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Influence of Structural Parameters of Wale-Knitted Fabrics on their Electrostatic Properties

Abstract
This work presents the electrostatic properties of knitted fabrics destined for protective clothing used to protect humans against static electricity. The aim of this research work is to estimate the electrostatic properties of knitted fabrics in dependence on the degree to which their structure is filled with basic yarn, and on the content of the electro-conductive yarn added. The knitted structures were developed for manufacturing by warp knitting, with the assumption that the electro-conductive yarn will be periodically worked into the background made of the basic yarn. Three variants of triple-needled wale-left/right-knitted fabrics were the test material. They differed in the degree to which they were filled with the background made from polyester (polyethylene terephtalate – PET) yarn. The electro-conductive yarn was introduced into the knitted fabric's structure in the form of vertical weft. The weaves applied resulted in anti-electrostatic knitted fabrics with a heterogeneous structure being obtained. We assessed the anti-electrostatic properties and selected usage properties of the fabrics manufactured. The results obtained confirmed that all the knitted fabrics we developed meet the requirements of standards concerned with anti-electrostatic protective clothing, and that their properties depend on the structural solutions applied.

Key words: *electrostatic properties, protective clothing, wale knitted fabrics, electro-conductive fibres, structural parameters.*

Introduction

The requirements for individual protective means, such as protective clothing, depend on the clothing's usage conditions, and include protection against chemical agents, heat, air pollutions, biological influences, dusts, and electric shocks [1 - 4]. Manufacturing particular individual textile protection products often requires the use of synthetic fibres, which are characterised by very low electrical conductivity, and at the same by a high ability to accumulate electric charges. This usually results in the necessity to guarantee the anti-electrostatic properties of the protective clothing in order to avoid the risk of an explosion initiator forming, i.e. a rapid discharge of electric charges accumulated on the clothing surface. This phenomenon is especially dangerous in the regions of explosive atmospheres which often occur in the chemical, petrochemical, food, and woodworking industries, among others.

Anti-electrostatic finishes containing particular chemical compounds (e.g. quaternary amine salts, modified esters of fatty acids, polyglycol derivatives, and esters of phosphoric acids) are traditional methods of increasing the electro-conductivity of textile products. Unfortunately these methods, which are based on depositing finish on the fibres' surface, do not assure stable improvement effects, regarding their low washing and abrasion resistance during use of the products. Stable anti-electrostatic effects may be achieved by modifying the fibre matter with specially selected chemical compounds, changes to the fibres' microstructure, and using anti-electrostatic dopes added to the polymer mass before spinning. However, the structure's modification may cause a decrease in the fibres' strength properties and accelerate ageing. The following methods of electrostatic protection textile materials by the use of electro-conductive fibres are the most effective: using metallic and metallised fibres, and fibres manufactured of polymers modified with particles of carbon black, graphite, metallic powders, and metallic salts of semiconductor character [5]. The efficiency of draining electrostatic charges from a textile product, thanks to the application of electro-conductive fibres, depends above all on the kind of raw materials used, and at the same on the material's structure, which should ensure good contact between the fibres and the rubbing surface [6, 7]. A special advantage of using electro-conductive fibres when manufacturing protective clothing is that the anti-electrostatic effect is very stable, in contrast to other methods, and does not depend on air humidity. An additional advantage is the possibility of using various chemical agents as finish in order to obtain other protective properties, by maintaining the anti-electrostatic features [8 - 12].

The basic aim of our research was to develop knitted fabrics with stable anti-electrostatic properties using yarns containing electro-conductive fibres. The subject of our investigation was also to determine in detail those properties of the fabrics manufactured in dependence on the structures applied [8, 13, 14]. Generally it is known that while considering the use of electro-conductive fibres, the following factors have the greatest influence on the electrostatic features: the fibres' electro-conductivity, the electro-conductive fibres' share in the total volume of the knitted fabric, the type of its arrangement in the fabric, the type of the basic yarn, and the structure of the textile material [15].

Research material

Wale-knitted fabrics with the structure of an anti-electrostatic non-homogeneous material were the subject of our research [16].

The background of the knitted fabrics was manufactured of polyester yarn (polyethylene terephtalate –PET) with a linear mass of 110 dtex f24.

VSc Lenzing 75% / PES 25% two-component yarn with a linear mass of 40 tex was used as the electro-conductive component of the fabrics. The polyester (PES) yarn component contained a fibre with carbon compounds of the Resistat type. The electrical yarn properties were characterised by the electrical resistivity factor ρ_G calculated in relation to the length unit according to Equation (1):

$$\rho_G = \frac{Z}{a_o} \times \overline{R}_P, \ \Omega/\text{m} \qquad (1)$$

where:

R_P – the average value of resistance measured, Ω

$Z = 25$ – the number of threads arranged parallel between the electrodes, and

$a_0 = 0{,}05$ – the distance between the electrodes, m.

The results of the electrical resistance measurements, which were carried out in the Laboratory of Testing Raw Materials and Textile Products of the Textile Research Institute, Łódź, are presented in Table 1. The tests were performed in accordance with standard [17] at a temperature of 22.4 °C, relative air humidity of 26%, and measurement voltage U = 10 V.

The electro-conductive yarn was inserted along the wales as vertical weft. The distances between the subsequent wefts arranged along the fabric's width were accepted in accordance with standard requirements for anti-electrostatic non-homogeneous materials [16, 18], which state that the distances between electro-conductive bands should not be greater than 10 mm.

The knitted fabrics were manufactured with the use of a RM6 warp-knitting machine, from Mayer (Germany), with a 32/2 S needle cut. Three variants of triple-needled wale-left-right-knitted fabrics, differentiated by the background's filling degree, were manufactured for our tests. The fabrics' background was made by two component weaves, the chain weave with open loops, and the following three interchangeable used weaves with closed loops: tricot (variant 1), woollen cloth (variant 2), and velvet (variant 3), all presented in Table 2.

The background of the knitted fabrics was made at full threading of the needle bars. As the result of differentiating the loop links' length of one of the component weaves, we obtained knitted fabric variants of the various background's filling degrees by the polyester yarn. As was mentioned previously, the electro-conductive yarn was inserted along the wales as vertical weft with convertible projection behind one needle at non-full threading of the needle bar of a 1×5 report. As the result of the weave combinations used, we obtained different arrangements of the electro-conductive yarn on the knitted fabric's reverse side, as well as a differentiated filling degree of the polyester background, which is visible on the photos in Figures 1.

Table 1. Electrical properties of yarn containing electro-conductive fibre.

Linear resistance R_p, Ω	average value of n = 10 measurements	**1.75 x 10^5**
	maximum value	1.92 x 10^5
	minimum value	1.29 x 10^5
	confidence interval for p=0.95, ± %	3,8
Linear resistivity ρ_G, Ω/m	**8.8 × 10^5**	

Table 2. Weave characterisation of the wale-knitted fabrics with an electro-conductive yarn content.

Denotation of knitted fabric's variant	Type of component weave		
	1st needle bar (upper warp)	2nd needle bar	3rd needle bar (lower warp)
1	chain	weft	tricot
2	chain	weft	woollen cloth
3	chain	weft	velvet

Subject field and methodology of research

Structural properties of the knitted fabrics obtained

The structural properties of finished knitted fabrics were determined for the following parameters:

- course density P_c and wale density P_w as the number of courses and wales respectively per 100 m [19];
- area density P_a as the product of course density P_c and wale density P_w; [20, 21];

$$P_a = P_c \times P_w, \qquad (2)$$

in the number of loops per dm²;

- coefficient of the linear filling Z_l of the background, as a ratio of yarn diameter D and yarn length *l* in the loop [20 – 22];

$$Z_l = D/l \qquad (3)$$

- coefficient of the area filling Z_a of the background, as a ratio of the longitudinal cross-section of the yarn forming the loop and the area of a single loop [20 – 22],

$$\boldsymbol{Z_p} = \frac{l \times D}{A \times B} \qquad (4)$$

where:

$A = 100/P_w$ – the width of a single wale of loops, mm,

$B = 100/P_c$ – the width of a single course of loops, mm,

D – the thickness of yarn in a free state, the so-called normal thickness;

- coefficient of volume filling Z_v of the background as a ratio of the volume of yarn inserted into the loop and the volume of the loop [20 – 22],

$$\boldsymbol{Z_V} = \frac{\Pi \times D^2 \times l}{4 \times A \times B \times G} \qquad (5)$$

where:

G – the knitted fabric thickness, mm.

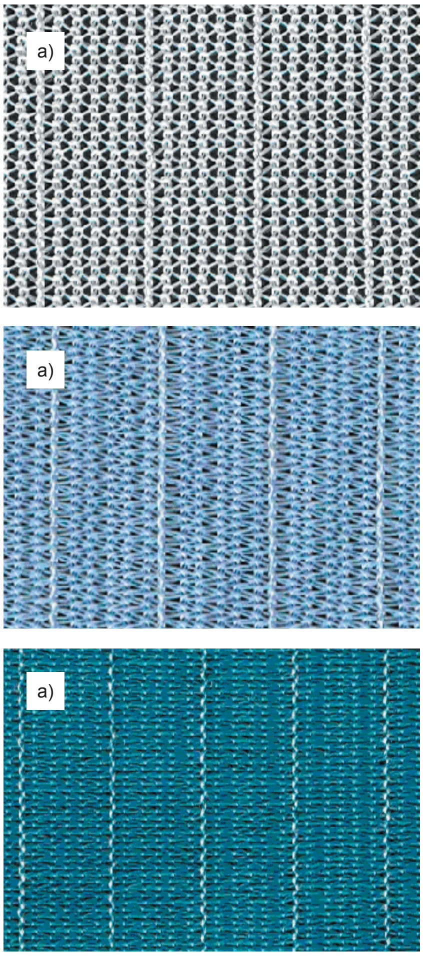

***Figure 1.** Photo of the knitted fabric's reverse side; a - variant 1), b - variant 2, c - variant 3.*

The average length of yarn l in the loop was determined in dependence on the area mass m, and the knitted fabric's structural parameters [23]:

$$l = \frac{m \times 10^4}{P_{rz} \times P_k \times Tt} \quad (6)$$

where:

m – the area mass of the knitted fabric without the content of electro-conductive yarn, g/m2

Tt – the linear mass of yarn of the knitted fabric's background, mm.

For our calculations of the yarn length in loop, the results of measurements of the area mass m_a in accordance with [24] were used, diminished by the mass of the electro-conductive yarn's content. The percentage shares of electro-conductive yarn were determined according to [25]. The background yarn diameter D was calculated on the basis of measurements with the use of an MP3 projection microscope, in accordance with the standard which describes the determination of chemical fibres' diameters [26].

The tests of the knitted fabric's structural parameters and of the content of component yarns were carried out in the Textile Technology Research Laboratory of the Tricotextil Institute of Knitted Techniques and Technologies, Łódź. The results are presented in Table 3.

Usage properties of the knitted fabrics obtained

The usage properties were determined for the finished fabrics. The following properties were assessed: area mass m_a [24], longitudinal k_l and transversal k_t dimension changes after washing [27 - 29], air permeability R [30], strength against ball punching W_p [31], one-directional stretching strength as the maximum force at stretch of the knitted fabric to break in longitudinal F_{max}-k_l and transversal directions F_{max}-k_t, and relative elongation at maximum force, while one-directionally stretched in longitudinal ε_{max}-k_l and transversal directions ε_{max}-k_t [32].

The tests of the knitted fabric's usage properties of the component yarns were carried out in the Textile Technology Research Laboratory of the Tricotextil Institute of Knitted Techniques and Technologies, Łódź. The results are presented in Table 4.

Electrostatic properties of the knitted fabrics obtained

The electrostatic properties of the finished knitted fabrics which we obtained were determined after 5 standard washing processes under conditions of preventive maintenance of the knitted fabrics, as applied in final products in accordance with the standards for protective clothing [33]. The following parameters were determined:

- surface resistance R_S, determined as the quotient of the value of direct current voltage connected to the fabric sample with the use of prescribed electrodes, to the intensity value of the electric current flowing on the sample's surface, in Ω.
- Through resistance R_V, determined as the quotient of the quotient of the value of direct current voltage connected to the fabric sample with the use of prescribed electrodes, to the intensity value of the electric current flowing perpendicular to the sample's surface, in Ω.
- Time of half-decay $t_{0.5}$ of the electro-static charge, determined on the basis of the period of discharging after which the value of the electrostatic field intensity E_R decreases to half of its initial value $E_{max}/2$, in s.
- Screening coefficient S, which allows us to estimate to what degree the value of the electrostatic field intensity for the given sample is reduced, compared with the initial value.

Tests of the electrostatic properties of the knitted fabrics were carried out in the Laboratory of Testing Raw Materials and Textile Products of the Textile Research Institute, in accordance with standards for fabrics intended for protective clothing [34, 35, 36]. The tests were performed at a temperature of 23.2 °C and relative air humidity of 25.5%. As the knitted fabrics' structural reverse side, with visible electro-conductive yarn, had been provided as the use-side in the final anti-electrostatic product, this side was accepted for the surface resistance measurements. The test results are presented in Table 5.

The measurements of the half-decay times ($t_{0.5}$) of the electrical discharges were performed by the induction method, based on impulse generation of the electrical charges with the use of an electrode [11, 12, 37]. The electrode was placed not on the sample's surface but at a specific distance from it. The charging degree of the sample tested is estimated by the value of the electrical

Table 3. *Test results of knitted fabrics' structural properties and the contents of the electro-conductive yarn in the knitted fabric.*

Denotation of knitted fabric's variant	1	2	3
Content of electro-conductive yarn in loop, %	6,1	4,6	4,0
Course density P_c, number of courses/dm	129	171	176
Wale density P_w , number of wales/dm	70	69	69
Area density P_a, number of loops/dm2	9030	11799	12144
Length of background yarn in loop/mm	8,1	8,7	10,7
Coefficient of linear filling of the background Z_l, -	0,027	0,025	0,021
Coefficient of area filling of the background Z_a, -	1,6	2,3	2,8
Coefficient of volume filling Z_V, -	0,54	0,68	0,78
knitted fabric's thickness G, mm	0,53	0,59	0,63

Table 4. *Usage properties of knitted fabrics with electro-conductive yarn.*

Denotation of knitted fabric's variant		1	2	3
Area mass of knitted fabric, total, m_a , g/m2		86	119	145
Area mass of the background m, g/m2		80.7	113.5	139.2
Air permeability R, mm/s		6260	3190	2150
Dimension change of knitted fabric after a single washing, %	longitudinal k_l	-3	-1.5	-1.5
	transversal k_t	0	0	-0.5
Dimension change of knitted fabric after 5 washings, %	longitudinal k_l	-4	-2.5	-2.0
	transversal k_t	-1	-1.0	-0.5
strength against ball punching W_p , daN		30.5	51.0	64.5
Maximum force at one-directional stretching, F_{max} , N	longitudinal k_l	330	240	210
	transversal k_t	130	350	580
Relative elongation at break (at maximum force) ε_{max} , %	longitudinal k_l	38.0	53.5	49.0
	transversal k_t	52.0	49.0	44.0

Table 5. Electrostatic properties of knitted fabrics with electro-conductive yarn.

Denotation of knitted fabric's variant		1	2	3
Surface resistance R_S. Ω	Average value of n = 10 measurements	2.57 x 10^5	1.52 x 10^5	1.49 x 10^5
	Maximum value	3.52 x 10^5	2.53 x 10^5	2.29 x 10^5
	Minimum value	1.29 x 10^5	0.98 x 10^5	0.83 x 10^6
	Confidence interval for p=0.95. ± %	21.3	23.5	25.2
Through resistance R_V. Ω	Average value of n = 10 measurements	1.3 x 10^{11}	1.2 x 10 ^{11}	1.3 x 10^{11}
	Maximum value	1.9 x 10^{11}	1.9 x 10^{11}	1.9 x 10^{11}
	Minimum value	9.3 x 10^{10}	7.1 x 10^{10}	8.7 x 10^{10}
	Confidence interval for p=0.95. ± %	17.8	22.8	21.0
Average time of electrical charge half-decay $t_{0.5}$. s		0.070	0.022	<0.01
Average screening factor *S*.-		0.453	0.485	0.485

field intensity E_R at the sample's side opposite to the side with the induction electrode working. The electrical field intensity values (E_R) obtained indicate the charging degree of the sample tested in relation to the initial field intensity values, which are the values measured without the fabric sample tested. The initial value of the electrical field intensity is the maximum value of the method applied. For materials which are pure dielectrics, the value of the electrical field intensity obtained by the measurement is equal to the maximum value, whereas for materials characterised by some electro-conductivity, the values obtained by measurements are smaller than the maximum value. The decreased value of the electrical field intensity E_R is related to the electrostatic charge drainage through the sample tested. The time period after which the value of the field intensity E_R is equal to the half-value of the maximum field intensity value $E_{max}/2$ is called the half-decay time ($t_{0.5}$) of the electro-static charge for the sample tested. The values of E_{max} and E_R of the electrical field intensity determine the screening factor according to the following equation:

$$S = 1 - E_R/E_{max} \quad (7)$$

Figure 2 presents an example of changes in the electrical field intensity with time for a knitted fabric sample (of variant 2) measured by the induction method for n = 3 measurements.

The discharging curves presented are characteristic of a non-homogeneous material. The knitted fabric samples included carbon compounds of the Resistat type in its structure, incorporated in the polyester component of the electro-conductive yarn. In this case, the neutralisation of the charge accumulated on the sample begins with a very rapid decrease caused by discharging initiated by the carbon content, and next proceeds slowly, as determined by the high-resistive polyester fibre. The half-decay times and the screening coefficients obtained in our tests verify the very good anti-electrostatic properties of the knitted fabrics manufactured.

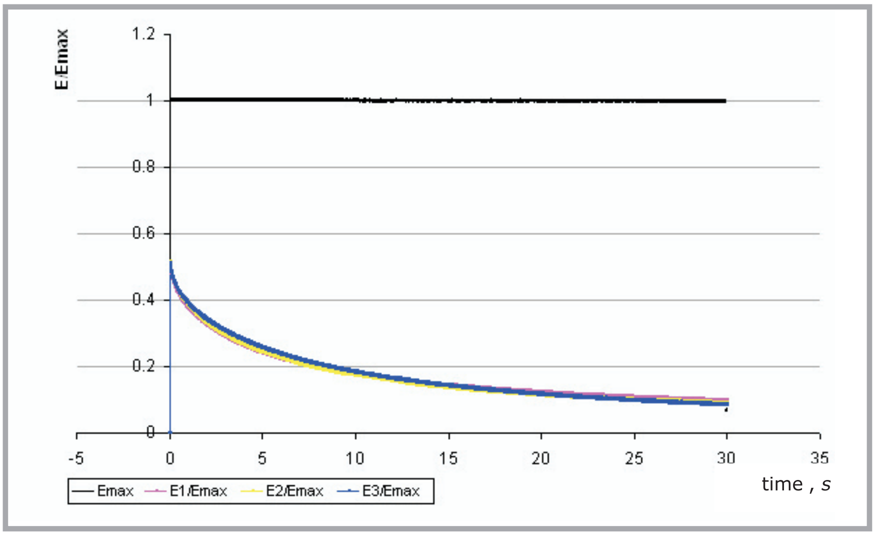

***Figure 2.** Changes of the electrical field intensity with time for a knitted fabric sample (of variant 2) measured by the induction method for n = 3 measurements.*

Analysis of research results and estimation of the electro-static properties of the knitted fabrics manufactured

The electrostatic properties of the knitted fabrics which we manufactured were analysed in relation to the requirements of a project of the European Standard for fabrics intended for anti-electrostatic protective clothing [18]. According to this standard, an electrostatic scattering material should be characterised by a surface resistance of $R_S \leq 2.5 \times 10^9$ Ω, a half-decay time of the electrostatic charge of $t_{0.5}$, 4s, or a screening coefficient of $S > 0.2$. Analysis of the results presented in Table 5 indicates that the knitted fabrics we developed meet the requirements of the above-mentioned standard.

A method of inserting electro-conductive yarn into the knitted fabric equal for all three variants was elaborated and applied. The differences in the content of the electro-conductive yarn mainly result from the background filling degree by the polyester yarn (see Table 3). Variant 1 of the smallest background filling degree is characterised by the highest share of electro-conductive yarn, whereas in contrast, the smallest share of electro-conductive yarn has variant 3 of the highest background filling degree. The analysis of results also indicated that the electrostatic properties depend not only on the content of electro-conductive yarn in the knitted fabric structure, but also on the structural features of the background. For example, Figures 3 and 4 show the dependencies of the surface resistance R_S on the share of electro-conductive yarn in the knitted fabric, and on the filling degree of the structure by the polyester yarn of the background.

From the dependencies presented, it can be seen that the knitted fabric variant of the highest background filling degree Z_a, and at the same time of the smallest content of electro-conductive yarn, is characterised by the smallest surface resistance R_S, which means by the best electro-conductivity. Similar dependencies may also be observed for the coefficient of volume filling Z_v of the knitted fabric's background, the area density P_a, and the fabric thickness *G* (Table 3).

Estimation of the materials' electrostatic properties on the basis of electrical resistances alone is unsatisfactory, as some materials of high resistance are characterised by low charging ability.

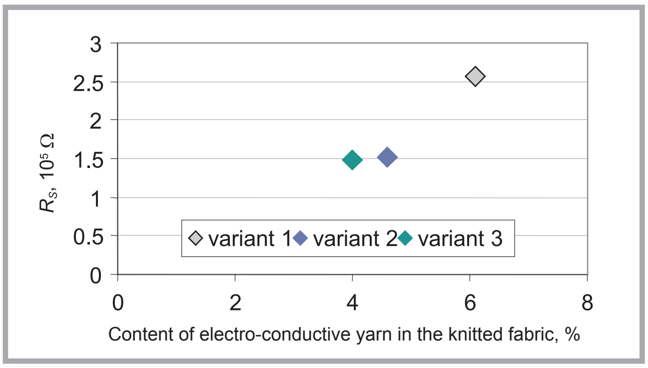

Figure 3. *Dependence of the knitted fabric's surface resistance R_S on the electro-conductive yarn content.*

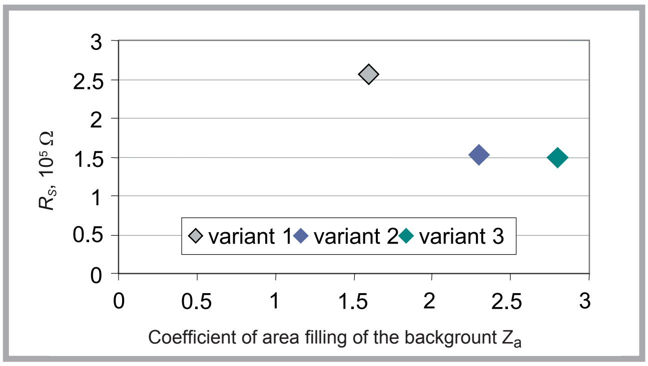

Figure 4. *Dependence of the knitted fabric's surface resistance R_S on coefficient of the area filling degree of the background Z_a.*

For example, cotton and polypropylene products are such materials. This is why the half-decay time of the electrical charge $t_{0.5}$ and the screening coefficient S are significant criteria for estimating the electrostatic features. The analysis of the test results indicated that the half-decay time depends to an essential degree on the filling of the knitted fabric's structure, and that the increase in filling the knitted structure by the background yarn essentially decreases the time of electrical charge decay. In contrast, such a dependency is not observed while analysing the screening coefficient S. The test results indicated that these values only depend on the content of electro-conductive yarn in the knitted fabric variants analysed.

Thanks to the type of arrangement of the electro-conductive yarn in the structures developed, we obtained fabrics characterised by high values of through resistance R_V. However, the requirements of the standards for anti-electrostatic materials do not describe any criteria for the through resistance R_V. Materials which are characterised by small through resistance, for example below 10^8 Ω, have additional advantages as protective clothing, on condition that they fulfil the demands concerned with the surface resistance R_S.

Final conclusions

The research results concerned with the electrostatic properties of knitted fabrics and the other usage properties verify the rightness of the technological solutions which we accepted.

The knitted fabrics developed not only meet the protective requirements concerned with static electricity, but are also characterised by high air permeability, which is an essential advantage in comparison to the anti-electrostatic woven fabrics which have hitherto been used.

In addition, the knitted fabrics developed are characterised by high dimensional stability.

The strength properties of the knitted fabrics result from the kind of structural solutions applied, and should be analysed in dependence on the final destination, for example as aprons, coveralls, uniforms, head-dresses, and elements of footwear.

The technology of manufacturing anti-electrostatic materials with the wale-knitting technique is an innovative solution regarding the hitherto used technologies of woven fabrics intended for protective clothing. The test results indicated that it is possible to impart electrostatic properties to knitted fabrics, while at the same time considering the other usage properties which depend on the destination of the fabrics.

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