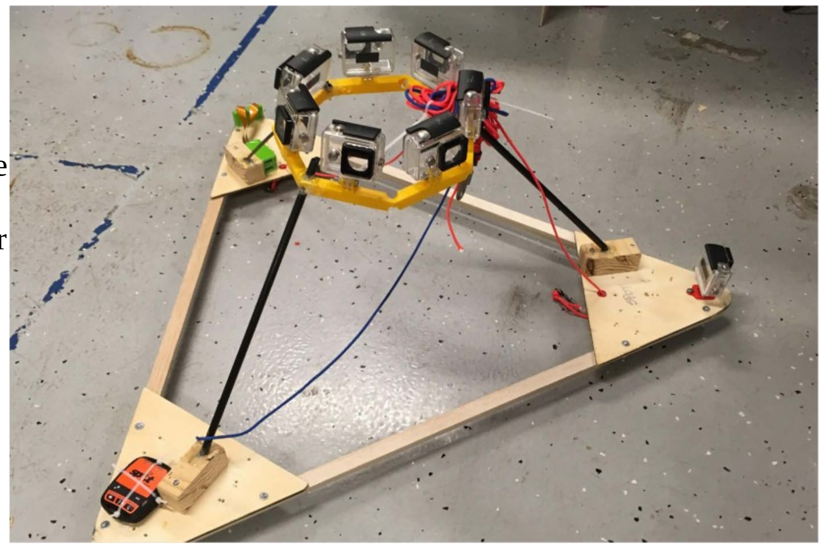
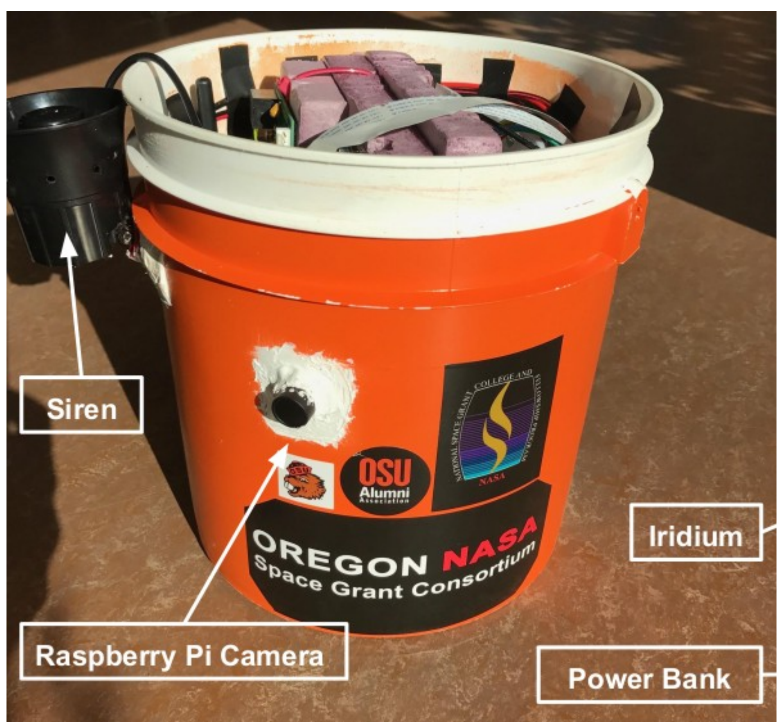
Now that the electronics have been refined, we need a way to mechanically protect the system and a reliable way to attach the system to the balloon. We can do this by creating an encasing around the electronics. The protective housing can provide multiple forms of protection, thermal protection against extreme cold for parts that don't need direct access to the atmosphere, crush and puncture protection against other payloads that might be on the same balloon or trees that the payload could land on, and a strong method of attachment to the balloon tether to ensure the payload is able to return safely to the ground using parachutes. Lets explore our options which can range from minimal to very involved.

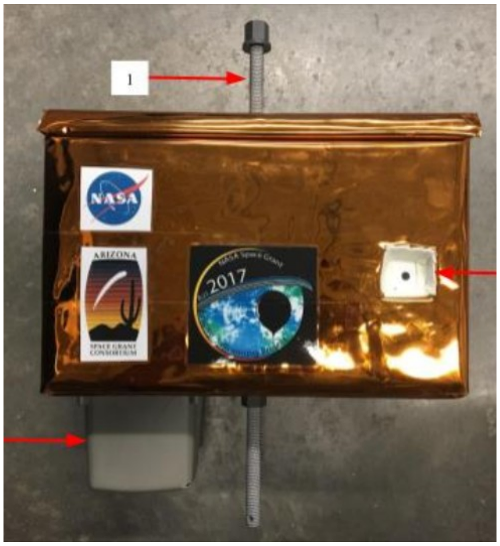
Here is an open frame payload made by University of Illinois at Urbana-Champaign made with the purpose of recording video and stabilizing swinging motion to improve video quality. The open frame facilitates a wide open field of view for the series of go-pro sized cameras facing in all directions. The camera mounts were 3d printed with the triangular base made from balsa wood and carbon fiber rods connecting the base to the camera mount and strong epoxy used as adhesive. Depending on the needs of the experiment, an open frame could be useful, but care must be taken to ensure the system is mechanically strong with a reliable recovery method that is not likely to break any piece.

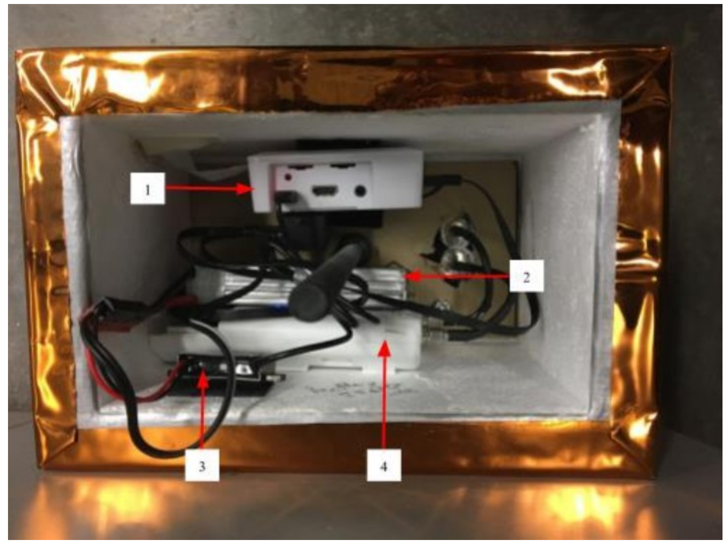


The following is a payload made by Linn Benton Community College part of Oregon Spacegrant Consortium. Their mission was to record atmospheric data with the payload launched from a boat offshore. Because the probable landing location would be even further offshore, the payload uses a plastic bucket for sealing water out of the inside with foam pads to mount the electronics in the center. This has very different operating environment considerations compared to payloads launched in Arizona, and shows how housing form requirements can change depending on the nature of the flight.

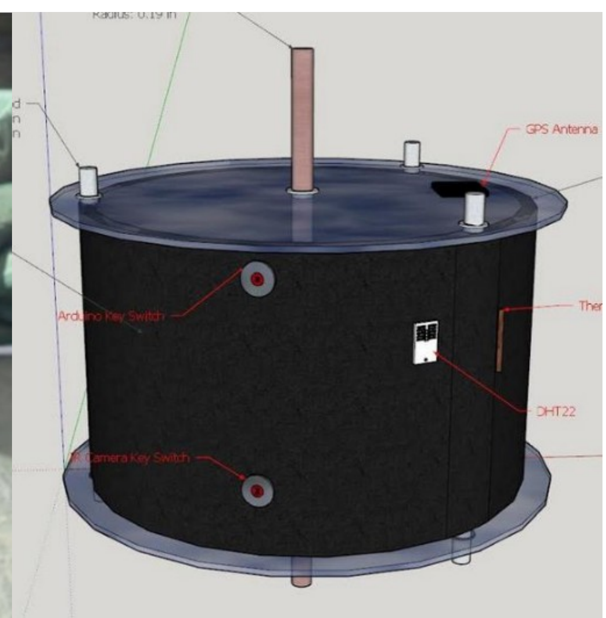


These are images of payloads made by Embry-Riddle Aeronautical University with a mission to transmit live video and image frames with the payload still in flight. The payload housing was made with rigid polystyrene for the bulk material covered in metal film for interference protection and a carbon fiber rod for tying the payload to the balloon tether. Foam based payload housings might be one of the most common materials for being strong enough for sufficiently lightweight contents, thermally insulating, and relatively cheap price.




The below pictures more closely resemble the housing choices made by Phoenix Community College. This is a payload made by the ASU ballooning team for studying weather effects induced by the 2017 solar eclipse including basic weather effects and thermal imaging. The walls are made out of hardened resin impregnated carbon fiber for its high strength and low weight with optical polycarbonate plates for the top and bottom lids and another plate in the middle section creating a top and bottom chamber. The polycarb was used because unlike many other optically clear materials, it allows deep infrared light to pass which allows the use of the thermal camera used. Additionally a plate was added to separate the inner space into isolated top and bottom chambers because the camera produced significant heat while recording that might have affected the sensor array in the top chamber.

Polystyrene housing might offer a cheap and relatively easy method for a housing option, but carbon fiber offers the ability to construct exotic shapes purpose built for the job. The housing needs to be lightweight and strong to protect the payload contents while not consuming too much of the 3lb weight budget Arizona payloads often have, so how does carbon fiber compare to polystyrene? When hardened with resin, the carbon fiber can have strength and stiffness comparable to metals, while various grades of foam can be broken apart by hand. What about weight per square foot of material used? A rigid insulation foam from Home Depot was calculated to be 0.245lb/ft$^2$, with a random all foam ice chest from Amazon was 0.137lb/ft$^2$. Compare this to a random sample of carbon fiber found on amazon weighing in at 0.092lb/ft$^2$, 63% lighter than the Home Depot insulation foam and 33% lighter than the ice chest foam. The trade off however is expense and fabrication complexity.

Like the other content in this workshop, this is meant to be an overview of basics ideas in fabrication using carbon fiber. Depending on the shape and size of the desired final product, some variation of these processes can be used. As with all other subjects in this workshop, you should do your own research to become more familiar with the process and you should practice on small segments of carbon fiber to get familiar and comfortable before committing to large pieces that might need to be thrown out due to imperfections. I'm not an expert in carbon fiber fabrication and there are many processes that can be used, so much of the information and products discussed here can be found online at uscomposites.com and on a Youtube channel called "Tech Ingrediants" and other sources.

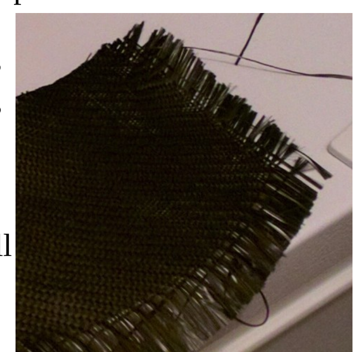
Carbon fiber often comes in fabric sheet rolls that are not initially rigid. The material is given rigidity by adding a hardening agent to lock the fibers in a particular configuration. This means hardened carbon fiber is a composite material, or a material made from multiple component materials to achieve intended properties. Generally speaking, to make a mechanical part using carbon fiber, you need the carbon fiber fabric, an epoxy resin which is the locking agent, and a hardener which acts as a catalyst to cure and harden the epoxy. Epoxy with various hardeners have different cure/hardening times and a few terms will be used to describe epoxies and hardeners when shopping around for different products. "Pot life" refers to the maximum time that the epoxy can remain in the mixing cup/pot, "set time" refers to the amount of time it takes for an epoxy to become a gel after being applied in a thin film, and "drying time" refers to the amount of time after application until the resin will harden enough for sanding. Further, different hardeners have different cure times spanning from minutes to hours. An epoxy with a very short pot life has the benefit of very fast cure time but doesn't allow very much time for working with and applying epoxy, which can make the process more error prone. A long pot life allows the maker to take their time applying epoxy and shaping the carbon fiber, but has the negative of needing to wait significantly longer for the resin to harden for cutting or sanding. Epoxy and hardener however often have a shortened cure time based on higher ambient temperature, which can be used with a long pot life epoxy to cut the wait time for curing. Epoxies also have different viscosities for different purposes. Because bubbles are undesired and can be a source for imperfections in the final product, some people recommend low viscosity infusion resin since it allows bubbles to pass more easily and can more easily fill between a fabric's fibers and completely saturate the material. "Spread tow" is also a type of carbon fiber with a weave pattern that makes the final product slightly thinner than normal carbon fiber, and thus requires less epoxy to fill between the fibers, which equates to less epoxy weight per area.

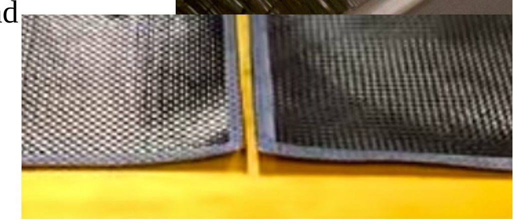
These materials can be harmful to the human body in different contexts, so caution should be taken and protection should be used. The epoxy can stick to skin and the vapors can give problems as well, so nitrile gloves, safety glasses/goggles, and a respirator or working in a well ventilated area is recommended. The resin can also ruin surfaces, so use tarps or plastic covering over the work area to catch any stray drips. After the epoxy dries, often the maker needs to trim material from the part. To do this, cutting tools like a hack saw or a Dremel tool can be used and sand paper or sanding blocks can be used to smooth any sharp edges. The cutting and sanding process however can throw lots of carbon or resin particles into the air, which can be harmful if breathed in. Cut outside and/or use a shop vacuum next to the cutter and a mask to avoid inhalation.

Basic consumables for the job:
- Carbon fiber fabric (spread tow fabric is a plus)
- Epoxy (low viscosity infusion resin is a plus)
- Hardener (if using short pot life variety, have a plan for heating while curing)

Basic tools needed for the job:
- Foam brushes, for applying epoxy
- Plastic cups for mixing epoxy with a hardener
- Tongue depressors / thick Popsicle sticks for mixing epoxy
- Tarp to catch epoxy drips (tabletops can use polyethylene film / cling wrap, taped down)
- Cellophane tape (for cling wrap)
- Particle mask / Respirator
- Nitrile gloves
- Safety glasses
- Dremel tool / saw
- Epoxy Pumps (for dispensing exact epoxy to hardener ratio)
- Bubble Buster corrugated aluminum roller (often used for fiberglass)

Test out the fabrication process by laying epoxy out on a smaller piece of carbon fiber. The fabric often comes in larger rolls that need to be cut, which can introduce the problem of the fabric unraveling. Decide how the desired test piece should be cut and lay clear tape over the sections to be cut, then cut through the middle of the tape. This will separate the fabric into subsections with the tape on the borders keeping the fabric ends intact. Depending on the type of end product, different levels of strength may be desired, so its important to pay attention to the cut direction in relation to the fabric pattern. Carbon fiber is strongest in the direction of the weave patterns, so a sheet cut in line with the weave grid will be strong pulling along that grid pattern, but weak when pulled diagonally. However, cutting the fabric at 45 degrees relative to the weave grid pattern will make the resulting material strong against diagonal pulls and weak against tension in the direction of the cuts. The fabric can however be layered to use both styles to get the best of both worlds at the cost of twice as much material used. Prepare a workspace by taping polyethylene film to the surface of a table covering as much area as possible.





Using epoxy pumps, pump into a plastic cup the ratio of resin to hardener specified by the hardener being used, then thoroughly mix with a tongue depressor. The resin and hardener must be emulsified to work properly, so it’s recommended to mix vigorously for 2 minutes while scraping the sides of the cup to ensure no liquids are sticking to the walls and not getting mixed. With the resin and hardener mixed, this begins the “pot time” and the clock is now ticking toward the material curing. While this happens, the resin and hardener will have an exothermic reaction with each other and heat up, and since the material actually cures faster with higher heat, this can create a runaway reaction and could set fire if left alone. So don’t leave the mixing cup by itself unattended, and when finished using the epoxy, dump out its contents to spread the material out allowing more heat to escape.

With the epoxy and hardener well mixed, pour some of the mixture onto a small area of the polyethylene film on the workspace and spread it out with the brush. Lay the small cut carbon fiber section onto the resin and use the corrugated roller to roll out the fiber, squeezing the epoxy through to the top of the fabric. This allows air to escape through the top of the fiber as the epoxy seeps into the fabric. Continually check the material from different light angles while rolling to find dry spots and use the foam brush to wet every region. After a layer of carbon fiber is thoroughly wet by the epoxy, additional layers of fabric can be added on top and pressed with the roller to squeeze the epoxy through to the top, adding more dabs of epoxy with the brush as needed. While doing every step, try to minimize bubbles as they represent structural imperfections that will propagate to the end product.

After the layers of carbon fiber are completely wet by epoxy, pick up the sheet by the taped edges and put it in another polyethylene protected area that can be warmed to accelerate the resin cure time. The part can be wrapped onto a mold to give it shape, but care must be taken to ensure that the epoxy will not stick to the mold permanently. To do this, apply a layer of “mold release” to the mold prior to adding the fiber to the mold. Mold release can be found at uscomposites.com. The part can be heated to temperatures around 113$^{o}$F to accelerate cure time, but take care to not overheat because this can damage the mold release or other elements. The accelerated cure time will depend on the hardener used.

Sometimes it’s desirable to use a vacuum environment to improve the quality of the part. If bubbles are a problem right after mixing the epoxy, a small vacuum chamber can be used to pull the bubbles out prior to applying coats to the carbon fiber. Vacuum bags can be used to improve the finish of the fiber by inserting the part with its mold into the bag with a layer of breather material and an absorbing material like cotton on the fiber facing away from the mold. Pulling a vacuum with the bag will pull bubbles out of the resin and pull the resin through the fiber and breather material to be absorbed into the cotton. With the bag void of air, the assembly can be warmed to speed up the cure time, but just like before, don’t heat too much to avoid damaging the bag or other molding materials.

After the part is cured and hardened, remove from the mold if used, and use a cutting tool and sand paper or sanding block to remove excess carbon fiber or bits of the mold that stuck to the part. This main section of resin impregnation into the carbon fiber provides most of the rigidity the part needs, but additional waves of epoxy and curing can be done to achieve nice surface finishes. If additional layers of epoxy are desired, each layer should be applied after the previous layer has set (gel) but not dried (hard). If adding more epoxy after drying, sand the previous layer to rough it up to give the next layer material to grab onto. Sometimes a part also has voids that the designer wants to fill. In this case, the epoxy can be thickened to the point it doesn’t run by adding “fumed silica”, a sort of powdered glass particles that act as filler/thickener for the epoxy. Fumed silica can also be found at uscomposites.com

After a part is finished, just as would be done with the electronics inside the housing, test it. When making any product it can be difficult to get everything done perfectly the first time, so I recommend trying the carbon fiber process on a small section and testing out working with the material. Cut it, sand it, strength test it and think hard about what the desired form of the payload housing would be and how this process can be used to make it and plan for multiple iterations. There is no “most important part” of a payload, without the housing the electronics fall out of the sky, without the electronics the payload is just an expensive box. So the housing should be diligently designed and tested to fit the needs of the payload and strength requirements of a balloon trip to the sky.