Essays on Nuclear Energy & Radioactive Waste Management

Ricardo Bastos Smith
(Org.)

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Introduction

The difficulty in utilizing nuclear energy mostly stems from the absence of information, which generates a cognitive dissonance in the population regarding such energy: even though it is one of the areas of greatest control and verification, when talking about nuclear energy, the first image that comes to the mind of many is that of the bomb; it is as if the ubiquitous electrical energy was rejected for being firstly introduced through the electric chair!

Therefore, it is necessary to bring up the topic of nuclear energy in order to gather it closer to common knowledge. This book can make this contribution.

In this perspective, some works previously presented and published in Annals of scientific events and magazines were collected here in this book, with the intention of being an instrument of explanation and dissemination about some basic points of nuclear energy, which is an advanced alternative that is already present in people's lives.

These studies were presented at congresses in Brazil and the United States from 2017 to 2019, prepared during the Postgraduate Course at the Master's level in Nuclear Technology at the Radioactive Waste Management Service of the Nuclear and Energy Research Institute (IPEN-CNEN/SP) in the city of São Paulo, Brazil. During the referred period of studies, I had the guidance of Prof. Roberto Vicente, PhD., who supervised my studies developed with other fellow researchers at IPEN, as well as those carried out in partnership with researchers from other Brazilian institutions and abroad.

Essays are presented with information on the main nuclear accidents, Chernobyl and Fukushima, on the biggest radiological accident in Brazil, in the city of Goiânia, and also on the radioactive waste from Goiânia that were brought to the city of São Paulo. There are also chapters on Knowledge Management regarding facilities that should have been decommissioned at IPEN over 30 years ago, on the fuel used in satellites sent to outer space, on radiation in beer and food in general, and about India's latest thorium-powered nuclear power reactor, in its final design phase, which benefits are discussed in comparison with the 12 Principles of Green Chemistry, along with the attempt in the last century to develop a similar reactor in Brazil. Last but not least, the book also presents the project work and the article resulting from my Master's thesis.

Nuclear energy sources, in their most diverse uses, demand responsibility from the people who produce and use them; it is up to all of us to learn more about them in order to better decide how to use them in the present and in the future.

Enjoy your reading!

Ricardo Bastos Smith
Organizer

Introdução

A dificuldade na utilização da energia nuclear decorre principalmente da falta de informação, que gera uma dissonância cognitiva da população com relação a ela: mesmo sendo uma das áreas de maior controle e verificação, ao se falar em energia nuclear, a primeira imagem a ela associada na mente das pessoas é a da bomba; é como se a onipresente energia elétrica fosse rejeitada por ter sido inicialmente apresentada por meio da cadeira elétrica!

É necessário, portanto, trazer à discussão o tema da energia nuclear e torná-la mais próxima do conhecimento corrente. O presente livro pode oferecer esta contribuição.

Nesta perspectiva, foram reunidos aqui neste livro alguns estudos apresentados e publicados anteriormente em Anais de eventos científicos e revistas, com a intenção de serem um instrumento de explanação e divulgação sobre alguns pontos básicos da energia nuclear, que é uma alternativa avançada e já presente nas vidas das pessoas.

Estes estudos foram apresentados em congressos no Brasil e nos Estados Unidos no período de 2017 a 2019, preparados durante o Curso de Pós-Graduação em nível de Mestrado em Tecnologia Nuclear no Serviço de Gestão de Rejeitos Radioativos do Instituto de Pesquisas Energéticas e Nucleares (IPEN-CNEN/SP) na cidade de São Paulo, no Brasil. Durante o referido período de estudos, tive a orientação do Prof. Dr. Roberto Vicente, que acompanhou o meu trabalho desenvolvido com outros colegas pesquisadores do IPEN, bem como aqueles realizados em parceria com pesquisadores de outras instituições brasileiras e do estrangeiro.

Os capítulos presentes no livro são de pesquisas que mostram informações sobre os principais acidentes nucleares, Chernobyl e Fukushima, sobre o maior acidente radiológico no Brasil, em Goiânia, e ainda sobre os rejeitos radioativos de Goiânia que foram trazidos para a cidade de São Paulo. Há também capítulos sobre a gestão de conhecimento com relação a instalações a serem descomissionadas no IPEN há mais de 30 anos, sobre o combustível utilizado em satélites enviados para o espaço sideral, sobre a radiação na cerveja e em alimentos em geral, e também sobre o mais recente reator nuclear de energia da Índia movido a tório, em fase final de projeto, onde seus pontos positivos são discutidos em comparação com os 12 Princípios da Química Verde, e a tentativa no século passado de desenvolvimento de um reator semelhante no Brasil. Finalmente, o livro inclui também o trabalho de projeto e o artigo resultante da minha dissertação de Mestrado.

As fontes de energia nuclear, em seus mais diversos usos, demandam responsabilidade por parte das pessoas que as produzem e as utilizam; cabe a todos nós conhecermos cada vez mais sobre elas para melhor decidirmos como empregá-las no presente e no futuro.

Boa leitura!

Ricardo Bastos Smith
Organizador

Summary

- 1 -

Project Basis for Automation of a Quality Assurance System in Radioactive Waste Management[1]

Ricardo Bastos Smith
Roberto Vicente
Nuclear and Energy Research Institute - IPEN-CNEN/SP, Brazil

Abstract: A low- and intermediate-level radioactive waste management facility is required to comply with Regulation 1.16 of the Brazilian National Nuclear Energy Commission “Quality Assurance for the Safety of Nuclear Power Plants and Other Facilities”. However, the text of this regulation is very generic and does not address the more specific controls necessary for the management of quality. Therefore, the objective of this paper is to identify such detailed controls in all applicable activities of the facility and to provide an implementation plan in the form of flowcharts, for further development of an automated system. This work takes as a basis the recommendations of the International Atomic Energy Agency and the rules and procedures implemented by the U.S. Department of Energy’s Office of Civilian Waste Management related to Quality Assurance. In such way, we intend to provide a more reliable implementation system of quality assurance for management of radioactive waste in Brazil.

Keywords: radioactive waste; quality assurance; automated system.

Resumo: Uma instalação para gestão de rejeitos radioativos de níveis baixo e intermediário deve cumprir com o Regulamento 1.16 “Garantia de Qualidade para a Segurança de Usinas Nucleoelétricas e Outras Instalações”, da Comissão Nacional de Energia Nuclear. No entanto, o texto deste regulamento é bastante genérico e não aborda os controles mais específicos necessários para a gestão da qualidade. Portanto, o objetivo deste trabalho é identificar estes controles

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[1] Poster presented at the 2017 Waste Management Symposia (WMS) on March 05-09, 2017 in the city of Phoenix, AZ, United States. Available at <http://www.xcdsystem.com/wmsym/abstract/poster2017/PosterFile_17317_0316011818.pdf>.

detalhados em todas as atividades aplicáveis da instalação, e fornecer um plano de implementação na forma de fluxogramas, para posterior desenvolvimento de um sistema automatizado. Este trabalho tem como base as recomendações da Agência Internacional de Energia Atômica, e as regras e procedimentos implementados pela Agência de Gestão de Rejeitos Civis do Departamento de Energia dos EUA relacionados à Garantia de Qualidade. Dessa forma, pretendemos fornecer um sistema de implemenntação de garantia de qualidade mais confiável para a gestão de rejeitos radioativos no Brasil.

Palavras-chave: rejeito radioativo; garantia de qualidade; sistema automatizado.

Introduction

Brazil is currently planning to construct the Brazilian Multipurpose Reactor - RMB, a nuclear research reactor with power of 30MW [1] intended for the production of radioisotopes, nuclear and materials research, among other additional scopes of research. When in operation, the facility will generate radioactive waste that will be treated, and safely and securely stored on site until it may be disposed of in an appropriate facility for final disposition of radioactive waste yet to be sited and constructed in Brazil. This paper deals with the management of this waste (Figure 1).

The term “management” is to be understood as a set of operational and administrative activities related to handling, characterization, processing, transportation, and storage of waste [2]. The operations to be performed in the waste management processes that are common to all wastes, include: a) waste storage; b) sampling of different waste streams; c) radiochemical analysis of waste samples; d) radiometric measurements of waste packages; and e) transportation of waste packages. In addition, specific process operations for each waste type include: a) compaction of compactable solid

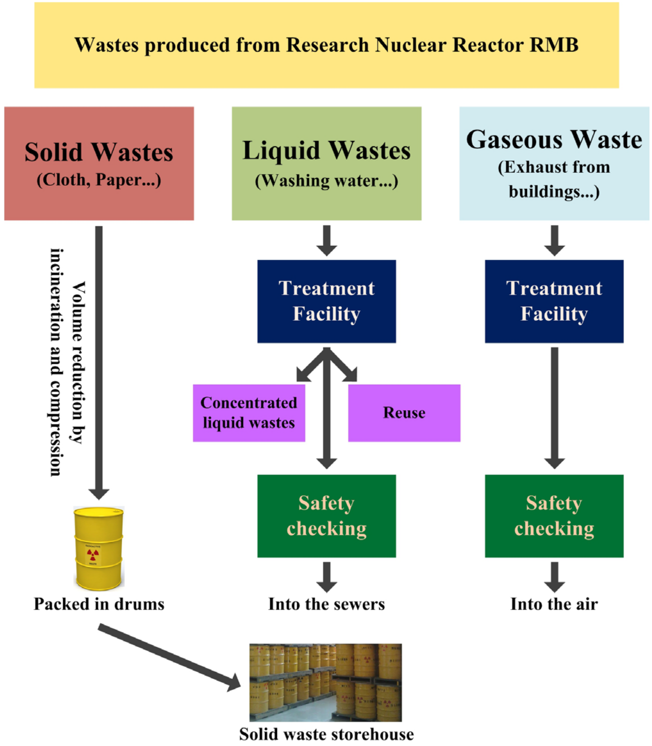

Figure 1 - Wastes produced by Research Nuclear Reactor RMB.

waste; b) fragmentation and encapsulation of non-compactable solid waste in cement grout; c) chemical preconditioning of liquid waste; d) volume reduction of wastewater by evaporation; and e) immobilization of liquid waste in cement.

In Brazil, the National Nuclear Energy Commission – CNEN is the agency responsible for controlling and regulating all processes related to nuclear energy. As a result, the design, construction, and operation of a low- and intermediate-level radioactive waste treatment facility must comply with the requirements of CNEN-NN-1.16 Regulation "Quality Assurance for Safety in Nuclear Power Plants and other Facilities". Furthermore, Brazil is one of the signatories of the Joint

Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management, sponsored by the International Atomic Energy Agency (IAEA), internalized in the national legal framework by Decree No. 5935 of October 19, 2006 [4]. Therefore, Brazil must comply with the provisions of Article 23 of the Convention, which states that "each Contracting Party shall take the necessary steps to ensure that appropriate quality assurance programs concerning the safety of spent fuel and radioactive waste management are established and implemented" [5].

One problem with the implementation of CNEN quality assurance regulation is that it applies to any type of nuclear facility, so it is quite generic and requires a more detailed set of actions needed to ensure compliance with applicable regulatory requirements – more specifically, the application of a quality assurance system in a radioactive waste treatment and storage facility.

Therefore, the objective of this study is to provide a list of actions in the form of flowcharts, for development of an automated system, which can assure compliance with the Brazilian Regulation. The recommendations of the IAEA Safety Standards and Technical Reports [7-15], as well as the rules of the U.S. Department of Energy (DOE) "Quality Assurance Requirements and Description, rev.21" from the Office of Civilian Radioactive Waste Management (OCRWM) [6] were used as guides for detailing the actions required. In this way, we intend to provide suggestions for a more efficient quality assurance system for the management of radioactive waste in Brazil.

Methods

The main effort in developing the management tool is to identify and detail each of the processes that will be controlled by the system, setting the input data, the unit operations of each process, output data and control points of the process, the types of reports, and other system components, focusing particular attention to the Items Important to Safety (IIS). The primary source of information is the experience of the Working Group at the Radioactive Waste Management Department (SEGRR) of the Nuclear and Energy Research Institute - IPEN / São Paulo, Brazil. The descriptions of the items were detailed enough in order to enable the preparation of a set of unit operations that together will perform the control actions required by the system.

The result of this detailing process is translated into algorithms, represented by process flowcharts. These algorithms describe the unit operations performed in the waste management facility. The operations included in the scope of this work are those necessary to control and register the Quality Assurance actions, in order to demonstrate that the regulatory requirements were met.

The IAEA recommendations [7-15] and the items of the DOE OCRWM quality assurance document [6] were analyzed and the requirements set out in those documents were correlated with the CNEN-NN-1.16 requirements. The correlation between the Brazilian regulation requirements and the requirements of those other documents is intended for detailing as much as possible the regulatory requirements. The CNEN-NN-1.16 document is by nature generic in the scope of the items that should be controlled and the actions for quality assurance. Nevertheless, this work respected the structure of the Brazilian regulation.

Every list of unit operations is associated with a logical flowchart that visually represents the processes, actions or events that start the processes, inputs and outputs, control points (logical errors), the databases required by the system, etc. The consistency between the various process-flow diagrams were checked before accomplishing the work.

Results

The requirements of CNEN NN-1.16 regulation may be divided into the following twelve categories:

1. Document Control
2. Design Control
3. Procurement Control
4. Control of Materials
5. Control of Processes
6. Inspection and Test Control
7. Control of Nonconforming Items
8. Corrective Actions
9. Quality Assurance Records
10. Audits
11. Systems and Quality Assurance Programs
12. Organization

For illustrative purposes, the steps to carry out the quality assurance actions for one sub-item of the item "2. Design control", above, have been chosen and are presented below. This item corresponds to the Section 4.5 – 'Design Control' of the CNEN regulation, and can be presented, in a free translation, as:

"*4.5 DESIGN CONTROL*
4.5.1 General Requirements
4.5.1.1 - design control policies should be established and documented to ensure that the applicable design requirements, such as design bases, CNEN standards and requirements, are properly incorporated in the specifications, computer design codes, drawings, procedures or instructions. "[3]

When analyzing the literature [6, 8], the set of detailed actions needed to be included in the computerized quality assurance system, in order to allow verification and change evaluation of design decisions, with reference to the "design bases" of the subsection 4.5.1.1, should become the following:

"*4.5.1.1 – (a) Control of Design Input Data*

A. Identification, documentation and approval of design input data.
B. Previous qualification of data resulting from scientific investigation.
C. Identification and tracking of unqualified data until they are qualified.
D. Justification, documentation, control and approval of design changes.
E. Identification and tracking of data based on assumptions until they are confirmed".

Subsequently, the unit operations for controlling the "design input data" are translated into the following set of procedures:

"Access to the 'design input data' page"
System page: "Design Input Data"
- User name (designer), date and time of access;

1. Choose a "structure" from the list, or enter a new one;
    - Inbox "Structure" to select from the list of structures already included in the database, and a button "Add Structure" that opens a blank text box, for inclusion of new item; the same structure is repeated for:
    - Inbox "Component";
    - Inbox "Element";
    - Inbox "Value";
    - Inbox "References";

After completion of the input of data, the system asks the data status:

- Inbox "Provisional" (Y or N);

Then the system exhibits a text box with the list of newly added values;

2. Click "Save." The system checks whether there is any blank field. If so, it displays the message "Blank fields are not allowed"; if not, it displays the message "Do you want to include more references?". If Yes, the system saves in Input Data Table, clears "References" and "Provisional?" fields, copies data "Structure", "Component", "Element" and "Value" from the newly recorded item and returns to the starting point;
3. If not, it saves data in Input Data Table, displays message "Do you want to include more elements?". If Yes, saves in Input Data Table, clears "Element", "References" and "Provisional?" fields. Copies data "Structure", "component" from the newly recorded item; returns to the starting point;
4. The same routine is repeated for components and structures. A click on "Exit" shuts down the system.

Design Input Data Table fields:

- Structure number;
- Login;
- Access number;
- Structure;
- Component;
- Element;
- Value;
- Reference;
- Provisional? (Y/N).

Each Structure Number has only one Login; only one Access Number; only one Structure; each Structure has one or more Components; each Component has one or more Elements; each Element has only one value; each Value has one or more References; each reference has an Y or N if provisional. Each Structure Number has an Y or N if it is the latest version.

The system sends a notification to the person identified in the system as the 'Reviewer'; a new sequence of unit operations is initiated with the reviewer accessing the system page "Input Data Review", and ends it with the reviewer 'accepting' the values entered into the system by the designer. Reviewer's unaccepted data prompt the system to notify the designer. The 'approval' by the person identified as the one who approves the input data ends the last sequence of operations. These three sequences are required to comply with requirement "A" in the subsection 4.5.1.1(A) above: "Identification, documentation and approval of design input data".

Finally, this list of operations is translated into a process flowchart which facilitates consistency checking, e.g., if the decision points - the logical deviations represented by diamonds in the following figure - or if the data inputs and outputs are properly displayed (Figure 2).

Conclusion

This paper was developed basically as a suggestion for guidance to fulfill the regulatory requirements specified in the National regulation related to Radioactive Waste Management. Extensive research was performed and over 150 pages were written with descriptions and flowcharts needed to implement the twelve regulatory requirements specified in CNEN-NN-1.16 [16]. All of the requirements were reviewed and detailed, and many of the more specific requirements related to radioactive waste management were included. Thirty-four flowcharts give a stepwise procedure to assure that the design, construction and operation of a radioactive waste management facility comply with the requirements of a robust quality assurance system.

Quality assurance is a continuous improvement process, and the professionals involved in the area need to be aware of

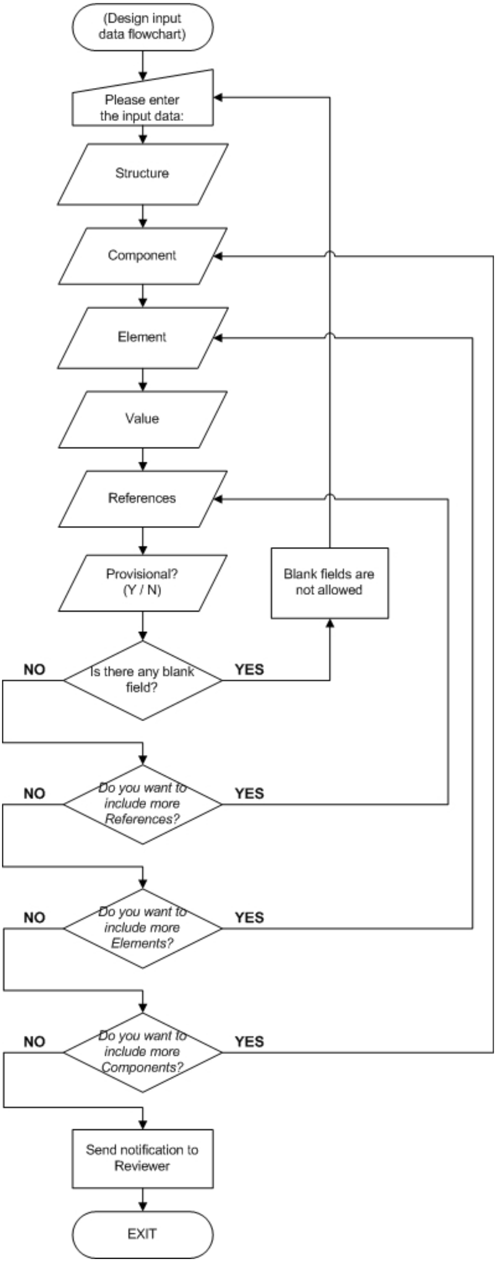

Figure 2 – Design Input Data Flowchart.

the current specifications, best practices, and all a variety of situations in order to better perform their jobs; after all, there is no assurance without knowledge. The idea of presenting different approaches on the same procedures may provide a better understanding toward the improvement of regulations. The optimization of quality assurance, allied to the clearness and organization of procedures and control requirements, will ultimately demonstrate that an organization is actually able to deploy nuclear resources safely and efficiently.

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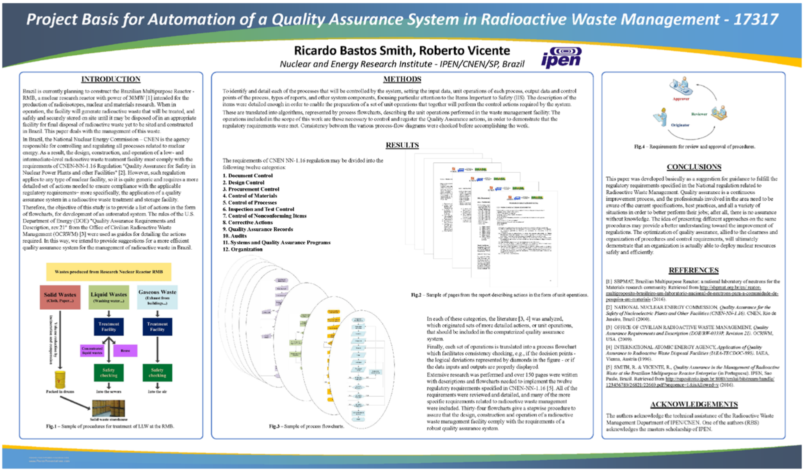

Project Basis for Automation of a Quality Assurance System in Radioactive Waste Management - 17317

Ricardo Bastos Smith, Roberto Vicente

Nuclear and Energy Research Institute - IPEN/CNEN/SP, Brazil

INTRODUCTION

Brazil is currently planning to construct the Brazilian Multipurpose Reactor - RMB, a nuclear research reactor with power of 30MW [1] intended for the production of radioisotopes, nuclear and materials research. When in operation, the facility will generate radioactive waste that will be treated, and safely and securely stored on site until it may be disposed of in an appropriate facility for final disposal of radioactive waste yet to be sited and constructed in Brazil. This paper deals with the management of this waste.

In Brazil, the National Nuclear Energy Commission – CNEN is the agency responsible for controlling and regulating all processes related to nuclear energy. As a result, the design, construction, and operation of a low- and intermediate-level radioactive waste treatment facility must comply with the requirements of CNEN-NN-1.16 Regulation "Quality Assurance for Safety in Nuclear Power Plants and other Facilities" [2]. However, such regulation applies to any type of nuclear facility, so it is quite generic and requires a more detailed set of actions needed to ensure compliance with the applicable regulatory requirements– more specifically, the application of a quality assurance system in a radioactive waste treatment and storage facility.

Therefore, the objective of this study is to provide a list of actions in the form of flowcharts, for development of an automated system. The rules of the U.S. Department of Energy (DOE) "Quality Assurance Requirements and Description, rev.21" from the Office of Civilian Radioactive Waste Management (OCRWM) [3] were used as guides for detailing the actions required. In this way, we intend to provide suggestions for a more efficient quality assurance system for the management of radioactive waste in Brazil.

Fig.1 – Sample of procedures for treatment of LLW at the RMB.

METHODS

To identify and detail each of the processes that will be controlled by the system, setting the input data, unit operations of each process, output data and control points of the process, types of reports, and other system components, focusing particular attention to the Items Important to Safety (IIS). The description of the items were detailed enough in order to enable the preparation of a set of unit operations that together will perform the control actions required by the system.

These are translated into algorithms, represented by process flowcharts, describing the unit operations performed in the waste management facility. The operations included in the scope of this work are those necessary to control and register the Quality Assurance actions, in order to demonstrate that the regulatory requirements were met. Consistency between the various process-flow diagrams were checked before accomplishing the work.

RESULTS

The requirements of CNEN NN-1.16 regulation may be divided into the following twelve categories:

1. **Document Control**
2. **Design Control**
3. **Procurement Control**
4. **Control of Materials**
5. **Control of Processes**
6. **Inspection and Test Control**
7. **Control of Nonconforming Items**
8. **Corrective Actions**
9. **Quality Assurance Records**
10. **Audits**
11. **Systems and Quality Assurance Programs**
12. **Organization**

Fig.2 – Sample of pages from the report describing actions in the form of unit operations.

Fig.3 – Sample of process flowcharts.

In each of these categories, the literature [3, 4] was analyzed, which originated sets of more detailed actions, or unit operations, that should be included in the computerized quality assurance system.

Finally, each set of operations is translated into a process flowchart which facilitates consistency checking, e.g., if the decision points - the logical deviations represented by diamonds in the figure - or if the data inputs and outputs are properly displayed.

Extensive research was performed and over 150 pages were written with descriptions and flowcharts needed to implement the twelve regulatory requirements specified in CNEN-NN-1.16 [5]. All of the requirements were reviewed and detailed, and many of the more specific requirements related to radioactive waste management were included. Thirty-four flowcharts give a stepwise procedure to assure that the design, construction and operation of a radioactive waste management facility comply with the requirements of a robust quality assurance system.

Fig.4 – Requirements for review and approval of procedures.

CONCLUSIONS

This paper was developed basically as a suggestion for guidance to fulfill the regulatory requirements specified in the National regulation related to Radioactive Waste Management. Quality assurance is a continuous improvement process, and the professionals involved in the area need to be aware of the current specifications, best practices, and all a variety of situations in order to better perform their jobs; after all, there is no assurance without knowledge. The idea of presenting different approaches on the same procedures may provide a better understanding toward the improvement of regulations. The optimization of quality assurance, allied to the clearness and organization of procedures and control requirements, will ultimately demonstrate that an organization is actually able to deploy nuclear resources safely and efficiently.

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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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[2] Poster presented at the 2017 International Nuclear Atlantic Conference (INAC) on October 22-26, 2017 in the city of Belo Horizonte, MG, Brazil. Available at: <http://repositorio.ipen.br/handle/123456789/28324>.

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}
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^{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].

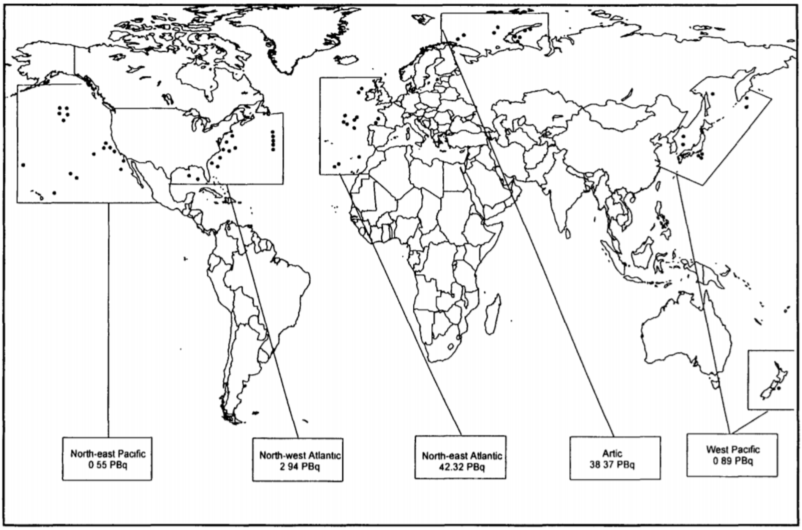
Dumping of Radioactive Waste at Sea

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.

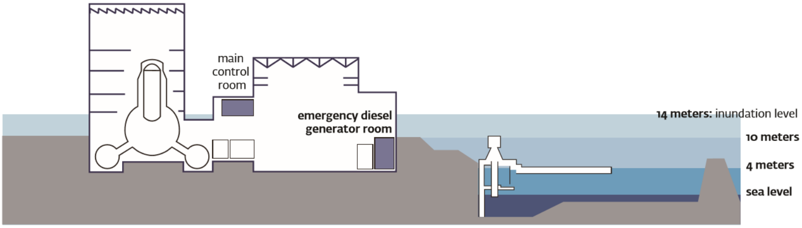
No harmful health effects were found in 195,345 residents living in the vicinity of the plant, who were screened by the end of May 2011. All the 1,080 children tested for thyroid gland

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].

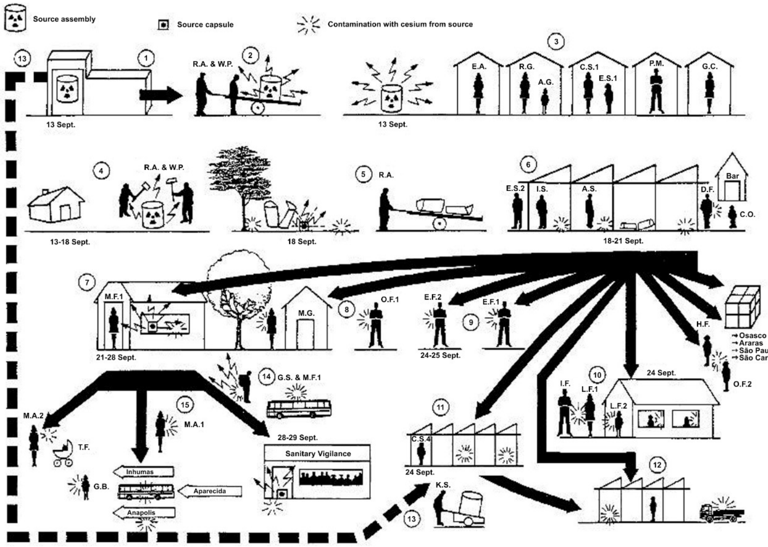
Figure 2 - Cross section of the Daiichi Fukushima plant showing the inundation level.

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 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 [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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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.

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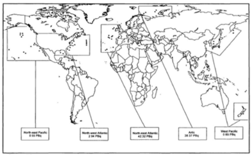
a. Source: [4].
b. Indicative value of isotope radiotoxicity. Source: [5].

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}	$1.0\text{-}10.0 \times 10^{10}$

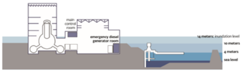
a. Source: [8].
b. Source: [10].
N/A: Not Available.

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].

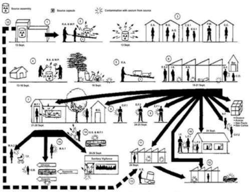
Figure 2: Cross section of the Daiichi Fukushima plant showing the inundation level.

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 **50.0×10^{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** [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.

ACKNOWLEDGEMENTS

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- 3 -

Opening the Goiânia Accident Unburied Waste Packages[3]

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Abstract: The year 2017 marks 30 years since the radiological accident in Goiânia, Brazil, which resulted from the leakage of Cs-137 from a teletherapy equipment. The contaminated material collected during the response to the accident was disposed of in Abadia de Goiás, about 20 km from Goiânia. However, in the initial 15-day period before the authorities were notified, contaminated paper bales and scrap metal were sold and transported to material recycling facilities in the State of São Paulo, one thousand kilometers away. These materials were later collected in steel boxes and drums, and stored in the intermediate waste storage facility of the Nuclear and Energy Research Institute - IPEN, in São Paulo. The objective of this paper is to describe the work performed to check the present condition of the paper bales waste boxes, reassess the reported Cs-137 activities, and evaluate possible treatment methods that can be applied to reduce the volume of waste. Prospective waste treatment methods are discussed.

Resumo: O ano de 2017 marca 30 anos desde o acidente radiológico em Goiânia, Brasil, que resultou do vazamento de Cs-137 de um equipamento de teleterapia. O material contaminado coletado durante a resposta ao acidente foi depositado em Abadia de Goiás, a cerca de 20 quilômetros de Goiânia. No entanto, nos 15 dias iniciais até a notificação das autoridades, fardos de papel e sucatas

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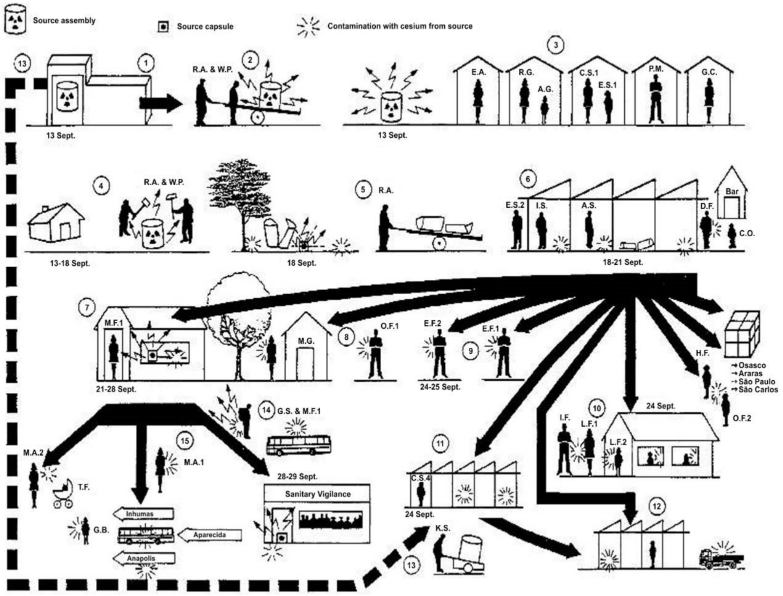
[3] Lecture presented at the 2018 Waste Management Symposia (WMS) on March 18-22, 2018 in the city of Phoenix, AZ, United States. Available at: <https://www.xcdsystem.com/wmsym/2018/pdfs/FinalPaper_18422_0124110238.pdf>.

contaminados foram vendidos e transportados para empresas de reciclagem de materiais no Estado de São Paulo, a mil quilômetros de distância. Esses materiais foram posteriormente recolhidos em caixas de aço e tambores, e armazenados na unidade intermediária de armazenamento de rejeitos do Instituto de Pesquisas Energéticas e Nucleares - IPEN, em São Paulo. O objetivo deste artigo é descrever o trabalho realizado para verificar o estado atual das caixas de rejeitos de fardos de papel, reexaminar as atividades reportadas do Cs-137, e avaliar possíveis métodos de tratamento que possam ser aplicados para reduzir o volume de rejeitos. Potenciais métodos de tratamento de rejeitos são discutidos.

Introduction

The Goiânia accident was one of the most publicized radiological incidents and with the most serious consequences related to non-nuclear power. Approximately one Cs-137 half-life ago, a couple of scavengers removed equipment used for teletherapy from a derelict clinic, took it to a scrapyard, ruptured the sealed source capsule and divided a significant fraction of the about 50.9 TBq of Cs-137 among many individuals, who marveled at its bluish shine. The next day, many of them started having acute radiation syndrome, but only 15 days later a Sanitary Vigilance official identified the cause of the illness that affected all those who contacted the material, and alerted the radiation protection authorities.

During this period, the cesium chloride from the sealed source was being dispersed between people and their homes, contaminating buildings and every object inside them, in their yards and among the domestic animals, and the materials they collected for recycling and stored in the scrapyards. A diagram based on a drawing made shortly after the discovery of the accident, trying to explain what happened, is presented in Figure 1 [1].



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.

Figure 1 - Diagram of the dispersion of Cs-137 in the Goiânia accident [1].

In the response to the accident, over 112,000 people had to be screened for radiation and 249 of them were found to have significant levels of contamination in or on their bodies. Twenty-four needed specialized medical care and four of the most exposed victims died within a month after the accident [2].

Three months were necessary for the complete cleanup of the contaminated sites, a work that involved about 600 professionals who took care of the victims, identified contaminated sites, decontaminated them, as well as managed the waste generated during these procedures.

During the cleanup operation, topsoil had to be removed from several sites and many houses were demolished. All the objects that were inside most houses were removed and examined for radiation, and in a number of cases, almost everything was beyond on-site decontamination capability. In the end, contaminated material amounting to 4.5 thousand tons was conditioned in packages as radioactive waste [3].

A repository with the same concept of the repository of L'Aube in France, or El Cabril in Spain, was built in the nearby municipality of Abadia de Goiás, about 20km from the initial contamination site, for disposal of this radioactive waste [4].

One important aspect of the decontamination and waste management work was the assessment of the collected radioactivity. Just after the response initiated, the rainy season in the Goiânia region was at the beginning and a copious amount of rain accompanied the process for recovery of the contaminated material. Approximately 10% of the initial activity is estimated to have been lost by dilution beyond the detection capacity during the response. Later work detected Cs-137 in water, sediment and other media, but no estimates of the total activity in each medium were calculated.

Another aspect that stands out in the Goiânia accident from other accidents involving sealed sources is that some of the contaminated material had been transported to locations up to 1,000 kilometers away from the initial incident, before the accident was recognized by the authorities. Besides Goiânia, the material was also taken to three nearby towns in the State of Goiás (Inhumas, Aparecida and Anápolis), as external and internal contamination of the bodies of the involved individuals or in their belongings.

Figure 2 - Contaminated paper bales collected and stored in the waste boxes in August 1988.

In the same way, recycling materials contaminated locations in four cities in the State of São Paulo. Scrap metal and paper bales were sold by the scavengers to recycling factories in the cities of São Paulo, Osasco, Araras and São Carlos. Approximately 8,000 kg of metal pieces, collected in the operations of decontamination of those factories (Figure 2), resulted in forty-three 200-liter drums, and 39,000 kg of discarded paper resulted in fifty 1.6 m3 steel boxes. The option of sending these waste packages back to Goiânia was discarded because of the anxiety and disturbance throughout the country after the accident. These drums and boxes containing the recovered wastes are currently stored in the intermediate radioactive waste storage facility of the Nuclear and Energy Research Institute, in the city of São Paulo. Figure 3 shows part of the packages in the storage room.

Final disposal of this waste is being evaluated under a technical and economic feasibility assessment for an alternative management. The purpose is to apply some sort of treatment to reduce the volume that will be transported to the final disposal facility, which is being planned for construction in Brazil in the near future. According to the Brazilian National Commission of Nuclear Energy (CNEN), this facility has a reference disposal cost of R$ 10,000 per cubic meter (US$ 3,000 or EU 2,600 per cubic meter approximately, by December 2017 exchange rates) [5], not including transportation by an estimated distance of 300 miles (about 500 kilometers) and handling costs. The total volume of the paper bales is around 80 m^3.

Figure 3 - Boxes with waste from the Goiânia accident today. The stains are scratches on the painting and corrosion points that were fixed.

One of the questions raised during the discussion about this work was the reliability of reported activity data, because at the time of conditioning, no significant effort was done to calculate the activity content of the boxes with a satisfactory degree of accuracy. In actuality, the activity values for the boxes were estimated based on calculations that assumed a homogeneous distribution of activity in the waste material and that used the highest exposure rate measured in the surface of the waste boxes; the model was quite simple and ignored the fact that the dose rates in each side of the box varied widely because of the hot spots in the waste. The calculations used the point-kernel method described by Rockwell [6].

The intended estimation of activity content for the waste boxes can take into consideration the exposure rates measured in each side and at different distances from the package surface. The calculations of activity content can make use today of the Microshield®[4] v.9.03 software package.

Therefore, the objective of this paper is to describe the work performed to check the present condition of the paper bales related to the dose rates, reassess the reported Cs-137 activities in waste boxes, and evaluate possible treatment methods that can be applied to reduce the volume of the waste.

Methods

A sample of 14 boxes was randomly selected from the 50 boxes in the storage. The boxes were weighed using the forklift scale, transported individually to a low background radiation area, out of the storage facility, and had their dose rates measured.

The measurement of the dose rates was used to estimate the activity by the dose-to-becquerel method, using the Microshield® v.9.03 software. Results of dose rate measurements at the distances of zero, 0.5 and 1.0 meter from

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[4] MicroShield® is a registered trademark of Grove Software, Inc.

each of the four lateral sides of the package surfaces were used to reduce the uncertainties of the estimates, as well as to model the distribution activity in each container as to better correlate with the measured dose rates.

The results of the measurements were used as input to calculate the estimated activities. To take into account the large inhomogeneity of the radioactive content, the measurement of each side was attributed to 1/9 fraction of the waste mass, as the modelling considers a 3x3 matrix of homogeneous regions, and used the MicroShield® to refine the initial estimates. The procedure was repeated until an acceptable distribution of activity was obtained, which correlates with the measurements (Figure 4).

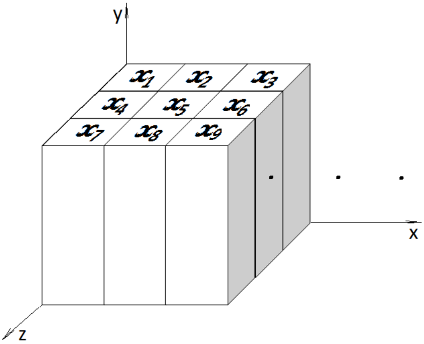

Figure 4 - Modelling of the MicroShield geometry (the dots are measurement points).

The dosimeters used for the measurements were the following (Figure 5):

- Kromek RayMon10®[5] radiation monitor;
- Eberline FH 40F2 radiation monitor.

Prospective waste treatment methods were discussed, such as wet combustion, incineration, biological degradation, among others.

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[5] Kromek RayMon10® is a registered trademark of Kromek Limited.

Figure 5 - Kromek RayMon10® & Eberline FH 40F2 radiation monitors.

Results & Discussion

Table I presents the results of the evaluation of dose rates differences between the measured and the calculated values that were based on the recorded activities of a sample of 14 waste boxes out of the fifty. The columns headed by ‘old’ and ‘current’ activities show the recorded activities for each box at the time of the conditioning of the waste and the calculated decayed present activity. The columns headed by ‘old’ and ‘current’, ‘measured’ and ‘calculated’ dose rates present the values obtained empirically in this work and those calculated with the recorded activities. It is clearly visible that the differences between values of corresponding points are not negligible, confirming that the recorded activities may be different from the actual values.

Table II presents the variations obtained between the calculated and measured dose rates. The difference between these values was expected, since the method used in the initial measurement in 1988 did not verify the four sides of the box in search of an average dose rate value.

Table I - Original and current waste boxes dose rates

		Old	Current	Old dose rate		Current dose rate (measured)			Current dose rate (calculated)		
Box	Packaging date	Activity (MBq)	Activity (MBq)	0.0m (μSv/h)	1.0m (μSv/h)	0.0m (μSv/h)	0.5m (μSv/h)	1.0m (μSv/h)	0.0m (μSv/h)	0.5m (μSv/h)	1.0m (μSv/h)
261	01/mar/88	3245	1619	200.0	13.0	43.1	16.8	8.3	93.4	38.8	18.0
339	02/mar/88	810	404	50.0	3.0	9.7	7.4	6.9	22.7	9.5	4.4
348	01/mar/88	1624	810	100.0	6.0	5.2	1.7	1.0	43.4	18.2	8.4
350	03/mar/88	2272	1134	140.0	9.0	0.4	0.3	0.4	42.6	18.9	8.6
352	03/mar/88	260	130	16.0	1.0	1.4	0.8	0.6	6.4	2.7	1.3
354	03/mar/88	1624	810	100.0	6.0	4.0	1.5	1.0	43.6	18.3	8.5
1334	01/mar/88	3245	1619	200.0	13.0	71.5	32.1	14.4	79.9	34.0	15.7
1336	03/mar/88	714	356	44.0	3.0	0.4	0.4	0.5	18.8	7.9	3.7
1339	01/mar/88	19462	9711	1200.0	75.0	215.4	92.9	42.7	521.0	218.8	101.2
1340	01/mar/88	648	323	40.0	3.0	1037.4	745.5	413.0	18.1	7.6	3.5
1346	01/mar/88	1624	810	100.0	6.0	24.9	7.7	3.7	45.2	18.9	8.7
1356	02/mar/88	1624	810	100.0	6.0	43.7	22.2	11.1	47.6	19.7	9.2
1357	01/mar/88	324	162	20.0	1.0	2.5	1.9	1.5	9.5	4.0	1.8
1377	03/mar/88	455	227	28.0	2.0	1.0	0.9	0.9	12.2	5.1	2.4

Note: The current measurements were performed on November 29 and 30, 2017.

Table II - Percent variation of measured and calculated dose rates and estimated activity concentration

Box	Recorded net weight (kg)	Measured net weight (kg)	Dose rate variations (%)				Current estimated activity concentration (kBq/kg)
			On contact		At 1 meter		
			Measured	Calculated	Measured	Calculated	
261	475	333	78	53	36	(-38)	4858
339	419	349	81	55	(-130)	(-47)	1157
348	460	378	95	57	83	(-40)	2142
350	315	627	100	70	96	4	1807
352	311	435	91	60	40	(-30)	298
354	349	375	96	56	83	(-42)	2159
1334	374	430	64	60	(-11)	(-21)	3763
1336	350	388	99	57	83	(-23)	918
1339	321	377	82	57	43	(-35)	25740
1340	372	349	(-2494)	55	(-13667)	(-17)	926
1346	365	353	75	55	38	(-45)	2294
1356	430	322	56	52	(-85)	(-53)	2514
1357	352	321	88	53	(-50)	(-80)	503
1377	300	377	96	56	55	(-20)	602

Note: the figures in captions are the negative values related to the comparison between the old and new numbers.

Some alternative approaches were considered for the reduction of radioactive waste volume in the stored boxes. The evaluation suggested as the one with the greatest potential would be the wet combustion, which consists in the use of an oxidizing reagent, a chemical reactor operating at room temperature and using a filtering system appropriate to the gases generated in the process.

The contaminated paper could also be transformed into pulp by inserting it in a recipient with hot water under agitation. The Cs-137 is very soluble and will be retained in the water, for later treatment. The expected result is of an extensive volume reduction of the paper pulp, possibly even reaching the unconditional clearance limit.

Other methods have been considered, such as incineration and biological degradation. However, due to the difficulty in obtaining the required equipment, as well as the licensing, these methods were disregarded. The method of biological degradation may already have started inside some boxes, by bacteria or fungi, but at the time it was not possible to evaluate the current state of the material. A visual inspection of the interior of the boxes requires a fume hood with insulation from the atmosphere to prevent contamination and dispersion of the material during opening, which is still under planning.

Conclusions

The current results indicate that none of the boxes checked are close to the clearance limit, which is 10 kBq/kg [7] – box 352 presented the lowest estimated value of 298 kBq/kg, almost 30 times over the limit. Without any sort of treatment, these boxes will not reach the clearance level in less than 150 years, at least.

The current values measured are more accurate than the previous ones measured 30 years ago, allowing a better analysis of its contents. Therefore, future works are being planned, including visual inspection, taking samples and exploring options to identify the best treatment method of volume reduction for final disposal.

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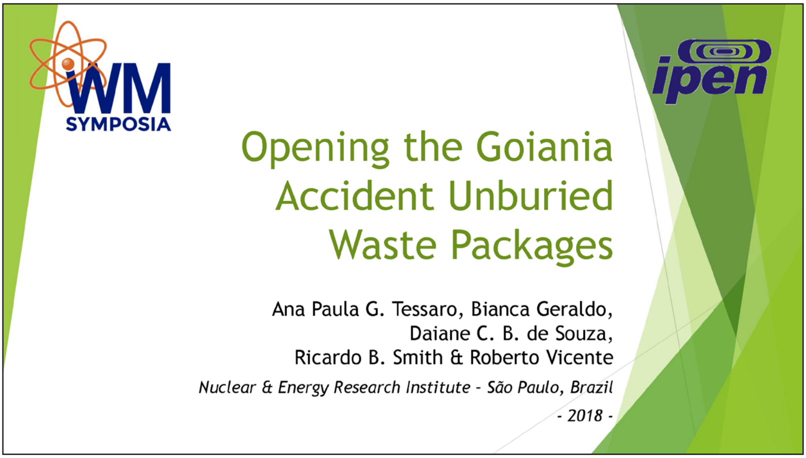

Opening the Goiania Accident Unburied Waste Packages

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- 2018 -

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Further Analyses of the Unburied Goiania Accident Packages[6]

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Abstract: In 1987, in the city of Goiania, Brazil, a derelict teletherapy machine was disassembled by scavengers and Cs-137 was released in the environment, unleashing the biggest radiological accident in Brazil. During the 15 days before the accident was acknowledged, some contaminated materials were sold and delivered to recycling factories in a few cities in the state of Sao Paulo, Brazil, in the form of metal scrap and recycled paper bales. The contaminated material was then collected, the metal scrap was conditioned in forty-three 200-liter drums, and the paper bales were stored in fifty 1.6 cubic meter steel boxes at the interim storage of the Nuclear and Energy Research Institute (IPEN), in the city of Sao Paulo, and there remained ever since. In 2017, 30 years later, initial analyses were performed at a sample of these boxes, checking for their activity, weight, and incongruences between the original values recorded at the time of collection and the measurement results 30 years later. The results indicated that none of the boxes checked were close to the clearance limit and that, without any sort of treatment, this radioactive waste should be stored for at least 150 years more. Visual inspection could not be performed at that time. Nowadays, some of the boxes were opened and samples from the contaminated material inside were taken for analysis. The main objective of this work is to report the results from the evaluation of the physical state of this material. After

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[6] Lecture presented at the 2019 Waste Management Symposia (WMS) on March 03-07, 2019 in the city of Phoenix, AZ, United States. Available at: <http://amz.xcdsystem.com/A464D2CF-E476-F46B-841E415B85C431CC_finalpapers_2019/FinalPaper_19161_0224053147.pdf>.

these analyses, the treatment options for volume reduction that were previously proposed were reviewed, and the method that best suits the current characteristics of the waste was chosen.

Resumo: Em 1987, na cidade de Goiânia, Brasil, uma máquina de teleterapia abandonada foi desmontada por catadores e o Cs-137 foi lançado no meio ambiente, desencadeando o maior acidente radiológico do Brasil. Durante os 15 dias anteriores à descoberta do acidente, alguns materiais contaminados foram vendidos e entregues a fábricas de reciclagem em algumas cidades do estado de São Paulo, Brasil, na forma de sucata de metal e fardos de papel reciclado. O material contaminado foi então coletado, a sucata metálica acondicionada em quarenta e três tambores de 200 litros, e os fardos de papel armazenados em cinquenta caixas de aço de 1,6 metros cúbicos no depósito intermediário do Instituto de Pesquisas Energéticas e Nucleares (IPEN), na cidade de São Paulo, e lá permaneceram desde então. Em 2017, 30 anos depois, foram realizadas análises iniciais em uma amostra dessas caixas, verificando sua atividade, peso e incongruências entre os valores originais registrados no momento da coleta e os resultados da medição 30 anos depois. Os resultados indicaram que nenhuma das caixas marcadas estava próxima do limite de liberação e que, sem qualquer tipo de tratamento, esse rejeito radioativo deveria ser armazenado por pelo menos mais 150 anos. A inspeção visual não pôde ser realizada naquele momento. Atualmente, algumas das caixas foram abertas e amostras do material contaminado em seu interior foram retiradas para análise. O objetivo principal deste trabalho é relatar os resultados da avaliação do estado físico deste material. Após essas análises, as opções de tratamento para redução de volume propostas anteriormente foram revistas, e o método que melhor se adequa às características atuais do resíduo foi escolhido.

Introduction

In 1987, a year and a half after the Chernobyl accident in the USSR, in the city of Goiania, Brazil, a teletherapy machine taken from a derelict radiotherapy clinic was disassembled by scavengers, and approximately 50.9 TBq of Cs-137 were released in the environment, unleashing the biggest radiological accident in Brazil [1].

The radioactive material, in the form of cesium chloride, was spread in the scrapyard, in a paper recycling company and among many individuals as well as their homes. Four persons died within a month after the accident, and a total of about 4.5 thousand tons of radioactive waste were collected during the cleanup operation, conditioned in boxes and disposed in a repository especially built for it, in the city of Abadia de Goiás, approximately 20km from the original contamination site [2].

Only 15 days after the beginning of the cesium dispersion was that the local sanitary vigilance acknowledged that some people were suffering from acute radiation syndrome and informed the authorities who proceeded on the identification and cleanup of the contaminated people and sites. During this time period, some contaminated materials were sold and delivered to recycling factories in the cities of São Paulo, Osasco, Araras and São Carlos, in the state of Sao Paulo, up to 1,000 km from the contamination site, in the form of metal scrap and recycled paper bales.

A new cleanup operation was performed. The contaminated material was collected; the paper bales were stored in fifty 1.6 cubic meter steel boxes, and the metal scrap was conditioned in forty-three 200-liter drums [3]. Because of the turmoil in the country and the sensibilization triggered by the radiological accident, as well as the transportation costs, it was not possible to deliver this waste to Abadia de Goiás. Therefore, it was brought to the interim storage of the Nuclear and Energy Research Institute (IPEN), in the city of Sao Paulo. The steel boxes and drums were there gathered in 1988, and besides the regular maintenances to fix scratches and corrosion points, the packages remained without any other verification until the year 2017.

With the 30 years of the greatest radiological accident in Brazil, the interest in analyzing this waste came up, aiming at comparing the old records with the current ones to be measured, and considering some methods for treatment of this waste in order to reduce its volume, as the project of a Brazilian radioactive waste disposal site is in progress, and in the coming years it will be necessary to transport this waste to its final destination.

Therefore, a sample of 14 boxes was selected, and measurements were performed in each box, from weight to dose rates at the sides and at different distances, to assess the heterogeneity of contaminated materials inside the boxes. The activities of each of the measured boxes were then calculated using the point-kernel method described by Rockwell, and the Microshield®[7] v.9.03 software package [4].

The results indicated that the estimated activities are in disagreement with those calculated 30 years before, and confirmed that part of this radioactive waste must be kept in storage for at least 150 years more, before reaching the clearance level. A few treatment methods were considered but only on a tentative basis, as it was not possible at the time to open any of the boxes and collect waste samples.

A new research was now performed aiming to conclude these analyses and determine the most appropriate treatment method for reducing the volume of this waste.

Methods

The objective of this research is to perform visual inspection of the waste inside the boxes, and to collect samples for laboratory analyses. Considering that no large enough cell with air containment is available and in order to avoid possible air contamination when opening the boxes, due to potential spreading of radioactive dust or microorganisms, a plastic cover that would serve as a containment (Figure 1) was assembled over the box.

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[7] MicroShield® is a registered trademark of Grove Software, Inc.

Figure 1 - Plastic cap over the waste box.

The cover allows samples to be taken from the box without the risk of contamination of the air or surrounding surfaces. Gloves were installed on the front and lateral sides of the cover to allow unscrew the bolts and lift the lid. An acrylic plate was added to the front of the cover for better visual inspection. Such actions aimed at ensuring the environment was kept clean and safe.

Plastic bottles were left inside the containment before assembling for the collection of the samples.

Samples were analyzed with respect to activity concentration, pH, humidity, and the presence of microorganisms.

Results

After opening three boxes, the presence of high moisture content was observed (Figure 2), as well as a marked reduction in paper volume of the order of 10 to 30% (Figure 3).

Figure 2 - Inside of the box that showed the highest moisture content. Note the water droplets formed by condensation in the underside of the box lid.

Figure 3 - The paper bale collapsed, reducing the volume by about 30% of the original height. By the touch, the mass appears like moist clay.

In 1988, the paper bales were filled up to the limit of the capacity of the boxes, as seen in page 45. Therefore, the volume reduction is associated with the moisture build up, which could only be explained by microbial action.

The paper bales, originally tied and wrapped in a plastic bag, have fallen apart and the paper degraded up to the point that the cellulose fibers appear broken in the examination under the microscope. The paper in all samples appeared as small fragments, visibly degraded [5], with colors varying from light brown to dark brown or black. In some parts of the box with the highest moisture content, it looked like a soft, wet mass, like moist clay.

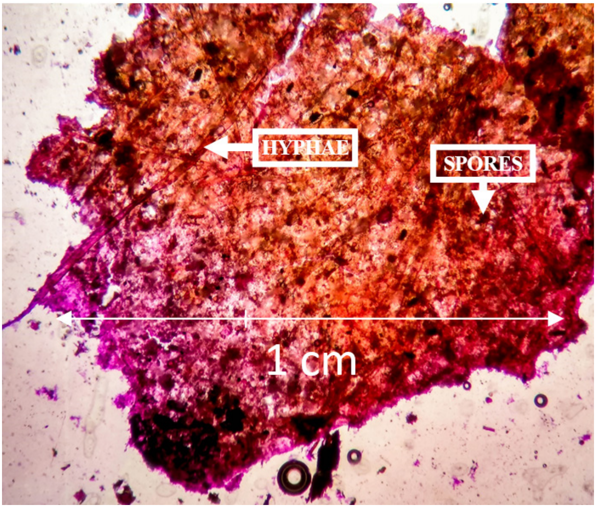

Figure 4 - Stained sample of degraded paper showing the original cellulose fibers and the microbial mass with the hypha and spores of fungi.

Examination under the microscope (Nikon, Eclipse E600) showed that microbial life thrives in the waste mass. Figure 4 shows a sample stained with gentian violet (Hexamethyl-p-rosaniline chloride) and confirms the presence of fungi.

Figure 5 shows a photogram, from a captured video of a living worm that was identified as a free-living nematode. It is certain that the bacteria are also present, but these microorganisms could not be identified in this examination of samples.

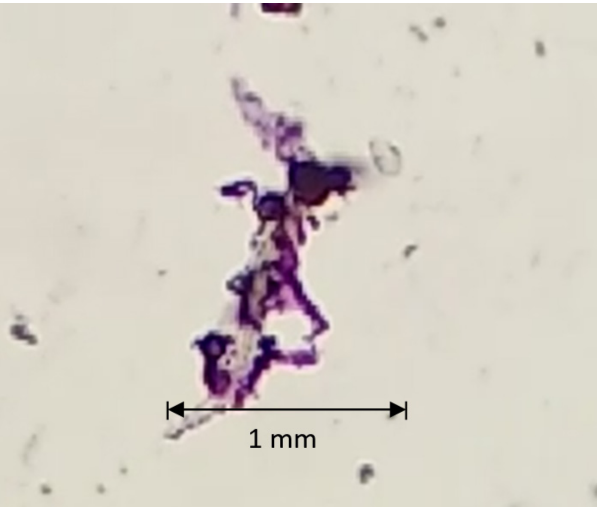

Figure 5 - A free-living nematode appears in this photogram of a video taken with a microscope from a stained sample of the paper mass.

Waste sample moisture content was measured with a moisture analyzer OHAUS, model MB200. Samples with approximately ten grams were kept at 100 oC until constant weight. TABLE I shows the results of both humidity and pH measurements.

The activity concentration of Cs-137 was also measured in samples of the three boxes, using passive gamma spectrometry, and the results are presented in TABLE II. Although the measurement of Box 350's sample may be already close to the discharge limits, further evaluations should be considered due to the high level of heterogeneity in the boxes, as explained by Tessaro, Geraldo, Souza, Smith and Vicente [4].

Table I - Results of Moisture Content and pH Measurements

Sample box no.	Initial sample weight (g)	Final sample weight (g)	Moisture content (%)	Heating time (min)	pH
350	10.381	5.220	49.7	100	6
350	10.005	4.550	54.5	180	6
340	10.243	5.880	42.6	90	7
1334	9.777	5.020	48.7	70	7

Table II - Activity Concentrations in the Samples of the Boxes

Sample box no.	Sample weight (g)	Radionuclide	Activity concentration (Bq.kg-1) (*)
350	37.12	Cs-137	19 ± 3
340	20.78	Cs-137	(2.24 ± 0.13) x 104
1334	21.19	Cs-137	(2.67 ± 0.13) x 106

(*) Confidence interval: ± 1 σ (68%)

Conclusions

The unexpected presence of a high moisture content inside the waste boxes had two consequences: the first and immediate one was that the opening of the boxes did not require a containment to prevent air contamination by spreading of radioactive dust or microorganisms. Because of that, the containment hood was not used in the next two boxes that were opened.

The second consequence was that the original idea of using physical-chemical methods to treat the waste and reduce its volume was abandoned in exchange of a method using microorganisms which attack the complex lignin molecule, as paper may contain up to 20% of lignin [6]. The microbial action on the paper bales proved to be equally effective in reducing the volume of this waste and, in addition, has the advantage of being less aggressive to the metallic boxes.

This result is suggestive of conducting a pilot experiment in order to evaluate the feasibility of using especially selected microbiota to further reduce the volume of the waste.

Time, cost, adverse factors and test running conditions, like temperature, humidity and the addition of chemicals that act as energy supply for the microorganisms are going to be used in the study design, prior to the performance of a full-scale treatment project.

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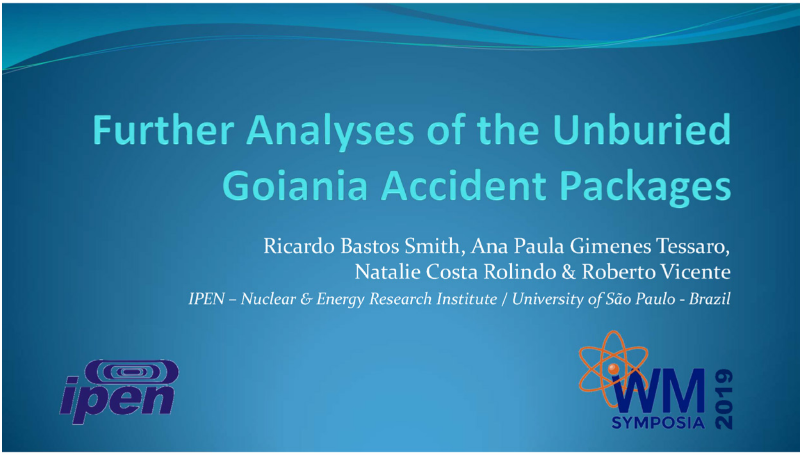

Further Analyses of the Unburied Goiania Accident Packages

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Advanced Heavy Water Reactor: a new step towards suatainability[8]

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Abstract: One of the great advances in the current evolution of nuclear power reactors is occurring in India, with the Advanced Heavy Water Reactor (AHWR). It is a reactor that uses thorium as part of its fuel, which in its two fueling cycle options, in conjunction with plutonium or low enriched uranium, produces energy at the commercial level, generating less actinides of long half-life and inert thorium oxide, which leads to an optimization in the proportion of energy produced versus the production of burnt fuels of the order of up to 50%. The objective of this work is to present the most recent research and projects in progress in India, and how the expected results should be in compliance with the current sustainability models and programs, especially "Green Chemistry", a program developed since the 1990s in the United States and England, which defines sustainable choices in its twelve principles and that can also be mostly related to the nuclear field. Nevertheless, in Brazil, for more than 40 years there has been the discontinuation of research for a thorium-fueled reactor, and so far there has been no prospect of future projects. The AHWR is an important example as an alternative way of producing energy in Brazil, as the country has the second largest reserve of thorium on the planet.

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[8] Lecture presented at the 2019 International Nuclear Atlantic Conference (INAC) on October 21-25, 2019 in the city of Santos, SP., Brazil. Available at: <https://doi.org/10.15392/bjrs.v8i3A.1368>.

Resumo: Um dos grandes avanços na evolução atual dos reatores nucleares está ocorrendo na Índia, com o Reator Avançado de Água Pesada (AHWR). É um reator que utiliza tório como combustível, que em suas duas opções de ciclo de abastecimento, em conjunto com plutônio ou urânio pouco enriquecido, produz energia comercialmente, gerando menos actinídeos de meia-vida longa e óxido de tório inerte, o que leva a uma otimização na proporção de energia produzida versus produção de combustíveis queimados da ordem de até 50%. O objetivo deste trabalho é apresentar as pesquisas e projetos mais recentes em andamento na Índia, e como os resultados esperados estão de acordo com os atuais modelos e programas de sustentabilidade, em especial a "Química Verde", programa desenvolvido desde a década de 1990 nos Estados Unidos e Inglaterra, que definem escolhas sustentáveis em seus doze princípios e que também podem se relacionar em sua maioria ao campo nuclear. Entretanto, no Brasil, há mais de 40 anos houve a descontinuidade das pesquisas de um reator a tório, e até o momento não há perspectiva de projetos futuros. O AHWR é um exemplo importante como forma alternativa de produção de energia no Brasil, uma vez que o país possui a segunda maior reserva de tório do planeta.

Introduction

For over 50 years India has had a nuclear programme under development known as the "Thorium Utilisation Programme for Sustainable Energy". Through three stages, the programme envisages the definitive transition to a fuel cycle based on the thorium element, due to its abundant sources and the shortage of uranium in the country.

The Advanced Heavy Water Reactor (AHWR) is the key component of the third stage. Already in the final stage of development, this new type of reactor when in operation will also contribute to the reduction of radioactive waste generation, as it will use a fuel cycle with a smaller production of actinides. In addition, the thorium oxide has an inert nature, which is beneficial for its deposition as a burnt fuel [1].

With the growing need for electricity for human beings, as well as the progressive depletion of fossil fuel reserves and concerns related to global warming, nuclear power is increasingly becoming an important option to contribute substantially in attending the global energy needs. According to Sinha [2], the Human Development Report's per capita electricity consumption data indicates that the world may need 3,000 to 4,000 nuclear reactors to meet this energy need.

In addition, the concern about human health and the environment through the reduction of pollution and waste production has increased since the mid-twentieth century, when the long-term negative effects of human activities since the Industrial Revolution, which is the great historical landmark of man's dominion over nature, became more and more present. It was clear that the search for cleaner production means, as well as the treatment of waste produced in the most diverse areas, would be a matter not only of well-being but even of survival.

Associations and entities have progressively emerged around the world with the specific objective of controlling and revising the procedures used in laboratories, industries and energy production facilities, in an attempt to minimize or even reverse the environmental damage. Therefore, this paper presents a brief history about the evolution of the concept of sustainable development and some of the main organizations involved, including the Green Chemistry programme. Afterwards, the main characteristics of the Advanced Heavy Water Reactor will be presented, as well as an analysis on how the Indian reactor seems consistent with these trends of increased safety and sustainability assurance, in correlation with the twelve principles of the Green Chemistry, and which of these principles can also be related to the nuclear area.

The nuclear power growth worldwide requires a satisfying technology response to safety and security challenges, the ability to operate with the lowest level of technology infrastructure in many developing countries, a high degree of fuel efficiency and more advanced options for waste management.

Sustainable Development

Sustainable development has been defined in many ways, but the most frequently quoted definition is from Our Common Future, also known as the Brundtland Report: “Sustainable development is the one that meets the needs of the present without compromising the ability of future generations to meet their own needs” [3]. It is the economic, social, cultural and scientific development of societies, ensuring more health, comfort and knowledge, but without depleting the planet’s natural resources. To this end, every form of relationship between man and nature must occur with the least possible damage to the environment. Policies, systems of trade, production, transformation and service, industry, tourism, agriculture, basic services, mining, and others must exist to preserve biodiversity and the human being, that is, to protect the life of the planet [4].

The post-World War II economic expansion, also known as the postwar economic boom or Golden Age of capitalism, was a period of economic prosperity in the mid-twentieth century which provoked the acceleration of environmental change processes, as a result of seemingly unlimited economic growth in terms of resource availability [5].

The continuing and intense deterioration of the environmental situation, initially marked by industrial pollution, set precedents for the struggle in taking into account the environmental issues. Therefore, there is nowadays a growing awareness and concern at all levels of society and practically every nation regarding the environmental problems.

In order to meet the social demands motivated by environmental accidents, increased pollution of the soil, water and air, and changes in the socio-political context worldwide, a series of actions were taken to create alternatives for the improvement of the environmental situation, which at that time already demonstrated its gravity.

Historically, the starting point of the environmental issue was the Intergovernmental Conference of Experts on the Scientific Basis for Rational Use and Conservation of the Resources of the Biosphere, or the Biosphere Conference, organized by UNESCO in 1968 in Paris [6]. This conference focused on the scientific aspects of biosphere conservation, as well as research in the field of Ecology. One of the most important warnings at the time was the report commissioned by the Club of Rome, an international association of intellectuals, scientists, and entrepreneurs, entitled “The Limits to Growth”, published in 1972, also known as the Meadows Report, which was commissioned to technicians and scientists at the Massachusetts Institute of Technology (MIT) in the United States [7]. The published results disclosed the warnings and presented two possibilities: the occurrence of changes in the economic growth standards, or an ecological collapse in the next hundred years.

The document nurtured the debate at the Stockholm Conference, also held in that same year, where an understanding about the relationship between environment and development was established, and the concept of a new type of development emerged: the Ecodevelopment - a proposition for new modalities of development, which promotes the knowledge produced by local populations for the management of their environment, as opposed to the homogenization of the models adopted until then.

Sequentially, the Stockholm Conference - United Nations Conference on the Human Environment took place, in which political, social and economic problems in the global environment were discussed, in an intergovernmental forum. The United Nations Environment Programme (UNEP) was then created, during some of these discussions. The concept of Ecodevelopment was gradually being replaced by the concept of Sustainable Development, which use comes from a document prepared in 1980 by the International Union for Conservation of Nature (IUCN) [8].

In the nuclear field, until 1982, some of the radioactive waste produced by the 13 most evolved countries in the area used to be placed in drums and thrown into the deepest places in the ocean. According to an inventory organised by the International Atomic Energy Agency, approximately 85.0×10^{15} Bq of radioactive waste were discharged into the ocean [9]. The emission of radioactive gases and aerosols because of the atomic tests in the atmosphere had already been halted in 1963 by the Partial Nuclear Test Ban Treaty; an order of magnitude greater than 1.0×10^{21} Bq is estimated of radioisotopes that were dispersed in the air by the 520 nuclear tests on Earth's surface [10].

Ten years after the Stockholm meeting in 1982, an assessment of the period was performed at a meeting sponsored by UNEP, in Nairobi, which suggested the formation of the World Conference on Environment and Development - UNCED, set up by the United Nations in 1983 to analyze environmental and developmental problems. This commission published in 1987 its report, which became known as the Brundtland Report, the book entitled Our Common Future [3]. Afterwards, the environmental issue received a further impetus and the concept of sustainable development started being used instead of the ecodevelopment term, and formed the basis for the discussion and reorientation of development policies and their direct relationship with environmental issues.

In the mid 1980s, a shift in paradigm occurred in the Organisation for Economic Co-operation and Development (OECD) countries. During the 1985 meeting of the Environment Ministers of the OECD countries, the focus was on Economic Development and the Environment, Pollution Prevention and Control, and Environmental Information and National Reviews. Between this meeting and 1990 several decisions and

Recommendations were formulated, which also provided the foundation for the Green Chemistry basics.

Internationally, the idea of command and control policy (often referred to as end-of-pipeline control) shifted towards an approach of pollution prevention [11]. The Pollution Prevention Act of 1990 in the United States marked a regulatory policy change from pollution control to pollution prevention as the most effective strategy for these environmental issues.

Based on the recommendations of the Brundtland Report, another conference was summoned by the United Nations General Assembly and held in Rio de Janeiro in 1992: The United Nations Conference on Environment and Development (UNCED), or ECO-92. This conference, also entitled Rio-92, was an important milestone for consideration on the environmental issue and its relationship with development. The debates centred on action strategies that could be adopted by all countries towards sustainable development, as well as conventions on climate change and biological diversity. Important documents were elaborated at Rio-92, such as the United Nations Agenda 21, which was a 40-chapter global action program adopted by 182 governments; and others, which also led to the Kyoto Protocol in 1997 [12].

The Agenda 21 and the Rio Declaration set essential policies for achieving a sustainable development model that meets the needs of the poor and recognizes the limits of development, in order to meet the global needs.

In 1997, the Rio +5 event was also held in Rio de Janeiro, discussing the actions and the proposals taken in ECO-92 that were not yet implemented. And in 2002, the United Nations organised the “World Summit on Sustainable Development”, when representatives from different countries met in Johannesburg, South Africa, seeking to advance the discussions that began ten years earlier, and to outline the guidelines for sustainable development. This meeting was nicknamed as Rio +10 [13]. The same occurred ten years later, at Rio +20.

In parallel to the Davos World Economic Forum in Switzerland, in 2001 the first World Social Forum (WSF) was held in the city of Porto Alegre, Brazil. A charter of social principles was drawn up after the first event, based on the participants' expectations and the meeting outcomes. With annual conferences and international participations, the WSF started being organised in other countries [14].

In September 2015, at the United Nations Summit, the 17 Sustainable Development Goals (SDGs) of the 2030 Agenda for Sustainable Development were defined, which officially came into force on 1st January 2016. Over the next fifteen years, with these new Goals that universally apply to all, countries should mobilize efforts to end all forms of poverty, fight inequalities and tackle climate change, while ensuring that no one is left behind [15].

Green Chemistry

As explained in the previous section, in the 1980s pollution prevention instead of end-of-pipeline control had to become the option of first choice. In that decade and in the 1990s, several environmentally conscious terms entered the chemical arena, such as: clean chemistry, environmental chemistry, green chemistry, benign chemistry and sustainable chemistry. The set of concepts now recognized as green chemistry coalesced in the mid- to late-1990s, along with a broader adoption of the term.

In the United States, the Environmental Protection Agency played a significant early role in fostering green chemistry through its pollution prevention programs, funding, and professional coordination. At the same time in the United Kingdom, researchers at the University of York contributed to the establishment of the Green Chemistry Network within the Royal Society of Chemistry, and the launching of the Green Chemistry journal [11].

Green chemistry is the design of chemical products and processes that reduce or eliminate the use or generation of hazardous substances. Green chemistry applies across the life cycle of a chemical product, including its design, manufacture, use, and ultimate disposal [16].

In 1998, Paul Anastas, a US EPA representative, and John C. Warner (then of Polaroid Corporation) published the first handbook on green chemistry [17], in which the breadth of the concept of such chemistry is demonstrated in twelve principles, as follows:

1. Prevent waste;
2. Maximize atom economy;
3. Design less hazardous chemical syntheses;
4. Design safer chemicals and products;
5. Use safer solvents and reaction conditions;
6. Increase energy efficiency;
7. Use renewable feedstocks;
8. Avoid chemical derivatives;
9. Use catalysts, not stoichiometric reagents;
10. Design chemicals and products to degrade after use;
11. Analyze in real time to prevent pollution;
12. Minimize the potential for accidents [16].

The Green Chemistry is regularly being applied nowadays in conjunction with the nuclear area, such as emerging separation techniques for nuclear fuel reprocessing and radioactive waste treatment [18, 19], as well as a practical example performed by Fuel America AREVA NP Inc. and the University of Idaho, in the extraction and purifying of enriched uranium from waste ash [20].

As presented by Lahiri, Choudhury and Sen [21], the development of new radiochemical methods is now dictated by the green chemistry mandates, especially in terms of choosing solvents and reagents. The practice of green chemistry has become an inevitable requisite in every facet of chemical process [22].

India's Nuclear Power Generation Programme

The nuclear power programme of India comprises three stages: the first stage is to build the Pressurised Heavy Water Reactor (PHWR) using natural UO_2 as fuel matrix, and heavy water as moderator and coolant. The isotopic concentration of natural U is 0.7% fissile ^{235}U and the rest is ^{238}U. The first two plants were of boiling water reactors based on imported technology. Subsequent plants are of PHWR type through indigenous research and development efforts. India has accomplished complete self-reliance in this technology, and this stage of the programme is in the industrial domain [23].

The future plans of stage one include setting up the VVER (Water-Water Power Reactor) type plants based on Russian Technology, which is under progress to augment power generation. MOX fuel (Mixed oxide) is being developed and introduced at Tarapur to conserve fuel and to develop new fuel technology.

The nuclear fuel cycle can be open, if the spent fuel is not reprocessed and it alludes to the disposal of the entire fuel after being subjected to proper packaging. This results in huge underutilization of the potential energy of uranium (around 2% is exploited). In the closed cycle, on the other hand, the spent fuel is reprocessed and partly used, and it also refers to the chemical separation of ^{238}U and ^{239}Pu, and further recycled while the other radioactive fission products are separated, sorted out according to their half-lives and activity, and appropriately disposed of with minimum environmental disturbance.

India exerts the closed cycle mode in lieu of its phased expansion of nuclear power generation, extending through the second and third stages. Indigenous technology for the reprocessing of the spent fuel, as well as the waste management programme, have been developed by India through its own comprehensive research and development efforts, and the reprocessing plants were set up and are in operation, thereby attaining self-reliance in this domain.

India's second stage of nuclear power generation envisages the use of ^{239}Pu obtained from the first stage reactor operation, as the fuel core in Fast Breeder Reactors (FBR). The characteristic features of the FBR are: ^{239}Pu serves as the main fissile element in the FBR; a blanket of ^{238}U surrounding the fuel core will undergo nuclear transmutation to produce fresh ^{239}Pu as more and more ^{239}Pu is consumed during the operation; in addition, a blanket of ^{232}Th around the FBR core also undergoes neutron capture reactions which leads to the formation of ^{233}U, which serves as a fuel for the nuclear reactors of the third stage of India's Nuclear Power Programme; and it is technically feasible to produce sustained energy output of 420 GWe from the FBR.

The setting up of ^{239}Pu fuelled Fast Breeder Reactor of 500 MWe power generation is in advanced stage of completion. Concurrently, it is proposed to use thorium-based fuel, along with a small feed of plutonium-based fuel in Advanced Heavy Water Reactors (AHWRs). The AHWRs are expected to shorten the period of reaching the stage of large-scale thorium utilization.

The third phase of India's Nuclear Power Generation programme is to have breeder reactors using ^{233}U fuel. India's vast thorium deposits permit the design and operation of ^{233}U fuelled breeder reactors. ^{233}U is obtained from the nuclear transmutation of ^{232}Th used as a blanket in the second phase ^{239}Pu fuelled FBR. Besides, the ^{233}U fuelled breeder reactors will have a ^{232}Th blanket around the ^{233}U reactor core which will generate more ^{233}U as the reactor goes operational, therefore resulting in the production of more and more ^{233}U fuel from the ^{232}Th blanket as more of the ^{233}U in the fuel core is consumed, helping to sustain the long-term power generation fuel requirement.

These ^{233}U/^{232}Th based breeder reactors are under development and would serve as the mainstay of the final thorium utilization stage of the Indian nuclear programme. The currently known Indian thorium reserves amount to 358,000 GWe-yr of electrical energy and can easily meet the energy requirements during the next century and beyond [23].

Advanced Heavy Water Reactor

The Indian thorium-based nuclear energy systems are being developed to achieve sustainability in respect of fuel resource along with enhanced safety and reduced waste generation. The three-stage nuclear program is supported by the AHWRs, as it is expected to shorten the period of reaching the stage of large-scale thorium utilisation.

AHWR300-LEU is a 300 MWe, vertical, pressure-tube type, boiling light water-cooled, and heavy water-moderated reactor. The reactor incorporates a number of passive safety features and is associated with a fuel cycle having reduced environmental impact. The schematic of the main systems is shown in Figure 1 [24].

The AHWR300-LEU fuel cluster (Figure 2) contains:

- 54 fuel pins arranged in three concentric circles surrounding a central displacer assembly.
- The Zircaloy-2 clad fuel pins in the three circles, starting from the innermost, contain 18%, 22% and 22.5% of LEUO$_2$ (with 19.75% enriched uranium) respectively, and the balance ThO$_2$. The average fissile content is 4.21%.
- The moderator to be used here is Heavy Water (D$_2$O).

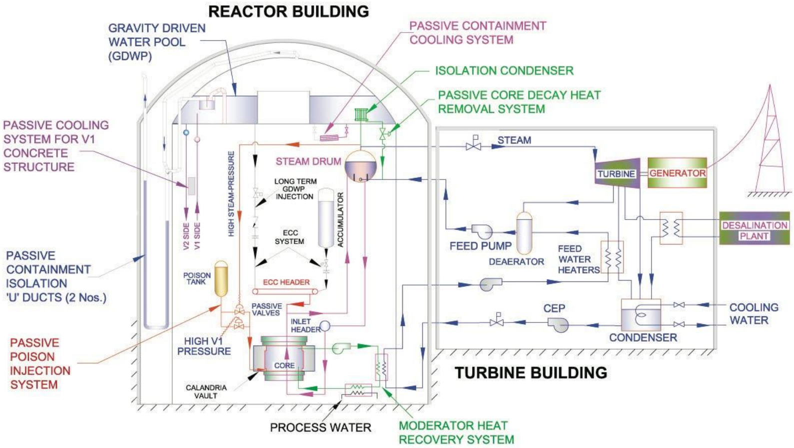

Figure 1 - Schematic of AHWR 300-LEU main systems (Source: [24]).

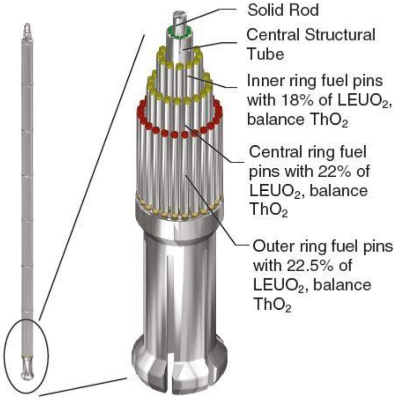

Figure 2 - AHWR300-LEU fuel cluster (Source: [24]).

The AHWR300-LEU possesses several features that are likely to reduce its capital and operating costs. Some of them are listed below:

- Using heavy water at low pressure reduces potential for leakages.

- Recovery of heat generated in the moderator for feed water heating.
- Elimination of major components and equipment such as primary coolant pumps and drive motors, associated control and power supply equipment and corresponding saving of electrical power required to run these pumps.
- Shop-assembled coolant channels, with features to enable quick replacement of pressure tube alone, without affecting other installed channel components.
- Inherent advantages of using high pressure boiling water as coolant: elimination of steam generators, and use of high-pressure steam.
- Production of 500 m^3/day of demineralised water in multi-effect desalination plant by using steam from LP Turbine (for plants located on the sea coast).
- Hundred years design life of the reactor [24].

In addition to better utilisation of natural uranium resources, as compared to a modern LWR, AHWR300-LEU offers significant advantages in terms of proliferation resistance. As a result of its mixed fuel, the 300 MWe plant produces only 21% of the Plutonium as compared to a modern LWR. Further, the Plutonium from AHWR300-LEU spent fuel contains approximately 56% fissile isotopes, while those from LWR spent fuel contains about 65% fissile isotopes. Also, fraction of ^{238}Pu in total plutonium, responsible for high heat generation, is around 10%, as against a much lower fraction in modern LWRs, therefore making the Plutonium from AHWR300-LEU spent fuel much less attractive for proliferation. Figure 3 shows a comparison of the total plutonium at different burnups, against other reactors. An additional aspect of proliferation resistance is the appreciable quantities (approx. 200 ppm) of ^{232}U in the uranium from spent fuel of AHWR300-LEU. The daughter products of ^{232}U emit high-energy gamma radiation.

This makes it possible to re-use uranium in other reactors in a proliferation resistant manner. It may be further noted that due to its significant percentage of thoria, conventional approaches for dissolution are highly inefficient, thus making reprocessing more difficult [25, 26].

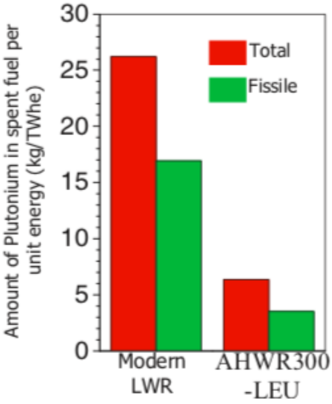

Figure 3 - Reduced environmental burden due to reduced waste generation as compared to modern LWRs (Source: [2]).

The AHWR300-LEU fuel contains a significant fraction of thorium as a fertile host. Thorium being lower in the periodic table, the quantity of minor actinides is significantly reduced. As compared to the modern LWR, referred to in the previous section, for the same amount of energy produced, AHWR300-LEU results in 37% less minor actinides (Figure 4). This will obviously lead to a reduced burden on waste disposal requirements, especially in view of the fact that a major portion of the future nuclear reactors may be deployed in countries with large population. Further, thorium oxide is eminently suitable for long-term storage because of the inert matrix. It is on account of this inert nature of the matrix, reprocessing of the AHWR300-LEU fuel poses relatively complex challenges. With this feature, even with a fuel cycle designed in a once

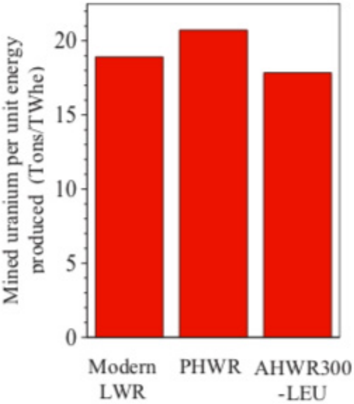

Figure 4 - Production of actinides (Source: [2]).

through mode, the spent fuel can be kept stored at the plant site for prolonged durations, in interim storage facilities [2].

A Compact High Temperature Reactor (CHTR) is being designed to have many features, which make it inherently safe. In addition, many passive systems have been incorporated for reactor shutdown and reactor heat removal under normal and postulated accident conditions. The reactor possesses the following inherent safety features:

- A strong negative Doppler coefficient of the fuel for any operating condition results in reactor power reduction in case of fuel temperature rise, during any postulated accident scenario.
- High thermal inertia of the all-ceramic core and low core power density results in very slow temperature rise of the reactor core components, as well as fuel during a condition when all heat sinks are lost.
- A large margin between the normal operating temperature of the fuel (around 1100°C) and the allowable limit of the TRISO (Tristructural Isotopic) coated particle fuel (1600°C) to retain fission products and gases results

in their negligible release during normal operating conditions. This also provides a healthy margin to take care of any unwanted global or local power excursions.

- A negative moderator temperature coefficient results in lowering of reactor power in case of increase in moderator temperature due to any postulated accident condition.
- Due to the use of lead-bismuth (Pb-Bi) eutectic alloy-based coolant having a very high boiling point (1670°C), there is a very large thermal margin to its boiling, the normal operating temperature being 1000°C. This eliminates the possibility of heat exchange crisis and increases the reliability of heat removal from the core. The coolant operates at low pressure.
- The coolant, which is maintained in inert gas atmosphere, is itself chemically inert. Even in the eventuality of accidental contact with air or water, it does not react violently with explosions or fires; in case of a primary system leakage, the coolant solidifies and prevents further leakage.
- The thermal energy stored in the coolant, which is available for release in the event of a leak or accident, is small [2].

Discussion

Considering the information on the AHWR300-LEU presented above, there are several attributes that can be related to the Green Chemistry principles:

Principle 1 – Waste prevention: as the AHWR300-LEU uses Thorium as a fertile host, the quantity of minor actinides is significantly reduced, and the thorium oxide produced as waste has an inert matrix, so is more suitable for long-term storage. It is important to recall here the convergence with the seventh principle of the radioactive waste management, as adopted by IAEA [27] in 1995, which states that the generation of radioactive waste shall be maintained in the lowest level achievable. This can be understood as less waste volume and mass, lower activity, shorter half-lives and reduced radiotoxicity of the radionuclides contained in the waste.

Principle 2 – Maximize atom economy: although the principles of Green Chemistry were conceived for the production of goods using chemical processes and expressed as the ratio of the product mass to the mass of reagents, it seems perfectly applicable to the generation of energy. Using the closed fuel cycle, the output of energy per unit mass of the primary fuel mined (kilograms of thorium or uranium), or raw material for the exploitation of the energy source, is much higher than any other fuel cycle, including renewables, fossil fuels and other nuclear fuel cycles.

Principles 3 and 4 – Design less hazardous chemical syntheses, and safer chemicals and products: the desirable characteristics of the discussed fuel cycle are intrinsically achieved by the design of the energy generation system, thus meeting the idea behind the principle of safety by design.

Principle 6 – Increase energy efficiency: this principle can be associated to the second principle, as pointed out earlier, in which the energy output per unit mass of mined and manufactured goods are much higher than the alternatives.

Principle 10 – Design chemicals and products to degrade after use: this is an intrinsic property of the waste that naturally decays the activity and reduces the associated danger, although the time necessary for some radionuclides present in the waste generated in the fuel cycle to become harmless may extend to very long periods.

Principle 12 – Minimize the potential for accidents: the many passive systems incorporated in the reactor prevent the accident conditions to occur, in case of forced shutdown and heat reduction, as well as the use of heavy water at low pressure, which reduces the potential for leakages.

Conclusion (The Brazilian Experience)

In the 1960s, Brazil was in research to choose which type of nuclear power reactor to be built, as well as which fuel to use. With great reserves of both uranium and thorium in the country (according to the 2018 NEA/IAEA report, Brazil has the second largest thorium reserve on the planet, after India [28]), it was up to the governing authorities to decide which system would be the most suitable.

In 1965 in the city of Belo Horizonte, the Thorium Group was created, a team of nuclear engineers that aimed to make Brazil autonomous in the design and construction of this type of reactor. The group's task was similar to that of India's Nuclear Programme. Researchers were sent for training in France, and the first Brazilian research facilities applied to power reactors were created. Several studies of heavy water reactor physics were performed in these laboratories, with heavy water supplied by the United States. However, around 1968, the leaders of the country's electric sector started to defend the choice of a reactor with light water and enriched uranium, which was eventually accepted by the federal government. The Thorium Group broke up shortly after this decision [29].

Fifty years ago, the idea of building a thorium-powered power reactor was set aside, and three PWR (pressurized water) reactors were built using light water and enriched uranium. The thorium reserves remained idle. At some point in the future, the price of uranium will increase due to its decreasing availability, which may cause the cost-benefit variable to tip in favor of thorium reactors; it is worth starting to think about this as soon as possible.

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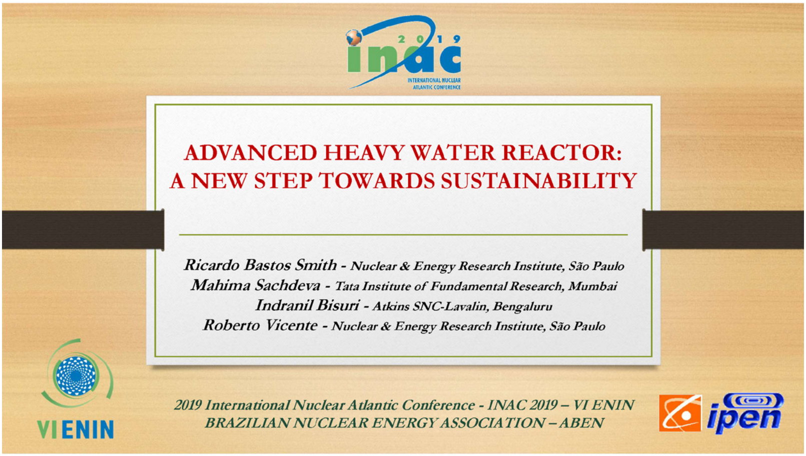

ADVANCED HEAVY WATER REACTOR: A NEW STEP TOWARDS SUSTAINABILITY

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Mahima Sachdeva - Tata Institute of Fundamental Research, Mumbai
Indranil Bisuri - Atkins SNC-Lavalin, Bengaluru
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- 6 -

Knowledge Management in the Decommissioning of Nuclear Facilities in Brazil[9]

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Abstract: In the second half of the twentieth century in Brazil, several nuclear facilities were built for the most varied objectives. The largest number of such facilities is at the Nuclear and Energy Research Institute in São Paulo (IPEN-CNEN/SP). For different reasons, some of these facilities had their projects finalized and were deactivated. Some of the equipment was then dismantled, but the respective nuclear and radioactive material remained isolated in the original sites awaiting the proper decommissioning procedures. The Celeste Project is an example of a facility where the nuclear material has been kept, and is subject to Argentine-Brazilian Agency for Accounting and Control of Nuclear Materials (ABACC) periodic inspections. Because of a number of interests, including financial and/or budgeting situations at the institutions, decades have passed without any further action, and the people who withhold information and knowledge about these facilities have already moved away from the area or are in the process of. Therefore, this work proposes an analysis about the knowledge management reflecting on the possible consequences for the decommissioning processes, in case of loss of the knowledge acquired.

Resumo: Na segunda metade do século XX, no Brasil, várias instalações nucleares foram construídas com os mais diversos objetivos. O maior número dessas instalações está no Instituto de

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Pesquisas Energéticas e Nucleares de São Paulo (IPEN-CNEN/SP). Por diversos motivos, algumas dessas instalações tiveram seus projetos finalizados e foram desativadas. Alguns dos equipamentos foram então desmontados, mas os respectivos materiais nucleares e radioativos permaneceram isolados nos locais de origem, aguardando os procedimentos de descomissionamento adequados. O Projeto Celeste é um exemplo de instalação onde o material nuclear foi guardado e está sujeito a inspeções periódicas da Agência Brasileiro-Argentina de Contabilidade e Controle de Materiais Nucleares (ABACC). Por uma série de interesses, incluindo situações financeiras e/ou orçamentárias das instituições, décadas se passaram sem qualquer outra ação, e as pessoas que retêm informações e conhecimentos sobre essas instalações já se afastaram da área ou estão em processo de afastamento. Assim sendo, este trabalho faz uma análise sobre a gestão do conhecimento, refletindo sobre as possíveis consequências para os processos de descomissionamento no caso de perda do conhecimento adquirido.

Introduction

Management with focus in knowledge is a recently new subject and consists in identifying and analyzing the existing knowledge, which helps in the optimization on development of some process (such as a company). It can be said that it is an area of multidisciplinary practice, encompassing management strategy, information system and information technology; and broader areas such as economics, psychology and marketing [1].

According to Drucker [2], knowledge management is the ability to manage, identify, map, classify, capture, distribute, create, multiply and store knowledge with efficiency, efficacy and effectiveness.

Historically, there has always been concern regarding retaining information and knowledge. From the stone age, cave paintings taught how to build weapons, portrayed the conviviality and pictured about the fire. In the same way, a few millennia before Christ, Mesopotamian peoples used imprinted symbols to disseminate their history, technologies and events. Another great example of knowledge management, considered as a model for centuries even after its destruction, is the Library of Alexandria, established in the third century BC, which was part of Mouseion, which means Museum, a religious and scientific institution that fostered a great number of researches. Much more than just a library, the strategy adopted by the managers of that time enabled it to become a nucleus of knowledge in various areas of culture, and as so it remained for several centuries.

Just like the Library of Alexandria, the Nuclear and Energy Research Institute (IPEN) exists with the mission of developing research and transmitting knowledge and information about the nuclear area, also exposing its multidisciplinarity. Founded in 1956 as the Institute of Atomic Energy (IEA), it opened the first research reactor in the southern hemisphere, and later sought to achieve Brazilian autonomy in the production of radioisotopes and nuclear fuel [3].

Despite the development in IPEN projects, no knowledge management plan was previously considered. Just like other major secular research institutions, a fraction of the knowledge has been lost over time, so that later decommissioned facilities would not have sufficient information records to prevent safe decommissioning from being costly and time consuming.

The objective of this work is to evaluate how the knowledge management strategy and science can contribute in the long term for the preservation of information that guarantees the safety of nuclear installations in their decommissioning processes.

The History of IPEN

The Nuclear and Energy Research Institute (IPEN) was founded under Decree No. 39872 of August 31, 1956, at the time under the name of Institute of Atomic Energy (IEA), after

Juscelino Kubitschek assumed the presidency of Brazil. Since the beginning, the growth of IPEN has been associated with IEA-R1, the first Brazilian research reactor, which came into operation in 1957, and had its official inauguration on January 25, 1958 (Figure 1). This reactor was provided by the United States through the “Atoms for Peace” program [4].

Figure 1 - President Juscelino Kubitschek activates the lever that starts the IEA-R1 nuclear reactor, during its official inauguration. The Governor of São Paulo at the time, Jânio Quadros, is watching. Source: [4].

Virtually since the beginning facilities for research and development started to be built, either in pilot plant or laboratory, for the different processes in the nuclear fuel cycle of uranium and thorium. The first laboratory-scale studies date back to 1959, carried out at the time in the Division of Radiochemistry of the IEA. The first uranium concentrate, known as yellow-cake, was supplied by Orquima business corporation, through the National Nuclear Energy Commission (CNEN), created in October 1956.

Orquima industrialized the uranium obtained from monazite sands. Since that time, IEA has developed several activities related to the fuel cycle initiated from the yellowcake, up to the present day at IPEN, resulting in the technology of producing silicide-based dispersion fuel plates (for MTR type research reactors, such as IEA-R1), and fuel based on UO2 pellets (for PWR type power reactors).

In 1960 a pilot unit for the purification of uranium concentrates was designed and installed, for training and preparing professionals specialized in uranium chemistry. In that decade the construction of the subcritical nuclear reactor (RE-SUCO) of the Federal University of Pernambuco took place, and the IEA Nuclear Metallurgy Division manufactured the UO2-based fuel elements for the reactor [5].

From 1960 on, in the IEA Nuclear Metallurgy Division, the development of another type of dispersion-based fuel began to be studied, for application in research reactors of swimming pool type. Between 1964 and 1965 the fuel elements were manufactured for the core of the Argonauta Reactor of the Institute of Nuclear Engineering (IEN). The U3O8 powder used was obtained from the United States through the International Atomic Energy Agency, under the “Atoms for Peace” program. Despite the low technological requirements of the Argonauta reactor fuel, the group responsible for it planted a seed that would germinate 20 years later in the 1980s, when IPEN dominated this manufacturing technology and started producing the fuel for its research reactor IEA-R1, which required a significant technological advance in manufacturing techniques.

In 1968 the Uranium Purification Pilot Plant was completed, which went into operation in 1969. This pilot unit fulfilled the purpose of evidencing the purification process.

The Brazilian government had the ambition to develop its own nuclear technology through a gradual process of technology transfer from an international partner that already dominated the entire nuclear fuel cycle. The difficulties in the transfer of technology imposed by the United States, particularly in the area of uranium enrichment, led the government to start dealing with West Germany, with the intention of deepening the scientific cooperation between the two countries. In 1975, the Minister for Foreign Affairs of the Federal Republic of Germany and the Brazilian Minister Antônio Azeredo da Silveira signed in Bonn the “Agreement on Cooperation in the Field of Peaceful Use of Nuclear Energy”, which covered practically the entire cycle, including:

- Prospection, extraction and processing of uranium ores;
- Conversion to UF6;
- Enrichment through the centrifugal jet;
- Reconversion of UF6 into UO2;
- Manufacture of pellets and assembly of fuel elements;
- Construction of 8 nuclear reactors of 1300 MWe over a period of 15 years;
- Reprocessing spent fuel [6].

In exchange, Brazil undertook to pay Germany the amount of 10 billion dollars, and to intensify its works on prospection, research, exploration and commercialization of natural uranium, with the objective of guaranteeing to the new partner a minimum quota of uranium ores for supplying the nuclear power plants in Germany. In fact, the nuclear agreement with Germany, besides projecting West Germany as a supplier of equipment and services in a market previously dominated by the United States, also enabled the implementation of the first large-scale program of peaceful use of atomic energy for a developing country.

At the same time, the former Brazilian Company of Nuclear Technology (CBTN) was transformed into a mixed economy company - Brazilian Nuclear Companies Business Corporation (NUCLEBRÁS), which, with an even broader sphere of activity, became responsible for the integrated nuclear program.

A number of other subsidiaries have been set up in the various areas of the nuclear fuel cycle, to achieve the ambitious nuclear technology transfer program from Germany.

In 1979, the Autonomous Program of Nuclear Technology (PATN) was born, directed by the armed forces: Navy, Army and Aeronautics. IPEN, which had been set aside of the official nuclear program with Germany, was included as a key component of PATN [7].

At that time an agreement was signed between the Ministry of Mines and Energy and the Secretariat of Planning, with the participation of the National Security Council and CNEN, aiming at the integration of the work carried out in the IEA in the areas of the Nuclear Fuel Cycle for the development of production technology of uranium hexafluoride (UF6). The Conversion Area emerged then as a result of the scientific and technological research and development work on the Nuclear Fuel Cycle. In 1980, the Conversion Project (PROCON) was created, an agreement between the Ministry of Mines and Energy and the Government of the State of São Paulo, for the production of UF6.

In 1981, an agreement was initiated with the Ministry of Navy, which regulates the participation of IPEN in the development program of nuclear propulsion technology, and defines an area to be assigned for the use of the Coordination of Special Projects (COPESP), currently the Technological Center of the Navy in São Paulo (CTMSP). After this agreement, the first uranium enrichment experiment is performed by ultracentrifugation, carried out in 1982 with centrifuges built entirely in Brazil. In that same year an agreement was established between the government of the State of São Paulo and CNEN, which reintegrates the activities of IPEN in the National Program of Nuclear Energy.

Continuing the development of the nuclear fuel cycle, in the 1980s the IPEN Nuclear Metallurgy Division was intensively contributing to the Navy in a joint effort to completely master the post-conversion phases of the Nuclear Fuel Cycle, increasing the efforts on the development of the reconversion, which comprises the steps of the cycle from the enriched UF6 to nuclear fuel in its final form, ready for use in the reactors.

During this period, the CELESTE Project, a set of laboratories for the PUREX (Plutonium Uranium Recovery for Extraction) reprocessing process was in progress at IPEN, with the construction of hot cells for handling the irradiated material. The CELESTE Project (Figure 2), when in operation, would produce radioactive waste with a level of activity with a higher order of magnitude than the waste which IPEN had experience with. This led to a research and training program on waste management in overseas institutions from 1982 onwards. Researchers were sent to the KfK (*Kernforschungszentrum Karlsruhe*) in Germany to study the storage and immobilization of high-activity liquid waste, and the general management of radioactive waste.

Figure 2 - CELESTE Project hot cells. Source: [8]

The first major item of the CELESTE Project waste management program was the TERRA Project, a tank park for the storage of liquid waste from the first stage of the fission product extraction. At that time, the predictions of the CELESTE Project coordinators were very optimistic about the processing capacity of the laboratory - 1.5 kg of burned fuel, with 30,000 MWd/ton. This capacity would lead to the generation of a few cubic meters of waste, with sufficient activity to require cooling during the storage, special transfer techniques and homogenization of the waste, with technologies still absent in the country, removal of radiolysis gases and thick shielding [9].

The results of the research program provided significant progress in the specialization of the staff. In 1983, the first cold operation of training in irradiated material processing technology took place. The following year, the first campaign of processing irradiated materials was carried out using plutonium samples provided by the International Atomic Energy Agency (IAEA). Nevertheless, these projects were delayed for years because of lack of resources until they were shut down in the late 1980s. The CELESTE Project laboratories were allocated to other activities or closed.

The operation of the Conversion Project - PROCON plants began in 1982 and was closed in 1997, and all the conversion technology, until the acquisition of UF6, was transferred to the Navy Technological Center in Aramar. After fulfilling its historical role, the IPEN Conversion Area enabled the development of the Brazilian nuclear technology, besides developing and encouraging the human resources area, training engineers, researchers and technicians in the execution of any operation, whether collecting scientific and/or technological data, or collection of production data involving the most diverse chemical processes that integrate the existing processing units [5].

All of these activities of the fuel cycle, culminating in the creation of PROCON, required support in the field of analytical chemistry, bolstering the creation and strengthening of a research group of unparalleled competence in this area, of international acknowledgement. In addition, PROCON acted as a dragging project for other important projects, such as the development of thorium production technology and the production of fluoride and rare-earth elements.

In the 1990s, radical changes in the Brazilian nuclear policy resulted in the discontinuation of the fuel cycle research and, ultimately, the closure of the associated pilot plants. Unfortunately, these changes interrupted decades of autonomous research and development efforts in the nuclear fuel cycle at IPEN, with significant losses for the country. Despite the existence of a local nuclear industry currently consolidated in Brazil, the difference between autonomous development and acquisition of technology must be made clear [10].

Since then, IPEN has faced the challenge of dismantling and/or decommissioning these old pilot plants. Most facilities in the nuclear fuel cycle have been discontinued since 1993. These facilities have played an important role in the technological development and staff training, with the transfer of technology to institutions in charge of "expanding" the units [11].

Activities in most pilot plants were interrupted more than 25 years ago because of the lack of resources needed to support the research. There are a number of challenges for the decommissioning and dismantling of these facilities, such as the dispersion of former operators into other activities or retirements, the lack of reliable data and designs from the premises, as most of this information resided in the operators' memory, in addition to the radioactive waste storage capacity that is already depleted in IPEN.

Some of these facilities at IPEN, for more than 25 years awaiting the decommissioning and dismantling procedures, receive timely visits from personnel of the Brazilian-Argentinian Agency for Accounting and Control of Nuclear Materials (ABACC) to verify and control the safeguarded materials.

This is a brief summary of part of the story related to these facilities and that leads us to some of the reflections that originated this work. Many questions related to the data, information, technologies and knowledge generated by these activities led to the following questions: Where are they? Are they organized? What is the safekeeping situation? Can they be recovered? The search for answers refers to the topic of Knowledge Management, an area of science that can help us optimize such management.

Knowledge Management

According to Carvalho [12], information is a set of event records within a context. Knowledge is the information that, properly processed, changes the behavior of a given system.

Knowledge needs management, storage process, care to keep its information, management and channels for its proper dissemination. Knowledge encompasses intellectual human capital, the ability to research and innovate.

Briefly, it can be said that Knowledge Management is a systematic and intentional process, being supported by the generation, codification and transmission of what is known [13].

As seen in Figure 3, knowledge can be classified into two basic types: implicit (tacit) or explicit. Explicit knowledge is the easiest to be put into words, recorded and documented, acquired, for example, by reading manuals, books and articles. The implicit (tacit) type is the hardest to be put into words and is acquired with exercise alone. Tacit knowledge is shown only by practice, just like a leader managing his/her team, a physician making a diagnosis, or a technician opting for a more appropriate method. Very difficult to quantify and explain, one can only learn from experience, from livingness [15].

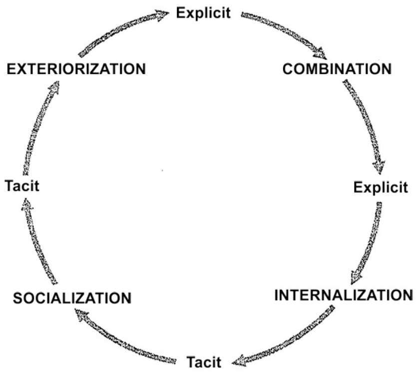

Figure 3 - Organizational knowledge conversion processes. Source: [14].

Some of the knowledge management objectives are:

- Support the generation of new knowledge;
- Identify and map knowledge and information assets linked to an organization;
- Make data accessible and useful by transforming it into information, sharing the best practices and technologies.

Some of the advantages pointed out by the adoption of a good knowledge management:

- Competitive advantage, with reduction of cost and production time;
- Greater appreciation of intellectual and human capital;
- Improvement of internal processes and greater fluidity (agility);
- More efficient decision-making processes and better results;
- Improvement of product and service quality.

The first step in management involves identifying the knowledge and defining which knowledge should be preserved. This is important for the efforts to be concentrated in the same direction, as there is knowledge that sometimes has no positive cost-benefit ratio. The next step is to transform this knowledge into processes so that, now explicit and organized, over time they are not tied to anything or anyone in particular. The third and final step is to identify which skills are important for obtaining the best results/optimization. Therefore, knowledge management corresponds to the use of a set of practices whose objective is to manage all the knowledge generated to be applied in other processes.

Some organizations face difficulties in implementing the knowledge management, such as high costs and problems in the organizational culture, as the implementation of a different culture or way of working, automating, or any kind of change, can lead to much divergence and problems. Therefore, looking forward to achieve greater effectiveness, the institution should plan and analyze every possible error so that the enterprise does not end up becoming a disorder, causing unnecessary expenses and losses to the organization [16].

In the context of this work

Essentially, "Knowledge Management (KM) is about knowledge creation, identification, apprehension and sharing. It is about getting the right knowledge in the right place at the right time, particularly if it influences an action or decision" [17].

Although information is not knowledge, it is an important aspect of knowledge, as it undergoes several transformations in which data is transformed into information, and information is transformed into knowledge, that is, the main feature of this management is based on data collection, which will later be processed to obtain a set of relevant information that will be aggregated and distributed in the form of knowledge within the organization [18].

As we have seen, knowledge is in the human and intellectual capital of the business, that is, in people. This is a key point in management, as it is necessary to identify and seek the best way to use this knowledge in the institution, focusing on better performance. Most of the professionals, if not all of them, who participated in activities related to the decommissioned facilities, are in other activities or no longer at IPEN. No matter the number of documents and information that still exist about the activities performed, it is necessary to recognize that part of the knowledge has been lost, as the intellectual capital is no longer available, that is, implicit knowledge. Therefore, it is understood that Information Management, combined with Knowledge Management, is a means and not an end to the success of a strategy.

In the past, the companies used to keep their knowledge well-kept and of restricted access, but with Knowledge Management the information is now transformed into knowledge and made available to any interested party. The key is to spread it throughout the organization, and not restrict it anymore [19]. At IPEN, part of the activities and practices established in these facilities are documented, however there is an inherent difficulty in finding them, as this information was considered to be restricted and of a confidential nature. Consequently, there is a challenge in knowing where they are.

The current moment is certainly not the most correct one, as the one mentioned by Servin [17], since the majority of the human capital involved in the activities of the facilities in question is no longer part of the group that is currently operational at IPEN.

The institution or company that intends to implement Knowledge Management needs to have clearly defined its strategic objectives and its vision for the future, as this will define the guidelines for which knowledge will be of interest to maintain or preserve. All the knowledge generated, when preserved, generates a cost inherent to the process and needs to be evaluated for its effective storage. Although it seems simple, this phase of implementation is fundamental to the success of this Management.

Therefore, this is a different situation, because in fact the proposal is to find the knowledge that was developed at that time, when there were no clear guidelines on strategic objectives or policies to do so. Once found, it is necessary to identify what is really important for the nuclear area, considering the current Brazilian nuclear policy and the interests of the institution, and to structure it in order to maintain it available for future generations or businesses. This will also allow to define profiles and competencies of potential future employees, establishing the minimum knowledge each one will need to develop for business participation. This practice is also known as Competency Management. The better this knowledge known by the employees, the greater the chances of improving business-related work processes.

One of the greatest challenges for the organizations is to apply the knowledge management in a way that is aligned to the business, directed to their strategic goals. There is no point in implementing the knowledge management without thinking about which results to achieve. Otherwise, knowledge management has little impact [20].

Final remarks

In view of the aspects presented in relation to the science of Knowledge Management, it is understood that the decommissioning and dismantling processes of the facilities that had their operations closed at IPEN in the 1990s would have been benefited today if the information needed to identify the premises, radioactive materials and plant operations planning had been transmitted, or even registered in accessible documents.

This is a work still under development, but in light of what has been analyzed so far, it is understood that it is necessary for IPEN to define or evaluate whether its strategic objectives already incorporate the aspects related and resulting from what these facilities have aggregated of technologies and knowledge, to clearly establish the need to implement the Knowledge Management, and also elaborate the policy for such making.

Knowledge Management is already available for application in multidisciplinary fields and may well be used in the nuclear area. The institutions should just consider the future, evaluating over time which information is important, and how it should be stored in a way that could be accessible when needed.

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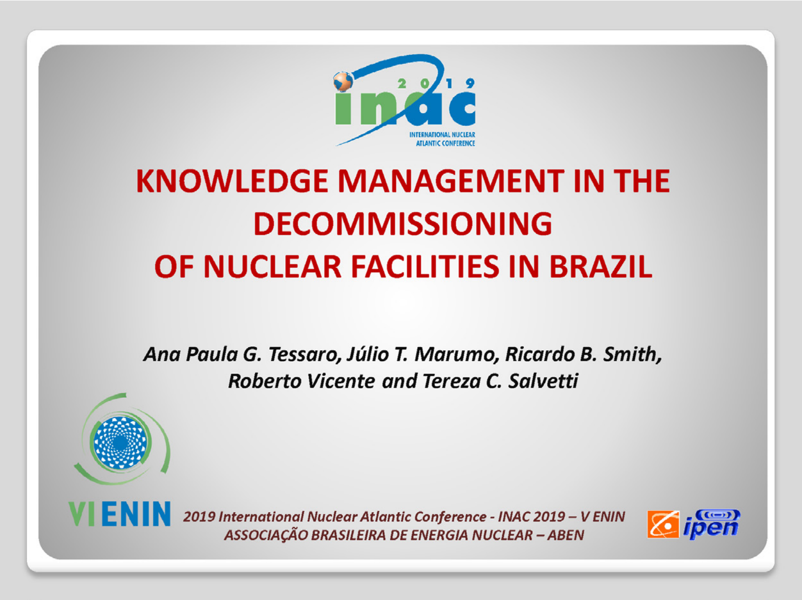

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KNOWLEDGE MANAGEMENT IN THE DECOMMISSIONING OF NUCLEAR FACILITIES IN BRAZIL

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Plutonium-238: The Fuel Crisis[10]

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Abstract: Plutonium-238 is currently still the best fuel to power satellites to be sent to deep space in regions where the solar panels can no longer efficiently receive the sunlight. For 50 years, the National Aeronautics and Space Administration (NASA) has used this radioisotope as a fuel in radioisotope thermoelectric generators (RTGs) installed on satellites such as Pioneer 10 and 11, Voyager 1 and 2, Cassini-Huygens and New Horizons, as well as the various rovers sent to the Moon and to Mars, among others. Plutonium-238 is not a naturally occurring isotope on the planet, it was produced in greater quantity during the Cold War period, as a byproduct of the production of Plutonium-239 used for nuclear bombs. However, after the shutting down of the Savannah River reactors in 1988 and the ending of the Soviet Union in 1991, the United States stock of Plutonium-238 has been increasingly reduced, which threatens NASA's future space projects. Commentaries on the options available to the United States, from restarting the production of this fuel, to possible alternatives for a new type of fuel or equipment that may supply the spacecrafts, are also presented.

Resumo: O plutônio-238 ainda é atualmente o melhor combustível para alimentar satélites a serem enviados ao espaço sideral, em regiões onde os painéis solares não podem mais receber a luz do sol com eficiência. Por 50 anos, a National Aeronautics and Space Administration (NASA) vem usando este radioisótopo como combustível em geradores termoelétricos de radioisótopos (RTGs) instalados em satélites como Pioneer 10 e 11, Voyager 1 e 2, Cassini-Huygens e New

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Horizons, bem como nos vários “rovers” enviados à Lua e a Marte, entre outros. O plutônio-238 não é um isótopo de ocorrência natural no planeta, foi produzido em maior quantidade durante o período da Guerra Fria, como subproduto da produção do plutônio-239, usado para bombas nucleares. No entanto, após o fechamento dos reatores do rio Savannah em 1988 e o fim da União Soviética em 1991, o estoque de plutônio-238 dos Estados Unidos foi se reduzindo cada vez mais, o que ameaça os futuros projetos espaciais da NASA. Apresentam-se também comentários sobre as opções que os Estados Unidos possuem, desde o reinício da produção desse combustível, até possíveis alternativas de um novo tipo de combustível ou equipamento que possa abastecer as espaçonaves.

Introduction

Plutonium-238 is a non-natural radioactive isotope and, unlike Plutonium-239, cannot be used for nuclear weapons, nor as fuel in nuclear reactors. On the other hand, it is an important fuel for space probes, especially because it is a relatively long-lived isotope, with half-life of approximately 88 years, it is an alpha particle emitter which generates a large amount of heat per unit mass, and therefore it is considered a reliable source on missions lasting up to 50 years [1]. Because of these characteristics, most of what is known about the outer planets of the solar system and their moons, is the result of the energy generated by Plutonium-238 [2].

As plutonium oxide, it is widely used by the National Aeronautics and Space Administration (NASA) as fuel for space missions whose equipment cannot depend on the solar rays when they are too far from the sun [3]. To this end, plutonium is encased in iridium capsule [4] and packaged in radioisotopic thermoelectric generators (RTGs), whose heat is then transformed into electrical current. Figure 1 shows a 5kg block of Plutonium-238, glowing in the high temperature reached by its own decay energy.

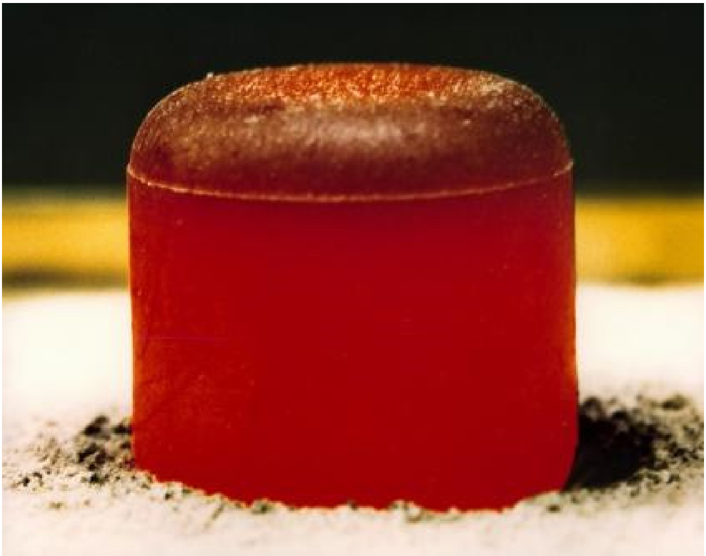

Figure 1 - Plutonium-238 made for the Cassini RTG mission to Saturn, or for the Galileo mission to Jupiter. Source: [4].

RTGs are the equipment that keeps satellites and space vehicles running because they convert the heat generated by the decay of Plutonium-238 into electricity, using devices called thermocouples. The thermocouple consists of two plates, each one made of a different metal that conducts electricity. The union of these two plates forms a closed electrical circuit, and by keeping the two junctions at different temperatures, it produces an electric current. Each of these junctions forms an individual thermocouple. In an RTG, the radioisotope fuel heats one of the junctions while the other remains unheated, being cooled by the space environment or a planetary atmosphere [5].

The first Plutonium-238-powered RTG sent by NASA into space was the SNAP-3B in 1961. Since then, RTGs have been used in Pioneer 10, Pioneer 11, Voyager 1, Voyager 2, Galileo, Ulysses, Cassini, New Horizons and the Mars Science

Laboratory, as well as the Curiosity robot, sent to planet Mars in two Viking modules, in addition to the scientific experiments left on the moon by the Apollo 12 and 14 to 17 crews [6].

Historically, the United States have produced Plutonium-238 primarily in two nuclear laboratories, generated as a byproduct of the production of Plutonium-239 to be used in bombs. At Hanford Site operations in Washington State, the Plutonium-238 was left mixed in a cocktail of nuclear waste. On those developed at the Savannah River Site in South Carolina, on the other hand, there was extraction and refinement of over 160 kilograms of such radioisotope during the Cold War to power NASA spacecrafts, as well as spy tools and spy satellites.

Both facilities were decommissioned in 1988, when the United States and the Soviet Union began dismantling their nuclear war facilities, and no further American production of Plutonium-238 was made. Russia still continued to remove plutonium from burnt nuclear reactor fuel at the Mayak nuclear industrial complex. In 1993 they sold their first batch to the United States, weighing 16 kilograms, for more than $ 1,500 a gram. Therefore, Russia became the only supplier on the planet. It is estimated that in 2005 the United States Department of Energy (DOE) had just about 10 kilograms reserved for future NASA missions. And to make matters worse, in 2009 Russia refused to agree to sell other 10 kilograms to the Americans; it is not known if it was because there was no more availability, but since then the Russians no longer provide plutonium [2].

With its inventory reduced and committed to already announced future missions, NASA banned new mission projects that would use Plutonium-238 fuel RTGs until a solution was found.

Given the situation above and based on a literature review on the subject, this paper aims to discuss the alternatives that have been used for the new production of Plutonium-238.

Alternatives

From 2013 on, NASA signed a contract with DOE to reactivate the production of Plutonium-238 at Oak Ridge. Such production, however, begins at the Idaho National Laboratory in Idaho Falls, where the Neptunium-237 isotope is chemically extracted from spent nuclear fuel.

The neptunium is then sent to the Oak Ridge National Laboratory (ORNL), where it is compressed into pellets in the shape and size of a pencil eraser. The pellets are then fitted one by one into long aluminum tubes, and taken to one of the lab's most historic buildings: High-Flow Isotope Reactor, the site of the largest neutron flux in the Western Hemisphere for more than 50 years (Figure 2). There is a 2.4-meter diameter beryllium cylinder with dozens of holes where the aluminum tubes with the pellets are inserted. In this way, they are fully exposed to the reactor core. After the insertion of the tubes, the entire assembly is taken into a pool, and the reactor is then turned on for 25 days. In this period, Neptunium-237 is bombarded

Figure 2 - High Flow Isotope Reactor control room, used to make Plutonium-238 in Oak Ridge. Source: [2].

by neutrons to become Neptunium-238, which spontaneously decays to Plutonium-238 emitting a beta particle.

After the completion of this procedure, the aluminum tubes are removed and taken to hot cells to remove the pellets from the tubes, and then dissolved in nitric acid. Plutonium-238 is extracted and concentrated as an oxide powder, and this powder is then compressed into fuel pellets [7]. After 30 years, the first 50g of Plutonium-238 returned to production in December 2015 [8].

It should also be noted that the procedures for measuring, mixing and pressing the powder ingredients were done manually until the beginning of 2019, when it was automated using robotic arms. This significantly reduced the technicians' exposure to gamma radiation from the neptunium oxide, and accelerated the pellet production from about 80 per week to up to 60 per day, to meet NASA's request for 1.5 kilograms of Plutonium-238 by 2025 [9]. The material is then delivered to the Los Alamos laboratory in New Mexico where the fuel cells are made.

In a proposal to complement the production of Plutonium-238 for NASA, a public-private partnership led by Technical Solutions Management (TSM) presented in 2017 a project for radioisotope production using a DOE-like production line: the DOE Pacific Northwest National Laboratory (PNNL) supplies Neptunium-237, which is sent to the Chalk River Laboratories of the Canadian Nuclear Laboratories (CNL), where the packages are assembled for the reactor. Afterwards, these packages are sent to the Ontario Power Generation (OPG) Darlington reactor for irradiation, generating Plutonium-238, which is then transported back to the CNL for the chemical processes. The next stage of the project is dependent on funding [10].

These RTG power systems were improved by NASA and DOE, which developed the Multi-Mission Radioisotope

Thermoelectric Generator (MMRTG). The system is designed to be used in a vacuum of space or in the atmosphere of a planet, and has higher performance and lifetime capabilities than the previous version. It was firstly used in 2011 on the Curiosity Mars rover, which landed with success on the red planet nine months later, in 2012, and so far, remains operational [11]. The excess of thermal energy from an MMRTG can be used as a convenient and stable source of heat to maintain proper operating temperatures for a spaceship and its instruments in cold environments [5].

At NASA's Jet Propulsion Laboratory in Pasadena, California, the skutterudites, materials for the next generation of RTGs, Enhanced Multi-Mission Radioisotope Thermoelectric Generators (eMMRTGs), are being developed, as seen in Figure 3. Skutterudites have complex structures with heavy atoms such as antimony. These materials have specific characteristics that make them useful in energy production

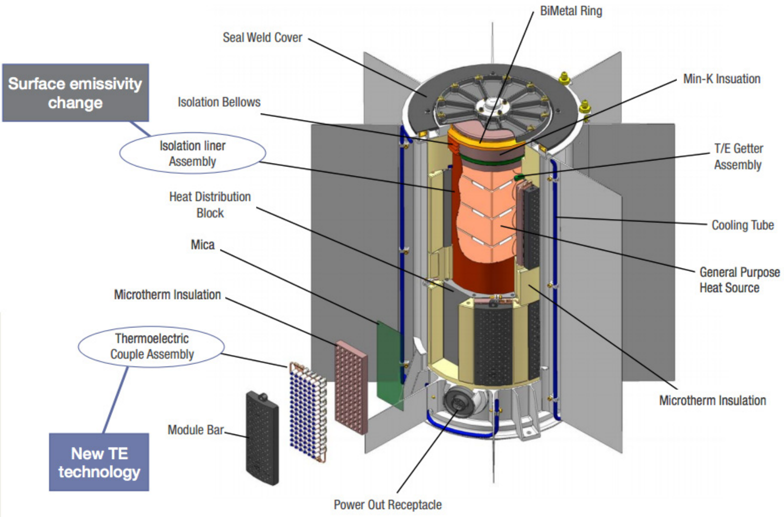

Figure 3 - Enhanced Multi-Mission Radioisotope Thermoelectric Generator (Source: [13]).

systems: they conduct electricity like metal and heat like glass, and can generate considerable electrical voltages [12].

Thermocouples made from skutterudites for the eMMRTG replace the tellurium thermocouples used in the MMRTG, with an increase in heat output from 25% to over 50%, thus requiring less Plutonium-238 [13]. The eMMRTG's debut mission has not yet been announced.

Conclusions

In recognition of the importance of Plutonium-238 production, the American Chemical Society (ACS) in November 2018 named the National Chemical Historic Landmark at the Savannah River Site Legacy Museum, in celebration also of the institution's former employees, who at the time of the Cold War worked there in secret, unable to tell family and friends what they were doing [14].

With confirmation of the return of fuel element production, in March 2018 NASA suspended the design ban on new space missions using Plutonium-238 RTGs [15]. In June 2019 NASA has announced that it will send in 2026 a Plutonium-238-powered drone to Saturn's largest moon, Titan, for checking for signs of life [16, 17].

Batteries like these have also been used on Earth in lighthouses and weather stations closer to the Arctic, where there is no other type of power source, mainly by the United States and the extinct Soviet Union. Due to the high production cost of Plutonium-238, most of the RTGs in these facilities used Strontium-90, despite presenting a shorter half-life of 28.1 years, very low energy density and emission of beta particles [18, 19].

The oil industry is also interested in RTG batteries for use at remote stations [20] and in the deep sea, especially on oil platforms. In Brazil there are evidences of Petrobras projects in this regard, but due to the state of confidentiality of such research, so far there has been no open information available to describe the operation and type of these energy sources in such circumstances.

Nuclear bombs have been of great concern to almost any individual on this planet, but nowadays they have become a dark distant memory, partly clouded after the Chernobyl and Fukushima nuclear accidents. This way, the production of Plutonium-238 no longer needs to have the obstacles and suspicions that the more easily fissile Plutonium-239 will be done again for military purposes. NASA has already secured the fuel for future outer space missions for decades to come.

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PLUTONIUM-238: THE FUEL CRISIS

Ricardo B. Smith[1], Fernanda Romero[2] and Roberto Vicente[1]

1. INTRODUCTION

Plutonium-238 (Figure 1) is a non-natural radioactive isotope that cannot be used for nuclear weapons, nor as fuel in nuclear reactors. On the other hand, it is an important fuel for space probes, being considered a reliable source on missions lasting up to 50 years [1]. Most of what is known about the outer planets of the solar system and their moons is the result of the energy generated by Plutonium-238 [2].

It is widely used by the National Aeronautics and Space Administration (NASA) as fuel for space missions whose equipment cannot depend on the solar rays when they are too far from the sun [3]. To this end, plutonium is packaged in radioisotopic thermoelectric generators (RTGs), whose heat is then transformed into electrical current [4].

RTGs are the equipment that keeps satellites and space vehicles running because they convert the heat generated by the decay of Plutonium-238 into electricity, using devices called thermocouples. The thermocouple consists of two plates, each one made of a different metal that conducts electricity. In an RTG, the radioisotope fuel heats one of the junctions while the other remains unheated, being cooled by the space environment or a planetary atmosphere [5]. They have been used since 1961 in probes such as Pioneer 10 and 11, Voyager 1 and 2, Galileo, Ulysses, Cassini, New Horizons and the Mars Science Laboratory, the Curiosity robot sent to planet Mars, among others [6].

The United States produced Plutonium-238 as a byproduct of Plutonium-239 used in bombs. The facilities which produced it were decommissioned in 1988 when the United States and the Soviet Union began dismantling their nuclear war facilities. Russia still continued to remove plutonium from burnt nuclear reactor fuel at Mayak. In 1993 they sold 16 kilograms to the United States for more than $ 1,500 a gram. In 2005 the United States Department of Energy (DOE) had just about 10 kilograms reserved for future NASA missions. And to make matters worse, in 2009 Russia refused to agree to sell other 10 kilograms to the Americans [2]. NASA banned new mission projects that would use Plutonium-238 fuel RTGs until a solution was found.

Given the situation above and based on a literature review on the subject, this paper aims to discuss the alternatives that have been used for the new production of Plutonium-238.

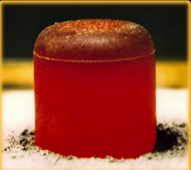

Figure 1: Plutonium-238 made for the Cassini RTG mission to Saturn, or for the Galileo mission to Jupiter. Source: [4].

Figure 2: High Flow Isotope Reactor control room, used to make Plutonium-238 in Oak Ridge. Source: [2].

2. ALTERNATIVES

From 2013 on, NASA signed a contract with DOE to reactivate the production of Plutonium-238 at Oak Ridge. Such production, however, begins at the Idaho National Laboratory in Idaho Falls, where the Neptunium-237 isotope is chemically extracted from spent nuclear fuel.

The neptunium is then sent to the Oak Ridge National Laboratory (ORNL), where it is taken to a beryllium cylinder at the High-Flow Isotope Reactor, the largest neutron flux in the Western Hemisphere for more than 50 years (Figure 2). The cylinder is then taken into a pool, and the reactor is turned on for 25 days. In this period, Neptunium-237 is bombarded by neutrons to become Neptunium-238, which spontaneously decays to Plutonium-238. After that, the aluminum tubes are dissolved in nitric acid. Plutonium-238 is extracted and concentrated as an oxide powder, which is then compressed into fuel pellets [7]. After 30 years, the first 50g of Plutonium-238 returned to production in December 2015 [8]. The procedures for measuring, mixing and pressing the powder ingredients were done manually until the beginning of 2019, when it was automated using robotic arms [9].

As a way to improve the engines at space, NASA and DOE developed then the Multi-Mission Radioisotope Thermoelectric Generator (MMRTG). The system has higher performance and lifetime capabilities than the previous version. It was firstly used in 2011 on the Curiosity Mars rover, which landed with success on the red planet nine months later and so far remains operational [11].

At NASA's Jet Propulsion Laboratory in Pasadena, California, the skutterudites, materials for the next generation of RTGs, the Enhanced Multi-Mission Radioisotope Thermoelectric Generators (eMMRTGs), are being developed, as seen in Figure 3. Skutterudites have complex structures with heavy atoms such as antimony: they conduct electricity like metal and heat like glass, and can generate considerable electrical voltages [12], and with an increase in heat output from 25% to over 50%, thus requiring less Plutonium-238 [13]. The eMMRTG's debut mission has not yet been announced.

3. CONCLUSIONS

In recognition of the importance of Plutonium-238 production, the American Chemical Society (ACS) in November 2018 named the National Chemical Historic Landmark at the Savannah River Site Legacy Museum, in celebration also of the institution's former employees, who at the time of the Cold War worked there in secret, unable to tell family and friends what they were doing [14].

With confirmation of the return of fuel element production, in March 2018 NASA suspended the design ban on new space missions using Plutonium-238 RTGs [15]. In June 2019 NASA has announced that it will send in 2026 a Plutonium-238-powered drone to Saturn's largest moon, Titan, for checking for signs of life [16].

Nuclear bombs have been of great concern to almost any individual on this planet, but nowadays they have become a dark distant memory. This way, the production of Plutonium-238 no longer needs to have the obstacles and suspicions that the more easily fissile Plutonium-239 will be done again for military purposes. NASA has already secured the fuel for future outer space missions for decades to come.

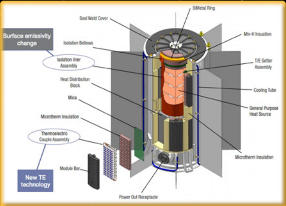

Figure 3: Enhanced Multi-Mission Radioisotope Thermoelectric Generator (Source: [13]).

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Determination of Potassium-40 in some Beer Styles[11]

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Abstract: The radiation from radioactive isotopes of the natural radioactive series of thorium (Th-232) and uranium (U-238 and U-235), as well as radioactive potassium (K-40), are the major contributors of natural terrestrial radiation. The K-40 is a radionuclide that occurs naturally in a fixed ratio with the stable potassium. Potassium is an essential element for humans and its concentration in the body is controlled by metabolic processes. Beer is a highly widespread drink and is consumed worldwide. One of the great characteristics of the variety of beers, in their styles, is the possibility of using innumerable ingredients in their production, such as different fruits, seasonings, leaves and roots, grains, malts and hops, and the choice of ingredients can interfere directly in their properties. The present study presents the K-40 determination in beers with different styles applying the technique of analysis by gamma spectrometry. Reference material IAEA-327-Soil was analyzed for validation of the methodology. The results differ mainly due to the different raw materials used in the beer production.

Resumo: A radiação de isótopos radioativos das séries radioativas naturais do tório (Th-232) e do urânio (U-238 e U-235), bem como o potássio radioativo (K-40), são os principais contribuintes para a radiação terrestre natural. O K-40 é um radionuclídeo que ocorre naturalmente em uma proporção fixa com o potássio estável. O potássio é um elemento essencial para o ser humano, e sua

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[11] Poster presented at the 2019 International Nuclear Atlantic Conference (INAC) on October 21-25, 2019 in the city of Santos, SP., Brazil. Available at: <https://inis.iaea.org/search/search.aspx?orig_q=RN:51010417>.

concentração no corpo é controlada por processos metabólicos. A cerveja é uma bebida muito difundida e consumida em todo o mundo. Uma das grandes características da variedade de cervejas, em seus estilos, é a possibilidade de se utilizar inúmeros ingredientes em sua produção, como frutas diversas, temperos, folhas e raízes, grãos, maltes e lúpulo, e a escolha dos ingredientes pode interferir diretamente em suas propriedades. O presente estudo apresenta a determinação do K-40 em cervejas de diferentes estilos aplicando a técnica de análise por espectrometria gama. O material de referência IAEA-327-Solo foi analisado para validação da metodologia. Os resultados diferem principalmente devido às diferentes matérias-primas utilizadas na produção de cerveja.

Introduction

Radioactive isotopes (radionuclides) are naturally present in the environment and in all kinds of matter. Radiation originates from radioactive materials found in soil, water and air, and can be detected in food and beverages such as beer, with the concentration of natural radionuclides varying according to several factors, such as local geology, climate and agricultural practices [1].

The radiation from radioactive isotopes of the natural radioactive series of thorium (^{232}Th) and uranium (^{235}U and ^{238}U), as well as the radioisotope of potassium (^{40}K), are the major contributors of natural terrestrial radiation [2]. Potassium-40 (^{40}K) is a radioactive isotope of potassium which has a half-life of 1.251×10^9 years. In approximately 89.28% of the decays, it turns into Calcium-40, and in 10.72% it decays to Argon-40 [3].

One of the great characteristics of the enormous variety of beers, in their styles, is the possibility of using the most different ingredients in their production: hops, malts, fruits and condiments, leaves and roots, grains, sky is the limit in the choice of ingredients, and it is up to the brewer to tailor the proportions and combinations in order to create a unique and pleasurable taste. But what would be your reaction if you read it, on a beer label, that it contains radiation? “Lo, how did such thing get here on the shelf?”

Technically speaking, every food is slightly radioactive. That is because every food and any other organic compounds contain carbon, which naturally exists in a mixture of its isotopes, including Carbon-14, which is radioactive. The calculation of the $^{14}C/^{12}C$ ratio is used for Carbon-14 dating, a method for identifying the age of fossils [4].

In the United States, the measurement of radioactivity in alcoholic beverages is even one of the best methods for quality control of the origin of alcohol in alcoholic beverages: in fact, non-radioactive alcoholic beverages in the United States are illegal; they should present at least 400 disintegrations per minute (DPM) for every 750 mL [5]. That is because the US government established that alcohol for consumption must originate from vegetables, such as grapes, grains or fruits. This way, the alcohol produced from petroleum is left out. Regardless of the reasons, since petroleum alcohol is chemically identical to natural alcohol, as safe as (or unsafe, depending on the point of view) and with exactly the same taste, how then to identify the difference between the two types of alcohol?

There is only one reliable test: to measure its radioactivity. The carbon of natural alcohol is originated from plants. Plants absorb carbon from the atmosphere through carbon dioxide. Carbon dioxide from the atmosphere is radioactive, due to the continuous bombardment of cosmic rays - particles that come from space and collide with the nitrogen atoms, forming carbon-14, which is radioactive. Only one atom in a trillion carbon atoms in the atmosphere is radioactive, but that is sufficient to be detectable.

The petroleum carbon also came from the atmosphere, but it was buried tens of millions of years ago, being isolated from atmospheric radioactivity. The radioactive carbon has a half-life of about 5,700 years, and after a hundred million years, it is almost impossible to have even one carbon-14 atom left. Of course, counterfeiters could get carbon-14 somehow and inject into their drinks, but that is beyond the capacity of the vast majority of them [5].

And it is not only of ^{14}C that there are radioactive isotopes in food: in minimum proportions, a good part of the Periodic Table is also within our favorite dishes. An element that stands out is potassium, which is essential for the human being and which concentration in the body is controlled by the metabolism. Potassium-40, its radioactive isotope, is found in various vegetables and fruits, especially in bananas, papayas, beets, sweet potatoes, oats, almonds, among others.

There is even an informal measurement for comparison of the radiation between different kinds of food, and even between practically any dose rates: the Banana Equivalent Dose (BED), which is much simpler to understand than the usual radiation units of measure (becquerels, sieverts, grays or rems). After all, is there anything more obvious than a banana? [6].

A BED is equivalent to 0.1 microsievert in a radiation dose [7]. Damn, should I eat fewer bananas then? Actually, the difference between a medicine and a poison is in its dose: for you to absorb a high radiation dose from bananas, close to being lethal, you should have to eat something around 40,000,000 bananas. Do not try this at home.

Anyway, beer surely tends to be far more attractive to be consumed, in quantity, than bananas; however, unlike these, because of the alcohol in it you will surely be asleep well before the first hundred thousand.

Even water can be radioactive, containing tritium atoms (the radioactive isotope of hydrogen, with two more neutrons). Part of such water comes with the rains, which bring the tritium produced by the cosmic rays in the upper part of the atmosphere; another part is produced by nuclear reactors on the planet [8]. In case you suspect you drank too much of this water, do not worry: grab a beer! Its diuretic properties will readily remove the excess tritium from your body [9].

The ethanol alcohol is a scavenger of free radicals caused by radiation, and therefore it is considered a radioprotector. However, this is of academic interest only and not suitable for clinical applications, because of its toxicity at radioprotective concentrations [10], [11]. Monobe and Ando [12] have shown that beer intake reduces chromosomal aberrations induced by radiation. However, another study found that the radioprotective effects of beer are not due to the alcohol contained in it, but to other ingredients [13].

Actually, for millennia beer has been produced with beneficial effects for humans, especially after the introduction of hops in its manufacture, around the 12th and 13th centuries [14]. Later in the 21st century, further studies have reported several beneficial characteristics of this beverage: in Germany, Scherr and others concluded that beer without alcohol has anti-inflammatory effects [15]; at the Medical University of Vienna, Ferk and others verified that flavonoids in hops prevent the growth of cancer cells [16]; its moderate consumption aids in cardiovascular health, as presented by Constanzo and others [17]; beer reduces the probability of having kidney stones [18]; and even protects against Alzheimer’s and cognitive impairment, according to an extensive research performed at Loyola University in Chicago [19].

Besides such benefits, this study aims to analyze different styles of beers and to evaluate if the concentration of Potassium-40 activity in them differ. Let’s get down to the results:

Materials and Methods

The gamma-spectrometric analysis technique was used to determine the concentration of Potassium-40 activity in the beer samples. The IAEA-327-Soil Reference Material [20] was used for validation of the gamma-ray measurement method.

The potential of this technique permits the study of gamma emitters in a wide range of energy. In gamma spectrometry, germanium is used as a semiconductor material for the detection system. Hyperpure Germanium detectors (HPGe) are the most utilized because of the high-energy resolution and the possibility of identifying radionuclides that emit gamma radiation and determining their activities. The detectors are connected to multi-channel analyzers and appropriate software for identification and quantification of radionuclides [21].

An aliquot of approximately 280 grams of each beer was hermetically sealed in an acrylic jar for the quantification of the radionuclide.

A Gamma Spectrometry system, model GX2518 from Canberra Industries, with HPGe detector and Genie 2000 software was used for data acquisition and processing.

Results

The IAEA-327-Soil Reference Material [20] was analyzed for validation of the measurement method used. Table 1 presents the certified value for the determination of the concentration of Potassium-40 activity and the result of the analysis of the reference material, which was considered satisfactory.

Table 1 - Reference material results

Certified Concentration ($Bq.kg^{-1}$)	95% Confidence Interval ($Bq.kg^{-1}$)	Measured Concentration ($Bq.kg^{-1}$)
621	612 - 630	638 ± 27

Beer is a highly-disseminated drink of intense consumption, and can be produced from various raw materials. The main ingredients are water, barley, hops and yeast, and this variety of ingredients, as well as the inclusion of others, will differentiate them in styles.

In the present study, a variety of beers in different styles were analyzed, with a total of six different samples. In Table 2 and Figure 1, the results obtained from the concentration of Potassium-40 activity in beers are presented. The uncertainties presented are the standard deviation of measurements.

Table 2 - Concentration of Potassium-40 activity in beer samples

Style	Origin	^{40}K (Bq.kg-1)
Standard American Lager (SAL)	Netherlands	17.58 ± 2.78
Catarina Sour with Coffee (CSC)	Lauro Müller, SC.	13.32 ± 2.54
Russian Imperial Stout w/ Banana (RIS)	Poços de Caldas, MG.	34.80 ± 3.56
IPA (IPA)	Campo Bom, RS.	26.57 ± 3.22
Weissbeer (WEB)	Germany	20.30 ± 2.92
Schwartzbier (SCH)	Petrópolis, RJ.	24.64 ± 3.86

Note: Trademarks have been omitted to protect rights.

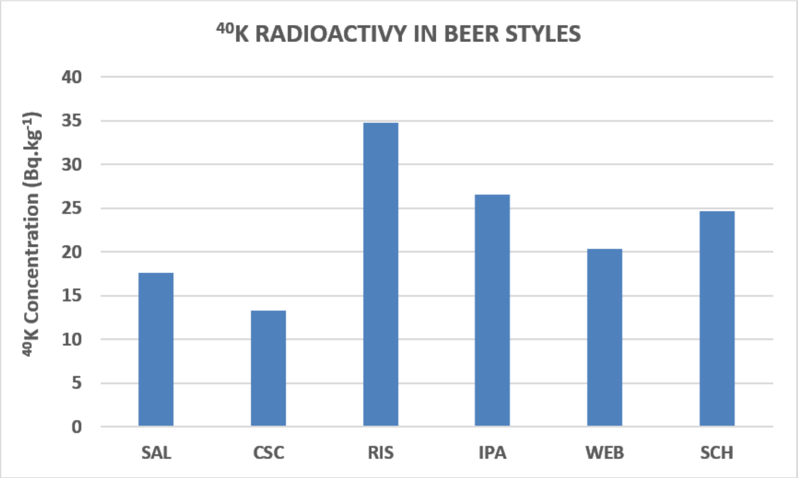

Figure 1 - Concentration of Potassium-40 activity in beer samples.

Potassium is an essential element for humans, and its concentration in the body is controlled by metabolic processes

[22]. It participates in the acid-base balance in the intracellular fluid, in the regulation of osmotic pressure, conduction of nerve impulses, muscle contraction, and cell membrane function. Its importance for human health continues being studied, emphasizing its positive effects and potential use in public health. A high intake of potassium has been shown to protect people from a number of conditions that affect the cardiovascular system, kidneys and bones [23].

The results of the concentration of Potassium-40 activity in the different styles of beers analyzed were compared by the average, with the value of 22.9 $Bq.kg^{-1}$ and standard deviation of 7.55 $Bq.kg^{-1}$ obtained, being able to conclude that there was a variation between the concentration values of potassium-40 activities in the different styles analyzed. Drinking one liter of beer corresponds, in average, to 15% to 20% of the daily intake of Potassium-40 for a normal adult.

Conclusion

After the analysis of six different styles of beers, it was possible to confirm that there were variations in the concentrations of Potassium-40 activities, which can be explained by the variety of ingredients in the production of such beers.

The world of beer is really fascinating: a plethora of new discoveries in the most unexpected areas and situations! Now you can impress your fellow brewers with this new information on radiation in beer: at the moment when you open an aging beer (aged in barrels, or even in the bottle), you can say “wow, this aroma of argon is marvelous!”...

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DETERMINATION OF POTASSIUM-40 IN SOME BEER STYLES

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1. INTRODUCTION

One of the great characteristics of the enormous variety of beers, in their styles, is the possibility of using the most different ingredients in their production: sky is the limit in the choice of ingredients, and it is up to the brewer to tailor the proportions and combinations in order to create a unique and pleasurable taste. But what would be your reaction if you read it, on a beer label, that it contains radiation? "Lo, how did such thing get here on the shelf?"

Technically speaking, every food is slightly radioactive [1] because any organic compound contains carbon, which naturally exists in a mixture of its isotopes, including Carbon-14, which is radioactive. The calculation of the $^{14}C/^{12}C$ ratio is used for Carbon-14 dating, a method for identifying the age of fossils [2].

In the United States, the measurement of radioactivity in alcoholic beverages is one of the best methods for quality control of the origin of alcohol in alcoholic beverages: in fact, non-radioactive alcoholic beverages in the United States are illegal; they should present at least 400 disintegrations per minute (DPM) for every 750 mL. That is because the US government established that alcohol for consumption must originate from vegetables and not from petroleum. But the two types of alcohol are exactly the same; there is only one reliable test: to measure its radioactivity. The carbon of natural alcohol is originated from plants, which absorb carbon from the atmosphere through carbon dioxide, which is radioactive due to the continuous bombardment of cosmic rays. The petroleum carbon also came from the atmosphere, but it was buried tens of millions of years ago, being isolated from atmospheric radioactivity. The radioactive carbon has a half-life of about 5,700 years, and after a hundred million years, it is almost impossible to have even one carbon-14 atom left [3].

And it is not only of ^{14}C that there are radioactive isotopes in food: in minimum proportions, a good part of the Periodic Table is also within our favorite dishes. An element that stands out is potassium, which is essential for the human being and which concentration in the body is controlled by the metabolism. Potassium-40, its radioactive isotope, is found in various vegetables and fruits, especially in bananas, papayas, beets, sweet potatoes, oats, almonds, among others. There is even an informal measurement for comparison of the radiation between different kinds of food: the Banana Equivalent Dose (BED), which is much simpler to understand than becquerels, sieverts, grays or rems. After all, is there anything more obvious than a banana? [4] A BED is equivalent to 0.1 microsievert in a radiation dose [5].

Damn, should I eat fewer bananas then? Actually, the difference between a medicine and a poison is in its dose: for you to absorb a high radiation dose from bananas, close to being lethal, you should have to eat something around 40,000,000 bananas. Do not try this at home. Anyway, beer surely tends to be far more attractive to be consumed in quantity than bananas; however, because of the alcohol in it, you will surely be asleep well before the first hundred thousand.

Actually, for millennia beer has been produced with beneficial effects for humans, especially after the introduction of hops in its manufacture, around the 12th and 13th centuries [6]. Later in the 21st century, further studies have reported several beneficial characteristics of this beverage: beer without alcohol has anti-inflammatory effects [7]; flavonoids in hops prevent the growth of cancer cells [8]; its moderate consumption aids in cardiovascular health [9]; beer reduces the probability of having kidney stones [10]; and even protects against Alzheimer's and cognitive impairment [11]!

Besides such benefits, this study aims to analyze different styles of beers and to evaluate if the concentration of Potassium-40 activity in them differ. Let's get down to the results:

2. MATERIALS AND METHODS

The gamma-spectrometric analysis technique was used to determine the concentration of Potassium-40 activity in the beer samples. The IAEA-327-Soil Reference Material [12] was used for validation of the gamma-ray measurement method. The potential of this technique permits the study of gamma emitters in a wide range of energy. In gamma spectrometry, Hyperpure Germanium detectors (HPGe) are the most utilized because of the high-energy resolution and the possibility of identifying radionuclides that emit gamma radiation and determining their activities. The detectors are connected to multi-channel analyzers and appropriate software for identification and quantification of radionuclides [13].

An aliquot of approximately 280 grams of each beer was hermetically sealed in an acrylic jar for the quantification of the radionuclide. A Gamma Spectrometry system, model GX2518 from Canberra Industries, with HPGe detector and Genie 2000 software was used for data acquisition and processing.

3. RESULTS

The IAEA-327-Soil Reference Material [12] was analyzed for validation of the measurement method used. Table 1 presents the certified value for determination of the concentration of Potassium-40 activity and the result of the analysis of the reference material, which was considered satisfactory. In the present study, a variety of beers in different styles were analyzed, with a total of six different samples. In Table 2 and Figure 1, the results obtained from the concentration of Potassium-40 activity in beers are presented. The uncertainties presented are the standard deviation of measurements.

Potassium is an essential element for humans, and its concentration in the body is controlled by metabolic processes [14]. Its importance for human health continues being studied, emphasizing its positive effects and potential use in public health. A high intake of potassium has been shown to protect people from a number of conditions that affect the cardiovascular system, kidneys and bones [15].

The results of the concentration of Potassium-40 activity in the different styles of beers analyzed were compared by the average, with the value of 22.9 $Bq.kg^{-1}$ and standard deviation of 7.55 $Bq.kg^{-1}$ obtained, being able to conclude that there was a variation between the concentration values of potassium-40 activities in the different styles analyzed. Drinking one liter of beer corresponds, in average, to 15% to 20% of the daily intake of Potassium-40 for a normal adult.

Table 1: Reference material results

Certified Concentration ($Bq.kg^{-1}$)	*95% Confidence Interval ($Bq.kg^{-1}$)*	*Measured Concentration ($Bq.kg^{-1}$)*
621	612 - 630	638 ± 27

Table 2: Concentration of Potassium-40 activity in beer samples

Style	*Origin*	*^{40}K ($Bq.kg^{-1}$)*
Standard American Lager (SAL)	Netherlands	17.58 ± 2.78
Catarina Sour with Coffee (CSC)	Lauro Müller, SC., Brazil	13.32 ± 2.54
Russian Imperial Stout with Banana (RIS)	Poços de Caldas, MG., Brazil	34.80 ± 3.56
India Pale Ale (IPA)	Campo Bom, RS., Brazil	26.57 ± 3.22
Weissbeer (WEB)	Germany	20.30 ± 2.92
Schwartzbier (SCH)	Petrópolis, RJ., Brazil	24.64 ± 3.86

Note: Trademarks have been omitted to protect rights.

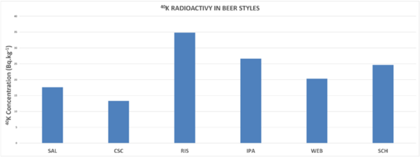

Figure 1: Concentration of Potassium-40 activity in beer samples.

4. CONCLUSION

After the analysis of six different styles of beers, it was possible to confirm that there were variations in the concentrations of Potassium-40 activities, which can be explained by the variety of ingredients in the production of such beers.

The world of beer is really fascinating: a plethora of new discoveries in the most unexpected areas and situations! Now you can impress your fellow brewers with this new information: at the moment when you open an aging beer (aged in barrels or in the bottle), you can say "wow, this radioactive aroma is marvelous!"...

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Antifragility and Radioactive Waste Management[12]

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Abstract: It is not possible to quantify the future, since it is unknown to us. Mathematical models fail when the ambiguity of facts overrides them. Nevertheless, the traditional risk management, with its difficulty in predicting elements that challenge the linear thinking, has in recent years had a strong partner: Antifragility. Unlike disciplines that seek to mitigate the risks of the unpredictable, antifragility views uncertainty as desirable and necessary. It is a recent discipline that breaks the paradigm of always being more effective and efficient; instead, the focus is on the fragile points of an institution, and how to incorporate in it the ability to get stronger over time, as it is subject to stress. Decision making is ultimately a bet. And when it comes to strategic decisions, these are usually high-risk bets because they financially affect the organization, or even the safety of a group, a city, or a country. And the vast majority of decisions are increasingly being made in situations without the full picture of a defined causal model being available. In the case of the nuclear area, it is a field of intense control due to the risk of excessive radiological exposure, and as such it requires a rigorous and continuous risk management, including the management of radioactive waste which is produced in its most various fields of action. Based on this approach, this work seeks to analyze possible fragilities in the institutional, staff and technological areas of the Radioactive Waste Management Service of the Nuclear and Energy Research Institute, in the city of São Paulo, and therefore present potential solutions under the perspective of antifragility, aiming at improving the safety of the human being and the environment.

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Resumo: Não é possível quantificar o futuro, pois ele nos é desconhecido. Os modelos matemáticos falham quando a ambiguidade dos fatos os anulam. No entanto, a tradicional gestão de riscos, com sua dificuldade em prever elementos que desafiam o pensamento linear, adquiriu nos últimos anos um forte parceiro: a Antifragilidade. Ao contrário das disciplinas que buscam mitigar os riscos do imprevisível, a antifragilidade vê a incerteza como desejável e necessária. É uma disciplina recente que quebra o paradigma de querer ser sempre mais eficaz e eficiente; em vez disso, o foco está nos pontos frágeis de uma instituição, e como incorporar nela a capacidade de se fortalecer com o tempo, uma vez que está sujeita ao estresse. A tomada de decisões é, em última análise, uma aposta. E quando se trata de decisões estratégicas, geralmente são apostas de alto risco porque afetam financeiramente a organização ou até mesmo a segurança de um grupo, cidade ou país. E a grande maioria das decisões é tomada cada vez mais em situações onde não se há a imagem completa de um modelo causal definido. No caso da área nuclear, é um campo de controle intenso devido ao risco da excessiva exposição radiológica, e como tal, requer uma gestão de risco rigorosa e contínua, incluindo a gestão dos rejeitos radioativos que são produzidos nos seus mais diversos domínios de ação. Com base nessa abordagem, este trabalho busca analisar possíveis fragilidades nas áreas institucional, de equipe e tecnológica do Serviço de Gestão de Rejeitos Radioativos do Instituto de Pesquisas Energéticas e Nucleares da cidade de São Paulo e, assim, apresentar potenciais soluções sob a perspectiva da antifragilidade, visando otimizar a segurança do ser humano e do meio ambiente.

Introduction

Radioactive waste is a problem, for many, unsatisfactorily solved so far, which has only been recognized about 60 years ago because of the expansion of the nuclear industry, but which has existed since mankind began mining on an industrial scale. It is very usual for mining and ore processing waste to contain thorium, uranium and their natural decay products. That is because the mining waste is usually radioactive because it contains radionuclides in a higher concentration than the original ore. Some of these decay products have a half-life of tens or hundreds of thousands of years; others are very toxic; still others are easily incorporated into plants or dissolved in water sources and are part of the food chain of the human being and other animals. Nevertheless, the living beings have developed some resistance to radiation, which means that there are no noticeable effects on the health of populations, with a few exceptions in the world where the amount of natural radiation is large enough and for the risk to be unacceptable.

Moreover, the nuclear industry has added to the radioactive waste of natural background a large amount of waste containing artificial radionuclides, the so-called anthropogenic radionuclides, which need to be isolated from the biosphere because of their high activity and which may cause unacceptable effects on human health and the environment. Much of this waste also has a long half-life, which makes the assurance of isolation for the time needed to decay to be not only a major technological challenge but also, surprisingly, of social relations.

Different treatments and final destinations are required for each type of radioactive waste, so that the radiological hazards, or even those of a more conventional nature, are low enough to be acceptable both today and in the distant future, while radionuclides have not yet decayed down to a level that no longer pose a danger to humans or the environment.

The ‘management of radioactive waste’, that could also be called ‘governance’, is the chain of interconnected and interdependent steps that ends with the placement of the waste back to the environment. Whatever the waste may be, its final destination is the earth’s environment. These management steps generally include: collection, characterization, treatment, conditioning, storage, transportation and, ultimately, discharge to the environment, if applicable, or disposal in a repository, all leading to the placement of waste in the environment so that the risk of negative effects on the health of humans and other living species is minimal.

In more rigorous technical terms, what needs to be minimized is not exactly the risk of introducing the waste in the environment, rather the combination of the risk and the costs incurred to keep radiation doses low enough. It is the application of the Principle of Optimization of Radiological Protection established in the regulations of each country.

Both discharge and disposal place the radioactive waste in the environment, and both of which should be applied in a way that minimizes radiological risk, but are opposite in strategy.

Discharge is the name given to the disposal of waste in any environment, such as sewage, river, landfill, atmosphere, etc. so that the radionuclides present will disperse and dilute in the environment. Although this, from the point of view of sustainability and environmental protection may seem unacceptable, it is the best solution for radioactive waste that can be ‘discharged’, that is, those for which the combination of activity and half-life allows them to be released directly into the environment in compliance with the regulations. The regulation establishes during the facility licensing process the annual discharge limits that are allowed for each physical state of the waste, for each radionuclide and for each facility. In other words, the release will be adopted when the impact on human and environment health is lower by dispersing the waste into the environment than isolating it from the environment.

The waste isolation from the environment is called disposal. It is the definitive placement of the waste in a location, without the intention of removing it, so that it gets isolated from the biosphere and that, even considering all conceivable scenarios of anthropic action or natural phenomena and processes, it is unlikely that anyone will ever be exposed to radiation from that waste or, if exposed, that the doses are so low that the corresponding health risks are acceptable.

In both the case of discharge and disposal, the risk must be less than the limits considered acceptable, set by the local regulation. In the case of radioactive waste, this risk can be estimated by the dose that the most exposed individuals will receive by their actions, and it is based on this that the limits for discharge and disposal are established.

All stages of waste management aim at discharge or disposal, and are defined so that one of these two alternatives is applied and results in the lowest risk. In the case of discharge, the most important aspects are the ways of radionuclide dispersion in the environment by which they may expose an individual to radiation, resulting in an acceptable dose. In disposal, the most important factor is the period of time of waste isolation, which is necessary for the radionuclides to decay and for the potential dose that an exposed individual would receive to be acceptable.

There is an international consensus that, for the waste that must remain isolated, the risk in the future must be, at most, the same as what is acceptable today. This is an ethical principle of protection for future generations so that they do not suffer health damage caused by radiation exposure of the waste generated today. This principle can be expressed as: the generation that has enjoyed the benefits provided by the application of nuclear technology has a moral duty to bequeath these wastes to future generations safely and without burden to them.

The questioning of what level of risk is acceptable today or in the future is also an aspect to be addressed. Different societies, and at different times, have different criteria for establishing what is and what is not acceptable, besides making incoherent choices about whether or not to take risky activities. This has been widely studied in various fields of human actions and what has been adopted as an acceptable risk in the management of radioactive waste is that corresponding to the level accepted by society in its safest activities in the world.

Considering a timescale of centuries or millennia, a review must be undertaken on the local anthropogenic actions as well as the impact of natural phenomena, such as adverse weather conditions, for example, which could deteriorate the natural and artificial barriers between the waste and the environment.

This storage period varies according to the half-life of each radionuclide and the concentration of activity in the waste. The higher these two quantities, the longer the waste will need to be isolated. There is waste that requires isolation for hundreds of years and others for millennia, so that the risk of environmental contamination and population irradiation is below the acceptable limits.

There is also international consensus that, with the current technology, isolation for a few centuries can be achieved in repositories close to the surface, by definition those built up to 30 meters deep. This destination is applied to the waste with low and medium activities, which is the one produced in the operation of nuclear power plants and the application of nuclear technology in medicine, industry, research and others, with a few exceptions.

There is also consensus that, for high activity waste generated from nuclear fuel recycling, or for some special waste from medical and industrial applications, disposal in deep cavities of more than 400 or 500 meters in appropriate geological formations ensures the isolation for the thousands of years needed for risk mitigation to reach acceptable values. In the international literature this disposal is called ‘geological disposal’.

These two types of disposal, near the surface or in a deep geological formation, have a common feature that relates to the subject of this work. It is the period of time of active control over the waste by a competent authority.

In the case of near-surface repositories, of which there are already a few dozen of them in operation in the world, there is a period of operation that lasts a few decades, during which the waste is disposed of, and after closure, there is a period of institutional control that lasts a few centuries. During the institutional control period, the repository is closed - no more waste is stored - but it remains under supervision. The institution responsible for it monitors the facility and the surrounding environment, controls the access to the site, intervenes in the event of any unforeseen occurrences, makes the maintenance of structures, regular reports, in short, it is responsible for the physical and radiological safety of the facility. By the end of the institutional control period, the waste will have already decayed to harmless levels and the repository location may be released for unrestricted land use.

An example of a near-surface repository is the one controlled by The Midwest Regional Center for Nuclear Sciences (CRCN-CO) in the city of Abadia de Goiás, Brazil, with the waste collected after remediation of the Cs-137 radiological accident in the city of Goiânia, in 1987. The institutional control of this location should be extended until the year 2298 [1].

In the case of deep repositories, at the end of operating time, which, as in the previous case, may also last a few decades, it makes little sense to foresee post-closure institutional control, because it will take many millennia for the activity to decay to harmless values. There is consensus that it is unrealistic to have expectations on an institution to last so long, and unacceptable to rely on it to ensure the safety of waste isolation in the long run. In this case, after closure, the physical and radiological safety of the repository must be of a passive nature, provided by the natural and artificial barriers interposed in the construction and closure of the facility.

Nevertheless, international experience shows that the entry into operation of deep repositories, when the waste begins to be stored, may take from many decades to even more than a century. This long period is due to the complexity and high cost of this type of facility. While not permanently placed in the repository, the waste should remain isolated in appropriate storages on the surface. Again, one or more institutions are responsible for ensuring the physical and radiological safety of this waste isolation.

What is in question, both in the case of the storage of high activity waste for up to more than a century, and in the case of institutional control of the low or medium activity repository for a few centuries, is the need for the institution to guarantee the safety of the facilities and the materials stored within. This is a physical and administrative control to ensure the effectiveness of measures taken to keep the waste isolated for as long as necessary.

The role of institutions is to ensure the stability of barriers and to analyze situations or events that may disrupt the isolation and guide the decision making, so that the establishment of preventive or, where appropriate, corrective actions avoids or at least minimizes the manifestation of damage to human health and the environment.

Institutions, agents and devices, whether natural or constructed, that work together to ensure the long-term isolation of waste, form a complex system subject to the action of stressors, both internal and external, which may incapacitate it to fulfill its function. Therefore, the long-term safety of radioactive waste can be analyzed from the point of view of engineering and system dynamics, in this case with the additional difficulty that the analysis of the forces acting on the system must extend over very long periods, farther than those in usual engineering projects.

The objective of this work is to introduce the concepts of waste management and antifragility, and reflect on the application of antifragile methods on the organization and regular procedures of waste management facilities, in search of a systematic approach that is not only stress-proof, but that over time is going to improve and strengthen the institution. Our initial focus will be at the Radioactive Waste Management Department of the Nuclear and Energy Research Institute (IPEN/CNEN), in the city of São Paulo.

Concepts

A few systems engineering concepts are going to be defined in order to properly analyze the Radioactive Waste Management Department of IPEN/CNEN. The definition of antifragility will be then introduced.

A system exists to meet needs that cannot be met by its individual components. Whether it is a department, a country's political system or an organization, the system is made up of multiple components, each one with its own specific functionality, hierarchically reunited and grouped into modules which perform functions. The functions of systems are the sum of the functions of their components and modules [2].

A system is defined as resultant if, when in operation, it presents predictable results which can be explained or reduced according to the behavior of its minor components. Otherwise, if the system has unexpected results and its behavior is not explained by its components, the system is defined as emergent. Emergence is the same as irreducibility, that is the inability to transfer methods, causalities, knowledge or explanations about the macro system to the components of its micro system, and vice versa [3].

Stressors are part of any environment in which a system operates. These stressors may compromise the functions of the system and compromise the successful completion of their assignments. If a system is functioning correctly, it is considered to be in an intended state. If the system is not working as it should, it is in an unintended state. Stressors are forces that fall outside the specified operating conditions and threaten to move a system from an intended to an unintended state [4].

In the characterization of systems in terms of their implications to stress, there are several approaches to consider, such as: risk analysis, reliability, vulnerability, and resilience. Risk analysis is a process of identifying potential risks based on the severity of the consequence and probability of occurrence. These risks are then classified, and the actions to be taken are prioritized based on objective criteria. One method option would be to rank probability and consequence on a scale of 1 to 5 [5]. A system's vulnerability is its exposure to stressors so that it will harm or wear out [6]; vulnerability is an exogenous matter of susceptibility, while fragility is an endogenous matter of weakness. The reliability factor is determined by the probability of a system to remain in an intended or faultless state while in operation [7]; systems are reliable as long as they are able to continue functioning and produce the desired results even when the operating conditions reach their extreme limits [8]. Finally, resilience is the ability of a system to quickly return to its intended or flawless state [9], or the ability of a system to absorb stress [10].

The stress created by stressors can originate from external risks, as well as from the internal interaction between system components. There are also extreme risks or dangers, located at the tails of a probability curve, occurring very rarely and that have potentially catastrophic consequences. These are usually not reducible to relationships of cause and effect. They are easily explainable in retrospect but not predictable beforehand. Risk analyst Nassim Taleb defines them as "black swans" [11].

An analysis based on the methods just mentioned seeks to improve the designs of the system; compare and identify systems that are more at risk than others; and develop strategies and policies for decision making, considering the most common risks. The general assumption in all these methods is that the dangers or stressful events will result in negative results for the system and, therefore, should be prevented.

Antifragility, however, is an approach that is not based on these assumptions; it considers the possibility that some systems may actually improve with stress. According to Taleb [12], the current management of systems prioritizes only well-known situations, with both micro and macro systems operating intentionally, and being prepared for future events that otherwise may jeopardize them. This way, if an unpredictable event such as a black swan occurs, these systems are fragile and unable to survive the impact of this event, if negative, or to perceive and take advantage of the event, if positive.

This condition of antifragility requires the system to be emergent, adaptive, have the ability to modify and make internal adjustments in response, or in anticipation, to external environmental changes. In systems with less complexity, these changes occur based on pre-established rules that enable a component to anticipate the consequences of certain actions. Based on such rules, the components respond within established constraints, without the essence of being adaptive. The complex adaptive systems (CAS), however, do not only respond to the dynamics of the environment, but they have the ability to learn from experiences [13]. Learning is different from adapting based on environmental experiences according to predefined structures based on internal sets of rules; it creates new, previously unknown, emerging structures. The CAS organizes itself and exhibits Darwinism-type or natural selection behaviors, such as those of biological systems [14]. The complex adaptive system uses intelligence to adjust its schema, and then applies the revised set of rules in future experiments. These adjustments over time allow the system to improve, as it experiences periodic risks and stress.

Taleb describes the fragile, robust and antifragile types in order to measure qualitatively how much a system has antifragility [12]. In the present work, the resilient type is considered at the same level of the robust one. From this perspective, stressors can compromise a system, demonstrating its fragility. The system can also resist the stressor, presenting its robustness, or suffer the effect of the stressor and then quickly return to its previous state, characterizing its resilience. And in the process of experiencing the stressor, the system can also react positively, take advantage of stress and somehow improve, therefore proving to be an antifragile system.

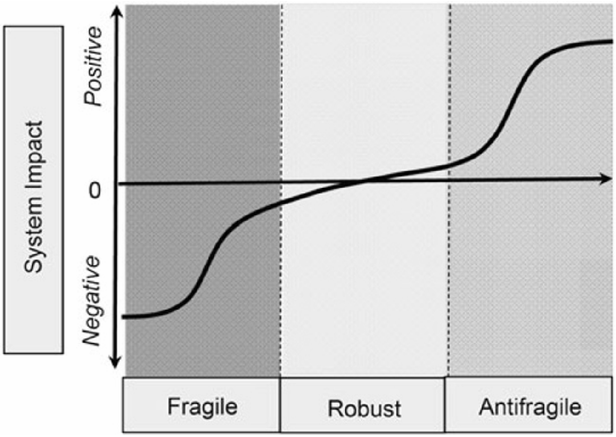

Figure 1 - Antifragility curve. Source: [15].

Johnson and Gheorghe [15] proposed the creation of an antifragility curve, as seen in Figure 1. When the system is in the Robust area, all the outcomes are known and intended. The system is operating according to design and intended expectations. As the curve moves to the left of the Robust area into the Fragile area, the stressors eventually dominate the system and the system declines in a failure state. All the outcomes in the Fragile area are unintended, but may include both known failure states and previously unknown failure states (including black swans). All the outcomes to the right of the Robust area are positive, which were previously unknown (including positive black swans).

The ability of a system to be open to the unexpected, to the unknown, is the only way to reach and collect the benefits of the serendipity.

Methods

Based on the concepts previously presented, an organization such as the Radioactive Waste Management Department at IPEN, which is also a system, in order to present antifragility in its processes, must have emergent, adaptive and complex characteristics. However, these conditions are qualitative rather than quantitative, which limits the effectiveness of a governance in intending to make a system more robust and/or antifragile. As a way around this situation, Johnson and Gheorghe [15] developed an approach with analysis criteria seeking to measure the concept of (anti)fragility of a system on a two-dimensional scale. This approach was used in a case study of an electric car manufacturer in South Africa, as described by Kennon, Schutte and Lutters [16]. The criteria used were the following:

- **Emergence**: With emergent results, there is little or no traceability between the micro and macro level results of a system; therefore, there is greater exposure to black swans due to the increase in the number of unintended states of the system.
- **Efficiency vs. Risk**: Efficiencies are often obtained at the expense of increased potential damage caused by stress. Less redundant system designs are more efficient, but also more fragile.

- **Requisite Variety**: Regulators in a system try to control the outcome and behaviors of the system. Black swans increase as a result of the insufficient number of regulators in relation to the number of agents (unpredictable behavior).
- **Stress Starvation**: Protecting a system from stress or trying to reduce uncertainty can cause weakness, fragility and expose it to dangerous black swan events.
- **Redundancy**: The duplication of components to achieve the same goal creates excess capacity in the system and is an effective tool for defenses against extreme stressors. Redundancy tends to stabilize systems and improve robustness.
- **Absorption**: Absorption in a system can be used to improve its robustness. The limits should be designed so that they increase the magnitude of the stress to be absorbed, and the length of time the system can withstand it while ensuring that it continues to operate; this way, it will increase the absorption capacity of the system.
- **Induced Small Stressors**: Some systems improve with greater exposure to stress. The controlled stress in a system can increase its robustness and potentially lead to antifragility, where the system “learns” from these controlled responses.
- **Non-monotonicity**: New information can be provided by stressors which induced negative consequences. New information can result in best practices and approaches. Stressors, when learned, can make a system better.

Next, an analysis of IPEN’s radioactive waste management system will be presented, using these criteria in an attempt to identify the fragility or antifragility of this organization.

Application

The Radioactive Waste Management is one of the departments of IPEN, which is a research facility that reports to the National Nuclear Energy Commission, which then reports to the Ministry of Science, Technology, Innovation and Communication. This work focuses only on IPEN internal processes, and a future work with a full picture that encompasses the effects of external organizations at the federal or even international level is already under development.

Based on what was previously presented, we can assume that the Radioactive Waste Management service of IPEN is somewhat limited as a complex adaptive system, because of its dependency on higher levels of federal governance. The absence of federal investments for about 30 years has shrunk the organization’s staff to less than half of employees since 1990 and most of them are close to retirement, which is probably the characteristic of greatest fragility, denoting a very low level of redundancy. The opening of hiring of new employees on an independent level according to the needs of each department could improve redundancy by reducing dependency.

With reference to the dependence of federal investments for the proper management of radioactive waste, another source of income should be provided. Every organization in Brazil that produces radioactive material must be responsible for its treatment and destination, which in most cases is to discharge it at the waste department of IPEN, and a respective fee is paid by the organization. Such income should be kept at the waste department for its own resources, instead of being forwarded to the higher levels. This is another characteristic of the low redundancy of the waste management department.

Considering that in the department of waste management of IPEN all procedures for reception, treatment and disposal of radioactive waste have already been well established, in accordance with the best practices and international safety and security standards, there is very little probability for creating unintended states for the system, therefore there is very low emergence in the department. The same occurs with the risk produced by stressors; in the technological area the chance is minuscule, with the chance for mistake only originating from the staff, who is more likely to suffer from emotional stressors.

The amount of absorption the waste management of IPEN can cope with is also very low because, as previously presented, the micro systems of procedures are all duly established and there are no different ways to perform the usual procedures of the department. This absence of absorption, allied to the low emergence, indicates the robustness of the department. Small stressors in the inner processes of the radioactive waste department do not seem to improve any situation either.

The aspect of non-monotonicity could be experienced for instance by promoting among the students the development of cases for treatment of some of the different types of waste already contained for many years in the storage facility of the department, aiming at new procedures for reducing the waste volume.

Conclusions

After this brief analysis we have come to the conclusion that the IPEN waste management department is a robust system that has continued to perform its function for decades despite the institutional changes, especially after the end of the military period of government.

On the other hand, the dependence on income from the federal government, as well as the inability to hire new technicians according to the needs of the department, denotes its weakness. Nevertheless, as the radioactive waste department is part of a bigger system, it also resembles the fragility of the macro system.

The next step of this work is to extend this approach to a broader level, also including the systems thinking approach according to Peter Senge's view, and the development of a causal loop diagram with the different perspectives of the different entities and organizations involved, aiming at a more expansive, complete and realistic overview.

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- 10 -

Design Bases for Automation of a Quality Assurance System in Radioactive Waste Management[13]

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Abstract: The design, construction, operation and decommissioning of a radioactive waste management facility requires compliance with the applicable regulations for nuclear quality assurance. However, although compliance is mandatory, in some countries the requirements are outlined for every type of nuclear facility, therefore they are generic and lack details of the actions necessary to ensure that the more specific quality objectives for a radioactive waste management facility are met. Besides that, the quality assurance system of such enterprise is complex, but ready-to-use, commercially available computer tools to assist managing the processes are still needed. The available quality management software requires either adaptation through the inclusion of specific data sets from the quality control program of a radioactive waste management facility, or the development of a customized tool. Therefore, the objective of this work is to search for a brief historical background of the emergence of Quality Assurance in the nuclear area in the Western world, providing information to form the engineering bases that allow the development of a computerized quality assurance system that may assist the quality manager to assure compliance with the applicable regulation in these countries.

Keywords: radioactive waste management; quality assurance; ASME-NQA-3; DOE/OCRWM-QARD; CNEN-NN-1.16.

Resumo: O projeto, construção, operação e o descomissionamento de uma instalação de gestão de rejeitos radioativos requer conformidade com os regulamentos aplicáveis à garantia da

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qualidade nuclear. No entanto, embora o cumprimento seja obrigatório, em alguns países tais requisitos são descritos para qualquer tipo de instalação nuclear, portanto, são genéricos e não detalham as ações necessárias para garantir que objetivos de qualidade mais específicos para uma instalação de gestão de rejeitos radioativos sejam atendidos. Além disso, o sistema de garantia de qualidade desta instalação é complexo,e ainda não há ferramentas computacionais comercialmente disponíveis já prontas para o uso para auxiliar na gestão de tais processos. O software para gestão de qualidade disponível requer uma adaptação por meio da inclusão de conjuntos de dados específicos do programa de controle de qualidade de uma instalação de gestão de rejeitos radioativos, ou então o desenvolvimento de uma ferramenta customizada. Desta forma, o objetivo deste trabalho é apresentar um breve histórico do surgimento da Garantia da Qualidade na área nuclear no mundo ocidental, fornecendo informações para formar as bases de engenharia que permitam o desenvolvimento de um sistema informatizado de garantia da qualidade que possa melhor auxiliar o gerente de qualidade para garantir o cumprimento da regulamentação aplicável nesses países.

Palavras-Chave: Gestão de Rejeitos Radioativos; Garantia da Qualidade; ASME-NQA-3; DOE / OCRWM-QARD; CNEN-NN-1.16.

1. Introduction

In recent decades, nuclear technology has turned into one of the most controlled and regulated fields of all industries. An ever more stringent set of requirements for design, construction, commissioning, operation and closure of facilities has been imposed to this sector as a means to achieving and maintaining the highest levels of safety. The escalating costs that resulted from this movement toward excellence required keeping the systems optimized and as safe as possible, with Quality Assurance (QA) in all stages of a nuclear project as a key factor for success.

Radioactive waste management, while may seem like a simple activity when compared to the complexity of other enterprises such as constructing or operating a nuclear reactor, also requires a rigorous control of processes. The predisposal facilities and, especially, the final disposal facilities are committed to the assurance of safety, so that the radionuclides present in the waste can be duly isolated from the environment, until their activity decays to levels that pose acceptable risks. To this end, a quality assurance system must ensure that such facility is designed in compliance with the technical requirements; the relevant properties of the natural environment of the site are adequately characterized; the technical data upon which engineering decisions are founded are documented and retained; and the data used in the licensing procedure are valid and accurate [1-3].

The complexity of the QA system of a radioactive waste management installation may also require computerized management tools, and no products have been found commercially in their final form ready for use; there are only programs for Business Process Management (BPM), such as IBM BPM [4] and MasterControl [5], among others, which require the introduction of a specific set of waste management data, so that they can be properly applied to the QA control of a radioactive waste management facility. An analysis must be carried out in each situation regarding the most suitable option: to develop such a data set in order to adapt any of the existing commercial systems, or to develop a customized computerized system. In either case, it will be also necessary to map the processes of the installation to be controlled.

Therefore, the objective of this work is to study the emergence of Quality Assurance in the nuclear area in the Western world, providing information to form the engineering bases that allow the development of a computerized quality assurance system that may assist the quality manager to assure compliance with the applicable regulation of radioactive waste management.

2. Materials and Methods

2.1. History

The policies of QA in radioactive waste management started at the beginning of the 1980s. Before that, there was no real control of the radioactivity dumped in the environment: until 1982, drums with the radioactive waste produced by the 13 most advanced countries in the area were thrown into the deepest places in the ocean; according to the International Atomic Energy Agency, approximately 85.0 x 10^{15} Bq of radioactive waste were discharged into the ocean [6]. And regarding the 520 nuclear tests on Earth's surface, which were halted in 1963 thanks to the Partial Nuclear Test Ban Treaty, it is estimated that an order of magnitude greater than 1.0 x 10^{21} Bq of radioisotopes were dispersed in the air, with the emission of gases and aerosols [7].

The scientific and engineering communities of the radioactive waste management program in the United States of America already had recognized QA as essential for the development of radioactive waste disposal projects [8, 9]. In Europe, besides the regulations developed in each country, the importance of a robust QA approach in the field of nuclear waste management was recognized by the European Commission. Therefore, in 1982 a workgroup was created to review the status of implementation of production standards and QA of radioactive waste management there. In 1992, the European Network of Testing Facilities for the Quality Checking of Radioactive Waste Packages (ENTRAP) was founded, an independent organization that promotes European collaboration in this field, with the objective of examining "the needs, incentives, scopes and ways of implementation of a European network of national QA/QC facilities for radioactive waste products" [10].

The practices that evolved in the construction and licensing of nuclear power plants started to be applied also to waste repositories. In 1989, the American Association of Mechanical Engineers (ASME) issued the ASME-NQA-3 - Quality Assurance Program Requirements for the Collection of Scientific and Technical Information for Site Characterization of High-Level Nuclear Waste Repositories [11]. In 1990, the US Nuclear Regulatory Commission (NRC) published a guidance on the application of QA for characterizing low-level waste disposal sites [12] and, in the next year, issued a more general guidance on QA in low-level radioactive waste disposal facilities [13].

In 1992, the Office of Civilian Radioactive Waste Management of the U.S. Department of Energy issued the first version of the "Quality Assurance Requirements and Description for the Civilian Radioactive Waste Management Program – QARD/OCRWM" [14], to be applied to the Yucca Mountain repository. Finally, other steps of radioactive waste management, such as waste treatment and waste packages were the object of development of QA programs at the same time [15, 16]. The trend reached the International Atomic Energy Agency (IAEA) in 1989, with the development of a technical document on the application of a QA program in the nuclear area in general [17], and another one more specifically designated for waste disposal facilities a few years later [18].

The Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management, organized by the IAEA in 1997, is the first legal instrument to address the issue of spent fuel and radioactive waste management safety on a global scale. In Article 23, it states that "...each Contracting Party shall take the necessary steps to ensure that appropriate quality assurance programs concerning the safety of spent fuel and radioactive waste management are established and implemented" [19]. Brazil internalized it in its national legal framework in October 2006 [20].

Getting back to Europe, in 1999 the Western European Nuclear Regulators' Association (WENRA) was established, comprising the Heads of Nuclear Regulatory Authorities of European countries with at least one nuclear power plant in the construction, operation or decommissioning phase, with the objectives of developing a common approach to nuclear safety, providing an independent capability to examine nuclear safety and providing a network for chief nuclear safety regulators in Europe to exchange experience and discuss significant safety issues [21]. One of the working groups established by WENRA is the Working Group of Waste and Decommissioning (WGWD).

2.2. Regulation Framework

The application of quality assurance to a waste management project requires establishing the proper basis of design for the system. "Design basis" mean the set of conditions, needs and requirements taken into account in the design of the facility, as well as the fundamental principles upon which the project is based. Applicable design inputs shall be appropriately specified on a timely basis and correctly translated into design documents [22, 23].

The North American standard NQA-3 was developed in accordance with the structure of Federal Regulation 10 CFR 50, Appendix B [24], presenting the following control items: Organization; Quality Assurance Programs; Design Control; Procurement Document Control; Procedures, Instructions, and Drawings; Document Control; Control of Purchased Material, Equipment and Services; Identification and Control of Materials, Parts and Components; Control of Special Processes; Inspection; Test Control; Control of Measuring and Test Equipment; Handling, Storage and Shipping; Inspection, Test and Operating Status; Nonconforming Material, Parts or

Components; Corrective Actions; Quality Assurance Records; Audits. A number of countries based their own QA nuclear regulations on the NQA-3, such as Brazil [25] and Egypt [26, 27].

In the United States there is not only one regulatory commission; the commercial facilities are regulated by the Nuclear Regulatory Commission (NRC), which only uses parts of the ASME-NQA in its regulatory guides, and are subject to 10 CFR 50, while government facilities such as those of the Department of Energy (DOE) normally follow the 10 CFR 830 (Nuclear Safety Management) Subpart A (Quality Assurance Requirements). The DOE regulates its own facilities based on the use of appropriate national and international standards for the implementation of its quality assurance requirements [28].

As previously mentioned, one of the sites controlled by the DOE is the Yucca Mountain Nuclear Waste Repository Project, in the state of Nevada, which had been underway since 1987 but is still in the licensing phase. In 1982 the Office of Civilian Radioactive Waste Management (OCRWM) was created, a department that was responsible for implementing the national policy for the disposal of radioactive waste. This department elaborated a document with requirements and descriptions of procedures, the DOE/RW-0333P - Quality Assurance Requirements and Descriptions [14], with its chapters being organized in the same structure as the 10 CFR 50.

The DOE/RW-0333P document was progressively revised and updated 21 times in order to reflect the most recent technological and legal changes, until 2010 when the department was shut down due to political issues and lack of funding [29]. This document was also based on the ASME-NQA framework and adapted to the requirements of a high-level radioactive waste repository. Although this document has been designed specifically for quality assurance in the management of high-level waste, the control requirements are similar as those used in a low- and intermediate-level waste management facility.

3. Results and Discussion

As consequence of this research, an analysis of the DOE/OCWRM-QARD was performed, with the identification of the items, services and processes that should be controlled. In order to develop a specific tool that directly assists in the development of a computerized system for recording and controlling the QA system of a radioactive waste management facility, a process mapping was then carried out through the development of a set of logical algorithms in the form of flowcharts, with the procedures for application and compliance with the QA requirements of the regulation in the various activities, items, services and processes. The flowcharts were designed respecting the 3-level requirements for origin, review and approval of procedures, with a set for each of the control items of 10 CFR 50, Appendix B.

The principle of these flowcharts is to graphically represent each action that should be recorded, during the phases of design, operation and decommissioning, together with control points for verification of the data entered, whether each piece of information was correctly provided in accordance with the corresponding regulations.

Each action should be placed within a geometric shape, with arrows to indicate the direction of the flow of information. The resources used and the products that result from the process can also be included in the structure. In this work, the preset rules and standards about flowchart symbols defined by the American National Standards Institute (ANSI) in the 1960s were used. Afterwards, the International Organization for Standardization (ISO) adopted the ANSI symbols in 1970 [30]. The current standard, ISO 5807, was revised in 1985 [31, 32].

As the goal is the computerization for automation of the QA control system, the flowcharts were created in the format of software pages: the first round for data inclusion, as seen in Figure 1:

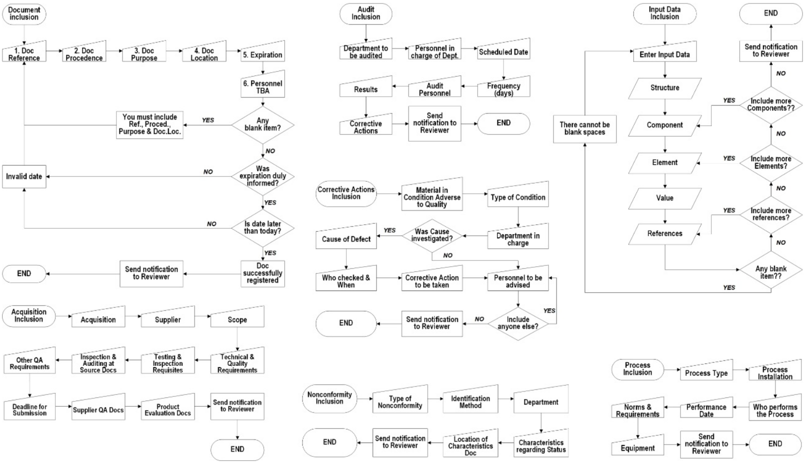

Figure 1 - Example set of flowcharts for including data.

Source: author.

The second round is for searching, consulting and editing previously added data, as presented in Figure 2; and after confirmation of the appropriate data, registration in the corresponding database and notification of the competent parties for reviewing and approval, as seen in Figure 3.

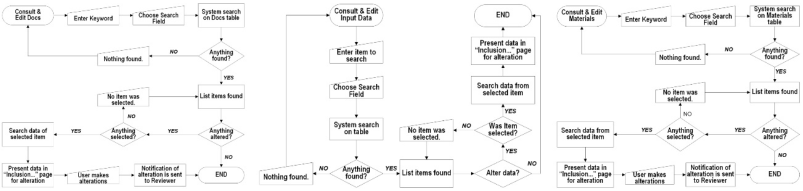

Figure 2 - Example set of flowcharts for consulting and editing data.

Source: author.

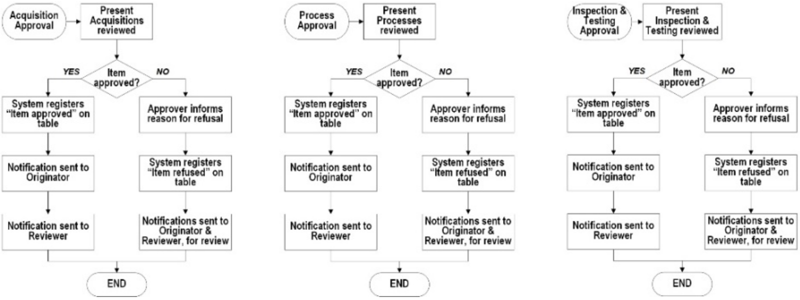

Figure 3 - Example set of flowcharts for reviewing and approval.

Source: author.

The quality control system applied to site performance and safety assessment software for the construction of repositories has already been well established through the best practices already in operation [33, 34]. Such practices can be equally used for software applied to QA in radioactive waste management, with due registration of changes in version and code, as well as verification, validation and approval in order to assure that the impact of any change is carefully assessed before updating the baseline [35].

The processes analyzed by such mapping are at the level of the most elementary operations, so that they can be properly redesigned according to the more specific procedures pertinent to each department or service of the nuclear waste management facility [36, 37]. The objective of working on this level is also to facilitate the comprehension at the time of practical use, which may allow an individual with less knowledge in the nuclear field, including a computer programmer, to understand with effortless ease the important safety procedures to be registered and controlled.

The analysis of the DOE/RW-0333P American regulation demonstrated, because of its more extensive specificity, that the information in this regulation addresses a great variety of situations in a radioactive waste management facility, which can ultimately minimize ambiguous interpretations of rule enforcement.

4. Conclusion

The results of this work with relation to the development of flowcharts and logical procedure sequences in the level of elementary operations, in spite of being primarily focused on the Brazilian regulations, may nevertheless be properly utilized for the process mapping in similar fields elsewhere. The validation of process mappings can be obtained only by considering that the confidence in the process results is increased due to the reduction of their uncertainty. This can be achieved through continuous process improvements, as new data and information become available and incorporated into progressive updates on modeling.

Although some situations need to be verified or further developed in other works, it is considered that the objectives of the present work have been met. Future studies are recommended to verify which methods should be most suitable for error mitigation and validation of the process mapping presented in this work, when applied to a radioactive waste facility. The full paper is available at the University's website [38].

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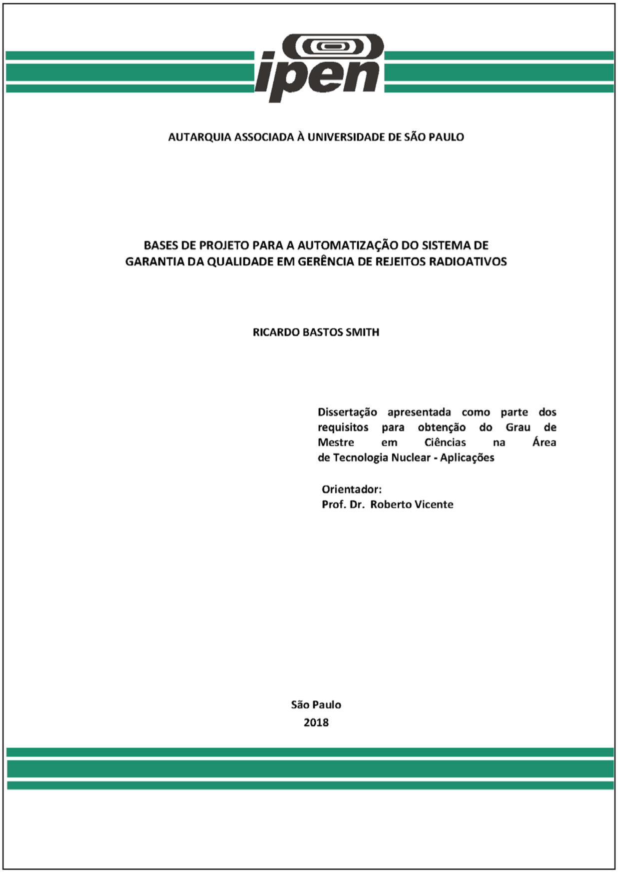

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AUTARQUIA ASSOCIADA À UNIVERSIDADE DE SÃO PAULO

BASES DE PROJETO PARA A AUTOMATIZAÇÃO DO SISTEMA DE GARANTIA DA QUALIDADE EM GERÊNCIA DE REJEITOS RADIOATIVOS

RICARDO BASTOS SMITH

Dissertação apresentada como parte dos requisitos para obtenção do Grau de Mestre em Ciências na Área de Tecnologia Nuclear - Aplicações

Orientador:
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São Paulo
2018

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