussbaum 1998, 1995, 1992, 1991, 1990; Menke et al 1991; Scholz et al 1997; Wedemeyer et al 2001). The time frame is daunting, given that Italians could not protect their Renaissance art treasures, even for a thousand years, and Egyptians could not secure the tombs of their Pharaohs, many of which were looted within several centuries.

Past nuclear waste management also offers little assurance for future certainty of safety because all US nuclear wastes stored away from reactors, to date, have eventually leaked – as at Oak Ridge, Tennessee; Maxey Flats, Kentucky; and Hanford, Washington (US GAO 1999, 1998; US Congress 1999, 1992; US OTA 1991; Shrader-Frechette 2002;1993, 1991). While experiences with US nuclear waste may not always be typical, this paper nevertheless focuses on them, both because the US has oldest nuclear program in the world, the largest amounts of wastes needing to be stored, and the most financial resources to do so sensibly and safely. The reader thus can judge whether, given these three strengths, the US situation provides a best-case analysis of typical waste-related problems that could be encountered by Canadians. Regardless of whether the US case is typical, however, its shortcomings indicate that, even with well-funded programs, excellent scientific expertise, and a long history of dealing with nuclear waste, both technical and ethical problems remain. Repeated government oversight panels have criticized government waste managers for not being aggressive enough about safety (US GAO 1998), for causing widespread environmental contamination and punishing whistleblowers (US Congress 1999), for repeated violations of environmental laws and regulations, and for therefore losing credibility and public trust (US GAO 1998). This is one reason that nuclear waste cleanup, at US government facilities, will now cost a trillion dollars, apart from the government-bailout of 600,000 nuclear workers, many harmed on the job by poor safety practices (US Congress 1999; Shrader-Frechette 2002, 1993). Waste-related uncertainty also arises from the fact that most of the scientists evaluating the waste issue have ties to the nuclear industry and thus have a conflict of interest, as the US GAO (1998) noted. Likewise waste experts often are not careful to distinguish their own <u>opinions</u> about waste management from <u>empirically confirmed conclusions</u> and often equally present both as scientific findings. For example, a recent US National Academy of Sciences expert panel said that it was able to do reliable performance assessments of permanent nuclear -waste repositories for a million years into the future (NRC 1995). Given such subjective opinions, it is not surprising that Nobel-Prize-winner Daniel Kahneman has said experts, in situations of uncertainty (like that of nuclear-waste policy), typically fall victim to an "overconfidence bias" about their ability to predict the future (Kahneman and Tversky 2000; Kahneman et al. 1982).

An overconfidence bias occurred in a recent US Department of Energy (DOE 2000) study affirming the safety of the permanent nuclear waste facility at Yucca Mountain, Nevada. After the DOE calculated predicted radiation doses from the site, the International Atomic Energy Agency (IAEA) – the pro-nuclear, UN radiation-safety agency – reviewed the results. Using the DOE's own data and models, the IAEA (2001) said the DOE predicted doses had an uncertainty of between 8 and 12 orders of magnitude. That is, the IAEA Yucca Mountain could cause people to receive radiation doses between a 100-million and a trillion times greater or less than the DOE claimed, when it said the facility should be approved and that doses from it would be negligible. Such uncertainty means there are no factual grounds, whatsoever, for saying future waste risks and radiation doses would be small. Yet the DOE never admitted this uncertainty.

2. Risk, Uncertainty, and Variability

In situations of both risk and uncertainty, reliable knowledge is not available. According to basic Bayesian probability concepts, scientific phenomena may exhibit certainty, risk, or uncertainty. Situations of <u>certainty</u> have probability 1. For example, all things being equal, it is certain (probability =1) that metals expand when heated. Cases of risk have some numerical probability greater than 0 but less than 1. For example, the risk of tossing "heads" on a fair coin has probability of 0.5. (In risk assessment, the risk of some activity often is defined as the average annual probability that it will cause a fatality). A risk, then, may be defined as an event whose occurrence has a reliable, empirically confirmed likelihood greater than 0 and less than 1. Cases of uncertainty cannot be defined in terms of probabilities, because of incomplete evidence and multiple unknowns. To assign a legitimate probability, one would need to do comprehensive experiments or to rely on frequency data, like those for the likelihood of automobile accidents for drivers of a given age/sex. But in cases of uncertainty, neither is possible (see Resnik 1987; Shrader-Frechette 1996; NRC 1994). Thus an uncertainty may be defined as an event about which there is not complete, reliable scientific and mathematical data and thus whose likelihood of occurrence is unknown and therefore a matter of models and conjectures. Mere "variability," however, is not uncertainty. Variability is simply the normal range of values that different members of a population exhibit, like differences in height among humans (NRC 1994, pp.191-196). In principle, such variability can be measured and hence is not uncertain.

Despite their name, "risk assessors" typically do not assess cases of risk (events whose occurrence has a reliable probability greater than 0 but less than 1). Instead they usually assess situations of uncertainty. Thus, technically speaking, "risk assessment" is misnamed. Indeed, if society had a completely reliable probability (knowledge of "risk") that some threat would occur, it would not need to do risk assessment. In part because they address cases of uncertainty, risk assessments usually have uncertainty or error margins from 4 to 6 orders of magnitude (NRC 1996, 1994; Shrader-Frechette 1991). That is, fatalities predicted by risk assessments usually are (later proved to be) 10,000 to 1,000,000 higher/lower than experts say; most predictions are too low (Kahneman and Tversky 2000; Kahneman et al. 1982).

3. Uncertainty and Nuclear-Waste Options

Because choosing successful policies for long-term management of waste and spent nuclear fuel presents a case of uncertainty, not risk or certainty, it is a decision for stakeholders and citizens, as well as experts. Experts can provide scientific, factual, and probabilistic information, but waste policy cannot be made merely on scientific, factual, and probabilistic grounds, for two main reasons. First, the policy must must confront situations of uncertainty, without long-term data and without reliable empirical probabilities. Second, the policy choices will affect citizens' welfare, rights, health, and security. Experts alone do not have the rights to decide either what rules ought to govern behavior under uncertainty or what norms ought to govern choices affecting citizens' welfare, rights, health, and security (see Cranor 1993; Maclean 1986; Thomson 1986; Goodin 1985; Rawls 1971; Dworkin 1977; Shrader-Frechette 2002, 1993, 1991). If not, then a waste-policy choice involves at least three goals or objectives: (i)making different kinds of scientific, mathematical, social, and cultural uncertainties as transparent as possible; (ii) clarifying alternative ethical and social norms (including assumptions and consequences) of different waste-policy options; and (iii) articulating just and equitable procedures for waste choices that both accommodate scientific findings and respond to democratic welfare, needs, rights, and duties – especially stakeholder rights to make decisions affecting them.

To illustrate the interplay among uncertainties and democratic norms involved in the waste-and-spent-fuel policy choice, consider the three most-discussed options:(1) onsite or at-reactor storage, (2) regional, monitored, retrievable storage, and (3) unmonitored, unretrievable, permanent disposal. (1) Onsite, (preferably) underground, monitored, retrievable storage at existing nuclear reactors now exists throughout much of the world. The US Nuclear Regulatory Commission says (1) is safe for at least 100 years (Radin, Klein, and Parker 1989). (2) Monitored retrievable storage (MRS) facilities, preferably underground and located regionally, would handle the waste from several reactors (Radin, Klein, and Parker 1989; Shrader-Frechette 1993). (3) Permanent, unmonitored, underground disposal of high-level waste and spent fuel is predicted to occur at places such as Yucca Mountain, Nevada (US DOE 2001, 2000, 1998; IAEA 2001). Options (1) and (2) are built on a philosophy of complete containment, whereas option (3) is built on a philosophy of "dilute and disperse," as experts know that wastes from a permanent unmonitored, unretrievable repository will escape; the only question is when and how they will do so (NNWPO 2002a,b; 1999; Roxburgh 1987, esp. p. 183; Shrader-Frechette 1993, p. 240;).

Major uncertainties with the onsite option (1) are (i) whether multiple reactor-storage sites represent more of an accident and terrorist threat than the existing reactors themselves, and (ii) whether decentralized handling of the waste is as efficient and trustworthy as at more centralized facilities. Some people claim that these 2 uncertainties are offset by at least 8 social and ethical benefits. Option (1) would (a) avoid waste transport, which (all agree) is the most dangerous, highest-risk aspect of nuclear-waste management (DOE 2001, 2000; NNWPO 2002a,b, 1999; NNWTF); (b) "buy time" while waste temperatures drop (making later storage easier/safer), while scientists learn from experience, and while nations "keep their options open" for waste-handling; and (c) enable leaks to be corrected, canisters to be exchanged, and people to be protected, because the waste would be monitored and retrievable. Option (1) also arguably would (d) be more equitable in imposing the risks and costs of the waste on the same people who received the benefits of nuclear-generated electricity and (e) force people who choose nuclear-generated electricity to bear the full costs/externalities of their decision, including waste management, and not to impose costs on others. Option (1) also would (f) allow society to avoid certain leakage from an allegedly permanent facility; (g) allow society to avoid imposing greater health risks on future generations, if the waste is monitored adequately; and (h) allow society to take advantage of later improvements in waste-management technology (Shrader-Frechette 1993; DOE 2001, 1998; Radin, Klein, and Parker 1989).

Major uncertainties with MRS option (2) are (i) whether regional MRS storage sites represent more of an accident and terrorist threat than would permanent or onsite facilities; (ii) whether MRS waste handling is as efficient/trustworthy as at a centralized facility; (iii) whether high transportation risks to regional MRS facilities, as compared to keeping wastes onsite, are offset by any advantages;(iv) whether any communities would willingly accept MRS facilities, given their storing materials from other areas and thus imposing an inequitable burden. Some people claim these 4 uncertainties with MRS option (2) are offset by 5 social and ethical benefits that are similar to those associated with option (1), namely benefits (b), (c), (f), (g), and (h) (Shrader-Frechette 1993; DOE 2001, 2000, 1998; Radin, Klein, and Parker 1989).

Major uncertainties with permanent option (3) are (i) whether such a national disposal site presents accident and terrorist threats less than MRS or onsite facilities; (ii) whether centralized waste handling is more efficient and trustworthy than at less centralized facilities; (iii) whether high transportation risks to national facilities would be offset by greater safety at the facility; and (iv) whether any community would willingly accept a permanent facility, given that none will do so now; that the waste would originate from other areas , that it might impose an inequitable burden on the local community, and that 80 percent of Nevadans opposes the Yucca Mountain facility (Slovic, Flynn, Layman 1991). The state is fighting the siting in the courts. Other uncertainties include (v) whether the government is justified in building a facility that (it admits) will leak and endanger future people; (vi) whether the government is justified in building a facility when the uncertainties about future exposures from it are as great as a trillion (IAEA 2001); and (vii) whether government is justified in building a facility where waste is unmonitored/unretrievable, so that leaks will be difficult to stop/correct. Some people claim these 7 uncertainties with option (3) are offset by at least 3 social and ethical benefits: (j) if one excludes transportation risks (getting waste to the facility), permanent disposal seems easier to manage, given economies of scale, than MRS or at-reactor storage. Also (k) because the disposal is permanent, the waste problem will be solved in the sense that future people will not need to monitor it (provided leaks do not occur too soon or too disastrously). (l) Locating a waste facility in a rural area seems preferable, in part because at-reactor or regional facilities tend to be closer to population centers (Shrader-Frechette 1993; DOE 2001, 1998).

Avoiding the highest risks, waste transport (DOE 2001; NNWPO 2002a,b, 1999; NNWTF); protecting future generations; and placing the nuclear- waste hazard among the people who benefit from nuclear electricity arguably would promote equity and fairness. To satisfy these values, as well as complete waste containment, and to allow time for improvement in waste-management technology, it is arguable that onsite option (1) is preferable to MRS option (2), which is preferable to permanent option (3), as already shown (Shrader-Frechette 1993;Radin, Klein, and Parker 1989). Although there is no easy waste choice, and there are many ways to list uncertainties and benefits, the earlier summary suggests onsite option (1) has fewer uncertainties and more benefits than MRS option (2), which is better than permanent option (3).

The preceding question of how to balance ethical norms (like distributive justice) with uncertainties (like societal ability to manage the wastes), however, is fundamentally an ethical/value issue, one that should be decided democratically because welfare, harms, and protections are at issue. As a consequence, the best (fairest, most democratic, most scientific) way to deal with uncertainty in nuclear-waste science/policy is not to offer a conclusion about any of the available options, at this point, but instead to provide a three-part analysis to guide democratic and scientific deliberation. This includes (i) determining the types of uncertainties in each option, (ii)offering classic scientific/technical strategies for reducing uncertainties and making them transparent, and (iii) suggesting classic democratic/procedural strategies for making decisions, under uncertainty, in the best (fairest, most democratic, most scientific) way. The remainder of this essay provides this three-point analysis. That accomplished, Canadians will have the basic resources for waste-related democratic decisions.

4. Six Types of Uncertainty

Among the many cases of scientific uncertainty, at least 6 are significant because of their relationship to environment-related questions like nuclear-waste policy (EPA 2001a; Shrader-Frechette 1996, 1993; 1991; NRC 1994). These are (1) framing uncertrainty, (2) modeling uncertainty, (3) inference-option uncertainty, (4) statistical or parameter uncertainty, (5) decision-theoretic uncertainty, and (6) policy-implementation uncertainty. This paper discusses the 6 types of uncertainties, gives examples of them, and shows how ignoring them has undermined waste management. The paper also offers classic scientific, ethical, and democratic procedures for addressing these uncertainties.

4.1. Framing Uncertainty

Consider framing uncertainty. A frame is a set of assumptions for interpreting data. For example, people could frame the question of a successful surgery in terms of percentage of patient deaths or percentage of 5-year survivals. Using one surgery frame, rather than another, causes statistically significant differences in numbers of people opting for the same surgery (see NRC 1996; Shrader-Frechette 1996). Those who frame the questions control the answers.

In the case of nuclear-waste policy, one can get contradictory answers about waste-site suitability, depending on the frame used. The US DOE required a two-value frame to decide whether or not to accept the Yucca Mountain site for permanent nuclear-waste disposal. Experts were required to support either a "suitability finding" or an "unsuitability finding" for the site; according to the frame, "if current information does not indicate that the site is unsuitable," then it is to be judged suitable (Younker et al. (DOE) 1992a, pp. E-5, E-11). Although policymakers frequently need immediate decisions about whether to accept or reject a proposal, this two-value frame is questionable because it ignores a third possibility, that because the situation is uncertain and data are unknown, no decision can be made. Independent DOE peer reviewers-scientists, from top US universities, said they accepted the Yucca Mountain site, in part, because they were forced to use the two-value frame (Younker et al. (Peer) 1992b, p. 46), not a three-value frame (accept/reject/unable to determine site suitability). The peer reviewers unanimously wrote: there is "not enough defensible, site specific information available to warrant acceptance or rejection of this site" (Younker et al. (Peer) 1992b, pp. 460, 257, 40-51).

Frame uncertainty cannot be resolved by any particular algorithm. Yet it is obvious that use of a two-value frame could lead to one nuclear-waste decision, while use of a three-value frame could lead to the opposite conclusion. Lessons to be learned are to (a) employ the three-value frame, except when conditions (ii) and (iii) can be satisfied and to (b) remember that those who frame the questions control the answers. Policymakers likewise should remember to (c) provide alternative frames for the same problem/hypothesis, so people can see policy effects of the different frames; to (d) guarantee that sensitivity analysis, formal quantitative uncertainty analysis, and peer review are done in all frames; and to deliberate about and (e) choose a democratically-derived position on whether/how to accept the Precautionary Principle (see Manson 2002, Farrow 2002, Konig 2002a,b, Myers 2002, Goldstein 2001, Kriebel and Tickner 2001, Morris 2001, Pelley 2001, Christen 2000, Hogue 2000,). To help ensure unbiased frames for waste-policy choices, decisionmakers also should ensure that all committees: (f) democratically devise and follow a democratic decision procedure, informed by science (NRC 1996); (g) provide equal representation for ethicists, attorneys, social, medical, and public-health scientists, as well as natural scientists/engineers; (h) include a Public Defender for the Future (Kasperson, Derr, and Kates 1983); (I) specify democratically chosen default rules for who bears the burden of proof and for proceeding under uncertainty (NRC 1996, 1994); (j) require social/ethical-impact analysis of policy choices; and (k) employ consensus conferences, science courts, or technology tribunals to decide on frames and make waste-policy choices (NRC 1996, 1994Shrader-Frechette 1991). In these ways, experts and stakeholders can cross-examine different scientific witnesses and arrive at democratically-derived ways to frame the problem (Shrader-Frechette 1991).

4.2. Modeling Uncertainty

In the face of data limitations (already mentioned), and given the problem of million-year waste security, scientists must construct models, as the DOE did for the Yucca Mountain site. They use the models to predict future site behavior, and if the model predictions are consistent with each other, scientists conclude the models are "verified" or validated"(DOE

1990). Despite such misleading language, however, million-year models can never be verified or validated, in the sense of being shown to conform with the facts. (Indeed, if scientists had the facts, they would not need to use mere models.) Because models cannot be shown to conform perfectly with all the facts, they are uncertain (Shrader-Frechette 1993) One reason for uncertainty is the problem of induction and the fallacy of affirming the consequent. This fallacy occurs whenever one postulates that a hypothesis is true/acceptable merely because some test result, predicted to follow from the hypothesis, actually occurs. In fact, however, failure of predictions can only falsify theories. As all scientists know, successful predictions cannot prove theories true, only that predictions are consistent with the hypothesis;any number of different predictions also could be consistent with the hypothesis (Fetzer 1991, 1989; Shrader-Frechette 1996, 1993).

At Yucca Mountain, government scientists did not address model uncertainty. They repeatedly "tested" hypotheses (e.g., about leaks) by checking whether model predictions and hypotheses were consistent. If they were, they concluded the hypotheses were "verified" (Costin and Bauer 1990; DOE 1990; Sinnock et al. 1986; Shrader-Frechette 1993). In using such "verification" and "validation" language, US DOE scientists mislead citizens about the factual basis of their claims. At the Maxey Flats, Kentucky, nuclear-waste repository, scientists used models to predict the waste would travel only half an inch in 24,000 years . Less than 10 years later, the waste was 2 miles offsite (Shrader-Frechette 1993). Their model assumed waste migration would be only vertical (downward). Instead, the waste also moved horizontally. Such cases suggest modeling uncertainty can be minimized by using alternative models/assumptions and by doing sensitivity analyses that reveal the degree to which a conclusion is dependent on a particular assumption. In the earlier example of the US DOE (2000) claiming radiation doses from Yucca Mountain would be negligible, the positive conclusion (in favor of the facility) arose because of DOE's failure to do uncertainty analyses of its models. When the IAEA (2001) did these analyses, it showed radiation doses could be a trillion times higher and cause catastrophic numbers of deaths.

Given such modeling uncertainties, scientists should (a) be wary of ever claiming their long-term models have been verified or validated and (b) avoid point estimates and instead provide <u>ranges and distributions</u> of all model values (see NRC 1996, 1994). They also should (c) list all modeling assumptions and simplifications; (d) provide alternative models/ assumptions; and (e) perform sensitivity, uncertainty, and peer-review analyses of alternative models (NRC 1996, 1994).

4.3. Inference-Option Uncertainty

Even if scientists agree that a particular model is the best to use in a given situation, uncertainties always arise because of "inference options." As defined by the US National Academy of Sciences (NRC 1983), these are judgments/opinions about scientific procedure/practice. Such inference options include deciding what data to omit, how to classify data, when measurements are flawed, when extrapolation is valid, which simplifications are legitimate, and so on. Different inference options can have a great effect on scientific conclusions. For example, when the IAEA studied Chernobyl-accident-caused deaths, the IAEA made the inference option that it did not need to study long-term carcinogenic or genetic effects and that a three-month study was adequate to assess the situation. As a consequence, the IAEA (1991) concluded that Chernobyl had caused no deaths, beyond initial acute fatalities at the beginning of the accident. In a classic report published later in <u>Nature</u>, however, scientists studying genetic effects over the next 8 years (rather than 3 months) concluded that Chernobyl caused a doubling of germline mutations, as far as 400 km. away from the accident, mutations almost certain to be fatal (Dubrova et al. 1996), as well as a 100-fold increase of thyroid cancers in Belarus, Ukraine, and Russia (Henshaw 1996, Rytomaa 1996, Savchenko 1995). Or, consider the inference option that there is no threshold for damage from ionizing radiation, an option accepted by the ICRP, IAEA, and virtually all professional, scientific, medical, and public-health associations. Using this inference option, scientific authorities argue that exposures to low-dose ionizing radiation (normal background) cause at least 3-to-6 percent of all annual fatal cancers (UNSCEAR 1994, Gonzalez 1994, Kovan 1995). However, if one rejects this inference option (as the nuclear industry and military groups tend to do) and says there is a threshold for damage from radiation, then one can claim harms at the level of background radiation are "negligible"(Clarke 1999). Likewise, in the earlier Maxey Flats example, scientists erred by 6 orders of magnitude because they used the inference option about downward-only waste migration(Shrader-Frechette 1993).

One of the most important inference options, in the case of policy for nuclear-waste management, is deciding whether to use a discount rate and, if so, what rate to use (see EPA 2001a,b; Heal 1998; NRC 1997, 55ff.; Schelling 1995, Price 1993, Anderson 1993). Economists typically (although they need not) use the inference option that long-term costs ought to be discounted (see, for example, Arrow 1996, 1966; Lazaro 2002). While this inference option seems reasonable, as the inverse of an interest rate, several factors make its use in nuclear-waste issues questionable. One reason is that, at a standard 6-percent discount rate, a billion dollars in several hundred years will count the same as one dollar now. A second worry is that it may be wrong to assume investments now can compensate for later costs, because no money is invested, or put in a trust, to pay off future costs. Third, most economists argue against welfare discounting and in favor of only commodity discounting (see Broome 1994, Cowen 1997, Nordhaus 1997, Cowen and Parfit 1992, Parfit 1984). They say welfare (like the value of human life) ought not be discounted, because the value of human life does not decline over time, and lives are not bought and sold. Yet, they claim that commodities (things traded on markets) can be discounted, because their exchange value differs over time (Heal 1998, Cowen and Parfit 1992). Fourth, in the nuclear-waste case, some say discounting is suspect because nuclear disposal can be shown cost-effective only by discounting welfare – discounting future lives lost (Kasperson, Derr, and Kates 1983).

In order to protect against inference-option uncertainties, policymakers ought (a) be wary of claiming their inference options are certain. They should (b) list all inference options used, including assumptions and simplifications; (c) provide alternative inference options; and (d) perform sensitivity analyses, formal uncertainty analysis, and peer review, for all models. Because choosing an inference options is, in part, a value judgment, they should (e) involve the public in decisions about who should bear the burden of proof and which default rules to use under conditions of uncertainty.

4.4. Statistical or Parameter Uncertainty

Because models are only as good as the data they use, much model uncertainty arises from statistical or parameter uncertainty. Statistics is a set of numerical methods and probability theories for analyzing data. Statisticians typically draw conclusions about a full data set (e.g., all subsurface rates of nuclear-waste transport), based on characteristics of a sample (e.g., rates based on 20 samples over 10 years at a site): they generalize from a small collection of data. As a result, there is always uncertainty in statistical generalizations (see NRC 1996, 1994).

A common source of statistical uncertainty is that the sample is too small, not random, or not representative of the full data set. Other uncertainties arise because of different interpretations of null or no-effect results. If a geologist has site seismic data for 20 years, and concludes, on the basis of these data, that no earthquake large enough to breach a repository will occur, he has drawn a null or no-effect conclusion. But one could interpret this null claim in contradictory ways: (A) that no repository breach will occur (because 20-year data is representative), or (~A) that it is impossible to know whether a breach will occur (given only 20-year data used for a million-year prediction). Statistical uncertainty often arises because statistical results are only as reliable as the power of the test. Low-power studies often give null or no-effect results because they are not sensitive enough to "capture" the desired effect, while higher-power studies are more likely to capture an effect, if it is there. When the US government interpreted data on formaldehyde risks, for example, it used a low-power study. It had only a 4 percent chance of detecting a doubling of cancers from formaldehyde (Mayo 1997; see NRC 1996, 1994). For null-effect studies to be plausible, one should be at least 95 percent certain of some outcome. Using techniques like low-power studies or small sample sizes is like searching for an electron with a flashlight, using the wrong tool/test for the job, then concluding no electrons exist.

Statistical uncertainty also arises because one cannot minimize the chance of both false-positive or type-I (rejecting a true null hypothesis) and false-negative or type-II (not rejecting a false null hypothesis) statistical errors at the same time. This is in part because the same null cannot be both true and false (see Shrader-Frechette 1991, 1993, 1996; Cranor 1993). Instead one must choose which error to minimize. On one hand, false positives, false claims of pollution harm, for example, would jeopardize industry/polluter interest, because they would have to pay for unnecessary protection. On the other hand, false negatives, false assurances of no harm, would harm the public/victims of pollution, because they would not be protected against harmful pollution. Choosing false positives puts the burden of proof on polluters. Choosing false negatives puts the burden of proof on pollution victims. Citizens cannot easily decide how to resolve the uncertainty, but they can decide where to place the burden of proof and how to devise statistical tests of hypotheses.

Placing the burden of proof on one or the other (polluters/citizens), leads to uncertainty because whoever bears this burden has the more difficult task. This difficulty may lead to the other side's falsely being judged correct. Pure scientists tend to risk false-negative over false-positive errors, because they would rather fail to recognize a result than to identify a result incorrectly; they judge errors of commission worse than omission. Citizens tend to risk committing false-positive over false-negative errors, because they say it is more important to protect the public than to enhance the welfare of polluters, because the public has rights to (and needs more) protection and ought not be used as means to industrial ends, especially when risk imposers receive the financial benefits (Shrader-Frechette 1991, 1993, 1996;Cranor 1993).

In the face of statistical uncertainties, policymakers (a) should be reluctant to use point estimates (instead of ranges and distributions of values) and to assume that dangerous technologies are innocent until proved guilty (see Samuels 1988, 1981;NRC 1994). They (b) should demand large, representative, random samples and high-power, high-confidence-level studies. Also necessary are (c) clear, careful interpretation of null or no-effect conclusions; (d) formal uncertainty analysis, sensitivity analysis, and peer review of all conclusions; (e) a listing of all assumptions and simplifications; and (f) testing with alternative parameters/assumptions. Policymakers should (g) calibrate all expert opinions, so that the reliability of different, even contradictory, expert opinions, can be assessed . Cooke (1992, 1982) discovered that expert opinions, under uncertainty, could be assessed reliably by weighting experts' opinions on the basis of their past predictions, for which frequency data were available. Showing that expert probability estimates about different phenomena are dependent, Cooke has been able to evaluate expert estimates in a variety of uncertain situations.

Statistical uncertainties are especially troubling in the case of nuclear waste because, given the dearth of data and the time frame of "perpetual" threat from the waste, it is impossible accurately to bound all the uncertainties. As a unanimous (14-member) expert peer-review team put it: "many aspects of site suitability are not well suited for quantitative risk assessment. In particular are predictions involving future geological activity, future values of mineral deposits and mineral occurrence models. Any projections of the rates of tectonic activity and volcanism, as well as natural resource occurrence and value, will be fraught with substantial uncertainties that cannot be quantified using standard statistical methods"(Younker et al. 1992bm p. B-2). Thus statistical uncertainty is a special problem for nuclear waste management, in large part because most aspects of waste problems remain unavoidably uncertain.

4.5. Decision-Theoretic Uncertainty

Even if scientists were correct in all their data, models, and frames, they would still face decision-theoretic uncertainty. Decision theory is a mathematical framework for choosing among alternative actions, given that one knows the probability $\underline{p}$ that each alternative will occur and the value or utility $\underline{u}$ associated with it. A major uncertainty in decision theory is whether, in a given situation, one should choose the course of action that maximizes average expected utility or welfare (expected utility = $\underline{p}$ times $\underline{u}$), or that minimizes the chance that the worst outcome will occur (see Resnik 1987; Shrader-Frechette 1991). The first rule is the average expected utility rule (AEU);the second is the maximin rule (M).
To see differences between the rules, consider a hypothetical example, that of building a permanent waste repository, versus building an onsite facility. Suppose scientists agree and are certain ($\underline{p}$ = 1) that the permanent facility will cause no negative effects on each 900 of 1000 people in a nation, but will cause 100 people to have statistically significant increases in their cancer risks, because they are already members of vulnerable groups, like the one-quarter of the population that includes children, pregnant women, the elderly, the sick, and so on. In such a hypothetical situation, one might assume the 900 healthy people would each have 90 units of utility, because they would benefit from the repository and not have to worry about waste problems, whereas the 100 higher-risk people would have utility or welfare of only 1 unit each, because the repository would increased their risk. If one made these assumptions about utility and used the AEU rule, average expected utility in this hypothetical situation would be 81.1 (see Resnik 1987). Suppose also that scientists agree and are certain ($\underline{p}$ = 1) that an onsite facility will cause no negative health effects, whatsoever, because the canisters will be exchanged before they leak, and the wastes will be monitored/guarded by failsafe human and electronic systems. In the second situation, suppose hypothetically that all 1000 people would each have 35 units of utility, because they would benefit from waste storage yet would worry that this would require continual guardianship. If one used the M rule, average utility in this hypothetical situation would be 35 (see Resnik 1987). In such a situation, despite their agreement on all data, utilities, and so on, those using the AEU rule would prefer permanent disposal, because its average expected utility was higher, 81.1 over 35, even though a minority of people would be hurt. Yet those following the M rule would prefer onsite storage, because it would avoid the worst outcome for anyone, namely that in which a minority had a utility of only 1 unit each (see Resnik 1987, Cooke 1992, Shrader-Frechette 1996, 1993,1991).

Consider another instance of alternative decision-theoretic rules, one that actually occurred. For North American nuclear reactors, the probability of a core melt is about 1 in 4 for their lifetimes (US NRC 1975). Two different assessments, one done by the Ford-Mitre Corporation (NEPSG 1977), and the other done by the Union of Concerned Scientists (UCC 1977), used identical probabilities, , models, and factual data in their nuclear risk assessments. In fact, the two studies differed only in the decision-theoretic rules they adopted. Ford -Mitre used AEU, and the Union of Concerned Scientists used M. As a consequence, Ford-Mitre concluded that commercial nuclear fission was safe/acceptable, whereas the Union of Concerned Scientists concluded that it was unsafe/not acceptable, purely because of the different decision-theoretic rules they used to interpret the identical data, probabilities and utilities (Cooke 1992, Shrader-Frechette 1991).

Which of the two major decision-theoretic rules should one use? Harsanyi (1975, 1977) of University of California, Berkeley, argues for AEU in situations of uncertainty, whereas John Rawls (1971), of Harvard University, argues for maximin in situations of uncertainty. Harsanyi's arguments are that one ought not to follow M and avoid the worst outcome, because many catastrophic events have only a negligible probability of occurring and because such a policy would force society to sacrifice greatly to benefit the least well-off people. Rawls, on the other hand, claims that one should follow M, in cases of uncertainty, because those most likely to be hurt deserve societal priority; because none of us wants to be in the situation of being worst off; and because the worst-off people have equal rights to life/well being, rights which the AEU rule ignores – in favor of mere utility or expediency (see Shrader-Frechette 1993, 1991). Regardless of who is correct, Harsanyi or Rawls, and which decision-theoretic rules are preferable, using either, in a situation of uncertainty, emphasizes some uncertainties over others and adopts some ethical assumptions rather than others. AEU rules tend to follow utilitarian ethical presuppositions (which maximize social welfare but ignore minorities of people who may be harmed). M rules tend to follow egalitarian ethical presuppositions, which maximize fairness or equal protection among people (see Shrader-Frechette 1993, 1991). In the waste-policy case, AEU rules would maximize average welfare, whereas M rules would maximize fairness or equal protection among people. In any pollution situation, especially that of ionizing radiation, the vulnerable minority most likely to be hurt, by using an AEU rule, is children, because of their developing systems and their lesser body masses. They are the "canaries in the coal mines." Yet adoption of either rule (AEU/utilitarian or M/egalitarian) is never completely certain, unless the underlying ethical norms are certain. Yet different rules tend to support different policy choices. With their emphasis on complete containment, transport risks, and long-term equity, M rules tend to support (1) onsite and (2) MRS options. With their emphasis on dilution/dispersal and overall utility, AEU tends to support (3) unmonitored, nonretrievable waste options.
Given decision-theoretic uncertainty, policymakers ought to (a) employ alternative decision-theoretic rules, utility assignments, probabilities, and scenarios, in order to monitor their effects on policy results; to (b) defend their selection of decision-theoretic rules on ethical, legal, economic, and utilitarian grounds; and to (c) allow the public to have the predominant voice in choosing decision rules, since this choice is essentially an ethical one. As in earlier cases, policymakers should (d) perform sensitivity, uncertainty, and peer-review analyses of alternative decision-theoretic rules.

4.6. Policy-Implementation Uncertainty

Even if all these areas of scientific measurement and assessment (previously surveyed) were certain, another area of uncertainty would remain. It concerns the way humans might implement some policy (EPA 2001a, 37). Practically speaking, the theoretically best waste policy might not be able to be implemented with reliable certainty, just as legally required or *de jure* racial integration has not always been implemented *de facto*. Risk assessors say policy-implementation uncertainty arises because risk is in part socially constructed: people's behavior affects the threats they face. For example, consider the policy-implementation uncertainty caused by the fact that, in a small metal-stamping plant in Pennsylvania, all the safety instructions, printed on the dangerous presses, were written in English. The punch-in-time instructions, however, for the largely Mexican-immigrant workers, were printed in Spanish. If implementing safe operation of these presses is in part a function of ability to read the English signs, then there may be uncertainty about the job hazard and the policy-implementation effects of the English signs (Hollander 1997). Analogously, there always would be policy-implementation uncertainty about how humans might apply and use even the best waste policy.

Some of the greatest policy-implementation uncertainties, regarding nuclear-waste management, concern biased regulatory agencies and whether future people's rights to free informed consent, due process, compensation, environmental justice, and equal treatment will be respected. Because waste issues are partially scientific/technical, will public participation be promoted in future decisionmaking(see NRC 1996; Shrader-Frechette 2002, 1993, 1991)? Such procedural and ethical questions are crucial because if the best policy is implemented in a biased, incomplete, or self-interested way, that policy will fail. Consider the case of US implementation of a system of DOE safety bonuses for subcontractors and contractors, working at US nuclear facilities and government laboratories. The bonus system is intended to reward those who "put safety first" by providing millions of dollars annually, above the contracted amounts, for companies with excellent safety records. Yet because the agency (DOE) has been dominated by the nuclear industries it supposedly regulates (US Congress 1999, 1998), virtually all companies annually have received extra millions of dollars in safety bonuses, even when they had no required monitoring programs for years, when workers were irradiated because of safety violations, and when they falsified safety records. The situation is so serious that the US Congress (1999), the US General Accounting Office (1999, 1998), and the US Office of Technology Assessment (1991) all recommended that the DOE be abolished and reorganized to stop such conflicts of interest. (No one has followed this recommendation.) The Congress, GAO, and OTA uncovered many accidents, worker radiation exposures, DOE retaliation against whistleblowers, and DOE coverup of safety problems (US GAO 1999, 1998; US Congress 1999, US OTA 1991; Shrader-Frechette 2002, ch. 7).

In order to protect against policy-implementation uncertainties, decisionmakers ought (a) not claim certainty for policy-implementation predictions. They should (b) list and defend all policy-implementation assumptions and simplifications; (c) trace alternative policy-implementation consequences, in the same model; and (d) perform sensitivity analyses, formal uncertainty analysis, and peer review, so as to reveal any dependence of policy-implementation conclusions on particular assumptions. Most importantly, because decisions about desirable policy implementation are, in part, value judgments, officials should (e) ensure the public has the predominant voice in decisions about which default rules to use under conditions of uncertainty and (f) use an iterative and phased approach to evaluating the waste issue, so that there are continual improvements in the relevant science and policy (see NRC 1995, 85; NRC 1999; EPA 2001b, 15.)

5. Technical and Procedural Strategies for Dealing with Uncertainty

To ameliorate and make transparent the 6 types of uncertainty mentioned earlier, this paper surveyed both scientific and ethical/legal/procedural strategies. The scientific strategies are needed because of the technical problems noted at the beginning of this report and because there is a tendency to accept scientific "guestimates" about the waste issue but not to recognize their unreliability. As already mentioned, this occurred when the DOE (2000) claimed doses from Yucca Mountain repository would be negligible, but the IAEA (2001) proved these dose claims were meaningless because they were uncertain by a factor of between 8 and 12 orders of magnitude. Given the tendency to accept uncritically scientific opinion, technical methods for exposing uncertainty must always be used, so as to make all uncertainties transparent. Ethical/legal procedural strategies for dealing with uncertainty are needed both because of human problems such as the overconfidence bias and vested interests (Kahneman et al. 1982), and because the issue of nuclear-waste management is also an ethical, and not merely a technical or scientific, question (Shrader-Frechette 1993). Although technical analyses are necessary for resolving the waste issue, they are not sufficient for doing so, and for at least two reasons: (1) The key issue regarding nuclear-waste management is how much risk is acceptable. Under what scientific, technical, ethical, social, legal, and compensatory conditions should people in a democracy accept the spent-fuel and nuclear-waste risk for themselves and their descendants? How safe is safe enough, fair enough, equitable enough, compensated enough, and voluntary enough? (2) As explained earlier, the time, degree, and likelihood of harm from managing nuclear waste, over the next million years, are not problems of Bayesian risk (with reliable probabilities of harm). Instead they present a situation of Bayesian uncertainty (where reliable probabilities are not available). Thus the key issue in this situation is ethical, not technical: "what policy behavior is acceptable, in situations of uncertainty?"

5.1 Dealing with Scientific/Technical Uncertainty

As already suggested, scientific/technical uncertainty can be alleviated and made transparent by ensuring, at least, that all waste-related frames/ choices/parameters/ inferences/studies/models/methods/policies must be

1. Done by avoiding point estimates and providing <u>ranges and distributions</u> of all values

2. Evaluated by means of formal, quantitative uncertainty analysis

3. Assessed by means of sensitivity analysis

4. Evaluated by means of required expert elicitation and calibration.

5. Corrected through intensive peer review by scientists and citizen representatives who have neither vested interests nor any conflicts of interest

6. Based on use of discount rates only for commodities, not for human or environmental welfare, and

7. Committed to funding/improving the relevant research agenda as a response to uncertainty.

5.2 Dealing with Social/Ethical Uncertainty

As already suggested, because all waste-related frames/choices/parameters/ inferences/ studies/ models/ methods/ policies involve the issue of choosing behavior under conditions of uncertainty (see Kohnlein and Nussbaum 1998, 1995, 1992, 1991, 1990; Menke et al 1991; Scholz et al 1997; Wedemeyer et al 2001), behavior that could promote or threaten welfare, they are essentially ethical choices. As such, this ethical uncertainty can be mitigated and made transparent by a number of procedural and democratic strategies including, at least:

8. Using alternative assessments, in a quasi-judicial proceeding, so that various assessments/ policies can be debated and regulatory agencies can avoid "capture" by special interests

9. Employing consensus conferences, science courts, or technology tribunals, so that experts and stakeholders/citizens have equal power in making policy

10. Including/funding equal numbers of ethicists, attorneys, social, medical, and public-health scientists – as well as engineers and natural scientists – on all scientific panels (NRC 1996)

11. Funding equal numbers of (and giving equal power/funding/representation to) citizen/stake-holder representatives/decisionmakers on all waste-related panels/boards

12. Ensuring that assessments include ethical-impact analyses that address problems such as environmental justice and violations of rights to know, to due-process, to equal protection, to life, to free informed consent, and to be compensated for harms/threats of harm

13. Guaranteeing a just decision process , including all citizens' full access rights to all waste data/deliberations; to due-process, to equal protection, to environmental justice; to life, to free informed consent, to know, and to be compensated for harms and threats of harm

14. Guaranteeing a fully-funded "Public Defender for the Future" on all waste-related committees

15. Specifying democratically chosen default rules for decisionmaking under uncertainty and for who bears the burden of proof, such as when to minimize false positives or false negatives

16. Clarifying and defending democratically chosen rules regarding the status of the Precautionary Principle, as an approach to prevention of waste-related harm; and

17. Using an iterative and phased approach to evaluating the waste issue, so that there are continual improvements in the research, science, and policy relevant to it.

6. Conclusion

The preceding analysis has surveyed both general problems with uncertainty and risk in nuclear waste management, as well as some particular examples, e.g., from the US DOE case. While some may claim the DOE problems have little to teach Canadians, it is important to remember some risk-assessment truisms about human error. According to the US Environmental Protection Agency (EPA), human error (not technical-system breakdown) is responsible for 90 percent of all technological catastrophes; the US Office of Technology Assessment (OTA) says that "more than 60 percent" of hazardous-materials accidents are the result of human error (Shrader-Frechette 1993, p. 69). If these EPA and OTA figures are correct, then the DOE-type human and institutional problems, evident in US Congressional and regulatory criticisms of the DOE, are likely fairly typical of any system in which there are human errors, conflicts of interest, desires to save money, and scientists' overconfidence biases already mentioned. Also keep in mind that all the preceding criticisms of DOE have come either from the pro-nuclear US government (Congress and oversight agencies) or from the pro-nuclear UN agency, the IAEA. Other nations may have agencies other than DOE, but "following the money," and the human errors associated with it and with other biases, suggest that the DOE problems may be representative of those almost anywhere. If they are, then there may be procedural ways to ameliorate both technical and social/ethical uncertainty

This paper does not draw a conclusion about the best waste-and-spent-fuel policy under conditions of uncertainty. That decision should be left to Canadians. It does, however, provide scientific, technical, ethical, and procedural strategies for making scientific and policy uncertainties transparent, so that citizens and their representatives can engage more easily in democratic decisionmaking regarding the best option under conditions of uncertainty.

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