DESIGNING OF RATIONAL STRUCTURE OF RANGE OF INSULATING PROTECTIVE CLOTHING ON THE BASIS OF THE PRINCIPLES OF TRANSFORMATION

L.D. Tretiakova, N.V. Ostapenko, M.V. Kolosnichenko, K.L. Pashkevich and T.V. Avramenko

Kyiv National University of Technologies and Design, Kyiv Polytechnic Institute
Nemirovicha-Danchenka Str. 2, 01011 Kyiv, Ukraine
cesel@ukr.net

Abstract: *The aim of this work is to develop a range structure of insulating change of clothes with predictable characteristics for the employees of nuclear power plants (NPP). It was applied a systematic approach to solve the assigned tasks, which made it possible to use the principles of transformation through the gradual changes in design and complete of protective clothing. The implementation of the assigned tasks was carried out using the method of structural optimization of construction of insulating protective clothing. The rational structure of range of insulating change of clothes with predictable coefficient of protection, weight and cost was formed on the basis of the principles of transformation by the method of structural optimization. It was obtained the formula for calculation of protection coefficient under constraints on weight, cost, number of material layers (taking into consideration the non-linearity of the objective function), under constraints and discretization of initial information for the packages of protective clothing. Structural and logical matrix for insulating change of protective clothing was formed. There were proposed a structure of insulating change of clothing for NPP employees, structural and technological solutions for the products from the product range. Task-oriented selection of modules and methods of their transformation within the designed object was carried out.*

Key words: *principles of transformation, protection coefficient, insulating protective clothing.*

1 INTRODCUTION

Protective clothes for the employees of nuclear power plants (NPP) belong to the personal protection equipment (PPE) and can be divided into the following groups:

- by the degree of insulation from the aggressive external environment – hermetic, insulating, filtering changes of clothing;
- by the types of hazards – clothing for protection against radioactive contamination, acids, alkalis, moisture, petrochemicals, organic solvents, industrial dust etc.;
- by the duration of use – one-time, with limited term of use, re-usable.

The system of personal protection of NPP employees solves three main tasks: compliance with the requirements to the working conditions, based on the analysis; provision of basic level of protection and reliability indicators; minimization of additional health threats and injury risks for the employees. That is why the selection of species range, completeness and its structure alongside with the materials and methods of details connections in protective clothing as the main component of the change of clothing is determined by the mutual influence of the task which are need to be solved. The effectiveness of the taken decisions depends on the determination of (1) harmful factors and ways of getting them inside the body; (2) characteristics of the materials; (3) topographies of influence of burden factors on the worker; (4) parameters of constructions; (5) manufacturing technology; (6) conditions and modes of use.

Therefore, the aim of designing the rational completeness of the protective clothing and packages of materials in terms of limited material, financial and human resources arises. In such conditions the multivariance of solutions of assigned tasks is quite possible.

A wide range of requirements to the protective clothes, the main function of which is to provide reliable protection against harmful and dangerous factors, is regulated by state standards [1, 2]. Well-known from the various modern sources are the principles of transformation in design of the modern clothes for different purposes, with the help of which you can modify the units of the clothes, details, clothing in general and its completeness to provide it with new functions.

2 EXPERIMENTAL

Nowadays the manufacturers of protective clothing try to combine all stages during the process of creation: from material development, design,

manufacturing to the realization stage of protective clothing. Complete implementation of such concept is associated with the need to overcome the methodological issues arising from the direct view of the employee as a consumer of the protective clothing, with the uncertainty of standards and methods of their assessment and also with the imperfections in approaches to the evaluation of changing work conditions and modes of work. Existing approaches in general do not provide the fully integrated solution for designing the reliable change of protective clothing with optimal parameters at the stage of design and mass production [3]. The nature and character of creative concept of work are associated with an individual vision of the authors, with the main trends of development of the project methods and consumers` requirements.

The selection of the optimal solution for the structure of insulating product range is based on the multivariate analysis due to the systemic approach that includes the consideration of the design subject as a system of interrelated material, functional, social and aesthetic elements. Such kind of approach requires the establishment of clear analytic connections in “environment – insulating protective clothing – NPP employee” system. The result of such design approach is the creation of change of protective clothing that meets all requirements. Systematic structural analysis is realized on the basis of principles of transformation, which predict the replacement of (change of) separate modules or their movement within the same form.

The analysis of working conditions at the NPP of Ukraine made it possible to single out the basic requirements to the insulating protective clothing. Complete set of Insulating protective clothing should provide complete protection against α-rays and β-rays of low energy, dust and aerosols with radionuclides, mechanical damages and general pollutions; it should be impervious to oil and water, resistant to alkalis and acids.

2.1 Overview of the modern design approaches

Under the influence of changing requirements to the protective clothing, desire to create products that meet the specific conditions of its use, the further changes in constructive solutions take place. Certain types of protective clothing are replaced by new, more relevant and appropriate in the current conditions. Protective clothing is created from the new polymer materials, which have light weight, increased level of protection against the complex negative impact of chemicals, water solutions, dust and aerosols, ionizing and non-ionizing radiation etc., it is comfortable to wear and could be utilized [4]. The low cost of such materials makes it possible to abandon from re-usable protective clothing that requires constant cleaning and repair. Single use of protective clothing provides an opportunity to reduce the environmental pollution and operating costs [5].

Most of polymeric fibers, suitable for manufacturing of new materials (polyethylene, polyvinylchloride (PVC) and polypropylene), are thermoplastic and provide an opportunity to replace inefficient and time-consuming way to connect clothing details by spinning connection method at more productive – welding method (thermocontact, by high-frequency currents, ultrasonic method). New technologies make it possible to create more advanced forms, systems of general, block and element by element redundancy, improve reliability and protection, taking into accounts the artistic and aesthetic requirements and constraints of additional risks in use.

At all stages of development of theoretical and practical design the following methods are reasonable to use:

- analysis of the problem situation, based on the information about the working conditions of certain categories of the employees;
- determination of concept and methods to solve the problems;
- selection of the material with necessary and sufficient protective characteristics;
- selection of construction methods for the base model;
- use of additional products, design and technological elements of protective clothing to ensure the necessary level of protection.

Insulating re-usable change of protective clothing of the proposed appointment is offered to be made from PVC-plastic, thickness 0.10 – 0.15 mm, surface density 110 - 180 g/m^2, rigidity 2.0 – 2.6 cH. The possibility of using such materials is confirmed by their long period of operation [6].

3 RESULTS AND DISCUSSION

The formation of the range structure of insulating change of protective clothing, which may consist of jacket, pants, semioverall, apron, gloves, armlets, shoe covers and other articles, is realized through the rational choice of assortment, based on the techniques and methods of increasing the protection, reliability and ergonomics indicators. There were proposed the components of insulating change of clothing that provided the optimal combination of protective function and comfort working conditions (Figure 1).

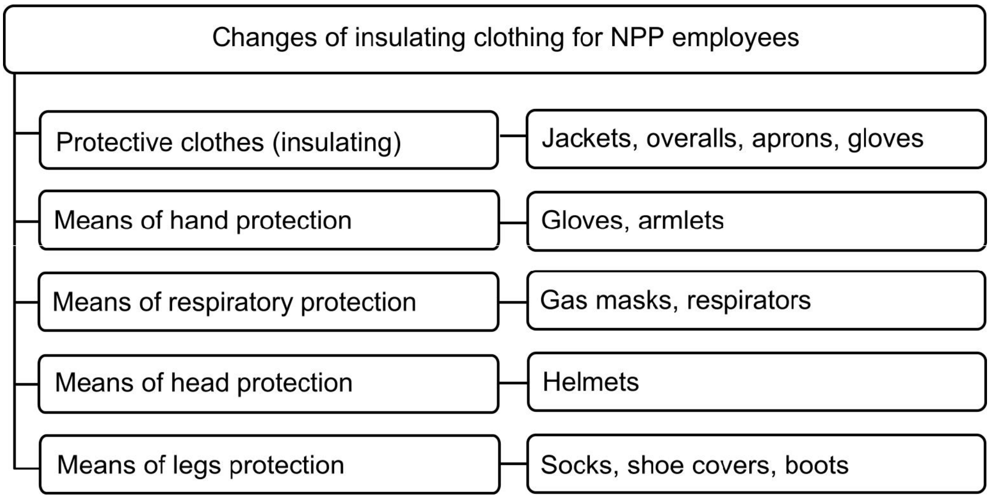

Figure1 Proposed structure of insulating change of clothing for NPP employees

It was found that the typical design feature of the protective clothing is the lack of pockets, clasps, belts, buttons and other protruding details, trims with textile clasps and glue stitches due to the limited possibilities of their deactivation. In addition, when creating the protection clothing, it is necessary to use the material with a smooth surface and construction that helps the liquid radioactive substances to flow down from the surface.

To improve the convenience, increase the speed of dressing and removing the clothes, taking into consideration the specific movements and postures of the employee, a central onboard fastener, stalemates, curtains, shoulder-straps etc. should be provided. In order to prevent from exposure and other professional injuries and diseases, the outer surface should not contact with the skin of the employee, constricted hem of the pants and sleeves with regulating degree of their fit and fastener on the strings will enable it. Deactivation of the protective clothing takes place every time after their use at the temperature of 45-55°C with their further storage in premises with a temperature of 3-15°C.

Structural optimization of PPE change of clothing lays in identifying the opportunity to achieve established parameters of protection, reliability and ergonomics during the process of design and exploitation within the elaborated design. Among the species range of insulating protective clothing, which is planned to be made of PVC-plastic, the preference is given to overalls. The improvement of protection characteristics is achieved by implementation of structural elements, additional layers of materials and reserve products (armlets, knee pads, shoe covers, gloves, etc.), additional structural elements (improved trims, shirrs, flexible inserts and air elements), (Figure 2).

The task of evaluation of the effectiveness of the measures, which are aimed to improve the protection level, can be summarized to the determination of the protection coefficients. Requirements to the insulating protective clothing are often contradictory. The securement of protective properties and increase of reliability and durability leads to the increase of the weight of the item. At the same time during the protective clothing exploitation additional risks for the health and safety of the employees may arise: deterioration of the thermal state due to overheating; increase of static pressure caused by additional weight; complication of working movements that will increase the duration of the work under the influence of external ionizing radiation.

Notwithstanding the meaningful variety of such tasks, all of them from the formal point of view [7] are summarized to one general point: to find the values of changing parameters X_1, X_2,…X_n, which provide the maximum or minimum of a given function $F = f(X_1, X_2 ... X_n, Y_1, Y_2 ... Y_n)$, at presence of limitation

$$F_o = f(X_1, X_2 ... X_n, Y_1, Y_2 ... Y_n) \leq or \geq \Pi_i$$

where $F = f(X, Y)$ – objective function (measure of efficiency, security, reliability or effectiveness of the system); X – vector of the variables of control; Y – vector of the variables of the state (uncontrolled variables); $F_o = f(X, Y)$ – functions of the value limits of i-indicator; Π_i – value of normalized or recommended i-value.

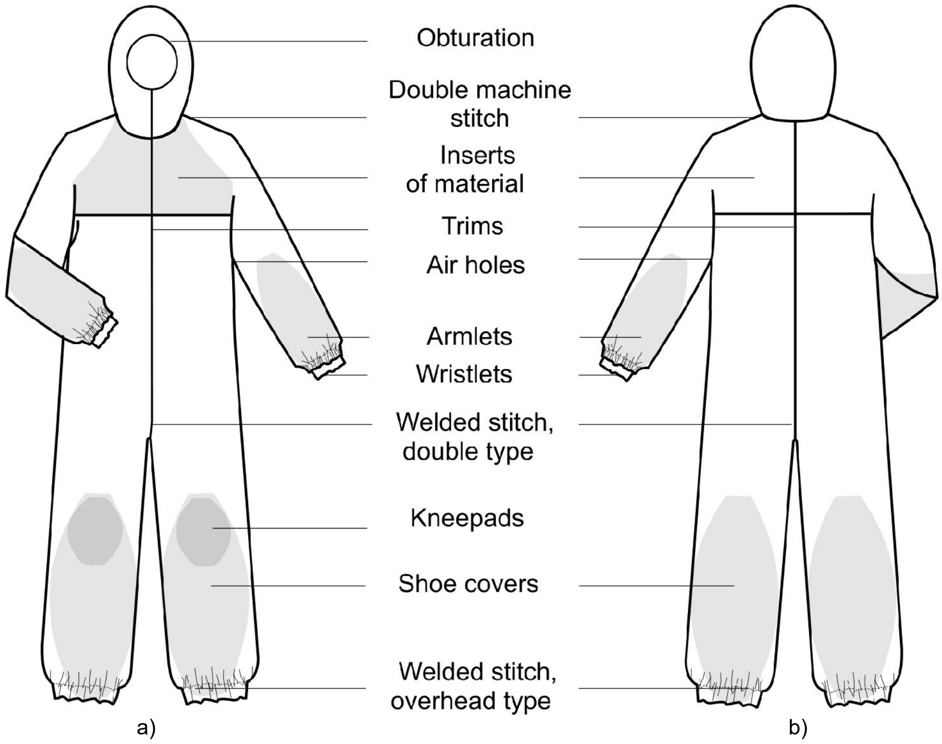

Figure 2 Base model of the product with additional structural elements: a) front view, b) back view

In such circumstances the method of normalized functions was used as a mathematical apparatus for the study of the problem, which belongs to the heuristic methods of optimization and provides an opportunity to get reasonable and univocal decisions in solving a number of problems of different nature [8]. The authors made the modification of computational algorithms of the method of normalized functions (algorithms of minimization and maximization) that made it possible to take into account the design specifics of the insulating clothing structure via:

- the use of area-modular calculation model;
- the compliance with standards of constraints;
- the measurement of uneven distribution of the impact of harmful factors and mechanical stresses as to the zones of the worker`s clothing;

the interconnection between the certain measures and means in design.The initial data is provided via the discrete sequence of standard parameters of protective clothing elements: $X_p, a_p, b_p\ (p = 1, 2 ...)$, where X_p – unknown variables; a_p, b_p – corresponding to p-standard parameter technical characteristics, needed for the formation of objective function and limitations. The reasonability of using such discrete sequence is caused by the fact that technical characteristics can't always be approximated accurately using the analytical dependencies from X_p, but in discrete sequence this characteristics can be taken as accurate ones (for example, a lot of elements are determined due to the catalogs, breaking force – according to the results of experimental researches and to the technical conditions).

Considering that the developer of the insulating change of clothing is tasked to achieve the protection coefficient at the level not less than defined, the formulation of the problem involves maximization of the objective function as a protection factors K_p:

$$F(X) = K_p \rightarrow max \quad (1)$$

Figure 2 shows the possible places for introduction of additional measures and their coded identification. The magnitudes of the basic parameters changes, which include material consumption, weight and cost of the product, as well as estimated parameters that vary during the optimization process (coefficient of protection, reliability, breathability, etc.), depend on the technological design, which in turn depends on the implementation of one or another measure. The list of measures considered with the relevant parameters of replaced items, listed in the Table 1.

Table 1 The list of the measures to optimize the insulating protective clothing

The name of variable elements, products	Coded identification	Indices of the elements	
		Additional cost Δ*C* [%]	Weight *m* [g]
Structural elements			
n-layer insertions of material	I_n (n =1, 2, 3)	30.0	380-550
trims	*T*	5.0	100
obturation of pants	*O1*	3.0	50
obturation of sleeves	*O2*	2.5	50
air hole	*AH*	15.0	10
Additional items			
armlets	*A1*	7.50	1200
knee pads	*P*	8.50	350
wristlets	*W*	2.0	250
shoe covers	*SC*	12.0	1500
gloves	*G*	11.0	120
apron	*A2*	25.0	1700
Technological elements			
double machine stitch	*S1*	15.0	
welded stitch, overhead type	*S2*	10.0	
welded stitch, double type	*S3*	10.0	

So, we have a discrete sequence of individual technical means and technical measures, which help to improve the protection factor that increases the cost ΔC_i and weight Δm of the product.

To formalize the procedure of calculation schemes preparation, the notation for variables of control X_i was introduced, the main characteristics of which were given in Table 1. Variables of control were presented as logical functions: notations « $\wedge,\vee$ » correspond to the signs of logic operations accordingly «AND» or «OR».

$$X1 := S1 \vee S2 \vee S3\,;\ X2 := I1 \vee I2 \vee I3$$
$$X3 := AH \wedge (I_n \vee A2)\,;\ X4 := A1 \vee G$$
$$X5 := P \vee SC\,;\ X6 := O1 \wedge SC \qquad (2)$$
$$X7 := A1 \wedge (W \vee O2) \wedge G\,;\ X8 := T$$

The process of optimization is carried out through the selection of volumes and priority of replacement of structural and additional elements, which allow the producers to improve the product. Area-modular scheme was used as the scheme for calculations that provides the division of clothing model at nine zones, which have different requirements [9]. The selection of the numbers and areas is connected with the topographic areas of the clothes and with the protection level of parts / areas of the body and internal organs. Module is source element that can be repeated and inserted into the clothing without changing its integral form. Products (for example, armlets), as well as their components (the layer of material), which can also have different functional purpose (trims), were used as a separate module. Every module of the product in the relevant area or areas has a specific purpose according to its protective functions and is characterized by certain technical and cost parameters (Figure 3).

The head (brain, breathing and vision organs) is singled into the first zone with coded symbol Z1 because its protection can be provided by means of head protection, means of face, eyes and breathing organs protection. The second zone includes neck with such a vital organ as thyroid gland. The front part of the human`s body is divided into two areas: chest, top of the abdomen (shoulder joint, esophagus, stomach, liver, lungs) (coded zone symbol Z3) and lower part of the abdomen (reproductive organs, urinary bladder, large intestine) (zone with coded symbol Z4). The back side of the human`s body, especially shoulder girdle, back, buttocks (lungs, red bone marrow) is the area with coded symbol Z5. The arms are divided into two zones (with coded symbols Z6 and Z7): the elbows and shoulders belong to zone Z6, the forearms belong to zone Z7. Two areas with coded symbols Z8 and Z9 include the lower extremities. Thus, upper legs and knees are included into zone Z8, lower legs and foots – into zone Z9.

Structuring of the measures with the use of logic functions enabled to form a matrix in which the possible measures are indicated in a row, the zones areas with confidence interval – in the columns (Table 2).

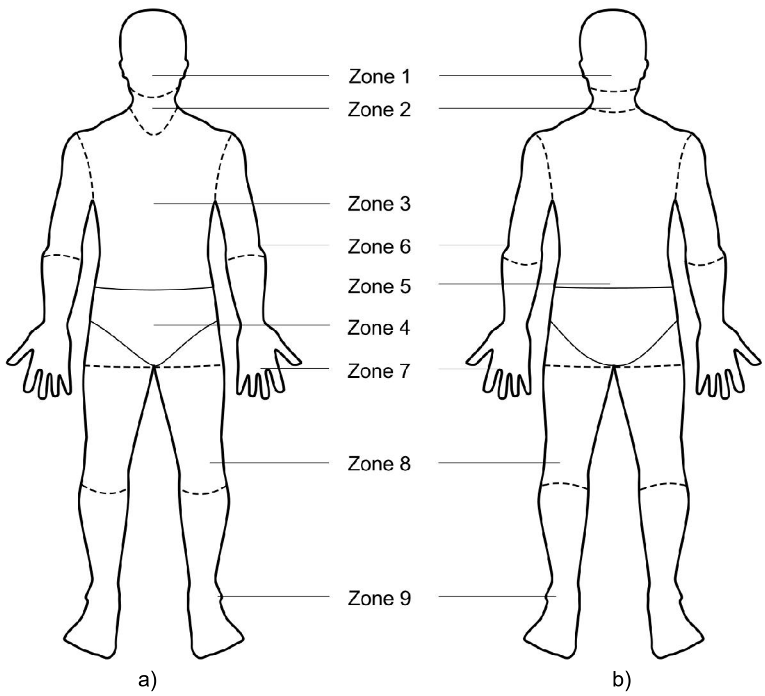

Figure 3 The appearance of the human body with zones notations: a) front view, b) back view

Table 2 Structural and logical matrix for the insulating change of protective clothing

List of measures	Name of zone (its area), $S_i \cdot 10^{-2}$ [m^2]								
	Zone 1 (10.5±0.4)	Zone 2 (0.26±0.01)	Zone 3 (2.4±0.09)	Zone 4 (1.45±0.06)	Zone 5 (4.2±0.16)	Zone 6 (2.3±0.16)	Zone 7 (1.74±0.1)	Zone 8 (3.6±0.25)	Zone 9 (4.0±0.23)
Additional layers of material	X2	X2	X3	X2	X3	X3	X2	X3	X2
Trims		X2vX8	X3vX8	X8					
Obturation	X8						X4vX7	X5	X6
Types of stitches	X1	X1	X1	X1	X1	X1	X1	X1	X1

The first column contains the list of possible measures in order to increase the protective properties, namely:

- addition of an extra layer of PVC-plastic in the head and neck areas, front part of the body, in the lower abdomen and inguinal fold areas;
- strengthening of the trims by replacing the open clasp on the buttons to clasp-zippers or replacing the clasp-zippers on model with improved physical and mechanical properties or on additional surface layer of the material along the length of the clasp;
- implementation of the obturation with a rubber elastic tape on the hood, on the sleeves and on the lower part of the pants or simultaneous use of the insulating protective clothing and shoe covers;
- usage of additional items: armlets, knee pads, shoe covers, gloves and wristbands;
- selection of the types of stitches when connecting the individual modules of the product.

The optimization task is formulated as follows: to maximize the objective function for the coefficient of protection against product β-radiation at presence of limitations on the quantity of additional layers of material in the module, on the total weight and value of the products.

The study of the protective properties of PVC [10] provides the possibility to determine the analytical dependence of the protective coefficient against the β-radiation in the following form:

$$K_{p\beta} = 0{,}153\frac{\sum_{i=1}^{9} n_i \cdot w_i \cdot S_{Mi}}{S_a} + 0{,}451 \to max \quad (3)$$

where S_{ii} - the area of the module of *i*-zone, cm^2; n_i, - the number of layers in the module; w_i - weight coefficient; i - the number of zones, i = 1,2…9; S_a - the total area of the product.

The increase of the protection coefficient can be achieved by changing every multiplier in the formula. The area and number of layers in separate modules belong to the structural measures. The weight ratio takes into account the unbalanced loads and

irregular impact of the ionizing radiation on the separate zones and should be adjusted during the optimization calculation at the presence of such limitations:

- by weight:

$$F(m): m \in \left[\sum_{i=1}^{9} m_i \leq m_{per} \right] \quad (4)$$

where m_i - the weight of the separate module in i-zone, g; m_{per} - permissible weight of the change of clothes, which is 3 kg;

- by the number of the layers of material in separate modules:

$$F(n): n \in [n \leq 2...k] \quad (5)$$

where n - the number of the layers of material in the separate module, which in some modules may not exceed three layers due to technological conditions;

- by the cost:

$$F(C): C \in \left[(\sum_{i=1}^{9} C_{Mi} + C_j) \leq C_{per} \right] \quad (6)$$

where C_{Mi} - cost of *i*-module; C_j - cost of the additional elements; C_{per} - acceptable cost of the clothing, which is determined by market conditions.

The criterion for optimal variant of structural and technological solution of the product is to ensure the necessary level of protection at the presence of limitation on the total weight of the clothing. As optimization criterion *KR* the next correlation is selected:

$$KR = min\left\{ \left(\frac{m_{j+1} - m_j}{K_{po} - K_{pj}} \right) \right\} = \left\{ \frac{\Delta m_j}{\Delta K_{pj}} \right\} \quad (7)$$

where K_{po} - protection coefficient that needs to be achieved according to the technological task for development; K_{pj} - protection coefficient for the *j*-step of optimization; ΔK_p - augmentation of protection coefficient; m_j - the weight of the clothing during the *j*-step of optimization; Δm - augmentation of the weight.

Integrated criterion of optimization varies depending on the level of protection and increase in weight in case of addition of extra layers of protective material or use of additional products.

Basic construction (Figure 2) has a certain protection coefficient, weight and cost. Such data was used as the initial information during the optimization calculation (zero step). Variables of control are set as a structural and logical matrix (Table 2). During the next steps of optimization using the criterion (7) the most effective measure is defined, which is fixed after reviewing of all possible modules for its installation. Then calculate the appropriate growth of the protection coefficient ΔK_p and growth of the weight Δm. The process continues until all means will be considered from the original sequence and achieved the desired protection coefficient. Development of protective clothing design is based on the specification, where the customer specifies the main requirements to the product, namely the desired protection coefficient, weight and cost. Limitations on total weight and cost of the product may cause a premature end of calculations when the limit values achieved. As a result of the optimization calculation we get an ordered set of measures to improve the protection coefficient on every step of weight and cost increment.

The considered algorithm is implemented as a computer program and, as a result of optimization calculation, for selected model the following results were introduced; to produce the insulation PC the technology of welding by currents of high frequency using double stitches was selected; strengthened obturation in zones Z5, Z6 and Z8 was introduced; double clasp and strengthened trims were set in Z3; one additional layer of protective material was added in Z1, Z2 and Z3; armlets, shoe covers and apron were used; air hole is provided in Z6. The sequence of implementation of the measures according to their effectiveness is presented at Figure 4.

The implementation of such consistent modules into the design and technological development of change of the insulating protective clothing provides the following results: the protection coefficient against β-radiation increased and was not less than 0,95; protection coefficient against α-radiation was 1; the increase of such protection coefficients led to the growth of the weight of the clothing on 56% in comparison with the original weight (less than 1800 g); the cost of the clothing increased on 80%.

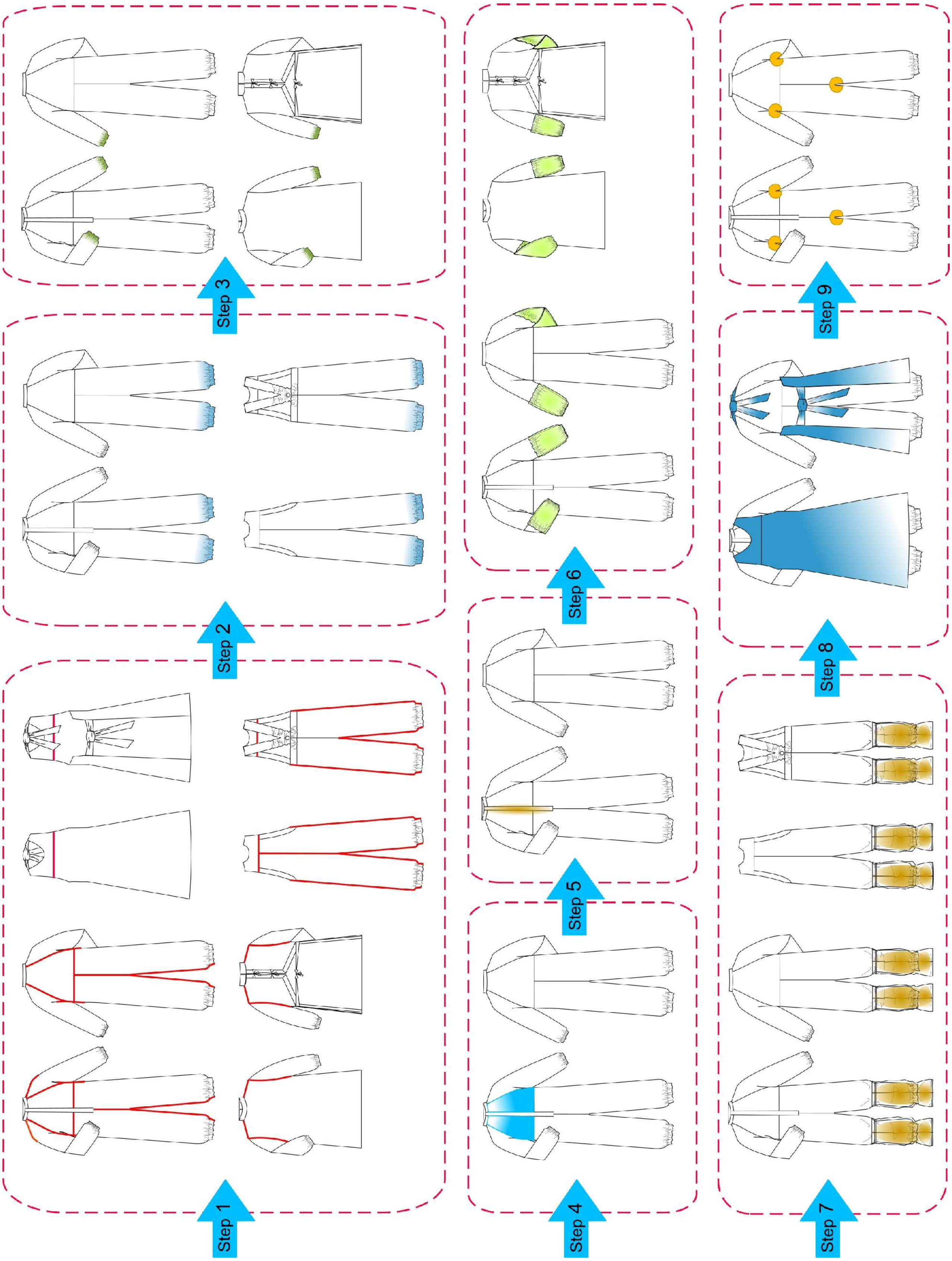

Figure 4 Example of the product range of insulating change of clothing with step by step realization of optimization calculation

4 CONCLUSIONS

It was proposed a new conception of the project design of protective clothing with specific functionality, based on the systemic approach which envisages the design of the product portfolio as a system of interrelated material, functional, social and aesthetic elements. Such systemic approach provides the establishment of clear analytic connections between the environment, separate parts of protective clothing and the processes, which take place with the participation of the workers and aimed at improving the protective effectiveness, reliability and efficiency of the personal protection system.

The research presents the new methodological basis for the process of design and technological development using the method of transformation. The method of transformation enables to develop the changes of protection clothes for specific operating conditions, taking into account the customer requirements on restriction of the impact of the harmful production factors, ergonomic characteristics and economic indicators. It was formed the range structure of the insulating change of clothes by developing the constructive and technological solutions for the components of the products for the employees of nuclear power plants on the basis of transformation principles by the method of structural step by step optimization, which allowed to make a targeted selection of modules and methods of their transformation within the projected object. The method aims to meet the challenges of maximizing the protection coefficient at the presence of limitations on weight and cost, taking into consideration the non-linearity of the objective function, limitations and discrete of the initial information for the packages of the protective clothing.

5 REFERENCES

1. DSTU ISO 8194-2004. Clothing for protection against radioactive contamination and pollution, 2004, p. 24
2. DSTU EN 1073-1-2001. Insulating suits and special ventilated clothes against radioactive contamination. Technical requirements and test methods. State Standard of Ukraine, 2003, p. 10
3. Ermylova V.V.: Modeling and artistic decoration of the clothes: Manual for media proff. education, 2nd edition, Publishing center “Akademiya”, 2004, p. 184
4. Sabit Adanur, Birgul Ascioglu: Nanocomposite Fiber Based Web and Membrane Formation and Characterization, Journal of Industrial Textiles 36, 2007, pp. 311-326
5. Tretiakova L.D.: Modern means of personnel protection for nuclear power plants in practice, Informational bulleting of safety 55(1), 2010, pp. 43-50
6. Tretiakova L.D.: Development of constructive and technological solutions for insulating changes of protective clothes for NPP workers, News of the higher educational institutions, Technology of the light industry, St. Petersburg, № 3, 2013, pp. 53-55
7. Bellman R., Dreyfus S.: Applied tasks of dynamic programming: Translation from English, A.A. Pervozvansky (Ed), Nauka, 1965, p. 563
8. Glover F.: Handbook of Metaheuristics, Kluwer Academic Publishers New York, 2003, p. 556
9. Tretiakova L.D.: Area-modular model for development of the changes of protective clothes, Reporter of the Khmelnitsky National University № 2, 2015, pp. 69-72
10. Tretiakova L.D.: Experimentally calculated evaluation of the protective properties of the materials against the ionizing contamination, Reporter of the National Technical University of Ukraine, Kyiv Polytechnic Institute, series Mining, Ed. 26, 2041, pp. 184-190