

# Dædalus Astronautics at ASU: Development of a Staging Sounding Rocket and Experimental Solid Rocket Motors

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Current efforts by the student members of the sole student rocket group at Arizona State University, Dædalus Astronautics, have been focused on the development of a high-powered dual stage sounding rocket design in preparation for the Third Annual Intercollegiate Rocket Competition hosted by the Experimental Sounding Rocket Association. The launch vehicle assembly is powered by several experimental solid rocket motors designed, mixed, and tested by Dædalus personnel and is capable of lofting a ten pound payload to an altitude of 10,000 feet AGL. Inherent in the construction of each rocket stage is the broad use of fiberglass and carbon fiber structural components throughout the entirety of the rocket, the majority of which is fabricated directly from raw materials. Also discussed in the paper is the design of an upper stage canard system with the singular purpose of providing roll stability to keep the rocket substantially more stable due to the enhanced resistance to small directional flight changes. Many design rules and procedures for successful motor mixing and testing as well as overall high-powered rocket construction methodologies are listed and explained in detail.

## Nomenclature

$AR$  = Aspect ratio  
 $b$  = Span  
 $\alpha$  = Angular acceleration  
 $\alpha'$  = Angle of attack  
 $T_{p_{ext}}$  = Thickness due to external pressure  
 $d$  = Diameter  
 $P_{ext}$  = External atmospheric pressure  
 $E$  = Modulus of elasticity  
 $l$  = Length of section  
 $r$  = Radius  
 $\sigma$  = Stress  
 $a$  = Burn rate coefficient  
 $n$  = Burn rate exponent  
 $P$  = Chamber pressure

## I. Introduction and History

Dædalus Astronautics @ ASU is an all-student group encompassing over 15 members of varying academic majors, gender, and race. The primary concentrations of the organization are to design, manufacture, test and launch an ever increasing family of complex sounding rockets and to perform educational outreach of math and science to primary and secondary schools throughout the Phoenix Metropolitan area. This extracurricular group, known to students and faculty alike simply as “Dædalus”, has had a continuing presence on the Arizona State University main campus for nearly seven years. With an excess of 60 years of combined experience in high powered model rocketry and dozens of rockets, the student members of Dædalus have been invited yet again to participate in the third annual Intercollegiate Rocket Launch Competition hosted by the Experimental Sounding Rocket Association (ESRA) in Utah. The objective of this competition is to deliver a 10-pound payload closest to 10,000ft AGL and recover the payload and all rocket parts intact, with extra points being awarded for novelty of payload design. Relying upon the team member’s extensive history with solid rocket motors, the new dual-stage and highly-composite Dædalus rocket “DARTS” (Duck And Run To Safety) has been designed and constructed over the course of several semesters.

Notably, Dædalus will be mixing its own solid rocket motors for both stages of the rocket as well as the lay-up and curing of the carbon fiber and fiberglass airframes. Furthermore, an active canard system is proposed to operate solely for roll maneuvering providing the second stage of the rocket control over its own spin stabilization. It is the purpose of this document to give a brief overview of the capabilities of Dædalus and to summarize the design and components used in the construction of DARTS.

### **A. History of Dædalus' Efforts**

Including the latest competition rocket, seven rockets have been designed in total; all utilizing a solid rocket motor apart from one hybrid. A brief synopsis of the latest four rockets is summarized below:

### **B. Previous High Powered Rockets**

**PleDEx** – An acronym for **Please Don't Explode**, PleDEx was the first of many new rockets for the newly formed Dædalus student group. The rocket weighed in at 46lbs and stood just under 10ft tall with a diameter of 7.66". Designed to take the load of a P-class impulse motor (9,022 to 18,044 lb-secs), the structure consisted of four aluminum longerons spanning the length of the rocket and was enclosed by pre-manufactured fiberglass tubes for added buckling strength. Due to altitude restrictions at Arizona launch sites, this rocket has been launched (and fully recovered) only twice to altitudes just over 7,000 feet, though its altitude capabilities are much more. PleDEx also makes use of an elaborate electronics package with GPS and altitude tracking with real-time telemetry to a personal laptop, in addition to three-axis accelerometers and pressure and temperature measurements.

**ExCD** – While it has often been referred to as “**Experimental Concept Development**”, the actual acronym stems from the name “**Explosions Cause Damage**”, keeping with the trend of wishful thinking for Dædalus' rocket names. ExCD is a rocket of gigantic proportions in the world of high powered model rocketry, making use of three (3) O-class motors (4,511 to 9,022 lb-secs each) for the first stage and an N-class motor (2,255 to 4,511 lb-secs) for the second all-composite stage. The second stage of the rocket can reach altitudes over 100,000ft at the BALLS launch site where such waivers are available, reaching speeds nearing Mach 4. Due for launch in late 2006, the rocket was cancelled one month prior due to the inability of Loki Research to complete the motors on time. As such, the second stage of the rocket was refurbished into the TLA series rocket, and Dædalus began investigating the mixture of their own solid rocket motors. However, the design of ExCD did win 1st place in the team category at the 2006 AIAA student conference in Irvine, California and will be revisited for the 2009 BALLS launch.

**TLA** – A clever acronym for **Three Lettered Acronym**, TLA was slated to be used as the second stage of ExCD, but instead was renovated for smaller altitudes. Using an M-motor, TLA has thus far had one partly-successful launch at a southern California site. While the projected apogee was predicted to be 17,000ft at a Mach number of 1.3, a faulty igniter caused a much delayed ignition. Referred to as a “hangfire”, the motor partly burned for over ten seconds on the launch pad before finally developing enough thrust to take off. The lost propellant resulted in a final altitude of approximately 9,500ft. Furthermore, due to a systematic naming error, the drogue and main parachute deployment ordered was re-versed, and TLA sustained body damage upon impact. However, the expensive electronics system (the same used in PleDEx), was completely unharmed, as was the motor. Refurbished parts from TLA are being used in the second stage of DARTS.

**RPR** – **Rocket Propelled Rocket** was built and designed for original use in the second annual Intercollegiate Rocket Launch Competition in Utah, but has since been flown in Arizona as well. This 10 foot tall rocket has an 8" diameter, comparable to the dimensions of PleDEx, but is substantially lighter due to heavy use of carbon fiber and fiberglass in the construction of the airframes, fins, and various other components. RPR was built with modularity in mind and can accommodate an expansive range of motors mixed by experienced Dædalus personnel, setting the maximum altitude upwards of 30,000 feet. Moreover, RPR's modularity has presented Dædalus members the opportunity to use the lower four foot carbon fiber section of RPR as the first booster stage on the DARTS rocket.

### **C. Educational Outreach**

Certainly worth mentioning is the primary and secondary school model rocket outreach program undertaken by Dædalus. Utilizing Estes Designer Special Kits (product #EST-1463), students are split into teams of four or five to compete verses one another on model rocket designs to meet a prescribed set of goals. Dædalus personnel spend hours teaching the students the fundamentals of rocketry and oversee the construction of the model rockets of varying size and shape. Finally, the program culminates with a launch of the model rockets either in the schoolyard of the respective school, or at the ASU recreational fields using A and B impulse motors (0.28 to 0.55 and 0.55 to

1.1 [lb-secs], respectively). This outreach program has proved to be a very powerful tool in invigorating the students about math and science, and has reached over 600 students aging from 10 to 18 years old. Summer 2008 will see an expansion of these outreach activities to incoming freshman as well as underrepresented middle and high school students in an ASU summer program. Current plans call for small altimeter payloads to experimentally validate the student's rocket launch with their altitude calculations, as well as an advanced rocket egg drop competition to further promote the choice of engineering as a career for these young students.

## **II. Flight Profile**

The flight profile for DARTs is different from anything Dædalus has attempted before due to the two stage design. DARTs will launch in a standard manner with one central booster motor designed and manufactured by Dædalus team members. At first stage burnout an electronic timer will initiate a pyrotechnic ignition system inside the second stage motor. At this point the second stage will separate from the first stage and continue the flight path. The upper stage motor will also be designed and manufactured by Dædalus. The ignition of a motor during flight and the separation of the upper stage from the lower stage present unique design challenges. After second stage separation the first stage will continue to increase in altitude until it reaches apogee at which time a large parachute will be deployed to facilitate a safe recovery. The upper stage will also have parachutes to slow the rocket during descent. Throughout the end of the climb an active roll control system will induce a roll rate which will be captured by an onboard camera. Each of these systems are fully discussed in the following sections.

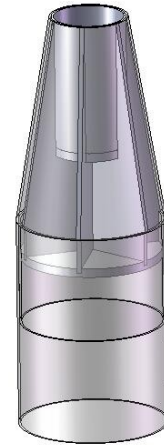
## **III. Staging**

The purpose of staging is to increase the overall performance of a rocket while still utilizing smaller motors by ejecting unused mass along the flight as the propellant is spent. Effectively the higher performance attributes to a higher final altitude. This is done by increasing the total impulse with two smaller motors rather than one large motor and decreasing the final burnout weight.<sup>2</sup> DARTs is a series staging rocket, meaning that its stages are aligned one on top of the other. In order to attain maximum performance of the whole system, the maximum burnout velocity must be reached.<sup>2</sup> The thrust from the first stage motor must accelerate the rocket with the combined mass of both stages. Once the first motor ends its burn the rocket's instantaneous velocity will be at a maximum before gravity starts to decelerate the body. Theoretically this is an optimum time to separate and launch the next stage. There is a decrease in mass due to the separation along with an initial maximum velocity from the first motor; so there is an increase in impulse once the next stage fires.<sup>1</sup> The thrust from the second stage motor can continue to accelerate the rocket until it burns out. At this point the maximum burn out velocity would be reached; in turn the rocket's momentum will cause it to continue to climb as it decelerates.<sup>2</sup> In practice if the drag acting on the rocket is close to the thrust that the motor can produce at the moment of separation, a delay before the second stage firing is sometimes used. This can allow for a decrease in velocity and a decrease in air density as the rocket continues to climb, which in turn would decrease the drag. The output of the motors which will be utilized for DARTs should not accelerate the rocket to velocities which will require a delay in staging to overcome drag, and since the mission altitude is 10,000 [ft] the burn out velocity of the first stage might not be high enough to sustain stability during a delayed second stage firing. Therefore an almost instantaneous second stage firing should be a relatively problem free and is therefore the optimum configuration for DARTs' mission.

The interstage coupler between the two stages is a key component in the design of this rocket. The first stage was designed and used originally for a previous single stage sounding rocket, RPR. Due to its strength and thrust capabilities, it was determined that this lower stage would be ideal to give stability for the first stage launch and a solid platform for the second stage to launch from. The second stage was designed to be just under half the diameter of the first stage. This not only will help keep the center of pressure below the center of gravity which will help with stability, but also allows enough room to properly couple with the first stage. Since both the upper and the lower stages of the rocket had their own design requirements the interstage coupler between the two was designed to fit the needs of both stages. It must transition between the 8.5 [in] diameter first stage and the 4.125 [in] second stage and do so in a smooth and rigid manner.

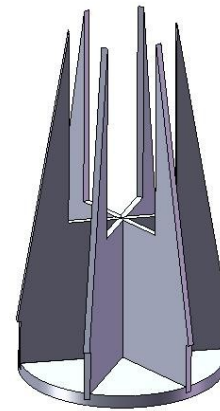
The interstage coupler will undergo a variety of stresses during flight. This includes buckling from the axial load being applied from carrying the second stage during the first stage burn. There will also be pressure forces acting on the second stage during flight. If the rocket is constructed in an axially symmetric fashion there should be no cause for concern, but if there is any misalignment or perturbation an uneven pressure distribution will form. This will cause a force perpendicular to the upper stage which will yield a large moment at the interstage coupler. These forces dictated the design of the interstage coupler.

The first stage provided a solid foundation on which to build the interstage coupler. At the top of this first stage there is an existing coupler from its previous use. The interstage coupler between the stages will slide over this part allowing secure attachment to the first stage. From there a transition section angles up to the lower diameter of the second stage. This can be seen in Fig. 1. Since the section would have to be extremely strong, an internal system of supports was designed. This consisted of six reinforcing braces; each one having an edge following the contour of the outside of the interstage coupler and the opposite side allowing for the section where the second stage would slide in. This can be seen in Fig. 2. These braces were made of 0.25" thick plywood and were equally distributed in a circular pattern around a center rod to provide a skeleton of the interstage coupler. In order to further support these braces multiple triangular slats were fitted between each support and secured into place with epoxy. The interstage coupler is wrapped with carbon fiber composite to give a final structure which is both very strong and still lightweight.

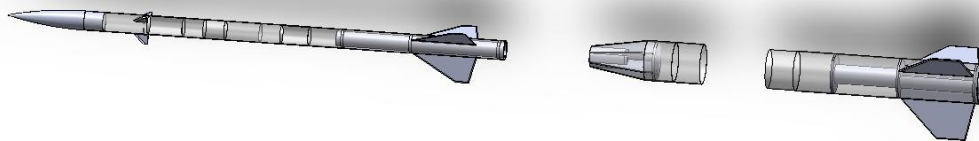


**Figure 1: Complete Interstage Coupler**

The actual connection between the interstage coupler and the second stage will be friction fit so that the bottom of this stage will slide securely into the coupler. When ignition of the second stage occurs this section will be subjected to heat and pressure for a short amount of time, so adequate thermal and structural protection is required. In order to shield from heat and withstand pressure an interface was designed for the upper stage to mate with the coupler. Three layers of the thin sheet steel were wrapped around the lower part of the second stage on top of a layer of mylar plastic with epoxy between each layer. Once the epoxy dried the interface tube was slid off of the upper stage, leaving a tight fit around the second stage. A cap was cut out of steel with the same diameter as the interface tube and attached to one end of its ends. This section was fitted into the corresponding space in the wood braces. In order to have the second stage fit into the coupler without putting strain on its fins or nozzle a small spacer was placed in the bottom of the interface to seat the bottom of the second stage against while leaving the nozzle free of contact. This section will provide a perfect barrier from heat and pressure, and should allow for rapid separation of the two stages due to the small volume that that surrounded the nozzle. Fig. 3 shows the complete separation of upper and lower stages along with the interstage coupler.



**Figure 2: Support brace configuration for interstage coupler.**



**Fig. 3: First and Second Stage Separation Including Interstage Coupler**

Separation from the lower stage and ignition of the second stage is what will determine the success or failure of DARTS. DARTS will be a routine launch until staging occurs, but ensuring the second stage launches cleanly will be a challenging task. A pressure charge can be used for separation, but there must be enough force to cleanly push the second stage away from the interstage coupler. This requires a high amount of pressure and a small volume for expansion. Also it must be guaranteed that the pressure charge fires directly after the first motor stops burning. This leaves a potential chance for error, which could lead to a trajectory change prior to second stage ignition. In order to

simplify the process and insure separation between stages the second stage will be launched directly from the first stage. The rocket motor ignition will cause a rapid pressure increase and effectively push the lower stage off. The risk of the volatile nature of this type of launch was taken into account, and it was determined that as long as the interstage coupler has proper protection from the motor's heat and pressure, there should be little or no damage to either section. The time it will take for separation to occur in this fashion will be short due to the amount of force being applied between the stages. This type of launch will ensure that the two stages separate, allowing for the second stage to continue cleanly toward the target altitude.

#### IV. Composites and Structures

DARTS is constructed primarily of composite materials. The main body tubes are constructed of both epoxy carbon fiber composite and epoxy fiberglass composite. Additional structural components were constructed out of carbon-phenolic honeycomb panels which were used for the fins and the motor case support rings. The reasons for choosing composite construction are two fold. First and foremost the lightweight and high strength to weight values are ideal for a minimum mass rocket. Due to altitude and payload requirements, it was necessary to minimize the rocket structure in order to achieve the highest possible altitude with the desired size motor. Secondly, the relative ease at which both carbon fiber and fiberglass composite could be constructed in a limited capability lab allowed Dædalus members to get hands on experience with the materials.

The carbon fiber composite is the stronger of the two materials and is therefore used in the first stage and lower body tube of the second stage of DARTS while the fiberglass is used solely in the upper body tube and nose cone. The reason for choosing two different materials is that while carbon fiber is stronger than the fiberglass and therefore the better choice pertaining to mass requirements, it does not allow for the transmission of radio signals. An RDAS RF telemetry system has been used extensively in past Dædalus rockets which allows for the real time telemetry to be relayed to a ground station during flight by means of radio transmission. It was necessary to have the electronics bay encapsulated in a body material conducive to the transmission of radio signals, which is precisely why fiberglass was chosen for the upper tube of RPR in order to facilitate this need.

The carbon-phenolic honeycomb panel was used to construct the fins and the motor case support rings in the first stage due to its high strength in resistance to bending loads. The resistance to bending loads is advantageous in these applications. The main functions of the supports rings are to keep the motor tube centered in the rocket and also to resist skin buckling or crippling due to aerodynamic loads. When firmly attached to the rocket tube skin the rings will resist any inward or outward buckling of the skin by resisting the corresponding bending moments generated. The use of this material in the fins allows for a stiff fin which would resist flutter effects that can be generated during transonic speeds. The resistance to flutter of the fins will provide a more stable trajectory during the boost phase and maximize the altitude obtained.

In order to design the thickness required for each body tube several rule of thumb preliminary estimates were used. These estimates were developed for use with standard materials, such as steel and aluminum alloys; however it was decided that for such a preliminary analysis with the composite material that the equation should hold within reasonable safety factors. The first of the considerations is the effect of construction and assembly on the material. As given in Ref. 3 the thickness required to compensate for tooling strikes and assembly procedures is given by the equation 1:

$$t_{p_{ext}} = 0.7d \left[ \frac{P_{ext}}{Ed} \right]^{0.4} \quad (1)$$

The external pressure was set to 10 [psi], as mentioned in the Ref. 3. The next load that was considered for this preliminary analysis was the buckling due to axial compression loading. The thickness required to resist a known axial stress is shown in equation 2.

$$t_b = 4r \frac{\sigma}{E} \quad (2)$$

This can be rearranged to solve for stress:

$$\sigma = 0.25 \frac{t}{r} E \quad (3)$$

However, the stress on the rocket tube is based upon several factors, including maximum thrust, maximum drag force and maximum acceleration. For this analysis only the maximum thrust force was considered because the other forces oppose this force and thus reduce the stress seen on the tube. The stress due to the maximum thrust can be represented by the following equation.

$$\sigma = \frac{T}{2\pi r t} \quad (4)$$

To find the required thickness in order to resist buckling due to axial compression it is first necessary to calculate the stress due to the maximum thrust. A MATLAB script was written to first pick an initial thickness value and

calculate the stress due to the maximum thrust. This same thickness was then used to calculate the stress at which buckling would occur. The stress values were compared and the thickness was increased until the buckling stress was equal to or greater than the stress due to the maximum rocket stress. This ensures that the rocket tubes will not buckle under the loading caused by the maximum stress within our assumptions. After calculating the thickness required to withstand the expected loads, a safety factor was applied to account for our assumptions and limited knowledge with composite materials.

## V. Roll Control System

As part of the competition's mission a ten pound payload must be carried along with the rocket's journey. A useful payload can take the form of measuring useful data or increasing the rockets performance. An important step in rocket optimization is the addition of passive or active control. If the rocket can be controlled on various levels the performance of the system can be readily changed if need be. One aspect of flight performance is roll rate. Depending on the need of the system, roll control can contribute to a variety of aspects. A consistent roll rate can stabilize the flight of rocket and diminish any aerodynamic flaws.<sup>3</sup> Lowering the roll rate can also be advantageous by allowing motion sensitive equipment to operate properly. Taking this into consideration it was decided that DARTS will carry a roll-control mechanism as its payload in addition to a complete set of GPS, telemetry, and a video camera system. The roll control system is shown in Fig. 4.

This mechanism will consist of three canard control surfaces located near the rocket's nosecone. These structures are designed to provide a rolling moment large enough to generate an angular acceleration of  $\alpha = 6 \text{ rad/s}^2$  under design mission conditions ( $h < 10,000 \text{ ft}$ ,  $v \approx 300\text{--}400 \text{ mph}$ ). This should allow for the control of the roll rate of DARTS. Although more stability would come from an increased roll rate, for this mission the mechanism will be used to raise and then immediately lower the roll rate and try to stop the rotation all together. This is for testing purposes of the system. If the roll-control mechanism can effectively correct the roll rate to zero, then it will be assured that it has enough control to adjust the roll rate to any specified angular velocity within in the range of the design mission conditions.

The roll control system will consist of trapezoidal canards with aft swept leading edges. This particular shape for the canards was selected due to its favorable stability and control characteristics, adequate aeroelastic stability, and favorable bending moment behavior.<sup>3</sup> In order to control the roll of the rocket, a servo motor is connected to each canard fin well above the center of pressure which will act to settle the fins in a downward facing manner should loss of power or torque be experienced. Originally the servos were connected to a BASIC Stamp electronic control system that takes data from an Analog Devices ADXRS610 300 deg/sec angular rate sensor to determine which deflection to apply to the fins. However, last minute difficulties with the analog to digital conversion chip forced our team to instead prescribe a set roll rate maneuver based off of timing after main motor ignition. An onboard video camera will capture this roll rate for later analysis and refinement of the system.

## VI. Recovery and Electronics System

The recovery process is composed of three segments. The first segment occurs shortly after separation of the first stage and second stage. The AED Rocket Data Acquisition System (RDAS) equipped in the first stage measures the decreasing pressure as the rocket climbs. Obviously after separation the first stage will start to descend once its residual momentum is depleted and the atmospheric pressure will increase. The RDAS measures this and initiates a pyrotechnic charge which jettisons the interstage coupler and deploys a full size parachute for the first stage. This occurs shortly after separation to allow for the second stage to leave the proximity of the first stage to prevent heat damage to the parachute from the second stage motor. The second stage rocket contains a smaller drogue parachute that will be stored just above the second stage motor. Once the rocket reaches apogee a separate RDAS will initiate the firing of a carbon dioxide charge which will jettison the upper part of the second stage structure and deploy the drogue parachute that will slow the rockets decent enough to have a controlled decent, but fast enough to lower the drift distance during decent. At approximately 1,000 ft. AGL the RDAS will initiate another charge that will eject

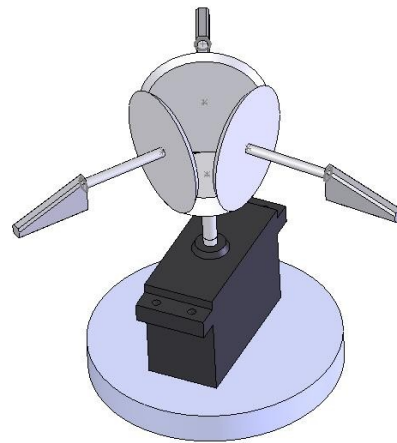


Fig  
ure 4: Simplified roll control system.

the main parachute to slow the decent enough to have the rocket land safely. This type of system should allow for lower drift distances when compared to a full size parachute being deployed at apogee.

The RDAS in the second stage is also equipped with a RF transmitter which relays data for in flight telemetry, accelerometer measurements, and data from a GPS unit. This information is used to trace the flight trajectory, forces acting on the rocket, and position. This data can be used to analyze the flight and more importantly help with location after decent. Several timing units are used for the second stage ignition. These timing units are initiated on liftoff by both a G-switch requiring 2.4 times the force of gravity for at least 0.5 seconds and the opening of a closed circuit. The timers are set to activate after a length of time equal to the burn time of the first stage motor. This activation will ignite an igniter system installed in the upper stage motor beginning the second stage burn.

## **VII. Experimental Solid Rocket Motors**

### **A. Motor Mixing Setup**

The method used to mix the solid rocket motors was adapted from a procedure in Experimental Composite Propellant by Dr. Terry W. McCreary, Ref. 6. The chief goals of the mixing procedure revolve around safety and repeatability. The work area is required to be kept clean and organized to avoid possible contamination between chemicals at all times. In order to maintain a safe environment any possible spark or heat producing source are prohibited from being in the work area. Repeatability is supported by proper records being kept in a bound notebook to avoid the loss of any mixing data. Any and all measurements and observations are recorded in the notebook and each page is dated for future reference. Once these protocols were established, the actual mixing of propellants could take place.

The order for propellant mixing and methods of measurement are very important to ensure a uniform final product. For this reason all mixing follows a strict written procedure. The first items to be mixed were the liquid chemicals including the binder, plasticizer, cross-linking agent, elastomer and any other liquid elements excluding the curing agent. Once all liquid chemicals are uniformly mixed the next chemicals to be mixed are the fuel and any additives. The fuel, normally aluminum or zinc for Dædalus' purposes, can be mixed in one batch due to the relative ease of mixing at this point. Additives consist of catalysts and burn rate modifiers as well as carbon black for opacity. The fuel is always carefully added to the mixture to avoid dusting, a potentially hazardous situation in which static electricity can cause ignition of airborne fuel particles. After thorough mixing of the fuel the oxidizer, ammonium perchlorate or AP needs to be added. The oxidizer should be added in small batches to ease mixing and to ensure uniform mixing. Once all oxidizer is mixed the final component to be added is the curing agent. The curing agent should be added in one batch and mixed until it is uniformly distributed.

Mixing was performed with an electric stand mixer, a method which involves a significant amount of time and attention to detail. The chemicals are added and mixed for a specified amount of time after which the mixing bowl is removed and the bottom is scraped to incorporate any unmixed chemicals. This process should be repeated at least three times per mixing step to ensure uniformity. Each mixing cycle should last at least five minutes but can last upwards of twenty minutes to ensure uniformity. With all chemicals uniformly mixed the composition is placed in motor liners with coring rods already installed. After several days time the propellant is cured and ready for integration into a motor casing for testing.

### **B. Motor Test Stand**

A rocket motor static test firing stand was designed and built by Dædalus team members to adequately validate motor designs. The stand was designed to be entirely modular so as to accommodate different sizes and types of solid rocket motors, ranging from the initial I-impulse motors used to validate propellant and mixing procedures, to the much larger M or N motors which are used in the actual launch of the sounding rockets. Included in this setup is a 2,000lb load cell, 0 to 1,000 [psig] pressure transducer, a National Instruments data acquisition, DAQ, system with 32 channel analog/digital capability and a custom built Lab View Virtual Instruments (VI) program for remote testing from a laptop. New additions include a voltage amplifier built by Dædalus team members to clean up the measured data points on subsequent motor tests and allow the DAQ to measure the output from the load cell in volts rather than the millivolts which the load cell outputs by default. The pressure transducer was manufactured by Omega Engineering, part number PX303-1KG5V, and allows for accurate measurement of chamber pressure during the motor burn. An aluminum adapter block was fabricated by Dædalus team members to adapt from the NPT-4 threading on the transducer to the ¼-20 bolt thread in the forward closure of the motor. This adapter along with the pressure transducer and motor are housed within a fiberglass tube which has the load cell mounted to the end. This apparatus is then pushed against a flat plate on the test stand during the thrust phase of the motor burn. Both the

pressure transducer and load cell data are recorded through the Lab View VI and the data is then analyzed at a later time.

### C. Initial Motor Testing

In order to minimize losses in the event of a mistake during the motor design and testing phase Dædalus opted to start with a small test motor. A commercial motor case (480 N-sec impulse) and corresponding supplies were purchased from Loki Research, and a small propellant batch was mixed using the directions listed in the above section. This propellant consisted of an HTPB binder, AP oxidizer, aluminum fuel, carbon black, and a curative. This propellant gave an initial design point for the larger M-class impulse design. Through the use of the freeware propellant combination software “PROPEP” it was found that the propellant could achieve an increase in Isp from 185 to 198 by using 20% aluminum in the propellant. Many iterations with PROPEP of varying aluminum percentages established the point of diminishing returns to be around 10% of the total mass. This yielded an Isp of 195.4, which is not quite as high as the 198 Isp with 20% aluminum, but the increase between 0% and 10% was four times larger than the increase from 10% to 20%. This lower aluminum percentage was also selected because incomplete aluminum combustion is a common observation in small solid rocket motors as seen by the large amount of smoke and light produced by extra aluminum burning outside the motor.

Two motors were cast using the following propellant formula: 70% AP, 10% aluminum, 18% HTPB, and 2% curative. Each motor consisted of three grains 2.8” in length. The core of one motor was drilled to be 0.375”, and the other motor was drilled at 0.5”. Both of these cores are larger than the nozzle throat which was predetermined to be 19/64”. The 0.5” core motor, Motor 1, had a Kn value, simply the ratio of burning area to nozzle throat area, of 280. The 0.375” core motor, Motor 2, had a Kn value of 239.8. Typically a higher Kn value corresponds to a higher chamber pressure, shorter burn time and higher thrust.

Through ballistic testing of the two motors described above values for the burn rate coefficient and exponent were determined. These values allowed for the propellant to be scaled up to be used in a M-impulse motor. The M-impulse motor was designed to have a relatively low Kn value due to the reduction in failure chamber pressure between the small 38 [mm] diameter motor casings and this casing which was 75 [mm]. The motor consisted of six grains 5.75” long with 1” cores. The nozzle used had a throat diameter of 60/64”, resulting in a Kn value of 232.1. These motors were all designed prior to the implementation of the pressure transducer in the testing setup and therefore keeping the Kn value low equates to a more conservative chamber pressure and a safer burn. The motor was expected to have a total impulse of 8000 [N-sec] and a burn time around 3.5 - 4 seconds. This motor was tested once prior to implementation in RPR at the Second Intercollegiate Rocket Competition in Utah. The test did not garner any useful data due to a failure in the method used to secure the test stand to the ground. Since the motor thrust is directed horizontally the test stand must be secured to the ground using steel stakes and concrete blocks. The motor produced far more thrust than expected and as a result the test stand pivoted on the front corner and settled in an upward firing position. This resulted in very choppy and inaccurate data. The motor was deemed to be a viable design since there was no evidence of over-pressurization and the burn completed smoothly.

### D. Recent Motor Testing

Since the initial round of motor testing during Summer 2007 a more complicated and higher impulse propellant was the next logical step. In order to determine this propellant composition a modified method of strand burning samples was used. This method involved the burning of equal length cylinders of each different propellant and measuring the burn time. The cylinders only had one burning surface so that the burn rate could be determined using the length of the cylinder. This method should yield results which are lower than the motor burn rate by 4 to 12%.<sup>7</sup> This method allowed for each propellant to be compared and the most energetic propellant determined. The results are shown in Table 1.

**Table 1: Strand Burn results.**

Additive	Percentage	Burn Rate
Carbon	0.5	0.028409
Iron Oxide	0.5	0.034083
Copper Oxide	0.5	0.032362
Strontium Nitrate	0.5	0.031576
Manganese Dioxide	0.5	0.030998
Strontium Nitrate/Iron Oxide	0.5/0.5	0.032648
Copper Oxide/Manganese Dioxide	0.5/0.5	0.035014

The propellants to note from above are the iron oxide, copper oxide and strontium nitrate. These three propellants performed the best when compared to the baseline, the propellant with inert carbon as the additive. The Strontium Nitrate/Iron oxide propellant also performed very well, though deceivingly the Copper Oxide/Manganese Dioxide propellant appears to be the best performing propellant. While this is true, the Manganese Dioxide on only propellant showed the least improvement over the carbon propellant and for that reason it was concluded that the copper oxide was the major catalyst in the Copper/Manganese propellant. Based on these results a combination of Copper Oxide, Strontium Nitrate and Iron Oxide were used as the additive in the final propellant to be characterized. The final composition of the propellant was designed to be: 17.75% HTPB, 0.25% Dioctyl Adipate (Plasticizer), 2% Isophorone Diocyanate (curative), 8% Aluminum, 71% Ammonium Perchlorate, 0.47% Iron Oxide, 0.33% Strontium Nitrate and 0.2% Copper Oxide.

With the propellant formula determined enough propellant was mixed and cast to form 2 ballistic test motors. The motors were designed to have neutral thrust curves and two different Kn values to allow for the determination of the burn rate coefficient and exponent. The first motor consisted of four 2" long grains with 0.5" cores and utilized a 0.375" nozzle throat diameter, this configuration resulted in a Kn of 198. The second motor consisted of four 2.1" long grains with 0.375" cores and utilized a 0.2968" nozzle throat diameter, this configuration resulted in a Kn of 281. These two motors were tested with the full set of measurement devices on the test stand. The resulting pressure and thrust data for motors 1 and 2 are shown in figures 5 and 6 respectively.

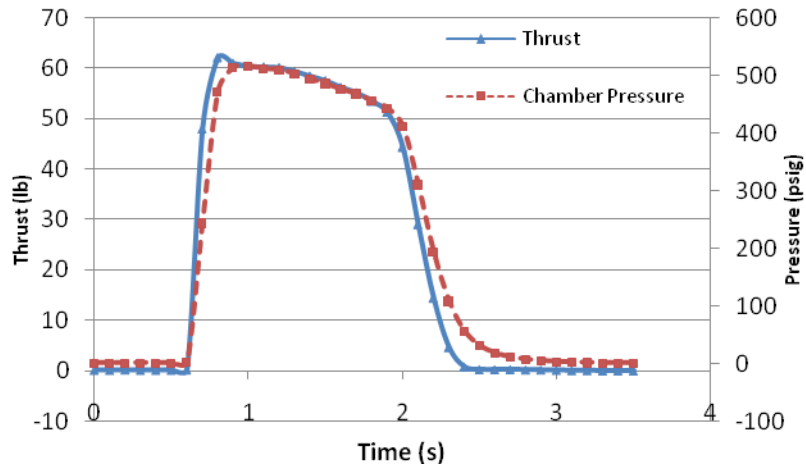


Figure 5: Motor 1 thrust and pressure vs. time.

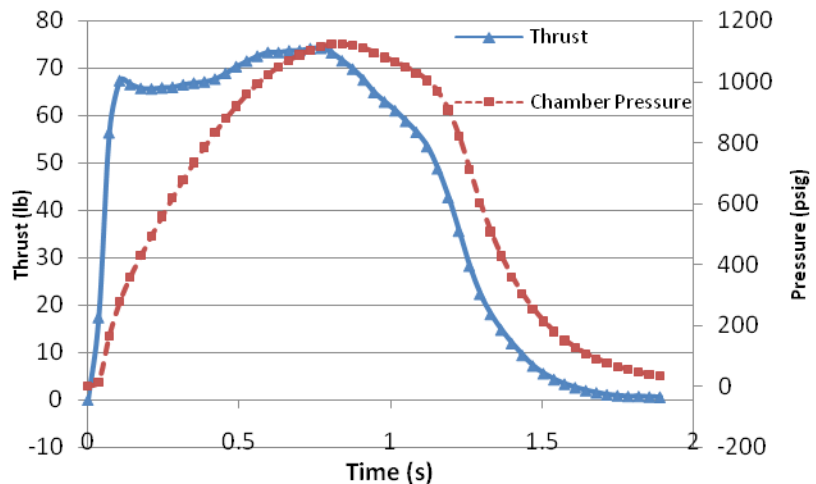


Figure 6: Motor 2 thrust and pressure vs. time.

The data gathered from motor 1 verifies that the pressure transducer and load cell are operating correctly. As can be seen the shape of the curves are almost identical which is to be expected. The data from motor 2 which was collected shortly after the data from motor one appears to show a significant lag in the pressure transducer. This lag is likely due to either a blockage in the adapter block caused by the first motor firing, or by the snubber which is used with the transducer in order to protect the transducer from spikes in chamber pressure. The effect of the snubber was likely not noticed on motor 1 because the pressures were significantly lower so there was no need for the “muffling” effect of the snubber. The total thrust produced by motor 1 was 75 [lb-s] (333 [N-s]), and the total thrust for motor 2 was 81 [lb-s] (360 [N-s]).

With the chamber pressure, burn time and motor dimensions the burn rate coefficient and exponent were able to be determined. The method for determining the burn rate coefficient and exponent first involved determining the burn rate by dividing the web thickness, average of the grain and core diameter, by the burn time. With this

parameter and the average chamber pressure, P, from the data above Veille's Law was used to determine the burn rate exponent, n, using a root finding method as shown in equation 9.

$$a = \frac{\text{Burn Rate}}{P^n}$$

$$\frac{\text{Burn Rate 1}}{P_1^n} - \frac{\text{Burn Rate 2}}{P_2^n} = 0 \quad (9)$$

The value of n was iterated upon until equation 1 goes to zero, and from that value of n a value for the burn rate coefficient, a, was determined. The values determined were a = 0.0273 and n = 0.3546, which fit into the ranges expected for an ammonium perchlorate and aluminum solid rocket motor.<sup>1</sup>

From these ballistic parameters and what was determined through the small scale tests; larger motors can be designed with relative confidence. The basic theory says that for a given propellant two motors with the same Kn will behave in a similar manner. Therefore a 75 [mm] diameter motor could be designed with a Kn of 281, and it would be expected to have a maximum chamber pressure of around 1100 [psig]. While this chamber pressure is well within the limitations of the smaller 38 [mm] motor casings, as the casing diameter increases the maximum allowable chamber pressure decreases. For that reason a chamber pressure under [800] psig is desirable per the manufacturer's recommendation. This recommendation is based on the yield strength of the casing material, and experimental results which the manufacturer has acquired. Until the casings are student designed, in which case the properties would be known with precision, the manufacturer's recommendation allows for design within the desired safety factors.

The next logical step in motor design involves more complicated grain geometries, which will require some specialized equipment as well as more complicated numerical modeling to ensure that the final motor design would be viable. It is the goal of Dædalus to eventually manufacture these more complicated grain geometries for use. For the rocket being designed currently two motors are required. The first will be a larger motor similar to the motor used at the Second Intercollegiate Rocket Competition in Utah. The overall chamber pressure will be increased slightly from the previous design through the use of catalysts in the propellant. The propellant being used is the propellant described above, for which extensive testing has been done to allow for proper motor sizing. This motor will be required to lift the combined weight of DARTS and bring it to a speed high enough to allow for smooth and safe staging. The second motor will be slightly larger than the ballistic test motors since it will only need to propel the upper stage of DARTs to the 10,000 [ft] altitude requirement. This motor will continue the acceleration started by the larger first stage motor and maintain the vertical trajectory, but is not intended to exert undue forces on the rocket.

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