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RADIATION AND MAN

THE 1973 SIEVERT LECTURE*

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THE HONOUR that has been bestowed upon me by selecting me as the first lecturer in this new series of lectures must be a reflection of the admiration that my colleagues still feel for Rolf Sievert and their hope that one of his pupils might be able to pay him a proper tribute in this first Sievert Lecture.

Let me, however, begin by claiming that this is an impossible task: no pictures, no descriptions, no quotations can do Rolf Sievert justice. Only life could bring into his stout body the vitality and the magnetism by which he mesmerized his environment. Those who were never subjected to that forceful vitality and to the cascade of ideas, innovations, plans and solutions that flowed from Rolf Sievert in a glittering, boisterous torrent will never be able to see in the dead pictures of Sievert the man he was to us who knew him.

Furthermore, it would not have pleased Sievert to have a lecture of this kind focussed on himself. He would have felt warm at heart by the honour shown to his memory by the creation of the Sievert Prize, but since he was a man who liked results, he would have felt embarrassed if this lecture did not leave the personal field soon enough for the technical areas of radiation protection to which he devoted his life.

I have chosen to talk about the general subject of "Radiation and Man," a subject as wide as Sievert's interests. Let us begin by appreciating that, thanks to the pioneering efforts of men like him, radiation safety problems are dealt with in a special way and with much more concentrated efforts than any other occupational or environmental risk.

For example, thanks to the efforts of ICRP, the International Commission on Radiological Protection—founded in Stockholm already in 1928—we have had for almost 40 yr an internationally applied set of dose limits which guarantee that no harmful *acute* effects will result from normal uses of radiation. We should recall that the prevention of immediate toxic effects is still the main problem in many conventional types of occupational or environmental protection, we may just recall substances such as mercury and DDT.

With the conventional standards of thinking, small doses of radiation would be considered not only safe but also often non-existent. Let us not forget that laws on food additives in many countries until recently have completely forbidden any presence of carcinogenic substances, but that the definition of a "zero quantity" has been "a non-detectable quantity." Had radioactive substances been chemically toxic instead of radioactive, many of them would, in the terms of the law, not have existed until new scientific detection methods had revealed their existence and complicated life for the health authorities.

Remember also that even the lung cancer risk from tobacco smoking, although now rather obvious, has been regarded with a good deal of skepticism until recently. Any possible *genetic* risk of smoking remains to be discussed. Risks of cancer from coffee, tea, alcohol, smoked food, etc. are sometimes discussed but never in a quantitative way. To most people, these are hypothetical risks or more or less accepted risks of living.

In the field of radiation protection, risks of cancer and hereditary defects have been assessed quantitatively for almost 20 yr and the possibility of such risks even after very small doses of radiation has been used as the basis of protective measures, although there is no *proof* that these risks really exist.

When we talk about risks we have a semantic problem. Different people mean different things when they say "safe." This may, indeed, be the heart of the matter in the current debates on radiation safety, and I shall take this point as the basis for my lecture.

I will start with a reference to Table 1 showing the radiation doses which we receive from natural

*This lecture appeared in Proc. 3rd International Congress of IRPA, September 1973. Since this did not receive wide distribution, the Editors of *Health Physics* have agreed to publish it, with IRPA responsible for page charges. We hope to publish future Sievert Lectures shortly after presentation.

sources of radiation:

Table 1. Annual doses from natural sources

Source	Annual dose mrad
Cosmic radiation	30
Terrestrial radiation	50
Internal sources (^{40}K)	20

This is a rough approximation of more detailed information which you may find in, for example, the 1972 report of UNSCEAR (United Nations Scientific Committee on the Effects of Atomic Radiation).

Of the three components of the total natural radiation dose, the dose from terrestrial radiation shows the largest variations and is also usually the largest component. Even if we exclude data from areas with particularly high concentrations of radioactive materials in the ground, such as the monazite-bearing regions in Kerala and Brazil, there are wide variations in the exposure rate on the ground and inside buildings. Observations on the variation in the radiation dose in buildings of various materials were published in several countries in the 1950s, and I shall only show a few data that have been widely published.

You can see from the U.K. data in Fig. 1, derived from Spiers, that a person in Scotland might get an extra 50 mrad/yr if he stays indoors

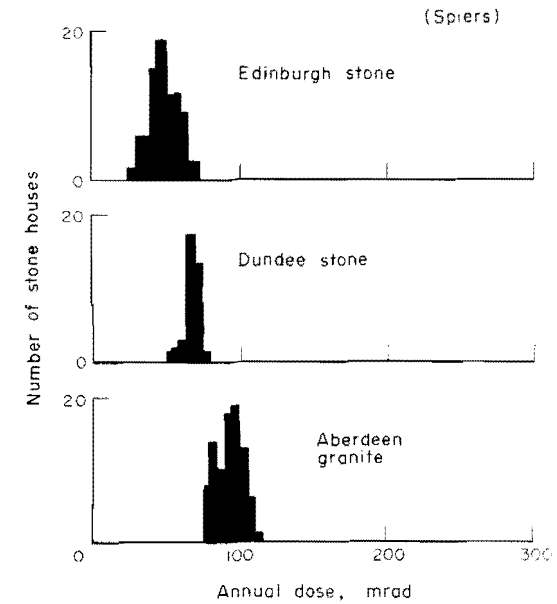

FIG. 1. Annual gonad doses from gamma radiation in Scottish buildings.

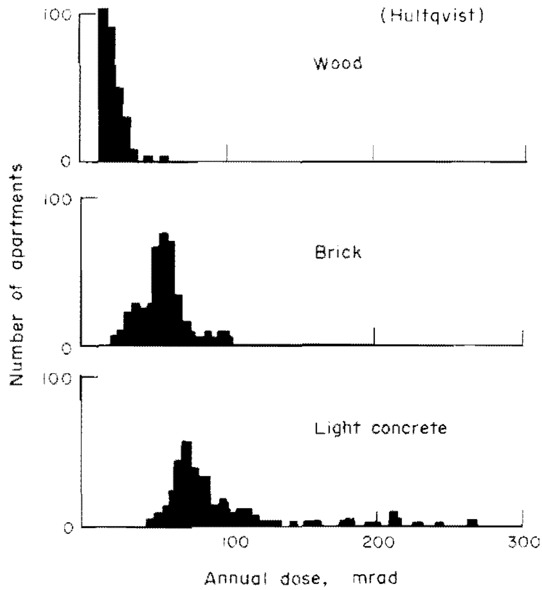

FIG. 2. Annual gonad doses from gamma radiation in Swedish apartments.

in a house of Aberdeen granite instead of in a house of Edinburgh sand-stone.

The Swedish data in Fig. 2, from Hultqvist, show that a person in some Swedish light-concrete houses might get an extra 200 mrad/yr as compared with a person in a wooden house.

These data may be familiar to many of you. I shall add a few more recent results which illustrate the variations in the natural radiation in buildings. You will see from Fig. 3 that there is little variation in the exposure rate in a house where no building material is particularly radioactive.

I have marked exposure rates in μR/hr with the contribution from the cosmic radiation subtracted but with no reduction for absorption in the body. You will obtain the annual depth dose in the gonads, assuming an absorption factor of 0.6 and 15 hr indoors per day, by taking each μR/hr equal to 3 mrad/yr.

Figure 4 shows the situation in a building with mixed materials and you can see that the exposure rate is higher near those construction elements which have a higher activity concentration and which are marked with black in the figure. In such a house the annual doses may differ with 10 or 20 mrads/yr between persons who stay for long periods in different rooms.

In Fig. 5 you will see the exposure rates in a house with extensive use of a material with comparatively high activity. Here the inhabitants may

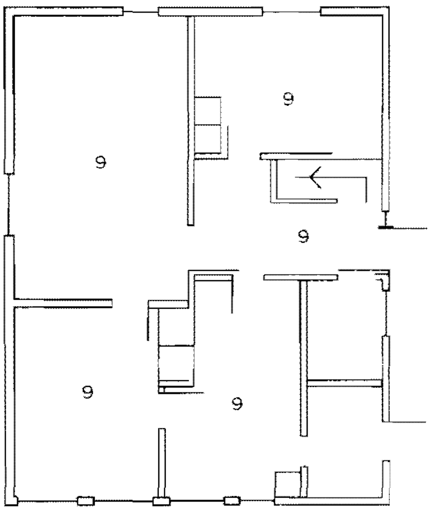

FIG. 3. Exposure rate (μR/hr) in an apartment with walls of light concrete of low activity.

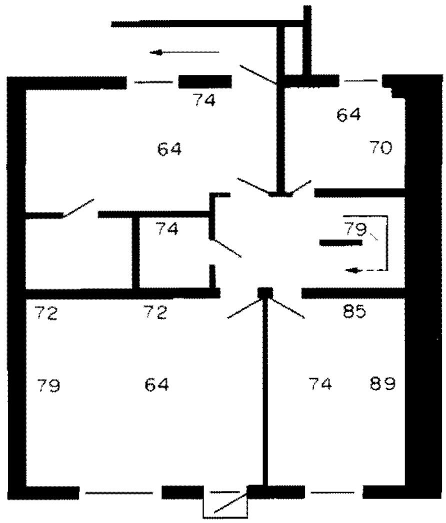

FIG. 5. Exposure rate (μR/hr) in an apartment with walls and other construction elements of light concrete of high activity.

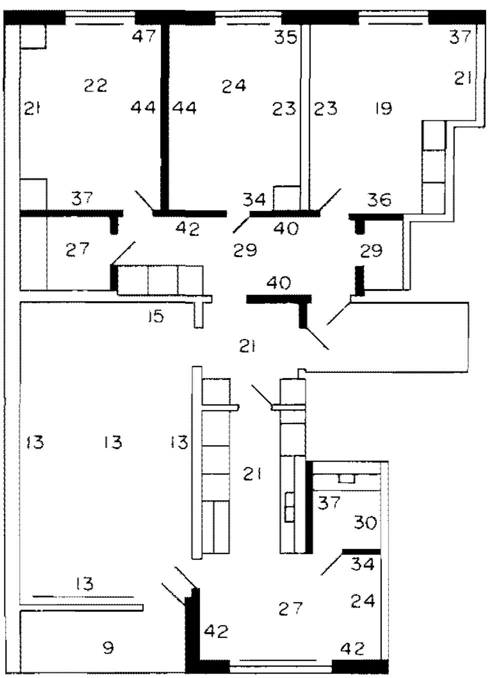

FIG. 4. Exposure rate (μR/hr) in an apartment with walls of mixed materials.

well receive actual depth doses which are more than 200 mrads higher than in a more normal house.

From 1956, that is for 17 yr, ICRP has given recommendations not only for the protection of workers but also for the protection of the public. All dose limits that have been recommended by ICRP have in common that they do not apply to doses from natural sources of radiation nor to doses received by patients in medical procedures.

These exceptions have been difficult for many to understand, but they are natural consequences of the cautious attitude that ICRP and radiation protection authorities are taking. If there were a threshold dose as indicated in Fig. 6, below which no cancer and no genetic harm could be caused by radiation, then the primary goal would naturally be to limit the total dose, irrespective of source, that would be received during the biologically relevant period. With that assumption, dose limits would have to apply to the sum of *all* doses, with no exceptions.

Even without any threshold but with a non-linear relationship between risk and dose, the same principle would have to apply (Fig. 7).

For the national authorities this would be a particularly nasty situation. The lack of threshold would mean that any additional dose, however small, would imply an additional risk. That risk, however, would not only depend upon the magnitude of the dose increment but also on the slope

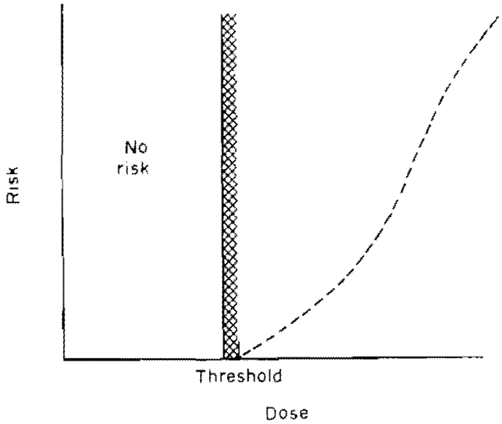

FIG. 6. The concept of a dose/effect relationship with a dose threshold for risks.

of the risk–dose curve. That slope would be different for each individual, depending upon his starting point on the curve, i.e. depending upon his total previous exposure. In risk–benefit assessments one would have to realize that one and the same dose might mean different risks to different individuals and in order to cope with this situation in a quantitative way one would need to have full records of all previous exposures. The potential bureaucracy that this could lead to is just frightening and it is possible that the authorities would have to stipulate an average slope of the risk–dose curve, to apply without knowledge of previous exposures. That would mean overestimating some persons' risk situation and underestimate that of others, but the assessment of the total expected harm would still be correct.

The present policy, however, is to assume that the risk–dose relationship is linear, even though this is by no means certain (Fig. 8).

In this case the slope is the same at all points, therefore the risk per rad, which I shall call the *risk coefficient*, is the same for all persons independent of previous exposures, and the risk from any additional dose is directly proportional to the dose increment.

On this assumption, and we have to recall that it is an *assumption* for protection purposes, any radiation exposures which are controllable can be made subject to risk–benefit assessments without knowledge of previous exposures. If such assessment is carried out for each source or project, dose limits may be considered superfluous. Nevertheless, the present attitude is to consider dose limits a valuable convention even though the more basic recommendation must be the one given in para.52 of ICRP Publication 9, namely that "all doses be kept as low as readily achievable, economic and social consideration being taken into account."

From what I have said now it can be concluded that it is not meaningful to give dose limits for natural radiation but that there is no reason to exempt natural radiation from *cost–benefit* assessments as far as countermeasures are concerned. Obviously no easily eliminated natural source of radiation should be accepted any more than other radiation sources.

I have now sketched the background for a general radiation protection philosophy. Any practice that results in radiation exposures should be subject to a *risk–benefit* assessment. If the possible risk is acceptable, then the practice should still not be accepted until it has also been shown by a *cost–benefit* assessment that the resulting exposure is so

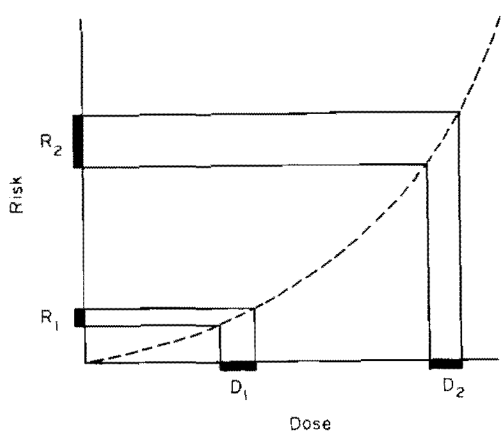

FIG. 7. The non-linear dose/effect relationship.

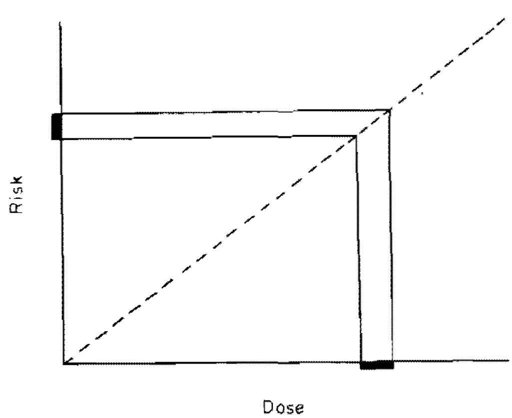

FIG. 8. The linear dose/effect relationship.

low that further dose reductions will not bring about a benefit which justifies the effort.

For the *risk*-benefit assessment, the risk coefficient, covering all expected incidence of cancer and all severe hereditary defects in the first generation offspring, is usually assumed to be a few times 10^{-4} per rad after whole-body exposure, perhaps 10^{-4} per rad after exposure at low dose rates and 3–4 times higher at high dose rates *if* the assumption of a linear dose–risk relationship is correct. In *cost*-benefit assessments there is some guidance in the knowledge that it is not unusual in current radiation protection practice to consider it reasonable to eliminate a radiation dose if it can be done at a cost of $ 100 per rad and person.

These two quantitative assumptions characterize present radiation protection activities except where special public concern may have influenced the decisions. It is interesting to note that the combination of the risk coefficient and the dose elimination cost with the values that I have just mentioned implies a value of $1,000,000 for each human life which might, on statistical grounds, be expected to be saved.

I am now getting into dangerous grounds and do not wish to be misunderstood to mean that the reverse thing is true, namely that it would be justified to risk a human life in order to save or gain a million dollars to society. Lives and dollars are not exchangeable quantities.

The interesting thing with a *low* risk, however, is that individuals tend to treat it as a nuisance more than as a reality, if they understand that it is low and if they try to comprehend its significance. It seems to be a fact that many people have the feeling that they better "understand" what a low dose implies if they are told what it is worth to pay to eliminate the dose. In my experience many persons who are knowledgeable in radiation risk assessments react immediately, perhaps with their spinal cord, when they are told the dollar equivalent of a radiation dose (the PQR-cost), and interestingly enough their immediate reaction on the PQR-cost will prove to give about the same result as their more scientific brain exercise when they make a direct risk assessment.

Take, for example, the natural radiation. I have shown that an extra annual dose of 10 mrad is not unusual in certain buildings. The individuals concerned may feel that this is rather insignificant when they are told that the PQR-cost (i.e. the cost which is justified in order to eliminate this extra dose) is as low as $1/yr. It is not unlikely that they feel that the risk is indeed insignificant, when they are told that it may amount to an extra lethal risk of the order of 1 : 1 million/yr. We are all subject to higher total risks than we wish to recognize, and we should really not care if our risk of dying in a given year is 1 : 389.453 or 1 : 389.301; for all we need to know in that case it is 1 : 400—which, incidentally, in many countries is the annual risk of dying at the age of 40.

Now I am getting back to the semantic problem I mentioned when we talked about the word "safe." Obviously, in normal language an extra dose of 10 mrad/yr is "safe." But that does not mean that the situation would still be acceptable if all individuals in, for example, the U.S. received the same extra dose. In reference to their individual risk situation this is still a negligible dose, but the total number of individuals that might be expected to suffer severely from this exposure—provided that our risk coefficient is true, which we don't know—is

$$N = P \times D \times C = 250$$

if $P = 250 \times 10^6$, $D = 10^{-2}$ rad and $C = 10^{-4}$ per rad.

Of course 250 cases of cancer and severe heriditary defects are *not* insignificant except in a statistical sense, and the practice that could cause this result is hardly "safe."

Why do we have this paradox, that a practice which causes an insignificant risk to each individual might still be unacceptable if we make a direct risk–benefit assessment of the practice as such? The reason is of course that when we checked the individual's risk we only really checked if the risk was insignificant in relation to his total risk situation and found that it was indeed negligible. We did not bother to check if that negligibly small risk was actually *justified* from the point of view of the benefit to each individual. That might not have been the case and if so we have no right to expect that the overall benefit from the practice outweighs the harm.

The lesson is that we have a practical risk threshold, below which extra risks are negligible to us as individuals. It takes rather high risks to change our total risk situation significantly. Therefore we may well accept relatively high variations in our radiation background without finding it necessary to check whether the extra doses are really justified. For the society as a whole a similar high risk threshold exists for additional risks to become so high that the harm becomes statistically significant and a social burden. But I maintain that in the risk–benefit evaluation of any given pratice the only relevant factors to be compared are the total harm

* The arbitary letters "PQR" were chosen as the symbol for this quantity by my friend Dr. Arne Hedgran, who invented the concept.

and the total benefit from the practice. If the benefit does not outweigh the possible harm we should be concerned. The degree of our concern should of course increase in proportion to the harm actually expected. If human lives are at stake, I think we are morally and ethically obliged to be worried long before the harm exceeds the threshold that makes it obvious.

Let me now complete the picture I have given of the natural radiation background by putting it in the frame of other exposures to which we are commonly subjected. The dominating one is the medical exposure, the major source being X-ray equipment for diagnostic examinations. According to UNSCEAR, the median value of the genetically significant dose from diagnostic X-ray examination is about 20 mrad/yr for some 30 studies that have been reported from various countries. Since the genetically significant dose involves weighting for child expectancy and does not include the many exposures of old patients in the averaging, the *per caput* gonad dose may be twice as high. The *per caput* mean marrow dose is even higher in some countries.

Although the medical exposures are only partial body exposures, they are given with high dose rates and with extreme individual doses which deviate much more from the average than we have seen for the doses from natural sources. In Table 2, I have indicated the significance of the medical exposures by showing you some PQR-costs based on $100 per rad, i.e. without having tried to compensate for the partial body exposure and the higher dose rate, two factors which work in opposite directions.

Table 2. PQR-costs of some medical examinations

Type of examination		Gonad dose (mrad)	PQR-cost ($)
Dental	(male)	0.1	0.01
Chest mass survey	(female)	3	0.30
Barium meal	(male	30	3
Urography	(female)	600	60

It is obvious that the *individual* significance of a correctly performed dental exposure is negligible, but the large number of examinations may still justify *general* protection efforts aimed at improving equipment and procedures. A urographic examination for example gives a dose which is not insignficant, and it may be justified to make protection efforts for $ 30 per examination in order to reduce the dose by 50%. The PQR-cost does not give direct guidance in the risk-benefit assessment; for this purpose the risk coefficients would have to be used.

It is worthwhile recognizing that, while an unnecessary dental exposure has a PQR-cost of 1 c., a retake of a urographic film, when the necessary diagnostic information might still have been obtainable from the first imperfect one, spoils protection efforts for a value of $ 60. If the PQR-cost had been an extra tax on the film, many unnecessary exposures might have been avoided. At least one would wish that it becomes an imaginary tax in the radiologist's mind.

With regard to the diagnostic uses of radionuclides I shall only comment upon the frequent use of iodine-131 for thyroid studies. Of a total of about 70,000 radionuclide investigations per year in Sweden about 50% involve the use of iodine-131. These 35,000 examinations cause an average thyroid dose of about 30 rad. The average PQR-cost of a thyroid examination will then be $ 300 on the basis of $ 10 per rad since the risk is mainly limited to thyroid cancer. This is not an insignificant radiation burden but many doctors may be ignorant of its significance. The total PQR-cost of the uses of iodine-131 for diagnostic purposes in Sweden is, with these numbers, $10 million/yr. At the usual ambition level it would be worth $1 million/yr to reduce the average thyroid dose in Sweden by 10%.

It should be obvious from what I have said, that the justification of any medical exposure must be based upon the result of risk-benefit analyses rather than upon comparisons with any dose limits. It is, however, likely that substantial reduction of doses to patients may be obtained merely by strict adherence to the standards and procedures recommended by ICRP in Publications 16 and 17 on the protection of the patient. The PQR-value of reducing the patient doses in, for example, the U.S. by as little as 0.1% seems to be about $1 million/yr.

Of course, risk-benefit assessments should also be made in the protection of the worker. Here, however, the risk-benefit situation is somewhat complicated since the worker stands a direct risk but is usually exposed to the benefit only indirectly, through his salary. It is against normal radiation protection practice to compensate higher doses by higher salaries, since that might eliminate the motivation for caution. On the other hand the protection authorities wish to induce the employers to keep the doses low.

The solution to this problem is to replace *risk*-benefit assessments by reference to agreed dose limits which guarantee that the individual risk will never be higher than risks which are accepted in other occupations, but to add the requirement that "all doses be kept as low as readily achievable," i.e. to retain the *cost*-benefit assessment.

To-day, the ICRP dose-limits are rarely exceeded in radiological work. Until relatively recently, nurses and assistants in gynecological radiotherapy departments at some major clinics used to be a group which received high doses because of the difficulties in applying shielding and distance protection. With modern techniques and less frequent use of radium, however, the doses have been much reduced, as you can see from Table 3, giving an example from Radiumhemmet in Stockholm:

Table 3. Annual staff doses at Radiumhemmet

Dose range (rad)	Number of workers in each dose range 1961–1971: 1961	1963	1965	1967	1969	1971
10–15	1	—	—	—	—	—
5–10	10	6	6	—	—	—
3–5	11	13	11	3	—	—
2–3	9	12	16	11	9	3
1–2	23	27	17	32	33	31
0–1	85	132	160	220	261	342

The elimination of the high doses corresponds to about 150 man-rands, i.e. a reduced PQR-cost of $ 15,000/yr after 1971 as compared to the situation 10 yr earlier. It is symptomatic, however, that this gain is neutralized by additional man-rads because of an increased number of employees who work with new sources of radiation in other departments.

If it is now rare that dose limits are exceeded, there are on the other hand some less encouraging observations. Accidents still occur in radiation work, analytical X-ray equipment and equipment for industrial radiography with either X or gamma rays being particularly frequent sources. The occupational exposures at nuclear power stations are relatively high and may continue to be so, possibly causing more man-rands than the environmental contamination from the same stations.

On the average, however, the occupational exposures are amazingly low, the over-all average being of the order of perhaps 200 mrad/yr, causing a whole-population *per caput* contribution of the order of a few tenths of a mrad.

With this background it is remarkable that the working conditions in mines, and not only in uranium mines, are such that many workers will inhale larger quantities of radioactive particles than the maximum values that can be derived from the ICRP recommendations. Miners are also the only present occupational group for which the cancer rate seems to be clearly correlated to their radiation exposures. Yet non-uranium miners are not even legally classified as radiation workers in some countries, for instance Sweden. The protection measures also take time to put in effect, but slowly give results (Table 4).

Table 4. Radon levels in Swedish mines (from Snihs)

Highest level of radon daughters (pCi/l)	Number of workers in mines in each category: 1970	1973
300	21	0
100–300	620	0
30–100	700	600
10–30	2000	2700
0–10	1400	1400

It remains for me to close this review by giving some references to environmental contamination. I would like to refer you to the reports of UNSCEAR and ICRP. Even though ICRP recommends dose limits to individual members of the public, it is obvious that there can be no follow-up of individual exposures. Radiation protection of the public and control of the environmental contamination in general can only be achieved by control of the sources. This also implies that each source or practice that can lead to radioactive pollution must be subject to both an assessment of the dose to individuals in the critical group and a risk–benefit analysis.

In both cases the annual dose *commitments* rather than the annual doses should be assessed, since otherwise some long-lived radionuclides may cause non-controllable future exposures.

The dose commitment for any organ or tissue is the infinite time intergral of the average value of the mean dose rate in that organ or tissue in the population of interest:

$$D_c = \int_0^t \dot{D}_{\text{average}}\, dt = \int_0^t \frac{1}{P} \sum_{i=1}^{P} \dot{D}_i\, dt.$$

If the population is constant in time, the expected total number of individuals who will be affected by any late deleterious effect will be the product of the population number P, the dose commitment D_c and the risk coefficient C:

$$N = P \times D_c \times C.$$

If the radiation exposures from the practice for which the dose commitment is calculated is not limited within any national or geographical borders, it is appropriate to calculate the dose commitment to the whole world population. This has been the practice of UNSCEAR. An alternative way to presenting the dose commitment as such is to present the product $P \times D_c$, which product may be called the *population dose commitment* from the practice and which is measured in man-rads.

The product of the population dose commitment and the risk coefficient may be called the *harm* *commitment.* The harm commitment is the true expectation of total harm from the given practice only to the extent that the assumption with regard to the value of the risk coefficient is correct.

It seems reasonable to expect that nuclear power from light water reactors can be obtained at an annual population dose commitment of less than 1 man-rad per installed MW of electric power, which will mean only a few mrads/yr in year 2000. This however, is on the assumption that there will be no significant contribution to the population dose by the mathematical expectation of doses from nuclear accidents and that the long-term waste disposal will also be so arranged that it will not contribute significantly to the population exposure.

According to the UNSCEAR reports, nuclear testing in the atmosphere has given a soft tissue dose commitment of about 0.12 rad to the whole world population, which corresponds to a population dose commitment of about 500 million man-rads. In terms of either risk or PQR-cost this is of little significance to the individual member of the population, the PQR-cost per person being $12, assuming $100/man-rad. The *total* PQR-cost of nuclear testing as such, however, is as high as 50 billion dollars.

We should therefore be grateful to those who succeeded in reaching agreement on the cessation of the heavy atmospheric testing 10 yr ago. Had testing continued only one more year at the same rate as during the period 1961–1962, it would have caused an additional dose commitment of some 150 million man-rads. With the expectation of less than 1 man-rad/MWyr from the normal operation of nuclear power reactors, that corresponds to 150 million MWyr or 1000 yr of operation of 150 power reactors at 1000 MW each.

As you have seen, radiation sources differ widely with regard to dose commitment and harm commitments, although we really only know what the harm might be, rather than what it is likely to be. In order to fill in the gaps in our knowledge and to make certain that radiation will be more beneficial than harmful to man in future years, yet another commitment is necessary. We have to commit ourselves to hard work, bright ideas and never-failing attention, just like the pioneers that we owe so much gratitude. Like Rolf Sievert.