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Relations of Equivalence of Conditioned Radioactive Waste

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The overall issue of waste management from the nuclear fuel cycle also includes the discussion about a financial evaluation of waste materials, therefore, an exchange of radioactive waste of different categories will be conceivable. The fundamental principle for equating different categories of radioactive waste categories is described. These relations of equivalence are determined on the basis of the relevant physical quantities, decay energies and half-lives on the various waste categories with particular emphasis being placed on the radiotoxicities involved as well as on the cost required for disposal. A closer examination of the factors influencing this determination shows that actually only two main parameters, namely costs of management and the radiologically weighted nuclide inventory of the waste are of importance. A correlation between the relevant costs and radiological inventory is given, thus allowing the establishment of relations of equivalence between the amounts of waste for an example described. Since comparing the different categories of radioactive waste arising from the nuclear fuel cycle is something quite new, the attempt was made to interpret the relations of equivalence obtained on the basis of plausibility considerations. The empiricism contained in these results is subject to verification in practice.

Objectives

The social and political opposition against peaceful use of nuclear energy that has emerged during the last decade has led to considerations which have also a decisive bearing on the waste management strategies.

In the early 70s technological and economic aspects were the primary considerations as to planning and design of waste management concepts. Radioactive wastes as they arose during reprocessing of irradiated fuel of a light water reactor were stored by the reprocessor himself, i.e. waste management from a nuclear power plant was taken care of by the reprocessor.

The reprocessing plants which are being planned today in Europe no longer adhere to this principle, but provide for the possibility of returning the radioactive waste generated in the facilities for reprocessing irradiated fuel elements to the country in which the waste originated.

Depending upon political factors, social opposition, economic situation and dimension of the nuclear programme of a respective country the following solutions of the radioactive waste management issue have been proposed:

- Integrated reprocessing and waste management concepts
- National concepts
- Regional (international) waste management centres.

Under the pressure of a further increase in the cost of nuclear energy utilization caused by a delay in implementation, and due to innumerable requirements to be fulfilled to obtain the necessary permissions for nuclear power stations, a delayed development, particularly in Europe, an economic solution of the waste management problems has begun to play a central role. Since the cost of waste management distinctly decreases with the increasing size of the waste management facilities, it is not only inefficient —especially for countries with small and medium-sized nuclear programmes (i.e., countries with up to 5 nuclear power stations)—to construct facilities for waste management, waste handling and conditioning plants of nuclear power stations (reprocessing, conditioning and storage plants), but sometimes even jeopardizes the peaceful use of nuclear energy as such.

This is why, on a political level considerations have been undertaken to change the approach of returning the waste to the agent having caused it in favor of the construction of supra-regional waste management centres, a strategy which would indeed be reasonable not only for economic but also for technical reasons.

A compensation for the wastes remaining with the operator of a waste management centre, to be given by the agent having caused the waste, may be assured by effecting a financial valuation (equivalence) of wastes. Technically and logically, this equivalence between wastes (or specifically between different waste categories) and financial valuation has been established as reasonable.

In the following the possibility of establishing such equivalences shall be developed, and their suitability for waste management concepts shall be quantitatively expressed.

Methodology

The equivalences to be defined for different waste categories, such as high level waste (HLW), medium level waste (MLW), low level waste (LLW), are determined by a number of characteristic parameters, such as quantity, radioactive inventory, radiotoxicity, type of treatment, cost of waste management, etc.

At the same time it must be stated that a conclusive unique relationship between all those parameters for the determination of equivalence numbers (figures expected to provide quantitative information on the financial valuation of radioactive material) cannot be established. A closer examination of the mentioned parameters shows however, that only two main parameters, namely cost and radiologically weighted nuclide inventory are of importance. As an example, it is obvious that the radiotoxicity of a given waste category is a decisive factor for the kind of treatment to be chosen.

Furthermore the question arises whether or not the weighted nuclide inventory can be reduced to the cost of waste management by adequately valuating it, since it is evident that costs of radiation shielding, transport and storage are also indirectly dependent on the nuclide inventory.

It is feasible to determine the equivalences of radioactive material of different categories by means of the established criterion of waste management cost. Thus the problem has been reduced to one with one independent variable. As the valid national and international regulations on radiation protection involve relevant costs for the considered nuclear technologies, the nuclide inventory contained in the radioactive waste is also expressed by the amount of waste management cost, though indirectly.

The determination of such financial equivalence does, however, involve certain problems, as a technical-scientific and thus an analytically logical relationship between the effective parameters and the costs cannot be established *a priori*. Since establishing such equivalences is something quite new, the first step is to separately determine the parameters "management cost" and "radiologically weighted inventory" before correlating them as well as possible.

Whereas the radiological inventory of radioactive waste is given and the time-dependence follows acknowleged laws of nature, the costs of the individual management operations do not follow these patterns. This proves that, as already mentioned above, a technical-scientific relationship between the equivalence numbers of the cost alone and those of the radiological inventories does not exist. This "subjective" integration of cost into the equivalence numbers deprives the latter of the clear technical-scientific character.

Therefore, the results have to be proved by plausibility considerations and the empiricism contained in this methodology will be subject to verification in practice.

Possibilities of Forming Sets of Equivalence

It was attempted to deduce a set of equivalence numbers (EN) possible (that are logically interpretable) for different waste categories.

These are the possibilities:

- EN based exclusively on the waste management cost of the individual waste categories
- EN derived solely from the comparison of radiotoxicities (hazard index)
- EN based on the comparison of the radiotoxicities, with the nuclide-specific leach resistance of the conditioned radioactive waste being also taken into account
- EN based on the establishment of a relationship between waste management cost and hazard index.

For the last case the valuation of the two parameters, cost and radiotoxicity, is assumed to be equal. The valuations of same for the purpose of establishing other equivalence numbers may, however, easily be different, if one parameter is legitimately a higher value than the other one. In one case the reasons may be economic aspects, whereas in the other case social aspects may be decisive. This necessitates a logical concept of establishing a relationship between the two parameters in order to enable summation of same within one waste category (with the values attributed being either equal or differing). This logical concept of establishing a relationship between cost and radiotoxicity seems feasible in the light of the amount of the financial compensation of the possible damage caused by the nuclide inventory.

The hazard evaluation for radioactive material provided for the German regulations on radiation protection have been applied. The values are defined as multiples of the maximum permissible concentration of radioactivity. These sums are added to the "other" costs of waste management.

Accordingly, radiotoxicity may be considered in the same way as the waste management cost when calculating an equivalence number for a specific waste category. The German regulations on radiation protection distinguish between α-, β- and γ-emitters, according to their different hazard potentials.

The specified system for the determination of equivalence numbers is described in a very general way so as to allow for further variation of waste properties and inventories.

Although the calculation of EN has been based on merely scientific and technical considerations, and has yielded results that lend themselves to logical interpretation, the empiricism contained in the methodology will be subject to verification in practice.

Example of Calculation

Wastes arising from the nuclear fuel cycle are classified into four waste categories: (1) the assumed waste form is todays standard, i.e. glass for HLW, (2) cement for MLW-α, (3) cement and bitumen are used as conditioning materials for MLW with low α-content, and (4) the LLW is generally solidified in cement after maximum compaction. Table 1 shows a comparative representation of the specific radioactivities and other parameters, such as quantity (m^3 per tonne uranium), volume per container (m^3/container) and specific number of HLW cylinders or MLW and LLW drums (container/tonne uranium) of the waste categories in conditioned form.

TABLE 1. Maximum Specific Radioactivity of Different Waste Categories (arised by fuel reprocessing[2-5]).

Item	Categories of Radioactive Waste			
	HLW	MLW-α	MLW	LLW
volume (m^3/tU)	0,1	1	0.8	3.2
material of conditioning	glass	bitumen	bitumen	concrete
spec. volume m^3/drum, cyl drum, cyl./tU	 0,13 0,75	 2 0,5	 0,4 2	 0,4 8
max. spec. radioactivity Ci/m^3 s^{-1} m^{-3}	 8.10^3 3.10^{17}	 $1,2.10^4$ 4.10^{14}	 (10)-10^3 (4.10^{11})-4.10^{13}	 0,05 2.10^9
content of actinides kg/tU kg/tPu	 0,2 0,04	 5 0,05	 0,1-1 10^{-3}-0.02	 — —

The cost of the individual waste management steps for radioactive wastes (as a result of reprocessing), such as treatment, transport, intermediate storage and final disposal are taken from the INFCE Study.[1]

For the purpose of the calculations the nuclide compositions of the various waste categories have been taken from the literature.[2-5]

The concentrations of the various radionuclides of LLW are, by a factor of 20, below those of MLW. Thus, the overall specific activity of LLW does not exceed 50 mCi/m^3 ($1.8 \cdot 10^9$ $s^{-1}m^{-3}$), hence fulfilling the criterion for LLW drums (10 mR/h = $2.6 \cdot 10^{-6}$ $Ckg^{-1}h^{-1}$ in one meter distance).

For HLW the nuclide-specific values given mainly depend only on fuel burn-up and the time of intermediate storage of the nuclear fuel after removal from the reactor. For the other waste categories the asssumptions made for the contributions of the various radionuclides are somewhat less accurate. The kind of process during operation of a nuclear facility as well as during waste treatment determines the composition of the waste. For this reason a distinction has been made between expected and maximum radioactivity levels for the individual waste categories. As it is currently practiced in nuclear technology, the equivalance numbers have been determined for maximum values. The radioactivities of different solid wastes have been determined according to the ICRP-regulations based on the maximum permissible concentrations of the various nuclides in water.

The equivalence numbers EN_1 to EN_4 or the four different definitions presented in the previous chapter, are shown in Table 2. Since these are relative values, any waste category can be taken as reference, e.g. EN(HLW) = 1. Here the equivalence number is the number of containers of a certain waste category which can be taken in exchange for one HLW cylinder.

As a first method of comparing radioactive material the costs may be taken. The EN_1 obtained in this way range between 1-15 for the four waste categories. About four MLW drums with an effective volume of 0.4 m^3 correspond to one HLW cylinder of 0.13 m^3.

Whereas this possibility of comparison is a merely "commercial" one, the radiological effect of the nuclides contained in the waste is decisive for the following comparison. The EN_2 take into account the differing biological effects of the individual nuclides by forming the dimensionless index of radiotoxicity. This ratio is the multiple required to dilute a given level of radioactivity to the maximum permissible concentration so as to comply with the conditions for introducing this material into surface waters.

The results (EN_2)—for a cooling time of approximately 10 a—reveal that the MLW categories exhibit almost identical radiotoxicity indices, whereas those of HLW and LLW differ each by a factor of 10^4 from these values.

It has to be stated that these comparative values of the hazard potential (of radiotoxicity) refer to untreated waste not stored.

To take account of the different materials for solidification and storage strategies for the various waste categories chosen in compliance with the different radiotoxicities, characteristic values of leach resistance of solidification material are considered as third alternative (EN_3).

The equivalence numbers of radiotoxicity determined with the leaching of the solidification material being taken into account, show that similarly to the cost comparison, and disregarding radiological arguments, about 2-3 MLW drums correspond to 1 HLW cylinder. This is a quantitative verification of the necessity of providing more expensive and sophisticated solidification for HLW in compliance

TABLE 2. Numbers of Equivalence EN_1 to EN_4 for Radioactive Wastes.

No.	Item	Categories of Radioactive Waste			
		HLW	MLW-α	MLW	LLW
1	cost: (\$/kgU)	100	60	60	60
2	(\$/drum, cylinder)	133,000	120,000	30,000	7,500
	EN_1	1	1,1	4,4	18
3	hazard.index	2.10^{12}	$2,5.10^{8}$	$2,4.10^{8}$	$1,2.10^{4}$
	EN_2	1	10^{4}	10^{4}	2.10^{8}
4	leach rate 1 ($gcm^{-2}d^{-1}$)	10^{-7}	10^{-4}	10^{-4}	10^{-3}
5	density d (gcm^{-3})	2,8	1,7	1,7	2,0
6	leach time t_A (a)	6.10^{5}	6.10^{2}	6.10^{2}	50
7	risk of release	7.10^{7}	3.10^{7}	2.10^{7}	10^{4}
	EN_3	1	2,3	3,5	7.10^{3}
8	coverage sum (\$/drum, cylinder)	4.130,000	2.600,000	220,000	40,000
9	overall sum	4.260,000	2.720,000	250,000	47,500
	EN_4	1	1,6	17	90

Note:
No. 3 hazard-index $\sum_i [C_i(MPC_i)]$
No. 6 leach time $t_A = V.d/(A.1)$, (V..volume, A..surface area)
No. 7 risk of release $\int \sum_i [C_i(t)dt/MPC_i]/t_A$
No. 9 overall sum = cost (No. 2) + coverage sum (No. 8)

with the requirements—as compared with that applied to MLW.

The last alternative cited is the correlation between the combination of the main parameters of cost and radioactivity. The amount of money to be paid in case of damage in the framework of the liability assumed as provided for by nuclear legislation is added to the cost of waste management of the individual waste categories. These coverage sums are defined as multiples of the maximum permissible concentration as provided for in the regulations of radiation protection.[6]

The equivalence numbers (EN_4) derived as the sum of cost and coverage sums according to nuclear legislation are in good agreement with the results from other methods, at least for HLW and MLW.

This correspondence is a "qualitative" confirmation of the correctness of the developed methods, since the results are largely dependent upon the chosen computational model. This fact is significant, as at present there are no other models available to compare our results.

Assessment of the Results

The calculation of equivalence numbers on the basis of maximum expected values of the radioactive content and the costs of the various waste categories yields logically interpretable results. Although there is no functional relationship between the equivalence numbers of different waste categories so calculated, such a relationship can be established, although in a somewhat speculative manner, by plotting—as shown in Figure 1—the EN_4 on a logarithmic coordinate versus the waste categories on the abscissa

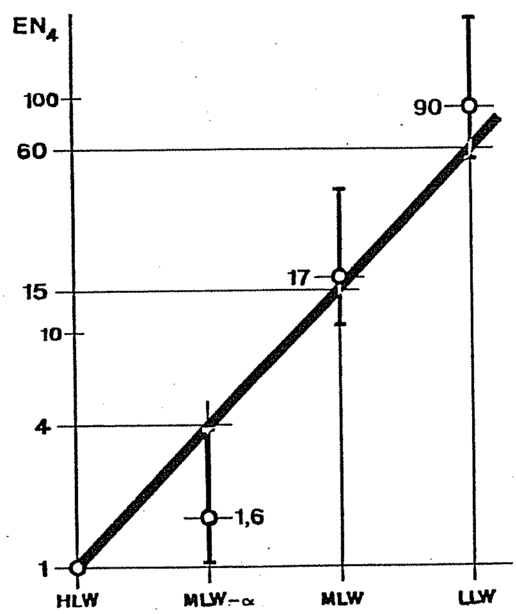

FIGURE 1. Plot of the EN_4 on a Logarithmic Coordinate Versus the Waste Categories on a Equidistant scale.

in equidistant units. This relationship is partly based on empiricism, but can logically be interpreted and thus allows a fit between the computational results within their limits of accuracy. This is of importance, since using the relevant literature, considerable ranges of variations are encountered as to costs and radioactive inventories.

If in the future the answers to the issue of waste management are of technical nature rather than of political, a financial assessment of radioactivity is also expected to be possible. Thus, nuclear waste projects on a supra-regional level could contribute to solve regional problems of waste management.

We hope to have succeeded in presenting several alternatives of a financial valuation of radioactivity.

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