The effect of diffusion on the evaporation rate of liquid hydrocarbons using nanosediments in lakes on Titan

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The Effect of Diffusion on the Evaporation Rate of Liquid Hydrocarbons using Nanosediments in Lakes on Titan

An Undergraduate Honors College Thesis

in the

Department of Mechanical Engineering

College of Engineering
University of Arkansas
Fayetteville, AR

By

Tyler Scogin
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I. Acknowledgements

The author would like to thank multiple people for their assistance for this undergraduate research. Dr. Vincent Chevrier, Principal Investigator for the Titan research team within the Keck Laboratory at the Arkansas Center for Space and Planetary Sciences at the University of Arkansas has provided invaluable input and direction for the work in this thesis. The author would also like to thank Ph.D. graduate student Sunny Singh, physics professor Dr. Lin Oliver, the author’s physics advisor Dr. Gay Stewart, as well the author’s mechanical engineering advisor Dr. Larry Roe for their respective input and contributions.
II. Introduction

Titan is our solar system’s second largest moon and is Saturn’s largest moon. It is bigger than Earth’s moon and larger than the planet Mercury with a radius of 2,575 km (or 1,600 miles). It is also quite cold, with an average surface temperature of approximately -178 degrees Celsius (equivalent to -289 degrees Fahrenheit).\(^1\) Besides Earth itself, there is only one other known place in the solar system with an earthlike cycle of liquids flowing across the body’s surface – Titan. This is part of why Titan is of great interest to scientists.

In 1980 NASA’s Voyager 1 took some photographs of the moon but these images could not get past the thick hazy atmosphere. A few years later in 1994 the Hubble Space Telescope took some more mapping of surfaces according to their reflectivity, resulting in images of bright and dark areas that suggested a landmass potentially with seas, but still garnered no proof of such.\(^1\) Figure 1 below shows images of Titan taken from the Voyager 1 and the Hubble Space Telescope (HST).\(^2\)

![Image of Titan](image.png)

**Figure 1.** Left: Voyager 1 image in 1980, from 4.5 million km.\(^2\) Right: Hubble image in 1994.\(^3\)
The scientific community had no real useful data on Titan until 2004 when NASA’s Cassini-Huygens mission sparked much excitement with its new discoveries about Titan. The Cassini orbiter took spectral images to study the structure and complex organic chemistry of the hazy atmosphere on Titan. The European Space Agency (ESA) built the Huygens probe which landed on the surface of Titan in January 2005 and transmitted 3 hours and 44 minutes of data. From this data it was discovered that Titan hosts large methane lakes and areas of windy hydrocarbon sand dunes. Images of Titan from Cassini are shown in Figure 2a and Figure 2b below.

**Figure 2a.** Cassini’s Titan flyby in 2013.
With an atmosphere mostly composed of nitrogen at nearly the same pressure (1.5 bar for Titan compared to 1 bar for Earth), Titan has been described as a possible analog for a “frozen” prebiotic Earth.\textsuperscript{6} It is thought that the photochemistry occurring in the atmosphere of Titan resembles what may have occurred within the atmosphere of early Earth with a combination of gases including H\textsubscript{2}, CO\textsubscript{2}, and CH\textsubscript{4}.\textsuperscript{7} These atmospheric processes create nanoscale hydrocarbon agglomerations known as tholins. Tholins are complex organic aerosols created in Titan’s atmosphere at an altitude above 1,000 km by organic molecules like methane and nitrogen.\textsuperscript{8} After formation, they precipitate out and fall into the liquid lakes on Titan. The presence of these particles may affect the evaporation rates due to both physical and chemical interactions. The study of Titan could provide a noteworthy glimpse into the atmosphere of prebiotic Earth before the abundance of O\textsubscript{2} came about with the presence of life forms breathing the atmosphere. Titan also has an active “hydrological” cycle complete with rivers and lakes of methane and ethane, similar to water on Earth.\textsuperscript{1} This research also supports NASA’s Science Goals and Objectives

\textbf{Figure 2b.} Titan methane and ethane seas Kraken Mare and Ligeia Mare and lakes taken from Cassini data 2004 to 2013\textsuperscript{5}. 
Investigation 1.1 of the Titan Explorer Flagship Mission Study, which states *Determine the composition and transport of volatiles and condensates in the atmosphere and at the surface, including hydrocarbons and nitrates, on region and global scales, in order to understand the hydrocarbon cycle.* The study of various hydrocarbons’ interactions with nanosediment within lakes on the surface contributes to the study of Titan’s hydrocarbon cycle.

Since it seems that Titan may be an analog for a frozen prebiotic Earth, complete with these rivers and liquid methane and ethane cycle that parallel the role that water plays on Earth, substantial information could be gleaned from the study of Titan. This information could better our understanding of what Earth was like when it was much younger, and thus it may be possible to apply this knowledge to the present state of Earth in a way that is scientifically useful to life on Earth now.

### III. Objectives

The objective of this research is two-fold. With the goal to further the study of Titan’s hydrological cycle, the effect that nanosediment has on liquids found in Titan lakes is addressed. The focus of this thesis was to determine the effect of possible homogenous mixing or diffusion on the evaporation rate of hydrocarbons analogous to those found on Titan. Future experiments will determine the effect of viscosity of a liquid such as methane (CH$_4$) or ethane (C$_2$H$_6$) and specifically determine the significance of the viscosity as it applies to waves on Titan lakes.
IV. Experimental Methods

The procedure involved several sets of experiments of different combinations of compounds. To record evaporation rate, the change in mass of the substance over an amount of time had to be recorded. Nanophase silica (SiO$_2$) was utilized as a surrogate for tholins. Being normally inert, any changes in evaporation rate due to the presence of the silica can be attributed to physical, rather than chemical, interactions. This allows us to separate these effects when later experiments with actual tholins may be conducted. One kilogram was ordered to have a sufficient amount for experiments. Nanophase silica is a silicon dioxide powder composed of particles with an average diameter of $10^{-9}$ m with an average density of 2.5 g/cm$^3$. This nanophase silica was intended to replicate the role of natural sediment that would be found in the hydrocarbon seas and lakes on Titan, much like sand or minerals found in Earth’s oceans and lakes.

The following list shows the plan for the sets of experiments necessary to more completely understand the “hydrological” cycle of Titan:

1. Evaporate pure liquids
2. Evaporate liquid and nanophase silica mixtures
3. Measure the viscosity of the liquid and nanophase silica mixtures
4. Simulate the wind effect that would create “waves” using a fan or pipes at room temperature to see the effect on evaporation rate
5. Simulate waves with the above wind effect in the Andromeda chamber (simulates Titan temperatures and pressures)

This thesis focuses on experiment sets numbers 1 and 2. Since most of the tests were to be done on the “bench” i.e. not in the pressurized chamber, a number of compounds were chosen that may have similar evaporative and viscosity properties as to those that would be seen on the
These compounds are diethyl ether, ethyl alcohol (ethanol), acetone, and hexane. Table 1 below shows the relative densities, viscosity, melting and boiling points in Kelvin, and saturation pressure of the relevant substances.

<table>
<thead>
<tr>
<th></th>
<th>Methane</th>
<th>Ethane</th>
<th>Diethyl ether</th>
<th>Acetone</th>
<th>Hexane</th>
<th>Ethanol</th>
</tr>
</thead>
<tbody>
<tr>
<td>Formula</td>
<td>CH4</td>
<td>C2H6</td>
<td>(C2H5)2O</td>
<td>(CH3)2CO</td>
<td>C6H14</td>
<td>CH3CH2OH</td>
</tr>
<tr>
<td>Density (g.cm⁻³)</td>
<td>0.4515</td>
<td>0.6515</td>
<td>0.7134</td>
<td>0.791</td>
<td>0.6548</td>
<td>0.789</td>
</tr>
<tr>
<td>Viscosity (mPa.s)</td>
<td>0.1934</td>
<td>1.281</td>
<td>0.224</td>
<td>0.3311</td>
<td>0.294</td>
<td>1.144</td>
</tr>
<tr>
<td>Melting T (K)</td>
<td>90.69</td>
<td>90.37</td>
<td>157</td>
<td>179</td>
<td>178</td>
<td>159</td>
</tr>
<tr>
<td>Boiling T (K)</td>
<td>111.51</td>
<td>184.33</td>
<td>308</td>
<td>330</td>
<td>342</td>
<td>352</td>
</tr>
<tr>
<td>Psat (kPa)</td>
<td>11.7</td>
<td>0.0011</td>
<td>58.94</td>
<td>24.61</td>
<td>17.6</td>
<td>5.95</td>
</tr>
</tbody>
</table>

**Table 1.** Properties of compounds used.¹⁰ Note: density and viscosity of liquids at 20°C. Density and viscosity of methane and ethane at their respective melting points.

As it can be seen from Table 1, with regard to viscosity, methane is quite similar to ether and ethane is similar to ethanol. This means that these are very suitable choices for substances to test for future experiments since they represent near perfect analogues for their Titan counterparts.

The purpose of the pure compound evaporation experiments was to gain a baseline understanding of what the maximum boundary for the evaporation rate of the compound can be. Without any material in the liquid to diffuse the substance, the liquid will evaporate at the highest rate possible at the given temperature and pressure (for all test runs room temperature and pressure were used, i.e. about 25°C and atmospheric pressure, 101.3 kPa. Ethanol was refrigerated during storage and was allowed to reach ambient temperature before conducting experiments). This set of experiments also served as a control for comparison with the compounds mixed with the nanophase silica. Compound silica mixtures should theoretically
have a lower evaporation rate than the pure compounds due to being in the diffuse state with added material. So for the set of pure liquid experiments the liquid just evaporated into the surrounding open air. For the set number 2 experiments involving the silica compound mixtures, Figure 3 illustrates the predicted events during the experiment.

Figure 3. Illustration of the mixture test setup a) at the beginning of the experiment and b) after evaporation has occurred at the end of the experiment.

Recording the mass of the mixture over time should theoretically yield a plot with a constant negative slope as the liquid layer evaporates like normal, from an initial time $t_0$, up until the point where the liquid layer meets the surface of the wet silica at $L_0$ at time $t$ in Figure 3. At this juncture or “kink”, the evaporation rate changes dramatically since it has to evaporate through a porous layer instead of open air like the simple liquid layer. This section would develop into a curve with an increasingly less negative slope approaching zero as time goes on and the silica completely dries up to a powder form once again. This plot could be broken up into two segments, the constant slope of the liquid layer and the curved plot of the diffusion layer. The ideal theoretical plot would look similar to Figure 4 below,
Figure 4. Theoretical plot of mixture evaporation data over time with “kink” at time t at L₀.

With the separated sedimentation as one option, the other possibility for the experiments was that the mixture would become one homogenous solution much like cloudy milk. This homogenous mixture would not “settle” similar to how sand settles out of water into which it has been mixed. Instead, the mixture would just evaporate continuously leaving a layer of solid silica behind. In this case, there would be no kink visible in the plot of the mass versus time, since there would be no transition point between different locations in the mixture as it is homogenous.

V. Procedure

For all experiments, a specific procedure was followed. Beginning with the pure liquid evaporation experiments, the petri dish to be used was measured and its mass recorded. The main container that the liquid was poured into was a 50 mL beaker. On average it was filled to approximately the 18 or 20 mL mark. The petri dish was placed on the balance and the balance was turned on and tared so that it read 0.000 g with the petri dish. Data for the first three
experiments were recorded differently than those following. For the first pure diethyl ether, pure acetone, and pure hexane experiments, the mass data was recorded by using a webcam recording of the balance reading. The webcam started recording after the balance was tared to zero. Next the 50 mL of the pure liquid was poured into the petri dish. The recording continued until the liquid was completely evaporated, or when it was clear that the surface of the liquid had been breached by the bottom surface of the petri dish and thus a uniform evaporation surface area had ceased. Figure 5 below depicts the equipment setup for the first three experiments.

![Equipment setup for first three pure compound evaporation experiments using webcam recording of balance mass data recorded on a computer hard drive.](image)

**Figure 5.** Equipment setup for first three pure compound evaporation experiments using webcam recording of balance mass data recorded on a computer hard drive.

The rest of the experiments were set up with a slight variation. The Andromeda chamber has a cable that is connected to the computer in the data acquisition and observing room adjacent to the chamber room. This cable connects to a computer with LabView software that was able to record mass data continuously without interruption indefinitely, unlike a balance operating under
typical use that is programmed to automatically turn off after a certain number of minutes or hours. This capability allowed for recording for long intervals of evaporation data collection without requiring the operator to be present continuously. Figure 6 depicts the use of the balance that was integrated with the Andromeda chamber data acquisition.

Figure 6. Balance reading integrated with the LabView software for Andromeda chamber data acquisition for uninterrupted data recording.

For the compound and nanophase silica mixture experiments, a similar procedure was followed. With the 50 mL liquid beaker prepared, a clean and empty 100 mL beaker was placed on the balance. The balanced is then tared to 0.000g, and next the silica was carefully removed from its container and collected into the 100 mL beaker until it reached approximately 3 g of silica. It was noted that 3g of silica was usually volumetrically equivalent to about 40 mL of the
liquid compound to yield an approximate 50/50 mixing ratio by volume. Figure 7 shows these beakers for comparison.

**Figure 7.** Approximate matching volume of pure liquid to be mixed with nanophase silica.

With the LabView program set to record data and the balance tared, both the liquid and the silica were added to a single 250 mL beaker and mixed with a glass mixing ladle. Using the Andromeda chamber’s LabView capability for data acquisition allowed for the remaining experiments to run overnight as well. Many hours of data collection were needed as the evaporation rate was predicted to decline with the added mixture of the silica. There were many more data points for these experiments relative to the first three, where the video recording was viewed at a later date and mass data points manually taken every 15 seconds of video.
VI. Results

Multiple sets of mass versus time plots yielded from the evaporation experiments. The first set of plots has an x-axis unit of seconds and a y-axis unit of grams. The three experiments that were recorded via camera data had significantly fewer data points since the mass time data was taken manually, compared to the Andromeda balance data that was able to run overnight until the petri dish was completely devoid of moisture. Enough data points were manually taken to ensure the ability to plot a line that would have a clear slope. This slope is the evaporation rate of the substance. To obtain the slope, a linear best-fit was applied to each of the evaporation plots. A total of 10 evaporation experiments were completed. The first experiment was a pure ether evaporation run. This is the same experiment shown with the laptop and webcam setup in Figure 5. With this first run, the balance already had the petri dish with the ether inside when it was turned on and it registered this mass as a negative mass. As the ether evaporated, the balance registered increasingly negative mass. This is reflected in the plot of mass over time in Figure 8 below.

![Graph of pure ether evaporation](image)

**Figure 8.** Plot of pure ether evaporation.
The second two experiments to be recorded via webcam were the pure acetone and pure hexane runs. Figures 9 and 10 display the evaporation of acetone and hexane, respectively.

**Figure 9.** Plot of pure acetone evaporation with best-fit.

\[ y = -0.00662x + 11.62436 \]

**Figure 10.** Plot of pure hexane evaporation.

\[ y = -0.0026x + 9.9023 \]
It should be noted that these first three runs were completed using a smaller diameter petri dish than the rest of the experiments and this mass was not included in the plots above. The smaller petri dish measured 10.4 cm in diameter, while the larger petri dish measured 13.75 cm in diameter. The following plots include the mass of this larger petri dish. This does play a role since evaporation is directly related to the exposed surface area, and is taken into account as discussed later. The remaining experiments were all run with the Andromeda chamber’s LabView data acquisition software overnight, and thus had many more data points. Typically, the data actually ran for about 100,000 data points. For these runs, the plots were cut off soon after the plateau of data where all liquid had evaporated. This was often around 40,000 data points. Figure 11 below displays the pure ethyl alcohol run.

![Pure Ethyl Alcohol Evaporation](image)

**Figure 11.** Plot of pure ethyl alcohol evaporation using Andromeda chamber balance.

Most of the experiments were repeated in an attempt to check that no one experiment was an outlier that was skewing the results. The next set of figures shows the evaporation plots for the
silica mixtures as well as some of the repetition of these experiments. Note that there is no kink in that data at all for any of the following evaporation plots. The two possibilities for the mixture experiments were that either there would be a noticeable kink in the data due to separation in the mixture as described earlier, or that the mixture would form a milky homogenous substance that would evaporate at a constant rate. All mixtures formed a homogenous result, yielding constant slopes for evaporation rate. Figure 12 and Figure 13 show the first acetone and nanophase silica mixture and first hexane silica mixture experiments, respectively.

![Acetone Silica Mixture 1](image)

**Figure 12.** Acetone silica mixture evaporation plot 1.
An intriguing phenomenon occurred with the hexane silica mixture experiment that was not seen in any of the other experiments. The same initial procedure was followed for the usual compound and silica mixture experiments with a 50/50 mixing ratio by volume. However, when the hexane and the nanophase silica were mixed together in the 250 mL beaker, the mixture formed was not the milky type of liquid mixture that typically resulted. This mixture was much more viscous and had properties similar to a slush or sludge from snowmelt, or applesauce for example. When this happened, much of the mixture stuck to the 250 mL beaker and thus even less of the substance transferred into petri dish than anticipated. The evaporation surface area was also not uniform in that state due to clumping and non-spreading viscous mixture so another 40 mL of hexane was added and mixed into the existing petri dish to yield a uniform evaporation surface area. The effect of not having an equal volume of hexane and silica particulate is unknown and needs to be further investigated with more experiments. It is plausible to conjecture that adding more hexane further diluted the mixture, which would increase the
evaporation rate since the mixture ratio would be shifted closer to being pure rather than an even 50/50 mixture ratio. Figure 14 displays the hexane petri dish.

Figure 14. Left: Initial hexane silica mixture, Top and bottom right: uniform surface area with additional hexane.

The remaining experiments are displayed in Figures 15, 16, 17, and 18 below.

![Graph](image)

**Figure 15.** Plot of first ethanol and nanophase silica mixture evaporation.
Figure 16. Plot of second ethanol and nanophase silica mixture evaporation.

Figure 17. Plot of acetone and nanophase silica mixture evaporation.
Finally, the data and resulting evaporation rates for all runs are summarized in Table 2 below.

<table>
<thead>
<tr>
<th>Substance</th>
<th>Evap area (m²)</th>
<th>Best fit slope (g/s)</th>
<th>Rate (kg/s)</th>
<th>Rate (kg/(s*m²))</th>
<th>Rate (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pure ether</td>
<td>0.03397</td>
<td>0.0065</td>
<td>6.58E-06</td>
<td>0.000193</td>
<td>2.71E-07</td>
</tr>
<tr>
<td>Pure acetone</td>
<td>0.03397</td>
<td>0.0066</td>
<td>6.62E-06</td>
<td>0.000194</td>
<td>2.46E-07</td>
</tr>
<tr>
<td>Pure hexane</td>
<td>0.03397</td>
<td>0.0026</td>
<td>2.6E-06</td>
<td>7.65E-05</td>
<td>1.16E-07</td>
</tr>
<tr>
<td>Pure alcohol</td>
<td>0.05939</td>
<td>0.0008</td>
<td>8E-07</td>
<td>1.34E-05</td>
<td>1.68E-08</td>
</tr>
<tr>
<td>Alcohol mix 1</td>
<td>0.05939</td>
<td>0.0008</td>
<td>8E-07</td>
<td>1.34E-05</td>
<td>1.70E-08</td>
</tr>
<tr>
<td>Alcohol mix 2</td>
<td>0.05939</td>
<td>0.0009</td>
<td>9E-07</td>
<td>1.51E-05</td>
<td>1.92E-08</td>
</tr>
<tr>
<td>Acetone mix 1</td>
<td>0.05939</td>
<td>0.0042</td>
<td>4.2E-06</td>
<td>7.07E-05</td>
<td>8.93E-08</td>
</tr>
<tr>
<td>Acetone mix 2</td>
<td>0.05939</td>
<td>0.0039</td>
<td>3.9E-06</td>
<td>6.56E-05</td>
<td>8.30E-08</td>
</tr>
<tr>
<td>Hexane mix 1</td>
<td>0.05939</td>
<td>0.0035</td>
<td>3.5E-06</td>
<td>5.89E-05</td>
<td>8.99E-08</td>
</tr>
<tr>
<td>Ether mix 1</td>
<td>0.05939</td>
<td>0.0111</td>
<td>1.11E-05</td>
<td>0.000186</td>
<td>2.61E-07</td>
</tr>
</tbody>
</table>

Table 2. Evaporation rate results summary.

One can notice from Table 2 that the evaporation surface area is the same for the first three experiments and then changes to a new one for the remaining runs. This allowable area does impact the evaporation rate since with a larger surface area, more of the liquid had direct access.
to the air and would thus allow for the change from liquid to gas to happen at a faster rate. So, larger surface area will lend to faster evaporation rates. However, these early runs are still comparable to the latter runs since the evaporation rate unit is based off of a common unit area, m² regardless of the absolute size of the actual evaporation surface.

VII. Analysis

A meaningful way to look at the data was to normalize all of the runs to one another. The mass of the petri dish was removed from the runs that originally retained it in the plots of the data. With this extra mass removed, now all data was directly comparable as only displaying a substance that was at least partially evaporating, instead of being distorted by the petri dish mass. So, the normalized mass for the following plots was found using Equation 1,

\[ m_{\text{normalized}} = \frac{m_t - m_{\text{petri dish}}}{m_{\text{total initial}}} \]

Eq. 1

Where

- \( m_{\text{normalized}} \) = normalized mass value (unitless)
- \( m_{\text{petri dish}} \) = mass of petri dish used (g)
- \( m_{\text{total initial}} \) = total mass including petri dish at the beginning of evaporation (g)
- \( m_t \) = mass value at time t including petri dish used (g)

Equation 1 was applied to all sets of mass data. The initial time used for each set of data was chosen based on when the liquid was actually poured into the petri dish. Typically the data had started to record before the pouring of the mixture or compound into the petri dish, so recording began at the highest mass value where evaporation begins with the time set as \( t = 0 \) for each run. Using Equation 1, the experiments were grouped on plots based on the common compound used.
For acetone, Figure 19 below displays the normalized evaporation. In the figure, it should be noted that the red “Silica mixture 1” is actually directly overlaid by the green “Silica mixture 2” plot, and thus they are nearly identical data sets.

![Acetone Evaporation](image)

**Figure 19.** Normalized data for acetone evaporation experiments.

The next three plots shown in Figure 20, Figure 21, and Figure 22 represent the normalized evaporation rates for the pure and silica mixture compounds of ether, hexane and ethyl alcohol respectively.
Figure 20. Normalized data for ether evaporation experiments. Only one ether silica mixture experiment was completed.

Figure 21. Normalized data for hexane evaporation experiments. Again, only one hexane silica mixture experiment was completed.
As seen in Table 2 and Figure 19, the evaporation rate of pure acetone was notably faster than the average evaporation rate of the acetone silica mixture. Table 3 below takes the pure evaporation rates of the compounds and uses the average of the mixture evaporation rates to find the ratio of how many times faster the pure compound evaporated relative to the average compound silica mixture evaporation rate.

<table>
<thead>
<tr>
<th>Compound</th>
<th>Pure rate (m/s)</th>
<th>Mixture rate 1</th>
<th>Mixture rate 2</th>
<th>Mix average</th>
<th>Pure/mix ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acetone</td>
<td>2.46E-07</td>
<td>8.93E-08</td>
<td>8.30E-08</td>
<td>8.62E-08</td>
<td>2.857</td>
</tr>
<tr>
<td>Ether</td>
<td>2.71E-07</td>
<td>2.61E-07</td>
<td>-</td>
<td>2.61E-07</td>
<td>1.036</td>
</tr>
<tr>
<td>Hexane</td>
<td>1.16E-07</td>
<td>8.99E-08</td>
<td>-</td>
<td>8.99E-08</td>
<td>1.298</td>
</tr>
<tr>
<td>Alcohol</td>
<td>1.70E-08</td>
<td>1.70E-08</td>
<td>1.92E-08</td>
<td>1.81E-08</td>
<td>0.941</td>
</tr>
</tbody>
</table>

Table 3. Comparison of normalized evaporation rates.

Table 3 shows that acetone evaporates almost three times as fast as when it was mixed with nanophase silica. Based on the overall pure-to-mixture ratio in Table 3, acetone had the greatest change in evaporation rate when the nanophase silica was added. This drastic effect can be observed in the normalized acetone plot in Figure 19. The second biggest effect on the
evaporation occurred with hexane at 1.298 pure-to-mixture evaporation rate. This is particularly interesting because, as noted in the results section, the hexane became a very viscous slush when the nanophase silica was added to it. Initially, it would seem that a more viscous substance would take longer to evaporate compared to a less viscous substance. This would mean that the data would not make sense with the acetone having such a bigger pure-to-mixture ratio evaporate rate. However, the assumption that a more viscous substance has a longer evaporation is not necessarily correct, so it may be reasonable to conjecture that the data was just displaying that the hexane silica mixture still evaporates faster than some compounds and slower than others despite being a slush-like mixture. This slush was an unexpected occurrence in the laboratory, and it may be fruitful to pursue the question of why the hexane mixture became a slush when none of the other compound-silica mixtures did. What are the properties of this slush? Can the effect be replicated reliably each time hexane is mixed with nanophase silica? This would be a logical step to pursue to see how this slush would relate to a hydrocarbon compound on the surface of Titan.

Next, there was some effect on the evaporation rate by silica for ethyl ether as indicated by the 1.036 ratio in Table 3. Neither of these effects was very drastic, and this is apparent when one looks at the normalized evaporation plots for both hexane and ether. It was clear from Figure 21 that the evaporation rate of hexane was more affected by nanophase silica particles than that of ether in Figure 20. The normalized plot of the alcohol runs in Figure 22 presents an interesting result in that all of the evaporation rates were very close to one another. In fact, it was the only compound where it appears that the addition of the nanophase silica actually increased the evaporation rate based on the ratio analysis in Table 3. This is especially interesting since in all of the other compound cases, the addition of nanophase silica to the compound decreased the
mixture evaporation rate. The next logical step here would be to run another experiment for the pure alcohol to see if the same result is reached.

VIII. Future Work

During this research, there was only time to complete the first two experiment sets. This was partially due to time constraints with regard to the moving of the laboratory to a new building in progress at the time of this writing. Future work should answer the questions raised above, and then explore the remaining experiment sets, which are repeated below for convenience.

3. Measure the viscosity of the liquid and nanophase silica mixtures
4. Simulate the wind effect that would create “waves” using a fan or pipes at room temperature to see the effect on evaporation rate
5. Simulate waves with the above wind effect in the Andromeda chamber (simulates Titan temperatures and pressures)

With regard to viscosity mentioned in set 3, there are numerous reasons why it is scientifically interesting to study viscosity of these liquids and mixtures. Essentially, there may be waves on the lakes and seas on Titan, similar to how waves exist on bodies of water on Earth. The movement of a body of fluid in the form of a wave is directly affected by the viscosity and surface tension of the fluid that makes up the wave.

There are three reasons why waves may not have been observed in seas and lakes on Titan. The first hypothesis is that the winds found on Titan may not be fast enough for an observable effect. This could change as the season on Titan changes, but the Cassini orbiter has not been there long enough to observe this change. A mission extension to 2016 should provide enough
evidence or lack thereof to observe the change of season. The second hypothesis is that the effect of the sediment and other chemicals that are found in Titan lakes form a type of “soup” that could change the overall viscosity of the mixture just enough so that the waves are not observable. With more types of substances added to the “soup”, it is logical that the viscosity would increase. The third hypothesis is that freezing has occurred on the surface such that a layer of ice acts as a protective cap for the lakes. Images taken from Cassini may be unable to reveal information to penetrate this protective layer of ice, even if there is wave-like motion occurring underneath the bottom layer of the ice. Or perhaps this ice layer acts as a physical barrier and prevents wave-like motion from occurring at all.

To explore this wave phenomenon, the fourth experiment should simulate the wind effect on the evaporation rate of hydrocarbons on Titan using a mechanism such as a fan or pipes at room temperature. The last experiment set 5 would explore the effect of wind on waves by performing the experiments at Titan temperatures and pressures. This would be achieved by placing the evaporation experiment with a fan inside the Andromeda Titan simulation chamber. This chamber uses nitrogen to cool down to the temperature of Titan, about -179° C (-290°F). It also matches the pressure on Titan; about 1.5 bar (Earth has an atmospheric pressure of 1 bar). This would be a unique opportunity to model the effect of waves on liquids that make up seas and oceans on Titan’s surface using the moon’s own atmospheric conditions.
References

   http://photojournal.jpl.nasa.gov/catalog/PIA01465