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NEW CHALCOGENIDE GLASSES IN THE $\text{Ag}_2\text{Te}-\text{As}_2\text{Se}_3-\text{CdTe}$ SYSTEM

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Abstract

Chalcogenide glasses from the $\text{Ag}_2\text{Te}-\text{As}_2\text{Se}_3-\text{CdTe}$ system were synthesized.

The basic physicochemical parameters such as density ($d$), microhardness ($HV$) and the temperatures of phase transformations (the glass transition $T_g$, crystallization $T_c$ and melting $T_m$) were measured. Compactness and some thermomechanical characteristics such as volume ($V_h$) and formation energy ($E_h$) of micro-voids in the glassy network, as well as the module of elasticity $E$ were calculated. The overall mean bond energy $<E>$, the mean coordination number $Z$, the mean bond energy of the average cross-linking/atom and the average bond energy per atom of the “remaining matrix” - $\Bar{E}_c$ and $\Bar{E}_{rm}$, as well as the average heteropolar bond energy $E_{hb}$, the degree of „cross-linking/atom“ $P_p$, the radial bond strength were determined.

The correlation between the composition and properties of the $\text{Ag}_2\text{Te}-\text{As}_2\text{Se}_3-\text{CdTe}$ glasses was established and comprehensively discussed.

Keywords: A. Chalcogenide glasses; A. Amorphous materials; B. Chemical synthesis
1. Introduction

Ion-selective electrodes (ISE) with membranes of chalcogenide glasses (CG) are becoming more widely used in an analytical practice. The membranes for heavy metal ion detection are produced by melting or by the pressing of insoluble metal-chalcogenides [1]. In comparison to polycrystalline chalcogenides, the glassy chalcogenidies show more stability in respect to electrolyte dissolving and resistance in aggressive environments [2]. Because of these properties, CG are more often used as membrane materials for construction of ISE for Ag(I)-, Pb(II)-, Fe(III)-, Cu(II) detection, instead of metal-chalcogenides [2-5].

In this respect, the development of new chalcogenide glasses on the basis of As$_2$Se$_3$ with metal-chalcogenides MeCh (Me=Zn, Cd, Hg, Co, Ni, Sn, Tl, Cr and others; Ch=S, Se and Te) with the aim of inventing new membrane materials is a prospective and interesting task. The research involves: 1) syntheses of new chalcogenide glasses; 2) investigation of their physicochemical properties, including density, microhardness, temperatures of glass transition, crystallization and complete melting, direct current (d.c) and alternating current (a.c) conductivity and others; 3) investigation of morphology using X-ray diffraction and mass-spectroscopy; 4) investigation of the composition using Auger electron spectroscopy [6].

The aim of the present report is to determine the glass-forming region and investigation of some, mainly physical-chemical characteristics, of chalcogenide glasses in the system Ag$_2$Te-As$_2$Se$_3$-CdTe.
2. Experimental procedures

The glass-forming region was determined with the help of 20 synthesized compositions of \((\text{Ag}_2\text{Te})_x(\text{As}_2\text{Se}_3)_y(\text{CdTe})_z\), where \(x, y, z\) are the mol \% \((x+y+z=100)\) of \(\text{Ag}_2\text{Te}, \text{As}_2\text{Se}_3\), and \(\text{CdTe}\) respectively - Table 1. The binary \(\text{As}_2\text{Se}_3-\text{CdTe}\) system has been studied in our previously work [7]. Starting components were \(\text{As, Te and Se with 5N purity and Ag and Cd with 4N purity.}\)

The samples of the system \(\text{Ag}_2\text{Te-As}_2\text{Se}_3-\text{CdTe}\) as well as the starting components \(\text{Ag}_2\text{Te}, \text{As}_2\text{Se}_3\), and \(\text{CdTe}\) were obtained through a direct mono-temperature synthesis in vacuumed quartz ampoules under the following conditions: three-stage increase of temperature to 650, 850 and 1100 °C with velocity 3-4, 2-3 and 2-3 °C min\(^{-1}\) and homogenized annealing at these temperatures 0.5, 1 and 2 h respectively combined with continuous vibrational stirring of the melt at the last-mentioned temperature. Followed by a reduction of the temperature to 900±10 °C and applying continuous vibrational stirring of the melt as it was annealed for 0.5 h and after that the melt was cooled in a mixture of water and ice.

The bulk glasses were analyzed by a visual, X-ray phase analysis (diffractometer TUR-M62 with CuK\(_\alpha\) radiation and a Ni filter) and electron-microscope (electron microscope EM400-Philips) analyses. The density \((d)\) of the samples was measured by a hydrostatic method using toluene as immersion fluid and the microhardness \((HV)\) was measured by Vickers’ method. A thermograph (DTA) was used to record the thermal characteristics of the samples. The module of elasticity \((E)\), the minimum volume of
micro-voids ($V_h$), the energy of their creation and the compactness ($C$) were calculated by the equations 1 and 2 [8].

$$E = 15HV; \quad V_h = 5.04 \frac{T_g}{HV}; \quad E_h = 30.729T_g,$$

(1)

$$C = d \left\{ \sum_i \frac{M_i x_i}{d_i} - \sum_i \frac{M_i x_i}{d_i} \right\} \left[ \sum_i M_i x_i \right]^{-1},$$

(2)

where $T_g$, $T_{cr}$ and $T_m$ – temperatures of glass transition, crystallization and complete melting; $M_i$ and $x_i$ – molar weight and fraction of the $i^{th}$ component.

3. Results and discussions

The synthesized bulk samples of Ag$_2$Te-As$_2$Se$_3$-CdTe system are with a strong lustre.

The results from the X-ray diffraction show that several compositions are typical glasses without peaks on the diffractograms – these compositions form the glass-forming region (for example p. 6). The compositions on the region boundary (p. 2, p. 8, p. 15, p. 18 and p. 19) show diffraction peaks with low intensity. The diffractograms of the samples outside the glass-forming region (for example p. 9) show strong peaks, these samples are crystalline Fig. 1.
The electronic microscopic observation shows a smooth and homogeneous surface of the samples from the glass-forming region; small crystalline regions are observed on the surface of the samples on the region boundary (crystalline phase); the surface of the samples outside of glass-forming region is rough and there are no regions on it belonging to a glassy phase.

The analysis of the scheme diffractograms Fig. 2 of the compositions lying on the boundary of the glass formation area shows the presence of reflexes of Ag2Te and As2Se3 (p. 2) and of Ag2Te+CdTe (p. 8, p. 15). In case of higher As2Se3 content (p. 18 and p. 19) decomposition of As2Se3 is observed in compliance with the scheme: As2Se3=2AsSe+Se, the evidence for which is the appearance of the reflexes of AsSe and Se, together with those of Ag2Te and CdTe.

Based on the syntheses carried out and the results obtained from the visual X-ray diffraction analysis and the electron microscopic analysis we outlined the region of glass-formation in the three-component system Ag2Te-As2Se3-CdTe, where x+y+z=100 and m=y/(x+y) – Fig. 3. It is extended to the area rich in As2Se3 and partially lies on the faces Ag2Te-As2Se3 (50-100 mol% As2Se3) and As2Se3-CdTe (0-15 mol% CdTe) of the Gibbs’ concentration triangle. No glasses were obtained in the system Ag2Te-CdTe. The maximum solubility of CdTe in glasses is ~ 15 mol % [7].

The investigated thermal characteristics of the samples Tg, Tcr and Tm, determined by DTA analysis are summarized in Table 2 and typical DTA-curves are shown on Fig. 4.

The introduction of Ag2Te or CdTe decreases almost in equal degree Tg, because their presence results in growth of the metal component of the chemical bond in the chalcogenide glasses.
The variation of the chemical compound composition affects also slightly the crystallization temperature \( (T_{cr}) \), which shows that for all examined compositions one and the same phase crystallizes. The temperature of complete melting \( (T_m) \) practically does not depend both on the \( \text{As}_2\text{Se}_3 \) content and on that of \( \text{Ag}_2\text{Te} \) and \( \text{CdTe} \).

The measured density values \( (d) \) of the investigated glasses are in the range 4.8-5.6 \( \text{g.c}\text{m}^{-3} \). At increase of the \( \text{Ag}_2\text{Te} \) content in the composition of the chalcogenide glasses at \( z=\text{const} \) and increase of the \( \text{CdTe} \) content at \( m=\text{const} \), \( d \) grows, because

\[
\text{d}_{\text{Ag}_2\text{Te}} > \text{d}_{\text{As}_2\text{Se}_3} \quad \text{and} \quad \text{d}_{\text{CdTe}} > \text{d}_{\text{As}_2\text{Se}_3} \quad (\text{d}_{\text{Ag}_2\text{Te}} = 8.5; \text{d}_{\text{CdTe}} = 5.86 \quad \text{and} \quad \text{d}_{\text{As}_2\text{Se}_3} = 4.75 \text{ g. cm}^{-3}).
\]

The visible deviation of the dependences \( d(m) \) and \( d(z) \) from the additive law is an indication for the chemical interaction between \( \text{Ag}_2\text{Te} \) and \( \text{CdTe} \) on the one hand and \( \text{As}_2\text{Se}_3 \) on the other, i.e. the first two compounds are embedded in the structure carcass of the glass and not dispersed in it as second (third) phase.

The measured microhardness values \( (HV) \) of the investigated glasses are in the range 57-85 kgf.mm\(^{-2}\). In case of increase of \( \text{Ag}_2\text{Te} \) content (at \( z=\text{const} \), as well as decrease of \( \text{CdTe} \) content (at \( m=\text{const} \)), \( HV \) decreases as \( HV_{\text{As}_2\text{Se}_3} > HV_{\text{Ag}_2\text{Te}} \) (respectively 150 and 38 kgf.mm\(^{-2}\)) and \( HV_{\text{CdTe}} > HV_{\text{Ag}_2\text{Te}} \) \( (HV_{\text{CdTe}}=60 \text{ kgf.mm}^{-2}) \) – Table. 3.

The elasticity modulus precisely reproduces the micro hardness of the glass and the dependences on the glass compositions \( E=f(m) \), at \( z=\text{const} \) and \( E=f(z) \), at \( m=\text{const} \) are interpreted in analogy with the dependences \( HV=f(m) \), at \( z=\text{const} \) and \( HV=f(z) \), at \( m=\text{const} \).
The minimum volume of the micro voids $V_h$ varies in the range $(8.9-12.5) \times 10^{-3}$ nm$^3$ and depends on the glass composition Table 3. The dependence $V_h(m)$ at $z=\text{const}$ passes through a flowing minimum at $m\approx 0.8$. It is logical to assume that at $m>0.8$ the effect of the glass formative As$_2$Se$_3$ is dominant as a result of which more and more distinctly the typical for the vitreous condition properties are revealed: the specimens become more loose ($V_h$ grows), the density $d$ and compactness $C$ - decrease, $T_g$ – increases, the structure becomes more stable ($E_h$ grows), etc. On the other hand, Ag$_2$Te introduction in the chalcogenide glass (at $z=\text{const}$) also results in $V_h$ increase because the chemical bonds break and the silver atoms and fragments (Ag-Te-Ag) close the broken chains as a result of which the structure network decreases and the disorder in the system grows. As a result of running of the above listed processes the energy for the formation of these micro voids $E_h$, as well as for the compactness $C$ also decreases with the increase of the Ag$_2$Te content in the chalcogenide glasses.

The effect of the third component CdTe on $V_h$ and $E_h$ is interesting. The structure unit of CdTe is CdTe$_{2/2}$. It has linear character and connects the broken chains in the chalcogenide glass while the structure unit of Ag$_2$Te (AgTe$_{1/2}$) breaks the long halogenide chains and closes them. As a result of this process the minimum volume of the micro voids $V_h$ diminishes. As higher is the CdTe content in the chalcogenide glasses so more stable becomes its structure and the energy necessary for the run of this process $E_h$ decreases. The decrease of $V_h$ in the chemical compounds leads to compression and its compactness $C$ increases.
The properties of the chalcogenide glasses are closely related to the overall mean bond energy which represents a function of the mean coordination number, the type and energy of the chemical bonds between atoms forming the glass.

We determined the correlation between the glass transition temperature $T_g$, the coordination numbers of glasses $<Z>$ and the overall mean bond energy $<E>$ in the covalent network of glassy samples of the system $\text{Ag}_x\text{As}_y\text{Cd}_z\text{Se}_m\text{Te}_n$ where $x$, $y$, $z$, $n$ and $m$ are in mol\% ($x+y+z+n+m=1$).

We calculated the mean coordination number of glasses $<Z>$ by the equation (4) suggested by Tanaka [9] using the coordination numbers $Z_{\text{Ag}}=2$ [10], $Z_{\text{As}}=3$ [11], $Z_{\text{Cd}}=4$ [12], $Z_{\text{Se}}=2$ [11] and $Z_{\text{Te}}=2$ [13].

\[
< Z > = x.Z_{\text{Ag}} + y.Z_{\text{As}} + z.Z_{\text{Cd}} + m.Z_{\text{Se}} + n.Z_{\text{Te}},
\]

(3)

The bond energies of heteropolar bonds ($E_{AB}$) can be calculated using Paulig’s relation [14]:

\[
E_{AB} = 0.5(E_{AA} + E_{BB}) + 23.(X_A - X_B)^2,
\]

(4)

where $E_{AA}$ and $E_{BB}$ - homopolar bond energies for A and B atoms and $X_A$ and $X_B$ - their electronegativity.

We determined the overall mean bond energy $<E>$ with the Tichy’s equation [11] of complex chalcogenide systems:
\[
\langle E \rangle = \bar{E}_c + \bar{E}_m,
\]

(5)

where: \( \bar{E}_c \) - the average energy of cross-linking/atom calculated with the equation (6);

\( \bar{E}_m \) - the average bond energy per atom of the “remaining matrix”.

\[
\bar{E}_c = p_p E_{hb}, \tag{6}
\]

\[
\bar{E}_m = \frac{2(0.5 < Z >).E_{<Z>}}{<Z>} \text{ at } R<1, \tag{7}
\]

where: \( E_{hb} \) is the average heteropolar bond energy for glasses with composition \( A_xB_yC_zD_mE_n \). It is calculated with the equation (8):

\[
E_{hb} = \frac{(xZ_AE_{A-D} + yZ_BE_{B-D} + zZ_CE_{C-D} + xZ_CE_{A-E} + yZ_BE_{B-E} + zZ_CE_{C-E})}{(xZ_A + yZ_B + zZ_C)}, \tag{8}
\]

where: \( E_{A-D}, E_{B-D}, E_{C-D}, E_{A-E}, E_{B-E}, \) and \( E_{C-E} \) are the heteropolar bond energies Ag-Se, As-Se, Cd-Se, Ag-Te, As-Te, Cd-Te – Table 4.
We calculated the R coefficient determining the content of chalcogen in glasses with the equation (9):

\[ R = \frac{mZ_D + nZ_E}{(xZ_A + yZ_B + zZ_C)} . \]  

(9)

When \( R > 1 \) the system is rich in chalcogen and has heteropolar bonds and chalcogen-chalcogen bonds.

When \( R = 1 \) the system has a stoichiometric composition because it has heteropolar bonds only.

When \( R < 1 \) the system is deficient in chalcogen and has heteropolar bonds and metal-metal bonds.

The studied system is deficient in chalcogen because \( R < 1 \) [\( R = 0.8872 \)].

In this case the degree of cross-linking/atom \( p_p \) (for \( R < 1 \)) is calculated with the equation (10):

\[ p_p = \frac{mZ_{Se} + nZ_{Te}}{(x + y + z + m + n)} , \]  

(10)

The average bond energy per atom of the “remaining matrix” \( E_{rm} \) (when \( R < 1 \)) is calculated by an equation (7).
In the equation (11) $E_{A-A}, E_{B-B}, E_{C-C}, E_{A-B}, E_{B-C}$ and $E_{A-C}$ are respectively the bond energies Ag-Ag, As-As, Cd-Cd, Ag-As, As-Cd and Ag-Cd – Table 4.

$$E_{\langle \rangle} = \frac{(E_{A-A} + E_{B-B} + E_{C-C} + E_{A-B} + E_{B-C} + E_{A-C})}{6}.\tag{11}$$

The values for $<Z>, \bar{E}_c, \bar{E}_m$ and $<E>$ are summarized in Table 5.

The values of $T_g$, according to $<E>$ [actually from $(0.38 < E > -0.47)$] are shown on Fig. 5.

A good correlation between $T_g$ and $(0.38 < E > -0.47)$ is observed. This dependence has a dimension not worse than $\pm 0.1 T_g$ and it can be explained very well with Arrhenius relation for viscosity ($\mu$), given in the following type:

$$\mu(T_g) = \mu_0 \exp \left(\frac{E_{\mu}}{kT_g}\right),$$

$$\tag{12}$$

This dependence is suggested by Tanaka [9], who accepts that $\mu(T_g) = 10^{13}$ Poise and $\mu_0 = 10^0 - 10^{-5}$ Poise.

Having in mind $\mu(T_g) = 10^{13}$ Poise and $\mu_0 = 10^{-3}$ Poise, for $T_g = f(E_{\mu})$ is received the expression:
\[ T_g = 314.6 \mu, \]

(13)

The experimental values of \( T_g \) and \(<E>\) follow the correlation:

\[ T_g = 119.68 <E> - 143.39 \]

(14)

By equation 13 and 14 \( E_\mu \) is defined:

\[ E_\mu = 0.38 <E> - 0.46 \]

(15)

By analogous way A and B constants in the correlation are determined:

\[ T_g = A(0.38 <E> - 0.46) - B \]

(16)

\[ T_g = 318.62(0.68 <E> - 0.46) - 2.9238 \]

(17)
The obtained values of the line slope (318.44 K.eV⁻¹) correspond exactly to the theoretically planned values (314 K.eV⁻¹), which is calculated through Tanaka’s model.

A correlation was established between the physico-chemical properties and the composition of glasses

4. Conclusion

(i) For the first time the area of glass formation in the three component system Ag₂Te-As₂Se₃-CdTe is outlined.

(ii) There are defined basic physical-chemical characteristics of the obtained chalcogenide glasses: density (d), micro hardness (HV) and compactness (C); softening temperature (Tᵣ), crystallization temperature (Tₐ) and melting temperature (Tₘ); elasticity modulus (E), volume of micro voids (Vₘ) and energy of micro voids formation (Eₘ), dependences between them and the composition being found out.

(iii) The full average energy of the chemical bonds <E> is calculated and correlation of the type Tᵣ=318.44(0.38<E>-0.47) is found out that is in compliance with the Tanaka’s model [9].
Acknowledgments. The authors acknowledge thankfully the financial support for this work from the Ministry of education and science (Fond “Scientific investigations”-contract TN-1503/05).

References

Table 1. Composition and state of the investigated samples from the (Ag₂Te)ₓ(As₂Se₃)ᵧ(CdTe)ᵣ system.

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<td>p. 5</td>
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* - № 12, 13 are studied in our previously work – [7]
Table 2. Thermal properties of the samples from the (Ag$_2$Te)$_x$(As$_2$Se$_3$)$_y$(CdTe)$_z$ system, where $m = y/(x+y)$

<table>
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<th>sample №</th>
<th>composition, mol %</th>
<th>m</th>
<th>$T_g$, °C</th>
<th>$T_{cr}$, °C</th>
<th>$T_m$, °C</th>
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<td>217</td>
<td>325</td>
</tr>
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<td>8 72 20</td>
<td>0.9</td>
<td>150</td>
<td>224</td>
<td>326</td>
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</table>
Table 3 Physical and thermomechanical properties of the samples from the 

\((Ag_2Te)_x(As_2Se_3)_y(CdTe)_z\) system, where \(m=y/(x+y)\).

<table>
<thead>
<tr>
<th>sample №</th>
<th>composition, mol %</th>
<th>d, g.cm(^{-3})</th>
<th>HV, kgf.mm(^{-2})</th>
<th>E, kgf.mm(^{-2})</th>
<th>V(_h), 10(^{-3})nm(^3)</th>
<th>E(_h), kJ.mol(^{-1})</th>
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<td>- 0.014</td>
</tr>
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<td>5.18</td>
<td>70</td>
<td>1056</td>
<td>11.8</td>
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<td>4.82</td>
<td>79</td>
<td>1190</td>
<td>12.0</td>
<td>5.80</td>
<td>- 0.076</td>
</tr>
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<td>10.7</td>
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<td>74</td>
<td>1118</td>
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<tr>
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<td>5.06</td>
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<td>0.013</td>
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<td>p. 16</td>
<td>16 64 20 0.8</td>
<td>5.50</td>
<td>78</td>
<td>1166</td>
<td>8.9</td>
<td>4.24</td>
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<tr>
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<td>5.22</td>
<td>85</td>
<td>1272</td>
<td>8.9</td>
<td>4.61</td>
<td>0.033</td>
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Table 4. Bond energy of the glasses from the \((\text{Ag}_2\text{Te})_x(\text{As}_2\text{Se}_3)_y(\text{CdTe})_z\) system.

<table>
<thead>
<tr>
<th>Bond</th>
<th>(E, \text{ eV})</th>
<th>Reference</th>
<th>Bond</th>
<th>(E, \text{ eV})</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ag-Ag</td>
<td>1.69</td>
<td>[15]</td>
<td>Ag-Se</td>
<td>2.10</td>
<td>[18]</td>
</tr>
<tr>
<td>As-As</td>
<td>2.07</td>
<td>[16]</td>
<td>Ag-Te</td>
<td>2.03</td>
<td>[18]</td>
</tr>
<tr>
<td>Se-Se</td>
<td>2.14</td>
<td>[16]</td>
<td>As-Se</td>
<td>2.26</td>
<td>[16]</td>
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<tr>
<td>Te-Te</td>
<td>1.65</td>
<td>[16]</td>
<td>As-Te</td>
<td>1.99</td>
<td>[14]</td>
</tr>
<tr>
<td>Ag-As</td>
<td>2.17</td>
<td>[14]</td>
<td>Cd-Se</td>
<td>1.32</td>
<td>[19]</td>
</tr>
<tr>
<td>Ag-Cd</td>
<td>4.54</td>
<td>[14]</td>
<td>Cd-Te</td>
<td>1.04</td>
<td>[19]</td>
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</table>
Table 5. Mean coordination number of glasses $<Z>$, overall mean bond energy $<E>$, $\bar{E}_c$ and $\bar{E}_{rm}$ of samples from the Ag$_x$As$_y$Cd$_z$Se$_m$Te$_n$ system.

<table>
<thead>
<tr>
<th>sample №</th>
<th>composition, mol %</th>
<th>$&lt;Z&gt;$</th>
<th>$\bar{E}_c$, eV</th>
<th>$\bar{E}_{rm}$, eV</th>
<th>$&lt;E&gt;$, eV</th>
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</thead>
<tbody>
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<td>0.30</td>
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<td>4.65</td>
<td>0.17</td>
<td>4.82</td>
</tr>
<tr>
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<td>2.35</td>
<td>4.74</td>
<td>0.15</td>
<td>4.89</td>
</tr>
<tr>
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<td>2.38</td>
<td>4.92</td>
<td>0.08</td>
<td>5.00</td>
</tr>
<tr>
<td>p. 9</td>
<td>13 30 2 45 8</td>
<td>2.30</td>
<td>4.35</td>
<td>0.26</td>
<td>4.61</td>
</tr>
<tr>
<td>p. 10</td>
<td>8 33 2 50 7</td>
<td>2.37</td>
<td>4.69</td>
<td>0.13</td>
<td>4.81</td>
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<tr>
<td>p. 11</td>
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<td>4.78</td>
<td>0.11</td>
<td>4.89</td>
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<td>2.41</td>
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<td>4.65</td>
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<tr>
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<td>2.44</td>
<td>4.51</td>
<td>0.22</td>
<td>4.72</td>
</tr>
</tbody>
</table>
Figure 1:
Figure 2:
Figure 3:
Figure 4:
Figure 5: