2021

Thermal and Thermophysical Properties of Anionic Amines and Their Aqueous Solutions for CO2 Capture in Confined Environments

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COLLEGE OF ENGINEERING

THERMAL AND THERMOPHYSICAL PROPERTIES OF ANIONIC AMINES AND THEIR AQUEOUS SOLUTIONS FOR CO_2 CAPTURE IN CONFINED ENVIRONMENTS

BY

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A Thesis

Submitted to the Faculty of the
University of South Alabama
in partial fulfillment of the
requirements for the degree of

Bachelor of Science

In

Chemical Engineering

May 2021

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ABSTRACT

Air revitalization for the International Space Station (ISS) has been identified by NASA as a mission critical need which requires improvement. The current method uses 13X zeolite, a solid adsorbent, to adsorb carbon dioxide. While this is effective, the zeolite adsorbent produces dust that is unwelcome on the space station. Furthermore, the adsorbent is too sensitive to humidity in moderate temperature gas streams [1]. Aqueous solutions of ionic amines show promise as a safe and efficient solution, as they do not volatilize and are not water sensitive [2]. Specifically, anionic amines have the most potential because of the amine functional group's ability to readily scrub CO_2 out of the air [3, 4]. There are several different anionic amine compounds the research group at South Alabama is analyzing that show promise for this application in confined environments. Different aqueous ionic amine solutions release different amounts of energy when they absorb CO_2, which can be useful in producing the heat needed to regenerate the solution after absorption, but also will require more energy to remove to carbon dioxide. To remove the CO_2 after it is chemically absorbed, the solution is to be heated and the carbon dioxide will return into the gas phase [5]. Ionic amines tend to be very viscous, but water can be added so the solution will flow more easily. However, water has a high heat capacity and will require more energy to heat the solution during regeneration and cool afterward. These circumstances – heat of absorption, viscosity, and heat capacities of the solutions – require our research team to find data for several different conditions to be able to determine the best ionic solution for air revitalization. For this project, the team will not pursue the logistics of viscosity, however, it will need to determine the thermophysical properties of the solutions at

different concentrations. The pure component thermophysical properties must also be known for these ionic amines to calculate the energetics of the reaction.

CHAPTER I

INTRODUCTION

1.1 Motivation

NASA has identified air revitalization on the International Space Station as an area of focus, with aqueous solutions of ionic amines as a potential solution [6]. NASA's Established Program to Stimulate Competitive Research (EPSCoR) selected the University of South Alabama for the Research Program Cooperative Agreement Notice Award. This award provides financial support to improve ISS air revitalization and the university's research and design competitiveness [6]. The team at South Alabama collaborating on this project consists of Dr. Davis, Dr. Reichert, Dr. Glover, Dr. Kevin West, three graduate students, and between two and six undergraduate students. This team will identify an ionic solution that proves to have the best results in the research lab. Figure 1. on page 8 shows the different ionic compounds that will be made and tested. One of the main goals of NASA in this project is to have the safest compounds being used, as well as safe byproducts in case of secondary reactions. Aqueous amines are currently used to absorb CO_2 in combustion flue gas streams, but corrosion, instability, high volatility, and high energy for regeneration are all big problems for using amines to capture CO_2 on the ISS for safety and energy reasons [4]. Amine functionalized ionic liquids readily absorb carbon dioxide and have no vapor pressure, which gives them promise as a safe and efficient method for air revitalization [3].

Removal of CO_2 in the International Space Station (ISS) has been a focus of NASA, because studies have shown that the elevated levels of CO_2 exposure are affecting astronauts' physical, neurological, as well as cognitive health [7]. The current method of removing CO_2 involves a solid adsorbent, 13X zeolite. The zeolite, however, produces dust and is less effective

in humid gas streams [9]. It has been a manageable problem with the approach currently used, but NASA is collaborating with the University of South Alabama to search for a more efficient method. Increased CO_2 levels at moderate amounts cause changes in blood pressure, heart rate, tissue pH, and blood solubility [7]. At just 3%, heart rate and blood pressure increase, while exercise tolerance decreases. Shortness of breath and headaches are common. Higher exposure results in confusion, heart palpitations, sweating, and chest pains. As levels rise to 10%, vomiting, disorientation, severe dyspnea occurs, with long term exposure resulting in seizures and loss of consciousness. High levels of CO_2 (35%) have even caused anxiety responses and panic attack like symptoms in healthy individuals [7]. Even at only 20-22%, death has been reported [7]. It is easy to identify the physiological changes that result from high CO_2 exposure, but it is more difficult to identify the cognitive effects that low concentrations can cause for a prolonged period of time. A study completed by Allen et al. showed that low-level elevated CO_2 exposure during a full day impaired performance on higher-order decision-making tasks, with higher levels of CO_2 linearly causing decline in cognitive functioning [8]. Mental health is very important on the ISS given that a team of astronauts must work together to complete goals in a very abnormal environment. On Earth, CO_2 concentration is consistently at 0.03% by volume. On the ISS, CO_2 concentration is consistently higher at around 0.5%, and can fluctuate much more quickly than Earth's standards [7].

1.2 Aqueous Amine Solutions

The removal of CO_2 gas from air has been an area of focus for many industries because of humanity's burning of fossil fuels. The combustion of fossil fuels release CO_2 and H_2O gas, in which CO_2 acts as a greenhouse gas that causes the rising temperatures of the Earth. Using amines for capture of CO_2 is currently the most effective and common method for post-

combustion flue gas streams, again because of the amine's ability to scrub gaseous CO_2. A CO_2 laden gas stream flows from the bottom of an absorption column where it is contacted with aqueous amine solution. Lloret and Vega have described aqueous amine solutions to have high volatility and corrosion. These properties cause the amine solution to degrade at high temperatures, requiring low pressure gas to counteract the degradation. This greatly lowers the capacity for absorption, however, because CO_2 is in low concentrations in the gas line. All of this considered, amine absorption is still the best way to scrub CO_2 out of the gas phase due to the effectiveness of amine capture and the reusability of the whole process [3]. In aqueous solution, Stowe and Hwang have shown that primary and secondary amines undergo 2:1 capture of CO_2 [5]. This means it takes two amine molecules for every one CO_2 molecule captured, which costs more money than 1:1 capture. The resulting products include one carbamate ion and a protonated amine ion. The amine attacks the CO_2 and forms a zwitterion. A zwitterion is a molecule that holds a true positive and negative charge at the same time, resulting in an overall neutral charge. Then, a second amine comes and takes one proton from the zwitterion to form the carbamate and ammonium ion [5].

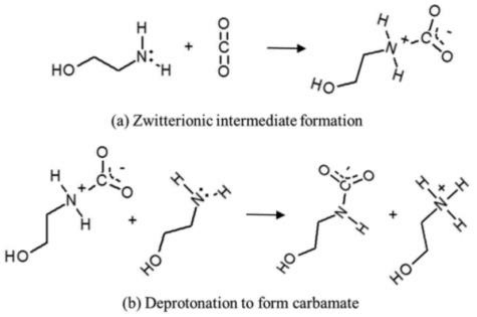

Figure 1. illustrates process of CO_2 capture by aqueous amines.

In addition to the 2:1 requirement of aqueous amines, solvent degradation accounts for about 10% of the cost of CO_2 scrubbing using this method [5].

1.2 Ionic Amines

Ionic liquids have been a key candidate for CO_2 removal from air because of the properties that resolve the problems stated above. They can be thought of as molten salts, with very high thermal stability and virtually no vapor pressure due to their Coulombic attractions [2]. Because of this they have a low volatility, they're stable, and they have low corrosivity. There are seemingly endless combinations of cations and anions to create the perfect ionic pair for specific tasks. As compared to organic solvents, IL's can physically absorb more CO_2, but without being modified, their chemical absorption capacity is too low to be practical for CO_2 removal [4]. By adding the aforementioned amine group to the cation or anion, many different IL's yield the potential for efficient CO_2 scrubbing. Amino acid ionic liquids (AAILs) are available at reasonable prices for industrial use, and they capture CO_2 better than most other compounds with amine groups found in them, such as pure amino acids or amino acid salts [4]. In 2001, the first ionic liquid was made for CO_2 capture at the University of South Alabama in 2002 by the Davis research group, with the amine group covalently bonded to the cation [2]. The uptake of CO_2 is completely reversible, which is beneficial because the same solution can be used continuously to scrub the air. The uptake of carbon dioxide is exothermic, so to remove the chemically bonded CO_2 from the ionic amine, it can be heated around 100°C for several hours in a vacuum. The Davis research group repeated this process five times, and no loss of efficiency was observed [2]. This discovery has put ionic liquids at the center of attention for CO_2 capture. The amine group undergoes the same mechanism as Stowe reported, forming the zwitterion briefly before forming a carbamate and ammonium ion. Carbamate ions, ammonium ions, and carbamic acids remain in equilibrium until the ionic amine is regenerated [4]. The CO_2 capacity varies from 2:1 to 1:1 this way, depending on external and molecular conditions. 2:1 capture

occurs when the zwitterion rearranges to make a carbamic acid, so it is desirable to keep the equilibrium favoring the zwitterion. By lowering the temperature or increasing the CO_2 partial pressure, 1:1 capture is favored. However, raising the CO_2 partial pressure is not practical to this application, because by the time the pressure is high enough, most of the astronauts have probably already died. Firaha and Kirchner have shown that attaching the amine to the anion instead of the cation increases absorption capacity, as well as increasing the cation size [4]. The same researchers have also shown that using the surface of the IL instead of the bulk favors 1:1 capture at moderate pressures [4].

The advances that have been made using ionic amines show promising results for capturing CO_2 in dry gas streams. When water is present in the gas stream, the behavior changes greatly [9]. The equilibrium between carbamate ions, ammonium ions, and carbamic acids is not the only one that exists in wet conditions. Carbonate and bicarbonate also form due to rapid proton exchange [9]. These are unwanted products not only because there is a less straightforward way to rid them from solution to regenerate the original solution, but they also change the pH of solution. If CO_2 is in excess of its stoichiometric balance, the carbonate/bicarbonate mode of capture dominates [9]. The carbamate still forms, but only briefly. In this application, excess CO_2 should not be a problem because normal levels of CO_2 in the ISS are around 0.5%. AAIL's have shown to perform 1:1 capture in dry gas streams, but the ionic liquids are often very viscous without the addition of water. Drawbacks such as high viscosity and 2:1 capture have encouraged Dr. Seo and his research team to focus on aprotic heterocyclic anions and phase change ionic liquids. Aprotic heterocyclic anions (AHAs) were observed to absorb CO_2 in 1:1 capture at pressures between 0 -1 bar and reversibly give it off with no efficiency loss [10,11]. Because there are not as many free protons in the heterocyclic

structure of the ionic liquid, the hydrogen bonding network is not as strong, so the viscosity doesn't notably increase [10,11]. However, over time the AHA can become protonated in the presence of water into neutral species. Because of this, useful absorbent is lost over several cycles [10]. Phase change ionic liquids greatly reduce the amount of energy needed to regenerate the original absorbent. This is because ionic amines can be synthesized to lower the melting point after sequestering CO_2 [12]. Many ionic amine's melting points increase when reacted with CO_2 because of the new possibility for hydrogen bonding. The extensive previous research done and Dr. Davis's experience making ionic compounds for industrial use has aided him in presenting the most promising ionic amines for this application. For this project, 1:1 capture is favorable, but not critical. Steric effects, solvent environment, and electron withdrawing/donating effects of substituents on the amine all contribute to the rearrangement of the zwitterion to the carbamic acid and cause 2:1 capture. The general method for constructing the ionic amines as described in the project proposal include the ring opening of cyclic sultones by primary amines. Separation techniques are then used to purify the ions used. The ionic compounds being synthesized feature an amine group in both the cation and anion. Capturing CO_2 as a carbamate is more achievable this way because there is a lone pair and a hydrogen on the nitrogen atom that discourages the rearrangement of the zwitterion.

The Departments of Chemistry and Chemical & Biomolecular Engineering at South Alabama are investigating several different ionic amine combinations to determine the best one for this project as shown in the EPSCoR Research Program Cooperative Agreement Notice Award 0002 2019:

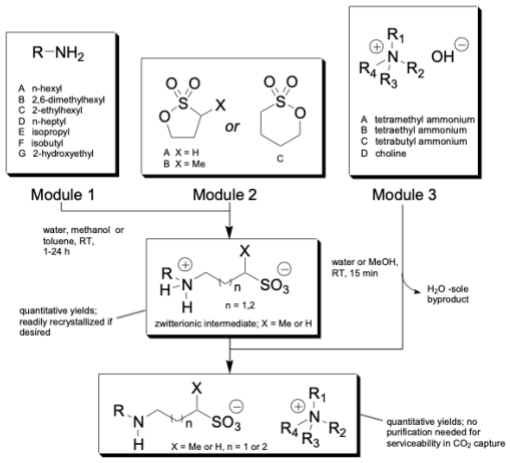

Figure 2. Shows the layout of ionic amines being produced as given in the project proposal.

Using this chart as a guideline, the chemistry department will produce eight compounds for analysis:

- tetramethylammonium taurinate
- tetramethylammonium homotaurinate
- tetramethylammonium N-propyl-homotaurinate
- tetramethylammonium N-methyl-homotaurinate
- choline taurinate
- choline homotaurinate
- choline N-propyl-homotaurinate
- choline N-methyl-homotaurinate

As can be seen, using ionic liquids for CO_2 capture has been a focus for several years, and scientists have continually discovered better and better methods for scrubbing. The original reason behind the ionic liquid research was to help reduce the emission of greenhouse gases

caused by the burning of fossil fuels [2]. There are several other applications, however, with air revitalization on the International Space Station being one of them.

CHAPTER II

METHODS

2.1 Characteristics of Interest

Solutions of nonvolatile ionic aqueous amines will demonstrate improved performance of capacity and energy requirements over monoethanolamine for CO_2 capture under air revitalization conditions. To validate this, the pure component thermophysical properties of several ionic compounds listed on page 9 will be determined. These properties are melting points, enthalpies of fusion, and heat capacities, and they will also be determined for different concentrations (20 mass% - 60 mass% ionic compound) of aqueous ionic solution. The enthalpy of absorption of CO_2 will be determined for choline taurine and will be compared to current aqueous amine solutions to demonstrate improved performance with negligible vapor pressure.

2.2 Density Measurement

The heats and rates of absorption are being compared for three different compounds at 30% mass solution: choline taurine, monoethanolamine, and 2-(2-aminoethyoxy) ethanol. In order to understand the impact the diffusion of carbon dioxide into the amine solutions has, a density measurement is required to convert from mass to volume of solvent. The DSA 5000 will be used to accurately measure density to six decimal points.

2.3 Differential Scanning Calorimeter

The Differential Scanning Calorimeter (DSC) will be used to determine thermophysical properties such as heat capacity and heat of fusion, as well as reaction behavior for absorption. NASA has granted the funds that allowed the Department of Chemical and Biomolecular

Engineering to purchase a new DSC and SDT for this project. The DSC will take data on aqueous solutions of ionic amines with concentrations ranging from 20% – 60% and pure with a temperature generally ranging from 0 – 70°C. This data will include melting point, enthalpy of fusion, and heat capacity. After the thermophysical properties are determined, data on CO_2 absorption can be taken. The experimental CO_2 partial pressure will range from 0 – 2 Torr to model the conditions on the International Space Station. The temperature will be held constant, with an inert nitrogen stream flowing over the ionic liquid. Then, the gas stream will be switched to carbon dioxide and the enthalpy of absorption can be determined. This is important to establish the conditions needed for solvent regeneration. The data will be compared against that of common aqueous amine solvents such as MEA to compare the heats and rates of absorption and desorption.

Figure 3. TA Instruments Discovery DSC 2500

2.4 Rotary Evaporation

The compounds being tested are hygroscopic, meaning they will absorb water from the air when left open to the atmosphere. Because of this, the compounds will be dried in a rotary evaporator. There is inert nitrogen on backflow to ensure no water-containing air is contacted with the dry ionic amine. The compounds are capped quickly and weighed in order to accurately determine the weight percentages when water is added.

CHAPTER III

RESULTS AND DISCUSSION

3.1 Melting Points of Pure Components

3.1.1 Choline Taurinate

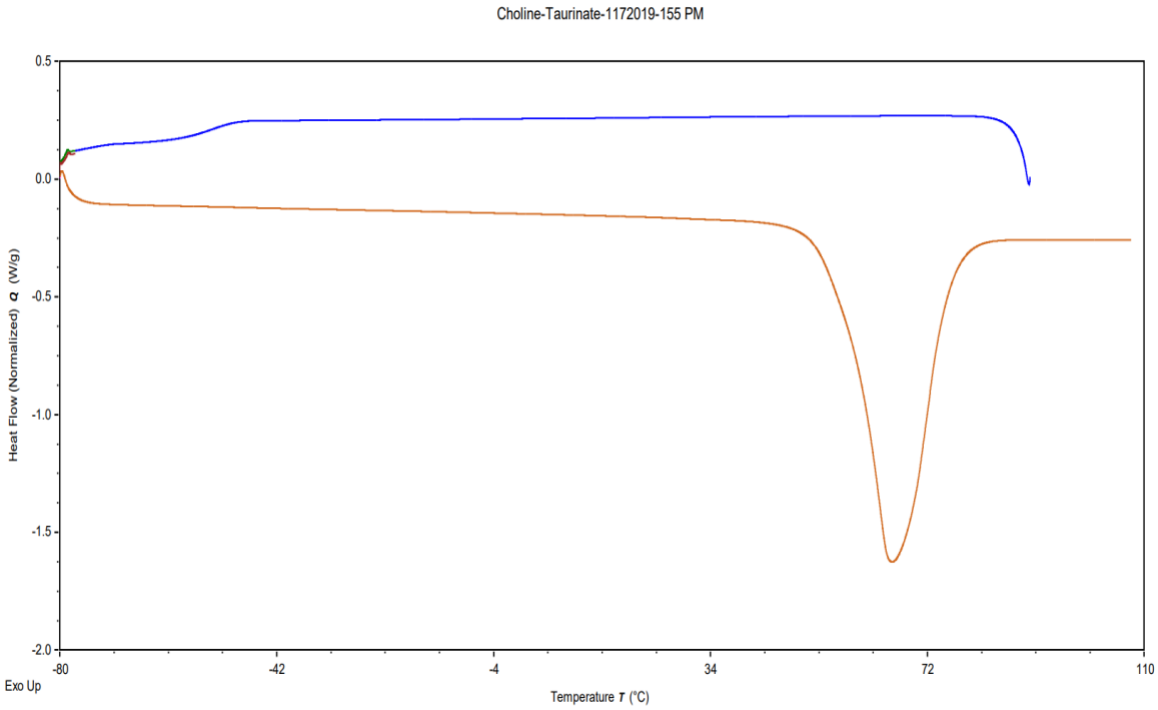

Figure 4. shows the melting point for choline taurinate as found by the DSC.

For the pure component melting point of choline taurinate, the solution was heated to 90°C and left isothermal at that temperature for 300 minutes (5 hours). This was to remove all water from the sample before determining the melting point. This strategy of leaving the sample isothermal for more than an hour was used for all the compounds. The sample was then cooled to -80°C and heated back to 110°C (figure 3). This was done using the DSC 2500 and the melting point was found to be 57.52°C± 0.09 °C

3.1.2 Tetramethylammonium Taurinate

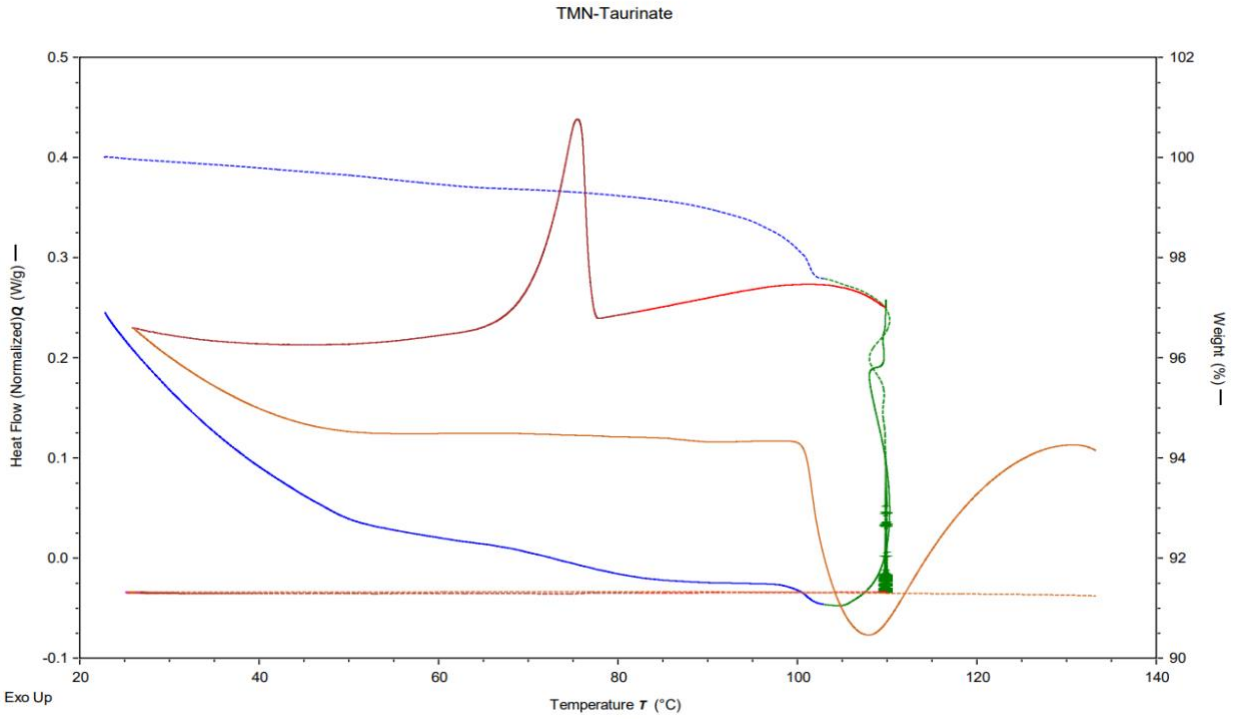

Figure 5. shows the melting point of tetramethylammonium taurinate as found by the SDT.

This run was completed on the SDT and reported for a project completed by a previous student [13]. For the pure component melting point of tetramethylammonium taurinate, the sample was heated to 110 °C and kept isothermal for 240 minutes to ensure all water was removed. Then, the sample was cooled to 25 °C to refreeze it before heating to 130 °C. The melting point peak was analyzed and found to be 103.4 ± 0.5 °C.

3.1.3 Choline n-methyl homotaurinate

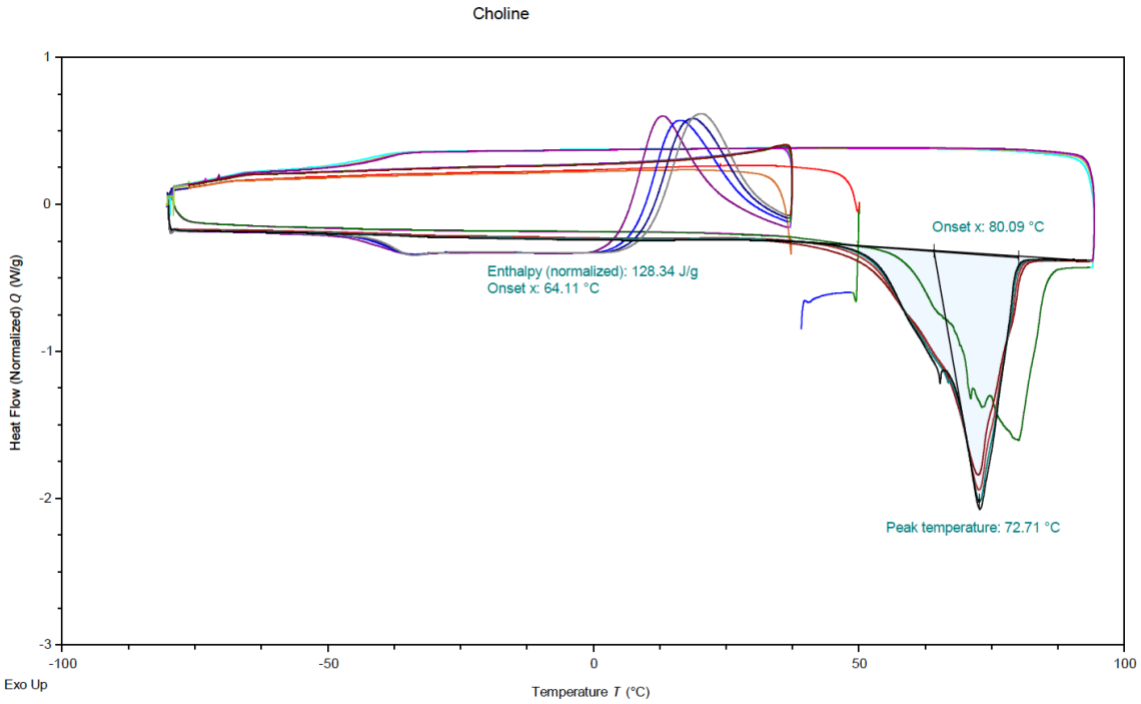

Figure 6. shows the melting point for choline n-methyl homotaurinate found using the DSC.

The pure component melting point of choline n-methyl homotaurinate was difficult to conclude due to the energetics of the molecule changing at a temperature right before the melting point. The DSC found the onset temperature of this peak to be 80.08°C, however this result is likely imprecise to the true melting point of this compound when it is in its most stable form because of the wide peak range the program is analyzing.

3.2 Heat Capacity of Aqueous Solutions

In order to observe the effect of composition on heat capacity, three different percentages of ionic amine in water, 20%, 40%, and 60%, were tested over a temperature range from 0-70 °C. After the data was taken, Excel was used to find the coefficients to model the solutions using the following equation:

$$Cp = a + bT + cT^2$$

The coefficients for each solution for each compound are shown in table n.

		a	b	c
Taurine Choline	20%	3.41997011	0	1.2815E-05
	40%	2.80405013	0.00465987	0
	60%	2.31924108	0.00562084	0
Tetramethyl ammonium taurinate	20%	2.90129177	0.00484001	4.9683E-06
	40%	2.59256132	0.0033355	0
	60%	2.34662274	0.00414389	0
946	20%	3.29700741	0	0
	40%	2.96102035	0.00385698	0
	60%	2.63659068	0.00442651	0
Choline n-methylhomotaurinate	20%	3.03337037	0	0
	40%	2.58350256	0.003065	0
	60%	2.25841757	0.00440246	0
Tetramethyl ammonium n-isopropylhomotaurinate	20%	2.98419868	0.00190631	0
	40%	2.49634895	0.00360757	1.4134E-05
	60%	2.14302692	0.00413838	6.2989E-06

Table 1. shows heat capacity coefficients for 20%, 40%, and 60% mass concentrations for five different compounds.

Most of the heat capacities give a linear result, with the c value equal to zero. The compounds that have a non-zero value for c have values that are very close to zero. This is because for many runs, the heat capacity data points begin to drop at higher temperatures, especially for low concentrations of ionic amines. There is more water present in these solutions that creates a higher vapor pressure in the T-Zero pans as temperature rises. The data points

begin to drop off because this vapor pressure consistently overcomes the force of the lid of pans causing it to deform and leak [14]. This allows for vapor to escape the pan, causing the mass of the sample to decrease. As mass leaves the pan, the heat capacity of the run drops.

3.2.1 Choline Taurinate

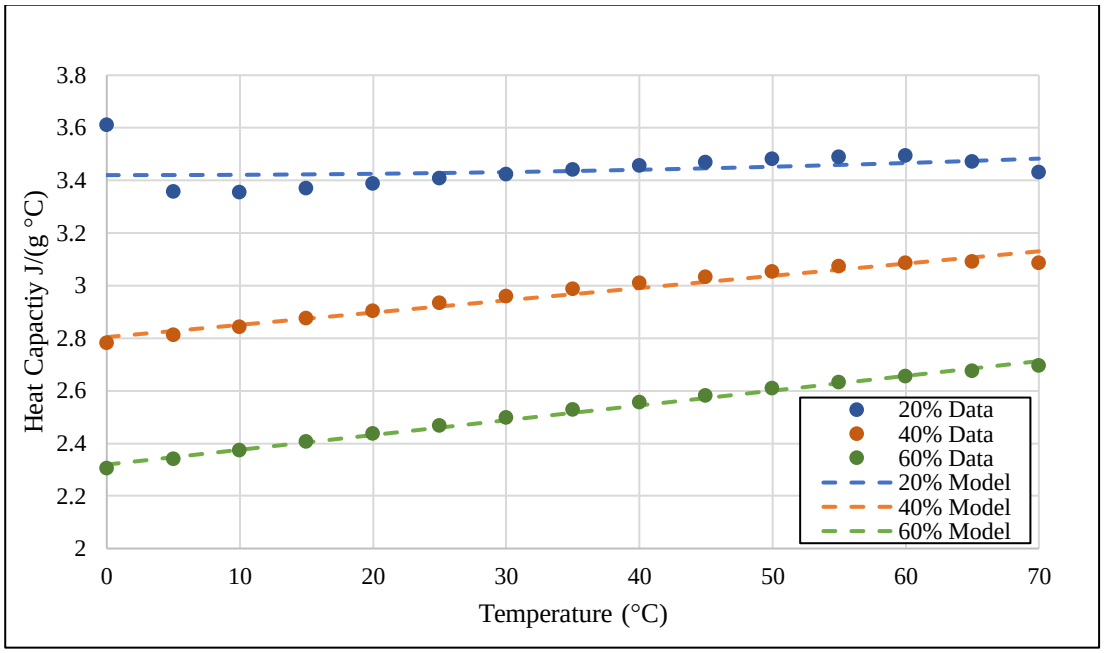

Figure 7. shows heat capacity of choline taurine and water solutions versus temperature.

As ionic amine concentration declines and water concentration rises, heat capacity increases. This shows that there is no ideal concentration of ionic amine that minimizes heat capacity. However, the heat capacity trendline for 20% concentration is higher by a larger difference than the other concentrations. The experimental data points begin to drop at 60°C for 20% and 40% concentration from the increased pressure in the pan causing deformation of the lid. At 0°C, the experimental heat capacity for 20% concentration is significantly higher than the model would suggest. At 80% mass of water, the likely explanation of this is the water

somewhat solidifies at temperatures below its pure component freezing point, and this affects the linear nature of the heat capacity curve of the aqueous solution at temperatures below 0°C.

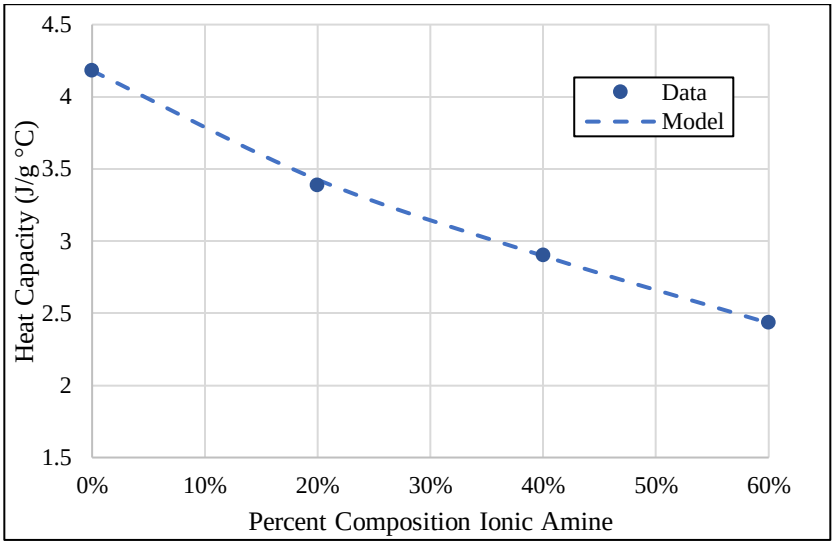

Figure 8. shows composition versus heat capacity at 20°C for choline taurine.

20°C was chosen to compare heat capacities for different concentrations because it is ambient air temperature and returns an accurate model. For choline taurine, the heat capacity declines linearly as composition of ionic amine increases.

3.2.2 Tetramethylammonium taurinate

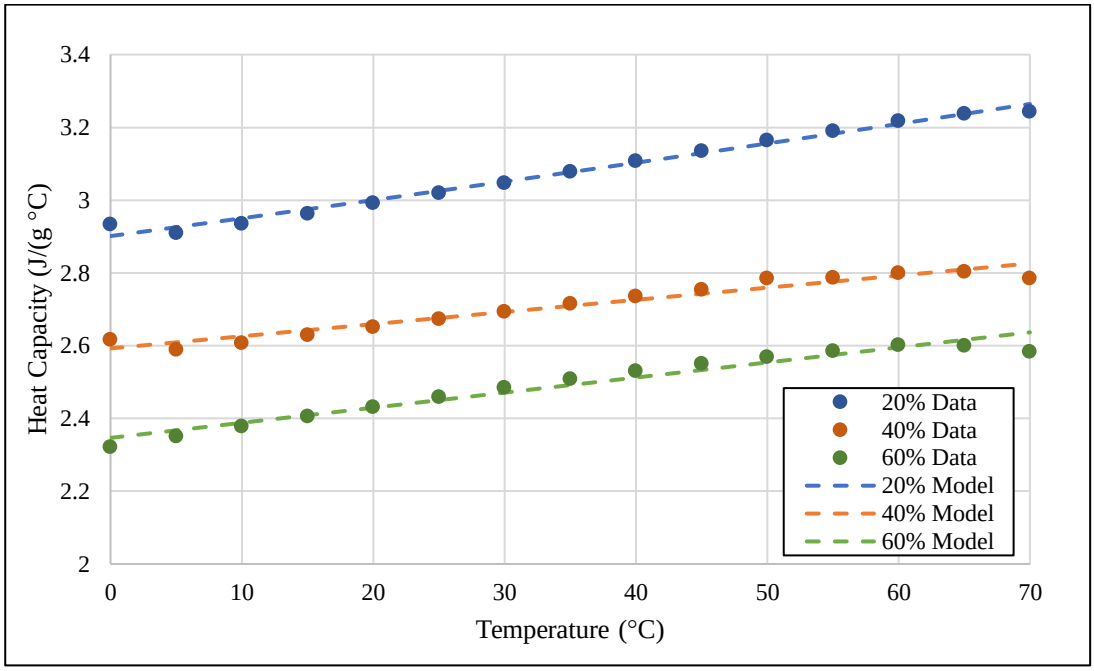

Figure 9. shows heat capacity of tetramethylammonium taurinate and water solutions versus temperature.

The same trends follow for this compound as compared to taurine choline, but they are not as pronounced. This suggests that tetramethylammonium taurinate is more hydrophilic than taurine choline, causing water to stay in solution more. The 20% concentration varies farther in heat capacity than the 40% and 60% solutions, as shown in figure n.

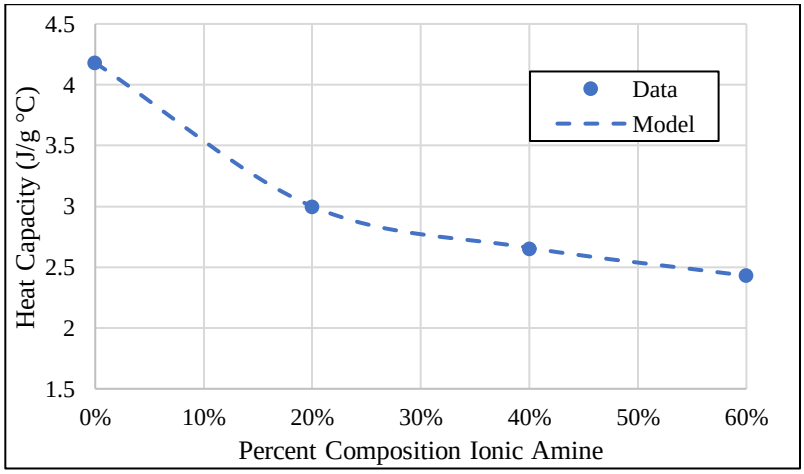

Figure 10. shows composition versus heat capacity at 20°C for tetramethylammonium taurinate.

3.2.3 Choline homotaurinate

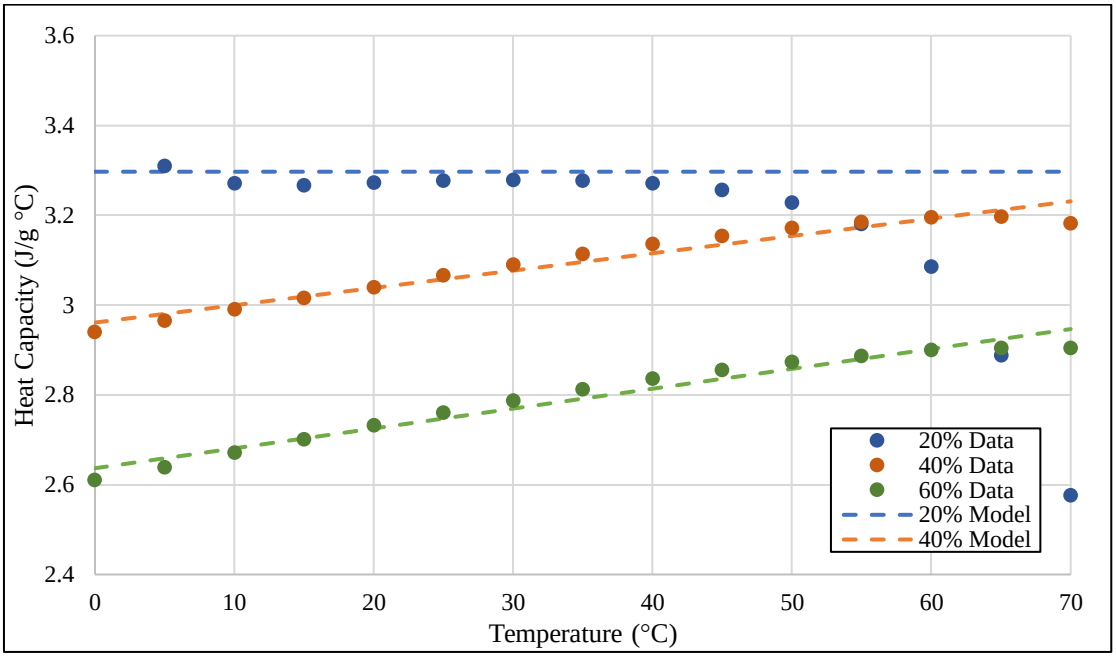

Figure 11. shows heat capacity of choline n-isopropyl homotaurinate and water solutions versus temperature.

The 20% experimental data for choline n-isopropyl homotaurinate begins to decline at 40°C severely. This compound does not hold the water in solution well for 20% mass concentration. A concentration increase of ionic amine again decreases the heat capacity, with the difference in the 20% solution heat capacity being slightly higher than the other two.

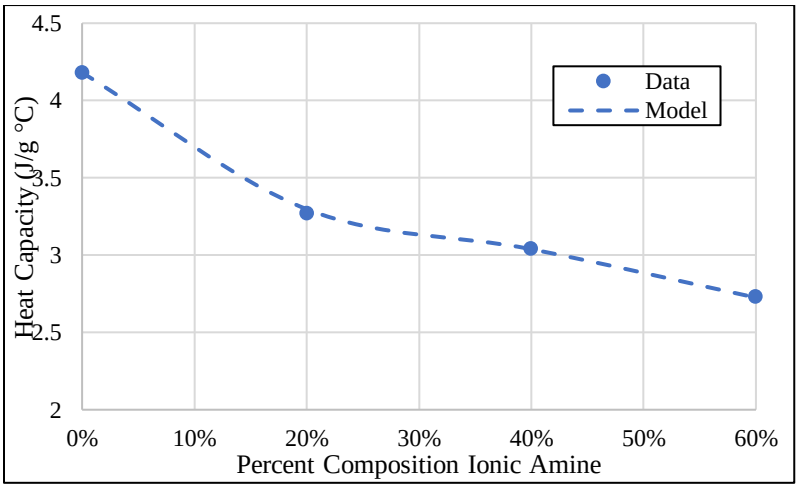

Figure 12. shows composition versus heat capacity at 20°C for tetramethylammonium taurinate.

3.2.4 Choline n-methylhomotaurinate

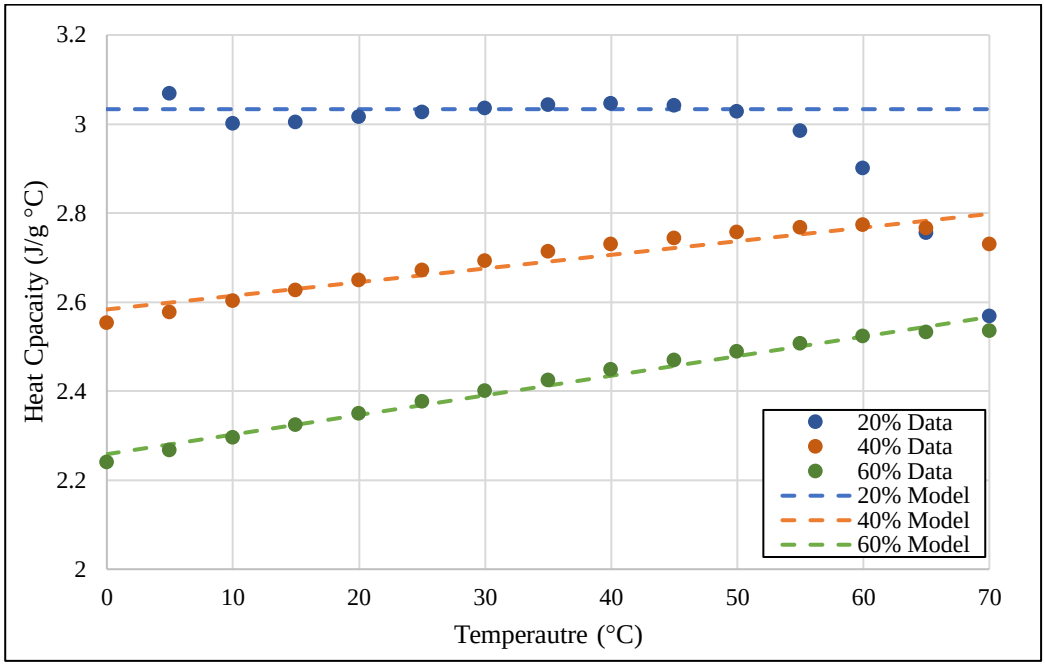

Figure 13. shows heat capacity of choline n-methyl taurinate and water solutions versus temperature.

This compound follows very similar trends to choline n-isopropyl homotaurinate. The 20% solution vapor pressure of water builds up considerably at 45°C. The overall heat capacities are lower for this compound than choline taurine and n-isopropyl homotaurinate, and the concentration has the same effect on heat capacity as the other compounds.

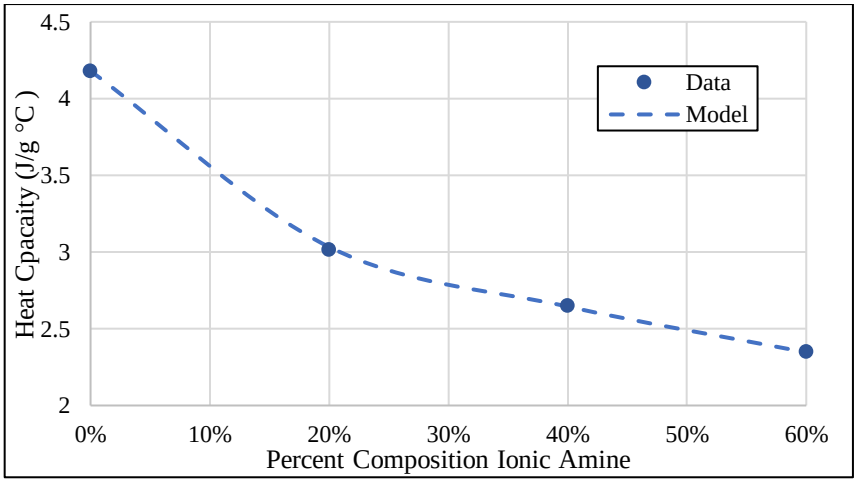

Figure 14. shows composition versus heat capacity at 20°C for choline n-methylhomotaurinate.

3.2.5 Tetramethylammonium n-isopropylhomotaurinate

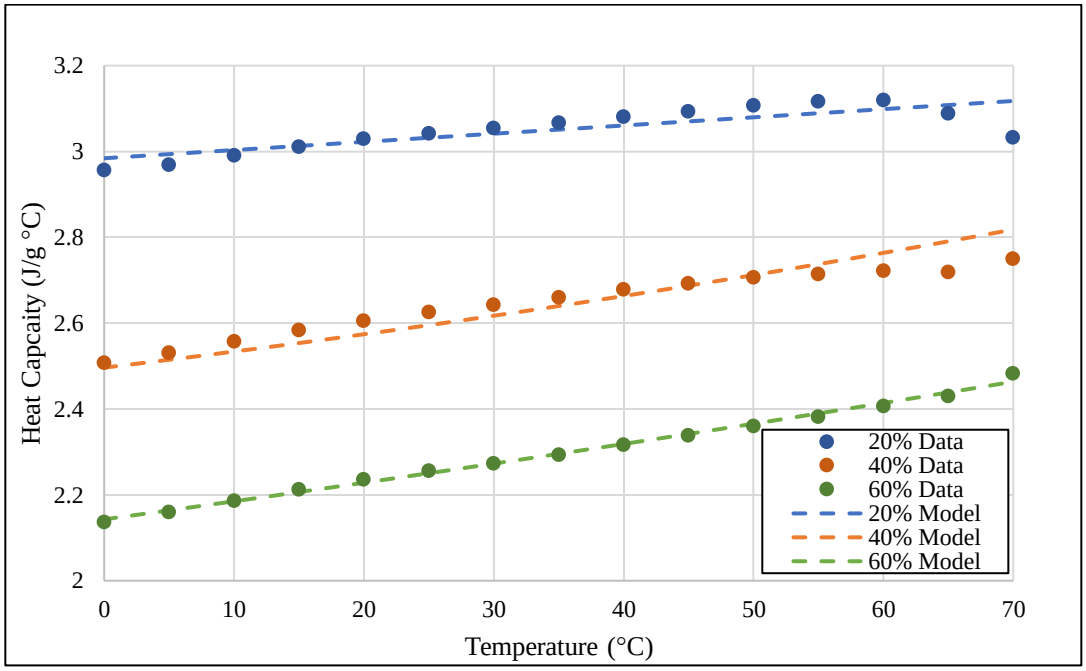

Figure 15. shows heat capacity of choline n-methyl taurinate and water solutions versus temperature.

This compound again shows the same trends as the others. Heat capacity increases with temperature, and leaks occur at higher temperatures. Heat capacity drops considerably with a small addition of compound, and continue to decreases as concentration increases.

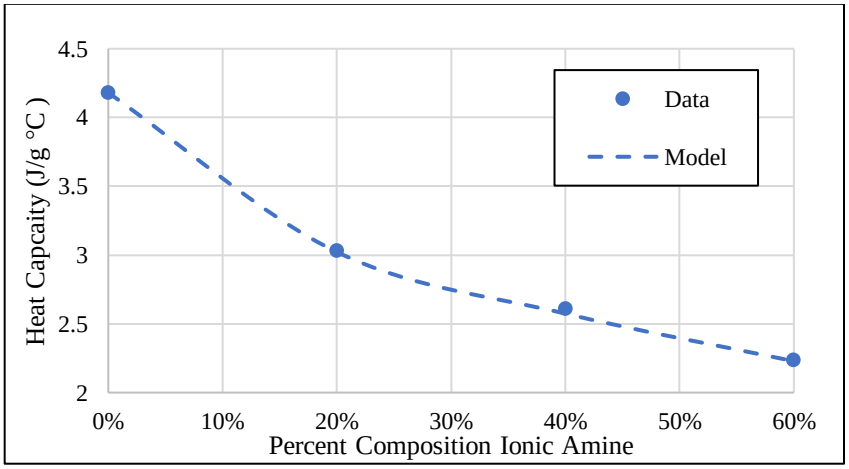

Figure 16. shows composition versus heat capacity at 20°C for tetramethylammonium n-

3.3 Heats of Absorption

The heat of absorption was compared for three different compounds. The following figures depict a heat cycling run for taurine choline and monoethanolamine on the differential scanning calorimeter, with the enthalpy of absorption analyzed using TA Universal Analysis.

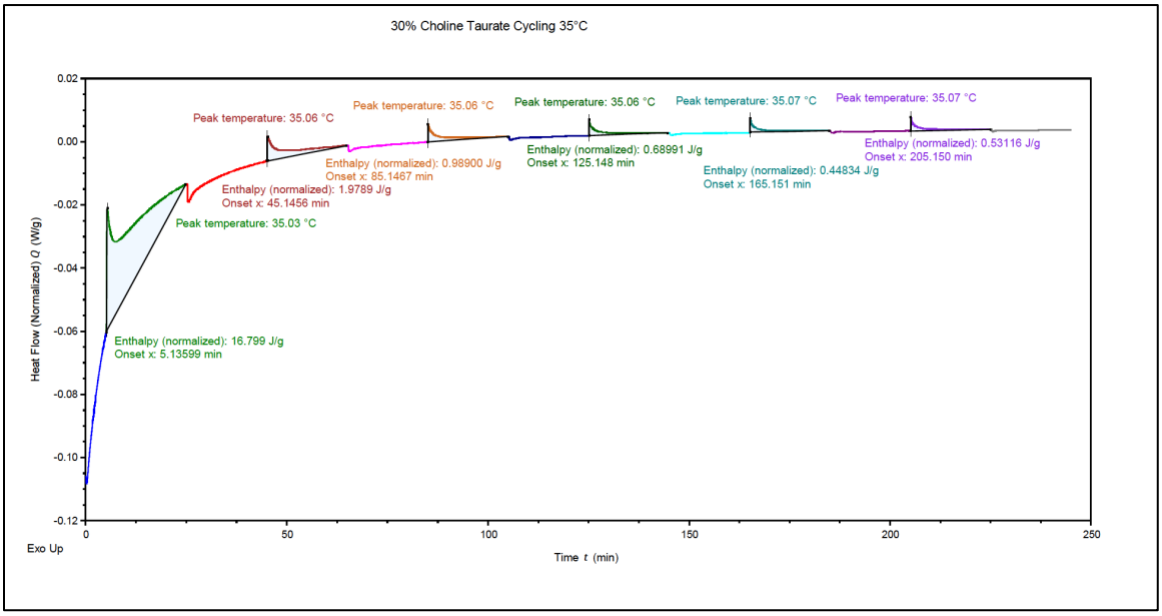

Figure 17. Shows heat flow versus time for choline taurine at 35°C, alternating between inert nitrogen gas and carbon dioxide.

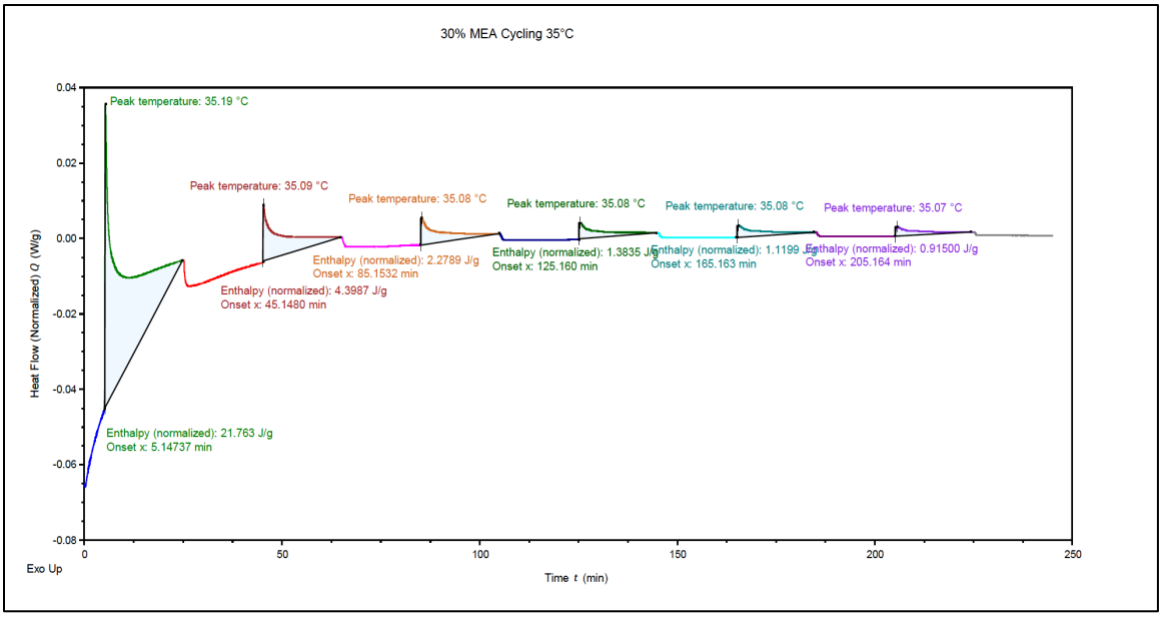

Figure 18. Shows heat flow versus time for monoethanolamine at 35°C, alternating between inert nitrogen gas and carbon dioxide.

		Average (J/g)	Standard Deviation
Choline Taurinate	20°C	2.5355	2.67233
Choline Taurinate	35°C	0.6646	0.23836
MEA	20°C	4.2777	2.02586
MEA	35°C	1.4241	0.60128
Ethoxy Ethanol	20°C	2.4487	0.55581
Ethoxy Ethanol	35°C	8.8222	0.69474

Table 2. Shows average heats of absorption found for three compounds.

The standard deviation values are high for this measurement. This is due to the fluctuating composition of the open pan under a gas stream. These values should serve more for a comparative purpose than accuracy.

Each compound showed the same pattern for the gas cycling runs, where the solution takes in energy for the first few cycles, until the heat flow zeroes out and the enthalpy of the final peaks becomes more consistent. This is because each compound was made at 30% mass of amine and 70% mass of water. The energy being absorbed into the solutions is used to vaporize some of the water in the solutions, until it reaches a stable concentration where the ionic attractions of the anionic amine hold the water molecules in solution so they do not vaporize anymore. This is confirmed by comparing the mass lost by each sample before and after the cycling run.

Sample Mass (mg)			
Choline Taurine	Before Run	After Run	Percent Loss
20°C	20.476	8.824	56.906%
35°C	20.694	8.38	59.505%
Monoethanolamine			
20°C	21.008	9.122	56.578%
35°C	22.098	9.482	57.091%
2-(2-aminoethoxy) ethanol			
20°C	19.586	8.482	56.694%
35°C	19.722	8.302	57.905%

Table 3. Shows percent mass loss of three different solutions before and after a cycling run alternating between carbon dioxide and nitrogen.

Because the percent loss of mass is comparable for all three compounds at their respective temperatures, it is assumed that the molecules that were vaporizing were mostly water. Using this assumption to calculate the final concentrations of the solutions after the run, the results are as follows:

Choline Taurine

- 69.61% for 20°C
- 74.08% for 35°C

Monoethanolamine

- 69.09% for 20°C
- 69.92% for 35°C

2-(2-aminoethoxy) ethanol

- 69.92% for 20°C
- 71.27% for 35°C

This shows that in order to keep an aqueous solution of these compounds that are less concentrated than the values above, a steady stream and method of mixing of water into these solutions is required. The temperatures tested for these runs were 20°C and 35°C. As temperatures rise above these, the solutions will lose more water than what is reported above.

3.3 Rates of Absorption

3.4.1 Density determination

Density measurements were taken for three compounds, with one being an ionic amine and the others aqueous amine solutions for comparative purposes. These compounds were choline taurine, ethanolamine, and 2-(2-aminoethoxy)ethanol. Their densities and standard deviations are reported in table n.

Average density and standard deviation measured in g/cm^3					
Choline Taurine		Ethanolamine		2-(2-aminoethoxy) ethanol	
20°C	35°C	20°C	35°C	20°C	35°C
1.06188	1.0507	1.0058	1.0034	1.0203	1.01627
±0.00003	±0.0001	±0.0002	±0.0005	±0.0009	±0.00009

Table 4. shows density for three different compounds at 20°C and 30°C. The DSA 5000 was used for accurate results.

Knowing the density of these compound is important when comparing the rate of absorption of the carbon dioxide into the amine solution. The rate it takes a solution to come to equilibrium with a CO_2 stream is an important factor in the process of CO_2 uptake. To understand and compare the effect this rate has on the absorption, the thickness of the layer of solution must be known. Because the cross-sectional area of the DSC T-Zero pans are the same, knowing the density and mass of the solutions in the pans allows for the thickness of the amine layer to be compared.

Max Percent Height Difference		
	20°C	35°C
Choline Taurinate	8.564%	13.748%
MEA	8.163%	12.387%
Ethoxy ethanol	8.888%	14.139%

Table 5. shows relative height differences of the three samples.

The maximum difference of the samples was 14%. This is not a significantly high difference, and it was due to the greater MEA content in the 35°C run.

The rates of absorption were compared for three compounds:

- Choline taurinate
- Monoethanolamine
- 2-(2-aminoethoxy) ethanol

Monoethanolamine is the industry standard for carbon dioxide absorption due to its uptake and regenerative capabilities for large concentrations of gas. 2-(2-aminoethoxy) ethanol is another effective aqueous amine, with a lower vapor pressure compared to MEA due to its larger size. These amines are being compared to an ionic amine, choline taurinate.

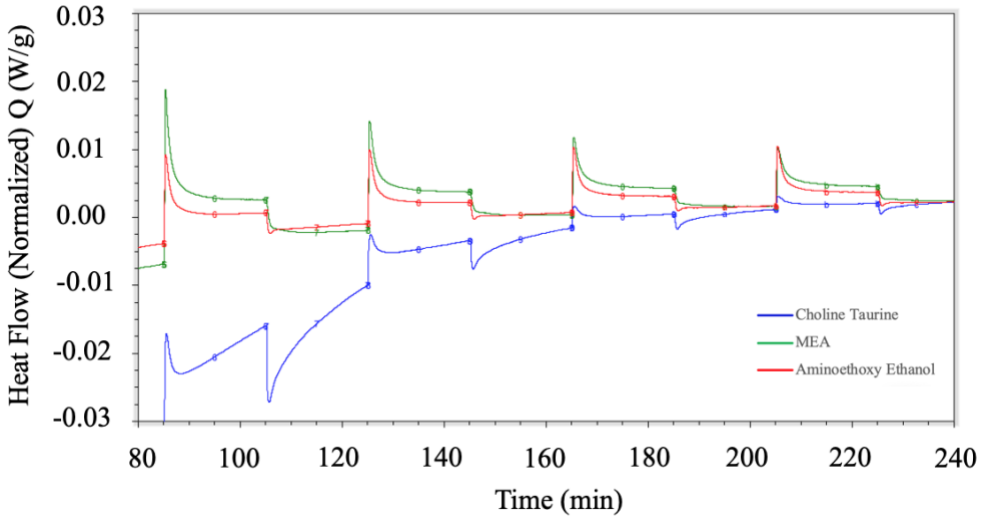

Figure 19. shows relative rates of absorption for choline taurinate, MEA, and ethoxy ethanol at 20°C.

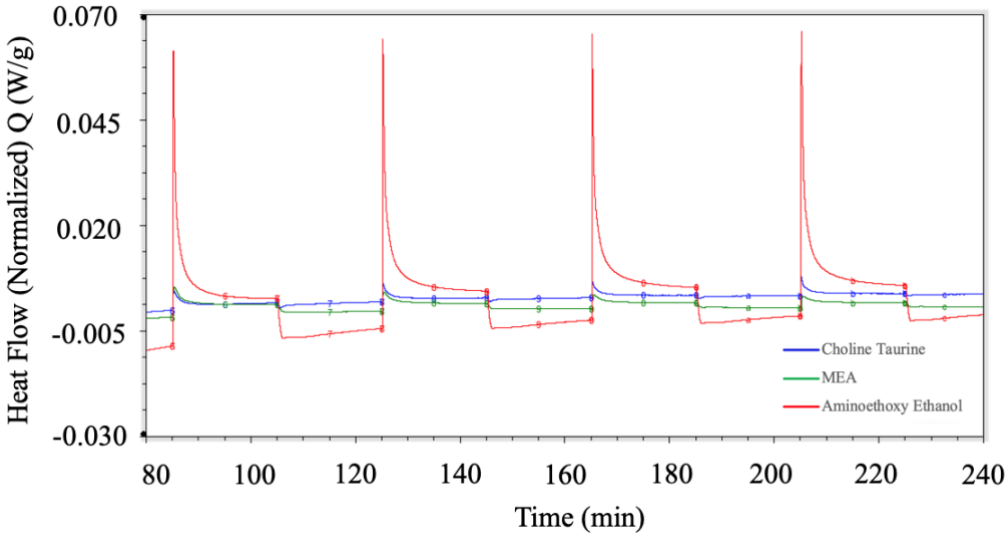

Figure 20. shows relative rates of absorption for choline taurinate, MEA, and ethoxy ethanol at 35°C.

The rates of absorption for these three compounds are very comparable. The time it takes for the absorption peaks and the desorption downward peaks to flatten is similar for all three compounds. At 20°C, the heat of absorption is also very close for each compound as well. Each

solution was within a height difference of 14% for 35°C, and 9% for 20°C. This shows that ionic amines possess very similar qualities compared to other common amine solutions for the rate of the absorption and desorption process.

CHAPTER IV

CONCLUSIONS

The current method of carbon dioxide removal on the International Space Station is insufficient for future goals. The solid zeolite adsorbent currently used produces dust and is too sensitive to humidity, causing extra down time of the system to do maintenance and clean up. Aqueous amine solutions do a great job of removing carbon dioxide in flue gas streams from combustion columns, but are too unsafe for confined environments due to their volatility and corrosion. Aqueous solutions of ionic amines have shown to be a promising solution for all these problems because they readily absorb CO_2 without possessing the volatility and corrosion that aqueous amine solutions do, and they do not produce dust or are humidity sensitive. The data taken for this project shows that these aqueous solutions of ionic amines are an excellent solution for air revitalization in confined environments compared to monoethanolamine.

Knowing the heat capacities of these solution is an essential piece in determining the energetics for a carbon dioxide removal and solvent regeneration process. Because these solutions must be heated and cooled to complete the uptake and release of CO_2, the heat capacity represents the largest energy requirement of the system. Just adding 20% ionic amine to a water solution decreases the heat capacity significantly. Adding more of the ionic amine causes the heat capacity to decrease linearly. Each compound experienced the same trend for the effect of temperature on heat capacity; as temperature increased, so did the heat capacity. For solutions with higher water content, raising the temperature caused water to vaporize and increase the pressure inside the pan to the point where leaks were made. This usually began between 60°C-70°C.

The rate of absorption for aqueous solutions of ionic amines is analogous to that of aqueous amine solutions such as MEA. Even for 30% solution, the aqueous ionic amine solution absorbed the maximum amount of CO_2 at a rate very close to that of MEA and ethoxy ethanol. The desorption rate was also just as similar. Using the density to calculate the film layer based on the mass of solution used, these results confirm the height of the compound had little effect on the rate. This shows that aqueous anionic amine solutions hold comparable rate qualities to other common amine solutions. Having a fast rate of absorption provides safer conditions for confined environments because this property ensures that an increase in carbon dioxide concentration would equally increase the rate of carbon dioxide removal, given an appropriate mass of solution for absorption was provided.

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APPENDICES

Appendix A: Melting Point

	Choline Taurinate Temperature (°C)	TMN Taurinate Temperature (°C)
	56.77	103.21
	57.58	104.52
	57.68	103.94
	57.55	102.81
	57.5	104.25
	57.38	102.8
	57.48	102.61
	57.45	
Average	57.42375	103.4485714
Standard Deviation	0.279025728	0.776775999

Table A.1 Melting point values for choline taurinate and tetramethylammonium taurinate

Appendix B: Heat Capacity

Temperature	Heat Capacity (Normalized)	Heat Capacity (Normalized)	Heat Capacity (Normalized)	Heat Capacity (Normalized)	Heat Capacity (Normalized)	Heat Capacity (Normalized)	Heat Capacity (Normalized)	Heat Capacity (Normalized)	Heat Capacity (Normalized)	Average	Standard Deviation	Objective Function	Model
°C	J/(g.°C)	J/(g.°C)	J/(g.°C)	J/(g.°C)	J/(g.°C)	J/(g.°C)	J/(g.°C)	J/(g.°C)	J/(g.°C)				
0		3.526	3.523	3.981	3.889	3.45	4.35	3.074	3.075	3.6085	0.44349424	0.18852989	3.41997011
5		3.527	3.527	3.505	3.5	3.454	3.171	3.083	3.076	3.355375	0.20638863	-0.0649155	3.42029049
10		3.551	3.549	3.464	3.478	3.476	3.133	3.096	3.087	3.35425	0.20904118	-0.0670016	3.42125162
15		3.571	3.573	3.47	3.487	3.499	3.133	3.114	3.103	3.36875	0.2121056	-0.0541035	3.42285351
20		3.593	3.595	3.484	3.504	3.522	3.148	3.129	3.119	3.38675	0.21465304	-0.0383462	3.42509615
25		3.618	3.62	3.503	3.524	3.544	3.164	3.14	3.13	3.405375	0.21993826	-0.0226045	3.42797955
30		3.636	3.639	3.522	3.541	3.566	3.175	3.149	3.142	3.42125	0.22415412	-0.0102537	3.4315037
35		3.66	3.663	3.539	3.56	3.588	3.19	3.157	3.154	3.438875	0.2294742	0.00320639	3.43566861
40		3.681	3.685	3.557	3.579	3.609	3.203	3.162	3.162	3.45475	0.23563698	0.01427573	3.44047427
45		3.699	3.703	3.571	3.593	3.627	3.213	3.161	3.168	3.466875	0.24182782	0.02095432	3.44592068
50		3.718	3.728	3.589	3.611	3.649	3.222	3.16	3.171	3.481	0.25076682	0.02899214	3.45200786
55		3.733	3.742	3.595	3.623	3.667	3.227	3.15	3.169	3.48825	0.25922453	0.02951422	3.45873578
60		3.749	3.759	3.582	3.637	3.685	3.235	3.135	3.167	3.493625	0.26801223	0.02752054	3.46610446
65		3.761	3.776	3.404	3.648	3.702	3.231	3.094	3.15	3.47075	0.28512491	-0.0033639	3.4741139
70		3.768	3.788	3.17	3.652	3.719	3.208	3.013	3.125	3.430375	0.32928708	-0.0523891	3.48276409

Table B.1 Heat capacity data for 20% solution of choline taurinate.

Temperature	Heat Capacity (Normalized)	Heat Capacity (Normalized)	Heat Capacity (Normalized)	Heat Capacity (Normalized)	Heat Capacity (Normalized)	Heat Capacity (Normalized)	Heat Capacity (Normalized)	Heat Capacity (Normalized)	Heat Capacity (Normalized)	Average	Standard Deviation	Objective Function	Model
°C	J/(g.°C)	J/(g.°C)	J/(g.°C)	J/(g.°C)	J/(g.°C)	J/(g.°C)	J/(g.°C)	J/(g.°C)	J/(g.°C)				
0	2.805	2.805	2.805	2.897	2.923	2.929	2.618	2.616	2.617	2.77944444	0.13130129	-0.0246057	2.80405013
5	2.841	2.839	2.838	2.926	2.953	2.961	2.644	2.643	2.644	2.80988889	0.13336645	-0.0174606	2.82734947
10	2.877	2.873	2.872	2.955	2.986	2.995	2.673	2.672	2.674	2.84188889	0.1349467	-0.0087599	2.85064882
15	2.908	2.91	2.91	2.987	3.017	3.026	2.701	2.702	2.702	2.87366667	0.13654944	-0.0002815	2.87394817
20	2.94	2.941	2.941	3.016	3.045	3.056	2.728	2.73	2.729	2.90288889	0.13758129	0.00564137	2.89724751
25	2.971	2.974	2.972	3.044	3.075	3.086	2.755	2.753	2.754	2.93155556	0.13993133	0.01100869	2.92054686
30	2.998	3.004	3.003	3.067	3.104	3.114	2.778	2.776	2.777	2.95788889	0.14210862	0.01404268	2.94384621
35	3.028	3.034	3.035	3.09	3.137	3.145	2.803	2.798	2.801	2.98566667	0.14509652	0.01852111	2.96714556
40	3.045	3.064	3.064	3.109	3.164	3.174	2.824	2.817	2.821	3.00911111	0.1479142	0.01866621	2.9904449
45	3.059	3.094	3.092	3.125	3.192	3.203	2.843	2.834	2.838	3.03111111	0.15174687	0.01736686	3.01374425
50	3.07	3.122	3.122	3.14	3.221	3.233	2.863	2.849	2.853	3.05255556	0.1564122	0.01551196	3.0370436
55	3.085	3.147	3.146	3.15	3.247	3.257	2.893	2.863	2.861	3.07211111	0.15907816	0.01176817	3.06034294
60	3.077	3.173	3.173	3.152	3.269	3.28	2.902	2.873	2.867	3.08511111	0.16502988	0.00146882	3.08364229
65	3.052	3.196	3.2	3.133	3.294	3.306	2.911	2.872	2.851	3.09055556	0.17733592	-0.0163861	3.10694164
70	2.984	3.221	3.226	3.07	3.318	3.33	2.925	2.863	2.817	3.08377778	0.19679036	-0.0464632	3.13024099

Table B.2 Heat capacity data for 40% solution of choline taurinate.

Temperature	Heat Capacity (Normalized)	Heat Capacity (Normalized)	Heat Capacity (Normalized)	Heat Capacity (Normalized)	Heat Capacity (Normalized)	Heat Capacity (Normalized)	Heat Capacity (Normalized)	Heat Capacity (Normalized)	Heat Capacity (Normalized)	Average	Standard Deviation	Objective Function	Model
°C	J/(g.°C)	J/(g.°C)	J/(g.°C)	J/(g.°C)	J/(g.°C)	J/(g.°C)	J/(g.°C)	J/(g.°C)	J/(g.°C)				
0	2.31	2.305	2.301	2.338	2.348	2.351	2.377	2.203	2.208	2.30455556	0.06132926	-0.0146855	2.31924108
5	2.343	2.339	2.334	2.375	2.386	2.388	2.412	2.23	2.235	2.338	0.0651575	-0.0093453	2.34734526
10	2.376	2.372	2.369	2.41	2.42	2.424	2.448	2.258	2.263	2.37111111	0.0681202	-0.0043383	2.37544944
15	2.409	2.405	2.401	2.444	2.457	2.459	2.483	2.286	2.291	2.40388889	0.07106589	0.00033527	2.40355362
20	2.441	2.436	2.432	2.48	2.491	2.494	2.517	2.312	2.317	2.43555556	0.0745505	0.00389776	2.4316578
25	2.469	2.468	2.463	2.512	2.527	2.531	2.551	2.339	2.343	2.467	0.0779086	0.00723802	2.45976198
30	2.499	2.496	2.493	2.545	2.559	2.561	2.585	2.363	2.366	2.49633333	0.08148773	0.00846717	2.48786616
35	2.527	2.525	2.522	2.579	2.595	2.596	2.619	2.387	2.39	2.52666667	0.08584142	0.01069633	2.51597034
40	2.555	2.552	2.551	2.611	2.625	2.629	2.651	2.408	2.412	2.55488889	0.09000756	0.01081437	2.54407452
45	2.582	2.578	2.577	2.641	2.654	2.659	2.682	2.427	2.43	2.58111111	0.09470803	0.00893241	2.5721787
50	2.605	2.605	2.603	2.672	2.684	2.689	2.714	2.446	2.448	2.60733333	0.09971961	0.00705045	2.60028288
55	2.626	2.628	2.629	2.701	2.709	2.716	2.74	2.462	2.464	2.63055556	0.10402898	0.00216849	2.62838706
60	2.645	2.653	2.652	2.727	2.735	2.746	2.769	2.477	2.478	2.65355556	0.10952638	-0.0029357	2.65649124
65	2.663	2.676	2.677	2.757	2.759	2.775	2.799	2.485	2.485	2.67511111	0.11805978	-0.0094843	2.68459543
70	2.675	2.696	2.7	2.782	2.78	2.802	2.824	2.494	2.492	2.69388889	0.12495444	-0.0188107	2.71269961

Table B.3 Heat capacity data for 60% solution of choline taurinate.

Temperature	Heat Capacity (Normalized)	Heat Capacity (Normalized)	Heat Capacity (Normalized)	Heat Capacity (Normalized)	Heat Capacity (Normalized)	Heat Capacity (Normalized)	Heat Capacity (Normalized)	Heat Capacity (Normalized)	Heat Capacity (Normalized)	Average	Standard Deviation	Objective Function	Model
°C	J/(g.°C)	J/(g.°C)	J/(g.°C)	J/(g.°C)	J/(g.°C)	J/(g.°C)	J/(g.°C)	J/(g.°C)	J/(g.°C)				
0	2.896	2.92	2.924	3.064	2.84	3.044	2.919	2.945	2.855	2.93411111	0.07596289	0.03281934	2.90129177
5	2.927	2.95	2.954	2.823	2.835	2.866	2.955	2.989	2.9	2.911	0.05842944	-0.014616	2.92561603
10	2.956	2.984	2.986	2.816	2.85	2.865	2.986	3.035	2.948	2.93622222	0.07457006	-0.0139665	2.9501887
15	2.984	3.014	3.018	2.831	2.866	2.881	3.018	3.077	2.991	2.96444444	0.08397189	-0.0105654	2.97500979
20	3.009	3.043	3.047	2.85	2.885	2.898	3.047	3.114	3.037	2.99222222	0.09103403	-0.0078571	3.0000793
25	3.033	3.069	3.073	2.871	2.906	2.919	3.078	3.152	3.077	3.01977778	0.09670416	-0.0056194	3.02539722
30	3.058	3.094	3.099	2.893	2.929	2.94	3.105	3.198	3.121	3.04855556	0.1035267	-0.002408	3.05096356
35	3.082	3.121	3.124	2.916	2.953	2.964	3.133	3.25	3.166	3.07877778	0.11135167	0.00199946	3.07677831
40	3.103	3.144	3.149	2.942	2.98	2.99	3.157	3.299	3.207	3.10788889	0.1170197	0.00504741	3.10284148
45	3.122	3.165	3.17	2.971	3.003	3.014	3.182	3.352	3.248	3.13633333	0.12415011	0.00718027	3.12915307
50	3.138	3.188	3.196	2.997	3.029	3.039	3.206	3.403	3.289	3.165	0.13158457	0.00928693	3.15571307
55	3.149	3.206	3.213	3.025	3.051	3.063	3.223	3.461	3.331	3.19133333	0.14121615	0.00881185	3.18252148
60	3.157	3.226	3.234	3.048	3.077	3.087	3.235	3.523	3.374	3.21788889	0.15314735	0.00831057	3.20957832
65	3.152	3.244	3.255	3.063	3.101	3.114	3.232	3.575	3.417	3.23922222	0.16512251	0.00233866	3.23688356
70	3.109	3.262	3.274	3.03	3.124	3.137	3.168	3.623	3.466	3.24366667	0.19032669	-0.0207706	3.26443723

Table B.4 Heat capacity data for 20% solution of tetramethylammonium taurinate.

Temperature	Heat Capacity (Normalized)	Heat Capacity (Normalized)	Heat Capacity (Normalized)	Heat Capacity (Normalized)	Heat Capacity (Normalized)	Heat Capacity (Normalized)	Heat Capacity (Normalized)	Heat Capacity (Normalized)	Heat Capacity (Normalized)	Average	Standard Deviation	Objective Function	Model
°C	J/(g.°C)	J/(g.°C)	J/(g.°C)	J/(g.°C)	J/(g.°C)	J/(g.°C)	J/(g.°C)	J/(g.°C)	J/(g.°C)				
0	2.812	2.593	2.727	2.523	2.522	2.525	2.599	2.623	2.628	2.61688889	0.09842947	0.02432757	2.59256132
5	2.595	2.558	2.576	2.552	2.552	2.555	2.626	2.649	2.655	2.59088889	0.04235695	-0.0183499	2.60923881
10	2.582	2.566	2.572	2.578	2.581	2.582	2.652	2.676	2.679	2.60755556	0.04695772	-0.0183607	2.62591629
15	2.595	2.579	2.586	2.605	2.607	2.607	2.68	2.705	2.707	2.63011111	0.05183976	-0.0124827	2.64259377
20	2.608	2.594	2.601	2.631	2.63	2.632	2.707	2.732	2.732	2.65188889	0.05595857	-0.0073824	2.65927125
25	2.628	2.611	2.619	2.654	2.656	2.656	2.731	2.757	2.752	2.67377778	0.05742338	-0.002171	2.67594873
30	2.65	2.631	2.636	2.676	2.679	2.679	2.754	2.78	2.77	2.695	0.05788566	0.00237378	2.69262622
35	2.673	2.653	2.659	2.697	2.701	2.704	2.775	2.801	2.786	2.71655556	0.05634738	0.00725186	2.7093037
40	2.694	2.675	2.682	2.717	2.724	2.726	2.798	2.82	2.799	2.73722222	0.05461405	0.01124104	2.72598118
45	2.716	2.697	2.707	2.733	2.742	2.745	2.816	2.836	2.805	2.75522222	0.05089641	0.01256356	2.74265866
50	2.852	2.719	2.73	2.745	2.762	2.766	2.835	2.85	2.81	2.78544444	0.05209153	0.0261083	2.75933615
55	2.764	2.737	2.751	2.758	2.778	2.782	2.851	2.862	2.805	2.78755556	0.04375246	0.01154193	2.77601363
60	2.779	2.757	2.773	2.766	2.796	2.801	2.868	2.873	2.786	2.79988889	0.04233924	0.00719778	2.79269111
65	2.78	2.776	2.797	2.772	2.814	2.818	2.878	2.877	2.734	2.80511111	0.04798814	-0.0042575	2.80936859
70	2.689	2.791	2.821	2.775	2.83	2.833	2.891	2.88	2.568	2.78644444	0.10143238	-0.0396016	2.82604607

Table B.5 Heat capacity data for 40% solution of tetramethylammonium taurinate.

Temperature	Heat Capacity (Normalized)	Heat Capacity (Normalized)	Heat Capacity (Normalized)	Heat Capacity (Normalized)	Heat Capacity (Normalized)	Heat Capacity (Normalized)	Heat Capacity (Normalized)	Heat Capacity (Normalized)	Heat Capacity (Normalized)	Average	Standard Deviation	Objective Function	Model
°C	J/(g.°C)	J/(g.°C)	J/(g.°C)	J/(g.°C)	J/(g.°C)	J/(g.°C)	J/(g.°C)	J/(g.°C)	J/(g.°C)				
0	2.383	2.27	2.27	2.313	2.29	2.281	2.357	2.369	2.371	2.32266667	0.0470983	-0.0239561	2.34662274
5	2.418	2.303	2.306	2.341	2.32	2.311	2.38	2.39	2.393	2.35133333	0.04416447	-0.0160089	2.36734219
10	2.452	2.337	2.338	2.372	2.351	2.342	2.4	2.412	2.414	2.37977778	0.04142094	-0.0082839	2.38806163
15	2.485	2.368	2.37	2.402	2.382	2.372	2.42	2.43	2.433	2.40688889	0.03908786	-0.0018922	2.40878108
20	2.514	2.398	2.401	2.432	2.411	2.403	2.438	2.448	2.448	2.43255556	0.0365175	0.00305504	2.42950052
25	2.546	2.431	2.431	2.461	2.441	2.434	2.461	2.469	2.467	2.46011111	0.03578912	0.00989115	2.45021996
30	2.576	2.458	2.459	2.488	2.468	2.46	2.481	2.49	2.485	2.485	0.0364863	0.01406059	2.47093941
35	2.605	2.485	2.489	2.517	2.495	2.487	2.502	2.509	2.498	2.50966667	0.03725252	0.01800782	2.49165885
40	2.635	2.515	2.516	2.542	2.521	2.514	2.516	2.521	2.507	2.53188889	0.03984484	0.01951059	2.5123783
45	2.664	2.543	2.541	2.563	2.544	2.538	2.528	2.53	2.51	2.55122222	0.04464521	0.01812448	2.53309774
50	2.693	2.567	2.568	2.588	2.566	2.559	2.54	2.535	2.509	2.56944444	0.05177623	0.01562726	2.55381718
55	2.731	2.59	2.591	2.61	2.587	2.58	2.549	2.532	2.501	2.58566667	0.06440885	0.01113004	2.57453663
60	2.805	2.615	2.612	2.633	2.608	2.603	2.555	2.518	2.483	2.60355556	0.09074705	0.00829948	2.59525607
65	2.772	2.639	2.637	2.647	2.624	2.619	2.563	2.458	2.454	2.60144444	0.09902665	-0.0145311	2.61597552
70	2.792	2.661	2.656	2.664	2.641	2.634	2.546	2.254	2.405	2.58366667	0.16159749	-0.0530283	2.63669496

Table B.6 Heat capacity data for 60% solution of tetramethylammonium taurinate.

Temperature	Heat Capacity (Normalized)	Heat Capacity (Normalized)	Heat Capacity (Normalized)	Heat Capacity (Normalized)	Heat Capacity (Normalized)	Heat Capacity (Normalized)	Heat Capacity (Normalized)	Heat Capacity (Normalized)	Heat Capacity (Normalized)	Average	Standard Deviation	Objective Function	Model
°C	J/(g.°C)	J/(g.°C)	J/(g.°C)	J/(g.°C)	J/(g.°C)	J/(g.°C)	J/(g.°C)	J/(g.°C)	J/(g.°C)				
0	4.907	4.472	4.636	6.602	6.916	5.455	4.233	3.982	3.94	5.01588889	1.09603575	1.71888148	3.29700741
5	3.335	3.308	3.409	3.319	3.31	3.341	3.267	3.242	3.253	3.30933333	0.05146601	0.01232593	3.29700741
10	3.228	3.245	3.35	3.298	3.286	3.332	3.235	3.224	3.237	3.27055556	0.04756604	-0.02645185	3.29700741
15	3.22	3.238	3.34	3.296	3.276	3.33	3.238	3.222	3.241	3.26677778	0.04584151	-0.03022963	3.29700741
20	3.231	3.24	3.334	3.306	3.27	3.34	3.25	3.228	3.25	3.27211111	0.04364185	-0.0248963	3.29700741
25	3.24	3.243	3.327	3.318	3.264	3.346	3.262	3.23	3.258	3.27644444	0.04246796	-0.02056296	3.29700741
30	3.25	3.238	3.31	3.334	3.259	3.353	3.272	3.229	3.263	3.27866667	0.04357178	-0.01834074	3.29700741
35	3.257	3.228	3.294	3.346	3.243	3.353	3.283	3.223	3.27	3.27744444	0.04714634	-0.01956296	3.29700741
40	3.264	3.213	3.267	3.358	3.22	3.344	3.292	3.21	3.271	3.271	0.05372383	-0.02600741	3.29700741
45	3.264	3.181	3.229	3.365	3.184	3.332	3.298	3.186	3.266	3.25611111	0.06710336	-0.0408963	3.29700741
50	3.257	3.137	3.149	3.365	3.134	3.313	3.302	3.146	3.254	3.22855556	0.08878782	-0.06845185	3.29700741
55	3.221	3.067	3.05	3.351	3.062	3.26	3.295	3.089	3.232	3.18077778	0.1146296	-0.11622963	3.29700741
60	3.131	2.968	2.868	3.245	2.954	3.161	3.249	3.003	3.196	3.08611111	0.14025017	-0.2108963	3.29700741
65	2.83	2.827	2.608	2.892	2.776	3.02	3.013	2.888	3.144	2.88866667	0.15677452	-0.40834074	3.29700741
70	2.278	2.664	2.159	2.347	2.52	2.838	2.558	2.745	3.081	2.57666667	0.29123959	-0.72034074	3.29700741

Table B.7 Heat capacity data for 20% solution of choline homotaurinate.

Temperature	Heat Capacity (Normalized)	Heat Capacity (Normalized)	Heat Capacity (Normalized)	Heat Capacity (Normalized)	Heat Capacity (Normalized)	Heat Capacity (Normalized)	Heat Capacity (Normalized)	Heat Capacity (Normalized)	Heat Capacity (Normalized)	Average	Standard Deviation	Objective Function	Model
°C	J/(g.°C)	J/(g.°C)	J/(g.°C)	J/(g.°C)	J/(g.°C)	J/(g.°C)	J/(g.°C)	J/(g.°C)	J/(g.°C)				
0	2.945	2.924	2.953	3.038	3.051	3.051	2.844	2.825	2.823	2.93933333	0.09408905	-0.02168701	2.96102035
5	2.952	2.953	2.986	3.066	3.076	3.077	2.87	2.851	2.851	2.96466667	0.09409835	-0.0156386	2.98030527
10	2.977	2.982	3.016	3.097	3.102	3.102	2.895	2.873	2.874	2.99088889	0.09592242	-0.0087013	2.99959019
15	3.004	3.007	3.045	3.126	3.125	3.125	2.919	2.895	2.898	3.016	0.0967613	-0.00287511	3.01887511
20	3.033	3.031	3.072	3.156	3.147	3.147	2.943	2.915	2.917	3.04011111	0.09853355	0.00195108	3.03816003
25	3.061	3.056	3.096	3.189	3.171	3.173	2.969	2.939	2.938	3.06577778	0.10034288	0.00833283	3.05744495
30	3.085	3.075	3.122	3.229	3.194	3.195	2.994	2.961	2.956	3.09011111	0.10383213	0.01338124	3.07672987
35	3.112	3.099	3.145	3.262	3.218	3.218	3.018	2.981	2.974	3.11411111	0.10678886	0.01809632	3.09601479
40	3.136	3.118	3.166	3.297	3.239	3.241	3.036	2.998	2.989	3.13555556	0.11148443	0.02025584	3.11529971
45	3.155	3.133	3.183	3.326	3.259	3.259	3.053	3.012	3.002	3.15355556	0.11531707	0.01897092	3.13458463
50	3.175	3.15	3.205	3.356	3.281	3.276	3.068	3.026	3.012	3.17211111	0.12034684	0.01824156	3.15386955
55	3.182	3.164	3.217	3.38	3.299	3.292	3.077	3.035	3.017	3.18477778	0.12566401	0.0116233	3.17315447
60	3.176	3.175	3.232	3.402	3.317	3.309	3.084	3.044	3.018	3.19522222	0.13196096	0.00278283	3.19243939
65	3.117	3.183	3.245	3.424	3.329	3.324	3.086	3.048	3.014	3.19666667	0.14229898	-0.01505765	3.21172431
70	2.963	3.188	3.252	3.441	3.34	3.333	3.075	3.04	3	3.18133333	0.17046847	-0.0496759	3.23100924

Table B.8 Heat capacity data for 40% solution of choline homotaurinate.

Temperature	Heat Capacity (Normalized)	Heat Capacity (Normalized)	Heat Capacity (Normalized)	Heat Capacity (Normalized)	Heat Capacity (Normalized)	Heat Capacity (Normalized)	Heat Capacity (Normalized)	Heat Capacity (Normalized)	Heat Capacity (Normalized)	Average	Standard Deviation	Objective Function	Model
°C	J/(g.°C)	J/(g.°C)	J/(g.°C)	J/(g.°C)	J/(g.°C)	J/(g.°C)	J/(g.°C)	J/(g.°C)	J/(g.°C)				
0	2.496	2.489	2.497	2.691	2.701	2.7	2.635	2.655	2.631	2.61055556	0.09112918	-0.02603513	2.63659068
5	2.533	2.523	2.531	2.725	2.735	2.731	2.658	2.664	2.653	2.63922222	0.08846861	-0.019501	2.65872322
10	2.572	2.557	2.565	2.764	2.767	2.766	2.683	2.684	2.679	2.67077778	0.08753539	-0.01007799	2.68085576
15	2.613	2.591	2.6	2.798	2.8	2.8	2.705	2.707	2.7	2.70155556	0.08595509	-0.00143275	2.7029883
20	2.655	2.627	2.636	2.834	2.829	2.83	2.725	2.73	2.719	2.73166667	0.08352245	0.00654582	2.72512084
25	2.695	2.66	2.668	2.866	2.862	2.861	2.742	2.748	2.735	2.75966667	0.08338315	0.01241328	2.74725338
30	2.736	2.694	2.702	2.9	2.889	2.89	2.757	2.767	2.745	2.78666667	0.08315648	0.01728074	2.76938592
35	2.778	2.727	2.736	2.932	2.919	2.922	2.772	2.78	2.751	2.813	0.08547076	0.02148154	2.79151846
40	2.82	2.759	2.766	2.962	2.944	2.945	2.786	2.792	2.75	2.836	0.08827372	0.022349	2.813651
45	2.854	2.787	2.794	2.989	2.968	2.966	2.794	2.798	2.743	2.85477778	0.09414454	0.01899424	2.83578354
50	2.885	2.817	2.824	3.015	2.994	2.994	2.803	2.804	2.729	2.87388889	0.10339058	0.01597281	2.85791608
55	2.912	2.844	2.85	3.038	3.016	3.014	2.805	2.801	2.704	2.88711111	0.1156627	0.00706249	2.88004862
60	2.941	2.872	2.876	3.06	3.038	3.036	2.805	2.794	2.672	2.89933333	0.13153992	-0.00284783	2.90218116
65	2.963	2.9	2.903	3.08	3.062	3.059	2.793	2.767	2.616	2.90477778	0.1571192	-0.01953592	2.9243137
70	2.988	2.928	2.929	3.1	3.084	3.082	2.769	2.715	2.539	2.90377778	0.19297913	-0.04266846	2.94644624

Table B.9 Heat capacity data for 60% solution of choline homotaurinate.

Temperature	Heat Capacity (Normalized)	Heat Capacity (Normalized)	Heat Capacity (Normalized)	Heat Capacity (Normalized)	Heat Capacity (Normalized)	Heat Capacity (Normalized)	Heat Capacity (Normalized)	Heat Capacity (Normalized)	Heat Capacity (Normalized)	Average	Standard Deviation	Objective Function	Model
°C	J/(g.°C)	J/(g.°C)	J/(g.°C)	J/(g.°C)	J/(g.°C)	J/(g.°C)	J/(g.°C)	J/(g.°C)	J/(g.°C)				
0	4.752	4.488	4.404	4.564	4.347	4.181	2.967	3.025	3.045	3.97477778	0.738422606	0.94140741	3.03337037
5	3.091	3.034	3.056	3.131	3.1	3.124	2.968	3.052	3.07	3.06955556	0.050244679	0.03618519	3.03337037
10	2.917	2.9	2.956	3.016	3.01	3.06	2.98	3.079	3.101	3.00211111	0.070341034	-0.0312593	3.03337037
15	2.904	2.886	2.947	3.008	2.999	3.057	3.002	3.108	3.129	3.00444444	0.084013557	-0.0289259	3.03337037
20	2.909	2.883	2.958	3.016	3.002	3.068	3.02	3.134	3.156	3.01622222	0.092831538	-0.0171481	3.03337037
25	2.919	2.876	2.965	3.025	3.004	3.08	3.036	3.16	3.18	3.02722222	0.101753105	-0.0061481	3.03337037
30	2.927	2.865	2.972	3.036	3.002	3.088	3.049	3.182	3.204	3.03611111	0.11112318	0.00274075	3.03337037
35	2.934	2.845	2.979	3.045	2.995	3.097	3.063	3.203	3.225	3.04288889	0.122233838	0.00951852	3.03337037
40	2.94	2.817	2.982	3.051	2.98	3.102	3.072	3.224	3.245	3.04588889	0.135670045	0.01251852	3.03337037
45	2.946	2.771	2.977	3.053	2.954	3.1	3.07	3.241	3.261	3.04144444	0.152665575	0.00807408	3.03337037
50	2.949	2.709	2.967	3.05	2.913	3.097	3.036	3.257	3.28	3.02866667	0.175427335	-0.0047037	3.03337037
55	2.943	2.603	2.943	3.02	2.85	3.082	2.857	3.272	3.293	2.98477778	0.215617588	-0.0485926	3.03337037
60	2.906	2.45	2.901	2.935	2.76	3.06	2.51	3.285	3.306	2.90144444	0.298769188	-0.1319259	3.03337037
65	2.717	2.219	2.843	2.645	2.649	3.024	2.118	3.286	3.308	2.75655556	0.416187791	-0.2768148	3.03337037
70	2.348	1.862	2.763	2.184	2.525	2.978	1.863	3.286	3.307	2.56844444	0.55463211	-0.4649259	3.03337037

Table B.10 Heat capacity data for 20% solution of choline n-methylhomotaurinate.

Temperature	Heat Capacity (Normalized)	Heat Capacity (Normalized)	Heat Capacity (Normalized)	Heat Capacity (Normalized)	Heat Capacity (Normalized)	Heat Capacity (Normalized)	Heat Capacity (Normalized)	Heat Capacity (Normalized)	Heat Capacity (Normalized)	Average	Standard Deviation	Objective Function	Model
°C	J/(g.°C)	J/(g.°C)	J/(g.°C)	J/(g.°C)	J/(g.°C)	J/(g.°C)	J/(g.°C)	J/(g.°C)	J/(g.°C)				
0	2.649	2.666	2.671	2.415	2.432	2.734	2.481	2.47	2.46	2.55311111	0.124034717	-0.0303915	2.58350256
5	2.678	2.693	2.697	2.434	2.452	2.76	2.505	2.496	2.485	2.57777778	0.126403894	-0.0210498	2.59882756
10	2.698	2.72	2.726	2.457	2.472	2.787	2.532	2.521	2.511	2.60266667	0.127673411	-0.0114859	2.61415256
15	2.723	2.748	2.755	2.475	2.492	2.812	2.559	2.544	2.538	2.62733333	0.130013461	-0.0021442	2.62947756
20	2.747	2.774	2.777	2.494	2.511	2.834	2.584	2.569	2.562	2.65022222	0.130904333	0.00541966	2.64480256
25	2.771	2.8	2.801	2.515	2.531	2.853	2.607	2.591	2.585	2.67266667	0.131561773	0.0125391	2.66012756
30	2.79	2.82	2.821	2.539	2.557	2.869	2.629	2.61	2.605	2.69333333	0.129343535	0.01788077	2.67545256
35	2.809	2.839	2.841	2.563	2.581	2.881	2.654	2.628	2.627	2.71366667	0.12635367	0.0228891	2.69077756
40	2.826	2.854	2.858	2.581	2.601	2.891	2.677	2.645	2.646	2.731	0.123905206	0.02489744	2.70610256
45	2.84	2.865	2.873	2.599	2.616	2.892	2.696	2.658	2.662	2.74455556	0.120536417	0.02312799	2.72142756
50	2.852	2.876	2.886	2.612	2.633	2.892	2.716	2.671	2.678	2.75733333	0.117137739	0.02058077	2.73675256
55	2.864	2.883	2.895	2.627	2.646	2.884	2.735	2.681	2.691	2.76733333	0.112568868	0.01525577	2.75207756
60	2.862	2.883	2.904	2.64	2.659	2.871	2.755	2.69	2.703	2.77411111	0.10581404	0.00670855	2.76740256
65	2.813	2.86	2.902	2.652	2.672	2.829	2.768	2.694	2.708	2.76644444	0.089367375	-0.0162831	2.78272756
70	2.743	2.691	2.897	2.663	2.681	2.702	2.782	2.698	2.714	2.73011111	0.07179562	-0.0679415	2.79805256

Table B.11 Heat capacity data for 40% solution of choline n-methylhomotaurinate.

Temperature	Heat Capacity (Normalized)	Heat Capacity (Normalized)	Heat Capacity (Normalized)	Heat Capacity (Normalized)	Heat Capacity (Normalized)	Heat Capacity (Normalized)	Heat Capacity (Normalized)	Heat Capacity (Normalized)	Heat Capacity (Normalized)	Average	Standard Deviation	Objective Function	Model
°C	J/(g.°C)	J/(g.°C)	J/(g.°C)	J/(g.°C)	J/(g.°C)	J/(g.°C)	J/(g.°C)	J/(g.°C)	J/(g.°C)				
0	2.271	2.269	2.269	2.251	2.257	2.257	2.182	2.208	2.205	2.241	0.033440245	-0.0174176	2.25841757
5	2.297	2.297	2.297	2.279	2.282	2.284	2.207	2.234	2.233	2.26777778	0.033907144	-0.0126521	2.28042987
10	2.329	2.329	2.329	2.306	2.308	2.311	2.234	2.26	2.258	2.296	0.03591657	-0.0064422	2.30244217
15	2.361	2.357	2.357	2.332	2.338	2.338	2.261	2.287	2.286	2.32411111	0.036716633	-0.0003434	2.32445448
20	2.391	2.383	2.383	2.359	2.362	2.364	2.287	2.313	2.311	2.35033333	0.037312866	0.00386656	2.34646678
25	2.422	2.412	2.412	2.384	2.386	2.389	2.312	2.339	2.336	2.37688889	0.038889087	0.00840981	2.36847908
30	2.452	2.435	2.435	2.408	2.412	2.413	2.334	2.359	2.358	2.40066667	0.040816663	0.01017529	2.39049138
35	2.484	2.459	2.459	2.431	2.437	2.436	2.357	2.385	2.383	2.42566667	0.041949374	0.01316298	2.41250368
40	2.511	2.482	2.482	2.455	2.459	2.459	2.38	2.407	2.403	2.44866667	0.043153795	0.01415068	2.43451598
45	2.541	2.504	2.504	2.474	2.479	2.479	2.401	2.424	2.422	2.46977778	0.045704972	0.01324949	2.45652829
50	2.568	2.523	2.523	2.493	2.497	2.498	2.421	2.441	2.439	2.48922222	0.047620315	0.01068163	2.47854059
55	2.589	2.542	2.542	2.507	2.515	2.515	2.44	2.457	2.454	2.50677778	0.048861482	0.00622489	2.50055289
60	2.606	2.558	2.558	2.523	2.532	2.534	2.46	2.471	2.467	2.52322222	0.049180224	0.00065703	2.52256519
65	2.609	2.567	2.567	2.537	2.547	2.547	2.473	2.482	2.461	2.53222222	0.049844202	-0.0123553	2.54457749
70	2.608	2.572	2.572	2.549	2.56	2.562	2.486	2.491	2.417	2.53522222	0.059031301	-0.0313676	2.56658979

Table B.12 Heat capacity data for 60% solution of choline n-methylhomotaurinate.

Temperature	Heat Capacity (Normalized)	Heat Capacity (Normalized)	Heat Capacity (Normalized)	Heat Capacity (Normalized)	Heat Capacity (Normalized)	Heat Capacity (Normalized)	Heat Capacity (Normalized)	Heat Capacity (Normalized)	Heat Capacity (Normalized)	Average	Standard Deviation	Objective Function	Model
°C	J/(g.°C)	J/(g.°C)	J/(g.°C)	J/(g.°C)	J/(g.°C)	J/(g.°C)	J/(g.°C)	J/(g.°C)	J/(g.°C)				
0	2.838	2.804	2.811	3.034	3.096	3.162	4.13	4.047	4.024	3.327333	0.569469	0.343135	2.984199
5	2.847	2.807	2.83	3.043	3.109	3.181	3.037	3.025	3.026	2.989444	0.131204	-0.004286	2.99373
10	2.865	2.824	2.851	3.064	3.129	3.209	2.992	2.985	2.991	2.99	0.130043	-0.013262	3.003262
15	2.884	2.84	2.87	3.088	3.154	3.234	2.987	2.978	2.991	3.002889	0.133618	-0.009904	3.012793
20	2.9	2.855	2.885	3.108	3.169	3.259	2.995	2.983	3.001	3.017222	0.136566	-0.005103	3.022325
25	2.912	2.865	2.897	3.124	3.184	3.276	3.004	2.985	3.011	3.028667	0.139173	-0.00319	3.031856
30	2.924	2.874	2.905	3.137	3.195	3.294	3.012	2.984	3.021	3.038444	0.142059	-0.002943	3.041388
35	2.932	2.887	2.919	3.145	3.211	3.313	3.019	2.983	3.029	3.048667	0.14476	-0.002253	3.050919
40	2.94	2.899	2.932	3.156	3.224	3.335	3.023	2.976	3.032	3.057444	0.148993	-0.003006	3.060451
45	2.946	2.911	2.944	3.171	3.236	3.354	3.021	2.96	3.032	3.063889	0.154335	-0.006094	3.069982
50	2.952	2.922	2.959	3.191	3.25	3.373	3.005	2.934	3.031	3.068556	0.162489	-0.010958	3.079514
55	2.932	2.935	2.978	3.209	3.255	3.389	2.944	2.885	3.02	3.060778	0.17779	-0.028268	3.089046
60	2.877	2.955	3.001	3.23	3.25	3.407	2.786	2.821	3.004	3.036778	0.213273	-0.061799	3.098577
65	2.76	2.971	3.023	3.265	3.098	3.415	2.485	2.732	2.972	2.969	0.282889	-0.139109	3.108109
70	2.402	3.075	3.142	3.3	2.805	3.47	2.007	2.651	2.934	2.865111	0.458362	-0.252529	3.11764

Table B.13 Heat capacity data for 20% solution of tetramethylammonium n-isopropylhomotaurinate.

Temperature	Heat Capacity (Normalized)	Heat Capacity (Normalized)	Heat Capacity (Normalized)	Heat Capacity (Normalized)	Heat Capacity (Normalized)	Heat Capacity (Normalized)	Heat Capacity (Normalized)	Heat Capacity (Normalized)	Heat Capacity (Normalized)	Heat Capacity (Normalized)	Average	Standard Deviation	Objective Function	Model
°C	J/(g.°C)	J/(g.°C)	J/(g.°C)	J/(g.°C)	J/(g.°C)	J/(g.°C)	J/(g.°C)	J/(g.°C)	J/(g.°C)	J/(g.°C)				
0	2.415	2.583	2.587	2.591	2.445	2.53	2.576	2.415	2.423	2.427	2.507222	0.080893	0.010873	2.496349
5	2.438	2.609	2.614	2.618	2.468	2.551	2.601	2.438	2.447	2.452	2.531556	0.082282	0.016815	2.51474
10	2.464	2.635	2.643	2.645	2.492	2.579	2.624	2.464	2.471	2.475	2.557444	0.083002	0.023606	2.533838
15	2.489	2.662	2.671	2.674	2.519	2.602	2.65	2.489	2.494	2.5	2.583333	0.084264	0.029691	2.553643
20	2.511	2.686	2.698	2.7	2.54	2.621	2.668	2.511	2.517	2.521	2.605778	0.085217	0.031624	2.574154
25	2.533	2.708	2.726	2.724	2.56	2.633	2.682	2.533	2.536	2.54	2.626111	0.086072	0.030739	2.595372
30	2.553	2.73	2.746	2.745	2.57	2.644	2.696	2.553	2.554	2.558	2.643444	0.087207	0.026148	2.617297
35	2.57	2.749	2.766	2.763	2.581	2.661	2.713	2.57	2.572	2.573	2.660556	0.088571	0.020628	2.639928
40	2.588	2.765	2.785	2.781	2.594	2.684	2.737	2.588	2.586	2.587	2.678667	0.090042	0.015401	2.663266
45	2.601	2.778	2.8	2.793	2.608	2.701	2.756	2.601	2.597	2.597	2.692778	0.090881	0.005467	2.687311
50	2.615	2.791	2.814	2.8	2.619	2.72	2.775	2.615	2.607	2.604	2.706222	0.091251	-0.00584	2.712062
55	2.625	2.793	2.824	2.8	2.618	2.736	2.791	2.625	2.612	2.607	2.713778	0.091932	-0.023743	2.73752
60	2.638	2.793	2.833	2.797	2.607	2.757	2.814	2.638	2.617	2.607	2.721556	0.094231	-0.04213	2.763685
65	2.642	2.78	2.833	2.782	2.581	2.772	2.831	2.642	2.613	2.596	2.719556	0.098852	-0.071001	2.790557
70	2.637	2.762	2.822	2.764	2.549	2.826	2.889	2.637	2.606	2.577	2.749857	0.118174	-0.068278	2.818135

Table B.14 Heat capacity data for 40% solution of tetramethylammonium n-isopropylhomotaurinate.

Temperature	Heat Capacity (Normalized)	Heat Capacity (Normalized)	Heat Capacity (Normalized)	Heat Capacity (Normalized)	Heat Capacity (Normalized)	Heat Capacity (Normalized)	Heat Capacity (Normalized)	Heat Capacity (Normalized)	Heat Capacity (Normalized)	Average	Standard Deviation	Objective Function	Model
°C	J/(g.°C)	J/(g.°C)	J/(g.°C)	J/(g.°C)	J/(g.°C)	J/(g.°C)	J/(g.°C)	J/(g.°C)	J/(g.°C)				
0	2.208	2.115	2.121	2.14	2.07	2.005	2.208	2.184	2.179	2.136667	0.067746	-0.00636	2.143027
5	2.23	2.134	2.146	2.165	2.094	2.028	2.234	2.209	2.204	2.160444	0.068363	-0.003432	2.163876
10	2.259	2.159	2.171	2.193	2.121	2.052	2.264	2.236	2.23	2.187222	0.069839	0.002182	2.185041
15	2.286	2.183	2.197	2.219	2.147	2.077	2.293	2.264	2.256	2.213556	0.070905	0.007036	2.20652
20	2.312	2.205	2.218	2.244	2.166	2.097	2.318	2.286	2.28	2.236222	0.072892	0.007908	2.228314
25	2.334	2.224	2.236	2.269	2.183	2.113	2.343	2.305	2.299	2.256222	0.075228	0.005799	2.250423
30	2.355	2.241	2.253	2.288	2.197	2.127	2.363	2.32	2.315	2.273222	0.077086	0.000375	2.272847
35	2.375	2.261	2.276	2.308	2.22	2.149	2.384	2.341	2.335	2.294333	0.076371	-0.001253	2.295586
40	2.393	2.286	2.297	2.327	2.246	2.175	2.403	2.367	2.363	2.317444	0.074542	-0.001196	2.31864
45	2.411	2.307	2.317	2.345	2.269	2.198	2.425	2.393	2.387	2.339111	0.074267	-0.002898	2.342009
50	2.431	2.326	2.336	2.37	2.292	2.218	2.451	2.415	2.411	2.361111	0.075463	-0.004582	2.365693
55	2.446	2.344	2.353	2.391	2.315	2.239	2.474	2.437	2.435	2.381556	0.075578	-0.008137	2.389692
60	2.468	2.366	2.371	2.416	2.344	2.266	2.502	2.469	2.465	2.407444	0.076534	-0.006561	2.414006
65	2.487	2.379	2.381	2.446	2.366	2.29	2.538	2.496	2.489	2.430222	0.080392	-0.008412	2.438635
70	2.5	2.419	2.415	2.472	2.44	2.367	2.574	2.589	2.572	2.483111	0.080524	0.019533	2.463578

Table B.15 Heat capacity data for 60% solution of tetramethylammonium n-isopropylhomotaurinate.

Appendix C: Heat of Absorption

	Mass Pure Compound (mg)	Required Mass of Water (mg)	Total Mass (mg)	Percent Amine
Choline Taurinate	2.77247	6.469096667	17.42671	30.098%
MEA	1.5791	3.684566667	15.39647	30.042%
Ethoxy ethanol	2.00467	4.677563333	16.79647	30.031%

Table C.1 Concentration of three amine solutions for heat of absorption runs.

		J/g	J/g	J/g	J/g	J/g	J/g	Average	Standard Deviation
Choline Taurinate	20°C	28.463	19.98	6.317	2.496	0.911	0.418	2.5355	2.672334123
Choline Taurinate	35°C	16.799	1.9789	0.989	0.68991	0.44834	0.5312	0.6646125	0.238355409
MEA	20°C	39.991	14.479	7.1527	4.16	3.239	2.559	4.277675	2.025858309
MEA	35°C	21.763	4.3987	2.2789	1.3835	1.119	0.915	1.4241	0.601276481
Ethoxy Ethanol	20°C	17.146	4.8668	3.19	2.5285	2.1679	1.9083	2.448675	0.555810078
Ethoxy Ethanol	35°C	40.705	13.217	9.7787	8.7714	8.6144	8.1241	8.82215	0.694741518

Table C.2 Enthalpy of absorption values analyzed by the DSC. Average and standard deviation are based off last four data points.

Choline Taurine	Mass Water (mg)	Mass Lost During Run (mg)	Mass Water Remaining (mg)	Mass of Amine (mg)	Percent Amine Concentration
20°C	14.3332	11.652	2.6812	6.1428	69.6147%
35°C	14.4858	12.314	2.1718	6.2082	74.0835%
Monoethanolamine					
20°C	14.7056	11.886	2.8196	6.3024	69.0901%
35°C	15.4686	12.616	2.8526	6.6294	69.9156%
Ethoxy Ethanol					
20°C	13.7102	11.104	2.6062	5.8758	69.2738%
35°C	13.8054	11.42	2.3854	5.9166	71.2672%

Table C.3 Percent amine concentration calculation for heat of absorption runs.

Appendix D: Rate of Absorption

	Average Mass of Sample (mg)		Density of Sample (g/cm3)		Volume of Sample (mm3)		Percent Difference	
	20°C	30°C	20°C	30°C	20°C	30°C	20°C	30°C
Choline Taurinate	14.65	14.537	1.061882	1.05074767	13.7963	13.8349	8.564%	13.748%
MEA	15.065	15.79	1.00582667	1.00336767	14.9777	15.7370	8.163%	12.387%
Ethoxy ethanol	14.034	14.012	1.02027333	1.01627433	13.7551	13.7876	8.888%	14.139%

Table D.1 Height variations in pans calculated using average mass before and after run and density found by the DSA 5000.