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# Influence of Metal Fiber Content and Arrangement on Shielding Effectiveness for Blended Electromagnetic Shielding Fabric

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More metal fiber content of blended electromagnetic shielding (EMS) fabric results in higher shielding effectiveness (*SE*) of the fabric. However, there is little information about the influence of the metal fiber content on the *SE* considering the fabric structure. This study constructs an index of metal fiber content per unit area (MFCPUA), and discusses the influence of the metal fiber content on the *SE* of the EMS fabric when fabric parameters are changed. Computations for the MFCPUA and the thickness and porosity of the metal fiber arrangement are given, and then experiments are designed to test the *SE* of different EMS fabric samples. According to the experimental results, the influence of the MFCPUA on the *SE* is analyzed and influence mechanism is discussed when the fabric weaves, emission frequencies and weft and warp densities are changed. The results show that the MFCPUA and the *SE* are in positive increase relation; the frequency and the *SE* are in the negative increase relation when the metal fiber content is unchanged. The influence of the fabric weave type on the *SE* depends on the length of the yarn floats; the *SE* values of fabric with the same weave are the same when the MFCPUA is the same regardless of the fabric density.

*Keywords*: blended electromagnetic shielding fabric; metal fiber content; shielding effectiveness; influence law; fabric structure.

## 1. INTRODUCTION

Blended electromagnetic shielding (EMS) fabrics apply to many fields of clothing, composite material, and flexible cover [1]. The shielding method is to add metal fibers to the fabric [2]. The main index of the shielding effect of the blended EMS fabric is shielding effectiveness (*SE*). The influence of metal fiber content and arrangement on the *SE* is a topic that has not been addressed very often.

Shielding effectiveness (*SE*) is the main index to evaluate the shielding effect on the electromagnetic wave when the EMS fabrics are designed, manufactured and assessed. There is little detailed information in current literature concerning the influence of the metal fiber content on the *SE*. However, existing researches about the *SE* of the blended EMS fabric mainly focus on the model construction [3], *SE* variation analysis [4], *SE* testing method [5–6], fabric performance testing [7–8], and the development of the EMI shielding fabric [9–11].

In above literatures, the relation between fiber content and the *SE* was also involved. However, those discussions were small parts in their total studies. They only listed a number of data variations, and did not completely analyze the relation between the metal fiber content and the *SE*, and theoretical explanation was also lack. Therefore, reference value of the literatures is little.

From fabric structure analysis, the content and arrangement of the metal fiber associate to a number of fabric parameters such as the fabric density, yarn density, metal content of single yarn, and fabric weave. There are also some researches about the fabric parameters. Su and Chern [12] manufactured testing fabrics by producing stainless steel hybrid yarns with conductive filler. They concluded that a denser structure had a higher *SE* and the EMSE of the fabric made from different genera of stainless steel had an optimum EMSE value at different measured frequencies. Lou and Lin [13] span the ply yarn and woven into fabrics by combining two or many different kinds of fibers. They obtained that the helix angle and tightness of the twist-wrapped yarn were changed so that the mechanical properties and EMI *SE* were enhanced. However, they did not give further discussion about the change of the metal fiber content. Ortlek et al. [14] studied the electromagnetic shielding feature of woven fabrics consisting of hybrid yarns. They described that the direction, density and settlement type of conductive hybrid yarn were important parameters of electromagnetic shielding feature of woven fabrics.

However, above researches only presented the influence of the fabric parameters on the *SE*. They did not analyze the influence by the content and arrangement of the metal fiber, which was important influence factors on the *SE*, making the influence mechanism of the metal fiber content on the *SE* was not known considering the fabric structure parameters.

This paper studies the influence of the content and arrangement of the metal fiber on the *SE* of the EMS fabric. A computation method for the metal fiber content of the EMS fabric is proposed and fabric parameters related with the arrangement of the metal fiber are taken into account. A number of experiments are designed to analyze the relation between the content and arrangement of the metal fiber and the *SE*. After analysis, the influence mechanism of the metal fiber on the *SE* is described theoretically, and the relation between the content and arrangement of the metal fiber and the *SE* of the EMS fabric is obtained, which can provide the reference for the design and evaluation of the EMS fabric.

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## 2. METAL FIBER CONTENT AND ARRANGEMENT DESCRIPTION

According to the electromagnetic theory, the shielding way of an ideal metal shield can be divided into reflection, multiple reflections and absorption, and most shielding relies on the reflection [15]. The metal fiber content and arrangement are important factors influencing the characteristic of the reflection, the multiple reflections and the absorption of the electromagnetic wave. Therefore, the descriptions of the metal fiber content and arrangement are necessary through parameters characteristic of the EMS fabric.

### 2.1. Metal fiber content per unit area (MFCPUA)

We use the $C_m$ (g/m$^2$) to describe the value of the metal content (MFCPUA) of fabric. The MFCPUA refers to the content of the metal fiber per unit area. Fig. 1 shows the schematic diagram of the MFCPUA.

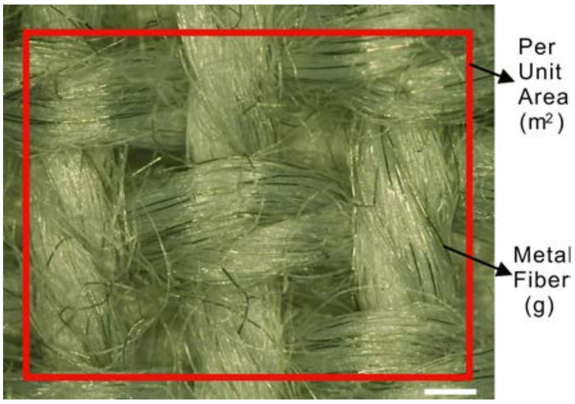


**Fig. 1.** MFCPUA schematic diagram (Scale bar: 153 μm)

Let $P_w$ (ends/10 cm) and $P_t$ (ends/10 cm) be the weft density and warp density of fabric, $N_{tex}$ (tex) denotes the yarn linear density, refers to the weight of a thousand meters yarn (g/km), $G_f$ (%) is the content of metal fiber in yarns represents the proportion of the metal fiber weight in yarn to the yarn weight. The MFCPUA is calculated as:

$$C_m = \frac{(P_w + P_t) \times N_{tex} \times G_f}{100} . \tag{1}$$

### 2.2. Metal fiber arrangement parameter

Equation (1) only gives the MFCPUA of fabric. The metal fiber arrangement with the same metal fiber content is different because of different structure parameters of the fabric, making the *SE* values of fabric different. Therefore, we introduce an equivalent thickness $t_e$ (m) and porosity $P_{fab}$ (%) besides the weft density $P_w$ and warp density $P_t$ to describe the metal fiber arrangement.

The equivalent thickness represents the equivalent distribution of the metal fiber at the fabric thickness direction. The definition is: suppose all metal fibers of an EMS fabric with an area of 1 m$^2$ are melted to make a metal sheet with an area of 1m$^2$, the thickness $t_e$ of the sheet can be obtained as:

$$t_e = \frac{C_m}{\rho \times 1000} . \tag{2}$$

Porosity is the ratio of the porosity area between the metal fibers of the fabric unit area to the total area, and it can be calculated as:

$$P_{fab} = 1 - \frac{K_d \sqrt{N_{tex}} (P_w + P_t - 0.1 \times K_d \sqrt{N_{tex}} \times P_w \times P_t)}{10} , \tag{3}$$

where, $\rho$ (kg/m$^3$) denotes the volume density of the metal fiber, $K_d$ is the diameter coefficient of yarn represents the indicator of the yarn thickness unevenness. $K_d$ is defined as [16]:

$$K_d = \frac{0.01189}{\sqrt{\delta}} , \tag{4}$$

where, $\delta$ (g/cm$^3$) refers to the volume weight of the yarn. The values of $\delta$ are different for different yarn materials and structures. The detail values are tested by experiments [17].

## 3. EXPERIMENTAL METHODS

We select BST21 stainless steel metal fiber blended yarn (manufactured by Shanghai Angel Textile Company, stainless steel metal fiber 25 %, cotton fiber 35 % and polyester fiber 40 %) to manufacture samples by sample loom (SGA598). Where, the diameter of the stainless steel fiber is 8 μm, the length is 45 mm, the relative conductivity $\sigma_r$ is 0.02, the relative magnetic permeability $\mu_r$ is 500. The yarn density is 2×28.1 tex, the yarn twist is 65/10 cm. The weaves of samples are plain weave, $\frac{2}{1}$ simple twill weave and $\frac{5}{3}$ satin weave. Then the sample densities are tested by manual counting with the density tester (Y511B). We choose three fabrics with same density as a group, and the three sample weaves of a group are the plain weave, twill weave and satin weave. Ten groups of samples are classified for analysis according to the density. The detail parameters of ten groups of samples are listed in Table 1.

**Table 1.** Experimental samples parameters and MFCPUA

| Group number | Fabric weave | Weft and warp density(ends/10cm) | MFCPUA (g/m$^2$) |
|---|---|---|---|
| 1 | There are three fabrics, the weaves are plain, twill and satin, respectively. The weft and warp yarns are BST21 yarns. | 340×220 | 38.86 |
| 2 | | 320×300 | 43.04 |
| 3 | | 380×300 | 47.20 |
| 4 | | 400×340 | 51.36 |
| 5 | | 420×380 | 55.52 |
| 6 | | 320×240 | 38.86 |
| 7 | | 360×260 | 43.04 |
| 8 | | 350×330 | 47.20 |
| 9 | | 420×320 | 51.36 |
| 10 | | 440×360 | 55.52 |

The fabrics listed in Table 1 are made as testing samples with the size of 65 mm×110 mm to test the *SE* using the waveguide system. The waveguide system is developed by Xi'an Technology University. The testing result of the waveguide system is more accurate than the coaxial planar system, and the testing method of waveguide system is in keeping with the actual use state of the fabric. The frequency range of the waveguide is 2200 MHz ~ 2650 MHz. the waveguide system is shown in Fig. 2.

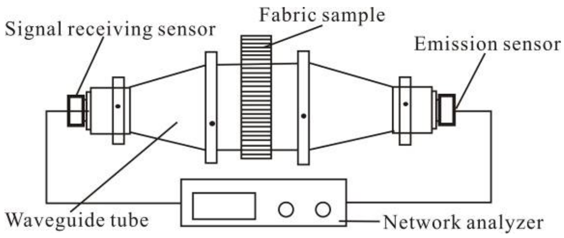


**Fig. 2.** Waveguide system

In the actual testing, the shielding effectiveness (*SE*, dB) of the fabric is calculated as [18]

$$SE = 20\lg\frac{E_0}{E_1}, \tag{5}$$

where, $E_0$ is the electric field intensity of one frequency point without shield, $E_1$ is the electric field intensity of one frequency point with shield.

## 4. RESULTS AND DISCUSSION

### 4.1. Relation between MFCPUA and *SE* under same fabric weave

Fig. 3 and Fig. 4 illustrate the *SE* variation of each group of the samples in Table 1.

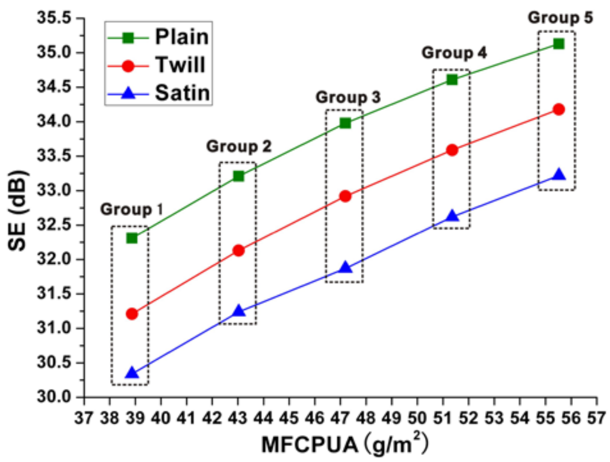


**Fig. 3.** *SE* of each group of sample from Group 1 to Group 5 in Table 1 ($f$ = 2400 MHz)

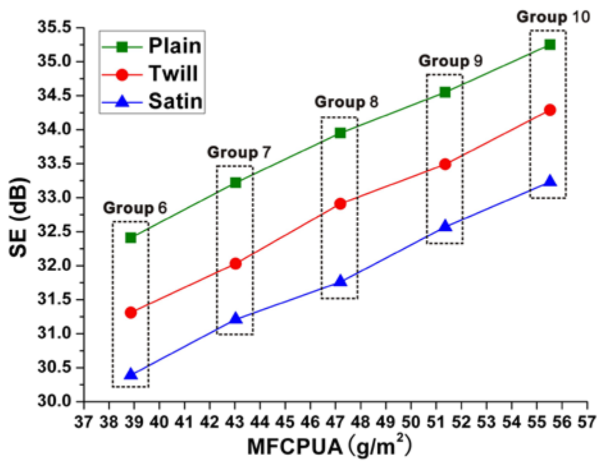


**Fig. 4.** *SE* of each group of sample from Group 6 to Group 10 in Table 1 ($f$ = 2400 MHz)

From Figs. 3 – 4, it is noticed that the *SE* is proportional to the MFCPUA of the EMS fabric when the weave type and the metal content of yarn are certain (for example, from the first group to the fifth group, and from the sixth group to the tenth group). Therefore, the relation between the *SE* and the MFCPUA can be expressed as:

$$SE \approx \kappa C_m, \tag{6}$$

where, $\kappa$ (dB·m$^2$/g) is the proportional coefficient of the *SE* according to the $C_m$, that refers to the relationship between $C_m$ and *SE*. Figs. 3 – 4 shows that the equivalent thickness increased with the increase of the MFCPUA, and the shielding performance of the fabric improved.

According to equation (1), the MFCPUA associates to the weft and warp density of the fabric linearly. The total density is the sum of the weft density and the warp density, the relation between the *SE* and the total density of the fabric is positive increase. Let the total density of the fabric be $P_s$, the equation (1) is substituted into the equation (6), and we can obtain:

$$SE \approx \kappa\frac{(P_w + P_t)\times N_{tex}\times G_f}{100}. \tag{7}$$

The total density $P_s = P_w + P_t$ is substituted into equation (7), then:

$$SE \approx \frac{\kappa\times N_{tex}\times G_f}{100}P_s. \tag{8}$$

Let $\frac{\kappa\times N_{tex}\times G_f}{100} = \kappa'$, then:

$$SE \approx \kappa' P_s, \tag{9}$$

where, $\kappa'$ (dB·10 cm/ends) is the proportional coefficient of the *SE* according to the $P_s$, that represents the relationship between $P_s$ and *SE*. Equation (9) illustrates that the *SE* of the fabric is approximately proportional to the total density under consistent fabric weave type, yarn density and the metal content condition. If we test the value of $\kappa'$ under different fabric parameters according to the experiments, we can fast evaluate the *SE* of the EMS fabric by the value of $\kappa'$ and the total density when we design the EMS fabric.

The above results are determined by the characteristic of the electromagnetic wave. Obviously, the increase of the total density results in the increase of the yarn coverage of the fabric and leads to low porosity ratio ($P_{fab}$). The leakage of the electromagnetic wave decreases for the hole and interstice among yarns decrease [18]. Therefore, the *SE* of fabric increases. Moreover, when the MFCPUA increases, the reflection and absorption of metal fibers against the electromagnetic wave increase [19], thus the *SE* of fabric increases.

### 4.2. Weave type influence on *SE* under the same MFCPUA

From Figs. 3 – 4, we can observe that the *SE* values of the fabric with different weaves are different under the same MFCPUA condition. The *SE* value of the plain weave fabric is largest, follow with that of the twill weave fabric, and the *SE* value of the satin weave fabric is smallest. The difference between the *SE* of the plain weave fabric and the *SE* of the twill weave fabric is more than that between the *SE* of the twill weave fabric and the satin weave fabric. The reason is that the yarn floats produce the *SE* difference. Fig. 5 shows the fabric weave diagrams of the plain, the twill and the satin. Comparing the three weaves, the floats in the satin weave is longest, the floats in the plain weave is shortest. The floats mean that the yarn does not close to the near yarn, which can produce interstices and electromagnetic leakage. Therefore, the more floats cause more leakage and the low *SE* of the fabric.

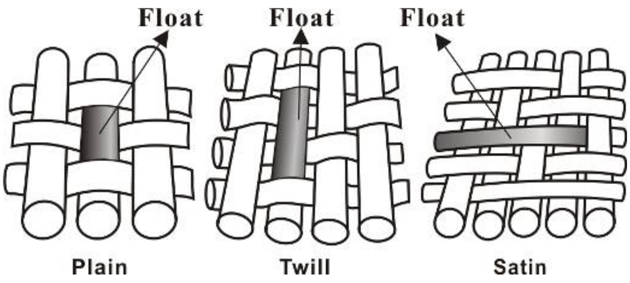


**Fig. 5.** Float schematic diagram of plain, twill and satin weave

### 4.3. Frequency influence on *SE* under same MFCPUA

The frequency is selected from 2200 MHz to 2650 MHz, and the *SE* testing frequency is in every 50 MHz. Experimental results show that the *SE* of fabric possesses decrease trend with the increase of the frequency regardless of the fabric weave. Fig. 6 gives the *SE* trend diagram of the first group fabrics under same MFCPUA condition.

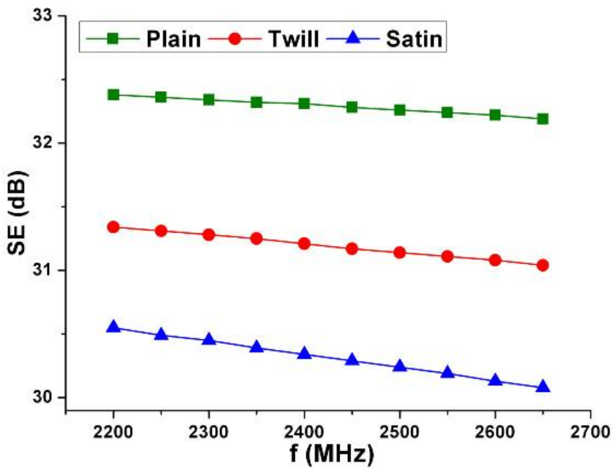


**Fig. 6.** Frequency influence on *SE* of the first group fabrics (MFCPUA = 38.86 g/m$^2$)

The *SE* of the stainless steel blended fabric decreases with the increase of the frequency when the frequency is in the range from 2200 MHz to 2650 MHz. The phenomenon is determined by the performance of the stainless steel metal. If the fabric is considered as an ideal shield, the *SE* can be calculated as [20]:

$$SE = 168.16 - 10\lg\frac{\mu_r f}{\sigma_r} + 1.31t\sqrt{f\mu_r\sigma_r}\ , \qquad (10)$$

where, $t$ (m) denotes the thickness of idea shield, $\mu_r$ refers to the relative permeability, $\sigma_r$ is the relative conductivity, $f$ denotes the frequency (Hz).

In above frequency range, the magnetic permeability of the stainless steel metal increases and the conductivity decreases with the increase of the frequency [21]. The second term in equation (10) increases and the third term remains a stable value, making the total *SE* value of the fabric decreases. Therefore, the *SE* of the fabric decreases with the increase of the frequency in the range from 2200 MHz to 2650 MHz..

### 4.4. Weft density and warp density influence on *SE* under same MFCPUA

Figs. 7 – 9 show the *SE* variation of samples listed in Table 1 under same MFCPUA and different weft and warp densities.

From above three figures, it is interesting to see that the *SE* values are consistent when the yarn density and the MFCPUA are consistent and the weft density and the warp density are changed. For example, the first group and the sixth group of fabrics in Figs. 7 – 9, the total densities are consistent, the MFCPUA values are the same, and the *SE* values are consistent though the weft densities and the warp densities are different. For the same reason, in the second group and the seventh group, the third group and the eighth group, the forth group and the ninth group, and the fifth group and the tenth group, the MFCPUA values are consistent and the weft and warp densities are inconsistent, but the *SE* values are consistent.

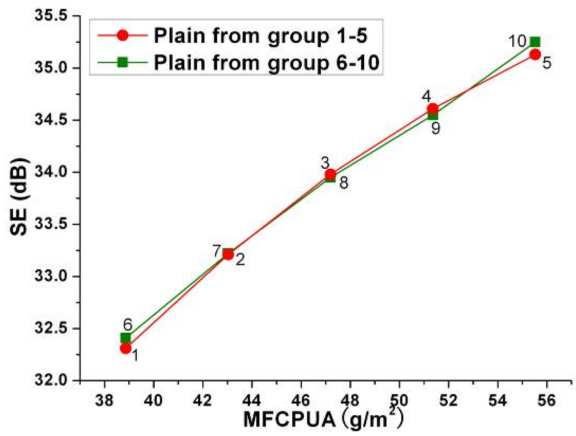


**Fig. 7.** *SE* of plain weave under same MFCPUA and different densities

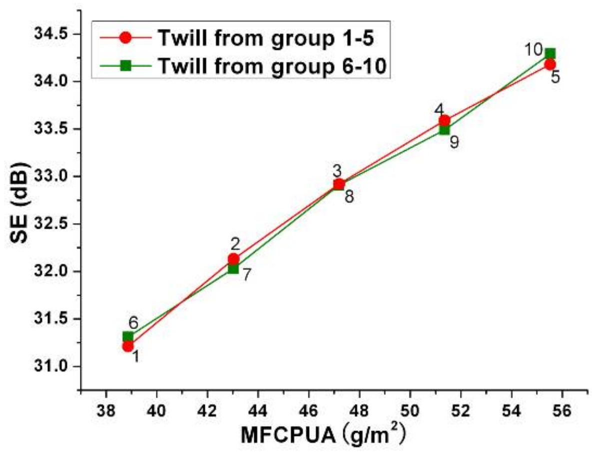


**Fig. 8.** *SE* of twill weave under same MFCPUA and different densities

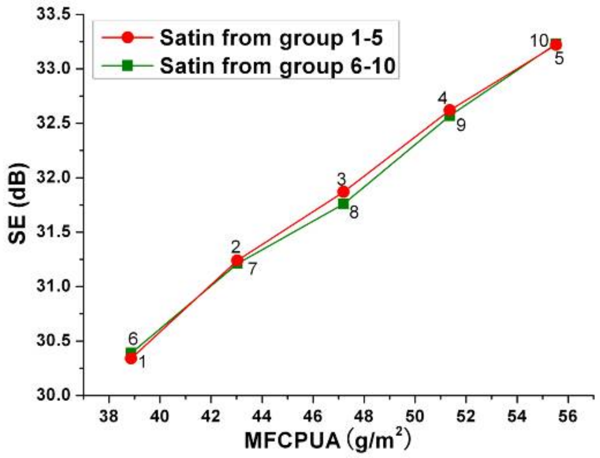


**Fig. 9.** *SE* of satin weave under same MFCPUA and different densities

We consider that above phenomenon is caused by the yarn hairiness. Yarn hairiness refers to fiber projections on the yarn surface, which widely presents in the fabric [22]. The total number of yarns per unit area is stable when the yarn density and the total density are unchanged. When the weft density and warp density are changed, the weave points are changed. There are a number of metal fibers in the interstice of yarns because of the hairiness, making it become a conductor. The metal fibers among yarns connect each other resulting in the fabric shielding effect. Therefore, though the weft density and warp density are different, the number of the metal fibers is consistent as long as the MFCPUA values are same. The EMS fabric possesses same *SE* value.

The above is an interesting phenomenon which is discovered for the first time. In existing density research of the EMS fabric [1 – 4], metal fiber research [12, 14, 15, 20, 21] and related study review [23], they only proposed that the *SE* of the fabric was changed with the change of the density. However, they did not discover and reveal the law that the *SE* was not influenced by the change of the warp density and the weft density when the total density was the same. The phenomenon has important directive significance. When we design the EMS fabric, we only consider the indicator MFCPUA and do not pay attention to the specific values of the warp density and the weft density.

## 5. CONCLUSIONS

1. The relationship between the *SE* of the blended EMS fabric and the MFCPUA is positive growth relationship under other parameters unchanged condition. The higher MFCPUA value results in the higher *SE*.

2. When the MFCPUA of fabric are consistent, the influence of the weave type on the *SE* is determined by the length of the float. The *SE* value of the plain weave is the highest, followed by that of the twill weave, and the *SE* value of the satin weave is the lowest.

3. For the same fabric, the frequency (during the range of 2000 MHz – 2650 MHz) is inversely proportional to the *SE* when the MFCPUA value is stable. The larger frequency causes the lower *SE*.

4. When the MFCPUA of fabric, weave type and yarn parameter are same and the weft and warp densities are different, the *SE* values of the EMS fabric are basically consistent as long as the total densities are same.

### *Acknowledgements*

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