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Technology Trends and Future Opportunities in Development of NBC Protective Clothing

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ABSTRACT

This article reviews a detailed and timely evolution of Nuclear Biological Chemical (NBC) protective clothing. The increased threat of NBC weapons underlines the need for NBC protective clothing for first responders, service personnel as well as civilians. The material selection criteria for protective clothing have been changed considerably with the development of advance technical fibers to sustain the threat of CWA and fulfill precisely need for the NBC suits. Because of advancement, in the use and delivery of Chemical Warfare Agent (CWA), the evolution of the NBC suit is presented. The chemical protection of NBC protective clothing needs to be precisely evaluated and thereby related standard test methods are also duly accommodated. This review documented the journey of the NBC suit right from charcoal based to activated carbon spheres (ACS), and recent developments on the materials aspects of various protective clothing.

Keywords: Protective Clothing; Chemical Warfare Agents; Activated Carbon Sphere; Activated Carbon Fabric

1. INTRODUCTION

NBC (Nuclear, Biological and Chemical) protective suit has a special purpose to protect the individuals from any type of NBC threats. There are mainly three steps related to Chemical Warfare Agents (CWAs) mitigation technologies: detection, protection and decontamination. The body protection step is taken care of by the NBC suit. The crucial factor is to develop adsorbents with high surface areas that can highly adsorb different hazardous chemical agents so that these adsorbents can be used in NBC Protective clothing for optimum protection[1]. During world war-1 a fully impermeable NBC suit came into the picture but it was not user friendly so, a chemical impermeable but air-permeable NBC suit was proposed. There is always a trade-off between air permeability and chemical protection of these special types of NBC Suits. If the air-permeability is higher, the chemical protection level will decrease[2]. Hence, balance must be retained between two extreme properties demanded for chemical protection and comfort.

NBC protective clothing comprises three layers: outer, middle, and inner layer. Keeping in the view of physiochemical properties of CWAs, the multi-functional outer layer which provides oil & water repellency, flame retardancy and as well as anti-static properties has been explored. DuPont invented woven fabric made of blended aramid fibres which are currently being used in the outer layer of NBC suit [4]. This aramid-based fabric provides inherent thermal protection to the wearer and it shows resistance to abrasion, tear and chemical penetration[4]. Contemporaneously, cotton, polyester and nylon fibre came into existence as an outer layer material and has been used for the development of NBC Suit earlier[5,6]. The above-mentioned outer materials are not having inherent FR properties and it is also difficult to achieve all properties i.e. oil and water repellent, flame retardancy in the same fabric. The inner layer (next to the skin) is intended to provide comfort to the wearer. Currently, knitted cotton fabric is being used in the inner layer of NBC protective clothing. Different manufacturers are using different fabrics such as nylon tricot, polyester knit, viscose knit and PV (Polyester and Viscose) blended knitted fabric as an inner layer[5-13]. The middle layer (adsorbent layer) is the main component of the suit which adsorbs the CWAs. Earlier, activated carbon in powder form impregnated in Polyurethane (PU) foam was used as adsorbent layer[14]. Further development came into existence such as granular

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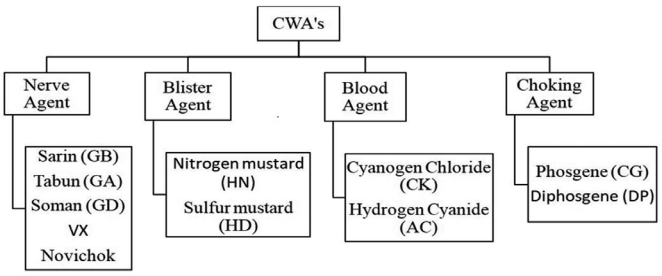


Figure 1. List of CWAs[17].

activated carbon (GAC) adsorbent. Currently, an activated carbon sphere (ACS) is being used in the middle layer of NBC protective clothing[9]. Further, activated carbon fabric (ACF) has also been developed from various precursors such as viscose rayon, phenolic resin, polyacrylonitrile (PAN) and pitches led to a new standard of adsorbent material which is recently being used in NBC protective clothing[11,15]. In future, some unique technologies such as selectively permeable membrane, metal-organic framework (MOF) and covalently organic framework (COF) will be explored in the place of filter fabric of NBC suit. The futuristic trends in NBC protection will be inclined towards the development of next-generation suits based on self-decontaminating properties, electrospun nanofibers-based textiles, molecularly imprinted polymers that can be used for further improvement in terms of physical and chemical protection.

2. CHEMICAL WARFARE AGENTS (CWAS)

CWAs are chemical weapons that can be in the form of liquid or gas and can cause sensorial irritation, injuries and in extreme cases even death. CWAs include nerve, blister, blood, vomiting, choking agent etc[16]. A list of CWAs is mentioned in (Fig. 1).

The nerve agent is the most toxic chemical among CWAs. They disrupt the central nervous system. These are stored as a liquid and disseminated as vapour or droplet liquid[17,18]. Blister agent is a chemical compound that causes intense affliction on the skin during contact and produces serum filled small bubble-like structure. Blood agents act as a barrier that prevents oxygen circulation from blood to cells which leads to asphyxiation. Another type of CWA is a choking agent which primarily causes irritation and inflammation of nose to lungs tissues.

The hydrophobic nature of CWAs depends upon $\log P_{o/w}$ value. $\log P_{o/w}$ is a ratio that indicates the octanol/water partition coefficient. The lower $\log P_{o/w}$ value defines the more solubility of substances in the water while the higher value indicates more solubility of substances in fatty solvents[18,19].

NBC Protective clothing is meant to protect the wearer from CWA's. So, for CWA adsorption, various adsorbents with a high surface area have come into the picture. The recent developments were introduced on the outer fabric to reduce the loading on the adsorbent layer. This multifunctional outer fabric having water and oil repellency properties can repel these CWA upto a certain extent. As some of the CWAs are hydrophobic (for example, HD,VX) and some are hydrophilic (for example Sarin), both water and oil repellency properties are required on outer fabric[13].

Some basic physical properties of basic CWAs are mentioned in Table 1.

3. EVOLUTION OF NBC SUIT

Though CWAs came into the global picture in the time of World War I and World War II, but this practice is not new to the world. In ancient civilisations, people were using chemical poison on the arrow tip to hunt animals. During World War I, a special type of rubber made impermeable chemical protective suit was developed for defence personnel of Germany. It was a two-piece suit and it had the property to protect the human body from CWAs as well as industrial toxic chemicals but it was highly uncomfortable for the wearer[2]. To overcome the above constraint with the impermeable suit, a special type of permeable suit was developed. After the Gulf war (1991) a special type of NBC protective clothing was designed by Alfred Karcher GmbH to overcome the problems in the hot atmosphere[22]. The activated carbon layer was sandwiched between two layers. Blucher, Germany proposed SARATOGA,[23] Joint Service Lightweight Integrated Suit Technology (JSLIST) NBC protective suit for US Army services[24]. In India, Defence Research & Development Organisation (DRDO) labs are involved in the development of indigenous NBC suits. DRDO has developed different NBC suits starting from charcoal, granular activated carbon and activated carbon sphere technology. NBC Suit MK-IV is based on ACS technology and the suit weights of approx 3.0 kg and shelf life of 5 years (in normal factory packed conditions). To improve this, NBC Suit Permeable Mk-V is developed

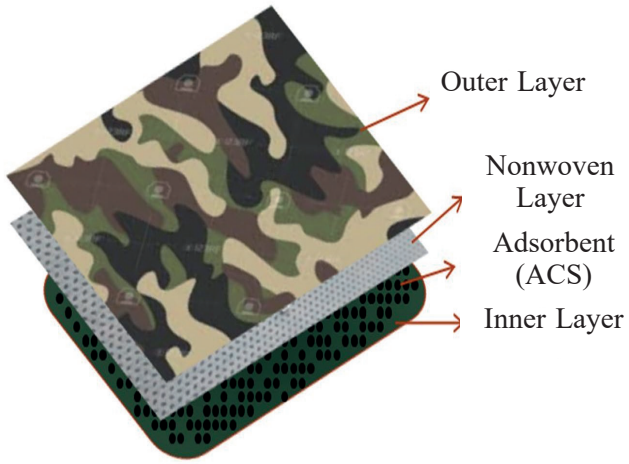
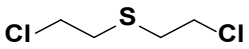
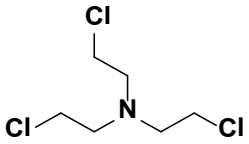
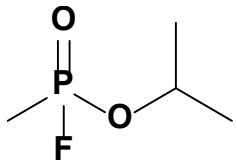
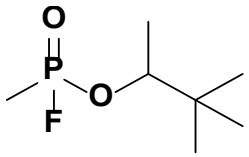
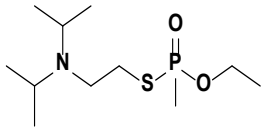
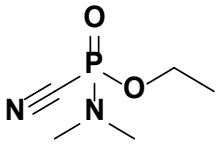
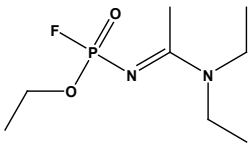
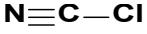
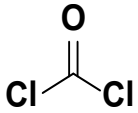


Figure 2. Construction of General NBC Suit material.

Table 1. Physical-chemical properties of different types of CWA's [20,21]

Sr. No.	CWA's Conventional Name	Structure	IUPAC Name	Boiling Point	log $P_{o/w}$	Vapour Pressure (mm Hg)
1.	Sulfur Mustard (HD)		bis(2-chloroethyl) sulphide	217 ºC	2.41-2.55	0.11
2.	Nitrogen Mustard (HN3)		Bis(2-chloroethyl)methylamine	143 ºC	1.306	0.0106
3.	Sarin (GB)		(RS)-Propan-2-yl methylphosphonofluoridate	158 ºC	0.3	2.1
4.	Soman (GD)		3,3-Dimethylbutan-2-yl methylphosphonofluoridate	198 ºC	1.78	0.40
5.	VX		Ethyl ({2-[bis(propan-2-yl)amino] ethyl}sulfanyl)(methyl)phosphinate	300 ºC	2.09	0.0007
6.	Tabun (GA)		Ethyl N,N-Dimethylphosphoramidocyanidate	247.5 ºC	0.38	0.07
7.	Novichok (A-234)		Ethyl N-[(1E)-1-(diethylamino) ethylidene]-phosphoramidofluoridate	258.1 ºC		0.0±0.5
8.	Cyanogen chloride (CK)		Carbononitridicchloride	13 ºC	0.71	1.987
9.	Hydrogen Cyanide (AC)		Hydrocyanic acid	25.7 ºC	0.66	742
10.	Phosgene (CG)		Carbonyl dichloride	8.3 ºC	1.58	1216

by improving the key parameters such as ACS crushing strength, washing cycle, and chemical protection. The NBC Suit Permeable Mk-V is lightweight (Weight for XL is 2.75 kg) in comparison to NBC Mk-IV, enhanced shelf life (Minimum 10 years), and better protective performance[13].

4. MATERIALS USED IN THE DEVELOPMENT OF NBC PROTECTIVE SUITS

NBC protective suits are the multi-layered laminated fabric that is produced by laminating individual layers of ACS or ACF, nonwoven textile material, knitted/ woven base fabric and free multifunctional outer woven fabric. The multifunctional outer fabric works as a flame retardant (FR), oil and water repellent, antistatic fabric. ACS or ACF is a good adsorbent material for CWAs. The general construction of NBC Suit material is shown in (Fig. 2). Activated carbon sphere (ACS) adsorbent has adhered to knitted/woven base fabric (inner layer fabric) which is further laminated with nonwoven fabric. After that, the outer woven fabric is stitched with the ACS adsorbent adhered laminated fabric[3.]. All over the world, different manufacturers are involved in the production of the NBC suits and the details are shown in (Table 2). The outer layer of the protective suit is consisting of woven fabric and are being manufactured by various manufacturers from different materials such as cotton, polyester, polyamide, nylon or cotton blend, PC (Polyester and cotton) blend modacrylic or cotton or para - aramid blend [5-13].

The additional functional properties are required in the NBC protective suit to protect the individual on the battlefield against flame hazards and provide water and oil repellency to reduce the penetration of CWA. The FR property of chemically modified fibre is not durable over the long term, especially after laundering. Aramid fibre is having inherent FR resistant properties. Inherent FR fibres are thermally stable fibre and they do not require an additional processing or chemical addition to increase flame retardancy. Hence, aramid woven fabric is used as an outer layer of the suit[13]. The oil and water repellent properties are achieved in the fabric by the application of fluorocarbon and its derivative chemicals. In NBC Suit Mk-V, the specified water repellency rating of the outer fabric is a minimum of 90 and the oil repellency rating is a minimum of 6. The antistatic property (specified antistatic value $<5.3\times10^{12}$) is a required parameter for NBC Suit as it repels the nuclear fall-out dust[13].

In India, activated carbon powder was used in the filter of the initial version of NBC suits which provides chemical protection properties; however, it had its shortcomings. The powder carbon adsorbent wears off during the brisk activity of the wearer. These suits were not very effective when used multiple times due to carbon shredding after washing. So, to overcome these types of disadvantages, ACS can be used in NBC suits. It is reported that ACS can be produced from various precursors (like polystyrene divinylbenzene, phenolic beads, pitch etc) by carbonisation and activation process. ACS is developed indigenously using sulfonated polystyrene divinylbenzene resin which is currently used in the development of NBC Suit Mk-V[13]. Some researchers produced ACS from polystyrene sulfonate beads and they compared surface area in case of carbon dioxide and steam activation. They found a higher surface area in the case of carbon dioxide activation (1266 m^2/g) compared to steam activation (949 m^2/g)[25].

The quality of ACS is generally specified by the iodine number, surface area, crushing strength, and the size of the particle. The preparation process of ACS used in NBC Suit Mk-V is briefly summarised in (Fig. 3).

The ACS is adhered onto the woven/knitted base fabric by using PU based adhesive. The base fabric used in the filter layer of protective clothing is generally made from different fibres such as polyester, rayon, nylon etc. ACS based these types of indigenous suits provide efficient protection to the wearers against CWAs. These suits are reusable and highly affordable because the inherent materials i.e. carbon spheres are hydrophobic so during laundering the spheres do not get deteriorated[13].

In the case of ACS, the CWAs in the gaseous form first enter the macropores followed by mesopores and micropores. However, if ACF is used instead of ACS, the adsorption will be accelerated because micropores are readily available on the surface of the fabric. ACF can be manufactured by pyrolysis process followed by chemical/ physical activation using PAN, Viscose, Pitch, Phenolic resin precursor fibres or fabric. During the processing of these precursors, thermal stabilisation can be done in an inert atmosphere (in presence of air or nitrogen). After thermal stabilisation, the carbonisation process is done at an inert atmosphere at 500°C or above. The basic requirement of the carbonisation process is to remove non-carbon atoms from the structure. After carbonisation, chemical/ physical activation is processed to get ACF with desired surface area[15,26]. The physical activation can be done using various hot gas or plasma and chemical activation can be done using incorporating chemical reagents. Due to activation, the already generated pores during the carbonisation stage are enlarged and some new pores are also generated[26]. The brief process of ACF preparation is discussed in (Fig. 4).

5. NBC PROTECTIVE SUIT CHARACTERISTIC PERFORMANCE

NBC protective suit protects the wearer against a variety of toxic chemicals that can penetrate dermally and are a threat to the combatant. Such NBC suits should be able to wear in all climatic conditions and should be compatible with other NBC accessories like gloves, boots and mask[27].

NBC protective clothing is expected to have the following main characteristic:

5.1 Lightweight

The lightweight characteristic of NBC protective

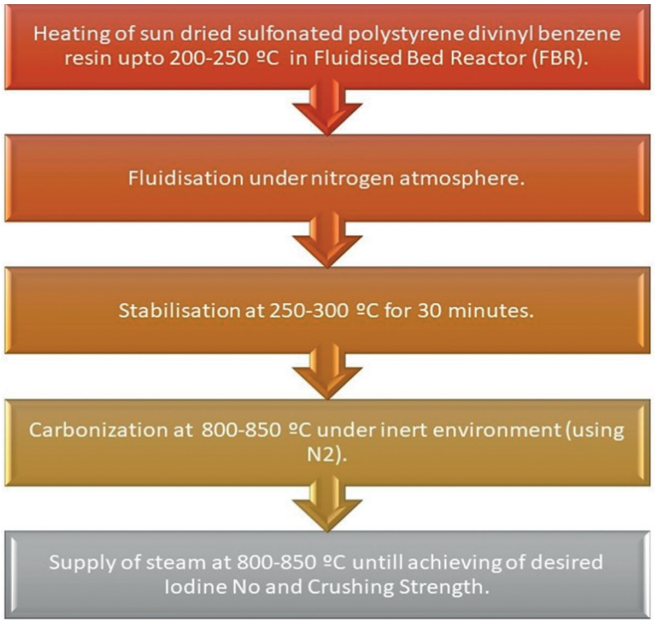


Figure 3. Flowchart of ACS preparation[13] .

clothing is essential for soldiers in a chemical warfare scenario for tactility. It also helps in the quick donning and doffing of suits over their uniforms in the stipulated time. In 1981, one-time usable Battledress over garment (BDO) consisting of coat and trouser is developed to protect the defence personnel against CWA. The BDO liner consists of charcoal-impregnated polyurethane foam and nylon tricot laminate. It adds approximately 11 pounds to the weight already carried by the soldier[15, 28, 29].

In 1995, JSLIST protective suit was developed to protect against CWA and radioactive fallout dust. The outer shell of the JSLIST ensemble was made of nylon/ cotton fabric. This ensemble was considered a standard NBC ensemble because it replaced the Battle Dress Over garment (BDO) and resulted in a 13 per cent total weight reduction[28]. OPEC CBRNe Ltd, UK developed the Kestrel CBRN Suit which is 30 per cent light in weight than conventional systems. This two-piece suit is made of FR, oil and water repellent polyester ripstop weave outer fabric with an activated carbon suit liner[6].

Blucher GmBH, Germany developed CBRN protective cover all. The weight of this suit is less than 5 pounds this one piece suit is made out of oil and water repellent polyester ripstop weave outer fabric with activated carbon liner[9]. In India, earlier two-piece NBC Suit Mk-IV consisted of a hooded jacket and trousers were used by the Indian Defence Forces. The weight of this suit for extra-large size was less than 3 kg. Now NBC suit Permeable Mk-V coverall has been developed (less than 2.75 kg for extra-large size)[13].

5.2 Enhanced Chemical Protection

Effective chemical protection for more than 24 hours for a particular concentration with the chemical in liquid, vapour and aerosol form is the key performance characteristic of the NBC suit. The chemical protection of protective clothing depends on many parameters like adsorbents such as activated carbon powder, sphere and fabric, the surface area of adsorbent, crushing strength of sphere, pore size and shape, the adhesive used for coating/laminating of an adsorbent[13]. Activated carbon adsorbents with a high surface area are intended to enhance chemical protection by adsorbing more CWAs. The surface area and pore size can be measured by using surface area and a pore size analyser. The material with higher micropore volume will adsorb more CWAs.

The crushing strength of activated carbon spheres is strongly dependent on the surface properties and can be determined using standard ASTM C 695. During transportation and other regular combat movements, lower crushing strength of ACS will lead to the crack in the ACS and therefore it will defeat the purpose of protection and may cause carbon shredding. However, simultaneously, the surface area and crushing strength cannot be increased, the high surface area will lead to low crushing strength as these properties are contrary to each other[30]. Hence, there is a need to develop balanced properties of surface area and crushing strength that can meet the requirement of NBC protection for first responders. The protection also depends on oil & water repellency of the outer fabric as it reduces the load on the adsorption Layer. Further non-woven also imparts an important role as it distributes the penetrated CWA at layer area[13].

5.3. Wear Comfort or Heat Stress

Heat stress in NBC protective clothing is an important factor in military practice. In the hot and humid climatic zone, there is always a danger of extreme overheating (heat stress) while wearing NBC protective clothing. High heat stress in the hot and humid climatic zone is resulting from interference of thermal balance (heat formation in an organism is equal to heat emission to the surroundings) with time[31]. Therefore, weight reduction and minimised physiological stress in NBC Protective clothing is required for the wearer's comfort.

In comparison with impermeable (rubber) clothing, the permeable NBC clothing has low heat stress due to relatively good exportation of air and moisture through the fabric[32]. Though low heat stress is encountered by permeable NBC suit, still it has some limitations in the hot and humid atmosphere.

The heat stress can be reduced by improving the air permeability property of fabric which leads to higher comfort to the wearer. But the main chemical protection performance of clothing is affected by improving the air permeability property of the fabric. Thus, it is very important to understand the relationship between chemical protection, air and moisture permeability. There are many instruments available that model the real situation of heat and moisture transfer from body surface through clothing material. One of the instruments which are

Table 2. Various ACS/ACF incorporated NBC protective suit material characteristics along with their manufacturers[5-13]

S. No.	Manufacturer	Product Name	Material	Suit Mass	Chemical Protection BTT	Wash cycle (times)	Shelf life (years)	Ref.
1	Tex-Shield, Inc., Washington, DC	SARATOGA™ Hammer Suit (Two-piece Garment)	**Outer layer**- 100% Cotton woven fabric **Inner layer**- Polyester knit coated with activated carbon spherical adsorbers covered with a non-woven laminate	NA*	>396 min. for GB and 253 min for HD	6	15	5
2	OPEC CBRNe Ltd, UK	KESTREL High Comfort and High Protection CBRN Over suit (Two-piece Garment)	**Outer layer-**Polyester/ cotton blended woven fabric **Inner layer**-100% activated carbon fibre laminated to a 100% polyester protective scrim	NA*	NA*	20	10	6
3	OPEC CBRNe Ltd, UK	ROC Civil Responder CBRN Suit (Coverall)	**Outer layer-**Polyester/ cotton blended woven fabric **Inner layer**-100% activated carbon fibre laminated to a 100% polyester protective scrim	NA*	NA*	NA*	20	7
4	OPEC CBRNe Ltd, UK	FALCON High Comfort and High Protection CBRN Over suit (Coverall)	**Outer layer-**Polyester/ cotton blended woven fabric **Inner layer**-100% activated carbon fibre laminated to a 100% polyester protective scrim	NA*	NA*	20	10	8
5	Blucher, Germany	SARATOGA CBRN Protective Coverall	**Outer layer-**Polyamide ripstop, oil and water repellent **Inner layer**-Polyester warp knit coated with spherical adsorbent covered with 100 % polyester non-woven	< 2.2 kg	12 hours against HD liquid and 12 hours against HD vapor	6 wash at 40º C	10	9
6	Shalon chemical industries limited , Israel	Air-Permeable NBC Protective Suit (Coverall)	**Outer layer-**Nomex or cotton **Inner layer**- Rayon knit with activated carbon beads or foam	NA*	6 hours against HD and GD liquid	NA*	10	10

S. No.	Manufacturer	Product Name	Material	Suit Mass	Chemical Protection BTT	Wash cycle (times)	Shelf life (years)	Ref.
7	Paul Boye, France	TOM NG Protective Suit (Two-piece Garment)	**Outer layer**-Camouflage printed woven fabric **Inner layer**-100 g/m^2 knitted activated carbon fabric	1.8 kg	24 hours against HD liquid	10	>5	11
8	CQC, UK	Raptor2 (Two-piece Garment)	**Outer layer**- Highly breathable and rugged ripstop outer. **Inner layer**-Lightweight activated carbon liner	1.8 kg	24 hours against HD liquid	20	15	12
9	DRDO, India	Mk-V (Coverall)	**Outer layer**- FR, oil and water repellent outer woven fabric **Inner layer**- Cotton knit fabric coated with activated carbon spherical adsorbent	<2.75 kg (XL)	24 hours against HD liquid and 6 hours against HD vapor	6	10	13

a sweating guarded hot plate was designed for the measurement of thermal resistance and water vapour permeability of fabrics. From this instrument, water vapour resistance (Ret) is measured under the steady-state condition and expressed in Pa.m^2/W. Ret is the measurement of evaporative heat loss resistance and its lower value signifies less resistance to moisture transfer through the fabric and therefore higher breathability[33]. Lin *et al.,* 2017 oil have reported that the JSLIST was better in thermal wearing performance than BDO. They evaluated the thermal comfort properties of JSLIST and BDO Suits by measuring water vapour resistance properties i.e. Ret (m^2.Pa/W). The Ret value of JSLIST and BDO was 6.1 and 8.6 respectively and this was tested by using a sweating guarded hot plate system[33].

5.4 Durability

The durability of the NBC suit is important from a safety and economic wise. No drop-off in performance due to wear or laundering is an essential characteristic of NBC protective clothing.

The JSLIST first entered service in 1997. The outer shell of the JSLIST over-garment is made from 50/50 nylon/cotton blended rip-stop fabric with a durable water-repellent finish. The liner of JSLIST consists of a polyester tricot knitted fabric coated with activated carbon sphere adsorbents covered with a non-woven fabric that adsorbs chemical agents[34]. This particular suit can be washed up to six washes after that its protection properties diminish. This suit can be stored for up to 10 years. In India, ACS based NBC Suit Mk-IV was developed and it was three times washable. Further, in NBC Suit Permeable Mk-V the wash durability has increased to six times with a shelf life of 10 years.

6. TESTING AND EVALUATION OF NBC PROTECTIVE SUITS

There are several Test standards available worldwide to evaluate the performance of NBC protective clothing including MIL-DTL-32102, IS 17377. In particular IS 17377 (2020), the swatches from the different places of the NBC suit are evaluated for sulphur mustard (HD) liquid challenge, HD vapour challenge, Expulsion, Inverted Expulsion, Mandrel against Indian standard which is adopted from US military standard[35,36]. These tests along with HD Breakthrough Time (HD-BTT) are also discussed in IS-17377. The detailed procedures of some important testing parameters are discussed in (Table 3).

7. FUTURE PROSPECTIVE AND CHALLENGES

The next-generation suits must have some special features like lightweight, more comfortable, self-decontaminating properties, optimised protection to CWAs. Some of these types of ideas are discussed here.

7.1 Self-Decontaminating Suit

Currently available NBC suits can only give protection against CWAs so if the suits are exposed to any type of CWAs, then it is difficult to dispose of and reuse them. So, to overcome this type of problem, the concept of self-decontaminating suits has come into the picture. The inherent meaning of self-decontamination means when the CWAs will come into the contact with the layers of the NBC suit, they will be converted into a non-hazardous

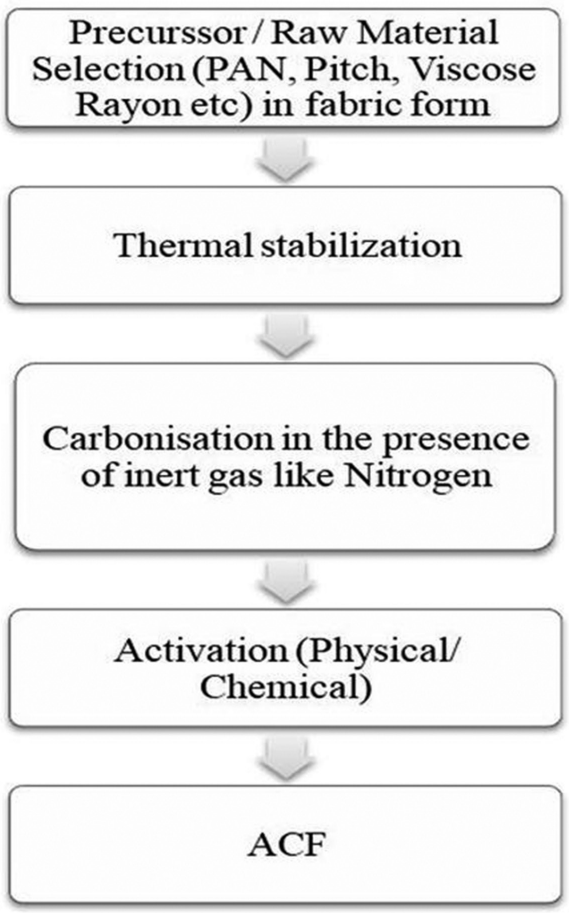


Figure 4. Flowchart of ACF preparation[15] .

chemical compound. If we consider CWAs, it mainly breaks down by the process of oxidation or hydrolysis. Sulphur mustard, which is a blistering agent, contains sulphur atoms that can be oxidised[40]. VX, the nerve agents are organo-phosphorus compounds that can be hydrolysed. So, if it is possible to insert a coating on the fabric of metal-organic frameworks (MOF),[41]polyoxometalates, these will lead to self-decontaminating properties of the fabric. UiO-66[40] is a type of MOF which is made of $Zr_6O_4(OH)_4$ has the property to hydrolyse the nerve agents[42].Some researchers synthesised mesoporous CuO and ZnO binary metal oxide nanocomposite for decontamination studies against GB. It exhibits a high surface area (84 m^2/g) in comparison with individual metal oxide nanoparticles. This nanocomposite decontaminated Sarin into isopropyl methyl phosphonic acid and methyl phosphonic acid[43]. So, in futuristic trends these types of chemical compounds and other new chemicals one can use to functionalize the NBC protective suits.

7.2 Electrospun Nanofibre Based Suit

Electrospinning is a fibre production process where the electrical forces are used to draw the charged threads of polymer solution which will melt and produce fibres. Some researchers have developed PAN by using the electrospinning method with the help of a polymeric solution made of raw PAN fibres and N, N-dimethylformamide (DMF)[44]. Then these PAN fibres are reacted with excess hydroxylamine in methanol at 70°C which leads to the generation of poly-acrylamidoxime (PAAO) functionalised fibres or it can be called PAN-Ox fibres. These PAN-Ox fibres can hydrolyse Diisopropylfluorophosphate (DFP) which is a simulant of CWAs. In future, these types of fibres made from the electrospinning process may be used for developing NBC suits. The main advantages of electrospun fibres are their structural beauty. These types of fibres have smaller diameters and larger surface areas so the filtration efficiency is much higher[45]. Some researchers have developed PA6 nanofibre using electrospinning technique and then laminated it onto a viscose substrate by hot press lamination process using resin. This provides good protection against CWAs in aerosol form[46]. Polyurethane based nanofibre functionalised with N-ChloroHydantoin can be used as NBC protective suit made from electrospinning technique and it also has self-decontaminating property. It has been tested on CEES and Demeton-S-methyl which act as simulants of sulphur mustard type blister agents and V-type nerve agents[47]. So in a futuristic approach, these types of fibres or fabrics can be used as NBC protective clothing.

7.3 Activated Carbon Fabric-Based Suit

To increase protection against CWAs, ACF laminated fabric can be used as a filter layer of NBC clothing for future research. ACF is highly porous due to which the adsorption capacity of ACF is better than other forms of activated carbon such as granular and powdered activated carbon. High surface area and average aperture of micropore of ACF lead to enhance adsorption and desorption at a faster rate. The manufacturing processes of ACFs from different precursors are different as fabrication processes depend on the nature of precursor fibres. Different types of precursors like PAN, polyvinyl alcohol (PVA), polyamides, manufactured manmade fibres like viscose rayon, pitch fibres can be used as a precursor for ACF[26]. Taiwan Carbon Technology Co. Limited is producing ACF by using various precursors such as Phenolic resin, cellulose, PAN, and Pitch. They have achieved surface area of ACF fabric in the range of 1000-2300 m^2/g and micropore volume 1-1.2 ml/g by using Phenolic resin precursor. By using PAN precursor, they have achieved surface area is 700–2000 m^2/g and micropore volume of 1.5–2 ml/g[48].

ACF can be manufactured in three steps. At first, these precursor fibres are stabilised in presence of air or inert gas. The next step is carbonisation where the precursor fibres are heated at higher temperatures (>500ºC) without any presence of oxygen. Next is the activation stage where the surface area is increased and the tarry materials which are inside of the pores are removed [14]. Activation can be done chemically or physically but the chemical activation process is not economically viable compared to physical activation[48]. Recently ACF based protective clothing is used worldwide. OPEC CBRNe Ltd,

Table 3. Physical & chemical protection testing standard for NBC protective clothing[14,28,30,35,37-39]

Sr. No.	Test Parameters	Brief Discussion	Purpose	Test Standard
1.	Water vapour resistance, m^2Pa/W	• In this test, a fabric specimen is placed above an electrically heated porous plate • Fabric specimen is placed with conditioned air onto plate ducted to flow across and parallel to its upper surface. • With the test specimen placed on the membrane, the energy flow per unit of area per unit time required to maintain a constant temperature at the plate is a measure of the rate of water evaporation.	Breathability and Comfort	ISO 11092
2.	Air permeability, $cm^3/sec/cm^2$	• The air permeability of fabric is determined by measuring the airflow rate passing perpendicularly through a known area of fabric.	Breathability and Comfort	ASTM D 737
3.	Liquid chemical agent challenge	• This test quantitatively investigates the permittivity of sulphur mustard (HD) through suit swatches in Liquid challenge/Vapour permeation dual flow mode for 24 hours. • A fabric sample of specified size is placed on the permeation chamber and a drop of HD is applied to the top surface of the fabric sample. • The amount of HD penetrated through the fabricis analysed by Gas Chromatography-Mass Spectroscopy (GC-MS). • Challenge level: 10 g/m^2, HD 24 Hours	Chemical Protection	IS 17377 Part-2 (2020), MIL DTL 32102A
4.	Vapour challenge	• This test quantitatively investigates the permittivity of HD through suit swatches in Vapour challenge / Vapour permeation convective mode for 6 hours. • A sample swatch of a specified dimension is placed in a vapour penetration close test assembly. • After six hours of exposure, the amount of HD agent penetrated through fabric swatch is collected by some adsorbent and finally, the concentration is analysedbyGC-MS. • Challenge level: 20 mg/m^3, HD 6 Hours	Chemical Protection	IS 17377 Part-2 (2020), MIL DTL 32102A
5.	HD-BTT test	• This test qualitatively investigates the penetration of sulphur mustard (HD) through suit swatches at 20°C temperature in ambient pressure for 24 hours. • In this method, a brass assembly is specially designed with a 12 µl droplet of HD applied on a cotton drill cloth. • A detection paper placed over the sample is examined through the glass plate at regular intervals of time to identify the moment of formation of blue spots. The HD-BTT time is measured in hours.	Chemical Protection	IS 17377 Part-1 (2020)

Sr. No.	Test Parameters	Brief Discussion	Purpose	Test Standard
6.	Mandrel test	• This test qualitatively investigates the penetration of sulphur mustard (HD) through suit swatches under stress for a 1-hour duration. • A rectangular fabric strip is placed above Three Color Detector (TCD) paper on a round glass mandrel. • A weight of 234 g is attached to each end of the strip so that strip is maintained at stress conditioned. • On the top surface of the fabric sample, six HD droplets of 4 µl are applied. • TCD paper is periodically checked for the sign of HD penetration for a 1-hour and is ascertained by the colour change of paper.	Chemical Protection	IS 17377 Part- 1 (2020), MIL DTL 32102A
7.	Expulsion test	• This test qualitatively investigates the penetration of HD through suit swatches under pressure for a 1-hour duration. • In the expulsion test, a fabric swatch of a specified dimension is placed above TCD paper on a glass plate. • A single drop of 4 µl of HD is applied on the top centre of the swatch and waits for 15 sec. If no sign of penetration is observed then a pressure of 70 g/cm^2 is applied on the surface of the swatch by applying 454 g weight.	Chemical Protection	IS 17377 Part- 1 (2020), MIL DTL 32102A
8.	Inverted Expulsion test	• In the inverted expulsion test, a single drop of 4µl of HD is applied on a glass plate. • After that fabric swatch of a specified dimension is placed on a glass plate with swatch sample outer surfaces in contact with HD liquid agent. • The TCD paper is placed above the fabric swatch and waited for 15 sec. • If no sign of penetration is observed then pressure is created on the surface of the swatch by applying 454 g weight. If no penetration is observed at the end of the 1-hour duration, the fabric sample is the pass for this test.	Chemical Protection	IS 17377 Part-1 (2020), MIL DTL 32102A
9.	Man-In Simulant Test for Protective Ensembles	• In this test, human subjects dressed in full chemical protective ensembles have thirty passive adsorbent dosimeters (PADs) on their body. The subjects are placed in the MIST chamber at a controlled temperature, humidity, wind speed, and methyl salicylate concentration (warfare agent simulant). • Following the test, the amount of simulant on each PAD is measured and related to a dosage inside the ensemble at that particular body region, and finally, a protection factor is calculated by creating a ratio of the dosage outside the suit to the dosage inside the suit.	Chemical Protection	ASTM F2588 – 12, (TOP) 10-2-022

UK has designed ACF based ROC Civil Responder CBRN Suit and FALCON High Comfort and High Protection CBRN Over suit[7,8]. In future, ACF based NBC suit will come into the market by optimisation of different process parameters involved in ACF preparation.

7.4 Molecularly Imprinted Polymer-based Suit

Molecular imprinted Material (MIM) fabrication on nano fabric structure is also a better choice for a next-generation suit for detection and decontamination of chemical and biological warfare agents. Detection, interaction and binding with the targeted chemical and bio-molecular species can be done by molecularly imprinted polymer (MIP) and these are the key features of MIM. Molecularly recognition capability of fibre through molecularly imprinted polymer can be done by spinning and surface modification methods[2]. Three dimensional imprinted approaches[49,50] like atom transfer radical polymerisation technique (ATRP) has been successfully used for the synthesis of MIP and characterised physical and chemical properties as well as effectiveness against CWAs and metal ions. As per researchers, ATRP is one of the successful techniques to develop a definite thickness with an easy coating of MIP on flat fabric surfaces without affecting the morphology of the parent fabric. Molecularly imprinted fibre has more adsorption capacity as compared to non-molecular imprinted fibres so it can be used as an adsorbent layer in next-generation NBC protective clothing [50].

8. CONCLUSION

NBC protective gears have consisted of NBC protective suits, gloves, boots and canister masks. Here only the technologies and materials of the NBC protective suit are discussed. The evolution of developing NBC protective suits was started during world wars and the up-gradation in terms of materials and technologies will carry forward in future. It is shown that activated carbon in terms of spheres or fabrics has played a vital role to obstruct CWAs. DRDO is indigenously developing NBC protective suits of different versions over the years and research and development activities are still under process for producing good quality suits in terms of chemical protection and comfort properties. In the futuristic approach, advancement on some special type of electrospun nanofiber-based composite suits having inherent self-decontaminating properties will come into the picture. A self-decontaminating suit is developed by functionalisation of existing technology and this type of suit is highly required because it may be reusable. But there will be some issues regarding the shelf-life of the suit because, after decontamination, the chemical molecules of the suit have deteriorated. So, optimisation is needed to fulfil the desired property. As the currently available NBC suits are not very lightweight with comfort characteristics, so many researchers are continuously focusing on the advancement of NBC suits in terms of various physical and chemical properties.

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