SAFETY ASSESSMENT USING FUZZY LOGIC BASED EXPERT SYSTEM

F. L. de Lemos
Centro de Desenvolvimento da Tecnologia Nuclear
Brazil

K. H. Hellmuth
Radiation and Nuclear Safety Authority
Finland

T. Sullivan
Brookhaven National Laboratory

ABSTRACT

In Finland Posiva is planning the construction of a spent nuclear fuel repository at a depth of about 500 meters in the crystalline bedrock. The process of site selection will be followed by a series of actions, aiming at site confirmation, including the construction of an underground rock characterization facility.

The construction of the disposal facility is planned to start in 2012 and emplacement of spent fuel canisters will begin in 2020. For the construction, operation and final sealing of the repository, separate permits and licenses will be required.

This paper discusses the use of the evidence theory as a basis of fuzzy logic-based expert system to enhance quantitative safety assessment. Fuzzy logic is based on the concept of fuzzy sets which can enable the use of linguistic expressions for data interpretation. This is especially fit for this work due to its capability to represent vague, imprecise and complex data. The evaluation of natural phenomena illustrates this. Laboratory tests and field experiments will collect large quantities of data. The data will have to be interpreted by statistical and evidentiary criteria to support decisions regarding the degrees of confidence on the safety of the waste canisters.

A fuzzy logic expert system could integrate all the data from the various calculations, along with their different data interpretation, in one framework. This will help simplify the demonstration of the decision-making process and serve as a support for further developments and discussions.

Laboratory tests are usually done under controlled conditions such as temperature, chemical concentrations and atmosphere. These data are then integrated to field data where there are more complex interactions between natural phenomena. Therefore, experts use linguistic expressions to describe observations, for example, "very saline waters" or "low microbial activity".

These expressions carry valuable information that, if not properly treated, can be lost. Evidence theory, extended to fuzzy sets concept, can be an option for this purpose.

INTRODUCTION

Safety assessment is comprised of several disciplines that have their specific methods of collecting and analysis of information, which will eventually be combined in a common framework to support a decision.

The complexity of the safety assessment process makes it difficult to identify and properly treat the uncertainties and, consequently, their propagation throughout the calculations. One of the main difficulties in addressing uncertainties is to find the most appropriate methodology for combining information from disparate analysis, otherwise valuable information can be lost, [1]. Due to the complexity of interactions, lack of data, and ignorance, very often experts have to use their professional opinion on selection of ranges of values or probability distribution functions, of parameters. In addition, linguistic terms to express the state of knowledge about a certain situation are often used. For example, experts use terms such as "low pH", "very unlikely", etc to describe their perception about natural processes. These two types of subjective uncertainty are important in safety assessment.

Knowledge is a collection of propositions [2] which are based on gathered information and data. The propositions have to be well understood in order to constitute knowledge. In safety assessment, much knowledge is expressed through linguistic expressions. These linguistic expressions can be arranged so that they lend themselves to calculation and, consequently, uncertainty propagation is made possible with a mathematical basis. This prevents the loss of knowledge in the decision process and allows experts and public to better understand the effects of propositions on each other and on the final result.

This work, applies evidence theory in combination with fuzzy logic principles to address uncertainties. With this methodology propositions are assigned with degrees of support or belief to its truthfulness.

Evidence Theory

The Dempster-Shafer theory was formalized by Shafer in 1976 for representing and reasoning with uncertain, imprecise and incomplete information. It is based on Dempster's original work on the modeling of uncertainty in terms of lower and upper probabilities, [4]. Dempster-Shafer theory reduces to standard Bayesian reasoning when there is accurate knowledge, and it is more flexible in representing and dealing with ignorance and uncertainty,[4].

Some important definitions needed to translate vague or subjective information into a quantitative mathematical form are, [3,4]:

1. Frame of discernment or universe of discourse: a set Θ is the frame of discernment if it contains mutually exhaustive possible answers to a question.

2. Basic probability assignment, or bpa, has the following boundary conditions:

$m(\phi)=0$; and $\qquad$ Eq (1)

$\sum_A m(A)=1$ $\qquad$ Eq (2)

Where ϕ is an empty set and A is a subset of Θ.

3. Belief functions, or support functions, are comprised of 2^Θ possible sets, where Θ is the number of mutually exclusive possible answers. In other words, $bel:2^\Theta \to [0,1]$ is a belief function if it satisfies:

$bel(\Theta)=1$ $\qquad$ Eq (3)

$bel(\bigcup_1^n A_i) \geq \sum_i bel(A_i) - \sum_{i<j} bel(A_i \cap A_j) + ... + (-1)^{n+1} bel(\bigcap_i A_i)$ $\qquad$ Eq (4)

$bel(\phi)=0$ $\qquad$ Eq (5)

The second axiom, equation (4), means that when $A_1, A_2,....A_n$ are pair-wise disjoint, i.e., $A_i \cap A_j = \phi$, then the degree of belief associated to the union of the sets is not smaller than the sum of the degrees of belief pertaining to individual sets.

The difference between belief functions, *bel (A)* and bpa, *m(A)*, is that *m(A)* is our belief committed to the subset A excluding any of its subsets while *bel (A)* is our degree of belief in A as well as all of its subsets,[4]. A belief measure is a quantity that expresses the degree of support, or evidence, for a collection of elements defined by one or more of the crisp sets existing in the power set of a universe,[3].

$bel(A) = \sum_{B \subseteq A} m(B)$ $\qquad$ Eq (6)

where B is a subset of A.

4. Plausibility function: $pl(A)=1-bel(\overline{A})$ $\qquad$ Eq (7)

Belief and plausibility can be thought of as the lower and higher limits of fuzzy measures. Belief measures are associated with preconceived notions while plausibility is associated with information that is possible or plausible,[3].

Combination Rule:

When the evidence for a certain fuzzy measure comes from more than one source, for example two experts, then a combined basic probability assignment can be calculated by:

$m_{12}(A) = \dfrac{\sum_{B \cap C = A} m_1(B).m_2(C)}{1-K}$ $\qquad$ for $A \neq \phi$ $\qquad$ Eq (8)

where:

$$K = \sum_{B \cap C \neq \phi} m_1(B).m_2(C) \qquad\qquad \text{Eq (9)}$$

Since belief measures are quantities that measure the degree of support for a collection of elements or crisp sets in a universe, it is entirely possible that the belief measure of some set A plus the belief measure of $\overline{A}$ will not be equal to unity, [3].

Fuzzy Propositions and Fuzzy Probabilities

In the Dempster-Shafer theory, the referential set Θ is defined as a set of crisp, or quantitatively well defined, elements and belief functions that are a measure on the support for the truth that an element belongs to a subset of Θ.
In this paper, the elements are propositions that constitute the knowledge regarding the processes that will lead to a corrosion rate on the Cu canisters. As the propositions are based on available information on complex natural processes, they can be considered as fuzzy propositions or fuzzy sets.
Therefore, we need to define belief functions for fuzzy elements, or fuzzy propositions.
According to [5], the degrees of belief and plausibility of a fuzzy event are defined as:

$$bel(A) = \sum_{A \in \Theta} m(A) \min_{x \in A}(\mu_A) \qquad\qquad \text{Eq (10)}$$

$$pl(A) = \sum_{A \in \Theta} m(A) \max_{x \in A}(\mu_A) \qquad\qquad \text{Eq (11)}$$

Where μ_A is the degree of fuzziness of the basic probability assignment. A value of degree of membership closer to 1 (one) means full membership, or a less fuzzy proposition, and a value close to 0 (zero) means a fuzzier proposition.

With equations 11 and 12 it will be possible to establish a consistent framework for comparison of levels of confidence in different approaches to calculating Cu corrosion under repository conditions.

Figure 1 shows a nesting diagram with representations of processes, (B_i), and propositions, or subsets of processes, (A_j), along with respective degrees of membership and basic probability assignment.
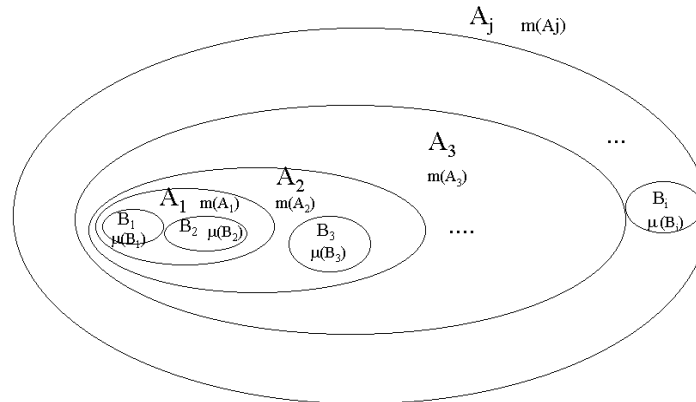
Fig. 1. Nesting diagram with representation of basic probability assignment, m(A$_j$), and degrees of membership μ (B$_i$).

Case Example – Corrosion of Cooper Canisters

As an example of application of the theory of evidence, extended to fuzzy logic, on safety assessment, a study for evaluation of the service life (in years) of the Cu canisters to be disposed of at the Finnish high level radioactive waste facility is presented, [6].

Spent fuel is expected to remain radioactive for hundreds of thousands of years and, therefore, ideally the canisters will have to be protective for the same period of time. As there is no practical means to guarantee such a long term performance, one has to rely on available information, laboratory tests and thermodynamic assumptions, as support for the truth in the proposition that the canisters will remain protective of the environment.

One also has to rely on various engineering models that describe service life in terms of phenomenological and functional models of the containers, the contents, and the operating scenario.

Two approaches for data analysis are presented according to [6]. The first approach is a combined mass-balance/transport model that calculates the maximum depth of general corrosion (mm) over some time period (100 + years). The second approach relies on a steady-state mass transport-reaction model that calculates the service life in years. Following Dempster-Shafer theory, the two approaches correspond to the two independent sources of information.

The frame of discernment is comprised of all the possible processes that can lead to corrosion of the Cu canisters. Each process is represented by a proposition. The frame of discernment in Dempster-Shafer theory is the same as the referential set in fuzzy propositions applications.

The frame of discernment, Θ, is supposed to contain mutually exclusive and exhaustive possible, and crisp, answers to a question. However, in the real world study it is not possible to take into account all the possible natural processes that will lead to a certain consequence, for example the corrosion rate of canister. For this study, the frame of discernment was defined as the processes that are believed to be the *most likely* to result in corrosion of the canister [6]. As a consequence

of the impossibility of considering all possible natural processes that will affect the service life of canisters, the total belief on the frame of discernment is necessarily less than 1, bel (Θ)<1. According to [7], there is a requirement of *reasonable assurance* on safety assessment, or degree of support, which means that there does not have to be 100% certainty in the truth in the propositions. The belief function is then used as a measure of the confidence one can put in the calculations.

Due to its complexity, the interactions between natural processes are often represented by simplified parameters. For example, the model for treatment of diffusion of aggressive agents through bentonite to the copper container was simplified, and the predicted corrosion of copper may be regarded as conservative. In other words, the more conservative, the fuzzier the description of a process will be, i.e., the real nature of the processes is not well defined and it will be represented by a lower degree of membership to a certain fuzzy set. Conversely, as more information is made available together with more sophisticated models, the predictions can be more realistic, i.e., it can be assigned a higher degree of membership to the truth of that proposition.

Methodology

For each approach [6], the corrosion assessment was divided into an initial period of aerobic (oxic) corrosion, followed by a longer period of corrosion under anaerobic (anoxic) conditions. During both periods, general corrosion and pitting were assumed to be possible. A total corrosion rate was calculated as a sum of general and pitting corrosion.

For the pitting process, two limits were studied, a lower and realistic rate based on a pitting factor of 2 (PF=2) for a lower limit (L), and an upper or higher (H) conservative limit with PF=5. Therefore, two limits for total corrosion, based on PF=2 and PF=5, were calculated. Table I has a representation of the corrosion processes according to the respective periods.

Table I. Representation of Corrosion Processes According to Initial and Long Term Periods and Different Methodological Approaches

Phase	Approach 1*			Approach 2*		
	General	PF=2	PF=5	General	PF=2	PF=5
Aerobic	G_{A1}	P_{AL1}	P_{AH1}	G_{A2}	P_{AL2}	P_{AH2}
Anaerobic	G_{N1}	P_{NL1}	P_{NH1}	G_{N2}	P_{NL2}	P_{NH2}
Total corrosion (General + localized)		0.66mm	1.63mm		0.1mm	22mm

*N stands for Anaerobic and *A* stands for aerobic.
Approaches 1 and 2 according to (6).

The corrosion estimates vary by over a factor of 100. At this point, the decision maker does not have a rationale to evaluate which of these corrosion estimates is appropriate for use in the decision process. It is the intention of this study to evaluate the support for the decisions used to calculate the corrosion rates for each estimate, and therefore provide the decision maker with additional information as to the reliability (degree of belief) in the estimate. In this regard the

Dempster-Shafer rule of combination will help to bring both approaches, which are independent sources of information, into the same framework.

Therefore, the belief functions for the lower and upper limits, or PF=2 and 5 respectively, and then combine them on a common frame will be calculated.

Approach 1

In this approach a combined mass-balance/ transport model was used by the Swedish Corrosion Institute 1983 and later revised by [6]. It is comprised of a set of propositions, A_1, that constitute the basis for the calculations.
The set of propositions is defined as:
$A_1 = \{G_{A1}, P_{AL1}, P_{AH}, G_{N1}, P_{NL1}, P_{NH1}\}$ Eq(12)

Where:
G_{A1}: represents a subset of processes that lead to the assumed general corrosion rate in the aerobic phase,
P_{AL1}: represents a subset of localized corrosion processes in the aerobic phase with pitting factor, PF=2.
P_{AH1}: represents a subset of localized corrosion processes in the aerobic phase, PF=5.
G_{N1}: subset of process of general corrosion during the anaerobic phase.
P_{NL1}: subset of localized corrosion processes during the anaerobic phase and PF = 2.
P_{NH1}: subset of localized corrosion processes during anaerobic phase and PF=5.

The propositions are as follows:
a) Aerobic Phase

- Corrosion during the aerobic period was supported by all of the trapped O_2 in the buffer material and a small fraction (~1%) of that in the backfilled tunnels above the deposition holes, the remainder being consumed by reaction with Fe(II) minerals. The combined general corrosion due to trapped O_2 and radiolytic oxidants was estimated to be 0.084mm, virtually all of which occurred in the first 1,000 years.

- Pitting was assessed using a pitting factor (PF), with a realistic value of 2 and a conservative value of 5. Thus the maximum penetration due to general corrosion and pitting during the aerobic phase was estimated to be between 0.17mm and 0.42 mm, for PF of 2 and 5 respectively.

b) Anaerobic Phase

- During the long-term anaerobic phase, corrosion was supported by HS- from a number of sources. Sulfide is present naturally in the MX-80 bentonite in the deposition hole and tunnel and in the groundwater. These sources of HS- were assumed to be supplemented by the microbial reduction of SO42- in the deposition hole, tunnel and groundwater.

- The corrosion rate was assumed to be limited by the rate of supply of HS- to the canister surface.

  After 106 years, an additional 0.27 mm of general corrosion was predicted due to HS-, of which 40% was of microbial origin. As for the aerobic phase, a PF of 2 or 5 was applied, to produce a maximum additional depth of corrosion (general + pitting) of 0.53mm (PF = 2) and 1.33 mm (PF=5).

- Adding the estimated depths of corrosion for the two periods produces an estimate of the total amount of corrosion on a Cu canister over a period of 10^6 years. For realistic (PF=2) and conservative (PF=5) assessments, the maximum predicted depth of general and localized corrosion is 0.70 mm and 1.75 mm, respectively.

This estimate is changed with two new factors taken into account.

- Microbial activity is unlikely in highly compacted bentonite, and therefore, the microbially mediated reduction of SO42- to HS- will not occur in the deposition hole. In this analysis, the microbially produced HS- in the deposition hole resulted in 0.023 mm general corrosion in 106 yrs.

- The thermodynamic and mass transport evaluation suggests the corrosion of Cu supported by the reduction of H2O may occur at high Cl- concentrations.

- The mass-transport-limited corrosion rate depends on the HS- and Fe(III) content of bentonite: because these species are assured to react with the corrosion products CuCl2- and H2 respectively, maintaining steep concentration gradients at the canisters surface.

- However, for HS- and Fe(III) concentrations of 1 mg and 3 mg per Kg of bentonite respectively, the predicted additional corrosion is < 0.001 mm in 106 years.

- The decrease in the extent of general corrosion during anoxic period due to absence of microbial reduction of SO42- in the deposition hole is much greater than the predicted incremental corrosion due to dissolution of Cu as CuCl2- supported by reduction of H2O.

- Therefore, after subtracting out the microbial corrosion, which was considered unlikely to occur, the maximum depth of general corrosion in the new analysis is 0.33 mm after 106 years.

Approach 2

In this approach the steady-state mass transport-reaction model was used: the repository system was described by boxes representing the buffer, canister, and a box in which various fast and slow chemical and mass transport processes were assumed to occur.

Evolution of repository conditions was divided into an aerobic and an anaerobic period. General corrosion was predicted based on a series of coupled chemical and mass-transport processes for various possible corrosion reactions.

The set of propositions is defined as:

$$A2 = \{G_{A2}, P_{AL2}, P_{AH2}, G_{N2}, P_{NL2}, P_{NH2}\} \qquad\qquad \text{Eq(13)}$$

Where:
G_{A2}: represents a subset of processes that lead to the general corrosion rate in the aerobic phase.
P_{AL2}: represents a subset of processes of localized corrosion in the aerobic phase, with PF=2.
P_{AH2}: subset of localized corrosion in the aerobic phase and PF=5.
G_{N2}: subset of general corrosion processes in the anaerobic phase.
P_{NL2}: subset of localized corrosion processes in the anaerobic phase with PF=2.
P_{NH2}: subset of localized corrosion processes in the anaerobic phase with PF=5.

a) Aerobic period

- In the aerobic period, the corrosion rate was predicted $=7.10^{-6}$ mm yr^{-1}.

- The rate determining process was shown to be diffusion of Cu (II) away from the canister surface. Any parameter which lead to an increase in the rate of Cu (II) diffusion (such as changes to the CO_3^{2-} concentrate and pH), which *affect the solubility of precipitated $CuCO_3.Cu(OH)_2$ resulted in an increase in corrosion rate*, whereas parameters which did not affect Cu(II) transport (such as the dissolved O_2 concentration) were predicted to have no effect.

- Because of the independence of the corrosion rate on $[O_2]$, the extent of corrosion during the aerobic period was estimated by multiplying the predicted corrosion rate by the length of the aerobic period, which was estimated separately.

- Pitting corrosion was again estimated using a pitting factor. In reference [6] it is proposed a realistic estimate of the extent of general corrosion and pitting during the aerobic period of 0.003 mm, based on a 65-year aerobic period and a PF of 5. A conservative estimate was also provided, based on 10-times higher corrosion rate, a PF=100, and a 280-year-long aerobic period, giving a maximum corrosion depth of 2 mm.

Anaerobic phase:

- During the anaerobic period, *corrosion was assumed to be supported* by either the reduction of Fe(III) (produced from the dissolution of Fe (OH)$_3$ impurities in the bentonite) or of H_2O/H^+ in the presence of HS$^-$. The predicted corrosion rates for corrosion supported by Fe(III) and HS$^-$ were 5.10^{-8} mm.yr^{-1} and 4.10^{-6} mm.yr^{-1}, respectively.

- Pitting corrosion was believed to be less severe during the anaerobic phase, so realistic and conservative PF values of 2 and 5, respectively, were used.

Combining the estimated corrosion depths for the aerobic and anaerobic periods estimated realistic and conservative corrosion depths after 10^6 years of 0.1 mm and 22 mm, respectively, [6].

Compared with the reference wall thickness of 50 mm, it was concluded that the canister lifetime would be $>10^6$ years.

Basic Probability Assignment

The universe of discernment, Θ, is comprised of all information related to the possible natural processes that could lead to Cu corrosion and presented as propositions. Some propositions are very unlikely to happen, while the likelihood of others are not well known either because of lack of data or because they have not been well studied.

Each one of the propositions, used in the two approaches, are a representation of complex interactions of natural processes. For example, in approach 2 it is stated that, in the aerobic phase, the rate-determining process is diffusion of Cu(II) which is influenced, amongst other parameters, by pH which is one of the parameters that affects the solubility of precipitated $CuCO_3.Cu(OH)_2$ and consequently can increase the corrosion rate. The pH level, on the other hand, is affected by some other parameters such as calcite dissolution and precipitation, pyrite dissolution, temperature, decrease in redox, partial pressure of CO_2. Redox will be affected by oxidation of pyrite and other Fe(II) accessory minerals, etc.

The complexity of the interactions generates vagueness in the importance of the processes on corrosion. In other words, the propositions become fuzzy and degrees of membership will be assigned to them for illustrative purposes as a measure of their fuzziness. Table II (a and b) shows the degrees of fuzziness for each proposition, $\mu_A(x)$, together with the basic probability assignment, bpa, or m(x). The basic probability assignments will be used as a basis for generating the belief functions for each approach, bel_1 and bel_2, according to equation (6), in support for the conclusions regarding expected canisters corrosion rates.

This table presents the corrosion processes for each phase, aerobic and anaerobic. As mentioned before, the most likely processes were included in the analysis, therefore, the sum of the basic probability assignment for each approach is 1, Eq. (2), by convention, [3]. The degrees of fuzziness is the measurement of how well the process is defined in terms of available data, boundaries, and ignorance. A value close to zero (0) implies that there is a very large degree of uncertainty in the process and a value close to one (1) implies that the process is understood well.

The term (General ∪ Pitting) is a representation of the combination of the general and the localized corrosion processes. As these processes are assumed to occur at the same time, they also have a separate representation. The values presented here are meant to be illustrative and further studies, based on experts opinion, are recommended.

Table IIa. Basic Probability Assignment According to Processes and Approaches, PF=2.

Corrosion Process	Approach 1	Approach 2

Aerobic	$m_1(x)$	$\mu_A(x)$	$m_2(x)$	$\mu_A(x)$
General	0.1	0.85	0.1	0.8
Pitting	0.1	0.8	0.2	0.8
General ∪ Pitting	0.2	0.8	0.2	0.8
Anaerobic				
General	0.1	0.9	0.1	0.8
Pitting	0.2	0.8	0.2	0.8
General ∪ Pitting	0.3	0.8	0.2	0.8

Table IIb. Basic Probability Assignment According to Processes and Approaches, PF=5.

Corrosion Process	Approach 1		Approach 2	
Aerobic	$m_1(x)$	$\mu_A(x)$	$m_2(x)$	$\mu_A(x)$
General	0.1	0.85	0.1	0.8
Pitting	0.1	0.7	0.2	0.7
General ∪ Pitting	0.3	0.7	0.2	0.7
Anaerobic				
General	0.1	0.9	0.1	0.8
Pitting	0.2	0.7	0.2	0.7
General ∪ Pitting	0.2	0.7	0.2	0.8

Results

The two approaches act as two independent experts that are analyzing the available information. The two limits for corrosion rate, with PF=2 and PF=5, are analyzed separately as they are based on different assumptions. In order to have a more general analysis, the values for each limit, from each approach, are not compared, rather the support or quality of the information that will provide the degrees of belief in the truth of each proposition or calculations of the lower and upper limits for each approach is studied.

The belief function is the product of the membership function and basic probability according to Eq.(11). Therefore the degrees of belief in the corrosion due to sum of aerobic and anaerobic processes corresponding to PF=2 and approaches 1 and 2 are:

$bel_1 (PF=2) = 0.85*0.1+0.8*0.1+0.2*0.8+0.1*0.9+0.2*0.8+0.3*0.8 = 0.815$
$bel_2 (PF=2) = 0.1*0.8+0.2*0.7+0.2*0.7+0.1*0.8+0.2*0.7+0.2*0.8 = 0.74$

The same reasoning is used for the other propositions, and are presented in Table III. In this table shows the degrees of belief for corrosion rates according to each approach as well as the combined degrees of belief and plausibility, bel_{12} and pl_{12} respectively.

Table III. Degrees of Belief and Plausibility for Corrosion Rate Limits for each Approach

Range limits	Low	Upper
Approach 1	$Bel_1 = 0.815$	$bel_1 = 0.735$
Approach 2	$bel_2 = 0.74$	$bel_2 = 0.74$
Combined	$bel_{12} = 0.74$	$bel_{12} = 0.74$
	$pl_{12} = 0.79$	$pl_{12} = 0.85$

The results show that the degrees of belief for the low limit can be as low as 0.74 and as high as 0.79 and for the upper limit, the degrees of support can be as low as 0.74 and as high as 0.85.

As mentioned before, there is a requirement of "reasonable assurance" that the safety standards will be met by the disposal facility. The results presented in Table III can be used as a measure of what can be considered as "reasonable". For example, experts and authorities can agree that degrees of belief ≥ 0.6 are acceptable or reasonable.

CONCLUSIONS AND DISCUSSION OF RESULTS

The requirement of "*reasonable assurance*" in the safety assessment is a recognition that it is impossible to have a perfect knowledge of all the natural processes that can affect the performance of the disposal facility. The use of the evidence theory can help on the very definition of what should be considered "*reasonable*".

As belief functions are the measure of the truth in a proposition, it can be used as a measure of how reasonable the truth is. One can, in agreement with stakeholders and experts, define "reasonable assurance" as a degree of belief in the range from 0.6 to 0.8, for example.

Therefore, in the case example, we can say, based on fuzzy math calculations, that there is a reasonable assurance, or support, in the results or conclusions for canisters corrosion estimates in both approaches.

One of the advantages of this methodology facilitates the comparison between the two approaches, showing why and where one approach has higher degrees of belief than the other. Therefore, based on the findings, actions for corrections and refinement of the approaches can be taken.

For example, the results presented in Table III show that for approach 1 there is a highest degree of belief, or support, for the low limit of corrosion rate than for the approach 2. This is an indication that there was a higher degree of confidence on the available information that supported the propositions that led to that result. After a detail analysis of the calculations, the stakeholders can conclude that further researches are recommended in order to improve the quality of the support for decisions.

The belief function is composed of basic probability assignment, bpa, and the degree of fuzziness, $\mu(x)$, or how well the event is defined.

For example, if a calculation is too conservative, there may be a high probability that the result will be within safety, however, the information will be too fuzzy, leading to unrealistic results and,therefore, a low degree of belief.

Dempster-Shafer theory can be particularly useful when there are two independent sources of information or, as in this case example, two independent computational approaches, because it provides a rule of combination of belief functions that aggregates them in the same framework and allows direct comparison between different options of calculations.

Therefore, it is possible to quantify the combined degrees of support (or belief) in the truth of the propositions.

The results of this paper show the degrees of belief and plausibility in the predicted limits of corrosion rates calculated according to the two approaches. These results are not meant to be definitive, rather it is intended to present the methodology as a means for analysis of propagation of uncertainty.

As can be seen from table II, it is possible to evaluate the support for the different subsets of information and its effects on the other ones. This approach can be repeated for all the other components of disposal facility and then the whole safety assessment can be inserted into a common framework, which is the basis of an expert system.

REFERENCES

1. Hellmuth, K.H., *Review of Documentation Supporting the Posiva Application for a Decision in Principle, Engineered Barrier System, Near Field, Far Field, Site Characterization*, Geochemical Aspects. Helsinki: The Finnish Radiation and Nuclear Safety Authority (STUK), 1999, 19p.

2. Zadeh L.; Knowledge Representation in Fuzzy Logic; IEEE Transactions on Knowledge and Data Engineering, Vol. 1 no.1, March 1989.

3. Ross T. Fuzzy Logic With Engineering Applications. New York: McGraw-Hill, 1995. 600 p.

4. Liu W., Hong J.: Reinvestigating Dempster's Idea On Evidence Combination; Knowledge and Information Systems (2000) 2:223-241; Springer-Verlag London Ltd.

5. Smets P.: The degree of belief in a Fuzzy Event; Information Sciences 25, 1-19 (1981); Elsevier North Holland, Inc.

6. King, F; Ahonen, L.; Taxén, C.; Vuorinen, U.; Werme, L.: Copper Corrosion Under Expected Conditions In A Deep Geological Repository. POSIVA 2002-01. Helsinki, Finland, 2002.

7. AEN /NEA; Confidence in the Long-term Safety of Deep Geological Repositories Its Development and Communication; OECD 1999.