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Design and Fabrication of an Accelerated Corrosion Chamber for Naval Applications

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Abstract

An improvement in capability to better manage and reduce degradation of materials in the Department of Navy (DON)'s assets requires a workforce educated and trained in the application of tools, principles, and practices of corrosion engineering. However, the current level of effectiveness of corrosion engineering curricula in universities is not sufficient to address the Navy's need to improve safety and reliability and reduce costs due to corrosion. The senior design (capstone) program in the mechanical engineering program at George Mason University (Mason) with the support of Navy has incorporated the corrosion test design challenges into the senior design course. In this paper, we present the design and development of an accelerated corrosion test (ACT) chamber for conducting corrosion tests under controlled environment. The ACT chamber will simulate both a constant and cyclic marine environment to determine the corrosion performance of materials and coatings. The ACT chamber is light weight, table-top, fully programmable, and safe to operate in laboratory environment, and therefore, preferred over commercially available ACT chambers.

Introduction

Corrosion of metal components in infrastructure, automobiles and aircraft is estimated to cost the global economy $2.5T annually [1]. It is estimated that by properly applying corrosion testing and protection this preventable deterioration could be reduced by up to 35% or $875B [1]. Failure to identify the root cause of corrosion, or even how a specific material corrodes can result in ultimate failure of the material during service. This could lead to catastrophic failure that would ultimately be exorbitantly costly [2]. The Navy invited our team to join in the challenge of developing an ACT chamber that more closely mimics real-world conditions in order to test how a material might corrode during service, and to better predict lifetime and repair cycle [3].

For the academic year 2020-21, a mechanical engineering capstone team at Mason was tasked by DON to continue a project that was started by two of our capstone teams in the previous academic year. The purpose of this project is to develop a chamber that will allow the DON to simulate metal corrosion in marine environments. Since naval assets are exposed to saltwater for long periods of time, components of these assets must be tested to determine their longevity and failure points before being used across the fleet. However, since corrosion damage can take time, an ACT method and apparatus to evaluate corrosion performance of materials in a short period of time is highly desirable. With this team's ACT chamber, the DON will be able to perform standard as well as customized accelerated corrosion tests to determine how materials and components will perform in a marine environment.

Problem Definition

There are several standardized ACTs which use atomized saltwater solutions to uniformly deposit salts, and then control temperature and relative humidity to induce corrosion [4]. Material engineers may select different ACT methods under different situations depending on the metal, the geometry, and the use of the part. An aggressive test may be used to force corrosion to see where a failure point might occur, while more representative tests may be used to compare the protection offered by different coatings. Some ACT chambers use temperature and lid opening to control relative humidity, but it is highly desirable for a chamber to be able to control both temperature and humidity independently and without opening. This minimizes the damage done to the lab by the salt solution and minimizes possible contamination of the specimens in the chamber. The goal of this capstone project was to design an ACT chamber which meets two ACT standards: ASTM B117 [5] and MIL-STD-810 Method 509.7 [6], shown in Figure 1. To the best of authors' knowledge, this is the first fully automated programable table-top ACT. There has been an effort for designing an ACT chamber [7], however, it was simply designed to generate constant environmental conditions with no such capabilities in our design.

Test Condition	ASTM B117	MIL-STD-810, Method 509
Salt Fog Exposure	Continuous	2-Phase Cyclic
Cycle Duration	N/A	24 or 48 Hours
[Cycle Type] Ambient	N/A	Room Temperature <50% RH
[Cycle Type] Salt Fog	35°C ± 2°C 95 – 98% RH 1 – 2 ml/hr/80cm^2	35°C ± 2°C 1 – 3 ml/hr/80cm^2 2.8 L/24hr/0.28m^3
[Cycle Type] SO_2	N/A	N/A
[Cycle Type] Dry	N/A	N/A
Salt Solution	5% ± 1% NaCl	5% ± 1% NaCl
Contaminates (By Mass)	≤0.3% Total Impurity <0.1% Non-Chloride Halides <0.3ppm Copper No Anti-Caking Agents	<0.1% NaI_2 <0.5% Total Impurity No Anti-Caking Agents
pH	6.5 – 7.2	6.5 – 7.2
Atomization Orifice	Not Defined	0.5 – 0.76 mm
Cycle Configurations (Salt Fog/Ambient)	N/A	24/24 48/48

Figure 1. ASTM B117 and MIL-STD-810 Method 509

Proposed Design and Final Design Selection

In order to begin designing to meet these standards, we made a basic list of requirements for our chamber based on the Statement of Work provided to us by the DON. Any proposed design should be able to meet the following requirements for consideration.

The prototype:

- Must be able to spray or fog samples with salt solution.
- Should have storage for salt solution to be used as fog in the chamber.
- Must be able to measure, record, and control temperature and relative humidity in the chamber.
- Should be able to conduct a variety of specific test methods.
- Must fit on a standard lab bench-top and operate from standard power.

- Chamber should be able to hold multiple flat specimens of $1'' \times 2''$ minimum at an angle between 60^o and 90^o
- Chamber should be able to accommodate full parts for testing.

Also, provided to us was a summarized version of various corrosion testing standards, shown in Figure 1. The team has investigated various methods to satisfy the requirements of this chamber. The main topics of interest were heating, exhausting, and humidifying systems. We also investigated different methods for spraying the salt solution at an appropriate flow rate and droplet size. The method considered for heating the chamber was heated flooring or heated walls. Exhaust methods utilized a salt filter and condensing system to prevent the corrosive fog droplets within the chamber from escaping into the surrounding lab environment. Implementing a humidifying bubble tower for increasing the relative humidity within the chamber and having fans for reducing the relative humidity appeared to be the most effective methods for controlling the humidity of the chamber. Lastly, to effectively spray the salt solution within the chamber, both air atomizing nozzles that utilize compressed air and hydraulic nozzles were investigated. Figure 2 shows a) final design CAD model, b) various stages of manufacturing, c) design completion, and d) LCD screen to setup test parameters.

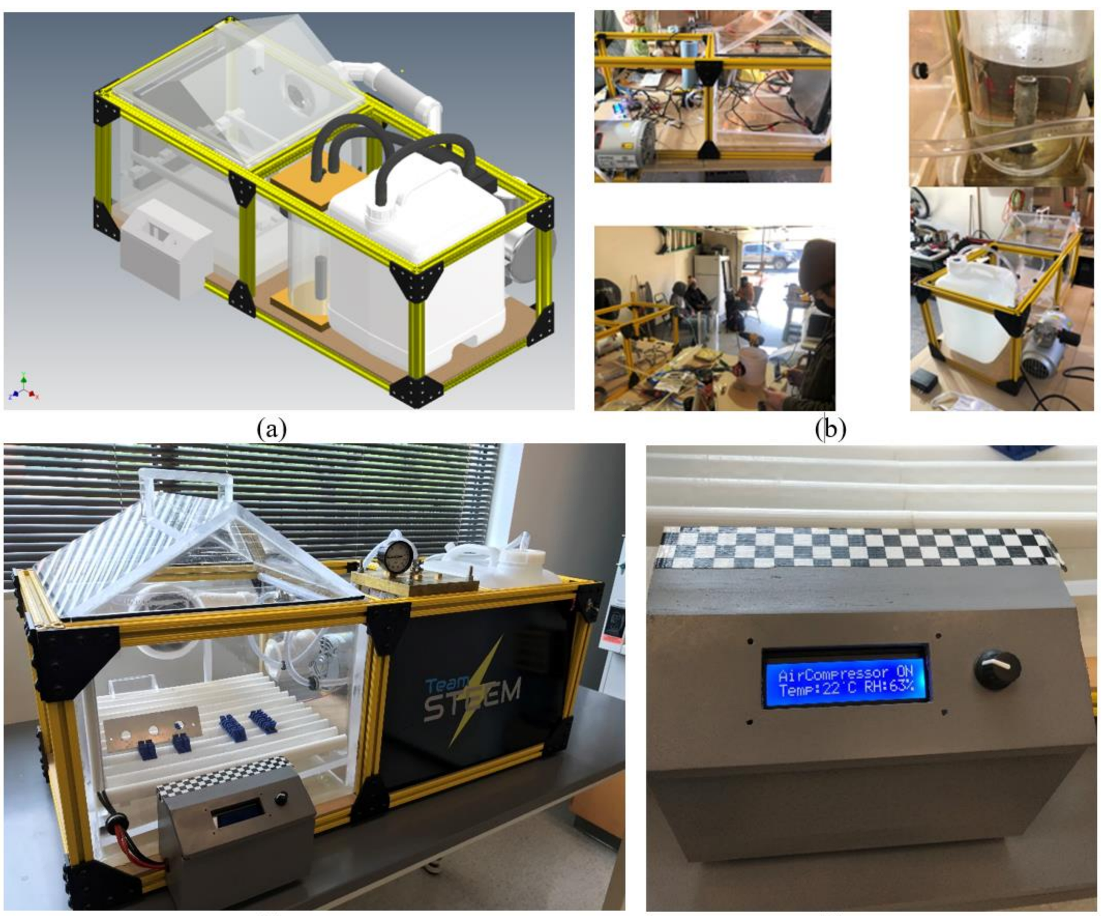


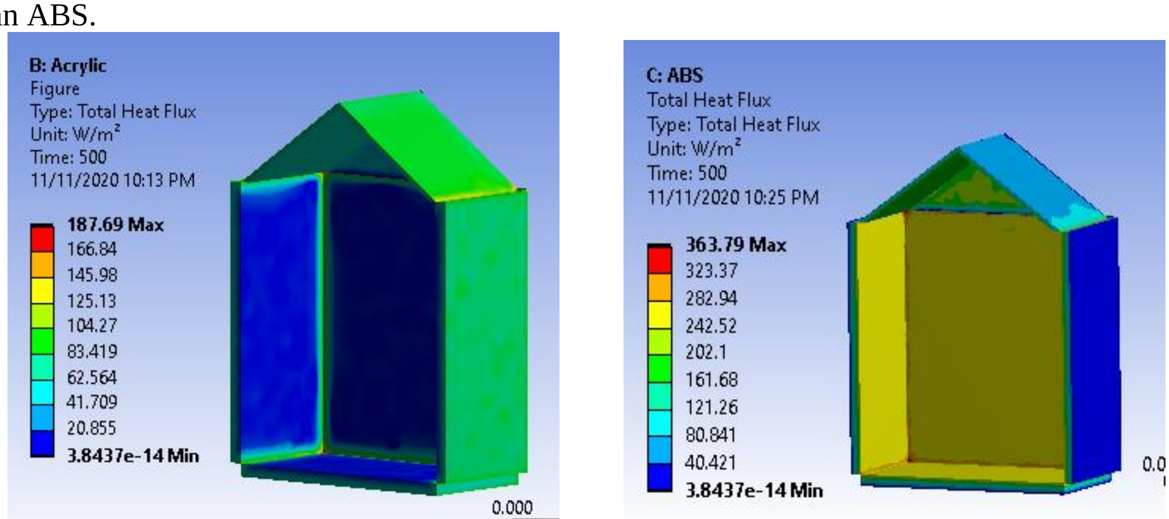
Figure 2. The ACT chamber: a) an isometric view of the chamber, showing the electronics housing at the front, b) various stages of manufacturing, c) final ACT chamber, and d) LCD screen for monitoring chamber condition and setting up the test parameters.

The capstone team included five students and one faculty advisor. Initially, the team had virtual weekly meetings with the advisor. However, closer to the end of the project, the team had bi-weekly meetings with the advisor. All team members would meet in the machine shop weekly, at designated times due to Covid-19 restrictions, to conduct assigned tasks. The role of each team member is as following: one student took the technical writer and manufacturing lead. The other student was responsible for CAD design of mechanical components. Third student took the lead for software development and another student took the role of financial officer, responsible for materials selection and component purchases. The fifth student was responsible for electronics and circuit design. After meeting with the advisor and getting the necessary information for drafting an initial design, the team began by researching material necessary for the artifact such as nozzles, plexiglass, metal framing, etc. The initial design had been critiqued by our advisor and with that feedback the team developed three different preliminary designs with different aspects while also meeting necessary standards.

Results

The designed ACT chamber was able to meet the requirements of both standards ASTM B117 and MIL-STD-810 Method 509.7. To get an accurate reading of temperature and relative humidity throughout the chamber, two DS18B20 waterproof temperature sensors and an Adafruit DHT22 temperature/humidity sensor were used with the Arduino. These devices each sends data to the Arduino at regular intervals of 750 milliseconds, which were averaged in the code and displayed to the LCD screen (Fig. 2d) as the test was conducted. The LCD screen provides the user with ability to select between the ASTM B117, MIL STD 810 24Hr cycle, and MIL STD 810 48Hr cycle tests. For the purposes of demonstrating our chamber on capstone day, a demo test was performed as well.

We further performed preliminary ANSYS simulations to determine the best material for the chamber housing. These simulations were used to verify whether ABS or acrylic would hold heat better. As shown in Figure 3, the acrylic had a lower total heat flux and could hold heat better than ABS.



(a) (b)

Figure 3. a) Total heat flux with Acrylic, and b) total heat flux with ABS

The chamber performance was evaluated by testing the functionality of each subsystem as the code for the corrosion tests were conducted. The key components that needed to be monitored were the temperature, relative humidity, and spray inside the chamber, which the team ensured stayed within the outlined standards during the wet and dry cycles. Due to time constraints, evaluation through a full two-week test period was not possible, but the temperature of the chamber was monitored over a long enough period to verify that the heating pad could maintain the required temperature of 35°C. As shown in Figure 4, the temperature of the chamber was measured over a two-hour period and was capable of reaching and maintaining 35°C. Additionally, the relative humidity within the chamber very quickly rose to 95% once the spray began, typically within a minute, and did not drop below 95% at any point between spray cycles.

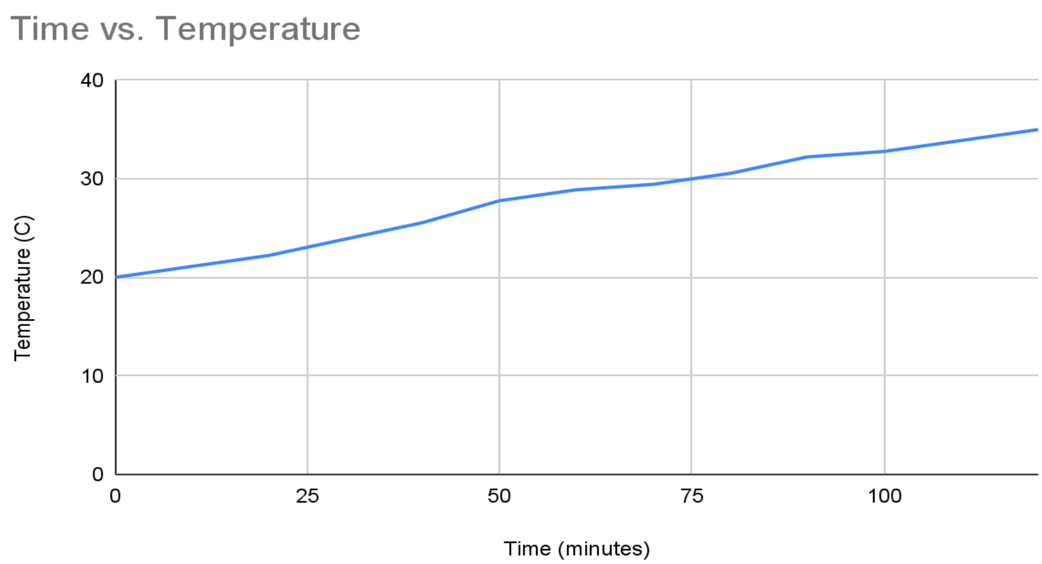


Figure 4. Performance results of heating pad after two hours

Since the dry cycle only requires the chamber to be maintained at ambient temperature and relative humidity below 50%, we also evaluated the effectiveness of the exhaust system in cooling the chamber down without the lid needing to be opened. The chamber temperature decreased quickly, dropping back down to ambient condition within an hour. The relative humidity remained above 90% and did not drop below the required 50% unless the chamber lid was opened. We were unsure on whether moisture gets inside of the humidity sensors and will not evaporate until the chamber lid is opened or if the relative humidity stays this high unless the air is vented outside through the lid opening. This problem persisted even after enclosing the humidity sensor to prevent any solution from directly landing on it. Overall, the exhaust did not quite meet expectations, and we have included potential solutions in the recommendations for future work. Many salt fog chambers do require the lid to be opened to reduce the relative humidity though, so while we were not able to reliably decrease this value using our current exhaust setup, we believe that our design can still be reliably used for corrosion testing. A recommendation for future work is to add a dehumidifying system to the chamber. This modification was beyond the time and budget of our team, however, can be readily added to the current design without major modifications to the structure of the chamber.

During the wet cycle, a constant salt fog can be maintained within the chamber and unless the lid is immediately opened, this fog does not leak. Since there is such a small amount of salt solution being sprayed at any given time, the solution tank should not need to be refilled for at least a couple days and there are no problems with the sprayed solution being drained from the chamber. Additionally, the code has been extensively tested and performed exactly as we expected it to. The exact timings between the air compressor and water pump turning on and off to create a fine mist were evaluated via trial and error, and the spray happened every 193 seconds as expected, where a mist was maintained for that entire duration.

Overall, the authors believe our performance results have shown that the chamber can be reliably used for its intended purpose, which is to run corrosion tests adhering to ASTM B117 and MIL-STD-810. Further testing and potential design changes need to be done on the exhaust to determine the exact reason for the relative humidity reading so high even after the temperature has dropped and the fog is gone. This should not have a great impact throughout tests since the lid would only need to be opened once every 24 to 48 hours for the MIL-STD-810 and not at all for the ASTM B117 test, which has no dry cycle.

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