ALARA AT NUCLEAR POWER PLANTS*

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ABSTRACT

Implementation of the ALARA principle at nuclear power plants presents a continuing challenge for health physicists at utility corporate and plant levels, for plant designers, and for regulatory agencies. The relatively large collective doses at some plants are being addressed through a variety of dose reduction techniques. Initiatives by the ICRP, NCRP, NRC, INPO, EPRI, and the BNL ALARA Center have all contributed to a heightened interest and emphasis on dose reduction. The NCRP has formed Scientific Committee 46-9 which is developing a report on ALARA at Nuclear Power Plants. It is planned that this report will include material on historical aspects, management, valuation of dose reduction ($/person-Sv), quantitative and qualitative aspects of optimization, design, operational considerations, and training. The status of this work is summarized in this report.

INTRODUCTION

NCRP Committee 46-9 was formed in the spring of 1989 to develop a report on ALARA at Nuclear Power Plants. The report is intended to be a document that provides both general and specific information and guidance on ALARA philosophy and practices especially as applied at U.S. nuclear power plants.

The 46-9 Committee consists of J.W. Baum (Chairman), W.R. Kindley, T.D. Murphy, D.M. Quinn, A.K. Roecklein, and R. Wilson. J.A. Spahn, Jr. of NCRP is Committee Secretary and B.J. Dionne is a consultant to the Committee. The Committee is collecting, analyzing, and developing information and recommendations on ALARA at nuclear power plants.

Chapters on Background and History of ALARA, Quantitative Methods in Optimization; ALARA Management, Policy and Administration (including training); Determining Effectiveness of an ALARA Program; Design; and Operational Considerations have been drafted and are under review.

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Two questions that are still under discussion are: (1) what is the relationship of ALARA to dose limits, below regulatory concern, and negligible individual risk? and (2) what monetary value ($/rem or $/cSv) is appropriate for current use in cost-benefit evaluations?

In trying to provide answers to these two questions, I have reviewed a considerable volume of literature and am surprised, as you may be, at some of the findings. These findings are summarized here, but have not at the time of this writing (September 1990) been reviewed by the Committee. For this reason, the recommendations should not be interpreted as those of the Committee. Rather, they are presented at this time in order to stimulate thinking and discussion since they are at the heart of the ALARA philosophy and process.

DOSE LIMITS VS. ACCEPTABLE SAFETY

Recent reevaluations of radiation risks by the National Research Council, National Academy of Sciences Committee (BEIR V, 1990) yield cancer plus serious genetic effect risk estimates of about 4×10^{-4}/cSv, or about four times greater than earlier studies (BEIR III, 1980). Concurrently, "safe" industry has an associated risk of about 5×10^{-5}/yr (fatalities) now compared to 10^{-4}/yr ten years ago. Also, society's perception of risk, and safety aspirations are apparently greater now than formerly. This is reflected in the little discussed (in the radiation protection community) Supreme Court decision on OSHA's benzene standard (U.S. Supreme Court). The Court carefully avoided a precise definition of "safe," but did offer the following guidance on what may be considered "significant" risk:

> "First, the requirement that a 'significant' risk be identified is not a mathematical straitjacket. It is the Agency's responsibility to determine, in the first instance, what it considers to be a 'significant' risk. Some risks are plainly acceptable and others are plainly unacceptable. If, for example, the odds are one in a billion that a person will die from cancer by taking a drink of chlorinated water, the risk clearly could not be considered significant. On the other hand, if the odds are one in a thousand that regular inhalation of gasoline vapors that are 2% benzene will be fatal, a reasonable person might well consider the risk significant and take appropriate steps to decrease or eliminate it."

Using the 4×10^{-4} risk coefficient from BEIR V (National Research Council 1990) and a 45-year worktime, this one in a thousand risk is equivalent to:

$$Significant\ Risk = \frac{10^{-3} risk/45yr}{4 \times 10^{-4}\ risk/cSv} \tag{1}$$

$$= 0.056\ cSv/yr\ (56\ mrem/yr)!$$

Therefore, according to this Supreme Court interpretation, an exposure of about 56 mrem/yr would present a significant radiological risk in which the implementation of steps to reduce or eliminate the risk is appropriate. This is two orders of magnitude below the new 10 CFR Part 20 limit for occupational exposure and illustrates why it is important to make sure doses are ALARA. Note that these risk values were average risks over a worker population, and individual values would be both larger and smaller.

Additional judicial opinion was provided by the U.S. Court of Appeals for the District of Columbia in its 1987 decision on EPA's standard on emissions of vinyl chloride (U.S. Court of Appeals 1987). In this decision, the Court put some limitations on application of cost and benefit tests. The Court indicated that the agency is required to first adopt a standard that determines the maximum amount of a pollutant beyond which adverse health effects take place and is then required to set an "ample margin of safety" below that level. The Court further stated that the agency did not need to find that "safe" means "risk free" and that the finding was not intended to bind the agency "to any specific method of determining what is safe" or what is an "ample margin." Once the agency has determined what constitutes a safe level of exposure it may use costs and technological feasibility to determine what is an "ample margin of safety" to establish limits beyond the safety level required by the law. This Court guidance indicates that cost-benefit analyses should only be used <u>after</u> the "safe" level has been achieved. There now remains a gray area between 5 cSv/yr (the ICRP/NCRP/NRC limit of tolerable risk) and the 0.056 cSv/yr significant risk level.

The NCRP suggested "that cumulative exposures should not exceed the age of the individual in years x 10 mSv (years x 1 rem)" (NCRP 1987). Using 4×10^{-4} risk/cSv, this would permit a 65-year-old person to accumulate a risk 26 times greater than the Supreme Court's 10^{-3} per lifetime guide. These considerations weigh heavily in the judgment that must be made on valuation of dose reduction for occupational exposures.

For non-occupational exposures, the Food and Drug Administration and the Environmental Protection Agency (EPA 1985) consider a lifetime cancer risk of 10^{-6} as insignificant and, therefore, clearly acceptable (Hallenbeck and Cunningham 1981). This risk is about one-tenth the negligible individual risk level of 10^{-5}/lifetime employed by the NCRP (NCRP 1987). The Nuclear Regulatory Commission in its Below Regulatory Concern (BRC) Policy (NRC 1990) implies an annual risk of 5×10^{-6} for individuals and 5×10^{-7} for populations are below regulatory concern. These were related to dose rates of 0.01 and 0.001 cSv/yr based on estimates of 5×10^{-4}/cSv for the general public.

An IAEA working group (IAEA 1990) has recently recommended values of 10 μSv/yr and 1 μSv/yr (0.1 mrem/yr) as limits for dose to the public from safety-related and non-safety-related consumer products, respectively.

The above values are compared with existing dose limits on Figure 1.

LIMITS ON ALARA?

The ALARA (optimization) process should be applied throughout the range of doses shown on Figure 1, from the dose limits down, even into areas of background radiation. Throughout this application, one should always consider both differential costs and differential benefits. Since it is the ratio of these two values that determines cost-effectiveness, which should be compared to the value of dose reduction, even doses below regulatory concern or below negligible individual risk levels should be considered. If the cost or effort is negligible, even a negligible (comparable) risk should be avoided.

The process will be self-limiting if costs of doing evaluations are included in the total since when the collective doses are small, the costs will be large in comparison and one soon reaches a point of no net benefit, or excessive large cost-effectiveness values ($/cSv). At this point, the process should stop.

Regulatory agencies are required to do cost-benefit evaluations in arriving at BRC, exempt, or trivial levels. However, there may still be need for some consideration of ALARA by those exempt from regulatory pressures. This can be the case, for example, if large numbers of individuals may be exposed and if simple (low cost) efforts could be implemented to avoid these small doses.

MONETARY VALUES OF DOSE REDUCTION

Application of quantitative methods in the ALARA process is essential if consistent, rationale, documentable, and coherent decisions are to be made. The level of effort must, of course, bear some reasonable relationship to potential dose savings that may be made.

To apply quantitative thinking to the decision process, a monetary value for dose reduction is needed. This value in $/cSv (or $/rem) can be used in cost-benefit studies as suggested by the ICRP in its Publications 22 (ICRP 1973), 26 (ICRP 1977a), 27 (ICRP 1977b), 37 (ICRP 1983), 45 (ICRP 1985), and 55 (ICRP, 1989). It can also be used as a cost-effectiveness guide in comparing and prioritizing various options for dose control in the design or operational phases of facilities (Baum and Matthews 1985).

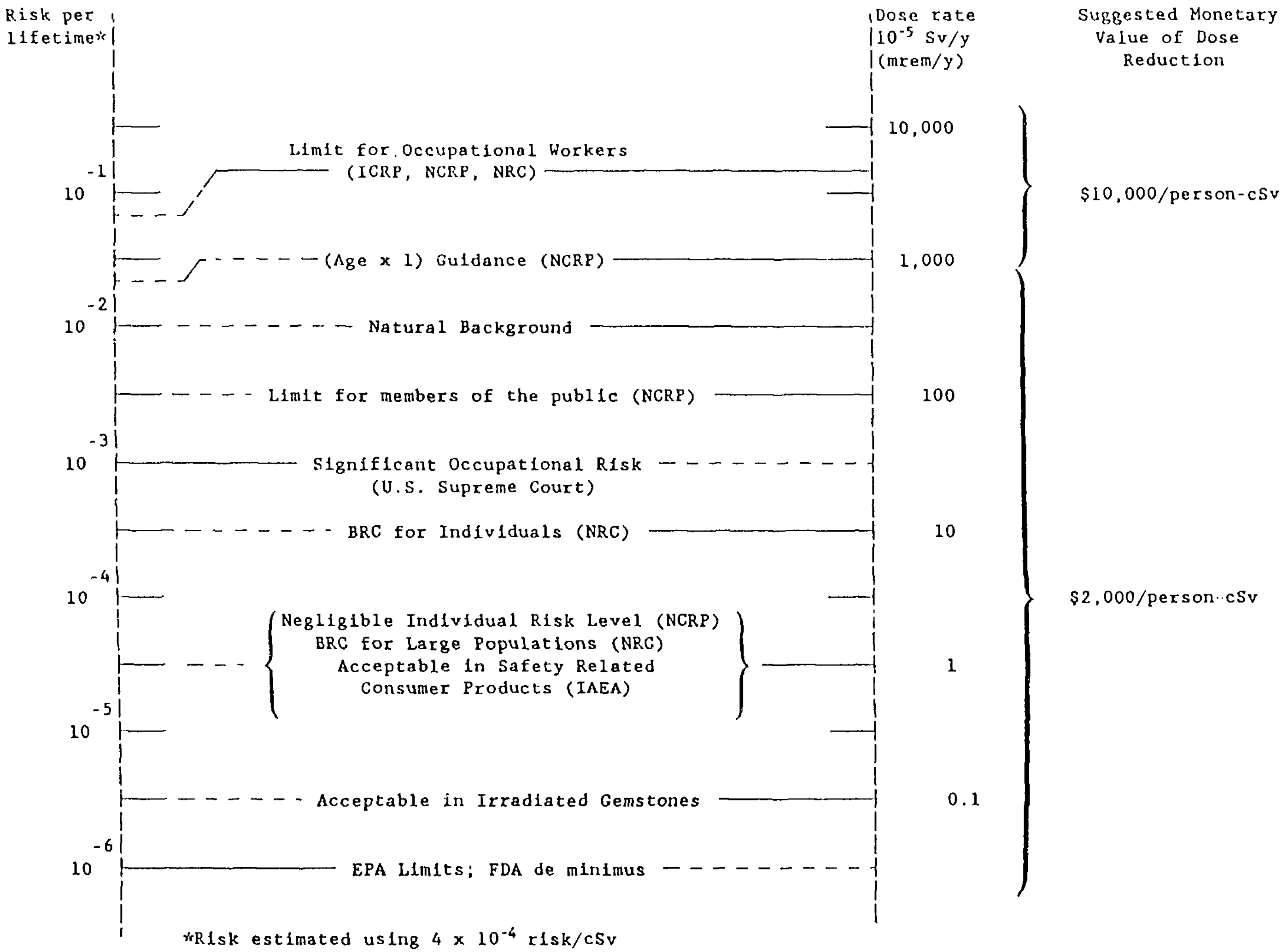

Figure 1. Comparisons of risk/lifetime, recommendations, dose rates, and suggested monetary value of dose reduction.

A review of previous thinking on the value of dose reduction and the related value of "statistical life" has been made to provide a basis for recommendations of an appropriate value for dose avoided. Results are summarized in Tables I through VI and discussed below.

Table I summarizes information available in the early 1970's. The values cited are from ICRP Publication 22 (ICRP 1973). Values were adjusted for inflation to reflect 1990 costs, and adjusted (increased) for higher 1990 risk estimates (BEIR V 1990). This latter adjustment is based on the assumption that larger values would have ((or should be) used if risks are found to be higher. Adjusted values range from $140 to $3,400 per person-cSv. These early values were based on rather little data or analysis and were specifically for doses low in comparison to dose limits. A medium value based on these findings would be about $2,400/person-cSv (1990 risk adjusted values).

Table I. Monetary Value of Dose Reduction Based on ICRP 1973 Summary

Author	Dollars/person-cSv in ICRP-22	1990 Equivalent* Dollars/person-cSv	1990 Values Adjusted for New Risk Estimates**
Dunster/ McLean	10 - 25	34 - 85	140 - 340
Hedgran/ Lindell	100 - 250	340 - 850	1,400 - 3,400
Otway	200	680	2,700
Lederberg	100 - 250	340 - 850	1,400 - 3,400
Cohen	250	850	3,400
Sagan	30	100	410
		Mean	≈ $1,900/person-cSv
		Median	≈ $2,400/person-cSv

* 1990 values adjusted for inflation are estimated as 3.4 times the 1970 values based on purchasing power of the dollar as reflected in consumer prices (U.S. Bureau of Census 1989).

** 1990 values were increased by a factor of four to account for higher 1990 risk estimates (BEIR V 1990) compared to a value of 10^{-4} commonly used in the 1970's.

In the early 1970's, the Atomic Energy Commission (now the Nuclear Regulatory Commission) suggested the use of \$1,000/person-cSv be used in evaluating costs and benefits of off-site exposures during design of nuclear power plants (AEC 1971). The same value was utilized by the NRC in 10 CFR 50 Appendix I (NRC 1975). This latter value and other values that have been used in U.S. nuclear facilities are summarized in Table II. Original values have been adjusted for inflation and new risk estimates to provide in 1990 dollars an equivalent monetary value per unit risk reduction or life saved. The studies of DOE contractor facilities by Gilchrist et al. (Gilchrist 1978) revealed that values between \$1,000 and \$10,000 per person-cSv were being employed in the 1970's. Discussions at a recent workshop (Baum, et al. 1989) revealed a similar range (\$1,000 - \$20,000) was being employed by DOE contractors at U.S. nuclear power plants in 1989, with most plants using about \$5,000. A 1989-90 study of major DOE facilities (Dionne, et al. 1990) revealed several were using a range from \$2,000 to \$60,000 as suggested by Kathren, et al. (Kathren, et al. 1980). The more recent values reflect not only the possible health effects detriments, but also some costs associated with operations such as hiring and training additional crews especially for high dose jobs. They may also reflect a trend toward greater acceptance of the "willingness to pay" approach to valuation of detriment rather than the older "human capital" and medical costs approach, and greater public and worker perception and concerns with safety, especially radiation.

The median value obtained from the four sources listed in Table II is \$10,000 per person-cSv. All values seem to reflect the earlier \$1,000 per person-cSv value which was an upper limit on values being proposed at that time.

Information from several studies on compensating wage differentials has been summarized recently (Jones-Lee 1989). In this approach, wage differentials are compared to risk differentials for various job categories to arrive at an implied value of "statistical" life. The value thus derived is, of course, biased and reflects more than just risk of death. Many of the higher risk jobs are lower wage brackets and thus may lead to underestimates of the average worker's willingness to accept risk for compensation. Counter-acting this bias is the fact that these higher risk jobs often involve discomfort, stress, or other disadvantages. These other factors presumably account for some of the wage differential.

Results of 9 U.S., 4 U.K., and 1 Austrian study are summarized in Table III. Values (in 1990 dollars) per statistical life range from \$250,000 for a study of differentials in the U.K. construction industry to \$15,000,000 for a study of various U.S. industries. The median value for all 14 studies was \$3,000,000 per life. Using a radiation risk coefficient of 4×10^{-4} (BEIR V 1990) risk/person-cSv (serious genetic effects plus fatal cancer) yields equivalent monetary value of dose reduction of \$3,000,000/life $\times 4 \times 10^{-4}$ life/person-cSv = \$1,200 per person-cSv.

Table II. Monetary Values of Dose Reduction
Used at U.S. Nuclear Facilities

Locations	Value Employed (dollar/person-cSv)	Approximate 1990 Equivalent Value Adjusted for Inflation and new risk estimates
Environs of Nuclear Power Plants (10CFR50, Appendix I)	$1,000 (1975)	$10,000*
DOE Facilities (1970's)	$1,000 (minimum)	$10,000
DOE Facilities (89-90)	$2,000 (minimum)	$4,000**
Nuclear Power Plants (89)	$1,000 - $20,000	$10,000**(avg.)
	Mean	≈ $7,000
	Median	≈ $10,000

*Adjusted for inflation using a 2.5 factor since 1975 and adjusted for higher 1990 risk estimates using a factor of four over 1970's values.

**Adjusted for risk estimates by a factor of only two since the 1989 values employed may have included some adjustments in anticipation of higher risk estimates.

Table III. Value of Statistical Life Based On Compensating Wage Differentials (1990 U. S. Dollars)*

Author(s)	Study Year (Country)	Estimated Value of Statistical Life In 1990 U.S. Dollars
Thaler and Rosen (1973)	1967 (USA)	$800,000
Smith, R.S. (1973)	1973 (USA)	$15,000,000
Melinek (1974)	1971 (UK)	$1,900,00
Smith, R.S. (1976)	1976 (USA)	$4,700,000
Viscusi (1978)	1969 (USA)	$4,900,000
Veljanovksi (1978)	1970 (UK)	$8,700,000
Dillingham (1979)	1970 (USA)	$760,000
Brown (1980)	1967 (USA)	$2,400.000
Needleman (1980)	1968 (UK)	$250,000
Olson (1981)	1973 (USA)	$10,000,000
Maria & Psacharopoulos (1982)	1975 (UK)	$3,600,000
Smith, V.K. (1983)	1978 (USA)	$1,100,000
Arnould & Nichols (1983)	1970 (USA)	$780,00
Weiss et al. (1986)	1981 (Austria)	$6,200,000
	Mean	≈$4,360,000
	Median	≈$3,000,000

$$\text{Implied Value of dose reduction} = \frac{\$3{,}000{,}00}{\text{life}} \times \frac{4\text{x}10^{-4}\ \text{life}}{\text{person-cSv}}$$

$$= \$1{,}200/\text{person-cSv}$$

*After Jones-Lee 1989, adjusted for inflation since study year.

Another approach to arrive at a value that reflects the average person's willingness to pay for risk reduction is through use of questionnaires. A number of major studies were summarized by Jones-Lee (Jones-Lee 1989). Results based on these are compared with a combined result from six smaller questionnaire studies reported by Cohen (Cohen 1980). In Cohen's studies, questions were asked of about 100 students in a course on energy and environment at the University of Pittsburgh in two successive years. The results of these surveys are shown in Table IV. Student answers yielded values from $40,000/life saved for safer cigarettes to $50,000,000 in electric rates per life saved by reductions of 1 in a million risk from a nuclear power plant. This set of results yielded a mean value of $2,300,000 per life saved and a median of about $3,800,000 (both in 1990 dollars). There is good agreement between Cohen's median value and the median value obtained from all values listed in Table V. These median values are also very consistent with the large and most recent study by Jones-Lee (Jones-Lee 1989) of willingness to pay for transport safety in the U.K.

Many highly cost-effective health and safety options have been cited by various reviewers (e.g., Cohen 1980; Siddall 1981; Graham and Vaupel 1981). Graham and Vaupel cite several options that would not only save lives but also save in costs (e.g., medical and/or property savings exceed costs of implementation). These include several traffic and auto safety actions such as mandatory air bags, mandatory passive seat belts, 55 mph speed limit, roadside hazard removal, vehicle inspection, traffic enforcement, and compulsory helmet usage by motorcyclists. Other examples in the area of home safety include a clothing flammability law and mandatory smoke detectors. The wide range of costs per life saved in medical screening, traffic safety and home safety options reveals a lack of consistency in how society spends its health and safety dollars. This inconsistency has many causes including strong influences of public perception and the difficulty of judging values and probabilities when small risks are involved. Knowing the cost-effectiveness of many of the other options, one tends to avoid excessive expenditures in any given area in hopes that at least a portion of the money thus saved would be used for more effective measures.

Since these other options are so numerous and lacking in robustness, they are not included in the listings employed here.

Table IV. Results of Student Questionnaire
on Willingness to pay for risk reduction (Cohen 1980)*

Proposed Safety Action	1990 Dollars/Statistical Life
10^{-6} reduction of nuclear risks	$125.000,000
10^{-3} reduction of coal plant risks	$300,000
Gov. Health Plan to save 1,000 lives	$6,250,000
Air bags in autos	$1,250,000
Safer cigarettes	$100,000
Safer transportation	$6,500,000
	Mean ≈ $2,300,000
	Median ≈ $3,800,000

*Values in Cohen were increased by a factor 2.5 to adjust for inflation since 1975.

Table V. Questionnaire estimates of the value of statistical life (based on Jones-Lee 1989 and Cohen 1980)

Authors	Nature of Study	Estimated Value of Statistical Life in 1990 U.S. Dollars
Acton (1973)	Small non-random[c] sample survey (n=93) of willingness to pay for heart attack ambulance (USA)	93,000
Melinek et al. (1973)	Non-random sample survey (n=873) of willingness to pay for domestic fire safety (UK)	480,000
Melinek et al. (1973)	Non-random sample survey (n=873) of willingness to pay for hypothetical "safe" cigarettes (UK)	150,000
Cohen (1975)	Student surveys	3,800,000
Maclean (1979)	Quota sample survey (n=325) of willingness to pay for domestic fire safety (UK)	4,700,000
Frankel (1979)	Small, non-random sample survey (n=169) of willingness to pay for elimination of small airline risk (USA)[c]	22,000,000
Frankel (1979)	Small, non-random sample survey (n=169) of willingness to pay for elimination of large airline risk (USA)[c]	95,000
Jones-Lee et al. (1985)	Large, random sample survey (n=1,150) of willingness to pay for transport safety (UK)	3,500,000
	Mean	≈ 7,300,000
	Median	≈ 3,500,000

Implied value of dose reduction=$3,500,000/life x 4 x 10^{-4} life/person-cSv
=$1,400/person-cSv

ADMINISTRATIVE, REGULATORY AND COURT GUIDANCE

Estimated costs/life saved for EPA's 1970 Clean Air Act ranged from 0 (Koshal and Koshal 1973) to $100,000 (Crocker, et al. 1979) for source air pollution control, and $7,800,000 (Council on Wage and Price Stability 1978) for control of carcinogens in water. These values can be compared to the 1975 NRC recommended value of $1,000/person-cSv for use in design of reactor effluent control systems. As shown in Table I, after adjustment for inflation and more recent risk factors, this yields $10,000/person-cSv or an equivalent value of $25,000,000/life saved. This is considerably more than required to meet limits in the EPA Clear Air Act or proposed limits on carcinogens in water (Graham and Vaupel 1981).

The Supreme Court's decision on OSHA's benzene standard was made in 1980 (U.S. Supreme Court 1980). The Court at that time affirmed a decision of the Court of Appeals for the 5th Circuit that had overturned the 1978 OSHA regulation on benzene. This regulation had reduced permitted 8-hr. time averaged exposures from 10 ppm to 1 ppm. The Court cited insufficient evidence of benefit based on work suggesting that the 1 ppm standard would avert only two cancer deaths every six years. Ignoring capital costs and using OSHA's estimate of $34 million/yr in 1978 operating costs, it appeared that the 1 ppm standard would cost $102 million per life saved (Graham and Vaupel, 1981). The Court based its decision on the criterion that the rule must provide a "significant" reduction of a "significant health risk."

Thus, when epidemiological studies on benzene and several quantitation risk assessments were published in the 1980's that indicated risks of 44 to 152 excess deaths per 1,000 workers exposed for 45 years at the 10 ppm level, OSHA reimposed the 1 ppm regulation in 1987 (U.S. Department of Labor 1987). Based on numbers of workers exposed, concentrations, and the newer risk estimates, about 5 leukemia cases per year could have been averted (Nicholson and Landrigan 1989) using the lower standard at a cost in 1990 dollars of about $68 million/yr or about $14 million per leukemia avoided. This is equivalent to an expenditure of about $5,600 per person-cSv based on risk estimates discussed earlier.

DISCUSSION

It should be noted that the Supreme Court does not use the term "significant" as defining a region below which risk is insignificant (or trivial) as evidenced by their suggestion that "a reasonable person might well consider the risk significant and take appropriate steps to reduce or eliminate it" (U.S. Supreme Court 1980). The OSHA 1 ppm benzene limit was imposed to reduce average worker risk to about 5×10^{-5}/yr at a cost of about $14,000,000/leukemia averted.

The U.S. nuclear industry is currently spending about $10,000/person-cSv for dose reduction efforts, or about $25,000,000 per cancer plus major genetic effects averted. This is about ten times higher than would be expected based on wage differential studies and societies' willingness to pay based on questionnaire studies. The difference may partly be a carryover of high values employed in the 1970's for reactor safety related to public exposures, which were projected to be small. The costs to avoid these small exposures in comparison to total plant costs were apparently justified even if not consistent with the cost-effectiveness of safety expenditures in other areas of public safety. A large part of the value of dose reduction currently employed at nuclear power plants may also reflect the costs of hiring additional workers to avoid individuals approaching their dose limits insurance and litigation costs, and other non-quantifiable factors such as worker and public relations concerns.

Table VI summarizes median values derived from the above studies.

Table VI. Summary of Results

Basic	Median Values 1990 Dollars/person-cSv
ICRP 73 Review	$2,400
U.S. Nuclear Facilities	$10,000
Wage Differentials	$1,200
Questionnaires	$1,400
	Mean ≈ $3,800
	Median ≈ $1,900

RECOMMENDATIONS

Considering the results from various studies and recommendations reviewed above, it appears that expenditures for radiation risk reduction in the U.S. have, in general, been in keeping with the 1970's guidance of the NRC, which was concerned with exposures to the general public. However, the Supreme Court's suggestions that significant health risk means about 10^{-3} risk over a worker's lifetime raises the question whether nuclear power plants should have an average of <60 mrem/yr/worker as an equivalent (in risk) goal. To achieve this objective, a nominal value for dose reduction of $2,000/person-cSv (the approximate median of values in

Table VI) is recommended for most operations and typical facilities. For exposures involving workers who may approach or exceed one cSv/yr, a higher value of $10,000/person-cSv is recommended in order to keep their exposures below the NCRP recommended (age x 1) guideline. This higher value is the approximate median of 1990 adjusted values employed at U.S. nuclear facilities as shown in Table II and is consistent with (about twice) the equivalent values related to the benzene standard. Since this value is related to an expenditure of an estimated $125,000,000 per fatality, it also seems bordering on the unreasonable based on data from other studies reviewed here. These monetary values are shown in Figure 1 along with the risk and dose guidelines discussed above. In using these values, one must, of course, bear in mind the uncertainties in the estimates of dose saved, risk per unit dose, and value placed on risk reduction. There is still a need for a judgment in the final decision process.

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