Project Number IQP-MQF 2832

An Interactive Qualifying Project, Submitted to the Faculty of

WORCESTER POLYTECHNIC INSTUTE

in partial fulfillment of the requirements for

The SLICCvac Medical Vacuum Cleaner

Solid • **L**iquid • **I**mmediate • **C**ontamination • **C**ontainment • **Vac**uum

by

Jackson Beall Ariel Garnet Rohan Jhunjhunwala

Professor M. S. Fofana, Advisor

Mechanical Engineering Department

Table of Contents

List of Figures

Abstract

Ambulance cleanliness is a large factor in the occurrence of HCAI's in the United States, due to current cleaning methods resulting in high rates of contamination. Thus, a suitable device, if equipped onboard ambulances, could allow EMS personnel to clean any contamination quickly and without having to finish the transport. If successful, this device could drastically decrease rates of HCAI's. The scope of this project was to design a suitable medical vacuum cleaner that effectively cleans a during-transport body fluid spill, requiring minimal effort by EMS personnel, and especially limiting their exposure to the dangerous contaminants. Designs were analyzed via computer simulations, and prototyped via additive manufacturing. The results of these designs imply that such a vacuum cleaner would provide excellent cleaning power with very little effort from paramedics, and effectively limit their exposure to dangerous pathogens. Furthermore, the designed cleaner would have a profound impact on the cleanliness of any ambulances which implement it, and this impact has worldwide implications about the future of EMS cleanliness.

1. Introduction

Hospitals focus on the cleanliness of its facility to uphold the most sterile environment to perform medical procedures because introduction of healthcare associated infections (HCAIs) can cause fatal consequences to any party involved. The ambulance is often not kept up by the same stringent cleaning procedures due to maximization of patient care being the utmost priority within given time constraints, small crevices inside the ambulance, and cleaning tools not being easily accessible when needed. When hazardous waste is deposited from a patient onboard an ambulance, the emergency medical service (EMS) personnel is first attentive to the patient's ailment before the sanitation of the ambulance is addressed, if and only if the patient is secure the biohazard can be attended. In most cases, the patient is delivered to the hospital before the ambulance can be cleaned. Gloves are the main form of personal protective equipment to avoid paramedic exposure to contaminants, sometimes face masks or goggles are used depending on the intensity of the mess. Cleaning procedures differ based on the method that the hospital requires; some paramedics clean the ambulance themselves while others rely on third party companies to perform the duty. An interview was conducted with an UMass Paramedic during which he confirmed cleaning was performed solely by in-house personnel. First, bio hazardous debris are removed by wiping up with towels or paper towels that must be disposed of in biohazard removal bags or bins in correspondence with environmental protection agency (EPA) and occupational safety and health administration (OSHA) regulations [1]. The visible surface that was exposed to contaminants is then soaked in either specialized ambulance cleaners or common household products such as bleach, and wiped with paper towels, which are then disposed of according to the same regulations. The biohazard waste bags or bins are either incinerated at an in-house or third party service. The method that is currently applied lacks the addition of technological advances that would better the efficiency of sanitation within the ambulance allowing for safer transportations of patients and paramedics involving an integrated system at a minimal cost alteration, limitation of cross-contamination, and easier use than presently utilized. The ambulance requires a compact, sterilized device that will eliminate cross-contamination, as well as provide reliability and simplicity when cleaning any bio hazardous substances, but be compatible to current cleaning expenses.

Our team's challenge is to design a device that will provide this alternative method for cleaning the ambulance. In order to satisfy the aforementioned goals, our team came up with the concept of the Solid/Liquid Immediate Contamination Containment Vacuum, or SLICCVac. The most prominent requirement of the SLICCVac is to isolate contaminants and to prevent cross-contamination. To these ends, the SLICCVac will feature disposable components, such as the vacuum nozzle, and the container into which the debris will be deposited. The container will be marked in accordance with OSHA regulations for biological and biohazard waste disposal. The container will also employ cyclonic filtration in order to isolate debris, and prevent contamination of non-disposable components [2]. Further filtration will also be employed, in accordance with HEPA regulations [3], Manufacture of the container, including all components necessary for cyclonic filtration must be able to be completed at minimal cost, in order to ensure that it can be disposed of after each use. Vacuum molding of polyethylene plastics is commonly used in low-cost applications, and such plastics are suitable due to low reactivity and high abrasion resistance [4]. Though ambulance electrical systems are capable of supplying the common house current of 115VAC, the SLICCVac will be powered from the 12VDC that is supplied by the engine to avoid power loss in the AC inverter [5]. Because of the power constraints, the SLICCVac's motor and vacuum turbine, or impeller, will have to be chosen carefully. The motor and impeller design will maximize vacuum pressure and flow rate, while minimizing electrical input power. After the design of each component is optimized, they will be combined together and located strategically in the ambulance cabin, so as to provide easy access, yet remain unobtrusive when not in use. The container, vacuum nozzle, and filtration system will be combined into one disposable unit that employs a quick-connect mechanism to be regularly replaced after cleaning. The motor and impeller will be housed in a compartment within the ambulance, and vent the exhaust air outside the ambulance. Based on our background research, including conversations with UMass paramedics, we believe that the SLICCVac will prove to be an effective and useful tool which addresses the serious problem of ambulance cleanliness.

Health care technology has continuously progressed in almost every field except emergency medical transportation. As we have seen in this chapter, ambulance cleaning procedures employ archaic methods which often leave the ambulance in unsanitary conditions due to the time required to perform them. Furthermore, these methods can expose ambulance personnel to dangerous biohazards. To address these inadequacies, we will develop the

SLICCVac. The SLICCVac is a vacuum-cleaning device that the EMS personnel will use to clean the ambulance during transport. The device will be easy to use, limit the paramedics' and patient's exposure to life-threatening diseases, and prevent contamination of other ambulance equipment. Chapter 2 provides a literature review wherein we will present the information contained in each reference text, and analyze it's pertinence to the SLICCVac project. The review will first examine those texts that discuss the history of EMS, followed by texts that describe current common cleaning procedures in ambulances. The next section will discuss the regulations that affect the SLICCVac, proceeded by two sections containing technical research, one about filtration techniques, and the other about current vacuum technologies. Chapter 3 will present the development and testing of the SLICCVac prototype, including all technical design documents and figures, as well as an examination of our results. The final chapter, Chapter 4, will contain an analysis and discussion of the project, with mention of limitations, significance of our results, including scope and application of the SLICCVac.

2. Literature Review

2.1 What is an Ambulance?

Ambulances are vehicles used to transport people from or between places of treatment. Within the United States, there are 15,276 ambulance services, which contribute to a total of 48,384 ground ambulance vehicles [6]. In 2010, there were between 130 million and 247 emergency department visits in the United States, and 10.5% of those visits were preceded with ambulatory medical care [7]. The history of the ambulance will be analyzed to discover the technological advances of the ambulance up until the current times. The present form of the ambulance will be explained, and distinct ambulance types and components will be presented. Ambulance passengers include EMS (emergency medical services) personnel and patients. The EMS is vital in maintaining the proficiencies of the ambulance and any care given during transport. People use the ambulance for a variety of reasons and need a reliable service that removes them from harm's way, rather than endangering them further.

2.1.1 Historical Background of Ambulance

Emergency medical services were informally founded during the Civil War era when it was necessary to have a mobile treating center to care for injured soldiers [8]. Battles were fought in many types of areas and conditions, so access to medical facilities was infrequent; and having access to a mobile medical center helped save more lives [8]. The first civilian ambulance was initiated in Mare Island, California in 1865 [9]. As shown in Figure 1, this first ambulance employed the most effective transportation method at the time; a horse-drawn carriage.

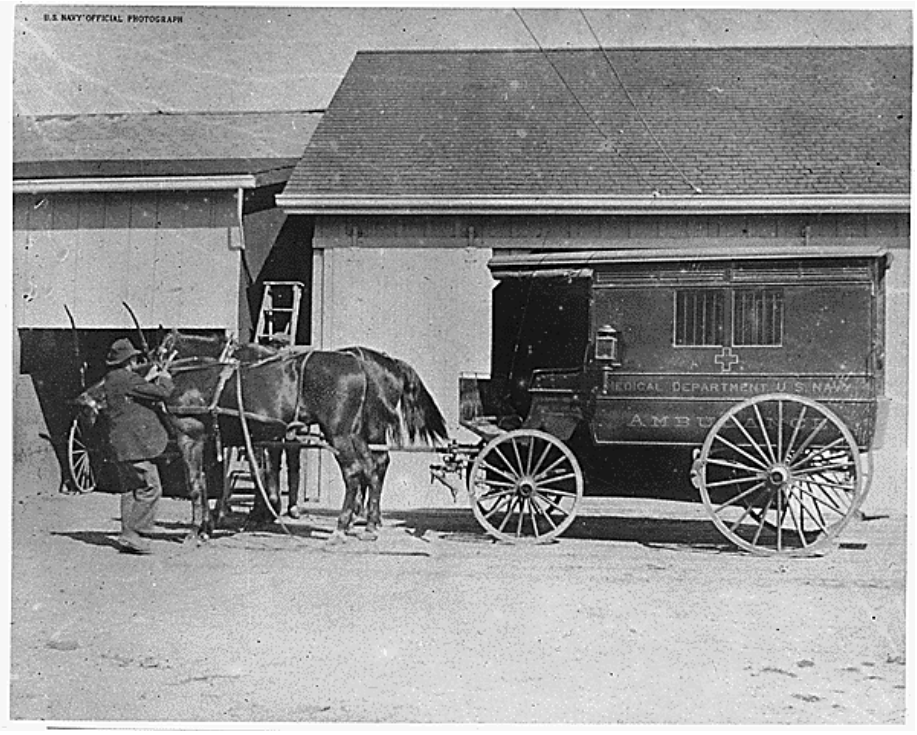


Figure 1: First Ambulance, 1865, US Navy Yard, Mare Island, CA

The overall stability, space, and reliability of the first ambulance were insufficient due to the limited technology that was available at the time, as well as the lack of knowledge and experience with mobile medical vehicles. During World War I, the medical personnel used carriages powered by electricity, steam, or gasoline to carry wounded soldiers to safety, and also began using a wider range of medical equipment [8]. Following WWI, civilian ambulances underwent significant changes, including the addition of a surgeon and radio dispatcher (in some cases). In 1950, the medical vehicle took on its official role as the ambulance that we recognize today [8].

Throughout the years, many articles of legislation have regulated emergency medical services, such as the National Highway Traffic Safety Act, the EMS Systems Act, and the EMS Agenda for the Future. The National Highway Traffic Safety Act of 1966 was enacted to standardize EMS training, recommend radio communication, and it also encouraged community involvement. The Department of Health, Education, and Welfare (DHEW) initiated the EMS Systems Act in1973, which established 300 new EMS programs, required radio dispatching, and consolidated EMS training. In 1996, the EMS Agenda for the Future was drafted to integrate

EMS into other medical professions, in addition to devising consistent instruction and certifications [8].

The history of the ambulance is important because it provides background information on the initial ambulance and its development, from which we can derive knowledge which is influential in developing modern ambulances. The ambulance is an essential societal device to save lives, but history reveals that no new major innovations have recently been made in the emergency medical service field. The ambulance may be due for revision and technological advancement.

2.1.2 Current Ambulance and its Components

The current ambulance standards, as stated by the Star-of-Life Ambulance, are defined by six distinguishing factors [5]. An ambulance must have driver and patient compartments. The driver compartment is the front of the ambulance, and it houses the driver and vehicle controls. The patient compartment must be able to hold one emergency medical service personnel and a patient, positioned on the primary cot to receive life-support as needed [5]. A full patient compartment, with the exception of the cot, or gurney, is shown in Figure 2.

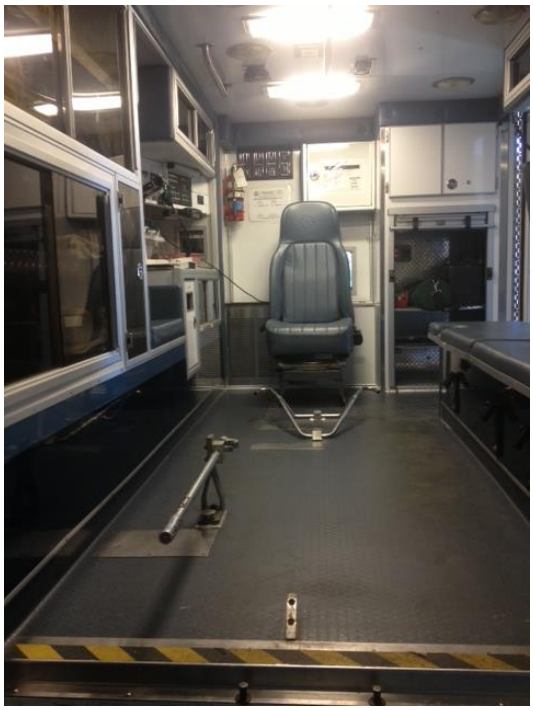


Figure 2: Photograph of the patient compartment of the ambulance

The ambulance must include life-saving equipment and supplies inside the ambulance for patient care. These necessary materials should be located in the drawers and cabinets on the sides of the patient compartment (Figure 2). All aspects of the ambulance must be safe, comfortable and must not aggravate the patient's injury or illness. Since the ambulance was created to assist civilians, all of its components should be designed to improve patient care [5]. A two-way radio communicator is required inside the ambulance, so communication can be maintained between the emergency departments. To ensure that the ambulance is visible to the outside environment during transport, ambulances must be equipped with audible and visual traffic warning signals [5]. Ambulances are found all over the world have the same purpose: to save lives. An example of an ambulance from Australia, Turkey, and Costa Rica reveals that ambulances have a similar appearance (Figure 3A-C).

Figure 3: Examples of ambulances around the world

The above examples all include very distinctive bright red markings on a white vehicle. Each vehicle has labels that notify the public of the nature of the machine and can be universally recognized. There are four different types of ambulances: Type I, Type II, Type III, and Type IV mini ambulances [10]. A Type I and Type II ambulances are nearly the same, except a Type I ambulance has a square patient compartment, mounted onto the chassis preventing access between the driver and patient compartments. In contrast, Type III ambulances have the square patient compartment mounted onto a cut-away chassis, so the EMS personnel may walk between the driver and patient compartment [10]. The photograph in Figure 3A displays a Type I model. Airports, chemical plants, oil refineries, and Advanced Life Support transports are the most

common places where Type I and III ambulances are employed. A Type II ambulance is built using a van type vehicle, modified with a raised roof (Figure 3B-C). Type II ambulances are mostly used for used for hospital purposes and carry equipment for Basic Life Support. [10] The mini ambulance (Type IV) is built upon a golf cart chassis, making it very versatile and more affordable, and also carry medical equipment for Basic Life Support [10].

2.1.3 Ambulance Personnel

An ambulance must have two EMS staff on board, one driver and one in the patient compartment, providing care to patients. The hierarchy of EMS personnel from lowest to greatest position is as follows: Basic (EMT-B), EMT-Intermediate, and Paramedic [8]. An EMT-Basic has the ability to aid in simple tasks (e.g. applying bandages or antiseptic), as well as to supply medications such as oral glucose, epinephrine auto-injectors (Epi-Pens), and oxygen. An EMT-Intermediate is the position between Basic and Paramedic, and is divided into EMT-I/85 and EMT-I/99. An EMT-I/85 has the skills to proctor several invasive procedures that an EMT-Basic cannot, such as IV therapy. [8] An EMT-I/99 can perform more complex procedures, including needle-decompression, electrocardiogram monitoring, and nasogastric tubing. In many cases, EMT positions are assigned on a volunteer basis [8]. Mark Wintle is member of a New Jersey EMS and displays the uniform used in his department in Figure 4.

Figure 4: Mark Wintle displaying an EMS uniform for New Jersey

The EMS uniform has the distinguishing EMT badge displayed on the arm and a name tag shown across the chest. EMT uniforms do vary from location to location, but the prominent badge is always clearly shown. EMS personnel wear these distinct and easily recognizable uniforms facilitating quick identification by civilians.

Paramedics are paid employees of either public or private medical institutions. They carry the highest authority over medical care until the patient arrives at the hospital, and they are able to perform a wide breadth of practices [8]. In the U.S, Paramedics are commonly identified by a badge with the word "PARAMEDIC" written across it, as well as the Star of Life logo as shown in Figure 5.

Figure 5: Paramedic badge baring the Star of Life logo

The badge, in Figure 5, stands out with the commonly acknowledged emergency service colors of red and blue. Although the Paramedic uniforms vary by location, the badge is consistently placed on the upper arm of the uniform and is visible at all times when working. EMT members and Paramedics often work together, but that depends on the medical facility. For example, Worcester, MA ambulance services employ only Paramedics for operation, while Boston, MA utilizes teams of EMTs and Paramedics.

2.1.4 Ambulance Emergency Usage

Ambulances are used for purposes involving both emergency and non-emergency care, though emergency situations are more common. The St John Ambulance Department of Western Australia possesses 466 ambulances, which responded to 194,445 cases in the metropolitan area and 23,495 cases in the country area in 2012 to 2013. [11] In the United States, there were about 16.2 million patients who arrived at hospital emergency departments by ambulance in the year 2003, or about 44,300 per day and 1,800 per hour [12]. The average number of ambulance arrivals for a given twenty-four hour time period in the U.S. is exhibited in Figure 6 [12].

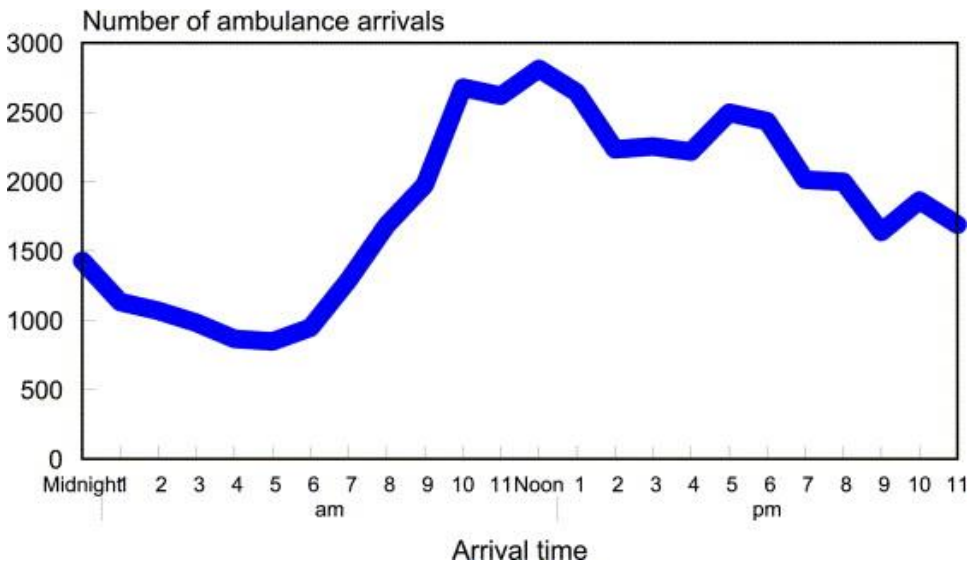


Figure 6: Emergency ambulance arrivals by hour

In the above figure, the greatest level of ambulance activity was between 10 AM and 1 PM. However, a rise in ambulance usage frequency can also be seen between 5 PM and 7PM. The highest number was at 12 Noon with about 2,800 ambulance arrivals, and the lowest was at 5 AM with about 750 arrivals. For each day of the week, the number of ambulance arrivals per minute is shown in Figure 7, for patients using the ambulance for illness as well as injury purposes. [12]

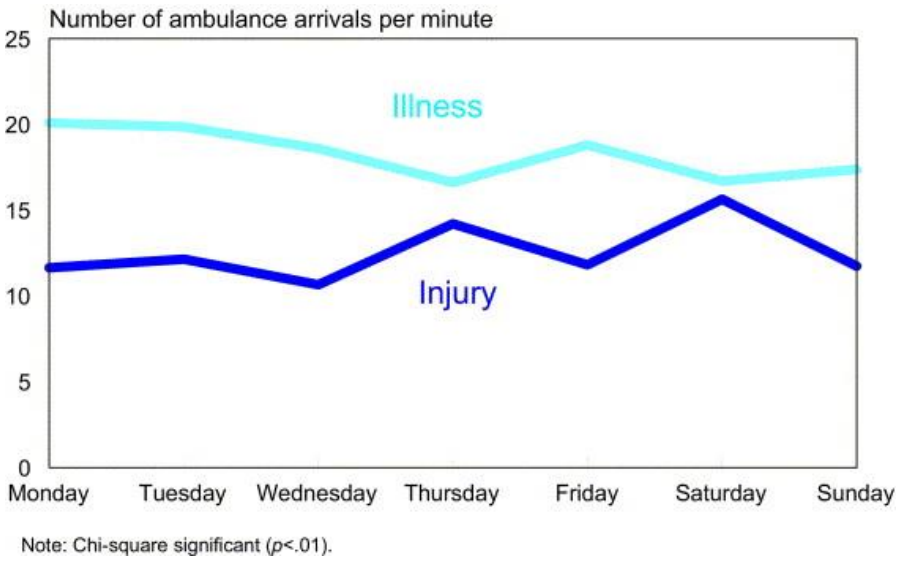


Figure 7: Emergency ambulance arrivals by day and type of condition

Figure 7 illustrates that 59.3% of patient visits in 2003 were due to illness, and 40.7% were due to injury/poisoning/medicinal reaction. [12] Ambulance arrivals due to illness and injury occurred at a moderately consistent rate throughout the week. Illness-related arrivals, represented by the light blue line, occurred more frequently than injury-related ones, represented by the dark blue line. The average number of ambulance arrivals per minute was about 31 (Figure 7). An overall downward trend of ambulance arrivals can be seen, and the highest level of ambulance activity occurred on Monday.

The greatest need of the ambulance is for illness-related purposes. Illnesses are usually accompanied by harmful contaminants that could potentially infect another individual. Cleaning measures must be employed in order to remove any contaminants before they are exposed to anyone else. Since there are times in the day during which the ambulance is in high demand demonstrates a need for an onboard cleaning apparatus which is easy to operate and access.

2.2 Cleaning Practices and Contamination in Today's Ambulance

Cleanliness of an ambulance is necessary to provide sanitary conditions to treat patients, so further complications do not arise. Before cleaning of an ambulance can begin, the correct personal protective equipment must be worn to prevent patient to EMS contamination. The basic outline of an ambulance cleaning procedure will be discussed later in this section, as will information on more extensive cleaning methods. Additionally, a segment will be devoted to the problems with the way in which EMS staff apply disinfectants and cleaners to kill bacteria. The section will conclude a presentation of an experiment conducted on a group of ambulances, revealing bacterial contamination, both prior to cleaning and after.

2.2.1 Personal Protective Equipment

Personal protective equipment, or PPE, is "equipment that will help the user against health or safety risks at work". [13] There are many injuries which PPE helps to prevent, such as inhalation of contaminants, tripping hazards, skin contact with dangerous substances, and particles splashing into eyes. EMS members use PPE when interacting with a patient, as well as when cleaning the ambulance. [13]

The extent of the contamination in an ambulance influences the amount of protective equipment used. At the very least, gloves are used while cleaning the ambulance. Medical gloves are commonly sold in blue, purple, or white. Figure 8 illustrates a pair of blue latex gloves:

Figure 8: Personal protective equipment: blue latex gloves

Gloves protect the user from abrasions, chemicals, and biological contaminants; and should be worn whenever contact with a patient and his or her bodily emissions is likely. [13]

Safety glasses are also a basic form of PPE and should be used to protect the eyes from chemical splash or contaminating projectiles. Feet must be completely covered by shoes which have a sole designed limit the danger of slipping. Filtering face masks are used to prevent contaminates from entering the respiratory system at the EMS personnel's discretion. To protect the whole body, an apron is often worn [13].

2.2.2 Standard Ambulance Cleaning Procedure

The cleanliness of an ambulance is important because it protects both the EMS personnel and patients from harmful contaminants. Exposure to contaminants could result in a healthcare-associated infection (HCAI), which could be costly to both the patient and EMS personnel. EMS personnel commonly perform regular cleaning, but extensive cleaning may be done on or off-site by a third-party, depending on the institution's policy. The Salt River Fire Department requires that the ambulance is "properly cleaned after every transport in a standardized manner;" which ensures a sterile environment to transport employees and patients. The Salt River Fire Department's ambulance cleaning procedure is outlined below. [1]

1. To be performed between calls and at the end of each shift
2. Wear appropriate PPE
    - Mandatory: goggles and gloves
    - If necessary: isolation gown, face mask, and/or booties
3. Pick up large debris with towels and paper towels
4. Wipe up liquid waste with paper towels
5. Spray with cleaning/disinfecting agent (ambulance specific or household product)
6. Wait 5-10 minutes
7. Dry with paper towels
8. Various ambulance equipment requires cleaning of specialized equipment such as patient restrain straps, portable suction units, and radio equipment

9. Collect all waste products and used cleaning supplies in red or bio hazardous specified bags/bins

10. Dispose of bags safely, either by the EMS department of by third-party companies

11. Wash hands

The ambulance cleaning procedure aids in maintaining sanitary conditions, which allow the EMS member to effectively treat the patient. Ideally, the ambulance is cleaned after every shift and transport, but the need for the ambulance sometimes prevents the employees from cleaning the ambulance as they properly should. The ambulance must be stationed at a medical facility in order to receive a cleaning due to the equipment required to properly perform the procedure and dispose of the waste [1]. The current cleaning method does not allow for quick clean-up, nor containment of biological waste while the ambulance is in use.

2.2.3 Vigorous Cleaning Efforts

Although the current cleaning policy is adopted by many agencies, there are some groups that require a more rigorous approach to cleaning ambulances. The United States Centers for Disease Control and Prevention estimated that HCAI's accounted for as many as 1.7 million medical cases and around 99,000 deaths annually in the United States. [14] As a preventive measure, ambulance cleaning should be performed for every patient, regardless of their physical state, since even healthy patients could deposit harmful contaminants. Even a uniquely skilled EMS personnel cannot provide effective care if contaminated equipment in the ambulance exposes the patient to dangerous bacteria and viruses [14].

Bacteria and viruses have the ability to adapt to various stimuli at relatively fast rates and have been found to be capable of surviving in even the most inhospitable environments. The first step in developing suitable cleaning procedures is to select a proper cleaning agent for a specific contaminant, and then using the cleaning agent in the correct manner. Each cleaning agent has particular concentration requirements, as well as a minimum soak time, and these must be upheld in order to successfully remove the contaminant. All products used should be regulated and

tested by the Environmental Protection Agency (EPA) to ensure they are safe for hospital use [14].

Before beginning to clean the ambulance, it is very important to use PPE. Large particles and trash should be picked up and disposed of in designated locations. A basic cleaner/disinfectant should first be applied to perform a pre-clean, followed by a soak in the specialized hospital grade disinfectant for the correct amount of time. It is imperative to clean all surfaces of the ambulance, even those that may not apparently need cleaning. Harmful particulates may be microscopic, so a simple visual inspection may not be sufficient. Special attention should be directed towards the door handles, radio equipment, cabinet handles, and ceiling handles.

An article written by paramedic Chris Kempt describes his use of a Shop-Vac to expedite the cleaning of the ambulance. [14] The Shop-Vac was used in the ambulance patient compartment, which allowed for easier access to hard-to-reach places, and allowed cleaning to be completed in less than half the time that normal cleaning methods take. Also, the Shop-Vac has the suction power to pick up both wet and dry material without actually having to touch the waste. Figure 9 displays the common Pro-Series Shop-Vac, sold Global Industrial.

Figure 9: Photograph of Shop-Vac

The Shop-Vac is a great tool that reduces labor time, but it does have some drawbacks. As Figure 9 illustrates, the Shop-Vac is an additional piece of equipment, not generally included in an ambulance. The size and shape of the vacuum does not facilitate ease of use and mobility,

preventing storage and use in some smaller areas of the ambulance. Also, the Shop-Vac is a very noisy machine that cannot be used during transport, as the noise may disturb sensitive passengers. The driver compartment requires cleaning too, as the steering wheel and controls may become ridden with particulates [14].

2.2.4 Bacterial Contamination after Cleaning

It is impossible to assess the effectiveness of any cleaning procedure unless a reliable method of measuring contamination levels can be developed. In a study conducted by Nigam et. al, specific locations in Welsh ambulances, from three regional areas of Wales deemed Region A, B, and C, were swabbed between January and December of the year 2000, both before and after performing cleaning procedures [15]. Seven main sites were chosen: inside cupboards/drawers, the steering wheel, Entonox (gas and air) masks, inside the suction bottle, the floor, and two distinct locations on the mattress. The vehicles were swabbed on monthly basis with a saline-wetted swab. [15] During the course of the study, Nigam et. al. found that cleaning procedures were inconsistent and often improvised. For example, the range of cleaning supplies used included mops, towels, pillowcases, and rags. Since Paramedics assign immediate patient care a higher priority than cleanliness, they often did not have time to perform the cleaning procedures. Each month a total of fourteen swabs, seven before cleaning and seven after, were sent to a laboratory to examine bacterial contamination for each participating ambulance. Region A had a total of twenty-eight participating ambulances, while Regions B and C had twenty-seven each. The average percentage of bacterial contamination in emergency vehicles from all regions, before and after cleaning, is illustrated in Figure 10.

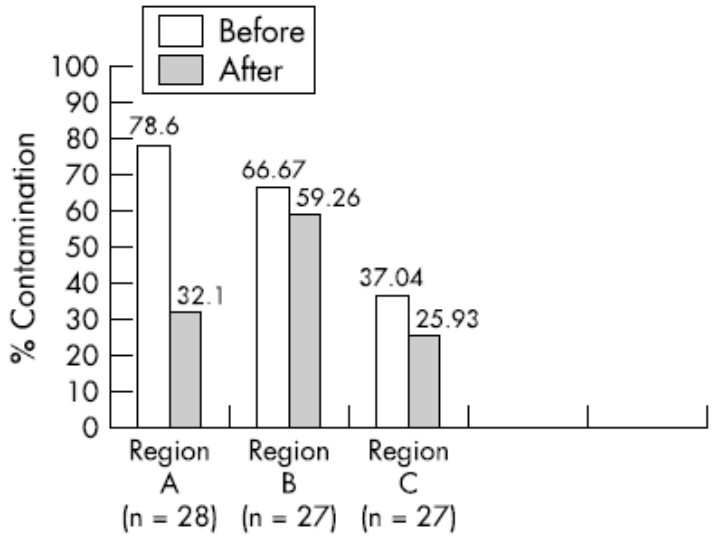


Figure 10: Contaminated sites in ambulances, before and after cleaning

The results from the experiment demonstrated that most areas inside the ambulance were contaminated with bacteria; showing contamination both prior to and after cleaning sessions [15]. Approximately 60.97% of all test sites were contaminated before cleaning, and about 35.37% were contaminated after cleaning. In Region A, 78.6% of sites were contaminated before cleaning, and 32.1% after cleaning. Region A demonstrated the greatest cleaning effectiveness, achieving a reduction in contaminated sites of 46.5%. Both Region B and Region C presented less than 10% reduction in contaminated sites, falling far short of Region A. The smallest number of contaminated sites was found in Region C, which started with 37.04% contaminated sites before cleaning, and ended with 25.93% after cleaning. (Figure 10) It should be noted that cleaning methods are likely ineffective below a certain threshold, so it is not necessarily the case that Region C had inferior cleaning methods.

Nigam et. al.'s experiment demonstrates that while cleaning procedures do reduce contamination levels in ambulances, there is significant room for improvement in cleaning procedures. The experiment shows that even after cleaning, at least 30% of test sites remained contaminated in all regions. This is a significant level of contamination for what should be considered a sterile environment, and such contamination is likely to cause devastating hazards to both EMS personnel and patients. The experiment further suggests that superior cleaning methods and devices be developed in order to mitigate these risks.

2.3: Vacuum Cleaner Technologies

2.3.1: Introduction and Physical Concepts

The original concept of using a flow of air to collect dust and dirt particles from a floor or carpet was introduced in 1860 by Daniel Hess. [16] Since Hess' invention, which used a hand-operated pump to generate vacuum pressure, significant enhancements to the vacuum cleaner have been made. The basic principles of developing adequate airflow, however, have remained the same. An image of Hess' original patent for the "Carpet Sweeper" can be seen in figure 11 below.

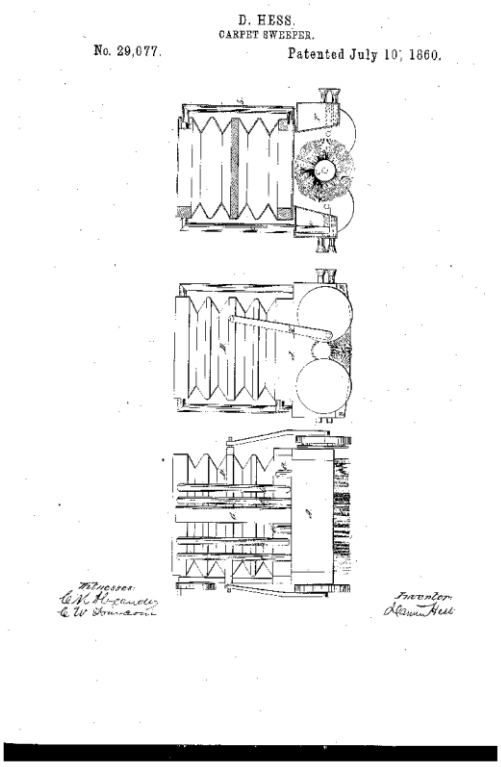


Figure 11: Hess' Carpet Sweeper, 1860

Collection of dust particles requires that mechanical work be done to move them into a collection vessel. Vacuum cleaners use the energy provided by flowing air to do the necessary work on the dust particles. This energy, when measured in watts, is often referred to as

"airwatts" and can be determined by multiplying volumetric flow rate by pressure, as shown in equation 1 [17]:

$$P(t) = pQ, \quad \text{(Eq. 1)}$$

where p is equal to pressure, and Q is equal to volumetric flow rate.

This air power is provided by an electrical energy source, and an electric motor coupled to a centrifugal fan converts the electrical energy into air power. The efficiency of the vacuum cleaner system, expressed as a percentage, can be calculated using equation 2:

$$\eta = \frac{pQ}{IV} \, X \, 100\% \quad \text{(Eq. 2)}$$

where η is the percentage efficiency, I is the electrical current drawn by the motor, and V is the voltage provided by the electrical power source. In modern household vacuum cleaners, the electrical energy is provided by a connection to the power grid, and in handheld versions it is provided by a battery.

2.3.2: Impeller Designs

In most conventional vacuum cleaners, the air power is generated by a type of centrifugal fan called an impeller. In today's electric powered cleaners, this impeller is spun at a relatively high rate of speed by an electric motor. The efficiency of a vacuum cleaner can be determined by comparing the input electrical power to the output air power, as discussed in the previous chapter. Both the efficiency of the motor and that of the impeller will affect the overall efficiency, however greater losses are incurred by the impeller. Thus, optimal impeller designs provide higher efficiency, though usually at the price of increased cost and complexity of manufacturing. An impeller's efficiency, $\eta_{impeller}$, can be calculated if the motor's output torque and angular velocity are known, as shown in equation 3:

$$\eta_{impeller} = \frac{pQ}{\tau\omega} \, X \, 100\% \quad \text{(Eq. 3)}$$

where τ is the motor torque, and ω is its angular velocity.

Oleyami Et al's publication on the efficiency of various impellers provides an overview of commonly used impeller configurations, as well as an explanation of the general principles of impeller efficiency. [18] Figure 12 shows a diagram of an impeller.

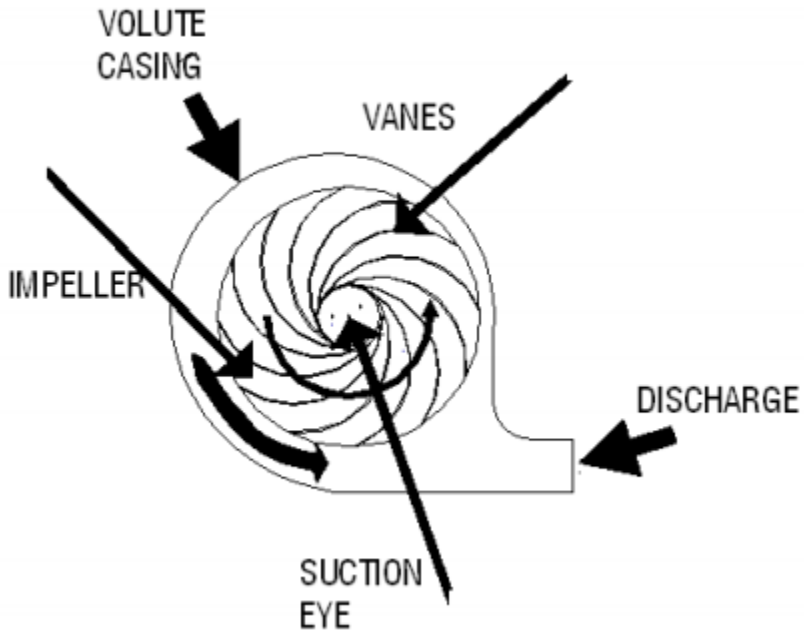


Figure 12: Sectional drawing of a blower

According to the article, Impeller vanes can be either forward curved, backward curved (as in the figure), forward inclined, or backward inclined. After testing each of these designs, the article describes the calculations of efficiency, and determines that the backward curved design has the highest efficiency. The Howden Group, a manufacturer of impellers, provides an explanation of the various vane configurations, and the results agree with Olyeami Et al, stating that the backwards curved impeller has the highest efficiency. [19] Figure 13 shows a chart of output air speed for each impeller type as determined by Oleyami et al. The green line, representing the backward curved impeller, can be seen above all the rest, indicating superior performance.

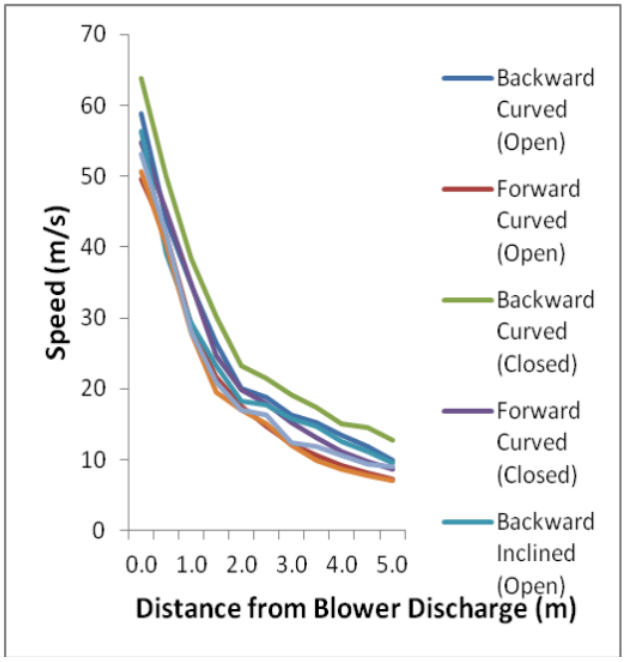


Figure 13: Air speed vs. Distance

Modern vacuum cleaners are usually classified as either "clean-air" or "dirty-air" systems, which differ mainly by their configuration. Dirty-air systems move debris through the impeller and into a collection vessel, whereas in clean-air systems, the impeller is placed after the collection vessel, and only air which is free of debris moves through it, hence the name "clean-air". In dirty-air systems, the impeller must be built to withstand the impact of debris flowing through it. According to Euler's Turbine Equation (Equation 4), the momentum provided by the impeller causes a change in pressure or temperature [20]:

$$c_p(T_{Tc} - T_{Tb}) = \omega(r_c v_c - r_b v_b). \quad \text{(Eq. 4)}$$

In Equation 4, the subscripts *b* and *c* represent the inlet and outlet of the impeller, and *r* represents radius, T_T represents temperature, and *v* represents linear velocity for the respective subscript. ω represents angular velocity, which is constant for both the inlet and the outlet, and c_p represents the specific heat if an ideal gas. This equation is derived using the Navier-Stokes equations and the law of conservation of momentum.

Thus, any momentum lost due to the weight of the impeller reduces efficiency. Dirty-air impellers must use thick, heavy vanes in order to cope with the impact of the debris. Additionally, the most efficient impeller geometry and curvature causes excessive stress on the vanes, so more robust geometry is used instead. As such, impellers used in clean-air systems are usually of higher efficiency. Figure 14a shows an image of a Kirby K-119078 dirty-air impeller [21], next to Figure 14b, the efficient, clean-air impeller from a Dyson DC34 handheld vacuum cleaner. [22]

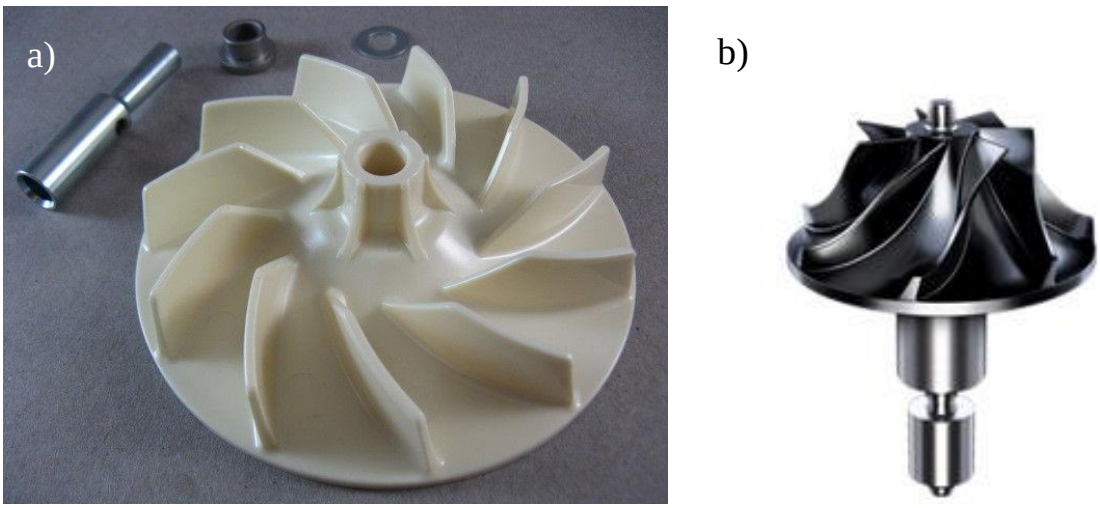


Figure 14: a) Kirby Dirty-Air Impeller, b) Dyson Clean-Air Impeller

2.3.3: Other Methods of Vacuum Generation

Though not intended for cleaning purposes, other vacuum devices exist in the medical industry. Two of the most common examples include dental vacuums for fluid removal, and fluid collection vacuums for surgical and laparoscopic use. These systems share a common method of vacuum generation; an air compressor. Because these systems are designed for liquids, a high volumetric flow rate is not required, rather a high pressure is desirable. Compressors provide high suction at the expense of flow rate.

Dental vacuums must be designed to minimize contamination, and are held to high standards of reliability and hygiene. The HTM 2022 regulates the flow of gas in pipelines for medical systems, which must be carefully observed when designing vacuum systems due to the high level of contamination of medical gases [23]. Medivac™ and similar systems are used onboard ambulances to remove fluid from patients during care. These systems work in a manner similar to the dental

vacuums, using compressors as the vacuum source, and disposable plastic containers as collection vessels. Figure 15 shows a typical collection vessel for such systems [24]:

Figure 15: Typical Medivac™ style suction vessel

2.3.4: Motors and Batteries

Today's vacuum cleaners utilize electric motors which spin the impeller to generate the vacuum pressure. The motors used in a household vacuum cleaner have the advantage of being powered by the high voltage AC electrical grid. Handheld or portable vacuums, however, must use batteries to provide the electrical power, which cannot supply high voltages. Thus, motors and impellers must be designed to provide high efficiencies. Modern vacuum cleaners incorporate cutting edge battery and motor technologies.

The geometry of the impeller is designed to produce as much airflow as possible per unit of rotational speed. Household vacuum cleaners that utilize 120V AC motors (in the US) can spin the impeller at very high angular velocities to generate the necessary airflow. At these high speeds, the motor will not be operating at its peak efficiency, but this is of little concern due to the excess power available from the grid. [25] Because this high voltage power source is not

available in battery powered applications, motors spin at lower speeds, requiring more efficient impellers. DC brushed motors were the universal motor choice until a modern breakthrough in motor technology called the *brushless DC (BLDC) motor*. Both motor types use two magnets, one "permanent" magnet with constant polarity, and one electromagnet which can be controlled by changing the direction of current flow. The rotating shaft of the motor, called the *rotor* is attached to one of the magnets, and the other magnet stays stationary – called the *stator*.

Conventional "brushed" motors use strips of metal which "brush" against a metal contact on the rotor called a *commutator*. The rotation of the commutator rapidly switches the direction of current in the electromagnet windings, also attached to the rotor. Permanent stator magnets surround the rotor, which is what causes the motor to rotate. A diagram of a brushed DC electric

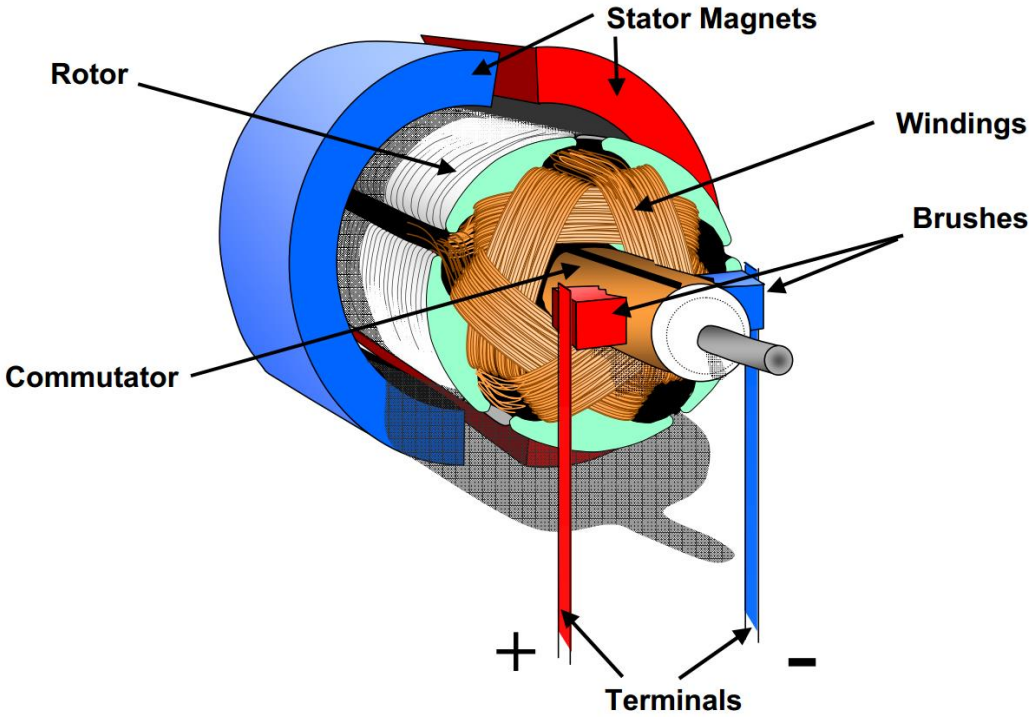


Figure 16: Diagram of a DC Brushed Motor

motor is shown in figure 16 [25]:

The BLDC was designed to omit the commutator and brushes, which cause friction and heat to build up, reducing the motor's efficiency. In addition, brushes will wear down over time, requiring replacement. A BLDC uses electronic circuitry to rapidly switch the direction

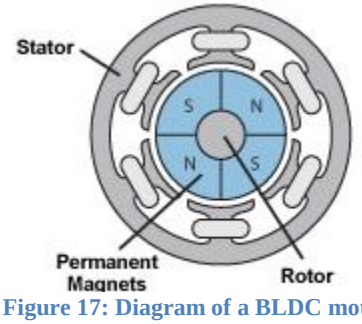


Figure 17: Diagram of a BLDC motor

of current in stator electromagnets, which changes the polarity of a magnetic field, similar to a brushed motor. This change in magnetic field "pulls" permanent magnets attached to the rotor around in a circle, causing the motor to rotate. A diagram of a BLDC is shown in figure 17. [26]

Because the BLDC motor has no mechanical contact between rotating parts, the motor is capable of achieving much higher efficiency, which is desirable for handheld vacuum cleaners. In one example, Dyson Ltd, a manufacturer of cutting-edge vacuum cleaner systems, uses a BLDC motor in their DC34 handheld vacuum cleaner to achieve an angular velocity of over 100,000RPM, which is more than 5 times most conventional brushed motor systems. [27] The most significant drawback to the BLDC system is the complexity of the circuitry required to switch the electromagnets with the appropriate timing. This makes BLDC systems more expensive and difficult to manufacture. Figure 18 [27] shows an image of the Dyson digital motor with supporting electronics, (bottom, three circular plastic assemblies) as well as a conventional motor (top). Both assemblies include impellers.

Figure 18: The Dyson digital motor

Because Dyson was able to achieve such a high angular velocity, they designed their impeller to be extremely small, so that it fits in a small, portable package while still delivering outstanding performance. Figure 19 shows a comparison between the Dyson digital motor with its impeller, and a typical motor-impeller pairing for a conventional handheld vacuum cleaner. [28]

Figure 19: Dyson digital motor next to conventional motor

To provide power for the motors, portable vacuum cleaners use battery packs, which are in most cases rechargeable. Modern battery packs are constructed with lithium-ion cells, which offer high charge density, low weight, and excellent performance. These battery packs must also include circuitry to regulate their charging and discharging, and ensure they remain within their operating ranges. Because modern devices such as vacuum cleaners are beginning to make use of more and more electronic circuitry, it is crucial that power sources can provide energy at a relatively constant rate throughout the discharge time. Lithium-ion batteries have much more consistent voltages than conventional NiMH or Ni-Cad batteries. Figure 20 depicts the discharge

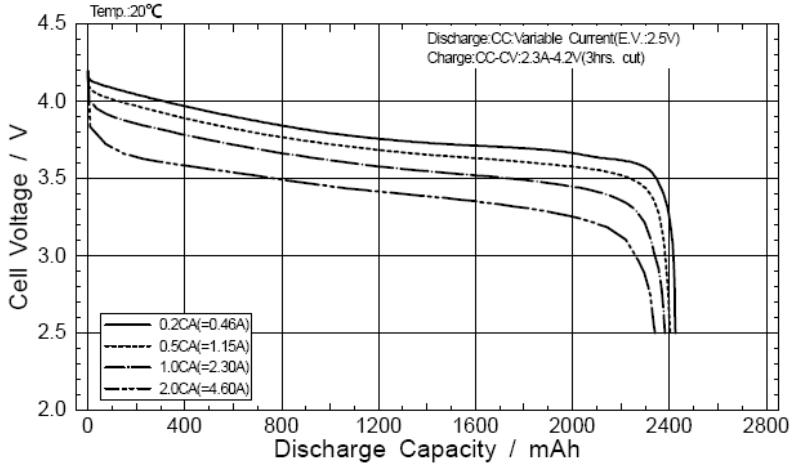


Figure 20: Li-Ion discharge curve

curve of a standard 18650 Li-Ion cell. [29]

The above figure shows a relatively flat voltage slope for most of the battery's life, until the very end, where the voltage drops off sharply. This is optimal for a vacuum cleaner setting where the device becomes useless below a certain speed threshold.

2.3.5: Conclusion

Since its conception in 1860, the vacuum cleaner has benefitted from technological revolutions that have culminated in what today is a sophisticated and invaluable appliance. Over a century of engineering has perfected the designs and configurations of impellers, motors, and power sources to outperform any previous generation of vacuum cleaners. By designing impeller geometry to incorporate a balance between aerodynamics and rigidity, modern vacuum cleaners are able to move debris into a collection vessel. The impeller is also designed carefully to match the specifications of the motor that drives it; be it brushless DC or brushed. While BLDC motors provide extreme velocities and very high efficiency, they are often impractical to implement due to their cost and complexity. Finally, electric power either in the form of batteries or a connection to the electric grid spins the motor to generate airflow.

Though the humble beginnings of the carpet sweepers of the 19th century may make the vacuum cleaner seem like a crude, cumbersome device, the fact remains that modern vacuum technology rivals that of even some advanced medical systems. Due to cutting-edge systems such as embedded microcontrollers, BLDC switched reluctance motors, and Lithium-Ion batteries, vacuum cleaners have reached a level of sophistication which enables their use in the medical industry, providing an elegant, hygienic method of immediate contamination containment, with minimal risk to medical personnel of exposure to dangerous pathogens.

2.4 Filtration

2.4.1 History of air filtration

The original human need for air filtration was, quite fittingly, in safety services. Firefighters were combating fires in dangerous smoke and entering smoke-filled buildings with little to no protection for their lungs. Smoke is a visible suspension of various types of particles in the air, predominantly made up of carbon monoxide and carbon dioxide, and can contain countless chemicals that pose danger to human health. [30] Inhaling smoke for even a short time can cause immediate effects, and further exposure can lead to serious health issues such as cancer, lung disease, and cardiovascular disease. [30]

Because of both the immediate and long-term dangers of breathing in smoke, firefighters needed some way of preventing the particulates from entering their lungs. Firefighters would use wet bandanas, shirts, or other fibrous materials to cover their mouths, and while these systems are better than nothing, they were not nearly effective enough in decreasing health risks for firefighters. In 1823 two brothers, John and Charles Deane, came up with a solution to the problem by using a hose to pump air into a knight′s helmet so that they could enter a burning barn to rescue several horses. [31] The brothers patented their concept and later applied it to scuba diving, but it marked the first instance of technology being used to prevent the inhalation of dangerous particulate matter.

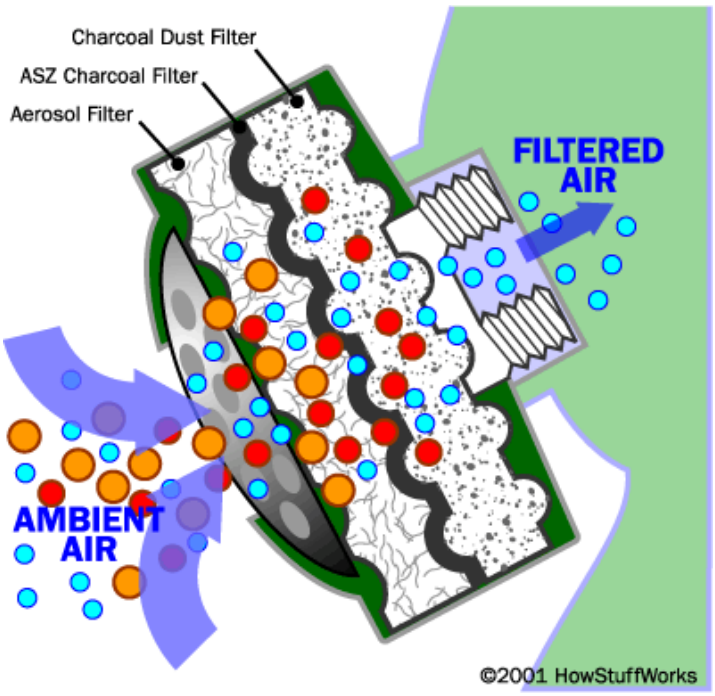


Figure 21: Gas mask functional description

The Deane brother's invention requires a source of breathable air, but it is a solution idea for atmospheres that are not safely breathable purely because of the particulate matter count, regardless of hazardous chemicals or other poisonous effects. Atmospheres that are lower in particulate count, but that are just as dangerous to human health, prompted another solution, a way of removing the dangerous particles and chemicals from the air so that it could be breathed without a stored clean air supply. In 1847, Lewis Haslett created the first gas mask, which allowed breathing through two openings; one to permit inhalation through a filter, and one to vent exhaled air back into the atmosphere. [32] The filter was typically made from wool or another porous material moistened by water and was able to filter out large particulates, but was not effective against poisonous gases. [32]

2.4.2 HEPA Filtration

Following Haslett's original gas mask dozens of inventors added their own solutions to the mix over the next 60 years, but it was World War I that brought forth the biggest advances in filtration technology to combat chemical warfare. Chlorine and Mustard gas killed hundreds of thousands of soldiers during World War I, but both sides were searching desperately for ways to filter the same poisons they were using against the enemy for the air their soldiers were breathing, and this research not only led to the modern gas mask, but also brought air filtration

one step closer to its peak. [33] World War II caused the final step in the quest to filter out the next deadly particulate to be taken.

The Manhattan Project, and the atom bomb, raised a number of serious questions that needed to be addressed by science and new technology, one of which was if it was possible to filter radiation particles out of the air. Nuclear weapons emit several different types of radiation: Alpha particles, Beta particles, and Gamma rays. Alpha particles are unable to penetrate human skin and Beta particles are not extremely dangerous to humans, but Gamma rays are both very penetrating and incredibly hazardous. [34] To filter the radioactive particles from the air, the U.S. Government developed HEPA filtration, which stands for High Efficiency Particulate Air. [34]

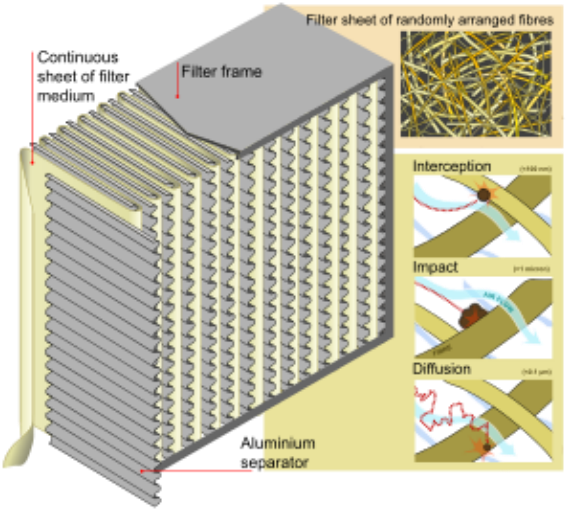


Figure 22: HEPA filter and functional description

HEPA filtration (Figure 22) is based on three principles: interception, impaction, and diffusion, which work together to remove at least 99% of airborne particles. Interception works

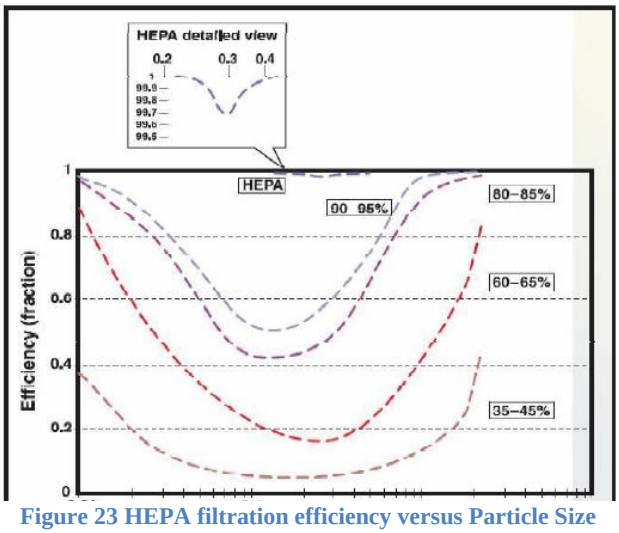


Figure 23 HEPA filtration efficiency versus Particle Size

by particles following a line of flow in the air stream coming within a small distance of a fiber and adhering to it. [35] Impaction is where larger particles are unable to avoid fibers by following the air stream and embed in one of them directly. Diffusion is an enhancing mechanism resulting from collision between gas molecules and the smallest particles of contamination, which impedes their path through the filter. The combination of these three distinct filtration techniques sets HEPA filtration systems above and beyond other filters, as can clearly be seen in figure 23, which is a graph of efficiency versus particle size for filters.

2.4.2 Filtration in Vacuums

The main purpose of the SLICCVac is to remove and limit contamination in an ambulance. As such, the design of the vacuum is partially disposable to prevent any contamination occur of the body of the SLICCVac. Because of the path of airflow through the vacuum, contamination of the impeller is probable unless there is a system in place to prevent any from reaching the impeller.

The shape of the vacuum container is designed to limit all liquid and solid contamination from reaching the filtration system, meaning that the only design criteria for the filtration system is airborne particles and contamination that can be accomplished by an air filter. Of a large variety of air filters, we decided on using a filter that meets the high-efficiency particulate absorption, or HEPA, standard. Filters that meet the HEPA standard are used in a large variety of applications, such as home appliances, automobiles, aircraft, and, appropriately, medical facilities.

There is a precedent for the use of HEPA filtration in a vacuum, as noted in the patent under the title: **HEPA filter cartridge for canister vacuums**. [3] Although this is not designed for the same type of vacuum as the SLICCVac, nor is its purpose the same, it is an excellent example of previous use to help create a HEPA filtration system for use in the SLICCVac. The standard definition of a HEPA filter is a system that will remove at least 99.97% of particles 0.3 microns in diameter. However, in some cases this loose definition can lead to filtration systems that are insufficient in their intended purposes. Particles that are outside of the size range commonly used for HEPA filters, such as sub-micron particles and larger particles such as dust, are notable challenges that may need to be overcome in the SLICCVac design.

Lydall, Inc. is the owner of a patent for a filtration system designed to combat this exact problem, titled **Composite dual layer hepa filter** [36]. This patent details an arrangement of various levels of filtration fibers that increases the size range of particles sifted from the airflow through the filter. Contaminant particles vary widely in size, and some of the most dangerous contaminants in ambulances are smaller than the 0.3-micron size that is the standard for HEPA filtration. Because of this, it is important that the SLICCVac have a filtration system that is able to catch these particles and prevent any spreading of contamination.

2.5 Regulations

2.5.1 Purpose of Regulation

Regulation is intended to set a series of rules and standards that set limits to what is allowed for the good of the subject. The government uses regulations to set base requirements for a subject so that each individual subject′s quality is above a legislated standard and obeys a series of functional requirements. Medical services are subject to a high number of regulations because of their life-saving focus, and ambulances are no exception. The General Services Administration is in charge of all regulations for ambulances, and is responsible for keeping these regulations organized and up to date in the Federal Specification for the Star of Life Ambulance. The most recent edition of this document is the KKK-A-1822F, which has been in place as the guide to all governing regulations for ambulances since August 2007. [5]

1966 marked the beginning of serious regulation for Emergency Medical Services with two important documents. The National Academy of Sciences and the National Research Council published a white paper titled Accidental Death and Disability: The Neglected Disease of Modern Society, which insinuated that ambulances were ″inappropriately designed, ill equipped, and staffed with inadequately trained personnel.″ [37] Furthermore, the Highway Safety Act of 1966 was passed, which created the Department of Transportation, and the DOT was given some authority over the EMS to help it improve its safety. [37] These documents marked the beginning of the modern era of Emergency Medical Services, with large increases to funding, better EMT training, and improved technology and safety in ambulances.

2.6 Conclusion

Through the analysis of these reference materials, many conclusions can be drawn, concerning both the need for a revolution in ambulance cleaning methods, and the most effective solution to this problem. As is made evident by the analysis of current cleaning procedures and the potential health hazards that these cleaning methods facilitate, ambulance cleanliness has historically been usurped by other ambulance features, such as medical equipment and pharmaceutical supplies, which Emergency Medical Personnel have deemed of greater importance. However, the above analysis of pertinent literature demonstrates that even the most technologically advanced ambulance can be extremely ineffective if the risk of exposure to HCAI's is high, either for Ambulance personnel or patients. As such, as ambulance technology increases in complexity and effectiveness, it is crucial that technologies be developed that improve sanitation as well. This, however, has not generally occurred to a satisfactory degree, the consequences of which can be devastating. Many engineers are familiar with the concept of Moore's Law, which originally described the exponential growth rate of transistors in computer hardware, and has since been expanded to describe a similar growth rate of technological advancement in general. Consideration of Ambulance cleaning technology begs the question; why has Moore's Law not held true for technological devices that assist paramedics in ambulance sanitation? In the following chapters, we will present a potential solution to this problem; a device designed specifically to effectively clean ambulances, utilizing the cutting-edge technologies that such an important task deserves.

3. Design and Analysis

3.1 Introduction

The SLICCVac has an overall goal of improving the ambulance in regards to its cleaning method. The purpose of this chapter is to provide the in-depth features of the SLICCVac features that allow for optimal functionality. The SLICCVac will clean, contain, and dispose of contaminants in the ambulance to limit the amount of cross-contamination. The problem statement and project objectives are summarized below and will be referred back to throughout Chapter 3. Additionally, the following chapter will present several CAD models and technical documents, which can also be found in Appendix B, along with additional views and two-dimensional versions.

3.1.1 Problem Statement

Ambulances are often subject to biological emissions, which pose potential hazards to patients and paramedics. This necessitates a cleaning device within the ambulance that can immediately contain waste more quickly and easily than current methods, in an effort to minimize cross-contamination.

3.1.2 Project Objectives

- Design suitable medical vacuum cleaner, meeting design specifications
- Research application and scope of project
- Benchmarking to determine need for such a device
- Provide insight into best practices for accomplishing manufacture and retail of product
- Consult EMS personnel to establish need and user interface
- Determine future goals for project
- Design critical components using prototyping techniques
- Suggest methods of testing designs and prototypes
- Compile findings into report which is conducive to further research

3.2 Design specifications and SLICCVac Overview

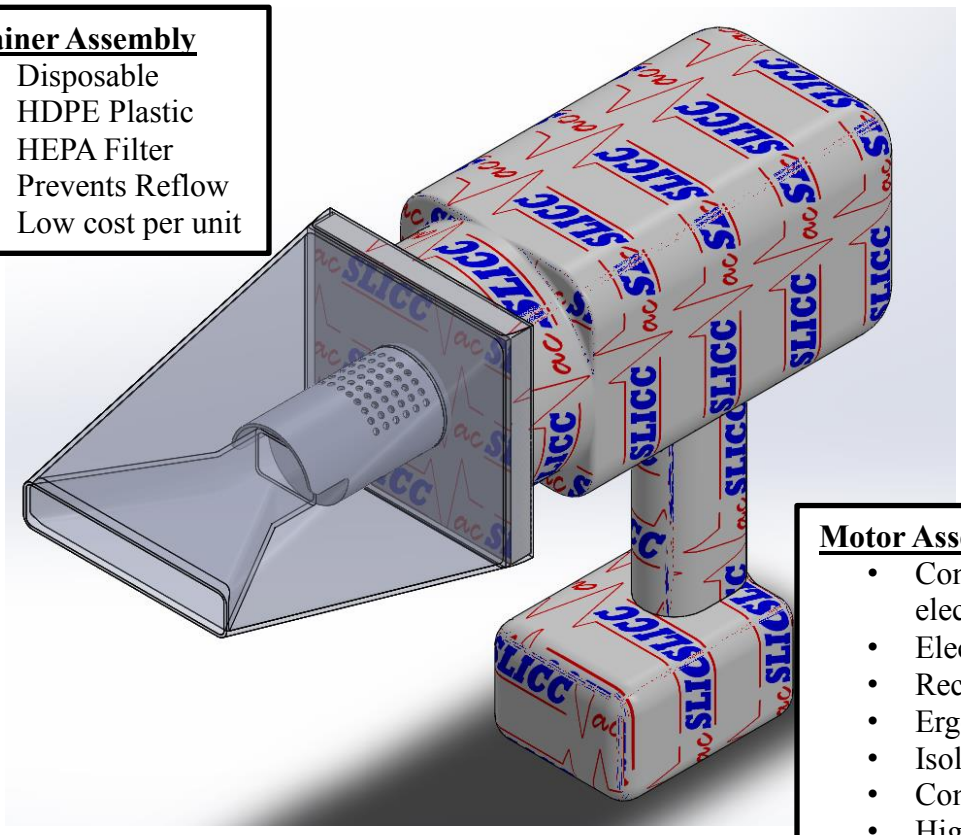
To fully address the problem statement, while realizing each of the project objectives listed in the previous section, a compact, portable vacuum cleaning device was designed, intended specifically for ambulance applications. In order to ensure that the features of this device satisfy the requirements of the EMS personnel who will use it, a list of design specifications was created. Each specification is measureable and specific, in order to facilitate useful testing results and allow for comparison to other similar vacuum systems. These design specifications were created as a result of benchmarking, both in terms of vacuum cleaning systems available on the market, and requirements that are specific to ambulance applications. The list of design specifications follows:

1. Must be able to remove solid waste of up to ¾ inch diameter
2. Must be able to remove liquid waste with kinematic viscosity (ν) of up to 35.0 cSt
3. Must consume less than 2A @ 120V, or 10A @ 12V from ambulance
4. Must produce less than 20dB noise at a distance of 1 meter
5. Operated in less than 1 minute (not including actual vacuuming time)
6. Prevents 99.97% of 0.3µm contaminants from entering motor assembly
7. Must provide at least 60 airwatts vacuum power
8. All components (SLICCVac, storage, charger) occupy $<0.5m^3$

Throughout this chapter, these design specifications will be referred to as DSX, where X is the corresponding number listed above.

To satisfy each of the design specifications, a vacuum cleaning device was designed and analyzed. This device, deemed the Solid/Liquid Immediate Contamination Containment Vacuum, or SLICCVac, is comprised of two major components; the motor, and the container. An overview of the device, including a list of major features of each of these components is shown in Figure 24.

Container Assembly
- Disposable
- HDPE Plastic
- HEPA Filter
- Prevents Reflow
- Low cost per unit



Motor Assembly
- Contains Motor, impeller, electronics
- Electronics monitor flow, psi
- Rechargeable Li-Ion Battery
- Ergonomic, familiar design
- Isolated from contaminants
- Compact form factor
- High efficiency Impeller

Figure 24: SLICCVac Overview

A "gun-type" configuration was chosen for the overall physical design of the SLICCVac, as it is familiar to many users, thus not requiring unneeded training or practice. The container assembly was modeled after many similar handheld vacuum systems, and adapted to allow compatibility with liquids as well as solids, and prevent reflow. In addition, a HEPA filter was added to the flow path of input contaminants, further isolating the motor from harmful

contaminants. An in-depth presentation of each design, as well as analyses of the major components is presented in the following sections.

Section 3.3 Impeller Design

3.3.1 Introduction

One of the most integral components of the SLICCVac, like almost all vacuum cleaners, is the Impeller. The impeller converts the mechanical energy supplied by the motor into "air power" as described in section 2.3.2. The impeller for the SLICCVac differs from that of a conventional handheld vacuum cleaner due to the high power required to clean the type of debris that the SLICCVac is likely to encounter. Most vacuum cleaner designer analyze dust particles, which are the most common type of debris in a conventional household. However, the SLICCVac must be designed to clean wet debris, which poses a challenge due to their high density, volume, and weight relative to small dust particles. While, as discussed in the aforementioned chapter, most conventional handheld vacuum cleaners use a low efficiency impeller designed for higher durability, the SLICCVac must be designed to utilize as much of the supplied power from the batteries as possible. As such, other measures must be taken to ensure the impeller lasts for the lifetime of the vacuum cleaner, and does not lose efficiency during its life cycle. To facilitate this design specification, the SLICCVac will likely utilize the "clean-air" configuration, employing advanced separation followed by HEPA filtration to remove any debris from the airstream before it reaches the impeller, reducing the risk of damage to the impeller. Additionally, while most vacuum impellers are constructed from ABS plastic, the design of the SLICCVac impeller will be conducive to CNC machining, so it could be machined from metals, providing excellent shear and tensile strength, with minimal compromise in terms of weight. However, if cost limitations are too great, the impeller design will be adequately durable if injection molded from ABS or other plastics.

Compromises in flow performance cannot be made in the design of the SLICCVac's impeller, since it will be required to provide higher power than most standard vacuum cleaners, and have limited power supply from the ambulance. As a reference, we can consider the Phillps MiniVac FC6148/01 handheld vacuum cleaner. This is the top-of the line handheld vacuum cleaner that the company sells, and has the best specifications in its product line. The product leaflet states that the vacuum has a maximum air power output of 22W [38]. DS7 shows that the SLICCVac requires 60W, nearly three times this power.

To allow the SLICCVac's impeller to provide this much power, vane geometry must be designed to provide high air speed. This must be done while still maintaining manufacturability and durability. Chapter 2 presented Euler's Pump and Turbine Equation, which is derived from the conservation of rotational energy. Determining impeller tip speed at the inlet and outlet is usually accomplished with velocity triangles, drawn at any chosen vane at both the inlet and the outlet. Theses triangles allow us to determine tip speeds which are then used as parameters for the Euler Pump and Turbine equation. Figure 25 shows a diagram of typical outlet velocity triangles for a backward-curved impeller. Such triangles are drawn on the inlet as well, and they are used as inputs to the Euler Turbine Equation.

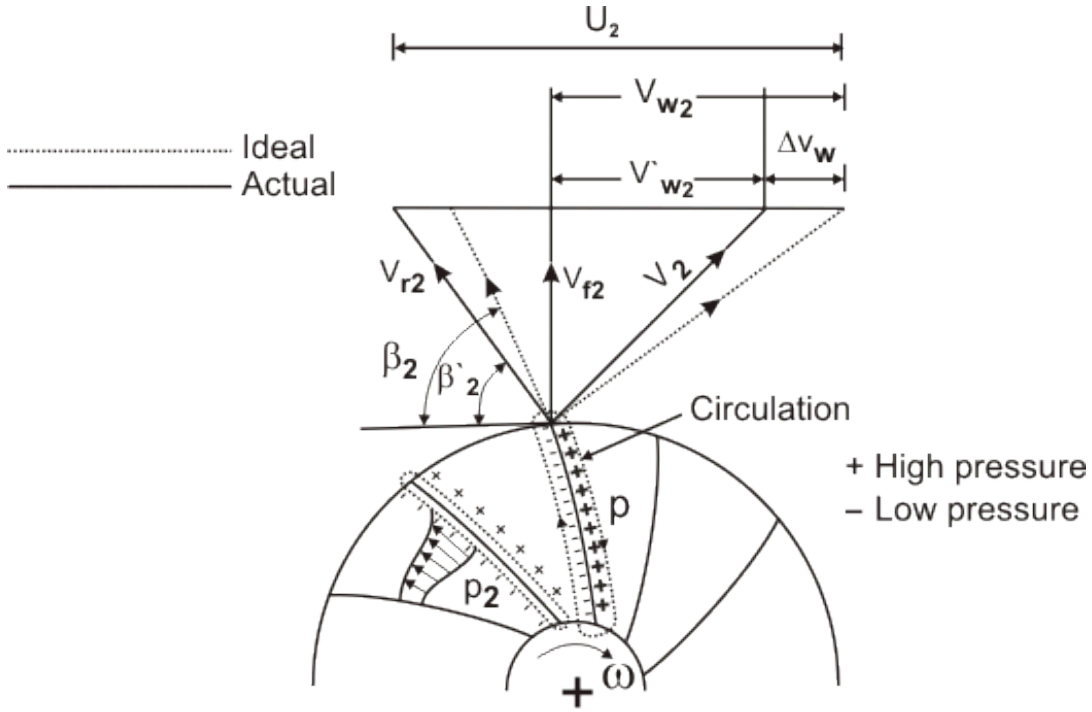


Figure 25: Impeller Outlet Velocity Triangles

The following derivations of Euler's pump and Turbine Equation can be used to relate the above parameters for impeller geometry to fluid parameters:

$$V_{w2} = (U_2 - V_{f2}) \cot \beta_2, \qquad \text{(Equation 1)}$$

where V_{f2} is the outlet linear fluid velocity, and

$$(U_2 - V_{f2}) \cot \beta_2 = (U_2 - \frac{Q}{A}) \cot \beta_2, \qquad \text{(Equation 2)}$$

where Q is the flow rate of fluid through the impeller, and A is the flow area at the outlet.

3.3.2 Benchmark Analysis of a Standard Impeller

Since the vanes are between high pressure and low pressure zones, they can potentially be exposed to high stresses. Impellers for vacuum cleaners like the Phillips Mini Vac mentioned earlier are normally of the closed, backwards curved type, and are constructed out of ABS plastic. Figure 26 shows a standard handheld vacuum impeller, with the top face, or closure, depicted as transparent, in order to display the vane geometry.

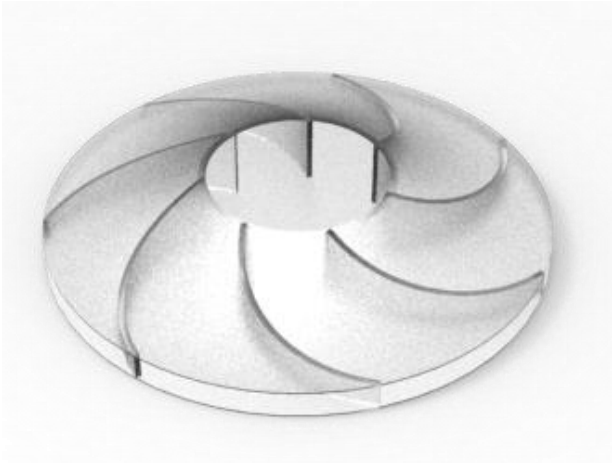


Figure 26: Typical Handheld Vacuum Impeller

Using CFD simulation software, Euler's Pump and Turbine equation can be calculated iteratively for several variations in inlet and outlet velocities at several locations on the impeller, providing a useful real-world approximation of the fluid velocity at the output, V_{f2}. For the above model, a simulation was conducted at ISO standard atmospheric pressure and temperature. A typical radial velocity for vacuum cleaner motors of 1800 rad/s, or about 18krpm, was chosen for the simulation. The simulation completed 190 iterations of the pertinent fluid mechanics

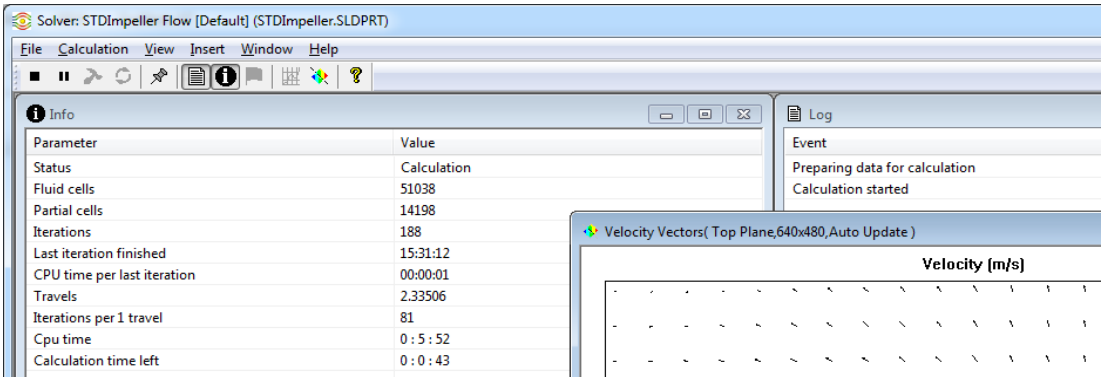


Figure 27: Flow Simulation CFD Solver

equations. An image of the solver software near the end of the calculations is shown in Figure 27.

The resulting simulation was then imported into SolidWorks, where graphical representations of output velocities were added to the model. Figure 28 shows a rendering of this image. The results of the maximum and minimum fluid velocities are shown in the legend to the

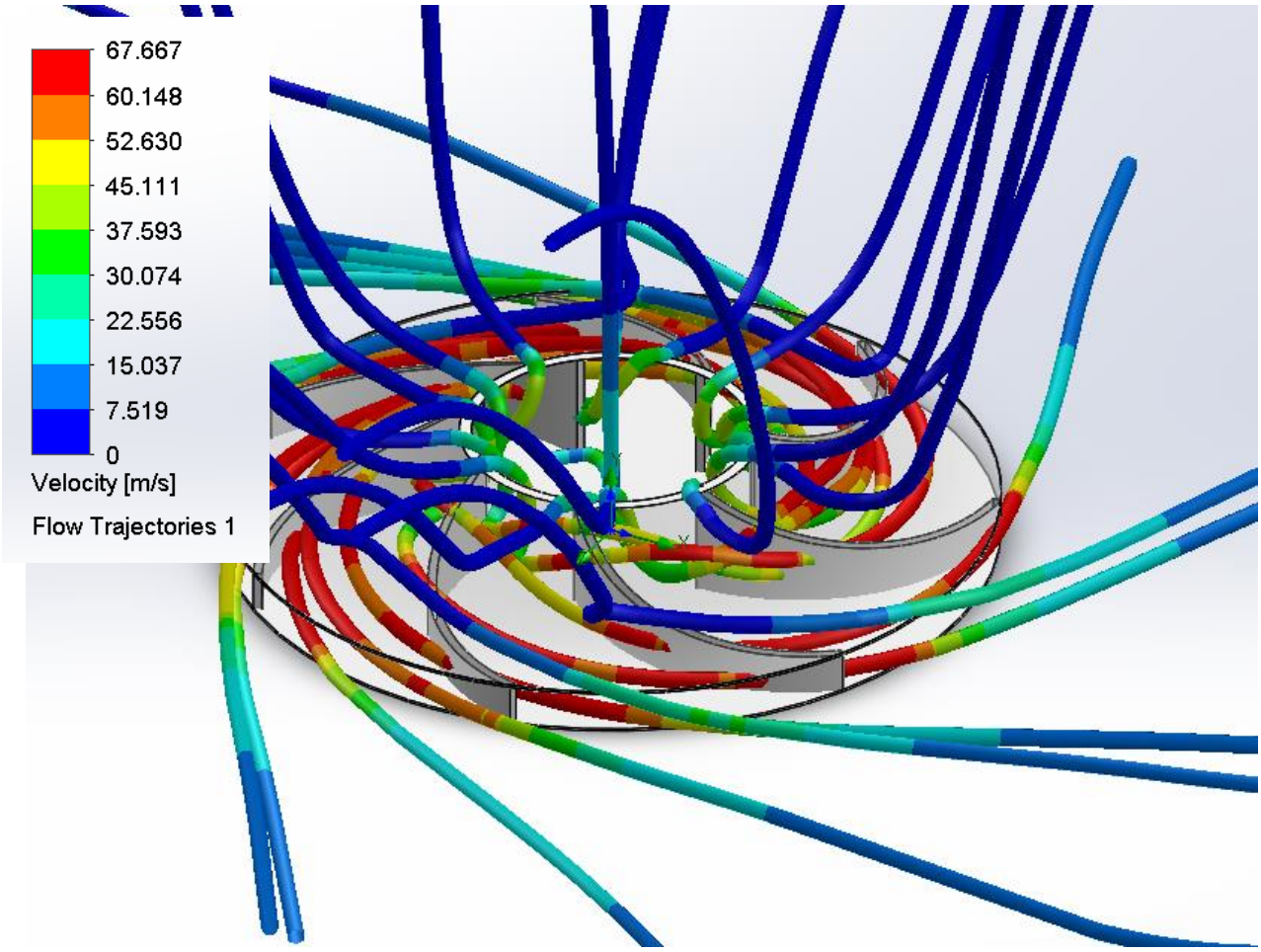


Figure 28: Flow Simulation Results of Typical Handheld Vacuum Impeller

left, and are color coded on the model accordingly.

These simulation results indicate a maximum fluid velocity of 67.667 meters per second. In a vacuum cleaner, the fluid exiting the impeller at the output is decelerated until it is at rest relative to the surrounding fluid. Thus, all the kinetic energy is converted into potential energy as described by the Bernoulli Equation:

$$z_1 + \frac{P_1}{\rho g} + \frac{v_1^2}{2g} = z_2 + \frac{P_2}{\rho g} + \frac{v_2^2}{2g} \qquad \text{(Equation 3)}$$

where z is height, or pressure head, P is pressure, ρ is fluid density, v is fluid velocity, g is the gravitational constant, and subscripts 1 and 2 refer to the 2 fluid states. In the case of a vacuum cleaner, since all the kinetic energy (represented by the $\frac{v_1^2}{2g}$ term) is converted into potential energy (represented by the $\frac{P_2}{\rho g}$ term). For our purposes, we can neglect the pressure head, since the geometry of the impeller is relatively small. Thus, Bernoulli's equation simplifies to

$$\frac{v_1^2}{2g} = \frac{P_2}{\rho g} \qquad \text{(Equation 4)}$$

Using the maximum velocity of 67.667m/s that was reported by the CFD simulation, and solving this equation for pressure, yields a pressure, P, of 2.804kPa.

To determine the stress exerted on the impeller's vanes, a computer simulator uses Finite Element Analysis techniques to iteratively solve pertinent stress equations. Fluid pressure can easily be used to calculate the amount of force exerted on the vanes, and the von Mises' yield criterion can then be applied to many "critical stress" points on the impeller vanes. The results are color-coded and projected onto the model in a similar fashion to the flow simulation results. The results of the FEA simulation are shown in Figure 29.

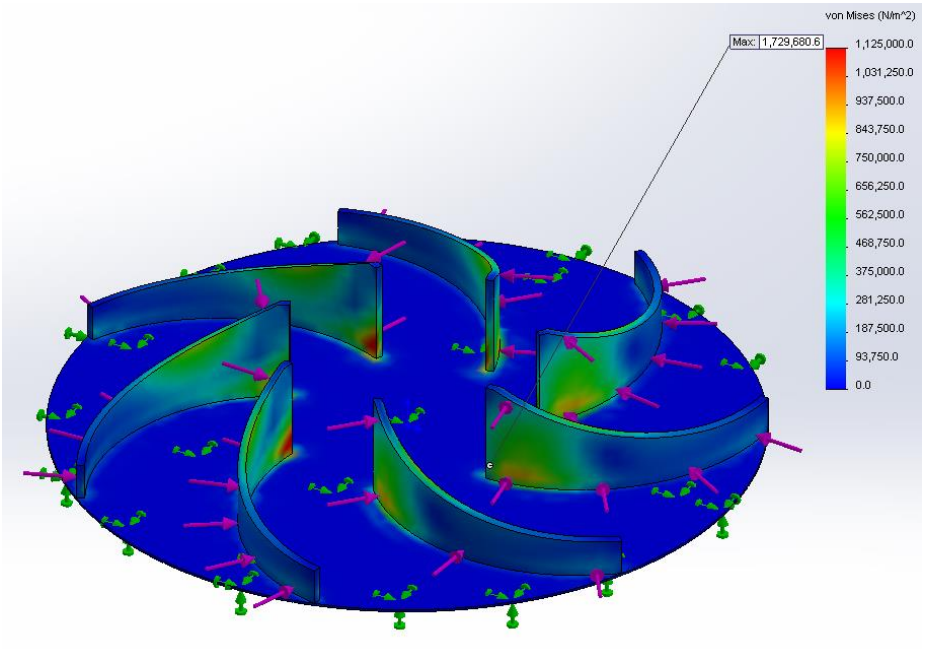


Figure 29: Von Mises' Stress Distribution for Typical Handheld Vacuum Impeller

Note that in this figure, the maximum value for stress is annotated as such. This value, 1.729MPa, is well below the ultimate tensile strength of ABS plastic (40MPa), however yield strength for polymers can be tested in several ways, and as such there is no accepted testing procedure for shear strength. Instead, the only parameter that can be obtained is ultimate tensile strength, as per the ASTM D638 – 10 [Appendix A].

The von Mises yield criterion indicate that total calculation of the von Mises stress depends on the vector summation of the Cauchy stress tensor components, which yields an approximation of the equivalent tensile stress, or σ_v. In a uniaxial stress application, this value is simply the same as the uniaxial stress, or σ_1. However, this becomes more complex in 3 dimensions, as the number of stress tensor components increases.

$$\sigma_v = \sqrt{\frac{(\sigma_{11}-\sigma_{22})^2+(\sigma_{22}-\sigma_{33})^2+(\sigma_{11}-\sigma_{33})^2+6(\sigma_{12}^2+\sigma_{23}^2+\sigma_{31}^2)}{2}} \qquad \text{(Equation 5)}$$

To solve this equation numerous times across the geometry of a component, FEA software is often utilized to complete a simulation, similar to the one shown in Figure 29.

3.3.3 Selection of SLICCVac Impeller Design

Once simulations were performed on the model of a standard vacuum cleaner, several iterations of novel designs attempting to satisfy the design specifications of the SLICCVac were created

and analyzed in the same manner. The selected final design was deemed to be the most optimal combination of flow performance, material selection, and manufacturability. A rendering of the resulting design is presented in Figure 31.

Figure 30: Rendering of SLICCVac Impeller

The geometry of the SLICCVac impeller is augmented from that of the typical impeller shown in the previous section in an effort to both improve flow performance as well as reduce stress on the vanes. Specifically, the bottom face of the impeller to which the vanes attach is not flat, as it is in the previous impeller, but rather a parabolic curve. This causes greater acceleration of fluid, which allows for higher exit velocities with the same impeller diameter. In addition, it increases the surface area of contact between the vanes and the bottom face, significantly reducing stress. Two extra vanes are also added, making the total number of vanes 9. This reduces the amount of force exerted on each vane, without major compromises in weight. Extra vanes also improve fluid performance, and smaller vane thickness, which is possible due to lower stress concentrations, reduce power loss due to drag. Finally, for improved durability over the life

cycle, the impeller could potentially be machined from aluminum, or other metals. The resulting flow simulation shows a marked improvement over the standard design, suitable for a high-performance vacuum cleaner. The same parameters for material properties, fluid properties, and angular velocity were set as before. Figure 31 shows an image of the flow simulations for the

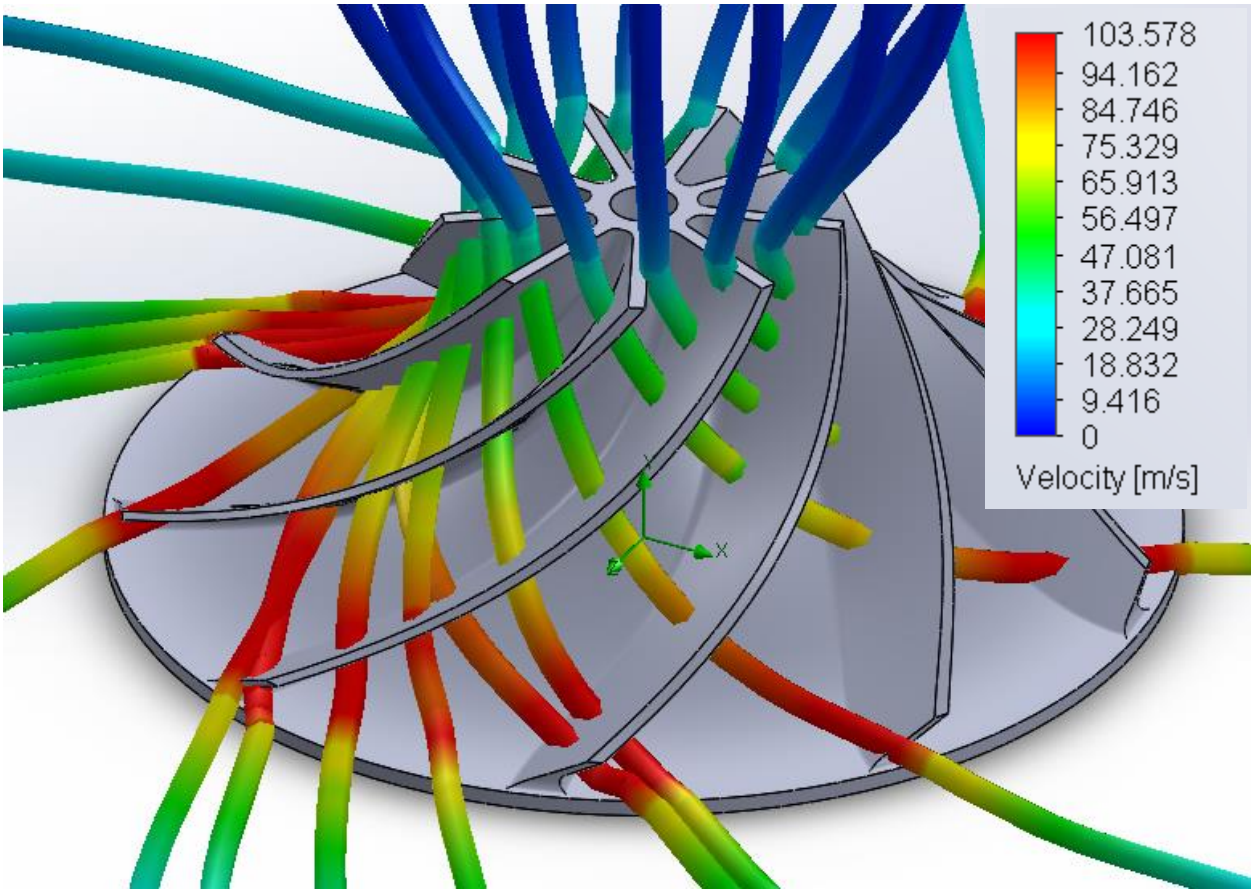


Figure 31: SLICCVac Impeller Flow Simulation

SLICCVac impeller.

The above flow simulation results state that the highest achieved velocity is 103.578m/s. Solving Bernoulli's equation as before, we can calculate that the pressure differential generated by the impeller to be 6.732kPa. To calculate the maximum power output of the SLICCVac at this velocity, we can simultaneously solve Equations 2 and 4, and then using the relation $P = pQ$, we can solve for air power *P*. The resulting equation becomes:

$$P = \frac{\rho V^3}{2} A \qquad \text{(Equation 6)}$$

In this case, *A* represents the single-vane cross-sectional inlet area, through which the fluid enters the channel between two vanes. Measuring this area in SolidWorks yields a value of 9.68×10^{-5} m^2. Using the value for *v* reported by the simulation, we can obtain a value for power of 67.48W. This is 7.48W more than is required by DS7, indicating better than expected performance. Many modern electric motors can easily operate at efficiencies of 80% or better. Use of a battery to power the motor would allow the motor to consume more power than specified in DS3, as long as the batteries do not require more power to charge. A power output of 150W is well within the capabilities of readily available batteries, and at 80% motor efficiency, that would allow 120W to be delivered to the impeller. The required efficiency of the impeller is then 50%, which is an achievable goal with today's manufacturing methods.

To demonstrate the reduction in stress concentrations in the SLICCVac impeller, the following FEA simulation was created in SolidWorks. Again, the parameters for the simulation were the same as they were for the standard impeller simulation. The FEA analysis is shown in

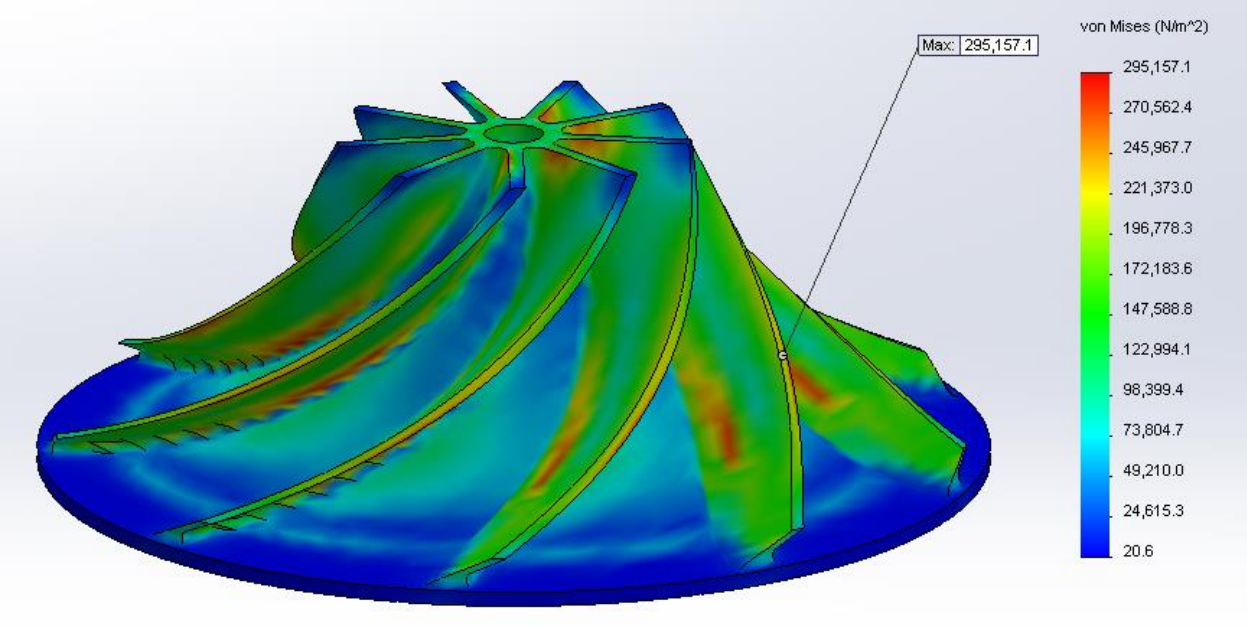


Figure 32: von Mises Stress Distribution for SLICCVac Impeller

Figure 32.

In this model, the maximum von Mises' stress is 2.95kPa, which is a very small fraction of the ultimate tensile strength of ABS plastic. For added strength, the impeller could be

machined from 7075 Aluminum alloy, which has a yield strength of over 500MPa. This allows a large margin of error, which would increase durability and longevity, important features in medical-grade devices.

3.3.4 Proposed Testing Procedure for SLICCVac Impeller

Testing the SLICCVac impeller will allow us to determine the accuracy of the simulated results presented in the previous section. Manufacturing defect, surface imperfections, frictional loss, and other real-world parameters are exceedingly time-consuming to simulate, and even the most accurate simulations cannot account for every source of power loss. Thus, only by testing can we determine if the proposed design will be effective enough to implement. Testing the impeller will require manufacturing supporting enclosures, as well as supplying mechanical power with a motor. An adequate proposed motor is the RS-550VC, developed by Mabuchi Motor Co. The specifications of this motor are discussed in later sections, as well as the manufacturer's pamphlet containing motor curves. Using this motor, suitable enclosures and

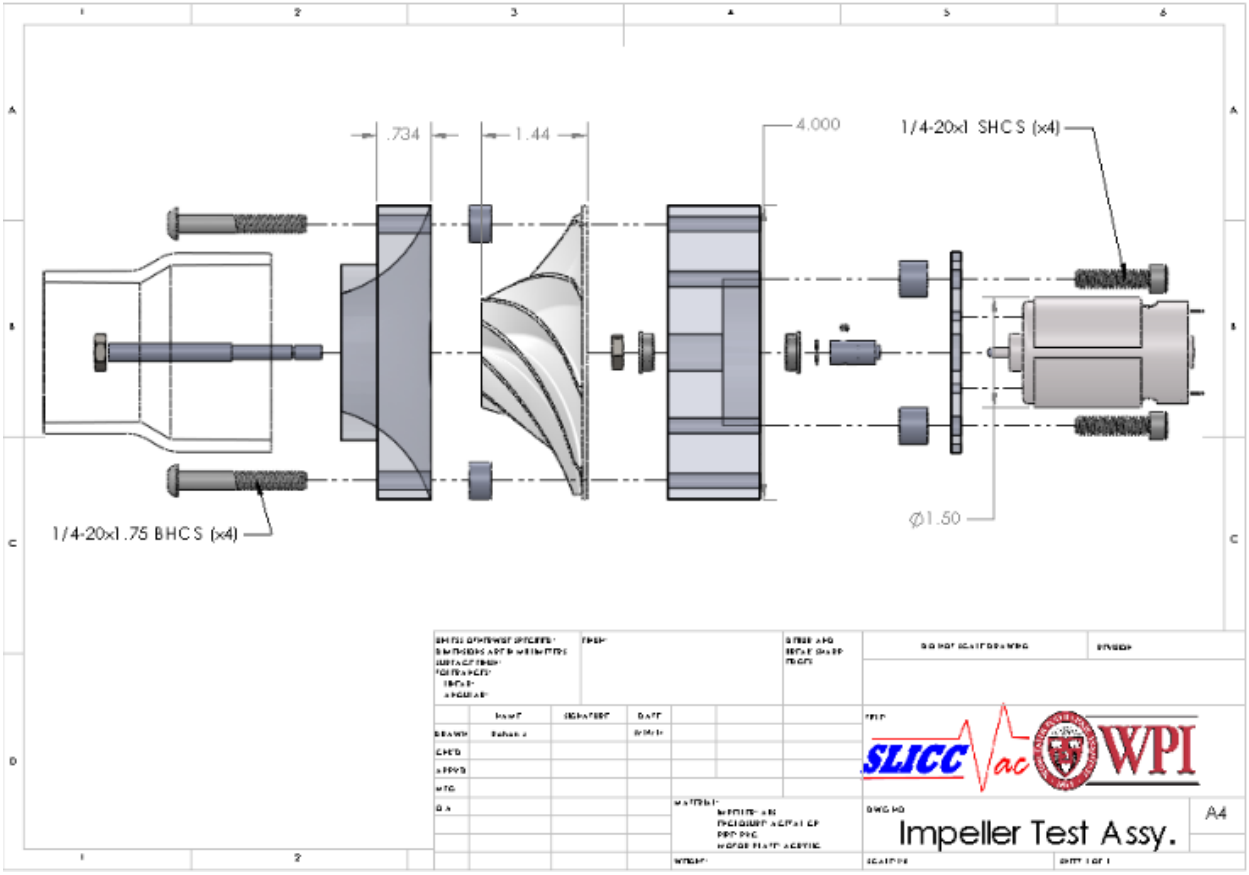


Figure 33: Drawing of Impeller Testing Assembly

power transmission mounts have been designed, and are displayed in Figure 33.

As stated in the drawing, the material used for the main enclosure section is Acetal Copolymer Polyoxymethylene. Commonly used as solid state bearings, this polymer is easy to machine and has a very low coefficient of friction, which is desirable to minimize drag.

Once the enclosures have been manufactured, the motor and impeller has been installed, and a suitable power source has been chosen, the remaining task will be to test impeller parameters, and compare them to the results of the simulation. Sensors to monitor current and voltage can be as simple as basic analog circuitry coupled with an Analog-to-Digital Converter (ADC). Using these parameters, motor curve charts can be uses to infer motor torque. Optical sensors which monitor angular velocity are readily available and surprisingly accurate, and can be in the form of photo tachometers or optical shaft encoders. Fluid parameters can easily be measured with Wheatstone Bridge pressure sensors are very inexpensive since they are comprised of a simple strain gauge, and can accurately measure small pressures. They can also be used in conjunction with a pitot probe to approximate volume flow rate. These devices can all communicate with CAMAC Bus modules running MIDAS DAQ, a common data acquisition system for scientific experimentation, however any form of DAQ may be used.

3.3.5 Manufacturing the SLICCVac Impeller

For the scope of this project, optimal material characteristics were not a concern since the SLICCVac impeller is still in the physical design stage, and testing is to be reserved for future experimentation. As such, rapid prototyping was a viable option for manufacturing the impeller. This allows a tangible model of the impeller to be created, and design revisions to be made upon it. In Figure 34, the SLICCVac Impeller has just finished production in a Stratasys Dimension ES1200 RP machine, which boasts high material density and a layer thickness of 0.01".

Figure 34: Rapid Prototyping the SLICCVac Impeller

In production, however, the material properties and geometry capabilities of a 3D printer will not be adequate for the SLICCVac Impeller. Thus, a more elaborate manufacturing process will be needed. Mass manufacturing techniques such as injection molding would be the most time-efficient method of manufacturing techniques for the impeller, however this would not allow for the material to be changed to metal if testing proves that that is necessary. As such, a 5-axis milling operation would provide optimal results. The impeller milling operation consists of two stages. In the first stage, the stock is machined from a disk, and in the second, the impeller vanes are roughed. In production there would likely be a third Swarf milling operation to finish the vanes as well, however the previous two operations yield a satisfactory result. In Figure 35, a simulation of the stock milling operation is shown, using ESPRIT CAM software.

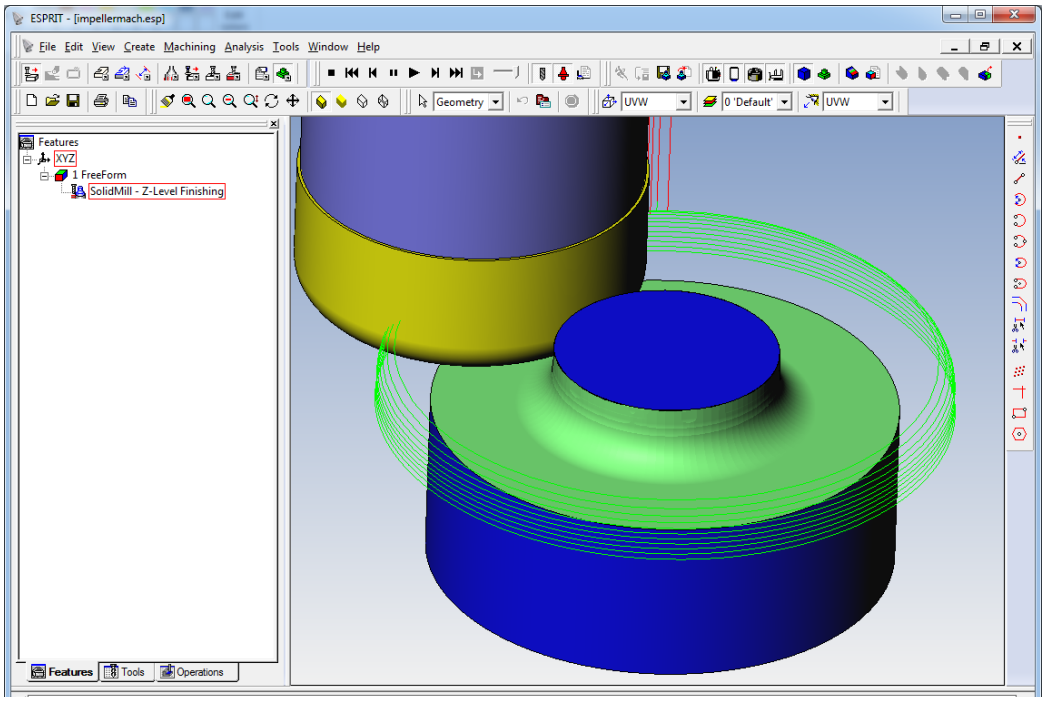


Figure 35: Stock Milling of SLICCVac Impeller

The above operation uses a 3” diameter bull nose end mill, with carbide inserts. Adjusting feeds and speeds would allow the operation to be performed on a wide variety of materials. After the stock is machined, the vanes are roughed with a ¼ inch ball end mill. The

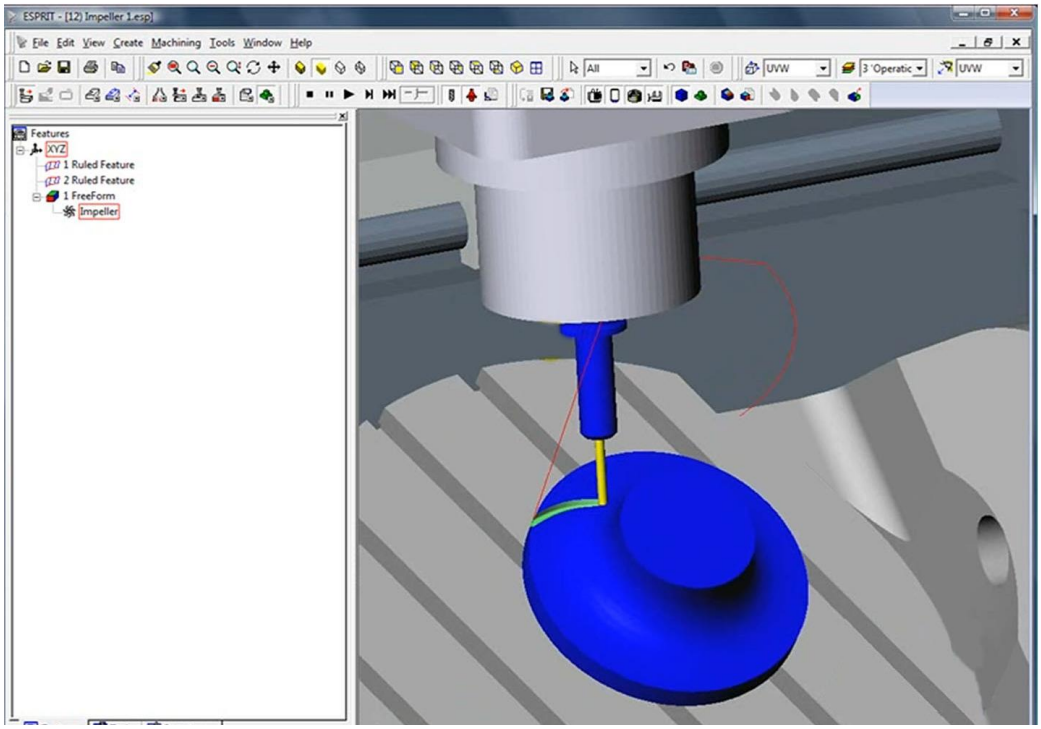


Figure 36: SLICCVac Impeller Vane Roughing

ESPRIT simulation of this machining operation is depicted in Figure 36.

Manufacturing an impeller is a fairly complex operation due to the geometry required for optimal flow. At WPI, only the Hass VM-2 mill outfitted with a Trunion table would have sufficient axes to manufacture the part. Thus, the above machining process may result in a comparatively expensive impeller compared to standard household vacuum impellers, but in a medical environment, greater cost is warranted if durability can be maximized. If the above milling operation were to be performed on 7075 Aluminum alloy, the resulting impeller would have unmatched strength, without significant weight compromise.

3.3.6 Conclusion

The impeller is one of the most crucial components of the SLICCVac since it enables the device to perform the demanding task of cleaning wet and dry debris, while only being supplied with the relatively small amount of energy available from the ambulance. Thus, the design and manufacture of the device must result in a very high efficiency impeller. The SLICCVac impeller as designed is both effective in terms of flow performance, and remains relatively simple to manufacture. Further testing will likely show that it is an ideal impeller for the SLICCVac.

3.4 Container Design

3.4.1 Introduction

As was presented in the SLICCVac Overview, the container is one of the two main components of the SLICCVac, and its prudent operation is essential to the success of the device. Thus, significant consideration was given to the design of the container, resulting in an effective design. Initial efforts to employ conventional cyclonic filtration were eventually thwarted by the technique's incompatibility with liquids and large solids. Thus, steps were taken to create a new design, which employed some similar methodology, however was not limited to dust-particle sized solids.

3.4.2 Container Design V1.0

The initial design consisted of an HDPE cylinder inside which was placed a cone, which directed the airflow to accelerate in a radial fashion, causing it to decelerate due to the drag force and fall to the bottom of the container. An image of this container design is shown in Figure 37

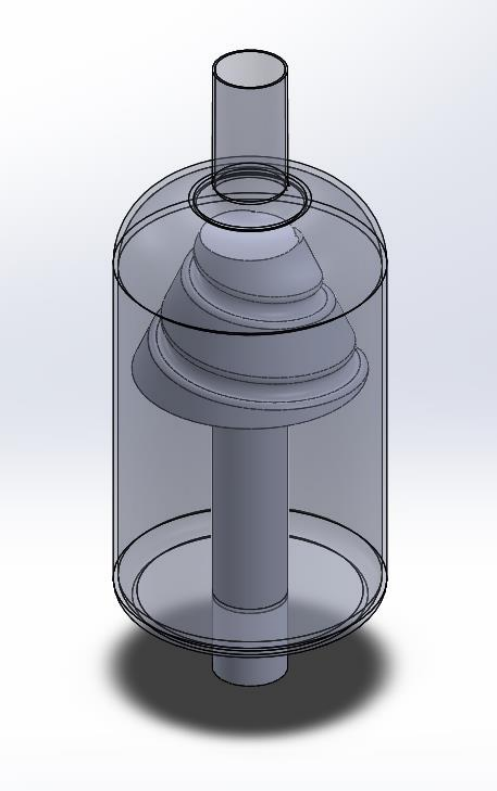


Figure 37: Container Design, V1.0

In the Figure, the cylindrical container is shown transparent so that the cyclone generator cone can be seen inside. Though this design had many of the necessary features to promote separation of the contaminants, simulations later revealed that the conic cyclone generator was ineffective at adequately accelerating the air. These simulations can be seen in Figure 38.

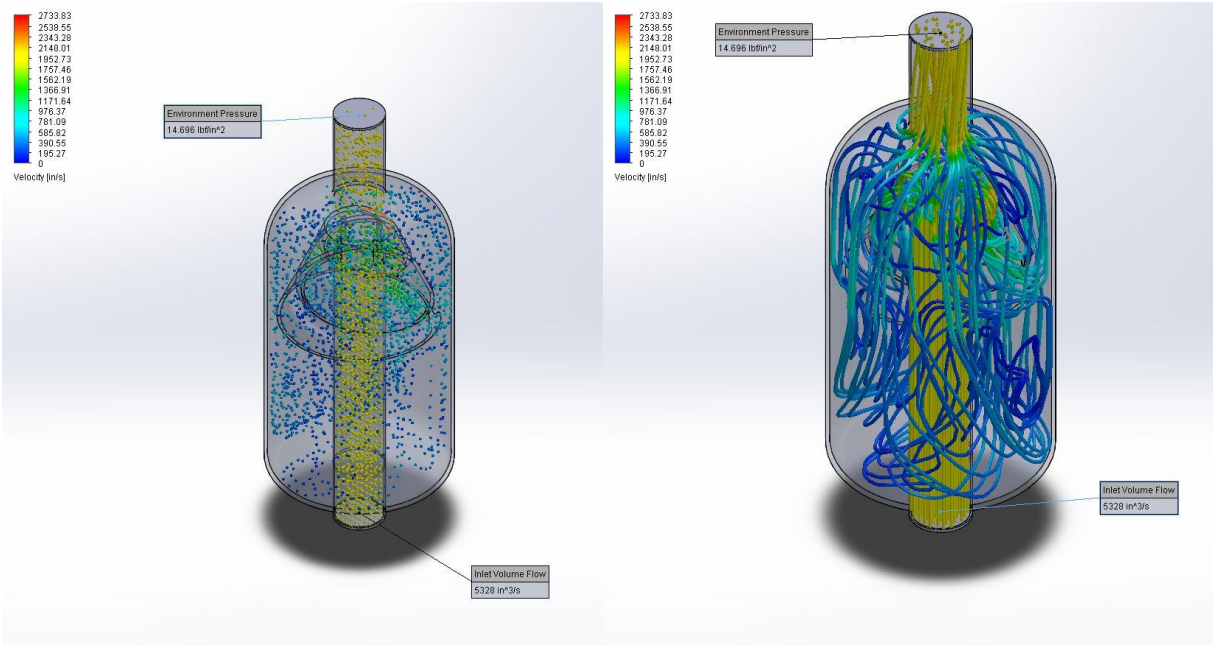


Figure 38: Flow Simulations for Container V1.0

The figures make it evident that that the flow provided by the container design does not cause radial acceleration. Instead, the flow is mostly vertical, which would not cause particles to fall to the bottom before exiting the container.

3.4.3 Container Design V1.2

The next iteration, V1.2, had a redesigned cyclone generator, and was more successful in causing the cyclonic motion of incoming air. Figure 39 shows the new cyclone generator design. Note that the remainder of the container did not change from V1.0.

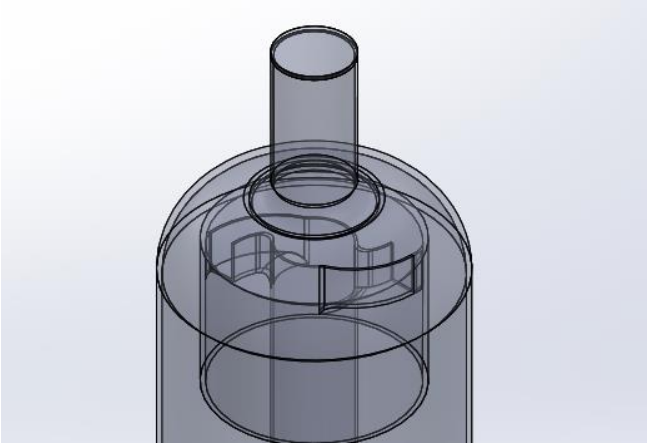


Figure 39: Container V1.2

This new cyclone generator directs the flow path into a circular motion as it exits the input tube. The effect of these "guide tubes" is to push the air into a circular motion in a more direct manner than the spiral indents in V1.0. To test the theory of this design, a similar flow simulation was performed. The results of this simulation are pictured in Figure 40.

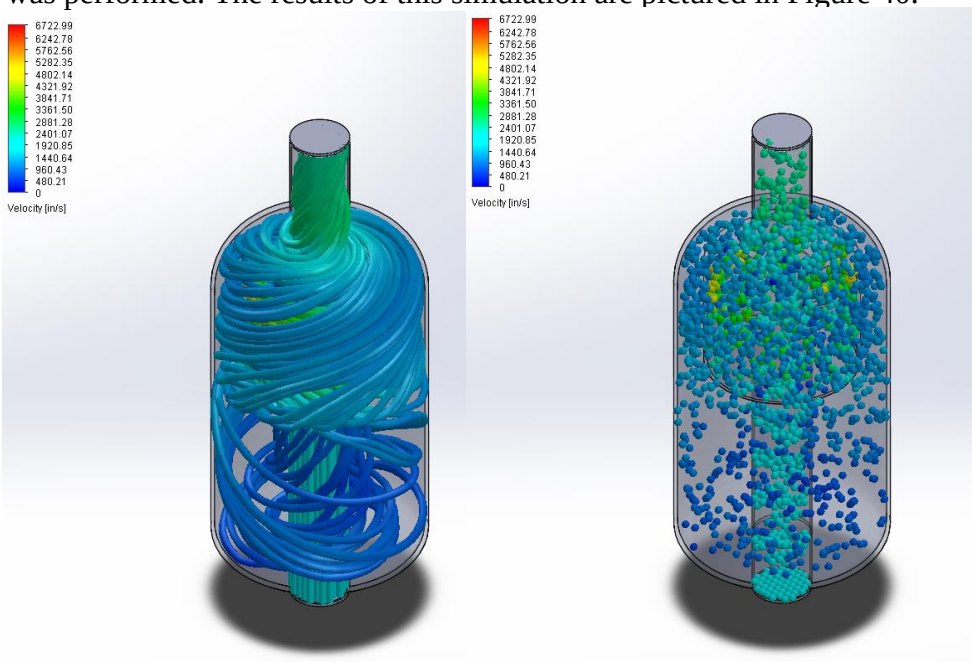


Figure 40: Flow Simulation for Container V1.2

These results show a marked improvement on radial acceleration, and many of the "flow tubes" pictured on the left hand side of the picture fall to the bottom of the container, indicating that the cyclonic filtration action is working effectively. However, the design of the cyclone generator for V1.2 was completed with less regard for manufacturability and storage. The cone-shaped

generator in V1.0 was possible to rapidly manufacture via vacuum molding, which is a widely used technique in manufacturing today. In addition, this type of design could be made to be stackable, greatly reducing storage space. The cylindrical enclosure of the container was also deemed too space-consuming, and furthermore it was unlikely for the refuse storage space to be completely used during a transport. Thus, the final container design was a created from the ground-up.

3.4.4 Container Design V2.0

From the simulations of versions 1.0 and 1.2, it was clear that implementing the cyclonic method was too taxing on manufacturability. Thus, the final design omitted the cyclonic filtration and settled for a "gravity separation" technique. This technique forces incoming contaminants downwards towards a crevice in the bottom of the container, while the impeller draws air in near the top. In this way, for the contaminants to get out of either the inlet or the outlet, they would have to go upward, against gravity. Since the liquid and solid contaminants that will be required to be cleaned by the SLICCVac have a high density, they will be difficult to pull back upwards. This design is much more conducive to both solid and liquid separation, whereas cyclonic filtration is limited to small-particle solids like dust. As before, the container is designed to be vacuum-moldable, to reduce cost and allow highly abrasion-resistant and non-reactive HDPE construction. The final design, V2.0 satisfies this requirement, and implements the gravity separation method outline above. A model of the container design can be seen in Figure 41.

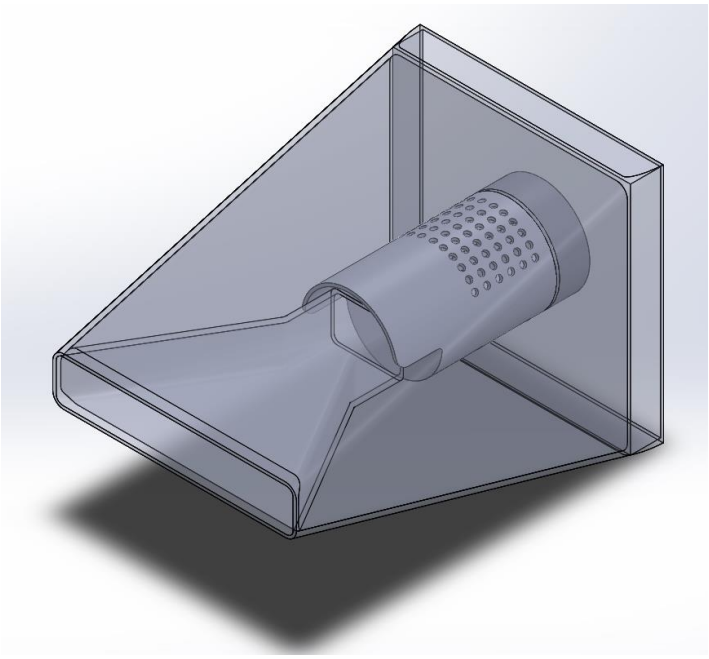


Figure 41: SLICCVac Container V2.0

The container features a wide nozzle, specifically designed for ambulance use. Contaminants that enter through the nozzle are directed downwards by an impact plate at the termination of a support tube. The impact plate removes a large percentage of the incoming particle's kinetic energy. Then, as the particles are directed to the bottom crevice of the container, they contact several other HDPE surfaces, and are decelerated by the drag force. By the time the air reached the intake armature at the top of the container, there are almost no particles in it. This design also includes a 3-inch HEPA filter as an added level of protection, housed inside of the intake armature. This custom designed filter uses a pod lenticular array of randomly arranged glass fibers. This particular HEPA filter media is known for two main features: it is exceptionally proficient at removing microorganisms such as bacteria, and it causes very little flow reduction. To analyze the effectiveness of the SLICCVac's novel gravity separation technique, the simulation shown in Figure 42 was created.

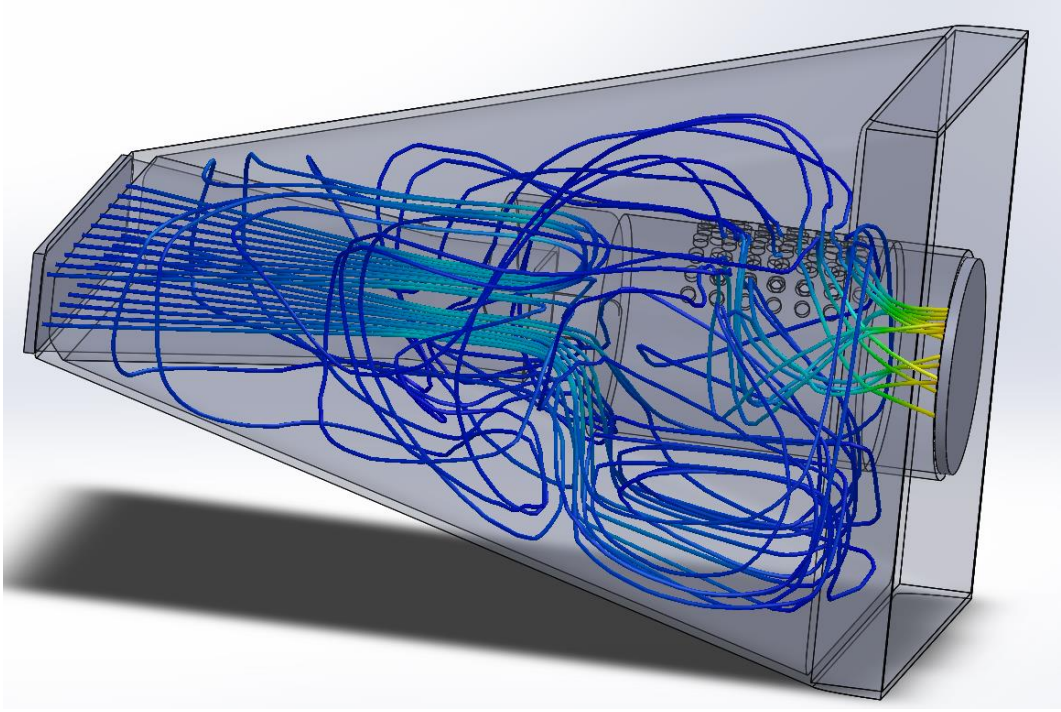


Figure 42: Flow Simulation for Container V2.0

The simulation shows that the incoming air from the nozzle of the container is directed downward and begins to spiral in the corner, indicating that particles would experience drag in that area, causing them to decelerate and settle at the bottom of the container.

The container also features HEPA filtration, however available heap filter were not of the appropriate form factor be compatible with V2.0 of the container. Specifically, the intake armature, which can be seen in Figure 41 as the center tube, with several holes for airflow, must be small enough so it doesn't occupy too much space in the container, yet large enough to accommodate a HEPA filter. HEPA filters made from common micro-porous membrane media are highly common, but to provide the specified filtration, they must be larger than the available space in the intake armature.

A specially designed filter for the SLICCVac utilizes modern materials that have enabled miniaturization of HEPA filters, using advanced manufacturing methods. Most of these materials are made from glass fibers, and precisely arranged in lattice structures to facilitate efficient filtration. The particular configuration chosen for the SLICCVac due to its low resistance to flow is the lenticular pod array. This filter media also allows for smaller filters, thus the SLICCVac filter measures only about 1.5 inches in diameter by 3 inches in length. A rendering of the SLICCVac HEPA filter is shown in Figure 43. The end caps are shown in black, and the cream-colored fins are the state-of-the-art fiberglass filter media. The intake armature is also pictured, colored transparent white so the filter underneath is visible.

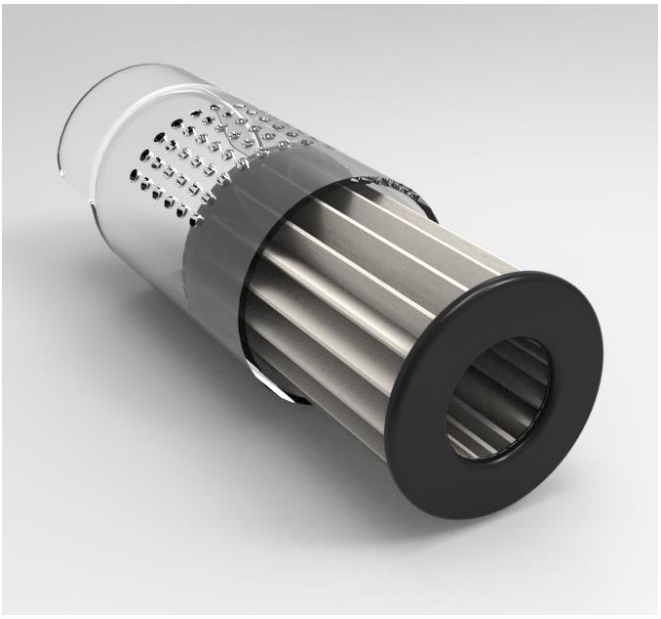


Figure 43: SLICCVac HEPA Filter and Intake Armature

3.5 Other Considerations

3.5.1 Motors

A motor is an important component to a vacuum because a motor is responsible for taking electricity from a source and converting it into mechanical power via suction and air flow rate [39]. The vacuum's ability to pick up particles is largely due to the motor's specifications. There are many different types of motors that vary in size, shape, and productivity depending on the purpose of the vacuum. Four significant characteristics used to assess a motor's performance are torque, current draw, speed, and power. These characteristics correlate with one another and can be used to determine the vacuum's overall efficiency.

Motors are used in a wide range of applications including electric toothbrushes, blenders, washing machines, and automobiles. Each motor works in the same manner, but its size and shape vary depending on loads the motor will be exposed to. The amount of force the motor's output shaft (rotating shaft that transmits to the output source) can rotate is known as torque (τ) [40]. The units of this variable are Newton-meters (N-m) (metric), or Foot-pounds (ft-lb) (English). The other three main characteristics are often expressed as a function of torque.

Current draw is the amount of electrical current that the motor obtains at any given load. This determines how many amperes (A) the motor uses from a voltage source by a load. The following equation demonstrates the calculation to receive the total amount of current used:

$$I(\tau) = \frac{I_{stall} - I_{free}}{\tau_{stall}} * \tau + I_{free} \quad , \qquad \text{(Eq. 7)}$$

The total current, in A, can be derived using torque, Stall current (I_{stall}), Free current (I_{free}), and Stall torque (τ_{stall}). The Stall current is the amount of current drawn when the motor is stalled, while Free current is the amount of current drawn when the motor has no load placed upon it, thus no torque. The Stall torque is the amount of torque necessary to stall the motor. Current draw is found to have a linear relationship with torque. As torque (or load of motor) increases, the amount of current drawn also increases. Therefore if draw is low then torque will be low, but if draw is high then torque will be high.

Speed (ω) is defined as the rotational velocity at which the output shaft spins and is measured in rounds per minute (rpm).

$$\omega(\tau) = -\frac{\omega_{free}}{\tau_{stall}} * \tau + \omega_{free} \quad , \qquad \text{(Eq. 8)}$$

In the above equation, free speed (ω_{free}) is the speed exerted by a motor when no load is placed upon it. Speed is derived as a function of torque, where an increase in motor load will result to a decrease in rotational velocity.

Power is the rate at which a motor can perform work. Overall, power is the measurement of how quickly a motor executes its intended job. The units of power are watts, as given in this equation.

$$\boldsymbol{P = \tau \cdot \omega,} \qquad \text{(Eq. 9)}$$

As the equation displays, power is computed by multiplying pi by torque and speed.

A motor's efficiency is the measurement of how much electrical energy is actually converted into the mechanical energy needed to operate its corresponding device. It is important that a motor has high efficiency because low efficiency means a lot of energy is being converted into heat. Too much heat can cause the motor to burn out, thus not very optimal. Efficiency is generally written as a percentage of the electrical input into the motor that is converted into functional mechanical energy [40].

Motors vary in cost depending on its size and durability. For the purposes of an internal ambulance vacuum and the cost constraints of an undergraduate research project, a RS-550VC-7525 Mabuchi Motor was chosen as the most suitable motor for this project. This type of motor is typically used in cordless power tools (e.g. drills, garden tools, and air compressors) and electric ride-on toys. Figure 44 shows a motor curve for the RS-550VC with efficiency, current, speed, and torque plotted at 12.0V.

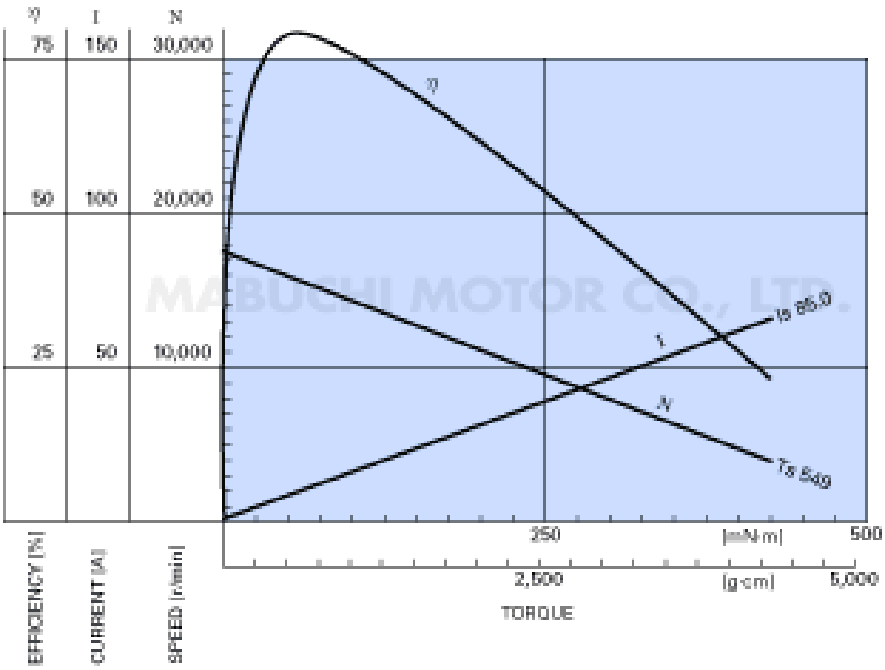


Figure 44: Motor Curve of a RS-550VC-7525 Mabuchi Motor

The design specifications of the SLICCVac state a requirement for consuming less than 10A when consuming 12.0V from the ambulance due to power usage regulations of ambulances. The ambulance already expends much electricity to a plethora of other medical and mechanical components, so the SLICCVac must use as little energy as possible. The RS-550VC-7525 consumes 1.20A when there is no load, and 10.1A at maximum efficiency. Although a bit greater than 10A at maximum efficiency, the RS-550 will still work for this project.

Power consideration was also a big component in deciding the motor to use. The RS-550 has an approximate output range of 5.0W to 100W. At maximum efficiency a RS-550VC-7525 motor has a power output of 95.9 watts. This will provide more than sufficient power to pick up both solids and liquids. The speed is relatively high varying from about 15krpm at rest and 18krpm at maximum capacity. A diagram of the components and dimensions in millimeters is shown in Figure 45

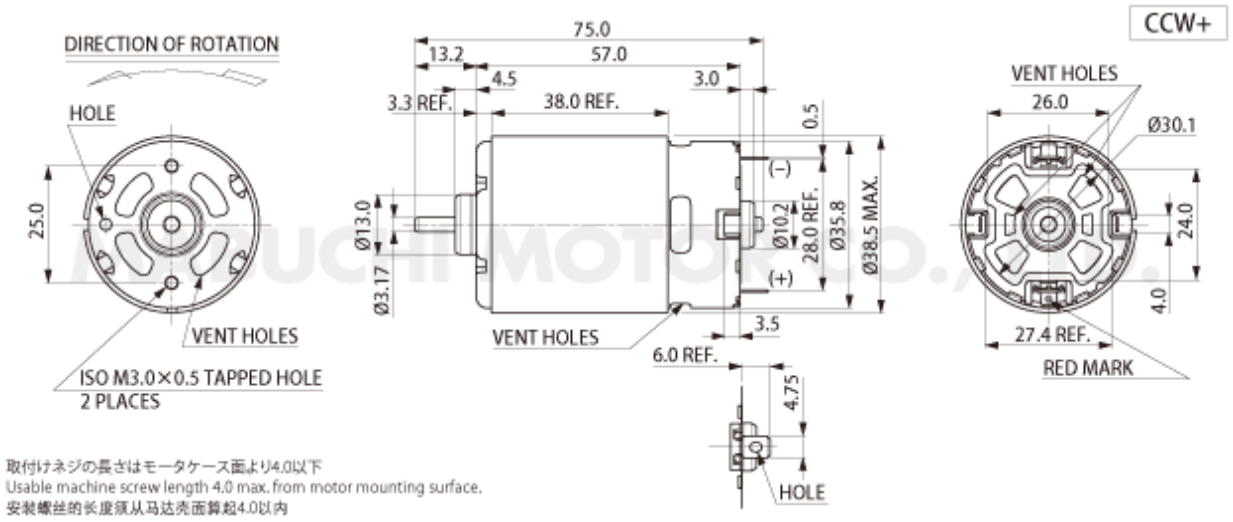


Figure 45: Components and Dimensions of a RS-550VC-7525

This Mabuchi Motor has an approximate weight of 247g, which will not add that greatly to the overall weight of SLICCVac [41]. The motor is compact, so it will not take up unnecessary space within the ambulance. Finally, the cost of the motor is reasonably marked at $6.75 making it a suitable purchase for this undergraduate project (although a motor was never acquired because of time limitations for prototype manufacturing).

In conclusion, a RS-550VC-7525 Mabuchi Motor functions at low, but adequate, power levels capable of picking up both solids and liquids via air suction. The efficiency of this motor is also sufficient for use in the SLICCVac. The motor has a low weight and compact size, which minimizes the product's overall weight and allows for convenient storage in the ambulance.

3.5.2 Batteries

The SLICCVac will require rechargeable battery packs, which are necessary to deliver power to the RS-550VC-7525 motor. Lithium-ion (li-ion) batteries have been used in a wide range of applications from cellular phones to hand-held vacuums and hybrid cars for their superior performance in regards to power and energy density over the leading competitors. Technological advances in li-ion battery research have created more opportunities in the development of portable devices and the increase of li-ion usage in durable consumer goods. Battery packs are an array of individual cells that differ in electrode and separator makeup depending on the manufacturer. When designing battery packs, the assembly should be balanced between the system load demands, reliability, and safety. The structure, design specifications, and safety levels of li-ion batteries make them suitable for application in the SLICCVac. The most common, and convenient, form of lithium-ion batteries is the 18650 cell. Figure 46 illustrates an example of a lithium-ion battery with a form factor of 18650 [42].

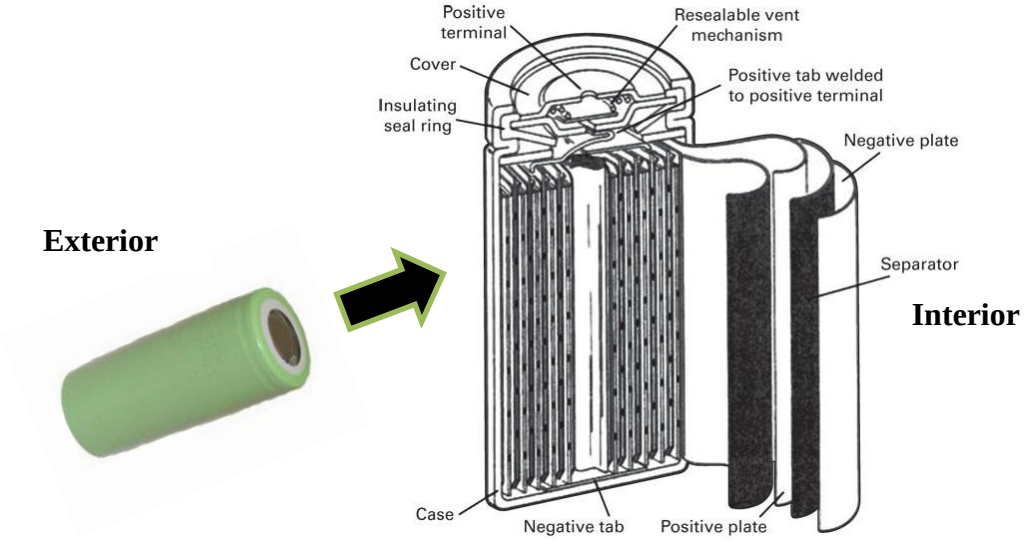


Figure 46: Exterior and interior views of 18650 form factor lithium-ion battery

The small form factor, as seen in Figure 46, and light weight of li-ion batteries cells allow for the fabrication of compact, feature-rich portable devices alongside extended run times. The cylindrical cells on the interior of the battery are constructed in a "jellyroll" fashion [43]. The average size of a li-ion cell is approximately 65 mm in length, 18 mm in width, and 18 mm in height [44]. Many cells are able to be combined in one battery pack because of the small size and shape. Lithium-ion batteries are often encased in steel shell, which reinforces protection by

adding axial and lateral strength to the cell; as seen in green in Figure 46. The current competitors against lithium-ion batteries are nickel cadmium (NiCd), nickel hydride (NiMh), and lead acid (LA) batteries. A comparison of different battery types is organized in Figure 47, where the three competitors (or legacy chemistries) are compared to three different li-ion type batteries [45].

	Lead Acid	Nickel Cadmium	Nickel Metal Hydride	Lithium Cobalt	Lithium Manganese	Lithium Iron Phosphate
Capacity	0.5	1.2	1.8	2.6->2.9AH	2.2-2.45AH	1.3-1.6AH
Voltage	2V	1.2V	1.2V	3.7V	3.7V	3.V
Energy Density(W/Kg)	35	45	70	167	110	100
Cycle Life	400	500	500	>500	>500	>1000
Life (Yrs) @ one charge/day	1	2	2	2	2	3
Charging Time	8 hrs	1.5 hrs	4 hrs	2-4 hrs	2-4 hrs	1-2 hrs
Self Discharge Rate (%/mo)	20%	30%	35%	10%	10%	8%
Safety	Good	Good	Good	Poor	Average	Good
High Temp Performance	Good	Good	Good	Average	Poor	Good
Cold Temp (0°F) Charge	Good	Fair	Fair	Fails	Fails	Fails
Cold Temp (0°F) Discharge	Good	Good	Poor	Poor	Good	Good

Figure 47: Cell chemistry comparison of competing batteries

From Figure 47 it can be interpreted that li-ion batteries have a greater voltage and capacity than the legacy chemistries. The SLICCVac requires a battery that is able to supply 10.1A continuous discharge to supply enough energy to the RS-550's peak efficiency, which high discharge li-ion 18650 batteries do supply. The nominal voltage of li-ion batteries is 3.7V with the potential of 4.2V per cell (Figure 47). The NiMh and NiCd batteries only provide 1.2V, so it takes more of these cells to have the capacity and voltage of the lithium-ion cells. The increase in the number of cells adds to the overall cost, weight, and complexity of the given battery. The SLICCVac would utilize four li-ion batteries with 3.7V each, so the maximum voltage would be 14.8V. The maximum voltage would result in a high motor speed (rpm). Table 1 relays that lithium-ion batteries have significantly larger energy densities that fell between 100W/kg and 167W/kg, compared to the competitors that fell between 35W/kg and 70W/kg. A greater energy density is ideal because that means there is a greater amount of stored energy in the battery's system, which can allow for more work to be performed.

The cell life and charge cycles are very important to the dependability of a battery [46]. The cell life cycle of the li-ion batteries is greater than then the standard legacy chemistries, which paves the way for a longer lifespan (Figure 47). A battery pack's construction and associated safety and monitoring circuits also play a role in extending cycle life cycle. The batteries are charged on a separate balancing li-ion circuit. The charging time of the lithium-ion batteries is less than the charging time under normal use as seen in Figure 47. Figure 47 additionally distinguishes that the lithium-ion batteries have faster charge rates than the three competitors, without affecting the cycle life. In order for the SLICCVac to require the least amount of upkeep and maintenance regarding battery replacement and charging times, the lithium-ion batteries would be more optimal than the conventional batteries of lead acid, nickel cadmium, or nickel metal hydride.

The safety mechanisms of lithium-ion batteries are proctored by internal components and monitoring circuitry [45]. Three aspects of battery safety are electrical integrity, thermal integrity, and mechanical integrity [44]. Electrical and thermal integrity are monitored by the internal components and the monitoring circuitry, while the mechanical integrity can be determined by analyzing the effects of intrusions upon the battery. The internal components and dedicated protection circuits monitor and manage the charge and discharge cycles, in addition to prohibit erroneous application and mishandling. The positive thermal coefficient (PTC) device is located at the top of the positive end of a li-ion battery. The PTC reacts with to high current discharge levels to increase the output signal. If the discharge output exceeds safe operating levels, the PTC can disconnect to prevent dangerous operation. The battery monitoring circuitry prevents unwanted side effects caused by overload or short-circuits; in other word, ensures the device is operating within the designated parameters. The monitoring circuitry can detect deficient or excessive charging or discharging rates of individual cells and induces shutoff process. The battery protection circuits will interface with the logic and controls to integrate all of SLICCVac's components into one "brain."

Finally, the mechanical integrity of lithium-ion batteries is high enough to be applicable in production of the SLICCVac. The cells of lithium-ion batteries have inherent safety and stability under normal and abusive conditions [47]. Small intrusions to a battery pack can result in detrimental events, thus high mechanical integrity is sought for. The average flow stress of a

lithium-ion battery's shell casing is about 500MPa and the fracture strain is about 0.03 as shown in Figure 4. The stress and strain values indicate that the battery would be able to withstand tension and compression forces, therefore the batteries would be able to endure damages should the SLICCVac be dropped or impacted.

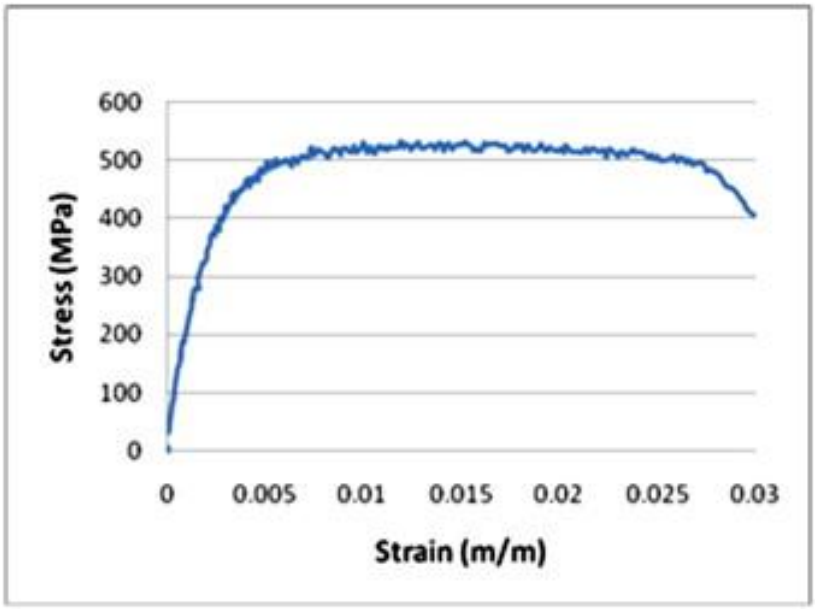


Figure 48: 18650 shell casing stress-strain curve

Many manufacturers are transferring to lithium-ion batteries due to the various advantages and advanced battery design [45]. The lithium-ion compact form 18650 batteries possess many characteristics that make them more favorable than standard battery types for use in the SLICCVac. The dimensions and form of a li-ion 18650 battery permit easy integration into the SLICCVac's ergonomic motor assembly compartment. Four of these batteries have adequate capacity (1.3-2.9AH per battery), voltage (3.7V per battery), and energy densities (100-167W/kg per battery) needed to create high motor rotational velocity in the RS-550VC motor (Figure 47). The life cycle for the li-ion cells would require the EMS to change the battery packs every two years, so these would not add overwhelming maintenance to the staff. The charging time for the battery packs would be about two to four hours, but each ambulance would be equipped with three or four additional battery packs in case of excessive need for SLICCVac (Figure 47). The safety and mechanical stability of cells is at a good level under normal and abusive conditions. Lithium-ion batteries carry intrinsic safety means to monitor and manage overall charging and

discharging. Imbalances to the discharge or charge of voltage will alert the battery protection circuit and provoke shutoff process.

3.5.3 Logic and Control

The logic and control of SLICCVac would be operated by Arduino Uno in the initial prototype and a custom ARM board in the final design; both of which are microcontrollers. A microcontroller is a portable data acquisition using onboard processing power and is found in items such as power strips and calculators. The advantages of microcontrollers are that they are small, portable, cheap, widely utilized, easily programmable, and do not require a computer to operate. The disadvantages are limitations in processing power and lack of ability to store data [48]. An Arduino is an Italian- made microcontroller that allows for easy use and adaptability in development. This prototyping platform is open source electronic, based on flexible and user-friendly software.

An Arduino Uno is a development board for the ATmega328 microcontroller. The Uno is said to have "plug in and use usability" due to simple connection mechanisms needed to get started. This board differs from all previous because it does not use the FTDI USB-to-serial driver chip, but instead a USB-to-serial converter (ATmega8U2 programmed). This is one of the Arduino components that would not be implemented on the final design, since programming would be accomplished via a 6-pin ICSP header. A picture of the front-side of an Arduino Uno is shown in Figure 49; a picture of the backside of an Arduino Uno is shown in Figure 50. A labeled diagram [49] of the front-side of an Arduino Uno is presented in Figure 51.

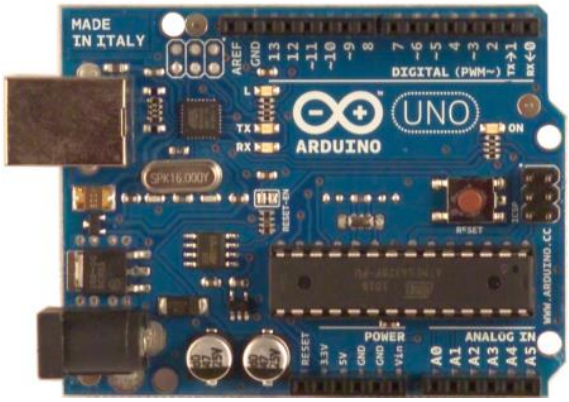


Figure 49: Front view of Arduino Uno

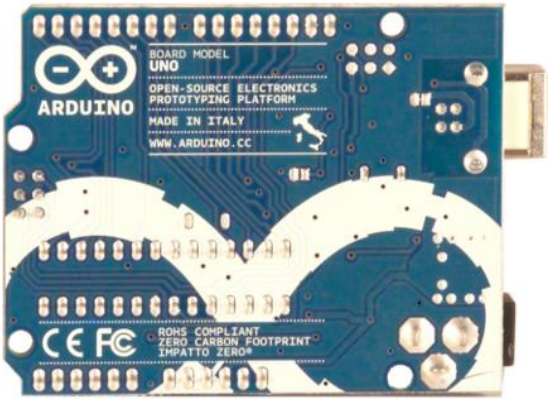


Figure 50: Back view of Arduino Uno

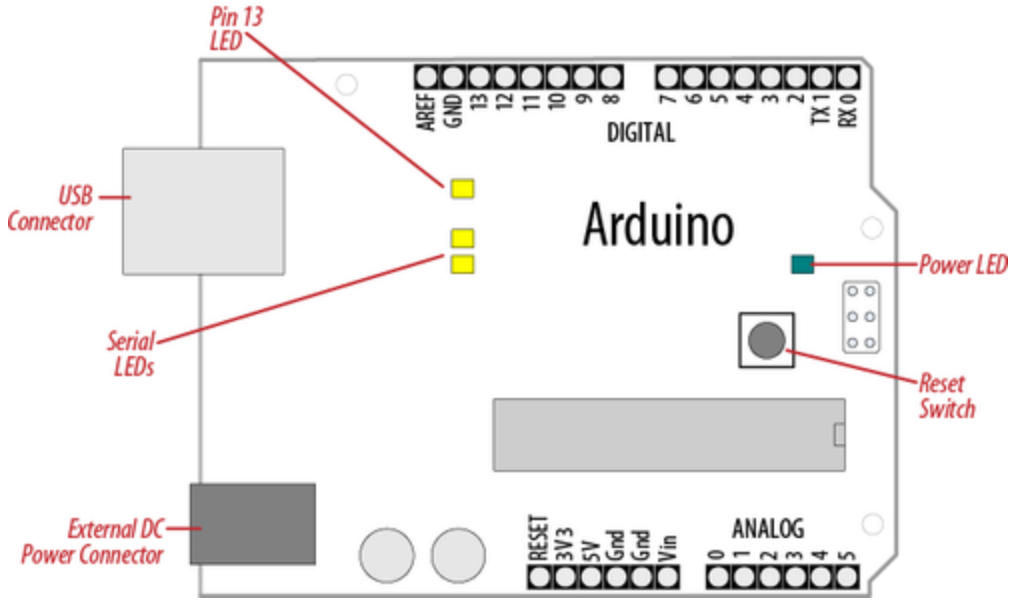


Figure 51: Labeled diagram of Arduino Uno

An Arduino Uno provides fourteen digital input/output pins, six analog inputs, USB connection, 16MHz ceramic resonator, power jack, ICSP header, and reset button. The Arduino lends itself to easy usage and programmable changes during the developmental stages due to its adaptable software. Programming occurs through Arduino programming language and Arduino development environment. A custom ARM board would be used in the final design to control, monitor, and help protect the functionality of the SLICCVac. The ARM will monitor the temperature and charge state of the lithium-ion battery pack. The battery level will be accurately displayed so the user can see it. Pressure and flow rate will be monitored to determine if there is a blockage in the container. Wetness of the HEPA filter will be assessed by the ARM used to signal to the wetness alert indicator. Lastly, the ARM will monitor the motor draw and speed with regulators that enable variable speed control. Other sensors and components are required to fully evaluate the SLICCVac's performance. Flow rate, pressure, and wetness will all be recognized by specific sensors and then transmitted to the board for processing. The custom board will have defined parameters, so an automatic shutoff will be induced should the parameters be breached. The microprocessor, as seen in Figure 52, is the main component which monitors these and other parameters [50].

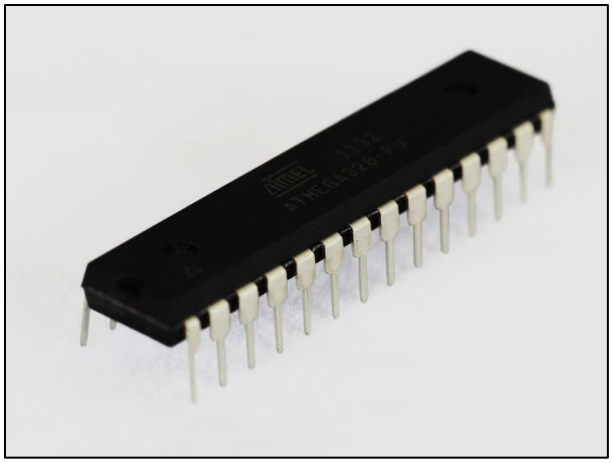


Figure 52: ATMega328-PU Microcontroller

As mentioned earlier, an Arduino Uno development board will be the basis of the control and sensing of the SLICCVac at the prototype stage, and a custom ARM board at the finalized design stage. The Uno provides ease of use and versatility for connections and software, which makes it a good tool for prototyping. The custom board will be in the final logic module to monitor the well-being of SLICCVac in regards to battery temperature and charge, vacuum pressure, motor current and draw, and moisture level of the HEPA filter. The board will communicate with four indicators for battery level, blockage alert, wetness alert, and vacuum motor speed to notify the EMS of any problems in operation.

3.5.4 Storage and Disposal/Cleaning

There are so many mandated items within the ambulance that aid in vehicle operation and medical procedures, so there is very limited empty space available in the ambulance. It is important the SLICCVac is stored in an inconspicuous location as to not impede EMS personnel's functions. As outlined by DS8, the storage location must be less than $0.5m^3$. A drug cabinet in the ambulance has been identified as having empty space. Figure 53 depicts the interior of an ambulance with the drug cabinet intended for SLICCVac storage is circled in red [51]. Figure 54 reveals the empty space behind the roll-up doors of the drug cabinet.

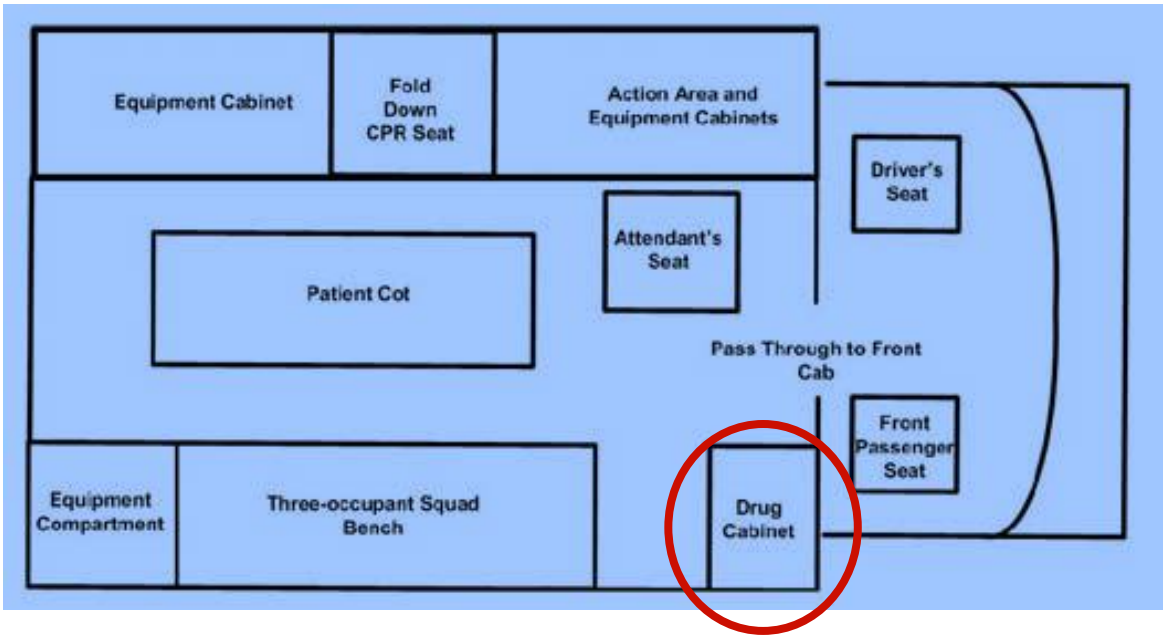


Figure 53: Labeled diagram of ambulance interior

Figure 54: SLICCVac storage location

The drug cabinet it located adjacent to the side entrance of the back caddy of the ambulance as seen in Figure 53. This location is hidden from patient view and does not interfere with an EMS's ability to perform his/her emergency medical duties. The storage location would house the battery charger and extra containers, as well as the SLICCVac when it was not in use. The SLICCVac container is designed to only let solid/liquids enter from one direction without any reflow (DS6). After one use, the container needs to be disposed to prevent any contamination from festering. The containers will be disposed of in accordance with isolated waste bags marked per OSHA 1910.1030. An OSHA approved biohazard bag is shown in Figure 55, where an OSHA approved bag is either red or clearly marked with a biohazard symbol [52].

Figure 55: OSHA approved red bio hazardous waste bag

The waste bags will be destroyed of following current ambulance waste systems, so by using either an on- or off-property incinerators. The non-disposable components of SLICCVac can be cleaned by wiping down with a bleach and water solution using paper towels. It is important to stress that when cleaning solids or liquids in the ambulance to do so immediately, so that pathogens may not be given opportunity to pose a threat to human health. The SLICCVac should not be placed on charger with a used container because containers are only meant for a single use; multiple uses of containers could lead to malfunction of the vacuum or potential cross-contamination.

3.6 Conclusion

The preceding chapter presented an in-depth explanation of the design of the SLICCVac, and through a rigorous analysis of these designs, proved that if implemented, they will enable the production of a highly effective vacuum cleaning device for EMS applications. The SLICCVac addresses many challenges not normally faced by conventional vacuum cleaner designs, which are introduced in an ambulance environment. Though certainly an area of focus for conventional vacuum cleaner design, separation of contaminants from non-disposable components is of utmost importance to the SLICCVac. The dangers of allowing the bacterial contamination that is normally found in ambulances to be left uncleansed are made evident in Chapter 2. Thus, the SLICCVac container is specifically designed to eliminate the possibility of contamination, using a two-strike methodology. First, the container uses a proprietary gravity separation technique that performs the initial separation of large particles and liquids. After this stage, the incoming contamination is almost completely removed. Even still, a custom-designed HEPA filter using modern composite materials to provide a revolutionary new filter media is implemented after the gravity separation stage, so that the chances of dangerous pathogens entering the impeller are less than 0.001%. Inside the motor assembly, the SLICCVac is designed with cutting-edge materials, making it one of the most modern and up-to-date vacuum cleaners on the market. The SLICCVac utilizes 18650 Li-ion batteries, which are becoming ubiquitous due to their increasing safety and energy density. Furthermore, the vacuum is controlled by an ATmega328 microprocessor, giving it more computing power than the navigation controls of the Apollo 11. Finally, to meet the stringent power limitations on an ambulance, the SLICCVac's custom impeller is more efficient than the vast majority of vacuum cleaner impellers on the market, allowing the SLICCVac to provide as much power as a Shop Vac, while consuming only as much power as a conventional handheld vacuum. These specifications make the SLICCVac the most suitable vacuum cleaner for ambulance applications that is available today.

4. Closing Remarks

As stated in our problem statement, the SLICCVac is a ″cleaning device″ specifically designed to ″immediately contain waste″, but how does it accomplish such a ubiquitous task? To break this down into well-defined and achievable goals, we created a list of specific design considerations to guide our designs. The purpose of this section of our paper is to investigate the design purpose of the SLICCVac, and to determine its ability to succeed in that purpose. First, we will break down the specific design considerations we followed in planning the SLICCVac. These considerations led us to establish the key design features that we followed during the design process of our project. Given the specific design considerations and the key design features of the SLICCVac, we will examine its possible applications in an ambulance, as well as other potential applications in industrial, commercial, and private settings. This section serves as an analysis of our success in creating a device that provides a solution to our problem statement and is both effective and marketable.

4.2 Applications of the SLICCVac

4.2.1 Introduction

The SLICCVac is intended for use by emergency medical technicians to simplify the process of cleaning the ambulance and to limit the spread of contamination, and it was designed to accommodate the limitations and necessities of use in such a specialized locale. These requirements are the driving factors defining our design specifications, and as such define the capabilities of the SLICCVac. The SLICCVac is easily held and operated in one hand, and the container section is detachable to prevent the spread of contamination after vacuuming up either solid or liquid contaminants, or both.

4.2.2 Use in an Ambulance

Contamination is one of the greatest dangers in an ambulance, for the patient but also the EMTs who can spend over a thousand hours in an ambulance every year. This contamination can cause anything from minor health issues to deadly diseases if left alone to incubate in the nooks and crannies of the ambulance. As we found in our background research, the standard practices for cleaning ambulances can be not only ineffective but also tedious and lengthy. The SLICCVac

is intended to serve as a solution, or at least an improvement this system, decreasing the time and difficulty of the cleaning procedure.

The SLICCVac differs from other vacuum cleaners in how it stores the waste it picks up during cleaning. The SLICCVac container is engineered to best follow the Occupational Health & Safety Administration′s regulation 1910.1030, which deals specifically with contamination in the form of bloodborne pathogens. In most vacuum cleaners the airflow, and therefore the contaminants, passes first through the impeller into the container, and then is filtered just before it exits the vacuum. The SLICCVac is fundamentally different in that the shape of the container directs the flow such that heavier particles are caught and held by gravity, and only airborne particles reach the HEPA filter that filters out any remaining contamination. This ensures that no dangerous particles escapes the container, leaving the main body of the SLICCVac contaminant free, and prevents any spreading of contamination.

The SLICCVac is intended for use as an on-the-go cleaning device, available during travel to the site of an accident and during the trip back to the hospital. This means that there needs to be a suitable space for storage of the device, as well as for additional containers and storage for used ones and a charger for the batteries. Ambulances have very little space that is not either already being used or is off-limits due to the federal regulation KKK-A-1822F. The limited number of spaces available is one of the driving factors behind our design specification that the entire SLICCVac and necessary components occupy a volume of less than half a cubic meter. In the shape of a cube, the dimensions of this space are just shy of 20 inches in each direction. However, if no such space is large enough for all of the components there is no reason that they need to be in the same place. For example, the actual SLICCVac and the battery charger might be in one location and the extra new and used containers might be stored in another place.

After our interview with several Emergency Medical Technicians at the UMASS Memorial EMS we were also given access to several ambulances to familiarize ourselves with the physical constraints of cleaning and to look for a place to store the SLICCVac when not in use. In our examination of the ambulance we looked into every compartment except those in the cab of the vehicle, including containers accessible only from the outside. Two locations in the main body of the ambulance stood out as possible candidates for storage of the SLICCVac and

its components. The first area is located at the front of the main body, on the right side adjacent to the wall and accessible from the outside. This space was created by the design shift to roll-up doors as can be seen below. The volume of this space is roughly half of a cubic meter, equivalent to our eighth design specification, and definitely large enough to hold a SLICCVac with space left over.

Figure 56: First Possible SLICCVac Storage Location

The second area that we found is slightly smaller but still large enough for our purposes. As seen below, it is located at the back right corner of the ambulance, and is accessible from the outside. It is not currently accessible from the inside, but there are no features or items located on the wall between this container and the inside of the ambulance, meaning that there is no reason it cannot be connected to the inside with a new opening.

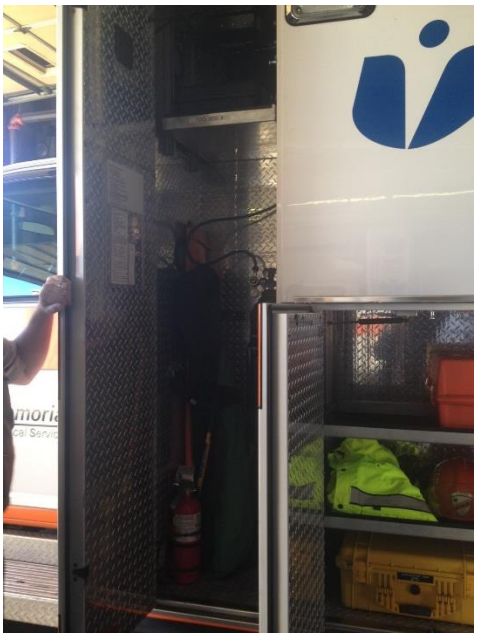


Figure 57: Second Potential SLICCVac Storage Location

4.2.3 Other Uses

While the SLICCVac is designed expressly for a certain purpose and a specific situation, it still maintains all of the capabilities of any generic vacuum of similar size, it has the potential to be just as useful in any situation that such a vacuum would be. Because of this, listing all of the many potential application of the SLICCVac is not only tedious but also unnecessary. However, the unique capabilities of the SLICCVac are particularly useful in a variety of other situations that we will visit briefly.

The high functional standards set for the SLICCVac were used to ensure that the device would be useable in an ambulance and an improvement over other cleaning methods, but those same standards open up the possibility of application in other fields. Because the SLICCVac meets the standards necessary for use in an ambulance, it is highly likely that it will also meet the standards of other health services such as hospitals or doctor′s clinics. And although cleaning a hospital does not pose many of the same challenges that cleaning an ambulance does, there are similar aspects that the SLICCVac is ideally suited to deal with. Some of the main contaminants that require cleaning in ambulances are blood and vomit, and as such any locale with a tendency for messes of either of these substances would be an ideal use for the SLICCVac.

4.3 Conclusion

The SLICCVac is a unique vacuum cleaner, demonstrating revolutionary applications of ever-improving modern technology in an industry that has seen little technological advancement in history. The vacuum cleaner market is primarily dominated by household applications, even though the technology could be extremely beneficial to society, were it applied to emergency medical services. Thus the SLICCVac was designed to augment the methodology used by conventional household vacuum cleaners to be suitable for ambulance applications. An extensive analysis of existing research and literature demonstrated that a dire need for such a cleaning device did indeed exist, both due to the potential for Healthcare Associated Infections and other serious health risks, and the lack of existing technology for ambulance decontamination. Addressing this need required prudent design considerations to limit the spread of contaminants that are potentially several times more dangerous than those found in the average household. This required innovations both in the container which holds the contaminants during cleaning, and the mechanisms which provide cleaning power for the vacuum. By increasing the efficiency of the components generally found in vacuum cleaners, and designing novel separation and filtering techniques, the SLICCVac effectively addresses the needs of a cleaning device stipulated by interviews and presentations with EMS personnel.

Though the most crucial features of the SLICCVac have been extensively designed, much research remains to be completed before the SLICCVac can be presented as a product to EMS purchasing departments. Future project groups at WPI who wish to continue the development of the SLICCVac will be tasked with both creating a prototype which implements the designs described in this report, as well as creating supplementary designs of auxiliary components. Once the prototype has been thoroughly tested as per testing protocols outlined in Chapter 3, consultation with companies who possess experience and expertise in vacuum cleaner design and manufacture would be prudent. After working with such companies, the SLICCVac could become a viable product for ambulance cleaning applications. Once implemented, the SLICCVac will lead to revolutionary new standards to reduce contamination in ambulances, lowering the rate of HCAI's, and improving the effectiveness of Emergency Medical Transport. In doing this, the SLICCVac will have revolutionary benefits in the Healthcare industry, improving the quality of life and benefitting many aspects of society, on a worldwide scale.

References

[1] Salt River Fire Department, "Arizona Salt River Fire Department Ambulance Cleaning Procedures," [Online]. Available: http://www.srpmic-nsn.gov/. [Accessed 13 February 2014].

[2] M. Petsch, "How Cyclonic Filtration Works," [Online]. Available: www.concentric.com/~petch/EncyclonWorks.htm.

[3] A. Eide, "HEPA Filter Cartridge for Canister Vacuums". U.S. Patent 8394161 B2, 12 March 2013.

[4] C. e. a. Vasile, "Practical Guide to Polyethylene," *RAPRA Technology*, 2005.

[5] U.S. General Services Administration, "Federal Specifications for the Star-of-Life Ambulance," U.S. General Services Administration, [Online]. Available: http://www.deltaveh.com/f.pdf. [Accessed 13 February 2014].

[6] American Ambulance Association, Ambulance Facts, American Ambulance Association, 2014.

[7] J. e. a. Hirshon, "America's Emergency Care Environment: A State-by-State Report Card," American College of Emergency Physicians, [Online]. Available: http://www.acep.org/uploadedFiles/ACEP/Membership/chapters/chapter_services/small_chapter_emails/COMPLETE%20NATIONAL%20REPORT%20CARD.pdf. [Accessed 3 March 2014].

[8] West Virginia Department of Education, "West Virginia Department of Education," 2014. [Online]. Available: http://wvde.state.wv.us/.

[9] U.S. National Archives and Records Administration, First Ambulance ,1865, US Navy Yard, Mare Island, CA, Mare Island, CA: U.S. National Archives and Records Administration, 1865.

[10] Metronix, Inc, "Ambulances - Type I, Type II, Type III and Type IV," [Online]. Available: http://metronixinc.com/site/ambulances.html. [Accessed 15 February 2014].

[11] St. John Ambulance Western Australia, "St John Ambulance WA: Extraordinary People Extraordinary Results," [Online]. Available: http://www.stjohnambulance.com.au/docs/corporate-publications/sja21229_annual-

report_2013_final . [Accessed 27 February 2014].

[12] C. W. L. F. M. a. R. H. V. Burt, "Analysis of Ambulance Transports and Diversions Among US Emergency Departments.," *Annals of Emergency Medicine,* vol. 47, no. 4, pp. 317-326, 2006.

[13] PPE, "Personal Protective Equipment," [Online]. [Accessed 13 February 2014].

[14] C. Kempt, "Clean EMS – Lifesaving practices in Ambulance Cleaning - Life Under the Lights," [Online]. Available: http://lifeunderthelights.com/2009/05/clean-ems-%E2%80%93-lifesaving-practices-in-ambulance-cleaning/. [Accessed 13 February 2014].

[15] Y. a. J. C. Nigam, "A preliminary investigation into bacterial contamination of Welsh emergency ambulances," *Emergency Medical Journal,* vol. 20, no. 5, pp. 479-482, 2003.

[16] D. Hess, "Carpet Sweeper". U.S. Patent 29077, 10 July 1860.

[17] R. W. e. a. Fox, Fox and McDonald's Introduction to Fluid Mechanics 8th edition, Hoboken: John Wiley & Sons, 2011.

[18] A. T. P. e. a. Oyelami, "Analysis of Radial-Flow Impellers of Different Configurations," *Pacific Journal of Science and Technology*, 2012.

[19] Howden Group Ltd., "Centrifugal Fans – Impeller Designs," [Online]. Available: http://www.howden.com/en/products/centrifugalfans/customengineered/impellerdesigns.htm. [Accessed 22 February 2014].

[20] F. White, "OCW," MIT Mechanical Engineering Department, 2005. [Online]. Available: http://ocw.mit.edu/courses/mechanical-engineering/2-25-advanced-fluid-mechanics-fall-2005/readings/07_pi_theorem.pdf.

[21] Highwire Group Inc., "Kirby K-119078 Impeller," Highwire, [Online]. Available: http://product-images.highwire.com/2430219/120-355833.jpg. [Accessed February 2014].

[22] Dyson Ltd., "DC34 Impeller," Dyson, [Online]. Available: http://www.dyson.com/medialibrary/Images/Dyson/Products/Features/Generic/DDM_feature.ashx?bc=White. [Accessed February 2014].

[23] NHS Estates, "HTM 2022 Medical Gas Pipeline Systems," *Health Estate Journal,* vol. 11, no. 7, 1995.

[24] Mountainside Medical, "1200cc Suction Canister," Mountainside Medical, [Online].

Available: http://www.mountainside-medical.com/media/catalog/product/1/2/1200cc-suction-canister__21604.png.

[25] J. Mouton, "Brushed DC Motor Basics," in *Microchip Technologies Integration Seminar*, Los Angeles, CA, 2006.

[26] Oriental Motor Co., "Brushless Motor Construction," [Online]. Available: http://www.orientalmotor.com/images/in_motion/brushless-motor-constructio.jpg. [Accessed February 2014].

[27] B. Simon, "Digital motors, software, and the rise of the internet of things," *ZDNet*, 2 August 2013.

[28] "Dyson's Compact Digital Motor," YTIMG, [Online]. Available: http://i1.ytimg.com/vi/OqKKnXqPdLs/hqdefault.jpg.

[29] "Li-Ion Discharge Curve," Imageshack, [Online]. Available: http://img692.imageshack.us/img692/246/liiondischcurve.png.

[30] New York Department of Health, "Exposure to Smoke from Fires," [Online]. Available: NY.gov.

[31] Scuba Ed's, "History of Scuba Diving," Scuba Ed's, [Online]. Available: http://scubaeds.com/10.html.

[32] "Gas Mask Filtration," Brinkster, [Online]. Available: http://www33.brinkster.com/iiiii/gasmask/page.html.

[33] B. Schnarr, "The History of Air Filters – Breathing Eas," [Online]. Available: TheHistoryOf.net. [Accessed 9 October 2011].

[34] World Nuclear Association, "Nuclear Radiation and Health Effects," [Online]. Available: http://www.world-nuclear.org/info/Safety-and-Security/Radiation-and-Health/Nuclear-Radiation-and-Health-Effects/. [Accessed N.d.].

[35] Donaldson Company, Inc, "HEPA Filtration Facts," Donaldson Company.

[36] S. a. W. H. C. -. L. I. Keeler, "Composite Dual Layer Hepa Filter". WO Patent 2007076015 A2, 5 July 2007.

[37] "EMS: A Historical Perspective," *National Association of Emergency Medical Technicians.*

[38] Phillips Ltd., "MiniVac FC6148/01 Specifications," [Online].

[39] D. E. Ristenbatt, "Suction Motor Design & Operation," Ristenbatt Vacuum Cleaner Service, Inc. , 2014. [Online]. Available: http://www.ristenbatt.com/xcart/Suction-Motor-Design-and-Operation.html . [Accessed 1 May 2014].

[40] I. Walters, "Behind the Design: Understanding Motor and Gearbox Design," FRC Designs, 24 June 2013. [Online]. Available: http://frcdesigns.com/2013/06/24/behind-the-design-understanding-motor-and-gearbox-design/. [Accessed 28 April 2014].

[41] Mabuchi Motor Co. LTD, "RS-550PC/VC," Mabuchi Motor, 2014. [Online]. Available: http://www.mabuchi-motor.co.jp/cgi-bin/catalog/e_catalog.cgi?CAT_ID=rs_550pcvc. [Accessed 28 April 2014].

[42] "Battery Packs/ Chargers/ Accessories," AA Portable Power Corp, 2013. [Online]. Available: http://www.batteryspace.com/. [Accessed 28 April 2014].

[43] D. Tuite, "Considering Lithium Batteries for the Battlefield," Defense Electronics, 10 June 2011. [Online]. Available: http://defenseelectronicsmag.com/components/considering-lithium-batteries-battlefield. [Accessed 28 April 2014].

[44] E. Sahraei, J. Campbell and T. Wierzbicki, "Modeling and short circuit detection of 18650 Li-ion cells under mechanical abuse conditions," *Journal of Power Sources,* vol. 220, pp. 360-372, 2012.

[45] M. Dimitrijevic, "Lithium Ion Battery Assembly Challenge," ECN Magazine, 14 January 2011. [Online]. Available: http://www.ecnmag.com/articles/2011/01/lithium-ion-battery-assembly-challenges. [Accessed 28 April 2014].

[46] M. Ecker, N. Nieto, S. Kabitz, J. Schmalstieg, H. Blanke, A. Warnecke and D. U. Sauer, "Calendar and cycle life study of Li(NiMnCo)O2- based 18650 lithium-ion batteries," *Journal of Power Sources,* vol. 248, pp. 839-851, 2014.

[47] E. P. Roth, C. C. Crafts and D. H. Doughty, "Advanced Technology Development Program for Lithium-Ion Batteries: Thermal Abuse Performance of 18650 Li-Ion Cells," *Sandia Report,* vol. 0584, pp. 1-139, 2004.

[48] A. Hoffmaster, *How to use Arduino,* Arduino, 2014.

[49] M. Margolis, "How to make sure your new Arduino board is working," O'Reilly Media, Inc. , 13 May 2011. [Online]. Available: http://answers.oreilly.com/topic/2696-how-to-make-sure-your-new-arduino-board-is-working/. [Accessed 1 May 2014].

[50] "ATMEGA328-PU ATmel 8 bit 32K AVR Microcontroller," Protostack Pty Ltd, 2014. [Online]. Available: http://www.protostack.com/microcontrollers/atmega328-pu-atmel-8-bit-32k-avr-microcontroller. [Accessed 1 May 2014].

[51] "Career Fire Fighter/EMergency Medical Technician Dies and Paramedic is Injured in a Three-Vehicle Collision - Nebraska," Niosh: Fire Fighter Fatality Investigation and Prevention Program, 31 May 2005. [Online]. Available: http://www.cdc.gov/niosh/fire/reports/face200333.html. [Accessed 2 May 2014].

[52] "Biohazard Waste Bags," RehabMart, 2014. [Online]. Available: http://www.rehabmart.com/product/biohazard-waste-bags-7845.html. [Accessed 15 April 2014].

[53] T. Maccallion, "Clean EMS - Cleaning Products May Be Wasting Your Agency's Time & Money - JEMS," [Online]. Available: http://www.jems.com/article/ems-insider/cleaning-products-may-be-wasting-your-ag. [Accessed 16 February 2014].

[54] J. A. Jeevarajan, *Safety Limitations Associated with Commercial 18650 Lithium-ion Cells*, Houston, Texas: NASA Johnson Space Center, 2010.

[55] "What Arduino can do," Arduino, 2014. [Online]. Available: http://www.arduino.cc/. [Accessed 30 April 2014].

[56] "Arduino UNO," [Online]. Available: http://docs-asia.electrocomponents.com/webdocs/0e8b/0900766b80e8ba21.pdf. [Accessed 30 April 2014].

[57] "Arduino Uno," Arduino, 2014. [Online]. Available: http://arduino.cc/en/Main/arduinoBoardUno. [Accessed 30 April 2014].

APPENDICIES

Appendix A – Regulations and Related Documents

NOTE: *This is an excerpt. See References for full Document*

1. OSHA 1910.1030

Labels.

1910.1030(g)(1)(i)(A)

Warning labels shall be affixed to containers of regulated waste, refrigerators and freezers containing blood or other potentially infectious material; and other containers used to store, transport or ship blood or other potentially infectious materials, except as provided in paragraph (g)(1)(i)(E), (F) and (G).

1910.1030(g)(1)(i)(B)

Labels required by this section shall include the following legend:

1910.1030(g)(1)(i)(C)

These labels shall be fluorescent orange or orange-red or predominantly so, with lettering and symbols in a contrasting color.

1910.1030(g)(1)(i)(D)

Labels shall be affixed as close as feasible to the container by string, wire, adhesive, or other method that prevents their loss or unintentional removal.

1910.1030(g)(1)(i)(E)

Red bags or red containers may be substituted for labels.

1910.1030(g)(1)(i)(F)

Containers of blood, blood components, or blood products that are labeled as to their contents and have been released for transfusion or other clinical use are exempted from the labeling requirements of paragraph (g).

1910.1030(g)(1)(i)(G)

Individual containers of blood or other potentially infectious materials that are placed in a labeled container during storage, transport, shipment or disposal are exempted from the labeling requirement.

1910.1030(g)(1)(i)(H)

Labels required for contaminated equipment shall be in accordance with this paragraph and shall also state which portions of the equipment remain contaminated.

1910.1030(g)(1)(i)(I)

Regulated waste that has been decontaminated need not be labeled or color-coded.

1910.1030(g)(1)(ii)

Signs.

1910.1030(g)(1)(ii)(A)

The employer shall post signs at the entrance to work areas specified in paragraph (e), HIV and HBV Research Laboratory and Production Facilities, which shall bear the following legend:

(Name of the Infectious Agent)
(Special requirements for entering the area)
(Name, telephone number of the laboratory director or other responsible person.)

1910.1030(g)(1)(ii)(B)

These signs shall be fluorescent orange-red or predominantly so, with lettering and symbols in a contrasting color.

2. Federal Specification for the Star-Of-Life Ambulance

NOTE: *This is an excerpt. See References for full Document*

1.1 SCOPE.

This specification identifies the minimum requirements for new automotive Emergency Medical Services (EMS) ambulances (except military field ambulances) built on Original Equipment Manufacturer's Chassis (OEM) that are prepared by the OEM for use as an ambulance.
The ambulances are front or rear wheel driven (4x2) and minimally warranted as specified in Section 6. Refurbishing and remounted vehicles are not covered by this standard. This standard applies to new vehicles only.
By definition an ambulance is a vehicle used for emergency medical care and patient transport. This specification is for the construction of ambulances, not for vehicles intended for use as fire apparatus. National and international standards exist for automotive fire apparatus. These standards can be obtained from organizations such as the National Fire Protection Association (NFPA).
Section 3 of this specification contains:
• Optional configurations.
• A worksheet to assist the purchaser in developing their procurement requirements.

1.1.1 DEFINITION OF AMBULANCE.

The ambulance is defined as a vehicle used for emergency medical care that provides:
• A driver's compartment.
• A patient compartment to accommodate an emergency medical services provider (EMSP) and one patient located on the primary cot so positioned that the primary patient can be given intensive life-support during transit.
• Equipment and supplies for emergency care at the scene as well as during transport.
• Safety, comfort, and avoidance of aggravation of the patient's injury or illness.
• Two-way radio communication.
• Audible and Visual Traffic warning devices.

1.1.2 PURPOSE.

The purpose of this document is to describe ambulances that are authorized to display the "Star of Life" symbol. It establishes minimum specifications, performance parameters and essential criteria for the design of ambulances and to provide a practical degree of standardization. The object is to provide ambulances that are nationally recognized, properly constructed, easily maintained, and, when professionally staffed and provisioned, will function reliably in pre-hospital or other mobile emergency medical service.

1.1.3 "STAR OF LIFE" CERTIFICATION.

The final stage ambulance manufacturer (FSAM) shall furnish to a purchaser an authenticated certification and label stating that the ambulance and equipment comply with this specification and applicable change notices in effect on the date the ambulance is contracted for. FSAMs making this certification are permitted to use the "Star of Life" symbol to identify an ambulance as compliant with the Federal specifications for ambulances. Use of the symbol must be in accordance with the purpose and use criteria set forth in published guidelines (Document Number DOT HS 808 721, Rev. June 1995) by the National Highway Traffic Safety Administration, an operating administration of the U.S. Department of Transportation.

2.1 THE FOLLOWING STANDARDS AND REGULATIONS FORM A PART OF THIS SPECIFICATION, TO THE EXTENT SPECIFIED OR REQUIRED BY LAW. UNLESS A SPECIFIC ISSUE OF A STANDARD OR

REGULATION IS IDENTIFIED, THE ISSUE IN EFFECT, ON THE DATE THE AMBULANCE IS CONTRACTED FOR, SHALL APPLY.

FEDERAL SPECIFICATIONS:

RR-C-901C — CYLINDERS, COMPRESSED GAS: HIGH PRESSURE, STEEL DOT 3AA AND ALUMINUM APPLICATIONS

FEDERAL STANDARDS:

Federal Standard No. 297 — Rustproofing of Commercial (Nontactical) Vehicles

MILITARY STANDARDS:

MIL-STD-461 Requirements for the Control of Electromagnetic Interference Characteristics of Subsystems and Equipment.
MIL-STD-1223 Non-tactical Wheeled Vehicles, Painting, Identification Marking, and Data Plate Standards.

LAWS AND REGULATIONS:

29 CFR 1910.1030: Blood borne Pathogens
29 CFR 1910.7 Definition and Requirements for a Nationally Recognized Testing Laboratory
21 CFR 820: Quality System Regulation
40 CFR 86: Control of Air Pollution from New Motor Vehicles and New Motor Vehicle Engines.
47 CFR, PART 90: Public Safety Radio Services (FCC)
49 CFR 393: Federal Motor Carrier Safety Regulations (FMCSR)
49 CFR 571: Federal Motor Vehicle Safety Standards (FMVSS)

2.2 OTHER PUBLICATIONS.

The following documents form a part of this specification to the extent specified. Unless a specific issue is identified, the issue in effect, on the date the ambulance is contracted for, shall apply.

THE TIRE AND RIM ASSOCIATION, INC.

Yearbook

NATIONAL FIRE PROTECTION ASSOCIATION

70 – National Electric Code
1901 – Standard for Automotive Fire Apparatus
3

SOCIETY OF AUTOMOTIVE ENGINEERS (SAE), INC., STANDARDS, AND RECOMMENDED PRACTICES:

J163 Low Tension Wiring and Cable Terminals and Splice Clips
J537 Storage Batteries
J541 Voltage Drop for Starting Motor Circuits
J553 Circuit Breakers
J561 Electrical Terminals, Eyelet, and Spade Type
J575 Tests for Motor Vehicle Lighting Devices & Components
J576 Plastic Materials, For Use In Optical Parts Such As Lenses and Reflectors of Motor Vehicle Lighting Devices
J578 Color Specification for Electric Signal Lighting Devices
J595 Flashing Warning Lamps for Authorized Emergency, Maintenance, and Service Vehicles
J638 Test Procedure and Ratings for Hot Water Heaters for Motor Vehicles
J639 Safety Practices for Mechanical Vapor Compression Refrigeration Equipment or Systems Used To Cool Passenger Compartment of Motor Vehicles
J689 Approach, Departure, and Ramp Break over Angles
J682 Rear Wheel Splash and Stone Throw Protection
J683 Tire Chain Clearance
J858 Electrical Terminals, Blade Type
J928 Electrical Terminals, Pin, and Receptacle Type
J994 Backup Alarms, Performance Test and Application
J1054 Warning Lamp, Alternating Flashers
J1127 Battery Cable
J1128 LowTension Primary Cable
J1292 Automobile, Truck, Truck-Tractor, Trailer, and Motor Coach Wiring
J1349 Engine Power Test Code, Spark Ignition and Diesel

J1318 Strobe Warning Lights
J2498 Minimum Performance of the Warning Light System Used on Emergency Vehicles

NATIONAL TRUCK EQUIPMENT ASSOCIATION / AMD:

AMD STANDARD 001 – AMBULANCE BODY STRUCTURE STATIC LOAD TEST
AMD STANDARD 002 – BODY DOOR RETENTION COMPONENTS TEST
AMD STANDARD 003 – OXYGEN TANK RETENTION SYSTEM STATIC TEST
AMD STANDARD 004 – LITTER RETENTION SYSTEM STATIC TEST
AMD STANDARD 005 – 12-VOLT DC ELECTRICAL SYSTEM TEST
AMD STANDARD 006 – PATIENT COMPARTMENT SOUND LEVEL TEST
AMD STANDARD 007 – PATIENT COMPARTMENT CARBON MONOXIDE LEVEL TEST
AMD STANDARD 008 – PATIENT COMPARTMENT GRAB RAIL STATIC LOAD TEST
AMD STANDARD 009 – 125V AC ELECTRICAL SYSTEMS TEST
AMD STANDARD 010 – WATER SPRAY TEST
AMD STANDARD 011 – EQUIPMENT TEMPERATURE TEST
AMD STANDARD 012 – INTERIOR CLIMATE CONTROL TEST
AMD STANDARD 013 – WEIGHT DISTRIBUTION GUIDELINES
AMD STANDARD 014 – ENGINE COOLING SYSTEM TEST
AMD STANDARD 015 – AMBULANCE MAIN OXYGEN SYSTEM TEST
AMD STANDARD 016 – PATIENT COMPARTMENT LIGHTING LEVEL TEST
AMD STANDARD 017 – ROAD TEST
4
AMD STANDARD 018 – REAR STEP AND BUMPER STATIC LOAD TEST
AMD STANDARD 019 – MEASURING GUIDELINES: CABINETS & COMPARTMENTS
AMD STANDARD 020 – FLOOR DISTRIBUTED LOAD TEST
AMD STANDARD 021 – ASPIRATOR SYSTEM TEST, PRIMARY PATIENT
AMD STANDARD 022 – COLD ENGINE START TEST
AMD STANDARD 023 – SIREN PERFORMANCE TEST
AMD STANDARD 024 – PERIMETER ILLUMINATION TEST
AMD STANDARD 025 – MEASURING GUIDELINES: OCCUPANT HEAD CLEARANCE ZONES

AMERICAN COLLEGE OF EMERGENCY PHYSICIANS (ACEP):

Guidelines for Ambulance Equipment

AMERICAN SOCIETY FOR TESTING AND MATERIALS (ASTM) STANDARDS:

F 920 Standard Specification for Minimum Performance and Safety Requirements for Resuscitators Intended for Use with Humans
F 960 Standard Specification for Medical and Surgical Suction and Drainage Systems
D 4956 Standard Specification for Retroreflective Sheeting for Traffic Control
D6210 Standard Specification for Fully-Formulated Glycol Base Engine Coolant for Heavy-Duty Engines
B117 Standard Practice for Operating Salt Spray (Fog) Apparatus
IPC-610D Acceptability of Electronic Assemblies

NATIONAL EMSC (EMERGENCY MEDICAL SERVICES FOR CHILDREN) RESOURCE ALLIANCE:

COMMITTEE ON AMBULANCE EQUIPMENT AND SUPPLIES
Guidelines for pediatric equipment and supplies for Basic and Advanced life support ambulances

AUTOMOTIVE MANUFACTURERS EQUIPMENT COMPLIANCE AGENCY(AMECA):

Approval of Motor Vehicle Safety Equipment (emergency lights and sirens)

AMERICAN NATIONAL STANDARDS INSTITUTE:

Z535.1 American National Standard for Safety Colors

For assistance in obtaining the referenced documents, contact the Department of Commerce, National Technical Information Service (NTIS).

2.3 ORDER OF PRECEDENCE.

In the event of a conflict between the text of this specification and the references cited, the text of

3. ASTM D638 – Testing Protocols for Plastics and Polymers

Abstract (Abstract): ADMET Inc., a provider of integrated materials testing systems, offers tensile and flexural test routines that are specific to the plastics industry. Its MTESTWindows(TM) Materials Testing System provides test routines for ASTM D790 and ISO 178 flexural properties testing and ASTM D638 and ISO 527 tensile testing. The plastics testing routines are included at no charge in MTESTWindows. Users can select the standard tests or develop and store customized tests for specific lab situations and test requirements.

ADMET Inc. combines high quality products and services with total cost effectiveness to deliver the industry's most efficient materials testing systems. Its products range from materials testing frames to software and specialized control units. The company offers new testing systems as well as retrofits of existing machines from ATS, Baldwin, ELE/Soiltest, Forney, INSTRON, MTS, Riehle, SATEC, Shimadzu, TestMark Industries, Tinius Olsen, United and others. Highly skilled engineers provide customers with personalized research and development services and support to make ADMET the most responsive materials testing equipment supplier. ADMET's loyal customer base includes leading manufacturers, testing labs, researchers and universities in aerospace, automotive, biomedical, construction, metals, plastics, textiles and other industries. ADMET can be reached at 800-667-3220, sales@admet.com or by visiting http://www.admet.com.

Full text: Marc Venet ADMET Inc. 781-769-0850 X13 mvenet@admet.com or Sandy McLaughlin Soucy Communications Group 978-266-1700 smclaughlin@scg-pr.com

ADMET Inc., a provider of integrated materials testing systems, offers tensile and flexural test routines that are specific to the plastics industry. Its MTESTWindows(TM) Materials Testing System provides test routines for ASTM D790 and ISO 178 flexural properties testing and ASTM D638 and ISO 527 tensile testing. The plastics testing routines are included at no charge in MTESTWindows. Users can select the standard tests or develop and store customized tests for specific lab situations and test requirements.

MTESTWindows is a software program that runs on personal computers with the Microsoft Windows operating system. It includes an external interface box that controls the movement of the load frame and acquires load, strain and deflection data. MTESTWindows can be used to update existing electromechanical and hydraulic test frames. It is also available with ADMET's full line of materials testing equipment including ADMET test frames that are designed for quality control, production and research and development applications.

"MTESTWindows is an extremely flexible system for tensile and flexural testing of virtually any material," commented Richard Gedney, ADMET founder and president. "For plastics, we've built in the test parameters so our customers can eliminate manual test operations and automatically calculate the

results. Operators simply select the D638 or D790 routines from a menu of available tests. MTESTWindows controls the test, reports the results and performs all of the necessary calculations."

MTESTWindows has one encoder input channel that measures crosshead position and uses up to three analog input channels to measure load, axial and transverse strain. It employs a high speed 32-bit microprocessor for precise closed loop control of electrohydraulic and electromechanical test frames and uses a Proportional Integral Derivative control algorithm with software selectable control modes for smooth transfer between load, position and strain control. MTESTWindows features monotonic, cyclic and segmented control profiles and offers up to 30 calibration tables per analog channel for multiple load cell and extensometer requirements with up to five calibration points per transducer.

MTESTWindows calculates key test parameters, such as ultimate tensile strength, offset yield strength, modulus of elasticity, total elongation, percent of elongation, and many more. Test reports include a stress-strain plot with all calculated test results. MTESTWindows can also generate reports, which include a statistical summary of test results. All data can be exported in ASCII delimited format for easy import into common spreadsheet and database programs.

The MTESTWindows materials testing system is available immediately directly from ADMET or through affiliated sales/service organizations. An MTESTWindows online brochure is available at: http://www.admet.com/assets/MTESTWindowsBrochure.pdf. Price quotes are available by contacting ADMET at 800-667-3220.

About ADMET

ADMET Inc. combines high quality products and services with total cost effectiveness to deliver the industry's most efficient materials testing systems. Its products range from materials testing frames to software and specialized control units. The company offers new testing systems as well as retrofits of existing machines from ATS, Baldwin, ELE/Soiltest, Forney, INSTRON, MTS, Riehle, SATEC, Shimadzu, TestMark Industries, Tinius Olsen, United and others. Highly skilled engineers provide customers with personalized research and development services and support to make ADMET the most responsive materials testing equipment supplier. ADMET's loyal customer base includes leading manufacturers, testing labs, researchers and universities in aerospace, automotive, biomedical, construction, metals, plastics, textiles and other industries. ADMET can be reached at 800-667-3220, sales@admet.com or by visiting http://www.admet.com.

ASTM--American Society for Testing and Materials

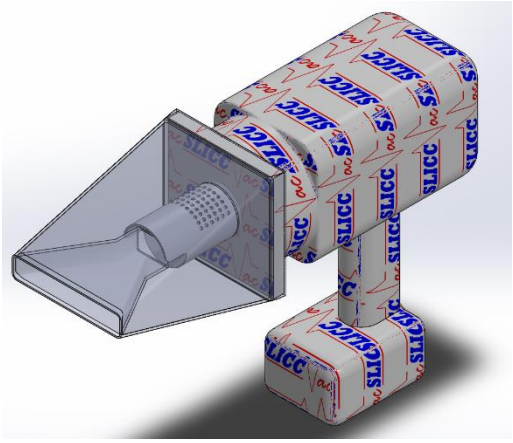
ISO--International Organization for Standardization

ASCII--American Standard Code for Information Interchange

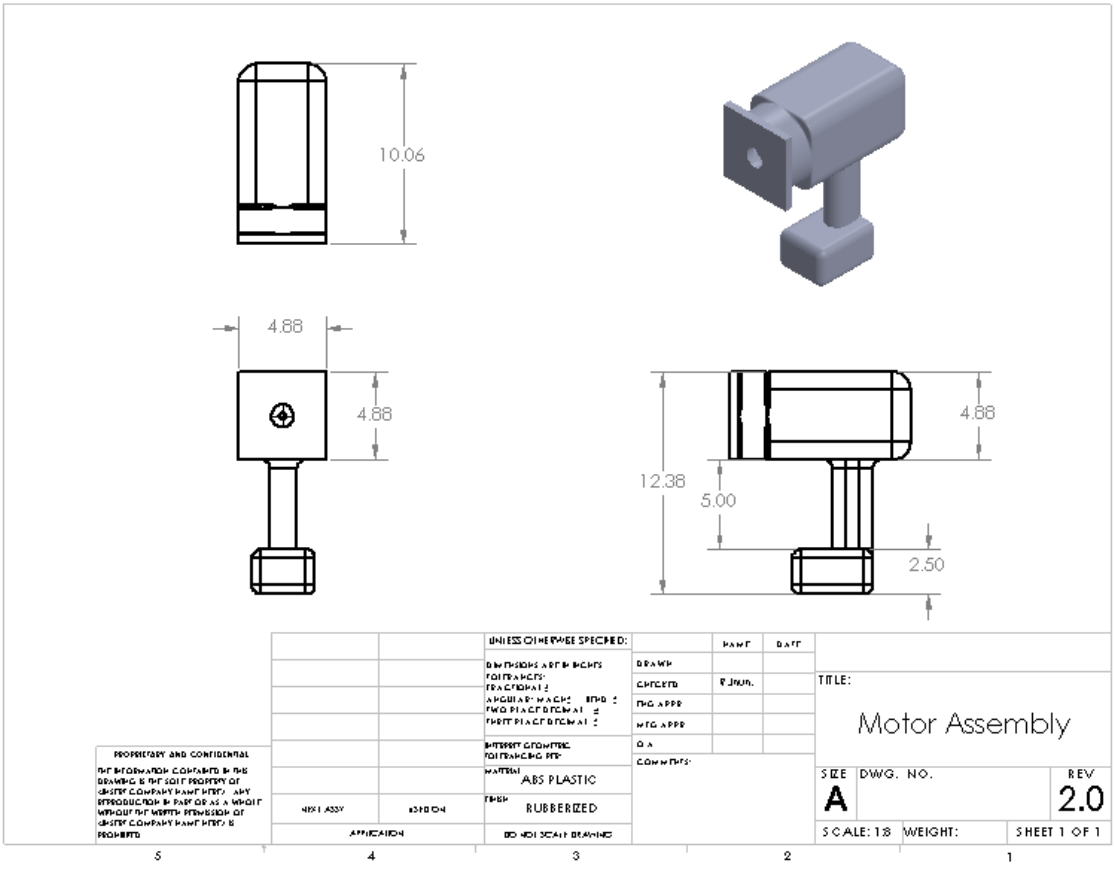
High resolution photo available - contact Sandy McLaughlin.

Appendix B – Technical Drawings and Documents

1. SLICCVac Overview

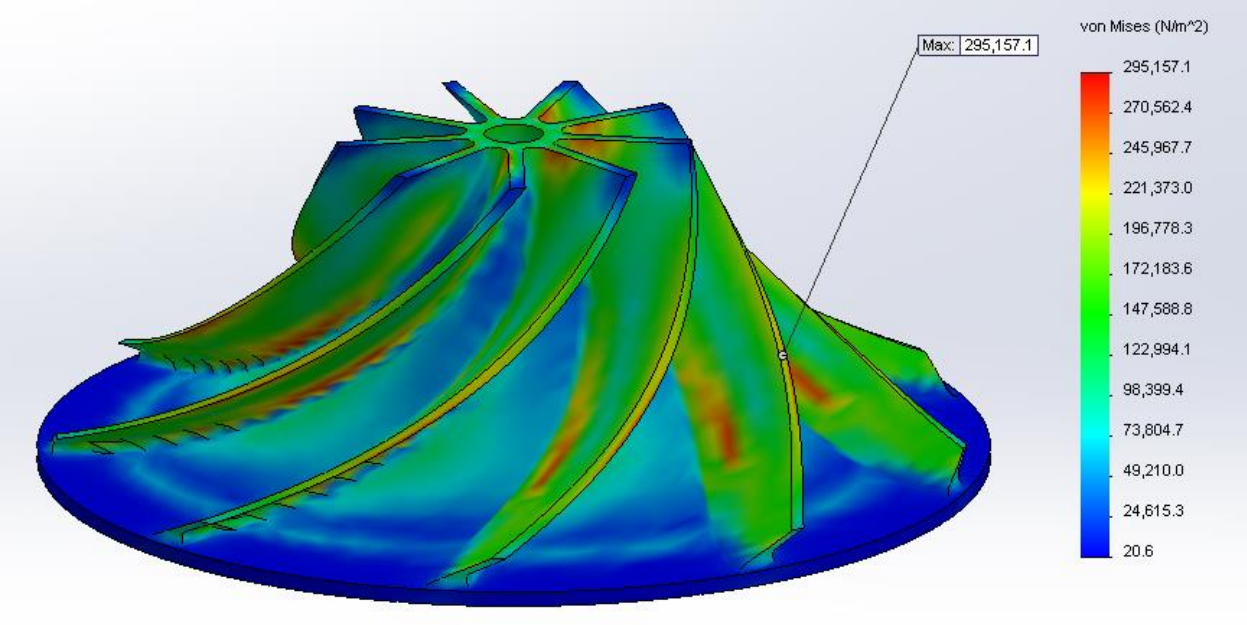


2. Technical Drawing of SLICCVac Motor

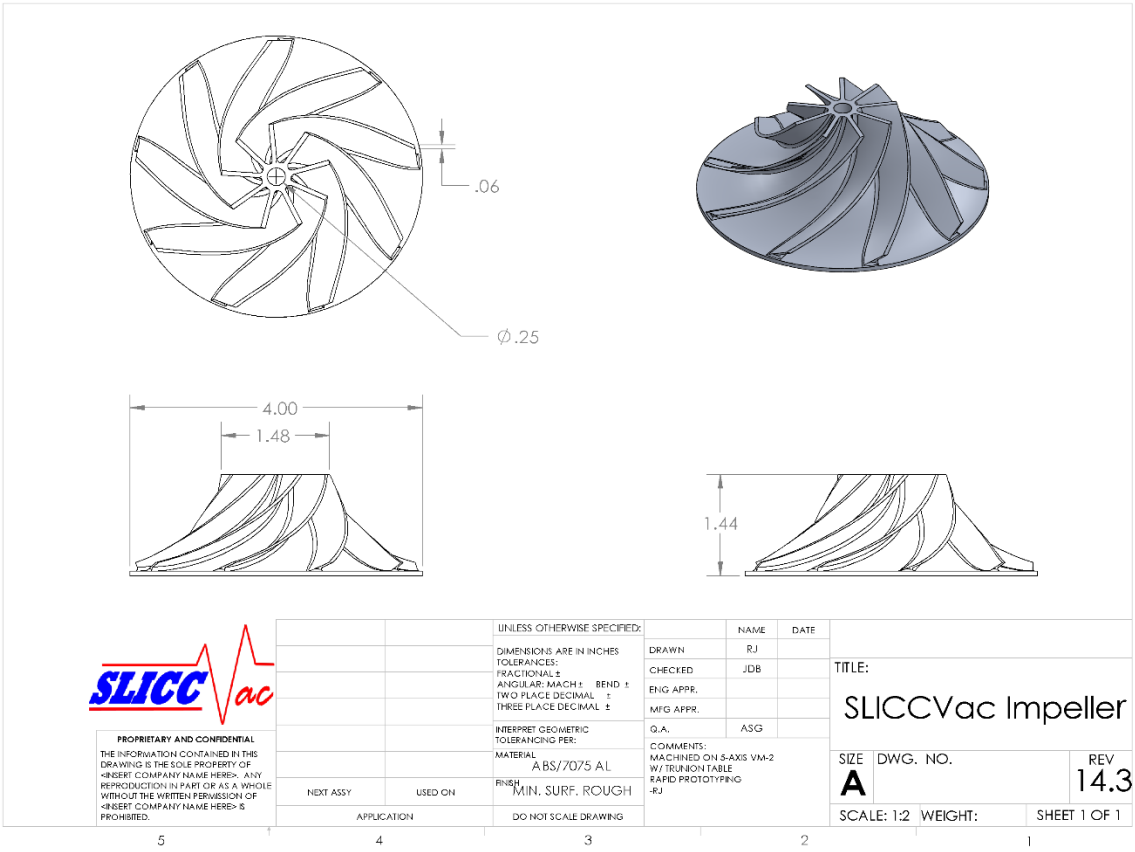


3. SLICCVac Final Impeller (Rev14.3) Grapical Rendering

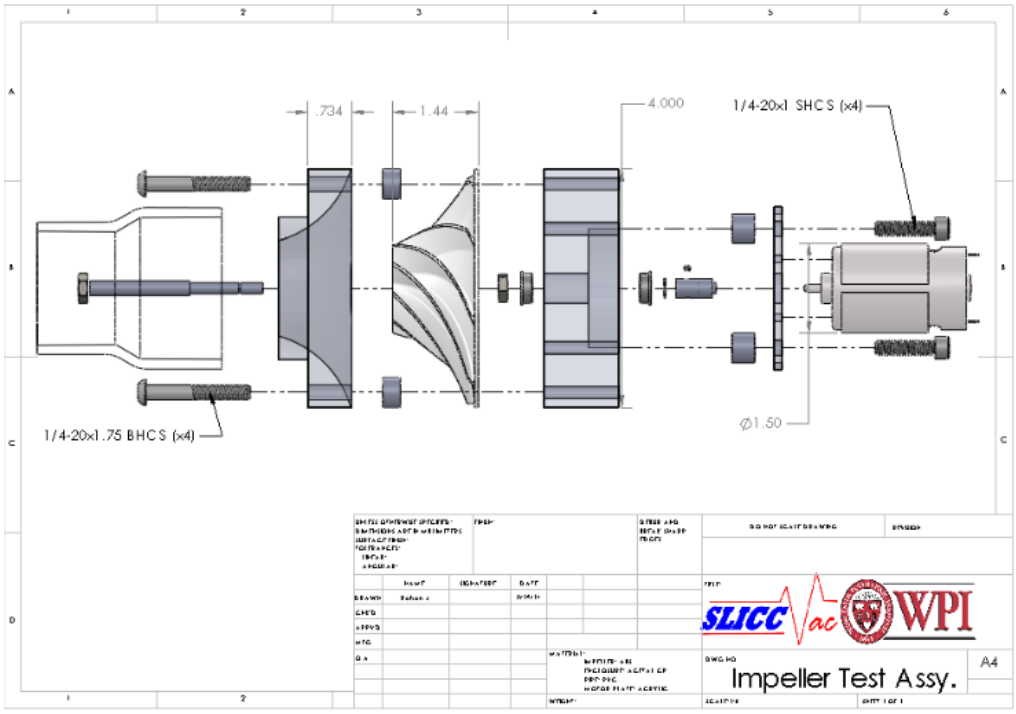
4. Impeller R14.3 Stress Analysis



5. Technical Drawing of Impeller R14.3

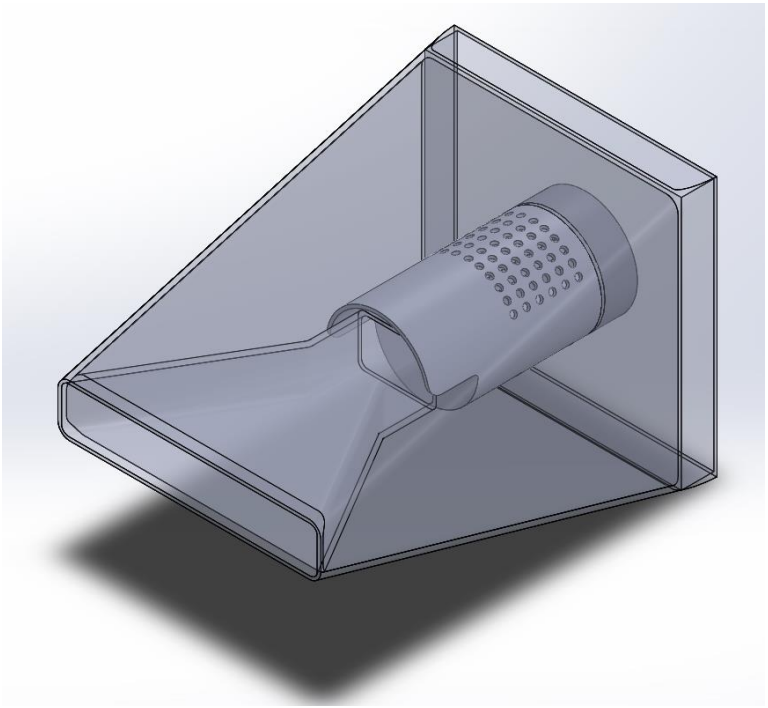


6. Technical Drawing of Impeller Testing Assembly



7. **Graphical Rendering of Impeller Testing Assembly**

8. **Model of Container V2.0**



9. RS-550 Motor Specification Sheet

RS-550PC/VC

MABUCHI MOTOR

OUTPUT：5.0W～100W (APPROX)

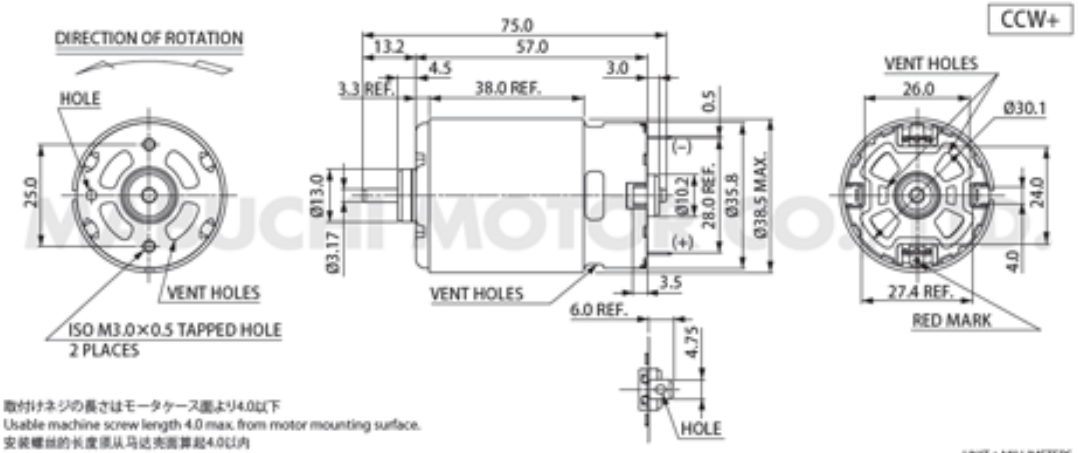
カーボンブラシ | Carbon-brush motors | 碳精电刷

代表的用途	工具：ドリル／ガーデンツール／エアーコンプレッサー 玩具・模型：乗用玩具
Typical Applications	Cordless Power Tools：Drill / Garden Tool / Air Compressor Toys and Models：Ride-on Toy
主要用途	工具：电钻、园艺工具、空气压缩器 玩具、模型：儿童电动汽车

WEIGHT：247g (APPROX)

MODEL		VOLTAGE		NO LOAD		AT MAXIMUM EFFICIENCY				STALL		
		OPERATING RANGE	NOMINAL	SPEED	CURRENT	SPEED	CURRENT	TORQUE	OUTPUT	TORQUE		CURRENT
				r/min	A	r/min	A	mN·m	g·cm	W	mN·m	g·cm	A
RS-550PC-8019	(*1)	6.0～9.6	7.2V CONSTANT	15300	1.40	13540	10.8	41.7	425	59.1	363	3700	83.0
RS-550VC-7525	(*1)	6.0～14.4	12V CONSTANT	17600	1.20	15730	10.1	58.3	594	95.9	549	5596	85.0

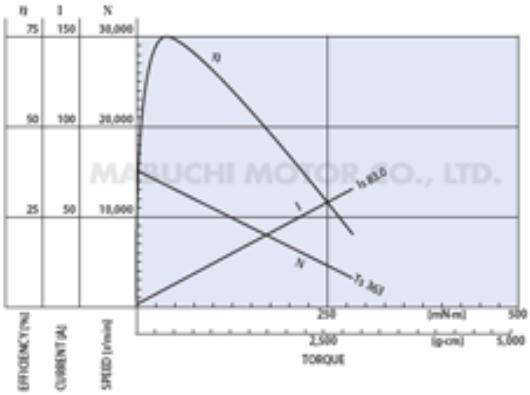
(*1) CCW逆角仕様(CCW+) | CCW shifted commutation (CCW+) | CCW逆角规格(CCW+)



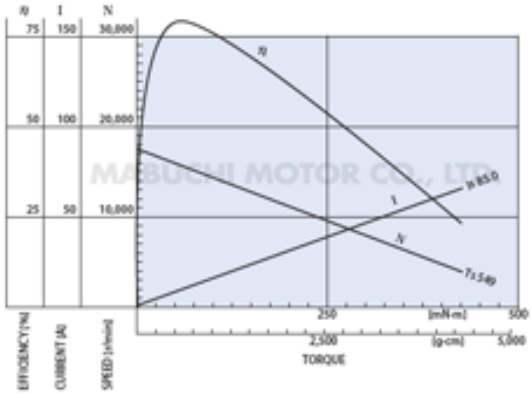
取付けネジの長さはモータケース面より4.0以下
Usable machine screw length 4.0 max. from motor mounting surface.
安装螺丝的长度须从马达壳面算起4.0以内

UNIT：MILLIMETERS

RS-550PC-8019 7.2V



RS-550VC-7525 12.0V



マブチモーター株式会社（本社 営業部）
MABUCHI MOTOR CO., LTD.
（Headquarters Sales Dept. | 总公司 营业部）

千葉県松戸市松飛台430番地 〒270-2280 Tel. 047-710-1106 Fax. 047-710-1132
430 Matsuhidai, Matsudo City, Chiba 270-2280, Japan Tel. 81-47-710-1106 Fax. 81-47-710-1132
E-mail : slsinq@mabuchi-motor.co.jp