Hydrophobic Coatings for Film Boiling Based Drag Reduction on a Torpedo Model

by

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B.S. Civil Engineering, University of Michigan (2009)

Submitted to the Department of Mechanical Engineering in partial fulfillment of the requirements for the degrees of Naval Engineer and Master of Science in Mechanical Engineering at the MASSACHUSETTS INSTITUTE OF TECHNOLOGY

June 2015

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Abstract

Previous research has shown that porous, hydrophobic surfaces exhibit a dramatic reduction in critical heat flux (CHF), the amount of heat over a surface area required to initiate film boiling. Film boiling is characterized by the presence of a vapor layer which remains as long as the surface temperature stays above the Leidenfrost point. This vapor layer has poor heat transfer characteristics but has the potential to reduce drag by acting as a buffer between the solid surface and the liquid.

The goals of this research were to quantify the drag reduction due to film boiling, examine the durability of the coating and explore the feasibility of this concept for application to a torpedo. A torpedo was chosen due to its high speed and reduced emphasis on durability, since it is only used operationally once. A hydrophobic coating was created in the laboratory using a layer-by-layer (LBL) process and its performance was compared to that of a commercial hydrophobic coating. Drop tests of uncoated and hydrophobic aluminum torpedo models were conducted in a custom-built apparatus housing a water column and a furnace, and recorded with a high-speed video camera in order to measure position versus time. Terminal velocity was extrapolated from the data and used to calculate drag coefficients. The data from this set of experiments showed that film boiling increased average terminal velocity by 23%, which corresponded to a 32% reduction in the drag coefficient.

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Acknowledgments

I would like to thank Professor Jacopo Buongiorno and Dr. Thomas McKrell of the Nuclear Science and Engineering department for supervising this thesis and guiding my research. Dr. McKrell’s advice helped me overcome countless experimental hurdles in the lab. Special thanks are due to Dr. Bren Phillips for his ideas, help during experiments and assistance with drawings for the torpedo drop assembly. The other members of Professor Buongiorno’s nanoparticle research group also helped me at various times and deserve credit. Thanks to Professor Michael Rubner of the Materials Science and Engineering department and Professor Robert Cohen of the Chemical Engineering department for allowing me to use their laboratory spaces for LBL coatings and contact angle measurements.

From the Mechanical Engineering department, thanks are due to my past and present 2N advisors: CAPT Mark Thomas, CAPT Joe Harbour, CDR Jerod Ketcham and CDR Weston Gray. I would also like to thank Dr. Yuming Lu for his help on hydrodynamics questions and Professor Alexandra Techet and James Schulmeister for allowing me to use the MIT water tunnel for model testing, even though that plan did not work out. My fellow 2N classmates also deserve recognition for their insights and friendship.

Additional gratitude is offered to GVD Corporation, Shannan O’Shaughnessy and Emily Anderson in particular, for their collaboration on this project and donation of coatings. Thanks also to Andrew Gallant from the MIT Central Machine Shop for his ideas and assistance with machining the parts that made the drop test possible.

Last but not least, I would like to thank my family for their unconditional support through the ups and downs of my work on this thesis. They provided encouragement whenever I needed it and helped me keep things in perspective.
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Chapter 1

Introduction

1.1 Motivation

Achieving higher speeds for a given amount of propulsion power, or alternately, achieving the same speed while using less propulsion power, have been goals of ship designers and sailors for centuries. Since testing new ideas on full-scale ships is cumbersome and expensive, model testing became a preferred method for verifying the proposed benefits of new concepts such as radical hull designs and special coatings. Recently, computational fluid dynamics (CFD) computer software packages have allowed for testing and analysis without any physical setup. These results are very powerful, but must be validated by physical experimental data to ensure accuracy of the computer models. As a result, CFD has not entirely replaced physical testing, but rather serves as an excellent supplement.

As underwater technology has become more advanced, research has expanded beyond surface ships to encompass submarines, torpedoes and unmanned underwater vehicles (UUVs). A torpedo is only effective if it can travel significantly faster than its target, thereby not allowing the target to outrun it. Additionally, the faster a torpedo goes, the less time a target has to react and maneuver and/or release countermeasures. Obviously high speed is valuable trait of a torpedo. Quick and accurate target acquisition and maneuverability during homing are also important traits. Reducing drag can help increase torpedo effectiveness by offering an attractive
choice: increase speed for the same amount of power or achieve the same speed with less power, opening up more space inside for additional electronics or payload.

The key component for reaching the aforementioned goals is drag reduction. Streamlined shapes help reduce drag through the water, but geometry alone cannot eliminate drag entirely. Therefore other concepts, including application of specialized surface coatings, bubble injection and supercavitation have been explored [1, 2, 3, 4, 5, 6]. These concepts continue to be the focus of ongoing research for a wide variety of applications. This project focuses solely on the application for a torpedo.

1.2 Objectives

There were several goals associated with this research topic, three of which were directly addressed by this project and several more which were outside the scope of the initial phase of the project. These are left as follow-on topics and areas for further study. The main objectives of this thesis were:

1. Quantify the drag reduction on a torpedo due to film boiling. This was done through drop tests conducted in a column of water in a Nuclear Science and Engineering laboratory at MIT. The model and apparatus sizing, as well as other important parameters and details, were selected based on a combination of expected results due to calculations and lessons learned from previous experiments.

2. Examine the durability of the coating. Durability during production, storage, transportation and operational use are all important. A large part of the reason why a torpedo was selected was the knowledge that it is only used operationally once, and therefore durability (or lack thereof) after exposure to film boiling would be less of a concern. However, durability is still a valued quality for any sort of future military or commercial application.
3. Assess the feasibility of the proposed concept to reduce drag on a torpedo with film boiling. The determination of feasibility of the idea is based largely on research objectives 1 and 2 above, but also includes practical concerns not directly addressed by testing.

Section 6.4 is devoted to addressing topics for further study.
Chapter 2

Background

Basic knowledge of a few topics related to heat transfer, surface characterization and drag are necessary background information for a reader of this thesis. Brief explanations of the Leidenfrost effect, boiling regimes, critical heat flux, contact angle and hydrodynamic drag are provided for review or familiarization. Related work is separated into two categories: prior research at MIT that provided the impetus for this project and a literature review of published papers about similar research.

2.1 Leidenfrost Effect

The Leidenfrost effect is a term for a phenomenon first documented by J.G. Leidenfrost in 1756. His publication, A Tract About Some Qualities of Common Water included the section On the Fixation of Water in Diverse Fire [7], in which he described observations of a drop of water levitating above a very hot surface (a spoon). Leidenfrost found that if the temperature of the surface was significantly above the liquid's boiling point, a thin layer of vapor would separate the liquid drop from the solid surface. He also found that the drop evaporated very slowly until the spoon had cooled to a certain point, at which the familiar hiss of boiling water could be heard and then the drop quickly boiled away. The temperature at which this vapor layer occurs has become known as the Leidenfrost temperature and is commonly written as $T_L$. 

19
Interest in the Leidenfrost effect has grown in recent years, owing to better understandings of and new thoughts on applications related to this phenomenon. A thorough review of research on Leidenfrost dynamics was published by Quéré in 2013 [8]. This review includes suggestions of future directions for exploration, one of which is drag reduction, the focus of this thesis.

2.2 Boiling Regimes

Boiling can be divided into four regimes: (1) natural convection, (2) nucleate boiling, (3) transition and (4) film boiling, as illustrated in Figure 2-1. Wall superheat is the temperature of the surface minus the saturation temperature of the liquid. Natural convection occurs at the lowest temperatures, just above saturation temperature. Nucleate boiling happens next as the surface temperature increases, and consists of vapor bubbles which detach from the surface and rise. At high heat flux values in this regime, bubbles are replaced by jets and columns. Nucleate boiling is very effective at transferring heat. The transition regime exists between nucleate and film boiling, and is less well understood than the other regimes. Film boiling occurs at still higher temperatures and has poor heat transfer characteristics compared to nucleate boiling. Point A on Figure 2-1 represents the critical heat flux, which is discussed in section 2.3. Point B on Figure 2-1 represents the minimum heat flux required to sustain film boiling; the surface temperature at this point is the Leidenfrost temperature.

2.3 Critical Heat Flux

Critical heat flux (CHF), also known as maximum heat flux, departure from nucleate boiling (DNB), burnout and the boiling crisis, is defined as the heat flux at which point nucleate boiling transitions to film boiling, in a heat flux controlled experiment. CHF depends on multiple factors, including surface characteristics such as roughness, wettability and porosity and liquid characteristics such as boiling point and subcooling. In nuclear engineering applications, it is desirable to have a very
high CHF because formation of a vapor film greatly reduces the heat transfer, which could lead to serious problems for operation of a nuclear reactor. However, in other applications where the presence of a vapor film is advantageous, a low CHF is ideal. For the case of film boiling based drag reduction, lower CHF values are better because that means less heat is required to generate a vapor film. The intent of testing was to operate solely in region 4 of Figure 2-1.

2.3.1 Effect of Subcooling

Subcooling refers to the temperature difference between a bulk fluid temperature and its saturation temperature. For example, at atmospheric pressure, the saturation temperature of water is 100°C. A beaker of room temperature water at 20°C would thus be considered to be 80°C subcooled.

Subcooling can have a large impact on CHF, and was a major hurdle encountered
early during this project. Since a torpedo operates mainly in the ocean, the water temperature is far below saturation. Thus it was desirable to test drag reduction in room temperature water, which represents a significant amount of subcooling. Ivey and Morris (1962) developed the following correlation for the effect of subcooling on CHF based on their experiments in water [9]:

\[
\frac{q''_{CHF_{sub}}}{q''_{CHF_{sat}}} = \left[1 + 0.1 \left(\frac{\rho_f}{\rho_g}\right)^{\frac{3}{2}} \frac{C_{pf} \Delta T_{sub}}{h_{fg}}\right] \tag{2.1}
\]

where:
- \(q''_{CHF_{sub}}\) is the critical heat flux with the given degree of subcooling
- \(q''_{CHF_{sat}}\) is the critical heat flux without subcooling
- \(\rho_f\) is the density of liquid water
- \(\rho_g\) is the density of water vapor
- \(C_{pf}\) is the specific heat of liquid water
- \(\Delta T_{sub}\) is the subcooling between saturation and bulk liquid temperature
- \(h_{fg}\) is the latent heat of vaporization of water

All properties were taken at 100°C.

Using equation 2.1, a \(\Delta T_{sub}\) value of 80°C yields a ratio of \(q''_{CHF_{sub}}\) to \(q''_{CHF_{sat}}\) of 4.8, indicating that the CHF in room temperature water will be almost five times higher than that of saturated water. This is a very substantial increase.

Sakurai (2000) presented a comparison of his data and older correlations, including that of Ivey and Morris, on the effect of subcooling on CHF [10]. A new correlation, equation 2.2, was derived taking into account the non-linear effect of high liquid subcoolings on CHF.

\[
\frac{q''_{cr,sub}}{q''_{cr,sat}} = \left[1 + 0.87 \left(\frac{\rho_l}{\rho_v}\right)^{0.69} \left(\frac{C_{pf} \Delta T_{sub}}{h_{lv}}\right)^{1.5}\right] \tag{2.2}
\]
where: $q_{cr, sub}$ is the critical heat flux with the given degree of subcooling  
$q_{cr, sat}$ is the critical heat flux without subcooling  
$\rho_l$ is the density of liquid water  
$\rho_v$ is the density of water vapor  
$C_{pl}$ is the specific heat of liquid water  
$\Delta T_{sub}$ is the subcooling between saturation and bulk liquid temperature  
$h_{lv}$ is the latent heat of vaporization of water

All properties were taken at 100°C.

Using equation 2.2, a $\Delta T_{sub}$ value of 80°C yields a ratio of $q_{CHF,sub}$ to $q_{CHF,sat}$ of 9.2, which is significantly higher than the Ivey and Morris prediction.

The large increase in CHF due to subcooling proved to be beyond the capacity of the heating method that was used during preliminary testing, a cartridge heater. As a result, a decision was made that final testing would be completed in 90°C water to minimize the effects of subcooling. Initiating and sustaining film boiling on a torpedo (model) with much greater subcooling is left as an area for relevant further research.

2.4 Contact Angle

Contact angle is the angle at which a liquid-vapor interface meets a solid surface. Measurement of a contact angle, $\theta$, is depicted in Figure 2-2. A surface with a contact angle less than 90 degrees is considered hydrophilic; conversely, a surface with a contact angle greater than 90 degrees is considered hydrophobic. A surface with a contact angle less than 5 degrees is superhydrophilic and a surface with a contact angle greater than 150 degrees is superhydrophobic. Examples of hydrophilic and hydrophobic surfaces are shown in Figure 2-3.

Throughout the testing in this project, static contact angles were measured to track the degree of hydrophobicity of coatings and the ensuing degradation of the hydrophobicity as a result of heating. Reported contact angles are the average of five separate contact angle measurements. Contact angles were measured using a VCA 2000 contact angle goniometer made by AST Products, shown in Figure 2-4, and VCA Optima XE software. A light source behind the sample illuminates the droplet,
which is captured by the video camera. The computer software processes the image of the droplet and calculates the contact angle by fitting a curve around the droplet given left intersection, right intersection and top points. A typical image of contact angle measurement from the software is depicted in Figure 2-5.
2.5 Hydrodynamic Drag

Drag is a force on an object moving through a fluid, which acts in the opposite direction of the motion of the object. In general, for streamlined bodies at Reynolds numbers for laminar or turbulent flow, total drag is a combination of form drag and friction drag.
2.5.1 Form Drag

Form drag, also called pressure drag, is the contribution of drag due to pressure differences related to the shape of the object moving through a fluid and the wake it creates. The equation for form drag is:

\[ D_{\text{form}} = \frac{1}{2} \rho U^2 C_D S \]  \hfill (2.3)

where:
- \( D_{\text{form}} \) is the form drag force
- \( \rho \) is the density of the fluid
- \( U \) is the velocity of the object
- \( C_D \) is the form drag coefficient
- \( S \) is the object’s projected area

2.5.2 Friction Drag

Friction drag, also called skin friction or viscous drag, is the contribution of drag due to viscous stresses on the boundary of the object. The equation for friction drag is:

\[ D_{\text{friction}} = \frac{1}{2} \rho U^2 C_f A_w \]  \hfill (2.4)

where:
- \( D_{\text{friction}} \) is the friction drag force
- \( \rho \) is the density of the fluid
- \( U \) is the velocity of the object
- \( C_f \) is the friction drag coefficient
- \( A_w \) is the object’s wetted area

2.5.3 Total Drag

Total drag is found by combining the forces from equations 2.3 and 2.4.

\[ D_{\text{total}} = \frac{1}{2} \rho U^2 (C_D S + C_f A_w) \]  \hfill (2.5)
where: $D_{total}$ is the drag force
$\rho$ is the density of the fluid
$U$ is the velocity of the object
$C_D$ is the form drag coefficient
$S$ is the object's projected area
$C_f$ is the friction drag coefficient
$A_w$ is the object's wetted area

For a bluff body, e.g. a sphere, total drag is dominated by the form drag component. In the case of a streamlined body, however, both form and friction drag make up significant portions of the total drag. It is fairly intuitive that the presence of a vapor film could decrease skin friction drag, but less obvious that it could also decrease form drag. This discovery is discussed in Section 2.6.2. Drag coefficients are dependent on Reynolds number, which is discussed in more detail in Section 3.3.2.

2.6 Related Work

2.6.1 MIT Research

Prior research at MIT investigated the separate effects of surface roughness, wettability and porosity on the boiling critical heat flux [11, 12]. The main objective was to see how these three characteristics affected CHF and to compare the results to previous correlations. Test results showed that porosity had a dramatic effect on CHF while roughness had almost no effect. Perhaps the most interesting finding was that both smooth and rough porous hydrophobic surfaces exhibited dramatic reductions in CHF, up to 97% compared to the reference sample. Though reducing CHF is undesirable for nuclear applications, it was noted in O’Hanley’s thesis (2012) that formation of a vapor layer could be beneficial for insulation or drag reduction purposes [11].

Subcooling trends have also been studied at MIT. In one set of sphere and rodlet quenching experiments, the Leidenfrost temperature for nanoparticle-coated metal rodlets and spheres was observed to increase by as much as 100°C in the presence
of 70°C subcooling [13]. This confirms the importance of subcooling on Leidenfrost temperature and CHF as discussed in Section 2.3.1.

Other recent research at MIT by Srinivasan et al. involved drag reduction in a Taylor-Couette flow. This research used a sprayable superhydrophobic surface and noted how the presence of the superhydrophobic coating effectively changed the no-slip boundary condition to one with an effective slip length of 19 microns for a connected plastron. A drag reduction of 22% was calculated, along with the observation that for this case drag reduction increased with increasing Reynolds number [14]. At the time of the writing of this thesis, additional research with this Taylor-Couette device was ongoing.

2.6.2 Literature Review

Recent literature contains numerous publications about research pertaining to drag reduction via the Leidenfrost effect and/or addition of hydrophobic and superhydrophobic coatings to surfaces. Vakarelski et al. conducted testing with spheres falling in FC-72 to demonstrate drag reduction via the Leidenfrost effect [15], and reported an extraordinary reduction in drag force of up to 85% was attainable. Their research showed that a vapor layer could reduce not only friction drag, but also form drag by moving the separation point aft on the object. Vakarelski et al. later investigated how to prevent vapor layer collapse and transition from film boiling to nucleate boiling by using textured superhydrophobic surfaces [16], and performed sphere drop tests in heated water, again reporting very notable reductions in drag force, this time observing a reduction of about 75% [17]. Similar testing of drag reduction with spheres and superhydrophobic coatings was completed by McHale et al. [2, 18], though heating was not a part of their tests, drag reduction was purely a mechanism of the effective slip boundary condition.

Spheres have been the subject of much research throughout the history of hydrodynamics owing to their symmetry. Though much theoretical and experimental data is available about them, they are not always the most useful geometry for testing. Cylinders, which depending on orientation can represent pipes, buoys or pylons for
offshore rigs are very practical for testing. The next level of complexity is to test an actual ship, submarine, etc. model. Drag reduction effects of a superhydrophobic coating on a ship model were tested by Dong et al., and they reported a 49% decrease in drag force due to the coating [1].

In summary, the literature review confirmed that hydrophobic or superhydrophobic coatings and the Leidenfrost effect both offer exciting opportunities to effect substantial reductions in measured drag forces. The related work supports the proposed concept to apply a hydrophobic coating and minimal heating to a torpedo to initiate and sustain film boiling and subsequently reduce drag.
Chapter 3

Experimental Design

3.1 Testing Options

Three different options for testing drag reduction on a torpedo model were identified at the beginning of the research. The first was a simple drop test in a column of water. Ball drops would be simpler than torpedo model drops, but less original. The second option was a model test in the MIT towing tank. An advantage of this type of test is direct drag force measurement; disadvantages included disruption of flow due to the attachment device and a maximum speed of 2 m/s or less, which would limit the Reynolds number. The third option was a model test in the MIT water tunnel. Advantages of a water tunnel test included direct drag force measurement and a maximum flow velocity of up to 10 m/s. The higher flow speed would allow the model to be tested at a higher Reynolds number, closer to the actual Reynolds number that a torpedo operates at when traveling at full speed. The main disadvantage was the complexity of constructing the required model attachment with the force sensor implemented.

An analysis of benefits and drawbacks for different aspects of each type of test is shown in Figure 3-1. A force test in the water tunnel was selected as the primary test and a drop test was selected as a backup option. As the project evolved, hybrids of these options were also considered. Ultimately, the unobtainable heat flux required by subcooling forced the project to the backup option of a drop test.
3.2 Reference Object

A torpedo was chosen as the reference object because it would benefit from a reduction of drag and would generally be expected to have a short life span in the water during operational use. The short life span helps alleviate some of the durability concerns associated with LBL coatings. Four different U.S. Navy torpedoes were considered as specific reference objects for this project. These were the MK 48 heavyweight torpedo and the MK 46, 50 and 54 lightweight torpedoes. Any of the four would have sufficed as a reference object for proof of concept. Ultimately, the U.S. Navy MK 54 lightweight torpedo was chosen over the other three. It was selected because it is the newest torpedo of the four and is significantly shorter than the MK 48, a quality that was advantageous for model construction. A profile view of the MK 54 torpedo is shown in Figure 3-2, and the principle physical characteristics of the MK 54 torpedo are listed in Table 3.1 [19].
Figure 3-2: U.S. Navy MK 54 torpedo.

<table>
<thead>
<tr>
<th></th>
<th>SVTT</th>
<th>Rotary Wing</th>
<th>Fixed Wing</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Length</strong></td>
<td>2.72 m</td>
<td>2.81 m</td>
<td>2.89 m</td>
</tr>
<tr>
<td><strong>Diameter</strong></td>
<td>All</td>
<td>324 mm</td>
<td></td>
</tr>
<tr>
<td><strong>Warshot Weight</strong></td>
<td>SVTT</td>
<td>275.3 kg</td>
<td>285.3 kg</td>
</tr>
<tr>
<td></td>
<td>Rotary Wing</td>
<td>282.6 kg</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fixed Wing</td>
<td>292.6 kg</td>
<td></td>
</tr>
<tr>
<td><strong>Exercise Weight</strong></td>
<td>SVTT</td>
<td>266.7 kg</td>
<td>276.7 kg</td>
</tr>
<tr>
<td></td>
<td>Rotary Wing</td>
<td>284.0 kg</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fixed Wing</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 3.1: Physical characteristics of MK 54 torpedo.

### 3.3 Similarity

Similarity parameters are important for model testing. They indicate whether different systems have similar flow properties, as well as provide guidance for approximating complex physical problems. If similarity parameters are ignored, there can be no guarantee that the results from model testing will be an accurate representation of a full scale prototype in the real world. Multiple types of similitude exist; geometric and dynamic similitude were focused on for this project.

#### 3.3.1 Geometric Similarity

It can be seen in Table 3.1 that the physical characteristics of the torpedo are slightly different depending on the delivery method. The rotary wing variant was used for scaling simply because it was closest to the average values of all three variants. A scale of 1:10 between model and prototype was originally decided upon because
it was as large as practical for use in the MIT water tunnel. A 1:32.4 scale was also considered, however this smaller size was rejected because it would result in a lower Reynolds numbers for the model. Also, perhaps more importantly, this small size increased the complexity of model design and fabrication. When the test plan changed from testing in the water tunnel to a drop test, geometric scaling was re-examined and it was determined that a 1:10 scale model was too large. As a result, a 1:20 scale model was ultimately selected for testing. Technical schematics of the 1:20 scale and 1:10 scale models can be found in Appendix A.

3.3.2 Dynamic Similarity

Dynamic similarity refers to parameters such as force ratios, stress ratios and pressure ratios. For this work, the most important dynamic similarity parameter was the Reynolds number, which is the ratio of inertial forces to viscous forces.

\[ Re_L = \frac{UL}{\nu} \]  

where:  
- \( U \) is the velocity of the torpedo  
- \( L \) is the length of the torpedo  
- \( \nu \) is the kinematic viscosity of water

At a velocity of 45 knots, the MK 54 torpedo has a Reynolds number of approximately \( 6 \times 10^7 \), which is very high. Ideally this number would be matched in model testing; however, due to physical limitations for a drop test in the lab, the Reynolds number could not be exactly matched. Therefore, the goal was to operate in the same flow regime (turbulent versus laminar) as the full scale prototype torpedo. Though it depends on the specific situation, the transition from laminar to turbulent flow is known to typically occur around a Reynolds number of \( 3 \times 10^5 \). Frictional drag data contains a transition region between laminar and turbulent flow that spans between \( 10^5 \) and \( 2 \times 10^6 \). Factors such as surface roughness and ambient turbulence affect precisely when the transition between flow regimes takes place [20].
Chapter 4

Experimental Setup and Procedure

4.1 Torpedo Model

The geometry of the model was carefully calculated to maintain geometric similarity, as discussed in Section 3.3.1. Copper and aluminum were both considered as base materials due to their high thermal conductivity, corrosion resistance and commercial availability and affordability. The major deciding factor between the two materials ended up being density; because aluminum is significantly less dense than copper, an aluminum model would weigh much less than a copper one. Lower weight was advantageous because a lighter model would have a lower terminal velocity and therefore would reach terminal velocity faster than a heavier model during a drop test. The model was sketched using Autodesk Inventor Professional 2015 software. A profile view of the model is shown in Figure 4-1. Coloring was added to highlight the similarity to sections of the MK 54 torpedo. Tail fins and propellers were left off the model to reduce complexity and labor in fabrication.

Three torpedo models were fabricated from multi-purpose 6061 aluminum alloy by the MIT Central Machine Shop to the specifications found in the drawing in Appendix A. Figure 4-2 shows a profile view of the model. The average weight of the models was approximately 62 g.
4.1.1 Surface Preparation

The exterior surfaces of the torpedo models were sandblasted, cleaned and oxidized before testing. Sandblasting was performed using an Econoline sandblaster to an average roughness ($R_a$) of 1.1 microns. For comparison, the average roughness of a machined surface is typically between 0.8 and 6.4 microns. Cleaning was performed using a Cole-Parmer ultrasonic agitator. The steps for cleaning were as follows:

1. Rinse model surface in sink with de-ionized (DI) water.

2. Set model in beaker with approximately 400 mL of acetone and place beaker in agitator for 5 minutes.

3. Flip model in beaker and leave in agitator for another 5 minutes.

4. Remove model from beaker and remove beaker with acetone from agitator.

5. Set model in beaker with approximately 400 mL of ethanol and place beaker in agitator for 5 minutes.

6. Flip model in beaker and leave in agitator for another 5 minutes.
7. Remove model from beaker and remove beaker with ethanol from agitator. After cleaning, the models were allowed to air dry for at least 30 minutes and then placed in a furnace at 275°C for 24 hours for oxidation.

4.2 Hydrophobic Coatings

Presence of a hydrophobic coating was important for reducing the CHF required to reach and maintain film boiling. Two different coatings were tested and analyzed during pool boiling tests. The first coating was applied to a sample in a MIT Materials Science and Engineering laboratory using the layer-by-layer technique. The second coating was applied to a different sample using a commercial process by GVD Corporation.

4.2.1 Coating by LBL Method

The layer-by-layer (LBL) coating was prepared to match the coating referenced in O’Hanley’s thesis. It consisted of LBL deposition of 50 layers of 50 nanometer diameter silica (SiO₂) particles, followed by chemical vapor deposition (CVD) of fluorosilane. The expected CHF of this coating was 30-38 kW/m² for saturated water at atmospheric pressure [11].

LBL deposition was accomplished using a Zeiss HMS Programmable Slide Stainer. The dipping arm was modified to support a small motor that would rotate the sample during dipping to prevent more accumulation of coating on the lower half. The dipping bins were also modified in order to support a longer sample than normal. A total of 8 bins were used: a cation bath, an anion bath and 6 rinses (3 for each). The postitive solution was poly(allylamine) hydrochloride (PAH) with pH of 7.5, the negative solution contained SiO₂ nanoparticles in a pH 9.0 buffer solution and the rinse baths held DI water. The steps of the process for creation of one bi-layer were:

1. 10 minutes in the PAH(+) solution bin.
2. 2 minutes in DI water rinse #1(+).
3. 1 minute in DI water rinse #2(+).

4. 1 minute in DI water rinse #3(+).

5. 10 minutes in the SiO$_2$(-) solution bin.

6. 2 minutes in DI water rinse #1(-).

7. 1 minute in DI water rinse #2(-).

8. 1 minute in DI water rinse #3(-).

The steps listed above were repeated 50 times to create the final coating. The Zeiss HMS Programmable Slide Stainer is shown applying the LBL process to a copper tube sample in Figure 4-3. Readers interested in more details regarding the LBL process are encouraged to read O'Hanley's thesis [11].

![Figure 4-3: LBL dipping setup.](image)

CVD of fluorosilane was conducted in a Thermo Scientific Thermolyne furnace. A small glass vial containing 5 mL of fluorosilane (1H,1H,2H,2H-Perfluorodecylethoxysilane) and open to the air was placed in a 500 mL glass graduated cylinder plugged with a silicone rubber stopper and heated in the furnace to 140°C for 30 minutes. Then the LBL-coated sample was gently placed in the glass cylinder along with the vial, the
beaker was again plugged and heated at the same temperature for another 30 minutes. The furnace was placed in a fume hood during the process in order to prevent accidental inhalation of fluorosilane vapor. Fluorosilane is responsible for making the surface of the LBL-coated sample hydrophobic.

Contact angle measurements were taken after fluorosilane deposition to verify the hydrophobicity of the surface. Five measurements, along with the average, are reported in Table 4.1. The surface proved to be hydrophobic, as expected.

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Contact Angle (degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1</td>
<td>140.8</td>
</tr>
<tr>
<td>#2</td>
<td>138.9</td>
</tr>
<tr>
<td>#3</td>
<td>136.5</td>
</tr>
<tr>
<td>#4</td>
<td>139.5</td>
</tr>
<tr>
<td>#5</td>
<td>140.7</td>
</tr>
<tr>
<td>Average</td>
<td>139.3</td>
</tr>
</tbody>
</table>

Table 4.1: Contact angle measurements on LBL sample.

4.2.2 Coating by GVD Corporation

GVD Corporation makes surface coatings for a variety of applications and is located in Cambridge, MA. The company makes a PTFE-based hydrophobic coating that is durable, can withstand temperatures up to 300°C and is relatively simple to apply to surfaces. This coating was applied to a sample using a vapor deposition process. Specific details regarding the coating and application techniques are proprietary information and thus not included here.

Contact angle measurements were taken on the sample to verify the hydrophobicity of the surface. Five measurements, along with the average, are reported in Table 4.2. The surface coated by GVD also proved to be hydrophobic.
Table 4.2: Contact angle measurements on GVD sample.

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Contact Angle (degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1</td>
<td>144.0</td>
</tr>
<tr>
<td>#2</td>
<td>141.3</td>
</tr>
<tr>
<td>#3</td>
<td>141.1</td>
</tr>
<tr>
<td>#4</td>
<td>144.3</td>
</tr>
<tr>
<td>#5</td>
<td>146.4</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td><strong>143.4</strong></td>
</tr>
</tbody>
</table>

4.3 Testing Description

Three rounds of preliminary testing were conducted before the drop test. Lessons learned from each preliminary test helped shape the details of the final drop test. The following sections describe the setup and procedure for each test. Test results are located in Chapter 5.

4.3.1 Pool Boiling Tests

Pool boiling tests were initially conducted to verify the assumption that a low CHF would be required to establish film boiling on a surface while submerged in water. Copper tubing was used as the sample for pool boiling tests due to its high thermal conductivity and commercial availability. The dimensions of the copper tube are listed in Table 4.3. One copper tube was coated using the LBL technique and another identical copper tube was coated by GVD Corp.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Dimension (in)</th>
<th>Dimension (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outer Diameter</td>
<td>0.875</td>
<td>22.23</td>
</tr>
<tr>
<td>Inner Diameter</td>
<td>0.745</td>
<td>18.92</td>
</tr>
<tr>
<td>Wall Thickness</td>
<td>0.065</td>
<td>1.65</td>
</tr>
<tr>
<td>Length</td>
<td>6</td>
<td>152.4</td>
</tr>
</tbody>
</table>

Table 4.3: Copper tube dimensions.

A high-temperature cartridge heater was selected for internal heating. Cartridge heaters are commercially available in a number of diameters, lengths, powers and volt-
ages, and are relatively inexpensive. The shape of the cartridge heater also naturally resembles the shape of a torpedo, as illustrated in Figure 4-4. Heat transfer calculations using empirical correlations for the heat transfer coefficient were performed in order to determine the power required by the heater to create and sustain film boiling on the model. Table 4.4 contains a summary of the characteristics of the cartridge heater used in preliminary experiments. The cartridge heater was connected to a 220 V DC power supply during testing. The heater fit snugly into the inner diameter of the copper tube.

![Figure 4-4: High-temperature cartridge heater.](image)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outer Diameter</td>
<td>18.92 mm</td>
</tr>
<tr>
<td>Length</td>
<td>152.4 mm</td>
</tr>
<tr>
<td>Power</td>
<td>2000 W</td>
</tr>
<tr>
<td>Voltage</td>
<td>240 V</td>
</tr>
</tbody>
</table>

Table 4.4: Cartridge heater characteristics.

Power to the sample (and thus heat flux), determined by measuring voltage and current, was controlled by adjusting the voltage via a knob on the power supply. K-type thermocouples made by Omega Engineering were used for water temperature measurements. Data was recorded using an Agilent Technologies 34980 Multifunction Switch/Measure Unit Digital Acquisition System (DAS) connected to a computer.

To perform the test, the sample was connected to the power supply and placed vertically in a 4000 mL glass beaker filled with just enough DI water to cover the sample but not the electrical leads. The water was at room temperature, approximately 23°C. Power to the sample was slowly increased by increasing the applied voltage and the copper tube was observed as it heated, starting with natural con-
vection, progressing to nucleate boiling and ultimately transitioning to film boiling. When film boiling was first observed, the power was decreased in an effort to avoid damaging the heater and/or the sample. This process was repeated twice on the LBL coated copper tube and three times on the GVD coated copper tube. Results from this testing are located in Section 5.1.

Figure 4-5: Pool boiling test.

### 4.3.2 Air Heating Tests

Air heating tests were conducted similarly to the pool boiling tests, with the major exception being that the samples were heated while hanging in air and then submerged into water versus being heated in the water. Figure 4-6 shows the sample hanging while being heated with a beaker of water nearby. The surface temperature of the copper tube was tracked using a K-type thermocouple tied on with metal lockwire. After heating to a certain temperature, the sample was submerged into the beaker of water and recorded on video. The type of boiling was observed and documented. The
maximum temperature a sample was heated to was 300°C, as this represented the upper temperature limit for the hydrophobic coating. This process was repeated seven times, gradually increasing the temperature before submersion each time. The pool water was replaced with fresh, room temperature water following each test. Results from this testing are located in Section 5.2.

![Figure 4-6: Air heating test.](image)

### 4.3.3 Furnace Heating Tests

The purpose of the furnace heating test was to verify that film boiling could be established and maintained for long enough to complete the drop test as planned. Figure 4-7 shows the setup for these tests.

The sample was made of a copper tube with the GVD hydrophobic coating that was plugged with a solid copper rod. The rod had been tapped and a stainless steel hook had been inserted so it could be handled without touching the surface of the sample. The rod was coated in DeoxIT L260Cp thermal grease to improve the uniformity of thermal conductivity. After the rod was inserted into the tube, the ends were sealed with silicone to prevent contamination of the water. The copper tube was an identical version to the one utilized in the pool boiling tests, but had been unused.
Figure 4-8 shows the sample.

A 4000 mL glass beaker was wrapped in insulation, filled with DI water and placed on a hot plate. The water in the beaker was heated to 90°C on the hot plate. The copper sample was heated for 30 minutes in the Thermo Scientific furnace to a temperature of 150°C. The sample was then transported from the furnace to the beaker using tongs. The cooling of the rod was recorded on video and the duration of the vapor film from insertion into water until quenching was noted. This process was repeated heating the rods to 200°C and 250°C. Two tests were performed at each rod temperature. Results from this testing are located in Section 5.3.
4.3.4 Drop Tests

After completion of the three rounds of preliminary testing, drop tests were conducted to measure velocity and quantify the drag reduction due to film boiling. Technical drawings for the drop test apparatus can be found in Appendix B. The drop test apparatus depicted in Figure 4-9 consisted of a seven foot long polycarbonate tube epoxied to a glass-filled polycarbonate piece. This piece served as the top half of a flange. The bottom half of the flange was made of stainless steel. An O-ring made from Viton fluoroelastomer was used to keep the flange connection watertight. The flange was bolted to a steel plate that was in turn connected to an extruded aluminum frame. The stainless steel flange piece held threaded stainless steel rods which supported a stainless steel platform inside the tube. The platform contained a wire rope end fitting. The stainless steel flange piece also had National Pipe Taper (NPT) fittings for a 1200 W immersion heater and a drain. Above the tube, another steel plate supported two 900 W ceramic furnace half cylinders for heating the torpedo model, and still above that, a third steel plate contained a small center hole for the wire rope to pass through. A stainless steel wire rope was connected on one end to the bottom end fitting mentioned previously, passed vertically upward through holes in both steel plates and then downward to suspend a 22.68 kg lead block for tensioning purposes. The wire rope was used to serve as a guide wire to keep the torpedo model exactly vertical during the drop tests. A nylon disk positioned around the guide wire served as an elevator for raising the model after each test. An aluminum support plate assembly was placed halfway up the tube for extra support. The entire aluminum frame was attached to an aluminum base plate, which in turn rested on four leveling feet. LED light strips were used to illuminate the tube from the rear.

During drop tests, water temperatures were maintained within ±1°C of the test condition value. Torpedo models were heated to within ±5°C of the test condition value. Specifics for each test condition are located in the experimental matrix, Table 5.4 in Section 5.4.1.
Figure 4-9: Views of drop test apparatus.
A Vision Research Phantom v12.1 high-speed camera was used to image the torpedo model as it fell in the water column. This model of camera is capable of recording more than 6200 frames per second at 1280 x 800 resolution. The camera was mounted on a tripod stand and rotated 90 degrees so 1280 pixels were available in the vertical direction. Phantom Camera Control (PCC) 2.14 software was used to display, edit and save videos for data processing. Figure 4-10 shows an image of a high-speed video frame obtained during a drop test. Results from this testing are in Section 5.4.

Figure 4-10: Screenshot of high-speed video from drop test.
Contact angle measurements were made on both the coated and uncoated torpedo models prior to testing. The surface of the uncoated model was hydrophilic, as the results in Table 4.5 show. The coated model was clearly hydrophobic by visual inspection, but contact angles could not be measured on it. Small water drops would stick to the needle rather than adhere to the model surface (as depicted in Figure 4-11) and large water drops would simply roll off the model due to its curvature. Dozens of attempts to measure contact angle on the coated model were made but none succeeded due to these issues.

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Contact Angle (degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1</td>
<td>48.0</td>
</tr>
<tr>
<td>#2</td>
<td>46.7</td>
</tr>
<tr>
<td>#3</td>
<td>42.1</td>
</tr>
<tr>
<td>#4</td>
<td>46.4</td>
</tr>
<tr>
<td>#5</td>
<td>42.9</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td><strong>45.2</strong></td>
</tr>
</tbody>
</table>

Table 4.5: Uncoated torpedo model contact angle measurements.

Figure 4-11: Attempt to measure contact angle on hydrophobic torpedo model.
Chapter 5

Experimental Results

5.1 Pool Boiling Tests

Pool boiling tests conducted on the LBL and GVD Corp coatings were useful for determining heat flux and subcooling requirements, as well as for assessing and comparing durability of the coatings.

5.1.1 LBL Hydrophobic Coating

The first test run for the LBL and fluorosilane coating successfully achieved film boiling on the surface of the copper tube, but at a higher heat flux than the approximately 34 kW/m$^2$ that was expected. Patches of film boiling were first observed when the heat flux was approximately 70 kW/m$^2$, and the size of the patches became larger as the heat flux was continuously increased up to the maximum power, 180 kW/m$^2$. When the power was shut off, a uniform film covered the surface of the tube while it cooled until it transitioned to nucleate boiling. The duration of the vapor film from power off to nucleate boiling was 18 seconds.

The second test run was performed in the same manner as the first, but exhibited different results. As the power was increased, the temperature of the pool water rose and nucleate boiling gave way to vigorous nucleate boiling. A transition to film boiling did not occur however, even when the pool temperature reached saturation
and the maximum power was applied. It was believed that the fluorosilane layer was damaged during the first pool boiling test run and that the hydrophobic properties of the surface were lost, resulting in a higher CHF required to initiate film boiling than could be applied. Contact angle measurements after the test confirmed that this was true, as shown in Table 5.1.

5.1.2 GVD Hydrophobic Coating

The first test run for the GVD coating produced film boiling on the middle and upper part of the sample first, and then uniform film boiling at a heat flux of approximately 100 kW/m². At this time the pool had warmed from 22°C to 93°C. The power was turned down in increments to see when the vapor film would be lost, and this happened at 20 kW/m². The power was increased again until film boiling was re-established at 80 kW/m², and then reduced gradually until the vapor film was lost at 20 kW/m². This was repeated one more time with the same effect.

For the second and third test runs, the power was immediately turned to the maximum to see if film boiling could be established in significantly subcooled water. For both tests, the transition from nucleate boiling to film boiling took around seven minutes, which was observed to correspond to the amount of time it took for the pool to heat to approximately 90°C.

5.1.3 Conclusions

The most important takeaways from the pool boiling tests were that film boiling was successfully achieved on both hydrophobic surfaces, but at a higher heat flux than anticipated and only when the water in the pool had heated from room temperature to close to saturation (100°C). The GVD Corp hydrophobic coating was more durable than the LBL coating, as it was able to produce and sustain a vapor film multiple times, whereas the LBL and fluorosilane coating only produced a vapor film the first time.
<table>
<thead>
<tr>
<th>Test Number</th>
<th>Sample Surface Temperature Before Being Submerged (°C)</th>
<th>Qualitative Observations</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1</td>
<td>110</td>
<td>Nucleate boiling</td>
</tr>
<tr>
<td></td>
<td></td>
<td>No film present</td>
</tr>
<tr>
<td>#2</td>
<td>150</td>
<td>Nucleate boiling</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Possible film briefly near top</td>
</tr>
<tr>
<td>#3</td>
<td>220</td>
<td>Nucleate boiling</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Possible film briefly near top</td>
</tr>
<tr>
<td>#4</td>
<td>240</td>
<td>Immediate quenching upon submerging</td>
</tr>
<tr>
<td>#5</td>
<td>270</td>
<td>Immediate quenching upon submerging</td>
</tr>
<tr>
<td>#6</td>
<td>290</td>
<td>Film lasted approximately one second before quenching</td>
</tr>
<tr>
<td>#7</td>
<td>300</td>
<td>Film lasted approximately one second before quenching</td>
</tr>
</tbody>
</table>

Table 5.2: Qualitative results of air heating tests.

Contact angle measurements were again taken on the sample after air heating tests. The average contact angle was 110°, slightly below the value measured after the pool boiling tests, indicating a further small degradation in the hydrophobicity of the coating.
5.2.1 Conclusions

The air heating tests showed that even if the sample was heated in air to the coating’s maximum temperature, it could not produce and sustain film boiling for any meaningful amount of time in a beaker of room temperature water. This issue therefore was less about losing heat from the sample to the water and more about the large amount of subcooling and its effect on CHF. Following this test, the issue of subcooling was investigated in greater depth and it was determined that a substantial increase in heat flux would be required to reach CHF in water with approximately 75-80°C subcooling, as discussed in Section 2.3.1.

5.3 Furnace Heating Tests

Building on the lessons learned in the pool boiling and air heating tests, furnace heating tests assessed the ability to sustain film boiling on a heated sample in only slightly subcooled (90°C) water. Table 5.3 displays the findings of the air heating tests.

<table>
<thead>
<tr>
<th>Test Number</th>
<th>Sample Temperature Before Being Submerged (°C)</th>
<th>Vapor Film Duration (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1</td>
<td>150</td>
<td>2</td>
</tr>
<tr>
<td>#2</td>
<td>150</td>
<td>2</td>
</tr>
<tr>
<td>#3</td>
<td>200</td>
<td>11</td>
</tr>
<tr>
<td>#4</td>
<td>200</td>
<td>10</td>
</tr>
<tr>
<td>#5</td>
<td>250</td>
<td>19</td>
</tr>
<tr>
<td>#6</td>
<td>250</td>
<td>17</td>
</tr>
</tbody>
</table>

Table 5.3: Results of furnace heating tests.

5.3.1 Conclusions

The furnace heating tests established the trend that the hotter the initial surface temperature of the sample, the longer the vapor film would exist before collapsing. This trend followed what was expected, since the vapor film collapses when the surface
cools to below the Leidenfrost temperature. These tests also validated the concept to heat the torpedo model to 250°C and drop it into a column of 90°C water for the drop tests. Calculations indicated that the torpedo model would fall for approximately one second during a drop test, so heating to 250°C was meant to provide a buffer to ensure a uniform vapor film was present throughout the entirety of the drop.

5.4 Drop Tests

5.4.1 Test Matrix

The experimental matrix for drop tests is shown in Table 5.4. At least ten runs were conducted for each test condition.

<table>
<thead>
<tr>
<th>Test Condition</th>
<th>Coating</th>
<th>Model Temp (°C)</th>
<th>Water Temp (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1</td>
<td>None</td>
<td>23</td>
<td>23</td>
</tr>
<tr>
<td>#2</td>
<td>None</td>
<td>90</td>
<td>90</td>
</tr>
<tr>
<td>#3</td>
<td>None</td>
<td>250</td>
<td>90</td>
</tr>
<tr>
<td>#4</td>
<td>Hydrophobic</td>
<td>23</td>
<td>23</td>
</tr>
<tr>
<td>#5</td>
<td>Hydrophobic</td>
<td>90</td>
<td>90</td>
</tr>
<tr>
<td>#6</td>
<td>Hydrophobic</td>
<td>250</td>
<td>90</td>
</tr>
</tbody>
</table>

Table 5.4: Experimental matrix for drop tests.

5.4.2 Test Condition #1

Test condition #1 consisted of an uncoated model at 23°C falling in water at 23°C (room temperature). This test condition was completed to serve as a baseline for comparison to all other test conditions.

Figure 5-1 shows the results of the test runs in this condition. Runs 6, 7, 8, 9 and 13 were the fastest and thus were analyzed further for terminal velocity.
5.4.3 Test Condition #2

Test condition #2 consisted of an uncoated model at 90°C falling in water heated to 90°C. This test condition was completed to understand the impact of heating the water from 23°C to 90°C. The model temperature tested was 90°C rather than 23°C to avoid excessive wait times for model cooling between tests.

Figure 5-2 shows the results of the test runs in this condition. Runs 2, 5, 7, 9 and 10 were analyzed further for terminal velocity.
5.4.4 Test Condition #3

Test condition #3 consisted of an uncoated model at 250°C falling in water heated to 90°C. This test condition was completed for comparison to the film boiling test condition, #6.

Figure 5-3 shows the results of the test runs in this condition. Runs 1, 4, 9, 10 and 11 were analyzed further for terminal velocity.
5.4.5 Test Condition #4

Test condition #4 was identical to condition #1 except for the addition of the hydrophobic coating on the torpedo model. This test condition helped determine how much, if any, impact the hydrophobic coating had on reducing drag in highly subcooled (room temperature) water.

Figure 5-4 shows the results of the test runs in this condition. Runs 3, 6, 7, 8 and 10 were analyzed further for terminal velocity.
Figure 5-4: Runs for test condition #4.

5.4.6 Test Condition #5

Test condition #5 consisted of a hydrophobic model at 90°C falling in water heated to 90°C. This test condition was completed to mimic condition #2 but with the addition of the hydrophobic coating.

Figure 5-5 shows the results of the test runs in this condition. Runs 4, 5, 6, 7 and 9 were analyzed further for terminal velocity.
5.4.7 Test Condition #6

Test condition #6 consisted of a hydrophobic model heated to 250°C falling in water heated to 90°C. It was the most interesting of all the test conditions, as this was the condition where film boiling was expected to occur.

Figure 5-6 shows the results of the test runs in this condition. Runs 2, 3, 4, 5, 6, 9 and 10 were analyzed further for terminal velocity.
5.4.8 Data Analysis

MATLAB by MathWorks was used for data analysis. A MATLAB script was used to process the high-speed videos to output position versus time to Microsoft Excel spreadsheets. Raw position versus time data was compiled in a master spreadsheet and unnecessary data points, such as repeated points before the torpedo model was released and points after the model had reached the bottom of the water column, were deleted from the set to create a clean set of data. The clean data was imported back into MATLAB and plotted to determine the fastest drops for each condition. The precision of the release affected how fast the drop was. The five fastest drops for each condition were further analyzed for terminal velocity, except for test condition #6, where seven drops were analyzed.

To extract terminal velocity from the data, first the clean position versus time was plotted in MATLAB. An example plot is shown in Figure 5-7. A fourth-order polynomial function was fit through the data points to represent the position curve. The derivative of this function was taken to create a corresponding velocity versus
Figure 5-7: Example position vs. time plot.

time curve. Velocity data points were created by evaluating the function at 0.02 s intervals over the time range of the torpedo fall. Finally, a curve in the form of equation 5.5 was fit through the velocity points using MATLAB’s Curve Fitting application to determine the terminal velocity. A representative curve is shown in Figure 5-8. Appendix C contains additional graphs for all of the data.

The equation governing the dynamics of the torpedo model during the fall is:

\[ W - F_B - F_D = (m + m_a) a \]  \hspace{1cm} (5.1)

where: \( W \) is the weight of the torpedo model 
\( F_B \) is the force due to buoyancy 
\( F_D \) is the force due to drag 
\( m \) is the mass of the torpedo model 
\( m_a \) is the added mass for the torpedo model 
\( a \) is the acceleration of the torpedo model

More specifically to this test case, the equation is:
\[ \frac{mg - \rho Vg - \frac{1}{2} \rho \left( \frac{dy}{dt} \right)^2}{\rho} \left( C_D S + C_f A_w \right) = (m + m_a) \frac{d^2y}{dt^2} \]  

(5.2)

where:
- \( m \) is the mass of the torpedo model
- \( g \) is the acceleration due to gravity
- \( \rho \) is the density of the fluid
- \( V \) is the volume of the torpedo model
- \( \frac{dy}{dt} \) is the velocity of the torpedo model
- \( C_D \) is the form drag coefficient
- \( S \) is the torpedo model’s projected area
- \( C_f \) is the friction drag coefficient
- \( A_w \) is the torpedo model’s wetted area
- \( m_a \) is the added mass for the torpedo model
- \( \frac{d^2y}{dt^2} \) is the acceleration of the torpedo model

Assuming the drag coefficients \( (C_D \text{ and } C_f) \) as constants and using initial conditions that position and velocity are equal to zero at time zero \( (y(0) = 0 \text{ and } y'(0) = 0) \), the solution to the differential equation 5.2 is of the form:

\[ y(t) = at - b\ln(1 + e^{ct}) + d \]  

(5.3)

where: \( a, b, c \) and \( d \) are constants

Taking the derivative of the equation for position, equation 5.3, yields an equation for velocity in the form of:

\[ \frac{dy}{dt} = a - \frac{bce^ct}{1 + e^{ct}} \]  

(5.4)

Equation 5.4 can alternately be written as:

\[ U(t) = U_T - \frac{ke^{-t/\tau}}{1 + e^{-t/\tau}} \]  

(5.5)

where: \( U_T \) is the terminal velocity
- \( k \) and \( \tau \) are constants
Once terminal velocity was found for each run, a slight correction was made to account for wall effects using an equation derived by Newton in 1687 [21]. Although this equation was originally derived for spheres, it was considered to give a decent representation of the wall effects for this testing and was better than ignoring wall effects altogether. The equation is:

\[
\frac{U_T}{U_{T\infty}} = \left[1 - \left(\frac{d}{D}\right)^2\right] \left[1 - 0.5 \left(\frac{d}{D}\right)^2\right]^{\frac{1}{2}}
\]  

(5.6)

where:
- \(U_T\) is the measured terminal velocity of the torpedo model
- \(U_{T\infty}\) is the corrected terminal velocity of the torpedo model
- \(d\) is the diameter of the torpedo model
- \(D\) is the inner diameter of the tube

Based on the geometry of the water column and torpedo model, the model was expected to reach 96% of its terminal velocity in an unbounded domain according to equation 5.6. Table 5.5 summarizes the average terminal velocity results of the torpedo drop tests. Film boiling increased the average terminal velocity by 23.1% (condition #3 vs. condition #6).
### Table 5.5: Average terminal velocity results for drop tests.

<table>
<thead>
<tr>
<th>Test Condition</th>
<th>Average $U_T$ (m/s)</th>
<th>Average $U_{T\infty}$ (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1</td>
<td>3.876</td>
<td>4.021</td>
</tr>
<tr>
<td>#2</td>
<td>4.710</td>
<td>4.886</td>
</tr>
<tr>
<td>#3</td>
<td>4.845</td>
<td>5.026</td>
</tr>
<tr>
<td>#4</td>
<td>3.848</td>
<td>3.992</td>
</tr>
<tr>
<td>#5</td>
<td>4.659</td>
<td>4.833</td>
</tr>
<tr>
<td>#6</td>
<td>5.965</td>
<td>6.187</td>
</tr>
</tbody>
</table>

For comparison of the drag reduction between models, an experimental drag coefficient, $C_{Exp}$, was used, where:

$$C_{Exp} = C_D S + C_f A_w$$  \hspace{1cm} (5.7)

Table 5.6 summarizes the changes in drag based on the drop test data. When all other conditions were equal, film boiling reduced the average $C_{Exp}$ by 32.1% (condition #3 vs. condition #6). It should also be noted that, as expected, heating the water also had a large drag reduction effect.

### Table 5.6: Drag coefficient results for drop tests.

<table>
<thead>
<tr>
<th>Test Condition</th>
<th>Average $C_{Exp}$ ($\pm \sigma$)</th>
<th>% Decrease from Condition #1</th>
<th>% Decrease from Condition #3</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1</td>
<td>0.0000472 (0.0000446, 0.0000497)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>#2</td>
<td>0.0000336 (0.0000327, 0.0000344)</td>
<td>28.8</td>
<td>-</td>
</tr>
<tr>
<td>#3</td>
<td>0.0000319 (0.0000289, 0.0000349)</td>
<td>32.4</td>
<td>-</td>
</tr>
<tr>
<td>#4</td>
<td>0.0000478 (0.0000473, 0.0000482)</td>
<td>-1.3</td>
<td>-</td>
</tr>
<tr>
<td>#5</td>
<td>0.0000343 (0.0000335, 0.0000351)</td>
<td>27.2</td>
<td>-</td>
</tr>
<tr>
<td>#6</td>
<td>0.0000216 (0.0000166, 0.0000267)</td>
<td>54.1</td>
<td>32.1</td>
</tr>
</tbody>
</table>

5.4.9 Uncertainty Analysis

An uncertainty analysis was conducted to characterize the randomness of data points gathered in the experiments. The standard deviation of the data reflects the consistency of different drops. Table 5.7 shows that the standard deviations
of terminal velocity for test conditions #1-5 were relatively small, but was notably larger for test condition #6. One possible explanation for this is that the presence of the vapor film made it more difficult for the MATLAB software to consistently analyze position versus time. Table 5.8 shows the subsequent standard deviations of experimental drag coefficient.

<table>
<thead>
<tr>
<th>Test Condition</th>
<th>Average $U_T$ (m/s)</th>
<th>Standard Deviation, $\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1</td>
<td>3.876</td>
<td>0.11</td>
</tr>
<tr>
<td>#2</td>
<td>4.710</td>
<td>0.06</td>
</tr>
<tr>
<td>#3</td>
<td>4.485</td>
<td>0.22</td>
</tr>
<tr>
<td>#4</td>
<td>3.848</td>
<td>0.02</td>
</tr>
<tr>
<td>#5</td>
<td>4.659</td>
<td>0.05</td>
</tr>
<tr>
<td>#6</td>
<td>5.965</td>
<td>0.71</td>
</tr>
</tbody>
</table>

Table 5.7: Standard deviation of $U_T$ results from drop test data.

<table>
<thead>
<tr>
<th>Test Condition</th>
<th>Average $C_{Exp}$</th>
<th>Standard Deviation, $\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1</td>
<td>0.0000472</td>
<td>0.0000026</td>
</tr>
<tr>
<td>#2</td>
<td>0.0000336</td>
<td>0.0000008</td>
</tr>
<tr>
<td>#3</td>
<td>0.0000319</td>
<td>0.0000030</td>
</tr>
<tr>
<td>#4</td>
<td>0.0000478</td>
<td>0.0000005</td>
</tr>
<tr>
<td>#5</td>
<td>0.0000343</td>
<td>0.0000008</td>
</tr>
<tr>
<td>#6</td>
<td>0.0000216</td>
<td>0.0000050</td>
</tr>
</tbody>
</table>

Table 5.8: Standard deviation of $C_{Exp}$ results from drop test data.

Several small sources of error come from the use of the high-speed video camera. In order to image the entire water column, the camera was mounted 3.35 m away from the drop apparatus. Based on the height of the image and the number of pixels available, each pixel corresponded to a length of approximately 1.6 mm. Parallax error could account for at most 1.8 mm of error at the most extreme angles of the torpedo model fall compared to the camera’s frame of view. Refraction error could be as much as 2.8 mm, slightly less than 2 pixels, at the extreme angles of the drop due to light refraction in the water column. Parallax and refraction error were both zero when the model reached the camera height, which was located at half of the water column’s height. The MATLAB script for processing the video to provide position versus time
was considered to have an error of ±2 pixels based on previous experiments. These position errors affected the velocity points and ultimately the terminal velocity value. Additionally, two other small sources of error in the calculation of $C_{Exp}$ arose from weight measurements and the changing density of the water, as it was maintained at ±1°C of the test condition value during testing.

The equation for experimental drag coefficient, $C_{Exp}$, at terminal velocity is:

$$C_{Exp} = \frac{W - F_B}{\frac{1}{2} \rho U_T^2}$$  \hspace{1cm} (5.8)

The error in $C_{Exp}$ from measurements can be estimated using a sum of squares method, where:

$$\frac{\sigma_{C_{Exp}}}{C_{Exp}} = \sqrt{\left(\frac{\sigma_W}{W}\right)^2 + \left(\frac{\sigma_{FB}}{F_B}\right)^2 + \left(\frac{\sigma_p}{\rho}\right)^2 + \left(\frac{2\sigma_{UT}}{U_T}\right)^2}$$  \hspace{1cm} (5.9)

The sources of data acquisition, measurement and processing errors were combined using equation 5.9, and the resulting errors for $C_{Exp}$ are shown in Table 5.9.

<table>
<thead>
<tr>
<th>Test Condition</th>
<th>$\sigma_{C_{Exp}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1</td>
<td>$2.72 \times 10^{-7}$</td>
</tr>
<tr>
<td>#2</td>
<td>$1.77 \times 10^{-7}$</td>
</tr>
<tr>
<td>#3</td>
<td>$2.12 \times 10^{-7}$</td>
</tr>
<tr>
<td>#4</td>
<td>$2.77 \times 10^{-7}$</td>
</tr>
<tr>
<td>#5</td>
<td>$1.96 \times 10^{-7}$</td>
</tr>
<tr>
<td>#6</td>
<td>$2.89 \times 10^{-7}$</td>
</tr>
</tbody>
</table>

Table 5.9: Errors in $C_{Exp}$ due to measurements.
In summary, the uncertainty from measurement instruments and methods is much smaller than that from scatter in the experimental data, especially for test conditions #3 and #6, which are of the most interest. The average reduction in $C_{Exp}$ due to film boiling was 32.1%. Incorporation of uncertainties leads to an interval for reduction of $C_{Exp}$ to between 7.6% and 52.4%. Gathering additional data through an increased number of drop tests would likely help reduce the uncertainty and better quantify the drag reduction due to film boiling.
Chapter 6

Conclusions

The goals of this research were threefold: quantify drag reduction due to film boiling, examine coating durability and assess the feasibility of the proposed concept. Each of these goals has been addressed in this research. Plentiful opportunities remain for follow-on or related work in this interesting area of study.

6.1 Quantify Drag Reduction

Potentially the most interesting objective of this research was to quantify the drag reduction due to film boiling. As reported in Section 5.4.8, film boiling did lead to an appreciable increase in terminal velocity, and thus a decrease in drag. The data from the drop experiments indicates an average drag reduction of 32.1%, which is quite significant. The Reynolds number corresponding to the terminal velocity in the experimental conditions where film boiling occurred was between $2.3 \times 10^6$ and $3.1 \times 10^6$, which falls into the lower end of the turbulent flow regime— the same flow regime that a prototype torpedo operates in while at high velocities.

6.2 Durability of Coatings

The issue of durability can be separated into two main categories: durability during operational use, i.e. when film boiling occurs, and durability during all other
situations, including production, transportation, handling and storage.

Coated samples were always handled with latex gloves and moved with the utmost care to avoid any scratches or contamination. In real life, scratches resulting from transportation, handling and storage would be much more likely than in the laboratory. This type of durability was not a major focus of the research, but would be important for a real world application.

The GVD Corp coating was more durable during pool boiling testing than the LBL coating, and thus was used for the remainder of the testing. It should be noted that for the real world torpedo application, film boiling would only need to be established one time during operational use, and therefore technically either coating would have sufficed. However, for testing purposes, it was important to repeat tests multiple times to observe trends and validate results. Durability has historically been a concern with LBL coatings and this research does not dispute that notion. Though more durable than the LBL plus fluorosilane combination, the GVD Corp coating also exhibited degradation after repeated tests.

6.3 Concept Feasibility

The conclusion of this research is that the idea of drag reduction by film boiling on a torpedo is feasible in that it is possible, but it is still far from ready for real world application. Although a substantial reduction in drag was found as a result of film boiling, it occurred under close to ideal laboratory conditions. The issue of subcooling was handled by testing in heated water; obviously this option is not available in the oceans and seas where torpedoes are used. Heat was applied to the torpedo model by leaving it in a furnace for approximately 30 minutes for testing; in real life, heating would likely need to be done quickly so the torpedo could be fired before the target escaped. There are hurdles that would have to be overcome before this concept could be applied on an operational torpedo, but they are not impossible.
6.4 Recommendations for Further Research

The following list presents some of the areas where the author believes this research could be expanded upon. It is by no means all-inclusive, but merely provides a suggestion of further work that would be valuable to this area of study.

1. Obtain a better understanding of how subcooling affects CHF for this particular situation. It turned out that subcooling had a dramatic impact on the ability to initiate and sustain film boiling during this project. While previous subcooling research has been conducted, often the surface geometry, material, working fluid or other specific parameters varied from what was desired for this research. A systematic series of tests could establish useful data on subcooling directly related to this application.

2. Obtain the boiling curve for the GVD hydrophobic coating. An accurate boiling curve would reliably provide CHF and the Leidenfrost point, which could save time and effort on future projects which utilize the same coating.

3. Develop a plan for safely providing heat to exterior of a torpedo. Sailors and engineers alike would be skittish about heating a live weapon to high temperatures before firing. Further research should include a more in-depth look of if and how the required amount of heat to establish film boiling could be applied to the surface of a torpedo and controlled once film boiling was initiated.

4. Model the effect of film boiling on drag reduction using CFD. This would eliminate the need to perform many physical experiments, which can be expensive and time consuming. CFD would provide a good supplement to the physical testing that was done and could be validated with a limited number of physical experiments.

5. Characterize the drag coefficient reduction specifically for form and friction drag. This research lumped form and friction drag coefficients together into an overall experimental drag coefficient, $C_{Exp}$, but accurately quantifying each
individually would be interesting and undoubtedly useful for more accurately
describing the effect of the film boiling vapor layer on drag. Ideally, this could
be done by expanding on the research of Srinivasan et al. [14].

6. Identify optimal regions for coating placement. The entire exterior surface of
each sample was coated for this research. Since models were small, this was
acceptable; however, on a full scale prototype, a larger area of coating would
result in higher coating costs. It is possible that coating only a specific section
of the surface would still lead to drag reduction but in a more cost-effective
manner.
Appendix A

Torpedo Model Drawings
Figure A-1: Schematic of 1:20 scale model.

Note: All dimensions are in mm
Figure A-2: Schematic of forward section of 1:10 scale model.

Note: All dimensions are in mm
Figure A-3: Schematic of aft section of 1:10 scale model.

Note: All dimensions are in mm
Appendix B

Torpedo Drop Assembly Drawings
TUBE DIAMETER TOLERANCES AS RECEIVED

DETAIL A
SCALE 1 / 4

DRAWN: Bren
CHECKED: QA
MFG: T=E
APPROVED: Bren

DIMENSIONS
SIZE
TOLERANCE: +/- 0.005 UNLESS NOTED
MATERIAL: POLYCARBONATE
SCALE: 1:20

REV: B
SHEET 1 OF 1
PLATE THICKNESS
TOLERANCE AS RECEIVED

.25

SECTION A-A
SCALE 1 / 4

2.00 ± .01
(X4)

7.50 ± .01

Ø .196 ± .001
THRU

CARBON STEEL

MFG
APPROVED

SIZE
REV

DWC NO

A

TopPlate

1:4

sheet 1 of 1
PLATE THICKNESS TOLERANCE AS RECEIVED

.50

\( \phi 6.25 \pm 0.05 \) THRU

1.55 \( \pm 0.01 \) (X 4)

\( \phi 3.97 \pm 0.01 \) (X 2)

\( \phi 7.25 \pm 0.01 \)

1.55 \( \pm 0.01 \) (X 4)

7.50 \( \pm 0.01 \)

22.5°

DRAF/T.
Bren 3/2/2015

QA

3/2/2015

MFG

TITLE

APPROVED

DRAWN

3/2/2015

CHECKED

3/2/2015

B:

BottomSupportPlate

C:

SCALE 1:4

SHEET 1 OF 1

+0.005 UNLESS NOTED

A

B: Bottom Support Plate

C: Carbon Steel

DRAWING NO: A

DIMENSIONS

TOLERANCE

SIZE  A  Bottom Support Plate  C

SCALE 1:4

REV

A

B

C

Page 84
FLANGE THICKNESS
TOLERANCE AS RECEIVED
.375

SECTION A-A
SCALE 1 / 4

GROOVE FOR
EPOXY OF
POLYCARBONATE
TUBE

\( \phi 3.97 \pm .005 \)
THRU (X 8)

\( \phi 5.000 \pm .005 \)

\( \phi 6.00 \pm .05 \)
THRU

\( \phi 3.00 \pm .01 \)

GROOVE FOR
EPOXY OF
POLYCARBONATE
TUBE

DRAWN
Ivan
3/2/2015

CHECKED
Lex
3/2/2015

MFG
Title

APPROVED

DIMENSIONS

INCHES

TOLERANCE

+/- .01 UNLESS NOTED

MATERIAL

GLASS FILLED POLYCARBONATE

SCALE

1:4

Sheet 1 of 1
PLATFORM THICKNESS TOLERANCE AS RECEIVED

- Platform Thickness
- Tolerance: 0.266 ± 0.01
- Thru: 60° TYP
- 10-32 Thread Thru
- Material: 304 Stainless

DRAWN: 3/2/2015
CHECKED: 3/2/2015
QA: _
MFG TITLE: Platform
APPROVED: _
DIMENSIONS: 1
SCALE: 1:1
SHEET 1 OF 1
ELEVATOR THICKNESS TOLERANCE AS RECEIVED

SECTION A-A
SCALE 1 : 1

Ø2.20±.01
(X 2 )
THRU

Ø2.85±.02

Ø3.25±.02

Ø1.75±.02

Ø0.094±.005
THRU

DRAWN
3/2/2015
MFG
APPROVED

CHECKED
3/2/2015
QA

HIGH ST. GLASS FILLED NYLON

TITLE
Elevator

SIZE
A

REV
B

DWG NO

SCALE
1:1

SHEET 1 OF
Appendix C

Data Plots for Drop Tests
C.1 Test Condition #1 - Run 6

\[ U(t) = 3.765 - \frac{7.532e^{-t/0.3769}}{1 + e^{-t/0.3769}} \]  \hspace{1cm} (C.1)
C.2 Test Condition #1 - Run 7

\[ U(t) = 3.951 - \frac{7.898e^{-t/0.388}}{1 + e^{-t/0.388}} \]

(C.2)
C.3 Test Condition #1 - Run 8

\[ U(t) = 3.801 - \frac{7.593e^{-t/0.3608}}{1 + e^{-t/0.3608}} \]  
\hspace{1cm} (C.3)
C.4 Test Condition #1 - Run 9

\[
U(t) = 4.021 - \frac{8.037e^{-t/0.4251}}{1 + e^{-t/0.4251}} \tag{C.4}
\]
C.5 Test Condition #1 - Run 13

\[ U(t) = 3.844 - \frac{7.685 e^{-t/0.3661}}{1 + e^{-t/0.3661}} \]  

(C.5)
C.6 Test Condition #2 - Run 2

\[ U(t) = 4.754 - \frac{9.509 e^{-t/0.4389}}{1 + e^{-t/0.4389}} \] (C.6)
C.7 Test Condition #2 - Run 5

\[ U(t) = 4.72 \times \frac{9.435e^{-t/0.4222}}{1 + e^{-t/0.4222}} \]  

(C.7)
C.8 Test Condition #2 - Run 7

\[ U(t) = 4.684 - \frac{9.374e^{-t/0.4529}}{1 + e^{-t/0.4529}} \quad (C.8) \]
C.9 Test Condition #2 - Run 9

\[ U(t) = 4.768 - \frac{9.533e^{-t/0.4436}}{1 + e^{-t/0.4436}} \]  

(C.9)
C.10  Test Condition #2 - Run 10

\[ U(t) = 4.626 - \frac{9.247e^{-t/0.4401}}{1 + e^{-t/0.4401}} \]  

(C.10)
C.11 Test Condition #3 - Run 1

\[ U(t) = 4.779 - \frac{9.557e^{-t/0.4591}}{1 + e^{-t/0.4591}} \]  \hspace{1cm} (C.11)
C.12 Test Condition #3 - Run 4

\[ U(t) = 4.929 - \frac{9.854e^{-t/0.4711}}{1 + e^{-t/0.4711}} \]  
(C.12)
C.13  Test Condition #3 - Run 9

Uncoated, Model 250 C, Water 90 C

\[ U(t) = 5.049 - \frac{10.1e^{-t/0.5122}}{1 + e^{-t/0.5122}} \]  \hspace{1cm} (C.13)
C.14 Test Condition #3 - Run 10

\[ U(t) = 4.971 - \frac{9.933e^{-t/0.4931}}{1 + e^{-t/0.4931}} \]  

(C.14)
C.15  Test Condition #3 - Run 11

\[ U(t) = 4.497 - \frac{8.99e^{-t/0.4766}}{1 + e^{-t/0.4766}} \]  \hspace{1cm} (C.15)
C.16  Test Condition #4 - Run 3

\[ U(t) = 3.844 - \frac{7.68e^{-t/0.3481}}{1 + e^{-t/0.3481}} \]  \hspace{1cm} (C.16)
C.17 Test Condition #4 - Run 6

\[ U(t) = 3.827 - \frac{7.648e^{-t/0.3476}}{1 + e^{-t/0.3476}} \]  

(C.17)
C.18 Test Condition #4 - Run 7

\[ U(t) = 3.877 - \frac{7.748e^{-t/0.3562}}{1 + e^{-t/0.3562}} \]  (C.18)
C.19 Test Condition #4 - Run 8

\[ U(t) = \frac{3.839 - 7.673e^{-t/0.3489}}{1 + e^{-t/0.3489}} \]  (C.19)
C.20  Test Condition #4 - Run 10

\[ U(t) = 3.854 - \frac{7.703e^{-t/0.3525}}{1 + e^{-t/0.3525}} \]  \hfill (C.20)
C.21 Test Condition #5 - Run 4

\begin{equation}
U(t) = 4.679 \frac{9.353 e^{-t/0.4402}}{1 + e^{-t/0.4402}}
\end{equation}
C.22 Test Condition #5 - Run 5

\[ U(t) = 4.636 - \frac{9.268e^{-t/0.4266}}{1 + e^{-t/0.4266}} \]  \hspace{1cm} (C.22)
C.23  Test Condition #5 - Run 6

\[ U(t) = 4.679 - \frac{9.355e^{-t/0.4182}}{1 + e^{-t/0.4182}} \]  \quad (C.23)
C.24 Test Condition #5 - Run 7

\[ U(t) = 4.72 - \frac{9.438e^{-t/0.4265}}{1 + e^{-t/0.4265}} \]
C.25 Test Condition #5 - Run 9

\[ U(t) = 4.58 - \frac{9.159e^{-t/0.4234}}{1 + e^{-t/0.4234}} \]  \hspace{1cm} (C.25)
Test Condition #6 - Run 2

\[ U(t) = 5.178 - \frac{10.35 e^{-t/0.4632}}{1 + e^{-t/0.4632}} \]  

(C.26)
C.27 Test Condition #6 - Run 4

\[ U(t) = 5.393 - \frac{10.78e^{-t/0.5512}}{1 + e^{-t/0.5512}} \]  

(C.27)
C.28 Test Condition #6 - Run 5

\[ U(t) = 6.048 - \frac{12.1e^{-t/0.6374}}{1 + e^{-t/0.6374}} \] (C.28)
C.29  Test Condition #6 - Run 6

\[ U(t) = 6.238 - \frac{12.47e^{-t/0.601}}{1 + e^{-t/0.601}} \]  \hspace{1cm} (C.29)
C.30 Test Condition #6 - Run 10

\[ U(t) = 6.967 - \frac{13.93e^{-t/0.681}}{1 + e^{-t/0.681}} \]  (C.30)
Bibliography


