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A Study on the Gamma-ray Attenuation Parameters of Some Commercial Salt Samples

Canel EKE*1

Abstract

The purpose of this study is to calculate self-attenuation correction factors, linear (LAC)/ mass attenuation coefficients (MAC), half value layers (HVL) and tenth value layers (TVL) of different brands of commercial salt samples using gamma-ray spectrometry equipped with high resolution germanium (HpGe) detector. The gamma-rays emissions of $^{22}\text{Na}$, $^{60}\text{Co}$, $^{133}\text{Ba}$ and $^{137}\text{Cs}$ point sources were counted with/without sample. The obtained gamma-ray spectra were analyzed using computer software. Self-attenuation correction factors and gamma-ray attenuation parameters of eleven different brands of commercial salt sample were calculated. The experimental MACs of salt samples were compared with those of NaCl compound utilizing WinXCom software.

Keywords: Self-attenuation correction factor, gamma-ray attenuation parameter, gamma-ray spectrometry, salt samples

1. INTRODUCTION

Gamma-ray spectrometry is used to determine activity concentrations of natural and artificial radionuclides in environmental materials. The accurate and precise determination of radioactivity concentration in samples is important in many areas including radioactive waste management, health physics etc. [1]. Several correction factors have to be determined to obtain reliable activity concentrations. One of them is the self-attenuation correction factor which is described as the ratio a reference specimen count rate to that of the sample [2]. The self-attenuation correction factor is calculated theoretically [3], experimentally [1,4] and by simulation methods [2, 5, 6, 7]. Usually, the self-attenuation correction factor is calculated using the Cutshall transmission method [4]. To obtain the most precise results the experimental approach should be used, in which point sources are placed upon the sample or reference specimen placed on the head of the detector [4, 6]. Values of self-attenuation correction factors vary depending on the density, geometry, the chemical
composition of the measured items as well as their attenuation coefficients [1, 6, 8].

The linear attenuation coefficient (LAC) is defined as the probability of interaction per distance unit [9]. Photons interact with material by three processes, namely the Photoelectric Effect, the Compton Effect and the Pair Production. The linear attenuation coefficient is the sum of the probabilities of these interactions as shown in the following equation:

$$\mu = \tau + \sigma + \kappa$$  \hspace{1cm} (1)

where \(\tau\), \(\sigma\) and \(\kappa\) are the aforementioned interactions, respectively. The Photoelectric Effect is dominant at low gamma-ray energies, the Compton Effect is dominant at mid-gamma ray energies, and the Pair Production is dominant at \(E_\gamma > 1.022\) MeV [11]. The mass attenuation coefficient (MAC) depends on the density of the sample.

There are various methods to obtain gamma-ray attenuation parameters in different areas. Gamma-ray attenuation parameters were calculated for soil [13], cane sugar of milk [14], diethylene glycol dissolved in ethyl alcohol [15], naphthalene dissolved in ethanol [16], dilute aqueous solutions of sugar \((C_6H_{12}O_6)\) [17], manganese (II) chloride [18], potassium chloride [19], ammonium sulfate [20], NaCl [31], lead nitrate [22], etc. [23, 24]. Furthermore, biological compounds [25], some amino acids [26], alcohol-soluble compounds [27, 28], medical plants [29, 30], different wood materials with different densities [31], environmental bulk sample 32, biological and geological samples [33], and many more. In literature, aqueous solution of salts samples were studied using different methods to calculate gamma-ray attenuation parameters [23, 24, 37, 38].

Gamma-ray attenuation parameters are highly relevant in radiation protection [20] because investigation of gamma-ray parameters of materials is important for applicability in science, technology, human health dosimetry, radiography, radiation shielding, etc. [23, 37]. In view of the importance of the attenuation parameters, the purpose of this study is to calculate gamma-ray attenuation parameters of salt samples and to give examples of application of the Cutshall et al. [4] transmission method using gamma-ray spectrometry. Also the experimental mass attenuation coefficients will be compared with obtained mass attenuation coefficients using WinXCom software [40] to check the accuracy of the results of this study.

2. MATERIAL AND METHOD

In this study to calculate gamma-ray parameters, eleven salt samples were used. Except for S6 which is dishwasher salt, the others are different brands commercial edible salts. S1, S2, S3, S5 and S7 are not refined while S4, S8, S9, S10 and S11 are refined. Densities of the samples are shown in Table-1 and Table-2. Densities \((\rho)\) of samples were calculated using \(\rho = m/V\) equation, where \(m\) is masses of the salt samples \(V\) is the volume of the salt samples.

The \(\gamma\)-ray emissions of radioactive point sources \(^{22}\text{Na}\) (1274 keV), \(^{60}\text{Co}\) (1173 and 1332 keV), \(^{133}\text{Ba}\) (81, 276, 302, 356 and 383 keV) and \(^{137}\text{Cs}\) (662 keV) were counted 1000 seconds using high purity germanium (HpGe) detector to calculate self-attenuation correction factors, linear-mass attenuation coefficients, HVL and TVL of eleven different brands of salt samples. The activities of these point sources are approximately 1 \(\mu\)Ci (37 kBq). The samples were put into 100 ml plastic container; its diameter and height are 61 mm and 53 mm, respectively. The samples were not been sieved because their crystals get same size but samples were shaked to increase density before the measurements. Gamma-ray spectra were analyzed using Maestro-32 software [34]. Wolfram Mathematica-8 [36] software was used in calculating the self-attenuation correction factors of sample versus energy referring to ultrapure water and air fitting function.

The self-attenuation correction factor \(C_f\) is calculated using the following well know equation which is called the Cutshall transmission formula [4].
\[ C_f = \frac{\ln \left( \frac{I}{I_0} \right)}{\frac{I}{I_0} - 1} \]  
\[ \text{(2)} \]

where, \( I \) is the count number of source inside the container with the sample and \( I_0 \) is the count number of the source inside the container (without sample). Firstly, the container was counted empty then it was filled with ultrapure water when the count number without sample was counted.

The LAC is calculated using the well-known (Lambert – Beer’s Law) equation \[ 10, 11 \],

\[ I = I_0 e^{-\mu_t x} \]  
\[ \text{(3)} \]

\[ \mu_t = -\frac{\ln \left( \frac{I}{I_0} \right)}{x} \]  
\[ \text{(4)} \]

where, \( \mu_t \) is the LAC of the sample, \( I \) is the number of incident photons counts passing through absorber material, \( I_0 \) is the number of incident photons counts passing through without absorber material, viz., the empty sample container, and \( x \) is the thickness of the absorber material, viz., the sample.

The mass attenuation coefficient (MAC) depends on the density of the sample and is calculated using the following equation \[ 9 \]:

\[ \mu_m = \frac{\mu_t}{\rho} \]  
\[ \text{(5)} \]

where, \( \mu_m \) is the mass attenuation coefficient of the sample, and \( \rho \) is the density of the sample. Also MACs were calculated using WinXCom software \[ 40 \]. Total cross-sections and attenuation coefficients also partial cross-sections for incoherent and coherent scattering, photoelectric absorption and pair production can be obtained using WinXCom for elements, compounds or mixtures \[ 40 \].

Half value layer (HVL) and tenth value layer (TVL) are generally relevant in gamma-ray shielding enforcement considerations. The HVL is described as thickness of shielding materials which reduces the radiation intensity by a factor of two whilst TVL reduces the intensity by a factor of 10 \[ 12 \]. The HVL and TVL are calculated using following equations,

\[ HVL = \frac{\ln 2}{\mu_t} \]  
\[ \text{(6)} \]

\[ TVL = \frac{\ln 10}{\mu_t} \]  
\[ \text{(7)} \]

3. RESULTS AND DISCUSSION

Self-attenuation correction factors of salt samples referring to air or ultrapure water environment, linear attenuation coefficients (LAC), mass attenuation coefficients (MAC), half value layers (HVL) and tenth value layers (TVL) of salt samples are shown in Tables 1, 2 and 3, respectively. As an example, the self-attenuation correction factor versus energy graphic referring to air sample and ultrapure water sample, variation of the LACs as a function of the gamma-ray energy of sample-1 and sample-4, variation of the MACs as a function of the gamma-ray energy of sample-1 and sample-4, their transmission rates of sample-1 and sample-4 at different gamma-ray energies are shown in Figures 1, 2, 3, 4 and 5, respectively.

The self-attenuation correction factor of salt samples referring to air is greater than that referring to ultrapure water as shown in Figure 1. Because densities of salt samples are greater than that of air and the density of water is higher than air also the self-attenuation correction factor mainly depends on the chemical components and on the integral density of the investigated material \[ 35 \]. The function of the self-attenuation correction factor versus the energy referring to the air sample and ultrapure water sample was fitted using the fitting function \[ C_f = aE^{b+c} \] where \( E \) is the gamma-ray energy, and \( a, b \) and \( c \) are the fitting parameters.

The LACs and MACs were fitted by the \( y = ax^b \) fitting function where \( y \) is the LAC or MAC, respectively, \( x \) is the gamma-ray energy, \( a \) and \( b \) are the best fit parameters. Because MACs are influenced by the density of the sample they are lower than the LACs. As shown in Figure 4, the values of MACs of sample-1 and sample-4 are
nearly equal although the density of sample-1 is 1.286 g/cm\(^3\) and 1.651 g/cm\(^3\) for sample-4. Conversely, the LACs of sample-1 and sample-4 are different since the LACs depend on the thickness of the samples. Although the thicknesses of the samples are equal in this experiment, the LACs are different. The LACs not only depend on density but also nature of samples. The MACs indicate similar values at certain energy for all samples so the compositions of salt samples are also similar. MACs of NaCl compound were calculated using WinXCom software [40] because the Na and Cl are main elements while the Mg, S, K, Ca, Mn, Fe, Br and Si are trace elements in commercial edible salt samples [39]. The MACs of salt samples obtained experimentally are lower than the results of MACs of NaCl compound obtained from WinXCom software [40] as shown in Table 4. These disparities in the results of the experimentally calculated and obtained from WinXCom [40] may be due about experimental setup especially from narrow-beam geometry in the source- detector settings [41].

The HVL and TVL increase with increasing incident gamma-ray energy (see Table 3). Thus, the transmission rate changes with the gamma-ray energy as shown in Figures 4 and 5 and the transmission rates of the sample-1 and sample-4 decrease with increasing thickness of sample.
Table 1. Self attenuation correction factors of salt samples referring to air

| Sample No | Density (g/cm³) | ⁹⁵ᵐBa (keV) | ¹³³Ba (keV) | ¹³³Cs (keV) | ⁶⁰Co (keV) | ²²Na (keV) | ⁶⁰⁰Co (keV) |
|-----------|----------------|-------------|-------------|-------------|------------|------------|-------------|
| 1         | 1.286          | 1.666±0.024 | 1.299±0.038 | 1.288±0.019 | 1.279±0.009 | 1.280±0.032 | 1.211±0.007 | 1.160±0.009 | 1.154±0.008 | 1.143±0.009 |
| 2         | 1.264          | 1.667±0.024 | 1.313±0.039 | 1.311±0.020 | 1.283±0.009 | 1.277±0.032 | 1.224±0.007 | 1.162±0.009 | 1.160±0.008 | 1.148±0.009 |
| 3         | 1.480          | 1.806±0.030 | 1.381±0.044 | 1.358±0.022 | 1.343±0.009 | 1.336±0.035 | 1.266±0.008 | 1.197±0.010 | 1.180±0.008 | 1.175±0.009 |
| 4         | 1.651          | 1.889±0.033 | 1.442±0.049 | 1.397±0.023 | 1.374±0.010 | 1.384±0.038 | 1.290±0.008 | 1.212±0.010 | 1.202±0.009 | 1.191±0.009 |
| 5         | 1.486          | 1.802±0.030 | 1.353±0.042 | 1.349±0.021 | 1.336±0.009 | 1.339±0.036 | 1.250±0.008 | 1.196±0.010 | 1.182±0.008 | 1.178±0.009 |
| 6         | 1.400          | 1.782±0.029 | 1.349±0.042 | 1.349±0.022 | 1.328±0.009 | 1.331±0.035 | 1.270±0.008 | 1.194±0.010 | 1.182±0.008 | 1.176±0.009 |
| 7         | 1.434          | 1.762±0.027 | 1.333±0.040 | 1.353±0.022 | 1.326±0.009 | 1.346±0.036 | 1.257±0.008 | 1.188±0.010 | 1.184±0.008 | 1.172±0.009 |
| 8         | 1.586          | 1.829±0.030 | 1.397±0.044 | 1.367±0.022 | 1.361±0.010 | 1.367±0.037 | 1.284±0.008 | 1.210±0.010 | 1.191±0.009 | 1.193±0.009 |
| 9         | 1.579          | 1.820±0.030 | 1.402±0.046 | 1.378±0.023 | 1.342±0.009 | 1.334±0.035 | 1.267±0.008 | 1.195±0.010 | 1.181±0.008 | 1.174±0.009 |
| 10        | 1.615          | 1.863±0.032 | 1.397±0.045 | 1.390±0.023 | 1.352±0.010 | 1.398±0.040 | 1.267±0.008 | 1.201±0.010 | 1.186±0.008 | 1.183±0.009 |
| 11        | 1.631          | 1.868±0.032 | 1.412±0.046 | 1.385±0.023 | 1.365±0.010 | 1.386±0.039 | 1.279±0.008 | 1.207±0.010 | 1.189±0.008 | 1.184±0.009 |
Table 2. Self attenuation correction factors of salt samples referring to ultrapure water

| Sample No | Density (g/cm³) | $^{133}$Ba (keV) | $^{137}$Cs (keV) | $^{60}$Co (keV) | $^{22}$Na (keV) | $^{60}$Co (keV) |
|-----------|-----------------|------------------|------------------|----------------|----------------|----------------|
|           |                 | 81                   | 276               | 302             | 356             | 383             | 662            | 1173            | 1274            | 1332            |
| 1         | 1.286           | 1.174±0.019         | 0.989±0.034       | 0.990±0.017     | 0.991±0.008     | 1.002±0.029     | 0.986±0.007     | 0.993±0.008     | 0.998±0.008     | 0.993±0.008     |
| 2         | 1.264           | 1.174±0.019         | 1.001±0.035       | 0.994±0.008     | 0.999±0.029     | 0.997±0.007     | 0.995±0.009     | 1.003±0.008     | 0.998±0.008     | 0.998±0.008     |
| 3         | 1.480           | 1.289±0.024         | 1.059±0.039       | 1.049±0.019     | 1.045±0.008     | 1.050±0.032     | 1.033±0.007     | 1.027±0.009     | 1.021±0.008     | 1.023±0.009     |
| 4         | 1.651           | 1.357±0.026         | 1.110±0.043       | 1.082±0.020     | 1.072±0.009     | 1.091±0.034     | 1.054±0.007     | 1.040±0.009     | 1.041±0.008     | 1.037±0.009     |
| 5         | 1.486           | 1.285±0.024         | 1.034±0.037       | 1.041±0.019     | 1.039±0.008     | 1.052±0.032     | 1.020±0.007     | 1.026±0.009     | 1.023±0.008     | 1.025±0.009     |
| 6         | 1.400           | 1.269±0.023         | 1.031±0.036       | 1.041±0.019     | 1.033±0.008     | 1.046±0.031     | 1.038±0.007     | 1.024±0.009     | 1.024±0.008     | 1.024±0.009     |
| 7         | 1.434           | 1.252±0.022         | 1.018±0.035       | 1.045±0.019     | 1.031±0.008     | 1.059±0.032     | 1.026±0.007     | 1.018±0.009     | 1.026±0.008     | 1.020±0.009     |
| 8         | 1.586           | 1.307±0.024         | 1.072±0.039       | 1.057±0.019     | 1.061±0.009     | 1.077±0.033     | 1.050±0.007     | 1.038±0.009     | 1.032±0.008     | 1.039±0.009     |
| 9         | 1.579           | 1.300±0.024         | 1.076±0.040       | 1.066±0.020     | 1.045±0.008     | 1.048±0.031     | 1.035±0.007     | 1.025±0.009     | 1.022±0.008     | 1.022±0.009     |
| 10        | 1.615           | 1.336±0.026         | 1.072±0.040       | 1.076±0.020     | 1.053±0.008     | 1.103±0.035     | 1.037±0.007     | 1.030±0.009     | 1.027±0.008     | 1.030±0.009     |
| 11        | 1.631           | 1.341±0.026         | 1.084±0.040       | 1.072±0.020     | 1.064±0.009     | 1.093±0.034     | 1.045±0.007     | 1.036±0.009     | 1.030±0.008     | 1.032±0.009     |
Table 3. Linear attenuation coefficient (LAC), mass attenuation coefficient (MAC), half value layer (HVL) and tenth value layer (TVL) of salt samples

| Sample No | $\mu_1$ (cm$^{-1}$) | $\mu_1$ (cm$^2$/g) | HVL (cm) | TVL (cm) |
|-----------|---------------------|--------------------|----------|----------|
| S1        | 0.212±0.005         | 0.103±0.006        | 3.264±0.074 | 10.841±0.247 |
|           | 0.165±0.004         | 0.080±0.005        | 6.711±0.038 | 22.295±1.256 |
|           | 0.168±0.004         | 0.085±0.005        | 6.420±0.352 | 21.328±1.168 |
|           | 0.169±0.004         | 0.087±0.004        | 5.361±0.268 | 21.128±1.168 |
|           | 0.165±0.004         | 0.080±0.005        | 4.688±0.220 | 17.809±0.891 |
|           | 0.168±0.004         | 0.081±0.004        | 5.758±0.297 | 15.574±0.731 |
|           | 0.169±0.004         | 0.080±0.005        | 5.821±0.232 | 19.128±0.898 |
|           | 0.170±0.005         | 0.080±0.005        | 5.812±0.224 | 19.128±0.988 |
| S2        | 0.212±0.005         | 0.108±0.006        | 3.262±0.074 | 10.838±0.246 |
|           | 0.168±0.004         | 0.085±0.005        | 6.420±0.352 | 21.328±1.168 |
|           | 0.169±0.004         | 0.087±0.004        | 5.361±0.268 | 21.128±1.168 |
|           | 0.165±0.004         | 0.080±0.005        | 4.688±0.220 | 17.809±0.891 |
|           | 0.168±0.004         | 0.081±0.004        | 5.758±0.297 | 15.574±0.731 |
|           | 0.169±0.004         | 0.080±0.005        | 5.821±0.232 | 19.128±0.898 |
|           | 0.170±0.005         | 0.080±0.005        | 5.812±0.224 | 19.128±0.988 |
| S3        | 0.250±0.006         | 0.129±0.006        | 2.768±0.062 | 9.194±0.207 |
|           | 0.169±0.004         | 0.087±0.004        | 5.910±0.140 | 17.809±0.891 |
|           | 0.165±0.004         | 0.080±0.005        | 5.463±0.129 | 15.574±0.731 |
|           | 0.168±0.004         | 0.081±0.004        | 5.757±0.297 | 19.128±0.988 |
|           | 0.169±0.004         | 0.080±0.005        | 5.821±0.232 | 19.128±0.988 |
| S4        | 0.272±0.006         | 0.148±0.007        | 2.547±0.057 | 8.461±0.191 |
|           | 0.165±0.004         | 0.080±0.005        | 5.463±0.129 | 15.574±0.731 |
|           | 0.168±0.004         | 0.081±0.004        | 5.757±0.297 | 19.128±0.988 |
|           | 0.169±0.004         | 0.080±0.005        | 5.821±0.232 | 19.128±0.988 |
| S5        | 0.249±0.006         | 0.120±0.006        | 2.781±0.063 | 9.237±0.209 |
|           | 0.168±0.004         | 0.081±0.004        | 5.758±0.297 | 19.128±0.988 |
|           | 0.165±0.004         | 0.080±0.005        | 5.463±0.129 | 15.574±0.731 |
|           | 0.168±0.004         | 0.081±0.004        | 5.757±0.297 | 19.128±0.988 |
| S6        | 0.244±0.006         | 0.119±0.006        | 2.840±0.064 | 9.434±0.213 |
|           | 0.174±0.004         | 0.085±0.004        | 5.820±0.300 | 19.335±0.996 |
|           | 0.165±0.004         | 0.080±0.005        | 5.463±0.129 | 15.574±0.731 |
|           | 0.168±0.004         | 0.081±0.004        | 5.757±0.297 | 19.128±0.988 |

Table 3. continue
Table 4. Mass attenuation coefficients (MACs) of NaCl compound

| Sample No | \(133^\text{Ba} \text{(keV)}\) | \(137^\text{Cs} \text{(keV)}\) | \(60^\text{Co} \text{(keV)}\) | \(22^\text{Na} \text{(keV)}\) | \(60^\text{Co} \text{(keV)}\) |
|-----------|----------------|----------------|----------------|----------------|----------------|
| S7        | 0.239±0.005   | 0.114±0.006   | 0.121±0.005   | 0.112±0.003   | 0.090±0.002   |
|           | 0.166±0.004   | 0.080±0.004   | 0.084±0.003   | 0.078±0.002   | 0.083±0.004   |
|           | 2.906±0.065   | 6.067±0.319   | 5.749±0.220   | 6.195±0.152   | 5.853±0.272   |
|           | 9.653±0.217   | 20.154±1.059  | 19.099±0.730  | 20.579±0.503  | 19.445±0.905  |
| S8        | 0.256±0.006   | 0.134±0.007   | 0.125±0.005   | 0.125±0.003   | 0.099±0.002   |
|           | 0.162±0.004   | 0.086±0.004   | 0.081±0.002   | 0.074±0.002   | 0.073±0.003   |
|           | 2.704±0.061   | 5.168±0.251   | 5.550±0.207   | 5.639±0.134   | 5.511±0.250   |
|           | 8.981±0.201   | 17.166±0.832  | 18.435±0.687  | 18.734±0.444  | 18.441±0.831  |
| S9        | 0.254±0.006   | 0.135±0.007   | 0.128±0.005   | 0.115±0.003   | 0.093±0.005   |
|           | 0.161±0.004   | 0.086±0.004   | 0.081±0.002   | 0.074±0.002   | 0.073±0.003   |
|           | 2.728±0.061   | 5.116±0.251   | 5.411±0.202   | 5.926±0.145   | 6.052±0.286   |
|           | 9.061±0.204   | 16.994±0.834  | 17.976±0.672  | 19.685±0.481  | 20.105±0.951  |
| S10       | 0.265±0.006   | 0.134±0.007   | 0.132±0.005   | 0.120±0.003   | 0.134±0.006   |
|           | 0.164±0.004   | 0.083±0.004   | 0.082±0.002   | 0.074±0.002   | 0.073±0.003   |
|           | 2.611±0.059   | 5.168±0.254   | 5.257±0.195   | 5.774±0.139   | 5.161±0.229   |
|           | 8.673±0.195   | 17.166±0.843  | 17.462±0.646  | 19.181±0.461  | 17.145±0.760  |
| S11       | 0.262±0.006   | 0.139±0.007   | 0.130±0.005   | 0.124±0.003   | 0.131±0.006   |
|           | 0.164±0.004   | 0.085±0.004   | 0.080±0.002   | 0.076±0.002   | 0.080±0.004   |
|           | 2.598±0.058   | 5.000±0.241   | 5.317±0.200   | 5.582±0.133   | 5.309±0.236   |
|           | 8.629±0.194   | 16.611±0.802  | 17.664±0.665  | 18.542±0.443  | 17.635±0.783  |

\[ \begin{array}{c}
\mu_m (\text{cm}^2/\text{g}) \\
0.234 \\
0.108 \\
0.104 \\
0.097 \\
0.094 \\
0.074 \\
0.056 \\
0.054 \\
0.053 \\
\end{array} \]
4. CONCLUSIONS

The self-attenuation correction factors, LACs, MACs, HVLs and TVLs were calculated experimentally by gamma ray spectrometry between 81 and 1332 keV. The self-attenuation correction factor of salt samples referring to air is higher than that referring to ultrapure water. There are differences between obtained experimental MACs of salts and the results of MACs of NaCl compound obtained from WinXCom software [40]. The LACs are different values for each salt samples whereas the MACs are same values at certain energy for all samples. The HVL and TVL increase with increasing incident gamma-ray energy. The transmission...
rate decrease with increasing thickness of sample at certain gamma-ray energy.

The self-attenuation coefficient is significant to accurate and reliable activity concentration of the samples. The attenuation coefficients are needed for different applications of radiation, e.g. dosimetry, radiography, tomography in industrial, agricultural and medical areas in science, technology, human health etc. [18, 20, 33]. The results of this study give information about self-attenuation correction factors, LACs, MACs, HVLs and TVLs of salt samples. Chemical components and physical properties of salt samples can be investigated using atomic and nuclear techniques the effect on attenuation coefficients in the future.

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