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A SYSTEMS ANALYSIS APPROACH TO NUCLEAR WASTE MANAGEMENT PROBLEMS

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I. Introduction

I am fortunate to have the opportunity of working in Vienna this year, and to participate in a joint research project of the International Atomic Energy Agency and the International Institute for Applied Systems Analysis. The primary task of this project is to study risk assessment principles and their application in judging the acceptability of technological developments. The primary focus has been on energy production systems, particularly nuclear energy.

Applied systems analysis is basically a means of providing a rational approach to problem solving by identifying and modeling interactions between the system under study and all other systems. This leads to a more thorough understanding of the system being studied and all its ramifications, thereby optimizing the decision-making process. Stated more simply, systems analysis is a way of thinking. It requires a clear statement of the elements of the problem, the objectives to be achieved, and the constraints under which one must operate. Having established these parameters, they are then modeled and by use of computers and other analytical tools, sensitivities of all factors are evaluated, effects of constraints are assessed, and optimal solutions derived within the framework of the stated objective functions.

This paper will discuss the application of systems analysis to the problem of nuclear waste management in general, and to off-gas treatment in particular. It will not deal with the details of modeling methods or calculations, but will concentrate on a discussion of the objectives and constraints which provide the framework for the analysis.

II. Determining Objectives and Constraints in Waste Management

The first and perhaps most difficult task is to determine the objective function. What is our desired objective in waste management? How would an acceptable solution be characterized? Pursuing this question, one might ask: Acceptable to whom? If the answer is: to the general public, then we are faced with another set of problems. How do we determine a priori what will constitute public acceptability? We know,

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for example, that in dealing with nuclear activities the public has a far different and more restrictive set of values and attitudes than in other technological areas. An understanding of the reasons for this disparity in viewpoints would be helpful in defining acceptable objectives. Levels of safety and environmental alterations which might prove to be quite acceptable in any other enterprise could, from the public's viewpoint, prove to be very objectionable if associated with some nuclear activity. For example, we are probably all familiar with the results of the Rasmussen Study [15] (Figure 1) which indicate that the probable hazard from nuclear reactors is far below those of other technologies which are relatively well accepted by the public. However, the extent to which such results go toward allaying public fears regarding nuclear energy is probably marginal at best. Public attitudes are formed by rather complex interactions of many factors [12]--mathematical probabilities being only one and, I suspect, not a very important one. Studies have shown that man is a rather poor intuitive statistician [14,17]. The success of lotteries demonstrates this point.

III. Public Acceptability of Risks

How then do we determine public acceptability of risks? This is a goal of our joint project on risk assessment. It might be of interest to know that the personnel working on our project are not only multi-national, currently representing eight nations, but also multi-disciplinary--including specialists in economics, sociology, psychology, psychiatry, and anthropology. Hopefully, this mix of physical and social scientists can achieve the necessary insights.

A possible clue to understanding societal response to technological risk situations may be obtained by viewing the sequence of events depicted in Figure 2. The sequence begins with the perception of a problem by some individual or group, after which it is called to the attention of the public. Publicizing the problem might take the form of a public address or perhaps a book. Rachel Carson's "Silent Spring" or Ralph Nader's "Unsafe at Any Speed" are examples. This stimulates discussion in the press and other communications media, which in turn arouses public concern. This concern may then be manifested as exerting pressure for action on public officials and legislative bodies. In technological areas--where remedies are not often apparent--research is funded to determine proper solutions. Hopefully, this research leads to a solution of the problem; but in fact, experience tells us this is seldom the case. Research reports and technical papers typically conclude with statements to the effect that: (1) the problem being investigated is indeed serious (nobody wants to work on trivial problems), (2) the results obtained to date are very encouraging, and (3) further study is certainly indicated.

In their desire to obtain continued funding for their project, researchers often tend to amplify or even exaggerate the seriousness of the problem. The news media then observe and publicize these findings, leading to further public concern, etc. Thus we have a self-perpetuating sequence of events. In time, public concern becomes reinforced to the extent that people become convinced of the extreme seriousness of the problem. They reason that if this were not the case, why would so much time, money, and effort have been expended? Perhaps in the field of nuclear waste management we are caught in such a cycle. One method of breaking this cycle might be to clearly define the problem and the desired objectives so that in the event a suitable solution is ever presented, it could at least be recognized as such!

A. Defining the Problem

A recent issue of Business Week contained an article entitled, "The Deadly Dilema of Nuclear Wastes" [18]. It contained the usual assortment of dire statements often found in the public press, i.e. that nuclear waste management is indeed a grave problem and that Pu-239 (its most dangerous long-term component) is the most hazardous substance known to man--so hazardous in fact that we are making a "Faustian bargain" in committing nuclear waste to the perpetual vigilance of future generations.

We have heard this type of argument so often that it has almost become an article of faith. I do not want to imply that Pu-239 is not a very dangerous material, but it is certainly not the most dangerous substance known to man. In fact, for interest's sake, I recently compiled a list of materials which, on the basis of per unit mass ingested, are more lethal than plutonium. On the list were such items as botulinus toxin, belladona, hemlock, oleander extract, certain bacteria and viruses, parathion and certain other insecticides--the list could be extended still further. However, it is also necessary to consider the persistence of Pu-239 with its half-life measured in tens of thousands of years.

Table 1 presents an interesting insight in this regard. In the year 2000, the projected quantity of Pu-239 committed to waste in the United States will be approximately 0.2 MCi^6. Assuming this to be one third of the world's total [2], we will have an annual worldwide waste production of 10^7 grams of this material. In the context of long-term waste commitment where ingestion would be the prevailing route of human exposure, this amounts to a production rate of roughly 3 x 10^7 lethal doses per year. Its persistence, as measured by its half-life, is approximately 24 thousand years.

Now let us look at another hazardous material: lead. By conservatively assuming that in 1973 [19], 10% of the total lead production is lost to waste, we have a waste commitment of 4×10^8 gm, which amounts to 4×10^7 lethal doses per year. If persistence is a major consideration, then lead with an infinite half-life is certainly a worse problem than plutonium. Yet we hear no advocates of rocketing waste lead to the sun, or talk of committing it to the bowels of the earth under perpetual surveillance. We hear no talk of Faustian bargains with this material, despite the fact that it will exist forever. Why?

I realize, of course, that the comparison is somewhat oversimplified by the fact that the effects of inhalation or chronic long-term low-dose exposures to either of these materials have not been considered; and both have such effects. I believe, however, that the comparison is <u>not</u> inappropriate and points up the inconsistency in public attitudes toward radioactivity as opposed to other hazards. In this regard, B.L. Cohen [4] of the Institute for Energy Analysis, USA, recently presented data indicating "that plutonium dispersal is neither a serious accident danger nor a very useful tool for terrorists". As regards nuclear waste management, Claiborne at Holifield National Laboratory, USA,[3] indicated that conventionally solidified waste could become less hazardous than naturally occuring pitchblende in tens of thousands of years. Our group at Lawrence Livermore Laboratory, USA, calculated that waste disposed of by the DUMP or in situ melt process would become 100-fold less hazardous than pitchblende in less than 1000 years [6]. Yet articles like "The Deadly Dilemma of Nuclear Waste" continue to appear, and we continue to search for an "acceptable" solution. Perhaps, as was stated previously, the effort might better be directed if we could at least define what constitutes an acceptable solution or objective.

Such an objective should be stated clearly, definitively, and preferably in quantifiable form. Platitudes and generalities, although they may prove politically expedient, constitute unworkable objective functions from a systems analysis standpoint. I refer here to such statements as, "to assure public health and safety". These only raise further questions such as, "how much assurance is needed?" Only where 100% absolute guaranteed safety is necessary would the solution be very easy. Where the only acceptable level of radioactivity resulting from nuclear operations is zero, then the one and only method of achieving this goal is to stop all nuclear activities. If, on the other hand, some level higher than zero is to be acceptable, then that level, or some optimization criteria, or cost-effectiveness guideline for achieving it should be clearly stated. Failure to do so can result in the squandering of large sums of money to achieve miniscule increments of safety--a practice not uncommon in the nuclear industry.

IV. Problems of Waste Gas Treatment

With this background then, let us look at the problem of waste gas treatment. The gases of primary concern at fuel reprocessing plants and waste management facilities appear to be krypton-85 and tritium. Since the environmental effects of these gases can be predicted with a minimum of equivocation, they lend themselves well to this type of demonstration. As a first step we shall specify our objectives and constraints:

OBJECTIVES

1. Minimize worldwide population radiation exposure;
2. Minimize costs.

CONSTRAINTS

1. Do not exceed radiation exposure standards.

For purposes of discussion these parameters have been simplified as much as possible. In the present case our constraint is that ICRP [13] and/or other appropriate standards must not be exceeded. The objectives are to minimize both cost and worldwide population exposure. One could, for example, choose as an objective to minimize exposures only to those residing within a fifty-mile radius of the point of release (as has conventionally been the practice). The objectives we have selected clearly imply some tradeoff between cost and population exposure: as the controls required for limiting exposure are increased, costs also increase and vice versa. Such tradeoffs are modeled in Figure 3. It can be seen that they follow the economic law of diminishing returns. It should be noted that in expenditures to reduce a particular hazard (either radiation or some other risk) at some given cost (C), the return per unit expenditure decreases as the total expenditure increases. It may also be noted that no matter how much money is expended, some further reduction could be attained by still further spending. Beyond some point, however, money might more efficiently be spent to reduce some other hazard. This point would be the intersection of the cost-effectiveness guideline and the diminishing-return curve. For radioactivity, a suggested cost-effectiveness guideline is approximately $200 per man-rem avoided [5]. This figure can be derived from guidance suggested by the BEIR (Biological Effects of Ionizing Radiation) Committee.

Table 2 gives source estimates for generation of tritium and krypton-85 from various activities [7,8]. Note particularly that in nuclear fission power reactors, krypton-85 production exceeds that of tritium by over an order of magnitude per unit of power production. Table 3 gives worldwide population dose estimates per curie of radioactivity released.

The resulting biological dose cost figures are based on the $200/per man-rem cost-effectiveness guideline. These figures indicate that for every curie of tritium released to the environment, a total of 10¢ worth of biological damage will result; therefore, expenditures for preventing tritium releases which are in excess of this figure could not be considered cost-effective. In other words, expenditures in excess of 10¢ per curie of tritium would be better allocated in other areas of health and safety where they would bring a greater return (in terms of hazard reduction) per unit investment. The cost-effectiveness guideline for krypton-85 is about $1.00 per curie. Therefore, because it is produced in greater quantities and causes greater harm per unit amount, one might conclude that krypton-85 control would be considered more worthy of attention than tritium control. This conclusion might be confirmed by viewing projected doses due to biospheric accumulation of these nuclides. Figure 4 indicates the effect of total tritium which is the sum of reactor produced, naturally produced, and residual tritium from atmospheric nuclear explosive testing. At present, the latter constitutes almost all of the biospheric burden. Reactor produced tritium is the only portion of the total over which we can exert any control. This amount will not become significant until the next century. Krypton-85, as we might suspect from the previous tables, produces a far greater exposure effect.

In light of this information, it is interesting to review some past practices--both in control measures and research relating to krypton-85 and tritium. Figure 5 compares levels of research effort on both nuclides as determined by the numbers of technical publications related to the health implications of population exposure. Here we find that the preponderance of the work has been devoted to tritium. From these data one might derive the hypothesis that the level of research effort bears little relationship to the severity of the problem. Pursuing this hypothesis, one might postulate a mystique associated with tritium which stimulates undue concern and is manifested by the expenditure of inordinately large sums of money on its study and on the development of control technology.

To cite a few potential examples of this phenomenon, Table 4 gives a summary of plans for reduction of tritium releases at the Savannah River Plant [9]. As can be seen from these data, their cost-effectiveness guideline for tritium control lies somewhere between $67,000 and $4.5 million per man-rem averted. Another example can be seen from the Rio Blanco experiment for nuclear gas stimulation in Colorado, where the tritium release control cost was $600,000 per man-rem averted [8]. Figure 6 shows a summary of tritium control costs for nuclear reactors [10]. From these we can estimate that with the currently available technology, the average cost for tritium control would be about $170,000 per man-rem averted.

On the other hand, at fuel reprocessing plants--the major source of krypton-85--it has been estimated that krypton-85 release control could be accomplished at a cost of about 4¢ per curie of $10 per man-rem averted [8]. Implementation of such controls is not presently required.

Obviously, in off-gas treatment and waste management programs, objectives and cost-effectiveness guidelines other than those we have suggested have been used although they may not have been explicitly stated. I believe it would clearly benefit the nuclear industry to better define rational approaches to radiation safety research and control.

Table 1. Long-term worldwide waste commitment.

	Plutonium-239 (Year-2000)	Lead (Year-1973)
Annual Waste Production (Gm/Yr)	1×10^7 (1)	4×10^8 (3)
Approximate Lethal Dose (Gm) (2)	0.4	10.0
Toxic Production Rate $\left(\frac{\text{Lethal Doses}}{\text{Year}}\right)$	3×10^7	4×10^7
Persistence (Half-life)	2.4×10^4 Yr	∞

Assumptions:

1. U.S. Projected for Yr. 2000 = 0.2 MCi (ORNL-4451)

   U.S. Nuclear Capacity in Yr. 2000 = 1/3 World Capacity (UCID-16670).

2. Via Ingestion of Soluble Material (see references [1] and [11]).

3. World Production (1973) - 4.2×10^3 Tons (U.S. Stat. Abs.). Assume 10% is lost to waste.

Table 2. Source term estimates.

Application		Estimated Potential Curies Released	
		^3H	^{85}Kr
Fission powered reactors (per MWe - Yr)	LWR	25	475
	LMFBR	35	430
Peaceful nuclear explosives (per kiloton yield)	Fission	33*	25
	Fusion	2×10^4	0
Controlled thermonuclear reactors (per MWe - Yr)	------	7	0

*Assumed upper limit based on announced values from the Rio Blanco event.

Table 3. Unit curie population dose and Biological Damage Cost estimates.

		^{3}H	^{85}Kr
Unit Release Population Dose (man-rem/ci)	Whole Body	4×10^{-4}	1.8×10^{-4}
	Skin		0.027
Biological Damage Cost ($/ci)		0.10	1.00

Table 4. Savannah river plant data [9].

Reduction Approaches or Plans for Tritium Releases

Source	Reduction Potential, man-rem	Cost $ 10^6	$/Man-Rem	Status
Reactor Leakage				
Leak Reduction	15	1	67,000	Under way
Reduction Inventory				
DW Plant	67	300 65	4,500,000	Rejected
GS Plant	67	300 55	4,500,000	Rejected
F.P. Tritium				
Collect, Store, Decay	6	65 2.5	10,800,000	Rejected
Product Tritium				
Leak Collection, Stripping	6	0.1	16,700	Under way
Hold Tanks, Strippers	75	10	134,000	Under Study
Inert Gas Systems		50	-	Under Study

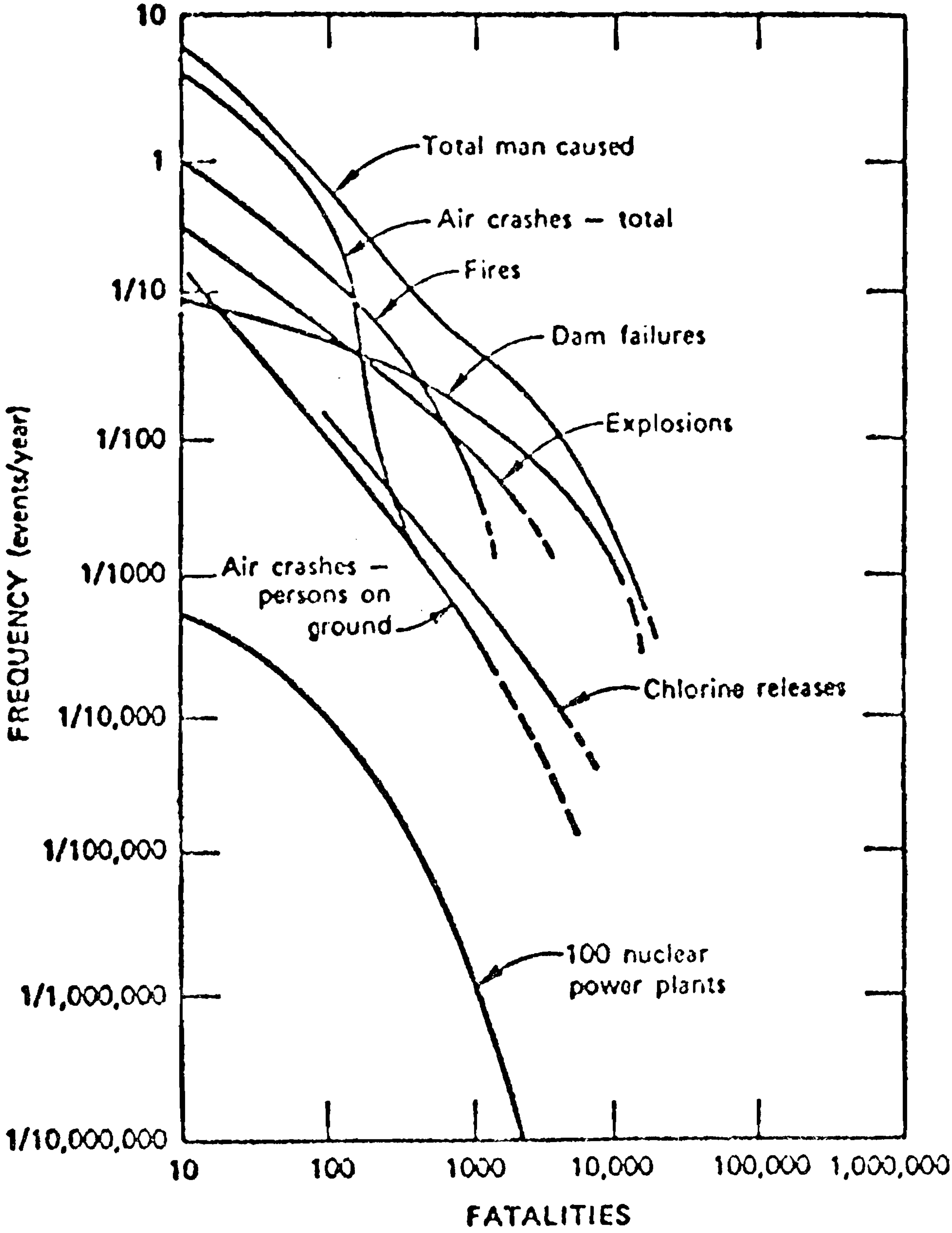


Figure 1. Frequency of fatalities due to man-caused events.

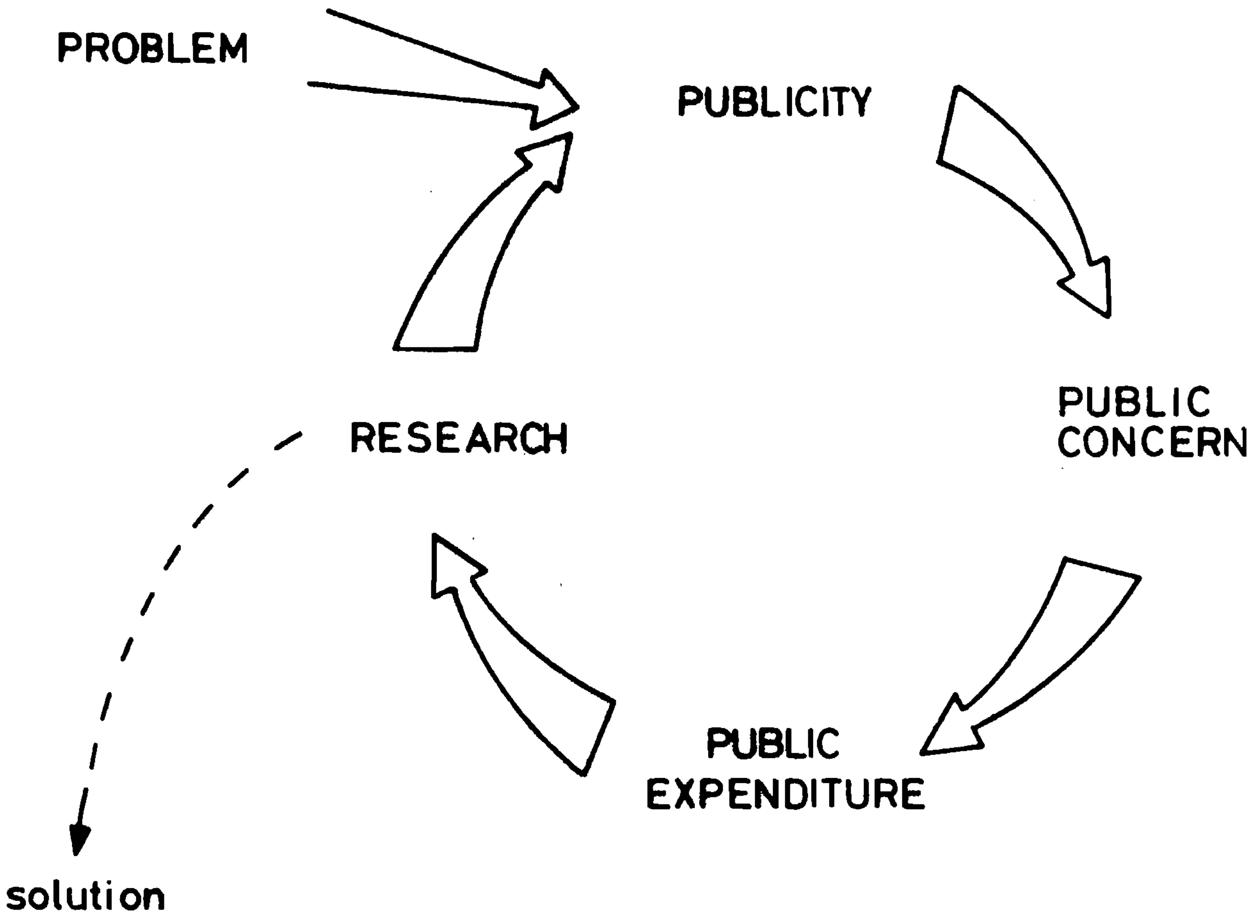

PROBLEM
PUBLICITY
PUBLIC CONCERN
PUBLIC EXPENDITURE
RESEARCH
solution

Figure 2 .

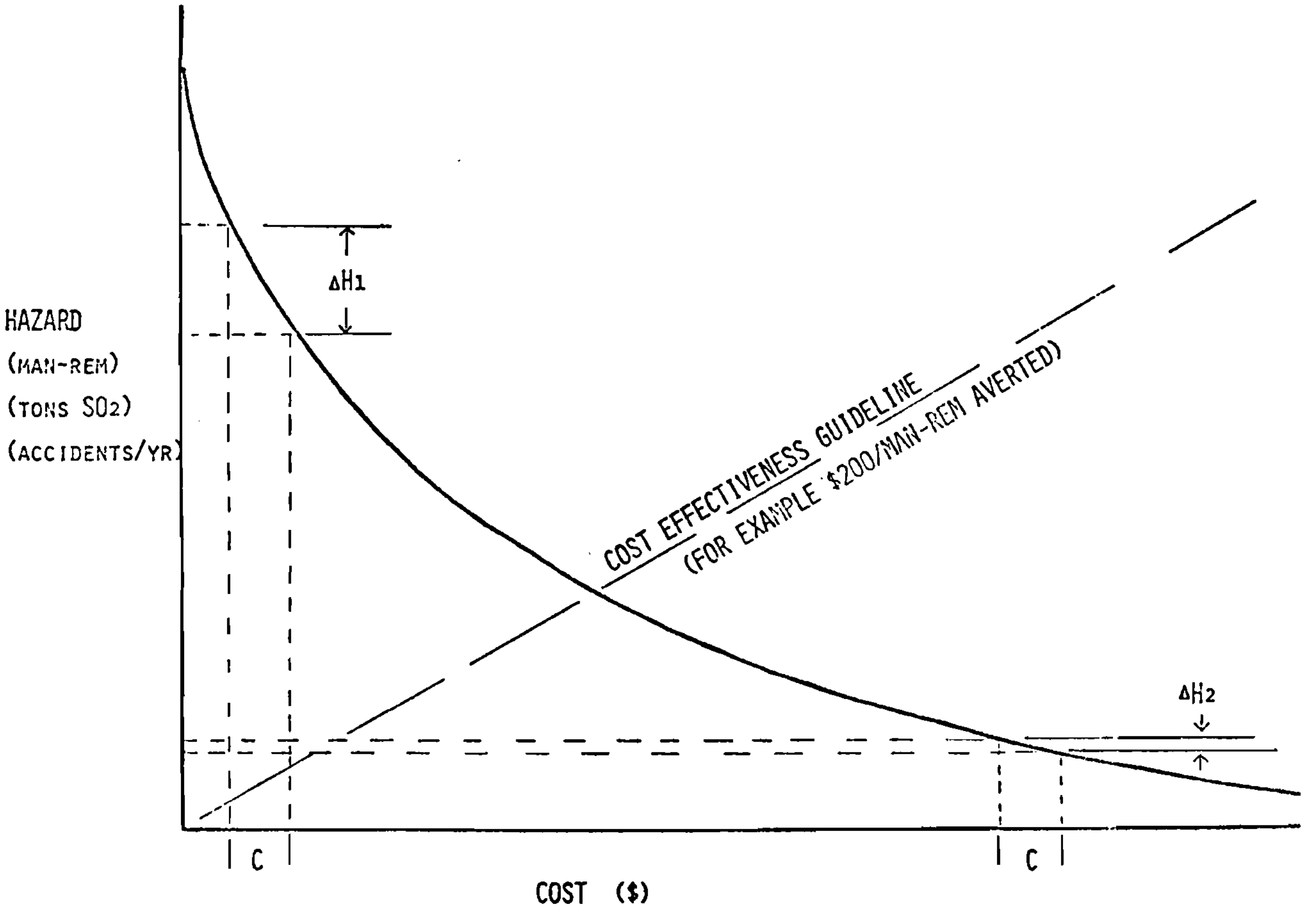

HAZARD
(MAN-REM)
(TONS SO2)
(ACCIDENTS/YR)
ΔH1
ΔH2
COST EFFECTIVENESS GUIDELINE
(FOR EXAMPLE $200/MAN-REM AVERTED)
C
C
COST ($)

Figure 3.

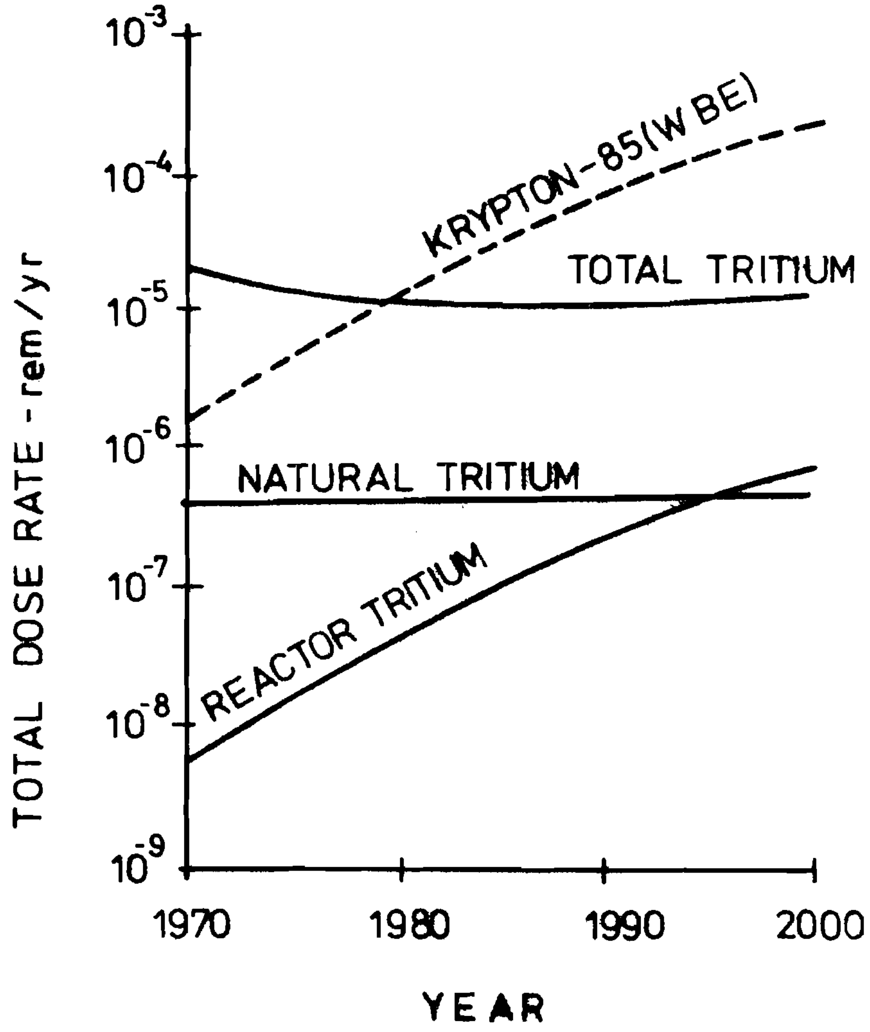


Figure 4. Whole body dose from Biospheric Accumulation.

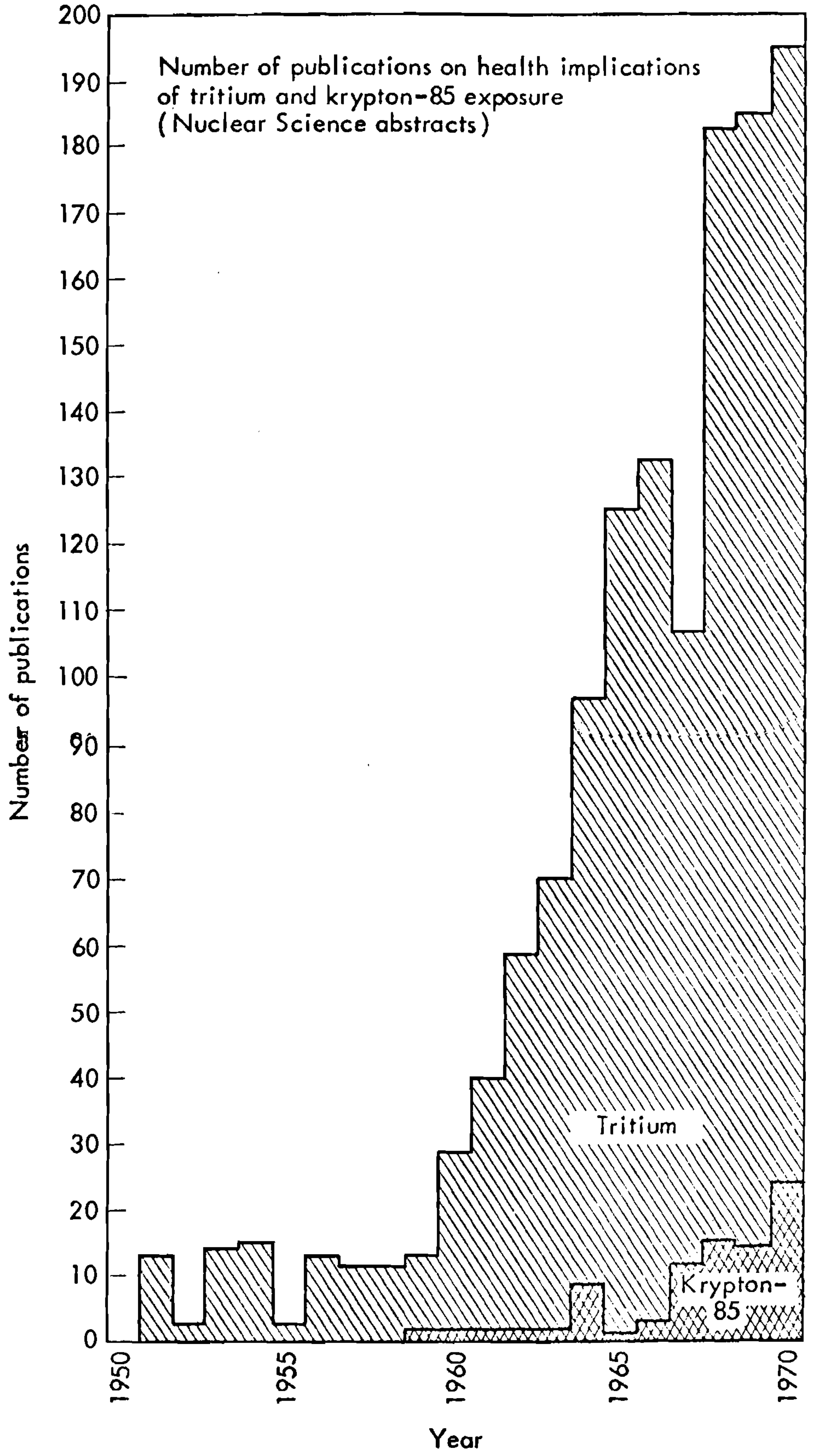
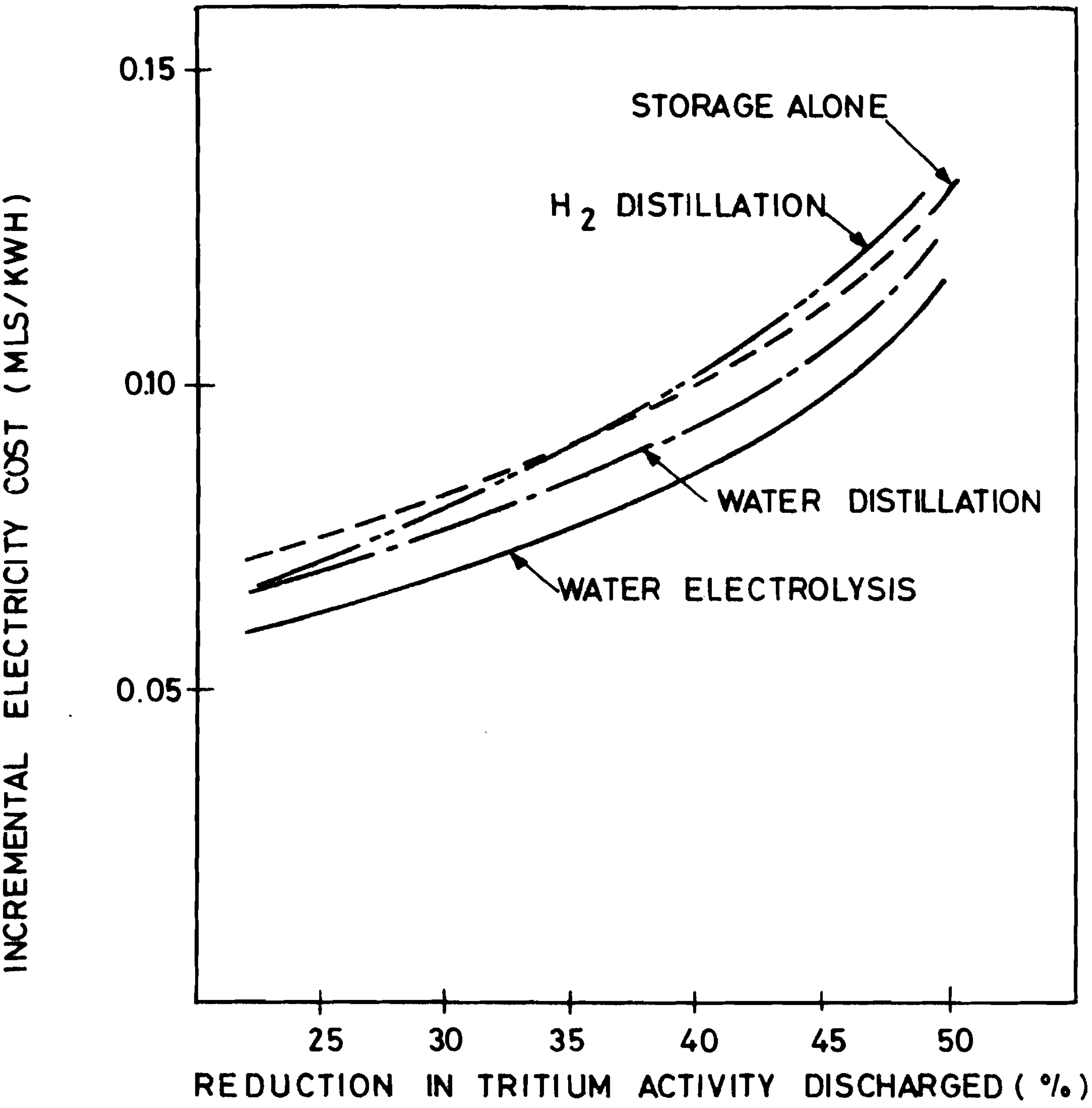

Number of publications on health implications of tritium and krypton-85 exposure (Nuclear Science abstracts)
Number of publications
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
Tritium
Krypton-85
1950
1955
1960
1965
1970
Year

Figure 5.



Assume 50 % Reduction :

$$\frac{0.1 \text{ MILS / KWhr} \times 10^{3} \text{ KW/MW} \times 10^{3} \text{ HR/YR} \times 10^{-3} \text{ \$ / MIL}}{0.5 \times 25 \text{ Ci/MW - YR} \times 4 \times 10^{-4} \text{ MAN - REM / Ci}}$$

$= 1.7 \times 10^{5}$ \$ / MAN - REM

Figure 6. Tritium reduction costs at nuclear power plants [10] .

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