USING FUZZY LOGIC TO ASSIST IN PERFORMANCE ASSESSMENT OF A NUCLEAR WASTE REPOSITORY

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ABSTRACT

Disposal of nuclear waste is comprised of many phases from siting the repository to its performance assessment for a period of hundreds or thousands of years. In each of the phases the analyst has to deal with a wide range of interactions. However, due to the high level of complexity, simplifications on the descriptions of the processes are inevitable.

Performance assessment of a repository is a very complex task. The success of the assessment of a repository will depend, among other factors, on how well we understand the geochemical processes that will affect the migration of the contaminants from the repository to the environment. Site characterization is an important step towards the achievement of this understanding and one important part of the repository performance assessment. In this paper we will focus on addressing the treatment of uncertainties when predicting performance. For illustrative purposes, we will present an example on the impact of redox fronts when investigating potential releases from the facility.

In conducting a performance assessment the analyst is confronted with the need to help decision makers to form a “good “ picture of the whole situation while dealing with the technical complexities of the problem and addressing the uncertainties resulting from the data and modeling assumptions. Treatment of uncertainty while retaining a defensible technical analysis needs to be balanced with making a transparent decision process for public acceptance.

This paper proposes the use of fuzzy logic based tools to cope with the challenge of translating ambiguous and subjective information, that support decisions throughout the performance assessment process, into unambiguous and objective information.

INTRODUCTION

Nuclear waste facilities performance assessment is a very complex task. The analyst has to understand many processes, including geochemical processes, that will affect the migration of the contaminants from the repository to the environment.

A typical performance assessment uses numerical or computer models that simulate the environmental conditions. The analysis requires a number of parameters that the analyst chooses in order to represent the interactions and processes involved.

To model all of the processes and events that may occur for the thousands of years over the spatial scale of the analysis is not possible. Simplifications are used to reduce the size and complexity of the computational model with the goal of retaining the most important processes and parameters that affect performance. These modeling simplifications lead to uncertainty in the predicted performance. There are other sources of uncertainties such as ignorance concerning actual environmental conditions, which comes from the lack of data and extreme complexity of interactions. Besides, there is the uncertainty in the future behavior of the system (repository plus environment) which can not be predicted based only on laboratory experiments.

The performance assessment has to consider the entire period that the waste may pose a threat to the public and environmental health. This can last for hundreds or thousands of years.

Uncertainties are often addressed through performing Monte Carlo analysis or other statistical evaluations. These analyses assign parameters a range of values and repeatedly sample through the range of all values to obtain a distribution of potential outcomes. While this is a mathematically defensible framework, it relies on having accurate data to support the range of parameter values. In contrast, site characterization reports often have terms such as: "very aggressive" soil conditions; "moderate "reducing conditions; etc, which are ambiguous and uncertain. This work proposes the use of a fuzzy logic approach to data analysis to help translate ambiguous site characterization data into a form useful for performance analysis.

Fuzzy logic is designed to deal with ambiguous concepts by representing scientific knowledge in terms of human language while keeping the same level of information. Therefore it can be appropriate to represent linguistic concepts These ambiguous data can be translated into fuzzy numbers that are represented in terms of membership functions. The approach is intended to make the analysis easier to understand by the decision-makers and public and at the same time simplify the calculations.

Data from Poços de Caldas, a well-studied region due to its high level of natural radioactive element deposits, will be used in the study. This fuzzy logic approach will help estimate the "best" parameter values to represent the hydrogeochemical interactions or conditions that affect the radionuclides mobility in soil.

In this work we present a screening calculation in order to compare results from fuzzy logic and deterministic (or crisp) approaches. This is followed by a discussion of the advantages of the fuzzy logic approach as compared to the more traditional 'crisp' approach.

In follow on work, the geochemical parameters selected based on fuzzy logic will be input into a computer code, BLT-EC. The output from BLT-EC will be interpreted in terms of the original fuzzy values. Finally a performance analysis will be performed using the fuzzy logic approach. The results of the performance analysis will be compared to results obtained using a more traditional approach.

UNCERTAINTY ANALYSIS

Uncertainties are intrinsic to environmental studies. A number of mathematical techniques exist for uncertainty analysis. This subject has already been treated in detail elsewhere(4). In this work we will use fuzzy logic for addressing uncertainties.

Fuzzy logic is an appropriate choice in this case due to its ability to deal with ambiguous information that comes from lack of data, complexity and ignorance regarding the actual geochemical processes involved in the radionuclides migration through the environment.

Natural analogue studies can help build confidence on computer codes used for performance assessment. Through the study of the natural processes that have been operating for thousands of years, one can proceed to code verification. This would be similar to a natural laboratory experiment without the human intervention. However, even in such cases, uncertainties exist as for example what environmental conditions existed over the relevant time scale within a time scale (10^6 years). Suppositions are then made as for what might have happened and tested against existing data and their interpretation through models.

In this study, we consider the Poços de Caldas site as an appropriate natural analogue study for describing long-term transport processes in the region. The knowledge gained from natural analogue studies can be used to obtain data necessary to project repository performance over thousands of years. A question remains on how the uncertainties encountered on the natural analogue studies can be translated to the performance assessment.

One problem, is the language used on environmental study reports. Even in the case of a well studied site such as Pocos de Caldas, there are conclusions that have more or less supporting evidence than others. Also, these reports have many ambiguous expressions such as "low pH", "very oxidizing conditions ", etc.

For each parameter in the models, we find ranges of values. As we proceed to a more realistic analysis, decision-makers should be awere of the different degrees of certainties for the different parameter values.

For example, one of the conclusions, on the Pocos de Caldas Project, is that the redox front has been moving with a rate between 2 and 20 m in 10^6 years. The report (1) provides different levels of support for each of these limits. This can have implications on the performance assessment. Instead of treating the values as if they had the same weight, we can keep the original information attached to the values. This would help others to understand the whole process, from data gathering to the final performance assessment results.

The whole process of performance assessment is comprised of a series of decisions. If we are able to report the weaknesses and strength along this chain, we will be able to determine the degree of belief we have on the final results.

KNOWLEDGE ENGINEERING - BELIEF AND PLAUSIBILITY

Knowledge engineering, with a strong mathematical basis, is a well established science of representing knowledge that is ambiguous in nature while treating all the ambiguous information in an objective way.(2)

Among the available tools, there is. The following text is an extension of the Dempster-Shafer probability theory to fuzzy sets (1,2).

Belief and plausibility can be translated as certainty and possibility respectively. Belief measure is a quantity, denoted *bel (A)*, that expresses degree of support, or evidence, for a collection of elements defined by one or more of the crisp sets existing on the power set of a universe.

Plausibility measure of this collection A is defined as the "complement of the Belief of the complement of A".

$$pl(A) = 1 - bel(\overline{A}) \qquad \text{(Eq. 1)}$$

The total belief, or evidence, for all elements or sets on a universe is equal to one by convention.

$$\sum_{A \in P(X)} m(A) = 1 \qquad \text{(Eq. 2)}$$

Fuzzy measures are very useful in quantifying uncertainty that are difficult to measure or that are linguistic in nature. In the report, on Poços de Caldas natural analogues, experts use linguistic terms to describe the environment and the situations that might have lead to the observed phenomena.

Some definitions

$$g: P(X) \rightarrow [0,1] \qquad \text{(Eq. 3)}$$

where

> *g (A)*: represents the degree of available evidence of the belief that a given element x belongs to a crisp subset A .
>
> *P(X)* is the power set of crisp sets.
>
> $$P(X) = \{\phi, \{A_1\}, \{A_2\}, ...\{A_n\},...\{A_1,A_2\}.....\{A_1, A_2, ..A_n\}\} \qquad \text{(Eq. 4)}$$

$A_1, A_2, ... A_n$ are subsets of A .

The belief measure represents the mapping of a crisp power set of a universe to a unit interval representing evidence, or:

$$bel : P(X) \rightarrow [0,1] \qquad \text{(Eq. 5)}$$

The collection of these degrees of belief represents the fuzziness associated with several crisp alternatives. This is not the same as the uncertainty associated to the boundaries of a set.Where there are *n* crisp subsets on the universe X.

For each crisp set *A Î P(X), bel (A)* is the degree of belief in set A based on available evidence which is given by the data and also the credibility (weight) assigned by experts.

Degree of belief and plausibility are also called in the Dampster-Shafer theory as lower and upper probability respectively.(3).

If we define B as a subset of A, then:

$$bel(A) = \sum_{B \subseteq A} m(B) \qquad \text{(Eq. 7)}$$

Note that m (A) is the degree of evidence in set A alone, whereas bel (A) is the total evidence in set A and all subsets (B) of A .

$$pl(A) = \sum_{B \cap A \neq f} m(B) \qquad \text{(Eq. 8)}$$

CASE STUDY

On this paper we will use an example from the Pocos de Caldas site related to redox fronts (1).

Redox fronts are a very important subject within nuclear waste repository performance assessment. Oxidizing water can ingress the repository developing spatially and temporally varying redox conditions. This will have a direct impact on radionuclides solubility and their capability for migration towards the environment.

Therefore, understanding the natural occurring redox front dynamics is of great importance for performance assessment (1).

In this work, all the information and conclusions by the original report authors (1) (experts) will be kept as is. Our objective is to add degrees of belief and plausibility associated to those conclusions based on the available information that support them.

The basic objectives of the mentioned report are (1):

- Identification of dissolution, transport and deposition processes within site in general and at the redox front in particular.
- Try to establish the time scales appropriate to the above processes and to evaluate the rate of movement of the redox fronts.
- Information relating to the long term (10^5 – 10^6 years) direction of the groundwater flow.

The data are from F1 drill core that intersects a redox front in three depths: 33.4 m, 42.00 m and 66.22m is used as source of data. At 33.4m and 66.22m the oxidizing segments of the rock overlie segments of the rock with reducing conditions. At the 42.00 m location, the rock in this area is reducing and overlies a segment of rock with oxidizing conditions.

Table I shows data form drill core F1 along with some parameters describing the condition of the rock and geochemical parameters. (1).

Some of the conclusions along with the respective evidences are:

- Direction of groundwater flow was parallel with the fracture system that intersects the drill core at 50 m depth.

  Evidences:
  - Inconsistent with observed flow at the present time.
  - Consistent with the probable direction of groundwater flow prior to mine excavations when redox fronts were formed and with Uranium concentrations in the uppermost section of the drill core.

- Processes such as dissolution, transport and redeposition have been operating within the last 10^6 years. These processes are affected by the redox conditions.

  Evidence:
  - Variations in the Uranium concentration profile and large variations in $^{234}U/^{238}U$ activity ratios.

- Redox front downward movement between 2 and 20m in 10^6 years at 33.4 m .

  Evidence:
  Assuming that excess ^{234}U have decayed to non-detectable levels in 4 half lives.
  - Ra/Th activity ratios
  - $^{234}U/^{238}U$ activity ratios
  - $^{230}Th/^{238}U$ activity ratios

Taking the item 3, downward movement of the redox front at the 33.4 m location, although it is stated that this movement has been calculated as being between 2 and 20 m in 10^6 years. After inspection of the report we can see that there are different degrees of evidence or support for each of these limit values.

For example, figure 1 shows a plot of the $^{234}U/^{238}U$ against the $^{230}Th/^{238}U$ activity ratios for samples 6-1 A, 10-1 A, 16-1 A and 26-1 A. In this figure, the relative positions of the samples suggests that 6-1 A and 10-1 A have been exposed to other processes in addition to simple decay. While the $^{234}U/^{238}U$ profile with depth could suggests simple U decay.

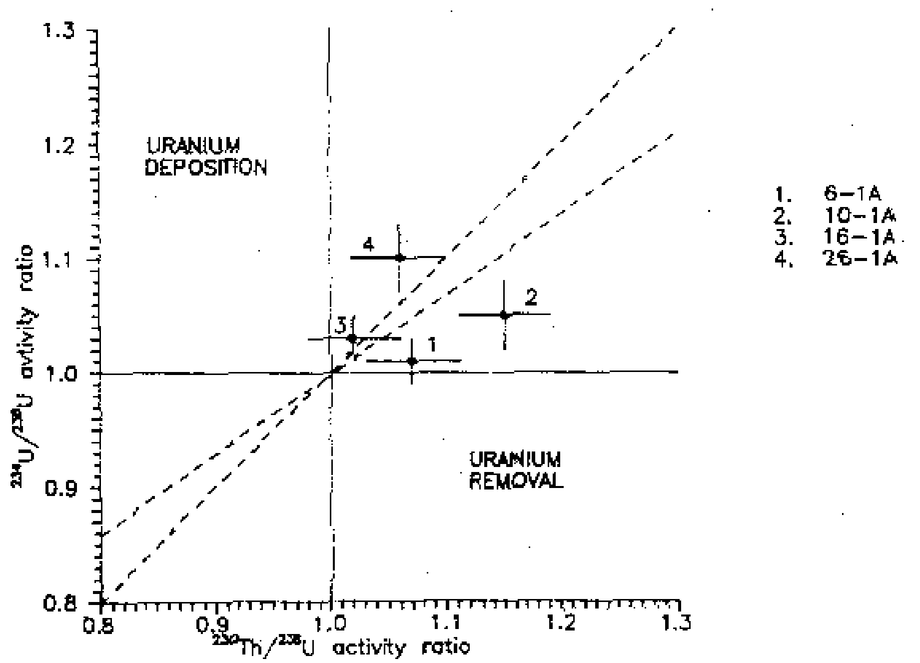

Fig. 1. 234U/238U activity ratio versus $230^{Th}/238U$ activity ratio diagram for samples from the oxidized rock in the F1 drillcore above the 33.44 m redox front.

Table I. List of samples from the drillcore which were analyzed for natural deacy series radionuclides(1).

Sample code	Depth (m)	Rock description
6-1 A	6.00	Porous, strongly fractured, oxidized phonolite
10-1 A	9.84	Porous, fined grained porphiridic, oxidized phonoite.
16-1 A	15.07	Oxidized phonolite, average sample, low U content.
26-1 A	25.22	Oxidized phonolite, average sample, low U content.
33-1 A	32.89	Redox frnt, oxidized side, low U content.
34-1 B-A	33.40	Redox front, oxidized side, low U content.
34-1 B-D	33.51	Redox front, reduced side, low U content.
34-1 B-F	33.65	Redox front, reduced side, low U content.
34-1 C	34.00	Very porous, fine-grained porphyiritic, reduced phonolite.
35-1 A	34.31	Porous, fine-grained porphyritic, reduced phonolite, fractured.
41-1 A	40.05	Massive, medium-grained porphyritic, reduced phonolite.
42-1 A	41.85	Redox front, reduced side, low U content.
42-1 B-B	41.95	Redox front, reduced side, U mineralization.
41-1 B-D	41.97	Redox front, reduced side, weak U mineralization.
42-1 B-F	42.01	Redox front, reduced side, weak U mineralization.
42-1 B-H	42.03	Redox front, reduced side, weak U mineralization.
42-1 B-I	42.04	Redox front, oxidized side, low U content
42-1 B-K	42.05	Redox front, oxidized side, low U content
43-1 A	42.10	Redox front, oxidized side, low U content
45-1 A	44.87	Massive, medium-grained porphyritic, oxidized phonolite.
47-1 A	46.10	Porous, inequigranular porphyritic, oxidized phonolite, strongly fractured.
50-1 A	49.83	Porous, fine-grained porphyritic, oxidized phonolite, fractured.
55-1 A	54.30	Porous, inequigranular porphyritic, oxidized phonolite, fractured.
60-1 A	59.80	Porous, medium grained, oxidized phonolite.
65-1 A	64.50	Porous, medium grained, oxidized phonolite.
66-1A-A	65.93	Redox front, oxidized side, low U content.
67-1A-B	66.19	Redox front, oxidized side, low U content.
67-1A-D	66.26	Redox front, reduced side, low U content.
68-1A–A	67.03	Redox front, reduced side, low U content.
71-1 A	70.10	Porous, argillic, medium-grained, reduced phonolite.
75-1 A	74.25	Porous, fine-grained, reduced phonolite.
75-1 B	74.96	Massive, fine grained, reduced phonolite.
80-1 A	79.80	Reduced phonolite, average sample.
96-1 A	96.00	Reduced phonolite, average sample
101-1 A	100.32	Reduced phonolite, average sample
104-1 A	104.00	Reduced phonolite, average sample.
110-1 A	110.00	Reduced phonolite, conductive zone, low U concentration.
111-1 B	111.00	Reduced phonolite, conductive zone, low U concentration.
113-1B	113.00	Reduced phonolite, average sample.
114-1A-A	113.09	Hydrothermally altered, porous reduced phonolite.
114-1A-B	113.19	Hydrothermally altered, leached, porous reduced phonolite.
114-1A-C	113.20	External part of fractured filling, maily K-feldspar, pyrite and zircon.
114-1A-D	113.21	Internal part of fractured filling, mainly clay minerals and pyrite.
121-1 A	120.19	Reduced phonolite, average samp le, low U content.
123-1B	123.00	Reduced phonolite.

According to the report authors, the conclusion of a rate of 20m in 10^6 years at the 33.44 m redox front should be taken with *caution* and "the decrease in $^{234}U/^{238}U$ activity ratio between 25 and 6 m *almost certainly* does not represent a simple decay of excess of ^{234}U" (1).

As a support for the rate of 2m in 10^6 years, there is the Th/^{234}U activity ratio for samples from 25.22 to 33.65 m on the oxidized side of the redox front, all lie within analytical uncertainty of equilibrium. Taking the maximum U concentration at 32.89 m as a deposition, than it can be estimated a downward movement at a rate of 2 m in 10^6years.

As already said before, all the information and conclusions from the report will be kept as absolutely correct and the limits 2 and 20 are considered to have 100% support evidence, i. e., according to equation 4:

$A=\{2,20\}$
$P(A) = \{\phi, 2, 20, \{2,20\}\}$
$m(A) = m(\phi) + (m(2) + m(20) + m(2 \cup 20) = 1$

We then consider the universe as 2-20m and m (A) = 1, or all x fall in the universe of the 2-20 m with 100% certainty.

However, if we compare the evidences we can find in the report, we can see that the evidences for 20m or 2m are different.

In this case, for simplicity, we will use expert opinion to assign degrees of belief to each limit value. This can be done based on the expressions used on the text, like "caution should be taken" , and "almost certainly ...".

If we consider that there is no such expressions for the limit of 2 m, we can consider this as a stronger value than 20m. Translating into numbers we have :

$m (2) = 0.4$
$m (20) = 0.2$
$m(2,20) = 0.4$

As these values are for singletons, it follows that:

$bel (2) = 0.4$
$bel (20) = 0.2$
$m (2 ,20) = 0.4 \quad \therefore \quad bel (2 \cup 20) = 0.4+0.2+0.4=1$

Other ways of assigning values to the degrees of supporting evidence can be used. One advantage of this methodology is this transparency and possibility of discussions over the values.

Continuing the calculations:

$pl(2) = m(2 \cap 2) + m(2 \cap (2 \cup 20)) = 0.4+0.4 = 0.8$

pl (20) = m(20 $\cap$ 20) + m(20 $\cap$ (2 $\cup$ 20))= 0.2 + 0.2 = 0.4
pl (2 $\cup$ 20) = 1.

The interpretation of this result is that the support evidence for limit of 2 m in 10^6 years has belief of 0.4 and can go up to 0.8. On the other hand, the evidences for limit value of 20 have a belief of 0.2 and possibly going to 0.6..

This means that there are different levels of support for the different limits and at the same time we can keep the information concerning what the expert believe could be closest to the truth.

One advantage of this methodology is that the degrees of belief can be changed, as more information is available, bringing transparency to the process. Also, this allows other people to discuss the results more objectively rather than subjectively.

The same reasoning can be used for the other conclusions, i. e., flow direction for the groundwater, and for the time scale for the processes. Also, it can be applied to all the parameters to be input to the performance assessment computer codes.

This means that instead of doing a deterministic calculation only, one can do a calculation using the degrees of belief and plausibility in addition. Therefore, the result could be in terms of how the experts believe the repository under analysis will pose a threat to the public and environment.

The final results of the performance assessment can be complemented with the degree of certainty and plausibility that the repository, under analysis will not modify the environmental conditions in a way that could threaten the public health.

In other words, the traditional safety indicators, dose and concentrations, can be complemented with this additional information, making it clear how uncertainties in ambiguous information have been treated in the analysis.

CONCLUSIONS

Environmental studies are a very complex task due to several factors such as lack of data, ignorance, and complexity. Although many tools exist to help analysts to deal with the uncertainties that are inherent to this field of science, they still need to use ambiguous terms when describing environmental conditions.

In this work it was shown how the ambiguous information can still be saved objectively as a complement to the traditional safety indicators as part of the performance assessment of a nuclear waste facility.

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