Essays on Nuclear Energy & Radioactive Waste Management

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- 2 -
30 Years of the Goiania Accident: a comparative study with other radioactivity dispersion events[2]

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Abstract: The year 2017 marks 30 years since the radioactive accident that occurred in the city of Goiania, capital of the state of Goias. It was the largest radiological accident in Brazil, and one of the largest in the world occurring outside nuclear facilities. Regarding the accidents at nuclear power plants, two of the biggest were Chernobyl in Ukraine, a year and a half before Goiania, and the Fukushima accident in Japan, in 2011. Different amounts of radioactive material were dispersed in the environment in each of these events. However, each one's main pathway of dispersion was different: the accident of Goiania was terrestrial, Chernobyl was at the atmosphere, and Fukushima was mainly in the ocean. This work aims to study these different amounts, comparing such activities. In addition, it proposes to compare the sea dispersion of Fukushima with the amount of radioactive waste dumped in the oceans, when the release of radioactive waste at sea was permitted. It also proposes to compare the Chernobyl aerial dispersion with the radioactive material dissipated in the atmosphere, resulting from the more than 500 atmospheric nuclear tests conducted between 1945 and 1962 by the United States, the former Soviet Union, England, France and China.

Keywords: Goiania accident; radioactive waste; radiological accidents; nuclear accidents.

Resumo: O ano de 2017 marca 30 anos desde o acidente radioativo ocorrido na cidade de Goiânia, capital do estado de Goiás. Foi o maior acidente radiológico do Brasil, e um dos maiores do mundo ocorrido

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fora de instalações nucleares. Com relação aos acidentes em usinas nucleares, dois dos maiores foram Chernobyl, na Ucrânia, um ano e meio antes de Goiânia, e o acidente de Fukushima, no Japão, em 2011. Diferentes quantidades de material radioativo foram dispersas no meio ambiente em cada um desses eventos. No entanto, a principal via de dispersão de cada um foi diferente: o acidente de Goiânia foi terrestre, Chernobyl foi na atmosfera e Fukushima foi principalmente no oceano. Este trabalho tem como objetivo estudar essas diferentes quantidades, comparando suas atividades. Além disso, propõe comparar a dispersão marítima de Fukushima com a quantidade de rejeitos radioativos despejados nos oceanos, quando ainda era permitido o lançamento de rejeitos radioativos no mar. Também se propõe a comparar a dispersão aérea de Chernobyl com o material radioativo dissipado na atmosfera resultante dos mais de 500 testes nucleares atmosféricos realizados entre 1945 e 1962 pelos Estados Unidos, antiga União Soviética, Inglaterra, França e China.

Palavras-chave: acidente de Goiânia; rejeito radioativo; acidentes radiológicos; acidentes nucleares.

Introduction

The year 2017 marks 30 years since the radioactive accident that occurred in the city of Goiania, Brazil. On September 13, 1987, two scavengers found a radiotherapy equipment abandoned in a former radiotherapy clinic, and without knowing what the unit was, but thinking it might have some scrap value, they took it home and tried to dismantle it. During this process, they accidentally opened a sealed source with Cesium-137. They later sold the pieces to the owner of a junkyard [1].

The cesium chloride that was inside the sealed source was glowing in the dark, bluish, no one there knew what it was, they marveled at its characteristics. Over a period of days, friends and relatives of the junkyard owner came and saw the phenomenon. Fragments from it were passed on to several families. Many people were directly irradiated by the source and were externally and internally contaminated by Cesium-137. Several persons became ill, showing gastrointestinal symptoms, and sought medical attention. Initially, the symptoms were not recognized as being due to irradiation [1].

However, one of the affected persons suspected that the illnesses that were spreading in her family were connected with that strange material, and took the remnants of the radioactive source to the health authorities. They contacted Brazil's National Nuclear Energy Commission (CNEN). CNEN immediately took action to control the accident and provided support to those involved [2].

This was the largest radiological accident in Brazil, and one of the largest in the world in terms of the number of victims of acute radiation syndrome. But after all, what was this quantitatively? And the nuclear accidents of the Chernobyl plants in Ukraine in 1986 and Fukushima in Japan in 2011, the most serious accidents ever to occur in the nuclear power industry, were they the greatest ones in relation to what? [3]

The dispersion of radioactive material occurred not only as a result of accidents but also by intentional human actions, especially in the decades after the discovery of the nuclear energy, when research and knowledge about radioactivity were still latent. From 1945 to 1962, there were a number of nuclear tests carried out in the open air, and the dispersion of radionuclides into the atmosphere reached levels that led authorities to ban these tests because of risk of fatally damaging life on the planet [4].

At the same time, some of the radioactive waste generated by the nuclear industry had been placed in drums and then dumped at sea since 1946, a practice then considered acceptable, and only halted in the year 1972, when limitations came into force [5].

Anyway, how much radiation has been dispersed in all these events? How much the environment has been damaged, as well as the human being? This paper proposes to better understand these numbers.

Radiation in the Atmosphere resulting from Nuclear Tests

The atomic age began at the end of World War II, when a number of countries launched the nuclear arms race. The United States, the USSR, the United Kingdom, France and China became nuclear powers during the 1945 – 1964 period [5].

The United States and the USSR were responsible for about 80% of all nuclear tests that were not underground; they performed, between 1945 and 1963, a total of 520 nuclear tests in the atmosphere. The most representative examples of these were the Castle Bravo Test, by the United States in 1954 – the first nuclear explosion of a hydrogen bomb, conducted on the Bikini atoll in the Marshall Islands; and the Tsar test, by the USSR in 1961, in the Novaia Zemlia archipelago, north of the Ural Mountains. These were the most powerful tests ever to be conducted in the atmosphere, which generated a severe environmental contamination [5].

According to the report released by the United Nations Scientific Committee on the Effects of Atomic Radiation, "the main man-made contribution to the exposure of the world's population has come from the testing of nuclear weapons in the atmosphere, from 1945 to 1980. Each nuclear test resulted in unrestrained release into the environment of substantial quantities of radioactive materials, which were widely dispersed in the atmosphere and deposited everywhere on the Earth's surface" [6].

Such outcome led to a large-scale international cooperation to eliminate the nuclear weapons testing. Therefore, in 1963, the Limited Test Ban Treaty (LTBT) came into effect, a treaty which stipulated a ban on nuclear weapons tests in all global environments, except for the underground [7]. France and

China did not sign this treaty, so they continued their nuclear weapons tests in the atmosphere until 1980. Nevertheless, the treaty had a genuine impact in limiting radioactive isotopes in the atmosphere in the two hemispheres from 1963 on [5].

The Preparatory Commission for the Comprehensive Nuclear-Test-Ban Treaty Organization related that "the National Resources Defense Council estimated the total yield of all nuclear tests between 1945 and 1980 at 510 megatons (Mt). Atmosphere tests alone accounted for 428 Mt, equivalent to over 29,000 Hiroshima size bombs" [8].

Table 1 presents an estimate of the total activity release of important radionuclides from the tests in the atmosphere.

Table 1 - Estimate of radionuclides released in the atmosphere during the nuclear tests

Radionuclide	Global dispersion (Bq)[a]	Annual limit on intake (Bq)[b]
^{3}H	1.9×10^{20}	3.0×10^{9}
^{14}C	2.1×10^{17}	8.0×10^{9}
^{90}Sr	6.2×10^{17}	8.0×10^{5}
^{95}Zr	1.5×10^{17}	1.0×10^{7}
^{106}Ru	1.2×10^{19}	3.0×10^{6}
^{125}Sb	7.4×10^{17}	9.0×10^{7}
^{131}I	6.8×10^{20}	2.0×10^{6}
^{137}Cs	9.5×10^{17}	6.0×10^{6}
^{140}Ba	7.6×10^{20}	5.0×10^{7}
^{144}Ce	3.1×10^{19}	9.0×10^{5}
^{239}Pu	6.5×10^{15}	5.0×10^{2}
^{240}Pu	4.4×10^{15}	5.0×10^{2}
^{241}Pu	1.4×10^{17}	2.0×10^{4}

a. Source: [9].

b. Indicative value of isotope radiotoxicity. Source: [10].

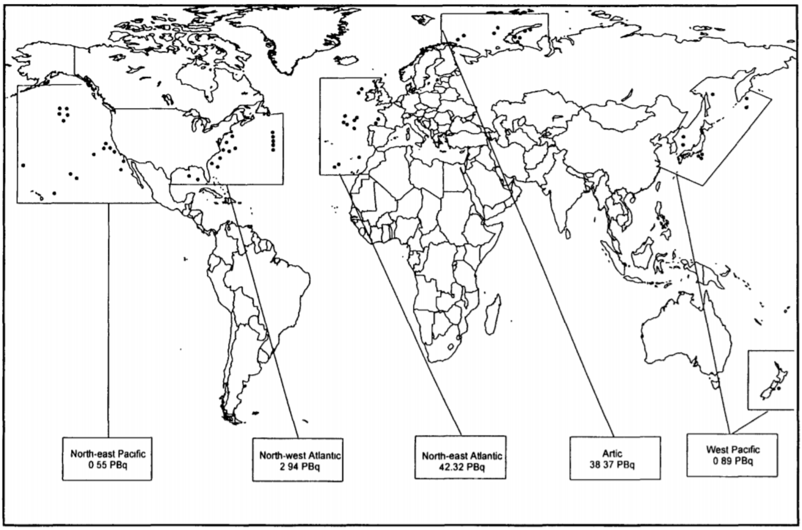
Dumping of Radioactive Waste at Sea

In 1946, the first sea disposal operation took place by the United States in the Northeast Pacific Ocean, about 80km off the coast of California. Such operations continued for the next 35 years, and included the disposal into the oceans of solid and liquid wastes, and nuclear reactor vessels with and without fuel. Most sea disposal operations were performed by many countries under national authority approval and, in many cases, under an international consultative mechanism, the Organization for Economic Co-operation and Development / Nuclear Energy Agency (OECD/NEA) [11].

In 1972, at the United Nations Conference on Human Environment, held in Stockholm, some principles for environmental protection were defined, and one of them addressed the development of General Principles for Assessment and Control of Marine Pollution. These were forwarded to the "Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter", held in London in the same year. The International Atomic Energy Agency (IAEA) was designated by the Contracting Parties as the competent international body in matters related to sea disposal of radioactive substances, regulating the suitability levels for dumping at sea.

These recommendations were established in 1974 and successively revised in 1978 and 1986, reflecting the increasing knowledge of relevant oceanographic behavior of radionuclides and improved assessment capabilities. The total prohibition of radioactive waste at sea came into force on February 20, 1994; nevertheless, almost every country had abandoned such practice more than 10 years earlier [11].

A global inventory of radioactive materials entering the marine environment from all sources began to be developed in 1988 by the IAEA and the Contracting Parties. In 1991 the International Agency released the report "Inventory of Radioactive Material Entering the Marine Environment: Sea Disposal of Radioactive Waste" [12]. Additional data were provided in the subsequent years by the former Soviet Union and the Russian Federation, as well as Sweden and the United Kingdom, therefore, in 1999, a revision was issued with the following estimates: “The first reported sea disposal operation of radioactive waste took place in 1946 and the latest in 1993. During the 48-year history of sea disposal, 14 countries have used more than 80 sites to dispose of approximately 85.0 PBq (2.3 MCi) of radioactive waste.” [11]. The locations where the wastes were dumped, as well as their activities, are presented in Figure 1.



Source: [11].

Figure 1 - Disposal at sea of radioactive waste worldwide.

The Chernobyl Nuclear Accident

On April 26, 1986, at 01:23AM local time, an accident occurred at the fourth unit of the Chernobyl nuclear power station, during an experimental test of the electrical control system as the reactor was being shut down for routine maintenance. The operators, in violation of safety regulations, switched off important control systems and allowed the reactor to reach unstable, low-power conditions. A sudden power surge caused a steam explosion that ruptured the reactor vessel, as well as part of the building in which the core was located. The radioactive nuclides released were carried away in the form of gases and smoke particles by air currents. This way, they were dispersed over the territory of the Soviet Union, over many other countries and, in trace amounts, throughout the northern hemisphere [13-14].

Severe radiation effects were almost immediately caused by this accident: 134 workers that were present on the site during that morning received high doses and suffered from radiation sickness; 28 of them died in the first three months, and another two soon afterwards. Moreover, in 1986 and 1987, around 200,000 recovery operation workers received doses between 0.01 and 0.5 Gy [6].

Table 2 below shows an estimate of the radionuclides released during the Chernobyl accident:

Table 2 - Current estimate of atmospheric releases during the Chernobyl accident

Radionuclide	Inventory (Bq)
^{90}Sr	3.3×10^{16}
^{103}Ru	6.5×10^{18}
^{106}Ru	2.4×10^{17}
^{140}Ba	$\sim 1.15 \times 10^{18}$
^{95}Zr	$\sim 1.76 \times 10^{18}$
^{99}Mo	2.5×10^{18}
^{141}Ce	$\sim 4.7 \times 10^{16}$
^{144}Ce	3.6×10^{16}
^{239}Np	$\sim 8.5 \times 10^{16}$
^{238}Pu	$\sim 1.15 \times 10^{17}$
^{239}Pu	$\sim 1.0 \times 10^{16}$
^{240}Pu	$>1.68 \times 10^{17}$
^{241}Pu	$>7.3 \times 10^{16}$
^{242}Cm	2.4×10^{17}

Source: [15].

The Fukushima Daiichi Accident

It was 02:46PM on March 11, 2011 when the biggest earthquake ever recorded in Japan began. Units 1, 2 and 3 of the Fukushima Daiichi Nuclear Power Plant were in operation; at the first sign of seismic activity, the emergency shut-down feature, or SCRAM, went into operation. The seismic tremors damaged the electricity facilities in town, resulting in a total loss of off-site electricity, so the emergency diesel generators went into operation to keep the vital systems working.

Fifty minutes later, a large tsunami wave of 14 meters height, caused by the earthquake, overwhelmed the plant's seawall (Figure 2) and totally destroyed the emergency diesel generators, resulting in loss of all power. With the back-up generators disabled, engineers were down to their final fail-safes for cooling the reactors: a heat-exchanging condenser and pressurized water-injection tanks. Both would only work for a few hours [16]. Next day on, there were hydrogen explosions at reactors 1, 2 and 3 caused by nuclear fuel rods experiencing extremely high temperatures, stripping the hydrogen out of the plant's steam [16-17].

Tokyo Electric Power Company estimates of releases to the ocean, over 26 March to 30 September, presented a total of about 11 PBq Iodine-131, 3.5 PBq Cs-134, 3.6 PBq Cs-137, with a total of 18.1 PBq apart from the atmospheric fallout. Relatively little radioactive material was released by the active venting of pressure inside the reactor vessels (routing steam through water and releasing it through the exhaust stacks) or by the hydrogen explosions [17]. The Technical Volume of IAEA on the Fukushima Daiichi accident presented the following estimate of atmospheric releases, on Table 3.

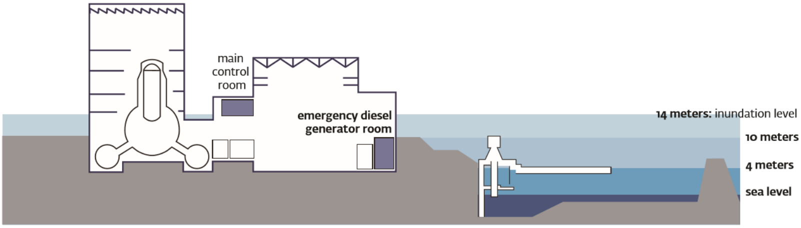
No harmful health effects were found in 195,345 residents living in the vicinity of the plant, who were screened by the end of May 2011. All the 1,080 children tested for thyroid gland

Table 3 - Current estimate of atmospheric releases during the Fukushima accident

Radionuclide	Inventory (Bq)
^{85}Kr	$6.4\text{-}32.6 \times 10^{15}$
^{133}Xe	$6.0\text{-}12.0 \times 10^{18}$
^{129m}Te	$3.3\text{-}12.2 \times 10^{15}$
^{132}Te	$0.8\text{-}162.0 \times 10^{15}$
^{131}I	$1.0\text{-}4.0 \times 10^{17}$
^{133}I	$0.7\text{-}300.0 \times 10^{15}$
^{134}Cs	$8.3\text{-}50.0 \times 10^{15}$
^{137}Cs	$7.0\text{-}20.0 \times 10^{15}$
^{89}Sr	$0.4\text{-}130.0 \times 10^{14}$
^{90}Sr	$0.3\text{-}1.4 \times 10^{14}$
^{103}Ru	$7.5\text{-}71.0 \times 10^{9}$
^{106}Ru	2.1×10^{9}
^{140}Ba	$1.1\text{-}20.0 \times 10^{15}$
^{95}Zr	1.7×10^{13}
^{99}Mo	8.8×10^{7}
^{141}Ce	1.8×10^{13}
^{144}Ce	1.1×10^{13}
^{239}Np	7.6×10^{13}
^{238}Pu	$2.4\text{-}19.0 \times 10^{9}$
^{239}Pu	$4.1\text{-}32.0 \times 10^{8}$
^{240}Pu	$5.1\text{-}32.0 \times 10^{8}$
^{241}Pu	$0.03\text{-}120.0 \times 10^{10}$
^{242}Cm	$1.0\text{-}10.0 \times 10^{10}$

Source: [18].

exposure presented results within safe limits, according to the report submitted to the IAEA in June. Anyway, while there was no major public exposure, let alone deaths from radiation, there were reportedly 761 victims of “disaster-related death”, especially old people uprooted from homes and hospital because of forced evacuation and other nuclear-related measures. The psychological trauma of evacuation was a bigger health risk for most than any likely exposure from early return to homes, according to some local authorities [19].



Source: [20].

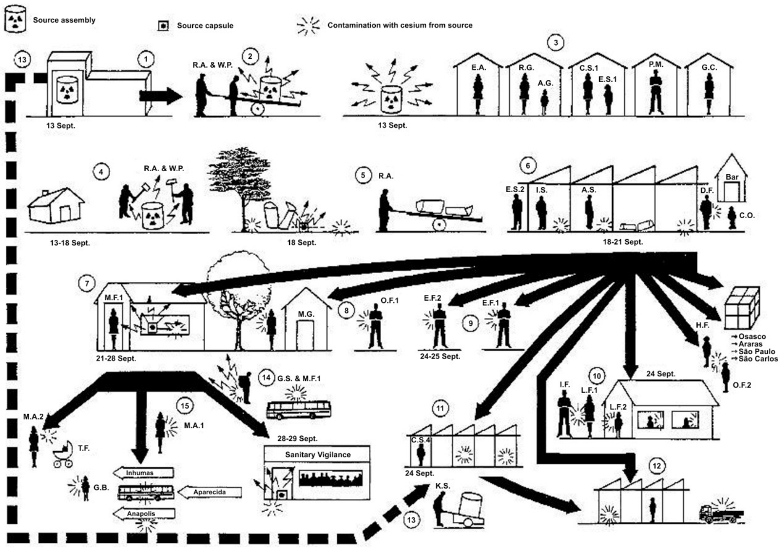
Figure 2 - Cross section of the Daiichi Fukushima plant showing the inundation level.

The Goiania Accident

The radioactive source that was in the teletherapy unit was in the form of cesium chloride salt, which is highly soluble and readily dispersible. In total, approximately 112,000 persons were monitored, of whom 249 were contaminated either internally or externally. Twenty persons were identified as needing hospital treatment; besides the medical treatment at the Marcilio Dias Naval Hospital in Rio de Janeiro to 14 of these persons, there were four casualties within four weeks of their admission to hospital [2].

The best estimate of the radioactivity accounted for in contamination is around 44 terabecquerels, compared with the known radioactivity of the cesium chloride source before the accident of 50.9 terabecquerels [2]. According to estimates of activities in the waste packages resulting from the response to the accident, around 10 percent of the radioactive source were never regained, and were dispersed in the environment [21]. Figure 3 presents a schematic diagram of dispersal of Cesium-137 in the city of Goiania and out of the state.

The dispersion of Cesium-137 in Goiania reached even the city of Sao Paulo, delivered in scrap metal and paper bales. Because they were contaminated, these materials were considered as radioactive waste; they were collected and are currently in the intermediate radioactive waste storage unit of the Nuclear and Energy Research Institute in Sao Paulo [21].



The diagram is based on a drawing made shortly after the discovery of the accident in attempting to reconstruct what had happened. Key: (1) the derelict clinic of the IGR; (2) removal of the rotating source assembly from an abandoned teletherapy machine by R.A. and W.P.; (3) source assembly placed in R.A.'s yard near houses rented out by R.A.'s mother E.A.; (4) R.A. and W.P. break up source wheel and puncture source capsule; (5) R.A. sells pieces of the source assembly to Junkyard I; (6) Junkyard I: the cesium chloride is fragmented and dispersed by I.S. and A.S. via public places; (7) D.F.'s house: contamination is further dispersed; (8) visitors and neighbors, e.g. O.F.1 are contaminated; (9) E.F.1 and E.F.2 contaminated; (10) I.F.'s house; other arrows indicate dispersion via visitors and contaminated scrap paper sent to other towns; (11) contamination is spread to Junkyard II; (12) contamination is spread to Junkyard III; (13) K.S. returns to the IGR clinic to remove the rest of the teletherapy machine to Junkyard II; (14) M.F.1 and G.S. take the source remnants by city bus to the Sanitary Vigilance; (15) contamination transferred to other towns by M.A.1.

Source: [22].

Figure 3 - Schematic diagram of the dispersal of Cesium-137 in Goiania.

Conclusions

The initial objective of this work, since the year 2017 marks 30 years since the radioactive accident that occurred in the city of Goiania, was the comparison between radiological and nuclear accidents and events. However, such objective turned out to be mostly unachievable: as shown, there are very large differences between a radiological accident and an accident in a nuclear power reactor, not only in terms of orders of magnitude, but also related to the variety of radioactive elements.

All these events released ^{137}Cs. However, the isotopic signature for the accident in Goiania was much simpler; it was a single isotope with a half-life of about 30 years. The nuclear accidents of Chernobyl and Fukushima, as well as the atmospheric releases of the nuclear bombs and the wastes dumped into the seas comprised more than a hundred different radionuclides.

The amount of contamination in Goiania was approximately 50.0×10^{12} Bq of Cesium-137, while in Fukushima the releases were between 7.0 and 20.0×10^{15} Bq, and around 8.5×10^{16} Bq in Chernobyl, of ^{137}Cs alone. Chernobyl accident released almost 2,000 times more Cesium-137 in the atmosphere, besides many other radioisotopes, than the cesium chloride spread in Goiania.

Despite the difficulty in comparing Fukushima Daiichi and the Chernobyl nuclear accidents, the Japanese Nuclear and Industrial Safety Agency estimated Fukushima as about one-tenth of the total activity released at Chernobyl [23].

In 1996, at the IAEA/WHO/EC International Conference in Vienna, the International Agency reported that "...the Chernobyl explosion put 400 times more radioactive material into the Earth's atmosphere than the atomic bomb dropped on Hiroshima; atomic weapons tests conducted in the 1950s and 1960s all together are estimated to have put some 100 to 1,000 times more radioactive material into the atmosphere than the Chernobyl accident” [24].

In the course of 48 years, approximately 85.0 PBq of radioactive waste were disposed in different parts of the sea throughout the planet. The Fukushima accident, conversely, released around 18.1 PBq of contaminated water in just a few months at the ocean east of Japan.

All in all, regarding human casualties, it has become clear that even a small quantity of a radioactive element, if gone astray, can become very dangerous and harmful. The safety culture has improved very much ever since; nevertheless, mankind has already been aware of the great hazards involved in an eventual lax management of nuclear technology, and has also acknowledged its great benefits in medicine, food control, energy production, and a number of other areas; the question whether to reduce its use until its extinction or to regain confidence from the public in general remains in the hands of the nuclear energy professionals.

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References

[1] W. Borges, Eu também sou vítima: a verdadeira história sobre o acidente com o césio em Goiânia, *Kelps,* Goiania, Brazil (2003).

[2] International Atomic Energy Agency (IAEA), Radiation sources: Lessons from Goiania, *International Atomic Energy Agency Bulletin*, 30(4), pp.10-17 (1988).

[3] A. L. L. Quadros, *Aprendizagem, inovação e comunicação: A Dinâmica Evolutiva de um Plano de Emergência Nuclear*,

PhD thesis at the Federal University of Rio de Janeiro, Rio de Janeiro, Brazil (2014).

[4] G. Silva, A (di)gestão do risco nuclear na França: o caso das Comissões Locais de Informação, *Mana*, 13(2), pp. 441-470 (2007).

[5] R. Prăvălie, Nuclear Weapons Tests and Environmental Consequences: A Global Perspective, *AMBIO*, 43(6), pp.729-744 (2014).

[6] United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), *Sources, Effects and Risks of Ionizing Radiation:* Report to the General Assembly, United Nations, New York City, USA (2000).

[7] P. Rubinson, Crucified on a Cross of Atoms: Scientists, Politics, and the Test Ban Treaty, *Diplomatic History,* 35(2), pp.283-319 (2011).

[8] *Nuclear Testing*. Retrieved from <https://www.ctbto.org/nuclear-testing/> (2010).

[9] *Information about source points of anthropogenic radioactivity* - Freedom of Nuclear Information Resource. Retrieved from <http://www.davistownmuseum.org/cbm/> (2008).

[10] Comissão Nacional de Energia Nuclear (CNEN), *Diretrizes Básicas de Radioproteção, CNEN-NE-3.01*, CNEN, Brasília, Brazil (1988).

[11] International Atomic Energy Agency (IAEA), *Inventory of Radioactive Waste Disposals at Sea*, IAEA, Vienna, Austria (1999).

[12] International Atomic Energy Agency (IAEA), *Inventory of Radioactive Material Entering the Marine Environment:* Sea Disposal of Radioactive Waste, IAEA, Vienna, Austria (1991).

[13] United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), *Sources, Effects and Risks of Ionizing Radiation*: Report to the General Assembly – Annex D: Exposures from the Chernobyl Accident, United Nations, New York City, USA (1988).

[14] Nuclear Energy Agency / Organisation for Economic Co-Operation and Development (NEA/OECD), Chernobyl: Assessment of Radiological and Health Impacts, *2002 Update of Chernobyl: Ten Years On*, OECD Publishing, Paris, France (2002).

[15] International Atomic Energy Agency (IAEA), Environmental Consequences of the Chernobyl Accident and their Remediation: Twenty Years of Experience, *Report of the UN Chernobyl Forum Expert Group "Environment"*, IAEA, Vienna, Austria (2006).

[16] J. Soble; M. Dickie, How Fukushima failed, *Financial Times Magazine,* May 06 (2011).

[17] *The Estimated Amount of Radioactive Materials Released into the Air and the Ocean Caused by Fukushima Daiichi Nuclear Power Station Accident Due to the Tohoku-Chihou-Taiheiyou-Oki Earthquake*. Retrieved from <https://www.tepco.co.jp/en/press/corp-com/release/2012/1204659_1870.html> (2012).

[18] International Atomic Energy Agency (IAEA), *The Fukushima Daiichi Accident*, IAEA, Vienna, Austria (2015).

[19] *Fukushima: Radiation Exposure*. Retrieved from <http://www.world-nuclear.org/information-library/safety-and-security/safety-of-plants/appendices/fukushima-radiation-exposure.aspx> (2016).

[20] The National Diet of Japan, The Official Report of The Fukushima: Nuclear Accident Independent Investigation Commission, *The National Diet of Japan*, Tokyo, Japan (2012).

[21] R. Vicente, *personal communication*, Nuclear and Energy Research Institute, April 26 (2017).

[22] International Atomic Energy Agency (IAEA), *The Radiological Accident in Goiania*, IAEA, Vienna, Austria (1988).

[23] P. D. Mclaughlin; B. Jones; M. M. Maher, An update on radioactive release and exposures after the Fukushima Dai-ichi nuclear disaster, *The British Journal of Radiology*, 85(1017), pp.1222–1225 (2012).

[24] International Atomic Energy Agency (IAEA), *Ten years after Chernobyl: What do we really know?*, IAEA, Vienna, Austria (1996).

30 YEARS OF THE GOIANIA ACCIDENT: A COMPARATIVE STUDY WITH OTHER RADIOACTIVITY DISPERSION EVENTS

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1. INTRODUCTION

The year 2017 marks **30 years** since the **radioactive accident** that occurred in the city of **Goiania**, Brazil. Two scavengers found a radiotherapy equipment abandoned in a derelict clinic, and accidentally opened a sealed source with **Cesium-137**. This was **the largest radiological accident in Brazil**, and one of the largest in the world in terms of the number of victims of acute radiation syndrome [1]. But after all, what was this quantitatively? And the nuclear accidents of the **Chernobyl** plants in Ukraine in 1986 and **Fukushima** in Japan in 2011, the most serious accidents ever to occur in the nuclear power industry, is there any possible comparison between these accidents and the one in Goiania?

Also, the dispersion of radionuclides into the atmosphere resulting from a number of **nuclear tests** from 1945 to 1963 reached levels that led authorities to ban these tests because of **risk of fatally damaging life on the planet**. At the same time, some of the **radioactive waste** generated by the nuclear industry had been placed in drums and then **dumped at sea** since 1946 until 1994.

Anyway, **how much radiation has been dispersed** in all these events? How much the environment has been damaged, as well as the human being?

2. RADIATION IN THE ATMOSPHERE RESULTING FROM NUCLEAR TESTS

The United States and the USSR performed, **between 1945 and 1963**, a total of **437 nuclear tests in the atmosphere**. According to the report released by the United Nations Scientific Committee on the Effects of Atomic Radiation, "**the main man-made contribution to the exposure of the world's population has come from the testing of nuclear weapons in the atmosphere**... each nuclear test resulted in unrestrained release into the environment of substantial quantities of radioactive materials, which were widely dispersed in the atmosphere and deposited everywhere on the Earth's surface" [2].

The Preparatory Commission for the Comprehensive Nuclear-Test-Ban Treaty Organization related that "the National Resources Defense Council estimated the total yield of all nuclear tests between 1945 and 1980 at 510 megatons (Mt). **Atmosphere tests alone accounted for 428 Mt, equivalent to over 29,000 Hiroshima size bombs**"[3]. Table 1 presents an estimate of the total activity release of important radionuclides from the tests in the atmosphere.

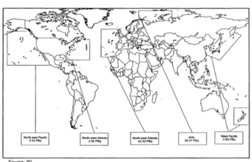
Table 1: Estimate of radionuclides released in the atmosphere during the nuclear tests

Radionuclide	Global dispersion (Bq)[a]	Annual limit on intake (Bq)[b]
^{3}H	1.9×10^{20}	3.0×10^{9}
^{14}C	2.1×10^{17}	8.0×10^{9}
^{90}Sr	6.2×10^{17}	8.0×10^{5}
^{95}Zr	1.5×10^{17}	1.0×10^{7}
^{106}Ru	1.2×10^{19}	3.0×10^{6}
^{125}Sb	7.4×10^{17}	9.0×10^{7}
^{131}I	6.8×10^{20}	2.0×10^{6}
^{137}Cs	9.5×10^{17}	6.0×10^{6}
^{140}Ba	7.6×10^{20}	5.0×10^{7}
^{144}Ce	3.1×10^{19}	9.0×10^{5}
^{239}Pu	6.5×10^{15}	5.0×10^{2}
^{240}Pu	4.4×10^{15}	5.0×10^{2}
^{241}Pu	1.4×10^{17}	2.0×10^{4}

a. Source: [4].
b. Indicative value of isotope radiotoxicity. Source: [5].

3. DUMPING OF RADIOACTIVE WASTE AT SEA

From 1946 to 1993, solid and liquid radioactive wastes were dumped into the sea. In 1999, the IAEA issued a global inventory with the following estimates: "...During the 48 year history of sea disposal, 14 countries have used more than 80 sites to dispose of **approximately 85.0 PBq** (10^{15} Bq) **of radioactive waste**." [6]. The locations where the wastes were dumped, as well as their activities, are presented in Figure 1.



Source: [6].

Figure 1: Disposal at sea of radioactive waste worldwide.

4. THE CHERNOBYL NUCLEAR ACCIDENT

On April 26, 1986, at 01:23AM local time, an **accident** occurred at the fourth unit of the **Chernobyl nuclear power station**. A sudden power surge caused a steam explosion that ruptured the reactor vessel and part of the building. **The radioactive nuclides released were carried away** in the form of gases and smoke particles by air currents, **over the Soviet Union** and **throughout the northern hemisphere** [7].

Severe radiation effects were almost immediately caused by this accident: **134 workers** that were present on the site during that **morning received high doses** and suffered from radiation sickness; **28 of them died in the first three months**, and other two soon afterwards. Moreover, in 1986 and 1987, **around 200,000 recovery operation workers received doses between 0.01 and 0.5 Gy** [2].

Table 2 shows an estimate of the radionuclides released during the Chernobyl and the Fukushima accidents.

Table 2: Current estimate of atmospheric releases during the Chernobyl and the Fukushima accidents

Radionuclide	Chernobyl Inventory (Bq)[a]	Fukushima Inventory (Bq)[b]
^{85}Kr	N/A	$6.4\text{-}32.6 \times 10^{15}$
^{133}Xe	N/A	$6.0\text{-}12.0 \times 10^{18}$
^{129m}Te	N/A	$3.3\text{-}12.2 \times 10^{15}$
^{132}Te	N/A	$0.8\text{-}162.0 \times 10^{15}$
^{131}I	N/A	$1.0\text{-}4.0 \times 10^{17}$
^{133}I	N/A	$0.7\text{-}300.0 \times 10^{15}$
^{134}Cs	N/A	$8.3\text{-}50.0 \times 10^{15}$
^{137}Cs	8.5×10^{16}	$7.0\text{-}20.0 \times 10^{15}$
^{89}Sr	N/A	$0.4\text{-}130.0 \times 10^{14}$
^{90}Sr	3.3×10^{16}	$0.3\text{-}1.4 \times 10^{14}$
^{103}Ru	6.5×10^{18}	$7.5\text{-}71.0 \times 10^{9}$
^{106}Ru	2.4×10^{17}	2.1×10^{9}
^{140}Ba	$\sim 1.15 \times 10^{18}$	$1.1\text{-}20.0 \times 10^{15}$
^{95}Zr	$\sim 1.76 \times 10^{18}$	1.7×10^{13}
^{99}Mo	2.5×10^{18}	8.8×10^{7}
^{141}Ce	$\sim 4.7 \times 10^{16}$	1.8×10^{13}
^{144}Ce	3.6×10^{16}	1.1×10^{13}
^{239}Np	$\sim 8.5 \times 10^{16}$	7.6×10^{13}
^{238}Pu	$\sim 1.15 \times 10^{17}$	$2.4\text{-}19.0 \times 10^{9}$
^{239}Pu	$\sim 1.0 \times 10^{16}$	$4.1\text{-}32.0 \times 10^{8}$
^{240}Pu	$>1.68 \times 10^{17}$	$5.1\text{-}32.0 \times 10^{8}$
^{241}Pu	$>7.3 \times 10^{16}$	$0.03\text{-}120.0 \times 10^{10}$
^{242}Cm	2.4×10^{17}	$1.0\text{-}10.0 \times 10^{10}$

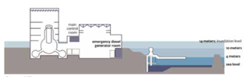
a. Source: [8].
b. Source: [10].
N/A: Not Available.

5. THE FUKUSHIMA DAIICHI ACCIDENT

It was 02:46PM on March 11, 2011 when **the biggest earthquake** ever recorded in Japan began. Fifty minutes later, **a large tsunami wave of 14 meters height**, caused by the earthquake, overwhelmed the **Fukushima Daiichi Nuclear Power Plant**'s seawall (Figure 2), resulting in **loss of all power**. There were hydrogen explosions at reactors 1, 2 and 3 caused by nuclear fuel rods experiencing extremely high temperatures, stripping the hydrogen out of the plant's steam [9].

Tokyo Electric Power Company estimates of releases to the ocean, over 26 March to 30 September, presented a total of about **11 PBq I-131, 3.5 PBq Cs-134, 3.6 PBq Cs-137, with a total of 18.1 PBq** [9] apart from the atmospheric fallout, shown on Table 2.

No harmful health effects were found in 195,345 residents living in the vicinity of the plant. Anyway, there were reportedly 761 victims of "disaster-related death", especially old people uprooted from homes and hospital because of forced evacuation and other nuclear-related measures. **The psychological trauma of evacuation was a bigger health risk** for most than any likely exposure [11].



Source: [12].

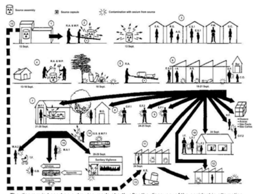
Figure 2: Cross section of the Daiichi Fukushima plant showing the inundation level.

6. THE GOIANIA ACCIDENT

In total, **approximately 112,000 persons were monitored**, of whom 249 were contaminated either internally or externally. Twenty persons were identified as needing hospital treatment; besides the medical treatment at the Marcilio Dias Naval Hospital in Rio de Janeiro to 14 of these persons, **there were four casualties** within four weeks of their admission to hospital [1].

The best estimate of the radioactivity accounted for in contamination is around **44 TBq**, compared with the known radioactivity of the cesium chloride source before the accident of **50.9 TBq** [1]. **Around 10 percent of the radioactive source were never regained**, and was dispersed in the environment [13]. Figure 3 presents a schematic diagram of dispersal of Cesium-137 in the city of Goiania and out of the state.

The **dispersion of Cesium-137 in Goiania reached the city of Sao Paulo**, delivered in scrap metal and paper bales. They were collected and are currently in the intermediate radioactive waste storage unit of the Nuclear and Energy Research Institute in Sao Paulo [13].



The diagram is based on a drawing made shortly after the discovery of the accident in attempting to reconstruct what had happened. Key: (1) the derelict clinic of the IGR; (2) removal of the rotating source assembly from an abandoned teletherapy machine by R.A. and W.P.; (3) source assembly placed in R.A.'s yard near houses rented out by R.A.'s mother E.A.; (4) R.A. and W.P. break up source wheel and puncture source capsule; (5) R.A. sells pieces of the source assembly to Junkyard I; (6) Junkyard I: the cesium chloride is fragmented and dispersed by I.S. and A.S. via public places; (7) D.F.'s house: contamination is further dispersed; (8) visitors and neighbors, e.g. O.F.1 are contaminated; (9) E.F.1 and E.F.2 contaminated; (10) I.F.'s house; other arrows indicate dispersion via visitors and contaminated scrap paper sent to other towns; (11) contamination is spread to Junkyard II; (12) contamination is spread to Junkyard III; (13) K.S. returns to the IGR clinic to remove the rest of the teletherapy machine to Junkyard II; (14) M.F.1 and G.S. take the source remnants by city bus to the Sanitary Vigilance; (15) contamination transferred to other towns by M.A.1.
Source: [14].

Figure 3: Schematic diagram of the dispersal of Cesium-137 in Goiania.

7. CONCLUSIONS

The initial objective of this work was **the comparison between radiological and nuclear accidents and events**. However, such objective turned out to be **mostly unachievable**: as shown, there are **very large differences between a radiological accident and an accident in a nuclear power reactor**, not only in terms of orders of **magnitude**, but also related to the **variety of radioactive elements**.

All these events released ^{137}Cs. However, the isotopic signature for the accident in Goiania was much simpler; it was **a single isotope**. The nuclear accidents of Chernobyl and Fukushima, as well as the atmospheric releases of the nuclear bombs and the wastes dumped into the seas comprised **more than a hundred different radionuclides**.

The amount of **contamination in Goiania** was approximately **50.0 x 10^{12} Bq of Cesium-137**, while in **Fukushima** the releases were **between 7.0 and 20.0 x 10^{15} Bq**, and around **8.5 x 10^{16} Bq** in **Chernobyl**, of ^{137}Cs alone. **Chernobyl accident released almost 2,000 times more Cesium-137 in the atmosphere**, besides many other radioisotopes, **than the cesium chloride spread in Goiania**.

Despite the difficulty in comparing Fukushima Daiichi and the Chernobyl nuclear accidents, the Japanese Nuclear and Industrial Safety Agency estimated **Fukushima** as about **one-tenth** of the total activity released at **Chernobyl** [15].

in 1996, at the IAEA/WHO/EC International Conference in Vienna, the International Agency reported that "...**the Chernobyl explosion put 400 times more radioactive material** into the Earth's atmosphere **than the atomic bomb dropped on Hiroshima**; **atomic weapons tests** conducted in the 1950s and 1960s all together are estimated to have put some **100 to 1,000 times more radioactive material** into the atmosphere **than the Chernobyl accident**" [16].

In the course of **48 years**, approximately **85.0 PBq** of radioactive waste were **dumped at sea** throughout the planet. The **Fukushima** accident, conversely, released around **18.1 PBq** of contaminated water in just **a few months at the ocean east of Japan**.

All in all, regarding human casualties, it has become clear that even a small quantity of a radioactive element, if gone astray, can become very dangerous and harmful. Safety culture has improved very much ever since; nevertheless, mankind has already been aware of the great hazards involved in an eventual lax management of nuclear technology, and has also acknowledged its great benefits in medicine, food control, energy production, and a number of other areas; the question whether to reduce its use until its extinction or to regain confidence from the public in general remains in the hands of the nuclear energy professionals.

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REFERENCES

1. V International Atomic Energy Agency (IAEA), "Radiation sources: Lessons from Goiania", *International Atomic Energy Agency Bulletin*, **30(4)**, pp.10-17 (1988).
2. United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), *Sources, Effects and Risks of Ionizing Radiation: Report to the General Assembly*, United Nations, New York City, USA (2000).
3. "Nuclear Testing", https://www.ctbto.org/nuclear-testing/ (2010).
4. "Information about source points of anthropogenic radioactivity - Freedom of Nuclear Information Resource", http://www.davistownmuseum.org/cbm/ (2008).
5. Comissão Nacional de Energia Nuclear (CNEN), *Diretrizes Básicas de Radioproteção, CNEN-NE-3.01*, CNEN, Brasília, Brazil (1988).
6. International Atomic Energy Agency (IAEA), *Inventory of Radioactive Waste Disposals at Sea*, IAEA, Vienna, Austria (1999).
7. United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), *Sources, Effects and Risks of Ionizing Radiation: Report to the General Assembly – Annex D: Exposures from the Chernobyl Accident*, United Nations, New York City, USA (1988).
8. International Atomic Energy Agency (IAEA), *Environmental Consequences of the Chernobyl Accident and their Remediation: Twenty Years of Experience, Report of the UN Chernobyl Forum Expert Group "Environment"*, IAEA, Vienna, Austria (2006).
9. "The Estimated Amount of Radioactive Materials Released into the Air and the Ocean Caused by Fukushima Daiichi Nuclear Power Station Accident Due to the Tohoku-Chihou-Taiheiyou-Oki Earthquake", http://rss.tepco.co.jp/en/press/corp-com/release/2012/1204659_1870.html (2012).
10. International Atomic Energy Agency (IAEA), *The Fukushima Daiichi Accident*, IAEA, Vienna, Austria (2015).
11. "Fukushima: Radiation Exposure", http://www.world-nuclear.org/information-library/safety-and-security/safety-of-plants/appendices/fukushima-radiation-exposure.aspx (2016).
12. The National Diet of Japan, *The Official Report of The Fukushima: Nuclear Accident Independent Investigation Commission*, The National Diet of Japan, Tokyo, Japan (2012).
13. R. Vicente, *personal communication*, Nuclear and Energy Research Institute, April 26 (2017).
14. International Atomic Energy Agency (IAEA), *The Radiological Accident in Goiania*, IAEA, Vienna, Austria (1988).
15. P. D. Mclaughlin; B. Jones; M. M. Maher, "An update on radioactive release and exposures after the Fukushima Dai-ichi nuclear disaster", *The British Journal of Radiology*, **85(1017)**, pp.1222–1225 (2012).
16. International Atomic Energy Agency (IAEA), *Ten years after Chernobyl: What do we really know?*, IAEA, Vienna, Austria (1996).