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Methodology for safety analysis of a nuclear-powered submarine applied to the Brazilian coastal zone

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1. Introduction

The Brazilian coastal zone encompasses a terrestrial extension of over 8,500 km, and its maritime area, comprising the territorial sea, extends 12 nautical miles from the coastline [1]. The maritime portion of the coastal zone harbors natural resources crucial for the country's economic development, particularly in terms of fisheries, mineral resources, and energy, such as phosphates, oil, and natural gas. Tourism focused on aquatic activities, water sports, and maritime transport also play significant roles in the economic importance of the Brazilian territorial sea [2].

In order to safeguard this region of paramount importance to the country, the Brazilian Navy employs various naval vessels, among which submarines stand out. Submarines are ships used in strategic scenarios, playing a vital role in the surveillance and protection of the national maritime environment. Currently, the Brazilian submarine force consists of 4 operational conventional submarines. Additionally, 2 conventional submarines are under construction and testing, and 1 nuclear-powered submarine is in the design phase [3].

The nuclear reactor responsible for generating the propulsion energy in nuclear-powered submarines allows these vessels to remain submerged throughout the mission. This characteristic underscores their capabilities in terms of concealment, mobility, endurance, and autonomy. The routine presence of submarines in a country's territorial sea occurs during situations such as departure or return to naval bases, coastal patrol missions, convoy escort, among other specific operations [4].

Nuclear submarines are strategic elements in forming a fleet, capable of effectively patrolling vast coastal areas. Despite their high reliability, accidents involving nuclear-powered submarines can lead to accidental catastrophic scenarios, directly impacting social, environmental, and economic aspects. Incidents involving this type of vessel stem from various sources, with outcomes ranging from low consequence to catastrophic events, such as the loss of numerous human lives, environmental accidents, and the loss of the vessel.

Demonstrated importance of ensuring the safety of a nuclear-powered submarine equipped with an onboard nuclear plant, as an accident involving such a vessel could result in catastrophic scenarios, this study aims to propose a qualitative safety analysis applied to a nuclear-powered submarine on patrol mission in the Brazilian territorial sea.

2. Methodology

The methodology employed for the development of the present work was divided into three stages: characterization of the study object, identification and classification of risks, and detailed analysis of the most critical event. In Fig. 1, the flowchart of the proposed methodology is outlined.

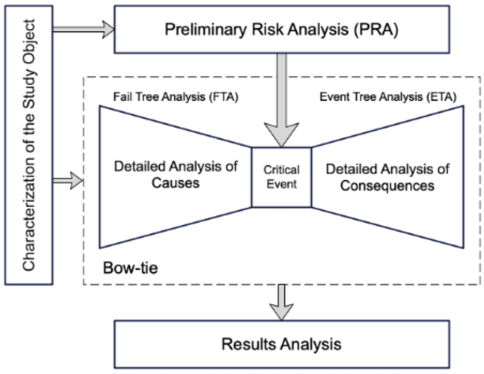

Figure 1: Flowchart of the methodological approach.

During the definition of the study object, the main characteristics of the Brazilian coastal zone and the nuclear-powered submarine were outlined. As a result, analysis premises were defined, as follows:
P1. The considered events are directly related to the safe operation of the nuclear plant.
P2. Only compartments of the ship related to the onboard nuclear plant were considered.
P3. Performance conditions of the ship during the mission were defined.
P4. The patrol operating depth was set at 60 meters.
P5. The emergency escape system was considered available.
P6. The military scenario considered in the analysis was "peacetime".
P7. Military exercises were not considered during the patrol period.

The stage of identification and classification of risks associated with the submarine's operation under the analysis conditions was developed through the use of Preliminary Risk Analysis (PRA). Due to the scarcity of information regarding adverse events associated with the operation of an onboard nuclear plant, associations were made with power nuclear plants. This allowed the identification of events associated with phenomena in the thermal cycle of the plant, events related to failures in equipment and components of the installation, and events resulting from external failures with the potential to compromise the safe operation of the onboard nuclear plant. At the end of this stage, it was preliminarily identified the main threats to the safe operation of the plant, as well as the possible causes of initiating events and their consequences. In addition, the use of the PRA technique allowed the identification of preventive barriers to initiating events and mitigating measures for the occurrence of undesirable events. Finally, risk factors were assigned to each event, and therefore the critical event posing the greatest threat to the submarine's operation on patrol in the Brazilian coastal zone was defined.

The qualitative detailing of the critical initiating event for the submarine was developed using the Bow-tie analysis model. In this method, the causes of the initiating event and preventive barriers were defined through the Fault Tree Analysis (FTA) technique, and the consequences and mitigating barriers were determined via Event Tree Analysis (ETA).

At the end of the detailing stage, the possible basic events were identified, along with the sequence of failures that would result in the undesirable event. Additionally, the potential consequences that the submarine, the onboard nuclear plant, and the ship's crew would face in the event of the critical occurrence were detailed.

3. Results and Discussion

During the development of the Preliminary Risk Assessment (PRA), 37 potential initiating events capable of compromising the safe operation of the submarine during patrol mission in the Brazilian coastal zone were identified. Based on the frequency of occurrence and severity of consequences, the risk factor was calculated for each event. Through these parameters, it was possible to construct a risk matrix and define the critical event as "fire originating from nuclear plant equipment or component". Fig. 2 illustrates the resulting risk matrix from the PRA.

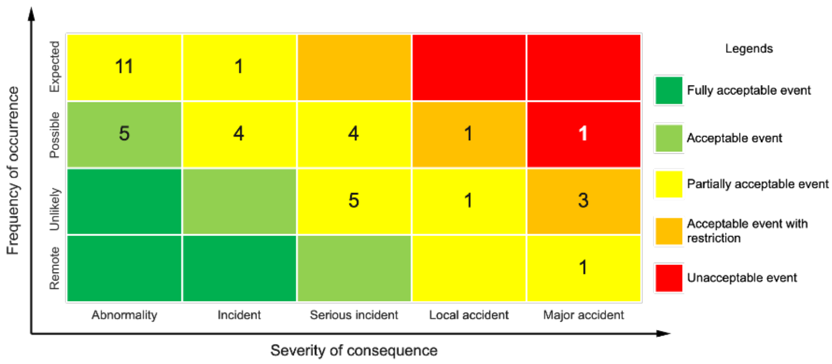

Figure 2: Risk matrix.

The detailed analysis of the critical event was conducted using the Bow-tie diagram method. The examination of potential causes for a fire initiated in the nuclear plant of the submarine began with a logical AND gate linking the presence of a heat source and a combustible agent. The oxidizing agent was not explicitly specified in the tree, given the presence of oxygen throughout the submarine's atmosphere. As a result, the FTA consisted of 1 top event, 30 intermediate events (at all levels), and 66 basic events. Overall, the findings indicated that the primary basic event with the potential to result in a fire in the onboard nuclear plant is associated with equipment and plant component maintenance procedure failures, being identified as the possible cause of the event in 9 instances (13.6%). In addition to maintenance procedure failures, it was observed that basic events related to some form of human failure, such as design/specification errors, operational failures, errors during equipment installation, imprudence during task execution, and handling of combustible materials, accounted for 36.4% of the basic events listed in the tree. Among the basic events not directly related to the human/operational interaction of the submarine, the most frequently listed events were associated with equipment/component manufacturing defects and failures in electrical protection barriers, representing 6.1% and 4.5%, respectively.

During the detailed analysis of the consequences of a fire in the submarine's nuclear plant, conducted through ETA, 39 possible scenarios were identified. These resulting scenarios were examined and categorized into four groups: minor incident (2), in which there is no harm to the crew, nuclear plant, or submarine; incident (9), where there is potential compromise to the nuclear plant or submarine equipment; accident (21), involving possible serious compromise to the nuclear plant, submarine operability, and injury/death of crew members; and severe accident (6), where there is a potential complete loss of the submarine, the onboard nuclear plant, and death of the entire crew.

4. Conclusions

The conducted studies underscored the significance of safety analysis applied to complex systems. Through the application of analytical models, potential threats to the operation of a nuclear submarine during patrol missions in the Brazilian coastal zone were identified, enabling the association of causes and consequences with undesirable events.

The employed models and techniques for risk assessment and management demonstrated practical applicability, and the obtained results were logically and visually presented, facilitating the evaluation of the analyzed scenarios and events. Specifically, the Preliminary Risk Assessment (PRA) model allowed for the identification of the most significant events affecting the ship's safety. For the academic aspect and the purpose of this work, the identification of the event "fire initiated in the nuclear plant" served as a suitable example for the detailed analysis and application of the Bow-tie diagram model. This qualitatively addressed model proved to be an effective tool in identifying possible causes and consequences of the critical event, making it possible to associate seemingly unusual causes with catastrophic events, such as the release of sparks due to static electricity in contact with a combustible agent leading to a catastrophic accident that may result in the complete loss of the submarine and death of the entire crew.

Although the qualitative assessments conducted here are not capable of probabilistically predicting the frequencies of each event, the analyses performed by the PRA and Bow-tie models provided a broad spectrum of possibilities for studying the safety of navigating a nuclear-powered submarine.

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