RE-ASSESSMENT OF THE SAFETY OF THE GOIÂNIA REPOSITORIES

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Abstract. *According to Brazilian Legislation, the National Nuclear Energy Commission, CNEN, is the governmental body responsible or the receive and final disposal of radioactive wastes in the whole country. The promulgation of regulations concerning waste management and disposal is also a responsibility of CNEN. In 1995 two repositories were constructed for the final disposal of the radioactive waste generated during the recovering operations of the Goiânia accident occurred in 1987 resulted from a violation of a teletherapy equipment . A long term safety assessment robust analysis were done at that time proving the safe of the two disposal repositories. After seven years of disposal a second safety assessment were done by the Brazilian Nuclear Energy Commission to re-evaluate the safety of the two systems and will be presented on this article. Also a comparison between the two results will be shown.*

Keywords: *Repository, Waste safety assessment, Environmental analysis*

1. INTRODUCTION

The violation of a teletherapy source in Goiânia, Brazil (Figure 1), at the end of September 1987, with subsequent spread of most of it's radioactive contents, i.e., 1375 Ci of Cs-137, over a large urban area (Figure 2) , brought about the need to estimate the quantities recovered during the decontamination work performed by CNEN [1].

Approximately 3.500 m^3 of wastes were generated, with an estimated overall activity lying between 47.0 TBq (1270 Ci) and 49.6 TBq (1340 Ci) in 1987.[2] Taking into account the decay period necessary for the contents of all packagings to reach a Cs-137 concentration level not greater than 87 Bq/g, it was possible to classify the drums and the metal boxes used into 5 groups, as described in Table 1. Also the following packages were used in Goiânia:

- 1 metal package for the headstock with the remain source (4.4 TBq and with 3.8 m^3 from group 5);
- 10 ship containers (374 m^3 with 0.4 TBq from Group 1), and;
- 8 special concrete packages (11.4 m^3 and 0.7 Bq from Group 5).

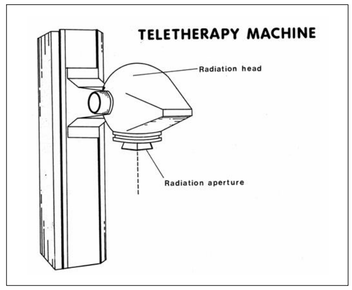


Figure 1. Teletherapy equipament

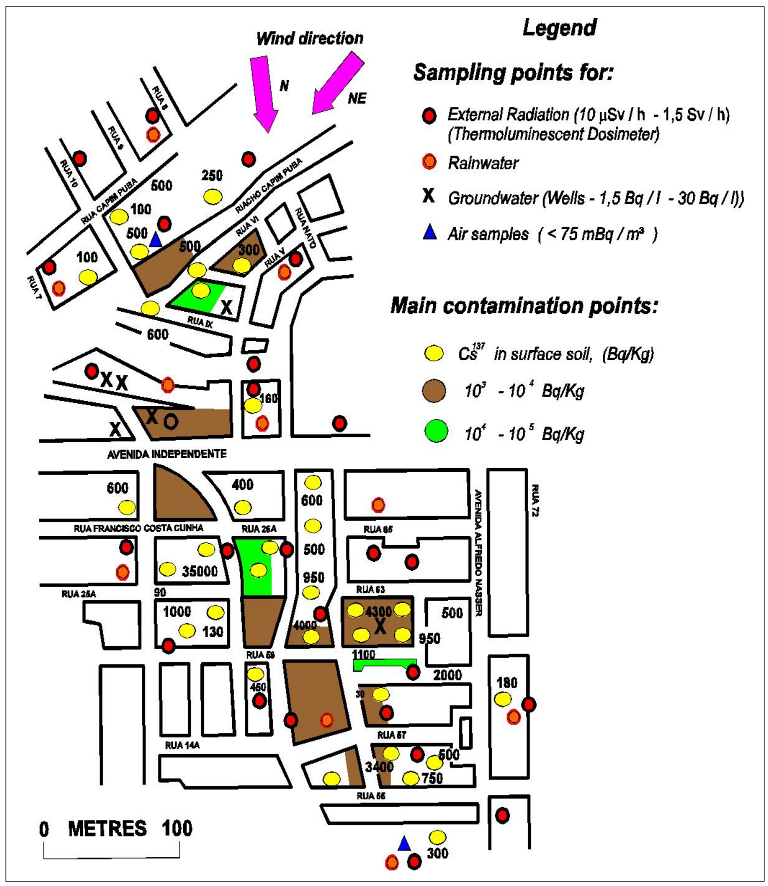


Figure 2- Contamination site map

According to the International Atomic Energy Agency (IAEA) [3] philosophy, all the radioactive wastes collected in Goiânia falls into the category of "LOW LEVEL SHORT LIVED" waste and the disposal option allows the emplacement at shallow depths, in engineered storage facilities as shown in Figure 3.

Table 1 - Goiânia waste inventory

GROUP (Time in years)	Number of Metallic Boxes	Volume (m^3)	Number of Drums	Volume (m^3)	Total Activity (TBq)	Total Volume (m^3)
I (t=0)	404	687	2710	542	0,06	1231
II ($0 < t < 90$)	356	605	980	196	0,476	801
III ($90 < t < 150$)	287	488	314	62,8	1,44	560,7
IV ($150 < t < 300$)	275	468	217	43,4	13,67	511
V ($t > 300$)	25	42,5	2	4	30,064	43
Total	**1347**	**2290**	**4223**	**844,6**	**45,71**	**3134,5**

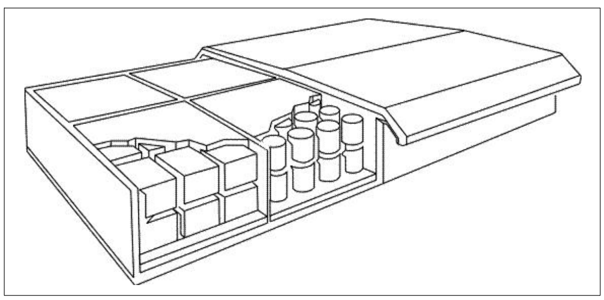


Figure 3 – Vault disposal facility type

It can be seen from Table 4 that approximately 33 % of the waste volume (Group 1) have specific activities not greater than 87 Bq/g. Furthermore, most of the recovered activity is distributed over only 16.5 % of the total volume, requiring a decay period greater than 150 years to reach acceptable concentration levels (Groups 4 and 5).

The remaining 40.8% of the waste volume (Groups 2 and 3), were placed into concrete containers (Figure 4) and (Groups 4 and 5) in metallic containers to improve its conditioning as well as to provide an additional engineered barrier in the near surface repository to be constructed.

Although the specific activities of the wastes classified as Group 1 are inferior to the value established in the regulation for dust bin disposal of solid wastes by users of radioisotopes, this group will not be considered exempt from control. The Brazilian Regulatory Body understands that the above mentioned exemption criteria was established for solid wastes generated by facilities that handle small quantities of radioactive materials. It is also understood that care should be taken to avoid the deliberate fractionating and dilution of wastes so as to achieve compliance with disposal regulations.

Figure 4 – Repackaged of the 200 l drums

Due to the facts mentioned previously, CNEN has proposed the construction of two repositories for the Goiânia wastes [4] .The first repository was constructed in 1995 for the wastes classified as Group 1. A Safety Analysis Report (SAR), was prepared based on a simple and robust model, which has shown that the radiological impact due to this disposal would be negligible [5]. This report was submitted to IBAMA (The Brazilian Organisation responsible for the environmental licence), to obtain exemption from the environmental licensing process without the submission of a Environmental Impact Report (EIR).

The second repository, for wastes from groups 2, 3, 4, and 5 were constructed, in 1996, very near the first one. For this facility, the State of Goiás prepared an Environmental Impact Report, and submitted to IBAMA for approval. A special Safety Analysis Report was prepared by a consultant organisation and was submitted to CNEN for evaluation [6].

Details of construction from both repositories can be seen Figures 5, 6, 7, 8, 9 and 10.

Figure 5- CGP construction

Figure 6 – CGP waste disposal

Figure 7 – CGP final view

Figure 8 –REP construction

Figure 9 –REP waste disposal

Figure 10 –REP final view

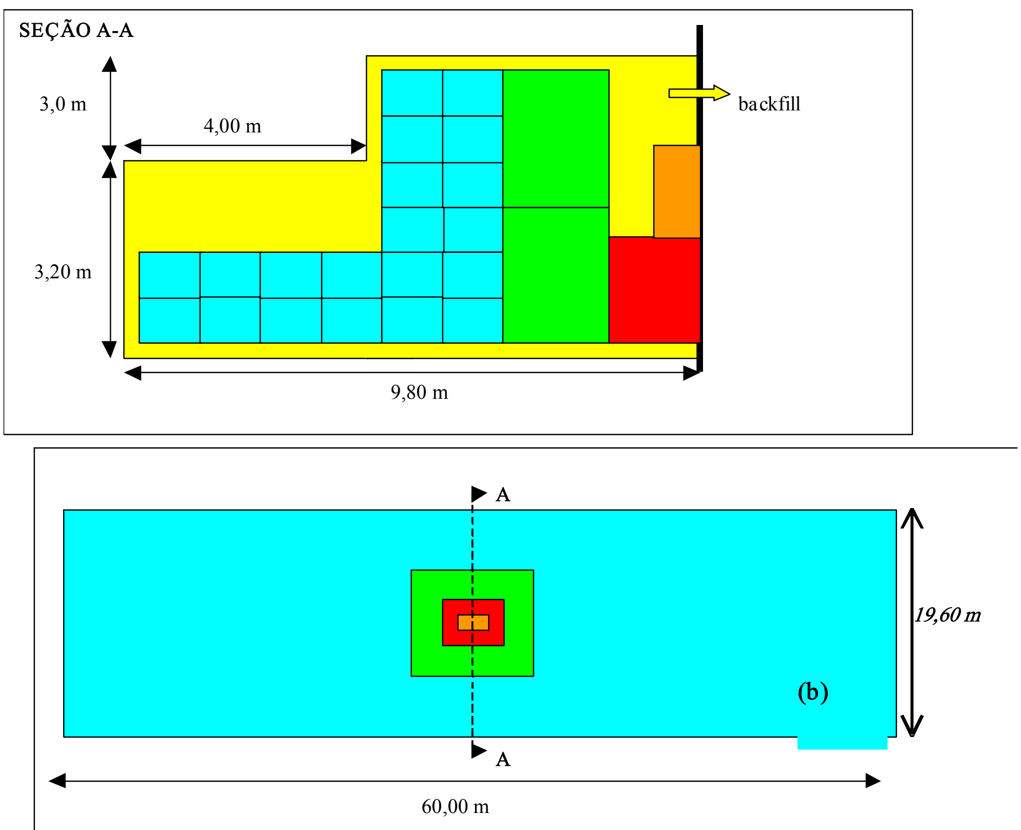


Figure 11 (a) cut view (b) Aerial view

(b)

2. THE FIRST SAFETY ASSESSMENT (1995)

The necessity of using predictive models to assess potential radiological consequences in safety assessments is well recognised (1) and can be divided in two complementary types: (i) detailed research models and (ii) simplified system models. The first type is used to evaluate design and engineering options and to provide a defensible basis for excluding processes not important to safety in the simplified system models. Simplified systems models may be used to conduct a more robust analysis once that the scenarios, models and data are chosen conservatively simplifying the discussion of some uncertainties related to the system and avoiding the necessity of extensive quantities of data.

A robust model or screening model can be developed considering that one of the main scenarios for the prediction of the impact of a near surface repository is related with the water pathway. The following scenarios related with the water pathway were considered: [7]

- (a) water ingestion (people will dig a well and take the water for consumption);
- (b) ingestion of contaminated vegetables due to water irrigation from the well;
- (c) ingestion of contaminated animal products (also due to water irrigation);
- (d) inhalation of contaminated soil due to irrigation;
- (e) external irradiation due to contaminated soil (also due to irrigation).

The dose factor was calculated considering a steady concentration of 1000 Bq/m^3 in the water well, the scenarios above, resulting in:

Annual Effective Dose Equivalent =4.19 x 10^{-5} Sv

Effective Dose Equivalent Commitment = 2.93 x 10^{-3} Sv.

The following pathways were considered for intrusion [8]:

- an agriculture scenario(a) - An inadvertent intruder is assumed to excavate into waste while constructing a foundation for a home at the location of the disposal units, and some of the exhumed waste is assumed to be mixed with native soil in the intruder's vegetable. Garden. The following pathways is assumed to happen: ingestion of contaminated vegetables from the garden, ingestion of contaminated soil from the garden in conjunction to vegetables intakes, external exposure to contaminated soil while working in the garden or residing in a home on the top of the disposal unit and inhalation of ressuspended radioactive material.`. A dose factor of 2.7x10^{-10} Sv/year per Bq /m^3 must be used.

- **discovery scenario (b)-** In this scenario an inadvertent intruder is assumed to excavate at the location of the disposal units and construct a foundation for a home, as in agriculture scenario. However, the intruder is assumed to encounter an intact engineered barrier that cannot be penetrated by normal excavation procedures. Since the intruder abandons excavation at the location and moves elsewhere. This scenario is subject to a dose limit of 5 mSv, related to a single acute exposure. The only pathway of this scenario is external exposure during time the intruder work at the site. The conversion factor for this case is equal to 1.2×10^{-12} Sv per Bq /m^3 and an additional correction factor of 0.25 must be applied to account for the waste dilution.

- **a post-drilling scenario (c)-** In the post-drilling scenario an inadvertent intruder is assumed to drill through the disposal unit for purpose of constructing a well, and drilled waste is assumed to be mixed with native soil in the intruder's vegetable garden. The same pathways as in the agriculture scenario are considered except that the volume of waste mixed with the garden soil is 10 times lower. The dose limit in this case is 1 mSv. The dose factor is equal to 3.0×10^{-13} Sv/year per Bq/m^3 .

The following hypothesis were considered for the geosphere in the analysis:

1. The establishment of an Institutional Control Period;

2. The continuos linear degradation of the cap, after construction of the repository allowing a higher infiltration rate each year (after 30 years the cap would completely fail);.

3. The infiltration rate at the surface of the cap is only a function of the water balance between water fall and evapotranspiration;

4. The unsaturated zone thickness bellow the repository bottom at the beginning of the analysis is neglected;

5. The concentration inside the repository in the water phase, each year, is calculated taking into consideration the adsorption coefficient of the waste (kd) and the available quantity of water, function of the water balance and the permeability of the cap;

6. Two cases were studied:

(a) Neglecting the permeability of the top of the vault due to the concrete thickness and applying Darcy law on the bottom of the repository to calculate the flow to the water table (model 1);

(b) Neglecting the permeability of the top and bottom of the vault and considering that all the water infiltrated each year leaches the waste based on the adsorption coefficient and flows to the aquifer (model 2).

7. Plume model in the aquifer.

The same data for the geosphere and biosphere used in the 1995 safety assessment will be used on the 2002 assessment.

3; RESULTS OF THE FIRST SAFETY ASSESSMENT (1995)

Figure 12 shows the doses expected for the critical group, based on the irrigation pathway, for a well located at 1 m and 2 m from the repository, from model 1.It can be seen that the maximum dose to the critical group due to the use of a water from a well located at 2 m from the repository, would always be lower than the allowed limit (0.25 mSv) even when the decay time in the unsaturated zone is neglected.

Figure 13 shows the maximum doses expected, as a function of the well distance, for the irrigation scenario, from model 2. It can be seen that for distances greater than 2.5 m the concentrations in the well would be below the allowed limit, for a dose of 0.25 mSv/year.

A conservative model for the unsaturated zone is to consider the water velocity to be equal to the infiltration rate, an adsorption coefficient five times lower than the value of the saturated zone and a small volumetric water content. This results in a transit time for Cs-137, for the 4 m thickness of the unsaturated zone, of at least 423 years.

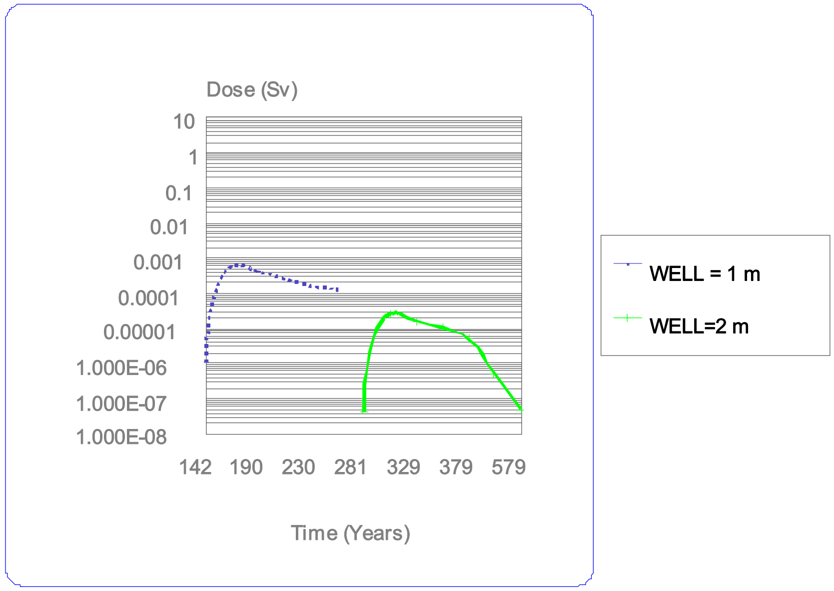


Figure 12 –Doses for the critical group

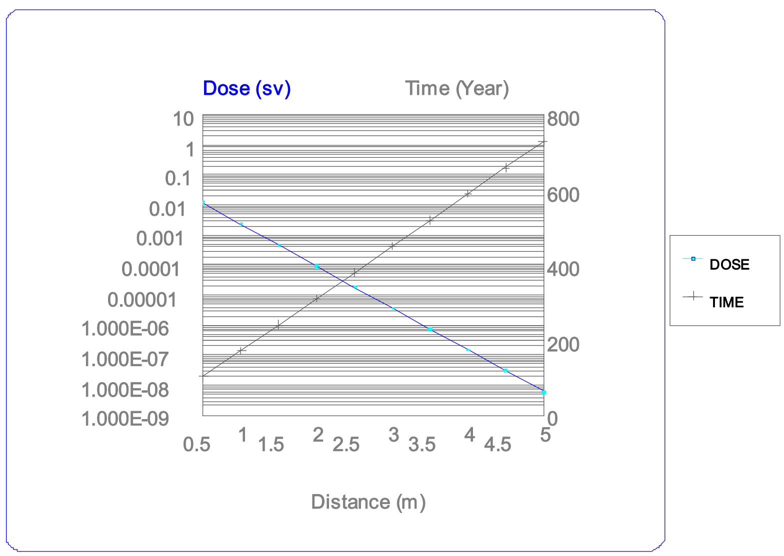


Figure 13 –Maximum doses as a function of the well distance

It can be seen from Fig 14 that the maximum concentrations, below the repository, when considered the transit time in the unsaturated zone, would be lower than the allowed concentrations at any time, showing that the groundwater pathway is not important.

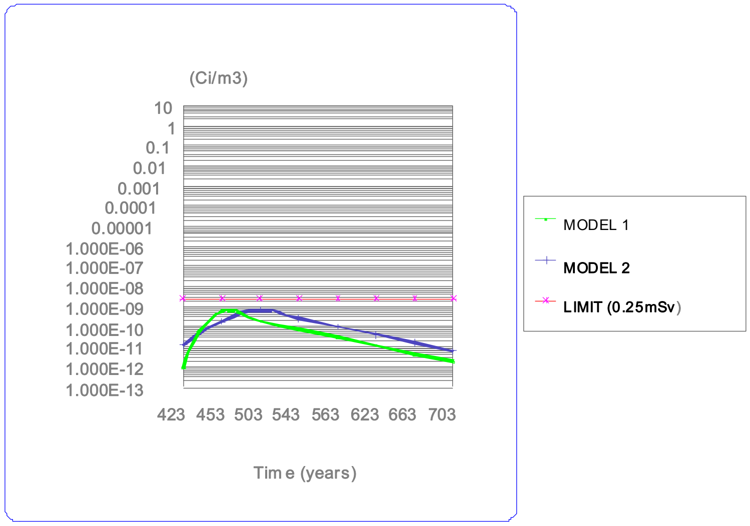


Figure 14 –Maximum concentration in a well located at the bottom of the repository considering the retention on the unsaturated zone

Figure 15 shows the expected dose to an intruder as a function of the institutional control period for the scenarios listed in 3.2. It can be seen from this figure that the doses expected to an intruder due to the agriculture Scenario (a) would be below the limit of 1 mSv/year, considering the possible time of occurrence for this scenario to be more than 300 years (disposal unit with engineered barriers).

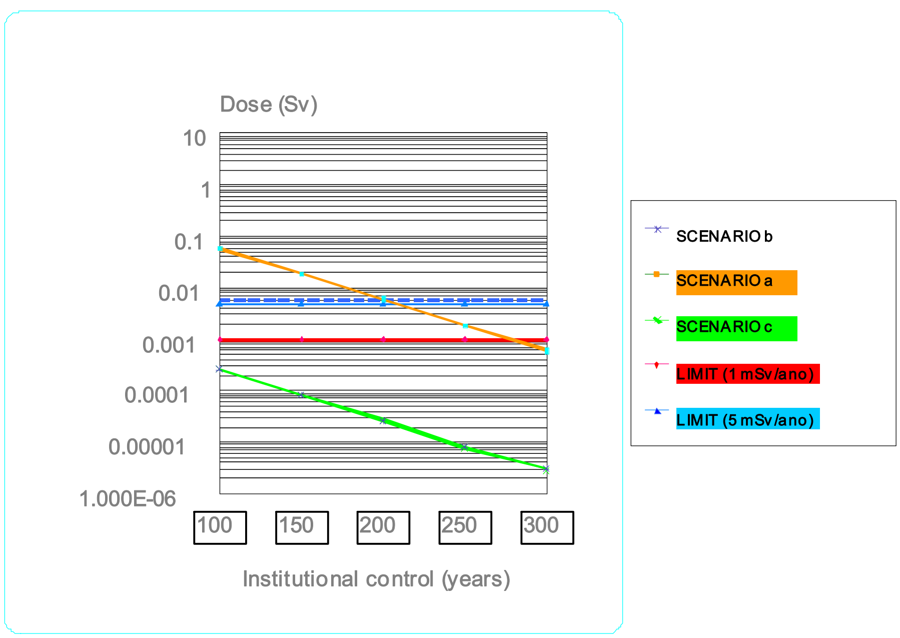


Figure 15 –Maximum doses due to the 3 scenarios of intrusion

For the discovery Scenario (b) the dose to the intruder would also rest below the limit of 5 mSv, whichever institutional control period established.

Although the curves for Scenario (c) and (b) are coincident, an institutional control period of approximately 50 years must be established in this case, by the Competent Authority, in order to respect the dose limit of 1 mSv/year for the intruder.

4. RE-ASSESSMENT OF THE GOIÂNIA REPOSITORIES (2002)

4.1 The Source Term and the Geosphere Model

The source term considered on this model is based on a conservative. An annual leaching fraction of the waste and consider that all the water which enter the repository leaves the disposal and enters the geosphere (neglects cap and the engineered barriers).

The equation governing the evolution of the residual mass or activity A_r in the disposal site is given bellow and states that the variation of the activity in the repository is proportional to the quantity of radioactive material present less the quantity that leach from it.

The equation governing the evolution of the residual activity Ar in the disposal is:

$$\frac{dA_r}{dt} = -(\lambda + F \times ALF)\, A_r \qquad (1)$$

Where:

A_r is the residual mass (or activity) as a function of time (Bq or g);

λ is the decay constant (1/y) in the case of organic or radioactive material;

ALF is the annual leaching fraction in (1/y)];

F is the fraction of the waste, which will be subject to the leaching and in our mode

The annual leaching fraction (*ALF*) is the ratio of the activity lost by leaching during the year t, *A(t)*, over the total activity remaining that year, $A_r(t)$. It is expressed as:

$$ALF = \frac{Inf}{H_d(\theta\omega + \rho_b K_d)} \qquad (2)$$

Where:

Inf, the annual infiltration rate (m/y);

H_d, the disposal height (m);

θ_ω, the kinematics porosity (-) or the moisture content;

ρ_b, the dry bulk density (kg/m^3);
K_d, the distribution coefficient (m^3/kg).

Then, the hazardous material that leaves the disposal and enters the geosphere is given by:

$$A(t) = A_r(t) \times F \times ALF \qquad \text{(Bq/y or g/y)} \qquad (3)$$

The initial condition is that on time equal zero all the mass or activity (A_0) is confined into the repository so:

$$A_r(0)=A_0 \qquad (4)$$

The solution of equation 1 is given by:

$$A_r(t)= A_0\, e^{-(\lambda+ALF)t} \qquad \text{(Bq or g)} \qquad (5)$$

and the quantity of hazardous material, which leaves the disposal and enters the geosphere, is:

$$A(t)=ALF \, x \, A_r(t) \qquad \text{(Bq/y or g/y)} \qquad (6)$$

The concentration $C(t)$ at the bottom of the landfill is given then by:

$$C(t)= \{A_0/[(m_t(\theta_\omega/\rho_b+ K_d)]\}e^{-(\lambda+ALF)t} \qquad (7)$$

Where:
m_t is the total mass of the landfill.

The unsaturated zone thickness below the landfill will be considered at the end of the analysis based on a transit time. (the same hypothesis adopted on the first analysis in 1995).

The model adopted for the saturated zone to be couple with the source term takes into consideration the well known one dimensional transport equation including dispersion, retention and decay of the contaminant in the aquifer.

$$K\frac{\partial C_d}{\partial t} = D\frac{\partial^2 C_d}{\partial z^2} - V\frac{\partial C_d}{\partial z} - \lambda K C_d \quad (8)$$

With the following initial condition:

$$C_i\,(x,\,0) = 0 \quad (8.a)$$

And boundary conditions:

$$C_i(0,t) = C(t) \quad (8\ b)$$

$$\frac{\partial C_1(L_1,\tau)}{\partial z} = 0 \quad (8.c)$$

Where, L_1 is the well position in (m);

R_i, is the retention factor in the aquifer for the radionuclide i, given by:

$$R_i = 1 + \rho_a\, k_d(i)/\theta \quad (9)$$

$k_d(i)$ is the adsorption coefficient for the aquifer for radionuclide i, in (m^3 /g);

ρ_a is the aquifer density in (g/m^3);

θ is the aquifer porosity;

D is the dispersion coefficient of the aquifer in (m^2/y);

V_p is the velocity of the radionuclide i in the aquifer in (m/y);

and λ_i is the decay constant of the radionuclide i in (1/y)

C_i is the radionuclide concentration in the aquifer at position x and time t in (g/m^3)

Traditionally this problem has been solved by Laplace Transform or by separating variables methods, and for some simplified boundary conditions and for infinite or semi-infinite domains a complete set of analytical solution can be obtained Bear [9] These solutions are very important as benchmarking, but of limited utility in the case of a realistic site. When is very difficult to obtain an analytical inversion of Laplace Transform and when is not possible to applied variable separation, the problem is usually solved using purely numerical methodology, such as finite difference.

On the other way, hybrid numerical-analytical methods such as the Generalized Integral Transform Method (GITT) have been growing in the last years [10] . In particular, this method present some important characteristics such as automatic error control and moderate computational cost, even when are analyzed multidimensional problems. A systematized description and applications of the GITT method may be found in Cotta [10]. The main idea of this semi-analytic method, with spectral characteristic, is to represent the field as an eigenexpansion and using the orthogonality property of the eigenfunction to transform the partial differential equation into a coupled ordinary system, e.g., reducing the number of independent variables to only one. in the case of one dimensional problem. The ordinary differential system is then solved numerically using scientific subroutine libraries with global error control procedure. Therefore, the numerical task is only in the solution of the ordinary differential system. The solution of this problem will be obtained via software MATHEMATICA [11]

4.2 Biosphere Model

For the modelling of the biosphere, two kinds of scenarios will be considered:

(a) Intrusion on the site resulting in: (i) direct inhalation of particulate due to contaminated soil (Scenario CRA), (ii) deposition on vegetables and ingestion by man (Scenario CRB); (iii) deposition on vegetables, ingestion by animals, meat consumption by man (Scenario CRC); (iv) deposition of grass, ingestion by the cow, transfer to milk and ingestion by man (Scenario CRD); (v) ingestion of contaminated soil due to ressuspension (Scenario CRE) and (vi) external dose due the radioactive hazardous materials (Scenario CRF).

(b) A residential scenario, that is, the existence of a house near the site (at the border) using water from a well: (i) Irrigation, ressuspension and inhalation (Scenario CWA); (ii) direct consumption of the water well – ingestion (Scenario CWB); (iii) irrigation of vegetables and consumption by man (Scenario CWC); (iv) irrigation of vegetables, consumption by animals, consumption of contaminated meat by man (Scenario CWD); (v) surface water contact, transfer to fish and to man (Scenario CWE);(vi) irrigation of vegetables, consumption by animals, transfer to milk and ingestion by man (CWF);(vii) irrigation and accidental ingestion of contaminated soil (Scenario CWG);(viii) irrigation and external exposure in the case of radioactive materials (Scenario CWH).

The following equations were used according to the type of scenario described above:

Intrusion

$$CRA(t)= CS(t) * T_{dust}*IR_{air} \quad (g/y) \qquad (10)$$

$$CRB(t) = CS(t) * T_{veg} *IR_{veg} \ (g/y) \qquad (11)$$

$$CRC(t)=CS(t)*T_{meat}* IR_{meat} \ (g/y) \qquad (12)$$

$$CRD(t)=CS(t)*T_{milk} *IR_{milk} \ (g/y) \qquad (13)$$

$$CRE(t)=CS(t)*IR_{soil} \ (g/y) \qquad (14)$$

$$CRF(t)=CS(t) * DFE*AE*2000 \ (h/y) \ (Sv/y) \qquad (15)$$

Residential

$$CWWA(z,t)=CW(z,t)*t*IRR*T_{dust}*IR_{air}/(h*\rho) \quad (g/y) \qquad (16)$$

$$CWWB(z,t)=CW(z,t)*IR_{water}*1000cm^3/L \quad (g/y) \qquad (17)$$

$$CWWC(z,t)=CW(z,t)*t* IRR*T_{veg}*IR_{veg}/(h*\rho) \quad (g/y) \qquad (18)$$

$$CWWD(z,t)=CW(z,t)*t*IRR*T_{meat}*IR_{meat}/(h*\rho) \quad (g/y) \qquad (19)$$

$$CWWE(z,t)=CW(z,t)*T_{fish}*IR_{fish}*1000 \ cm^3/L \quad (g/y) \qquad (20)$$

$$CWWF(z,t)=CW(z,t)*t*IRR*T_{milk}*IR_{milk}/(h*\rho) \quad (g/y) \qquad (21)$$

$$CWWG(z,t)=CW(z,t)*t*IRR*IR_{soil}/(h*\rho) \quad (g/y) \qquad (22)$$

$$CWWH(z,t)=CW(z,t)*t*IRR*DFE*AE*2000 \ h/y/(h*\rho) \quad (Sv/y) \qquad (23)$$

Where:

$CS(t)$ = Mass concentration of the hazardous substance in the landfill (g/g) given by:

$$CS(t) = (A_0/m_t) \ e^{-(\lambda+ALF)t} \qquad (24)$$

T_{dust} = Dust ressupension in (g/m^3);

IR_{air} = Inhalation rate in (m^3/y);

T_{veg} = Transfer factor for vegetables in (g/kg);

IR_{veg} = Vegetable ingestion rate in (kg/y);

T_{meat} = Transfer factor for meat in (g/kg);

IR_{meat}= Meat ingestion rate in (kg/y);

T_{milk}= Transfer factor for milk in (g/L);

IR_{milk}= Milk ingestion rate in (l/y).

IR_{soil}= Soil ingestion rate in (g/y);

AE= Specific activity in (Bq/g);

t=1 y

ρ = Soil density in (g/cm^3);

DFE = Conversion factor for infinite source (15 cm thickness) in (Sv/h)/(Bq/g).

CW(z,t) = Concentration in the well in (g/cm^3);

IRR = Irrigation rate in (cm/y);

h = Thickness of contaminated soil = 15 cm;

IR_{water}= Ingestion water rate in (l/y);

T_{fish} = Transfer factor for fish in (l/kg);

IR_{fish}= Fish consumption in (kg/y);

For the risk cancer assessment a factor of 0.05/Sv can be used for radioactive materials and the ingestion and inhalation dose factors (Sv/Bq) can be taken from ICRP [12].

For a radioactive material the cancer risk is obtained multiplying the quantity inhaled or ingested in g (based on the scenarios considered) by the specific activity (Bq/g) and by the dose factor cited before.

The main data related to the geosphere can be seen on Table 2 and the main data for biosphere on Table 3.

Table 2 – Geosphere data

Parameters	Values	Observations	References
Evapotranspiration Pluviometric Rate	1.457 m 1.5923 m	annual average 1986 - 1991 annual average 1986 - 1991	[13] [13]
Concrete permeability	3.1536×10^{-4} m/a	literature data	[14]
Aquifer Velocity Dispersivity	14.6 m/a 0.01 –0.1 m	maximum local	[15]
Saturated Zone Thickness	28 m	Well 1	[16]
Kd	0.463 m^3/kg	97 % confidence	[17]

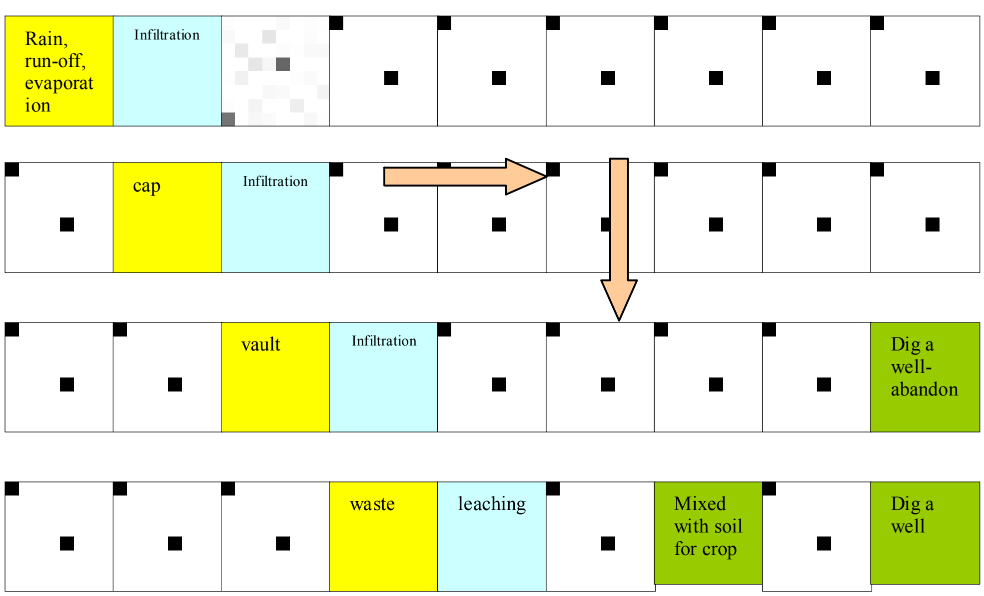
Soil/waste Density Aquifer Porosity	1715 kg/m^3 0.39	related with the higher aquifer velocity	[18] [15]
Waste Porosity	0,1	conservative value	-----------
Vault High	4.38 m	project	-----------
Vault area	19.6 X 60 m^2	project	-----------
Concrete thickness	0.2 m	project	-----------
Vault width	19.6 m	project	-----------
Fraction of waste in contact with the water	100 %	conservative	-----------

Table 3 – Biosphere data

FOODSTUFF	ACTUAL	USED IN THE MODEL
POTATO	5,7 kg/a	22-34 kg/a
CEREALS	78 kg/a	23-123 kg/a
ROOTS/VEG/LEAVES (IR_{veg})	21,4 kg/a	56-113 kg/a
EGGS	3,2 kg/a	2-4 kg/a
PORK	3,2 kg/a	0-5 kg/a
BEEF (IR_{meat}))	21,5 kg/a	5-21 kg/a
MILK (IR_{milk})	22,7 l/a	88-240 l/a
POULTRY	5,3 kg/a	2-15 kg/a
TRANSFER FACTOR`S AND OTHERS CONSUMPTION RATES	VALUE	USED IN THE MODEL
IR_{air}	8000 m^3/y	8000 m^3/y
IR_{water}	730 l/y	730 l/y
IR_{fish}	0 kg/y	0 kg/y
IR_{soil}	36.5 g/y	36.5 g/y
IRR	0.2 m/y	0.2 m/y
T_{dust}	1.92x10^{-4} g/m^3	1.92x10^{-4} g/m^3
ρ_{veg}	1 kg/l	1 kg/l

ρ_b	1.5 g/cm^3	1.5 g/cm^3
ρ_{meat}	1.1 kg/l	1.1 kg/l
ρ_{milk}	1.03 kg/l	1.03 kg/l
T_{veg} (g/kg)	13,36	13,36
T_{milk} (g/l)	6,94	6,94
T_{meat} (g/kg)	28,6	28,6
T_{fish} (l/kg)	2000	0
DOSE FACTORS	VALUE	USED IN THE MODEL
EXTERNAL DOSE CONVERTION FACTOR (DFE) (Sv/h)/(Bq/g)	$1,1x10^{-7}$	$1,1x10^{-7}$
DOSE INGESTION CONVERTION (FCING) Sv/Bq	$1,4x10^{-8}$	$1,4x10^{-8}$
DOSE INHALATION CONVERTION FACTOR (FCINH) Sv/Bq	$8,7x10^{-9}$	$8,7x10^{-9}$

Figure 16 shows the impact matrix generated for the assessment presenting the main scenarios considered in the present analysis. Table 4 shows the comparison between {Dose due to a pathway (D)/water concentration in a well (Cw)}given in [(Sv/y)/(Bq/m^3)] for the biosphere models adopted on the first analysis (1995) and in the revised model developed now (2002). Note that in the analysis of the residential scenario (2002) the cap effect and the engineered barrier (vault) was neglected on this new assessment while on the first assessment (1995 -model 1) a linear failure of the cap/vault in 30 years was supposed to occur.



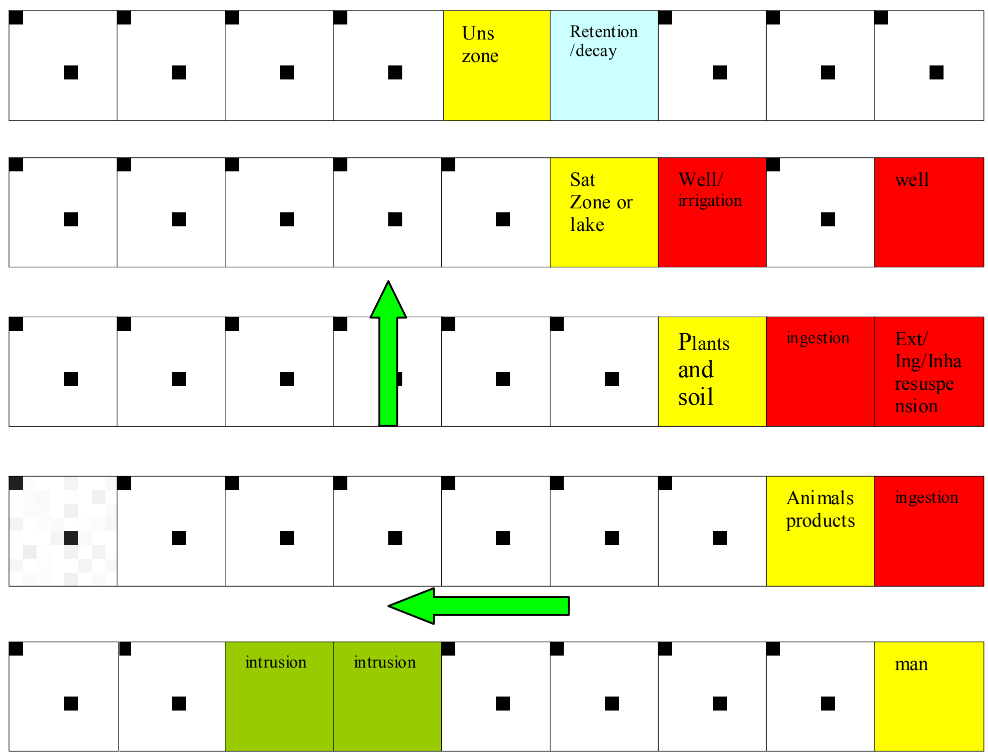


Figure 16 –Interaction matrix for scenario generation

Table 4 – Comparison between Annual Dose/Cw for the biosphere models adopted on the first analysis (1995) and the model adopted in 2002

Residential Scenarios	*1995 [(Sv/y)/(Bq/m³)]*	*2002 [(Sv/y)/(Bq/m³)]*
Water ingestion (people will dig a well and take the water for consumption).	Yes	1.022×10^{-8} Dose due to CWWB
Ingestion of contaminated vegetables due to water irrigation from the well.	Yes	1.879×10^{-12} Dose due to CWWC
Ingestion of contaminated animal products (also due to water irrigation)-meat and milk.	Yes	$1.496 \times 10^{-14} + 2.592 \times 10^{-13}$ Dose due to (CWWD +CWWF)
Inhalation of contaminated soil due to irrigation	Yes	1.2×10^{-15} Dose due to CWWA
External irradiation due to contaminated soil (also due to irrigation).	Yes	1.96×10^{-11} Dose due to DWWH
Total	4.19×10^{-8}	1.03×10^{-8}

Intrusion Scenarios	*1995 [(Sv/y)/(Bq/m³)]*	*2002 [(Sv/y)/(Bq/m³)]*
Direct inhalation of particulate due to contaminated soil	Yes an agriculture scenario	$7.88x10^{-15}$ (Yes -Scenario CRA)
Deposition on vegetables and ingestion by man	Yes an agriculture scenario	$1.23x10^{-11}$ (Yes -Scenario CRB)
Deposition on vegetables, ingestion by animals, meat consumption by man	No	$1.64x10^{-13}$ (Yes-Scenario CRC)
Deposition of grass, ingestion by the cow, transfer to milk and ingestion by man	No	$1.70x10^{-12}$ (Yes -Scenario CRD)
Ingestion of contaminated soil due to ressuspension	Yes an agriculture scenario	$2.98x10^{-13}$ (Yes -Scenario CRE)
External dose due the radioactive hazardous materials	Yes an agriculture scenario	$1.28x10^{-10}$ (Yes-Scenario CRF).
Total agriculture scenario	**$2.7x10^{-10}$** yes	**$1.4x10^{-10}$** Yes
Discovery scenario	$1.2x10^{-12}$ (*0.25) yes	$1.2x10^{-12}$ Yes
Post-drilling scenario	$3.0x10^{-13}$ yes	$3.0x10^{-13}$ Yes

5. RESULTS OF THIS ASSESSMENT (2002)

Figure 17 shows the doses expected for the critical group, based on the irrigation pathway (residential scenario), for a well located at 1 m and 2 m far from the repository in order to compare the with those found in 1995 and a dispersivity of 0.1 m(Figure 12).

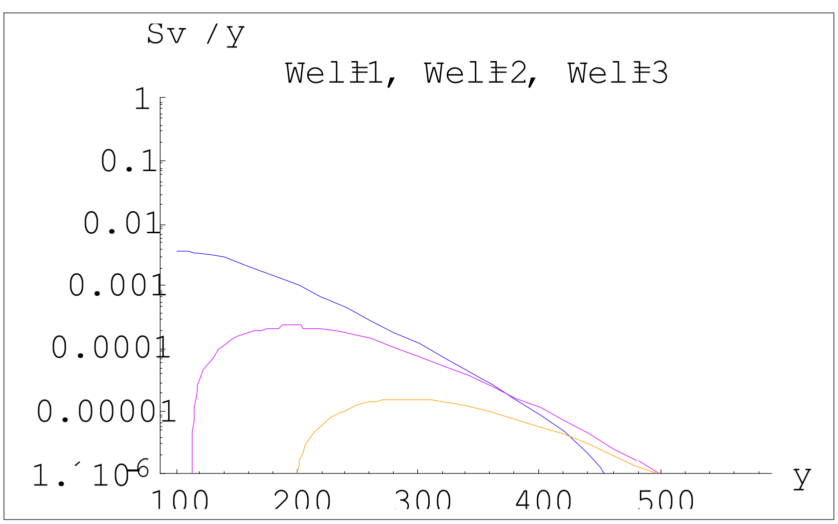


Figure 17 – Doses for the critical group-residential scenarios

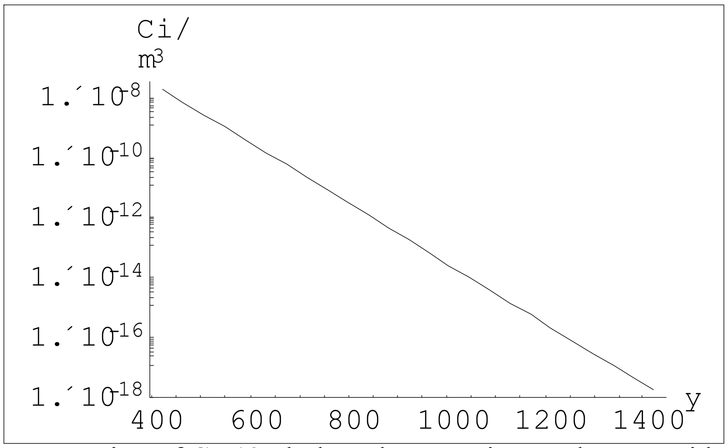


Figure 18 – Concentration of Cs-137 below the repository when considered the retention of the unsaturated zone

It can be seen that the maximum doses in a well located at 1 meter (0.004 Sv/y) and 2 m ($3x10^{-4}$ Sv/y) due to a possible residential scenario are of the same magnitude of the respective values calculated in 1995 (Figure 12). Also it can be shown that a well located 3 meters from the repository could not impact man with doses higher than $2x10^{-5}$ Sv/y (< 2.5 $x10^{-4}$ Sv/y allowed for this repository), the same result obtained in 1995 assessment (See Figure 13). Figure 18 shows the concentration of Cs-137 in the aquifer just below the repository when considered the effect of retention of the unsaturated zone (transit time of ≈423 years- a lower retention coefficient than that considered in the saturated zone).

Taking into account the dose /concentration conversion factor for the residential scenario shown on Table 4 ($1x10^{-8}$ (Sv/y)/(Bq/m^3)) and the dose limit of $25x10^{-5}$ Sv/y we can obtain the maximum concentration allowed in water (25000 Bq/m^3 ≈6,8 $x10^{-7}$ Ci/m^3). From the results shown on Figure 18 it can be seen that the concentration on well just below the repository (considering the complete failure of the cap and the vault) will be, in the worst situation, lower than the limit above confirming that the residential scenario (water irrigation pathway) are not of importance in the Goiânia case.

Figure 19 shows the doses expected due to the three scenarios of intrusion of the first assessment and one scenario similar to the agricultural scenario of 1995 but with the possibility of ingestion of contaminated crop by cow and consequently exposure to man due to the ingestion of vegetables, beef and milk resulting, and results as expected, in a larger dose in the case of occurrence of this scenario (See Table 4).

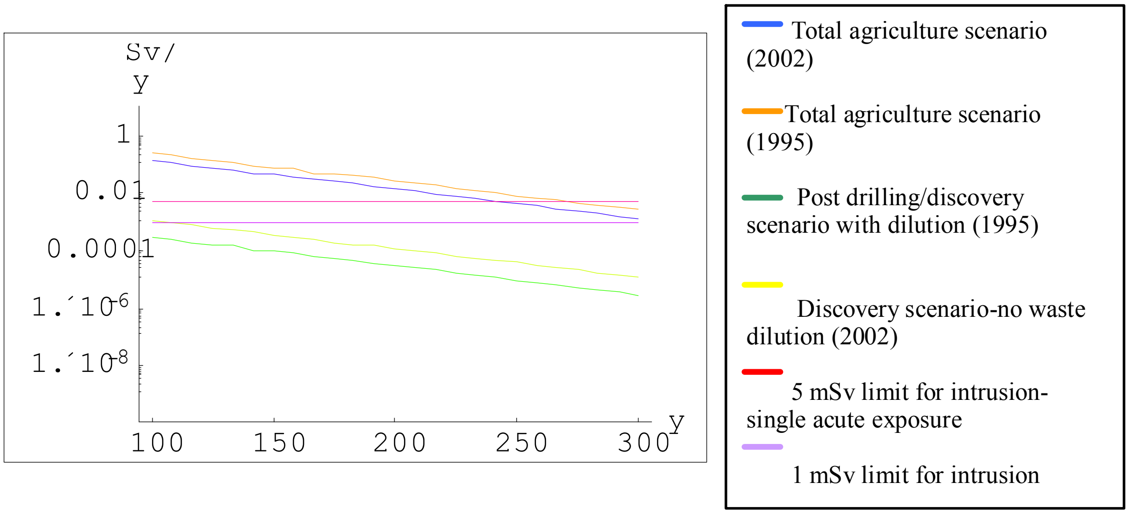


Figure 19 – Concentration of Cs-137 below the repository when considered the retention of the unsaturated zone

It should be pointed out that the agriculture scenario can only happened when the engineered barrier is completely destroyed (the concrete is transformed in sand and mixed with the waste). Many countries establish a period between 300 and 500 years for the complete transformation of the concrete barriers, based on technical experiments, although. cracks and modification on it's permeability can occurred before this period of time. It can be seen from Figure 19 that after approximately 280 years the doses related to a probable agriculture scenario would be lower than the allowed established limit for intrusion of 1 mSv/y.It should also be pointed out that on the post drilling scenario (with dilution waste factor of 0.25) analysis a limit of 1 mSv is applied resulting in a necessity of establishment of a minimal institutional control period of 50years confirming the results obtained in 1995.

Based on a discovery scenario a limit dose for intruder of 5 mSv is applied due to a single acute dose and an institutional control period of 40 years would be necessary (in the case of no waste dilution) or .no institutional control period in the case of a waste dilution factor (0,25).

6. CONCLUSIONS

The re-assessement of the Goiânia repositories safety (2002) confirms the results obtained in 1995 that is:

- The water pathways related to a possible residential scenario near the site is negligible in the case of the Goiânia repository when considered the retention factor (transit time of Cs-137) of the unsaturated zone (natural barrier). The maximum concentration, at any time, below the repository would be below the maximum value allowed of 25000 $Bq/m^3 \approx 6,8 \times 10^{-7} Ci/m^3$, that could result in a dose for an individual of the critical group of 0.25 mSv/y;
- It was also neglected on the geosphere model (water migration-residential scenario) the cap durability and the engineered barrier. A first order leaching rate was adopted;
- The habits consumption for the individual of the critical group was over estimated when compared to the real consumption habits of the population nearby the site today (see Table 4);
- Three intrusion scenarios were considered and the most dangerous one would be the agriculture scenario. If you suppose that it can happen only after the complete degradation of concrete (300 to 500 years) it would be of no importance since after 280 years the doses would be lower than the allowed limit of 1 mSv/y. If in the case of Goiânia the concrete transforms into sand before the usual time of 300 to 500 years an institutional control period of approximately 280 years would be necessary;
- If one neglects this possibility (degradation of concrete in time lower than 300 years) the most important scenario would be the post drilling scenario and an institutional control period of 50 years would be necessary;
- It should also be pointed out that the results of seven years of environment monitoring plan (EMP) at the site proved that is very unlikely to find in the future dangerous concentrations of Cs-137 in the aquifer for the population living near the site (Concentrations lower than the detection limit of 200 $Bq/m^3 \approx 5.4 \times 10^{-9} Ci/m^3$ were obtained until today).

Finally it is important that, every five years or every tens years from now (2002), depending on the EPM results, and no doubt before the end of the institutional control period of 50 years, a new evaluation of the safety of the Goiânia repositories be done by the Brazilian Nuclear Energy Commission, specially by the Waste Management Department expertise's, based not only on the probably improved local data quality such as: (i) geosphere information (ii) demographic grown information; (iii)variation of possible consumption habits by the population *but also based on the improving capacity and knowledge of CNEN.*

Acknowledgements

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REFERENCES

[1] IAEA- *"The Radiological Accident in Goiânia"* – International Atomic Energy Agency – IAEA – Vienna – (1988).

[2] HEILBRON, P., BRANDÃO, R., *"The Goiânia Source Inventory",* Waste Management Conference 93, Tucson, Arizona, U.S.A., February (1993).

[3] Safety Series 111-G-1.1 *"Classification of Radioactive Waste"* – A Safety Guide – International Atomic Energy Agency –Vienna- (1994).

[4] HEILBRON, P., et al, *" Waste Management in Brazil: Basis to Build The Final Repository for the Radioactive Wastes From The Goiânia Accident"*, Waste Management Conference 92, Tucson, Arizona, USA, February, (1992).

[5] HEILBRON P et al, *"Safety Analysis Report (SAR) of CGP"* Brazilian Nuclear Energy Commission- Internal Report – Brazil- (1995).

[6] YAKOPORI - "*Report about the Safety of the Goiania Repositories"*-CNEN INTERNAL DOCUMENT-WASTE MANAGEMENT DEPARTMENT –(1995).

[7] HEILBRON, P , et al *"Preliminary Safety Assessment of the First Brazilian Repository"*- Planning and operation of low level waste disposal facilities – proceedings of an International Symposium on Experience in the planning and operation of low level waste disposal facilities organised by the International Atomic Energy Agency (IAEA) held in Vienna, 17-21 June (1996).

[8] KOCHER, D., *"Potential impact of DOE'S performance objective for protection of inadvertent intruders on low level waste disposals at OAK RIDGE NATIONAL LABORATORY"*, Waste Management Conference 93, Tucson, Arizona, U.S.A. (1993).

[9] BEAR J., *"Hydraulics of Ground Water"* – McGraw-Hill Series in Water Resources and environmental Engineering – United States of America- (1979).

[10] COTTA, R.M. , *"Integral Transforms in Computational Heat and Fluid Flow."* CRC Press, Boca Raton, FL. (1993).

[11] MATHEMATICA- SOFTWARE MATHEMATICA 3.0, Wolfram Research Inc. Champ., Illinois (1996).

[12] ICRP, International Commission on Radiation Protection –*"Recommendations of the International Commission on Radiation Protection",* ICRP Publication 60, Ann. ICRP21, 1-3, (1991).

[13] ÁVILA, F., et al, *"Projeto Abadia - Relatório Preliminar de Estudos Hidrológicos",* Convênio CPRM/CNEN, (1992).

[14] TAPLIN, D., CLARIDGE, F., "Performance of Engineered Barriers for LLW ", INFO - 0274, Atomic Energy Control Board, Canada, September (1987).

[15] PESSOA, P., *"Projeto Abadia de Goiás-Relatório Preliminar de Estudos Hidrogeológicos",* Convênio CPRM/CNEN, (1992).

[16] JUSTO, L.*,"Projeto Abadia de Goiás - Relatório de Geologia"*, Convênio CPRM/CNEN, (1992).

[17] GODOY, J., et al, *"Cálculo do coeficiente de absorção do solo de Abadia de Goiânia",* Internal report, (1991).

[18] PVPO, G. , *"Projeto Goiânia - Relatório Geotécnico Final"*, RT-04/CNEN, (1992).