Value Tradeoffs for the Hanford Tank Waste Remediation System (TWRS) Program

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Summary

The Tank Waste Remediation System (TWRS) program at the Hanford Site of the Department of Energy has adopted a logical approach to making decisions that uses decision analysis to structure and analyze decision alternatives and public values to evaluate them (Robershotte, et al., 1995). This report is the third in a series to support this effort. The first (Armacost et al., 1994) identified a set of objectives (called "ends objectives") that characterize the ultimate goals and desires of Hanford decision makers and stakeholders. The second report (Keeney and von Winterfeldt, 1996) developed operational measures for these ends objectives (called "ends measures") and it also developed a set of performance objectives and associated performance measures that are more directly related to how well decision alternatives in the TWRS program perform to achieve the ends objectives.

The present report describes the development of quantitative value tradeoffs for both the ends measures and the performance measures. First, five national value experts were interviewed to obtain value tradeoffs for units of the ends measures identified in Keeney and von Winterfeldt (1996). The results of this assessment are shown in Table S1. Second, the implied value tradeoffs for the units of the performance measures were calculated from the value tradeoffs for units of the ends measures provided by the national experts. When calculating the value tradeoffs for the units of the performance measures, very simple quantitative relationships between ends and performance measures were assumed. The results of this calculation are shown in Table S2.

The results of this report shown in Tables S1 and S2 should be considered preliminary and largely illustrative of the principles for developing value tradeoffs. The report lists several important caveats and recommendations for how future work can improve on the assessment of value tradeoffs.

Table S1: Tradeoffs for Ends Measure Units*

Ends Measure	Ends Measure Unit	Tradeoff per Unit of Ends Measure
Years of worker life lost	One Year	\$100,000
Years of worker sickness/injury	One Year	\$20,000
Years of public life lost	One Year	\$250,000
Years of public sickness/injury	One Year	\$50,000
Discharges into the Columbia River	One Major Discharge	\$5,000,000
Restricted acres - groundwater	One Acre	\$1,000
Restricted acres - perm. waste disposal	One Acre	\$5,000
Workers forced to leave the area	One Worker	\$20,000
New (non-Hanford) job created	One Job	\$25,000
Restricted acres - Native American use	One Acre	\$5,000
Disturbed religious/archeological sites	One Site	\$1,000,000
Compliance violation scale	One TPA Milestone Violation	\$2,000,000
Technology innovation scale	One technology with 100m benefits	\$7,000,000
Governmental Cost	\$1 Million	\$1,000,000

* Tradeoffs are rounded geometric averages of tradeoff elicited individually from five national experts

Table S1: Tradeoffs for Performance Measure Units**

Performance Measure	Performance Measure Unit	Tradeoff per Unit of Performance Measure
Worker Exposure, Normal Operations	1,000 person-rem	\$3,600,000
Worker Exposure, Accidents	1,000 person-rem	\$5,100,000
Public Exposure, Accidents	1,000 person-rem	\$12,600,000
Amount of HLW Shipped Off-Site	1,000 cubic meters	\$37,775,500
Time to Interim Stabilization	One Year Exceeding TPA Milestone	\$1,000,000
Time to Closure of Tanks	One Year Exceeding TPA Milestone	\$400,000
Low Level Waste Left on Site	1,000 cubic meters	\$7,620,000
Total Life Cycle Cost	\$1 million	\$650,000

** Tradeoffs were calculated using the tradeoffs in Table S1 and simple models relating performance measures to ends measures.

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1. Introduction

The Tank Waste Remediation System (TWRS) program has adopted a logical approach to making decisions that uses decision analysis to structure and analyze decision alternatives and public values to evaluate them. To incorporate public values into TWRS decision making, managers need to know how the performance of decision alternatives can be measured to reflect these values, and how to make tradeoffs, if these values are conflicting. In the past, each new decision problem required development of a new set of values and measures and assessment of a new set of tradeoffs specifically tailored to this problem.

Given the similarity between TWRS decision problems, this "re-invention" of public values is not very practical. Therefore, the TWRS program initiated an effort to develop a consistent set of public values, associated measures, and value tradeoffs that could be used as a starting point for an analysis of most TWRS decision problems.

This report is the third in a series describing the results of this effort. The first report (Armacost, von Winterfeldt, Creighton, and Robershotte, 1994) assembled a large list of public value statements from existing reports and it provided some structure to this value list. Most importantly, this report identified a set of "ends" values, that characterize the expressed ultimate goals and desires of Hanford decision makers and stakeholders.

The second report (Keeney and von Winterfeldt, 1996) developed operational measures for these ends objectives. Realizing that it is often hard to actually provide estimates on these measures, this report also provided a set of "performance measures" that more directly relate how well a decision alternative in the TWRS program achieves its objectives. To bridge the gap between performance measures and ends measure, the report also drew qualitative relationships between the two types of measures.

The present report describes the development of quantitative value tradeoffs for both the ends measures and the performance measures. First, five national "value" experts were interviewed to obtain value tradeoffs for units of the ends measures identified in Keeney

and von Winterfeldt (1996). Second, the implied value tradeoffs for the units of the performance measures were calculated from the value tradeoffs for ends measures provided by the national experts. When calculating the value tradeoffs for units of the performance measures, simple quantitative relationships between ends and performance measures were assumed.

This report is organized as follows. In the Section 2, the ends and performance measures and their qualitative relationships are briefly reviewed, following Armacost et al. (1994) and Keeney and von Winterfeldt (1996). Section 3 describes the process and results of interviews with five national value experts to develop value tradeoffs for units of the ends measures. Section 4 describes the logic and results of developing value tradeoffs for the performance measures. Section 5 discusses the uses and limitations of the tradeoffs presented in this report for TWRS decision making.

2. Public Values and Measures

The main result of the report by Armacost et al. (1994) was a list of ends objectives that reflected the ultimate concerns of decision makers, the public, and specific stakeholders with Hanford clean-up. These ends objectives are:

- Protect public/worker health and safety
- Protect the Columbia River
- Protect the environment
- Enable future use options to occur
- Capture economic development locally
- Protect rights of American Indians
- Ensure compliance
- Enhance technology development
- Reduce cost

Keeney and von Winterfeldt (1996) developed a list of measures that operationalize the meaning of these ends objectives. The purpose of these measures is to communicate to TWRS managers and engineers how to practically interpret the fairly general statements of values and concerns in the above list. Table 1 shows the list of ends objectives and the proposed ends measures.

It is not easy to estimate the achievement of a given set of TWRS alternatives on some of these ends measures. For example, it is very difficult to estimate the long term public health effects of leaving low level waste on the Hanford Site. It is much easier to estimate the type and amount of waste left on site, which will be the major cause of potential long term health effects. Similarly, it is quite difficult to estimate the employment impacts of Hanford operations over the next 50 years, but it is much easier to estimate government expenditures at Hanford, which is the contributor to employment. To facilitate the ease of measurement, Keeney and von Winterfeldt proposed the use of a set of "performance measures" which have direct causal relationships to the ends measures, and which are much easier to measure.

The proposed performance measures are:

- Worker exposure, normal operations (in person-rem)
- Worker exposure, accidents (in person-rem)
- Public exposure, accidents (in person-rem)
- Amount of high level waste (HLW) shipped off site (in cubic meters)
- Amount of low level waste (LLW) left on site (in cubic meters)
- Time to interim stabilization (in years)
- Time to closure of tanks (in years)
- Total lifecycle cost (in 1996 dollars)

The performance measures are causally related to the ends measures. Figure 1 shows these relationships in a qualitative influence diagram. To interpret the figure, consider a

Table 1: ENDS OBJECTIVES AND MEASURES FOR TWRS DECISIONS

ENDS OBJECTIVES

ENDS MEASURES

Protect public/worker health and safety

Years of worker-life lost
Years of worker sickness or injury serious enough to miss work
Years of public-life lost
Years of public sickness or injury serious enough to miss work

Protect the Columbia River

Number of incidents at which a discharge into the Columbia River exceeds clean water standards

Protect the environment

Acres of Hanford restricted because of groundwater contamination

Enable future use options

Acres of Hanford permanently allocated for waste disposal

Capture economic development locally

Number of workers forced to leave area
Number of new (non Hanford cleanup) jobs created

Protect rights of the Native Americans

Acres of Hanford not available for Native American use
Number of disturbed and/or inaccessible religious or archaeological sites

Ensure compliance

Compliance scale

Enhance technology development

Technology innovation scale

Reduce cost

Net cost of clean up to the government (discounted dollars)

Figure 1: Relationships Between Performance Measures and Ends Measures

TWRS alternative that produces 350,000 cubic meters of LLW that are left on site. This low level waste may have possible impacts on the water quality of the Columbia River, expressed as the ends measure "Exceedances of clean water standards". It may also have impacts on the groundwater, expressed as the ends measure "Restricted acres for groundwater use." The LLW may also have implications on public health, through a path of LLW performance, long term public exposure, ending in the ends measures "Years of public lives lost" and "Years of public injury or illnesses". Since the LLW disposal takes land, it will affect the ends measure "Acres available for Native American use" and possibly on "Disturbed religious or archaeological Sites". The amount of LLW will have ends measures implications on "Compliance" and "Technology Innovation".

Not every performance measure has such complicated relationships to ends measures. For example, the amount of HLW shipped off site may affect, through high-level waste performance, long term public exposure and thereby the ends measures "Years of public lives lost" and "Years of public injury or illnesses." The amount of HLW also has implications, through shipping accidents, on all four ends measures related to public and worker health and safety. In addition, the amount of HLW shipped will have some implications on compliance and technology innovation.

Several performance measures have only one major implication on ends measures, e.g. "Time to closure of tanks" which is only related to "Compliance." Note that Figure 1 only draws those relationships from performance measures to the ends measures that are required to determine an alternative's performance on the ends measures. For example, the amount of HLW has significant cost implications as well as the others mentioned above. However, cost is already accounted for by mapping a direct relationship between the TWRS alternative and total lifecycle cost.

As stated above, working with performance measures is typically much easier and more straightforward than working with ends measures. There is, however, one major complication: It is not at all clear, how to assess tradeoffs among the performance measures. For example, what is an appropriate answer to the question: "Should a

decision maker prefer to eliminate 1000 cubic meters of LLW or to eliminate 1000 rems of worker exposure due to accidents?" Similarly, "Should a decision maker prefer to reduce the time to closure of tanks by 1 year or to eliminate 100 cubic meters of HLW?" The reason why these questions are difficult - perhaps even impossible - to answer directly is because the respondent would have to have a complete mental model of all the causal relationships of how the performance measures affect the ends measures. As a result, it is difficult to develop an appropriate model of the tradeoffs among performance measures when evaluating TWRS alternatives.

Obtaining tradeoffs for the ends measure is, in contrast, a relatively easy task. For example, many people would agree that a year of public life lost is more important than a year of a worker life lost, because members of the public are, in a sense, "innocent bystanders", while workers take the risks knowingly and with some compensation for taking them. Even if people do not agree with this value judgment, they would find ways to reason about it, e.g., by arguing that a life is a life and that it should not matter whether the person is a worker or a member of the public.

Since tradeoffs for ends measures can be obtained more easily than tradeoffs for performance measures, it should be possible to first assess tradeoffs for the ends measures and then calculate back the "implied" tradeoffs for the performance measures. For example, assume that one values the loss of one year of a worker life to be equivalent to the loss of \$100,000. Further, assume that 1000 rems statistically cause the loss of a worker life, which, on average means losing 30 years of expected life. Then the 1000 rems should be valued the same as the loss of \$3,000,000.

It is important to point out that for the purpose of these backward calculations of tradeoffs, one does not need to know the complete functional relationship between the performance measure and the ends measures. Assuming that the relationships are reasonably linear, it is sufficient to know the relationships at two points. Since zero impact on the performance measure means zero impact on the ends measures for all relationships, it is sufficient to find one point, e.g. how one unit on the performance

measures translates into one unit on the ends measures. When a single performance measure affects many ends measures, it is usually reasonable to simply add the units across the ends measures.

To determine the tradeoffs for performance measures, four steps are therefore required:

1. Determine unit tradeoffs for the ends measures.
2. Determine how many units of the ends measure results from one unit of the performance measure.
3. Multiply this number of units of the ends measure times the unit tradeoff of the ends measure to determine the contribution to the unit tradeoff of the performance measure to that ends measure.
4. When the performance measure leads to consequences in terms of several ends measures, repeat steps 1-3 and add up the resulting contributions to obtain the unit tradeoff for the performance measure.

Step 1 is an important result in and by itself. The process of developing these unit tradeoffs for ends measures and the results are described in the next section, followed by a description of the calculation of the tradeoffs for the performance measures (steps 2 to 4).

3. Development of Value Tradeoffs for Ends Measures

Value tradeoffs for the fourteen ends measures were obtained in five separate interviews with nationally known experts who have thought hard about appropriate value tradeoffs for public decisions and who also have substantial knowledge about risk and environmental issues. The experts were:

David Bell, Professor, Harvard Business School

John Garrick, President, Pickard, Lowe and Garrick

Warner North, Senior Vice-President, Decision Focus, Inc.

Howard Raiffa, Professor Emeritus, Harvard Business School

Christopher Whipple, Vice President, ICF Clement Associates

Three of these experts have been involved in work at Hanford. All of them have worked on major National Research Council Committees, and three have been members of the Council's Board on Nuclear Waste Management. While it is certainly desirable to increase the number of experts in this exercise as well as to involve non-experts, obtaining value tradeoffs from these nationally known experts is a reasonable starting point for developing a set of baseline value tradeoffs.

The interviews were conducted by the authors, both separately (three interviews) and jointly (two interviews). The interviews typically lasted between one and one-half hours and two hours. The interviewer first introduced the purpose of the tradeoff elicitation and showed the expert the list of ends measures for which tradeoffs were to be assigned. The interviewer also explained that the result of the assessment should be a set of tradeoffs expressed as equivalent dollar costs per unit of the ends measure. While this was always the end result of the interview, the actual tradeoff questions did not always directly ask for an answer to the question "How much money should society spend for a reduction of one unit of the ends measure?" Instead, in many cases, tradeoffs between non-monetary ends measures were established and the results were then used to calculate the implied unit cost tradeoffs.

To provide the expert with a perspective when making tradeoffs, the interviewer emphasized that these tradeoffs should be prescriptive, i.e., they should reflect how the expert thought society should allocate its resources, not how specific organizations do allocate resources. One expert provided answers in terms of "politically appropriate" tradeoffs which accounts for some differences between the tradeoffs that he would have considered more reasonable for society as a whole. In other cases, specific ends values,

especially those related to compliance and standards evoked spirited discussions about the appropriate tradeoffs. In all cases, these discussions were incorporated into the interview summary, so that both the ambivalence of the experts, the ranges of answers and the reasoning for different answers could be recorded. In addition, the interviewer asked for and recorded information that the expert would find useful in providing more informed answers to the tradeoff questions.

It is important to note that the intent of these interviews was to obtain a first-cut idea of appropriate value tradeoffs and suggestions to improve them. Hence, the discussion did not include an in-depth probing for the basis of expressed values nor did it include a complete set of consistency checks. The probing was more about what information would be useful to guide the values assigned and it involved a few selected consistency checks.

Tables 2 through 6 provide the results of the individual interviews. To illustrate the results, consider Table 2 with the tradeoffs of expert A. This expert felt more comfortable with assessing value tradeoffs for years of worker sickness than for years of life loss. He assumed that all costs of sickness were paid for by insurance and that the worker would continue to draw a salary from the employer during the leave. He then directly assigned a value tradeoff of \$10,000 per year of worker sickness, based on his assessment of a fair compensation for a worker for one year of illness. The expert also felt that one year of worker life lost was 10 times more important than one year of worker sickness. This led him to assign a value of \$100,000 to one year of worker life lost. The expert also considered one year of public life lost or one year of public sickness to be somewhat more important than those of workers. By assigning a 30% higher value, he arrived at the corresponding tradeoffs of \$130,000 per year of public life lost and \$13,000 per year of public illness or injury.

Many of the other value tradeoffs of this expert are explained in column 3 of Table 2. A few of these tradeoffs need more explanation. The expert assigned a high value tradeoff

Table 2. Results of Preliminary Value Elicitation with Expert A

1. Unit of Ends Measure	2. Value Tradeoff	3. How Value Tradeoff was Determined	4. Useful Information
X_1 = year of worker-life lost	\$100,000	1 year of life lost for worker equivalent to 10 years of sickness.	What is the age of workers who die?
X_2 = year of worker sickness or serious injury	\$10,000	Direct assessment assuming that sick workers are financially compensated by insurance.	Are sick workers compensated? How and how much?
X_3 = year of public-life lost	\$130,000	A public life-year is weighted 1.3 times a worker life-year in X_1 .	What is the age of people who die?
X_4 = year of public sickness or serious injury	\$13,000	A public year of sickness is weighted 1.3 times a worker year of sickness in X_2 .	Are sick members of the public compensated? How and how much?
X_5 = a discharge into the Columbia River that exceeds clean water standards	\$30,000,000	Direct assessment assuming there are no consequences to human health, but there are consequences to fish, agricultural uses of water, and psychological impacts that cause human effects. Checks indicated this is equivalent to 300 years of worker life-lost and 600 acres permanently restricted because of waste storage.	<ul style="list-style-type: none"> • A description of the discharge. • A description of the full consequences of the discharge.
X_6 = An acre of Hanford restricted because of groundwater contamination	\$50,000	Tradeoff set equal to acre value for X_7 .	
X_7 = An acre of Hanford permanently allocated for waste disposal	\$50,000	Direct assessment assuming there would always be at least one acre for storage. Hence, this value tradeoff neglected the 'existence of waste' value of eliminating that last acre.	The potential uses of the land, value of their uses, and the number of individuals interested in the uses.
X_8 = A worker forced to leave the area	\$10,000	The assessment assumes that the move provides an equivalent job. Value tradeoff is set equal to a year of worker sickness of X_2 .	Describe clearly the scenario that is meant by a worker forced to leave the area.

Table 2, continued

X₉ = A new (non-Hanford cleanup) job created	\$8,000	Direct assessment assuming this is slightly less important than a worker forced to leave the area in X ₈ .	Be specific about the details of the job created.
X₁₀ = One acre of Hanford not available for Native American use	\$10,000	Direct assessment assuming this is an acre not available accounted for in X ₆ or X ₇ . The value tradeoff assumes this acre is of interest to Native Americans, so the group of individuals not able to use the acre is larger than otherwise would be the case. Assumes acre is not a special site. The value is much less than the restriction of an acre because of groundwater contamination, as it is on top of that value.	The Native Americans should be asked these tradeoffs. Information about their reasoning would be useful. How many areas of Hanford are of interest to Native Americans? Why are these of interest?
X₁₁ = One disturbed or inaccessible religious or archeological site important to the Native Americans	\$100,000	Direct assessment plus logical check that the value is equivalent to 10 acres of X ₁₀ . Assessment assumed less than 10 such sites exist and each is at most a few acres in size.	What are the sites? How many? What size? Obtain Native American value judgments on this.
X₁₂ = One violation of the Clean Water Act	\$100,000	Direct assessment based on importance of showing respect for the law. This assumed that the violation was not intended, but that it would be publicly known that the violation occurred.	What is the legal liability for a violation? What consequences are assumed to result? Are there prison terms or fines?
X₁₃ = \$1,000 life-cycle cost	\$1,000	Simple reasoning	

(\$30 million) to a discharge into the Columbia River, X_{11} , but he was unsure about the nature of the discharge. He made the assumptions that the discharge had no health effects, although there might be some effects on the flora and fauna, and the discharge might create fears and other psychological effects on people. He would assign higher tradeoffs, if the violation had health impacts, if programs would be delayed, fines imposed, etc.

Expert B's tradeoffs and the reasoning behind them are quite straightforward (see Table 3). He assigned large value tradeoff (\$1 million) for one disturbed or inaccessible religious or archaeological site important to Native Americans. When making this tradeoff, he assumed that the site was significant, and that it would cost about \$1 million to avoid impacting the site (e.g., by re-routing a planned road). He also assigned a very large value tradeoff (\$100 million) to avoid one compliance violation, which he defined as one violation of a major Tri-Party Agreement (TPA) milestone (notice that this is a somewhat different definition of the unit for this measure than expert A's). His reasoning was that the management of the TWRS program would probably be willing to spend a significant amount of money to avoid such a violation, perhaps as much as 10-25% of their annual budget. Expert B was one of the two experts (the other one being expert E), who assigned a tradeoff to technology benefits. He stated that the "spin-off" benefits from technologies are often highly exaggerated, especially for specialized technologies like those involved in Hanford clean-up. He therefore assigned a value of about 10% of the direct benefits to the benefits of technology transfer and spin offs.

The issue of the proper definition of a unit for performance measure X_5 (discharges into the Columbia River exceeding the clean water standard) came up again with expert C (Table 4), who felt that the value tradeoff would depend tremendously on the nature of the discharge. At one extreme, if there were serious consequences, he would assign as much as \$20 billion to this discharge. If, on the other hand, the discharge was not serious, he would assign a value tradeoff of only \$1 million. Since the spirit of the performance measure is to capture the latter event (the former being captured in the health measures), the lower tradeoff was carried further into the analysis.

Table 3. Results of Preliminary Value Elicitation with Expert B

1. Unit of Ends Measure	2. Value Tradeoff	3. How Value Tradeoff was Determined	4. Useful Information
X_1 = year of worker-life lost	\$100,000	Started with \$1 to \$10 million per worker life, with 30 remaining years of average life expectancy, leaning towards the lower end, e.g., \$3 million	What is the implied value of a worker life for OSHA regulations of accident risks?
X_2 = year of worker sickness or serious injury	\$30,000	Considers lost time, lost productivity and pain and suffering. About \$3K for one month.	Statistics for the cost of lost productivity and for compensation for pain and suffering?
X_3 = year of public-life lost	\$300,000	A public life-year is weighted 3 times a worker life-year in X_1 .	
X_4 = year of public sickness or serious injury	\$90,000	A public year of sickness is weighted 3 times a worker year of sickness in X_2 .	
X_5 = a discharge into the Columbia River that exceeds clean water standards	\$5,000,000	Direct assessment assuming a major discharge, but no consequences to human health. Includes the precursor and signal concerns with such an event and considers actions to remediate.	<ul style="list-style-type: none"> • cost of remediation • percentage of Ci in spill relative to site
X_6 = An acre of Hanford restricted because of groundwater contamination	\$1,000	Only loss of use is drilling and drinking local groundwater, otherwise use real estate value.	Real estate value
X_7 = An acre of Hanford permanently allocated for waste disposal	\$20,000	Ten times the value of an acre not accessible to Native American use, because of permanent restriction	
X_8 = A worker forced to leave the area	\$20,000	Compensation for 6 months of lost wages and work and replacement cost.	Replacement cost for an average Hanford worker.

Table 3, continued

X₉ = A new (non-Hanford cleanup) job created	\$20,000	Assumed to be of same value as avoiding to force a worker to leave the area	.
X₁₀ = One acre of Hanford not available for Native American use	\$2,000	Double the value of an acre with restricted use due to groundwater contamination, as long as it is just another acre of land and has no special significance to the Native Americans	
X₁₁ = One disturbed or inaccessible religious or archeological site important to the Native Americans	\$1,000,000	Assumes a significant site, based on avoidance cost. Could be as low as \$100,000 and as high as \$10 million, depending on the significance of the site	How significant is the site?
X₁₂ = One violation of a major TPA milestone	\$100,000,000	25% of the TWRS budget to avoid missing the interim stabilization milestone. Could be as low as 10 million and as high as one year's budget (400 million)	How important is the violation?
X₁₃ = One major new technology with direct benefits of \$100 million	\$100,000	10% of direct value for spin-off potential, generally low for nuclear waste technologies	What are the technologies?
X₁₄ = \$1,000 life-cycle cost	\$1,000	Simple reasoning	

Table 4. Results of Preliminary Value Elicitation with Expert C

1. Unit of Ends Measure	2. Value Tradeoff	3. How Value Tradeoff was Determined	4. Useful Information
X_1 = year of worker-life lost	\$200,000	1 year of life lost for public is 2.5 times as significant as a year of life lost for worker. The main difference is the voluntary acceptance of risk.	What is the age of workers who die?
X_2 = year of worker sickness or serious injury	\$40,000	As above, a public year of sickness is 2.5 times as important as a worker year of sickness.	How and how much are sick workers compensated? What are the injuries and sicknesses and the proportions of each?
X_3 = year of public-life lost	\$500,000	Direct assessment, somewhat higher than would be assigned to non-nuclear related statistical fatalities.	What is the age of people who die?
X_4 = year of public sickness or serious injury	\$100,000	Averaged over seriousness of the sickness or injury; assessed as 20% of a year of public life lost	What are the injuries and sicknesses and the proportion of each?
X_5 = a discharge into the Columbia River that exceeds clean water standards	\$20,000,000 (Serious discharge) \$1,000,000 (Not serious)	Value tradeoff is very dependent on the nature of the discharge. A serious discharge is where radionuclides are discharged that bioaccumulate in the food chain. As a result 1000 statistical fatalities occur with doses not recognized. The value tradeoff is \$5 billion for the 1000 statistical fatalities (as they are not counted in X_3) and \$15 billion for the stigma. A not serious discharge is pollutants that readily degrade in a few hours (i.e., short half-life). The value tradeoff is \$1 million	Details about the discharge are needed. What are the consequences of the discharge on humans and animals? What are the subsequent changes in behavior.
X_6 = An acre of Hanford restricted because of groundwater contamination	\$125	Groundwater contamination assumed to mean no surface exposure. Value tradeoff is 5% of an X_7 acre.	Clarify the restriction of surface uses due to any groundwater contamination.
X_7 = An acre of Hanford permanently allocated for waste disposal	\$2,500	Define permanent as for at least 1000 years. Assumes location is not directly at the Columbia River. Assumes site chosen is an old reactor site or a good new site for disposal. Values at approximately \$1.5 million per square mile.	What is the cost to acquire National Park land? This would provide an upper bound.
X_8 = A worker forced to leave the area	\$40,000	The realities of our economy is that some people need to move to find jobs. Assumes 6 months without job, but with social benefits.	How long is the worker forced to leave the area without a job?

Table 4, continued

X₉ = A new (non-Hanford cleanup) job created	\$20,000	Direct assessment assuming this is less important than a worker forced to leave the area in X ₈ . Must consider other federal investments to create jobs and maintain equity.	Clarify whether jobs created are permanent. How much does it cost to create jobs in other fields and areas?
X₁₀ = One acre of Hanford not available for Native American use	\$2,500	Direct assessment assuming land not available permanently and that a treaty with the tribe is violated by not returning the land for Native American use.	Clarify the specific interests and claims of the Native Americans.
X₁₁ = One disturbed or inaccessible religious or archeological site important to the Native Americans	\$100,000,000 (Currently undisturbed) \$5,000,000 (Previously disturbed)	Value tradeoff depends substantially on the type of disturbance. High value tradeoff is for a currently undisturbed, low value tradeoff is for previously disturbed site. Both cases are for sites that are of special significance, not just a location where ancestors once walked.	What are the sites? How many? Indicate why each is significant. Are they undisturbed?
X₁₂ = One violation of a major compliance agreement of regulation	\$15,000,000	Assumes a violation of a TPA. The value of the TPA is because it preeomotes the maintaining of an open negotiation process and one where citizens can participate. Direct assessment mainly due to the public participation aspect.	What is the legal liability for a violation? What consequences are assumed to result? Are there prison terms or fines?
X₁₃ = \$1,000 life-cycle cost	\$1,000	Simple reasoning	

Similar reasoning led this expert to assign a range of value tradeoffs to the religious or archeological site important to Native Americans. At the high end, he considered a value tradeoff of \$100 million to be appropriate, if the site was currently undisturbed and significant. A site that had been previously desecrated, on the other hand, would have a much lower value tradeoff (\$5 million).

Expert D (Table 5) made a distinction between what he felt were appropriate tradeoffs from a prescriptive societal perspective, and what he thought were politically appropriate tradeoffs. Here we report only the latter, noting that in several cases the prescriptive tradeoffs were significantly lower than the politically appropriate ones. His assessment of \$93.75 for an acre of restricted ground water use was based on an assessment of \$12,000 per square mile. All other tradeoffs were quite straightforward and are explained in column 3 of Table 5.

Expert E's tradeoffs are explained in column 3 of Table 6. He also stated that the spin-off benefits of a major technology should be counted as a percentage of the direct benefits. He assigned \$50,000 to the spin-off and technology transfer benefit of one major technology with significant direct benefits to Hanford. However, "significant direct benefits" were not further defined in the interview. He also stated that it would be reasonable to assign the technology spin off and transfer benefit to be a percentage of the direct benefits, but did not state any specific percentage. Assuming that significant direct benefits are \$1 million, the assigned tradeoff of \$50,000 implies a 5% transfer and spin-off benefit, or \$5 million for a technology with \$100 million direct benefits.

Table 7 summarizes the results of the assessments of value tradeoffs of the five experts. The last column of Table 7 shows the rounded geometric average value tradeoff across the five experts. The experts show substantial agreement on many value tradeoffs, especially those concerning health and safety (X_1 to X_4), jobs lost or created (X_8 and X_9), acres restricted for Native American use (X_{10}), and technology benefits (X_{13}).

Table 5. Results of Preliminary Value Elicitation with Expert D

1. Unit of Ends Measure	2. Value Tradeoff	3. How Value Tradeoff was Determined	4. Useful Information
X_1 = year of worker-life lost	\$100,000	1 year of life lost for worker equivalent to 10 years of sickness.	What is the age of workers who die?
X_2 = year of worker sickness or serious injury	\$10,000	Direct assessment assuming that sick workers are financially compensated by insurance.	Are sick workers compensated? How and how much?
X_3 = year of public-life lost	\$130,000	A public life-year is weighted 1.3 times a worker life-year in X_1 .	What is the age of people who die?
X_4 = year of public sickness or serious injury	\$13,000	A public year of sickness is weighted 1.3 times a worker year of sickness in X_2 .	Are sick members of the public compensated? How and how much?
X_5 = a discharge into the Columbia River that exceeds clean water standards	\$30,000,000	Direct assessment assuming there are no consequences to human health, but there are consequences to (fish, agricultural uses of water, and psychological impacts that cause human effects. Checks indicated this is equivalent to 300 years of worker life-lost and 600 acre permanently restricted because of waste storage.	<ul style="list-style-type: none"> • A description of the discharge. • A description of the full consequences of the discharge.
X_6 = An acre of Hanford restricted because of groundwater contamination	\$50,000	Tradeoff set equal to acre value for X_7 .	
X_7 = An acre of Hanford permanently allocated for waste disposal	\$50,000	Direct assessment assuming there would always be at least one acre for storage. Hence, this value tradeoff neglected the 'existence of waste' value of eliminating that last acre.	The potential uses of the land, value of their uses, and the number of individuals interested in the uses.
X_8 = A worker forced to leave the area	\$10,000	The assessment assumes that the move provides an equivalent job. Value tradeoff is set equal to a year of worker sickness of X_2 .	Describe clearly the scenario that is meant by a worker forced to leave the area.

Table 5, continued

X₉ = A new (non-Hanford cleanup) job created	\$8,000	Direct assessment assuming this is slightly less important than a worker forced to leave the area in X ₈ .	Be specific about the details of the job created.
X₁₀ = One acre of Hanford not available for Native American use	\$10,000	Direct assessment assuming this is an acre not available accounted for in X ₆ or X ₇ . The value tradeoff assumes this acre is of interest to Native Americans, so the group of individuals not able to use the acre is larger than otherwise would be the case. Assumes acre is not a special site. The value is much less than the restriction of an acre because of groundwater contamination, as it is on top of that value.	The Native Americans should be asked these tradeoffs. Information about their reasoning would be useful. How many areas of Hanford are of interest to Native Americans? Why are these of interest?
X₁₁ = One disturbed or inaccessible religious or archeological site important to the Native Americans	\$100,000	The value is equivalent to 10 acres of X ₁₀ . Assessment assumed less than 10 such sites exist and each is at most a few acres in size.	What are the sites? How many? What size? Obtain Native American value judgments on this.
X₁₂ = One violation of the Clean Water Act	\$100,000	Direct assessment based on importance of showing respect for the law. This assumed that the violation was not intended, but that it would be publicly known that the violation occurred.	What is the legal liability for a violation? What consequences are assumed to result? Are there prison terms or fines?
X₁₃ = \$1,000 life-cycle cost	\$1,000	Simple reasoning	

Table 6. Results of Preliminary Value Elicitation with Expert E

1. Unit of Ends Measure	2. Value Tradeoff	3. How Value Tradeoff was Determined	4. Useful Information
X_1 = year of worker-life lost	\$40,000	Started with \$.5 to \$1 million per worker life, with an average of 25 years of remaining life expectancy, used \$ 1 million	Nature of exposure; identifiability of fatality; programmatic impacts?
X_2 = year of worker sickness or serious injury	\$13,000	Assumes that worker is fully compensated and that risks are pooled; valued at 1/3 of a year of a worker life lost.	Seriousness of sickness, length of sickness for an individual?
X_3 = year of public-life lost	\$125,000	Started with \$5 million/life lost for member of public using a multiplier of 5 on X_1 . Also, assumed 40 years of remaining life expectancy in public instead of 25 years for workers.	
X_4 = year of public sickness or serious injury	\$40,000	A year of public sickness or serious injury was valued at 1/3 of a year of public life lost.	
X_5 = a discharge into the Columbia River that exceeds clean water standards	\$5,000,000	Direct assessment assuming a major discharge, but no consequences to human health. Further assumes that there are some, if minor effects on river and river uses. Could be as low as 0 and as high as tens of millions, depending on size of spill.	<ul style="list-style-type: none"> • effect on river uses? • significance of the spill? • source of the spill (e.g., K basin)? • Programmatic impacts?
X_6 = An acre of Hanford restricted because of groundwater contamination	\$2,000	Considers very long term restrictions, similar to the permanent allocation in X_7	How long will the contamination last?
X_7 = An acre of Hanford permanently allocated for waste disposal	\$2,000	Assumes land value of about \$2,000/acre and that there already are other areas that are permanently allocated for waste disposal	
X_8 = A worker forced to leave the area	\$20,000	Compensation for 6 months of lost wages moving expenses	What are the ripple effects and social costs of losing a worker from the area?

Table 6, continued

X₉ = A new (non-Hanford cleanup) job created	\$20,000	Assumed to be of same value as avoiding to force a worker to leave the area	
X₁₀ = One acre of Hanford not available for Native American use	\$10,000	Assumes that this is an "ordinary" acre of Hanford and that Native American Indians are able to use this land for fishing, hunting and gathering. Five times an acre that is of no interest to the Native American Indians.	
X₁₁ = One disturbed or inaccessible religious or archeological site important to the Native Americans	\$1,000,000	Assumes a significant site that is currently disturbed. Main considerations were the costs of remediation of this site.	How significant is the site?
X₁₂ = One violation of a major compliance agreement or regulation	\$1,000,000	Assumes a real compliance problem with State enforcement and fines. Considered mainly the equivalent cost of programmatic impacts	Is this a violation of an important regulation or agreement?
X₁₃ = One major new technology	\$50,000	Should be counted as a percentage of the direct benefits as "spin-off" benefits	What is the technology and what is the value of its direct benefits?
X₁₄ = \$1,000 life-cycle cost	\$1,000	Simple reasoning	

TABLE 7: SUMMARY OF VALUE TRADEOFFS FOR UNITS OF ENDS MEASURES

Ends Measure Unit	Tradeoff Made by Expert					Rounded Geometric Mean
	A	B	C	D	E	
X1: Year of worker life lost	\$100,000	\$100,000	\$200,000	\$100,000	\$40,000	\$100,000
X2: Year of worker sickness/injury	\$10,000	\$30,000	\$40,000	\$10,000	\$13,000	\$20,000
X3: Year of public life lost	\$130,000	\$300,000	\$500,000	\$500,000	\$125,000	\$250,000
X4: Year of public sickness/injury	\$13,000	\$90,000	\$100,000	\$50,000	\$40,000	\$50,000
X5: Discharge into the Columbia River	\$30,000,000	\$5,000,000	\$1,000,000	\$3,000,000	\$5,000,000	\$5,000,000
X6: Restricted acre - groundwater	\$50,000	\$1,000	\$125	\$94	\$2,000	\$1,000
X7: Restricted acre - perm. waste disposal	\$50,000	\$20,000	\$2,500	\$156	\$2,000	\$5,000
X8: A worker forced to leave the area	\$10,000	\$20,000	\$40,000	\$25,000	\$20,000	\$20,000
X9: A new (non-Hanford) job created	\$8,000	\$20,000	\$20,000	\$100,000	\$20,000	\$25,000
X10: Restricted acre - Native American use	\$10,000	\$2,000	\$2,500	\$25,000	\$10,000	\$5,000
X11: Disturbed religious/archeological site	\$100,000	\$1,000,000	\$5,000,000	\$2,500,000	\$1,000,000	\$1,000,000
X12: Major compliance violation	\$100,000	\$100,000,000	\$15,000,000	\$100,000	\$1,000,000	\$2,000,000
X13: Technology with \$100m benefits	n.a.	\$10,000,000	n.a.	n.a.	\$5,000,000	\$7,000,000
X14: \$1,000 Life Cycle Cost	\$1,000	\$1,000	\$1,000	\$1,000	\$1,000	\$1,000

On the other measures, the experts tradeoffs show fairly large differences. First, regarding discharges in the Columbia River, the high value tradeoff by expert A (\$30 million) is 30 times higher than the low value tradeoff. This probably reflects differences in the scenarios of this discharge that the experts assumed rather than differences in values. Second, there is a fair amount of disagreement on how to value a restricted acre (X_6 and X_7). It appears that the experts that assigned low value tradeoffs (C and D) thought primarily of the commercial value of the land, while the experts that had high value tradeoffs thought more of intrinsic values and possibly the concerns that would be raised with these restrictions. There also are significant differences on the value tradeoff for a disturbed religious or archeological site with tradeoffs ranging from \$100,000 to \$5,000,000. These differences seems to reflect differences in the assumptions about the significance of the site rather than true value differences (recall that one expert would increase his tradeoff to \$100 million, if the site was truly significant and previously undisturbed). The large range of value tradeoffs for a compliance violation is similarly due to different assumptions about the nature of the violation.

Overall, the rounded geometric averages appear to be a very reasonable starting point for a base case value analysis. With additional work on clarifying the definitions of several performance measures and their units, it should be possible to obtain closer agreement among experts.

4. Development of Value Tradeoffs for Performance Measures

The general logic of calculating tradeoffs for performance measures from tradeoffs for ends measures was explained in Section 2. The specific calculations can best be explained with the example results in Table 8. In this table the value tradeoff for one unit (1000 person-rem) of the performance measure "Worker Exposure, Normal Operations" is calculated. Recall that this performance measure is related to three ends measures:

TABLE 8: MATCHING ENDS MEASURES (EMs) AND PERFORMANCE MEASURES (PMs)

PERFORMANCE MEASURE: Worker Exposure, Normal Operations
PERFORMANCE MEASURE UNIT (PMU): 1000 Person-rem

ENDS MEASURE	EMU (Ends Measure Unit)	EMU per PMU (Perf. Measure Unit)	Assumptions	Tradeoff per EMU	Tradeoff per PMU
Years of Worker-Lives Lost	1 Year	30	1000 Rems = 1 Fatality; 1 Fatality = 30 Life-Years Lost	\$100,000	\$3,000,000
Years of Worker Sickness or Injury	1 Year	25	1000 Rems = 5 Illnesses; 1 Illness = 5 Years of Illness	\$20,000	\$500,000
Compliance	Violation of a Major TPA Milestone	5.00%	1 exceedance of worker exposure standard per 5,000 rem of exposure; 1 violation of worker standard = 25% severity of a TPA violation	\$2,000,000	\$100,000
VALUE TRADEOFF PER PMU (1000 person-rem)					\$3,600,000

1. Years of worker lives lost
2. Years of worker sickness or injury
3. Compliance (measured in percent of a violation of a major TPA milestone)

First, implied tradeoffs for the performance measure unit (PMU = 1000 rems) are calculated from the expressed tradeoffs for each of the three ends measure units (EMUs). For years of worker lives lost, the EMU is one year (column 2 of Table 8). Assuming that 1000 person-rems is equivalent to one statistical fatality, and that one worker fatality reduces the average life expectancy by 30 years, 1000 person-rems cause 30 lost worker years to be lost. This result is shown in column 3 of Table 8 labelled EMU per PMU. Now all one has to do is multiply the value tradeoff for the PMU (\$100,000 per lost year) by the EMU/PMU ratio (30) to obtain the equivalent value tradeoff for one PMU unit (\$3,000,000).

A similar reasoning is applied to the second ends measure (years of worker sickness or injury) that is affected by the 1000 rems. Here we assumed that 1000 person-rems cause five cancer illnesses, and that each of these illnesses lasts five years - without leading to death. As a result, the EMU/PMU ratio is 25, and the implied value tradeoff for 1000 rems of worker exposure is $25 * \$20,000 = \$500,000$.

To illustrate a quite different reasoning process, consider the third ends measure, compliance, that is affected by the performance measure of worker exposure. The unit of the ends measure is one violation of a major TPA milestone, such as the date for completion of interim stabilization. In this case we assume that a hypothetical exposure of 5000 person-rems over the life of operations would likely involve one violation of a worker standard. We further assume that this violations would be 25% as serious as violating a major TPA milestone. Thus 1000 rems would be 5% as serious as a violation of a major TPA milestone. This result is shown in column 2 of Table 8 as the EMU/PMU ratio of 5%. One violation of a major TPA milestone had a value tradeoff of

\$2,000,000. Thus, 5% of this tradeoff (\$100,000) is the contribution of compliance to the value tradeoff of a 1000 person-rem worker exposure.

The last step in this calculation is to add the three contributions to value tradeoff from the three ends measures. This results in an aggregate value tradeoff of \$3,600,000 per 1000 person-rem of worker exposure. Note that this addition assumes that the components contribute independently to the overall value tradeoff.

In spite of the many assumptions made in the calculation of the value tradeoff for worker exposure, the results are not dissimilar from studies of over a decade ago which postulated a tradeoff of \$1000 per person-rem (or \$1 million per 1000 rem). Adjusting the \$1000 per person-rem tradeoffs for inflation and including the compliance component would lead to very similar results to those in Table 8.

Tables 9 and 10 show the results of the calculation of tradeoffs for the performance measures "Worker Exposure, Accidents" and "Public Exposure, Accidents". The reasoning for the EMU/PMU ratio, which is very similar to that in the previous case, is described in the fourth columns of these tables. Notice that for accidents we assume that 40 years are lost for a fatality. This is because accidents are likely to involve higher doses and lead to a development of cancer for younger adults.

Table 11 shows the results for a more complex calculation of the value tradeoff for 1000 cubic meters of high level waste. This performance measure has implications for worker and public health and safety and technology benefits. The calculations for the work health and safety implications can best be illustrated with the impacts on years of public life lost. There are two components to this. The first is through transportation accidents. The second is due to long term radiological impacts from the nuclear waste repository over thousands of years. The Environmental Impact Statement for the Tank Waste Remediation System (TWRS-EIS, Department of Energy, 1996), as well as other risk assessments of the nuclear waste repository indicate that the public radiological impacts due to 1000 cubic meters of HLW will be minimal. They are therefore ignored in this

TABLE 9: MATCHING ENDS MEASURES (EMs) AND PERFORMANCE MEASURES (PMs)

PERFORMANCE MEASURE: Worker Exposure, Accidents
PERFORMANCE MEASURE UNIT: 1000 Person-rem

ENDS MEASURE	EMU (Ends Measure Unit)	EMU per PMU (Perf. Measure Unit)	Assumptions	Tradeoff per EMU	Tradeoff per PMU
Years of Worker-Lives Lost	1 Year	40	1000 Rems = 1 Fatality; 1 Fatality = 40 Life-Years Lost	\$100,000	\$4,000,000
Years of Worker Sickness or Injury	1 Year	50	1000 Rems = 10 Illnesses; 1 Illness = 5 Years of Illness	\$20,000	\$1,000,000
Compliance	Violation of a Major TPA Milestone	5.00%	1 exceedance of worker exposure standard per 5,000 rem of exposure; 1 violation of worker standard = 25% severity of a TPA violation	\$2,000,000	\$100,000
VALUE TRADEOFF PER PMU (1000 person-rem)					\$5,100,000

TABLE 10: MATCHING ENDS MEASURES (EMs) AND PERFORMANCE MEASURES (PMs)

PERFORMANCE MEASURE: Public Exposure, Accidents
PERFORMANCE MEASURE UNIT: 1000 Person-rem

ENDS MEASURE	EMU (Ends Measure Unit)	EMU per PMU (Perf. Measure Unit)	Assumptions	Tradeoff per EMU	Tradeoff per PMU
Years of Public-Lives Lost	1 Year	40	1000 Rems = 1 Fatality; 1 Fatality = 40 Life-Years Lost	\$250,000	\$10,000,000
Years of Public Sickness or Injury	1 Year	50	1000 Rems = 10 Illnesses; 1 Illness = 5 Years of Illness	\$50,000	\$2,500,000
Compliance	1 Violation of a Major TPA Milestone	5.00%	1 exceedance of worker exposure standard per 5,000 rem of exposure; 1 violation of worker standard = 25% severity of a TPA violation	\$2,000,000	\$100,000
VALUETRADEOFF PER EMU (1000 Person-rem)				\$12,600,000	

TABLE 11: MATCHING ENDS MEASURES (EMs) AND PERFORMANCE MEASURES (PMs)

PERFORMANCE MEASURE: Amount of High-Level Waste Shipped Offsite
 PERFORMANCE MEASURE UNIT: 1000 Cubic Meters

ENDS MEASURE	EMU (Ends Measure Unit)	EMU per PMU (Perf. Measure Unit)	Assumptions	Tradeoff per EMU	Tradeoff per PMU
Years of Worker-Lives Lost	1 Year	5.3	Transporting 15,000 cubic meters = 4 lives lost in accidents; 50% workers; 1 fatality = 40 life-years lost	\$100,000	\$533,000
Years of Worker Sickness or Injury	1 Year	13	1 fatality = 5 serious injuries 1 serious injury = 10 life-years lost	\$20,000	\$260,000
Years of Public Lives Lost	1 Year	5.3	Transporting 15,000 cubic meters = 4 lives lost in accidents; 50% public; 1 fatality = 40 life-years lost	\$250,000	\$1,332,500
Years of Public Sickness or Injury	1 Year	13	1 fatality = 5 serious injuries 1 serious injury = 10 life-years lost	\$50,000	\$650,000
Technology Innovation Benefits	One technology with \$100m direct benefits	5 major tech. with \$100m benefits each	Value of disposing of 1000 cubic meters of HLW is \$500 million; 10% savings due to tech. transfer=\$50 million	\$7,000,000	\$35,000,000
VALUE TRADEOFF PER PMU (1000 cubic meters of HLW)					\$37,775,500

calculation. However, the TWRS-EIS estimates that there will be about 4 fatalities from transportation accidents when shipping 15,000 cubic meters of waste from the Hanford site to the repository. We assume that 50% of these fatalities are members of the public and that there is an associated 40 years lives lost per fatality. Thus we have 80 years of public lives lost, divided by 15 (to normalize for 1000 cubic meters), resulting in 5.33 years of public lives lost per 1000 cubic meters of HLW. This number is recorded as the EMU/PMU ratio in column 5.33 of Table 11. The remaining calculation is to multiply this ratio with the value tradeoffs for one year of public lives lost (\$250,000) resulting in a value tradeoff for 1000 cubic meters of HLW of \$1,332,500.

The calculations for the ends measure "Technology Benefits" are somewhat different. First, reducing HLW goes hand in hand with new technology for separating the HLW component of the Hanford tank wastes. Thus the lower the HLW component, the more improved the technology is. This improvement would primarily pay off as a direct cost savings for treating and disposing the HLW. According to the value experts, about 7.0% of that direct benefit should be counted as technology transfer and spin off benefits. Using figures from the TWRS-EIS, we estimate that the cost of treatment and disposal of 1000 cubic meters of HLW is about \$500 million. Assuming further that this expense is worth the benefits, we assign a direct benefit to eliminating 1000 cubic meters of HLW of \$500 million. Since this is five times the benefit of the unit definition of the technology innovation benefit measure, the EMU/PMU ratio is 5. Multiplying this ratio with the \$7 million value tradeoff for the ends measure unit, we obtain a value tradeoff of \$35 million for 1000 cubic meters of HLW.

Similar reasoning is applied to the remaining Tables 12-15. Clearly some assumptions in these calculations are more easy to defend than others. For example the translations from rems to fatalities and illnesses is fairly straightforward. On the other hand, there are many critical assumptions that need to be examined more closely. For example, one assumption in Table 12 was that 1000 cubic meters of low level waste disposed of at the Hanford site lead to a very small (0.001) chance of causing an exceedance of a clean water standard over the life-time of the disposal. This assumption was made primarily for

TABLE 12: MATCHING ENDS MEASURES (EMs) AND PERFORMANCE MEASURES (PMs)

PERFORMANCE MEASURE:
PERFORMANCE MEASURE UNIT:

Low Level Waste Left on Site
1000 cubic meters of LLW in glass (including 48 Ci/ cubic meter)

ENDS MEASURE	EMU (Ends Measure Unit)	EMU per PMU (Perf. Measure Unit)	Assumptions	Equiv. \$ per EMU	Equiv. \$ per PMU
Exceedance of Clean Water Standard	1 Exceedance	0.001	Very small chance of exceeding standard with 1000 MT of glass	\$5,000,000	\$5,000
Area Restricted for Groundwater Use	1 Acre	100	1 acre to dispose 1000 MT = 100 acres of restricted groundwater use	\$1,000	\$100,000
Area Restricted for Disposal	1 Acre	1	1 acre to dispose 1000 MT	\$5,000	\$5,000
Area Restricted for Native American Use	1 Acre	100	About the same area as restricted for ground water use	\$5,000	\$500,000
Disturbed Religious or Archeological Sites	1 Site	0.01	10% chance that an acre used for waste disposal would include such site	\$1,000,000	\$10,000
Technology Innovation Benefits	One major techn. with \$100m direct benefits	One major techn. with \$100m direct benefits	Value of processing and disposing 1000 cubic meters of LLW is \$100 million 10% savings due to tech. transfer=\$10 million	\$7,000,000	\$7,000,000
VALUE TRADEOFF PER PMU (1000 metric tons of LLW)					\$7,620,000

TABLE 13: MATCHING ENDS MEASURES (EMs) AND PERFORMANCE MEASURES (PMs)

PERFORMANCE MEASURE: Time to Interim Stabilization
PERFORMANCE MEASURE UNIT: Years

ENDS MEASURE	EMU (Ends Measure Unit)	EMU per PMU (Perf. Measure Unit)	Assumptions	Tradeoff per EMU	Tradeoff per PMU
Compliance	1 Violation of a Major TPA Milestone	0 for < 3years .50 for each add. yr.	TPA interim stabilization milestone is 1999, exceeding it by two years is a major violation	\$2,000,000	\$0 if < 3 years, 12.5 million/yr. otherwise
VALUE TRADEOFF PER PMU (Years to Interim Stabilization)				if < 3 years otherwise	\$ 0 \$1,000,000

TABLE 14: MATCHING ENDS MEASURES (EMs) AND PERFORMANCE MEASURES (PMs)

PERFORMANCE MEASURE: **Time to Closure of Tanks**
 PERFORMANCE MEASURE UNIT: **Years**

ENDS MEASURE	EMU (Ends Measure Unit)	EMU per PMU (Perf. Measure Unit)	Assumptions	Tradeoff per EMU	Tradeoff per PMU
Compliance	1 Violation of a Major TPA Milestone	0 for < 24years .20 for each add. yr.	TPA closure milestone is 2020; exceeding it by 5 yrs. is a major violation	\$2,000,000	\$0 if < 24 years, \$5/yr. million otherwise
VALUE TRADEOFF PER PMU (YEARS (Years until Tank Closure)				if < 24 years otherwise	\$ 0 \$400,000

TABLE 15: MATCHING ENDS MEASURES (EMs) AND PERFORMANCE MEASURES (PMs)

PERFORMANCE MEASURE: Total Life Cycle Cost
 PERFORMANCE MEASURE UNIT: \$ 1 million

ENDS MEASURE	EMU (Ends Measure Unit)	EMU per PMU (Perf. Measure Unit)	Assumptions	Equiv. \$ per EMU	Equiv. \$ per PMU
Total Life Cycle Cost	\$ 1 million	1	Dollar for dollar	\$1,000,000	\$1,000,000
Workers Forced to Leave the Area	1 Worker	-5	Loss of \$1 million = loss of 5 jobs	\$20,000	(\$100,000)
New Jobs Created (Non-Hanford) or Lost	1 Job	-10	For each Hanford job gained or lost, two other jobs are created or lost	\$25,000	(\$250,000)
DOLLAR TRADEOFF PER PMU (\$ 1 Million)				\$650,000	

illustrative purposes and will need to be checked very carefully. The point of this report is not to defend every assumption and calculation in detail, but to provide an illustration of the overall approach and a starting point for further refinement.

The results of the calculations of the value tradeoffs for the performance measures are summarized in Table 16. Overall, one should have more confidence in the value tradeoffs for the ends measures (Table 7), since they were obtained directly, without making many assumptions about the relationships between performance and ends measures. Thus, we suggest that the results in Table 16 be considered as very preliminary.

5. Uses and Limitations of the Value Tradeoffs

The TWRS program has developed a systematic approach to making decisions that involves the following steps (see Robershotte et al., 1995):

- 1) Define the frame of the decision
- 2) State issues
- 3) Develop a set of alternatives
- 4) Formulate decision values
- 5) Translate decision values into a set of measures
- 6) Evaluate alternatives
- 7) Present the results to the decision body

Previous reports (Armacost et al., 1995; Keeney and von Winterfeldt, 1996) have developed values, objectives and measures to assist decision makers and specialists in steps 4 and 5. This report is to provide help in step 6. Step 6 consists of two very distinct parts. The first is the (factual) estimation of how the alternatives perform on the measures of objectives. The results of these estimations are typically summarized in an alternatives by objectives matrix. The cells in this matrix describe, in terms of the measures, how well an alternative achieves each of the objectives.

TABLE 16: SUMMARY OF TRADEOFFS FOR PERFORMANCE MEASURE UNITS

Performance Measure	Unit	Dollar Tradeoff	Normalized Weight per Unit	Notes
Worker Exposure, Normal Operations	1,000 person-rem	\$3,600,000	5.24%	
Worker Exposure, Accidents	1,000 person-rem	\$5,100,000	5.29%	
Public Exposure, Accidents	1,000 person-rem	\$12,600,000	13.06%	
Amount of HLW Shipped Off-Site	1,000 cubic meters	\$37,775,500	39.15%	
Time to Interim Stabilization	Years	\$1,000,000	1.04%	if > 3 years
Time to Closure of Tanks	Years	\$400,000	0.41%	if > 24 years
Low Level Waste Left on Site	1,000 cubic meters	\$7,620,000	7.90%	
Total Life-Cycle Cost	\$1 million	\$650,000	0.67%	

Often this summary is sufficient for decision making, for example, when it becomes clear that one alternative is best on all or almost all measures. Sometimes the implications are not so clear and difficult tradeoffs need to be made. In that case, it is useful to develop a formal evaluation model that aggregates the information about alternatives across objectives. All value models that aggregate across objectives require the use of value tradeoffs. In the past, these value tradeoffs were elicited from decision makers and, in some cases, from stakeholders, separately for each decision problem.

This report began the development of a set of tradeoffs that can consistently be applied to a variety of TWRs decisions. The report provides two sets of tradeoffs: For units of ends measures (Table 7) and for units of performance measures (Table 16). These tradeoffs should be considered preliminary, subject to further elicitations and analysis. However, they provide a starting point for building a value model and to conduct sensitivity analyses with it.

To use the tradeoffs, the analyst who supports the decision maker has to first decide whether to work with the set of ends measures or with the set of performance measures to evaluate alternatives. In most cases, this choice will depend on the available information and the resource constraints of the analysis. With less information and less resources, using performance measures is the more practical and economic choice.

The analyst then has to assemble the information about the alternatives in the form of an alternatives by objectives matrix. Making the simplifying assumption that all measures are linearly related to the overall decision value, an alternative A_j can then be evaluated by

$$C(A_j) = \sum w_i * c_i(A_j),$$

where $C(A_j)$ is the overall equivalent cost (negative value) of alternative A_j , w_i is the tradeoff for one unit of the i -th measure from either Table 7 or Table 16, and $c_i(A_j)$ is the

estimate of A_j expressed in units of the i -th measure. Subsequently, the alternatives are rank ordered in terms of overall equivalent cost, with the alternative having the lowest equivalent cost being best.

While the tradeoffs in Tables 7 and 16 are a starting point for this evaluation, several caveats need to be stated combined with suggestions for improvements. Regarding tradeoffs for ends measures:

Caveat: These tradeoffs were based on the judgments of five experts who have thought deeply about value issues, risk issues, and environmental issues. Yet, they do not necessarily represent all experts in this area and they certainly do not represent all the groups that may have an interest or stake in the implications of decisions about Hanford.

Recommendation: A broader range of experts should be involved in eliciting value tradeoffs as well as groups of non-experts. The experts themselves stated that on some issues they felt that others (e.g. Native Americans) were better judges of the value tradeoffs.

Caveat: The experts in the tradeoff elicitation often stated that they needed more information to make an informed judgment. In some cases assumptions were made to substitute for this information. The tradeoffs that we obtained are only as valid as these assumptions.

Recommendation: The measures and their units should be more clearly defined to provide a common base for making tradeoffs. Also information about the severity of some of the consequences (for example of a toxic spill into the Columbia River) should be described to assist in the tradeoff assessment.

Caveat: In some cases the experts' value tradeoffs are different because they used different assumptions and definitions.

Recommendation: A common set of definitions and assumptions should be developed to assist the tradeoff assessment.

Regarding tradeoffs for performance measures, the following caveats and recommendations are important:

Caveat: The calculations of tradeoffs for performance measures used many strong assumptions about the relationships between a performance measure and an ends measure and the results are only as valid as these assumptions.

Recommendation: These assumptions should be checked, using existing models and knowledge about the relationships between performance and ends measures. The assumptions about the relationships should be revised as appropriate.

Caveat: The calculation of tradeoffs for performance measures assumed that the overall tradeoff for a unit in a performance measure is additive across ends measures. This may not necessarily be true.

Recommendation: The additivity assumptions needs to be checked carefully with existing models and data that relate performance measures to ends measures. Revisions should be made where appropriate.

Caveat: The calculations of tradeoffs for performance measures was not independently checked against some other method for assessing tradeoffs on performance measures.

Recommendation: It would be desirable to assess tradeoffs on performance measures directly from experts and to compare and reconcile the results with the calculated ones.

6. References

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