Essays on Nuclear Energy & Radioactive Waste Management

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- 9 -
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.

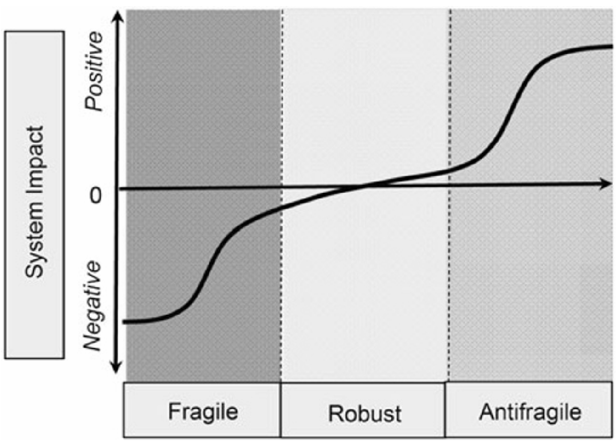

Figure 1 - Antifragility curve. Source: [15].

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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