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COMPARISON OF COST EFFECTIVENESS OF RISK REDUCTION AMONG DIFFERENT ENERGY SYSTEMS : FRENCH CASE STUDIES

Report n° 162

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Final Report of the Co-ordinated Research Programme on : "Comparison of Cost Effectiveness of Risk Reduction Among Different Energy Systems"

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INTRODUCTION

This report presents the three French case studies performed in the framework of the co-ordinated research programme on: "Comparison of Cost-Effectiveness of Risk Reduction Among Different Energy Systems".

I - Cost-Effectiveness of Robotics and Remote Tooling for Occupational Risk Reduction at a Nuclear Fuel Fabrication Facility

Jacques LOCHARD

1. INTRODUCTION

This case study, related to the design stage of a fuel fabrication facility, presents the evaluation of alternative automation options to manipulate mixed oxide fuel rods in a quality control shop [1]. It is based on a study performed in the framework of the "MELOX project" developed by COGEMA in France.

The methodology for evaluating robotic actions is resulting from a research work part funded by the IAEA under the co-ordinated research programme on "Comparison of Cost-Effectiveness of Risk Reduction among Different Energy Systems", and by the Commission of the European Communities under the research and training programme on radiation protection.

2. BACKGROUND

Reducing occupational exposure during maintenance work and preserving at the same time the economic viability of nuclear installations will be one of the major challenges for the nuclear industry in the next decade. Maintenance activities are by far the main contributors to occupational exposure in nuclear facilities: about 75% of the total annual occupational collective dose in European BWRs and up to 85% in PWRs [2], about 60 to 65% in French reprocessing plants [3, 4, 5].

Maintenance companies are more and more concerned about possible shortages of skilled labour for performing these routine or special maintenance tasks. Some maintenance tasks may become impracticable to perform using human labour if they keep relying on highly specialized and trained operators without any change in the radiation fields or the work duration of the tasks. In this general context the development of robotics and remote tooling for reducing doses during major repetitive maintenance work, in a cost- effective way, is becoming a key element in many radiation protection programmes at nuclear facilities.

From the economic point of view, however, taking into account the cost of the development of robotics, utilities' owners will be unwilling to invest in new machinery unless it has been shown to result in savings in operational costs. An economic barrier is formed by the large investment required to develop new products specifically for nuclear applications and it is clear that the cost of the detriment, even if the potential for dose reduction is quite large, is not a sufficient factor to outweigh alone the cost of developing robots.

3. DESCRIPTION OF THE METHODOLOGY

3.1. Introduction

The methodology for evaluating the costs and effectiveness of robotics actions is based on the general framework developed by the IAEA [6]. Past evaluation of particular radiation protection actions in nuclear power stations following this approach had already shown a potential for reducing doses and saving operational costs at the same time [7]. The model proposed here is an attempt to systematically take into account the operational cost savings of implementing risk reduction measures. In fact one should consider the objective factor on which the potential cost savings rely . Working in an hostile environment involves lower productivity due to bad working conditions and, consequently leads to extra labour and protection costs. Any actions that tend to move back towards normal productivity (either by reducing the sources or the working time) lower these costs and can be seen as a productive investment.

Figure 1 illustrates the basic relations on which the model relies. Each curve on the figure corresponds to the set of combinations of ambient dose rates D and work durations T resulting in the same level of exposure S. Introducing robotics reduces occupational exposures related to a given operation (from S1 to S2) by reducing both the total work duration on the job (from T1 to T2), and the ambiant dose rate (from D1 to D2) as operators are generally performing new tasks in different ambient dose rates. The economic dimension is introduced through the investment and operating maintenance costs of the robotic systems as well as the variation of the various operating costs that are affected by the work duration reduction T1 - T2, i.e. the differential in plant availibility, labour cost and radiological protection costs.

Practical implementation of this model involves consideration of all the relevant characteristic parameters : the working conditions in controlled areas (ambient dose rates, use of protective devices, radiological protection assistance...) as well as the various costs involved i.e. protection and operating costs.

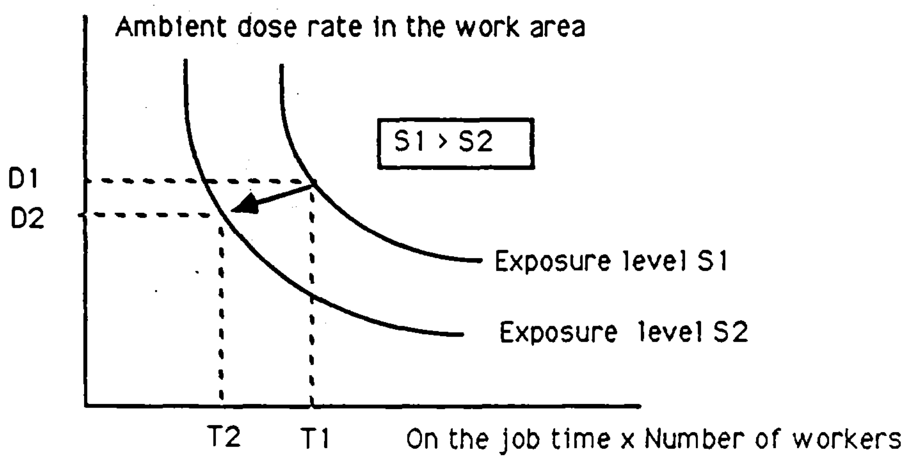

FIG.1. Impacts of robotics and remote tooling on basic parameters governing occupationnal exposures at nuclear facilities.

3.2. Cost of implementation

The various costs associated with the implementation of robotics or remote tooling to be considered in the evaluation are the following:

- investment costs, which include purchase price of the equipments (robots, tooling, sensors, etc.), installation costs (facility and process modifications for example) as well as initial programming and personnel training costs. These last costs can represent a relatively large portion of the total investment cost.

- operating costs, which include scheduled maintenance and reprogramming costs, personnel costs (supervisors and production workers running the equipment), training costs for the maintenance and operating personnel and decontamination costs after use [8].

3.3. Operation costs saving

Apart from exposure reduction, the installation of remote handling systems or robots in nuclear facilities can provide several benefits to the user such as:

- labour cost reduction;
- reduction in radiation protection services, protective equipment and health physics staff;
- increase in production capacity by shortening of outage time in the case of NPPs which results in replacement power cost savings;
- improvement of productivity by introducing constancy of pace in operation and better efficiency of equipment.

The labour cost reduction can result either from a shortening of the task duration to be performed or from a reduction of the radiation incremental labour cost due to the change in the working conditions. This radiation incremental labour cost notion elaborated by Ontario Hydro's analysts [9] expresses the differential cost between a normal task (non-radiological) and a task performed within a radiation field. It results from the summation of two terms. The first one is the differential in wages due to the extra labour time imposed by the handicap of working within radiation fields. This includes the effects of the exposure limit (combined with the dose rate) as well as the impact of wearing protective equipment such as gloves, air-supplied suits, etc. The supplementary work time imposed by protective equipment can be quantitatively estimated by the use of worker utilization factors which express the loss of productivity. The second term is the wage cost related to the training time of operators. This includes radiation protection training, training in the use of protective equipment, mock-up training, trade certification testing, etc.

3.4. The cost-effectiveness of risk reduction analysis

Cost-effectiveness analysis allows one to present the effective trade-off between the risk reduction and the economic impact of implementing alternative robotics or remote tooling systems. The various costs components have to be aggregated either on an annual or on a total present worth basis and compared with the dose reduction achieved. In the first case, the annual saving in labour and protection service costs plus the eventual increase in production capacity is treated as a revenue and substracted from the annual expenses of operating the robots - annual maintenance plus depreciation, insurance, etc - to obtain the amount of annual net benefit or cost. In the second alternative, the present value of annual savings over the lifetime of the equipment is subtracted from the total implementation cost - investment plus present value of annual maintenance costs - to obtain the total present worth benefit or cost of operating with robotics.

Figure 2 presents a graphic display of a set of independent hypothetical robotics options ranked according their cost-effectiveness ratio. Only efficient actions have been represented that is to say it is neither possible to find a more effective option (in term of dose reduction) for the corresponding benefit or cost, nor a more beneficial or less costly action for the same level of residual risk. The graph differs from the classical cost-effectiveness of risk reduction curve [6] as it includes the beneficial options when operation cost savings outweigh the costs of implementation. Point O is the level of exposure before taking any action. The left hand side of the Y-axis shows the beneficial actions. Assuming a rational economic behaviour, the utility or the firm will first implement action A which presents the highest benefit -risk reduction ratio, then option B (It is to note that if priority is given to risk reduction, action B will be implemented first and then A). After B the shape of the curve refers to the actions resulting from extra expenditure, which generally follows the law of diminishing returns. Point Q is a virtual equilibrium point where savings are compensating costs. O Q is the potential for zero cost risk reduction.

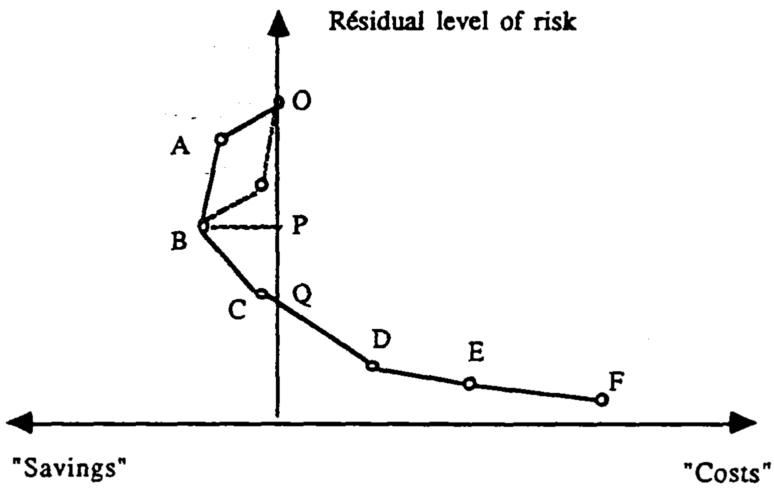

FIG.2. Cost-effectiveness of risk reduction curve.

The eventual selection of options on the right hand side of the Y axis, representing the trade-off between the cost increase and the residual risk level, will depend on the price the utility or the firm is willing to pay to avert an extra unit of dose (the cost-effectiveness ratio). This refers to the adoption of a reference value for the so called monetary cost of the man-sievert which has been a matter of debate for many years. No real consensus exists on the subject and a large range of values have been proposed in the literature [10].

4. THE FUEL FABRICATION FACILITY CASE STUDY

4.1. The reference system

In the production process of the mixed oxide fuel rods, all rods before they are assembled as fuel elements need to be controlled within a quality control shop. As the various types of control are taking different times, an intermediate storage system has to be introduced to store the fuel rods (which are laid down on "transfer tables") between two controls. Because of potentially high level dose rates, the transfer tables are introduced into shielded "drawers" during their intermediate storage time.

The first option considered to operate the system, was a fully manual one, in which all elementary tasks (transfers between each control, opening and closing of drawers...) are performed directly by workers. Taking into account the ambient dose rates within the various areas of the shop, as well as the tasks duration, the calculation (based on figures extrapolated from past experience in existing fuel fabrication facilities or resulting from modelling) showed that the fully manual option would have lead to an annual collective dose of about 0.7 man-sievert.

To satisfy the design target of 5 mSv per year per worker adopted by the operator of the plant, the fully manual option would have required more than a hundred of workers per year. Considering the high level of collective exposure and the cost of operating such a system due to the large number of operators, a semi-automatic option (semi-automatic 1) based on manual transfers between each control but with automatic opening and closing of the drawers was adopted as reference system to evaluate the effectiveness of more automatized options.

4.2. The protection actions

Two basic alternatives were evaluated.

- semi-automatic 2, with a motorization of the transfer tables between each control, but still with a manual handling between the transfer tables and the drawers.
- fully automatic in which no operators are needed any more for the transfers. For this option only exposures related to the controls themselves are remaining.

Table 1 presents the labour time and collective doses associated to the three alternative options.

TABLE 1. Characteristics of the alternative automation options.

Options	Work duration (hours)	Annual collective dose (man mSv)		
		Transfers	Controls	Total
Semi-automatic 1	16 h 13	92	13	105
Semi-automatic 2	11 h 21	71	9	80
Automatic	0 h	0	9	9

4.3. Cost-effectiveness analysis

Table 2 presents the results of the cost-effectiveness analysis. Taking into account the investment annuity and the annual operation costs, it can be seen that the best option is the full automatic one. Its adoption, although US $ 10,000 per year more expensive than the semi-automatic 1 option, results in annual savings in operation costs of about US $ 300,000 because of the reduced labour requirement.

TABLE 2. Cost-effectiveness analysis of occupational risk reduction.

Options	Annual exposure (man mSv)	Annual costs (US dollars)		
		Investment	Operation	Total
Semi-automatic 1	105	28,000	682,000	710,000
Semi-automatic 2	80	30,000	455,000	485,000
Automatic	9	36,000	384,000	420,000

This case study has demonstrated that the cost of implementing the robotic system is largely outweighed by the benefits expressed in terms of operating costs saved and reduction in occupational exposure. This result confirms previous evaluations made by EPRI, which indicate cost savings ranging from US $ 100,000 to US $ 1 million in net present value per robot [8] .

5. CONCLUSION

From the point of view of the utilities and firms, the robotic and remote tooling options for risk reduction will be more readily adopted if simultaneously the potential cost savings are clearly demonstrated. This first evaluation has shown that robotics are particularly effective when the ambient dose rates are sufficiently high that it is impracticable or not feasible use workers who can only remain at their tasks for very short periods of time, thereby causing a substantial increase in labour costs. But it is also clear that remote tooling and robotics will be economically justified only for those maintenance tasks which are sufficiently well structured or repetitive i.e. normal maintenance or special maintenance works for a set of standardized installations. In this context multi-purpose robotic systems which permit the distribution of the investment cost over a wide range of applications would appear promising.

Beyond the specific results related to this case study, the applications of the cost-effectiveness model demonstrate that improving safety and protection does not necessarily mean an increase in investment and operating costs: there is also the possibility of saving both doses and money at the same time. This is strong argument for promoting safety and protection which must be given an equal weighting with respect to the other production objectives, such as quality or efficiency. In fact the cost-effectiveness of risk reduction approach is one of a number of new instruments that are available for considering the operational structures of industrial systems and treating occupational risk reduction on the same management principles that are applied to quality, costs and production.

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II - Cost-Effectiveness of Protection Actions to Reduce Occupational Exposures in Underground Uranium Mines

Jacques LOMBARD and André OUDIZ

I - INTRODUCTION

The primary objective of this study is to present an analysis of protection actions against alpha energy due to short-lived Radon (Rn) daughters in an underground non sedimentary uranium mine. A set of combinations of simple protection (e.g. parpen wall isolating old stopes, increase in ventilation rates or installation of an electrostatic filter) options has been evaluated.

The evaluation of the risk reduction options requires the knowledge of the effective dose equivalent (i. e. the indicator to express the risk) as a function of the considered options. For this purpose a mine model has to be defined, that will help modelling the alpha contamination due to short-lived Rn daughters. Finally a computer program has been established, that calculates the effective collective dose equivalent associated with the various protection options. Therefore, this study is able to point out the most "cost-effective" options to reduce occupational exposure.

II - DESCRIPTION OF REFERENCE SYSTEMS AND THE BACKGROUND OF THE COMPUTER MODEL

2. 1 - The mine model

The calculations of the effective collective dose equivalents due to ^{222}Rn daughters (Radium A, B and C) are made by using a simplified representation of a non-sedimentary mine. One can imagine a mine as a more or less complex combination of a set of simple elements designated here by the term "branch". Each branch consists of a main gallery, an old stope and ten active ones (see figure 1).

Collective effective dose equivalent calculations will be limited to one such branch.

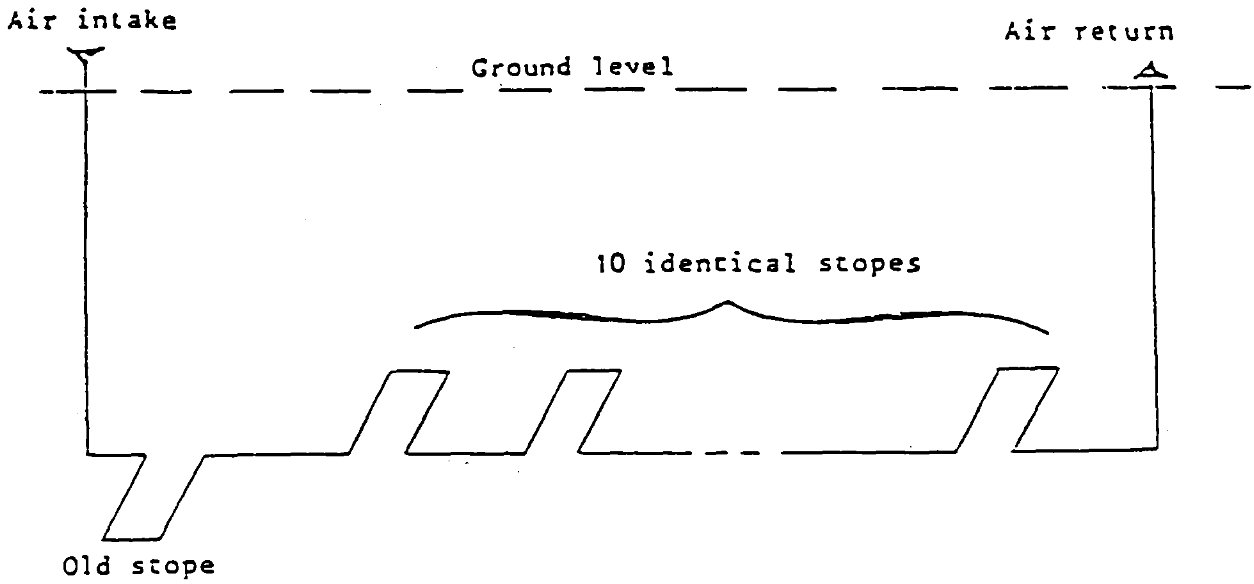

Figure 1 : The considered mine model

The square section of the gallery and its stopes has an area of 16 m^2. All stopes are identical rectangular parallelepipedes with length, height and width of 12 m, 4 m and 4 m respectively.

We assume a descending section mine and, therefore, that in the stope, only the ceiling is quasi-sterile. A figure of 10^{-4} for uranium tenor in quasi-sterile zones is assumed and one of 2 10^{-3} for tenor in the ore. Furthermore, the mean age of ^{222}Rn emanating from the old stope is assumed to be 25 mn.

For reasons having to do with the modellizing of the alpha energy evolution in the stopes, we divide them into two sections of equal dimensions : a working section and an air return section (see Fig. 2).

The personnel employed in a branch consists of seventeen miners, distributed among the various zones of the mine according to their activity.

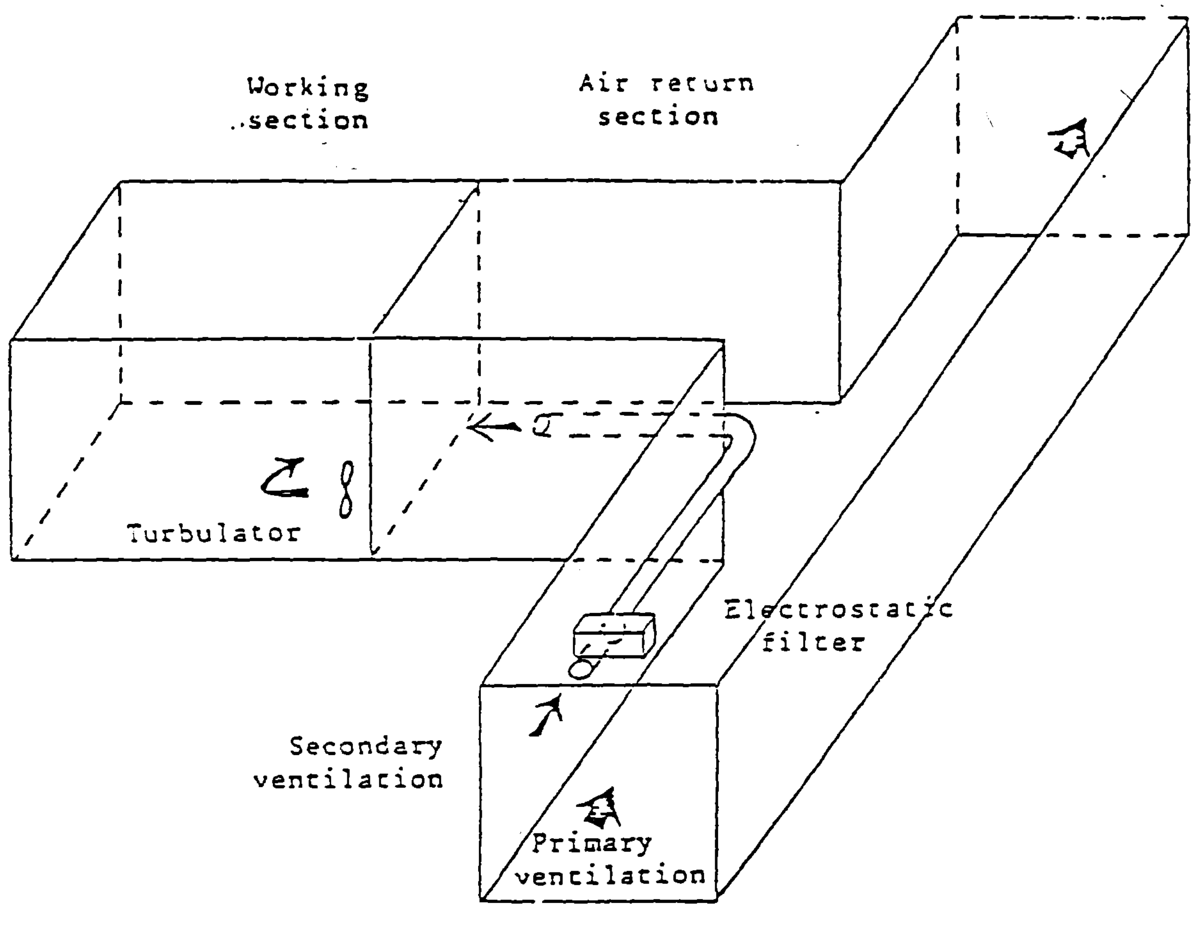

Figure 2 : Stope characteristics and associated protection options

The workers are distributed into three groups 1, 2 and 3 listed in the table 1 with their staying times in the gallery and the stopes.

Table 1 : Distribution of the workers

Group	Number of workers	Percent of time spent in : Gallery	Stope sections: Working	Stope sections: air return
1	4	-	100	-
2	4	-	50	50
3	9	50	25	25

2. 2 - The alpha contamination model

The branch contains ten active stopes. In order to have at our disposal equations valid for any branch independent of the number of stopes, we considered the branch as being a sequence of ten "gallery-stope" pairs.

2. 2. 1 - The alpha energy evolution in the gallery

The alpha energy is calculated based on the concentration of short-lived ^{222}Rn daughter atoms. These concentrations are obtained by solving a system of differential equations relating the concentrations of ^{222}Rn and its daughters as functions of time. The concentration equations thus obtained involve the whole set of parameters related to the characteristics of the mine (volume, area, ^{222}Rn emanation flow, contribution of the old stope), and to the protection options (primary ventilation rate, eventual presence of a parpen wall sealing the old stope). Presented as an example, is the expression of the QRGT concentration of ^{222}Rn in primary air at the entrance of the active stope :

$$QRGT = QRS_0 e^{-\lambda_R t_s} + \frac{\varphi_G S_G}{\lambda_R V_G}\left[1 - e^{-\frac{\lambda_R V_G}{DP}}\right]$$

Where

QRS_0 is the concentration in the gallery of ^{222}Rn atoms emanation from the old stope or from the preceding active stope of the "gallery-stope" pair whose age is ts.

φ_G is the flow of ^{222}Rn emanating from the gallery's walls.

S_G and V_G are respectively the area and volume of the gallery of the "gallery-stope" pair considered.

λ_R is the ^{222}Rn decay constant.

DP is the primary ventilation rate.

The more complex expressions for the QAGT, QBGT and QCGT concentrations of radium A (^{218} Po), B (^{214} Pb) and C (^{214} Bi) have also been derived (further details are given in /2/).

2. 2. 2 - The alpha energy evolution in the stope

In order to properly account for the phenomenon of air stagnation caused by the presence of the working face that acts as a "cul-de-sac", the evolution of alpha energy is modellized by the use of compartment model. In this way, two distinct sections are considered in each stope : the working section containing the working face, and the air return section that leads to the gallery. Two facts are assumed here : first, that the concentration of atoms is uniform in each section and second, that in both sections, the number of atoms entering equals the number of atoms leaving.

Here again, the equations that give the concentrations of short-lived ^{222} Rn daughters in both sections, involve the parameters related to the influence of protection options (secondary ventilation rate, presence of electrostatic filters, etc...). These parameters are briefly described in the following lines.

2. 2. 3 - Model parameters accounting for protection options

We consider here the way they are accounted for in the modellization of alpha concentration. These options are : increase of the primary and secondary ventilation rate, isolation of old stopes by parpen walls, introduction of so-called turbulators (small flow rate fan) or of electrostatic filters.

The parpen wall has as a result the elimination of the concentrations QRSO, QASO, QBSO and QCSO of ^{222}Rn and its short-lived daughters originating in the old stope.

The turbulators increase the flow rate by 1 m^3/s thus accelerating the air circulation of the working section. The electrostatic filter's role is accounted for mathematically by the introduction of a multiplying coefficient, that reduces the short-lived daughter concentration originating in the gallery and entering the stope.

2. 3 - The calculation of the effective dose equivalent from the alpha energy

If the short-lived ^{222}Rn daughter concentrations are given, then it is possible to calculate the potentiel alpha energy inhaled by the various groups of miners and, subsequently, the associated effective dose equivalent, using the factor proposed by the International Commission of Radiological Protection /3/ for optimization purposes :

HE/IP = 2,5 Sv per Joule

HE : Effective dose equivalent per unit of potential alpha energy intake (IP).

2. 4 - The conversational computer model

In order to have in hand a tool flexible and capable of handling the modification of protection related parameters, we have worked out a conversational program in APL. This program computes, by iterating as many times as the number of "gallery-stope" pairs, that is 10 times in our case, the effective individual dose equivalent for a worker staying in any of the three zones (gallery, working or air return section). At the end it provides the effective collective dose equivalent absorbed by the seventeen miners as well as effective individual dose equivalent concerning each group.

III - DESCRIPTION OF PROTECTION ACTIONS

The efficiency of the various options envisaged above is function of the other. Due to this interdependency one must envisaged a comparison of complete protection stratgegies or actions.

A protection action is a combination of elementary protection options. The elementary options are the following : (see Fig. 2 above).

a) - Parpen wall : putting up or not a wall isolating old stopes ;

b) - Primary ventilation rate : choosing among four primary ventilation rates : 20, 30, 60 or 120 m^3/s ;

c) - Secondary ventilation rate : choosing among three secondary ventilation rates : 3, 5 or 11 m^3/s ;

d) - Turbulator : introducing or not a small power rating fan (≈ 2 KW) into the working section in order to better ventilate the working face ;

e) - Filters : placing or not electrostatic filters (1, 2, 3 or 4) that would filter the primary air entering the stope and hold back the short-lived ^{222}Rn daughters.

The cost of the protection action is the sum of the costs of the elementary options of which it consists. With a cost-effectiveness analysis in prospect, one has to take into account the equipements' lifetime in order to be able to proceed to meaningful comparisons of actions. A period of ten years has been fixed as a mine operating lifetime, and all costs related to this period, investment and operating, have been calculated.

The following total costs were obtained. For reasons of simplicity, no discount rate was involved in the calculations. The table 2 presents also the investment and operating costs of each elementary option (in 10^3 $ 1980). Taking into account is lifetime (6 months for a parpen wall, 2 months for a electrostatic filter cell...).

Table 2 : Costs of protection options

Options for a 10 yr operating period	Investment cost (I) 10^3 $	Annual Operating & maintenance cost (OM) 10^3 $	Total cost Formula	Total cost for the 10 yr period 10^3 $
Parpen walls	2.12	0	20 I	42.4
Primary ventilation				
20 m^3/s	10.4	8.5	I + 10 x OM	95.4
30 m^3/s	10.8	21		220.8
60 m^3/s	19.7	45.4		473.7
120 m^3/s	39.3	90.8		947.3
Secondary ventilation				
3 m^3/s	1.9	3.3		55.8
5 m^3/s	3.8	7.1		116.6
11 m^3/s	8.8	26		365.6
Turbulator	1.2	0.9	12 I + 10 x OM	23.4
Electrostatic filter				
each cell	2.87	0	60 I	172.2

IV - MAIN RESULTS

The cost-effectiveness analysis shows that among all the 240 possible actions there is only nine "cost effective" actions. All the results of the analysis are shown in the table 3.

Table 3 : cost-effectiveness analysis results

PROTECTION ACTIONS						Ci	Di	$\alpha i = \frac{Ci - C(i-1)}{D(i-1) - Di}$
i	W	T	F	PV	SV	(10^3 \$)	Man.Sv.	(10^3 \$/Man.Sv)
R	N	N	0	20	3	151.2	7.04	-
1	Y	N	0	20	3	193.6	4.54	17
2	Y	N	0	30	3	319	2.5	61.5
3	Y	Y	0	30	3	342.4	2.28	106.4
4	Y	Y	0	60	3	595.3	0.89	181.9
5	Y	Y	0	60	5	656.1	0.7	320
6	Y	Y	0	120	5	1 129.7	0.29	1 155
7	Y	Y	0	120	11	1 378.7	0.19	2 490
8	Y	Y	4	120	11	2 067.5	0.14	13 776

W, T : implementation (Y) or not (N) of wall or turbulator ; F : number of filters per stope ;
PV, SV : primary and secondary ventilation rates in m^3/s ; Ci : total cost over a 10 year period ;
Di : "radon" effective collective dose equivalent for 10 years ; αi : cost-effectiveness ratio

Before attacking the problem of choosing a protection action among the 9 cost-effective ones, it is fitting to make a few comments on the cost-effectiveness analysis results. The introduction of walls that isolate "old stopes" is the action that follows the minimal action. This is not surprising since with little expense one third of daughter elements are eliminated. A mine without such walls would not be conceivable these days. The next action consists of increasing the primary ventilation. This action is also classic and it is no wonder, that it is so well ranked. On the other hand, the good position occupied by the turbulator (ahead of increasing the secondary ventilation) is rather surprising. This is due to the low cost of these small power rating fans and to the fact that they act mainly on the working face from where comes the highest potential risk. Introducing a turbulator prior to increasing the secondary ventilation rate reduces the advantage of the latter option (going from 3 to 5 m^3/s) which is now pushed down to 6th place. The most puzzling fact though, is the last place occupied by the electrostatic filters. One could assign a priori a better rank to this device. This equipment filters the various ^{222}Rn daughters at the entrance of each stope and could therefore eliminate a good deal of the risk. However, these filters work efficiently only if the ventilation rates are relatively low. The increase then of the primary ventilation (up to 30 and then to 60 m^3/s) reduces their advantages.

V - DISCUSSION AND CONCLUSIONS

Before proceeding to the selection of the ALARA or "optimal" option, is is necessary to check if each cost-effective actions comply with the individual dose limit of 50 mSv/y. The total individual dose should then be considered. To the evaluation of the radon dose, the external gamma irradiation and the dose due to the inhalation of dust should be assessed.

The external gamma irradiation depends essentially on the uranium tenor. The risk varies depending on whether one is in the working or the air return section or in the gallery. An individual who works 2000 hrs/yr in each of the mine zones would be exposed, because of the external irradiation, to a dose of 10^{-3} Sv/yr in the gallery, 3.3 10^{-3} Sv/yr in the air return section and 4.5 10^{-3} Sv/yr in the working section. For the three groups of miners we have then an individual external irradiation of, 4.5 10^{-3} Sv/yr for group 1 (drillers, which are the most exposed workers in a mine), 3.9 10^{-3} Sv/yr for group 2 and 2.45 10^{-3} Sv/yr for group 3.

The average annual inhaled quantity of ore dust, in french mines, is 104 Bq/yr, according to /4/, i.e about 6 % of the annual limit of intake for a mix of ^{238}U, ^{234}U, ^{230}Th, ^{226}Ra, ^{210}Po at the equilibrium (≈ 1700 Bq/yr). It may be assumed that the ore dust will add about 6.10^{-3} Sv/yr to the group 1 which is particularly exposed (6 mSv ≈ 200 Bq/yr).

The results listed below and dealing with the individual dose equivalents are related to the group of workers taking into account (table 4).

Table 4 : Variations of the driller effective individual dose equivalent

PROTECTION ACTIONS						Di	EIDEi	αi
i	W	T	F	PV	SV	Man.Sv.	10^{-3} Sv/yr	(10^3 \$/Man.Sv)
R	N	N	0	20	3	7.04	60.5	-
1	Y	N	0	20	3	4.54	45.4	17
2	Y	N	0	30	3	2.50	33.0	61.5
3	Y	Y	0	30	3	2.28	30.6	106.4
4	Y	Y	0	60	3	0.89	22.1	181.9
5	Y	Y	0	60	5	0.70	20.4	320
6	Y	Y	0	120	5	0.29	17.9	1 155
7	Y	Y	0	120	11	0.19	16.9	2 490
8	Y	Y	4	120	11	0.14	16.6	13 776

D_i : Radon daughters effective collective dose equivalent for a 10 year period.
EIDEi : Driller effective individual dose equivalent (Rn + γ + dust).
αi : Cost-effectiveness Ratio

The evolution of the total cost and the radon daughters effective collective dose equivalent for the nine "cost-effective" protection actions is described figure 3.

Before even proceeding to select the "optimal" protection action, we can right away eliminate action (R) by which the exposure of drillers would exceed the annual individual dose limit of 50 10^{-3} Sv/yr (about to 60 10^{-3} Sv/yr). The choice is then limited to the last eight "cost-effective" actions.

In order to determine which of the protection actions is "optimal", a reference man-Sievert value has to be fixed.

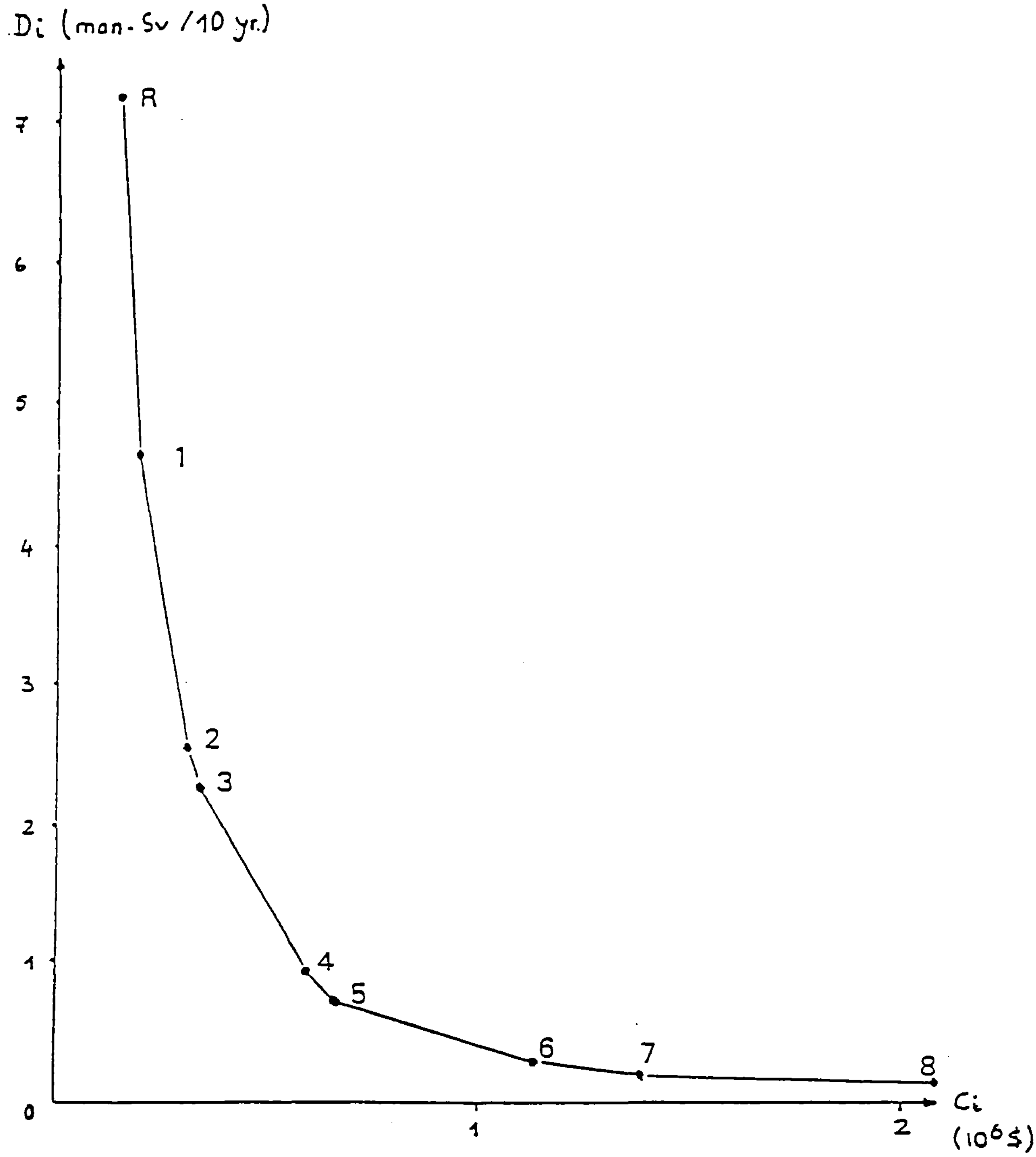

Figure 3 : The cost-effectiveness curve

Till to-day a large number of values have been proposed for this key-parameter. The 1000 to 100,000 $ range seems reasonable for the man-Sievert implicit costs associated with protection measures. These values correspond to these given in the field litterature a few years ago /5/. For the lower range values, action 1 is the "optimal", for the middle ones ($\alpha \approx$ 60,000 $) it would be action 2 and for the higher values ($\alpha \approx$ 100,000$) the 3 could be envisaged. Let it be noted, moreover, that action 2 is the one that best reflects the protection actions that would presently be employed in such a mine. Consequently, we will discuss the eventual implementation of actions 1 or 3 in reference to action 2.

Adopting action 1 (the minimal protection action) involves a reduction of the primary ventilation rate from 30 to 20 m^3/s and, because of this, an increase of the maximal individual dose equivalent from 33 to 45.4 10^{-3} Sv/yr and of the effective collective dose equivalent (+ 55 %). This increase seems not realistic and Action 1 seems not better than Action 2.

Choosing action 3 introducing a turbulator in each stope allows for a relatively small extra cost, a more equitable distribution of the dose among the 3 groups, with group 1 in particular, benefitting the most. This concern for equitable distribution however, goes beyond traditional "optimization" objectives such as set by ICRP 26 /5/ but corresponds to the new orientation proposed by ICRP 37 /6/. That's why this action 3 seems, as regards to this analysis, the most appropriate one.

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III - Cost-Effectiveness of Safety Measures to Reduce Public Risk Associated with the Transportation of UF_6 by Truck and Trains

Philippe HUBERT and Pierre PAGES

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1 - INTRODUCTION

The present case study deals with the problem of uranium hexafluoride transportation by truck and train. It consists of a probabilistic risk assessment of the potential hazards to the public that can arise from the trafic that will take place in France in 1990. The specificity of UF_6 is that it presents both chemical and radiological hazards. But, whatever the transported material, road traffic entails a risk of its own. Thus three kinds of risks are assessed for natural, depleted and enriched uranium hexafluoride. These assessments are the basis of a cost-effectiveness analysis which deals with such safety measures as using a protective overpack, avoiding populated areas and escorting the trucks.

2 - METHODOLOGY AND REFERENCE SYSTEM

The methodology of the study is sketched in Figure 1. Since probabilistic risk assessment and ALARA studies have become quite frequent, as exemplified in the last PATRAM symposium, the general methodology will not to be described further. We shall straightforwardly address the successive steps as illustrated in Figure 1.

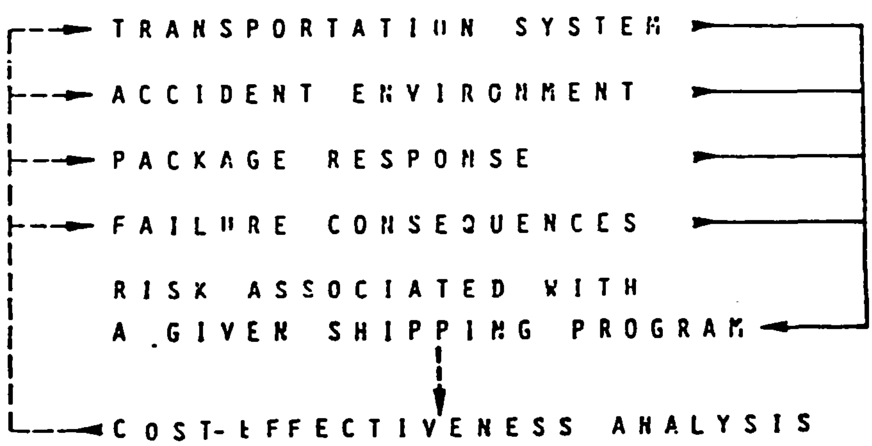

Fig. 1. Schematic flow chart of the study

The reference year 1990 has been chosen for the purpose of this study. At that time the EURODIF enrichment plant situated in the Rhône Valley will operate at full capacity. France will be a net exporter of enriched uranium. The transportation system is assumed as follows. Natural uranium enters the only enrichment plant. Enriched uranium is shipped to the two French fuel fabrication plants that will use 60 % of the whole production, while the remaining quantities will be shipped to the foreign customers. A simplification arises from the fact that the conversion plant (12,000 t capacity of natural uranium), the enrichment plant (capacity of 2 400 t of of uranium enriched at 3.25 %) and one of the fabrication plants (500 t enriched uranium capacity) are located on the same industrial site. Depleted UF6 is also stored on that same site. Accordingly, three classes of shipping routes have been considered :

- Class I : the interplant movements within the Pierrelatte industrial area,
- Class II : the medium range (85 km) shipments in the Rhône Valley from enrichment to fuel fabrication plant, and
- Class III : the long-range shipments corresponding to international exchanges. Only the traffic on the French territory was taken into account. Average shipping distance in this case is 900 km. This traffic takes place along he major lines of communication of the country, which means that the density of population is significantly higher than French average.

Depleted and natural UF_6 are transported in an industrial container, know as 48 Y and whose average load amounts to 12 t of UF_6 (8.1 t of U). Trucks carry each a single container while rail cars carry two of them. Enriched UF6 is shipped in a container known as 30 B. Its content is 2.1 t of UF_6 on the avrage. In case of truck transport, five packages are shipped together ; a rail car generally carries seven packages. Table 1 sums up the mean features of such traffic, which could be associated with a 100-GWe nuclear fuel cycle at equilibrium.

TABLE 1
UF6 Traffic in France in 1990[a]

	Depleted	Natural	Enriched
Truck	1 000 t (III)	1 000 t (III) 12 000 t (I)	500 t (III) 900 t (II)
Train		1 000 t (III)	500 t (III)

[a](I), (II), (III) are the different classes of shipping routes corresponding respectively to 5, 85, 900 km.

3 - ACCIDENT ENVIRONMENT AND PACKAGE RESPONSE

In comparison with the classical studies on UF_6 transportation (1,2), the approach adopted in the French studies (3) is mostly empirical. The methodology has been exposed by Sousselier (4). In the case of mechanical stresses, a statistical analysis of accident data was used both to assess the distribution of severity indicators and to derive an empirical relationship between failure and severity. Accident data were recorded on transportation accidents involving hazardous materials. Then a relationship specific to the UF6 containers was assessed by comparing them to ordinary tanks. In the case of fire, only the distribution of fire duration was taken from statistical data ; thermal analyses and experiments resulted in the use of two thresholds in fire duration corresponding respectively to a limited release and to explosion. Since the first risk assessment of UF6 transportation, experiments and models have been developed in the CEA (5). The 48Y package proved to be more sensitive to fire than first expected. Eventually a 60-min threshold was adopted for explosive failure when the whole package is exposed to a fire. A 30-min threshold was used in the case of a local heat source leading to a limited release. Tables 2 and 3 present the results of these steps for rail and road transportation. Only the accidents involving fire lead to important release fractions. The good safety record of rail is obvious when looking at the probability per km of occurrence of an accident. Considering the mathematical expectancy of released quantity, the same conclusion can be derived.

TABLE 2

Risk of releases in rail transportation (accident rate : $9E^{-8}$)

Accident scenario	Occurrence of scenario given an accident	Risk of opening given the scenario		Release fraction given an opening	Expected release fraction given an accident	
		48 Y	30 B		48 Y	30 B
Derailment	0.701	0.075	0.016	0.001	$5E^{-5}$[a]	$1E^{-5}$
Collision	0.227	0.016	0.003	0.001	$4E^{-6}$	$7E^{-7}$
Partial heating	0.004	0.060	0.3	0.1	$2.4E^{-4}$	$1.2E^{-4}$
Global fire	0.00048	0.44	0.3	1.	$2E^{-4}$	$1.5E^{-5}$
Trivial 0.067	0	0	0	0	0	

[a] $1E^{-3} = 0.001$

TABLE 3

Risk of releases in road transportation (accident rate : 9E-8)

Accident scenario	Occurrence of scenario given an accident	Risk of opening given the scenario 48 Y	Risk of opening given the scenario 30 B	Release fraction given an opening	Expected release fraction given an accident 48 Y	Expected release fraction given an accident 30 B
Collision or overturn	0.924	0.015	0.003	0.001	1.4E-5[a]	2.8E-6
Partial heating	0.038	0.5	0.33	0.1	1.9E-3	1.3E-3
Global fire	0.006	0.7	0.41	1.	4.2E-3	2.4E-3
Trivial 0.067	0.032	0	0	0	0	0

[a] 1E-3 = 0.001

4 - MAIN RESULTS

4.1 - Health consequences

The different accident sequences can result in three release fractions (0.001, 0.1 and 1). In the last two cases the release height was assumed to be 25 m ; the first case was considered as a ground release. Together with these release fractions, three materials had to be considered: natural, depleted and enriched uranium. A Gaussian plume model was used for atmospheric transfer. Three kinds of health effects had to be considered: acute toxicity of HF (lethal dose: inhalation of 50 mg), acute toxicity of UO_2F_2 (lethal dose: inhalation of 150 mg) and the radiological risk. The latter involves here only delayed effects and risk is assessed through the committed dose risk (3.6 $Sv.g^{-1}$ for enriched uranium, 0.9 $Sv.g^{-1}$ for natural uranium, 0.56 $Sv.g^{-1}$ for depleted uranium).

According to these assumptions the acute toxicity of UO_2F_2 is not a matter of concern, since the lethal concentration of HF is reached before the threshold for UO_2F_2 which is furthermore subject to quick deposition on the ground. However that result is very sensitive to the adopted value for the lethal dose. If it were 100 mg in the case of UO_2F_2 as suggested by Geffen (1), this material would be responsible for all acute effects, and such effects would be 5 times higher than computed with the adopted hypothesis. The occurrence of immediate deaths due to HF toxicity is observed in only one accident sequence ; that is the release of the total cargo of a 48 Y container. Even so, fatalities occur in only one of the selected classes of meteorological conditions. The casualties associated with such a sequence were estimated to range from 40 in urban areas to 0.3 in rural areas. The averaged figure along a long range itinerary (class III) is 2.6. This figure could be compared to the 0.15 delayed health effects resulting from the radiological collective dose of 7.2 man-Sv.

In addition to the dispersion model a demographic model was necessary. The representation of the French population density in a grid of 10 by 10 km was the basis for computing the densities along the shipping routes. Further simplifications allowed us to distinguish only the three classes of itineraries previously described. The class III corresponds to an average density of 530 hab-km^{-2}, the class II to 1870 hab-km^{-2} and the class I to 300 hab-km^{-2}.

4.2 - Risk associated with the 1990 shipping program

Combination of all the preceding analyses allows computation of the risk to the public due to accidents during the transportation of UF_6 in the case of the shipping program described in Table 1. The total risk is 1.5 E-3 per year, which includes both expected acute deaths due to toxicity of HF and late radiological effects assessed through the ICRP relationship (50 man-Sv = 1 health effect). The risk ratio per km appears 10 times higher than with the PNL study (1). The higher population density accounts for a large part of this difference (600 hab-km^{-2}) instead of 90). Figure 2 allows some interpretation of the global risk. The three kinds of shipped materials generate approximately the same risk. Even when related to t-km or package-km the risks are of the same order of magnitude. The lowest risk is the one of enriched UF_6 shipments; however this relies on the assumption that the five packages which constitute the usual cargo of a truck have independent behaviours under accidental stress. If they were dependent, the five could burst out in a single accident and HF concentration might then reach the lethal threshold; adopting this hypothesis results in 4E-4 effects for the annual risk of enriched UF_6 shipments.

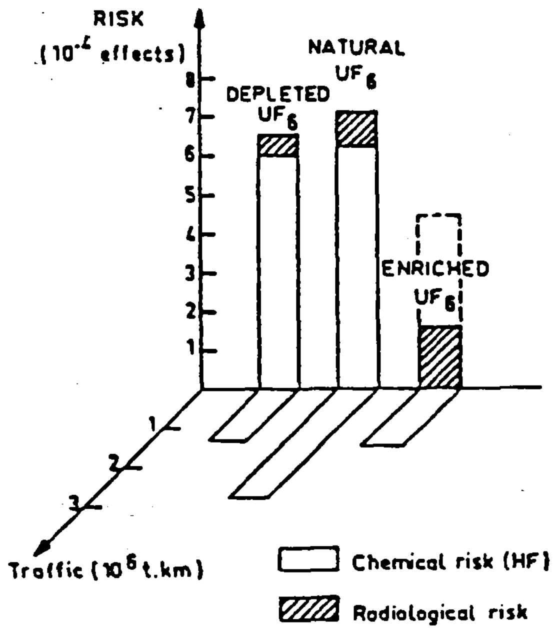

Fig. 2. Radiological and chemical accidental risk associated with the transport of UF_6 in France in 1990.

The radiological risk appears to be about one-tenth of the chemical risk; it is also associated with more frequent events of lower consequences. The chemical risk is itself one-tenth of the number of casualties due to the road accidents linked to this program. Another conclusion on the risk analysis is that such a program would result in one accident every three years, one release every 90 years and one release severe ebough to result in fatalities every 900 years. All these comparisons are intended to provide some basis for appraising the level of risk of the program.

5 - DISCUSSION AND CONCLUSIONS

Associated with the French traffic envisaged for France in 1990 (see Table 1) the cost-effectiveness ratios of some safety measures have been computed within the framework of the risk assessment model. Five of these alternatives are presented here (see Table 4). Two of them consist of rerouting respective rail and road traffic in order to avoid highly populated areas, namely Lyon and Paris. The average density is then lowered by a factor of three, and so is the risk attributed to natural UF_6 which is shipped along these routes. The rerouting option was also envisaged for enriched UF_6 traffic; in this case the Rhône Valley is avoided and density drops to one-twentieth of its previous value. The escort option was also envisaged. It is not very cost-effective as far as only the UF_6 risk is considered, but the interest of that option is its impact on the risk due to the road traffic itself. The adoption of a protective overpack for road transportation was examined last. It turned out to be the most cost-effective alternative.

The results that appear in Table 4 are ranked according to their cost-effectiveness ratios. However the interpretation of such a ranking requires an appraisal of the sensitivity of the model. The overall accuracy of the analysis is submitted to the same restrictions as any probabilistic risk analysis, although the structure of the system studied here is comparatively simple. But three specific features of this cost-effectiveness analysis should be stressed in this respect. First, when the model is used for comparing two options, the overall uncertainty need not always be taken into account. That is the case when the option only involves populations densities. Second, one should not forget uncertainty about the costs. These can depend on many parameters. For instance the use of train instead of truck is generally cheaper, which makes shifting from road to train an ideally optimal solution. But this can be among when inherent costs of a train are taken into account, such as loss of flexibility in duration of the journey. In that case it appears meaningless to relate cost and effectiveness with other criteria to reach an optimal decision.

TABLE 4

Cost-effectiveness ratios for some safety alternatives

Description of the alternative	Avoided effects (expected deaths)	Costs (US $)	Cost-effect. ratio ($ spent per life saved)
1. Rerouting rail traffic of natural UF_6 (Class III itinerary)	$2.7\ 10^{-6}$	$6.8\ 10^{3}$	$2.5\ 10^{9}$
2. Escorting road traffic of natural UF_6 (Class III itinerary)	$6.2\ 10^{-4}$	$80\ 10^{3}$	130.10^{6}
(idem, but road traffic victims taken into account)	$3.1\ 10^{-3}$	$80\ 10^{3}$	$26\ 10^{6}$
3. Rerouting road traffic of enriched UF_6 (Class II itinerary)	$6\ 10^{-5}$	$1.4\ 10^{3}$	$24\ 10^{6}$
4. Rerouting road traffic of natural UF_6 (Class III itinerary)	$4.6\ 10^{-4}$	$7.6\ 10^{3}$	$16\ 10^{6}$
5. Protective overpack natural UF6 on road (Class III itinerary)	$4.6\ 10^{-4}$	$5.7\ 10^{3}$	$12\ 10^{6}$

A third point is that the computed risks are mainly HF inhalation risks which are better known than dose-effect relationship at low doses of radiation. This must be kept in mind when comparing these cost-effectiveness ratios with figures obtained in other examples of ALARA analyses in the nuclear field.

Such comparisons are indeed necessary to fully understand the meaning of the results of cost-effectiveness analyses. When a priori figures are given they range from \$30 (value derived from GNP per capita) to \$1 000 per person-rem (6), that is between \$ 15 and \$5E+6 per life saved. The ratios obtained here are somewhat higher even with the most cost-effective options.

On the other hand the comparisons with a posteriori figures, that is with the cost-effectiveness ratios of some safety options actually in use in the nuclear industry, entails a different conclusion. For example, the implicit cost of human life associated with the present system for liquid radwastes treatment in the french PWR plants has been estimated to \$30E+6 per life saved (7). The implicit value of human life is not, by far, the only criterion to decide upon the opportunity to reduce the risk of a given activity. As a matter of fact, the decision to reduce risk is prior to most ALARA studies. The aim of the analysis is thus to choose the best among alternative actions. The type of study presented here not only applies to this problem, but is also more reliable than when used in a more general decisional context.

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