

## **Introduction to ARES**

The ARES (Aeronautical Research for Engineering Students) rocket is a continuation of the Unity rockets started over a decade ago as a collaboration with BYU, Utah State, University of Utah and Weber State. The initial project was designed to give students hands on experience designing and building sounding rockets with the goal to progressively launch from altitudes of 10,000 feet to 100,000 feet. In 2004, after a successful launch together, the schools decided that each school had enough expertise to individually design, build, and launch their own sounding rockets, so students at BYU began designing the ARES rocket.

The ARES rocket was designed as an improvement over the Unity rocket in at least the following two areas:

1. ARES would be capable of reaching altitudes of 100,000 feet, as contrasted with the approximate 4,000 foot altitude attained by Unity.
2. ARES would have detachable aluminum skins rather than a composite honeycomb airframe structure to allow easy access to the various systems inside the rocket, thus promoting modular development of the rocket subsystems.

By fall 2005, most of the design work for the rocket was complete and many parts had already been donated by outside sponsors or retained from the previous Unity rocket. A complete CAD model and basic structural analysis of the rocket had been prepared. Nitrous oxide and HTPB were decided as the oxidizer-fuel combination and basic oxidizer plumbing and thin-walled pressure tanks had been procured. A motor casing and nozzle were available. Most of the fiberglass and carbon-fiber structural stringers, and the lay-up molds for the nose cone and boat tail were fabricated.

All of the team members now working on the project started either at or after the above work had already been completed and hence "inherited" an already-designed but yet-to-build rocket. Obviously, since its conception in 2004, ARES has involved generations of students. Hence, "inheriting" the rocket has allowed us, the current group of students, to finalize the rocket in preparation for launch. The downside to inheriting the rocket, however, has been a lack of continuity due to a lack of communication between successive student directors and team leads, and a change of faculty advisers one year ago.

Because those now serving as team leaders are generally unaware of the detailed design decisions made early on in the ARES design process, our report will not focus on the specific design of the rocket. Rather, each of the team leads will detail the status of their respective subsystem - airframe, avionics, motor, oxidizer and recovery - at the time that they were appointed and will explain what work their team has done on the rocket since we, the current group of students, began work. Further, the report will describe some of the difficulties each team has encountered as a result of not understanding details of how the rocket was designed. We hope that this approach will accurately document the work that we've done in finalizing ARES for launch and will serve as a case study for how to

manage “generational” student engineering projects that must be passed along year after year.

## **Airframe System**

The airframe system was one of the major reasons BYU undertook to develop its own rocket. Students at the time of conception wanted to develop a rocket with a greater range by decreasing the rocket’s mass. Previous rocket designs, specifically the Unity IV, had utilized solid, composite tubes, often in modular sections, to provide the rocket with structural support. Although this design provides a strong and secure airframe, it was believed an alternative framing system could be implemented. After BYU determined to develop its own rocket after the successful Unity IV launch decided on a composite C-beam framing system to make up the airframe. Most of the C-beam pieces are fiberglass composite with carbon-fiber composite pieces in the section around the motor mount. These composite beams provide structural support due to their C shape which maximizes the local moment of inertia with less material than a solid piece would require. Also, the C-beams are highly anisotropic because the fibers are oriented axially in the resin. The C-beams are joined axially with aluminum brackets and axially with aluminum, semi-circular ribs.

Eight skin sections made from aluminum sheet provide the outer protection and appearance to the rocket. They are fastened to the C-beams with 20—1/4” bolts that screw into threaded aluminum brackets attached to the underside of the beams with epoxy. When our team began working on the rocket in earnest, the composite framing was all complete but the skins were not aligned nor were the tabs attached. The correct alignment and skin attachment order were determined through much trial and error. This creates a body that is not as clean or smooth as a solid piece or two, but it increases modularity. Several times in working on the rocket, we have been able to simply remove one or two sections of the skins to gain access to the system requiring attention. On launch day, we will only need to remove one section of skin in order to fill the oxidizer tank and unlock the avionics system.

The most recent work done on the airframe system has been the development of the launch lugs and launch rail. Initially, the plan was to design the lugs to be used with the ESRA (Experimental Sounding Rocket Association) launch rail. However, because our initial plan was to launch just a few weeks before this competition, their launch rail would not have been available. Therefore, we designed lugs and our own, simple launch rail. The design for the lugs on this rocket is unique because of the C-beam framed body. Because the weight of the rocket will be resting nearly entirely on a single lug while on the launch rail, it must necessarily be attached to the most rigid and secure section of the rocket. For this reason, we designed the main, bottom lug to attach to the bottom section of the thrust plate where it meets the motor casing. The lug has an upper and lower lip on the inner end through which a 1/2” hole is drilled. A single 1/2” x 4” bolt joins the lug to the rocket by running through the upper lip, the thrust plate, an aluminum buffer plate, the upper motor casing lip and finally the bottom lug lip. The lug itself was ground down

on the inside track to allow it to fit flush with the circular thrust plate/motor casing assembly. In this way, the lug was attached rigidly and securely without radial rotation. The original material for the lug was aluminum but we soon learned from conversations with USU students that an aluminum lug would not rub well against a steel rail guide and thereby distort the rocket's initial trajectory. Therefore, we elected to use nylon for its low coefficient of friction and adequate material properties. The rail guide for our launch rail is a piece of steel perlin. Therefore, the front end of the lug, which extends out of the skins nearly an inch, has notches milled out of the sides to allow mating with the rail guide.

The primary concern in designing the lugs was failure on the rail due to the nearly 500 lbs. static weight of the rocket. Although the nylon's shear strength is at least 5 kpsi, more than adequate, the lug likely would not withstand a large torque at the interface between the lug and the rail guide. With the rocket's center of mass presumably near the center, a moment arm equal to the radius of the rocket body exists. To counteract this moment, an opposing moment is created using the upper lug. This lug is smaller and attaches to the rocket through two aluminum framing ribs. This lug not only restricts the rocket from rotating at the bottom lug but also serves as an initial guide for the rocket on launch.

In recent months, the launch rail was the main task of the Airframe Team. With the rocket's airframe complete and the ESRA rail unavailable, we chose to devote our efforts to building our own launch rail. Because it is intended to only be used with this rocket for one or two launches, many of our design choices were cost and expediency driven. We decided on a triangular cross section, steel truss design. We used angle iron and steel channel as the main components. Initially, we believed we would need two sections of truss to create 40 ft. of rail length. With two sections, we could mount one section on the rail support and lifting mechanism. The other section could then be stored underneath during transport and then attached on site. For the base, we used Dr. Bowman's trailer to which we attached a rail support made of 4" steel tubing on 5" channel skids that are detachable from the trailer. To mount the truss, we designed four mounting pillow block bearings. The main pivot is 1 1/2" steel rod mounted on blocks. This rod will hold the weight of the rocket and the truss almost entirely once raised. To raise the rail, we installed two 8 ton hydraulic jacks. A kinematics analysis was performed to determine the placement that would allow the rail to raise to 90 degrees. The main downside to this design was the choice of steel. It increased the weight of the truss and therefore the bending moment at the base at the point of attachment for the jacks. Although the support system performed well, some truss members have deformed under the loads when raised.

## **Avionics System**

The ARES (then Unity) project last launched a rocket in December 2003. It used an ancient Campbell Scientific CR10 Datalogger as the core of its avionics system and

DTMF radio tones for controlling the rocket. Due to problems with the recovery system, the avionics system in that airframe was destroyed.

The avionics team began designing a new system for the next iteration of the rocket in 2004. A senior electrical engineering student developed the design, which was based on a system of custom circuit boards with purpose-built electronics managed by microcontrollers running custom software. Using lessons learned from the previous launch, the system was well adapted to the project's technical needs.

Although—and perhaps because—it was a technically brilliant system, the new design had one flaw: it was too complex for most electrical engineering students to understand. After the original designer graduated, no one understood the system well enough to continue the work. At this point, the team made the decision to abandon most of the custom electronics in favor of COTS components where possible.

A new design emerged in 2005 that was centered around a VersaLogic Bobcat PC/104 486 single-board embedded computer. The flight computer provided a common PC platform that students were more familiar with, thus decreasing the barrier to entry for new project members. We installed Linux on the system and wrote custom software to control everything.

The other main component of the system is the Gadgetboard. The Gadgetboard is a general purpose I/O board designed by one of the previous avionics team members. The Gadgetboard provided us with two key things:

- Analog to digital converters for measuring sensor data
- Relays and MOSFETs for controlling actuators

The Gadgetboard connects to the flight computer over a standard RS-232 serial connection and provides a simple interface for the flight computer to communicate with the outside world.

The flight computer and Gadgetboard form the core of the avionics system. There are several sensors, actuators, and communication devices connected to this core, including:

- Three pressure transducers that measure oxidizer system conditions.
- A voltage divider that measures battery charge.
- A potentiometer that measures oxidizer valve position.
- Two solenoids that open and close the oxidizer valve.
- A servo that releases the nose cone (and thus the parachute).
- Igniters.
- A packet radio for communication with the ground.

Safety was a key concern in the avionics system design, and there are multiple safety interlocks:

- A master power key switch electrically disconnects the main batteries from the rest of the system.

- An output enable/disable key switch electronically disconnects the actuators from the rest of the system, thus allowing the avionics system to be powered without the risk of a safety accident.
- The control software must receive the ARM command (along with a password) before it will actuate any output device.

System power may be supplied by either internal or external battery power, seamlessly switched by a switchover circuit. The external battery (a 12V lead-acid automotive battery) provides a large power reserve for the potentially long period while the rocket is on the ground during the launch sequence. Shortly before launch, external power is disconnected and the system switches to internal power, supplied by a pair of 8V 3300mAh NiMH RC car batteries. Both power sources feed a switching power supply that smoothes the power and generate several required voltage levels.

## **Motor System**

### *The Motor Pour*

At the time we took over the project, all we knew about the motor was it is made of Hydroxyl-terminated polybutadiene (HTPB). The previous team left us with a motor that was too short. We were not sure how to get the HTPB to cure properly, so we set up several small samples with different curative ratios until the HTPB cured. We burned a few of the small samples to test the burn. After all the tests, we determined a 16:1 ratio HTPB to curative (PAPI 94) produced the best motor material. The mixture turns a pale yellow. We needed the mixture to be black in order to absorb the radiation given off during combustion. To accomplish this we added enough Lamp Black to turn the mixture black.

Before pouring the motor, we had to acquire all the right materials. The previous team left no information on where to get the large cardboard tubes to pour the motor in, which left us searching for a company willing to custom-make our motor tube. We also had difficulty finding a six pointed star tube with the correct surface area with which to form the inside port for the motor. The thrust calculations had already been made with that specific surface area, so we were stuck to those dimensions. We ordered a pool flotation noodle with the right diameter, intending to cut it down to the star shape. After a few attempts to cut it down with razorblades, we noticed the surface area of the circular pool noodle is about the same as the surface of the six pointed star, so we decided to leave the inside surface of the motor round.

The previous team left no instructions on how to pour the motor. We used a paint mixer attachment for a drill, but put it in a drill press. The drill press served as a mixer to stir the HTPB and curative for 15 minutes before putting it in the motor tube.

Our first attempt at pouring the motor was a disaster. The wooden plug at the bottom of the motor tube to keep the HTPB mixture in was a little small. Realizing duct tape is the cure to all sizing problems; we taped the plug to the bottom of the tube. Once we had

sizable amount of mixture in the tube, the tape gave out and the HTPB mixture poured out the bottom of the tube.

The next attempt erred on the side of precision and caution. We carefully made a plug that fit tightly. We secured and sealed it with epoxy and a second plug. This time our seal held, and we successfully poured the entire motor without misfortune.

After the HTPB cured completely, we had to come up with a way to get the pool noodle out of the motor. We heard that the previous team burned theirs out, but we wanted to be more careful with our motor. We used a hot wire to cut the foam out. It worked better than we all thought, and safer than the burning option.

It was difficult picking up where people left off because we were limited to their design without knowing how they planned to accomplish it. It would have saved time to stay in contact with the previous team to learn how they planned to pour the motor. However, it was a valuable learning experience to experiment with the motor on our own.

### *The Igniters*

When we began working on the igniters, we had a report from many years before, giving the dimensions and procedure to make the igniters. The igniters are made in two parts. The igniter cap is made from a  $\frac{3}{4}$ " pipe coupling and cap. An Estes C6-3 engine is epoxied to the cap with wires going out two holes drilled in the coupling. The other half of the igniter is a  $\frac{3}{4}$ " steel pipe nipple 6" long. The igniter fuel fits inside this pipe. The pipe then screws into the coupling, completing the igniter. An electric current through the wires lights the igniters.

The goal for igniters is to provide a 6" flame for 12 seconds. This provides enough time and heat to allow the motor to ignite. In order to accomplish this, we essentially made two small solid rockets that are started with Estes engines. We mixed magnesium powder, ammonium nitrate, and HTPB to get a reliable and safe flame.

We made our first igniter using the fuel recipe in the report from a previous project. We took it to a remote park to test, and all it did was smoke. No fire. After some research, we determined the ammonium nitrate needed to be ground a little to provide more surface area. We tried a second one with ground ammonium nitrate, which still did not ignite. We decided to try different ratios to see if it would burn.

The original mixture seemed a bit too dry and crumbly, so we tried adding different amounts of HTPB. We found a good consistency that ignited consistently. However, during one of these tests, we realized something was wrong with the Estes engines; they were exploding after they lit. The epoxy was creating a seal so when the parachute pop occurred, it was forced out the wrong end, creating an explosion. To fix this, we removed the parachute pop from the back of the Estes before gluing them to the cap.

After fixing the Estes engines, we needed to produce a flame with our igniter fuel for twelve seconds. Our current igniters only stayed lit for about five seconds. We talked to

some professors on campus and came to the conclusion that we were not packing our fuel enough. If the fuel is not packed enough it will not burn for twelve seconds, but if the fuel is packed too much it will not ignite; the balance is delicate. We tested a few igniters until we came up with the correct way to pack the igniter fuel.

Working on the igniters, we discovered documentation left by the previous team and found it quite useful. We also found left over materials to make the igniters. In the documentation, they left us a detailed enough procedure that we were able to follow, so we did not have to come up with igniter fuel on our own. However, if we had been in better touch with those before, we could have avoided the other time consuming hiccups that I've previously detailed.

## **Oxidizer System**

When we took over the oxidizer system we had parts of the main plumbing, the pneumatic valve, the solenoids, a small Nitrogen tank and plastic tubes. We also Inherit 3 custom aluminum tanks. All the pieces were disassembled and not many documentation available. It was challenging to try to figure out how all the system fit together. We tried to get in contact with old team members.

### *System Assembly & Modification*

The first thing done to the oxidizer system was the reinforcement of the aluminum tanks. We reinforced them with carbon fiber filaments. After having the tanks wrapped, we proceed to hydro test them to 2000 psi. Once the tanks were testes the first part of the assembly was put together, this is, the oxidizer tank (aluminum wrapped tank) with the main plumbing block which holds the pressure check valve, the filling valve and the oxidizer pressure transducer. After this main block it's the big ball valve that lets the N<sub>2</sub>O out. The valve is connector to a pneumatic valve which actuates and opens the ball valve. The rest of the main plumbing comprises of a large 5000 psi hose connector to a custom made shower head which creates the theoretical flow rate for the system. To activate the pneumatic actuator, there was a little N<sub>2</sub> tank which supplied with the necessary pressure to activate the actuator.

All the calculations for the oxidizer where based on previous rockets specially UNITY IV. We didn't have a chance, although we planned, to do a static test to do a thrust curve calculation. The amount of oxidizer calculated to reach 10000 feet with our current weight is of about 40 pounds.

### *Redesign*

The little pneumatic system was very unreliable, because it used swage locks with plastic hoses. These hoses were worn out, and because of that, many leaks were present. In addition many Tees and fittings were present in the system, adding to the difficulty of finding leaks. In order to solve this problem we decided to change the small N<sub>2</sub> bottle current system to a more compact system, also we decided to replace the plastic hoses to metal tubing, first copper and the stainless steel. Today the system is leak proof.

Another major change we did to the system is the filling valve. We were using 2 one way swage lock valve. After testing filling times and how hard it was to fill, we decided to change the 2 valves to one 3-way valve, which proved very useful in later tests.

### *Experience*

In working with the oxidizer system we learn a great deal in inert gases behavior and manipulation. In addition we learned the art of carbon fiber reinforcement, because we help wrap the oxidizer aluminum tank.

## **Recovery System**

### *The Parachute System*

——The parachute system consists of a large (25 foot diameter) old army parachute which is pulled out by a smaller (6 foot diameter) drogue chute. Both of these parachutes are stored in a cardboard tube at the top of the rocket. There is a long streamer attached to the drogue chute to ensure that it is pulled out enough to catch air. The large parachute is connected to the thrust plate of the rocket by parachute chord. The large parachute has been tested in winds up to 18-23mph in which case it easily lifted over 400 lbs. During the testing the parachute was not damaged and appears to be sound for use in our rocket.

### *The Nose Cone*

——The nose cone was made previous to my being assigned to the rocket project. It is made of a composite and filled with foam with a Styrofoam interior maintaining the desired interior shape. At the base of the nose cone there are four wooden blocks, one at each quarter. These blocks interface with the spring system through loose wooden dowels. Attached to one of these wooden blocks is a hinge system that interfaces with a circular aluminum web at the top of the rocket. Directly across from the hinge on the opposite wooden block is a hook through which the reduced-force separating system interfaces. At apogee the nose cone separates completely from the rocket and has its own drag-chute / parachute system that is stored inside the nose cone itself.

### *The spring system*

——There are 4 total springs for the nose cone ejection. They are placed equal distances apart and are mounted with aluminum elbows and with high-quality epoxy onto the composite beams that run the length of the rocket. The springs are encased in PVC and attached at the bottom of the PVC to prevent them from springing out. We decided on using wooden dowels to interface between the springs and the nose cone providing compression of the springs. These dowels are loose and not permanently attached to anything so at ejection they will be lost. The reason for this is that we felt four long wooden dowels permanently attached could easily catch the parachute up and not allow full deployment, thus jeopardizing the rocket. The dowels interface with four wooden blocks that are epoxied inside the nose cone.

### *Servo*

——The servos being used are HS-75 BB retractor servos. These servos are landing gear retractable servos which hold one of two possible positions with approximately a 170 degree turn between the two. We are using the servos to pull the pin from the reduced-force separation system. The reduced-force separation system requires an estimated force of 7 lbs for a 1.32” long pin. The torque listed by the manufacturer for the HS-75BB retractor servo is 7.12 lbs\*in (113.87 oz\*in). A 1.3125” pull required a lever arm of 0.66” (considering a straight line connecting the two ends of the lever arm at the two respective positions). With a lever arm of 0.66”, the force produced by the servo would be 10.78 lbs. which gives a safety factor of 1.54. These numbers have been verified by testing. During testing a load of 7.5 lbs. was required to pull the pin; the servo was successful.

### *Servo Support System*

——The servo support system is designed as a simple way to keep the pin and the lever arm of the servo in the same plane and in fixed position relative to each other. It is made of aluminum and can be broken up into individual parts. It integrates with the reduced-force separation system and holds the location of the pin rigid. It also holds the servos upside down and rigid, ensuring that the actuating plane of the servo lever arm is lined up with the pin’s plane of release.

### *Reduced-force Separation System*

——The reduced-force separation system was purchased from a local paragliding company and is used for paraglide tow-release systems. The system has been used in numerous cases where the lives of paragliders depend on the system and has proven reliable. It consists of a long thick black strap with a loop on one end to be secured inside the rocket which then connects to two thin white loops that interconnect to produce a reduced-force separation system triggered by the pulling of a pin. Testing has consistently shown that the force required to pull the pin to release the system is 7.5% of the load on the system itself. Thus with a 100 lb. load the required force to pull the pin is 7.5 lbs. The estimated load from the compression of the springs is 60 lbs. total. The estimated load from the moment of the nose cone is 27 lbs. So the total anticipated load is 87 lbs. Thus the required force to pull the pin is 6.5 lbs.

### *Challenges*

——There were many challenges for the recovery team coming into a project that has already partially been done by others. One of the biggest problems was the apparent black hole of information surrounding the rocket that was already made. There was no sure design of the nose cone separation system. This system had to be designed from scratch with no design requirements other than common sense. We had hints of what the previous system had been but these hints proved to be misleading. The system went through two designs as a result. We weren’t sure if the parachute we had was capable of surviving and safely returning the rocket. We weren’t sure if the parachute was even large enough to safely return the rocket. As a result the parachute had to be tested extensively. We didn’t know how heavy the rocket would be at apogee. We didn’t know how fast it would accelerate upwards. We didn’t know a lot of critical information in the design of a rocket’s recovery system. As a result, we had to make some good guesses,

run tests, and do extensive research on previous rocket launches in order to design our system.

### **Student Director's Comments**

I became student director after being involved with the rocket for a year; previously, I'd worked on the airframe team and been the airframe team lead. Listening to the other team leaders, many of whom were more experienced than I, I was able to quickly grasp the big picture of the ARES rocket. After a number of months, I realized that I knew more than any one person about the rocket in general and that I was most effective in coordinating work between the various teams. I will share two lessons I've learned from Project ARES, one that we've done fairly well and one that we need to implement.

First, I've found that my primary role as student director is to provide the big picture for our team. That picture includes the overall perspective of how the separate subsystems integrate into the rocket and how changes in one system may affect another system. The big picture also includes understanding how the subsystems fit together and in what order the rocket must be built, assembled, and launched. Finally, the big picture includes the overall time table detailing how to prepare for launch week by week. Communicating this big picture to team leads in leadership meetings and to the whole rocket team proved my biggest challenge and responsibility.

Second, I've found myself wishing multiple times that previous rocket team members had more thoroughly documented their work. More documentation of design decisions would have helped us know which of our current questions had already been addressed and which still needed to be solved. Justification for those decisions would have helped us predict what modifying the system might lead to down the road. Diagrams of how the various subsystems should be assembled would have saved us time in having to guess and check how parts were designed to fit. Finally, keeping a written inventory of what parts we have and haven't ordered and received would save a lot of time spent hunting for and buying new parts.

### **Conclusion**

ARES has allowed dozens of engineering students to design, build and launch a sounding rocket. The project has involved generations of students and has thus run into communication problems from one generation to another. These problems could be alleviated with more thorough documentation of design decisions, of inventories, of procedures and of diagrams. Altogether, the project has been a great success by allowing a group of rocket-enthusiastic students to far exceed anything they would have been able to do on their own in pursuit of their dream: launching the high-powered ARES rocket.