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RISK AND SAFETY IN THE NUCLEAR INDUSTRY AND CONVENTIONAL NORMS OF SOCIETY*

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Abstract

In the present study the societal acceptance of various risks is analyzed and rules of risk acceptance as a function of different parameters (e.g., expected benefit, intensity of effect) are spelled out. The monetary value of a human life is estimated, based on investments in safety of different human activities.

The acceptable risks and safety investments in different human activities are then compared with risks and safety investments of the nuclear industry. Safety investments required to reduce the radioactivity releases and risks from nuclear power stations to ALAP (as low as practicable) levels are taken as a study case. It is found that risks in the nuclear industry are several orders of magnitude lower and safety investments per human life saved are several orders of magnitude higher, as compared with risks and safety investments in other human activities.

*The paper expresses the author's personal opinion and the conclusions drawn do not necessarily represent those of the Soreq Nuclear Research Center.

INTRODUCTION

The nuclear industry expends large sums of money to increase safety, thereby decreasing occupational risk and hazards to the population living in the environs of a nuclear installation. From the point of view of the approval of society of public expenditure it is, however, interesting to compare the safety expenditures in the nuclear industry with those of other industries and human activities. Such a comparison might be made on the basis of the monetary value allocated to a human life saved by safety improvement.

In the present preliminary study conventional norms of society and of human attitudes concerning risks, safety and the value of human life are examined and different approaches to the quantification of risks and of the value of human life are discussed. Risk and safety investments made by the nuclear industry are then analyzed and compared with those in other areas of human activities. The main emphasis is given to the continuous and normal operation of nuclear reactors. This preliminary evaluation suggests that the present trend of incremental investments to further reduce radiation doses to the population from normal and continuous operation of nuclear reactors, appears to be excessive.

CONVENTIONAL NORMS OF SOCIETY CONCERNING THE VALUE OF HUMAN LIFE, RISK, AND SAFETY

Although the value of a human life was estimated as early as in the Biblical days (e.g., Leviticus 27, 19-20), such a quantification remains, until now, a controversial matter, made difficult by the sensitivity of the subject and by the sense of "cruelty" and/or "morality" which accompanies such a study. It is, therefore, interesting to review first the conventional norms of society regarding the risk and safety of different human activities.

Risk is defined (Rowe, 1975) as the probability of occurrence of undesirable effects as a result of an action or of a lack of action. This definition indicates that although death is the most dramatic effect, it is certainly not the only nor the most important effect characterizing a given risk. The causation of disease, or disability may be more important as an index of risk, both from the humanitarian, social welfare and societal points of view, and from the standpoint of the economic burden imposed upon society.

It is important to emphasize that societal norms cannot sharply differentiate between hazardous and non-hazardous activities. No human activity can be characterized by absolute safety. Human activities may be classified according to their relative safety or risk. Consequently, the following rule of societal acceptance of risk may be spelled out:

1) Society accepts certain risks as a natural aspect of human life.

Thus, it is known since early times, that people who live in dangerous areas (e.g., earthquake sensitive areas) return to them even after the occurrence of catastrophies (Kates et al., 1973).

Although the definition of conventional norms of society is speculative, several other rules may be stated qualitatively. The criteria of societal acceptance of risks may be classified according to characteristics of activities, effects, past experience and safety expenditure.

Activity characteristics criteria. Human activities may be divided into two classes: voluntary and involuntary (Starr, 1972). A voluntary activity is defined as an activity which is initiated by an individual or a small group of people expecting a certain benefit (economic benefit, pleasure, etc.) from it. An involuntary activity is imposed upon the individual by nature, by a group of people or by society as a whole, without giving the individual the liberty to influence or change the activity. A person may possibly not be able to estimate the benefit which he might expect as an individual from a given involuntary activity. Starr (1972) analyzed the societal attitude towards voluntary or involuntary risks and reached the conclusion that:

2) Society is willing to accept risks higher by (up to 3) orders of magnitude for voluntary, as compared to involuntary activities.

This difference is due not only to the larger benefit obtained (or seemingly obtained) by the individual from a voluntary activity, but also to the feeling that one masters, and may control more effectively, the risks involved.

Another rule of societal attitude towards risks (Starr et al., 1972) may be stated as follows:

3) Society is willing to accept certain risks, if the expected benefit from a given activity is larger than the expected risks.

However, this rule is not applicable in all facets of societal behavior, since most people prove to be poor evaluators of expected benefits.

Effects criteria. There are human and societal attitudes towards the effects of different activities which even in a semi-qualitative or speculative manner cannot be described as a societal norm. Thus, for example, it seems impossible to predict how society will react towards an activity which might result in a small number of deaths, as compared to an activity which might cause a rather large number of diseases and disabilities.

Such a problem could be posed, for example, in siting a nuclear reactor. Two sites might be available: one site (A) with a rather large exclusion area (free of any population), but with a relatively large population density immediately surrounding the exclusion area, and another site (B) having a restricted exclusion area, but with a very low population density within a large area surrounding the exclusion area. Consider for the purpose of illustration, a very severe hypothetical nuclear reactor accident. In site A it might result in many diseases and disabilities, while in site B it might result in few such casualties. However, because of the small size of the exclusion area in B, a catastrophic accident might also cause a number of immediate or delayed deaths.

It seems that no answer can be given to the question, what is considered "preferable' as a societal norm: a larger number of diseases and disabilities or a small number of deaths. It is an ethical question which is not easily answered or framed within societal or behavioral norms. However, qualitative rules may be spelled out which concern societal behavior as related to activities producing identical effects.

Thus, Rasmussen (1975) and coworkers, in analyzing the probabilities and effects of nuclear accidents, point out that the societal reaction to two activities might be different, although their average risk might be similar or even equal. In an example, they compare two activities: one, in which the frequency of accidents might be one per year with a result of one death per accident, and the other, in which the frequency of accidents might be one per 10,000 years with a result of 10,000 deaths per accident. They conclude that society would react much more severely to an accident of the second type, because of the larger number of casualties, without giving consideration to the low frequency of this type of accident.

Hence, the following rule may be stated:

4) Society is frightened by large numbers of casualties, notwithstanding their low frequencies.

Past experience criteria. Societal attitude toward risk, as related to habit or experience may also be included within the present framework of conventional norms of society. Although Firth's (1959) study indicates that societal attitude toward risk is attenuated by habit and experience, the studies of Otway (1975) and Golant and Burton (1969) indicate contrary results. In these latter studies the societal attitude towards different physical, natural and other hazards was investigated both in Canada and in Austria and it was found that people react more severely to risks to which they have already been exposed in the past. This conclusion may also fit the public attitude towards nuclear technology, the acquaintance with which was made through the horrible experience of the atomic bomb disaster during the second World War.

Thus, the following rule may also be spelled out.

5) Society reacts more severely to risks to which it has been exposed in the past.

Safety expenditure criteria. In a study of nuclear waste management problems, Cohen (1975) shows that within the process of minimizing the hazards of a certain activity, the initial expenditures generally diminish the hazards substantially. However, subsequently, the same expenditure as made initially decreases only insignificantly the marginal hazards of the activity. This result, which is represented by the law of diminishing returns, also indicates that no matter how much money is invested in increasing the safety of a certain activity, its hazards cannot be reduced to zero, since as indicated previously, no human activity is absolutely safe. Zero hazards of any activity can be attained only by discontinuing the activity.

Another conclusion which may be drawn from the law of diminishing returns, is that there should be an optimum of safety investments in a certain activity and further expenditures should not be made in it, but rather in other activities in which the optimum has not yet been reached. This would give the maximum return from over-all societal safety investments.

However, in fact, society does invest, to diminish certain risks, amounts of money which are by orders of magnitude larger than those invested in diminishing the same quantitative risk encountered in other activities.

Although a "cruel" example, it is known that society spends large sums of money to keep a person alive even if he is in a physiological state of vegetation. Society spends comparable sums of money to find a lost person. On the other hand, society may not be willing to make expenditures which are lower, by orders of magnitude, in areas such as the erection of railroad barriers, etc., where there is almost a certainty that a person will be killed due to the lack of the safeguards.

Thus, the following rule may be spelled out:

6) Society is willing to spend more, by orders of magnitude, to save the life of a person whose identity is known, as compared to expenditures made to save a "statistical" life, i.e. of a person whose identity is unknown.

QUANTIFICATION OF RISK

It was indicated in the previous section (rule 3) that society accepts certain risks commensurate with the benefits expected from a given activity. While benefits are generally (although not always) quantifiable, the quantification of risks is much more difficult. It seems that, notwithstanding the serious ethical questions which may be raised, the most understood and approved basis for quantification of risks is the monetary basis. This also involves the assignment of a monetary value to a human life.

The following are among the different methods of quantification of a human life value (Linnerooth, 1975):

a) Capitalization of a person's potential of production: Generally, a potential of production of 20 years (6,000 working days) is assumed for a standard man; the potential of production is multiplied by the mean yearly or daily wage.

b) Surveys made in the U.S.A. some time after the occurrence of catastrophies (earthquake, flood, etc.) indicated that whenever the ratio between the property loss and the number of human lives lost in a catastrophe was higher than about \$200,000/person, most of the interrogated people remembered the property damage and forgot the loss of human lives. This ratio might therefore be chosen as the value of human life.

c) The average life insurance policy and court awards may also be indicative of the value of human life.

In the present study, the capitalization of a person's potential of production was chosen as the method of quantification of the human life value. Considering the mean wage in Israel, the human life value in Israel is about US\$100,000.

Let us now consider the conventional societal norms as related to safety expenditures to save human lives, and take as an example the expenditure for the installation of car safety belts (Wilson, 1975). In the case of Israel, we assume that the cost of a set of car safety belts is \$30, the number of new cars per year is 30,000 and the number of yearly death casualties prevented by installation of safety belts in new cars is ~30. Then,

$$\text{the value of one human life} = \frac{30{,}000 \text{ cars} \times \$30/\text{car}}{30 \text{ persons}} = \$30{,}000/\text{person}.$$

Comparison of this number with the sum of \$100,000 considered to be the value of a human life in Israel, indicates that even an expenditure of more than \$100 per set of car safety belts would be reasonable.

However, it is doubtful if people would be willing to invest this relatively large sum of money for this purpose. Thus, it may be assumed that, if consideration is given to the readiness of society to invest in car safety belts, the value of a human life in Israel would be about [illegible],000 rather than $100,000, as previously calculated.

RISK AND SAFETY IN THE NUCLEAR INDUSTRY

Potential risks of the nuclear industry may be due to the (very low) release of radioactivity to the environment during continuous and normal operation and to the (very low) probability of release to the environment of large amounts of radioactivity, following an accident. However, the severe safety measures and precautions taken in the nuclear industry make it one of the safest and cleanest industries and reduce the population risks to a degree which is lower, by orders of magnitude, than that encountered in other industries and human activities.

The recent Rasmussen (1975) report, dealing extensively with the probability of accidents in nuclear reactors and their effects on the environment, considers operation of 100 nuclear power plants in the U.S.A., and shows, for example, that:

a) The frequency of accidents which would result in 100 death casualties in the population living in the neighborhood of the nuclear plants, would be 1 accident in 100,000 years. The frequency of a similar accident in other human activities (e.g. air flights) or even in natural disasters (e.g. earthquakes, hurricanes) is 1 accident in several years up to 1 accident in 100 years.

b) The significance of such a low frequency of nuclear accidents for a population of 15 million people living within a radius of 20 miles of 100 nuclear reactors in U.S.A. is a yearly risk of 2 death casualties (as compared to 4,200 fatalities due to car accidents) and of 20 sickness casualties (as compared to 375,000 injury cases due to car accidents).

It is interesting to compare the human risk involved in the release of radioactivity due to normal and continuous operation of nuclear power plants with the risks of other human activities and natural hazards. Table 1 shows the human risk due to different causes. It is seen that the risk from normal and continuous operation of the nuclear industry, to the population living at the fence of a nuclear installation is comparable to that from accidental electrocution. However, several remarks should be made about the figures appearing in Table 1:

1) The risk indicated for workers in industry and manufacturing is an average risk for extremely safe as well as unsafe enterprises.

2) The occupational risk of $5x10^{-4}$ death/person-year for the nuclear industry and the risk of $5x10^{-5}$ death/person-year to the popu-

lation at the fence of a nuclear plant is calculated on the basis of the standards which were established for tolerable radiation doses. Had the risk been calculated on the basis of the actual radiation doses caused by the operation of the nuclear industry, the figures would have been much lower, by four to five orders of magnitude.

3) The risk of $5x10^{-5}$ death/person-year as indicated for the population living at the fence of a nuclear industry is based upon the tolerable radiation standards for the population, which were valid up to last year in the U.S.A. However, in May 1975, these standards were lowered drastically (U.S. NRC, 1975). It is therefore interesting to evaluate the new radiation standards from the point of view of tolerable risks, in comparison to those of other human activities and to estimate the cost of further reduction of marginal radiation doses caused by the nuclear industry. Consequently, the value of "human life" based on safety investments in the nuclear industry will be estimated and compared to that in other human activities.

POPULATION TOLERABLE RADIATION STANDARDS

Up to last year, the U.S. radiation standards for continuous and normal operation of nuclear reactors, specified for the population living in their surroundings, were as follows:

500 mrem/yr for individuals of the population living at the fence of the nuclear reactors.

170 mrem/yr for the population-at-large.

The present U.S. standards reduce the tolerable radiation doses for individuals living at the fence of a nuclear installation by a factor of about 60, while no standard is presently specified for the population-at-large. However, it is evident that due to the new limitation of the radiation dose at the fence of the nuclear installation, the radiation dose to the population-at-large will also be reduced accordingly. A further guideline is provided within the new standards indicating that the integrated population radiation doses should be calculated and a cost-benefit analysis should be performed, and that safety investments of about $1,000 per reduced man-rem dose should be considered acceptable. Let us now analyze the significance of the new radiation standards as compared to standards established in other facets of human activities.

Comparison of standards and risks

Starr et al. (1972) compared the standards established for radiation doses, SO_2 and NO_2 and showed that among all the atmospheric pollutants standards, the radiation standard is the only one which is below the natural background level. Their study also included the level of medically perceivable effects and the lethal levels.

Table 2 shows the ratio between the maximum permissible standards of the different pollutants compared by Starr et al. and the corresponding background levels, lethal levels and levels of medically perceivable effects. Besides the fact that the radiation dose standard is the only one below the natural background level, it is interesting to note that the ratio between the levels of medically perceivable effects and the maximum permissible standard and between the lethal levels and the maximum permissible standard for the different pollutants is, by orders of magnitude, higher for radiation as compared to SO_2 and NO_2.

An interesting means of comparison of risks caused by the nuclear industry and other human activities is the comparison of the shortening of the life-span for different facets of life.

In a study of risks involved in different aspects of life it is shown (Cohen, 1974) that human life is shortened by: 1,800 days - due to city pollution; 3,000 days - due to smoking one pack of cigarettes per day; 500 days - due to being 10 pounds overweight; and only by 10 days - due to a radiation background of 170 mR/yr (which was formerly the U.S. radiation standard for the population-at-large). Translation of the radiation risk to other risks shows that living in a background level of 170 mR/yr is equivalent from the point of view of life-span shortening, to being 100 g overweight, or to smoking 1 pack of cigarettes per year or to spending 2 days per year in a city. Estimating the radiation risk by the number of days of life lost indicates that the significance of the new U.S. radiation standard for individuals at the fence of a nuclear installation, would be a life-span shortening of less than one day.

The question may then be posed: is it reasonable to request a further reduction in radiation-level standards, when even with the former standards, the risk involved from the normal operation of nuclear industry was, by orders of magnitude, lower than from other aspects of human life? In relation to this question it is also interesting to evaluate the cost of safeguards required to further reduce the radiation levels to the population from the standpoint of the law of diminishing returns, i.e. to analyze whether the further investments in safety are justified by the diminution of risks.

Safety investment to further reduce radiation levels

A case study of a nuclear power plant sited in an area of a population density of 400 persons/km^2 and having an exclusion radius of 1 km was chosen to investigate the justification of further safety investments from the point of view of diminution of risks and the "value of human life". The integrated population radiation doses during normal and continuous operation of the plant, was calculated for a ground-level release during average atmospheric conditions, and for two different cases: assuming that the tolerable whole body radiation dose at the fence of the plant is: a) 8 mrem/yr (new U.S. standard) and b) 500 mrem/yr (former standard). Using the integrated population radiation doses, an estimate was made of the radiation-caused casualties expressed as the number of death cases per year, due to somatic and genetic effects. It is assumed that the risk of death from all radiation malignancies, including serious genetic detrimental effects is 10^{-4} deaths/man-rem (ICRP, 1975).

Table 3 shows the results of these computations. It is seen that if 500 mrem/yr is assumed to be the tolerable radiation dose at the fence of the plant, the integrated population radiation dose would be

4,200 man-rem/yr, which may result in less than one death case per year. If the tolerable radiation dose at the fence of the plant is assumed to be 8 mrem/yr, the integrated population radiation dose would be 67 man-rem/yr, the result of which may be less than one death case in 100 years.

Let us now consider the safety investment required to reduce the radiation dose at the fence of a nuclear power plant from 500 mrem/yr to 8 mrem/yr, and analyze it from the point of view of conventional societal norms for safety investments. Assuming (as in section "Quantification of Risk") that the value of a human life is $100,000, an approximate estimate could be made of what could be considered to be a "reasonable" safety investment.

The "reasonable" safety expenditures (capital and operational) to reduce the integrated population radiation doses is calculated as follows, based on the data of Table 3 and assuming a 30-year lifetime for a nuclear power plant:

$$4.2\times10^{-1} \text{ deaths/yr} \times \$100{,}000/\text{human life} \times 30 \text{ yrs} = \$1.2\times10^{6}$$

Thus, an investment of $1.2 million during the lifetime of the nuclear power plant might be considered acceptable from the standpoint of conventional norms of society, to reduce the radiation dose at the fence of the plant from 500 to 8 mrem/yr. However, the actual safety expenditures required are estimated to be (Sagan, 1972) 6 to 10 million dollars as capital investment and about half a million dollars per year as operational expenditures, i.e. a total of 21 to 25 million dollars for the 30-year lifetime of the power plant. It thus appears that the estimated actual safety expenditures required to further reduce the radiation doses at the fence of a nuclear plant are about 20-fold higher than what might be considered "reasonable" according to the conventional societal norms. The value of a human life saved by reducing the radiation dose at the plant fence appears thus to be $\$2 \times 10^6$, i.e. 20-fold higher than the value estimated by capitalization of a person's potential of production.

However, this value of human life still appears to be far lower than that of other evaluations, reflected in actual safety expenditures in the nuclear industry. Considering $1,000/man-rem as an acceptable expenditure (as indicated by the 1975 US guides) and assuming a probability of 10^{-4} deaths/man-rem, the value of a human life would be:

$$\frac{\$10^3/\text{man-rem}}{10^{-4}\ \text{deaths/man-rem}} = \$10^7/\text{human life}$$

The cost per man-rem for radiation reduction at the Brown's Ferry nuclear plant reached about $2,000 (Sagan, 1972) while the cost of reduction of tritium release at the Savannah River plant reaches the equivalent of $67,000 per reduced man-rem (Cohen, 1975). The cost of one death avoided in these plants would be $20 million and $670 million, respectively! These values should be compared with, for example: $30,000 per death avoided by using car safety belts in Israel and $20,000 per death avoided by collimation of X-ray machines (Villforth, 1974).

CONCLUSION

The present preliminary study shows that the incremental safety investments needed to further reduce the radiation doses in the environment during normal and continuous operation of nuclear plants, (~~expressed as~~ cost per death avoided), are extravagantly high as compared to safety investments in other human activities and in other facets of human life.

Although the question of how much money should be spent to save a human life appears to be a cruel and immoral one, it should not be avoided, especially if one is dealing with public expenditures. Considering that there is a limit to the economic means available, societal expenditures for reducing risks should be spread, as much as possible, over all human activities to get the maximum return from investments.

Indeed, a good reason to invest more in the safety of the nuclear industry, as compared to other human activities, is to acquire public acceptance and confidence. However, even considering the "cost of acquiring public acceptance and confidence", the incremental safety investments in the nuclear industry seem to be excessive.

Further studies should be encouraged concerning the risks and safety investments in all facets of human activities and man-made hazards. Then, it would be possible to rationalize and optimize expenditures for safety improvement in all hazardous human activities, in order to get the maximum return from these investments.

TABLE 1

Human Risk Due to Different Causes

(death/person-year)

Cause	Risk*
Disease	10^{-2}
Cancer (natural)	10^{-3}
Industry (occupational)	10^{-3}
Manufacturing (occupational)	$(3 \text{ to } 5)\times10^{-4}$
Nuclear industry (occupational)	5×10^{-4}
Respiratory diseases) Motor vehicle accidents)	3×10^{-4}
Nuclear industry (population at fence)	5×10^{-5}
Electric current	5×10^{-6}
Natural hazards	10^{-6}

*The risk figures were calculated from studies made by: Sowby (1974), Simpson et al. (1974) and Hull (1975).

TABLE 2

Comparison of Maximum Permissible Exposure to

Radiation, SO_2 and NO_2

	SO_2*	NO_2*	Radiation
Level	(ppm)	(ppm)	(mR/day)
Background	0.0002	0.01	0.35 (130mR/yr)
Maximum permissible exposure	0.03	0.05	0.03 (8mR/yr)
Medically perceivable effect**	0.02	2	$2x10^4$ (20R)
Lethal**	0.5	500	$5x10^5$ (500R)
Ratios of levels			
Maximum permissible / Background	150	5	~0.1
Medically perceivable effect / Maximum permissible	0.6	40	$\sim 6x10^5$
Lethal / Maximum permissible	17	10^4	$\sim 10^7$

* with particulates

**one-day level

TABLE 3

Integrated Population Radiation Dose and Effects from Normal and Continuous Operation of a Nuclear Power Plant*

Whole body radiation dose assumed to be tolerable at the plant fence (rem/yr)	Integrated population radiation dose (man-rem/yr)	Radiation effects (deaths/yr)
$8x10^{-3}$	67	$6.7x10^{-3}$
$5x10^{-1}$	4,200	$4.2x10^{-1}$

*Assumptions: 1) exclusion radius of 1 km; 2) population density: 400 persons/km^2; 3) ground-level release during average atmospheric conditions; 4) probability of radiation effects: 10^{-4} deaths/man-rem.

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