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LAWRENCE LIVERMORE LABORATORY
University of California/Livermore, California

THE SOCIOECONOMIC IMPACT OF LOW-LEVEL
TRITIUM RELEASES TO THE ENVIRONMENT*

Jerry J. Cohen
Gary H. Higgins

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THE SOCIOECONOMIC IMPACT OF LOW-LEVEL TRITIUM RELEASES TO THE ENVIRONMENT*

Jerry J. Cohen and Gary H. Higgins

Lawrence Livermore Laboratory, Livermore, California 94550

ABSTRACT

In accordance with current guidance, tritium releases must be kept below quantities where MPC levels are exceeded, and should be kept as low as "practicable." Determination of practicability requires an analysis of benefit versus risk considerations.

Such an analysis has been performed for certain general cases. It is based on a mer value of \$250 (a "mer" is the amount of benefit required to justify a radiation exposure of one man-rem) and considers the nature of tritium distribution in the biosphere as well as certain demographic factors. It also assumes that constraints imposed by exposure guides are observed. The analysis indicates that sums greater than ~\$0.10/Ci spent for the control of low-level tritium releases might be considered more than would be justified by the environmental risk.

The assumptions and calculations are reviewed in detail. The possible social and moral implications of such an analysis are also discussed.

Work performed under the auspices of the U. S. Atomic Energy Commission.

The development of nuclear energy has been accompanied by an increasing concern over tritium releases to the environment. Over the past 10 years research on the subject has proliferated. The rate of publications on health implications of environmental tritium is shown in Fig. 1. This information indicates an increase of approximately 20-fold in the number of these publications over the past 10 years. Also shown, for purposes of comparison, is the number of publications related to krypton-85.

Elaborate systems are being developed for the reduction of tritium produced and released from reactors. In the Plowshare Program, large sums of money have been expended toward the development of a low tritium-producing nuclear explosive for gas well stimulation. With all this activity and concern, one might well reflect on the question, "How serious is the tritium problem?" Research begets more research, and quite often we can get so involved exploring the details and intricacies of a subject that we can easily lose our general perspective. It is the purpose of this paper to explore the position of tritium in the scheme of things, or stated differently, to determine the social and economic impact associated with environmental tritium.

This determination requires some basis for comparison that will be commonly understood; a scale, if you will, on which to measure the seriousness of the problem. For this purpose, we shall make use of a form of benefit-risk analysis.

As has been stated many times, the risk of radiation exposure should be balanced against any benefit associated with such exposure. Some studies

involving benefit-risk analysis have already been performed,¹⁻³ although these are still at a preliminary level. The objective of benefit-risk analysis is to determine rational, definitive, and generally accepted means of evaluating the potential benefits of any given operation, or technology against the possible risks.

Two years ago, the use of a new unit called the "mer" was proposed.⁴ The mer is defined as that amount of benefit required to justify an exposure to 1 rem. The tangible and, hopefully, comprehensive mer equivalents proposed were 25 days of life, 2000 motor vehicle miles and, most important, \$250. Use of the latter figure would conveniently enable one to calculate, in dollars, the biological cost of various radiation exposures, and compare this to the cost of remedial measures necessary to reduce or avoid such exposures. This approach implies a monetary value for a statistical human life, specifically \$250,000.⁴

Some scientists have objected to assigning such values for low-level radiation doses and/or statistical human life.⁵ These objections range from morality implications to dispute over linear extrapolation of radiation damage from high to low doses. We can understand most of these arguments, particularly when applied from the viewpoint of any given individual who compares his own risk to his own benefit, using his own prejudice or opinion. If it is averaged over large enough groups, however, we believe this approach is neither immoral nor unreasonable; it is merely the explicit reflection of a type of value judgment which frequently is made by society.

The value of the mer was originally determined partially on the basis of a poll of individuals professionally knowledgeable on radiological

effects. Subsequently, other authors⁶⁻⁹ (Table 1), using various assumptions, have also provided estimates on the monetary value of biological damage due to radiation exposure. Despite the varying assumptions on which they are based, these estimates show a remarkable consistency. The \$250 we have chosen is the highest, or most conservative, of these values. As we apply it, we assume a linear relationship for radiation damage which also results in a very conservative estimate of the environmental cost.

Other assumptions we shall use in our analysis are:

1. All activities are conducted in such a manner that the limits set by all appropriate standards and guidelines are not exceeded.
2. MPC limits are valid indicators of human exposure. Anyone continually exposed to the 168 hr/week exposure limit for uncontrolled areas would receive an exposure of 500 mrem/yr, and this relationship may be linearly scaled.
3. Any quantity of released tritium could, in time, expose everyone in the world to its potential effect.
4. The environmental half-life for tritium is equal to its radiological half-life, and its mean environmental residence time (MERT) is equal to its mean radiological life. This conservatively infers that no "sink" which takes up tritium in such a manner to make it biologically unavailable exists in the biosphere. For tritium the MERT equals approximately 17 yr.

5. Some physical constants required for this analysis are:

- Mass of the atmosphere¹⁰ = 5×10^{21} g.
- Volume of the atmosphere (at NTP conditions, sea level, 0°C) = 4.2×10^{24} cm³.
- Volume of the hydrosphere¹⁰ = 1.41×10^{24} cm³.
- World population¹¹ = 3.5×10^9 .

Now, with this background, given the information that tritium has been released to the environment we can attempt to determine, in dollars, the worldwide biological damage that will be done.

The cost of radiation damage to human population is equal to the product of: Average individual exposure, times the number of individuals exposed, times the number of \$/man-rem, times the average duration of the exposure. The average exposure is equal to the average concentration of the radionuclide in the biosphere, divided by the appropriate MPC, times 0.50 rem/MPC. For example, the radiation damage cost which can be attributed to the releases of tritium to the atmosphere is:

$$\frac{0.5 \text{ rem/MPC-yr}}{4.2 \times 10^{18} \text{ m}^3 \times 2 \times 10^{-7} \text{ Ci/m}^3/\text{MPC}} \times 3.5 \times 10^9 \text{ people} \times 17.0 \text{ yr}$$

$$\left[\begin{array}{c} \text{Individual exposure} \\ \text{(rem/Ci-yr)} \end{array} \right] \quad \left(\begin{array}{c} \text{World popula-} \\ \text{tion} \end{array} \right) \quad \left(\text{MERT} \right)$$

$$\times \$250/\text{man-rem} = \$9.0/\text{Ci}$$

$$\left(\begin{array}{c} \text{mer} \end{array} \right) \quad \left(\begin{array}{c} \text{Cost of} \\ \text{biological} \\ \text{damage} \end{array} \right)$$

Note that the MPC used is that for air. If the tritium were released to the hydrosphere both the volume for dilution and MPC would be different and the value obtained is then only 0.002 \$/Ci.

Tritium released to the biosphere partitions between the hydrosphere and the atmosphere. Jacobs¹² (Table 2) predicted dose rates due to accumulation of tritium in the world. He postulated that tritium would accumulate in the hydrosphere, but assumed only the top 75 m of the ocean was available for dilution. He concluded that the annual dose rate from each curie of environmental tritium would be about 10^{-14} rem/yr. Using this value in the first term labeled "exposure" in the equation above, we obtain:

$$10^{-14} \text{ rem/Ci-yr} \times 3.5 \times 10^9 \text{ people} \times 17 \text{ yr} \times \$250/\text{man-rem} = \$0.15/\text{Ci}.$$

The present inventory of the world supply of tritium is due to that naturally formed plus that which is man-made, largely from the atmospheric weapons tests of the late 1950's and early 1960's. Begemann¹³ estimated this is distributed 99.8% in the hydrosphere and 0.2% in the atmosphere. If new releases of tritium distribute in this way, the average biological damage cost is about \$0.02/Ci.

Tritium formed naturally in the upper atmosphere is distributed approximately 90% in the hydrosphere and 10% in the atmosphere.¹³ Assuming this latter distribution, a biological damage cost of ~\$0.90/Ci can be determined. This information is summarized in Table 3.

There seems to be no way to be certain which distribution will apply; however, prejudice seems to be that new releases will distribute

more like the previous releases of man-made tritium. In any event, the value \$0.90/Ci probably represents an upper limit and the value \$0.10/Ci seems a reasonable order-of-magnitude estimate which we will use in future discussions. This is slightly smaller than the value based on Jacobs' estimate. We believe it is reasonable to assume that over a 17-yr period some exchange should occur across the oceanic thermocline. This would increase the available hydrosphere from the 75-m depth used by Jacobs and therefore increase the dilution.

As a comparison, one may apply the same type of analysis to krypton-85 releases. In this case the calculations are less equivocal, since one may safely assume the atmosphere is the only region of dilution. The calculation follows:

$$\frac{0.5 \frac{\text{rem}}{\text{MPC-yr}} \times 3.5 \times 10^9 \text{ people} \times \$250/\text{man-rem} \times 15.5 \text{ yr}}{4.3 \times 10^{18} \text{ m}^3 \times 3 \times 10^{-7} \text{ Ci/m}^3\text{-MPC}} = \$5/\text{Ci}.$$

One practical application would be a quantitative evaluation of the radiation hazard associated with natural gas supplies stimulated by nuclear explosives as compared to the benefit which might be derived. To perform this analysis we can use the model of Werth et al.¹⁴ who considered a 28-well, nuclear-stimulated (N.S.) gas field supplying part of the total supply to the Los Angeles Basin. According to this model (Table 4), over the first 6 yr of operation 350 billion ft³ of N.S. gas will have been supplied. This gas will have had an average concentration of 4.25 pCi/cm³ of tritium and 27.5 pCi/cm³ of ⁸⁵Kr. Over the first 20 yr of operation,

the field will have produced about $9.3 \times 10^{11} \text{ ft}^3$ which may be assumed to be about half the total producible. During the first 6 yr of production, however, the wells will be purged of essentially all residual gaseous radioactivity. Over this period, the biological damage cost due to radiation exposure can be determined for both the local and worldwide population.

Nelburger¹⁵ estimates that under average Los Angeles meteorological conditions, the daily dispersive air volume $\approx 1.6 \times 10^{12} \text{ m}^3$. Based on an average of one air change per day, over the initial 6-yr period this would amount to a total of $\sim 3.5 \times 10^{15} \text{ m}^3$. Therefore, for tritium the cost of biological damage to the local population (risk) would be:

$$\frac{4.2 \times 10^4 \text{ Ci} \times 0.5 \frac{\text{rem}}{\text{MPC-yr}} \times 7 \times 10^6 \text{ people} \times \$250/\text{man-rem} \times 6 \text{ yr}}{3.5 \times 10^{15} \text{ m}^3 \times 2.7 \times 10^{-7} \text{ Ci/m}^3\text{-MPC}} = \$2.3 \times 10^5.$$

The above calculation assumes that all the tritium is released to the air only and, for local population, all exposure is via the air. For ⁸⁵Kr these same conditions would obviously hold, and the cost (risk) would be:

$$\frac{2.7 \times 10^5 \text{ Ci} \times 0.5 \frac{\text{rem}}{\text{MPC-yr}} \times 7 \times 10^6 \text{ people} \times \$250/\text{man-rem} \times 6 \text{ yr}}{3.5 \times 10^{15} \text{ m}^3 \times 3 \times 10^{-7} \text{ Ci/m}^3\text{-MPC}} = \$1.3 \times 10^6.$$

It is realized that exposures to the local population would not be uniform, and that certain individuals might receive doses far in excess of the average while others would receive far less. As previously stated, however, it is assumed that all exposures would remain below MPC levels. In fact, Werth et al.¹⁴ estimate that under the conditions assumed in the model, the maximum individual exposure (unvented heaters, tight building, etc.) would be 2.4 mrem/yr, well within exposure guidelines.

For worldwide population exposure, the biological damage costs would be:

$$\text{For tritium: } 4.2 \times 10^4 \text{ Ci} \times \$0.10/\text{Ci} = \$4.2 \times 10^3.$$

$$\text{For } ^{85}\text{Kr: } 2.7 \times 10^5 \text{ Ci} \times \$5/\text{Ci} = \$1.4 \times 10^6.$$

A summary of these costs is given in Table 5 which also shows the benefit from supplying this gas. This benefit is exactly equal to the price paid for it. If it were less the customer would not buy it; if it were more the suppliers would demand a larger price. (This is exactly true only in a free market. Natural gas prices are regulated, and for this commodity the value is only approximately equal to the price.) Thus, for an average consumer price of gas of \$0.60 per 1000 ft³ or more and an increment of gas equal to 350 billion ft³, the benefit is \$210 million. The benefit-risk ratios are therefore 369 or 72.4, depending on whether the entire production period is considered or only the 6 yr during which radioactivity is released. The ratio indicates that producing incremental gas via nuclear explosive stimulation may easily be considered of overall societal benefit, even though it carries some radioactivity. This conclusion would still be justified with quite different and larger values for the mer.

A "best environmental choice" of energy sources for a given consumer area requires benefit-risk analysis for each source. It is beyond the scope of this paper to perform a complete benefit-risk analysis of nuclear gas stimulation, but one other energy source can be compared using this approach. Nuclear power reactors produce almost 10^{-3} Ci of tritium and 0.02 Ci of ⁸⁵Kr per MWh(e). According to our previous

example, a Flowshare-associated natural gas would contain about 10^{-4} Ci of tritium and 0.008 Ci of ^{85}Kr per MWh ($1000 \text{ ft}^3 \approx 10^6 \text{ BTU} \approx 0.3 \text{ MWh}$). It can therefore be seen that per unit energy produced, the gas would be a better environmental choice. We must hasten to add that this is not a condemnation of nuclear power reactors. The electrical energy from reactors is, of course, not the same as the thermal energy from the combustion of gas. At current prices, per unit of energy, the electricity sells for about five times more than the gas. Additionally, not all the tritium and ^{85}Kr is released from a reactor, although practice varies from reactor to reactor and time to time.

Currently, and for the foreseeable future, the major producer of radioactivity will be nuclear-fission-powered reactors. Table 6 shows the quantities of tritium and ^{85}Kr produced in typical reactor operations.¹⁶ The relative biological damage cost due to release of these nuclides is \$2.50 and \$2500 per MW(e)-yr, respectively. These figures, when viewed in light of those in Fig. 1, indicate that perhaps our priorities have been misplaced. The effort devoted to the study of the biological effects of tritium seems out of proportion to those devoted to ^{85}Kr , and the expenditures made to reduce both may be out of all proportion to their impact on mankind. This would be especially true if suggestions for the elevation of the MPC values for tritium¹⁷ by a factor of 10 to 100 and of ^{85}Kr (Ref. 13) by a factor of 40 are accepted. Any increase in the MPC will reduce the cost of biological damage per curie.

Determination of the biological cost of released radioactivity in monetary terms can be a powerful tool to use in benefit-risk evaluations such as those now required by the National Environmental Policy Act. At least, it can provide a definitive basis for judgment.

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Table 1. Assumed biological cost of radiation damage.

Author	Cost (\$/man-rad)
Cohen (LLL), 1969	\$250.00
Hedgran, Lindell (Sweden), 1970	\$100.00
Dunster (UK), 1970	~\$ 10.00 ^a
Otway (LASL), 1971	\$200.00
Lederberg (Stanford), 1971	\$100.00

^a"A few pounds sterling."

Table 2. Predicted effect of tritium accumulation in the biosphere.^a

Year	Total accumulated tritium (10^6 Ci)	Av dose rate (rem/yr)	rem/Ci-yr
1970	0.3	2.8×10^{-9}	} $\sim 10^{-14}$
1975	2	1.5×10^{-8}	
1980	6	5.5×10^{-8}	
1985	16	1.5×10^{-7}	
1990	32	2.8×10^{-7}	
1995	58	5.0×10^{-7}	
2000	96	8.2×10^{-7}	

^a Data from Ref. 12.

Table 3. Environmental tritium partition and effect.

Basis	Relative Mix % atmosphere/hydrosphere	Estimated cost of biological damage (\$/Cl)
All Atmosphere	100/0	9.0
All Hydrosphere	0/100	0.002
Total World Tritium	0.2/99.8	0.02
Naturally Formed Tritium	10/90	0.9
Only top 75 m of		
hydrosphere are		
available for dilution		
(Jacobs' assumption)	0/100	0.15
Cohen - Higgins		
estimated cost	—	0.10

Table 4. Nuclear explosive stimulated natural gas supply to Los Angeles Basin.^a

Time period (yr)	Volume supplied (10 ⁹ ft ³)	Av concentration pCi/cm ³		Total curies	
		tritium	⁸⁵ Kr	tritium	⁸⁵ Kr
0 - 6	350	4.25	27.5	4.2×10^4	2.7×10^5
6 - 20	580	negligible	negligible	—	—
20 - ∞	~ 930	negligible	negligible	—	—
Total	1860	—	—	4.2×10^4	2.7×10^5

^aBased on model of Werth et al. for 28-well gas field.

(~ 9% of total L. A. supply for initial 6-yr period).

Table 5. Summary of data from Los Angeles Basin 28-well N. S. gas field (Werth Model).

A. Biological damage costs (risk), in dollars.

	To Local Population	To Worldwide Population	Total
Tritium	\$ 230,000	\$ 4,200	\$ 234,200
Krypton-85	1,300,000	1,400,000	2,700,000
Total	1,530,000	1,404,200	2,934,200

B. Benefit (assume price of gas to consumer = \$0.60/MCF).

Period	Total gas supplied	Consumer cost (benefit)
Initial 6 yr	$3.5 \times 10^{11} \text{ ft}^3$	$\$2.1 \times 10^8$
Total	$1.86 \times 10^{12} \text{ ft}^3$	$\$1.1 \times 10^9$

C. Benefit/risk ratio.

1. Only initial 6 yr considered

$$\frac{2.1 \times 10^8}{2.9 \times 10^6} = 72.4$$

2. Over total production period of gas field

$$\frac{1.1 \times 10^9}{2.9 \times 10^6} = 379.3$$

Table 6. Quantities of tritium and ⁸⁵Kr typically produced by nuclear power reactors (fission).

Nuclide	Production rate (Ci/MW(e)-yr)	\$/Ci	\$/MW(e)-yr
Tritium	~ 25	0.10	\$ 2.50
Krypton-85	~475	5.0	\$2500.00

FIGURE CAPTION

Fig. 1. Number of publications on health implications of tritium and krypton-85 exposure (Nuclear Science abstracts).

Cohen - Fig. 1