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Study of radiation protection vestments for maintenance of mobile nuclear power plants

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ABSTRACT

Most radiation exposure to personnel comes from inspection, maintenance, and repair within the reactor compartment. The objective of this paper was to discover the garment that, at the same time, presents the best result for the attenuation of ionizing radiation, as well as good ergonomics for the maintenance professional of mobile nuclear plants. For this, market research was carried out and, as a result, nine Radiation Protection Vestments (VPRs) were found, from five different manufacturers and from three countries, the United States, Japan and China; and which are feasible to be acquired. To choose the VPR, the optimization techniques of CIPR 55 were used: Multi-Attribute Utility Analysis and Multi-Criteria Outranking Analysis. Based on the information provided by the manufacturers, five attributes were chosen for comparison: protection cost, percentage of ionizing radiation attenuation, weight, discomfort, and surface decontamination of the vestment. To verify the robustness of the analytical solution, the values of the scaling constants were re-calculated, where it was observed that the analytical solution found is strongly influenced when the protection cost is changed, as it is the highest cost VPR among all those surveyed. The VPR chosen by both optimization techniques was the STEMRAD 360, which has the highest attenuation of ionizing radiation, as well as being the VPR with greater emphasis on ergonomics.

Keywords: Ionizing radiation, radiation protection vestments, optimization techniques.

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1. INTRODUCTION

It is known in the nuclear reactor compartment there is an atmosphere of noble gases that usually contain radioiodines or other fission products that cannot be detected quickly and easily [1]. The United States Department of the Navy's Nuclear Propulsion Program Report concluded that most radiation exposure to personnel is caused by inspection, maintenance, and repair within the reactor compartment. [2]. After the removal of the fuel elements containing the fission products, more than 99.9% of the radioactive material remaining is an integral part of the structural alloys that form the components of the nuclear plant and that were activated by the bombardment of neutrons during the operation of the reactor [2].

The use of Radiation Protection Vestments VPR is directly related to dose reduction in the individuals, and its use has been shown to be effective and enforces the ALARA principle. [3]. Some ergonomic problems of VPRs, such as sizes not suitable for the target audience (anthropometric problems); discomfort with the weight and temperature of the clothing material; integrity failures (unnecessary exposure); non-compliance with legislation regarding the availability and use of clothing (awareness ergonomics), among others, are pointed out as the main justifications for their non-use [4], with the weight of lead aprons reported as the main reason [5].

According to KALOSHKIN et al [6], the growing demand on the use of radioactive materials as well as production of radioactive waste leads to the development of items that promote greater radiation safety. New methods of protection against harmful radiation should be developed and implemented. One of the approaches that has been observed is the development of new radiation protective composite materials containing no toxic lead that requires a special disposal procedure.

Several authors have found that the use of tungsten nanoparticles in a polymer matrix are efficient in protecting against ionizing radiation [6], [7], [8] and [9]. Other authors have researched a light and comfortable fabric, with high efficiency of protection against ionizing radiation in composite materials from the use of bismuth oxide III (Bi_2O_3) in a polymeric matrix [10], [11].

With the present increase in the number of research and power reactors under development in Brazil, such as the o Laboratório de Geração de Energia Nucleoelétrica (LABGENE) and the Reator Multipropósito Brasileiro (RMB) both projects located in Iperó-SP; the construction of the third plant of the Central Nuclear Almirante Álvaro Alberto, also called Angra 3, located in Angra dos Reis-RJ;

and the development of the Brazilian Nuclear Propulsion Submarine (SN-BR) project, therefore, it is of interest not only to these programs, but to all sectors that work with ionizing radiation at a global level, the development and research to improve radiological protection and selection of existing VPRs that will be used by operators and maintenance teams at these nuclear facilities.

In the case of a Mobile Nuclear Plant (PNM) for naval propulsion, in addition to fulfilling their fundamental function, which is to avoid contamination, the VPRs must meet the requirements of radiological protection and ergonomics for users within a limited space. Thinking about the maintenance inside the reactor compartment, the operators must be trained, exhaustively, in order to reduce the exposure time; must respect the distances for inspections and maintenance on each equipment inside the reactor compartment; and they must use a VPR that provides an adequate protection and that contributes to the proper execution of the tasks.

As a result of this paper, a survey of the main existing garments was carried out, analyzing which would best meet the ergonomic and radiological protection requirements for the maintenance of a mobile nuclear power plant, used for naval propulsion. For comparison and selection, the decision-making aid techniques of publication 55 of the CIPR [12] were used, based on the attributes defined with the information provided by the manufacturers. After sensitivity analysis of the solution found, the vestment that best meets the requirements of radiological protection and ergonomics for the user of maintenance in mobile nuclear plants was chosen.

2. MATERIALS AND METHODS

The main activities to carry out this paper were the research of available radiological protective vestments and the application of decision-making techniques from publication 55 of the CIPR.

2.1. Vestments Research

Initially, market research was carried out in order to find the clothes available and feasible to be acquired. The research was conducted on internet search engines, e.g., Google, Bing, Yahoo. In many cases, additional information was obtained through email inquiries as well as articles published by garment manufacturers. From the research carried out, nine garments were found, from five different manufacturers and from three countries, the United States, Japan and China.

During the research, standard lead apron garments were eliminated, due to the numerous ergonomic problems presented in [4] and [5]. Only for the purpose of applying the optimization techniques, the ProTech Plus model from UNITECH was selected as a base case, as it is the model, which according to the manufacturer, is used in more than 50% of the world's nuclear reactors, also supplying shipyards naval, DOE facilities in the United States (U.S. Department of Energy), fuel manufacturers, among others.

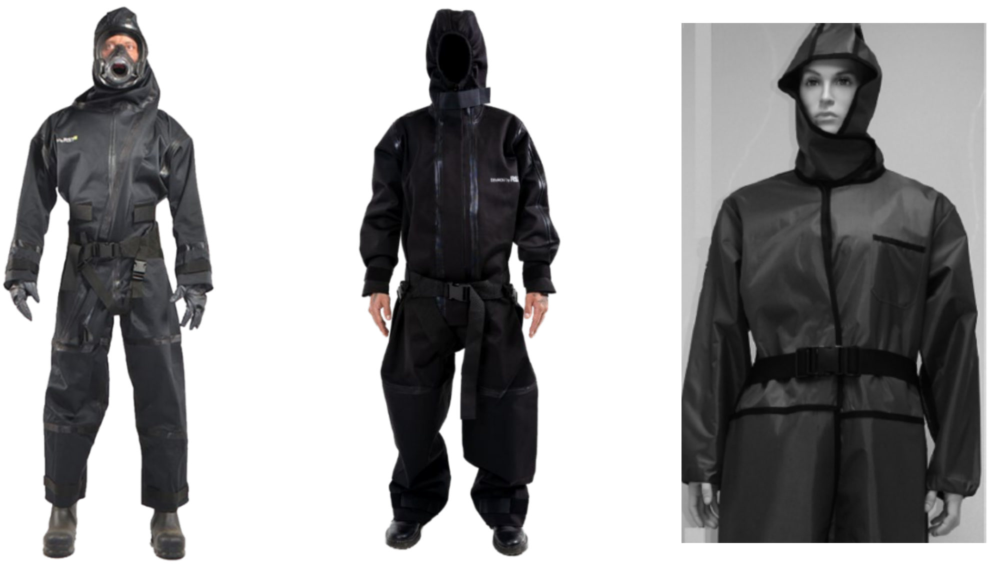
The main manufacturers found were the following: The Radiation Shield Technology (RST), of American origin, is the holder of the DEMRON patent, which is a water and gas tight polymer composite of PE, PVC and inorganic salts of high atomic number elements (excluding lead), it is laminated between textile layers. The Yamamoto Corporation (YMC), of Japanese origin, is the BIORUBBER patent that consists of heavy metal (primarily lead) alloys dispersed in synthetic material with regular honey-comb structure of cells and laminated into special anti-adhesive BRS layers. And manufacturer STEMRAD), of American origin, in which its main garment has a selective armoring architecture and of variable thickness, which optimizes protection, uses as primary materials of the protection core: virgin lead, stainless steel and Teflon, wrapped in a Kevlar fabric.

Recent works published by KOZLOVSKA et al [13][14] were compared different garments, focusing on the aspect of radiological protection. Photos of individual VPRs are presented in Figure 1 and Figure 2. In Table 1 are presented individual VPRs parameters (weight, cost, Ionizing Radiation Attenuation (IRA), superficial decontamination, and VPR discomfort) by their respective producers and origin.

2.2. Optimization Techniques

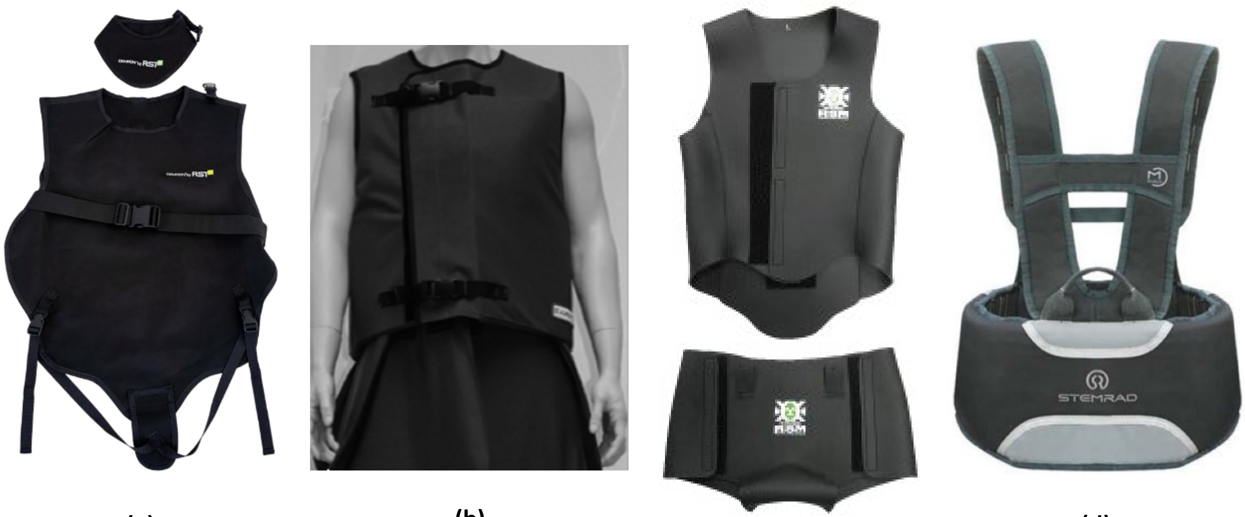
The optimization techniques used for the comparative study of the VPRs were: Multi-Attribute Utility Analysis and Multi-Criteria Outranking Analysis, details explained in publication 55 of the CIPR [12]. Here we will provide a summary to better understand the work performed.

Figure 1: Whole body VPR: (a) DEMRON Full body suit, (b) DEMRON Class 2 Full body suit, (c) HKX 1558 Whole body Anti-Radiation Wear.



(a) (b) (c)

Figure 2: Local VPR: (a) DEMRON Radiation torso vest for 1, 2 or 4 plies, (b) Df vest (W-2mm), (c) BIORUBBER RSM E-400 Vest and Pants, and (d) STEMRAD 360$^{\gamma}$.



(a) (b) (c) (d)

Table 1: Parameters of radiation shielding protective vestments.

Name	***DEMRON Full Body Suit***	***DEMRON Class 2 Full Body Suit***	***HKX 1558 Whole Body***	***DEMRON Torso Vest 1Ply***	***DEMRON Torso Vest 2Ply***	***DEMRON Torso Vest 4Ply***	***Df Vest (W-2 mm)***	***BIORUBBER RSM Tipo XI E-400 4mm***	***STEMRAD 360ᵞ***
Producer	RST	RST	GHB	RST	RST	RST	ATR	YMC	STEMRAD
Country	USA	USA	CHN	USA	USA	USA	JPN	JPN	USA
Shielding layer material	DEMRON	DEMRON	Lead compounds, dispersed in vinyl	DEMRON 1 ply	DEMRON 2 plies	DEMRON 4 plies	Tungsten dispersed in resin	BIORUBBER E-400	STEMRAD
Weight (kg)	5,20	4,8	10,10	2,54	2,57	4,30	18	13,9	14
Cost ($USD)	1.999,00	3.199,00	950,00	699,00	1.199,00	2.100,00	2.750,00	2.540,34	6.000,00
IRA to ^{137}Cs (%)	1	1	4	2	3	5	16	6	41
Superficial decontamination	Yes	Yes	Yes	Partial	Partial	Partial	Partial	Partial	None
VPR discomfort (apparently)	Some discomfort	Some discomfort	Difficult to work	Comfortable	Comfortable	Comfortable	No discomfort	Comfortable	Very comfortable

2.2.1 Multi-Attribute Utility Analysis

In the Multi-Attribute Utility Analysis, points are associated with the relevant attributes or a priority function with multiple attributes. Thus, if the points for option *i* are higher than those for option *m* then, by definition, *i* takes precedence over *m*. If the points are equal for the two options, then there is no preference for one option over the other.

After quantifying the radiological protection options and specifying the attributes, criteria must be included to classify the importance of each attribute in relation to the others. This is carried out through a utility function, *uj*, giving the relative desirability of the possible outcomes for the factor j. Generally, the best outcome or lowest adverse consequence for each factor is assigned a utility, *uj*, of 1 and the worst consequence a utility of 0.

From the single utility functions, *uj*, expressing the various utilities of the *n* factors associated with each protection option *i*, a multi-attribute function, *Ui*, must be obtained. This function provides the figure of merit or "total utility" of each option *i*. The Multi-attribute utility function can be expressed by equation 1:

$$U_i = \sum_{j=1}^{n} k_j \, u_j \tag{1}$$

where *kj* is a scaling constant expressing the relative importance, or weight, assigned to each factor, *j*.

The scaling constants were obtained by the substitution rates method. In the evaluation for reasons of substitution, attributes are placed in descending order of importance, and then the relative importance of each attribute in relation to the most important attribute is assigned. In this study, the dominating attribute to selection of VPRs was assigned to Ionizing Radiation Attenuation.

Scaling constants are usually normalized by applying equation 2:

$$\sum k_j = 1 \tag{2}$$

In Multi-Attribute Utility Analysis, the analytical solution is given by the option that makes the total utility, U, maximum.

2.2.2 Multi-Criteria Outranking Analysis

This technique presents advantages over the aggregative techniques in the process of optimization of radiological protection when the attributes of the protection options are very heterogeneous. This occurs when they cannot be sorted in ascending or descending order with respect to options or when they can only be evaluated qualitatively.

The bases of Multi-Criteria Outranking Analysis used in the optimization of radiation protection are two, namely:

1. Advantage index (Ad) – that expresses the amount by which option *i* is preferred to option *m*
    - When *i* is preferred or equivalent to *m* for all *j* attributes: $Ad_{i,m} = 1$
    - When *i* is never preferred or equivalent to *m* for all *j* attributes: $Ad_{i,m} = 0$
    - When *i* is preferred or equivalent to *m* for some *j* attributes: $0 < Ad_{i,m} < 1$

In calculating the advantage index, it is possible to incorporate criteria for the importance attached to the attributes, as those in the multi-attribute utility analysis, using scaling constants k_j:

$$Ad_{i,m} = \sum k_j a_j \tag{3}$$

Where a_j is the advantage index for the attribute *j* and is equal to 1 if option *i* is better than or equal to option *m* for this attribute, otherwise it is equal to 0.

2. Exclusion criterion (Ec) – that expresses the degree to which the disadvantages of option *i as* compared with option *m* are significant for the attributes where *i* is not preferred or equal to *m*. This criterion rejects all options that do not meet the fundamental requirements:
    - When the drawbacks associated with the choice of option *i*, rather than *m*, are very substantial: $Ec_{i,m} = 1$; and
    - When the drawbacks associated with the choice of option *i*, rather than *m*, are too small: $Ec_{i,m} = 0$.

The point where the loss becomes "very substantial", known as the "exclusion threshold", must be defined. If an attribute is judged "not important enough" to eliminate options, the exclusion threshold should be chosen in such a way as to prevent the pairwise comparison of an exclusion criterion from resulting in 1.

3. RESULTS AND DISCUSSION

For the study of vestments, the following attributes were selected:

- Protection cost;
- Attenuation of ionizing radiation;
- Weight;
- Discomfort; and
- Superficial decontamination.

The cost of protection is one of the most important attributes for the selection of radiation protection vestments, as it will allow the analysis of those clothing that are outside the cost-effectiveness curve, as well as relating the importance of each attribute to the cost of protection. Thus, contributing to the fulfillment of the ALARA principle of radiological protection, verifying the economic and social reasonableness for the selection of VPRs.

The attenuation of ionizing radiation was the most important attribute chosen for the selection of VPRs. To compare the attenuation of ionizing radiation between the garments, the attenuation values related to ^{137}Cs were selected, since all the garments under analysis have the experimental results of this radionuclide.

From the comparison of the weight of the vestments, it was possible to observe those that require less physical effort to use the equipment, consequently, causing less ergonomic problems, fatigue and musculoskeletal injuries in workers.

By the qualitative attribute of discomfort of the VPR, the growth constants were determined from the information provided by the manufacturers themselves. And to analyze the surface decontamination attribute, it was taken into account whether the garment has any surface treatment that allows surface decontamination and whether the vestment is full-body or for local protection. In local protective clothing, it is necessary to use a supplementary dermal protection garment, against radiation from alpha and beta particles, to protect the head, upper and lower limbs that are uncovered.

To facilitate the identification of the garments under analysis, the local protective garments were shaded in blue and the full-body protective garments in green. In Table 2 presents the vestments under analysis and the main characteristics for analysis.

Application of Multi-Attribute Utility Analysis for vestments selection

For partial priorities, it was considered that all attributes are linear functions and, therefore, were obtained from the equation of the line: ax + by + c = 0, where the two extreme points are known (0 for the most adverse consequences and 1 for the best consequences) and the other options have intermediate values.

Second, the importance of each attribute was assigned in relation to the protection cost and then it was normalized by applying equation 2. To make this relationship, it is necessary to answer the following question: how much are you willing to pay if you go the smallest single dose? Answering this question for all relevant attributes, we have the following equations:

$$k(A) = 1{,}7\ k(X)$$

$$k(C) = 1{,}3\ k(X)$$

$$k(P) = 0{,}7\ k(X)$$

$$k(D) = 0{,}3\ k(X)$$

Applying equation 2 ~~2~~, k(A) + k(X) + k(C) + k(P) + k(D) =1, substituting, we have:

1,7 k(X) + k(X) +1,3 k(X) + 0,7 k(X) +0,3 k(X) = 1

Substituting the value of k(X), we have the following growth constants:

k(A) = 0,34; k(C) = 0,26; k(X) = 0,20; k(P) = 0,14 and k(D) = 0,06

The scaling constants were obtained from the linear equations for each attribute and with the definition of the importance of each attribute, it was possible to obtain the value of the total priorities following the technique Multi-Attribute Utility Analysis, as shown in Table 3. For the greatest importance, being the attenuation of ionizing radiation and the discomfort of the garment, the vestment that presented the highest value of the total priorities was option 9, STEMRAD 360γ.

Table 2: Main parameters of VPR options.

Cod. option	Protection options (VPRs)	Price (USD)	% IRA to ^{137}Cs	Weight (kg)	Discomfort	Superficial decontamination
0	**ProTech Plus (caso básico)**	$50	0	-	-	YES
1	**DEMRON Class 2 Full Body Suit**	$3.199,00	1	4,8	Some discomfort	YES
2	**DEMRON Full Body Suit**	$1.999,00	1	5,20	Some discomfort	YES
3	**DEMRON Radiation Torso Vest 1Ply**	$699,00	2	2,54	Comfortable	PARTIAL
4	**DEMRON Radiation Torso Vest 2Ply**	$1.199,00	3	2,57	Comfortable	PARTIAL
5	**HKX 1558 Whole Body Anti-Radiation Wear**	$950,00	4	10,10	Difficult to work	YES
6	**DEMRON Radiation Torso Vest 4Ply**	$2.100,00	5	4,30	Comfortable	PARTIAL
7	**BIORUBBER RSM Tipo XIE-400 4mm**	$2.540,34	6	13,9	Comfortable	PARTIAL
8	**Df Vest (W-2 mm)**	$2.750,00	16	18	No discomfort	PARTIAL
9	**STEMRAD 360γ**	$6.000,00	41	14	Very comfortable	NO

Application of Multi-Criteria Outranking Analysis for vestments selection

For this analysis, the same attributes and scaling constants obtained by the previous technique were used.

In order to reduce the number of excess relationships, options 1 and 2 that obtained the worst results by the Multi-Attribute Utility Analysis were removed from the analysis of multiple criteria. Another reason for elimination is that both vestments have the lowest attenuation value of ionizing radiation.

This technique compares each option *i* with the other *m* options for each attribute and assesses whether option *i* is preferable to option *m*. Analyzing options 3 and 4, it can be seen that option 3 has an advantage over option 4 only in terms of protection costs, being equal in terms of weight, discomfort and surface decontamination, with option 4 being more advantageous in terms of radiation attenuation. ionizing. Therefore, using the calculated growth constants, the growth constants of the attributes where option 3 is more advantageous or equal to option 4 are added.

As the objective of the present work is to select the VPR that allows the execution of maintenance tasks in addition to being able to attenuate ionizing radiation, comfort during the use of protective equipment was the attribute selected for the exclusion criterion. The discomfort caused by the use of vestment was adopted as exclusion criterion (Ec), being defined as the exclusion threshold, Ec = 0.4. Applying the exclusion criterion for the considered options, the final table comparing the protection options is created, which can be seen in Table 4.

Comparing the non-excludable options and checking the advantage index values, we find that option 4 exceeds 3, options 6 and 7 exceed option 8 but do not exceed each other, and that option 9 exceeds all other options, therefore configuring itself again as the analytical solution.

It was observed that, even using different techniques and using an exclusion criterion for discomfort caused by the vestment, the result of the analytical solution was not affected. Option 9, STEMRAD 360 γ, continues to be considered optimal, showing that the overall result of an analysis depends on the input data and criteria specified and not on the details of the analytical technique.

Sensitivity Analysis

To verify the robustness of the analytical solution obtained, a sensitivity analysis was performed varying the values of the growth constants as follows:

1. Inversion of the initial values of the attenuation amounts of the ionizing radiation k(A) for the discomfort of the RPV (k(C)).

2. Keeping the importance of the attenuation of ionizing radiation k(A) and lowering the value of discomfort importance of the VPR k(C), equaling the weight factor of the garment (k(C) = k(P) = 0.7k(X)).

3. Considerable reduction for the importance of attenuation of ionizing radiation k(A) = 1.3k(X) and equating with the weight factor of the garment (k(C) = k(P) = 0.7k(X)) , and the consequent increase in the importance of the cost of protection.

4. consequent rise in the importance of the cost of protection.

Table 3: Multi-attribute utility analysis for the options considered for VPR selection.

Protection options	**Partial utilities**					**Scaled partial utilities**					**Total Utility**
	u(X)	u(A)	u(P)	u(C)	u(D)	k(X)·u(X)	k(A)·u(A)	k(P)·u(P)	k(C)·u(C)	k(D)·u(D)	$U_i = \sum_{j=1}^{n} k_j u_j$
1	0,49	0	0,85	0,25	1	0,20·0,49	0	0,14·0,85	0,26·0,25	0,06·1	0,34
2	0,73	0	0,83	0,25	1	0,20·0,73	0	0,14·0,83	0,26·0,25	0,06·1	0,39
3	1	0,02	1	0,75	0,5	0,20·1	0,34·0,02	0,14·1	0,26·0,75	0,06·0,5	0,57
4	0,89	0,05	1	0,75	0,5	0,20·0,89	0,34·0,05	0,14·1	0,26·0,75	0,06·0,5	0,56
5	0,94	0,07	0,51	0	1	0,20·0,94	0,34·0,07	0,14·0,51	0	0,06·1	0,35
6	0,71	0,10	0,89	0,75	0,5	0,20·0,71	0,34·0,10	0,14·0,89	0,26·0,75	0,06·0,5	0,53
7	0,62	0,12	0,26	0,75	0,5	0,20·0,62	0,34·0,12	0,14·0,26	0,26·0,75	0,06·0,5	0,43
8	0,58	0,37	0	0,5	0,5	0,20·0,58	0,34·0,37	0	0,26·0,5	0,06·0,5	0,40
9	0	1	0,26	1	0	0	0,34·1	0,14·0,26	0,26·1	0	**0,64**

Table 4: Multi-Criteria Outranking Analysis for VPR selection.

m	3	4	5	6	7	8	9
i				**$Ec_{i,m}$**			
3		0,66		0,66	0,66	0,66	0,40
4	0,80			0,66	0,66	0,66	0,40
5							
6	0,66	0,66			0,66	0,66	0,40
7	0,66	0,66		0,66		0,66	0,40
8	0,4	0,40		0,40	0,40		
9	0,60	0,60		0,60	0,74		

It was observed that for the first two sensitivity analyses, the result of the analytical solution was not affected, with option 9 (STEMRAD 360γ) still being considered optimal by the two techniques under study. However, with a considerable reduction in the importance of the attenuation of ionizing radiation and equating the discomfort of the RPV with the weight attribute, a change in the analytical solution was observed, influenced by a greater relevance of the cost of the protective clothing, with option 9 been overtaken by option 3.

4. CONCLUSION

From the studies it was possible to know the main radiological protection VPRs that are produced and commercialized internationally. Using the aid techniques for decision making, it was shown that the STEMRAD 360γ vestment best radiological protection equipment with a focus on the attenuation of ionizing radiation and the comfort of the equipment.

With the sensitivity analysis of the scaling constants, we were able to conclude that the optimal solution is strongly influenced when greater importance is given to the protection cost. However, in the case of selecting a vestment for the maintenance of a nuclear plant, the protection cost is not so relevant in view of the attenuation capacity and discomfort caused by the vestment.

As a suggestion for continuing the study of the STEMRAD 360γ vestment, it could be acquired in order to prove its ability to attenuate ionizing radiation by laboratory tests of radiation attenuation, as well as to unveil the materials and process of its manufacture of the garment. A survey of ergonomics and comfort in the use of clothing could also be carried out by teams specialized in maintenance of nuclear plants, as well as by teams of first combat against nuclear accidents of the Brazilian Navy.

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