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The Development of a Planetary Suit Concept Demonstrator by the North Dakota Space Grant Consortium

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ABSTRACT

Over a one-year period beginning in March, 2005, and with a materials budget of approximately $25,000, the North Dakota Space Grant Consortium developed a pressurized planetary space suit concept demonstrator in conjunction with institutions of higher education across the state. This project sought to combine educational instruction in space suit design and manufacturing while simultaneously developing a usable test article incorporating technical approaches appropriate to the project's schedule and budgetary constraints. The North Dakota Experimental (NDX) Suit serves as a testbed for new planetary suit materials and component assemblies. Designed around a dual-plane enclosure ring built on a composite hard upper torso (HUT), the NDX is designed for an operating differential pressure of 26.2 kPa. In order to test a two-chamber suit concept, the NDX features a neck dam assembly that divides the helmet breathing cavity from the body below the neck. For safety purposes during testing, this helmet is also quickly removable. All restraint layer joints and fabric assemblies are sewn with readily available materials and equipment and are ruggedly constructed for a long-duration test campaign. Because of the geographical distances between different component groups, all suit assemblies are designed to be modular and adjustable upon final suit integration. The NDX pressure bladder is a sewn fabric garment coated with latex made to the same dimensions as the restraint layer. The NDX features a backpack that conforms to the HUT and houses communications equipment. Life support system gases are provided to the suit through umbilicals from a separate supply. Wireless biomedical sensors mounted inside the suit and helmet monitor such parameters as heart rate, respiration rate, carbon dioxide concentration, oxygen concentration, body temperature, and relative humidity. This telemetry is sent to a base station via a Bluetooth® hub for monitoring and recording. An evaluation program in both a laboratory setting and at a field site is designed to test performance and usability while ensuring safety. Ultimately, this project has provided a baseline set of knowledge for further planetary research and development within the state of North Dakota.

INTRODUCTION

Mars-analogue research activities on Earth can benefit from a pressurized planetary suit concept demonstrator that simulates many of the challenges future explorers will face during extravehicular activities. Recognizing the iterative nature of planetary suit development, knowledge gained by designing, constructing, testing, and evaluating such a suit on Earth can be applied to future planetary suit development projects. To this end, the North Dakota Space Grant Consortium (NDSGC) developed a planetary simulation suit that serves as a baseline experience for further pressure suit research while providing a unique educational experience for undergraduate and graduate students in the state. By developing the suit with the participation of other educational institutions in North Dakota, this project also aims to cultivate a knowledge and experience base needed for future space suit development projects.

The construction of the North Dakota Experimental (NDX) suit demonstrates that innovative space suit research can be pursued with readily available materials and with a relatively low materials budget of $25,000. Because this suit is primarily a learning and research platform, the NDX incorporates a mixture of novel and proven concepts, materials, and components. The project also demonstrates that the preservation of technical knowledge acquired during the development of a suit must be effectively recorded and transmitted to others in order make further progress. As such, this paper summarizes the progress made to date on the NDX suit and describes future development and testing plans. Results from these future laboratory and field tests will be used to modify the suit and to develop new planetary suit concepts.

TECHNICAL OBJECTIVES

Broad technical objectives were initially formulated in order to guide the early concept definition process within the bounds of developing a two-chamber suit. Though not evaluated during this program, the potential for reducing life-support system loads by utilizing a two-chamber suit will be investigated in the future by NDSGC researchers. Given available resources, these objectives were formed in terms of general suit usability rather than specific component technical parameters. Additionally, the team recognized early on that the creation of a suit to meet specific parameters is highly dependent upon a solid base of prior experience with pressurized suit mechanics and construction. As this represents a first attempt at planetary suit development, lessons learned from this project can be used in the future to create higher fidelity requirements for future suit research.

- Pressurized to 26.2 kPa (Apollo suit pressure) to simulate the challenges of operating within a planetary suit.
- Able to don/off the suit in no greater than 10 minutes.
- Conduct standard geological field study and construction activities with modified tools
- Test the mobility effects of new rugged restraint layer materials for future suit applications.
- Able to operate a motorized rover while seated.
- Able to quickly remove the helmet in an emergency.
- Function safely in the suit unaided for 1.5 hours
- Re-supply of suit consumables in less than 5 minutes.
- Able to operate in the suit for 4 hours without compromising user health.
- Able to accommodate a drinking bag for the user.
- Able to communicate to a remote station with voice and video data.
- Contain a communications system to transmit suit telemetry and biomedical data.
- Must be able to accommodate a liquid cooling garment.
- Excellent helmet field of view.

SUIT DESIGN AND DEVELOPMENT

PROJECT AND CONCEPT PHILOSOPHY

As a central feature of the NDSGC planetary suit project, the distribution of work to various institutions of higher education in North Dakota presented both unique opportunities and challenges to the design team at the University of North Dakota. While the design, construction, and testing of the suit was greatly enabled by the diversity of participating institutions, the arrangement presented organizational challenges as well as concept definition constraints. The project's organization focused the design team's attention to a fairly modular and adjustable concept to account for the dispersion of work and the relative inexperience of student team members with pressurized suit mechanics. To simplify the design work, the suit was designed and built for one particular individual. As the project progressed, this arrangement proved to be very beneficial as changes to suit systems could be made without significant ramifications to other suit components. This also facilitated the educational experience of the project by allowing experimentation with various ideas as the project progressed. The high degree of modularity and the early understanding that the suit components would have to be adjustable to a sufficient level upon final suit assembly drove the design team to develop a unique planetary suit demonstrator. Overall, the design team recognized early on some of the following project constraints and enablers:

- Within the bounds of producing a pressurized walking suit, technical objectives were flexible as the organizational and technical challenges became better understood.
- The overriding concern for safety governed all design decisions even if safety considerations compromised initial technical objectives.
- Schedule, budget, and facility limitations necessitated the use of innovative and adaptable component designs. Parallel solutions to some design problems were simultaneously pursued when resources permitted.
- Mechanical interfaces such as seals, connectors, and clamps were sufficient for the demonstration of the suit's concept, but were not designed to meet the needs of a hypothetical future operational suit.
- Material choices were made without specifically considering all planetary environmental factors. Materials were selected on the basis of safety, durability, and cost for the purposes of testing at an analogue site.
- Communication and telemetry architectures were sufficient for test purposes only, but could be better refined in the future.
- Although an enclosed life support system is an integral part of a planetary suit, a separate, stand-alone pressurization and oxygen feed system was sufficient for initial suit testing. A backpack was built to store communication and electrical power equipment with the option of including a LSS at a future date.
- The educational benefits of the project were in direct proportion to the amount of student involvement. Although some components and parts could only be acquired through outsourcing, students were directly involved in integrating these components into a workable suit.
- Space suit development is a highly iterative process. This project was seen as baseline experience for further research in planetary suits. Lessons learned during the course of this project

were recorded in order to improve future suit efforts in North Dakota.

With these basic technical, educational, and programmatic requirements and assumptions, the design team proceeded to consider a range of suit concepts. In addition to investigating current and previous planetary suit concepts, the team simultaneously assessed indigenous capabilities and resources. Based on these reviews, both a hypothetical mechanical counter-pressure suit and full hard suit were deemed impractical for the team to pursue. A suit utilizing either a bladder/restraint-layer approach or a single-wall laminate (SWL) construction was also considered. A SWL suit was deemed to have a prohibitively large number of expensive and complex mechanical interfaces. For the purposes of long-term field research and testing, this type of suit would also have been more difficult to maintain and repair.

Based on these reviews and objectives, a suit concept emerged for a modular, mostly soft suit with very few mechanical interfaces. This suit has the advantage of being constructed with readily available materials, tools, and techniques. This increased the likelihood of creating a test article within the budgetary and schedule constraints. For the purposes of a walking suit, however, this approach introduced significant mobility uncertainties that may affect suit usability and a planned field test campaign. The team recognized that even if such suit concept could hypothetically function well on the Moon or Mars, a requirement of the project is to evaluate the suit in a 1g environment. Despite these concerns, the suit architecture offers significant margins for adjustment during initial suit assembly.

For the purposes of constructing a two-chamber planetary suit, combining both a composite partial hard upper torso with soft goods was judged to have the highest level of modularity and adjustability. The HUT provides a rigid structure on which to mount the neck dam assembly that mitigates helmet distention under pressurization. Because mounting the scye bearings to the hard upper torso results in a fixed geometry, another type of torso was designed to increase geometry flexibility during donning/doffing and initial suit assembly. Instead of mounting the scye bearings directly to the HUT, the bearings are mounted to fabric panels that are in turn mounted to the HUT. In conjunction with proper restraint strap mounting, this mounting method gives more adjustability to the scye bearing geometry after the suit is assembled. Upon establishment of this general suit outline, the team proceeded to simultaneously develop individual suit components.

HUT SIZING AND CONSTRUCTION

Neck Dam Assembly

The neck dam assembly that divides the helmet breathing cavity from the rest of the body is taken from the Russian VKK-6 partial pressure suit. This aperture is designed to receive and lock into place the GSh-6 helmet while the latex dam conforms to the neck, as seen below in Figure 1. For a planetary suit, the use of a two-chamber system potentially allows for a decrease in life support system loads by using a separate gas system for the pressurization of the body and decreasing the effective volume of the breathing cavity. The HUT was sized to incorporate this assembly in the NDX suit. Because of its relatively small diameter, it was recognized early that the neck dam assembly would rub against the back of the test subject's neck while walking. Though this problem is mitigated as much as possible, this type of assembly could be improved and enlarged for future two-chamber research suits. With its simple two-action latch, this assembly also satisfies the mandated requirement of using a quickly removable helmet in the NDX suit.

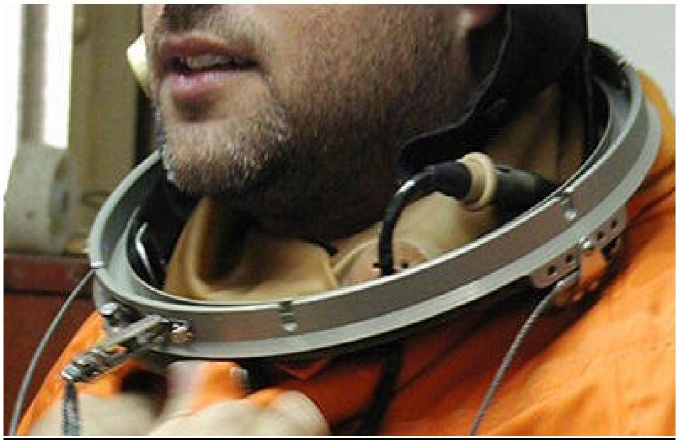

Figure 1: Neck Dam Assembly

HUT Mockup

The design of the HUT began with a series of crude enclosure ring experiments to assess the implications of various cross-sectional shapes on donning/doffing and mobility. It was assumed that the front of the enclosure ring should be at the same vertical position as the test subject's sternum in order to permit bending of the waist. The use of simple mockups led the team away from a circular cross section to a highly modified racetrack shape. Minimization of HUT cross-sectional area not only decreases the pressure elongation force in the torso, but also improves both torso and shoulder mobility. Initially, only flat and tilted single plane enclosure rings were considered. With additional experimentation on a fiberglass splash, a dual plane enclosure ring was designed after the HUT molds were manufactured.

Figure 2 below shows the final mockup of the HUT with a mock helmet. This mockup permitted easy changes to the HUT and neck dam assembly geometry. The addition of simple metal rings representative of scye bearings allowed for further donning/doffing experiments. Plastic sheets were used to represent an initial guess of the HUT skin cutouts. Based on a long series of modifications, this HUT shape was finalized.

Figure 2: HUT/Helmet Mockup and CAD Model

Measurements of the mockup were taken and a three-dimensional computer model of the HUT was drawn using the Pro/Engineer Wildfire computer-aided design (CAD) program. This model can also be seen in Figure 2 above. As the mockup shape represented the interior dimensions of the HUT, the CAD model was drawn to take into account an estimated 3 mm HUT wall thickness. This thickness estimate is based on analysis of expected HUT pressure and applied loads and prior experience with composite sandwich construction techniques.

Plug and Mold Construction

The plug of the HUT was constructed using a sliced foam and template construction technique. Each Formica template was a vertical cross-sectioned slice made from the CAD model and sandwiched with standard pink housing insulation. The foam and Formica segments were sandwiched together on a jig, sanded, and surfaced finished to produce the plug.The plug was made longer than the actual CAD model in order to take into account the potential need for producing additional composite parts below the expected enclosure ring location.

The plug was then prepared with release agents and a two-part gel coat and fiberglass mold was constructed. Although the process is time intensive, the mold was constructed so that multiple identical parts could be manufactured. The early construction of the mold also allowed for further refinement of the HUT.

HUT Splash

Before materials were selected for the final HUT, a fiberglass splashed was manufactured in order to further test donning/doffing, neck dam assembly mounting, and arm bearing geometry. Based on further evaluations of donning and doffing, the shape for a dual plane enclosure ring was cut from the splash. This significantly improved unassisted donning and doffing although it introduced much greater complexity to the design and manufacture of the enclosure ring.

Figure 3 below shows the CAD model of the HUT and helmet after experimentation with the splash. This experimentation resulted in greater cutouts from the HUT to accommodate the scye bearings and improve shoulder mobility. The figure also illustrates how the arm bearings and HUT are attached with fabric panels. Restraint straps from the HUT to the scye bearings (not shown) allow for adjustment of the bearing location and angular position.

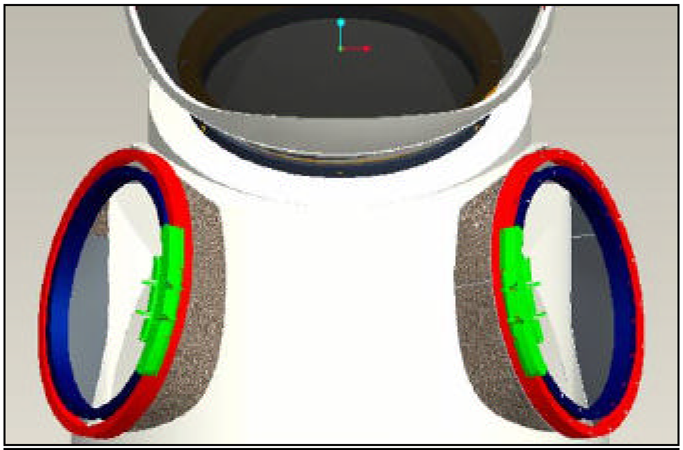

Figure 3: Initial HUT Model with Attached Scye Bearings

Enclosure Ring and Lower Composite Part

Because the HUT molds were constructed before the finalization of the enclosure ring, the switch from a single plane to a dual plane enclosure ring presented additional design challenges. If the ring were milled from a solid block of aluminum, properly mating this to a preexisting HUT introduces significant uncertainties. Even though the ring would be manufactured using the CAD file, the HUT plug is a handmade part that is not an exact physical duplicate of the model. Because of the involvement of multiple institutions in the NDX project, both an aluminum enclosure ring and a composite enclosure ring were pursued. Both approaches have manufacturing and performance tradeoffs that are reflective of the different material properties. The aluminum ring option is much more straightforward, but could not be manufactured within the allotted timeframe. For attachment, the aluminum ring would have been bolted to the HUT and sealed whereas the composite ring could be attached directly to the HUT with epoxy.

As seen in Figure 4, a composite ring was finally manufactured on the existing torso and attached to the lower composite part. The ring protrudes from the HUT approximately 3 mm and is constructed with the same composite sandwich as the torso. This overlap enclosure ring guides the two halves together and provides a surface for the mounting of rudimentary seals. The mounting of seals and latches was sufficient for testing purposes, but requires further refinement to improve durability. Latches that provide sufficient clamping force for the enclosure ring were procured from a commercial vendor and mounted to the torso. The design and manufacturing of the enclosure ring is an area that has taught the NDX team critical lessons that will be applied to future suit designs.

The lower composite part, also seen in the Figure 4, features a flange that extends from the torso and provides a flat surface for the mounting of the lower soft goods. The lower composite part was carefully cut from the hard upper torso, thus minimizing the gap between sealing surfaces. A metal ring of the same cross-sectional shape as the torso was manufactured with two brackets for the attachment of the lower torso restraint straps. The restraint layer and bladder are compressed between the metal ring and composite flange by use metal fasteners.

Figure 4: Dual Plane Enclosure Ring Geometry

HUT Material Selection and Construction

The materials for the HUT were selected on the basis of strength, rigidity, ease of hardware attachment, and mass. Based on an evaluation of expected pressure and applied loads on the HUT, a variety of composite sandwiches were considered. To significantly improve the part's rigidity without substantially increasing mass, a Nomex® honeycomb core material was tested in two different types of carbon fiber sandwich coupons. Because an aluminum enclosure ring may have been bolted to this part, a simple plate shear out test was performed on one of these coupons. On the basis of these tests, the potential aluminum enclosure ring attachment area utilizes a 10-layer sandwich while the rest of the HUT uses a 4 layer sandwich. The honeycomb material is used throughout the HUT. This material lay-up decreases mass and saves material while resulting in rigid and strong part.

Figure 5: Construction of the Final HUT Skins

As can be seen in Figure 5 above, the HUT was manufactured in two halves, cut to size, and joined together inside the mold. Based on the HUT splash tests, the cutout areas were identified in the mold and transferred to the final part. The neck dam assembly is easily mounted to the HUT from the inside of the part. The shoulder soft goods are mounted to the inside of the HUT with use of metal fasteners and aluminum bar segments that conform to the internal HUT shape. A pressure gauge, pressure hose connector, and communications port are mounted through the HUT wall.

HELMET GEOMETRY AND SIZING

Helmet Sizing

The helmet is sized to accommodate the GSh-6 neck ring diameter while providing sufficient volume and field of view. As a helmet for planetary use, it is designed to provide an excellent view of the terrain at the test subject's feet. Commercially available Plexiglas® domes of various diameters were identified early in the project for possible use as helmet plug material. This selection of standard domes greatly simplified the sizing and construction process. Initial wood and wire frame models of the helmet were made at the same time as HUT sizing. Figure 6 below shows the helmet that incorporates the neck ring while utilizing 2 standard-size half domes. The helmet also has sufficient volume to incorporate communications equipment and critical biomedical sensors.

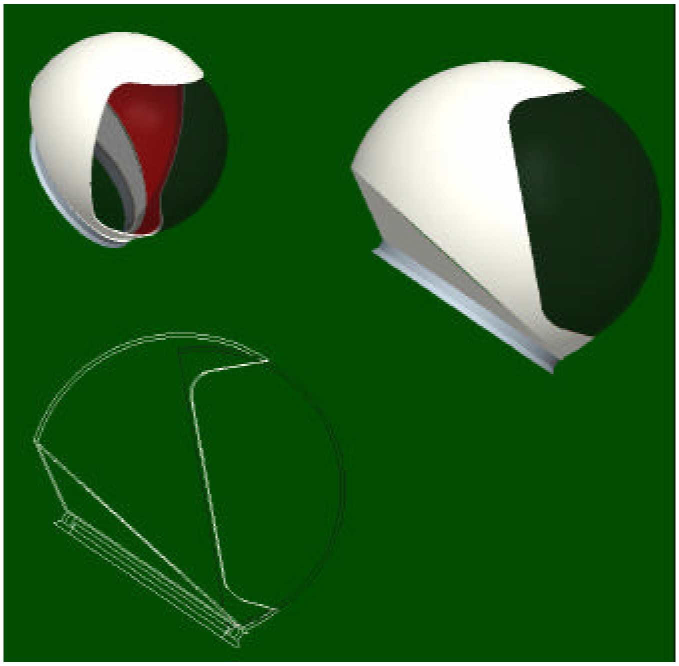

Figure 6: Initial Helmet CAD Model

Helmet Attachment Ring

Because the HUT incorporates the neck dam assembly for the GSh-6 helmet, a steel 6-peg helmet ring very similar to the original Russian model was designed. The design was modified, however, to improve the part's suitability in a planetary suit and ease of attachment to the NDX's composite helmet. Based on a simple load analysis, the material was thickened and a flange was added to the design, as seen in Figure 7 below. The upper flange allows for the attachment of the helmet in way that differs from the original Russian design and improves the hermetic seal of the helmet.

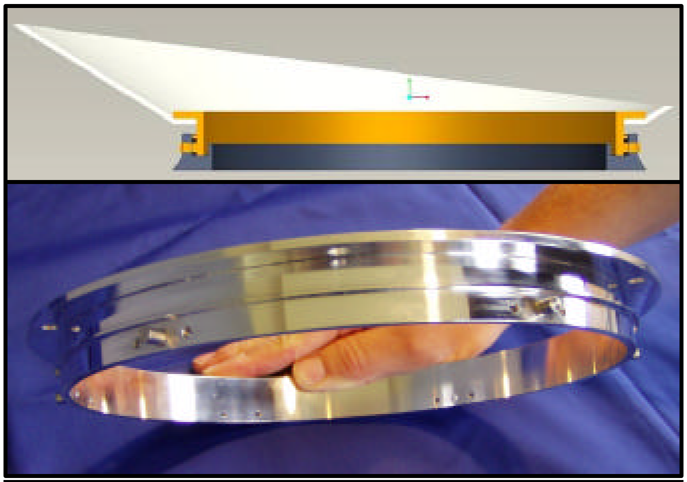

Figure 7: Helmet Attachment Ring CAD Model and Final Part

Construction and Assembly

The construction of the helmet utilized a plug and mold construction technique. The plug was made from a combination of two Plexiglas® domes that were cut and joined in order to fit a shaped foam insert. This foam insert provided the transition from the spherical helmet section to the helmet neck ring. After the plug was surface finished, a two-part fiberglass mold of the helmet was made. An initial fiberglass splash of the helmet was then made in order to finalize the visor cutout geometry. It was also used as a mockup for biomedical sensor mounting. A similar composite sandwich is used on the helmet as the HUT. In the helmet, however, the Nomex® honeycomb core material is used in select locations to improve rigidity in certain areas, such as around the neck ring. Figure 8 below shows the helmet skins after being removed from the molds. The helmet attachment ring is mounted to the helmet shell before the two halves are permanently joined together. The two helmet halves are then joined together by composite strips on the inside and outside of the helmet shell. The visor is a Plexiglas® half dome cut down to fit into a carbon fiber flange on the helmet. The flange is made to join and seal the visor to the helmet shell. Upon integrating these parts, a pressure hose connector was mounted through the helmet wall. Like the design of the enclosure ring, the construction of the helmet has taught the NDX team valuable lessons that will be applied to future suit projects.

Figure 8: Rear View of Uncut Helmet Skins

SCYE BEARING ASSEMBLY

In order to provide shoulder rotation, a commercially available thin-section ring bearing is incorporated into a team-designed housing. The sealed Kaydon® ring bearing has a 203.2 mm bore and is strong enough to withstand expected loading conditions. As seen in Figure 9, the housing is designed so that the restraint and bladder layer (exaggerated thickness) from both the arm and torso is internally attached with a back plate and 20 equally spaced bolts. Twenty threaded holes on the outside of the housing provide mounting locations for the restraint strap brackets. The housing is manufactured out of steel. There are two brackets for the arm side of the housing and two brackets for the HUT side of the housing. The restraint straps are secured with simple bolted clamps as elsewhere in the suit. To ensure pressure integrity, these holes are not drilled all the way through the housing.

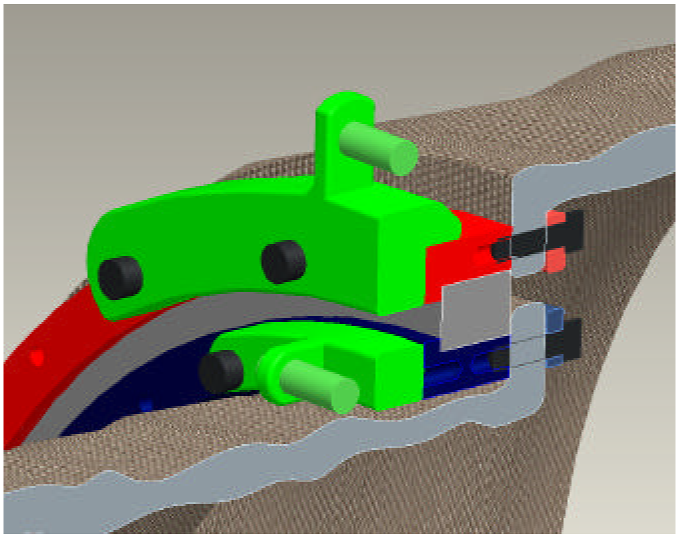

Figure 9: Cutaway View of Scye Bearing Assembly

Unfortunately, the scye bearing housings were not ready in time to be incorporated into the suit by the project's deadline. As seen in Figure 10 below, however, they have been manufactured and will be tested in an existing stand-alone pressurized arm demonstrator. In addition to performance concerns, the housing may have reduced the effective arm bore to a point where donning the suit may not be possible. This reduction in bore will be evaluated in the splash before possibly integrating the bearings into the suit. In any event, the evaluation of this housing will serve as a useful baseline for future planetary suit work.

Figure 10: Machined Scye Bearing Housing

LOWER TORSO SOFT GOODS

The lower torso was designed and manufactured by project consultant Gary L. Harris and consists of five separate sections that are attached together through lacing and restraint straps. Although measurements were taken of the test subject, the fabric goods were designed to be highly adjustable upon final suit integration. The brief section is attached to the lower section of the HUT and connects to the knee joint assembly. Industrial cold weather work boots were modified and attached to the ankle joint assembly. The cardanic ankle joint connects restraint straps leading upward through the knee joint with straps leading downward around the boot. Figure 11 below shows the assembled lower torso.

Figure 11: Lower Torso Soft Goods

A simple asymmetric flat panel convolute joint is used in both the lower and upper torso. Other types of joints were rejected because they are either self-abrading or are too complicated to manufacture. This type of joint is relatively easy to build with sewing machines and is constructed with stitching-redundant features. Additionally, the nylon bands of the convolute joint are glued and stitched into place. Nylon restraint straps were selected on the basis of strength, elongation properties, and availability. Though other textiles were considered, including Cordura® and Gore-Tex®, the restraint layer is a very strong material that is flame and cut resistant. It consists of a blend of 60% para-aramid and 40% polybenzoxazole fibers. One goal of the test campaign is to evaluate the robustness of this material for future intravehicular and extravehicular suit use.

UPPER TORSO SOFT GOODS

The elbow and upper arm joints also utilize the same asymmetric flat panel convolute joint as the lower torso and are constructed from the same restraint layer material. Before actual suit hardware was constructed, a prototype elbow joint with one asymmetric segment was constructed at the University of North Dakota. The joint was pressurized to the suit design pressure of 26.2 kPa and easily manipulated through a wide range of motion. The final arm consists of five convolute segments for the elbow and five similar segments for the upper arm joint. A rigid metal ring is mounted around the circumference of the arm in between the elbow and upper arm joints. Lacing near the glove connector provides some length adjustability. Simple bolted clamps are used to secure the restraint straps. As previously discussed, the arm is bolted onto the scye bearing housing. A fabric flange was sewn into the arm using a mandrel and stressed fabric technique. Being a research suit, there are minor differences between the left and right elbow joints in order to test different variations of the same joint type.

PRESSURE BLADDER

The pressure bladder for the lower and upper torso consists of a latex coated fabric sewn with the same patterns as the restraint layer. Liquid latex is applied to one side of the fabric with either a spray gun or foam brush. Because the bladder is easily removable, any punctures can be repaired during field testing. Alternatively, a used bladder can be swapped for an inexpensive new one.

OUTER GARMENT

After final suit assembly, an outer garment was sewn that covers the restraint layer, mechanical assemblies, and backpack. This garment mitigates the collection of dust on the suit and protects the suit components from abrasive wear during field testing. Beyond this simple protection, the outer garment was not a primary consideration for the project.

GLOVES AND CONNECTORS

Because glove design is a major challenge in pressurized suit design, it was recognized early that the gloves for the NDX suit would be relatively simple. Rubber chemical gloves were retrofitted with a restraint layer to prevent ballooning around the palm, backhand, wrist, and lower forearm. The glove restraint layer is manufactured from a material similar to the suit's restraint layer and features a simple flat panel convolute to permit bending of the wrist. A malleable palm bar is attached with Velcro®.

Each glove is attached to an aluminum connector assembly. The wrist side of the connector has an outer diameter of 101.6 millimeters while the arm side of the connector has an outer diameter of 127.0 millimeters. As seen in Figure 12 below, the wrist connector features twenty tapped holes around the circumference of the diameter transition segment. To prevent leakage, the holes do not puncture the connector's inner wall. The tapped holes are used to mount the four restraint strap brackets per connector. These brackets link the glove and arm restraint straps. The pressure bladder and restraint layers are sealed to the connector using an adjustable circular clamp and a sealant compound.

Figure 12: Glove Connectors with Restraint Straps and Brackets

BACKPACK

The backpack is designed to be lightweight and to partially conform around the HUT in order to stabilize the backpack load. It is sized to accommodate batteries, communications equipment, lights, cameras, and a hypothetical life support system. The backpack is attached with simple nylon straps. The geometry of the backpack also takes into account the projection of the enclosure ring and latches from the HUT. The backpack is constructed using a fiberglass and core material sandwich for improved rigidity. Figure 13 below depicts the suit with the outer garment and backpack attached while the test subject is simulating geology field activities.

Figure 13: Suit with Outer Garment and Backpack in Field Testing

ELECTRONIC SYSTEMS

Biomedical Sensors and Voice Communication

A critical project goal is the accurate collection and transmission of physiological data during all phases of suit testing. A suite of biomedical information is collected in the suit and helmet, wirelessly transmitted to the backpack, and then transmitted to the test base station. The following list describes the biomedical sensor, sensor quantity, information collected, and the location of the sensor in the NDX suit.

- AccuHeart ECG (1)
  This is the heart rate sensor that is attached to a chest strap worn by the test subject. It is normally used by for patients needing constant heart rate monitoring.
- MLT1132 Piezo Respiration Belt Transducer (1)
  This is the respiration sensor on the chest strap.
- 225-050Y Relative Humidity and Temperature Sensor (2)
  This is the sensor that monitors humidity and temperature in the air. One is located inside the helmet and another inside the suit.
- TGS 4151 Carbon Dioxide Sensor (2)
  This is the sensor that monitors the carbon dioxide levels. Two sensors are located in the helmet for redundancy.
- KE-25 Oxygen Sensor (2)
  This is the sensor that monitors oxygen levels. Two sensors are located in the helmet for redundancy.
- DS60 Analog Temperature Sensor (2)

This is the sensor that monitors the test subject's body temperature. These sensors are located on the chest strap worn.

A WRAP Access Server™ from BlueGiga Technologies is located in the backpack and receives and stores sensor data from the Bluetooth® modules that are located next to the sensors. The use of Bluetooth® permits multiple suits to be tested simultaneously without risking sensor interference. A schematic of the biomedical sensor suite is shown in Figures 14 and 14 below.

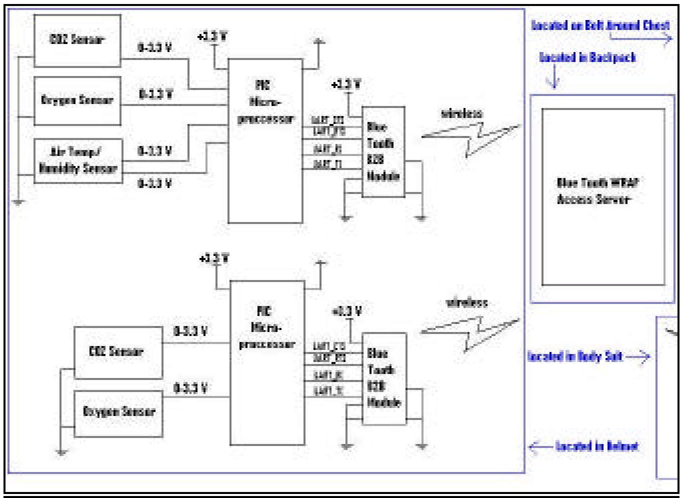

Figure 14: Helmet Biomedical Sensors

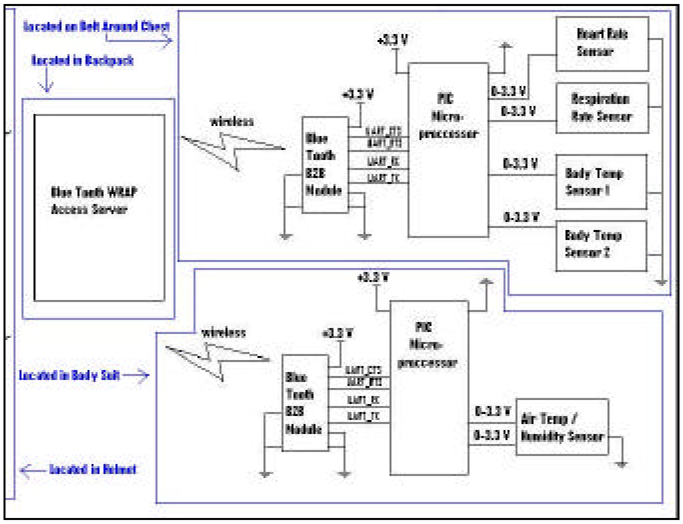

Figure 15: Suit and Chest Strap Biomedical Sensors

Verbal communication from the test subject was provided by a wireless radio connected through the HUT. It was activated by a push-button control located on the wrist. A snoppy cap was built that incorporates both headphones and a microphone. Multiple observers are able to communicate to the test subject via radio.

FUTURE TESTING AND EVALUATION

Laboratory Testing

After the NDX suit was assembled, it was initially only pressurized unmanned to approximately 7 kPa differential. Because of safety concerns, the suit is never pressurized to more than this value with the test subject inside. To accomplish this low pressure, gas is allowed to escape the suit through the helmet connection assembly. However, the suit will be subjected to rigorous laboratory testing to verify the design and construction. The fabric, composite, and metal components will be tested unmanned by over pressurizing the suit to three times the design pressure. A previously manufactured arm will be subjected to increasing pressure until it bursts. The integrity of the suit's seals and locking mechanisms will also be thoroughly tested over a number of pressurization/depressurization cycles. Additionally, mechanical forces will be applied to the pressurized suit to simulate expected man-loading conditions. The suit's biomedical sensors were tested and measurements evaluated before the test subject was allowed to use the suit pressurized. The torque and range of motion of each joint will be tested, recorded, and compared to other fabric suits. The overall suit leak rate will also be assessed.

Field Testing

A week-long testing campaign in the Badlands of North Dakota was conducted in the first week of May, 2006. This site, as seen in Figure 16, is located just east of Theodore Roosevelt National Park and contains numerous geological features representative of a Martian site of potential scientific interest. The test campaign simulated probable Martian EVA science and construction activities while providing a unique opportunity to evaluate the suit in an outdoor setting. The test subject followed a test plan of increasing difficulty, culminating in the operation of an all-terrain vehicle, all the while remaining under constant monitoring. At the end of the field testing week, the suit was placed into a team-designed Martian dust simulation chamber to study the accumulation of dust on suit components. Although only conducted at low pressure, the lessons learned during this test campaign will be applied to future suit designs. To name a few, such lessons include donning/doffing techniques, pressure bladder improvements, helmet fogging mitigation, suit cooling and comfort, communications improvements, and test campaign planning and logistics.

Figure 16: Suit testing in the Badlands

CONCLUSION

The North Dakota Space Grant Consortium has developed a planetary suit concept demonstrator while simultaneously providing a unique educational experience to undergraduate and graduate students in the state. Manufactured with relatively inexpensive materials and techniques, the project demonstrates the useful pressure suit technology research can be conducted across a multi-institutional cooperative framework. Though the suit constructed has not demonstrated all of the initial design goals, research is continuing in order to make significant improvements to the baseline suit. Based on the test of results of the NDX, this project will serve as a starting point for future planetary research within the state of North Dakota.

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Additional information on the NDSGC planetary suit project can be found at: http://human.space.edu