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A METHODOLOGY FOR MAKING ENVIRONMENTAL AS LOW AS REASONABLY ACHIEVABLE (ALARA) DETERMINATIONS

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ABSTRACT

An overall evaluation concept for use in making differential cost-benefit analyses in environmental as low as reasonably achievable (ALARA) determinations is being implemented by Rockwell Hanford Operations. This evaluation includes consideration of seven categories: 1) capital costs; 2) operating costs; 3) state of the art; 4) safety; 5) accident or upset consequences; 6) reliability, operability, and maintainability; and 7) decommissionability. Appropriate weighting factors for each of these categories are under development so that ALARA determinations can be made by comparing "scores" of alternative proposals for facility design, operations, and upgrade.

This method of evaluation circumvents the traditional basis of a stated monetary sum per person-rem of dose commitment. This alternative was generated by advice from legal counsel who advised against formally pursuing this avenue of approach to ALARA for environmental and occupational dose commitments.

CONTENTS

BACKGROUND

Existing radiation protection programs are based primarily on maintaining personnel exposure and dose to the general public below federally established limits (and in many cases below somewhat more restrictive control levels established by employers). In addition, because as low as reasonably achievable (ALARA) is not a totally new concept, many radiation protection programs are already aimed at reducing occupational and environmental doses to ALARA. However, the phrase "as low as reasonably achievable" contains the philosophical concept of "reasonable" which is difficult to quantify. Currently ALARA determinations are the result of a complex and largely subjective evaluation process. A system or mechanism for making ALARA determinations in an orderly manner using qualitatively and quantitatively defensible bases is needed. For this type of assessment, most existing ALARA evaluation practices are impractical or inadequate.

Determination that a particular action is ALARA requires three distinct decisions: first, a decision must be made as to which situations or designs are to be analyzed for possible investment to reduce exposure; second, a decision must be made as to which alternative to recommend for each situation or design concept analyzed; and third, management must decide which alternative to implement.

The first decision can be made by developing criteria and standards which pertain to situations requiring ALARA determinations. Then the analyses must be performed. It is at this point that ALARA analyses can be used for evaluation of each of the possible alternatives. Recommendations as to the apparent best course(s) of action can then be made, but final decisions must await review of the entire project or situation with respect to parameters other than simple dose reduction. A defensible point value approach is the recommended method of arriving at a final decision.

INTRODUCTION

A methodology for doing ALARA evaluations for releases of radioactive materials to the environment, based upon a point value system, is presented herein. This methodology goes beyond the more traditional cost of reduction per man-rem saved approach and factors in nontraditional costs such as the cost of construction in expected accidental deaths. Also considered is a projected impact to the environment from the postulated environmental release which is not directly related to calculated radiation doses to people.

The point value system developed is based upon establishing categories and assessing the overall value of each category in terms of expected costs or expected benefits. Categories initially included are:

- Capital Cost
- Operating Cost
- Safety
- Accident Consequences
- State of the Art
- Reliability
- Operability
- Maintainability
- Decommissionability.

This evaluation scheme is used to compare the total cost of doing a project with the projected total impact on the environment if the project is not done. Project costs include both monetary and industrial safety considerations, and environmental impacts include calculated population doses and calculated impacts not directly related to human radiation doses.

MONETARY CONSIDERATIONS

Costs associated with a facility and operation exhibit a significant portion of the evaluations undertaken in any decision-making process whether by an individual or within a large, complex organization. This ALARA protocol relies heavily on costs because of the above reality.

Cost assignments are made on the basis of best available estimates as follows:

Total Cost = Capital Cost + (Annual Operating Cost x Service Life)

A point assignment is made on the basis of one point per $1,000. (See Appendix for rationale.)

Capital cost estimates are required at an early stage of a design development. Costs of modifications, upgrades, retrofits, etc., can usually be estimated from previous experience if more definitive data are not available.

Operating cost may be more difficult to determine, especially over the service life of the facility. Components of operating cost would include:

- Maintenance
- Personnel
- Utilities
- Raw materials.

Service life also presents a problem in that in many cases estimates will be required. Professional experts should be consulted for those cases where precedent or explicit statements of the service life are missing.

Decommissioning costs could also be very significant if the initial design did not consider ease of decommissioning. However, since estimates of these costs are subject to large errors, due to time and technology constraints, they are not addressed directly here but rather they are indirectly addressed later as a portion of the total cost.

SAFETY CONSIDERATIONS

Safety and accident consequences are quantified on a basis of 100,000 points per death regardless of whether that death can be attributed to an industrial accident or radiation dose (see Part 1 of the Appendix).

INDUSTRIAL SAFETY

If a project being evaluated involves significant work with heavy equipment or hazardous materials, then an estimate of the expected probable deaths from the work should be made.

For example, statistics kept by the National Safety Council (NSC, 1981) show that 0.07 deaths can be expected from one million man-hours of construction activities. Therefore, if the project being evaluated will require 10,000 hr then statistically speaking 0.0007 deaths can be expected for a point assignment of 70 at 100,000 points per death.

ENVIRONMENTAL RADIATION SAFETY

Assessments for environmental safety are also made at the rate of 100,000 points per death, however in this case the conversion is made to points per person-rem by applying a projected mortality rate of 8×10^{-5} early cancer deaths per person-rem for an average population, as developed from epidemiological and statistical studies and reported by the National Research Council (Alexander, 1982 and BEIR, 1980). For calculational convenience this is rounded up to a probability of 10^{-4} early cancer deaths per person-rem, which is equivalent to 10 points per person-rem.

Environmental radiation safety assessments are made using a two-tiered approach. First, the direct calculated dose commitments are determined using models such as DACRIN, GRONK, FOOD, and ARRRG (Houston, 1974; Soldat, 1974; and Napier, 1980). Second, an assessment to estimate indirect detriments to the environment is made. This second assessment promotes an awareness of environmental detriment even though dose assessment models indicate a limited impact.

The assessment of indirect detriments is done in two steps. Determination of the maximum possible cumulative dose equivalent commitment to a hypothetical population is the first step. This calculation ignores any pathway analysis and assumes that all radioactive material is incorporated into the population until it has decayed. Equation (1) is a formulation of this parameter.

$$P_{DC} = \sum_{i=1}^{k} \frac{Ai\ Bi}{qi} \int_{o}^{\infty} e^{-\lambda i t}\, dt \qquad (1)$$

where: P_{DC} = population cumulative dose equivalent commitment

$\sum_{i=1}^{k}$ - summation for "k" radionuclides released

Ai = total activity of radionuclide "i" released

Bi = dose equivalent conversion factor for radionuclide "i"

qi = maximum permissible body burden for radionuclide "i"

λi = the mean life of radionuclide "i"

t = time.

In the case of noble gases which do not become incorporated into the metabolic processes of the body, it will be necessary to perform analogous computations to evaluate the equivalent P_{DC}. Point assignments of 10 points per person-rem are made based on the above calculation.

The second step involves evaluation of the effluents in order to infer a fraction of the above P_{DC} point assignment. This quasi analytical evaluation assesses the impact of the environmental detriment imposed by the releases postulated. Four assessments are performed:

1. The "bubble concept" is utilized to determine the impact of these effluents on the total bubble from the site*

2. A pathway factor is used to qualitatively assess the degree of difficulty for these effluents to be a part of a population dose equivalent

3. A time to decay factor assesses the total time these materials can be expected to remain radioactive*

4. The concentration of the radionuclide in the effluent is compared to the concentration guides for unrestricted release (DOE, 1981).

The summation of the factor values is converted to a negative power of ten [i.e., $10^{-(s+a+t+c)}$] which is then multiplied with P_{DC} point total. This point total is added to the total from the environmental dose assessment. For example, suppose a facility were to release 20,000 Ci of ^{3}H in an airborne effluent and the P_{DC} point total is calculated to 2×10^{9} points (Eq 1). Suppose the bubble will be increased, pathway availability is high, total decay time is less than 10^{4} yr, and the concentration is at Table I (DOE, 1981) concentration guides. The summation of the factor values in this case is 6; therefore the multiplier is 10^{-6}, and as a result, 2,000 points would be assessed in this situation.

The summation of all of the points from the safety assessment will then be carried forward with cost assignments.

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*See the Appendix for explanation of bubble concept and total decay concept.

Table 1 contains suggested values for these assessments.

Table 1. Effluent Evaluation Factors.

Parameter	Range	Factor value
Bubble Concept		
Size(s)	Increase Stable Decrease	1 2 3
Pathway		
Availability(a)	High Medium Low	1 2 3
Time to Total Decay (p=0.95)		
Time (τ)	$\tau>10^6$ yr $10^4<\tau<10^6$ yr $\tau<10^4$ yr	1 2 3
Radionuclide Concentration		
Concentration*(c)	>Table I >Table II and <Table I <Table II	1 2 3

*Table I and Table II refer to the appropriate concentration guides in DOE 5480.1A (DOE, 1981). See the Appendix for explanation of bubble concept and total decay concept.

ACCIDENT CONSIDERATIONS

Safety analysis reviews provide accident scenarios and consequences in terms of frequency and severity. The appropriate parameters and values can then be utilized to assign point values for costs incurred. These costs would include monetary losses and expenditures, and personnel and population exposure to radiation. In addition, the public relations aspect must be considered along with other identified accident consequences.

A quasi-analytical approach may serve to estimate accident consequences where safety analysis review data are not available and intangibles require incorporation. Table 2 indicates such a methodology.

The sum of the factor values presented in Table 2 provides a scale factor which determines the point assignment. That assignment is made by considering the sum as a percentage value and multiplying it by the total of the cost and safety considerations developed to that point.

TABLE 2. Accident/Upset Conditions, Consequence Evaluation Factors.

Parameter	Range	Factor value
Accident severity	High	3
	Medium	2
	Low	1
Accident frequency	High	3
	Medium	2
	Low	1
Effectiveness of mitigating actions or designs	High	1
	Medium	2
	Low	3
	None	4
Public relations impact	High	2
	Low	1
Cleanup costs	High	3
	Medium	2
	Low	1
Uncertainty of measurements	High	2
	Low	1

STATE OF THE ART

State of the art is a generic term used in this context to denote the ability to change procedures, design, equipment, and facilities to reflect the current level of sophistication of technological improvements in all fields of endeavor related to waste management and fuels reprocessing. A failure to apply recognized state of the art in any aspect of operations involving materials or agents hazardous to health may cause the perpetrator to be held liable for damages in tort actions (Tressler, 1969 and Hutton, 1966). Another purpose of a viable ALARA program is to force advances in effluents control techniques. On this basis, state of the art takes on added significance (BEIR, 1977).

These considerations add impetus to improving facilities and operations with the objective of reducing detriments, both occupational and environmental. Status quo is not a viable ALARA option. Table 3 contains suggestions for assessing state of the art.

TABLE 3. State of the Art Factors.

Degree of state of the art	Factor value
High	0
Medium	5
Low	10

The state of the art factor value selected is treated as a percentage to be multiplied by the sum of the costs and safety. This product is then considered the state of the art contribution to the total score.

RELIABILITY - OPERABILITY - MAINTAINABILITY

These three categories are grouped together because they are interrelated. The successful implementation of these categories into a facility design can reduce occupational and environmental detriments to values much less than those experienced with less than adequate reliability, operability, and maintainability. Again a qualitative approach is used in lieu of more detailed information. Table 4 lists suggested values.

TABLE 4. Reliability-Operability-Maintainability Factors.

Parameter	Range	Factor values
Reliability (R)	High (redundancy)	0
	Medium	5
	Low	10
Operability (O)	High (human factors)	0
	Medium	5
	Low	10
Maintainability (M)	High (ease of maintenance)	0
	Medium	5
	Low	10

The sum of the three factor values for a specific case is treated as a percentage of the total cost (C_T) plus safety (S) point score. The product of this multiplication is then added as the reliability, operability, and maintainability portion of the total point score (i.e., R+O+M = X%, X% x (C_T+S) = value).

DECOMMISSIONABILITY

Decommissioning, or the ease of decommissioning, must be given proper consideration in order to do an ALARA analysis. Facilities which are not designed with decommissioning in mind can lead to unnecessary costs and exposure of personnel and the public to radiation in the future (Hinson, 1980 and MacDonald, 1980). In evaluating the decommissioning of a facility or design we must consider inventories of radioactive materials, ease of decommissioning in terms of removal and/or renovation efforts, and the facility design flexibility to accomodate other activities at the end of the normal service life. Other works (Hinson, 1980; Manion, 1980; and MacDonald, 1980) provide basic considerations.

Three basic alternatives are available for decommissioning (Manion, 1980). These are:

1. Permanent in situ protective storage of all or part of all residual inventory of radionuclides

2. Temporary protective storage followed by removal of all hazardous residual radionuclides to an approved storage/burial facility and release of the site for unrestricted use

3. Temporary protective storage followed by removal of most of the hazardous residual radionuclides to an approved storage/burial facility and release of the site for limited use as a controlled facility.

Suggested values for qualitative decommissioning factors are presented in Table 5. These can be used in lieu of more precise analysis when not available.

TABLE 5. Decommissionability Factor Values.

Range	Remarks	Factor value
High	No design effort	0
Medium	Some design effort	5
Low	Extensive design effort	10

This factor value is treated as a percentage of the cost plus safety point score. The product of this operation is added as the decommissioning portion of the total score.

EXAMPLE EVALUATION

As an example let us define a hypothetical situation where a facility is processing radioactive materials and discharging water contaminated with Strontium-90 at Table I (DOE, 1981) concentrations at a rate of 1,000 gal (3.8×10^3 L) per day. This water is discharged to a subsurface disposal facility and the plant is located in an arid region 50 mi from the nearest groundwater user. We want to know if it would be reasonable to install a water treatment device to clean the water to drinking water quality. Intuitively we believe that it will not be cost effective since the discharge is below ground (no airborne transport pathway) and the nearest drinking water well is 50 mi. away (insignificant groundwater transport).

COST CONSIDERATIONS

Let us assume the treatment plant will cost one million dollars to build and 50 thousand dollars per year to operate for a 20-yr expected lifetime. Construction will require 10 thousand man-hours to complete and operation will require 50 hr/yr of construction-type activities. Therefore the total projected cost is given an evaluation point total of 2,000 for monetary costs. Expected deaths from industrial accidents yield a point total of 77 for a total of 2,077 (Table 6).

TABLE 6. Project Implementation Costs.

Item	Cost	Point value
Construction	$1,000,000 10,000 man-hr	1,000 70
Operation (20 yr)	$1,000,000 1,000 man-hr	1,000 7
		Total 2,077

SAFETY CONSIDERATIONS

The environmental impact of such a release would normallly be addressed in a facility Safety Analysis Report or similar documentation. That documentation should define the population and maximum individual dose commitments according to established dose models. Let us assume that the calculated population dose commitment is 2.3 person-rem.

The assessment for indirect enviromental detriment is done by calculating the maximum possible population dose using Equation 1 and modifying that dose according to the factors given in Table 1.

The absolute maximum possible population dose for 20 yr of plant operation at Table I (DOE, 1981) concentrations is 1.73×10^8 person-rem.

That dose is modified according to Table 1 as follows:

- The total bubble size is expected to increase. Factor value equals 1
- The pathway analysis indicates that the availability to the environment is low due to subsurface disposal and no near water wells. Factor value is 3

- Time to total decay is calculated to be 1,920 yr. Factor value is 2
- Release concentration is at the Table I value (DOE, 1981). Factor value is 1.

These factor values total to 7 for a total calculated indirect environmental impact of 17.3 person-rem ($1.73 \times 10^8 \times 1 \times 10^{-7}$). Therefore the total environmental impact calculated for this evaluation is approximately 19.6 person-rem. The point value for the potential benefit of cleaning up this effluent to drinking water quality is 196 points thus far.

The safety considerations relative to industrial accidents during construction and operation were addressed earlier under the cost considerations heading.

ACCIDENT CONSIDERATIONS

Accident considerations for this situation being evaluated are such that operation of the plant without the proposed modification should be safer than with the modification. If we assume that the Safety Analysis Report indicates that the factors for accident conditions are as listed in Table 7, then we can also assign applicable values for the proposed change (also shown in Table 7).

STATE OF THE ART

We must assume that the existing effluent treatment system is not equivalent to the current level of sophistication available in the industry. Therefore we will assign a state-of-the-art factor value of 10 as indicated earlier in Table 3. The new equipment proposed is assumed to be state of the art; therefore a factor value of zero is assigned.

RELIABILITY-OPERABILITY-MAINTAINABILITY

These categories are evaluated as shown in Table 8. The proposed new system is assumed to be more complex and therefore less reliable.

Table 7. Accident/Upset Factors for Example Evaluation.

Parameter	Factor values for	
	Status quo	Proposed modification
Accident severity	1	2
Accident frequency	1	1
Effectiveness of mitigating actions or designs	2	2
Public relations impact	1	1
Cleanup costs	1	2
Uncertainty of measurements	1	1
Totals*	7	9

*The totals shown in Table 7 will be converted to percentages and used to assign point values later.

Table 8. Reliability, Operability, and Maintainability Factors for Example Evaluation.

Parameter	Factor values for	
	Status quo	Proposed modification
Reliability	0	5
Operability	0	0
Maintainability	5	5

DECOMMISSIONABILITY

Decommissioning of the existing disposal system is assumed to be via deactivation and in situ disposal with no significant removal and handling of radioactive materials. Therefore no design effort is required and a factor value of 0 is assigned.

The new system is assumed to require some design effort for decommissioning and a factor value of 5 is assigned.

FINAL EVALUATION

Finally, all the factors and values discussed are drawn together as shown in Table 9 and the total point value for the status quo is considerably lower than the value for the proposed modification. Therefore the modification is not reasonable to pursue.

Table 9. Example Evaluation.

Parameter	Factor values for	
	Status quo	Proposed modification
Construction costs	0	1,000
Construction accidents	0	70
Operation costs	0	1,000
Operation accidents	0	7
Environmental impact	196	0
Accident consequences	14 (7%)	187 (9%)
Reliability	0 (0%)	104 (5%)
Operability	0 (0%)	0 (0%)
Maintainability	10 (5%)	104 (5%)
State of the art	20 (10%)	0 (0%)
Decommissionability	0 (0%)	104 (5%)
Totals	240	2,576

CONCLUSIONS

The preceeding sections have outlined a methodology by which differential cost-benefit analyses in environmental ALARA determinations can be carried out in a systematic fashion. This methodology is not intended to be the final word on performing these analyses, but it is rather a mechanism by which to initiate ALARA considerations at an early stage of the design process. Continuing refinement with use should improve this methodology as more experience is gained.

ACKNOWLEDGEMENT

This paper reflects part of the work currently being done at Rockwell Hanford Operations to develop methodologies for doing ALARA evaluations which optimize benefits to radiation workers, the public, and the environment. That greater work is being headed by G. C. Strickland, K. M. Tominey and ourselves.

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APPENDIX

1. POINT VALUE RELATIONSHIPS

R. L. Kathren (Kathren et al., 1980) developed current values of a person-rem for use in ALARA evaluations and concluded that if dose reduction can be achieved at a cost of $\leq$\$2,000 per person-rem, then it should be done. Similarly, he concluded that if it would cost $\geq$\$60,000 per person-rem, then it probably should not be done. We have chosen to use \$10,000 per person-rem, since our evaluation techniques are somewhat conservative. We achieve this by assigning one point per \$1,000 and 10 points per person-rem and, since the early cancer death risk from radiation is about $1x10^{-4}$ per person-rem, we assign 10^5 points per death from nonradiation attributed causes.

2. THE BUBBLE CONCEPT

The U.S. Environmental Protection Agency (EPA) routinely applies a multiple source or bubble concept in determining the allowable effluent release levels in an area with more than one producer of such effluent. This concept is applied by calculating the maximum allowable ambient concentration of a pollutant (and thereby, the areal environmental detriment), using that value to determine the maximum allowable release levels, and allocating individual relase limits to the various pollutant sources within the area or bubble.

A modification of that concept can be applied to radioactive effluent releases from an area of multiple release points. That modification could be applied by calculating the amount of air or water that would be required to dilute the total quantity of airborne or waterborne effluents to DOE Order 5480.1A, Chapter XI, Table II concentrations (DOE, 1981). That calculation could be based on total effluents released, total decayed effluents, or any subportion thereof.

For example, historical airborne effluent release records indicate that the current worldwide inventory of ^{239}Pu and ^{90}Sr, which are the result of Hanford Site 200-Area airborne releases, may be as high as 1.36 Ci and 14.9 Ci respectively. If all this material had been retained in the local air, it would take 8×10^{14} ft^3 of air to dilute the ^{239}Pu and $9 \times 10^{+9}$ ft^3 of air to dilute the ^{90}Sr to Table II concentrations (DOE, 1981). The ^{90}Sr bubble size is a small percentage of the total and does not affect the radius of the equivalent hemispherical bubble.

3. TIME FOR TOTAL DECAY OF RADIOACTIVE MATERIAL

The classical treatment of the decay of a radioactive material predicates exponential decay behavior with the passage of time and is valid for the large number of excited nuclei which will undergo radioactive decay (Evans, 1955). The exponential decay description does not lend itself to predictions of the time interval necessary for all of the excited nuclei of a radioactive species to decay.

An equally rigorous approach assumes a population of excited nuclei with its inherent constant half-life and is formulated to determine the amount of time required for all members of the population to decay with a specified degree of confidence (Jackson, 1965). In the limiting condition of requiring absolute certainty that all members of the population have decayed, this approach predicts the passage of an infinite period of time, which is in agreement with the traditional treatment.

In the following paragraphs the latter approach is used to provide estimates at the 95% confidence level of the time required for decay of given radionuclide populations. The number of atoms in a population of a given radionuclide is directly proportional to the product of the half-life and the activity. A unit activity of a radionuclide with a half-life of one year has fewer parent nuclides than does the same activity of a radionuclide with a half-life of one million years. Therefore, the time interval in terms of the number of half-lives will increase with increasing half-life for the same initial activity at the reference time.

Radioactive materials discharged to the environment in effluents can be assumed to be radiologically detrimental during the period of time in which any radioactivity remains. An estimate of the period of time which a given activity, A, (in microcuries) of radioactive material with half-life, T 1/2 (in years) will require to completely decay at a specified confidence level (i.e., probability that all atoms have decayed is 95%) can be made in the following manner (Jackson, 1965). This estimate is of use in comparing the duration of effects of discharge of different radionuclides to the environment.

The number of atoms, N, present is

$$N = 1.68 \times 10^{12} A T_{1/2} \qquad (1)$$

where

1.68×10^{12} = constant to convert μCi to disintegrations per second, year to seconds, and the conversion from decay constant to half-life.

A = activity of the radionuclide in μCi

T 1/2 = half-life of the radionuclide in years.

Since a particular radionuclide has either decayed or not decayed, the probability, Po, of all N atoms decaying in n half-lives is

$$Po = [1-(1/2)^n]^N \tag{2}$$

Equation 2 can be rewritten as

$$\ell n \, Po = N \ell n \, [1-(1/2)^n] \tag{3}$$

An approximation of the natural logarithm on the right hand side of Equation 3

$$\ell n[1-(1/2)^n] \simeq (1/2)^n \tag{4}$$

Substituting into Equation 3

$$\ell n Po = -N(1/2)^n \tag{5}$$

and solving for n

$$n = \frac{\ell n N - \ell n[\ell n(\frac{1}{Po})]}{\ell n 2} \tag{6}$$

If the probability of total decay is assumed to be 0.95, Equation 6 can be evaluated as

$$N = 44.9 + 1.44 \, \ell n \, AT_{1/2} \tag{7}$$

For example, 1.0 μCi of ^{239}Pu, T 1/2 = 24.390 years, will require 59.5 half-lives (1.45 x 10^6 years) to have a probability of 0.95 that all the plutonium has decayed. There will, of course, be ^{235}U daughters in existence at this time. Table 1 is a listing of some radionuclides of concern in effluents and the time required for all of the activity to decay with a probability of 0.95.

TABLE 1. Time to Total Decay (p = 0.95) of 1.0 μCi of Various Radionculides.

Radionuclide	No. of half-lives	Total time (yr)
^{3}H	48.5	6.0×10^2
^{60}Co	47.3	2.5×10^2
^{85}Kr	48.3	5.2×10^2
^{90}Sr	49.7	1.4×10^3
^{106}Ru	44.9	4.5×10^1
^{134}Cs	45.9	9.5×10^1
^{137}Cs	49.8	1.5×10^3
^{154}Eu	48.0	4.1×10^3
^{155}Eu	47.1	2.2×10^2
^{239}Pu	59.5	1.5×10^6
^{241}Am	53.7	2.3×10^4

The use of this concept is best illustrated by an example. Assume that a fuels reprocessing plant will emit an estimated 1×10^6 Ci/yr of ^{85}Kr to the atmosphere when in operation. How much time will be required for all of the ^{85}Kr from a 10-yr campaign to decay with a probability of 0.95? The first step is to calculate the time interval for 10 MCi to decay to 1.0 μCi, (i.e., 460 yr). From Table 1, another 520 yr is required to complete the total decay (p = 0.95), for a total time interval of 980 yr.

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