THE GOIÂNIA SOURCE INVENTORY

P.F.L. Heilbron and R.O. Brandão
Comissão Nacional De Energia Nuclear
General Severiano Str, 90 - Room 404
Botafogo - Rio De Janeiro
R.J., CEP:22294.900, Brazil

ABSTRACT

At the end of September 1987, the violation of a teletherapy source in Goiânia (Goiás State, Brazil), with subsequent spread of most of it's radioactive contents,i.e. 1375 Ci of Cs-137, over a large urban area, brought about the need to estimate the quantities recovered during the decontamination work performed by CNEN (National Nuclear Energy Commission), the Brazilian Regulatory Body.

Data on external dose rates of packages, recorded on inventory cards, were used to estimate the radioactivity of each package, using the Kernel spot method, which assumes a homogeneous distribution of radioactivity within a cylindrical geometry and introducing modifying factors to account for additional shielding.

Approximately 3.5×10^3 m^3 of wastes were generated, with an overall estimated activity lying between 47.0 TBq (1.27×10^3 Ci) and 49.6 TBq (1.34×10^3 Ci), as will be shown in this work.

The wastes are temporarily stored in an area of about 8.5×10^4 m^2 at a site near the village of Abadia de Goiás, 23 km far from Goiânia downtown.

The results of this work were used as a starting point to the design of a repository for final disposal of all Goiânia wastes since it allowed the segregation of that material into 5 categories, according to established specific activities intervals with different conditioning requirements.

INTRODUCTION

In the month of September, 1987, an abandoned teletherapy Cs-137 device was stolen in the city of Goiânia, capital of the Brazilian State of Goiás, and sold to a scrap metal dealer for the market value of the lead and iron shielding.

As a consequence of the violation of the radioactive source, Cs-137 was spread over many areas, by several pathways (air transport, deposition, resuspension by wind, uptake by plants, etc.) and persons, domestic animals, houses, plants, toys, clothing, cars, furniture etc, were contaminated. Fig. 1 and Fig. 2, show respectively, the place of the accident and the main contaminated areas (1).

In the beginning of October of that year, a team composed by health physicists and engineers was assigned to deal with the radioactive waste. One of the first actions was to initiate the filling of a report form to identify the origin, the physical state, combustibility, compressibility, dose rates at the surface and at 1 meter from the packages, etc., to estimate the quantity of Cs-137 recovered in each packaging.

MODEL TO ESTIMATE THE ACTIVITY OF CS-137 *RECOVERED IN* EACH PACKAGE

The method used to evaluate the quantities of Cs-137 recovered in each packaging is based on the "Point Kernel" theory, which takes into account the source geometry, the self absorption of the medium, the surface exposure rate, the density of the waste and the build-up factors for any additional shielding.

The first step to estimate the source inventory was to establish the geometries of the sources, considered to be equal to the shape of the packagings used to conditioning the wastes.

The following packagings were employed:

- 40, 50, 100 and 200 liter steel drums for paper, clothing, corpses of animals, plants, hospital wastes, soil, small objects, etc.
- 1.7 m^3 metallic boxes to hold soil, remnants in general and large pieces of different sort;
- 32 m^3 maritime containers for large contaminated paper roller, and large pieces of furniture and,
- 200 liter cylindrical concrete recipients used to reduce, whenever necessary, external exposure rates to levels not greater than 1 R/h, to conform with the transport requirements established in the Regulations (Safety Series Number 6), for the exclusive use mode.

The 40, 50 and 100 liter steel drums were placed into 200 liter steal drums, and the empty spaces were filled with concrete to allow extra shielding.

Fig. 1. Plan showing the location of Goiania in relation to Rio de Janeiro (1348 km) and Sao Paulo (919 km), where the major radiological protection resources are situated, and giving an impression of the relative size of the contaminated area of the city.

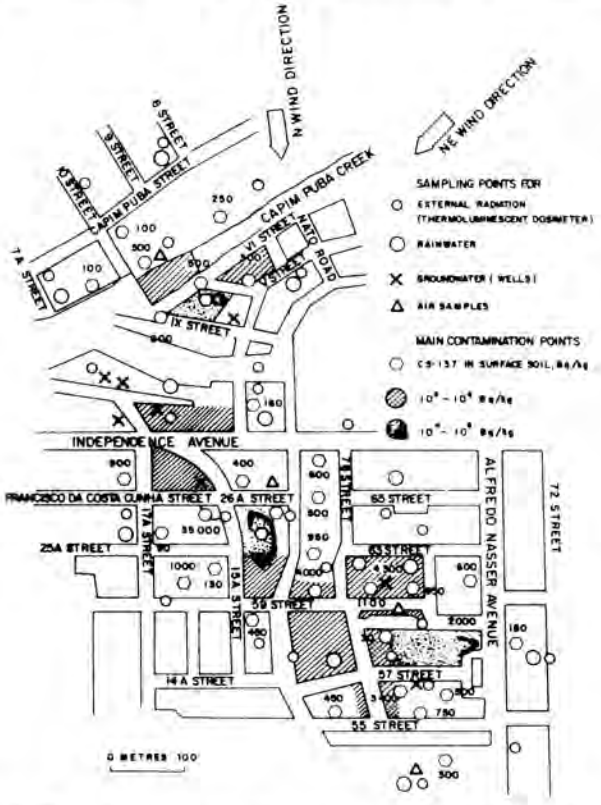

Fig. 2. Plan of the Aeroporto section of Goiania showing the locations of the principal sites of contamination and the sampling points.

Once the geometries of the sources were defined, a computer program was developed, taking into account some simplified considerations in a such way that, knowing i) the package dimensions and extra shielding, ii) the expected density of the collected waste and iii) the surface exposure rate of each package, the activity could be determined.

The following hypothesis were adopted:

- point Kernel Theory;
- cylindrical geometry for all packagings;
- foton flux equation for cylindrical geometry (2), given below:

$$\varphi = \frac{Sv \times [G(\mu s \times h/2, 2 \times \mu s \times r)]}{(2\mu s)} \qquad \text{(Eq. 1)}$$

where

S_v = volumetric source, in Bq/cm^3;
μs = absorption coefficient of the waste, in cm^{-1};
h = height of the cylinder, in cm;
r = radius of the cylinder, in cm;
ϕ = foton flux, in fotons/cm^{2}s.

- least square method to adjust the G function above;
- build-up factor based on Taylor Equation for all extra shielding;

$$B(\mu x) = A1\, e^{-\alpha 1 \mu x} + (1-A_1)\, e^{-\alpha 2 \mu x} \qquad \text{(Eq. 2)}$$

where:

x = shielding thickness, in cm;
μ = attentuation coefficient of the shielding, in cm^{-1};
$\alpha 1$, $\alpha 2$ and A1, coefficients for each specific shielding and function of the energy gamma source;
B(μx) = build-up factor of the shielding;

- the build-up and the attenuation coefficients were considered only in the case of extra shielding as, for example, the thickness of concrete between the 40, 50 or 100 liter drum and the external 200 liter drum);
- photon energy of 0.66 MeV;
- uniformly distributed source;
- the mass attenuation coefficient for all wastes was considered as that for dry soil (0.0783 cm^2/g) and corrected for the multiform densities of the collected waste.

Based on the earlier hypothesis, the surface exposure rate of each package can be shown to be given by:

$$x = \varphi \times e^{-\mu x} \times B(\mu x) \times E \times \mu abs/\delta \times fc \qquad \text{(Eq. 3)}$$

where

ϕ = foton flux (Eq. 1);
B(μx) = build-up factor (Eq. 2)
x = shielding thickness, in cm;
μ = shielding attenuation coefficient, in cm^{-1};
E = photon energy, in MeV;
μ_{abs}/δ = mass absorption coefficient for air, in cm^2/g;
f_c = conversion factor, equal to 0.000065765 (g R s/MeV h);
X = surface exposure rate, in R/h.

The constants for the build-up factor were taken from (3), for a gamma energy of 0.5 MeV and the attenuation coefficients from (4).

The surface exposure rate is linear with respect to the content activity. When the geometry and the density of the waste are fixed, simple linear equations can be obtained to determine the source inventory. The equations are shown in Table I, as a function of the package and waste densities of 0.5 g/cm^3, 1.0 g/cm^3, 1.6 g/cm^3 and 1.8 g/cm^3.

Records on all relevant information concerning the collected waste are kept in a DBIII plus program that provides the following reports:

- quantities of packages collected in each contaminated area;
- total activity collected in each contaminated area;
- total inventory;
- position of each package located in the temporarily storage at Abadia de Goiás;

A simple point source theory was employed to estimate the 121 Ci of activity that remained in the source headstock disk of the teletherapy unit, with the help of the value for the exposure rate of 40 R/h, at 1 meter from the source, measured at the time of the accident with a teletector instrument.

Considering uncertainties of 20% and 10% for the measured values of exposure rate and distance, respectively, a final uncertainty of about 40% results, that is:

Activity remaining in the headstock = 121 ± 48.5 Ci.

TABLE I
Equations for the Calculation of Activity as a Function of the Surface Exposure Rate

	DENSITIES			
PACKAGES	0.5 g/cm^3	1.0 g/cm^3	1.6 g/cm^3	1.8 g/cm^3
40 l	500X/4585	500X/3260	500X/2039	500X/1834
100 l	500X/2519	500X/1534	500X/963	500X/856
200 l	500X/1476	500X/766	500X/478	500X/425
200 l(100 l)	500X/1455	500X/886	500X/556	500X/494
Metal Box	500X/228	500X/114	500X/71	500X/63
SCP	500X/83	500X/43	500X/27	500X/24
200 l (40 l)	500X/691	500X/456	500X/287	500X/259

Obs: SCP-> (Special Concrete Package)
X-> Surface Exposure Rate in mR/h
The result of activity in mCi

RESULTS

The following results were obtained after the computation of the available data:

- lower value for the recovered activity = 1269.3 Ci;
- number of metallic boxes = 1342;
- number of 200 liter drums = 4137;
- waste volume in drums = 827.4 m^3;
- waste volume in metallics boxes = 2281.4 m^3;
- weight of wastes in metallic boxes = 3650.2 t;
- weight of wastes in drums = 827.4 t;
- total waste volume = 3430.4 m^3, computing the containers volumes 320 m^3 and the total SCP volume 1.6 m^3;

Table II shows the main contaminated areas, based on the activities of the wastes recovered.

DISCUSSION

The most important uncertainties, which could not be eliminated in the inventory calculation, and their consequences are listed below:

- instrument calibration: the variety of instruments used during the recovering works were calibrated with a Cs-137 point source of low activity, resulting in an uncertainty in the exposure rate measurement, when applied to cylindrical sources;
- most of the measurements were performed inside the contaminated areas having a background radiation higher than average, leading, consequently, to an underestimate of the activity of each package.

The data on surface exposure rate was selected to be used in the model, instead of the 1 meter exposure rates data, to minimize the influence that nearby sources might have had in the measured values.

The value adopted for the waste mass attenuation coefficient was that for dry soil (0.0783 cm^2/g).

The mass attenuation coefficient for the soil is a function of the humidity and the gamma energy, as indicated in Table III.

In order to estimate an upper activity limit for the waste collected, a saturated soil with 40% of humidity was assumed, having a mass attenuation coefficient of approximately 0.0828 cm^2/g.

Considering that the G function doesn't change much for the packagings used in Goiânia, the upper activity limit is obtained by simply multiplying the result for dry soil by 1.058, value that represents the ratio between saturated and dry soil coefficients, since the influence of the G function on the flux calculation is eliminated. An upper value of 1336 Ci was thus obtained.

CONCLUSIONS

The extension of the accident occurred in Goiânia and the uncertainties associated with the data obtained in situ made it difficult to determine, with accuracy, the total activity collected during the decontamination work.

TABLE II
The Main Contaminated Areas Based on Waste Recovered

Place	Activity Ci	Number Drums	Number Boxes
57 str	821.000	606	381
S. Division	121.000	---	---
26/15 str	267.366	1227	567
P 19 str	52.500	500	197
17 A str	5.336	36	30

TABLE III
Mass Attenuation Coefficient for Soil as a Function of Humidity and Gamma Energy

	ENERGIES	
% H2O	0.5 MeV	1.0 MeV
0	0.086359 cm^2/g	0.063029 cm^2/g
20	0.087379 cm^2/g	0.063779 cm^2/g
25	0.088908 cm^2/g	0.064905 cm^2/g
40	0.090438 cm^2/g	0.066031 cm^2/g

The chemical form of the Cesium source (chloride) favored its dispersion in the environment, with subsequent formation of organic and inorganic wastes of various densities. Besides, it was not possible to weight the packages collected and to determine its homogeneity.

Considering an uncertainty of 1% for the density estimates (based on the variation of the Brazilian clay soils), 20% for the various instruments employed and 1% in the calculation of the G function, results in a total uncertainty of approximately 22% .

The application of the model here presented, with the above considerations taken into account, lead to the following results:

- minimum activity recovered = 1269 ± 301 Ci
- maximum activity recovered = 1337 ± 316 Ci

Since the original source had a known activity of 1375 Ci, the recovered quantity is expected to lie between 70% and 100% of the total.

REFERENCES

1. The Radiological Accident in Goiânia, International Atomic Energy Agency, Vienna (1983).
2. THEODORE ROCKWELLL, "Reactor Shielding Design Manual", first edition - D. Van Nostrand Company, Inc - N.Y.
3. Reactor Physics Constants, ANL-5800, 2 nd ed. (1963).
4. J.R.LAMARSH, "Introduction to Nuclear Engineering".