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An as Low as Reasonably Achievable Cost Benefit (Optimization) Analysis for the Shield Design Criterion at the Hanford Waste Vitrification Plant

Prepared for the U.S. Department of Energy
Office of Environmental Restoration and Waste Management

Westinghouse Hanford Company Richland, Washington

Hanford Operations and Engineering Contractor for the U.S. Department of Energy under Contract DE-AC06-87RL10930

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AN AS LOW AS REASONABLY ACHIEVABLE COST BENEFIT (OPTIMIZATION) ANALYSIS FOR THE SHIELD DESIGN CRITERION AT THE HANFORD WASTE VITRIFICATION PLANT

1.0 INTRODUCTION

1.1 BACKGROUND

The Hanford Waste Vitrification Plant (HWVP) is undergoing design and will be constructed at the Hanford Site in Richland, Washington. This facility will vitrify pretreated, Hanford defense, liquid high-level and transuranic wastes into borosilicate glass. The glass will be poured into stainless steel canisters for eventual interment at a geologic repository. Shielding is required in certain process and storage areas of the HWVP to limit exposure of personnel from external sources of radiation. Optimization of the radiation shielding was employed to balance the increased cost of shielding above the reference baseline of 5.0 μSv/h with the reduction in detriment to operating personnel during the lifetime of the facility.

The thickness of radiation shielding required to limit exposure of personnel from radioactive materials within the process cells in the HWVP to acceptable levels is a function of the following parameters:

- The type and activity of the radioactive material in the source
- The distribution of source material within the source
- The geometrical distribution of sources within the process cells
- The materials of construction of the shield
- Geometrical consideration of the source(s) and shield
- The acceptable exposure rate on the "clean" side of the shield; i.e., the side normally occupied by personnel.

All these parameters interact in a complex fashion. Usually, the designer is faced with the issue of specifying a shield thickness, which becomes dependent on the remainder of the parameters including a specified, acceptable dose equivalent rate.

Baseline requirements for shielding for design purposes are contained in U.S. Department of Energy Orders 6430.1A, *General Design Criteria* (DOE 1989), and 5480.11, *Radiation Protection for Occupational Workers* (DOE 1988). The requirement in Order 6430.1A is for the equivalent of 5.0 μSv/h. There are two design requirements specified in Order 5480.11 for design of new facilities:

- Optimization as discussed in the International Commission on Radiological Protection (ICRP) Publication 37 (ICRP 1983)

- Dose equivalent rates should be as low as reasonably achievable (ALARA) and not exceed 5.0 μSv/h.

Additional guidance on acceptable exposure rates is provided in a Westinghouse Hanford Company (Westinghouse Hanford) radiological design manual. For full access time in a controlled area, the initial design level requirement is 2.0 μSv/h. This dose equivalent rate has been used for design of shielding in HWVP.

1.2 PURPOSE

The purpose of this paper is to provide an ALARA basis for the shield design criterion for use in the HWVP. Estimates are provided for the increased construction costs to implement the ALARA shield design criterion as well as the cumulative reduction in personnel exposure during the life of the HWVP.

2.0 METHOD

2.1 OPTIMIZATION OF SHIELD DESIGN

Optimization of the design of a simple planar shield is developed in the ICRP, Publication 37 (ICRP 1983). This optimization balances the reduction in detriment of personnel exposure against the added cost of increasing the shield thickness from the baseline criterion dose equivalent rate. By determining the minimum of the total cost (cost of detriment plus cost of additional shielding) with respect to the added thickness of shielding required, the optimum shield design criterion can be determined. Equation 1 is the result of this determination assuming that the buildup factor does not change appreciably for the small increment of change of shielding thickness in the present case.

$$H_U e^{-\Gamma w} = \frac{X_V \, h1}{\alpha N f_t T_L \rho \Gamma} \tag{1}$$

where

$H_U e^{-\Gamma w}$ = the optimum shielding design criterion dose equivalent rate

H_U = the baseline shielding design criterion dose equivalent rate

$e^{-\Gamma w}$ = additional shielding attenuation provided by the extra thickness of shielding, w, and the linear attenuation coefficient of the shielding material, Γ

X_V = the cost of emplacing the shielding material (concrete)

hl = the area (product of h times l), accessible to personnel, of the shielding surfaces

α = the cost per person-Sv

Nf_t = the product of the total number of personnel employed in the facility, N, times the fraction of time, f_t, that they spend in radiation zones. Note that different types of job assignments will have different values of f_t.

T_L = the lifetime of the facility

ρ = ratio of average exposure rate received by personnel to the maximum rate adjacent to the extra shield.

2.2 PARAMETER VALUES

Calculation of Eq. 1 is straightforward. A consistent set of units will ensure a correct numerical answer. The determination of the parameter values, however, is not a simple matter at this point (during completion of Preliminary Design and initiation of Detailed Design of the HWVP).

Specific values for each of the parameters are not available on an *a priori* basis; however, a range of values around the best estimates of the present values can be provided. Table 1 provides the best estimates of these values and the suggested range.

2.3 CALCULATIONAL PROTOCOL

Because six of the parameters in Table 1 cannot be assigned a unique value, the calculation of the optimum shield dose equivalent rate design criterion must be completed while sampling from a distribution of each of these parameters. A Monte Carlo simulation was used to select values for each of the parameters presented in Table 1. A triangular distribution of the parameters was assumed over the range listed. The apex of the distribution represents the most probable value.

The triangular distribution was chosen because the calculational process was simplified as compared to a more mathematically complex distribution. No inference as to the validity of this distribution to this application should be implied from this assumption.

Random numbers were used to select a value for each of the six parameters from the ranges indicated in Table 1. These values along with the two singular values were then used to calculate the "optimum" shield design criterion for this particular set of parameter values. This process was repeated 3,000 times, or cases. The resulting distribution of the "optimum" shield design dose equivalent rate criterion is the item of interest.

Table 1. Range and Most Probable Values for Parameters in Equation 1.

Parameter	Minimum value	Most probable value	Maximum value	Remarks
X_V	785	1,050	1,050	Concrete emplacement cost ($/m^3)
hl	11,100	12,500	13,900	Shield wall area (m^2)
α	N/A	250,000*	N/A	Detriment cost ($/person-Sv)
Nf_t	283	315	347	Equivalent rad workers (FTE)
T_L	20	40	40	Plant life (yr)
ρ	0.05	0.10	0.20	Ratio avg/max dose rate
Γ	10.5	15.0	18.7	Attn coeff (m^{-1}): concrete of 2.35 g/cm^3
H_U	N/A	5.0	N/A	Baseline requirement (µSv/h)

*Based on Westinghouse Hanford Company guidance on cost benefit analysis.

FTE = Full-time equivalent
N/A = Not applicable

An additional set of calculations was carried out for each case based on the particular values of the parameter selected for the case in question:

1. Eq. 1 was solved for the thickness, w, of additional concrete required. From the thickness of extra shielding and the shield wall area, hl, the volume of concrete required to effect the required dose equivalent rate reduction can be calculated. Once the volume of concrete is known, the additional cost of the concrete, C_T, can be calculated based on the cost of emplacing concrete, X_V. Eq. 2 shows this relationship.

$$C_T = \frac{-hlX_V}{\Gamma} \ln\left(\frac{X_V\, hl}{\alpha Nf_t T_L \rho H_U}\right) \tag{2}$$

2. Given the cost of the additional emplaced concrete, the collective dose equivalent saved during the life of the plant can be calculated based on the realization that the cost of concrete is exactly equal to the cost of the detriment. The cost of the detriment is α times the total collective dose equivalent saved, D_T, Eq. 3.

$$D_T = \frac{C_T}{\alpha} = \frac{-hl}{\alpha\Gamma} \ln\left(\frac{X_V\, hl}{\alpha N f_t T_L \rho H_U}\right) \tag{3}$$

Again, the distribution of these parameters for a specified range of the shield design criterion is of interest rather than a value for a specific case.

3.0 RESULTS

The smoothed probability density distribution of the optimum shield design criterion is shown in Figure 1. The median value of this distribution is 1.4 μSv/h. The Westinghouse Hanford Company shielding design criterion of 2.0 μSv/h is greater than the median value while the baseline criterion, 5.0 μSv/h, is larger than the maximum value, 4.8 μSv/h, in 3,000 cases.

The 95th percentile value is of interest for the purpose of identifying the value of the shielding design criterion such that there is a 95 percent confidence that the "optimum" shield design criterion for the HWVP would be greater than the one selected. This shield design criterion is 0.8 μSv/h and incurs the greatest additional construction costs along with providing the greatest cumulative staff collective dose equivalent reduction.

Table 2 summarizes the results of the 3,000 cases. Included are the percentile rankings in the distribution along with the cost of the additional shielding and the collective dose equivalent saved.

Figures 2 through 10 provide the actual frequency distributions of the input parameters to Eq. 1 as well as the distribution of the optimum dose distribution, cost of emplacing the extra shielding, and the estimated savings in collective dose equivalent during the lifetime of the plant.

4.0 DISCUSSION

The method proposed in this paper provided the desired results. Rather than expending a great deal of energy on the precise definition of the values of the parameters in Eq. 1, repetitive calculations were performed while allowing the input parameters to vary over a rather easily defined range of

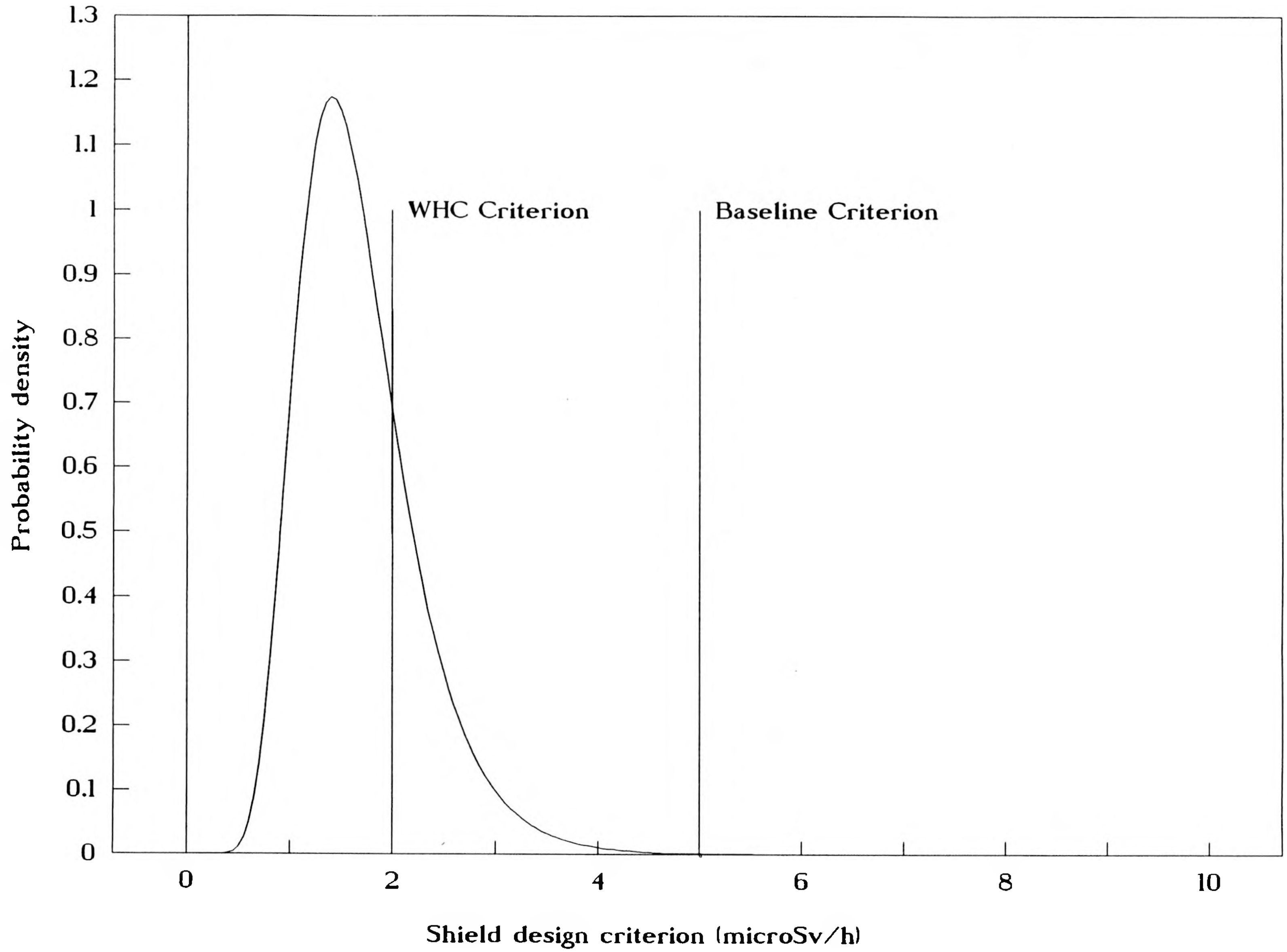


Figure 1. Smoothed Distribution of Optimum Shield Design Criterion (based on 3,000 cases).

Table 2. Summary of Estimated Cost Impact and Dose Equivalent Reduction from Implementing Optimum Shield Design Criterion.

Source of criterion	Shield design criterion (μSv/h)	Percentile ranking (%)	Cost of implementing ($1,000)	Collective dose saved (person-Sv)
Baseline	5.0	0	0	0
Westinghouse Hanford design guidance	2.0	17	801	3.20
Median value	1.4	50	1,060	4.24
95th percentile	0.8	95	1,367	5.46

Westinghouse Hanford = Westinghouse Hanford Company

values with a triangular probability distribution. The effect of these variations is easily discernible on the probability distribution function (Figure 1).

The results clearly indicated that the baseline criterion, 5.0 μSv/h, was not optimum for any combination of the Eq. 1 parameters. The Westinghouse Hanford guidance of 2.0 μSv/h is within the range of optimum values; however, a more conservative approach would have been to use the 95th percentile value, 0.8 μSv/h.

The status of design development of the HWVP, presently engaged in Detailed Design activities, precluded adoption of the 95th percentile shield design criterion. Based on the additional costs that would be incurred by reevaluating the design of all of the shields within the facility, the decision favored was to continue with the 2.0 μSv/h shield design criterion, which had been employed in shield design activities to this point.

Figures 2 through 7 show the actual frequency distributions of the parameters that are used to calculate the optimum shield design criterion. The distribution provides a check on the range of parameter values specified in Table 1.

Figure 2. Distribution of Concrete Emplacement Costs:
Interval is $5 (based on 3,000 cases).

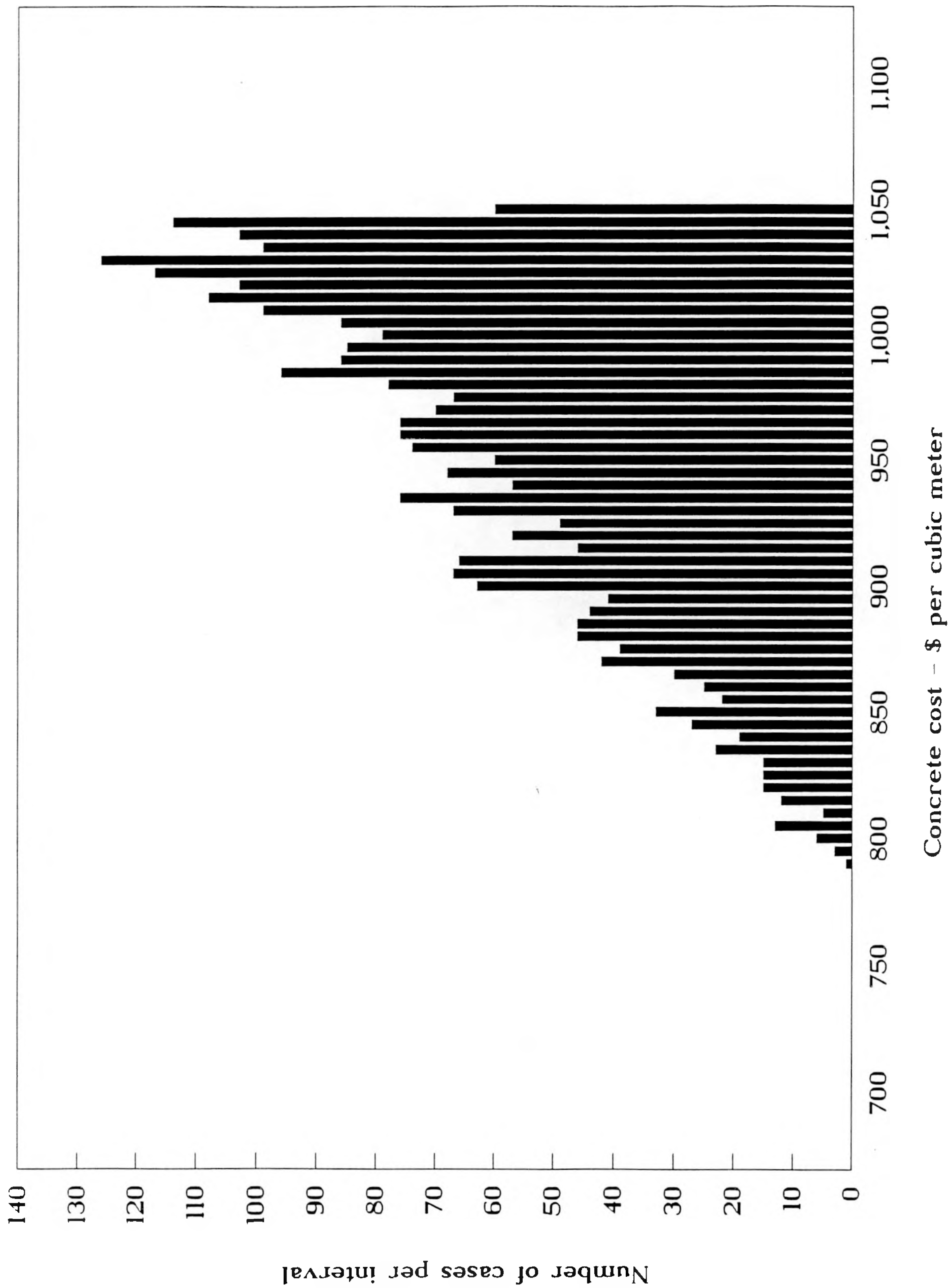
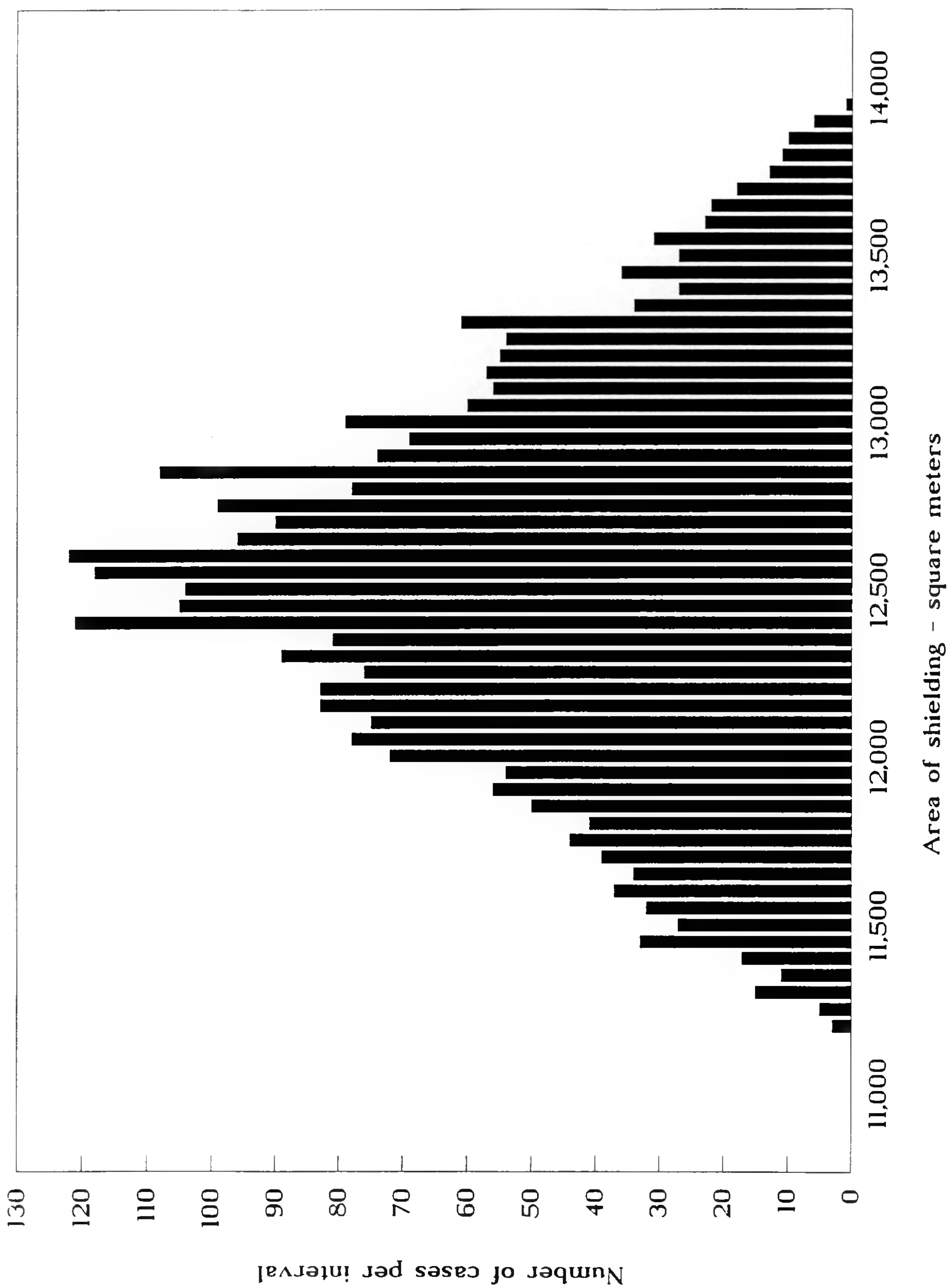


Figure 3. Distribution of Shield Area: Interval is 50 m^2 (based on 3,000 cases).



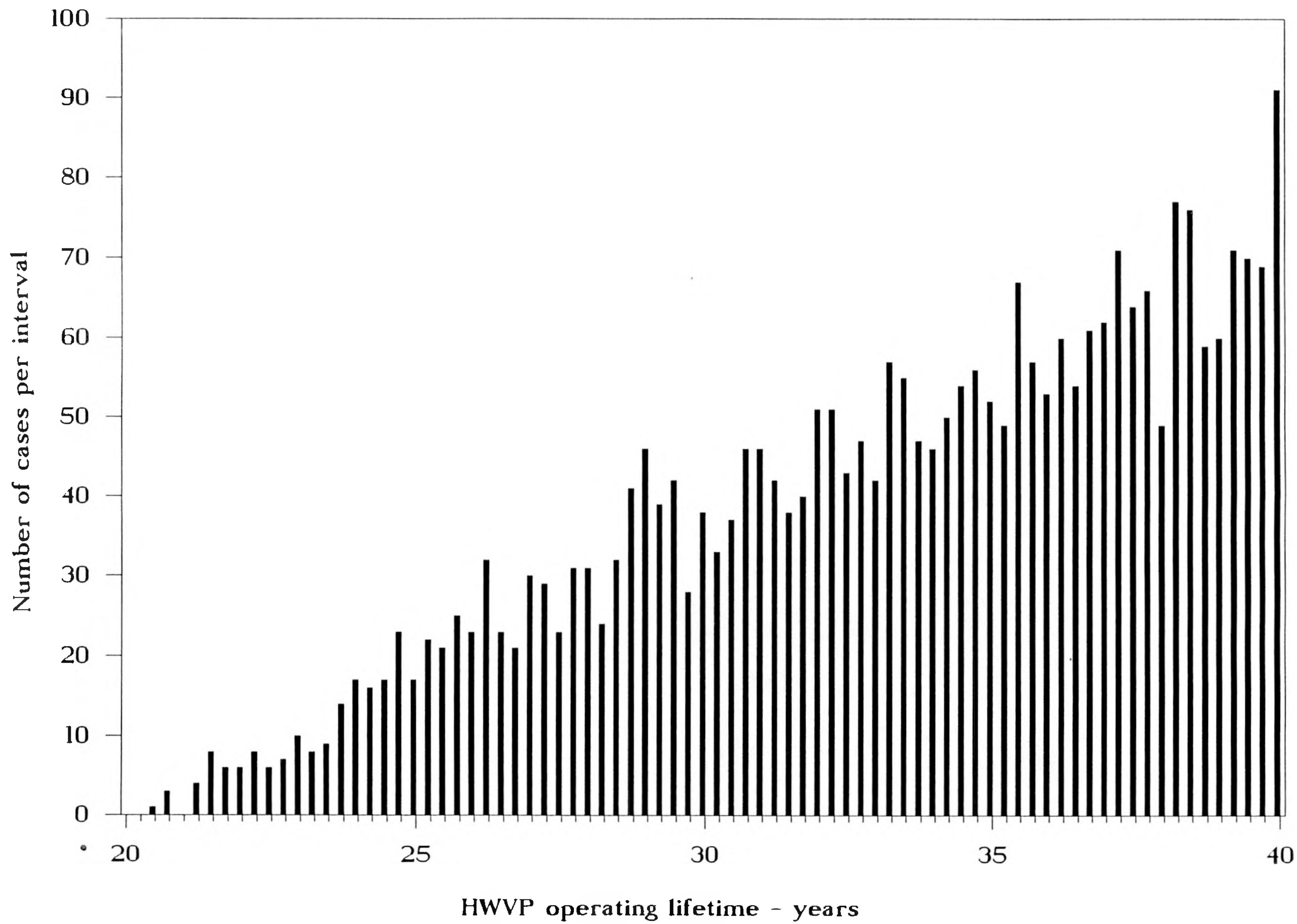


Figure 4. Distribution of Plant Lifetime: Interval is 0.25 Years (based on 3,000 cases).

Figure 5. Distribution of Ratio of Average to Maximum Dose Equivalent Rate: Interval is 0.0025 (based on 3,000 cases).

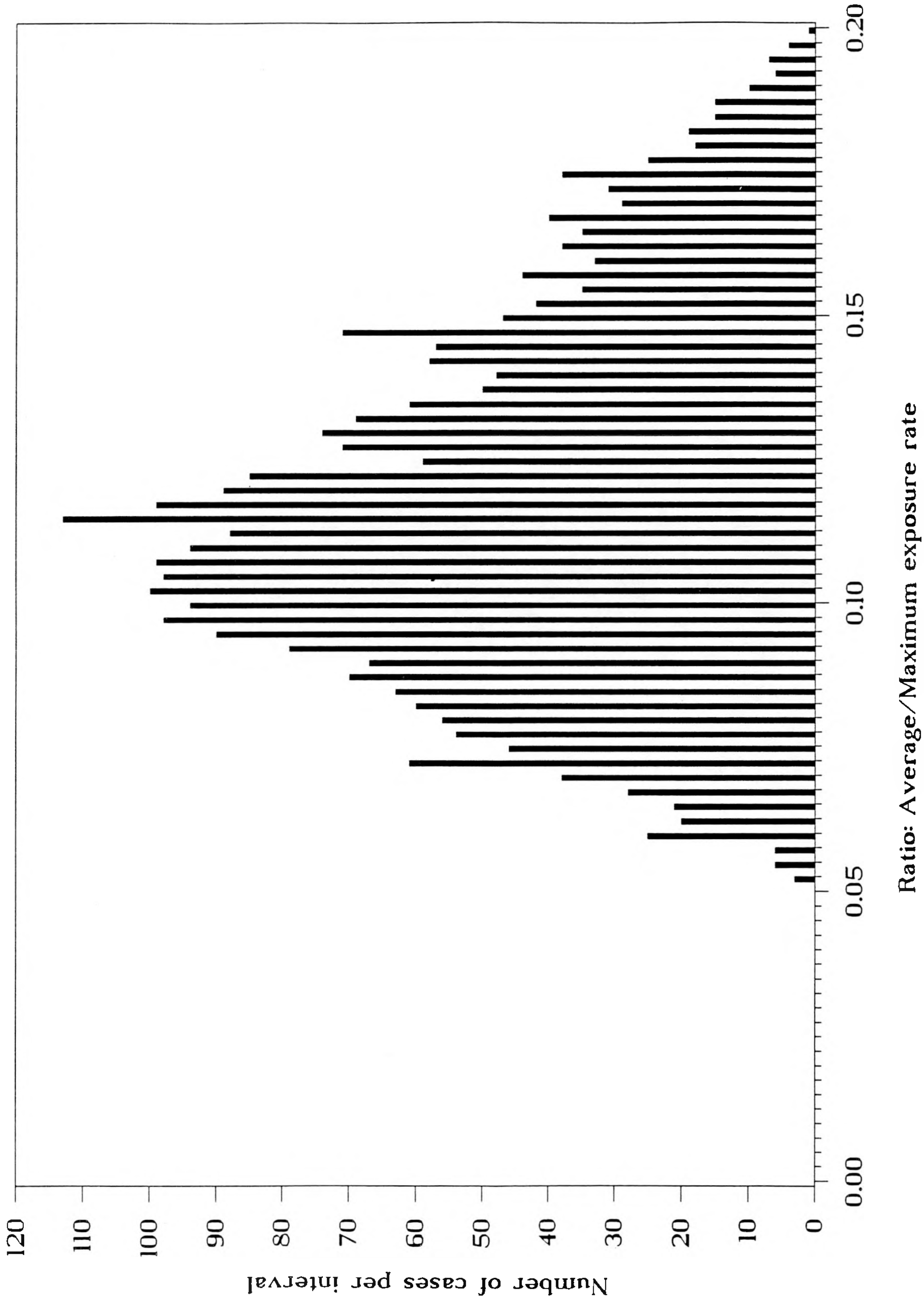


Figure 6. Distribution of Linear Attenuation Coefficient: Interval is 0.20 per Meter (based on 3,000 cases).

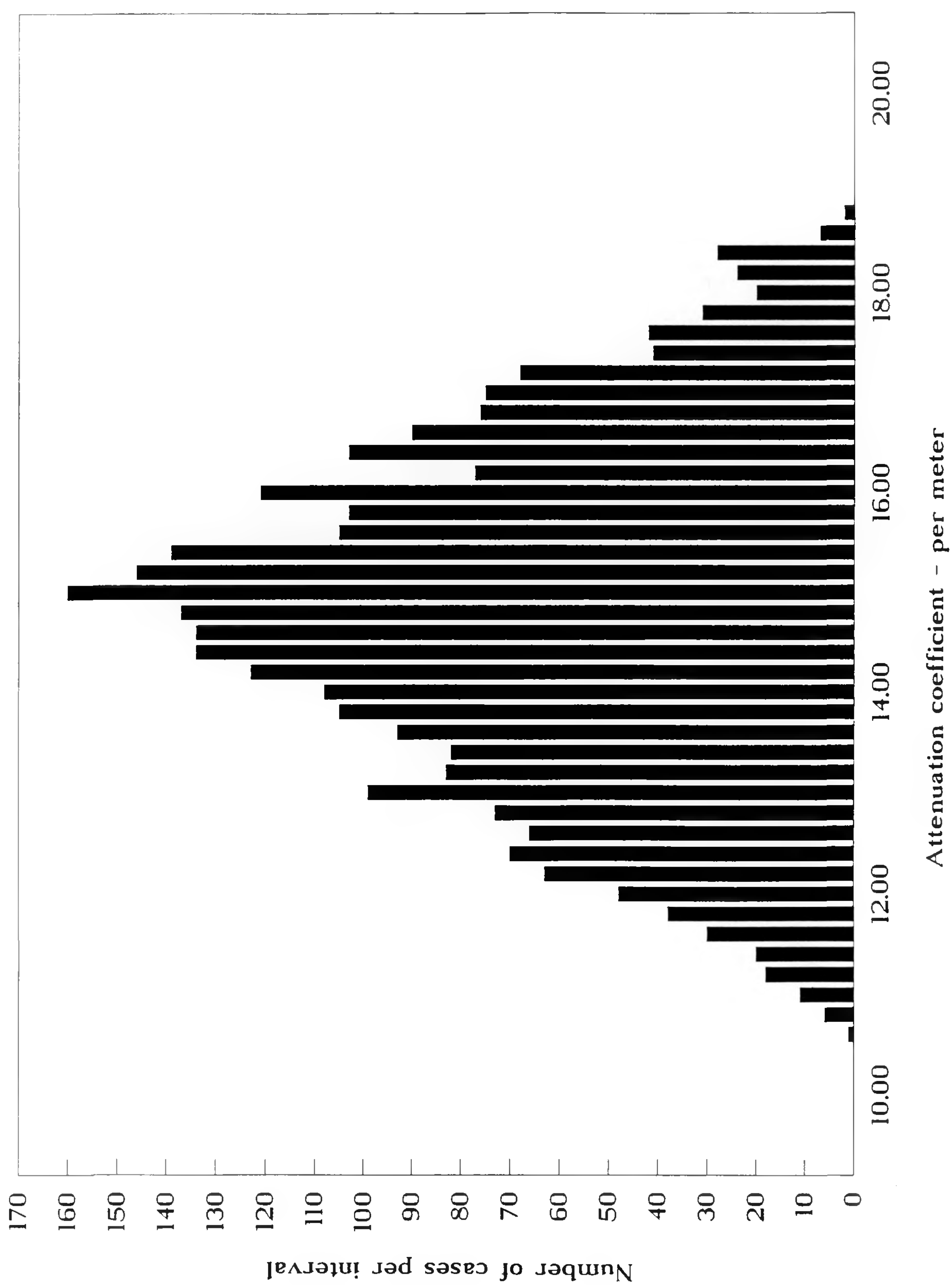
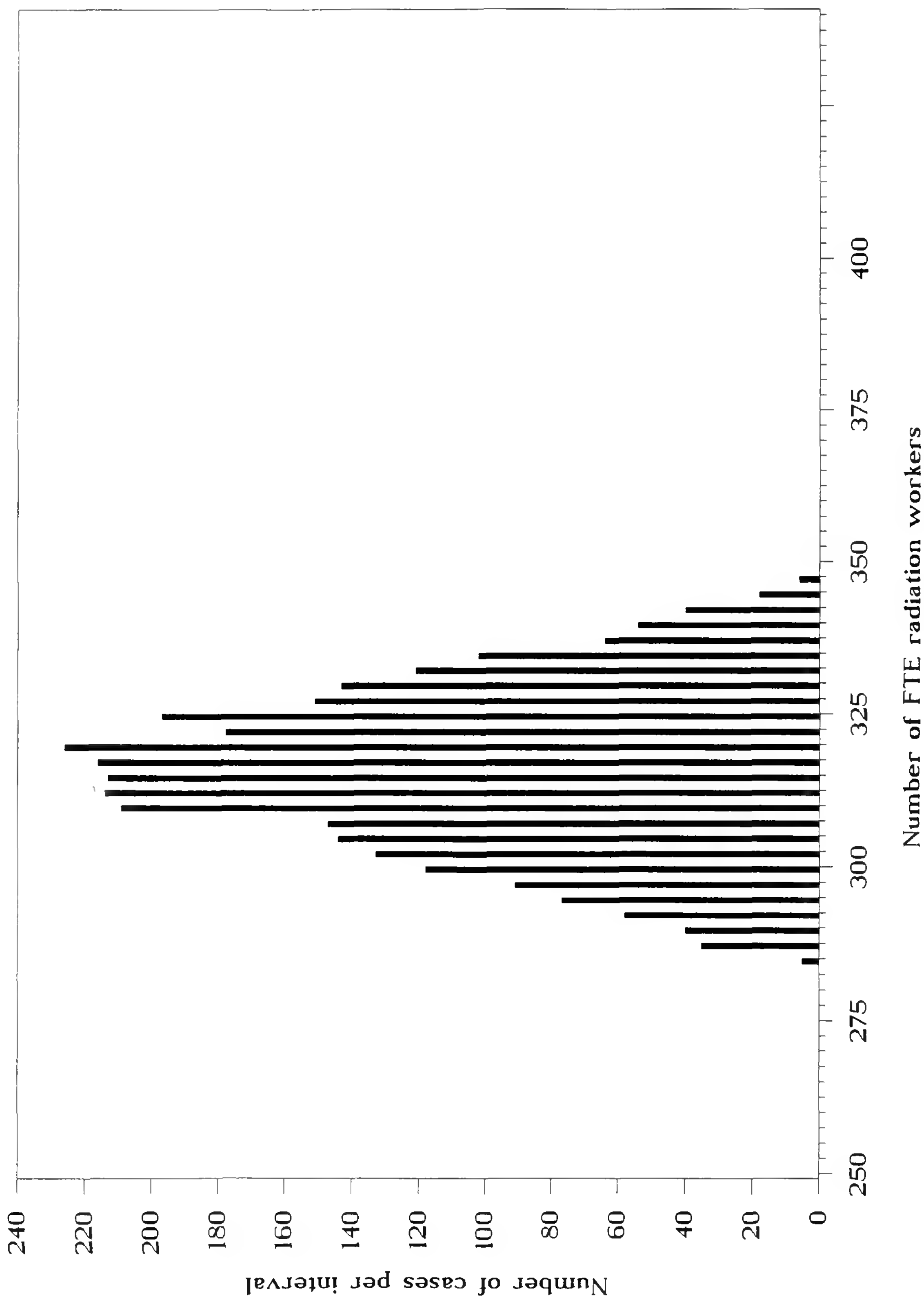


Figure 7. Distribution of Number of Full-Time Equivalent Radiation Workers: Interval is 2.5 Workers (based on 3,000 cases).



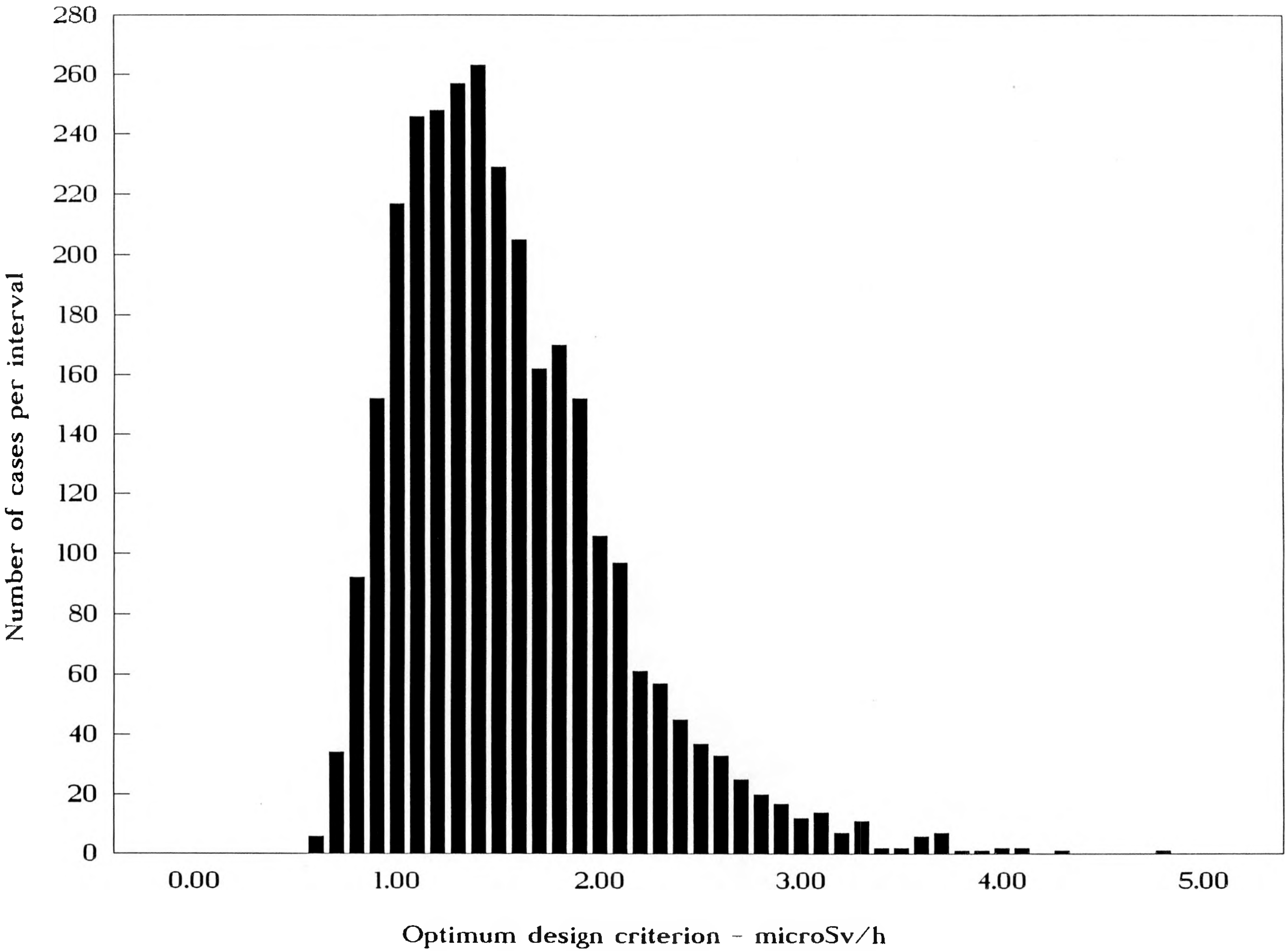


Figure 8. Distribution of Optimum Shield Design Criterion: Interval is 0.1 μSv/h (based on 3,000 cases).

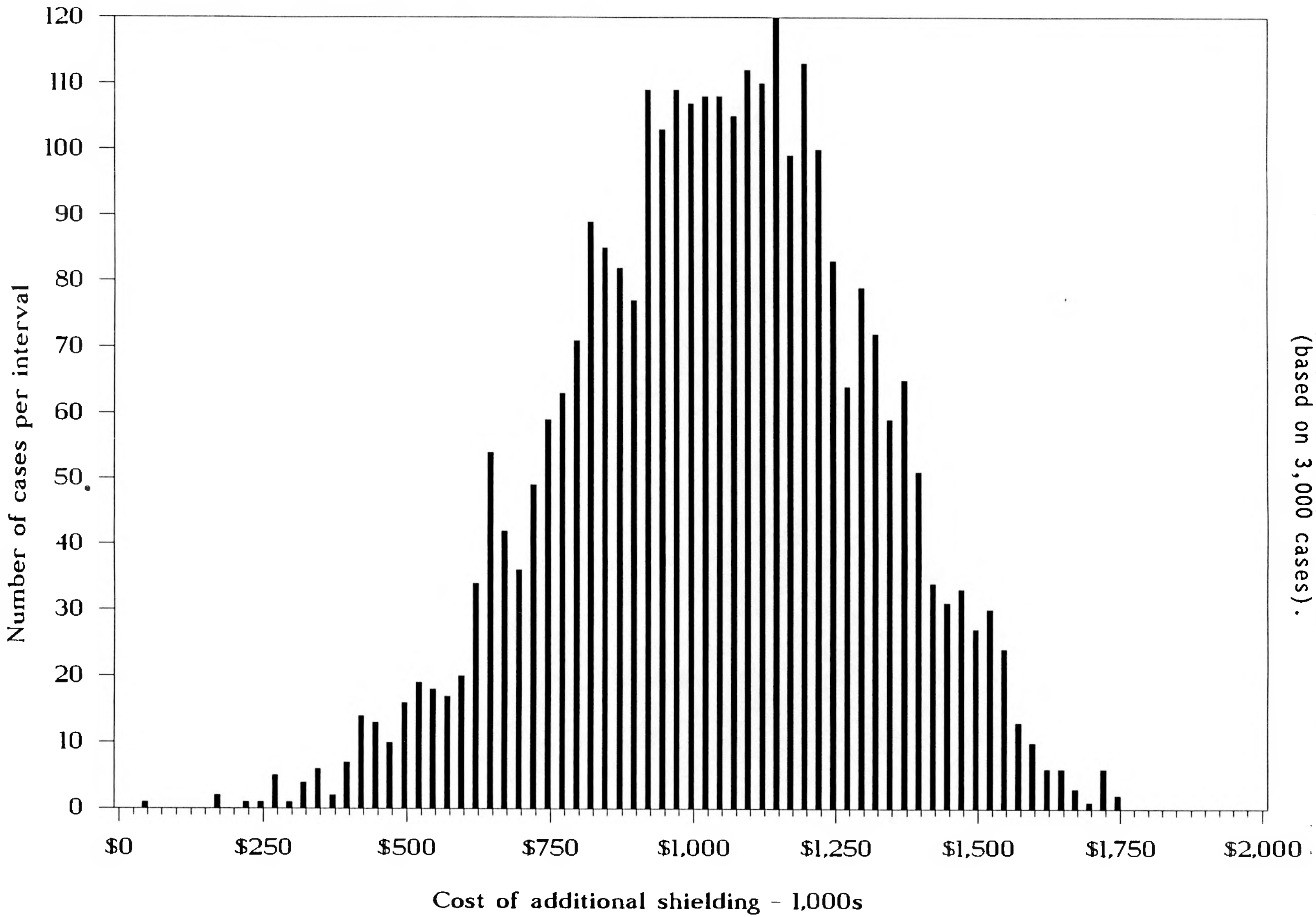


Figure 9. Distribution of Cost of Additional Shielding (from 5.0 μSv/h Baseline): Interval is $25 (based on 3,000 cases).

Figure 10. Distribution of Collective Dose Equivalent Saved (from 5.0 μSv/h Baseline): Interval is 0.1 Person-Sv (based on 3,000 cases).

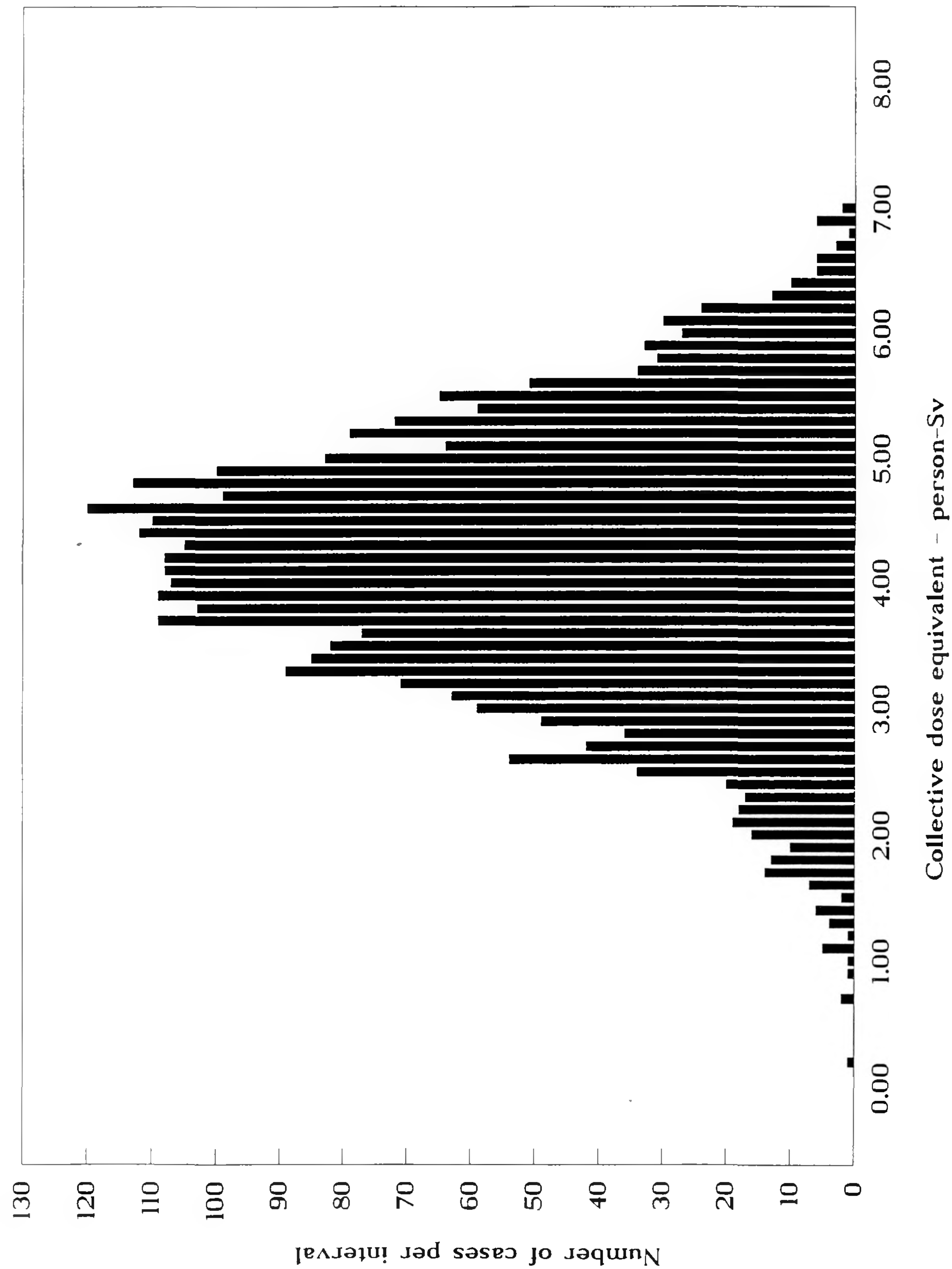


Figure 8 is the histogram from which the smoothed probability distribution (Figure 1) of optimum shield design parameters was derived. Qualitatively this distribution appears to be log-normal. No tests were run to determine the validity of this observation.

5.0 REFERENCES

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DOE, 1989, *General Design Criteria*, DOE Order 6430.1A, U.S. Department of Energy-Headquarters, Washington, D.C.

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