RELIABILITY STUDY OF THE AUXILIARY FEED-WATER SYSTEM OF A PRESSURIZED WATER REACTOR BY FAULTS TREE AND BAYESIAN NETWORK

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ABSTRACT

This paper aims to present a study of the reliability of the Auxiliary Feed-water System (AFWS) through the methods of Fault Tree and Bayesian Network. Therefore, the paper consists of a literature review of the history of nuclear energy and the methodologies used. The AFWS is responsible for providing water system to cool the secondary circuit of nuclear reactors of the PWR type when normal feeding water system failure. How this system operates only when the primary system fails, it is expected that the AFWS failure probability is very low. The AFWS failure probability is divided into two cases: the first is the probability of failure in the first eight hours of operation and the second is the probability of failure after eight hours of operation, considering that the system has not failed within the first eight hours. The calculation of the probability of failure of the second case was made through the use of Fault Tree and Bayesian Network, that it was constructed from the Fault Tree. The results of the failure probability obtained were very close, on the order of 10^{-3}.

1. INTRODUCTION

The Almirante Álvaro Alberto Nuclear Power Plant (CNAAA), composed of the Angra I and Angra II nuclear power plants, has an important participation in the technological development and in the complement of electric power supply to the Brazilian national grid. CNAAA's plants are active in power generation with the use of PWR (Pressurized Water Reactor), which is the most used reactor model in the world for the production of nuclear energy and also for the propulsion of ships and submarines. Probabilistic Safety Analysis (PSA) (Keller e Modarres, 2005) is an important tool to ensure that reliability levels estimated in the base design of an installation are maintained. Through the use of this tool it is possible to identify previously possible accidents arising from the normal operating cycle of an installation. PSA is a tool for quantifying the risk associated with the operating cycle of an installation, which can be used both in the design phase and in the operation of the installation. Through this analysis it is possible to obtain significant probabilistic data about possible failures of systems, structures and components, thus providing a numerical estimate on the safety levels that an installation is subjected to. The PSA is divided into three stages: Level 1: The design and operation of the

plant are analyzed for the purpose of identifying sequences of events that may cause damage to the core and the frequency of core damage can be determined (calculated); Level 2: Chronological progression of the event that was determined (calculated) in Level 1 and models of containment failure with the possibility of release of radioisotopes; Level 3: Quantifies the public health risk and the socio-environmental impacts of radiative release. In this work we will deal with PSA only at level 1.

The main objective of this work is to present a study on the probability of failure of the Auxiliary Feed-water System (AFWS) using the Fault Tree Technique and Bayesian Networks. The secondary objectives are: produce a bibliographic review of both methodologies; describe the AFWS; build Fault Tree and Bayesian Network of the system in question; and compare the methodologies. The relevance of this work and its main contribution are due to the comparison between two methodologies capable of estimating the probability of failure of the Auxiliary Feed-water System (Fault Tree and Bayesian Network Technique), besides the bibliographic review presented, which is a synthesis Bibliographies of the area. The organization of this work was as follows: Chapter 2 briefly summarizes the history of nuclear power plants, the origin of nuclear power and the origin of reactor safety regulations and probabilistic methods, in order to subsidize necessary information To understand the origin of the use of nuclear energy and its safety standards, in addition, it presents the history of the two methodologies used. The third chapter is composed of the description of the system used as an illustration case for applying the proposed methodology. Chapter 4 presents the methodology of Fault Tree Analysis and Bayesian Networks methodology. The fifth chapter presents both the Fault Tree and the AFWS Bayesian Network after eight hours of not failure operation and the respective results. Chapter 6 presents the final considerations and the seventh the bibliographical references.

2. HISTORICAL REWIEW

The Rasmussen Report, as the document "Reactor Safety Study" - RSS (WASH-1400), NUREG - 75/014 (WASH 1400), was created at a time when several nuclear power plants were being built, which led to nuclear reactor safety analysis becoming an issue Public security. Although Fault Trees were used for almost all major safety-related systems, it was realized that their overall analysis for an entire nuclear power plant was very complex, given the constraints of time and resources. This led to the development of the event tree. Its function was to model the approximate timeline of possible accident scenarios. This document is considered the first Probabilistic Safety Analysis (PSA). From then until the end of the 1980s over 70 PSAs were developed for power reactors around the world to show the public the low risk of Nuclear Power Plants.

The use of PSA is a safety management tool for nuclear power plants and offers immediate benefits to those who use their techniques in design and operation, and to all those involved in increasing reactor safety. The implementation of PSA can reduce the frequency of transients and accidents, and benefit the nuclear industry as a whole. (HIRATA, 2009, p.14)

The technique of Bayesian Networks was created by Thomas Bayes, a Presbyterian Reverend who lived in the early 18th century (1701-1761) in England. Bayes published a single book of mathematics called The doctrine of fluxions - the name fluxion was given by Isaac Newton for the derivative of a continuous function (called fluent). Based on this book, Bayes was elected in 1752 to the Royal Society, a British scientific entity. Two years after his death, a friend, the philosopher Richard Price (1723-1791), presented to the Royal Society an article he found among the papers of Bayes, with the name "An essay towards solving a problem in the doctrine of chances" ('Essay seeking to solve a problem in the doctrine of probabilities'). In this article was the demonstration of the famous Bayes Theorem. After its publication, the work fell into

oblivion, from which it was only rescued by the French mathematician Pierre-Simon Laplace (1749-1827), who revealed it to the world. (PENA, 2006, p. 24).

3. DESCRIPTION OF THE SYSTEM

Based on document WASH-1400 or NUREG-75/014 (US NUCLEAR REGULATORY COMMISSION, 1975, p.II-102), the function of the Auxiliary Feed-Water Supply System (AFWS) is to provide water to the secondary side for operation Of the steam generators after the loss of water from the main feed. The system shall be designed to ensure that the required flow can be delivered when necessary and for as long as the system function is required. This includes selecting the proper characteristics of the main pump and providing a sufficient supply of auxiliary feed water. System design and pump selection should also address upper flow limits that can be imposed to mitigate the mass and energy effects released within containment and prevent cooling of the reactor system at an excessive rate. (AMERICAN NUCLEAR SOCIETY, 1991) Fig. 1 is a simplified diagram of the Auxiliary Feed-water System. Due to the need for AFWS, the three pumps, two electric and one turbine, can be started automatically or manually. Electric pumps start automatically when:
1. A signal of the SICS (Safety Injection Control System) appears;
2. The external power loss is detected;
3. The main water pumps turn off;
4. Low water level is detected in a steam generator.
The turbine is started automatically when a low water level is detected in a steam generator or the external power loss is detected. All pumps are aligned with the 110,000 gallon condenser tank (approximately 416.395 liters) through separate suction lines always, except when maintenance is being performed on a pump. The three pumps provide water for two connectors that penetrate the containment. Within the containment, each steam generator can receive the condensate from any connector.
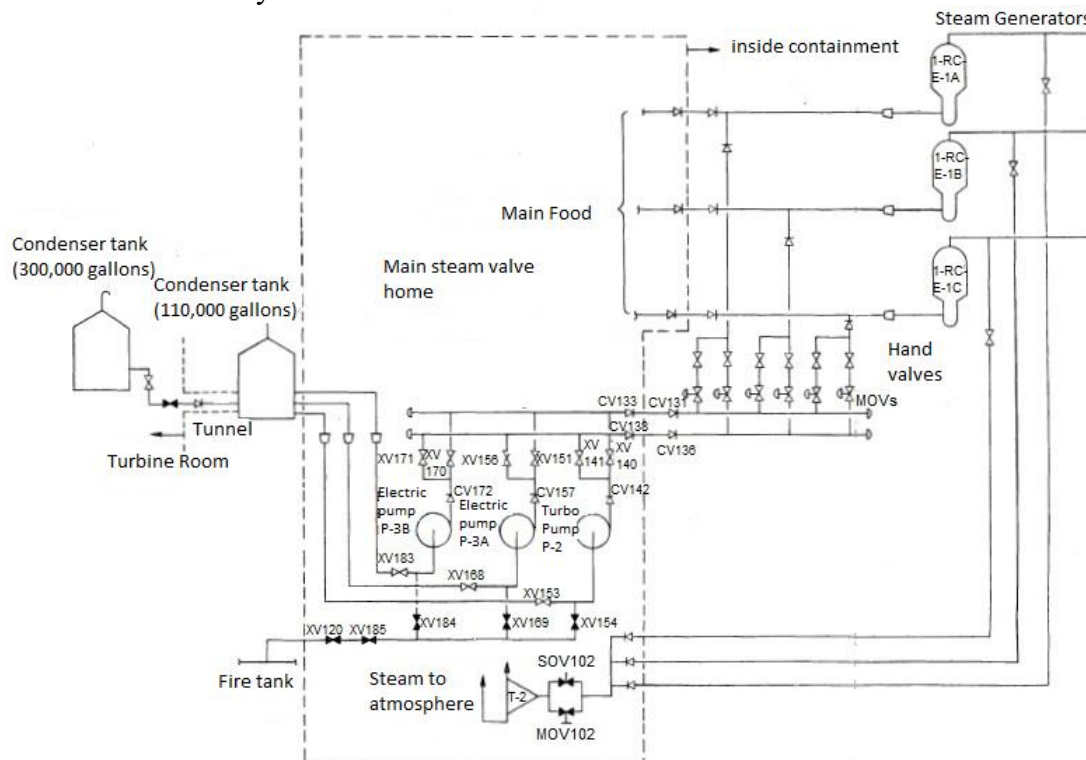

Figure 1- AFWS Simplified Diagram (Source: Nureg-75/01)

All the decay heat produced can be removed by any of the three pumps that deliver feed water to any of the three steam generators. The amount of feed water required decreases over time, and the operator can decrease the flow to the steam generators by turning off the redundant pumps, and then, using the engine valves operated within the containment, decrease the flow as necessary to match the steam produced and the released. The 110.000 gallon condenser tank holds enough water to maintain continuous cooling for approximately eight hours. If the AFWS is required for a long period of time, the operator must take action to activate additional water sources. There are two sources available, a 300.000 gallon (about 1.135.620 liters) storage tank, and the fire that makes available at least 400.000 gallons (approximately 1.514.165 liters) with up to 400 gallons per minute from the containment well . Each of these additional water sources requires manual valve operation. As indicated in the flow diagram, the fire valve is activated by the operation of manual valves in the Main Steam Valve Housing (MSVH), while the 300.000 gallon storage tank is activated by the operation of a valve Manual in the turbine building. A) The decay heat can be removed by the primary system delivering at least 350 gpm (exiting from either pump) to the secondary side of any of the three steam generators. B) Three auxiliary water feed pumps are available, one steam driven and two powered. The two electric pumps use separate emergency train. C) Condensate sufficient for eight hours of decay heat cooling is available through the (normally open) with valves, for all three pumps. The safety water supply is available for prolonged operation. The AFWS was analyzed from three separate initiator events:

• A small piping rupture (SPB) or transients involving loss of main feed water flow for which the AFWS is necessary, but excluding the external power loss;
• Loss of network (external power);
• High energy break (main steam or feed water or valves) in the main steam valve house.

For the first two events, system failure probabilities were estimated for the first eight hours after the crash, including system downtime, and for the next 24 hours if the operation succeeds for the first eight hours. The third event was estimated as a start or demand value for failure.

Using detailed AFWS plant design information, a Fault Tree can be constructed to determine how the system can fail in terms of AFWS basic component failures. Postulated faults included evaluation of failure modes of pipes, valves, control circuit components, pumps and electric power. In addition to component failures, human errors that could result in component failures were also considered. Before building the System Tree, let's talk a bit about the technique.

4. METHODOLOGY

In this work, the *Fault Tree* methodology, widely used in reliability studies in several industrial sectors, and the *Bayesian Networks* methodology, which is a method of modeling and decision alternative to the commonly used methods, will be used. Both methodologies will be directed to the Auxiliary Feed-water System, denoted by the acronym AFWS.

4.1 Fault Tree

Fault Tree Analysis is a deductive process that consists of constructing a logical diagram (fault tree), starting from an undesired event, called "top event", and looks for the possible causes of such an event. The process consists of investigating the successive combinations of component failures until reaching the so-called basic faults (or basic events), which constitute the limit of resolution of the analysis.

The main function of a Fault Tree is to translate a physical process into a structured logic diagram, in which simple events, the basic events, lead to a more complex event, the top event.

Using Boolean Algebra procedures it is possible to calculate the probability of failure of the top event from the probabilities of the basic events.

We will use the SAPHIRE computational code. A qualitative analysis of FT presents information about the importance of some events, as well as identifying the combinations of basic events that lead to the top event. By converting the Fault Tree into equations, through Boolean algebra, we can identify the smallest "path" of events that lead to the top event. A Cut Set is a set of basic events such that if all these events occur, they will imply the occurrence of the top event. A set of cuts is considered minimal if it cannot be reduced without ceasing to be a set of cuts. The technique of the minimum cut sets is one of the techniques most used in the analysis of Fault Trees, since they generate simpler and equivalent trees to those constructed previously.

The top event can be written as an equation that depends on the logical gate that connects it with its antecedent events, in turn, the antecedent events can be written also in function of its events antecedents, using appropriate rules for the logical gates that connect them to these events, and so on, until the top event is described in an equation that only contains basic events. According to information from NUREG-6952 (U.S. NUCLEAR REGULATORY COMMISSION, 2008, p.iii), SAPHIRE is a computer code developed for performing a complete Probabilistic Risk Analysis (PRA) using a personal computer with a Windows operating system (BORGES, 2014). The code is funded primarily by the United States Nuclear Regulatory Commission (NRC) and developed by the Idaho National Laboratory (INL). The main role of this laboratory is to develop and test the code, but it plays an important role of technology transfer through interface and support to SAPHIRE users.

4.2 Bayesian Network

As the number of variables increases, it becomes more difficult to answer questions about the joint probability distribution of a data domain.

In using the Bayes' theorem, the occurrence of conditional independence between random variables describing the data can simplify calculations to answer questions and also considerably reduce the number of conditional probabilities that need to be specified. The data structure called Bayesian networks represents the dependence between the variables and gives a concise specification of the joint probability distribution. (LUNA, 2004, p.21).

According to Russell and Norvig (1995, p.436-437) a Bayesian network is a graph with the following characteristics:

1. A set of random variables are the nodes of the network;

2. A set of arrows or arcs oriented connects pairs of nodes. The intuitive meaning of an arrow from an X node to a Y node is that X has direct influence on Y;

3. Each node has a conditional probability table that quantifies the effects parents have on the node. The parents of a knot are all those knots that have arrows pointing at it;

4. The graph has no directed cycles, ie it is a directed graph, but acyclic.

Briefly, Bayesian networks are directed acyclic graphs that represent dependencies between variables in a probabilistic model. Because probabilistic reasoning is one of the great advantages of Bayesian networks, it is possible to make rational decisions even when there is not enough information to prove that action will work. As stated in Almeida (2006, p.17), the conditional probabilities and the probabilities of the output node must be provided. The probabilities of each input node are calculated using the theory of probability from the already explained values. In a Bayesian network it is possible to observe the propagation of an input data in the whole network, allowing to verify the amount of information of that specific data. According to Luna (2004), the propagation of evidence on a Bayesian network allows estimates of probabilities to be obtained when information is added to this network. The propagation of

evidence consists of calculating the a posteriori probabilities for each variable. The a posteriori probability function measures the influence of the evidence on each variable. The heart of Bayesian theory is the inversion formula, also called Bayes' Theorem.

We will use Netica Computational Code. Netica is a powerful, easy-to-use and complete computational code for working with Bayesian networks. Computational code can use networks to perform various types of inference using the fastest and most modern algorithms. Given a new case that we have limited knowledge, Netica will find the appropriate values or probabilities for all unknown variables. Netica can use influence diagrams to find the best decisions that maximize the expected values of specified variables. It also builds conditional plans, since decisions in the future may depend on observations yet to be made. Netica can be used to transform a network in a number of ways. Variables that are no longer of interest can be removed without changing the overall relationships between the remaining variables (technically, probabilities are "summed" when we do not know the value of the variable, and a more complex operation is used when we do). Probabilistic models can be exploited by operations, such as reversing individual network links, removing or adding causal influences, optimizing a decision at the moment, etc. These operations can be done with just a click of the mouse, which makes Netica very easy to exploit, and great for teaching concepts of Bayesian networks.

5. RESULTS

In this section, the Fault Tree and Bayesian Network methodologies will be applied to the Auxiliary Feed-water System of a commercial nuclear power plant whose reactor is a PWR. The application was directed to reactors of the PWR type, since it is precisely this type of reactor in operation in Brazil in the Angra - I and Angra - II plants.

5.1 Fault Tree Result

The AFWS assumes the role of cooling the secondary system if the normal feed-water operating system fails. Two Fault Trees are then built for this system, the first calculates the probability that the system will failure in the first eight operating hours, and the second takes into account that the system succeeded in the first eight hours of operation and calculates the probability of failure after these eight hours. Fig. 14 shows a simplified AFWS scheme.
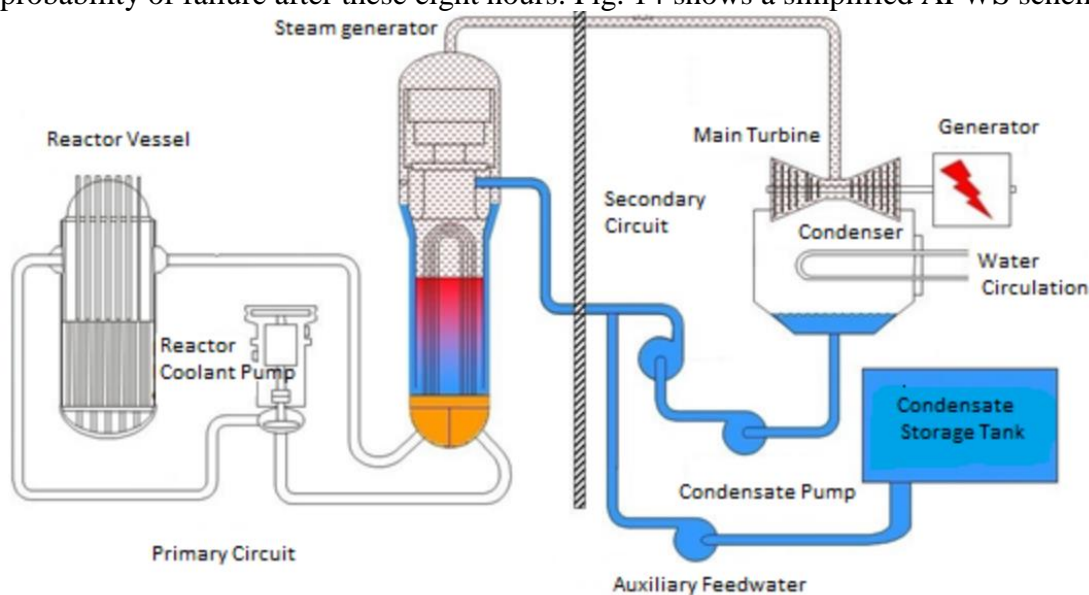

Figure 2 - Simplified AFWS Schema (*Source: Lochbaum (2015)*)

Since the probability of failure of the AFWS in the first eight hours of operation is very low, 1.08×10^{-25}, we will use the Fault Tree of the second case for study. To illustrate, Fig. 3 presents the Tree of the first case generated by SAPHIRE computational code.
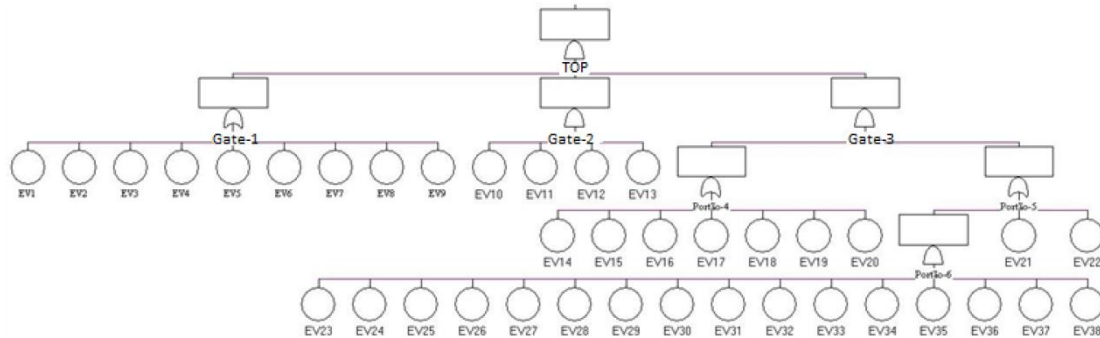

Figure 3 - AFWS Fault Tree (first 8 hours of operation)

To build the Fault Tree of the second AFWS case, we need the failure probabilities of each event. To facilitate construction, events have been renamed. The following table presents the events, their descriptions, and their probabilities of failure for the second case. These values were consulted in Nureg-75/014 (U.S. NUCLEAR REGULATORY COMMISSION, 1975) (see Table 1).

Table 1 - Events and Probabilities of Failures (after 8 hours of operation)

EVENT	DESCRIPTION	FAILURE PROBABILITY
EV1		ε
EV2		$2,4 \times 10^{-4}$
EV3		$5,4 \times 10^{-4}$
EV4	Events associated with electric pump failure A	ε
EV5		ε
EV6		$3,7 \times 10^{-2}$
EV7		ε
EV8		$2,4 \times 10^{-4}$
EV9		$5,4 \times 10^{-4}$
EV10	Events associated with electric pump failure B	$5,4 \times 10^{-4}$
EV11		ε
EV12		$3,7 \times 10^{-2}$
EV13		ε
EV14	Events associated with lack of water in the fire-fighting tank	ε
EV15		$5,4 \times 10^{-4}$
EV16		$5,4 \times 10^{-4}$

EV17		ε
EV18	Failure of main-steam line or pipe breakage in MSVH	$7,5 \times 10^{-5}$
EV19	Tubing Solder Failure nº 2 (containment side)	$1,0 \times 10^{-7}$
EV20	Tubing Solder Failure nº 2 (MSVH side)	$1,0 \times 10^{-7}$
EV21	Tubing Solder Failure nº 1 (containment side)	$1,0 \times 10^{-7}$
EV22	Tubing Solder Failure nº 1 (MSVH side)	$1,0 \times 10^{-7}$
EV23	Rupture of pipe nº 2 of 6 "	$3,6 \times 10^{-8}$
EV24	Rupture of pipe nº 1 de 6''	$3,6 \times 10^{-8}$

The events that show probability of failure ε do not contribute significantly to the unavailability of the system. In this case, ε represents a value very close to 0. In the AFWS Fault Tree (after 8 hours of operation), see Figure 16, each of the events 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23 and 24 is a Set of Minimal Cuts, since Is the smallest set of basic events that contributes directly to the occurrence of the Topo Event, since Gate 2 is an OR gate and the Topo Event is also an OR gate. The events that most contribute to the unavailability of the system are events 15, 16 and 18, because these events are the Minimal Cuts Sets with the highest probability of failure. Although events 6 and 12 have a higher probability of failure, they are connected to an AND gate with 12 events, that is, the 12 events need to occur in order for the system to become unavailable, so the gates 6 and 12 do not significantly influence the Unavailability of the system.
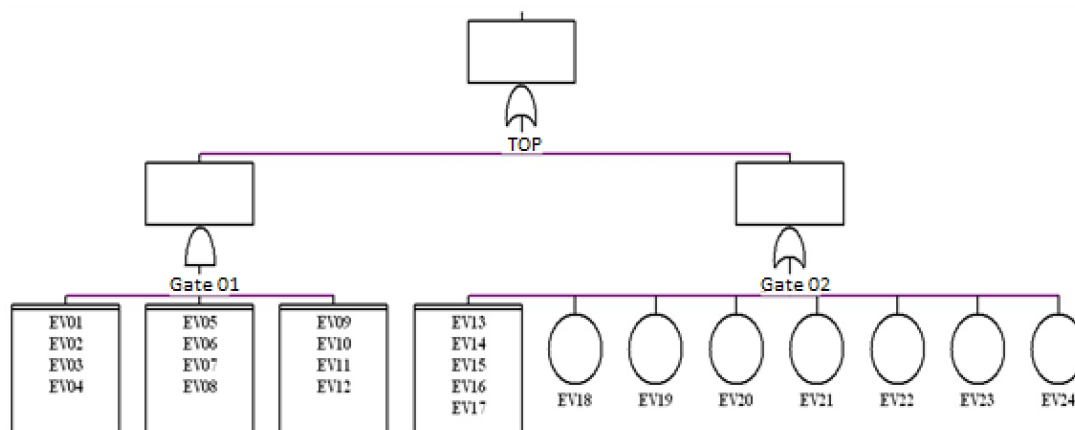

Figure 4 - AFWS Fault Tree (after 8 hours of operation)

The SAPHIRE computational code generated as a result that the probability that the system fails after eight hours of operation is $1.155 \times 10\text{-}3$, as we can see in Fig. 5.

Figure 5 - Probability of AFWS Failure (after 8 hours of operation)

The AFWS Fault Tree can be simplified, see Figure 19, by grouping some events with same type faults using the Boolean Algebra rules to obtain the failure probabilities of the new events, as shown in the table 2.

Table 2 - Failure Probabilities of Simplified Tree Events

GROUPED EVENTS	NEW EVENT	DESCRIPTION	FAILURE PROBABILITY
EV1			
EV2			
EV3			
EV4			
EV5		Events associated with the lack of flow of electric pumps A and B	ε
EV6	EV1		
EV7			
EV8			
EV9			
EV10			
EV11			
EV12			

EV13			
EV14			
EV15	EV2	Lack of water in fire fighting tank	$1{,}08 \times 10^{-3}$
EV16			
EV17			
EV18	EV3	Failure of main steam line or pipe breakage in MSVH	$7{,}5 \times 10^{-5}$
EV19			
EV20	EV4	Main Pipe Weld Failure	$4{,}0 \times 10^{-7}$
EV21			
EV22			
EV23	EV5	6" Main Pipe Rupture	$7{,}2 \times 10^{-8}$
EV24			

The simplified Fault Tree, presents the same result as the previous Tree, as we can see in Fig. 6. In this new Tree, each basic event is a Set of Minimal Cuts.
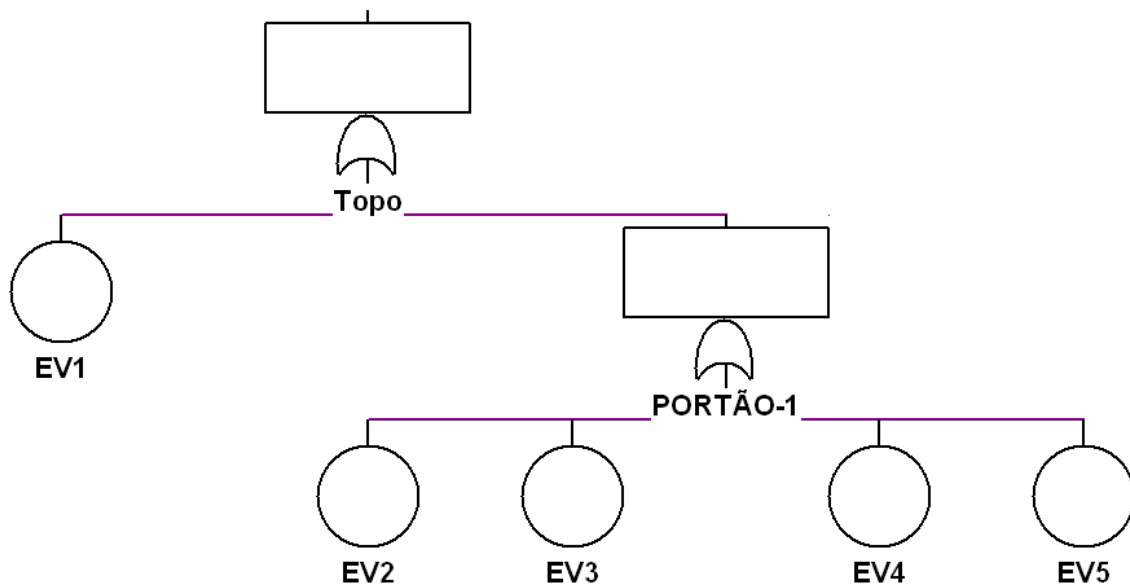
Figure 6 - Simplified AFWS Fault Tree (after 8 hours of operation)

Figure 7 - AFWS Failure Probability after 8 hours of operation using the Simplified Tree

5.2 Results from the Bayesian Network

5.2.1. Bayesian Network Fault Tree Conversion

To convert an FT to a Bayesian Network we need to create a node for each FT element, such as events and logical gates. In the Bayesian Network each element must be represented only once. After creating the nodes, we need to connect them according to the gates of the Fault Tree. After the nodes created and connected by arcs, we need to create a table of conditional probabilities for each gate. This table depends on the logical gate of the FT, whether it is an AND gate or OR.

We can observe that the appearance of the Bayesian Network is the same for both the AND gate and the OR gate. What will interfere with the result is the probability table of each gate.

To complete the Bayesian Network, the parent nodes must be completed with the probabilities a priori, the same as the basic events of the Fault Tree.

5.2.2. Construction of the Bayesian Network

For our study, the RB based on the simplified FW AFWS will be constructed after 8 hours of operation. Due to the number of basic events that each Fault Tree gate possessed prior to simplification, the construction of the Bayesian Network would be very laborious, since each event has two possibilities: failing or not failure, and since there were twelve events for each gate, the Probability table of each gate would have 2^{12} possible combinations, that is, 4.096 possibilities of combinations of events to fail or not.

Then, in Fig. 7, there is the Simplified Bayesian Network of the Feed-water Auxiliary System, after 8 hours of operation, built in the Netica computational code. The probabilities are

represented as percentage, so the probability of the system to fail is 0.12%, that is, the probability is 0.0012, which in scientific notation can be represented by 1.2×10^{-3}, a result very similar to that found by the Tree of Faults, 1.155×10^{-3}. The small difference is due to the rounding that Netica does in very small values.

Then, Fig. 8 shows the probability table of Gate 1, which is an OR gate, and Fig. 9 shows the Table of Probabilities of the Top, which is also an OR gate in the Fault Tree.
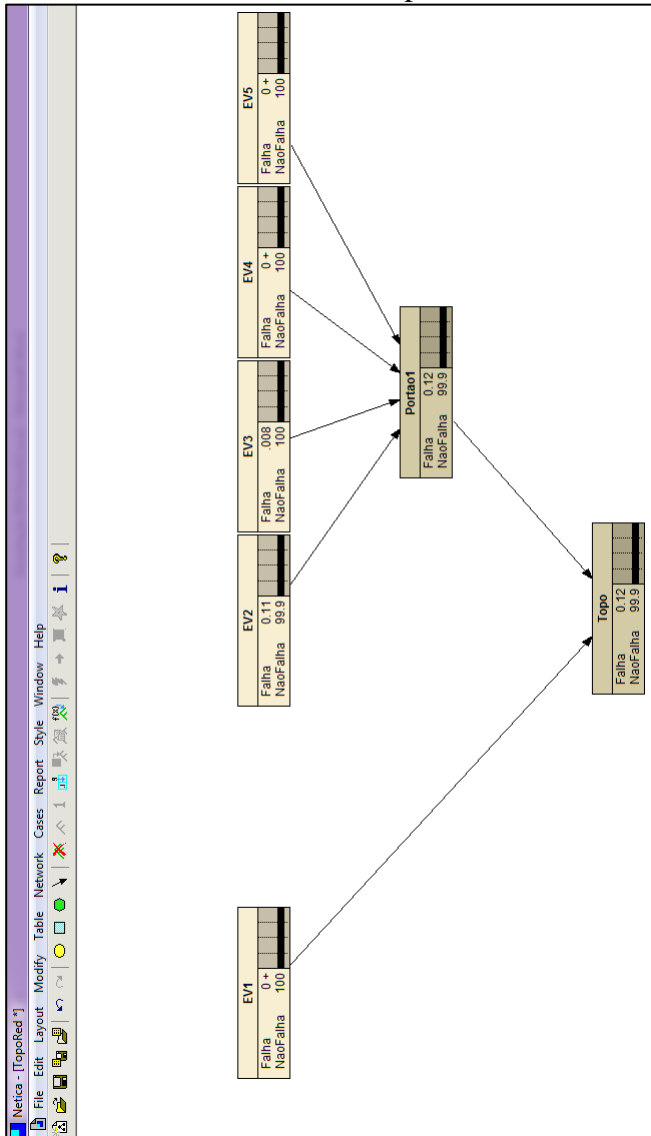
Figure 7 - AFWS Bayesian Network (after 8 hours of operation)

Figure 8 - Probability Table of Gate 1(Where it reads Falha reads Fail and NaoFalha NotFail)

Figure 9 - Top Probability Table (Where it reads Falha reads Fail and NaoFalha NotFail)

In the Bayesian Network, clicking "Fail" on the "Top" child node shows the failure probabilities (in percentage) of each parent node (basic event) so that the Top has 100% probability of failure, Fig. 10.
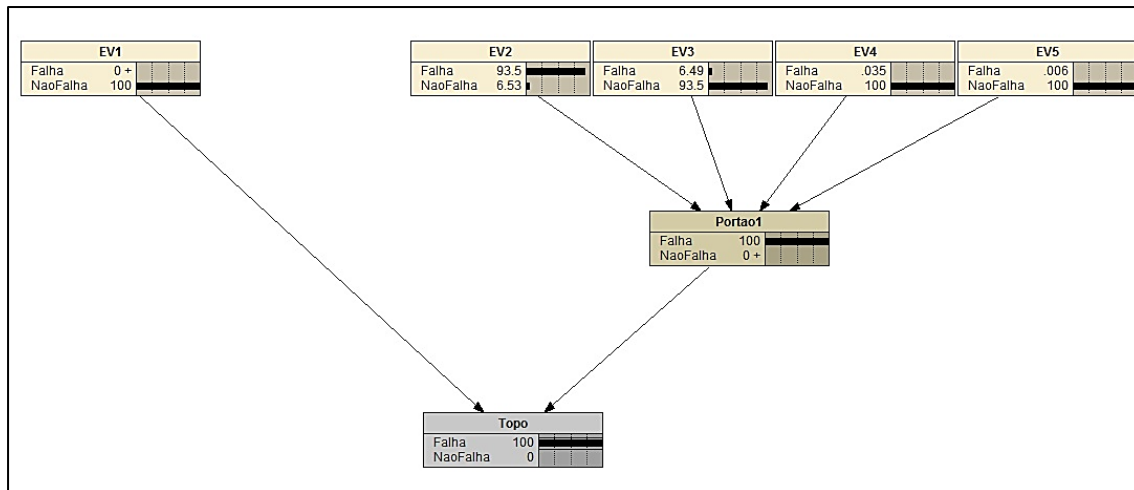
Figure 10 - Failure probability of the parent nodes so that the child node has 100% probability of failure

It is also possible to observe what happens to the probability of failure of the Top if we consider that a certain parent node is likely to fail or not to fail at 100%. To verify this, simply click "Fail" or "Do not Fail" on each parent node. The Bayesian Network will automatically update itself. As in the Simplified Fault Tree used to construct the Bayesian Network each basic event is a Set of Minimal Cuts, when we consider that one of the parent nodes is 100% likely to fail, it causes 100% failure of the Topo.

CONCLUSIONS

This work made possible the study of two methodologies that are widely used today because of their ease of understanding and precision of results and, finally, they are applied to the Auxiliary Feed-water System. It has been confirmed that it is possible to obtain a Bayesian Network (BN) equivalent to the Fault Tree (FT), provided that the corresponding probability tables are constructed for each corresponding logical gate. It was verified that both the Fault Tree and the Bayesian Network presented very close results, differing only in the fourth decimal place of the probability of failure of the system in question. FT presented as a result that the system failure probability is 1.155×10^{-3}, whereas BN presented as a result 1.2×10^{-3}. It is possible to observe that the Fault Tree is the simplest methodology to work when the failure probabilities of each basic event are available, since the different logical gates are already well defined. The Bayesian Network, because it does not have logical gates, but simply nodes representing both basic events and gates, intermediate events and top, is more laborious in this case, since we need to define the probability table for each corresponding logical gate of the Fault Tree, the which can demand in an immense work, depending on the amount of events of each gate. In the case of AFWS Fault Tree after eight hours of operation, before it was simplified, it had twelve events at each of the two logic gates, which would require a table of probabilities of 4.096 lines each, simply to "teach" the computational code to matching the failure probabilities of the basic events. On the other hand, the Bayesian Network makes it possible to estimate the probability of failure of the parent nodes if it considers that the Topo (child node) has a 100% probability of failure.

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