Proceedings of the 33rd European Safety and Reliability Conference (ESREL 2023)
Edited by Mário P. Brito, Terje Aven, Piero Baraldi, Marko Čepin and Enrico Zio
©2023 ESREL2023 Organizers. *Published by* Research Publishing, Singapore.
doi: 10.3850/978-981-18-8071-1_P316-cd

The Role of Physical Parameters on the Overflow Probability of a radioactive near surface repository for low & intermediate level wastes: The Case of Abadia de Goiás

P. F. Frutuoso e Melo, D. G. Teixeira

COPPE, Graduate Program of Nuclear Engineering, Federal University of Rio de Janeiro, Rio de Janeiro, Brazil, frutuoso@nuclear.ufrj.br, dteixeira@nuclear.ufrj.br

A. S. M. Alves

Eletronuclear S. A., Rio de Janeiro, Brazil. E-mail: asergi@eletronuclear.ufrj.br

In an earlier work, a model has been developed for evaluating the overflow probability of the radioactive waste near surface repository of Abadia de Goiás, Brazil for safety and licensing purposes. Water infiltration inside the repository is influenced by a set of design and physical parameters. However, an analysis on the variability of these parameters has not yet been performed. This paper discusses the variability of each of these parameters and possible dependencies among them and also time dependencies. This analysis is important for a future sensitivity analysis concerning the overflow probability. It is simpler to analyze the influence of those parameters that are not rates, e.g., the repository internal base area, because an eventual shape variability does not bring any difficulty since it is just a matter of varying the shape and dimensions. Some parameters, like the internal porosity of the repository are dimensionless. The analysis of rate parameters, like the rainfall rate, is more complicated and dependencies have been detected. If one considers that the rainfall rate is the highest available, the overflow probability might be as high as 99%, as estimated in the mentioned earlier work. In this sense, a realistic sensitivity analysis on the overflow probability is due so that the most influential parameters can be identified and design and operational modifications on the safety side implemented.

Keywords: Radioactive waste repository, rainfall rate, evapotranspiration rate, porosity, degradation, water infiltration, overflow probability.

1. Introduction

A model (Gabcan et al, 2023) was developed for evaluating the overflow probability for risk-informed decision-making (Sousa et al, 2012) in the analysis of water infiltration inside the radioactive waste near surface repository of Abadia de Goiás, Brazil. Water infiltration inside the repository is influenced by a set of design and physical parameters.

This paper discusses the variability of each of those parameters for evaluating the overflow probability in order to allow for a future sensitivity analysis to be performed. Parameter dependencies and also time dependencies are analyzed. Notice that some of these parameters are site-dependent.

The parameters are: internal area of repository base; repository base width, lengh, and thickness; evapotranspiration rate; degradation function of the repository ceiling; irrigation rate into the repository; hydraulic conductivity of concrete; repository wall thickness; internal porosity of the repository; rainfall rate; surface runoff; height of the liquid column inside the repository; and initial value of the infiltrated liquid height.

It is simpler to analyze the influence of those parameters that are not rates (as the repository internal base area), because an eventual variability (for example, a rectangular base or a squared base) does not bring any difficulty since it is just a matter of varying the shape and dimensions considering some restriction as, for example, a constant perimeter.

Some parameters, like the internal porosity of the repository are dimensionless and eventual fluctuations are also easier to consider.

The analysis of rate parameters (as the

rainfall rate) is more complicated. It is standard to establish an institutional time period control for the repository and this parameter may vary from some tens of years to some hundreds [in the case of the Abadia de Goiás repository, it is equal to 50 yr (Tranjan Filho et al, 1997)]. If one considers that the rainfall rate is the highest available and for the case of the Abadia de Goiás this figure may be found in Marcuzzo et al (2012), the overflow probability may be as high as 99% for 300 yr (Gabcan et al, 2023), which is an unrealistic number.

In this sense, each of the above parameters is analyzed in this paper, its variability is searched for in the literature and when no data is available possible ranges are proposed based on discussions with the regulatory body personnel.

This paper is organized as follows. Section 2 displays a survey of all parameters involved in the analysis. Section 3 is dedicated to the dimensionless parameters. Section 4 discusses the parameters involving lengths and areas. Section 5 discusses the rate parameters. Section 6 discusses the influence of all parameters together. Conclusions are the subject of Section 7.

2. Parameter Survey

As discussed in Alves (2014), Alves et al (2015) and Gabcan et al (2023), the physical parameters necessary for the evaluation of the overflow probability are synthesized in Table 1.

It can be seen that there are three types of parameters: those that are dimensionless, those that are lengths or areas and those that are rates. There are two dimensionless parameters, which are listed first in Table 1. Both refer to physical properties of the repository material. The initially assigned values for them have been discussed with the Brazilian regulatory body.

It is considered that water from rain and irrigation penetrates the repository due to existing cracks in the ceiling, formed during a period of degradation and concrete aging. It is also assumed that the mixture formed by water and radionuclides will pass through these cracks, in case of overflow of the repository. The degradation function of the repository ceiling is the percentage of degradation, so that $0 \leq F_d \leq 1$.

It was assumed that the degradation function of the repository roof is constant. This is not a reasonable assumption if one considers that the time period of the analysis might be as high as 300 yr (equivalent to 10 half-lives of ^{137}Cs). To consider a constant value means that a conservative value is to be used, from the safety analysis viewpoint.

Table 1. Parameter List*

Symbol	Description	Unit
F_d	Degradation function of the repository ceiling	-
n_1	Internal porosity of the repository	-
A_b	Internal area of repository base	m^2
b_1	Repository base width	m
b_2	Repository base length	m
E	Repository base thickness	m
L	Repository wall thickness	m
x	Height of the liquid column inside the repository	m
x_0	Initial value of the infiltrated liquid height	m
e'	Evapotranspiration rate	m/yr
i'_r	Irrigation rate in the repository	m/yr
K_c	Hydraulic conductivity of concrete	m/yr
p'_m	Average rainfall rate	m/yr
r'	Surface runoff	m/yr

*From Alves et al (2015).

The percentage volume of voids in concrete is termed porosity (internal porosity here). This parameter gives the void fraction of the concrete used in the repository (Neville, 2012).

It is considered that the leakage of radioactive material from the repository will occur through pores in the base and concrete side walls of the repository (Alves et al, 2014).

Table 2 displays the point values for both dimensionless parameters discussed so far. It is worth mentioning that these values have been established jointly with the regulatory body.

Table 2. Values of Dimensionless Parameters*

Parameter	Value
F_d	0.10
n_1	0.10

*From Alves et al (2015).

Next, there is a group of seven parameters related to lengths or areas. Five of these parameters are related to the repository dimensions and the remaining two are related to the liquid mixture (water + radionuclide inside the repository).

The initial design of the repository provided for a rectangular shape but with restrictions on the ratio length (b_2) / width (b_1) due to possible seismic vulnerability (Tranjan Filho et al, 1997). Although it has been considered a 3 to 1 ratio, in reality, the idea was to build three concrete vaults for the Abadia de Goiás repository. Once the length and width are defined, the repository area will be defined. Table 3 presents the point values considered (including the repository area).

The height of the liquid column inside the repository varies in the interval displayed in Table 3. There is a lower height value (Tranjan Filho et al, 1997) and the design height of the repository is the upper limit. Also, the initial value of the liquid height is equal to the lower liquid height already displayed.

Table 3. Values of Length and Area Parameters*

Parameter	Value
A_b [m^2]	1,176
b_1 [m]	60
b_2 [m]	19.6
E [m]	0.20
L [m]	0.20
x [m]	[10^{-4}; 4,.38]
x_0 [m]	10^{-4}

*From Alves et al (2015).

Finally, there are five rate parameters, all water-related. In this case, we should consider that these are site-specific (evapotranspiration, irrigation, and average rainfall) or material-specific (hydraulic conductivity and surface runoff) parameters. In this sense, point values for the first three parameters should be searched for in relation to the Abadia de Goiás region. On the other hand, values of the material-related parameters are easier to find because they are not site-specific.

Table 4 presents the point values initially considered. Also in this case, these mean values have been set according to discussions held with personnel from the regulatory body. Notice that some parameters are site-specific.

Table 4. Values of Rate Parameters*

Parameter	Value
e' (m/yr)	1.457
i'_r (m/yr)	0
K_c (m/yr)	3.15E-04
p'_m (m/yr)	1.592
r' (m/yr)	0

*From Alves et al (2015).

3. Dimensionless Parameters

The first parameter is the degradation function of the repository ceiling (F_d). As mentioned earlier, this parameter is restricted to the range $0 \leq F_d \leq 1$.

It has been assumed that this parameter is constant over time, even considering that the repository institutional control period might be 300 yr. It is not reasonable to consider a constant degradation parameter in such a long time period. In fact, it is more reasonable to consider that this parameter grows monotonically with time.

As there are no available data on this parameter, we start by assuming that it is represented by a monotonically increasing exponential function of the kind:

$$F_d(t) = 1 - e^{-\alpha t} \tag{1}$$

where α is a constant to be estimated. Note that Eq. (1) follows the condition $0 \leq F_d \leq 1$. Other assumptions could have been considered, like a straight line with null descent and positive slope. Eq. (1) reaches a convenient asymptotic value.

As we do not know, in principle, the value of α, we can show how it influences the degradation parameter. Fig. 1 presents a sensitivity analysis on this parameter.

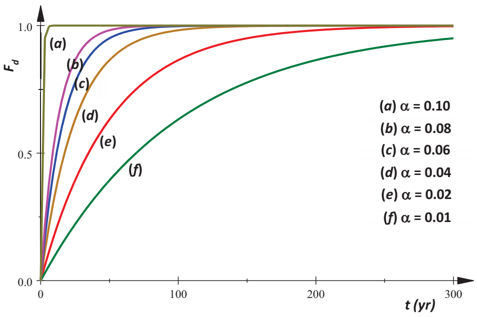

Fig. 1. A time-dependent degradation function

The higher the value of parameter α, the steepest the degradation function. In this case, the idea of using a mean value is not reasonable: it would be advisable to make $F_d(t) = 1$ for the institutional period of 300 yr. On the other hand, as seen in Table 2, the point value used for the parameter is 0.1, which corresponds to an institutional time period of less than 20 yr.

As the institutional control period to be initially used is 50 yr, it is advisable to have an idea of F_d values for this institutional control period. Table 5 presents the results for this case considering the same values for the α parameter displayed in Fig. 1.

Table 5. F_d values for 50 yr

α (yr^{-1})	F_d (50 yr)
0.01	0.393
0.02	0.632
0.04	0.867
0.06	0.950
0.08	0.982
0.10	0.993

From Table 5, it can be seen that for a 50 yr institutional control period, even for α = 0.10 the degradation function is close to one.

If one considers the use of a mean function value for the degradation function, by using Eq. (1) one has:

$$\overline{F}_d(300)= \frac{1}{300}\int_0^{300}(1-e^{-\alpha t})dt, \qquad (2)$$

where the mean value is obtained for an institutional control period of 300 yr. Eq. (2) yields:

$$\overline{F}_d(300) = \frac{e^{-300\alpha} + 300\alpha - 1}{300\alpha} \qquad (3)$$

Fig. 2 displays Eq. (3) in terms of the α parameter.

It is seen that even using a mean degradation value, it is reasonable to consider some value close to one, unless parameter α is much smaller than 0.1. Fig. 2 also displays the mean degradation function for an institutional control period equal to 50 yr.

One concludes that the use of the value displayed in Table 1 might not be realistic.

The analysis concerning this parameter is highly dependent on the institutional control period. In practice, the institutional control period will be 50 yr (Tranjan Filho et al, 1997).

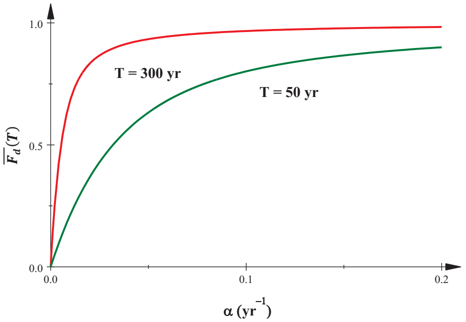

Fig. 2. Mean degradation function values in terms of parameter α (T = institutional time)

The second dimensionless parameter is the internal porosity of the repository.

Porosity (void fraction) is a measure of the void spaces in a material, and is a fraction of the volume of voids over the total volume, between 0 and 1. If concrete is not properly compacted it may contain voids which will contribute to its porosity (Neville, 2012).

As seen in Table 2, the concrete porosity of the repository has been taken as 0.1. This value is a consequence of a common agreement between the researchers at the time of the project and the regulatory body.

A search was made in the literature to find information on possible variations of this parameter.

De La Cruz et al (2015) discuss porosity and permeability of conventional concrete and another type of concrete (with proportions of natural zeolite additions). They mention that typical values for the natural concrete porosity range between 9 and 10%. This means that the assumption made for the repository concrete is quite reasonable. On the other hand, when the percentage of zeolite added is 5%, no difference from the reference concrete is observed and considering a rate of 10% porosity increases to almost 13%.

Chen et al (2013) discuss the influence of porosity on physical parameters of cement mortar. The results are presented in terms of experimental data and fitted curves, and in all cases, porosity varies typically in the range of 10% - 35%.

Concrete can be a very porous material. It starts off as a dry mixture made of cement, sand and stone. Once clean water is added, the cement chemically reacts and forms a paste that binds the sand and aggregates together. As wet concrete dries, hardens and cures, water evaporates out. This leaves behind a network of very small tunnels where water used to be. On average, 10%-15% of a concrete slab has these tiny pores (Gambrick, 2023).

It is clear from the literature presented that it would be advisable to check the influence of the porosity on the probability of overflow for the range [9%, 35%], even though different types of concrete are considered. Although this is a conservative interval, it implies that pervious concrete specimens are also being taken into account.

4. Length and Area Parameters

The five parameters related to the repository itself have been defined in its design. An initial appraisal of the base shape was performed in Gabcan et al (2023) by considering two possibilities: rectangular base and squared base, and no significant difference was obtained in terms of the overflow probability. As design parameters, it is not reasonable in principle to consider significant variations on these parameters, although it is advisable to investigate their role. However, it is advisable that the overflow probability is re-evaluated considering the possibility of three joint vaults, as mentioned in Section 2.

Discussions with experts from the regulatory body have led to the conclusion that it is advisable to consider the possibility that the repository base length and width be varied in the range 10 m $\leq b_1, b_2 \leq$ 100 m. On the other hand, one should bear in mind that the ratio between the base length and width should not be very high because of seismic issues, as already mentioned. It is advisable to establish a limit for the ration b_1/b_2. Concerning the repository base thickness and wall thickness, further discussions have led to the range $0.1 \leq E, L \leq 1$ m.

The two length parameters related to water depend on design: the repository liquid height (which directly affects the overflow probability) and the initial infiltrated liquid height.

Regarding the liquid height, a wider variation range can be considered (as a result of discussions with the regulatory body personnel): this height can be considered to vary in the interval 10^{-4} m $\leq x \leq 15$ m (compare this range with that of Table 3).

Table 6 summarizes the numerical information concerning the length parameters.

It has been a consensus between all experts consulted that the least height of the infiltrated liquid height is not to be varied (see its value in Table 3). This is due to the fact that an initial value different from the one taken does not affect the dose rate to a member of the public (Tranjan Filho, 1997).

Table 6. Length Parameters: Data information

Parameter	Point value (m)	Range (m)
b_1	60	[10, 100]
b_2	19.60	[10, 100]
E	0.20	[0.1, 1]
L	0.20	[0.1, 1]
x	4.38	[10^{-4}, 15]

Variations in length parameters should be considered with care because of material costs also.

5. Rate parameters

The discussion of rate parameters is more complex. If we start by considering that the reference time might be the institutional control period of 300 yr, it is quite evident that the use of a rate point value for this time period can bring quite different results from those considered in smaller time periods. Furthermore, it is not physically reasonable to assume a mean rainfall rate over such a long period of time, for example. As mentioned earlier, the institutional control period will probably be equal to 50 yr.

Evapotranspiration is the combined processes by which water moves from the earth surface into the atmosphere. It covers both water evaporation (movement of water to the air directly from soil and water bodies) and transpiration (movement of water from the soil, through roots and bodies of vegetation, on leaves and then into the air). Evapotranspiration is an important part of the local water cycle (Vörösmarty et al, 1998), (Goyal & Harmsen, 2013).

It is clear that this rate is site dependent, so the consideration of possible variations is to be searched by restricting the search to the region where the repository is located.

On the other hand, the evapotranspiration rate depends on the rainfall rate (Alves, 2014):

$$e_r' = f_e . p_m' \qquad (4)$$

where the evapotranspiration rate (e_r') is a fraction (f_e) of the rainfall rate (p_m'). This makes sense because the amount of evaporated water, for example, cannot be greater than the amount of rainwater collected. Notice that field data gathered should be considered so that the dependency on the rainfall rate is taken into account. An analysis should be performed concerning the evapotranspiration data gathered in the region of Goiânia (to be next discussed) with the rainfall rate (which is also site dependent). Discussions with the technical personnel recommends that the fraction factor (f_e) be varied in the range $1\% \leq f_e \leq 99\%$.

According to Casaroli et al (2018), considering the city of Goiânia, the variation in the evapotranspiration rate ranged from a minimum value of 1283.03 mm/year (1996) to a maximum value of 1484.42 mm/year (2014), a total of 22 data points. Data collection was carried out from 1994 to 2015. Note that the data has been gathered on a yearly basis. This means that one can use mean values per year, although seasonal variations cannot be perceived. The point value for the evapotranspiration rate displayed in Table 4 falls in this interval.

Abadia de Goiás is located about 20 km from Goiânia. It should be noted that the data have been collected in the city of Goiânia and not in Abadia de Goiás, but the distance between both is small enough to consider the gathered data reasonable data for the analysis. This choice is due to the fact that data referring specifically to Abadia de Goiás has not been found in the literature.

It should be noted that the data on the evapotranspiration rate found can be statistically analyzed to provide useful information for simulation purposes. That is, goodness of fit tests (Soong, 2004) can be employed to fit a probability distribution to them for simulation purposes.

The irrigation rate can also be seen as a fraction of the rainfall rate. In fact (Alves, 2014):

$$i'_r = f_i . p'_m \tag{5}$$

so that the irrigation rate (i'_r) is a fraction (f_i) of the rainfall rate (p'_m). The rainfall rate is easy to obtain, as will be discussed later. So, the irrigation rate can vary from zero ($f_i = 0$) to the rainfall rate ($f_i = 1$). Initially, the staff has considered the first possibility (see Table 4) but further discussions have recommended that $1\% \leq f_i \leq 99\%$, so that an irrigation rate should always be taken into account. It is seen that a null irrigation rate is unrealistic. It is important to stress that the rainfall rate influences both the evapotranspiration rate and the irrigation rate, so that the consideration of simulation models to evaluate the overflow probability of the repository should take this feature into account.

The hydraulic conductivity of concrete is the next rate parameter to be discussed. The hydraulic conductivity refers to impervious concrete here.

Gjörv & Löland (1980) present data on the hydraulic conductivity of concrete as follows: the variability of the hydraulic conductivity depends on the external environment: for the case of air, 0.48×10^{-12} m/sec $\leq K_c \leq 0.61 \times 10^{-12}$ m/sec. For the case of water, 0.98×10^{-12} m/sec $\leq K_c \leq 1.00 \times 10^{-12}$ m/sec. Notice that the mean value presented in Table 4 does not belong to any of the presented intervals (in fact, it is higher than the values presented in both intervals). It is also worth noting that the variability is very small.

Schneider et al (2012) present data on the hydraulic conductivity of concrete and mortar for use in the radioactive near surface repository facility in Dessel, Belgium. They present an interval for the hydraulic conductivity of concrete as follows: 5.67×10^{-13} m/sec $\leq K_c \leq 1.00 \times 10^{-11}$ m/sec. The mean value presented in Table 4 belongs to this interval. We recommend the use of this data for sensitivity analyses.

Cardoso et al (2011) report that in regions around Goiânia (as is the case with Abadia de Goiás) the interval 1400 mm/yr $\leq p'_m \leq$ 1600 mm/yr is displayed. Costa et al (2012) present rainfall data for the period 1974 – 2008 and give the interval 1162 mm/yr $\leq p'_m \leq$ 1932.8 mm/yr. They gathered data from 50 rain stations in the state of Goiás. Notice that the observation period is quite significant. Finally, Marcuzzo et al (2012) report an interval of 1249.1 mm/yr $\leq p'_m \leq$ 1755.7 mm/yr. They gathered data from 150 rain stations in the midwest region of Brazil. Notice that both papers present rainfall intervals for statistically significant periods of time, althought the first one discusses data gathered from the state of Goiás. In this sense the data from Costa et al (2012) should be used.

Surface runoff is the unconfined flow of water over the ground surface. It occurs in the case excess rainwater (or other sources) can no longer sufficiently rapidly infiltrate into the surface (Masten & Davis, 2020). It is clear that this parameter is strictly dependent on other rate parameters like the rainfall rate.

The surface runoff depends on other rate parameters as follows (Alves, 2014):

$$r' < p'_m + i'_r - e' \qquad (6)$$

This restriction makes sense. In order to make its evaluation viable, one can write (Alves, 2014):

$$r' = f_r(p'_m + i'_r - e') \qquad (7)$$

where, like the cases discussed in relation to Eq. (4) and Eq. (5), $1\% \leq f_r \leq 99\%$.

One should bear in mind that the choice of the rate parameters discussed in this section should be made with caution because a set of restrictions are to be taken into account. For example, due to the restriction set by Eq. (6), factor f_r cannot be 100%.

After discussing rate parameters, one must consider an overall analysis in order to avoid values of those parameters that lead to scenarios without physical meaning.

In order for the repository overflow to occur the following condition must be fulfilled:

$$\frac{dx}{dt} > 0 \qquad (8)$$

where x is the liquid height in the repository (Table 1). For this inequality to hold, it is necessary that (Alves, 2014):

$$\theta = F_d(p'_m + i'_r - e' - r') > 0 \qquad (9)$$

and

$$\frac{\theta}{n_1} > \frac{K_c}{n_1}\left[\frac{x+E}{E} + \left(\frac{b_1+b_2}{b_1 b_2 L}\right)x^2\right] \qquad (10)$$

On the other hand (Alves, 2014):

$$c(t) = \frac{1}{n_1}(K_c - \theta) \qquad (11)$$

It should be noticed that Eq. (10) is more general than Eq. (11) since when $x \to 0$ Eq. (10):

$$\frac{\theta}{n_1} > \frac{K_c}{n_1} \qquad (12)$$

thus, indicating that $c(t) < 0$.

In this sense, a detailed analysis should always be performed in order to choose the values for the rate parameters because they present dependencies with other rate parameters and also with other parameters listed in Table 1.

6. Discussion

The analysis performed in this article is fundamental for deciding on possible values for the parameters listed in Table 1, which are used for estimating the probability of overflow for the near surface repository of Abadia de Goiás.

As discussed in Gabcan et al (2023), mean values for all parameters of interest have been chosen so that the overflow probability could be estimated. However, some of these choices do not have clear reasons for being chosen. An example was the surface runoff, which was assumed to be zero. In that reference, an initial sensitivity analysis was performed on the rainfall rate and some important conclusions were drawn. Also, the geometrical shape of the repository base was changed from rectangular to squared. It became clear that a deeper sensitivity analysis would have to be performed and interval ranges for the parameters should be searched for and physical restrictions investigated.

Dependencies were identified and interval ranges redefined. In this sense, a more realistic sensitivity analysis can be performed.

7. Conclusion

With the parameter ranges set and the identification of dependencies among them, it is now possible to perform a detailed and meaningful sensitivity analysis with focus on the overflow probability of the near surface repository, which is the next step on the research. This sensitivity analysis will help make realistic decisions. One important issue here is the possible variability of some parameters (as the ceiling degradation) during the theoretical institutional control period. The analysis is to be developed for an institutional control period of 50 yr.

The sensitivity analysis can be performed with the help of the generalized perturbation theory (GPT) (Souza et al, 2022).

Another investigation that is worth making is the analysis of optimal solutions (Schwefel, 1995; Cagnoni et al, 2000) for the overflow probability (that is, which sets, if any, of the input parameters give the lowest overflow probabilities?).

Also, simulation analyses (Ross, 2022) will be possible considering expert opinion (Kelly & Smith, 2011) in order to allow for representing the variability of the relevant parameters for those cases where no data is available in the literature.

Acknowledgement

The help of many professionals regarding specific details is gratefully acknowledged. One of the authors

(PFFM) would like to acknowledge his support from the Brazilian National Council for Scientific and Technological Development (CNPq) through grant 303139/2019-6.

References

Alves, A. S. M., (2014). *Deterministic and Stochastic Safety Analysis in a Water Infiltration Scenario of a Near Surface Repository for Radioactive Waste Disposal* (in Portuguese), D.Sc. dissertation, COPPE, Federal University of Rio de Janeiro, Rio de Janeiro, RJ, Brazil.

Alves, A. S. M., Frutuoso e Melo, P. F., Passos, E. M., Fontes, G. S., (2015). Stochastic and deterministic models to evaluate the critical distance of a near surface repository for the disposal of intermediate and low-level radioactive wastes. *Nuclear Engineering and Design, 287*, 57–67.

Cagnoni, S. et al, 2000. *Real-world Applications of Evolutionary Computing*. Springer-Verlag, Berlin.

Cardoso, M. R. D., Marcuzzo, F. F. N., Melo, D. C. R. (2011). Temporal and spatial mapping of rainfall in the metropolitan region of Goiânia (in Portuguese). *Proceedings of the 15th Brazilian Symposium on Remote Sensing*. Curitiba, PR, 4594-4601

Casaroli, D., Rodrigues, T. R., Martins, A. P. B., Evangelista, A. W. P., Alves Júnior, J., (2018). Rainfall and Evapotranspiration Patterns in Goiânia, GO (in Portuguese). *Brazilian Journal of Meteorology*, *33(3)*, 247-256.

Chen, X., Wu, S., Zhou, J., (2013). Influence of porosity on compressive and tensile strength of cement mortar. *Construction and Building Materials, 40*, 869-874.

Costa, H. C., Marcuzzo, F. F. N., Ferreira, O. M., Andrade, L. R. (2012). Spatialization and Seasonality of Rainfall in the State of Goiás and Federal District (in Portuguese). *Brazilian Journal of Physical Geography, 1*, 87-100.

De La Cruz, J. C., Colorado, D., del Campo, J. M., (2015). Comparative study on porosity and permeability of conventional concrete and concrete with variable proportions of natural zeolite additions. *Journal of Construction, 14(3)*, 72-78.

Gabcan, L., A.S.M. Alves, F. C. da Silva, D. G. Teixeira, and P.F. Frutuoso e Melo, Evaluation of the Overflow Probability from the Abadia de Goiás Repository by the Fokker-Planck Equation Using the Trotter's Formula, to be submitted to the Nuclear Engineering and Design journal.

Gambrick, 2023. *Is Concrete Porous*?, page site: https://gambrick.com/is-concrete-porous/, accessed on February 2023.

Gjörv, O. E., Löland, K. E. (1980). Effect of Air on the Hydraulic Conductivity of Concrete. In: Sereda, P. J. (Ed.), *Durability of Building Materials and Components*, American Society for Testing Materials, West Conshohocken, PA. 410-419.

Goyal, M. R. Harmsen, E. W. (Eds.) (2013). *Evapotranspiration: Principles and Applications for Water Management*. CRC Press, Boca Raton, FL.

Kelly, D., Smith, C., 2011. *Bayesian Inference for Probabilistic Risk Assessment, A Practitioner's Guide*. Springer, London.

Marcuzzo, F. F. N., Cardozo, M. R. D., Faria, T. G., 2012. Rain at Cerrado of Brazil Middle-West Region: Historical Analysis and Trends (in Portuguese), *Geographic Studio, 6(2)*, 112-130.

Masten, S. J., Davis, M. L. (2020). *Principles of Environmental Engineering and Science*. McGraw-Hill Educational, New York.

Neville, A. M. (2012). *Properties of concrete*. Pearson Education Limited, Harlow, UK.

Ross, S. M. (2022). *Simulation*. Academic Press, London.

Schneider, S., Mallants, D., Jacques, D. (2012). Determining hydraulic properties of concrete and mortar by inverse modelling. *Proceedings of the Materials Research Society Symposium, 1475*, 367-372.

Schwefel, H., -P., 1995. *Optimization of Computer Models*, Wiley, New York.

Soong, T. T. (2004). *Fundamentals of Probability and Statistics for Engineers*, Wiley, New York.

Sousa, A. L. B., Duarte, J. P., Saldanha, P. L. C., Frutuoso e Melo, P. F., 2012. The Role of Risk-informed Decision Making in the Licensing of Nuclear Power Plants. In: Zhiyong Zhang (Ed.), *Risk Assessment and Management*. 1ed. Cheyenne: Academy Publishing, 177-192.

Souza, L.F.A., Teixeira, D.G., Frutuoso e Melo, P.F., da Silva, F.C. (2022). Sensitivity analysis of the accident rate of a plant equipped with a protection channel under aging by the generalized perturbation theory. *Annals of Nuclear Energy, 176,* 109278.

Tranjan Filho, A., de Martin Alves, A.S., dos Santos, C.D.P., dos Passos, E.V., Coutinho, F.P.M., (1997). *Repository of Radioactive Cesium Waste – Abadia de Goiás Conception and Design* (in Portuguese). National Commission of Nuclear Energy, Rio de Janeiro.

Vörösmarty, C. J.; Federer, C. A.; Schloss, A. L. (1998). Potential evaporation functions compared on US watersheds: Possible implications for global-scale water balance and terrestrial ecosystem modeling. *Journal of Hydrology*. **207**(*3*), 147–169.