Final Prototype Report

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Detecting Toxic Substances: Vaporizer for a Mass Spectrometer

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EXECUTIVE SUMMARY

First responders all over the US are being armed with small, portable mass spectrometers with which they can test suspicious gases and powders. Usually the powders tested are flour or sugar, but, sometimes, the responders encounter dangerous toxins like anthrax or asbestos. However, the mass spectrometer is unable to perform as well on powders as it can on gases. Our product solves this issue by acting alongside the mass spectrometer to vaporize a powder and send it to the mass spectrometer. The product vaporizes the solid by heating it up to sixty degrees celsius and keeping the temperature stable for a minute. After a minute passes, the chamber can either be cleaned out easily, or, in the more likely case that the suspicious powder is simply sugar or flour, the vaporizer can be refilled immediately and will stay at the sixty degrees celsius for another minute. This cycle can be repeated until the tester needs to be cleaned due to detecting a toxic substance. This provides a time effective way to test many samples. The product's battery is designed to last over four hours which mirrors the battery inside the mass spectrometer it is designed to work alongside.

INTRODUCTION

Over the past months a lot of work has been invested in creating a product that meets all expectations and requirements. In order to make this a successful project, following the right steps and having a good organization was necessary. It all started with a simple concept that soon evolved into a clear goal: a small and durable vaporizer that stays within the budget and due date. This project was requested by a client that needed the device as an accessory for mass spectrometers. The purpose of this accessory is to make it easier for the user to analyze solid samples in the mass spectrometer. The device must heat and vaporize powders in order for them to be transported into the mass spectrometer in the form of gas. The most important requirements are for it to be portable, easy to clean, safe and have a controlled temperature profile. For the purposes of this report, controlled temperature profile will be defined as heating the device to 60ºC ± 2-3ºC, maintaining this temperature, and eventually cooling back down to ambient temperature after the user finishes taking samples. This is the most crucial requirement of the device in order to ensure that the powders will be fully vaporized. To be sure that the chamber is completely clean, the mass spec should not detect anything after two minutes of cleaning it. Then, for it to be safe, its outside temperature has to always stay below 40℃. The temperature control is easy to check because it depends on whether the powder vaporized or not. Lastly, for it to be portable, it has to weigh less than 4 lbs and occupy less than 150 in^3 of space.

BASIS FOR DESIGN SELECTION

Through the main objective of the project, to vaporize a powder, there are four main functions required to make this project a success. Those functions are: a controlled temperature profile, controlling the vapor, insulating the outside, and displaying time and temperature information. Each function had a couple of different options for each task within it, and, in order to make the whole product work, it is important to pick the best option for each function.

For the controlled temperature profile, there are three main subfunctions: Heat the substance, cool the chamber, and measure the temperature. For the heating of the substance, the top two options are using nichrome heating coils or using power resistors. Nichrome heating coils initially seemed to be the best option until trying to find a way to electrically and thermally insulate them. There are many options to thermally insulate but electrically insulation proved to be too tricky and expensive for our project. Thus, we shifted to power resistors and found that they are more than capable of heating our chamber and they are also already electrically insulated. The other aspect of heating the chamber was determining the power source. Since it is handheld, it should have an internal battery rather than having to plug into the wall. So the decision between replaceable and rechargeable batteries had to be made. The power resistors required more volts than a normal replaceable battery could provide so it was decided that this device would use a rechargeable battery.

The next function was deciding how to control the vapor. After debating between using disposable capsules and having a permanent chamber, it was decided to use a permanent chamber that is cleanable and has a filter on it to ensure that no powder enters the mass spectrometer. After looking into cost, this was determined to be the cheapest option as manufacturing multiple disposable capsules would drive the price of the product up.

Another important aspect of the design was how to get the chamber to 60ºC without the outside getting too hot to touch and without the battery and arduino heating to too high of a temperature. To do this, we determined two potential options: using a phase change material such as wax, or using an insulating material. We decided on an insulating material as we intended to keep the device at near its maximum operating temperature for a long time. Using the solid insulation, we decided to use Teflon for its properties and calculated how thick we would need to layer the teflon to keep the battery working and allow a user to touch the outside.

The last function to solve was displaying the time and temperature. Our two main options are using a few LEDs to inform the user on time and temperature or using an LCD display. The LCD display would have been able to display more information than the LEDs; however, one of the main overall objectives of this product was to make it durable. Having two small LED lights rather than a fairly large LCD screen makes the device much more durable as well as less expensive.

EVALUATION OF RESULTS

The most important design priority is the controlled temperature profile. As defined in the *Introduction*, this is defined as reaching the desired temperature of 60ºC ± 2-3ºC, maintaining this temperature for one minute, and then cooling back to ambient temperature. While not required, the initial metrics for a controlled temperature profile also included heating to temperature within 60 seconds, and cooling to 40ºC within 2 minutes. These metrics, however, were made with the intention that the device should be able to test multiple samples in a short time period. While the device does not reach the initial metrics, it does achieve the intention of these metrics. After heating to temperature, the device maintains the 60ºC temperature until the user turns off the device. This means that the user can swap samples every 60 seconds with no cool down period. The device is thermally insulated enough that the user can safely handle the device while at temperature. The device can heat a sample to 60ºC ± 2-3ºC, maintain it at temperature for up to 4 hours with a 12V rechargeable battery, and multiple samples can be run efficiently and quickly; according to this redefinition of the metrics, all metrics for a controlled temperature profile have been met.

The next design priorities are related to the device's safety, durability, and portability. The metric for safety required that the exterior of the device does not exceed 40ºC. The device maintains a cool exterior temperature throughout the heating cycle, and it also contains a fuse for additional safety protection from the high-voltage battery. The metric for durability was that the device should survive a 5 foot drop and should be of IP-53 rated quality. While this metric was not met, the device is encased in a strong, plastic box, and the device components are surrounded by anti static foam that can absorb a smaller impact. The IP-53 rating requires the device to be splashproof and dustproof. The box containing our device satisfies both of these requirements. Lastly, the metric for portability required that the device be smaller than the mass spectrometer, or less than 150 in^3 and less than 4 lbs. The device is approximately 132 in^3 and approximately 2.69 lbs in weight, so all portability metrics have been met.

Finally, the device must be easily cleanable after a toxic substance has been discovered. This can be done by inserting a ram with a cloth or wipe into the chamber and wiping away any residue from the toxic substance. This cleaning should only take two minutes, and the mass spectrometer should not be able to detect any toxic substance left after this cleaning.

SPECIFICATIONS

The device is approximately 8.25" x 5.125" x 3.125", or a total of 132 in^3. It weighs 2.69 lbs. It vaporizes small 5g samples of unknown powders by heating to 60ºC ± 2-3ºC and maintaining this temperature for 60 seconds per sample. It can be reloaded with no cool down time for up to 4 hours. It can be attached to a mass spectrometer via the plastic tubing provided by the device. The total cost of producing this device is $274.71, and this cost would significantly drop if multiple units were made.

APPENDIX : MODELING RESULTS

Power and Heat Calculations:

First, the heat energy required to raise the temperature of the aluminum chamber to 60ºC from ~20ºC was calculated.

$$Q_{aluminum} = mC_V \Delta T$$

$$Q = (22.8g)\,(0.9\,J/(g * ºC))\,(60ºC - 20ºC) \approx 928\,J$$

Then, the power required to heat the chamber to this temperature within one minute was calculated. This value is idealistic, however, and only 20% efficiency is assumed.

$$P = W / t = 928\,J / 60\,s = 15.5\,watts$$

$$P_{actual} = 15.5 / 0.20 \approx 80\,watts$$

To produce this power, four power resistors were selected. Each power resistor has a resistance of 6Ω and a power output of 20 watts. These resistors are wired in parallel to produce an equivalent resistance of 1.5Ω. A 11.1-volt LiPo battery was selected, thus giving a current of 7.4 A.

Power and Heat Modeling:

Several trials were run to test the controlled temperature profile. Heating the chamber to 60ºC and then stopping the power resulted in the internal temperature coasting to a much higher temperature than desired, roughly 90ºC. Using this information, experiments were conducted using different stopping temperatures to result in a final temperature of 60ºC ± 2-3ºC. A graphical representation of a sample temperature curve can be found below under *Figure 1*. Eventually, the following model was established for starting temperatures below 38ºC.

$$stopTemp = 0.713 * startTemp + 12$$

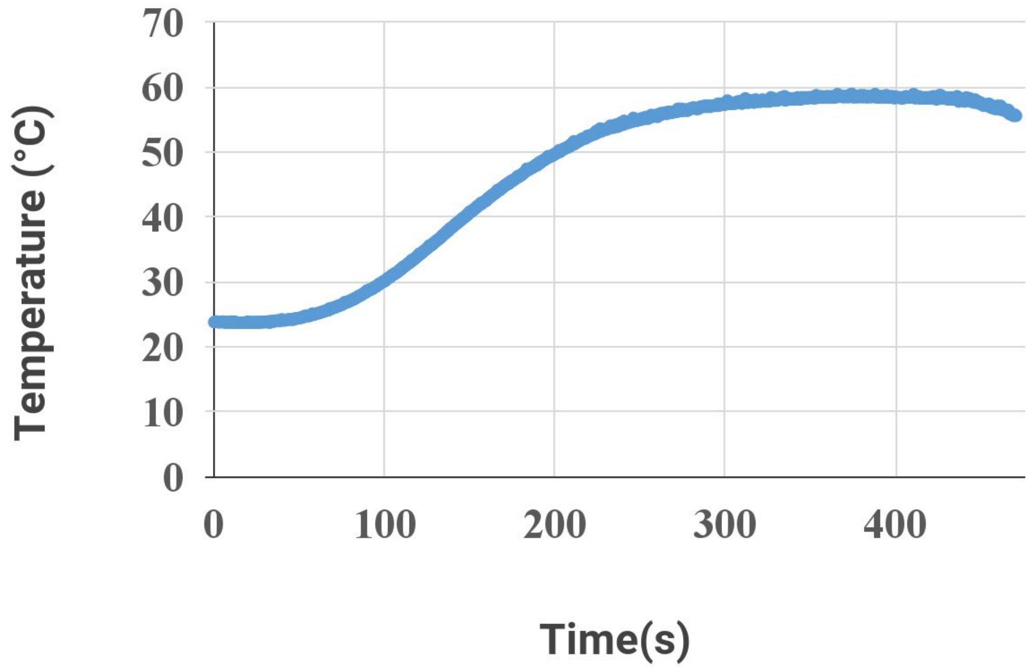

Figure 1: This graph shows the temperature curve for a starting temperature of 25ºC and a stopping temperature of 30ºC. The temperature coasted to 58ºC and maintained this temperature for an extended period of time.

For starting temperatures above 38ºC, the steady state duty cycle was implemented immediately after starting. This will ensure that the device reaches the steady state temperature of 60ºC. In order to maintain this temperature, the device uses pulse width modulation. Several experiments were performed investigating the duty cycle and the ratio of on time versus off time. The data showed that a 10 second duty cycle requires 0.4 seconds on and 9.6 seconds off in order to maintain the steady state temperature of 60ºC and offset the loss of heat.

APPENDIX: BILL OF MATERIALS

Part	Dimensions	Weight (lbs)	Function	Price	Quantity
Thermistor	n/a	0	Measure Temperature	$0.69	1
Arduino	2.96” x 2.1” x .59”	0.0125	Control	$24.95	1
LED	0.095" x 0.133" x 0.15"	0	Provide time and temp information	$8.49	2
200 Ω Resistor	n/a	0	Protect LED, Allow temp to be read	$.01	1
6 ohm / 20 watt Power Resistor	1/2" x 1/2" x 2 3/8"	0.3527396	Heat chamber	$6.60	4
Battery	5.43"x1.85"x1.5"	1.02074	Power	$84.00	1
Aluminum Tube	3/4" x 3/4" x 3" (5/8" inner)	0.049	Chamber	$3.73	1
Masterkleer PVC Clear Tubing	1/16" thick, 5/16" outer diameter	0	Evacuate vapor into mass spec	$5.50	1
Air Filter	1/2" x 1/2" with 0.07" thickness	0	Filters any powder from entering the mass spec	$3.04	1
Perf Board	1 1/2" x 1 3/4"	0.05	Control with arduino	$18.99	1
Teflon Fabric	1'x6" with 0.015" thickness	0	Thermally insulates chamber	$9.04	1
Rubber Stopper	Trade Size 7; 5/8" x 5/8" x 1"	0.0106	Plug for intake/output for chamber	$5.22	5
Relay Shield	2.96” x 2.1” x .50”	0.05	Switch	$9.00	2
Fuse	n/a	0	Current Protection	$0.80	3
Battery Charger	External; n/a	n/a	Charge the LIPO	$22.99	1
Battery Charger Cable	External; n/a	n/a	Connect the charger	$8.66	1
Battery Connector	n/a	0	Connect the battery to the perf board	$8.98	1
Wires	n/a	0	Circuitry	$3.95	
Super-Cushioning Anti Static Foam Sheet	2" Thick Polyethylene, 12" x 12"	0.1222	Shock absorption	$19.95	1
Push Button	6.75mm diameter	0	On/Off control of device	$2.07	1
High Temperature Grease	n/a	0	Lubrication of rubber stopper	$9.95	1
Utility Box	8 1/4" x 5 1/8" x 3 1/8"	1	Contains device	$18.10	1
Total		*2.69 lbs*		*$274.71*	

APPENDIX: SKETCH