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CapSat-1: The Demonstration of a Novel Capacitor-Based CubeSat Electrical Power System in a 1U CubeSat

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Abstract

The CapSat-1's proposal was submitted to NASA's CubeSat Launch Initiative (CSLI) in November of 2018 on behalf of an extracurricular program known as The Wolverine CubeSat Development Team (WCDT), located within the Weiss School - a K-8th gifted program in Palm Beach Gardens, Florida . The WCDT had launched a CubeSat prior, known as the WeissSat-1 – and remains as the only middle school program nationwide to have successfully launched a CubeSat with NASA's CSLI [1]. The CapSat-1 was submitted in accompaniment with other CubeSat proposals, and these students from the team have presented at NASA headquarters, multiple International Astronautical Congresses, the International SmallSat Conference, and many others local, state, and nationwide[3]. The Weiss School was specifically selected to present in these conferences for its aerospace engineering experience and novelty of allowing younger adolescent students to develop their own satellite missions.

The CapSat-1 is a technological demonstration, selected on March 14th, 2019 through NASA's tenth annual CSLI round [2]. It is designed to validate a capacitor-based electrical power system (EPS) in a 1U CubeSat. Currently, all CubeSats use lithium-ion polymer (LiPo) batteries as their primary source of power. Capacitors have been proven to be safer, more cost/volume-efficient, and more temperature-durable than LiPo batteries. This mission would validate their power/voltage efficiency and compare that to the status quo of the EPS in CubeSats today. The CapSat-1 will be primarily utilizing solar power from its panels, with a secondary power supply of a LiPo battery in the case of the capacitors potentially failing. The mission itself has a secondary mission of technological demonstration. It would be measuring the charge-discharge cycle of a capacitor as a function of time with regards to radiation and heat impacts, with a direct comparison of a LiPo battery (the control). Capacitors have already been proven through terrestrial research to have much greater durability, safety, and longevity than the LiPo battery, and this project would prove one aspect of these batteries that has not been established: their voltage and power consumption efficiency in the radiating/heat-inducing conditions of the space environment compared to the standard LiPo battery. This CubeSat will launch as a 1U, and its launch date is expected within mid-to-late 2021. The CapSat-1 was classified by NASA with a secondary mission of technological demonstration, and a primary mission of education – by giving younger engineers the opportunity for hands-on experiential learning with how to develop, build, test, and fly a satellite.

Key Words: Capacitor, Charge-Discharge Cycle, CubeSat, Electrical Power System, Lithium Ion Polymer Battery

Acronyms/Abbreviations
American Institute of Aeronautics and Astronautics (AIAA), Commercial-off-the-Shelf (COTS), CubeSat Launch Initiative (CSLI), Discharge Time per Unit COTS Cost (Dis/C), Discharge Time per Unit Volume (Dis/V), Electrical Power System (EPS), Lithium-Ion Polymer (LiPo) Battery, Low Earth Orbit (LEO), National Aeronautics and Space Administration (NASA)

Nomenclature (Variable, Unit)
Capacitance (C, Farad), Cost (c, dollar), (Discharge Time (Dis, minute) Flowing Current Through the Capacitors (I, ampere), Time (t, second), Total Charge of the System (Q, coulomb), Total Resistance of the System (R, Ohm), Voltage of the Capacitors (V_C, volt), Volume (V, cm^3)

1. Introduction

1.1 The Status Quo of the CubeSat EPS

CapSat-1 is intended to advance the current industrial standard for the CubeSat EPS. CubeSats have been utilized for a plethora of scientific and technological missions since 2003 [3]. Since then, the EPS component of these CubeSats has remained the same with little to no significant evolution. The LiPo battery, as the primary and most integral subcomponent of the EPS, has been utilized mainly for its high energy density, meaning that it can store a much greater amount

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of sheer charge than most other options for a much longer period of time in orbit. The significant downsides of this means of power supply (which, arguably, outweigh its benefits) are that this high energy density (coupled with the harsh heat and radiation conditions of the space environment) can result in the outer insulating layer of this LiPo battery corroding in the heat. When a LiPo battery's external body corrodes, this potentially causes the battery to both short-circuit and damage the exterior chassis of the CubeSat itself. Aside from safety, the nominal temperature range of a space-grade LiPo battery only spans within -50°C-55°C, whereas the average temperature ranges of LEO span within -170°C and 123°C. To conclude, there are two significant reasons as to why LiPo batteries have been utilized over any other alternative: energy density, and cost. Capacitors, which are the primary experimental group of the CapSat-1, test to disprove the notion of the status quo truly being insurmountable by any other product [4].

1.2 WCDT History

The Wolverine CubeSat Development Team (WCDT) was established in 2015 by The Weiss School science teacher Mr. Kevin Simmons and is composed of sixth through eighth grade students. Mr. Simmons is the founder of BLUECUBE Aerospace, which aims to build, launch, utilize, and educate using CubeSat technology with student teams [5]. In December 2018 WCDT has successfully launched WeissSat-1, a 1U CubeSat selected in the 24th round of NASA's Educational Launch of Nanosatellites (ELaNa), and in the 8th annual round of CSLI-affiliated missions. WCDT has also launched 3 high altitude balloons (HAB) as a means of training for building the WeissSat-1 [6]. Students of the WCDT also compose legislation and are attendees of many legislative blitzes, led by their educator Ms. Shawna Christenson, the founder of the Aerospace Public Policy Institute (APPI) and a Space Foundation Teacher Liaison. As part of their work in APPI, students participate in legislative blitzes and work on resolutions at the State and Federal level to help expand STEM education and increase public awareness of the educational benefits of the CubeSat Launch Initiative. The state resolution introduced by the WCDT and promoted by Florida representative Brian Mast is known as the House Congress Resolution 85 (formerly, as the House Congress Resolution 109), which was developed to promote and prioritize NASA's CSLI program in hopes of providing educational STEM development for educational programs to design CubeSat missions [6]. The WCDT program has also presented within a plethora of local, statewide, national, and international conferences to promote the implementation of its younger students in the STEM pipeline at a young age [7]. At the local level, the WCDT middle school program oversees a high school chapter of the Palm Beach County AIAA chapter and has participated in numerous AIAA-hosted banquets. The WCDT has also attended the Michigan Space Forum, a nationally held conference promoting aerospace and space exploration, and has both attended and presented in the International Astronautical Congress for the past two years, as well as the International Smallsat Conference.

1.3 CapSat-1 Background and Project Basis

For the basis of the CapSat-1 mission to have been successfully planned and detailed, its student Co-Investigator developed a science fair project in the 2019/20 school year that directly compared the voltage and power efficiency per both unit volume and COTS cost of two different capacitor models and the standard LiPo battery as the control of the experiment) [8]. This experiment was conducted in the confines of a simulated space environment (a thermal incubator) that reached temperature ranges of 10°C to 60°C. The conclusive results of this experiment gave a detailed and accurate set of potential expected results of the CapSat-1 mission itself [9]. This experiment additionally uncovered the specific capacitor model that the CapSat-1 would eventually use in orbit, which will be Maxwell's 2.5F capacitor version [10]. Both this project and the CapSat-1 mission itself are designed to validate its technological validation mission statement: "The Demonstration of a Novel Capacitor-Based CubeSat Electrical Power System in a 1U CubeSat." The eventual goal of the mission is to prove that a parallel set of capacitor batteries can not only compete with but supersede the benefits of a standard LiPo battery in a CubeSat in the space environment [11]. This could both economically evolve the CubeSat market and promote a greater number of CubeSats to be launched and produced in shorter stints of time, which could then revamp and advance the impact of the CubeSat industry.

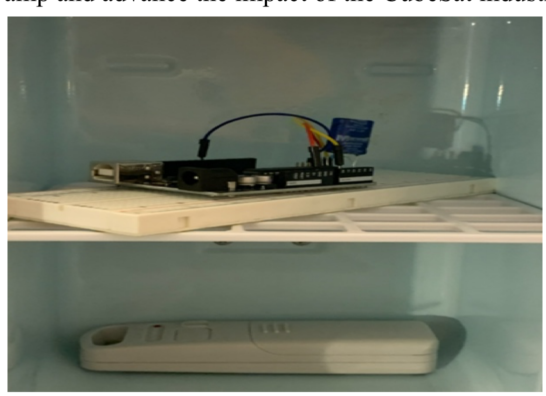

Fig. 1. Capacitor Thermal Testing for a 2019/20 Science Fair Experimental Project, Photo Courtesy Samer Elhoushy

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1.4 CapSat-1 Team Background

At the inception of its mission concept, the CapSat-1's mission statement was originally formed by a group of three students in the 7th grade, who were each members of The Weiss School's WCDT program. The 7th Co-Investigator of this mission submitted this proposal to NASA's 10th annual round of CSLI program submissions and is the primary corresponding author of this manuscript. A total of 25 CubeSat mission proposals were submitted to this round, and, out of these, 16 were selected nationally, including the CapSat-1 mission, which was selected with the company of the Massachusetts Institute of Technology (MIT), The NASA Ames Research Centre, Purdue University, and Yale University. Prior to the mission's selection, the CapSat-1 original proposal team members participated in a preliminary design review (PDR), which was reviewed by NYRAD CEO Rhonda Lyons, retired Pratt and Whitney engineer Randy Parsley, and Nearspace Launch (NSL) Inc. President Hank Voss. After its selection, the CapSat-1 mission also underwent a Critical Design Review (CDR). Each of these reviews were sourced by NASA's 2007 Systems Engineering Handbook, which is an informative paper that lists all necessary requirements for a CSLI-affiliated CubeSat in its lifetime [12].

2. Material and Methods

2.1 Materials

The entirety of the CapSat-1 mission will be executed in a 1U CubeSat form factor, meaning that the totality of "materials" used for said mission will fit in the volume frame of 1 liter (10cm by 10cm by 10cm). The capacitor payload itself will consume nearly half of this payload space, with two separate arrays of (approximately) 10 capacitors in a parallel circuit - these capacitors each have a capacitance of 2.5 Farads, and are distributed by Maxwell, with a total of 20 capacitors used in the system). As each set of 10 capacitors will each be in parallel, the overall capacitor schematic of the CapSat-1 will consist of one large series circuit consisting of two individual parallel circuits. This will allow the mission's capacitors to be individually independent of each other, minimizing risk if one of these 20 capacitors were to fail midst experimentation. The communications system of the CapSat-1 mission will be sourced and purchased from the NSL Inc. aerospace organization, and it will be in the form of an omnidirectional patch antenna placed on one face of the exterior of the CubeSat itself. The EPS of the mission itself will also be integrated into the NLS LiPo-based system, as the LiPo batteries will act as a power supply to the capacitors to reduce the risk of failure. The NSL Fastbus will be incorporated into the CapSat-1, meaning that the chassis of the satellite will also be sourced from NSL, and will be composed solely of anodized aluminium [13].

2.2 Procedures

A power up sequence will commence through the lithium ion polymer battery and the CapSat-1's capacitors 30 minutes after deployment. Once the CapSat-1 mission is shipped and stored within the International Space Station, it will be deployed via a NanoRacks 6U deployer in a solar-synchronous orbit. A backup array of lithium ion polymer batteries will be charged within the CapSat-1's frame and will power the capacitors themselves to ensure that a lack of proper exposure of the mission's solar panels from the surface of the sun would not impact its ability to charge.

The CapSat-1 will then transmit voltage data at a rate of approximately 90 bytes per packet, with one data point being sent every 10 minutes. After the CapSat-1 mission makes one full orbit around the Earth, which will take an estimated 85-100 minutes, the telemetry of the CapSat-1 will be sent in the form of the total charge inputted into the capacitors themselves, their output voltage over a certain period of time, their total current and leakage current, and the total amount of time it takes for each capacitor to fully charge and discharge. On the brighter side of the Earth, these pieces of data will be transmitted once every 10 minutes, with each data packet (presumably) containing 90 bytes of data. This data will be sent in hopes of validating a capacitor's ability to store, receive, and supply charge to a 1U CubeSat in the harsh conditions of space for as long of a timeframe as possible.

After half an orbit to the dark side of the Earth, a mode will be initiated that transmits data much less frequently, at a rate of once per every 20-25 minutes. The CapSat-1, as it is an experimental technological validation mission, will try to minimize as many variables as possible to both reduce its risk of failure and optimize its accuracy and practicality in the space environment. Therefore, to execute this, the CapSat-1's data transmission rate will be lowered to one packet per 20-25 minutes when it faces the darker side of the Earth to ensure that it still receives enough of a power supply for the mission to maintain itself. The experimental variables that will be collected over this period of time will still be identical to the ones collected on the brighter side of the Earth to maintain the mission's data accuracy, but this data will just be transmitted at a much lower rate (meaning the size of the packets themselves will be identical regardless).

This cycle is then repeated over a 6-month period of testing. Over the ~90 minute orbital time of the CapSat-1 mission, the same exact variables of "total charge inputted into the capacitors themselves, their output voltage over a certain period of time, their total current and leakage current, and the total amount of

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time it takes for each capacitor to fully charge and discharge" will still be collected at the exact same rate over its mission lifetime, both on the brighter and darker sides of the Earth. The capacitors themselves will be able to withstand in the space environment for years on end in these conditions, but the CubeSat itself is only estimated to live in its orbit for six months to one year.

If the primary capacitors do not charge, there will be an additional second set of capacitors arrayed in a parallel circuit that will immediately be charged if at least one of the capacitors in the primary set is not able to transfer charge. As both of the capacitor sets will all be in a parallel circuit, they will all be independent of each other, meaning that if one of the capacitors in the primary set were to malfunction, only one other capacitor in the secondary backup set would be needed to power on and transfer charge. This, again, minimizes the failure of the CapSat-1 mission while still conserving accuracy and practicality. There will be a total of twenty capacitors in this array, meaning that the primary (experimental) set will consist of ten capacitors, while the other will also consist of that same amount.

3. Theory and Calculation

The theory implemented for the CapSat-1 mission is based on energy density, and the nominal charge/discharge patterns of a capacitor. The energy density of a material is calculated with respect to its electric field strength, its mass, and its permeability in free space. The permeability in free space for a capacitor is a measure of the resistance encountered through its electric field in a vacuum. This resistance value, accompanied by the electric field strength of the capacitor, will provide its energy density per the unit mass of said capacitor. A LiPo battery also utilizes a similar theory. This theory, though, concludes that a standard LiPo battery has a much greater energy density than a capacitor [14]. But, as the equation for energy density does not account for volume, it can then be concluded that capacitors are potentially both safer and more volume efficient than LiPo batteries (which this mission plans to conclude). The second of the CapSat-1's primary theories will be the standard discharge curve of a capacitor over time. The below equation will be used to calculate the rate at which a capacitor's voltage charges, surges, and discharges at certain time stamps, and with respect to temperature and radiation exposure in the space environment. Calculating the calculating energy density used prior to its launch and collecting live data of its charge/discharge curves in the space environment will determine its overall volume efficiency in comparison to a LiPo battery [15].

3.1 CapSat-1 Equations Used

The CapSat-1 mission has consisted of two primary stages: the preliminary stage of its science fair project counterpart, and the eventual mission itself. The science fair project utilized a ratio of total discharge time and the unit volume/cost of each battery component to determine which battery is most efficient [16], and the CapSat-1 CubeSat itself will be utilizing the below equation to determine the overall voltage efficiency of the capacitors tested over time.

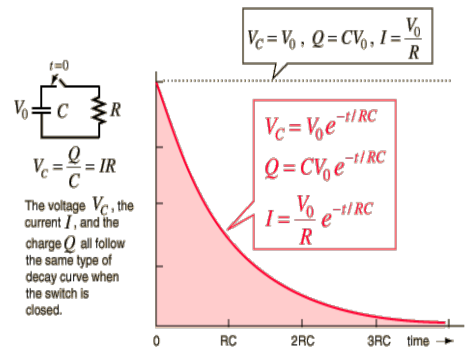

Fig. 2. Capacitor's Charge and Discharge Formula and Curves, Images Courtesy of Hypherphysics

Though the science fair project measured for a different group of results, the results of said project were interpreted to determine the battery type that will be used on the CapSat-1 mission. However, as the CapSat-1 will last for months on end in LEO, an extra variable pertaining to radiation exposure for extended periods of time must also be considered. When analysing and finalizing what specific data points will be sent with the CapSat-1, its Co-Investigator communicates with NSL to ensure how many particular packets of data can be sent from each of the communication system's individual "pins", and how frequently those data points will be sent. As the CubeSat itself contains an EPS-based payload (specifically because the mission's capacitors will secondarily act as a battery system inside of the CubeSat), the battery voltage and leakage current data, which would already be sent in the form of telemetry in a standard CubeSat, would be sent in integration with the mission's payload-based data, allowing for a much more efficient and data-effective CubeSat.

$$U = \frac{1}{2}\epsilon_0 E^2$$

Fig. 3. Standard Formula for Energy Density, in the Case of a Capacitor's Electric Field, Courtesy of BYJU

3.2 Standardly Defined Numbers

Capacitance of the Capacitor Selected for Experimentation (2.5F), Cost of the Capacitor Selected for Experimentation ($4.71), Cost of the 1.5F

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Experimental Capacitor ($4.16), Cost of the LiPo Control Battery ($14.97), Volume of the Capacitor Selected for Experimentation (4.13cm^3), Volume of the 1.5F Experimental Capacitor (3.78cm^3), Volume of the LiPo Control Battery (19.96cm^3),

4. Results

Table 1. Average Voltage Efficiency of Major Energy Storage Components

Average	1.5F Capacitor [17]	2.5F Capacitor [18]	Li-Ion Polymer Battery (control)
Charge Time (min)	**3.92**	**6.37**	**21.26**
Discharge Time (min)	**3.87**	**4.43**	**N/A**
Dis/V (Min/cm^3)	**1.025**	**1.073**	**1.065**
Dis/C (Min/$)	**0.69**	**.94**	**1.42**

4.1: Preliminary Results

The two primary sets of results in correlation to the CapSat-1 mission are pre-concluded and predetermined results from its accompanying science fair project, and the actual expected results of the mission itself. The originating science fair project measured the efficiency of three battery types: a 2.5-Farad capacitor, a 1.5-Farad capacitor, and a LiPo battery (as a control). The project concluded the total charge and discharge time for each battery at six different temperatures within the confines of a thermal incubator (10°C, 20°C, 30°C, 40°C, 50°C, and 60°C), as an increased time can result in a greater efficiency and greater voltage output. This value of discharge time was divided by volume to form a ratio, to conclude how efficient each battery was per unit volume. From this, it was concluded that the 2.5-Farad capacitor was actually most voltage-efficient per its individual volume. From that project, it was concluded that the 2.5-Farad capacitors will be utilized on the CapSat-1 mission itself.

The student researcher also determined a power efficiency per the unit COTS product cost of each battery tested through this experiment. This, surprisingly, helped the researcher come to the conclusion that the LiPo batteries were most cost-efficient out of all three batteries tested, but that the 2.5-Farad capacitor was not significantly less efficient as the student researcher presumed.

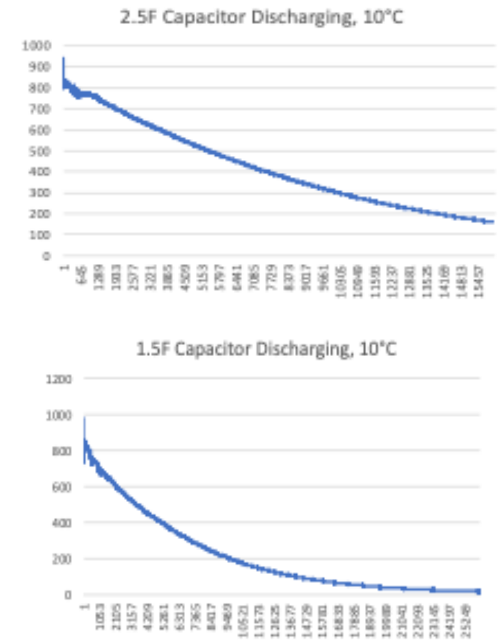

Figure 4. 2.5F (top) and 1.5F (bottom) Capacitors' Discharge Curves at 10°C, Samer Elhoushy [b]

4.2: Expected Results

The second set of results throughout the entirety of the CapSat-1's development lies in the actual expected results of the mission itself when it is eventually launched and deployed into a LEO. As the mission will be detecting the peaks and troughs of its capacitors' charge and discharge cycles respectively, it will be measuring not only total voltage across the parallel array of capacitors, but the total net and leakage currents throughout the system, and the total time that it takes for the capacitors to charge and discharge as a function of both time and radiation exposure/temperature.

It is likely that the lifetime of the mission's capacitors will surpass that of the CubeSat mission itself, as the radiation-tested 2.5-Farad capacitors have been marketed to withstand approximately 500,000 charge and discharge cycles. This value, as concluded through the CapSat-1's original science fair-based experimentation, would amount to a total estimated lifetime of nearly one year from all twenty capacitors used in the CapSat-1 mission. With that being the expected payload lifetime of the CapSat-1, it will also be expected that the peak voltage of the capacitors themselves will decrease proportionately over time with respect to an increased radiation exposure over time in orbit. It will be expected that this voltage efficiency value will be inverse-proportional with both radiation exposure and temperature extremes reached in the space environment.

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5. Discussion

The CapSat-1 CubeSat in it of itself will not be entirely dependent on capacitors as a primary power source throughout experimentation. Though the original mission's procedures involved the EPS of the CubeSat being primarily and solely powered by the capacitor payload, it was concluded that a LiPo battery-based power system would accompany its payload by supplying a primary source of power to the capacitors. With that, the capacitors would then transfer that power throughout the rest of the CubeSat. This will still allow the data collected from the experiment to be entirely gathered by the payload alone, while minimizing the risk of the capacitors themselves not being able to power on upon deployment. This was concluded in spite of the original plan was for the capacitors to be solely power by the CapsSat-1's solar panels, which increases the risk of the mission powering up altogether.

Fig. 5. 2.5F Capacitor used in Experimentation, Image Courtesy Maxwell Technologies

Additionally to the mission's two sets of 10 parallel capacitors, there will be an internal system connected to the EPS of the CubeSat (that is licensed by NSL Inc.) known as the Blackbox system. This system, similarly to the Blackbox found on an aircraft, would transmit telemetry data back to Globalstar's communications network if the CapSat-1 were to abruptly fail in orbit (if even the backup set of capacitors are unable to transmit power). The two sets of capacitors will be held within the CapSat-1 1U formfactor with two separate parallel circuit arrays, and each set will allow current to flow based on the previous individual capacitor charging and discharging (as it is a parallel circuit, one of the capacitors in each set could fail, but each of the other nine capacitors in the set will still function nominally).

6. Conclusions

In summary, the goal of the CapSat-1 mission is to shift the near and distant future of a CubeSat-based EPS market to a more efficient, safe, more durable, and more volume-conservative and less intrusive power system. Two out of three of the hypotheses that the student researcher proposed in the initial science fair experimentation were nullified. This provided insight into the future of the CubeSat's EPS component. If one wanted to consider volume over cost and voltage output, then the 2.5F capacitors, if there are enough of them within a CubeSat, could theoretically compare to lithium-ion polymer batteries in the space environment. There are many variables to consider when finding the best EPS component, but capacitors do serve as a viable option, and this was proven through experimentation in a simulated space environment.

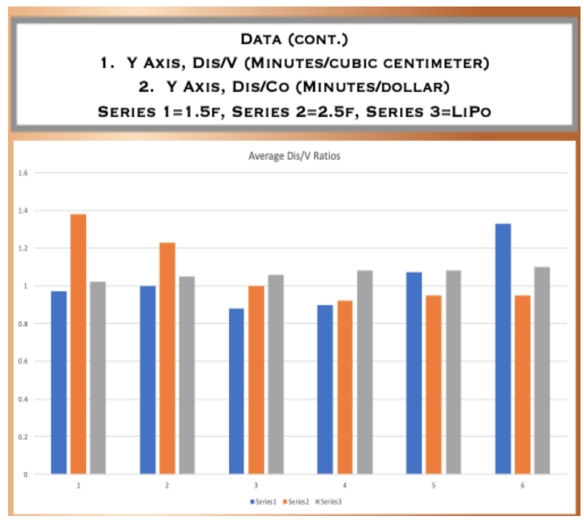

Fig. 6. Chart Showing Dis/V Ratios of Each Battery Model in Preliminary Testing, Samer Elhoushy [b]

Though the original charge and discharge time values for each capacitor were much lower than the LiPo battery's charge time by a factor of approximately 7, the volume of said capacitors are proportionately smaller than a LiPo battery. Accounting for this, the Dis/V unit volume efficiency of the 2.5F capacitors is minutely higher than the LiPo battery's Dis/V ratio on average over each temperature level. This then validates the above statement that, if a larger number of these 2.5F capacitors were to be fit within a 1U CubeSat form factor, it could match and potentially even supersede the volume efficiency of the EPS status quo.

From the results of this science fair experiment, the student researcher not only concluded the specific capacitor type that will be utilized within the CapSat-1 mission upon its deployment in LEO but uncovered the expected data and results upon its launch in LEO. The goal of the experiment is three-fold: to technologically validate a novel capacitor-based EPS technology that could potentially grow the demand for CubeSats being launched, to revitalize the CubeSat market industrially,

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and to provide young middle school students with the opportunity to develop a CubeSat mission through hands-on learning, to grow today's younger workforce for the aerospace field.

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