Application of fuzzy methodology in the safety analysis of the Püspökszilágy radioactive waste repository, Hungary

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Abstract: The authors present the results of their safety analysis on the radioactive waste repository of Püspökszilágy, Hungary, carried out by fuzzy methods. The six main radioisotopes stored in the facility were studied under normal conditions of evolution for the next 100 000 years. Uncertainties of the evaluation have been expressed by fuzzy numbers. Activity concentrations were calculated for all stages of the evolution separately, ending with the arrival of the radionuclides in the biosphere.

Keywords: fuzzy sets, uncertainties, radioactive waste, safety assessments

1 Introduction

Safety assessments for radioactive waste repositories were carried out so far by traditional deterministic and probabilistic methods. For theoretical reasons, these methods are unable to quantify some types of uncertainty related to the safety assessment. The authors elaborated a new, "uncertainty oriented" methodology, based on the application of fuzzy methodology (Bárdossy and Fodor 2001a and b). In 2002 a safety assessment was carried out by the authors, using the new methodology, on the Püspökszilágy radioactive waste repository. The results of this estimation procedure are outlined in this article, considering that the readers are familiar with fuzzy set theory and fuzzy arithmetic.

2 The Püspökszilágy radioactive waste repository

The repository is situated 32 km to the northeast of Budapest in a region of low hills. It has been constructed in the seventies and was finished in 1976. It is a surface repository located on the flat top of a low hill. The repository was designed for the disposal of low and medium level radioactive wastes, produced by the scientific-research reactor of the Hungarian Academy, by hospitals and by some industrial firms. For two periods low and medium level wastes of the Paks nuclear power plant were also transported to the repository. The full capacity of the repository is 5120 m^3 at present. Two safety assessments have been performed in 2000: one by AEA Technology (United Kingdom) and one by ETV-ERŐTERV (Budapest), both using deterministic methodology.

The geology of the site is relatively simple. The hill consists of Quaternary loess of 5 to 30 m thickness. Lenses of fluvial gravel and sand have been detected on the base of the loess by drilling. The Quaternary is underlain by a sequence of Oligocene age, consisting of marine clay, clayey silt and silt. Its thickness is 400 to 500 m. The hill is elongated in NW/SE direction and is flanked by two creeks, being the hydrogeologic bases of the groundwater system.

3 The safety asessment

3.1 Characterisation of the waste disposal and the normal evolution scenario

The first step of any safety assessment is the establishment of a waste inventory. The inventory of the Püspökszilágy repository comprises 4765 waste shipments. The waste has been disposed in four types of disposal units:

Type A: Large concrete vaults filled by plastic bags and metallic drums

Type B: Stainless steel wells (40-100 mm Ø) for sealed radiation sources

Type C: Small concrete vaults filled by metallic drums

Type D: Stainless steel wells (200 mm Ø) for sealed radiation sources

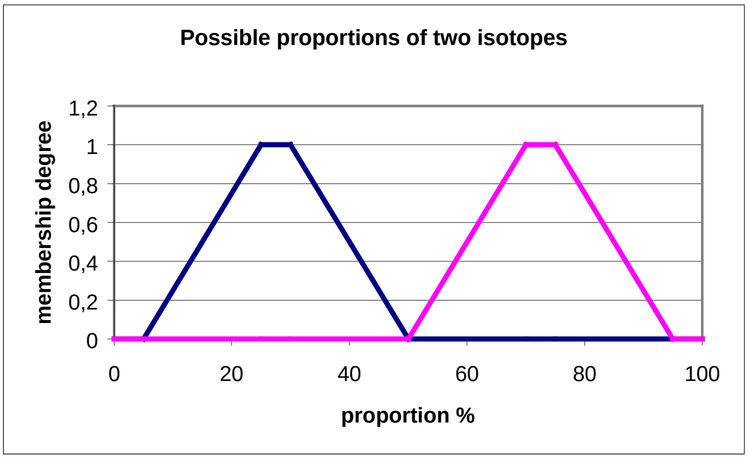
Most of the waste was disposed in A type units. All types of disposal units were covered by a concrete slab, followed by 3 to 4 meter earth.

The following radioisotopes were selected for the safety assessment: ^{3}H (half-life 12,3 years), ^{90}Sr (29,1 years), ^{137}Cs (30,0 years), ^{63}Ni (96,0 years), ^{14}C (573 years), ^{239}Pu (24100 years).

The following normal evolution scenario was established: The repository will be closed on January 1, 2006. It is estimated that the concrete slab cover will collapse gradually after 500 years. This allows direct infiltration of meteoric water into the repository. Leaching of the radioisotopes will start and the solutions will migrate downward, to reach the groundwater level, situated about 20 meters below the bottom of the repository. Hydrogeologic investigations established that the groundwater slowly migrates mainly in eastern direction to reach finally the Szilágyi creek. A smaller portion migrates in SW direction to reach the Némedi creek. The dissolved radionuclides will reach the biosphere along these two creeks.

3.2. Calculation of waste activity in the repository

The activity of the six selected radioisotopes was calculted separately for all the waste shipments listed in the inventory. Unfortunately, in several cases only the order of the proportions was indicated in the inventory in the presence of two or three radioisotopes. This circumstance represents a significant uncertainty for the calculations. This problem can be solved by the construction of corresponding fuzzy numbers, with the help of a simple linear programming model. In the presence of two radioisotopes an order of $5 \leq x_1 \leq 50$ % and $50 \leq x_2 \leq 95$ % could be obtained easily. The corresponding fuzzy numbers are presented in Figure 1a. In the presence of three ranked isotopes three fuzzy numbers have been constructed as shown in Figure 1b. In this case the optimal solution of the underlying linear programming problem yielded the following estimates: $5 \leq x_1 \leq 30$; $5 \leq x_2 \leq 45$; $35 \leq x_3 \leq 90$, with $x_1 + x_2 + x_3 = 100$ %. This way the activity concentration af all uncertain cases could be established and the error propagation could be taken into account.



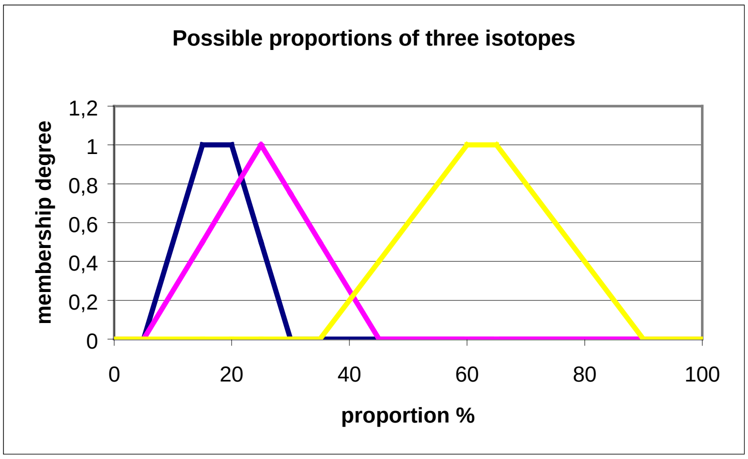
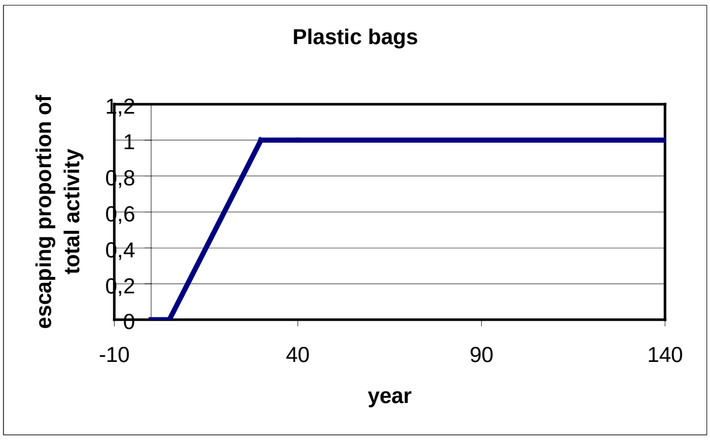
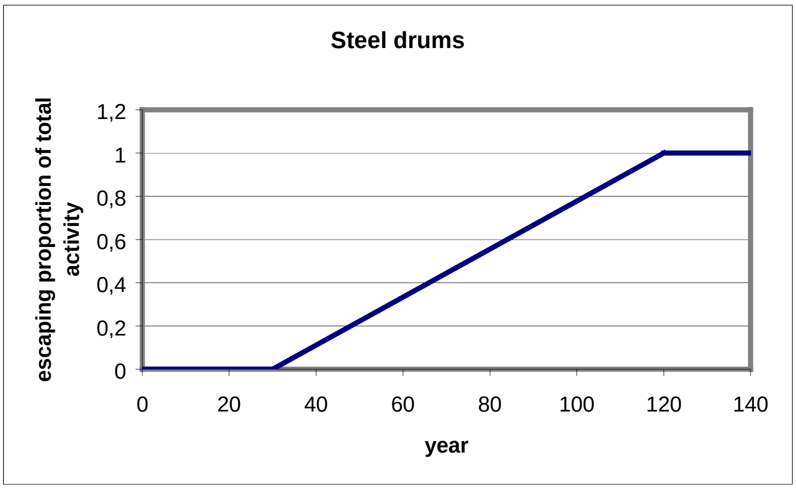


Figure 1. Possible radioisotope proportions in waste packages, as expressed by fuzzy numbers.a) proportions of two isotopes, b)proportions of three isotopes

3.3. Calculation of the decay of waste packages and disposal units (types)

For the decay of the different waste packages official estimates were made by ETV-ERŐTERV based on experiments and international experiences. Fuzzy numbers were constructed by us for the three main types of waste packages, as presented in Figure 2a,b,c. The shortest estimated lifetime was accorded to the plastic bags, their decay starting in only 5 years. The metallic drums have a longer lifetime, up to 120 years. The sealed metallic radiation sources are considered to be the most stable ones, their decay ranging from 800 to 1500 years. These differences are well expressed by the fuzzy numbers.





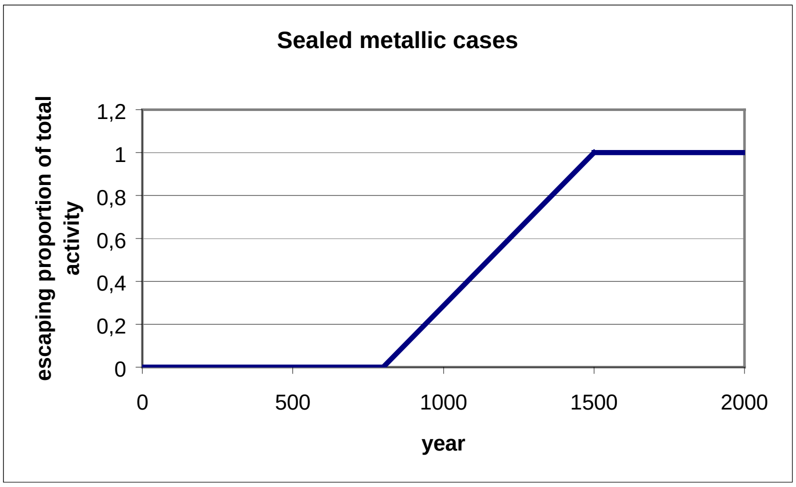
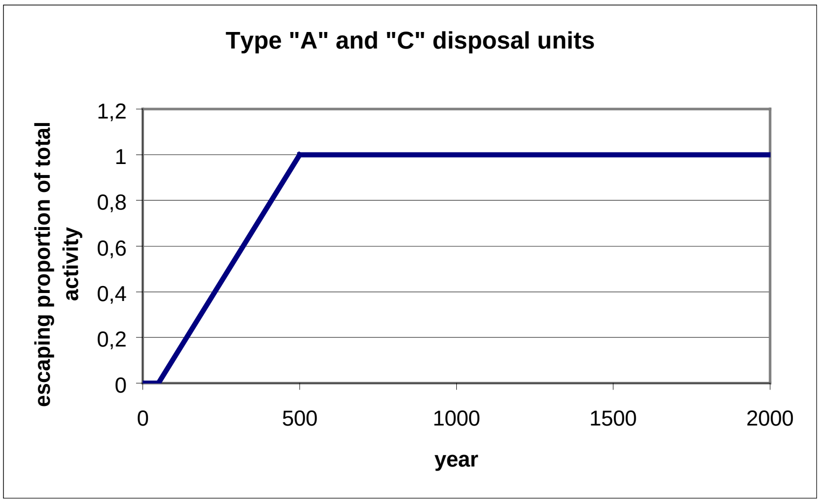
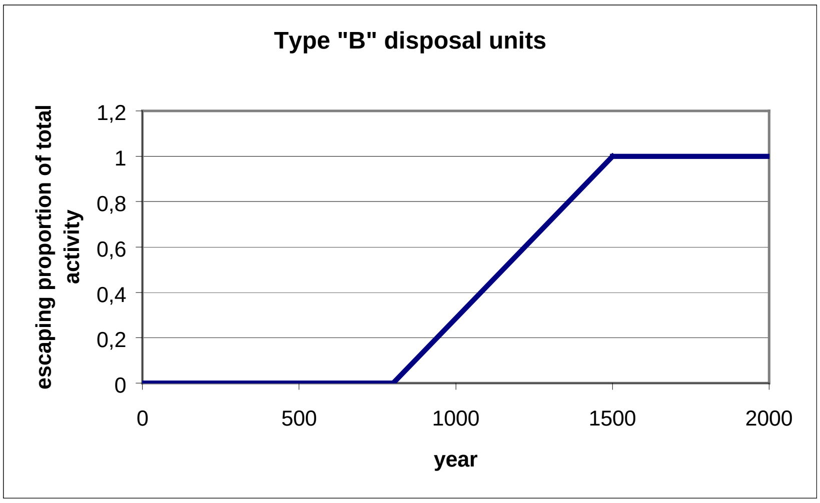


Figure 2. Decay time of different waste packages, as represented by fuzzy numbers. a) plastic bags, b)steel drums, c)sealed metallic cases

It should be stressed, that below the minimum value of the fuzzy number zero escape of radioisotopes is estimated by us. On the other hand, when reaching the full membership degree 1, no more protection is estimated by the given waste package. Summary tables were calculated starting with the reference date of 01/01/2006 and ending at 100 000 years after, and indicating the minimum and the maximum values of each fuzzy number.

For the four types of disposal units again official decay estimates were furnished by ETV- ERŐTERV. Corresponding fuzzy numbers were constructed for the four types, taking into account the uncertainties of the estimates (Figure 3a,b,c,d). The same fuzzy number was constructed for the types A and C, as their official estimates were identical. The shortest decay time-interval was estimeted for them (30 to 500 years). The D type steel wells are more safe with an estimated lifetime of 250 to 600 years. The highest safety is assured by the B type steel wells, their decay starting only after 800 years. Here again no protection was calculated by us after reaching the full membership value of the given fuzzy number.





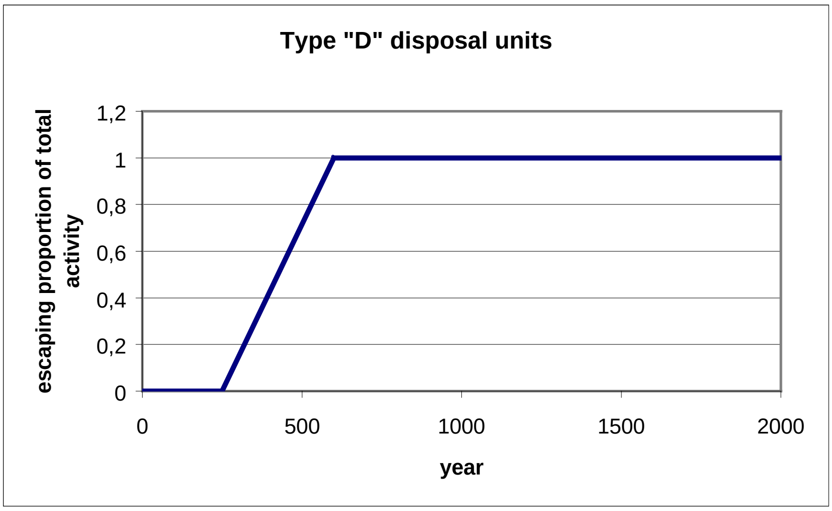


Figure 3. Decay time of different waste disposal units, as represented by fuzzy numbers. a) A and C type disposal units, b) B type disposal units, c) D type disposal units

3.4. Calculation of the source activities of the leached radioisotopes

Here again fuzzy numbers were constructed, taking into account the uncertainties of the input data. In addition the leaching rate λ_ℓ had to be calculated, by using the following formula:

$$\lambda_\ell = \frac{q}{z \cdot (\theta + \rho \cdot K_d)}$$

where q = amount of meteoric water infiltrating the radioactive waste (mm/year)

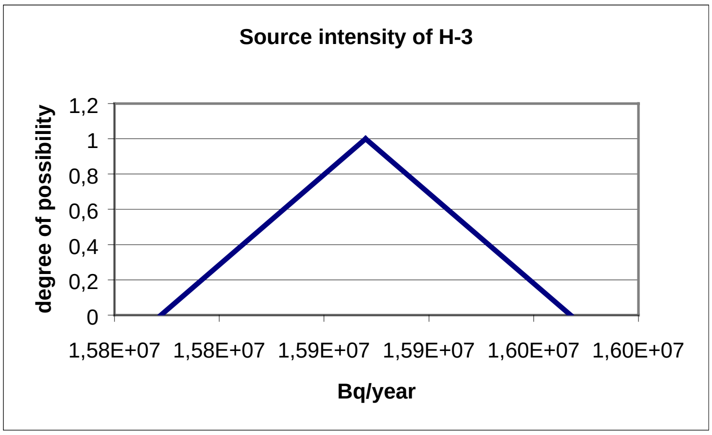
z = height of the disposed waste type (at Püspökszilágy average is 5.6 m)

θ = humidity of the waste

ρ = bulk density kg/m^3

K_d = sorption coefficient

The uncertainties of the components of this equation are also significant and have been taken into account in the corresponding fuzzy numbers. (Figure 4a,b,c,d,e). The results of the activity calculations were listed in tables for 58 time levels ranging from 1 to 100 000 years after the reference date, separately for all the six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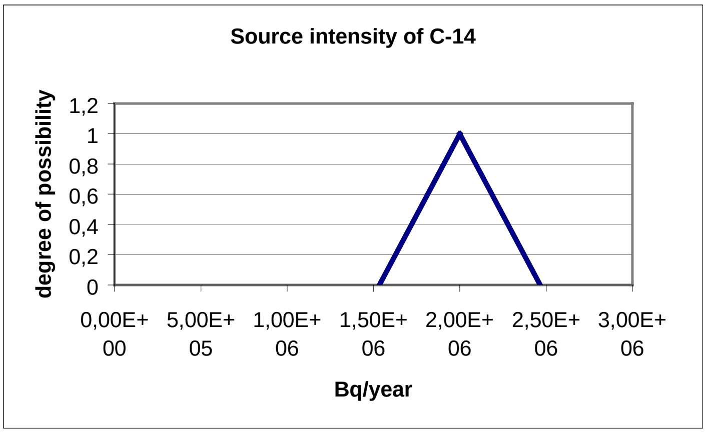
Bq/year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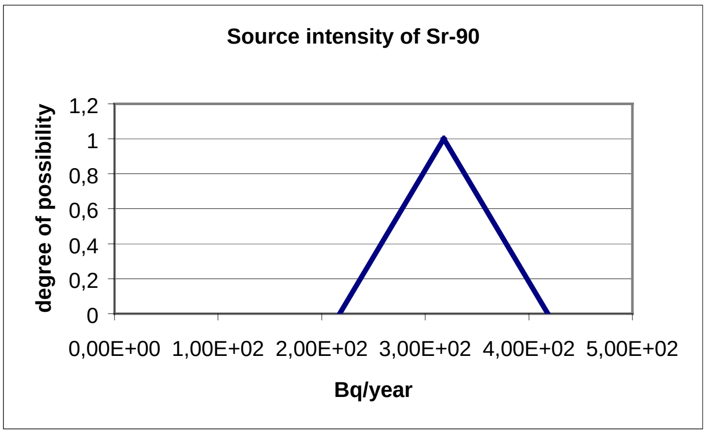
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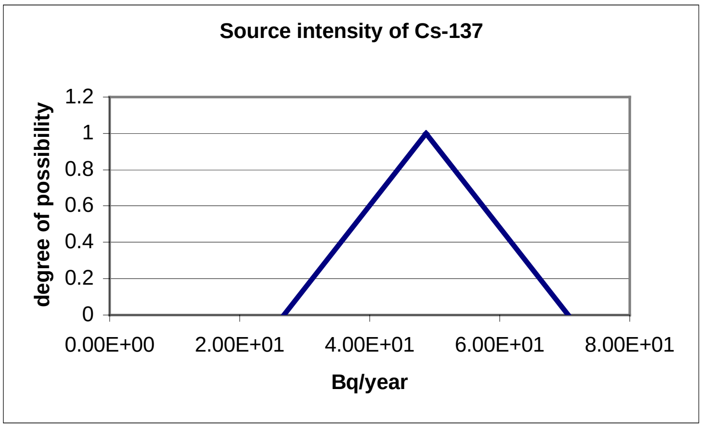

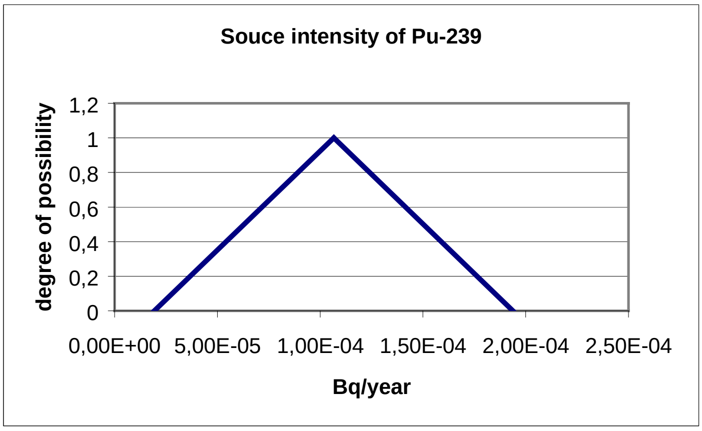

Figure 4. Source intensities of selected radioisotopes as represented by fuzzy numbers. a) tricium isotope (^{3}H), b) carbon isotope (^{14}C), c) strontium isotope (^{90}Sr), d) cesium isotope (^{137}Cs), e) plutonium isotope (^{239}Pu)

radioisotopes. The different half-lifes of the isotopes were also taken into consideration. The numeric values of the tables are represented also in the form of diagrams (Figure 5a,b). They express the activity changes occuring just below the bottom of the repository. Instead of the curves of the traditional diagrams stripes are shown expressing the minimum and maximum values of the corresponding fuzzy numbers. The broader the stripe the more uncertainty is related to the given estimation. The amount of uncertainty is quite different for the selected radioisotopes, highest with ^{14}C and lowest with ^{3}H. The small „bulge” above the 1000 years level for ^{63}Ni corresponds to the amount of the sealed packages in stainless steel wells (type B) characterised by the highest stability.

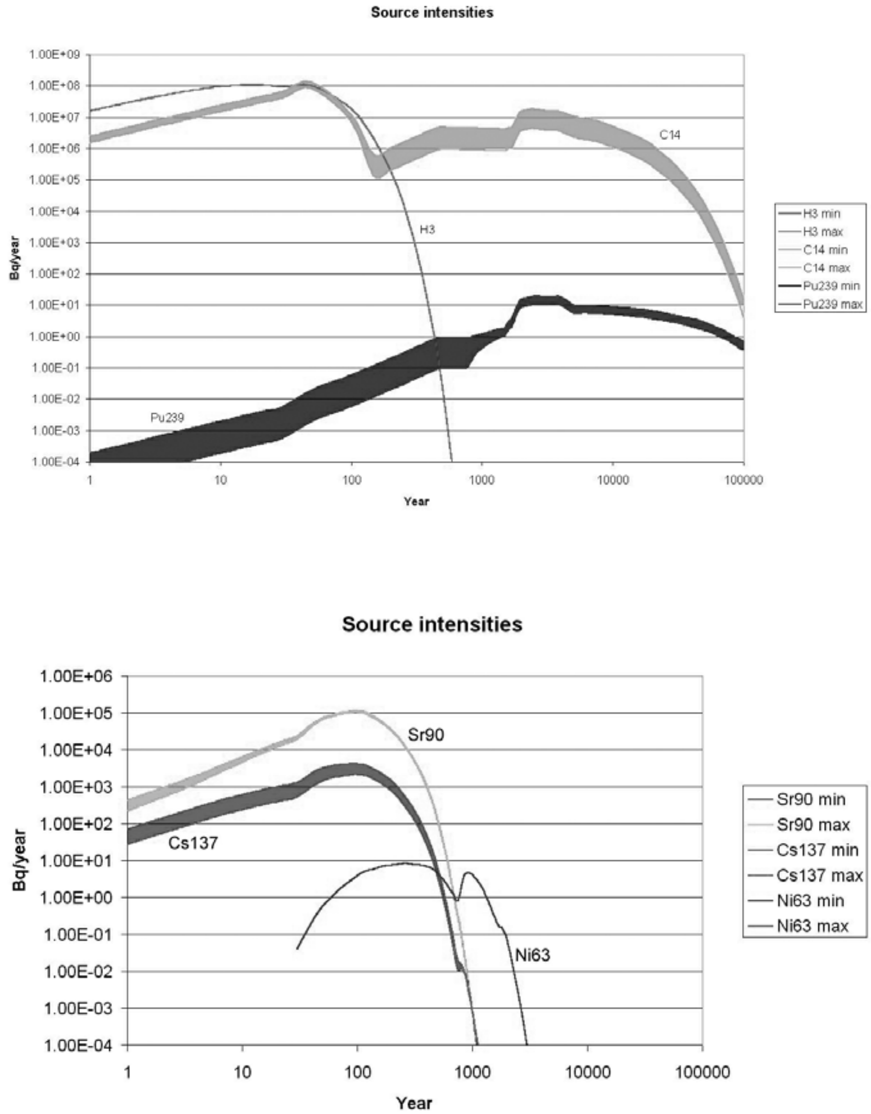

Figure 5. Evolution of source intensities in the future 100 000 years (the stripes represent the support – min/max intervals – of the corresponding fuzzy numbers) a) the evolution of tricium, carbon and plutonium isotopes, b) the evolution of strontium, cesium and nickel isotopes

3.5. Activity changes during the downward migration

Accepting the established hydrogeologic model, the infiltrated meteoric water migrates down-ward in the insaturated zone after leaving the bottom level of the repository. The speed of this migration is very different depending on the permeability of the given rock and the amount of precipitation. The estimated most possible migration time, down to the groundwater level comprises 40 to 60 years and cannot be more than 80 years. Other experts stressed that in the case of long, strong rains the entire zone becomes saturated for a while, resulting in a considerable increase of the downward migration speed. A fuzzy number was constructed by us taking into account all these considerations (Figure 6).

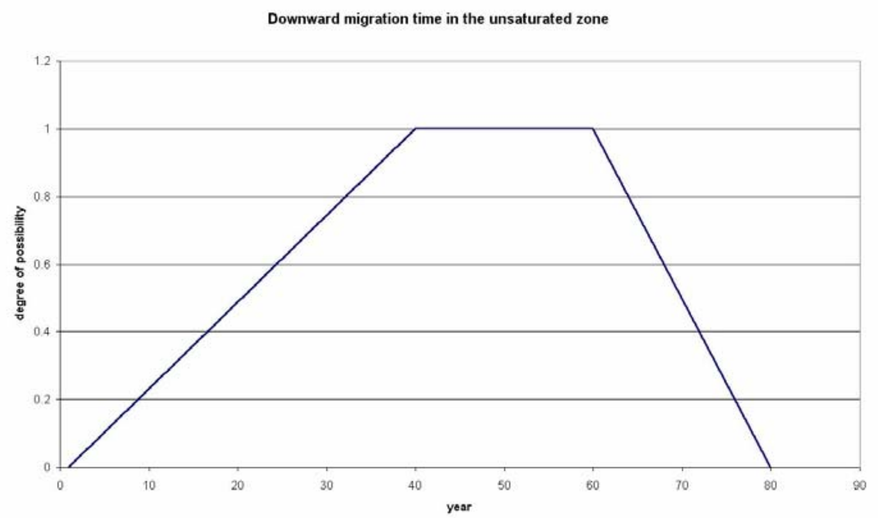

Figure 6. Fuzzy number representing the downward migration time of infiltrated meteoric water in the unsaturated zone

The minimum migration time is only one year! During the downward migration no significant dilution occurred according to the hydrogeologic model. Numeric maximum and minimum values of the fuzzy numbers have been calculated for all the 58 time levels and the results are presented in the form of diagrams in the same way as in the foregoing chapter (Figure 7a,b). The diagram represents the situation at the arrival of the radioisotopes to the groundwater level. The diagrams are very similar to the foregoing ones, all changes are due to the migration in the insaturated zone.

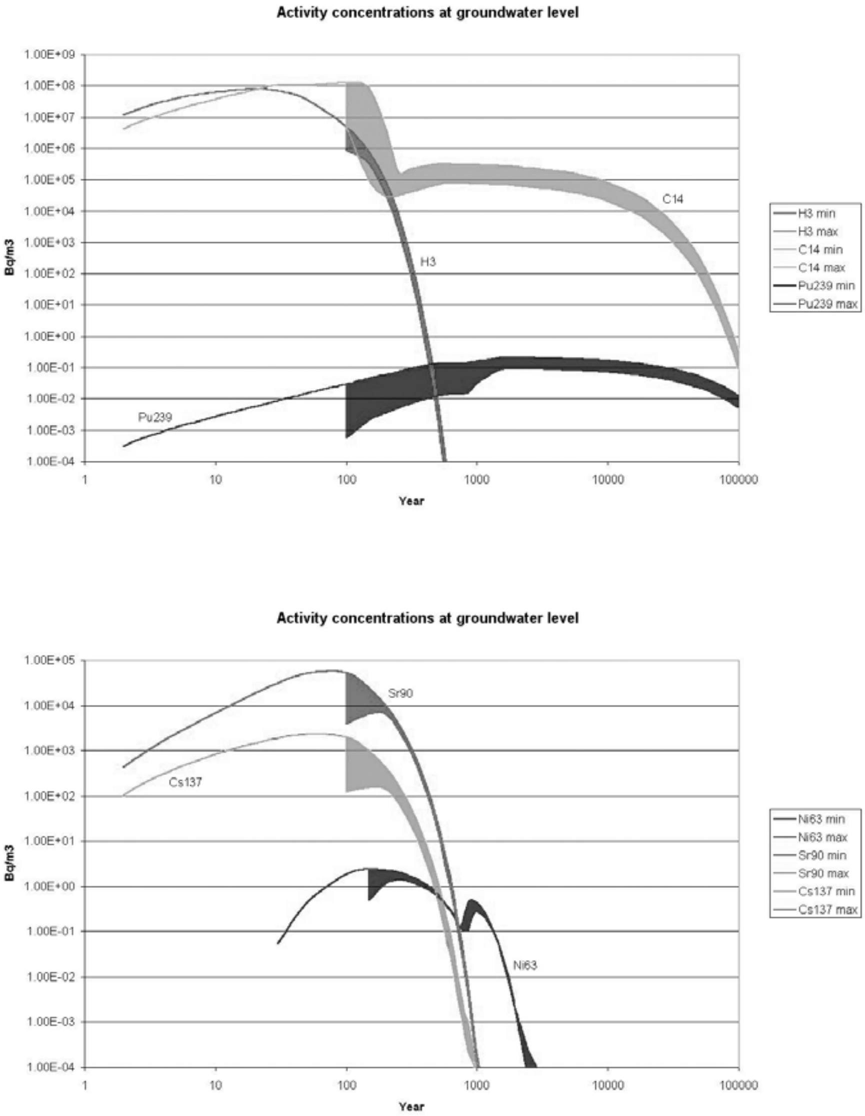

Figure 7. Evolution of activity concentrations at the arrival of the isotope solutions to the groundwater level (the stripes represent the support – min/max intervals – of the corresponding fuzzy numbers). a) the evolution of tricium, carbon and plutonium, b) the evolution of strontium, cesium and nickel isotopes

3.6. Activity changes during lateral migration in the saturated zone

After reaching the groundvater level, that is the saturated zone, the water migrates laterally downward in the direction of the Szilágyi and Némedi creeks. Both creeks are 100 to 110 m below the plateau level. Recent hydrogeologic investigations of ATOMKI (Debrecen) revealed that most part of the groundwater migrates along the Quaternary gravel terrasses (not continuous lenses) and along the weathered top zone of the Oligocene sediments. The migration pathes have been also determined (no migration fans are formed). Thus it takes about 1000 to 1100 meters for the groundwater to reach the Szilágyi creek and 400 to 500 meters to reach the Némedi creek.

The migration time from the former stage to the two creeks could be calculated only with high uncertainty, as within identical layers measurements of the filtration coefficient found differences more than one order of magnitude. This is why the official estimates for the migration time are rather vague: from the plateau to the Némedi creek 100 to 150 years and to the Szilágyi creek even 150 to 500 years. We estimate that about 70-80 % of the infiltrated meteoric water migrates towards the Szilágyi creek and only 20-30 % towards the Némedi creek. As the goal of this article is only to show the new methodology, we decided to discuss only that part of the migration that reaches the Szilágyi creek.

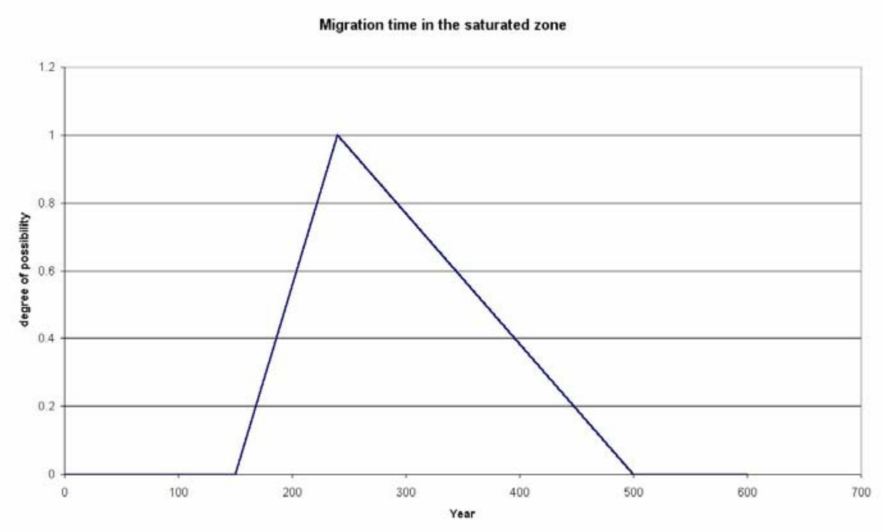

Figure 8. Fuzzy number representing the migration time of radioisotope solutions in the saturated zone from the plateau to the Szilágyi creek

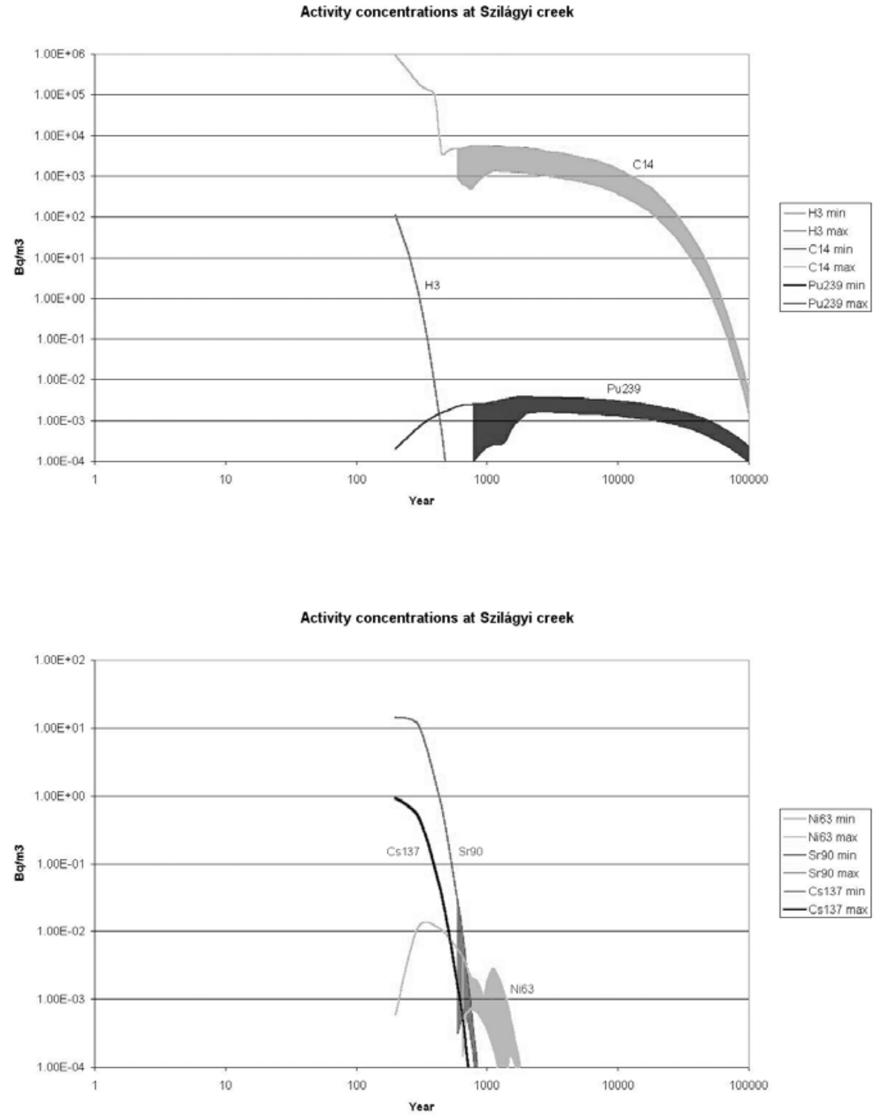

Figure 9. Evolution of activity concentrations at the arrival of the isotope solutions to the Szilágyi creek (the stripes represent the support – min/max interval – of the corresponding fuzzy numbers). a) the evolution of tricium, carbon and plutonium, b) the evolution of strontium, cesium and nickel isotopes

The fuzzy number representing the uncertainty of the migration time to the Szillágyi creek is presented in Figure 8. Laboratory measurements showed that the sediments of the migration path can absorb 20 to 80 % of the dissolved radioisotopes. Taking a conservative stand only 20 % absorpion was taken into account by us. Activity concentrations have been calculated by us with the above outlined conditions for the location where the radioisotopes reach the Szilágyi creek, in other words the biosphere. The numeric results for the 58 time levels are documented in tables and are represented as diagrams in the same way as for the foregoing stages (Figure 9a,b). The radioisotopes appear at this place only 150 years after the reference date (01/01/2006) in the "minimum case" and after 500 years in the "maximum case". The stripes representing the uncertainty of the estimates are broadest for the 14C and the 239Pu isotopes, but they are relatively narrow for the other isotopes. 14C represents the highest activity concentration when arriving to the Szilágyi creek.

The activity concentrations can be easily recalculated into dose rates and dose equivalents. The results show that these values remain all the time below the limits declared by the Hungarian law of environmental protection. Finally, it should be mentioned that our results are in good agreement with those obtained by the traditional methods. The surplus is the sound quantification of the uncertainties.

4 Conclusions

1) The modeling of the uncertainties by fuzzy numbers is relatively easy and the calculation process can be followed step-by-step from the input data to the end results, including the error propagation.
2) The main advantage of the fuzzy method is its ability to quantify uncertainties of the safety assessment. Thus it offers a measure for the reliability of the given safety assessment.
3) The calculation of fuzzy numbers for all stages of the future evolution helps to reveal errors, committed by measurements and by traditional evaluations.
4) The authors consider that the method is suitable for underground repositories of high-level wastes as well. It is recommended to involve mathematicians familiar with the fuzzy set theory into such calculations.

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