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APPLICATION OF PROBABILISTIC RISK ASSESSMENT IN NUCLEAR AND ENVIRONMENTAL LICENSING PROCESSES OF NUCLEAR REACTORS IN BRAZIL

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ABSTRACT

The nuclear accident at Fukushima Daiichi, occurred in Japan in 2011, brought reflections, worldwide, on the management of nuclear and environmental licensing processes of existing nuclear reactors. One of the key lessons learned in this matter, is that the studies of Probabilistic Safety Assessment and Severe Accidents are becoming essential, even in the early stage of a nuclear development project. In Brazil, Brazilian Nuclear Energy Commission, CNEN, conducts the nuclear licensing. The organism responsible for the environmental licensing is Brazilian Institute of Environment and Renewable Natural Resources, IBAMA. In the scope of the licensing processes of these two institutions, the safety analysis is essentially deterministic, complemented by probabilistic studies. The Probabilistic Safety Assessment (PSA) is the study performed to evaluate the behavior of the nuclear reactor in a sequence of events that may lead to the melting of its core. It includes both probability and consequence estimation of these events, which are called Severe Accidents, allowing to obtain the risk assessment of the plant. Thus, the possible shortcomings in the design of systems are identified, providing basis for safety assessment and improving safety. During the environmental licensing, a Quantitative Risk Analysis (QRA), including probabilistic evaluations, is required in order to support the development of the Risk Analysis Study, the Risk Management Program and the Emergency Plan. This article aims to provide an overview of probabilistic risk assessment methodologies and their applications in nuclear and environmental licensing processes of nuclear reactors in Brazil.

1. INTRODUCTION

The revival of nuclear energy has been threatened by the nuclear accident in Japan, and the nuclear industry still faces the challenge of ensuring a skeptical public that new reactors are safer than the older, and almost disaster-proof. The recent disaster that caused damage in four reactors of the Japanese Nuclear Power Plant Fukushima Daiichi, showed dramatically the importance and the need of the knowledge of the mechanisms of control, safety and licensing of nuclear power plants [1]. One of the key tools in this management is the Probabilistic Safety Assessment (PSA), which makes up the analysis and management of risks arising from Severe Accidents. Probabilistic Safety Assessment is the terminology used in Brazil regarding to Probabilistic Risk Assessment.

Brazil has two nuclear power reactors, Angra 1 and Angra 2, which generate about 3% of the total electricity in the country, and a third reactor (Angra 3), which is under construction. The licensing process of Brazilian nuclear reactors is carried out by two governmental agencies, as followed:

- The environmental license is managed by Brazilian Institute of Environment and Renewable Natural Resources - IBAMA.
- The environmental license is granted by IBAMA after previous judgment of Brazilian Nuclear Energy Commission - CNEN [2].

Brazilian licensing rules have undergone recent improvements, which includes the requirement of preparing and submitting levels 1 and 2 Probabilistic Safety Assessment as a document required for issuing the Construction Permit. In Level 1 PSA, the plant is analyzed in order to identify the sequences of events that can lead to core damage and the core damage frequency is estimated. It provides insights into the strengths and weaknesses of the safety related systems and procedures envisaged as preventing core damage. In Level 2 PSA, the progression of core damage sequences identified in Level 1 PSA is evaluated, including a quantitative assessment of phenomena arising from severe damage to reactor fuel. It identifies ways in which associated releases of radioactive material from fuel can result in releases to the environment and estimates the magnitude of the release of radioactive material to the environment. From this requirement, the risk of Severe Accidents, inherent in nuclear projects, will be analyzed and managed with the proper depth in the stages before implementation. This allows the elimination of possible failures related to safety in the design and construction of the plants, and the consequent improvement of the reliability in the operation of these plants.

Revisions to the regulatory recommendations of the International Agency of Energy Atomic (IAEA), the post-event international scene in Japan, normative documents of United States Nuclear Regulatory Commission (USNRC) and other international organizations concerned with nuclear area, reinforce the need for continuous review and updating of licensing procedures, safety assessment and reliability in the light of lessons learned [1]. PSA has been highlighted in these documents, and recommended its implementation as a key aspect for ensuring safety and reliability of nuclear reactors.

In this article, we see a review of the licensing process of the Brazilian nuclear power plants under the environmental and nuclear licensing, with an emphasis on methods of probabilistic safety ~~a~~ssessment and environmental risk management.

2. LICENSING PROCESS OF NUCLEAR REACTORS IN BRAZIL

2.1 General considerations

In Brazil, the licensing process of nuclear reactors is driven by two governmental agencies [3]:

- Environmental Licensing - IBAMA;
- Nuclear Authorization is issued by CNEN, which also responsible for the standardization, regulation, inspection, and promotion of research and development of nuclear technology.

Therefore, the licensing of Brazilian nuclear power plants differs on two fundamental points that the process conducted in countries with more advanced nuclear legislation. The licensing process, in these nations, have the following characteristics:

- It has only one agency responsible for both environmental and nuclear licensing;

- This agency is concerned only with normative, regulatory and licensing functions, minimizing possible conflicts, and making the most agile and quick licensing processes.

2.2 Nuclear Licensing

2.2.1 Agency and Steps of Licensing

CNEN has also the following responsibilities:
- Research and development of nuclear energy;
- Supervision of medical and industrial radioactive facilities, research institutes and nuclear power plants regarding aspects of: radioactive protection, security, safeguard, as well as storage, transport and use of radioactive and nuclear materials and wastes;
- Preparation of laws and regulations relating to the nuclear area.

The nuclear licensing process consists of several steps, regulated by the standard CNEN NE-1.04 [4]. The phases of nuclear licensing are the following:

- Site Approval;
- Construction Licensing (full or partial);
- Authorization for Use of Nuclear Material;
- Authorization for Permanent Operation.

a) Site Approval

The application of Site Approval, to be submitted to CNEN, must be accompanied by a document called Site Report, which shall contain, among others, the following information:
- Purpose and capacity of the facility;
- Relationship and quantity of radioactive materials to be contained;
- Special features that may have significant relationship with the probability or consequences of an accidental release of radioactive material;
- Safety features that will be included and restraint systems intended to prevent the release of radioactive materials or radiation;

b) Construction Licensing

b.1) General Aspects

The application of the Operating Authorization should contain, in addition to the implementation schedule of works, the following documents:
- Preliminary Safety Analysis Report (PSAR), in accordance with the requirements set out in standard CNEN NE-1.04 [4];
- Preliminary Plan for Physical Protection, according to the standard CNENNE-2.01 [5];

The granting of the Operating Authorization observes the following:
- Applicant's qualification to manage the execution of the works in accordance with legal requirements;
- Compliance with all technical instructions required;

- Minimum guarantees that the nuclear power plant can be built at the proposed site, without risks to health and safety of people involved and the environment.

With the approval of the Construction License, the licensee shall maintain close communication with the CNEN, during construction in order to report any abnormalities, alterations, delays and accidents. These communications will be made through periodic reports.

b.2) Preliminary Safety Analysis Report (PSAR)

The PSAR shall contain, among others, the following information:

- Description and safety analysis of the facility site, particularly with respect to the characteristics that affect the design and site selection criteria;
- Description and analysis of the facility, considering the design features and operation, features and innovations of the same, in addition to features related to safety;
- Preliminary design of the facility including project selection criteria and the "design basis", i.e. description of the set design variables, considering permissible values and conditions under which these variables must be controlled. This reduces the possibility of occurrence of "postulated accident", which are accidents that may occur during the life of the nuclear power plant;
- Information relating to building materials, dimensions and designs, and other important data to ensure that the enterprise is operated as the "design basis" informed, with adequate margin of safety;
- Preliminary analysis and evaluation of the project of the facility, in order to assess the risks to health and safety of the population involved. This analysis should consider the safety margins during operation of the facility, and necessary adjustments to prevent accidents and reduce the respective consequences;
- Identification and management of risks to the safety and health of workers and the population involved in the execution of works;
- Preliminary emergency plan and procedures, which must ensure the compatibility of future emergency plan with the plant site and design features. The plan and procedures must be made according to standards required by the Protection System to the Brazilian Nuclear Program (SIPRON), as well as IAEA recommendations.
- Description of the Preliminary Fire Protection Plan.

c) Authorization for Using of Nuclear Material

This authorization aims to allow the applicant to use and safekeeping of fissile material for the operation of the nuclear plant. It will be granted after the verification that the facility is properly prepared to receive this material, and meets the requirements of the standard CNEN NE-2.02 [6], specified equipment and specified material.

d) Authorization for Operation

d.1) Overview

The authorization for operation is granted in two stages, namely:

a) Authorization for Initial Operation (AOI)

The application for this permit shall include the following information: operating schedule; Final Safety Analysis Report (FSAR), as defined in the standard CNEN NE-1.04 [4]; Final Plan of Physical Protection, according to the standard CNEN NE-2.01 [5].

In order to grant the AOI, among others, the following conditions must be met:

- Completion of the construction in accordance with the laws, regulations and regulatory requirements;
- Proper warranty of operation without undue risks to the health and safety of population and to environment;
- Financial guarantee submitted by the applicant, according to the Civil Liability for Nuclear Damage Law (Law Nr. 6453/77 of 10/17/1977);

b) Authorization for Permanent Operation (AOP)

The AOP's application should consider, among others, the following documents:

- Complementary data not presented in the application of AOI;
- Report showing the development of activities and results obtained during the initial phase of operation, under the AOI;
- Demonstration that the plant is properly constructed, according to the Construction License and AOI.

The following aspects, among others, will guide the grant of the AOP:

- Ensuring that the proper conduct of the operation on a permanent basis will not bring undue risk to the health and safety of population and to environment;
- Possession of the Authorization for Using of Nuclear Material;
- Technical qualifications of the applicant Assurance, according to current legislation.

d.2) Final Safety Analysis Report (FSAR)

The FSAR should describe the facility presenting the "design basis", operating limits and the overall safety analysis of the facility and must include, among others, the following information:

- Results of environmental and meteorological monitoring programs developed since the granting of the construction license;
- Description and analysis of components and equipment, concerning facility safety issues;
- Description of items the nuclear reactor and auxiliary facilities, such as core cooling system, instrumentation and control systems, electrical systems, containment, engineered safety features, auxiliary and emergency systems, energy conversion systems, handling systems radioactive waste and fuel;
- Final analysis and evaluation of the project as built, as well as the behavior of their components, in order to assess the risk to the health and safety of the population, resulting from plant operation and considering information provided in PSAR;
- Information on the operation of the system, namely: quality assurance program of the applicant; pre-operational tests and initial operation program; driving program of normal

operation, including maintenance, monitoring, testing and periodic testing of items; identification of potential risks arising from the construction of the nuclear plant, and the necessary administrative measures to eliminate or reduce these risks;
- Description of the emergency plan.

2.2.2 New Guidelines for Nuclear Licensing of Nuclear Reactors

The Construction License for the Angra 3 plant, granted by CNEN on May 25, 2010, among others, the following conditions [7]:

- Requirement of PSA levels 1 and 2 program, considering the full implementation of it before granting the AOI;
- Requirement of a report concerning the design basis and management criteria for Severe Accidents;
- Preparation of a chapter within the FSAR, discussing the Probabilistic Safety Assessment, having been based on Chapter 19 of the regulatory standard NUREG 0800 [8].

On September 13, 2010, CNEN had required the inclusion of the PSA in the Angra 3 FSAR [9]. This PSA program is currently under review by the applicant and has not been disclosed. The report concerning the design basis and management criteria for Severe Accidents was submitted to CNEN in 2011.

The PSA requirement by CNEN in the nuclear licensing process is an important advance in Brazilian nuclear legislation since it makes mandatory the use of probabilistic methods in the safety analysis and risk management of Severe Accidents for nuclear reactors. The PSA should be fully implemented before the start of operation of Angra 3. This intends to enable the correction of possible plant failure designs and improvements in facility safety systems.

2.3 Environmental Licensing

2.3.1 Regulatory Body and Licensing Steps

IBAMA is the governmental agency responsible for environmental licensing of industrial plants [10]. In addition to this award, IBAMA shall perform, among others, the following functions [11]:

- Environmental monitoring;
- Control and monitoring of environmental quality;
- Authorization of the use of natural resources.

The National Environmental Council - CONAMA establishes the rules and regulations relating to environmental licensing. Such a body was established by Law Nr. 6938/81, which establishes the guidelines of the National Environmental Policy [12].

The environmental licensing process has three distinct steps, namely:

a) Preliminary License (LP)

The Preliminary License (LP) is granted in the planning phase and design of a new project or activity, and contains the criteria to be met in the phases of location, installation and operation. The granting of the LP should consider municipal, state and federal land use plans. The required information include, among others:

- Conception, characterization and justification of the project;
- Analysis of possible impacts to the environment and measures to be adopted for the control and mitigation of environmental risks.

b) Installation License (LI)

The Installation License (LI) is granted after assessment of documentation from Executive Project and presentation of the plans, defined programs and projects.

For approval of the LI, it is necessary to provide the evidence of compliance with the conditions of the LP, as well as the detailed project information, processes and technologies adopted for the elimination, mitigation or compensation of environmental impacts caused, as well as environmental monitoring program.

c) Operation License (LO)

The Operation License (LO) authorizes the start of the operation of the activity or project. The same will only be issued after the necessary evaluations of the operation of its pollution control systems, and meet the conditions contained in the LP and LI.

For nuclear facilities, IBAMA requires the issuance of the Construction License for the CNEN, in order to conduct the process on the LO. The IBAMA, when necessary, defines pre-operation procedures, in order to adjust and harmonize the characteristics of the project to the environmental licensing process.

2.3.2 Environmental Impact Study and Environmental Impact Report (EIA/RIMA)

For licensing activities with significant environmental impacts, the constructor must present the EIA/RIMA, as part of documents to obtain the LP.

As established by CONAMA Resolution Nr. 237/97, it is up to IBAMA check the environmental degradation potential, defining the environmental studies relevant to the respective licensing process the activity or project.

Some types of projects may be asked to carry out additional studies, incorporated into the EIA, the IBAMA criteria. This request will come included in the Reference Terms presented by IBAMA.

The Risk Analysis Study (EAR) is one of the additional studies that may be required. Risk analysis is used to assess the implementation and operation of an activity or project, with regard to the dangers involving the operation with hazardous products such as flammable toxic chemicals, explosive or radioactive materials [13]. In design phase, it is used to assess, for example, processes involving the handling of potentially dangerous products and

simulate, prior to the implementation of the activity, the possible consequences of the future operation for the population and environmental quality of the region. In projects or activities in operation, it is used to assess the dangers involving both the emission of pollutants, as the management of dangerous products and its consequences in the event of accidents, either to the employees or to public in general.

2.3.3 Current Status of Nuclear Reactor Licensing

A) General Aspects

Over the years, it is clear that recent developments in the Brazilian nuclear sector has incorporated new technologies for risk analysis, using probabilistic methods. These studies have been conducted since the design phase of the facilities. In this section, we introduce some of these studies.

B) Brazilian Multipurpose Reactor (RMB)

The Brazilian Multipurpose Reactor (RMB) is a project of a nuclear research reactor that has, among its purposes, make radioisotopes, which are the basis for radiopharmaceuticals used in nuclear medicine and for the production of radioactive sources used in applications in industry, agriculture and the environment, among others areas. Besides the production of radioisotopes, the RMB also has the basic functions to conduct irradiation tests of nuclear fuels and structural materials used in power reactors, as well as conducting scientific research with neutron beams in several areas of knowledge [14].

About production of radioisotopes for applications in medicine, the principal focus of RMB Project is the Mo-99 (Molybdenum 99m). In their radioactive decay, it produces Tc-99m (Technetium-99m), which is used as radiopharmaceuticals in nuclear medicine examinations for to diagnose tumors, cardiovascular diseases, renal dysfunction and pulmonary problems, among others.

On September 5, 2015, IBAMA granted the Preliminary License (Nr. 500/2015) for the RMB, which should be installed in the city of *Iperó, São Paulo* state. This license was granted after review and approval of the Environmental Impact Assessment (EIA) and Environmental Impact Report (RIMA) of RMB [15]. This document was accepted by IBAMA in September 2013, and submitted to public hearings in the regions close to the project [16].

The EIA/RIMA of the RMB is a composite document of four volumes. The fourth volume presents the Environmental Impact Studies, containing [15]:

- Environmental Impact Assessment;
- Environmental Programs and Environmental Compensation;
- Risk and Accident Analysis.

The following Figure 1shows a flow chart of the steps of the study. The evaluation criteria for environmental impacts were qualitative, i.e., they were assigned certain degrees of greater or lesser impact, as assessments by the team responsible for the studies. An example is presented in the following Table 1, which shows the criteria to Nature.

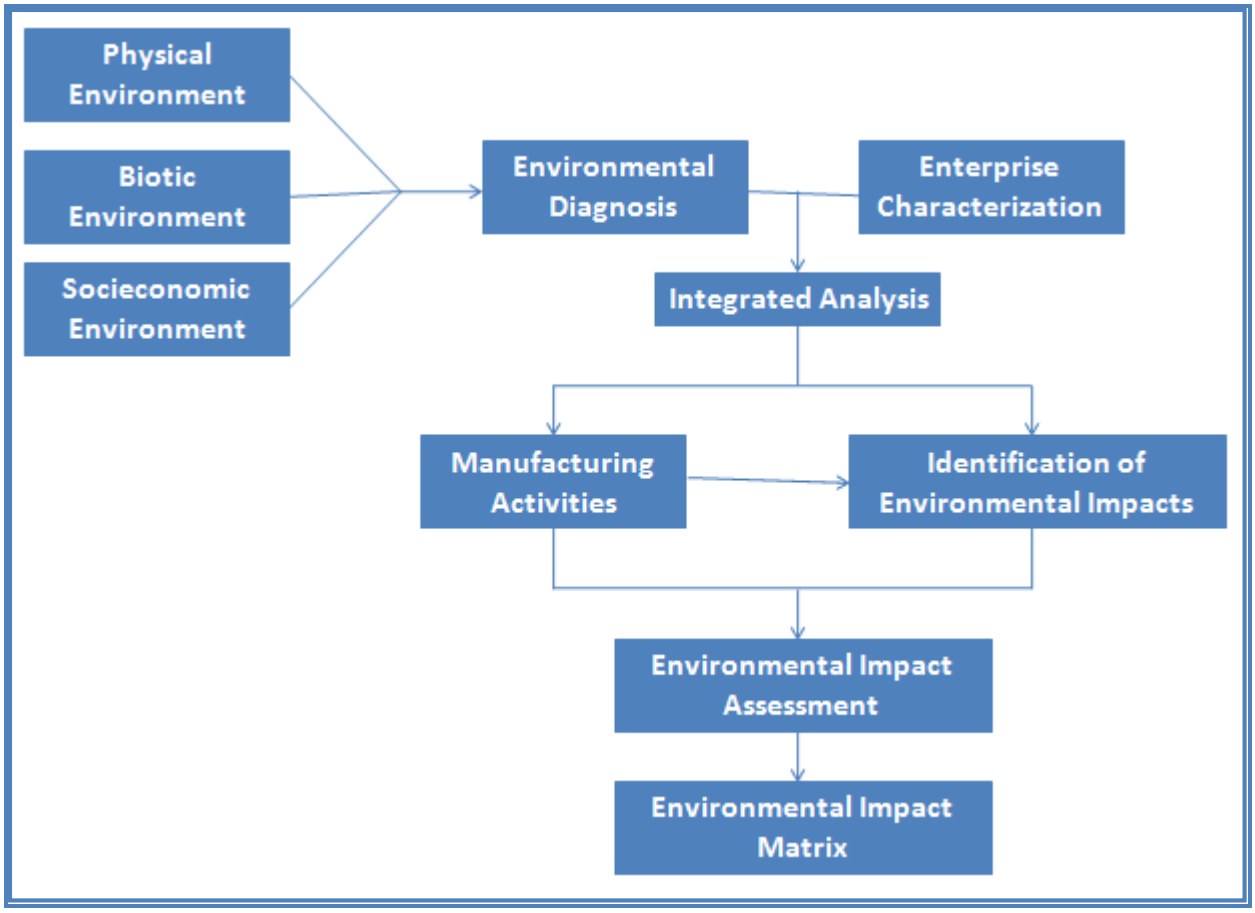

Figure 1: Stages of environmental impact assessment [15].

Table 1: Evaluation criteria environmental impact – nature [15]

Assessment Criteria - Nature	Code
Positive or beneficial	P
Negative or adverse	N

The potential environmental impacts associated with risk situations should be evaluated according to their probability of occurrence, according to following criteria:
• Certain - if there is evidence of many instances in the past (at least one case in one to two years, for example);
• Probable - if there is evidence of some events in the past (at least in one case in three or four years, for example).
• Unlikely - one whose possibility of occurrence is minimal, appearing only in exceptional cases or noncompliance.
These criteria are demonstrated in Table 2:

Table 2: Probability evaluation criteria [15]

Assessment Criteria - Probability	Code
Certain	CT
Probable	PR
Unlikely	PP

The process of evaluation of environmental impacts and their respective probabilities was made for all activities relating to the construction and operation of the RMB. The results are used for to build an Environmental Impact Matrix. From this matrix, the risk management actions were defined, leading to the Environmental Impact Report (RIMA) of the project.

3. LICENSE OF BRAZILIAN REACTORS

Some important conclusions can be pointed out, through the analysis of the regulatory requirements for nuclear and environmental licensing of nuclear reactors in Brazil. They are presented below.

3.1 Nuclear Licensing

a) Site Approval Phase

It should be noted, as the information required at this stage, the previous requirement of a risk analysis regarding the activities and installations, in order to identify and block possible emissions of radioactive material [4]. However, there is not an objective indication of the way that this analysis should be done, that is, whether deterministic or probabilistic methods for the evaluation of potential accidents will be used, and what are the tools to be developed for the quantification of probabilities and consequences thereof.

It is required that the nuclear plant to be built must have its project grounded in a reference plant of the same order of power and ensure a safe operation. However, there are no indications that the technology of this reference plant should be as updated as possible in order to ensure higher levels of safety in the design and operation, considering the nuclear technology evolution.

It is noteworthy that new nuclear power plants projects in countries like the U.S. have been preceded by Probabilistic Safety Assessment and a study of Severe Accidents [8]. However, it is not explicitly stated in Brazilian standard obligation to have these previous studies.

b) Construction License Phase

The standard CNEN-NE-1.04 [4] defines as mandatory requirement to analyze the application of the Construction License, the Preliminary Safety Analysis Report (RPAS).

This report requires, among other things, a preliminary analysis of the installation project, from the point of view of risks to health and safety of the population involved and the environment. The same will be done considering the "design basis", i.e., operational

conditions that must be controlled in order to prevent the occurrence of "postulated accidents", the accidents that could occur in a nuclear plant.

The approach in this case is deterministic, as considered in this analysis of process variables to be controlled to block the risk of postulated accidents. Severe Accidents are not considered in this study, which are accidents that can lead to the meltdown of the nuclear reactor and require a probabilistic safety assessment, including the probabilities of a series of triggering events [8].

c) Phases of the Authorization for Operation and Authorization for Permanent Operation

For these phases, one of the documents to be submitted by the applicant is the Final Safety Analysis Report (FSAR). This report presents the conclusions regarding the management of risks to the environment, health and safety of those involved. There are no references in the items provided for in FSAR, regarding the Probabilistic Safety Assessment and study of Severe Accident.

d) New Guidelines for Nuclear Licensing

After disclosure of the conditions of license of construction of the nuclear plant Angra 3, as well as the ordinance promulgated in the Official Press (DOU) [9], there is a positive outlook on the use of Probabilistic Safety Assessment (PSA) in the nuclear licensing process for new Brazilian nuclear power plants, during the design, construction and operation stages. This approach should bring greater reliability to these plants as part of prevention of severe accidents.

3.2 Environmental Licensing

For facilities with potential environmental impact, liked nuclear plants, IBAMA requires for issuing the Preliminary License, the issuance of the Environmental Impact Assessment (EIA) and Environmental Impact Report (RIMA).

The EIA is not a probabilistic analysis to study environmental risks, as is does not describe and quantifies risk according to their probabilities of occurrence and their consequences. The RIMA has the necessary actions for mitigation and elimination of environmental hazards sources by setting up so in a document management of environmental risks.

The EIA and RIMA of the Angra 3 have recently been published in site available to the public [17].These documents include, among others, the following questions:

- Technical, economic, environmental and locational justifications for implementing Angra 3;
- Identification and assessment of environmental impacts / mitigation and compensation measures;
- Safety and risk analyzes, in addition to emergency action planning inherent in the management of Angra 3.

Therefore, the EIA/RIMA of nuclear power plant Angra 3 shows an evolution in relation to nuclear power plants Angra 1 and 2, to make available to the public in general, an environmental risk analysis study for this project. However, risk analysis studies are qualitative, i.e. does not take into account quantitative estimates of probability and consequences of possible environmental accidents.

4. CONCLUSIONS

The risk analysis methods related to nuclear and environmental licensing in Brazil has been deterministic, that is, based on the study of design basis accidents and postulates, that is, accidents that may occur in adverse situations.

There is, in this case, the need of a probabilistic study of the occurrence of Severe Accidents, which are accidents that can cause the reactor core meltdown and lead to consequences that are more serious to the facility, environment, and people. These studies require the use of sophisticated mathematical models.

Despite the Probabilistic Safety Assessment (PSA) be recommended by the International Atomic Energy Agency (IAEA) and used for many years in licensing nuclear reactors located in prominent countries in the nuclear-generation, like the United States, Canada and France, the Brazilian regulations do not require the implementation of such studies in the licensing of national nuclear reactors.

From 2010, with the provisions arising from the construction license of the nuclear power plant Angra 3, this scenario should be changed. The licensing of this new plant will include a chapter on the PSA, considering the study of Severe Accidents and its management. It is expected, therefore, increased reliability and operational safety of nuclear power plants in Brazil.

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