Development of Rapidly Deployable Structures for Military Applications:
A System Based Approach to Command Post Facilities

by

Jakob A Hopping

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Abstract

Today's battlespace is the most dynamic in recorded history. Accompanying other military improvements, Command and Control (C2) technology has also been modernized. In spite of advances in technology, it currently takes six times as long to deploy a Command Post (CP) as it did eight years ago. This decline in performance results in poor communication with forward units due to an increased distance between the units and the CP. This performance decline also increases the danger posed to command centers by enemy elements in the rear.

Although each component of a modern CP functions well, CP structures are slow to deploy because many of the components of the command structure are developed separately to fulfill specific functions. Separately, these components are quick and innovative. Combined, they are cumbersome and labor intensive to assemble. The command structure must be viewed as a system that requires an encompassing solution. This thesis presents a rapidly deployable CP structure developed using a system based approach. The functional elements of a Command Post were analyzed and a comprehensive structure was designed to enhance the speed of CP establishment. Also, the appropriate background theory for structural and safety analysis was developed and applied to the resulting design.

The proposed design, termed the Automated Command Post (ACP), is capable of establishing Command and Control in a mere fifteen minutes from start to finish; this is a 92% improvement over existing CP structures. In order to maximize the potential usefulness of the physical space within the ACP, the recommended ACP layout was constructed by modifying existing command post layouts using network theory. The ACP is an air-supported structure that requires a nominal pressure of only 0.036 psi to withstand up to 75 mph winds. Also, the ACP inflation system has an estimated fuel cost of only ½ a gallon per day to maintain this pressure.

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Biographical Note

Jakob A Hopping is a candidate for a Bachelor of Science in Mechanical Engineering with a focus in Entrepreneurial Management and a Minor in Political Science at MIT. Jakob's work experience includes over eight years with the United States Marine Corps Reserve, two years as a personal trainer and health fitness instructor, and many years in grass-based dairy farm management.

While serving in the Marine Corps Reserve, Jakob was activated in support of Operation Enduring Freedom from December 2001 – December 2002. He started his Marine Corps career in1998 as an Infantry Rifleman before becoming a Ground Operations Specialist in 2004, and then later becoming an Intelligence Specialist in 2005. Jakob has worked with a regimental sized Combat Operations Center (COC) for seven years. During these seven years, Jakob has seen COC technology change from paper maps and thumbtacks to digitized media displays and network communications. Additionally, he has personally used many of the Command Post (CP) systems that were used and are currently being used by the Marine Corps.

Acknowledgements

I would like to thank Dave Custer for his invaluable input during the early stages of this thesis, and Cam Brensinger for providing hope that the desired functionality of the Automated Command Post could be accomplished. Also, this thesis would not be complete without the help of my two thesis advisors Zhong You and John Ochsendorf who provided guidance and asked more questions than I can answer. Lastly, I thank my wife, Amy, for being so supportive through the long nights of work and my son, Kaleb, for trying to understand why Papa had to spend so much time in the library room.

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1.0 Introduction

Current military Command Post (CP) structures do not adequately meet the requirements imposed by an increasingly dynamic battlefield. Battlefield maneuver occurs at a faster pace than ever before in history, and this faster advance is accompanied by a porous battle edge. Many antagonistic elements are deliberately bypassed by a porous front push and left behind the main maneuvering attack elements. This leaves certain enemy units and groups intact and behind the main advance with the capability of a rear based strike on Command and Control (C2) facilities.

The fast pace of the battlefield and the existence of enemy contingents to the rear of the main advance pressure Combat Operations Centers (COCs) to be capable of rapid deployment and redeployment. As the time required to establish a COC goes up, the distance over which communications with forward units occurs also increases. Increased distances stretch the limits of current communications capabilities and place forward elements which need Fire Support Control (FSC) and commanding guidance from the COC at a higher risk of communications failure. The inability of a COC to redeploy also increases the hazards posed to it by rear enemy elements. The longer it takes to dismantle a COC and transport it to another location the greater potential exist for damage to be inflicted on C2 capabilities by rear operating enemy elements.

The CP facilities in use currently are sluggish and require a large amount of time to deploy and redeploy. This cumbersome and labor intensive nature of the command structures today does not meet the functional requirements imposed upon it by the elements of fast-paced maneuver and enemy contingent forces operating behind the Forward Edge of the Battle Area (FEBA).

The purpose of this thesis is to develop an Automated Command Post (ACP) which provides a deployable system tailored specifically to the needs of tactical military command. This thesis focuses on identifying the reason current deployable structures are inadequate, and then takes advantage of the author's extensive CP experience in designing a comprehensive solution which enhances all aspects of COC operation.

The ACP is tailored specifically to meet the identified system requirements of military tactical command centers. This thesis takes a global approach in the tailoring process. First, some historical deployable structures are introduced. Then the problem addressed by this thesis is firmly articulated. Next, the overall background of tent-like structures, with a special focus on those currently used in the military today, is developed. After the background, the methods of design are discussed and then followed by a development of the background theory necessary to properly analyze the suggested ACP design. Once the background theory has been developed, the design itself is described element by element with each decision explained. Areas not fully explored by this thesis and suggestions for further research are then discussed after the design is fully explained, and, finally, the end design is summarized in a concluding section.

1.1a Problem Statement Historical Background

Historically, many societies have developed and used simple, mobile structures with multi-use characteristics and quick assembly. These structures range from the large and intricate nomadic pavilions of early Arab societies in the African desert to the small and efficient design used by the Mongols – the Yurt. Overall, most of these structures are tent-like and serve the purpose of housing people or goods in a variety of situations. The Mongols used the Yurt for housing people and goods when invading territory. Similarly, the Native American plains tribes used a Teepee when migrating to different hunting and crop growing grounds.

Much like the societies of old, today's military has many uses for rapid deployment structures. Common applications of such structures range from the housing of military personnel and equipment to providing locations that facilitate military C2. Current military tactics require that C2 centers use complex computer aids located in large tents that are numerous and collocated with each other. This configuration of tents and equipment is called a Combat Operations Center (COC). Although current COC tents are easier and faster to set up than permanent structures of the same size, they are cumbersome and difficult to use. Some COC configurations use so many tents that they are jokingly referred to as "tent cities" (see figure 1). This is problematic. As the number of tents and equipment utilized increases, the time required to establish the structures also increases.

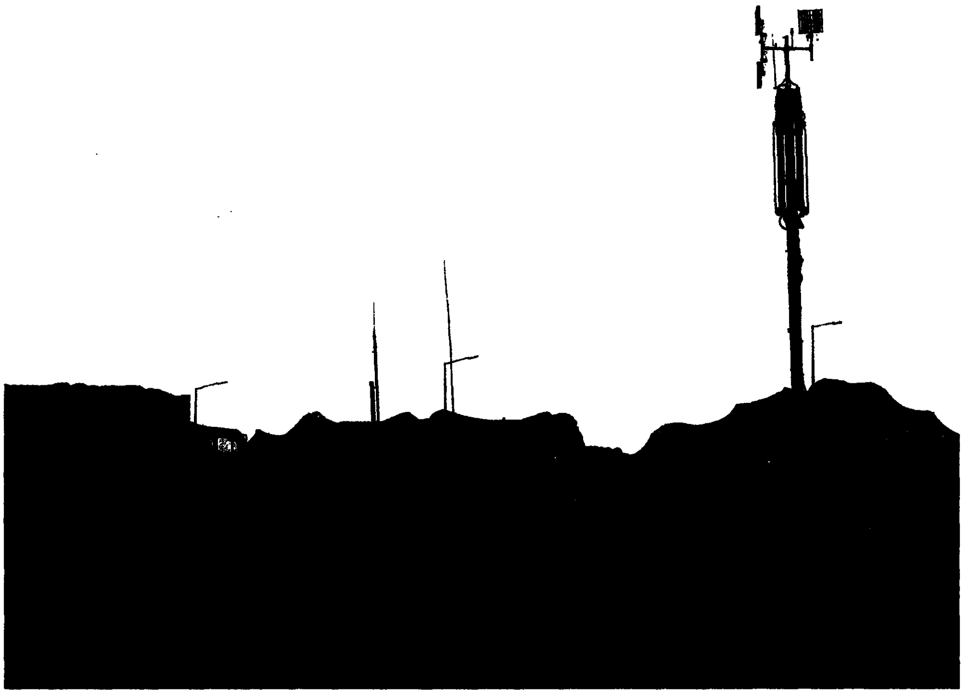

Figure 1: "Tent-City" composed of a NATO Command and Control (C2) facility with many connected and collocated tents. Notice the camouflage netting over the exterior of the structures.[1]

Time is the single most important factor in setting up command structures. Increased infantry mobility through the use of Infantry Fighting Vehicles (IFVs) and the employment of indirect contact tactics has resulted in a front line which moves faster than ever before in history. Indirect contact tactics are methods of avoiding long engagements with the main enemy force in an established defense. Rather than engaging the bulk of the enemy directly, infantrymen use the speed of IFVs to punch through the enemy location and establish a credible threat to the rear of the opponent's location.

Because the majority of tactical radios transmit over relatively short distances, 10-50 kilometers, fast approach warfare tactics decrease the amount of time that command centers can communicate with the forward elements under their command without the

[1] AFSOUTH, Images (2003 September 02). Photos of NATO Support to Turkey. May 1 2006, NATO OTAN: <http://www.afsouth.nato.int/operations/NATOTurkey/photos%20patriots/DSC00603.jpg>

establishment of radio relay and retransmission sites. Because of this, it is vital for a CP to be capable of setting up with minimal manpower and time.

1.1 Problem Statement

The United States military, in particular the United States Marine Corps, has a demonstrated need for a rapidly deployable, tactical, command structure system. The functional requirements of this system are:

1) The system must be transportable via existing military vehicles with overall dimensions that do not exceed the capacity of existing trailers and other towed equipment.
2) The system set-up time must be 30 minutes or less (time begins at the initiation of equipment unload and ends when the facility can assume command of the battlefield).
3) The system must provide environmental control that will protect computing systems from detrimental heat, cold, and humidity.
4) The system must have enough space to facilitate coordination of information and intelligence among work groups.
5) The structure must minimize infrared emissions and be compatible with existing camouflaging techniques.

This thesis outlines the main categories of current tent structures and explains the specific requirements of a CP in more detail. Current CP structures are examined according to satisfaction of the above identified functional requirements. Proposed improvements are developed, and the ACP is then designed specifically to meet the developed requirements. Finally, an analysis of the improved design, the ACP, is made.

2.0 Existing Tent Structures and Methods of Design

The background of rapid deployment structural designs is presented here; then closely followed by a more detailed explanation of the military need. A critique of the existing military command structures then follows, and, lastly, the methods of ACP design are presented.

2.01 Current Rapid Deployment Structural Designs

Older tent structures tend to be of a pole and fabric design. In these structures, poles provide the structural integrity of the tent, and fabric provides protection from environmental factors such as: wind, rain, and sun. Examples of such older structures are the Yurt and the Teepee. Similar mechanical designs are used more today such as the Scott tent. Some tent designs that are not as old as the Yurt and Teepee have made use of the tent fabric as a structural member in tension. The lower density of structural poles needed for support, provides structural stability at lower weight. Examples of such designs are the Civil War four-man tent, the Army General Purpose (GP) tent, and many of the tents provided by recreational companies for large outdoor events. More recently, tents that utilize pressure inside a completely sealed fabric for structural support have been developed. The pressure gradient between the atmospheric pressure and the inside structure pressure creates a net pressure and resultant upward force on the tent. Examples of such structures are sports facility "bubbles" and carnival "fun tents." Other modern tents use pressurized air beams for structural support. In those designs the air beams perform a mechanical function similar to the poles in a pole supported tent. Examples of such tents are tents made with NEMO's air supported technology.[2]

2.01a Pole Supported Tents

Both the Yurt and the Teepee use a wooden frame for structural support with a fabric covering for wind and weather proofing (see figure 2). The Yurt is a structure that when formed it resembles a traditional building. It has a great weight to occupancy ratio of

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[2] "Air Supported Technology." NEMO Equipment. 14 Dec. 2005 <http://www.nemoequipment.com/products_tech_inflatable.asp>.

about 50 Kg per occupant. However, the Yurt lacks the flexibility of deployment enjoyed by the Teepee. A Teepee is easier to transport than the Yurt and is more tent-like in function. The Teepee is unique among tent-like structures. In addition to its mobility and weather resistance, the Teepee has a ventilation capability that allows a fire inside of the tent. The structural design of the Teepee influenced many modern pole structures. One such structure is the well known Scott tent. The Scott tent, pictured in figure 3,

Figure 2: Mongolian Yurt (left) and American Teepee (right). The Yurt can be easily carried by livestock and weighs about 250 Kg making it about 50 Kg per occupant. The American Teepee has a similar weight ratio and transportability. Additionally, the Teepee is a more traditional tent design with unique ventilation capabilities.[3,4,5]

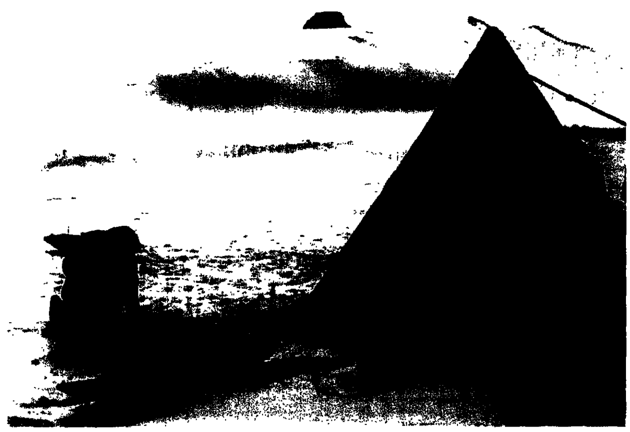

Figure 3: The Antarctic expeditionary Scott tent. This shelter uses hollow aluminum poles and provides excellent shelter at a minimal weight.[6]

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[3] Yurt Living. 16 Dec. 2005 <www.yurtliving.com/>.

[4] "School Reports: South Dakota Fact and Information." *Kids' Page*. South Dakota Govenor's Office. 16 Dec. 2005 <http://www.state.sd.us/governor/Main/kids/SR.htm>.

[5] Melin, Nicholas O'Brien. "Application of Bennett Mechanisms to Long-Span Shelters." *P.hD Thesis: Magdalen College - Univeristy of Oxford.* Trinity Term 2004.

[6] "TIGER in Antrartica." *Trans-Iron Galactic Element Recorder*. 13 Nov. 2001. NASA. 16 Dec. 2005 <http://tiger.gsfc.nasa.gov/tiger_11_13.html>.

was designed by Captain Robert Scott for use in the Antarctic. The Scott tent was one of the first modern deployable tents, and it utilizes lightweight aluminum poles for structural support. It is clear that the structural design of the Scott tent has many similarities to the Native American Teepee.

2.01b Tensioned Fabric Tents

The Civil war four man tent living quarters is an early example of a tent that utilized tensioned fabric for structural support. One of the benefits of this type of design is its scalability. The four man tent used during the Civil War is a small scale version of the General Purpose (GP) tent commonly used by the military today, see figure 4. The only limit in the scaling of a tensioned fabric structure is the weight of the fabric itself. Advances in fabric strength per weight result in an increase in the size of tent that can be made with tensioned fabric. Many tents provided by recreational companies for outdoor events are tensioned fabric tents similar in design to the Civil War four man tent living quarters and the GP tent.

Figure 4: The Civil War tent used to house four fighting men (left), and the General Purpose (GP) tent used currently for many military applications (right). Modern outdoor party tents are of a similar design to these two tents as well.[7,8]

2.01c Air Bubble Tents

Air bubble tents are air supported structures that utilize a pressure difference between atmospheric pressure and that created inside a fabric bubble by a blower system for

[7] "William Britain Civil War Tent." *Collectable Toys Online*. Trinkets to Treasures. 16 Dec. 2005 <http://www.trinketstotreasures.com/wb71.htm>.
[8] "Tents & Supplies." California Army Navy Surplus. 16 Dec. 2005 <http://www.calarmy.com/tents/>.

structural stability (figure 5). Because there is no internal frame, the shape of the fabric and the stresses caused by the internal pressure defines the overall shape of the erected structure. This type of system is commonly used to create rather large structures for a relatively low cost. Because of this air bubble tents are often used to create large outdoor athletic facilities such as covered tennis courts or swimming pools at a relatively low cost.

2.01d Air Beam Tents

The most recent innovation in tent structural design is the implementation of an air beam for structural support (see figure 5). Air beams provide a great degree of transport flexibility as well as a reduction in weight from metallic frames. The general structural concepts of an air beam tent are similar to a pole supported structure; however, due to the complete freedom of movement during the setup process a there is great flexibility in designing the packaging and shape of these structures.

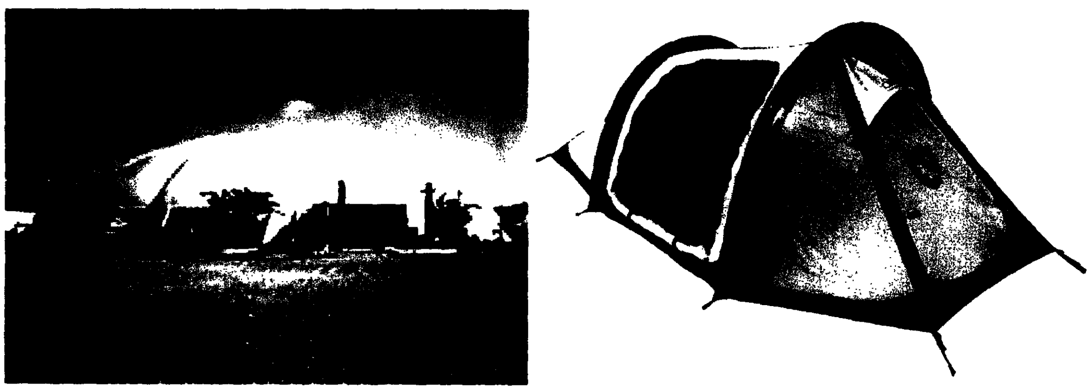

Figure 5: Air bubble tennis facility (left) and the air beam supported Sako from NEMO Equipment (right). The flexibility in shape and design of air supported structures cannot be matched by traditional frame or tensioned fabric structures.[9,10]

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[9] "Air Supported Structures." *Architectural Fabrics. Shelter-Rite.* 16 Dec. 2005 <http://www.architecturalfabrics.com/airsupported.html>.

[10] "Tent Features." NEMO Equipment. 16 Dec. 2005 <http://www.nemoequipment.com/products_tents.asp>.

2.02 Demonstrated Military Need

Military command centers need to be capable of displacing (from one location to another) and setting up quickly. Easy deployment is necessary in order to maintain communication with forward units, escape enemy counterassaults to the rear of the forward line, and provide the commander with the use of high tech intelligence multi-media, unit tracking programs, and the Common Operational Picture (COP). The resources provided by the command center are vital components to the tactical decision making process; however, these components are of little use if the structure that houses them is incapable of keeping up with the operational tempo of today's fast paced battlefield.

Tactical C2 in today's battlefield takes advantage of a plethora of high-tech audio and visual media tools which aid in conveying information to the tactical commander. Without this information, appropriate decisions cannot be made in the timely manner necessary for saving lives and accomplishing assigned missions. In spite of the advancements in information handling technology, the structures, designed to provide an environment conductive to information coordination, have become increasingly difficult to set-up, disassemble, transport, and re-locate. This cumbersomeness is due to the increased size of camouflage netting utilized, the greater complexity of tent mechanics, and the large wiring infrastructure that must be created each time the command facility is set-up.

Set-up times for a regimental sized command structure have gone from thirty minutes (starting of equipment offload to operational time) eight years ago to three or more hours today. This time increase is accentuated by the increased speed at which the battlefield front moves with modern US warfighting tactics. Fast moving front line forces quickly reach the limit of their ground based communications. The communications equipment currently employed has a line of sight range of 10-50 km prior to emplacement of relay and retransmission sites. This short range can place great strain on a tactical command center's ability to control the battlefield if set-up times are in excess of an hour.

Additionally, the adoption of a porous front line in current tactics makes the chance of a hostile encounter with a small but completely intact enemy unit more likely than it was in World War I and II. During World War I and II, a more marked and impermeable forward battle edge was the preferred tactic, and engagements with intact enemy units to the rear of the battle front were rare. During the Iraq offensive, many completely intact enemy units were purposefully passed by the forward edge of troops in order to secure key positions beyond certain Iraqi troop holdings. Although this did not result in many attacks on CPs left open in the rear, CPs were undamaged because the Iraqi units lacked the discipline to carry out operations without communications from higher headquarters. Thus, these Iraqi units which were left unscathed by the main thrust of coalition forces disbanded rather than utilizing their advantageous rear position to attack. In future conflicts, this favorable lack of unit discipline and cohesiveness in enemy troops should not be assumed nor anticipated. Tactical command centers must be prepared to not only provide the security necessary for such possible threats but to also relocate rapidly to more secure locations while maintaining command of the battle space to which they are assigned.

The main reason command structures today require so much time to set up is that each component used in the command post is designed separately with little thought as to how long it might take to create a complete CP. In particular, little has been done to combine the internal wiring, CP tent, and external camouflage netting – the three most time consuming components of the setup process. In the review of current command structures, the critique most often levied is this lack of compatibility with the required uses of the tents which results in slower deployment times.

2.03 Current Military Command Structures

Some military command post tent structures currently used are similar in design to those used during the Civil War. Civil War field command tents used a canvas fabric suspended in tension between wood poles and guy-wires staked into the ground. Today the commonly used General Purpose (GP) Tent in use by the US military is of a similar design. Other tents, such as the Modular Command Post Tent (MCP), use a modular aluminum frame for structural support. The fabric in these soft-walled tents is usually made of polyester and it plays no part in structural stability.[11] However, the design of these tents is similar to the design of the Mongolian Yurt. Other than fabric and material advancements, not much has changed in the design of many of the CP tents used today.

2.03a Deployable Rapid Assembly Shelter (DRASH)

The DRASH tent is commonly used by the Marine Corps for C2. A few years ago it was the preferred tent and it was difficult to receive funding approval from Headquarters Marine Corps for a different tent system. A pole supported frame tent structure, the DRASH tent folds and unfolds in a spider-like manner for setup and takedown. Figure 6 shows this spider-like action. The DRASH tent is a complex design that is prone to inadvertent stresses during the deployment and re-deployment phases. These unintentional stresses will, over time, result in plastic deformation of the scissor-like structural support members. These deformations eventually cause a blockage during tent deployment which results in an overloading of the deformed support and subsequent fracture. Replacing the broken support can take an hour or longer which makes repair of this tent a liability. In addition to this shortcoming, the DRASH tent does not incorporate other system requirements such as camouflage netting, power wiring, and intranet wiring necessary to a functional CP. Installing each of these other items separately increases the setup time when using the DRASH system regardless of how fast the actual tent can be set-up.

Figure 6: Spider-like folding and unfolding process for deployment of the DRASH command tent system.[12]

[11] "Modular Command Post Tent (MCP)." Outdoor Venture Corportation. 14 Dec. 2005 <http://www.outdoorventure.com/tent_systems/mcp.html>.
[12] DRASH - Total Solution Provider. 16 Dec. 2005 <http://www.drash.com/>.

2.03b Base-X

Like the DRASH system, the Base-X is a spider-like folding and unfolding pole supported design. Figure 7 schematically shows the process by which the Base-X tent is deployed, and figure 8 shows an example command post setup with several Base-X tent structures arranged in a modular configuration.

Figure 7: The sequential unfolding and setup process for the Base-X tent.[13]

The Base-X tent is much like the DRASH tent in design and the shortcomings are similar. Repair is a lengthy process, and breakage can be easily caused by accidental stresses during the deployment phase. The tent system does not integrate enough of the components commonly used within the tent to effectively reduce the time for setup even if the tent setup time is minimal.

Figure 8: Base-X command post configuration with attached environmental control elements (left). Modular Command Post (MCP) tents configured in a typical setup with attached support vehicles (right).[14,15]

[13] "Expedition Shelters." Base-X. 16 Dec. 2005 <http://www.base-x.com/military/index.html>.
[14] "Command and Control." Base-X. 16 Dec. 2005 <http://www.base-x.com/military/command.html>.
[15] "Modular Command Post Tent (MCP)." Outdoor Venture Corportation. 14 Dec. 2005 <http://www.outdoorventure.com/tent_systems/mcp.html>.

2.03c Modular Command Post (MCP)

The MCP is an older, conservative CP design. An example of a COC setup using the Modular Command Post is portrayed in figure 8. Although the MCP does not incorporate any system features such as climate control like the Base-X or DRASH designs, it has a relatively lightweight packed configuration and takes up minimal space. Its simplicity makes it the most robust design currently used as a Command Post structure, and it requires the fewest people to set-up. In spite of these advantages, the Modular Command Post still has moving joints that are prone to failure. The MCP also has very long setup times due to the lack of integration with other vital aspects to a CP setup such as: power, heating & cooling, intranet, and camouflage netting.

2.04 Methods of Design

The Automated Command Post has several distinctive parts to its design process. The first part articulated is the simple mechanical theory to explain the behavior of the planned design. This background theory is developed in the next section and formulas listed there are utilized through this thesis for desired calculations. Following the theoretical model is a short record of the actual decision process with each of the individual elements and the decisions involved in the element design process described in detail. As each piece and consideration of the design is portrayed, the appropriate theoretical analysis is also used. The organizational nature of the structure is examined, and the architectural properties are closely modeled. The modeled architectural properties are specifically engineered to enhance the ability of the structure to meet the coordination and information flow requirements of a Command Post. Following the description of the Automated Command Post components is a discussion of the portions of the analysis which are not fully explored and suggestions for further improvements are made. Finally, conclusions regarding the Automated Command Post and the final product as described via individual components are given.

2.04a Interviews

As the design process unfolded, informal and formal interviews with potential users and with peers were used to help guide the design process. Many of these interviews resulted in rapid progress and change in the design of the ACP. The results from these interviews have been vital to furthering this research, and each person positively contributed to the project as a whole.

2.04b Model Building

A scale model of the proposed ACP was constructed to aid in visualization of the mechanisms employed and to gain an intuitive feel for the air supported mechanics in general. This understanding was coupled with mechanics modeling and theory building to aid in providing for the safe engineering of the structure. All the appropriate precautions for fire, rupture, doorway fault, proper anchorage, and local buckling were taken in the final product.

2.04c Research

Many mechanical concepts and difficulties presented in the design of the Automated Command Post (ACP) are explored in detail by existing publications. Research into such published details served to form a library of knowledge that proved useful when designing the ACP. The publications used range from academic tomes to theses on large scale deployable structures. These publications are used throughout the following sections to aid in the application of certain principles to the design of the Automated Command Post. In the following pages, the results of the above described methods are explained with the background theory, design, discussion, and conclusion.

3.0 Background Theory

The Automated Command Post has many functional mechanical elements which require theoretical formulas modeling their behavior in order to effectively design each element. Not every design element is modeled in this background theory section; however, many of them are modeled. The main elements which are examined in detail are: the fabric stresses, the leakage rate of the air within the tent at optimal pressure, the subsequent energy cost of structural support, the force loading and buckling mode of the camouflage netting supports, the infrared radiation emissions from the structure, and the necessary anchoring force. The background formulas for each of these main components of analysis are presented here; however, the application of each model to the ACP is presented with calculations in the design section of this thesis.

3.01 Fabric Stress

The fabric stresses can come from four sources: internal air pressure, self-weight, snow loading, and wind loading. Rain loading is also possible; however, this can be approximated as an increase in self-weight in all but the most extreme of cases. Each of these cases is outlined below with a theoretical model presented for the case in question.

3.01a Internal Air Pressure

The general stress formula for revolved air supported thin shells presented below closely follows the derivation of Douglas Wright of the University of Western Australia, Department of Mechanical and Materials Engineering.[16] First, the desired shape is rotated about the upright axis thereby forming a thin shell of uniform thickness (t) and then stresses resulting from an internal pressure (p) are modeled. This rotated axisymetrical shape is shown in figure 9. If we consider an element located at the point A (defined by φ, $\delta\varphi$, $\delta\theta$) in the meridian (r-z) plane (shown in figure 9), then the components of the pressure and stress in the direction of the outward normal due to the

[16] Wright, Douglas. Thin Shells of Revolution - Heads. May 01 2005, Notes on Design and Analysis of Machine Elements: <http://www.mech.uwa.edu.au/DANotes/pressVessels/shells/shells.html>

internal gauge pressure p and the meridional stress (σ_φ) and circumferential stress (σ_θ) are:

pressure: $p\cdot\delta A = p(r\cdot\delta\theta)\cdot r_\phi\cdot\delta\phi$, (1)

meridional stress: $-2\cdot\sigma_\phi\cdot(t\cdot r\cdot\delta\theta)\cdot\sin\left(\frac{\delta\phi}{2}\right)$, and (2)

circumferential stress: $-2\cdot\sigma_\theta\cdot(t\cdot r_\phi\cdot\delta\phi)\cdot\sin\left(\frac{\delta\theta}{2\cdot\sin(\phi)}\right)$. (3)

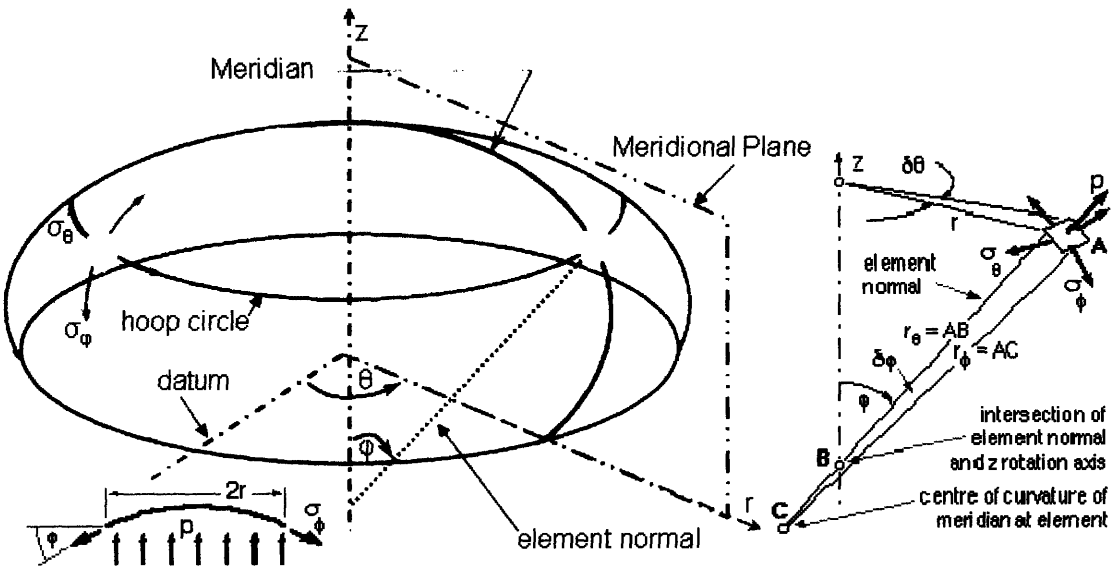

Figure 9: The conceptual rotation of the meridian about the z-axis (upper left). The rightmost figure shows the element at point A where the local surface normal cuts the z-axis at the point B, and AB is defined as the radius r_θ. The center of curvature lies at C on the normal, and AC is the instantaneous radius of curvature of the meridian r_φ. The bottom left figure shows the vertical equilibrium in the dished area above the hoop circle.[17]

If we note that $r = r_\theta \cdot \sin(\varphi)$ and take the limits while holding the element δA in equilibrium, we arrive at the membrane equation:

$$\frac{\sigma_\phi}{r_\phi} + \frac{\sigma_\theta}{r_\theta} := \frac{p}{t} \; ; \tag{4}$$

and considering the equilibrium in the dish area above the hoop circle shown in figure 9 we can show that:

$$\pi\cdot r^2\cdot p = 2\cdot\pi\cdot r\cdot t\cdot\sigma_\phi\cdot\sin(\phi)\,. \tag{5}$$

[17] Wright, Douglas. Thin Shells of Revolution - Heads. May 01 2005, Notes on Design and Analysis of Machine Elements: <http://www.mech.uwa.edu.au/DANotes/pressVessels/shells/shells.html>

Combining equations 4 and 5 we can express the membrane stress components in terms of the rotated geometry, r_θ and r_φ:

for meridional stress $\sigma_\phi = \left(\frac{p}{2 \cdot t}\right) \cdot r_\theta$, (6)

and for circumferential stress $\sigma_\theta = \sigma_\phi \cdot \left(2 - \frac{r_\theta}{r_\phi}\right)$. (7)

The automated command post is composed of an elliptical end cap combined with a cylindrical bottom element. Thus, the solutions to the stress equations 6 and 7 as well as the ones derived below for self-weight, snow, and wind loading that we are concerned with are those that apply to the particular geometry of a cylinder and an ellipsoid. In the case of the cylinder:

$r_\theta = \frac{D}{2}$ and $r_\phi \rightarrow \infty$. (8)

Plugging into equations 6 and 7 for the meridional and circumferential stress in the cylindrical portion the following is obtained:

$\sigma_\theta = p \cdot \frac{D}{2 \cdot t}$ and (9)

$\sigma_\phi = \frac{\sigma_\theta}{2}$. (10)

In the case of the ellipsoid, an ellipse of semi-major and semi-minor axes a, b, is formed with an eccentricity defined as follows:

$\varepsilon = \sqrt{1 - \left(\frac{b}{a}\right)^2}$. (11)

Then, defining u to be a function of r such that: u = f(r) we find that, for the ellipse, u is the following:

$u = \sqrt{1 - \varepsilon^2 \cdot \left(\frac{r}{a}\right)^2}$ where $\frac{b}{a} \le u \le 1$. (12)

Plugging into equations 6 and 7 we obtain the following stress relationships for the ellipsoid top portion of the ACP:

$r_\phi = \left(\frac{a^2}{b}\right) \cdot u^3$ and $\sigma_\phi = \left(\frac{p \cdot a^2}{2 \cdot b \cdot t}\right) u$; (13)

$r_\theta = \left(\frac{a^2}{b}\right) \cdot u$ and $\sigma_\theta = \sigma_\phi \cdot \left(2 - \frac{1}{u^2}\right)$. (14)

3.01b Self-Weight

The self-weight, snow loading, and wind loading formulation presented here closely follows the material set forth by Frei Otto in *Tensile Structures*.[18] The fabric weight is expressed as a weight per unit surface area. This formula is usually expressed as

$$W = \rho t \cdot g. \tag{15}$$

Since ρ is the density of the material, g is the gravitational acceleration constant, and t is the thickness of the material; W is the weight per unit surface area. The component of the gravitational force acting in the direction of the membrane can then be found by discovering the tangential component trigonometrically. This results in the following identities, which are displayed in figure 10: $F_\varphi = W \sin\theta$, $F_\theta = 0$, $F_r = -W \cos\theta$.

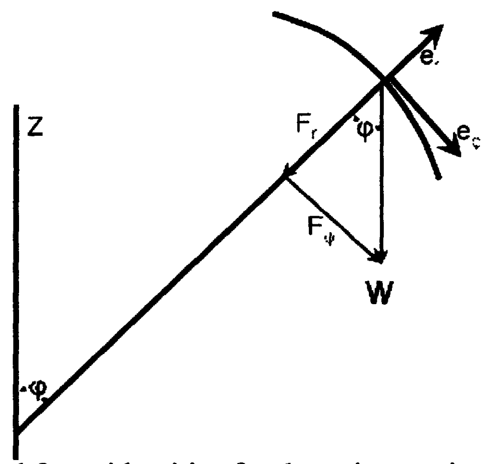

Figure 10: The gravitational force identities for the axisymetrical membrane; W is the total gravitational force.[19]

In the previous identities, F_φ is the force in the meridional direction, F_θ is the force in the circumferential direction (this is perpendicular to the gravitational force W and thus equal to zero), and F_r is the force in the radial direction or perpendicular to the fabric.

The general formula of axisymetrical self-weight loading is the following:

$$\sigma_{\phi gravity} = \frac{-W}{t \cdot R_\theta \cdot \sin^2\phi} \cdot \int_0^\theta R_\phi(\chi) \cdot R_\theta(\chi) \cdot \sin(\chi)\, d\chi \text{, and} \tag{16}$$

$$\sigma_{\theta gravity} = \frac{-W \cdot R_\theta \cdot \cos\phi}{t} - \frac{R_\theta}{R_\phi} \cdot \sigma_{\phi gravity}\ , \tag{17}$$

[18] Otto, Frei and Trostel, Rudolf. *Tensile Structures*. Cambridge, MA: The MIT Press, 1973. Pg: 185-194

[19] Otto, Frei and Trostel, Rudolf. *Tensile Structures*. Cambridge, MA: The MIT Press, 1973. Pg: 187

and the integration in formula 6 goes from $\chi = 0$ to $\chi = \theta$.

Plugging in the R_φ and R_θ for an ellipsoid from equations 13-14 and integrating we arrive at the following simplified gravitational stresses:

$$\sigma_{\phi_{g\text{-ellipsoid}}} = \frac{-W}{t} \cdot \frac{a^2 \cdot u^3 \cdot \theta^3}{3 \cdot b}, \text{ and} \tag{18}$$

$$\sigma_{\theta_{g\text{-ellipsoid}}} = \frac{-W}{t} \cdot \frac{a^2 \cdot u}{b} \cdot \left(\cos(\phi) - \frac{\theta^3}{3} \right). \tag{19}$$

3.01c Snow Loading

Snow loading can take two forms; it can be a top accumulation or a standard distribution per unit area of the membrane. Both forms are presented here for examination. First we will solve the standard distribution per unit area of the membrane. This first form has two solutions depending upon the angle φ_0. The first case is for snow acting upon the entire membrane. It goes as follows:[20]

$$\sigma_{\phi snow} = \frac{-s}{t \cdot R_\theta \cdot \sin^2 \phi} \cdot \int_0^\phi R_\phi(\chi) \cdot R_\theta(\chi) \cdot \sin(\chi) \cdot \cos^2(\chi)\, d\chi, \text{ and} \tag{20}$$

$$\sigma_{\theta snow} = \frac{-s \cdot R_\theta \cdot \cos^3 \phi}{t} - \frac{R_\theta}{R_\phi} \cdot \sigma_{\phi snow}, \text{ for } \phi \le \phi_0 \le \frac{\pi}{2}. \tag{21}$$

In the above equation, s is the vertical snow load per unit surface area of the membrane and the remaining variables are as previously defined in formula and geometric depictions. The second formula for the standard distribution condition is for when the snow only acts upon the upper part of the membrane. The equation is:[21]

$$\sigma_{\phi snow} = \frac{\sigma_{\phi snow}\left(\frac{\pi}{2}\right) \cdot R_\theta \cdot \left(\frac{\pi}{2}\right)}{R_\theta(\phi) \cdot \sin^2 \phi}, \text{ and} \tag{22}$$

$$\sigma_{\theta snow} = \frac{-R_\theta}{R_\phi} \cdot \sigma_{\phi snow}, \text{ for } \frac{\pi}{2} \le \phi \le \phi_0. \tag{23}$$

[20] Otto, Frei and Trostel, Rudolf. *Tensile Structures*. Cambridge, MA: The MIT Press, 1973. Pg: 187-188
[21] Otto, Frei and Trostel, Rudolf. *Tensile Structures*. Cambridge, MA: The MIT Press, 1973. Pg: 187-188

The above is the representation of the standard "distribution according to DIN 1055, p.5, by vertical load per unit area."[22] S is equal to 75 kg/m^2. The drawing on the right in figure 11 depicts the snow load on the inflated shell and possible membrane shape changes due to a distributed snow load.

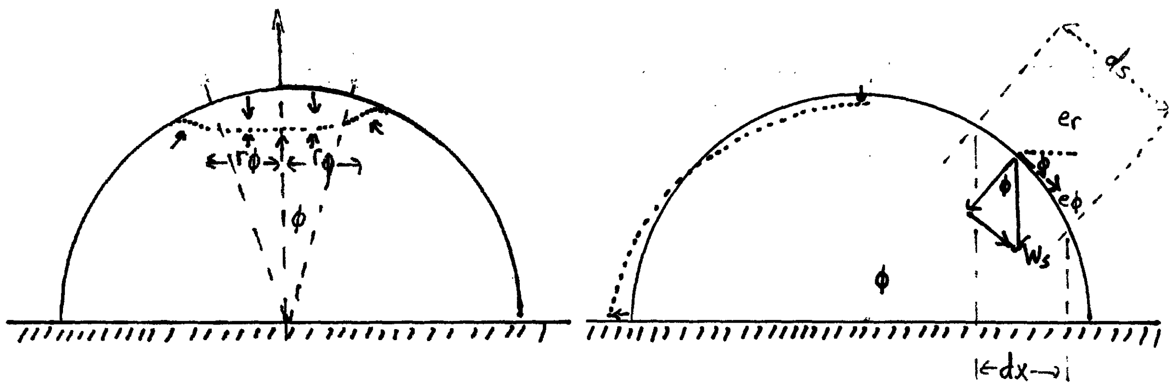

Figure 11: Loading and possible local buckling form for an accumulated snow load on an axisymetrical membrane (left), and the loading and possible deformation form for a standard distribution snow load (right).[23]

The accumulated snow load only affects the area that the snow has accumulated on. This measure assumes that the snow will not build up with a uniform distribution as was assumed above. The left schematic in figure 11 depicts this type of snow load with a possible deformation pattern. The below formulas mathematically describe this behavior. The first set is outlined here:[23]

$$\sigma_{\phi snowpartial} = \frac{-s}{t \cdot R_\theta \cdot \sin^2\phi} \cdot \int_0^\phi R_\phi(\chi) \cdot R_\theta(\chi) \cdot \sin(\chi) \cdot \cos^2(\chi)\, d\chi \text{, and} \tag{24}$$

$$\sigma_{\theta snowpartial} = \frac{-s \cdot R_\theta \cdot \cos^3\phi}{t} - \frac{R_\theta}{R_\phi} \cdot \sigma_{\phi snowpartial} \text{, for } 0 \le \phi \le \phi_1 .$$

And the second set is here:[23]

$$\sigma_{\phi snowpartial} = \frac{\sigma_{\phi snowpartial} \cdot (\phi_1) \cdot R_\theta(\phi_1) \cdot \sin(\phi_1)}{t \cdot R_\theta(\phi) \cdot \sin^2\phi} \text{, and} \tag{26}$$

$$\sigma_{\theta snowpartial} = \frac{-R_\theta}{R_\phi} \cdot \sigma_{\phi snowpartial} \text{, for } \phi \ge \phi_1 . \tag{27}$$

These equations readily provide solutions for the desired axisymetrical snow loading.

[22] Otto, Frei and Trostel, Rudolf. *Tensile Structures*. Cambridge, MA: The MIT Press, 1973. pg: 187
[23] Otto, Frei and Trostel, Rudolf. *Tensile Structures*. Cambridge, MA: The MIT Press, 1973. pg: 188

3.01d Wind Loading

Wind loading is unique from the previous fabric stresses; because, it cannot be realistically modeled as an axisymetrical load. From *Tensile Structures* by Frei Otto *et al* the summarized derivation is as follows. First, we assume that the loading of the membrane due to wind is modeled as pressure acting along the surface normal called *n*, such that the following is true:

$$p_\phi = p_\theta = 0, \text{ and } p_r = -n. \tag{28}$$

Then for the sake of modeling stresses in a static state we will assume that the wind is blowing from the negative x-axis toward the positive x-axis with a wind pressure described by constants n_0 and n_1 as follows:

$$n = n_0 + n_1 \cdot \sin(\phi) \cdot \cos(\theta). \tag{29}$$

The constant n_0 is the axisymetrical wind loading factor and the constant n_1 is non-symmetric in the meridional plane and symmetric in the circumferential plane. The corresponding sectional loads are then described, and by plugging into the previously derived anti-symmetrical loading formula the following relationship for the meridional and circumferential stresses, respectively, is found:

$$\sigma_{\phi_{wind}} = f_{\phi_{n1}} \cdot \frac{\cos(\theta)}{t} \text{ and} \tag{30}$$

$$\sigma_{\theta_{wind}} = -n_1 \cdot R_\theta \cdot \sin(\phi) \cdot \cos(\theta) - \frac{R_\theta}{R_\phi} \cdot \sigma_{\phi_{wind}}. \tag{31}$$

Where the meridional factor is found by:

$$f_{\phi_{n1}} = \frac{n_1}{R_\theta{}^2 \cdot (\phi) \cdot \sin^3 \cdot (\phi)} \cdot \int_0^\phi \left(\zeta(\chi) - z(\phi) - R_\theta(\chi) \cdot \cos(\chi)\right) \cdot R_\phi \cdot R_\theta \cdot \sin^3 \cdot (\chi)\, d\chi. \tag{32}$$

Calculating the actual wind pressure to input into the above formulation is not an easy task. The pressure on a structure due to wind varies from a plunging pressure on the front (windward) face of a structure to a grabbing suction on the top and rear (leeward) surfaces.[24] The magnitude and direction of these pressures as characteristically seen in a hemispherical shell exposed to winds is shown in figure 12.

[24] Wagner, Craig H.. "Determining Wind Loads On Buildings." *Architectural Testing* 01 May 2006 <http://www.nwda.net/Determining%20Wind%20Loads%20On%20Buildings%20part%202.pdf>.

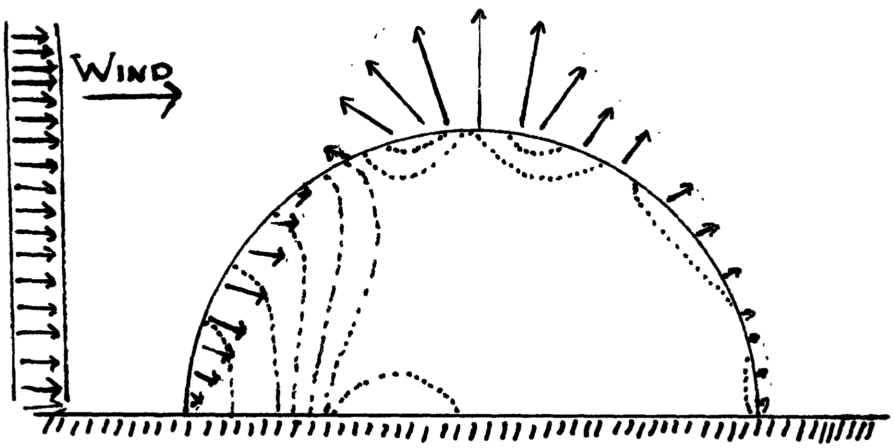

Figure 12: The magnitude and direction of forces on the membrane due to a constant wind pressure. The surface lines depict lines of constant stress.[25,26]

Generally, a good estimate of the pressure due to wind can be found through the Bernoulli's equation for streamline flow: $p_{wind} = \frac{v_{air}^2}{2} \cdot \rho_{air}$.[27] This simplification equates the pressure to the kinetic energy of the wind due to bulk velocity. Using this simplification based upon the stopped wind pressure, we find that a "fresh gale blowing at … 48mph will exert a pressure of 296 Pascals [or 0.3% atm] on a building."[28] Elaborating on these further and applying multiplying factors to adjust for the variations exhibited with greater height, and shape we can express the above formula as:[29]

$$p_{wind} = \frac{v_{air}^2}{2} \cdot \rho_{air} \cdot F_{shape} \cdot F_{height} = \frac{v_{air}^2}{2} \cdot \frac{P_{atm}}{R_{air} \cdot T_{air}} \cdot F_{shape} \cdot F_{height}, \tag{33}$$

where the wind pressure is in terms of the velocity of the wind (V_{air}), the density of the air (ρ_{air}), and two scale factors (F_{shape} and F_{height}). F_{shape} is on the order of 0-1 and compensates for the aerodynamic qualities of the building shape, and F_{height} is on the order of 0-3 and it incorporates the increased gust and velocity potentials encountered at

25 Dietz, A. E., and Proffitt, R. B. and Chabot, R.S. and Moak, E. L.. *Wind Tunnel Test and Analyses for Ground-Mounted Air- Supported Structures.* Technical Report 70-7-GP. Natick, MA: U.S. Army Natick Laboratory, 1969. pg: 256-257

26 Zingoni, Alphose. *Shell Structures in Civil and Mechanical Engineering.* Oxford: Thomas Telford, 1997. pg: 115

27 Ochshorn, J. "Wind." *Building Structures and Construction.* Cornell University. 01 May 2006 <http://instruct1.cit.cornell.edu/courses/arch264/cuhk/courseNotes/wind/wind.html>.

28 "Wind Pressure & Flow Around Buildings." *The Vent-Axia Ventilation Handbook.* 01 May 2006 <http://www.vent-axia.com/sharing/windflow.asp>.

29 "Wind speed and wind pressure." *KNMI Hydra Project.* 16 Jan 2006. Royal Netherlands Meteorological Institute. <http://www.knmi.nl/samenw/hydra/faq/press.html>.

greater heights.[30] For the case of the automated command post, we will use an assumed F_{shape} of 0.8 and F_{height} of 1.5. This formula gives the wind pressure in Pascal based upon the shape and height of the structure as well as the design wind velocity.

3.01e Equivalent Stresses

This general form of the stresses within air supported membranes will be applied to the particular shape of the ACP and equivalent stresses determined. The equivalent stress can be determined using the Mises equivalent stress equation:

$$\sigma_{mises\_eq} = \sqrt{\frac{1}{2}\cdot\left(\sigma_{\phi} - \sigma_{\theta}\right)^2 + \left(\sigma_{\theta} - \sigma_r\right)^2 + \left(\sigma_r - \sigma_{\phi}\right)^2}. \tag{34}$$

Since the fabric shell is thin relative to the size of the radius of the enclosure (r/t >10), the fabric lacks the ability to carry shear stresses; thus, σ_r is negligible. The only stresses "felt" by the fabric are biaxial in nature resulting from the tensile application of σ_{φ} and σ_{θ}. Therefore, the equivalent stress can be rewritten in the following form:

$$\sigma_{mises\_eq} = \sqrt{\frac{1}{2}\cdot\left(\sigma_{\phi} - \sigma_{\theta}\right)^2 + \left(\sigma_{\theta}\right)^2 + \left(\sigma_{\phi}\right)^2}. \tag{35}$$

3.02 Buckling of Camouflage Canopy Support

The camouflage canopy is traditionally supported by hollow Aluminum tubular sections. Because the slenderness ratio $\frac{L'}{r_{gyr}}$ for this structure is about 350, where L' is the effective length of the column and r_{gyr} is the radius of gyration, failure of the canopy supports will take the form of buckling. The radius of gyration is given by the square root of the second moment of inertia divided by the cross sectional area which is $r_{gyr} = \sqrt{\frac{I_A}{A_c}}$, where the area moment of inertia is $I_A = \frac{1}{4}\cdot\pi\left(r_o^{\,4} - r_i^{\,4}\right)$ and the cross sectional area is $A_c = r_o^{\,2}\cdot\pi - r_i^{\,2}\cdot\pi$. In the previous equations, R_o is the outside radius and R_i is the inside radius of the hollow cylindrical cross section. The effective length L' is

[30] Ochshorn, J. "Wind Data." *Building Structures and Construction.* Cornell University. 01 May 2006 <http://instruct1.cit.cornell.edu/courses/arch264/cuhk/courseNotes/wind/windData.html>.

given by the total length of the supporting pole times the effective length constant, k, (L' = L · k). In the case of the camouflage canopy, the effective length constant k is equal to one. This is because, as shown in figure 13, the lack of mechanical connection with the ground and the flexible nature of the canopy holding onto the supporting pole from above are both best modeled as pin joints. Euler's effective length constant for a pinned-pinned column is k = 1.

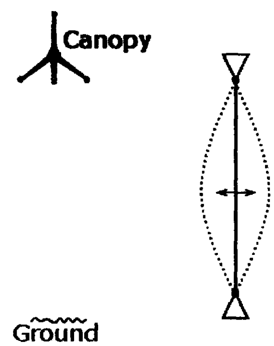

Figure 13: The poles supporting the camouflage netting are best modeled as a pinned-pinned long column.

The critical buckling stress of the canopy supports is found via the following equation:

$$\sigma_{buckling} = \frac{\pi^2 \cdot E \cdot I_A}{L^2}, \tag{36}$$

where E is equal to the Young's modulus of elasticity for the material and the other values are as previously defined.

In spite of the relatively simple calculation for the buckling stress of the camouflage support poles, calculating the actual forces from the camouflage netting is not so simple. Usually, numerical methods are necessary to calculate the stresses within a tensioned membrane such as the camouflage netting. However, for our purposes some simplifying assumptions give a reasonable calculation of loading force for the support poles.

The stresses on the outer netting poles will not exceed those already endured by existing camouflage netting poles; thus, no additional calculation is necessary for those pole emplacements. This is primarily because the relative density of poles surrounding each ACP module is high. However, the center pole will span a larger distance with a higher weight factor than the current poles are exposed to. Therefore, the center pole should be stronger than the current poles, and an estimate of the potential stresses should be given. If we imagine that the maximum possible stress on the center netting support for each module of the command post is created when the other poles are not installed, then the following diagram in figure 14 depicts the maximum loading on the center pole.

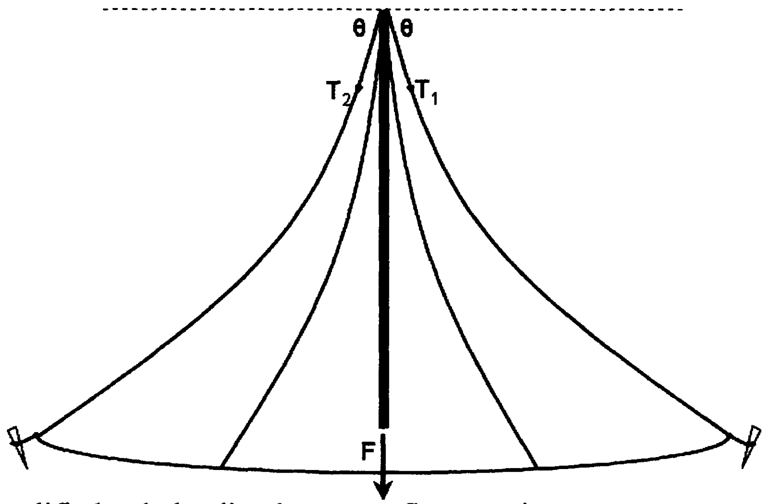

Figure 14: Simplified pole loading by camouflage netting.

In the above figure the force downward on the pole is given by:

$$F = T\cdot\sin\theta, \tag{37}$$

with T equal to the tension in the camouflage netting, and θ is as defined in figure 14. The minimum force (F) that can be experienced is found by this:

$$F_{min} = W_{cn}, \tag{38}$$

where the weight of the camouflage netting (W_{cn}) is equal to the following equation:

$$W_{cn} = A_{cn}\cdot\frac{\text{Mass (cn)}}{\text{Area}}\cdot g. \tag{39}$$

In equation 39, A_{cn} is the area of the camouflage netting which is multiplied by the mass of the netting per unit area and the gravitational acceleration constant (g). The resultant stress on the support pole can be found by this equation:

$$\sigma = \frac{F}{A_c}, \text{ with Ac as found above } (A_c = r_o^2\cdot\pi - r_i^2\cdot\pi). \tag{40}$$

Applying a safety factor of three, the design stress is less than or equal to one-third the calculated buckling stress:

$$\sigma_{design} \le \frac{1}{3}\sigma_{buckling}. \tag{41}$$

Note that this is a rudimentary calculation of center pole stress that should be verified via numerical analysis and with a finalized shape prior to manufacture. However, this model provides an excellent first approximation of the design criteria.

3.03 Air Leakage Rate

For the Automated Command Post, the rate of air leakage due to pressurization is dependant upon the internal gauge pressure and the size of the openings though which the air can leak. Ramskill has published many closed form solutions to this particular type of formulation, and the equations presented below are simplifications of these derivations.[31] The calculation of the ACP leakage rate is simpler than other leakage problems. This simplification of derivation is due to the establishment of the assumption of constant pressure. At constant pressure the rate of air flow out of an orifice of a particular size will not vary with time; thus, the instantaneous rate of air leakage is equal to the average rate of leakage so long as the inflation system is capable of maintaining close to constant pressure in spite of said leak. There are two main types of leak flow rate formulations: choked and non-choked.[32] The Automated Command Post is non-choked because of its low gauge pressure.

If we consider that the gauge pressure required for the Automated Command Post is very small (i.e. on the order of 0.3% of atmospheric pressure), then we can assume that the rate of air leakage through a hole in the ACP fabric will be sub-sonic in nature. Since the pressure differential is small, the velocity of the air flow is not restricted by the maximum speed of information flow through air and no supersonic restrictions are imposed on the system. Theoretically, if the ratio of internal absolute pressure over external absolute pressure is less than $[(k + 1) / 2]^{k / (k - 1)}$, where k is equal to the specific heat ratio of air, then the resultant flow is non-choked.[33] The specific heat ratio of air (k) is equal to the

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[31] Ramskill, P.K., "Discharge Rate Calculation Methods for Use In Plant Safety Assessments", Safety and Reliability Directory, 1986, United Kingdom Atomic Energy Authority

[32] "Accidental release source terms." *Wikipedia.* 2006. 01 May 2006 <http://en.wikipedia.org/wiki/Accidental_release_source_terms>.

[33] Beychok, Milton R.. "Calculating Accidental Release Flow Rates." *Fundamentals Of Stack Gas Dispersion.* 01 May 2006 <http://www.air-dispersion.com/feature2.html>.

specific heat of air at constant pressure (c_p) divided by the specific heat of air at constant volume (c_v). These equations are presented below for clarity:

$$R_{air} = 287 \frac{J}{kg \cdot K}, \quad c_{v_{air}} = 716 \frac{J}{kg \cdot K}, \text{ and } c_{p_{air}} = R_{air} + c_{v_{air}}. \tag{42}$$

R_{air} is the specific gas constant for air and the other variables are as defined above. The flow ratio which determines whether the escaping velocity is choked or non-choked is given by the following:

$$k = \frac{c_{p_{air}}}{c_{v_{air}}} \text{ and} \tag{43}$$

$$Flow_{ratio} = \left(\frac{k+1}{2}\right)^{\frac{k}{k-1}}. \tag{44}$$

Leaks resulting from a ratio of absolute pressure inside the ACP over the external absolute pressure which is less that equation 44 will be non-choked. As stated above, above the ultra-low pressure in the ACP does indeed yield this result. This is empirically shown with the following:

$$P_{atm} = 101325\,Pa \text{ and } P_{ACP} = 0.036\,psi + P_{atm}. \tag{45}$$

Thus the ratio of pressures is equal to $\frac{P_{ACP}}{P_{atm}} = 1.002$ (46)

which is much lower than the flow ratio obtained from equation 44 above. The flow ratio for air is $Flow_{ratio} = 1.893$, and, since the ratio of absolute pressure within the Automated Command Post over the exterior atmospheric pressure is less than this ratio, the observed velocity of escaping air from inside the ACP through a hole is non-choked.

This observation is shown by the following inequality:

$$\frac{P_{ACP}}{P_{atm}} < \left(\frac{k+1}{2}\right)^{\frac{k}{k-1}}. \tag{47}$$

In the case of non-choked air flow through leaks, the following relationship describes the behavior of the leakage rate (L_r):

$$L_r = C_d \cdot A_{tear} \cdot P_{ACP} \cdot \sqrt{\frac{2}{R_{air} \cdot T} \cdot \left[\frac{k}{(k-1)}\right] \cdot \left[\left(\frac{P_{atm}}{P_{ACP}}\right)^{\frac{2}{k}} - \left(\frac{P_{atm}}{P_{ACP}}\right)^{\frac{(k+1)}{k}}\right]}. \tag{48}$$

The leakage rate in equation 48 is expressed in terms of the previously defined terms and the area of the hole through which the air is leaking (A_{tear}) times a discharge coefficient (C_d). Under the square root, T is equal to the temperature of the discharged air in absolute degrees Kelvin (°K). The discharge coefficient is shape dependent and non-dimensional. Generally, a C_d value of 0.72 is accepted as a reasonable value for most thin wall pressurized container leaks.[34] However, laboratory measurements show that C_d does vary considerably especially in cases with low values of Reynolds number.[35] Research on the determination of the discharge coefficient of a thin-walled orifice published in the *Journal of Tribology* shows many empirical results with C_d values averaging around 0.8[36] In spite of this, 0.72 is accepted as a reasonable estimate of the discharge coefficient for this particular application.

3.04 Energy Cost of Structural Support

Since the Automated Command Post is air supported, there is an inherent energy cost associated with maintaining the required air pressure. The replacement of the volume of air lost due to the leakage rate calculated in section 3.03 is accomplished through work being done on the ACP by a blower system. Figure 15 graphically illustrates this described behavior. The structurally maintaining phenomenon illustrated below is, by definition, an open system with the following relationships by the first and second laws of thermodynamics respectively:

$$\frac{dE_{cv}}{dt} = \frac{dQ}{dt} - \frac{dW}{dt} + \sum_{in}\left[\frac{dm_{in}}{dt}\cdot\left(h + \frac{v^2}{2} + g\cdot z\right)_{in}\right] - \sum_{out}\left[\frac{dm_{out}}{dt}\cdot\left(h + \frac{v^2}{2} + g\cdot z\right)_{out}\right] \text{ and} \tag{49}$$

$$\frac{dS}{dt} = \sum 1\cdot\frac{dQ}{T(dt)} + \frac{dS_{gen}}{dt} + \sum_{in}\left(\frac{dm_{in}}{dt}\cdot s_{in}\right) - \sum_{out}\left(\frac{dm_{out}}{dt}\cdot s_{out}\right). \tag{50}$$

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[34] Beychok, Milton. "Source Terms for Accidental Discharge Flow Rates." *Online Chemical Engineering Information.* 01 May 2006 <http://www.cheresources.com/discharge.shtml>.
[35] "Orifice, Nozzle and Venturi Flow Rate Meters." *Engineering Tool Box.* 01 May 2006 <http://www.engineeringtoolbox.com/orifice-nozzle-venturi-d_590.html>.
[36] Charles, S.. "Determination of the Discharge." *Journal of Tribology* Vol. 127(2005): 679-684.

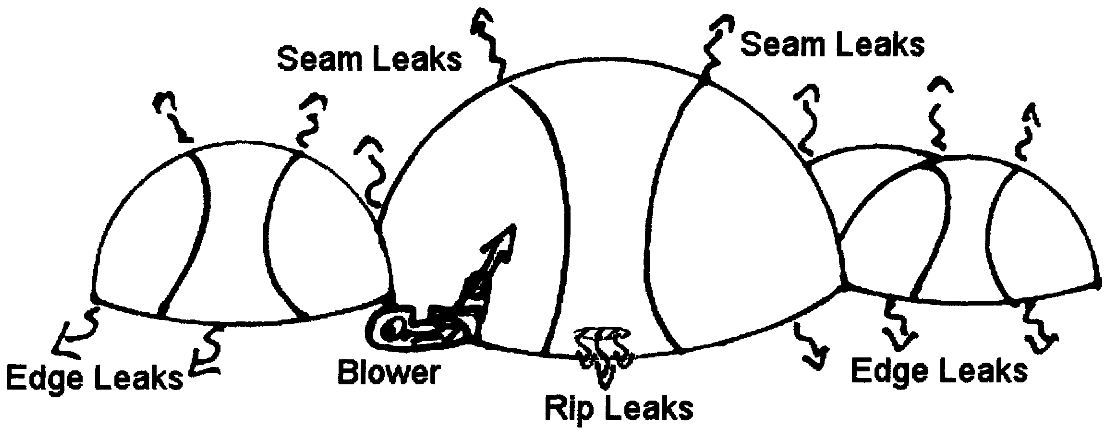

Figure 15: Maintaining the structural support of the Automated Command Post requires automatically replacing escaping air via a blower.

Formula 49 states that time rate of energy change in the control volume is equal to the time rate of heat flow into the system minus the time rate of work conducted out of the system plus the net time rate of change of stored energy via mass transfer. The net time rate of change of stored energy via mass transfer in the system is equal to the flow of mass with summed energy modes ($m \cdot h$ = enthalpy, $m \cdot v^2/2$ = kinetic energy, and $m \cdot g \cdot z$ = gravitational potential energy) in minus the flow of mass with summed energy modes out. Likewise, formula 50 states that the rate of accumulation of entropy in the control volume is equal to the net entropy transfer into the control volume plus the rate of entropy generation in material plus the net rate of entropy addition via mass driven entropy inflows and outflows.

The command post itself can be assumed to be in steady state; however, this assumption is only useful to show that the input energy is equal to the output energy. In the steady state case, the above general analytical approach to the dynamic support of the Automated Command Post can be further simplified by assuming that the rate of mass flow in is equal to the rate of mass flow out, the change in gravitational potential energy is negligible, and the change in kinetic energy is negligible. These and other assumptions are presented briefly below:

In steady state, the mass entering the command post is equal to the mass leaving the command post, or, in other words, the time rate of change of mass within the control volume (the ACP) is equal to zero.

$$\frac{dm_{cv}}{dt} = \sum\left(\frac{dm_{in}}{dt} - \frac{dm_{out}}{dt}\right) = 0 \quad \text{therefore } \Delta m_{in} = \Delta m_{out} \text{ ;} \tag{51}$$

Likewise the volume of the command post is constant under a constant pressure. Thus the rate of work performed on the mass of air already within the command post is equal to zero.

$$V_{ACP} = \text{Constant and } P_{ACP} = \text{Constant therefore } \frac{dW}{dt} = \int P\,dV = 0. \tag{52}$$

Because the change in gravitational potential energy and the change in kinetic energy is negligible we can exclude them from the formula.

$$\frac{(\Delta v_{in})^2}{2} = \frac{(\Delta v_{out})^2}{2} \text{ and } g\cdot z_{in} = g\cdot z_{out} \text{ .} \tag{53}$$

The density of the air is given by the following formula:

$$\rho_{air} = \frac{P}{R_{air}\cdot T} \text{ ;} \tag{54}$$

and the time rate of mass leaving the command post can be found by the following:

$$\frac{dm}{dt} = L_r\cdot\rho_{air} \text{ .} \tag{55}$$

The enthalpy of the air is given by the below:

$$h = c_{p_{air}}\cdot T \text{ .} \tag{56}$$

Combining formulas 51-56 with formula 49 we arrive at the following simplification:

$$L_r\cdot c_p\cdot\frac{P_{ACP}}{R_{air}} + \frac{dQ_{out}}{dt} = B_r\cdot c_p\cdot\frac{P_{atm}}{R_{air}} + \frac{dQ_{in}}{dt}. \tag{57}$$

L_r is as defined in equation 48, and Q_{out} is described in equation 66. B_r is the blower rate, and the other variables are as previously defined. This formulation could prove useful in determining the total energy cost including that of environmental control. However, it is useful to find the total work required by the blower system to support the ACP per unit time in an isothermal state using the setup described in figure 16.

If we model the blower system as a mass that provides a constant pressure at a variable volumetric rate equal to the volumetric flow exiting the Automated Command Post via leaks (L_r) as found above in equation 48, then the following formula describes the rate of work placed into the system by the blower:

$$W_{rate} = p_{ACP} \cdot \frac{\Delta V}{t}, \tag{58}$$

where the rate change in volume ($\Delta V/t$) is equal to L_r and p_{ACP} is the gauge pressure of the Automated Command Post.

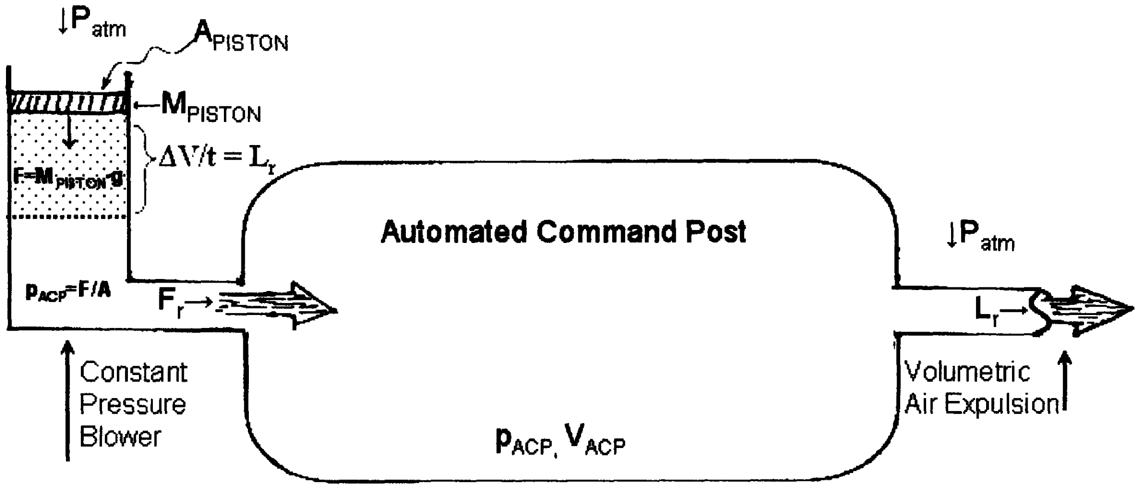

Figure 16: Simplified model of the work required to maintain constant pressure in the Automated Command Post given a leakage rate (L_r). The rate of work is equal to the rate of leakage times the given gauge pressure inside the command post.

The rate of fuel use by the blower system is then calculated by dividing the work rate from equation 58 by the available energy output of the blower system. The available energy output of the blower system is found by multiplying the efficiency (η) of the blower times the available energy density of the fuel that the blower uses to perform work. Therefore the basic energy cost per unit time of static structural support for the ACP is found by:

$$Fuel_{rate} = \left(\frac{1}{\eta}\right) \cdot \frac{W_{rate}}{E_{density}}. \tag{59}$$

This energy cost calculation is in volume of fuel per unit time; it is useful to calculate this number as gallons of fuel per minute.

3.05 Camouflage and Thermal Radiation Blocking

There is no rigorous mathematical model or methodology for determining the degree to which objects can be sighted via the visible light spectrum; however, reduction of thermal signatures employs some basic concepts of heat transfer by conduction, convection, and radiation. The more qualitative aspects of visible light recognition reduction are presented in the design section of this thesis under *integrated camouflage netting*. The background theory presented here deals solely with the reduction of thermal radiation off of the surface of the command post structure.

The steady state flow of heat from inside a structure to the outside environment or vice versa is dependent upon the temperature difference between the two environments, the boundary material's resistance to heat flow, and the surface area over which this transfer of heat occurs. If the material resistance to heat flow goes down or if the surface area over which the transfer occurs goes up, then the steady state flow of heat goes up. Likewise, larger temperature gradients produce larger heat flows between the two environments. The surface area of the Automated Command Post is complex because it incorporates a spheroid top attached to a cylindrical bottom. This yields an unwieldy formula for heat flux through the wall of the ACP. Because the ACP is very large and the height of the cylindrical portion is rather close to the large radius of the oblate ellipsoid top of the ACP a spherical approximation of surface area can be made which is close to the actual surface area. Figure 17 graphically shows a hypothetical module for the ACP with dimensions a, b, and h.

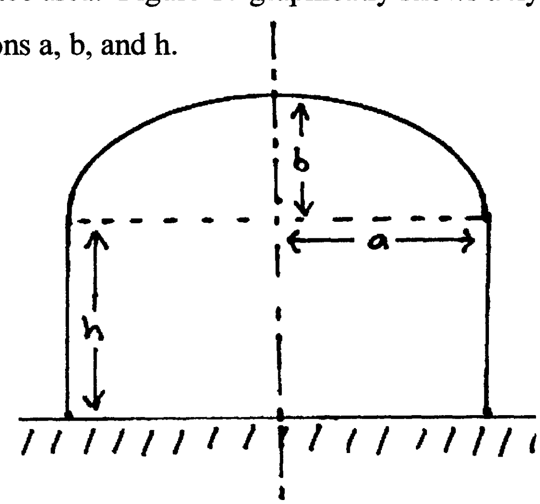

Figure 17: The dimensional determination of a single ACP module. Representative dimensions would be a = 10', b = 7.5', and h = 6'.

The eccentricity of the ellipsoid top is given by:

$$\varepsilon cc = \sqrt{1 - \frac{a^2}{b^2}} \text{, and} \tag{60}$$

the surface area of this ellipsoid top is given by:[37]

$$A_{spheroid} = \pi \cdot \left(2b^2 + \frac{a^2}{\varepsilon cc} \cdot \ln\left(\frac{1 + \varepsilon cc}{1 - \varepsilon cc} \right) \right). \tag{61}$$

Likewise the surface area of the cylindrical portion of the ACP is calculated using:

$$A_{cylinder} = 2\pi \cdot a \cdot h. \tag{62}$$

Therefore, the total surface area of the ACP is found via:

$$A_{total} = \frac{1}{2} \cdot A_{spheroid} + A_{cylinder}. \tag{63}$$

If we model the ACP as a sphere with a radius given by:

$$r_{sphere} = \frac{(h + b + a)}{2}, \tag{64}$$

then the estimated surface area is found by ½ the surface area of a sphere with said radius r_{sphere}. This area is given by the following:

$$A_{est} = 2 \cdot \pi \cdot \left(\frac{h + b + a}{2} \right)^2. \tag{65}$$

This spherical approximation has an error factor of 5-10% for the range of geometries considered for the ACP.

The rate of heat flow out of this spherical model is given by this equation:

$$q_r = \frac{4 \cdot \pi \cdot k_{eff} \cdot \left(T_{ACP} - T_e \right)}{\left[\frac{1}{\left(r_{sphere} - t \right)} - \frac{1}{r_{sphere}} \right]}, \tag{66}$$

where k_{eff} is the effective resistance of to the flow of heat, T_{ACP} is the temperature of the air inside the command post, T_e is the temperature of the air outside the command post, and t is the overall thickness of the command post wall. The various resistances to heat flow in the command post wall are defined by the following three equations:[38]

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[37] "Ellipsoid." *Wikipedia.* 01 May 2006 <http://en.wikipedia.org/wiki/Ellipsoid>.

[38] Incropera, Frank P, and DeWitt, David P. *Fundementals of Heat and Mass Transfer*. 5th. Danvers, MA: John Wiley & Sons, 2002.

$$R_{cond} = \frac{1}{4 \cdot \pi \cdot k_{eff}} \cdot \left[\frac{1}{(r_{sphere} - t)} - \frac{1}{r_{sphere}} \right], \tag{67}$$

$$R_{cov_{in}} = \frac{1}{h_{in} \cdot 4 \cdot \pi \cdot (r_{sphere} - t)}, \text{ and} \tag{68}$$

$$R_{cov_{out}} = \frac{1}{h_{out} \cdot 4 \cdot \pi \cdot r_{sphere}}. \tag{69}$$

The variables above are as previously defined with h_{in} and h_{out} being the effective coefficient of convection on the inside and outside walls of the ACP, respectively. The total resistance to heat flow in the command post is found by summing the resistances from equations 67 to 69. This total resistance is shown in the below equation in accordance with the principle of thermal resistances in series as shown in the graphical depiction of a potential ACP wall with representative temperature distributions (figure 18):

$$R_{total} = R_{cov_{in}} + R_{con} + R_{cov_{out}}. \tag{70}$$

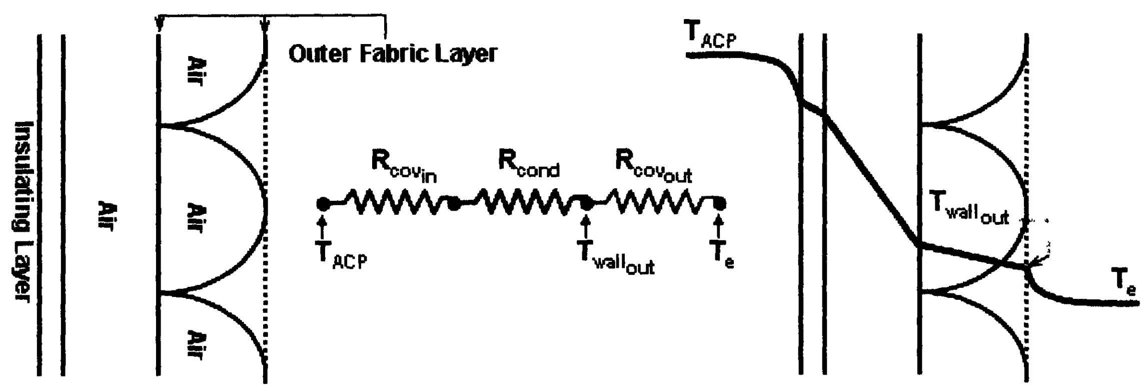

Figure 18: The composite nature of the ACP wall as designed (left), the equivalent resistance diagram (center) with the conductive resistances lumped, and the expected temperature profile through the ACP wall (right). Note that the temperature profile is drawn with the assumption of a positive heat transfer into the environment; however, this relationship is also true for a negative heat transfer into the environment. In the later case, the temperature is increasing downward.

Finally, the rate of heat transfer from equation 66 can be related to the total resistance via this equation:

$$q_r = \frac{(T_{ACP} - T_e)}{R_{total}}. \tag{71}$$

Using equation 70 and 71, it can be shown that the temperature of the outside wall is found with:

$$T_{wall_{out}} = T_{ACP} - q_r \cdot \left(R_{wall_{out}}\right), \tag{72}$$

where $R_{wallout}$ is equal to the total resistance minus the outside convective resistance ($R_{total} - R_{covout}$) or to the resistance of the inside convection plus the wall conduction ($R_{covin} + R_{con}$).

Thermal imaging resolves the difference in radiative heat transfer that two objects have to the outer environment. This observed difference via thermal imaging is dependent upon a variation of surface temperatures. If the surface temperature of two rocks is very similar or if the difference is smaller than most other temperature differences nearby, then thermal imaging will not be able to resolve the two separate rocks. Likewise, if the temperature of the outside layer of the command post (as found in equation 72) is similar to the temperature of the air surrounding the command post, thermal imaging will have difficulty detecting the presence of the command post exterior wall. This relationship can be seen from the general equation for radiative heat transfer below: [39]

$$q_{rad} = h_r \cdot A \cdot (T_{far} - T_{sur}). \tag{73}$$

In equation 73, A is the surface area of the object emitting the heat, T_{far} is the temperature of the environment far away from the surface of the emitting object, T_{sur} is the surface temperature of the emitting object and hr is defined by this equation:

$$h_r = \varepsilon \cdot \sigma \cdot (T_{far} + T_{sur}) \cdot \left(T_{far}^2 + T_{sur}^2\right), \tag{74}$$

where ε is the emissivity of the emitting object's surface, and σ is the Stefan-Boltzmann constant ($\sigma = 5.67 \times 10^{-8}$ $W/m^2 \cdot K^4$). By equation 74, if the surface temperature of the ACP is close to the surface temperature of the surrounding air, there will be little discernable difference in the resulting thermal radiation from each. Thus, the Automated Command Post surface will be camouflaged from thermal imaging. This does not mean, however, that high temperature internal elements will not be discernable.

[39] Incropera, Frank P, and DeWitt, David P. *Fundementals of Heat and Mass Transfer*. 5th. Danvers, MA: John Wiley & Sons, 2002.

3.06 Anchorage Requirements

The anchorage requirements for air supported structures are large; because, unlike most conventional structures the primary forces exerted on the air-supported membrane are in the upward direction. This oddity is due to the lack of traditional support elements which greatly increase the gravitational weight of the structure, the internal pressurization with a net upward component, and the uplift "sucking" action created by the flow of wind over the structure. Figure 19 graphically displays the uplift generally experienced by a structure due to wind. In a traditional structure, this is easily counterbalanced by the self weight of the building. However, in air supported structures, this counterbalance must be provided with a ground anchorage system.

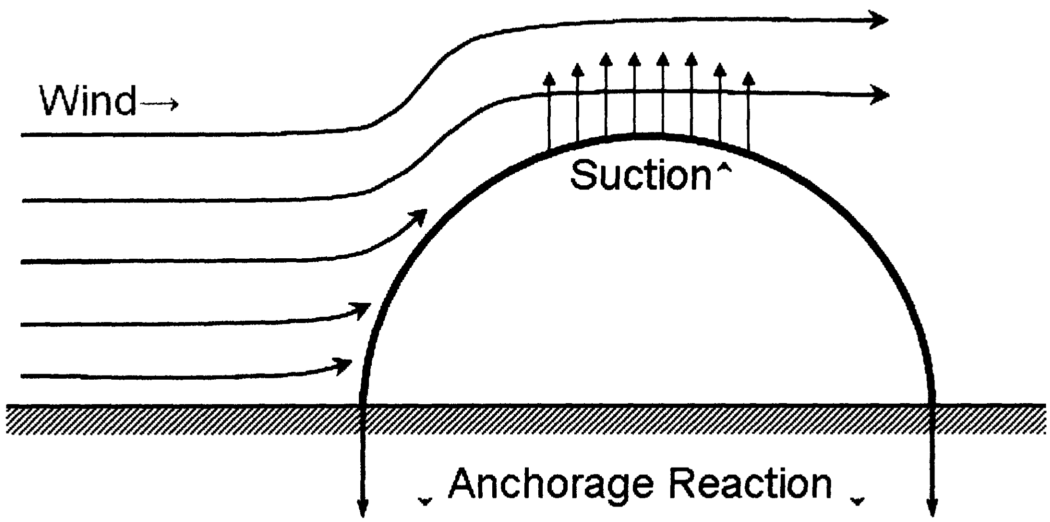

Figure 19: The upward lift caused by wind passing over a structure.

The ACP design makes use of a catenary cable anchorage system; because, this is a very flexible and inexpensive system that provides the greatest degree of freedom in packaging.[40] This method of anchorage as well as the selection criteria is explained in more detail in the design section. However, the base calculation of anchorage requirements is presented here.

The anchorage provided must exceed the maximum edge forces exerted by the structure, and these maximum forces can be determined by the fabric stress equations presented

[40] Dent, Rodger N. *Principles of Pneumatic Architecture*. London: The Architectural Press, 1972. pg: 110

previously. The only source of upward force on the ACP is wind loading and internal pressurization. Since the anchorage system is non-dynamic, the max wind lift on the structures edge must be countered universally around the edge of the structure. Because of the assumption that anchorage is required everywhere at value high enough to counter the effective wind pressure, it is acceptable to model the wind pressure up as an axisymetrical force. Here, the mathematically advantageous route has been taken by modeling the wind uplift as an increase in internal gauge pressure. This is, namely, to model the uplift created by wind loading as an increase in internal pressure equal to the upward suction created by the wind. Subtracted from this calculation is the net weight of the structure divided by the circumference to account for the downward forces due to gravity per unit length of the edge. Applying these generalizations to equations 9 and 10 we can determine the force per length required to anchor the Automated Command Post. A standard safety factor of three has been applied to the following:

$$\text{anchorage} = \frac{3}{2}\left[\left(p_{internal} + p_{wind}\right)\cdot a - \frac{W_g \cdot A_{ACP}}{a\cdot\pi}\right], \tag{75}$$

where W_g is the overall weight of the structure and p_{wind} is the upward suction pressure due to wind. The other variables are as defined previously. This formula gives the anchorage requirements in force per unit length.

4.0 Design of the Automated Command Post

The design of the Automated Command Post is unique in that it is primarily aimed at finding a good solution to one particular unique problem or application as described in the beginning of this thesis. In spite of this singular purpose of design, great care has been taken to articulate a product which can be used for purposes other than that which it was primarily designed for. In particular, the Automated Command Post can be used for many military or civilian applications that are not related to Command and Control or battlefield operations. Any application that can benefit from a moderate-sized, rapidly-deployable, modular structure with a low weight and cost to volume ratio will benefit from use of the Automated Command Post. This section describes some of the alternative ideas explored in the design process and then carefully presents the individual components of the final design. Many finalized components have alternate configurations listed with various additional benefits itemized. In general, this section follows a logical sequence of macro-scale to micro-scale ideas. However, there are a few exceptions to this rule.

4.01 Preliminary Ideas

In the beginning of the research into the best overall mechanism for use in the Automated Command Post, it became clear that the first decision would have to be between an air supported structure or a mechanically supported structure like those commonly in use today. Functional factors between these two main categories were compared, and a few of these tradeoff comparisons are presented in this section. First and foremost in this overall mechanism selection phase was the ability of each mechanism to meet the speed requirement for set-up and take down. The primary reason a faster command post is needed is to enable forward area commanders to utilize the same computational tools afforded rear commanders during a time of accelerated offense. The current Command Post structures take so long to erect that they prohibit the use of the decision making tools currently available for use during more static phases of combat. The following sections explain this initial process of mechanism decision.

4.01a Mechanical versus Air Supported

There are many criteria by which a mechanical system can be compared to an air supported system; however, in this brief highlight of this decision, the following criteria are used: speed of set-up / take down (i.e. how fast can the structure be deployed and made functional for Command Post operations and how fast can it be re-deployed to another location), the energy cost to maintain the structure (i.e. how much fuel is burned just to maintain the structural integrity of the structure), and the generic robustness of the design (i.e. how resistant is the structure to bullet impacts and how reparable is it).

The speed of set-up and take down has been identified as the major decision making factor between the mechanical versus air supported designs. However, the actual speed of set-up or take down is difficult to measure or estimate accurately without a full scale model field test. That said, an objective comparison can be obtained by making a few realistic assumptions based upon the author's Command Post experience.

The process of Command Post set-up for a mechanical structure follows four basic steps:

<u>Step 1: Setting up the camouflage netting.</u>

This step entails the rolling out of the camouflage netting and then erecting it in an impromptu style. The goal is to create a large enough area under the net, free of netting supports, and that is high enough to allow the main tentage structure to be erected underneath the camouflage netting in between the pole supports. Figure 20 shows this process being performed in Norway by the 25th Marine Regimental Headquarters.

The best way to physically describe this process is to imagine a circular sheet of heavy fabric approximately 75' in diameter and then suspending this sheet with a coordinated effort. Figure 21 graphically depicts this coordinated effort. First, individuals must be stationed around the netting to maintain the structural integrity of the net throughout the set-up. What this means is that these individuals will keep the netting from shifting as stresses are applied by the poles to suspend the netting high enough to allow the deployment of the Command Post tents. Also, these individuals must prevent shifting as wind pressure by natural winds is applied during the set-up process.

Figure 20: Step 1: Setting up the camouflage netting. This is a photo of this process as performed by 25th Marines Regimental Headquarters during Battle Griffin February 2005 in Norway.

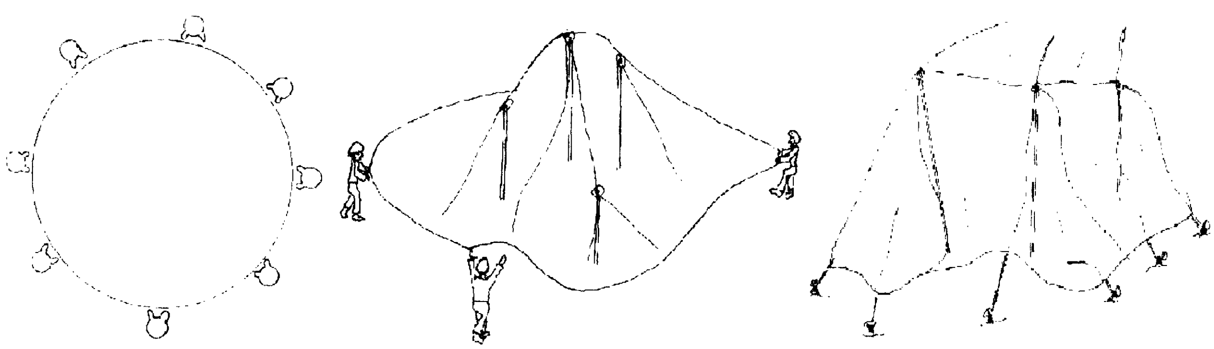

Figure 21: The erection of the camouflage netting. First the net is spread out and personnel assigned to maintain its stability (left). Second, poles are pushed up inside of the net to create a space for the tents (middle). Last, upon satisfactory installment of the poles the netting is affixed to the ground with stakes to prevent further movement (right). As the stakes are driven into the ground the personnel on the perimeter are one-by-one allowed to progress to other tasks.

Once the perimeter is securely maintained in place by individuals stationed around it then another group of people must begin crawling under the netting and establishing the poles to suspend the fabric in the air. The poles must be placed far enough apart and set high enough to provide ample space for the set-up of the Command Post tent structures. After the proper uplifted space has been created the edges of the netting are then staked down to the ground in order to replace the positive structural control previously provided by the individuals holding the perimeter of the netting.

It is important to note here that environmental controls prevent the staking of the netting directly to the ground. Because of concerns for the welfare of animals that may get entangled in the netting (one example is the desert turtles in the Mojave desert of California) the edge of the netting must be suspended at least six inches off of the ground. Because it effectively restricts both aerial and ground recognition, the netting is the primary source of visual and thermal camouflage for the Command Post; thus, it must also be staked no more than three feet off of the ground. The restriction of staking from six inches to three feet also provides an element of speed reduction; because, it is often difficult to maintain the netting off of the ground.

Step one, setting up the camouflage netting, usually takes about an hour to complete. Smaller net sizes have a faster erection process, and winder conditions or sub-optimal soil types (very sandy or very rocky) make the erection process take longer.

Step 2: Erection of mechanical Command Post tents

If there is enough personnel available, this step begins as soon as the poles have been placed within the camouflage netting creating the space for the command structure to be erected. This enables the tents to be set-up simultaneously with the staking of the camouflage netting exterior. However, the netting set-up is very manpower intensive; thus, if the command unit is providing its own military security while setting up the structure, there will not be enough personnel available to start step two prior to the completion of step one. The erection of the mechanical Command Post tents involves the formation of teams familiar with the set-up of the tents used and then setting up the tents in the manner prescribed by the tent design. Each of the different Command Post tents in common use (Base-X, DRASH, MCP), as described in the introductory portion of this thesis, have different set-up methods and times associated with set-up. However, it has been this author's experience that the more complex tents which take longer to set-up also provide a much larger square footage of usable space per tent. Thus, to a first approximation, it would be accurate to state that set-up times per square foot are similar for all command tents commonly used.

Step two, erection of mechanical Command Post tents, usually takes about thirty minutes to complete.

Step 3: Movement of furniture into structure

Once the camouflage netting and the tents have been erected and properly secured against the event of wind gusts, the tables and chairs and printers and computers and projectors and radios and other functional elements of the Command Post must be placed into the structure. This process takes about thirty minutes to complete.

Step 4: Wiring and communications check

All the radios, computers, printers, and servers must be wired with power and connectivity in order for the command post to be functional. This step is very tedious, and it is very much like hooking up a big screen television with a surround sound twenty-five times over. Once, the wiring is completed everything must be turned on and checked for operability prior to the command post take control of the battlespace.

Step four, wiring and communications check, usually takes about an hour.

Overall, the set-up of a mechanical command post is around three hours from start to finish (declaration of functionality). As pointed out earlier in this thesis, this process takes longer than it should, and it is vital that this time span be shrunk. The time span for take down is considerably faster at approximately two hours; however, this is also prohibitively slow. Faster set-up and take down times have been observed by the author, but faster times also come with an increased risk of structural failure. Repairing broken parts due to over rushed set-up or take down can take from one to three hours. This time set back effectively mitigates any time gains experienced through faster set-up or take down.

Since the two largest time components are in step one and step four (setting up the camouflage netting and in wiring the command structure), combining these steps with steps two and three (setting up the Command Post tents and installing the furniture) would yield the greatest time improvement. In the early conceptualization faze of this thesis, a sketch of such a model was drawn. This conceptualized model for the Automated Command Post is portrayed in figure 22.

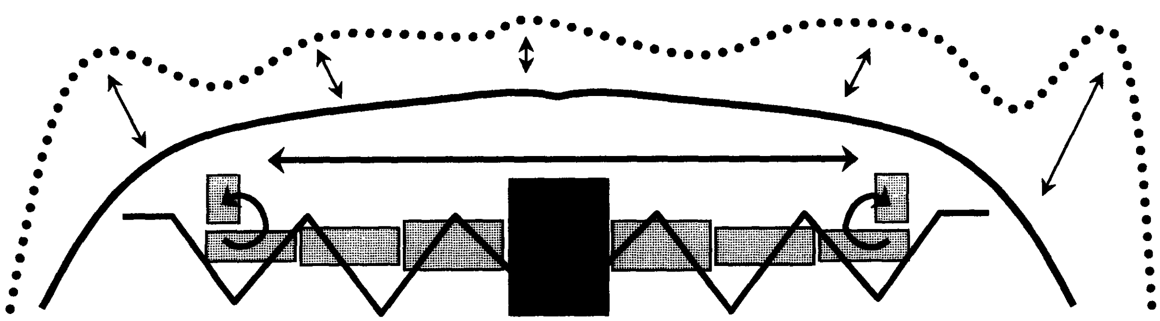

Figure 22: Sketch model of an early Automated Command Post conceptualization.

This sketch visualizes the concept of a trailer borne command post that unfolds from the trailer that hauls it without elaborate unloading. Other features portrayed here include an integrated table which slides out from the trailer and unfolds at the ends. There is also a functionally attached camouflage netting which surrounds the command post and is pushed into its final shape by expandable rods. In this sketch, the camouflage netting is a part of the tent so setting it up would not require extra time. Also, the wiring component could easily be integrated into the sliding out tables and the hauling trailer. Although, in concept, this idea is a great way to create a Command Post structure, several key issues hinder its actual development.

Firstly, most of the mechanisms which were considered for use in the ACP have difficulty operating with a fabric covering. As the fabric covering thickens and as the amount of extra material increases, the difficulty planning for the fabric expansion and recovery in the deployment of the structure increases. In fact, the greatest source of failure in the Command Post tents currently in use is the fabric. In other words, stresses in the folding and unfolding mechanism caused by bunched fabric inappropriately located far exceed the carrying stresses experienced by the structure from wind, self-weight, and snow while deployed. These stresses, caused by the wayward fabric, warp and fracture the mechanism resulting in time intensive repairing delays. It is very difficult to imagine a mechanical structure that can easily cope with a second layer of fabric that is more loosely attached than the primary layer. In fact, the author did not manage to effectively model any mechanical structures which would be able to deploy with an integrated camouflage netting as pictured above in figure 22.

Because an air supported structure does not utilize any mechanical folding elements for structural support, there are few restrictions on incorporating a second layer of fabric for camouflage netting. An innovative technique is needed to create separation between the netting and the structure; however, this is more than a small challenge. The design chosen for this job is presented later in the *Thermal Shielding & Camouflage* section of this thesis.

In addition to incorporating the camouflage netting, wiring run in the air supported structure can be left in place. If the walls of the air supported structure contain the Velcro straps necessary to allow the stable configuration of the power and net wiring, then there would be no need to redo the wiring every set-up and take down. The absence of mechanical elements would allow the wires to fold as necessary for take-down. Upon re-deployment, the wiring step would be already completed. It is clear that an air supported tent can easily be created which incorporates several of the time consuming steps currently required by the mechanical designs being used into one simple and fast step. This is strong evidence that a mechanically supported tent cannot compete with the air supported design in terms of incorporating the desired final configuration into the set-up for speed. However, this may come at higher energy cost (power to maintain the pressurized tent) or a structural vulnerable to being "popped." The suitability for a pneumatic structure in these terms is presented below along with more detailed calculations of these factors.

4.01b Suitability for Pneumatics Ascertained

One distinctive difference between a purely mechanical design and a pneumatic one is that the energy cost to maintain the structure (i.e. how much fuel is burned just to maintain the structural integrity of the structure) is non-zero for the pneumatic option. The mechanical structure may take a lot of manpower to erect, but, once established, it requires no external energy input to withstand environmental stresses. An air supported design, on the other hand, does require constant air input, and, thus, external energy to withstand environmental stresses.

The energy required to maintain an air supported structure is directly related to the volumetric rate of air leakage. Current building codes recommend that the volumetric rate of air leakage meet or exceed 30 cfm per occupant. The maximum occupancy of the command post would be during a briefing. An estimate of the occupancy during a command brief is roughly one-third of the total number of personnel within a headquarters company. The total number of personnel within a headquarters company is approximately 150; thus, the total max occupancy is 50. This yields a volumetric rate of leakage equal to 1,500 cfm. However, it is possible for the volumetric rate of air leakage to be higher than this estimate due to a large unplanned air leak. The volumetric rate of air leakage through unplanned holes is dependant upon the design internal air pressure.

A design pressure of 0.036 psi, the equivalent of one standing inch of water, will provide structural stability in extreme conditions with winds up to 60-70 mph.[41] Assuming an internal air pressure of 0.036 psi, then the volumetric rate of air leakage out of a 21 square foot hole (e.g. a 3' x 7' open doorway) is roughly 48,000 cubic feet per minute.[42] The amount of work required to maintain the design air pressure with leakage is equal to the constant pressure difference from atmospheric times the volume pumped from outside the structure. The rate of work to maintain this design air pressure is the amount of work performed divided by the period of time through which it was performed. This relationship is derived in equation 58, which is restated here for convenience:

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[41] Lutes, D. A. "CBD-137. Air-Supported Structures." *Canadian Biulders Digest*. May 1971. National Research Council Canada. 01 May 2006 <http://irc.nrc-cnrc.gc.ca/pubs/cbd/cbd137_e.html>.
[42] Lutes, D. A. "CBD-137. Air-Supported Structures." *Canadian Biulders Digest*. May 1971. National Research Council Canada. 01 May 2006 <http://irc.nrc-cnrc.gc.ca/pubs/cbd/cbd137_e.html>.

$$W_{rate} = p_{ACP} \cdot \frac{\Delta V}{t} \cdot \tag{58}$$

Where p_{ACP} is equal to the internal gauge pressure and $\Delta V/t$ is equal to the rate of volumetric change. If we take $P = 0.036\text{psi}$ and $1{,}500\text{cfm} \le \frac{\Delta V}{t} \le 48{,}000\text{cfm}$, then we achieve a rate of work between 175 and 5,623 Watts ($175.7\text{W} \le W_{rate} \le 5{,}623\text{W}$). The rate of fuel use is equal to the rate of work divided by the useable energy density of the fuel. The energy density of diesel, the most common fuel in use by military vehicles, is greater than 130,000 BTU per gallon.[43] The useable energy density of fuel is determined by multiplying the efficiency of the engine times the energy density of the fuel. In the case of diesel engines, efficiencies of 32% can be obtained.[44] However, a more conservative assumption of 20% efficiency will be used for our calculation here. The rate of fuel use equation from background theory equation 59 is as follows:

$$\text{Fuel}_{rate} = \left(\frac{1}{\eta}\right) \cdot \frac{W_{rate}}{E_{density}}, \tag{59}$$

where η is the efficiency of the engine, W_{rate} is the rate of work as calculated above, and $E_{density}$ is the energy density of the fuel. In the case of minimal leakage (1,500 cfm), the rate of fuel use is ½ a gallon of diesel per day; but, in the case of leakage caused by a large opening (48,000 cfm), the rate of fuel use is 18 gallons of diesel per day ($0.553\frac{\text{gal}}{\text{day}} \le \text{Fuel}_{rate} \le 17.71\frac{\text{gal}}{\text{day}}$). Although the cost of fuel in combat situations is expensive, even the most extreme of scenarios does not, at 18 gallons of diesel per day, yield a rate of fuel use that would make the automated command post a prohibitively expensive structure.

In estimating the actual expense of the fuel, we make use of the Army's overall budget numbers. Currently, "the Army goes through 200 million gallons of fuel a year, resulting in annual expenses of $3.5 billion, including transportation and labor."[45] A quick calculation shows that this results in an average cost of $17.5 per gallon of fuel. The maximum cost per day of maintaining an air supported structure using the fuel

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[43] "Energy density." *Wikipedia.* 02 May 2006 <http://en.wikipedia.org/wiki/Energy_density>.
[44] Ferreira, Omar Campos. *Efficiency of Internal Combustion Engines.* 01 May 2006 <http://ecen.com/content/eee7/motoref.htm>.
[45] Erwin, Sandra I.. "Army's Next Battle: Fuel, Transportation Costs." *National Defense Magazine.* Apr 2002. <http://www.nationaldefensemagazine.org/issues/2002/Apr/Armys_Next.htm>.

consumption requirement and the average cost of fuel calculated above would be $310, and the more likely cost given normal operation with a leakage rate at the recommended level for ventilation using the calculations above would be $9.68 per day. Overall, it appears that the cost of maintaining an air supported structure is a small price to pay in order to reduce the total set-up and take down time of the main command post structure and thereby render it more effective in the fast paced modern day battlefield.

Another concern that must be addressed when choosing an air supported structure is the generic robustness of design (i.e. how resistant is the structure to bullet impacts and how reparable is it). This question, in the case of the air supported structure, is partially answered given the above calculations of energy cost. A large hole of twenty-one square feet (the equivalent of a 3' x 7' doorway) did not raise the rate of airflow required to maintain the structural integrity of the structure beyond a reasonable level for a blower system to be designed to provide. Therefore, it follows that an air supported structure would be robust enough to handle a moderate number of punctures to include bullet impacts before stability became an issue. A mechanical structure, however, can withstand any number of bullet impacts and punctures within its membrane shell without any impact on functionality. That said, if a bullet or shrapnel impact hits a structural support, it may be difficult to dismantle the structure for displacement until the joint is repaired. Repair times for most mechanical structures can take from one hour to three hours depending upon the extent and type of damage. The air supported tent would never need to be repaired in order to displace and most punctures could be repaired with a simple patch at a time that is convenient for the headquarters element. Holes can be easily identified at night by looking for light escaping the tent and then sealing the holes which are found. If no light is escaping, then the hole is not large enough to matter.

The air supported structure is clearly a good alternative to a purely mechanical structure because of its ability to more fully integrate the camouflage netting and the wiring within the structure. This integration results in reduced set-up and take down times for air supported structures. There is also an added robustness of the air supported structure in terms of vulnerability to gunshots or other mishaps. Additionally, the negative aspect of enhanced energy cost is not large; especially when compared to the benefits. However, in an effort to not gloss over this subject entirely, it is important to explore other alternatives to the air supported or mechanical structure.

The air inflated structure is a structure that is erected and maintained by a double membrane filled with air at a positive gauge pressure. This usually takes the form of supporting tubes filled with air. An example of an air inflated structure can be seen in figure 23.

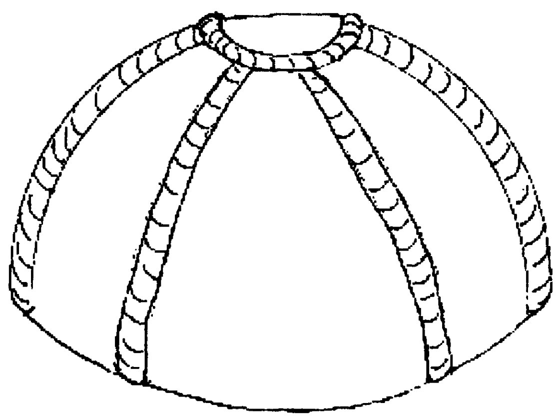

Figure 23: An air inflated structure with airbeam ribs providing the main structural support

Air inflated structures possess many of the same benefits as the air supported structures investigated thus far. They have the same flexibility of set-up and take down such that internal wiring and external camouflage netting can be integrated into the design; however, an air inflated structure requires much less energy to maintain than an air supported design because it has a very low volumetric rate of air leakage. In spite of these positive aspects, the air inflated structure shares one weakness with the mechanical structure in that it is more susceptible to failure due to disruption or puncture of the supporting air beams. A simple compartmental design can reduce the impact of this type of event on the structural stability of the command post tent. Figure 24 graphically depicts this compartmentalization concept. Air inflated structures and this type of compartmentalization in particular present a difficulty in repair. As in the air supported structure, holes can easily be repaired with a patch; however, identification and access to the hole is more difficult. Leaks may need to be identified with the aid of a soap and water, and the airbeams may need to be removable from the structure in order to effectively provide for reasonable repair.

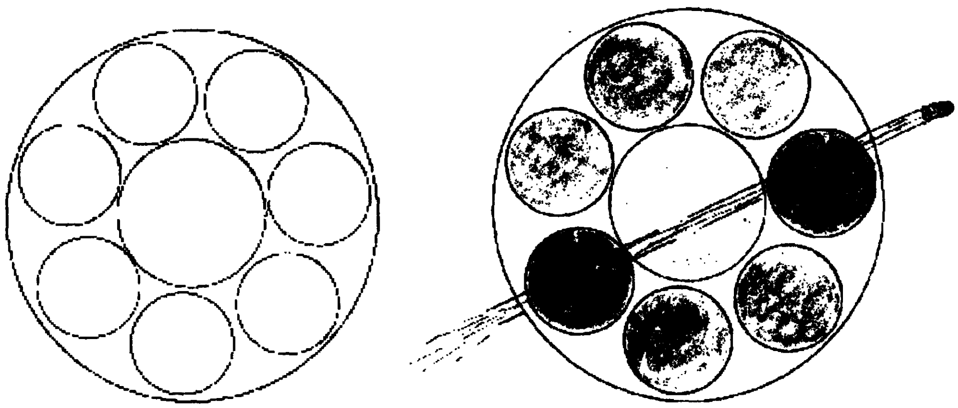

Figure 24: The basic compartmentalized airbeam concept (left). A graphical depiction of a catastrophic event puncturing an airbeam (right). The inner circle is a constraining fabric which presses the compartmentalized tubes against the outer wall. Regardless of the location of the bullet 57% of the airbeam's load bearing capacity remains unharmed.[46]

The air supported structure is the structure that affords the greatest flexibility and should be the primary design; however, in deference to the strengths of the air inflated structure, an alternative air inflated design with many of the same characteristics exhibited by the air supported design could easily be developed.

This section discussed the merits of three types of structures, and a summary of the findings in this section can be seen in the criteria alternative matrix presented in table 1 below.

Table 1: Results of overall structural design comparison.

Criteria / Design	Speed of Set-Up	Speed of Take Down	Energy Cost to Maintain	Robustness	Total
Mechanical	–	–	+	–	-2
Air Inflated	+	0	0	0	+1
[redacted]					

The mechanical design cannot integrate the setup or take-down components; thus it will definitely be the slowest to take down or to set-up. Also, the robustness of the

[46] Ochsendorf, John. Progress Meeting. 31 Mar 2006.

mechanical structure is a negative because failure of the mechanical members is highly likely due to the bunching of fabric. However, the mechanical design requires the lowest energy to maintain. The air inflated takes less energy to maintain than the air supported, but both take more energy than the mechanical design. Both air designs can be easily repaired with a patch; although, the air inflated design will require more work on average to find the leak that needs to be patched. The speed of set-up is very fast for both air designs, with the air inflated taking an advantage due to the lower volume of air required to complete the set-up process. Take down for the air supported design is faster because it is easier to create large pathways letting out the air during takedown. The long and skinny tubular nature of the ribbed air inflated design will tend to trap air during the take down thus making it more cumbersome and slower. This thesis will develop an air supported design as the primary source of mechanical support; however, many of the concepts could easily be transferred to an air inflated design if desired.

4.02 Choice of Shape

The shape chosen for the Automated Command Post must meet the requirements previously stated within this thesis and those newly explained here. Namely, it must be scaleable, modular, maximize usable space, and minimize stress concentrations in the fabric. These factors are presented below with the considerations for each.

4.02a Modularity

Not every command post structure or other application involving the use of the ACP will require the same usage of space as that required by the particular regimental headquarters with which the author has vast experience. Thus, great care must be taken to ensure that the design of the ACP is adaptable to other configurations. One method of providing flexibility of application in the design is to make the ACP modular. Three different sized modules are created in the design presented in this thesis; however, other modules could be created with different shapes in order to maximize the applicability of the ACP to other situations. The shapes of the three modules chosen are the same, scaled to different dimensions. This is done to provide flexibility with some degree of uniformity to simplify the analytical process. Figure 27 shows a cutaway of the three module sizes and shapes selected for the ACP.

4.02b Stress Concentrations

In order to simplify the calculation of the fabric stresses and to reduce the overall stress, the Automated Command Post (ACP) was designed from a combination of axisymmetric shells of revolution. Generally, there are limitations in the shape that an air-supported structure can take.[47] In reality, the only shape that a membrane can take with uniform stress conditions is a soap film shape; however, there are many soapbubble shapes. As the desired shape of the membrane deviates from a soap film shape, the stresses begin to differ and the equivalent stress increases. Taking this generalization one step further we can think of taking a sphere and slowly making it more and more cube like. As the spherical fabric cut is modified to approach the shape of a cube, stresses in the inflated membrane which are perpendicular and close to the "edges" increase. When the shape desired is a cube these stresses perpendicular to the edges become theoretically infinite and the shape distorts until a rounded and pleated structure is formed.[48] The pleats are the result of local buckling in the shape as the stresses parallel to the edge approach zero and the stresses perpendicular approach infinity. A graphical representation of this phenomenon is shown in figure 25.

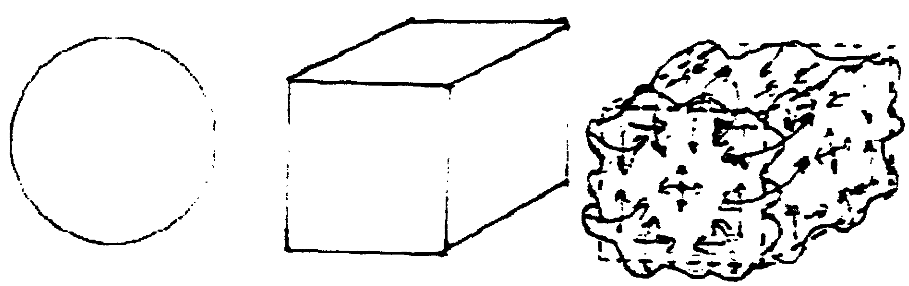

Figure 25: As the desired shape deviates from a sphere (left) the propensity for buckling increases. The originally cube shaped fabric structure (middle) experiences local buckling and distortion into a lumpy flattened sphere as it is pressurized (right).

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[47] Lutes, D. A. "CBD-137. Air-Supported Structures." *Canadian Biulders Digest.* May 1971. National Research Council Canada. 01 May 2006 <http://irc.nrc-cnrc.gc.ca/pubs/cbd/cbd137_e.html>.
[48] "Air Supported Structures." 01 May 2006 <http://www-ec.njit.edu/civil/fabric/air.html>.

Extreme deviations from a soap film shape will distort upon pressurization and exhibit undesirable stress concentrations. D.A. Lutes writes in the Canadian Builders Digest that "every point in the surface of ... [an air supported membrane] ... must be in equilibrium under the loads imposed. If these conditions are not provided by design and patterning, the envelope will wrinkle and distort until equilibrium conditions are established. Distortion of this type results not only in poor appearance but also in stress concentrations that could result in failure of the structure."[49]

The ACP makes use of a shape combination that results in a stress discontinuity at the joint of the two shapes. The bottom cylinder will tend to press outward to a greater degree than the ellipsoid top does. In fact, application of equations 9,10 and 13,14 yields the following graph shown in figure 26.

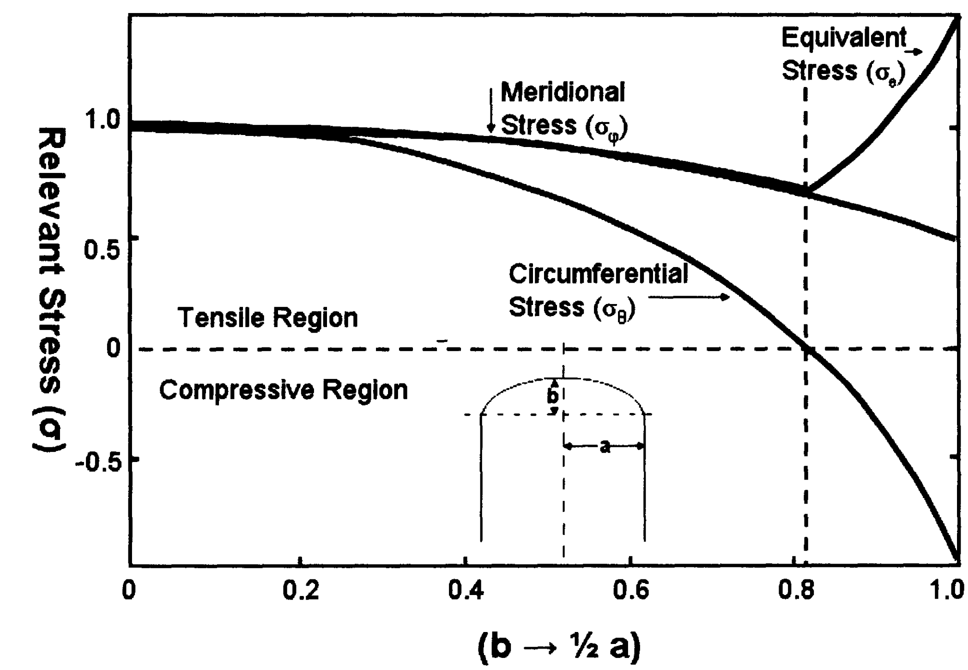

Figure 26: As the radius of ellipsoid rotation approaches ½ the radius of the cylinder to which it is joined the circumferential stresses decrease and become negative. Since the fabric cannot sustain a compression stress, ellipsoid end caps are constrained to not be any flatter than $b = a / \sqrt{2}$. Values of b which are smaller than this constraint result in pleating of the membrane surface and a resultant weakening of the structure.[50]

[49] Lutes, D. A. "CBD-137. Air-Supported Structures." *Canadian Biulders Digest.* May 1971. National Research Council Canada. 01 May 2006 <http://irc.nrc-cnrc.gc.ca/pubs/cbd/cbd137_e.html>.

[50] Wright, Douglas. Thin Shells of Revolution - Heads. May 01 2005, Notes on Design and Analysis of Machine Elements: <http://www.mech.uwa.edu.au/DANotes/pressVessels/shells/shells.html>

The cylinder will have a greater circumferential stress at the point of the seam than does the ellipsoid and this leads to a stress concentration around this seam. However, the stress concentration does not propagate far. The stress concentration becomes "insignificant at a distance of about five times the wall thickness from the junction."[51] The benefit of useable space as discussed in the next section explains more fully why this particular discontinuous stress shape was used.

In the development of the ACP, it is assumed that the principle sources of fabric stress are the internal air pressure and the self-weight stresses. Although, "both wind-induced and self weight stresses ...for the sizes of domes generally encountered in practice ... are of relatively low magnitudes, wind-induced effects are noted to be less important that self-weight effects." This result is applicable to any variation of dome geometry which is not slender (high height to base radius ratio); thus, "one would therefore be justified in ignoring wind effects in preliminary design."[52] The derivations for the self weight and internal air pressure stress factors are presented in the background theory section of this thesis.

Setting θ equal to zero, φ equal to π, u equal to 1, and t equal to 1mm in equations 9,10, 13,14, and 18,19 the values for the maximum fabric stress can be calculated as follows: Cylinder circumferential stresses are: self-weight (0) and internal pressure ($\sigma_\theta = p \cdot \frac{D}{2 \cdot t}$); meridional stresses are: self-weight ($\sigma_{\phi g} = \frac{h \cdot W}{t}$) and internal pressure ($\sigma_\phi = \frac{\sigma_\theta}{2}$). Ellipsoid top circumferential stresses are: self-weight (0) and internal pressure ($\sigma_\theta = \sigma_\phi$); meridional stresses are: self-weight ($\sigma_{\phi g} = \frac{-W}{t} \cdot \frac{a^2}{b} \cdot (\cos(\pi))$) and internal pressure ($\sigma_\phi = \left(\frac{p \cdot a^2}{2 \cdot b \cdot t}\right)$). For the modules shown in figure 27, the equivalent stresses resulting from an internal pressure loading 0.036 psi and a self weight induced by fabric that weighs 20 oz per square yard (typical of impermeable fabrics) are shown in table 2.

Given that a usual value for the tensile strength of fabric used in air supported membrane is 1.5×10^8 N/m^2, the stresses calculated in table 2 do not require special care in fabric

[51] Wright, Douglas. Thin Shells of Revolution - Heads. May 01 2005, Notes on Design and Analysis of Machine Elements: <http://www.mech.uwa.edu.au/DANotes/pressVessels/shells/shells.html>
[52] 118-119 shell stuctures

selection or reinforcement. The shape chosen for the ACP does not create unmanageable stresses within the enclosing fabric.

Table 2: Calculated and equivalent stresses in Automated Command Post by module size due to internal pressure and self weight. All values are in 10^5 Pascal.

All values (1×10^5 N/m^2)	**Stress Derivative**	**Internal Pressure (σ_p)**		**Self Weight (σ_g)**		**Equivalent Stress (σ_e)**
Module Size	***ACP Component***	σ_θ	σ_φ	σ_φ	σ_θ	σ_e
Main Module	***Ellipsoid Top***	5.04	5.04	0.27	-	7.33
	Cylindrical Bottom	7.57	3.78	0.12	-	9.00
Intermediate Module	***Ellipsoid Top***	3.78	3.78	0.20	-	5.50
	Cylindrical Bottom	5.67	2.84	0.12	-	6.78
Annex Module	***Ellipsoid Top***	3.03	3.03	0.16	-	4.40
	Cylindrical Bottom	4.54	2.27	0.12	-	5.45

4.02c Usable space

The sphere is a shape that has uniform stress, and, consequently, one of the lowest stress values. But the sphere does not provide a very effective use of space and results in a much larger structure than desired. Although the half sphere is the simplest shape to analyze, the hemispherical dome requires a larger base to provide a space that is useable in terms of height. In order to create a useable height quickly, each command post module was placed on a cylindrical base of a 6 foot height. This will still prove to make doorways low and cumbersome for use, however, it is the minimum height that provides relatively good functionality. The height should be kept as low as possible to aid in camouflage and to provide lower values of wind disturbance. Because of this, the minimum functional height was selected. Figure 27 shows the cross sectional view of the three modules created with this concept and the relevant dimensions for each. The ellipsoid tops were chosen to keep the overall height of the structure as low as possible while still keeping stress concentrations low. As was shown in the above analysis, the maximum equivalent stress within the fabric is much lower than the tensile strength of most commonly used fabrics.

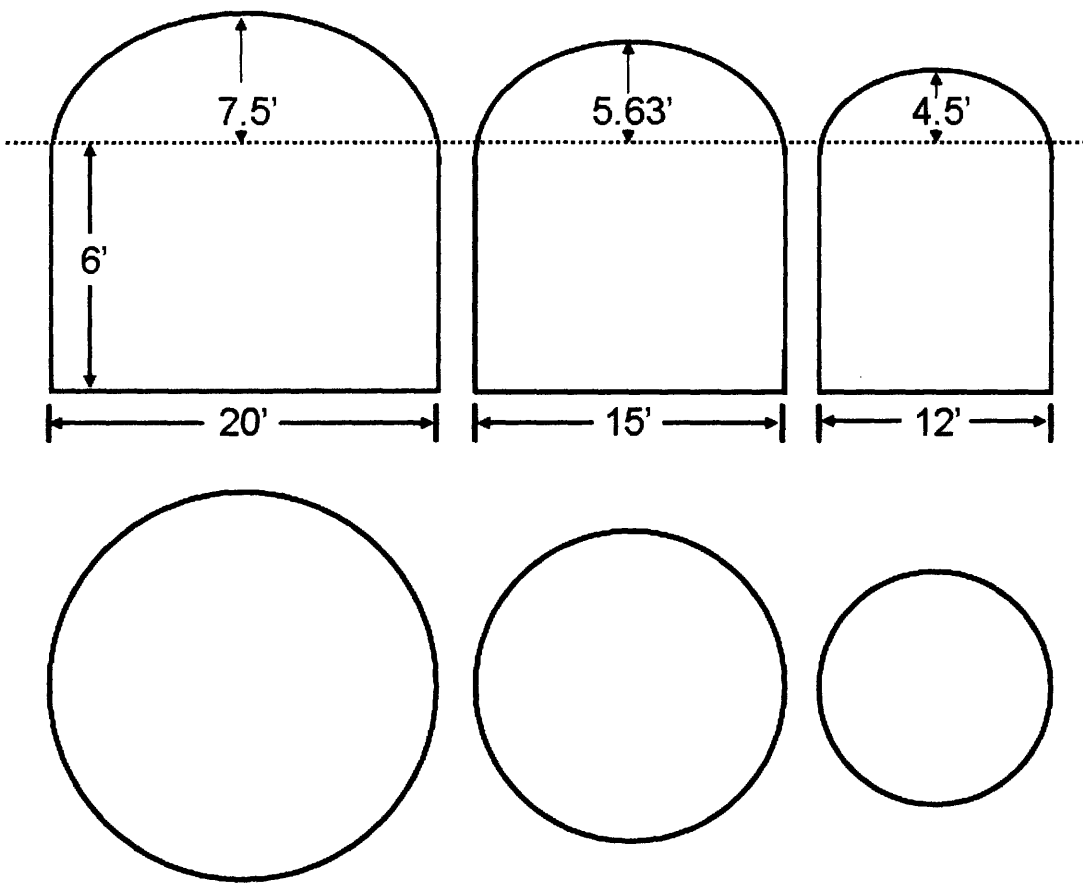

Figure 27: The shape of the automated command post modules. The main module on the left is the nexus to which the other modules attach.

4.03 Anchorage Design

There are many methods used to anchor air supported structures. And although many of these methods possess significant advantages in stress concentration and holdown capability, most do not possess the flexibility required for the Automated Command Post. The ACP requires fast emplacement anchors with the flexibility to fold up with every re-packaging. In addition to versatile anchoring, the ACP requires a rather large pound per foot of perimeter anchorage capability.

The anchorage holdown requirements are primarily determined by the effect of wind loading which provides, by far, the largest upward forces. Equations 33 and 75 allow us to solve for the uplift from internal and wind pressure that the anchorage needs to counteract. If we take the value of the internal pressure of a 20 ounce per square yard fabric to be the nominal 0.036 psi, and design for a 75 mph wind load, we arrive at the value of 300 pounds of anchorage equivalent per foot of perimeter. This value includes a standard safety factor of three, and it is in line with the Canadian Builders Digest's figure of "234 lb per ft of perimeter" with similar values of fabric weight and internal pressure along with a 60 mph wind load.[53]

The 300 lbs/ft of anchorage will be provided in a dual manner using a catenary cable with stake anchors and a fabric sleeve with sandbags to provide the necessary anchorage in as little time as possible. Figure 28 shows this dual system along a section of ACP perimeter.

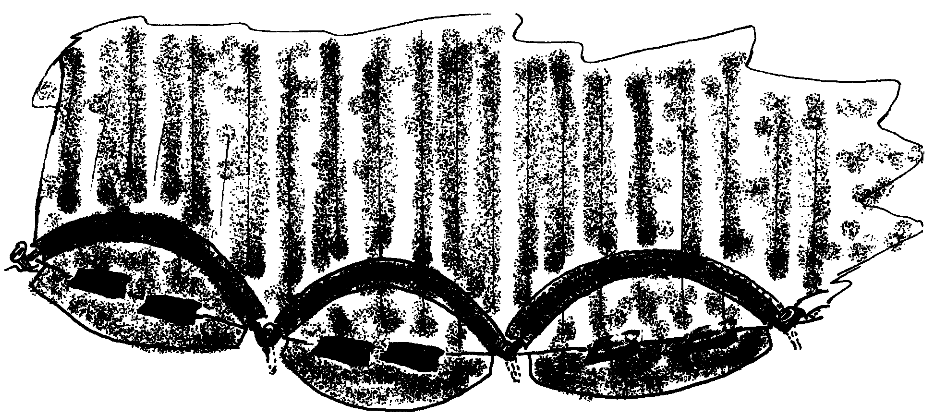

Figure 28: Dual anchorage system. Catenary cable staked to the ground and fabric tabs with sandbags between arcs.

The actual spacing of the catenary cables and fabric tabs will be dependent upon the holding capability of the stake anchors. The variations in stake holding capability by shape and soil type are not discussed here. The initial estimate of stake and sandbag density is one stake per yard with two sandbags placed between each stake. This would equate to an equivalent holding capability of 700 lbs per stake with 100 lbs per sandbag. This is a slight overestimate of soft soil holding potential; however, it is an appropriate estimate for average soil types and stakes at sufficient depth (18-24").

[53] Lutes, D. A. "CBD-137. Air-Supported Structures." *Canadian Biulders Digest.* May 1971. National Research Council Canada. 01 May 2006 <http://irc.nrc-cnrc.gc.ca/pubs/cbd/cbd137_e.html>.

4.04 Access Design

This thesis does not go into great detail when describing the access design of the Automated Command Post; however, a few things must be noted. The following port types are required: outside doorways, integrated vehicle ports, and connected module ports. Each of these ports should contain the same components or meshing apparatus in order to allow the greatest degree of reconfiguration and module use. The theoretical stress concentrations created in the fabric by ports is not elaborated on here; however, the basic shape presented here is the functionally required shape to insure constant stress throughout the ACP membrane around the access port. Figure 29 shows a basic concept for the tri-connection port.

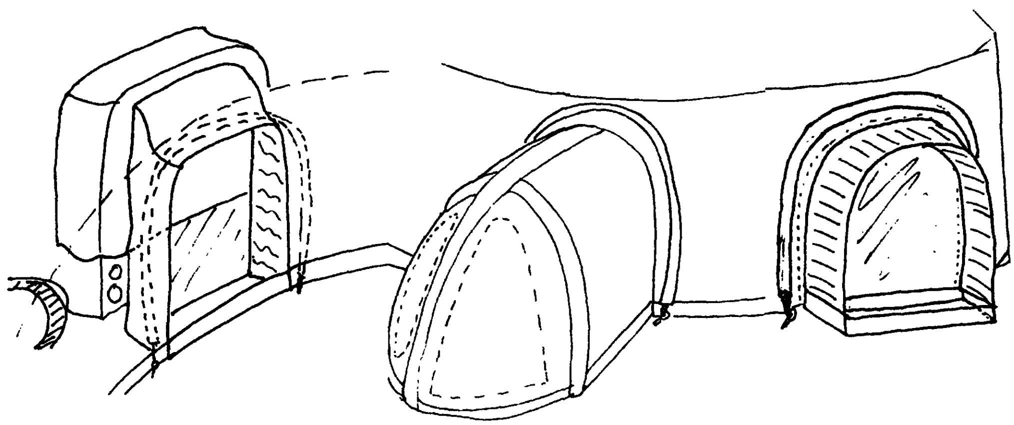

Figure 29: The three access ports are: a HMMWV connector boot (left), an air beam supported air lock (middle), and a module to module connection (right). Notice that the main seal is the same for all three access ports with a fabric enclosed cable hoop designed to eliminate the propagation of stresses into the seal attachment interface. This enclosed cable will also reduce any stress concentrations that would otherwise occur.

The main module will have eight ports, the secondary module has four, and the smallest module has three. The particular modular configuration suggested with this design is presented in the conclusion.

In addition to ports, the interior of the ACP must allow flexibility in layout and design. Wall separators and dividers should be capable of multiple Velcro configurations, and there should be a plethora of Velcro loops on the floor, walls, a ceiling to run power, audio visual, intranet, and communications cabling through. These loops will act as a semi-permanent attachment. Further detail on the access design is needed to ensure adequate ACP system design and performance. However, these details may require a full scale model to completely define and analyze. Further research into the access design is omitted here.

4.05 Inflation System

The blower inflation system was described as a constant pressure variable volume fan in the background theory section. In general, this is the ideal setup. For many air supported structures, the air leak potential and safety requirements dominate the inflation system design. This is also the case for the ACP. However, this may not be readily apparent. The need for fast setup times increases the importance of a heavy volume initial air flow during setup; thus, the time for filling is an important aspect of the blower system. However, upon calculation the rate of possible fluid flow escape as calculated in the energy cost section (48,000 cfm) is much higher than the volumetric flow rate required to initially inflate the ACP within a 5 minute time span.

The setup time of the ACP can be calculated to a first approximation as follows. The volume of the ellipsoid top to the ACP is found by:

$$V_{ellipsoid_i} = \frac{4}{3}\cdot\pi\cdot\left(a^2\right)_i\cdot b_i, \tag{76}$$

and the volume of the cylindrical bottom is found with:

$$V_{cylindrical_i} = \pi\left(a^2\right)_i\cdot h_i\,. \tag{77}$$

In the above equations, a_i, b_i, and h_i are the radius, height of ellipsoid, and height of cylinder of each ACP module (*i*), respectively. There are four ACP modules, or, in other words, *i* ranges from 0 to 3 ($i = 0..3$). The dimensional values for each ACP module is found in the corresponding i^{th} entry of the following matrices:

$$a = \begin{pmatrix} 10ft \\ 7.5ft \\ 7.5ft \\ 6ft \end{pmatrix} \text{ and } h = \begin{pmatrix} 6ft \\ 6ft \\ 6ft \\ 6ft \end{pmatrix} \text{ and } b = 0.75a \quad . \tag{78}$$

The volume of each Automated Command Post module can be found by taking one half the ellipsoid volume and adding it to the cylindrical volume for each module like the following:

$$V_{module_i} = V_{cylindrical_i} + \frac{1}{2} V_{ellipsoid_i}. \tag{79}$$

Then the overall ACP volume is found as the summation of each individual module volume like such:

$$V_{ACP} = \sum_{i=0}^{n} V_{module_j}, \text{ for } n = 3.$$

In the case of the above numbers for the proposed ACP, the volume of the ACP is 6,302 cubic feet ($V_{ACP} = 6.302 \times 10^3\ ft^3$). Therefore the average fill rate of a constant pressure variable volume blower as given by this equation:

$$Fill_{rate} = \frac{V_{ACP}}{fill_{time}}, \tag{80}$$

is 1,260 cfm ($Fill_{rate} = 1.26 \times 10^3 \frac{ft^3}{min}$) when the desired fill time is 5 min ($fill_{time} = 5mir$),

Although further articulation of the blower system is left for a future calculation, the above calculation shows that the flow rate required for a very short setup time is much smaller than that required to maintain the structure in the event of an open door (48,000 cfm). Thus, the following must be stated to make it clear the proper safety concerns have been addressed: In accordance with common practice, the inflation setup will include at least double the capacity needed to maintain structural stability under reasonable leak conditions as defined in the background theory because it has been found that the a doorway sized leak (hole) will create the need for a higher volumetric rate of flow than that required for rapid setup. The backup blower capacity should be set to automatically start upon experiencing a pressure drop. .

4.06 Thermal Shielding & Camouflage

The concept of camouflage generally applies to the application of deception principles to reduce the shear visibility of an object that has military importance. Visibility deception in the modern age also includes the reduction or scattering of thermal signatures of tactical military equipment and facilities. The purpose of camouflage techniques is to minimize detection from thermal imaging devices as well as to reduce the chances of sighting via more traditional visible light methods. For a command post, it is vital that it be protected from both overhead and ground based reconnaissance. Overhead reconnaissance has been less of a threat in recent years due to allied air superiority; however, to assume that every future battlespace will enjoy allied air superiority would be short sighted. Ground based reconnaissance is also a threat, even to rear based command structures; thus, proper side camouflaging techniques are required. This section focuses primarily on reducing the thermal signature of the command post. However, methods for visual recognition reduction based on camouflaging theory are also presented in this section.

Prior to discussing the methods of infrared signature reduction and the principles of visibility camouflage, it must be pointed out that there are three categories of thermal signature that a command post can exhibit. Figure 30 shows these three categories pictorially, and each will be discussed below.

Figure 30: The three possible infrared signatures of the ACP. The ACP could be hotter than the surrounding environment (left) or it could be close to the environmental temperature (middle), or it could be cooler than the environment (right).

In all three scenarios, the exterior command post vehicles will have a high heat signature. This vehicle signature is easier to see at night or during cold weather, but except in periods of a hot and high solar isolation like a summer desert day it is almost always detectible. Methods of disguising the signatures of the vehicles are not discussed here; although the principles utilized in this section could be applied to the vehicles as well. Because of the internal climate control, the command post itself will have two recognizable signatures that when the CP is hotter than the surroundings and that when it is colder. The two detectable categories of thermal signature that the command post exhibits may require different tactics to combat. This section focuses primarily on the reduction of the case in which the ACP is much hotter than the surrounding environment.

4.06a Ribbed Sides & Insulative Interior Panels

As shown in equation 71, one action that can be taken to reduce the thermal signature of the command post is to keep the surface temperature of the structure close to the same as the temperature of the surrounding air. Increasing the thermal resistance of the ACP wall will decrease the difference between the outside wall and ambient external air temperatures. One simple method for increasing the resistance of the ACP walls to thermal conduction is to pleat the wall surface allowing air pockets to form. Figure 31 shows a cross-sectional and three dimensional drawing of these air pocketed pleats. Without the pleats, the "coefficient of heat passage ... is approximately $k = 6.19\ W/m^2\ {}^oK$"; with the pleats, this coefficient is lowered to $k = 4.16\ W/m^2\ {}^oK$.[54]

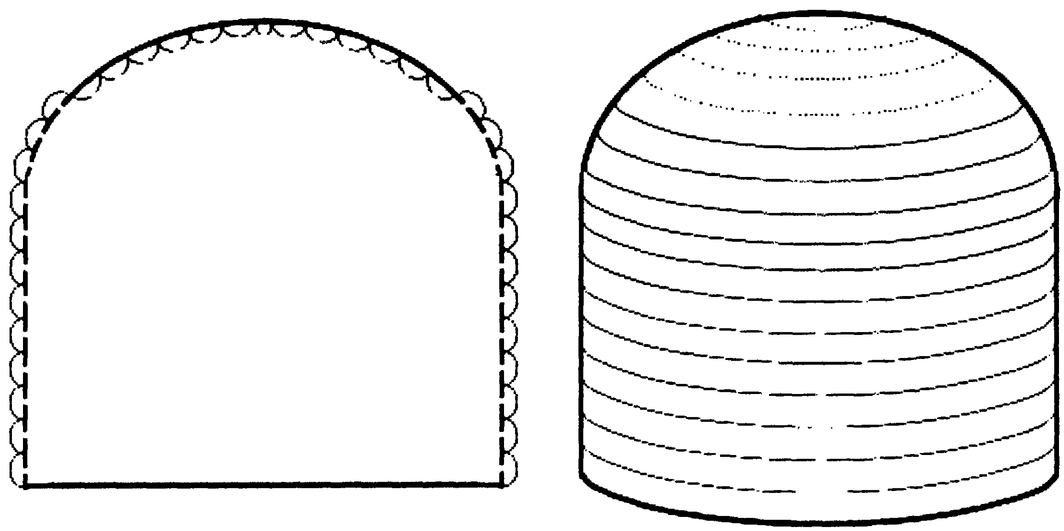

Figure 31: Cross-sectional (left) and 3-d view (right) of the ribbed outer wall design which lowers the coefficient of heat passage (k) by 2.03 $W/m^2\ {}^oK$.

[54] Firt, Vladimir. *Statics, Formfinding and Dynamics of Air-Supported Membrane Structures*. Boston: Martinus Nijhoff Publishers, 1983. pg: 20-22

Along the same line of reasoning, the coefficient of heat passage can be further reduced by affixing an insulative fabric layer at a small distance (r_{minus}) from the inside of the outer command post fabric wall. Figure 18 showed this layering concept during the derivation of the thermal flow exiting the command post in the background theory section of this thesis. A thin insulative layer attached 10 cm from the inside of the ACP fabric shell can further reduce the effective transmission of heat to approximately 3.08 W/m^2 ^{o}K.

Unfortunately, merely increasing the thermal resistance of the wall to conduction will not perfectly stop the transmittal of an infrared image from within the command structure. Even if the surface temperature of the ACP is exactly equal to the ambient temperature, a thermal signature could still be present. If there are objects within the command post at a temperature significantly higher than that of the outside environment, then "heat waves" usually in the infrared range of the electromagnetic spectrum will emanate from those objects and many of those waves will not be completely blocked by the existence of layered fabric insulation. These escaped infrared waves will create a large signature that is easily detected by external thermal imaging devices. Although hot objects within the command post will emit infrared radiation that travels through the walls and is visible to sensitive thermal imaging devices, this effect is reduced by the layered insulation. Furthermore, the application of a thin highly reflective layer within the ACP fabric wall could effectively reduce these radiative factors to a minimum by reflecting up to 97% of the infrared waves back into the command post. Figure 32 describes this concept of thermal signature blocking.

In spite of the positive effects of the reflective layer on reducing the flow of unwanted heat information into the environment, an unwanted side effect of the added reflective layer could be boosted isolative reflectivity. The amount of solar thermal energy reflected from the ground is roughly the same in a given area with similar soils. However, the automated command post with the internal reflective layer may not absorb the thermal radiation to the same degree as the local soils. Therefore, on brightly lit days with large amounts of sunshine the command post would stand out as a high thermal zone even if the signature did not posses any actual interior thermal information. The overall quantitative impacts of thermal image blocking using the above insulative concepts are not fully developed in this thesis. This does not pose a problem as thermal image blocking is a very low priority given that only a few countries field quality thermal sights to maneuvering elements. However, the thermal radiative factor must be considered in future refinements of this design.

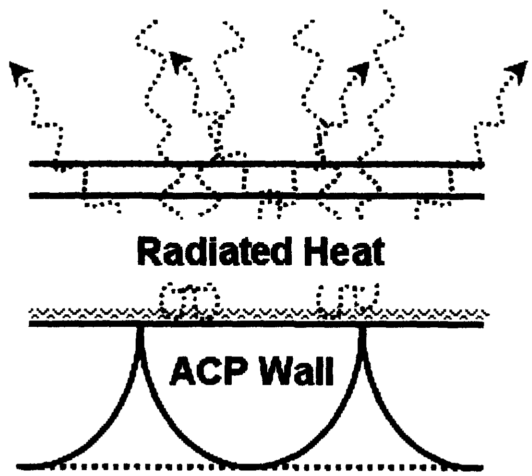

Figure 32: Inclusion of a thermally reflective layer in the fabric of the ACP may diminish the emitted thermal signature.

4.06b Integrated Camouflage Netting

The main factors which lead to visual recognition are: shape, shadows, texture, color, position, and movement.[55] Movement and position are factors that are situation dependent. However, the shape, shadows, and color of the command post are physically determined. Designing the shape, shadows, and color of the ACP specifically to maximize the ability to conceal the command post will increase the usefulness of the structure to military operations. Regardless of the surface color of the ACP, non-permeable fabrics such as those suitable for use in the ACP will have a smooth texture that yields an unnatural shine. This shine can most easily be mitigated by using standard camouflage netting applications over the ACP. In addition to the textural camouflage enhancements that the netting provides, the netting also aids in breaking up the regular shape of the ACP. The overall shape of the ACP is better than traditional box shaped tents in that the curved edges and resultant curved shadows are slightly more difficult to

[55] *Basic Warrior Training.* Camp Pendleton, CA: United States Marine Corps, 1998. pg: 5-1 to 5-11

detect than the more linear outlines of other command structures. However, the camouflage netting further breaks up the uniform shape and silhouette of the ACP thereby improving the degree to which the command facility blends in with the natural environment. Camouflage netting also provides the most proven and simplest guard against thermal imaging. Figure 33 shows actual photographs taken with and without camouflage netting. The degree of improvement and absolute necessity of the integrated netting is easy to see from these photos. The single most important application of camouflage in a command post is the camouflage netting.

In addition to being the single most important camouflaging application in terms of visual and thermal image deception, erection of the camouflage netting also comprises one of the largest time expenditures during the set-up process of a traditional command structure. Integrating this necessity into the setup process of the ACP will further enhance the many benefits of the ACP.

Figure 33: Light armored vehicle without camouflage netting (left), same vehicle with camouflage netting (middle), and the infrared image given with camouflage (right). The netting provides premier visual and thermal image disruption.[56]

The case has been made that it is imperative for the camouflage netting to be integrated with the ACP thus making the setup and takedown a simple one step procedure with items such as camouflage netting, power wiring, and network wiring integrated into one structural system. There are some concerns, however, that must be addressed with the integrated camouflage netting. Some of these concerns are expressed in the following section; however, this is by no means an exhaustive recount. Many items such as a

[56] "Military Camouflage Netting." *Cammo Net Home*. Alnet . 01 May 2006 <http://www.camouflage-fabric.com/camouflage-netting.shtml>.

numerical analysis of the shape and stress loading within the camouflage netting are left for further research.

In order for the camouflage netting to be integrated to the command post, it must be attached to the fabric of the ACP membrane. However, in order for the netting to be effective it must also be suspended as a layer that is three or more feet away from the surface of the outer surface of the command post. Plus, the netting will need the freedom to take non-uniform shapes allowing for maximum camouflage. These criteria are contradictory in nature.

Direct attachment of the netting to the command post membrane would yield the largest degree of integrated stability. Namely, the chances of undue stresses in the ACP membrane occurring because of misalignment of the camouflage netting would be null. But, the netting would not be of a flexible shape nor would it be suspended at least three feet from the structure surface. Attachment of the netting to the command post via cables would allow the required space; although, it would also decrease the stability of the integration. This cable attachment still does not provide for the desired shape flexibility as well. The cable attachment would, however, provide an inadvertent method of structural stability in the event of blower failure. If the blower that provides the ACP with the internal pressure difference fails, then the structure will slowly collapse. Attachment of the camouflage netting to the ACP via cables would allow the netting support poles to bear the self-weight of the structure as an emergency means of support.

However, using the netting poles as a means of emergency support dramatically increases the loading on these long and slender poles. By equation 36, the number of support poles will need to be increased thereby decreasing the amount of distance between the poles and decreasing the chance that a pole will buckle. Because the poles are tubular sections slid into each other, stress concentrations in the fitted edge further increase the chances of buckling for the poles. Increasing the number of support poles on the outer edge of each ACP module is relatively easy. But, increasing the number of support poles in the center of the support structure also increases the number of fabric sleeves that must be attached the ACP membrane, and, subsequently, increases the odds of a large leak propagating from a seal failure in the joining of the fabric sleeve.

These difficulties cannot be met with a single solution. The integrated camouflage netting design proposed here allows for most criteria to be met fully. This design is presented in figure 34. A single reinforced column will support the camouflage netting from the center of each ACP module, and standard netting poles will fringe the edges of these same modules. This single point of exit from the ACP leaves only one fabric sleeve and only one point with a high risk of forming a pressure leak. This area can be inspected regularly and repaired as necessary. Since the only true connection between the ACP and the camouflage netting is this single fabric sleeve, it is imperative that this sleeve be strong enough to withstand slight pressures during the deployment and re-deployment of the ACP. In the event of pressure failure, the ACP will slowly collapse around the single center pole. The resultant fabric stress will be less than that experienced during setup; thus, the sleeve should be rugged enough to withstand such an event.

Figure 34: Integrated netting design with single module. Midpoint is the single point of integration allowing ultimate speed and flexibility in set-up and takedown.

4.07 Designing Usage Enhancement

The Automated Command Post must be much more than just a tent which sets up fast. It must also be a working space that is conducive to information flow and transfer along natural and unused pathways. Creating such an architectural space in an air supported structure is by definition built into the structural design. This is because the shape and appearance of the structure directly affect its load bearing qualities. This section deals primarily with identifying the organizational composition of a command post and its respective internal communication flows. Once these have been identified, these aspects will be applied to produce a structure that emulates and supports these natural flows. It must be noted, however, that it is beneficial for the design of the structure to support flows of information that do not usually occur as well. In general, the more inter-coordination between cells in a command post, the better each individual cell can perform because they do not have to repeat work already done by another cell. However, one must be careful to allow cell autonomy as well; because, much of the work produced by a cell is more efficiently produced in the presence of a high density of that particular cell's members.

4.07a Organizational Structure of a Command Post

The overall organizational structure of a command post is based upon grouping by function. In fact, the generalization can be made stating that the military groups by function. In spite of this, the operation of a command post takes on more of an interdependent mixture of grouping by product and by function. The next section *Networks and Communication* will capture this unique phenomenon in preparation for its application to the physical design. A chart showing the defined organizational structure of a command post can be seen in figure 35. In the diagram, the structure is defined as a primary flow stemming from the commanding officer down to the functional groups. These flows are modified by the plans cell, which is usually headed by the executive officer or the S-3 (operations officer). The plans cell also possesses representatives from each of the other functional groups (these representatives are usually the primary officers which are referred to as the S-4 or the S-6 and so on). Equally important in the modification of this flow of power and direction from the commanding officer is the input from the company office which is headed by the company first sergeant. The plans cell usually modifies information pertaining to operational dynamics; whereas, the company office usually inputs structural order and rigid accountability. This particular function will be further explained in the next section.

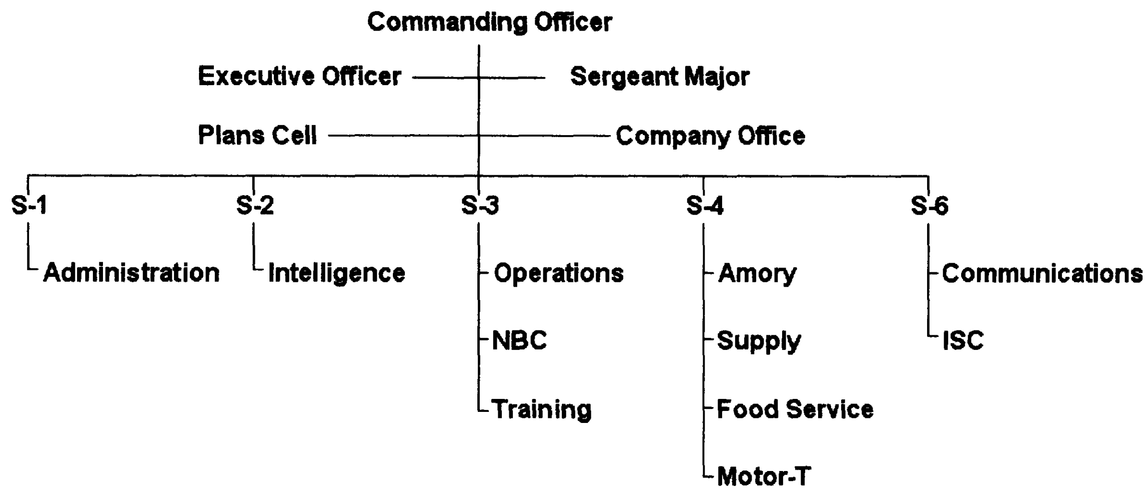

Figure 35: Organizational structure of a regimental sized command post.

Although the S-1, S-2, S-3, S-4, and S-6 shops integrally mean: administration, intelligence, operations, logistics, and communications; in Figure 35, they refer to the primary officer in charge of each of these groups. The representative groupings beneath each of these primary officers are the functional groups that they direct. Many of the groupings beneath the primary officers are composed mostly of enlisted personnel; however, this is not the only case. Nuclear, Biological, and Chemical (NBC) has a top officer as does supply just to give two examples.

Overall, the organizational structure of a command post is hierarchically flat with much opportunity for decentralized inter-coordination.[57] The plans cell with its membership composed of the top S-shop leaders could be viewed as forming a partial matrix organization with the way it influences command post proceedings. This is an oddity because the members of the plans cell are also the members of the standard hierarchy. In spite of this, the resulting influences of the plans cell are distinctly different from those directed through the normal flow of authority. The figure above does not pictorially depict this concept of a partial matrix organization formed by redundant tasking of leaders; however, some of the interconnections in the network diagram presented in the next section reflect this occurrence in principle. There are not many conclusions that can

[57] Greenberg, Jerald. *Managing Behavior in Organizations*. 4th. Upper Saddle River, NJ: Pearson Prentice Hall, 2005.

be drawn as to what the best architectural command post configuration is based on the organizational structure, but defining the structure does yield some useful insight into the inter-workings of the command post thereby giving a frame through which the network and communications patterns can be interpreted.

4.07b Networks and Communication

Often the overall picture of how an organization works cannot be fully understood from the organizational chart. Much of the operational dynamics are better explained by looking at a network chart which depicts the flow of information and reliance within an organization without regard to the hierarchy.[58] The author's depiction of the regimental command post network is presented in figure 36. The architectural space within the command post should be designed to inherently support this existing information flow and provide for the formation of new interconnections thereby enhancing the overall performance of the Combat Operations Center (COC).

The flow of information depicted by the diagram reflects the author's observations in conducting command post activity. Many of the interconnections are the same from commander to commander or from shop leader to shop leader. However, some of the interconnections depicted here do not occur with certain figures in particular positions within the structure of the headquarters element. The diagram is not intended to show the absolute flow of information at any given time; rather, it depicts what is a representative flow at any given time. For example, one commanding officer may never formulate a direct pathway for information flow to the intelligence, operations, or NBC sections as depicted by the dotted line. He instead may deal only with the primary officers of the S-2 and S-3 sections, respectively. Another commanding officer may form a strong information flow to the main section as well as with the primary officers thereby allowing a more complex flow of information.

[58] Krackhardt, David and Hanson, Jeffrey R. Informal Networks: The Company Behind the Chart, *Harvard Business School Publishing (Cases),* 93406, 1-8.)

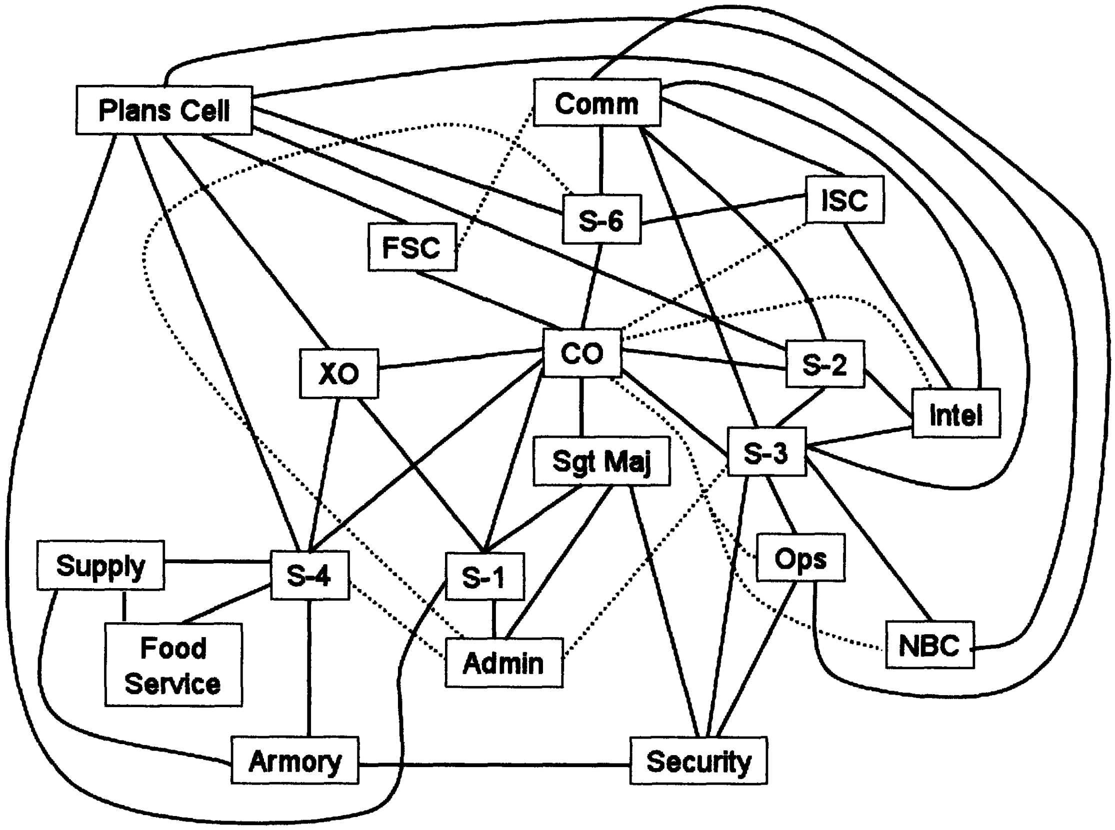

Figure 36: The informal network for a regimental command post. Some connections vary depending upon the people involved, but, the picture presented here captures much of the flow that is often observed. As with the hierarchy chart, the S-shop designators (like S-1 or S-3) refer to the primary officer in charge of that element; whereas, the shop descriptors (such as Intel or Admin) refer to the main body of that functional shop.

The later configuration for the commanding officer is advantageous because the degree of knowledge to which he is privy is greater than the former. However, this presents a complication for the primary shop officers in that they are not privy to all primary information flows. This complication is not necessarily a restriction on the performance of these primary figures, but it does require the development of a looser leadership style than some military leaders are comfortable with using.

In general, there is a heavy concentration of information flow around the S-3 (operations) and the S-2 (intelligence) sections with a heavy degree of communications and ISC (S-6) inter-reliance. This is something which would be difficult to discern from the organizational chart in the previous section. The network diagram can be used to find gatekeepers and key managers of information flow that are not evident in the organizational chart. For example, as mentioned in the previous section, the plans cell shows up just as dense as the commanding officer in terms of key contacts. This reflects the true nature of control over the internal operation of the command post that the plans cell has which is not reflected in the organizational chart. A more complete organizational chart would reflect this as a redundant partial matrix with a flow through the top from the commanding officer and a weaker flow through the side from the plans cell. This setup is redundant because the plans cell shares the same personnel as the primary leaders of the regimental headquarters without any real new outsider influence.

Other communications densities to notice are that of the S-3, communications, S-2, and intelligences rated at first, second, third, and fourth respectively. The density apparent around the S-4 is misleading because the flow around it is mostly internal to its own shop (see the organizational chart). Figure 37 shows a modified organizational chart which incorporates the network relationships in an effort to capture the active organization as it empirically operates.

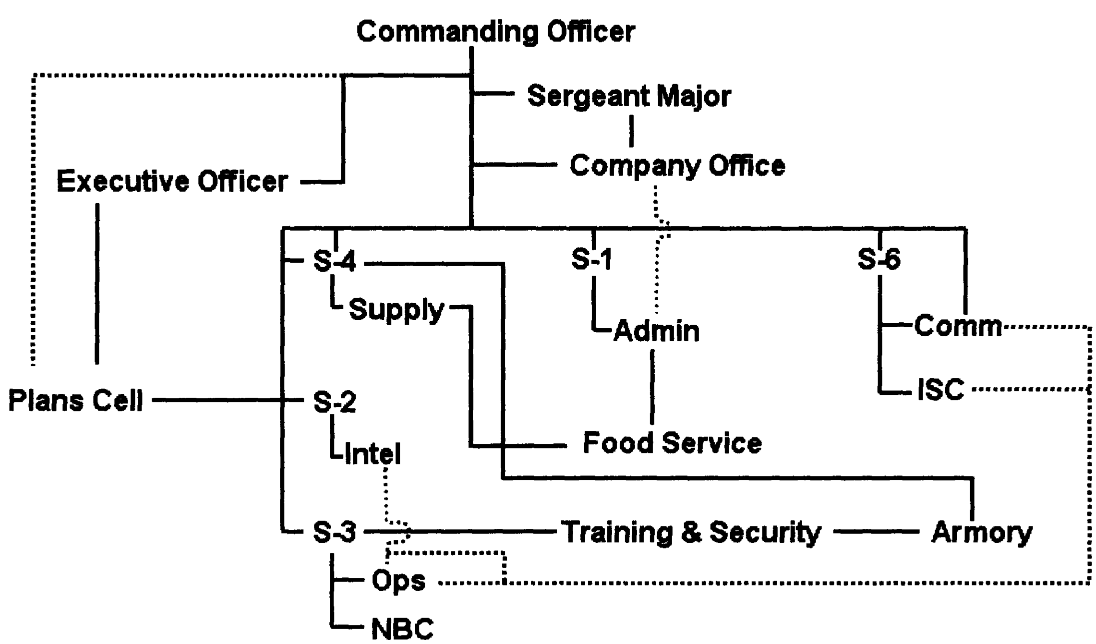

Figure 37: Modified organizational chart formed by combining the traditional organizational chart with the information network. This diagram depicts a more realistic image of the organizational structure of a regimental headquarters element.

4.07c Physical Space Enhancements

The physical space of the Automated Command Post must support and enhance the information network and the organizational hierarchy of the Combat Operations Center. "Designing knowledge space is a critical component of a knowledge management strategy. The designer needs to create a balance between privacy and exposure, recognizing that organizations, like cities, consist of two types of interactions – structural and human."[59] It is important to provide the space for integrated work as well as cells for shop specific activity. In order to maximize inter-communication the total distance between groups must be kept low; however, if the groups are placed to closely together then the efficiency of shop-specific expertise density is diminished. Figure 38 shows an empirical relationship found by Professor Thomas Allen of MIT's Sloan School of Management between the distance of work stations and the resultant probability of communication between those work stations.

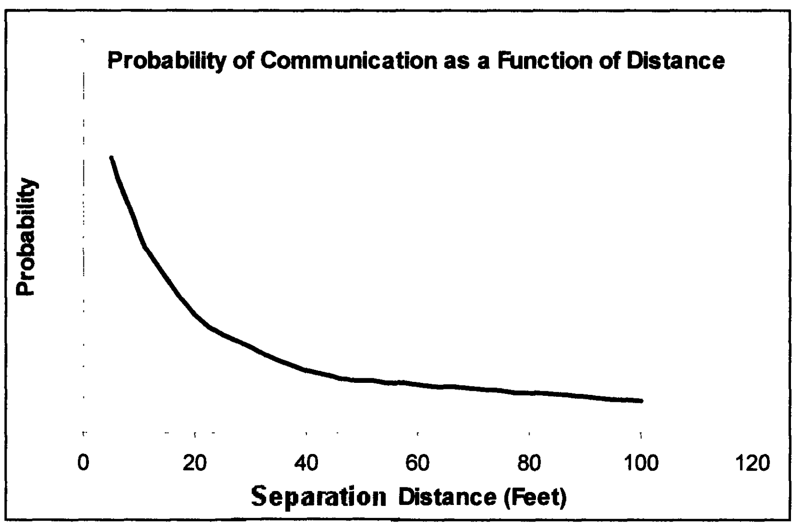

Figure 38: The empirical relationship between the distance at which workstations are placed apart and the probability of communication between operators of those workstations found by Professor Thomas Allen of MIT Sloan School of Management.[60]

[59] Ward, Victoria. "Can The Design of Physical Space Influence Collaboration?." *Pool Business & Marketing Strategy.* 01 May 2006 <http://www.poolonline.com/archive/issue8/iss8fea5.html>.
[60] Allen, Thomas . "Architecture and Communication." *Lecture Notes: MIT Sloan School of Managment.* MIT OpenCourseWare. 01 May 2006 <http://ocw.mit.edu/OcwWeb/Sloan-School-of-Management/15-990Fall2003/LectureNotes/index.htm>. Slide 95.

Using this as a guide, the Automated Command Post will place all coordinating workstations within 0-20 feet of each other in order to maximize coordinative activity. Additionally, the working cells will be placed more than 30 feet apart when possible to maximize in cell efficiency.

The layout of the command post is one of the few particulars of the COC which has changed the most in the author's experience. It is difficult to find the right balance between space and time to set-up. This effort to balance has led to many changes in internal formation. However, there are several common themes to most configurations used. These common themes in interior organization of the command post bear remarkable similarities to the network schematic formed in the previous section. This similarity in previous use to the network necessities is a manifestation of the artifacts of the command post culture. It is necessary to preserve these physical artifacts in the internal structure so as to not upset the balance of culture that drives the inner workings of the Combat Operations Center.[61] An initial concept with these themes emplaced can be found in figure 39. This schematic is not modular in formation; thus, it is not precisely representative of the formation that would need to be formed in order to accommodate the needs of other uses for the ACP. However, this representation is a great depiction of the ideal architectural set-up for a regimental headquarters command post. The interior schematic for the modular design is presented in the conclusion of this thesis.

[61] Schein, Edgar H. "Organizational Culture & Leadership." *notes compiled by Ted Nellen.* 01 May 2006 <http://www.tnellen.com/ted/tc/schein.html#10>.

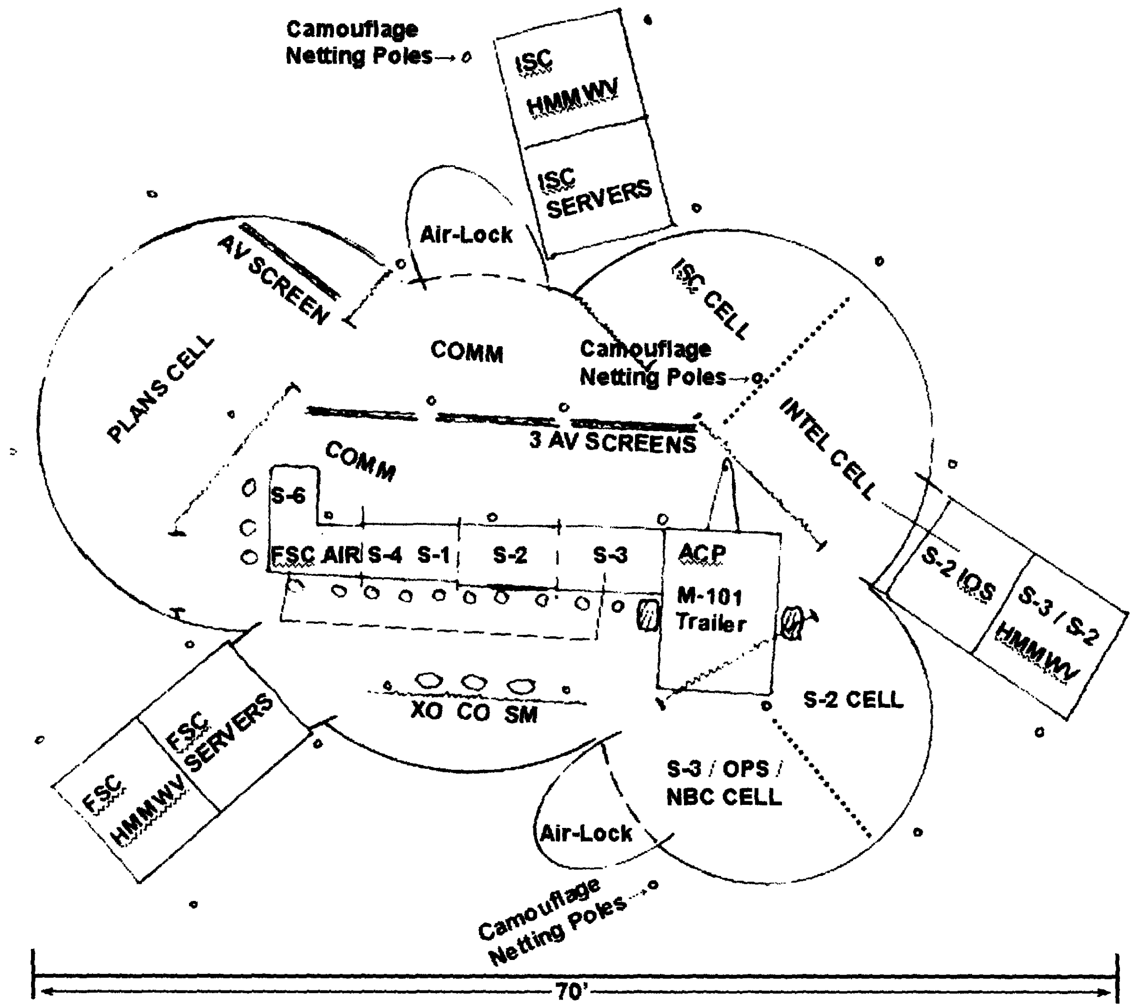

Figure 39: Initial concept of internal command post arrangement using the concepts outlined in the organizational and networking analysis.

5.0 Discussion

There are many elements of the Automated Command Post that have not been fully explored, and some of the areas presented within this thesis need further refinement. In spite of this, it is unlikely that the findings of the previous sections will be significantly changed with subsequent study. The next step in developing the ACP should be to conduct a numerical analysis and to draft the components in greater detail after confirming their final shape with the numerical analysis. Some other categories lacking detail are also presented for discussion in the following sub-sections.

5.01 Safety

The command post does not pose any significant catastrophic failure risk, and if it did experience such a failure it is not large enough to inflict serious harm to a conscious adult. There are numerous emergency exits located throughout the ACP as denoted by the final floor plan in the conclusion section, and the materials comprising the sides of the command post are non-flammable in design per the recommendations of international code. But, given a large enough fuel source the ACP wall is capable of melting. Thus, precautions should be taken to ensure that fuel sources are kept a reasonable distance from the walls of the ACP. Also, the ACP is not designed to withstand winds above 75 mph. It is possible to up this designed wind speed by increasing the internal air pressure; however, the camouflage netting and many other components of the CP are not rated for winds above 50 mph. In conditions of severe weather, the ACP should be deflated and C2 activities should be conducted from a safer location.

5.02 Theory

The theoretical model for the mechanical properties of the Automated Command Post often relies upon assumptions which may not hold for air supported structures like the one proposed here. Some of these assumptions have been carried over from the Love-

Kirchoff assumptions.[62] In particular, the mathematical model for fabric stress relies upon the following assumptions[63]:

1) $r/t \geq 10$ with t being uniform and constant

2) The applied pressure, p, is the gage pressure (p = absolute pressure – atm pressure)

3) Material is linear-elastic, isotropic and homogeneous.

4) Stress distributions throughout the wall thickness will not vary

5) Element of interest is remote from geometric discontinuities

6) Working fluid has negligible weight

In the most exact sense, many of these assumptions are generally invalid for air supported structures; however, upon closer examination, these assumptions are often close enough to be acceptable. As for assumption 1, the thickness of the fabric is consistent enough to be considered uniform and the ratio r/t is much greater than ten. In fact, r/t is on the order of 10^3; and, because of this very thin wall, the stress distribution through the wall thickness is non variant and biaxial in nature. Assumption 3 is by far the worst. Air supported membrane structures are in general non-linear because the fabric stress-strain relationship is usually non-linear.[64] Figure 40, from *Pneumatic Structures: A Handbook on Inflatable Architecture*, shows the results of fabric loading tests. The empirically measured data shows the non-linearity of fabric in both uniaxial and biaxial loading. In spite of this, for relatively low gauge pressures and sufficiently stiff fabrics the linear assumption is a good approximation. Assumption 4 is directly tied to the thin walled assumption and is more precise for thinner walls than for thicker ones. Finally, assumption 6 is only valid for smaller structures in relatively mild dynamic situations. In static analysis, the mass of the air contained within the structure does not have any impact on the analysis. Thus, this model is acceptable for static load analysis; however, under dynamic impact this is not always the case. Because the ACP is small, the mass of the air

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[62] Zingoni, Alphose. *Shell Structures in Civil and Mechanical Engineering*. Oxford: Thomas Telford, 1997. pg: 11

[63] "Pressure Vessels: Combined Stresses." Washington Mechanical Engineering. 01 May 2006 <http://courses.washington.edu/me354a/chap12.pdf>.

[64] Dietz, A. E., and Proffitt, R. B. and Chabot, R.S. and Moak, E. L.. *Wind Tunnel Test and Analyses for Ground-Mounted Air- Supported Structures*.Technical Report 70-7-GP. Natick, MA: U.S. Army Natick Laboratory, 1969. pg: 110

used to inflate the ACP is roughly less than 10^2 Kg. This mass is insignificant except in the most pronounced of dynamic situations.

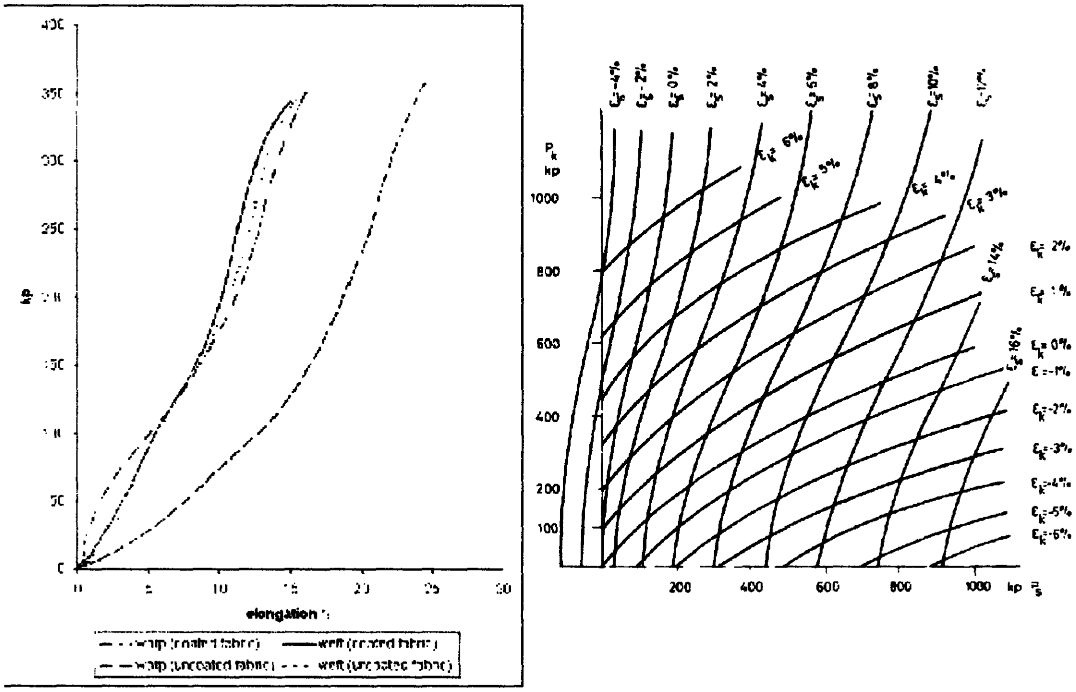

Figure 40: Stress-strain curve for a coated and uncoated polyester fabric specimen under uniaxial tension (left), and biaxial tension (right).[65]

5.03 Design, Analysis, & Mechanics Modeling

For the most part, classic mechanics modeling was used to examine the capabilities of the designed system. As stated previously, the next step will be to subject scale models to tests and to conduct a numerical analysis of the ACP design presented in this thesis. In addition to the mechanics modeling, the development of a longevity model could prove useful in predicting the overall cost of the ACP. Other field test could also yield key insight into some unfinished topics within this thesis. In particular, test of the infrared thermal blocking capability of the ACP with still photos over a period of time should be conducted with various parameters adjusted. Usage studies with an operating headquarters could also help identify flaws in the design and provide solutions for a better configuration that would otherwise be unapparent. These and other studies should be conducted to finish the beginning which is presented here.

[65] Herzog, Thomas. *Pneumatic Stuctures*. New York: Oxford University Press, 1976. pg: 140

6.0 Conclusion

Today's battlespace is the most dynamic in recorded history. This rapid movement was seen in the record breaking front line advances of Operation Iraqi Freedom during 2003. It is in part made possible through a deliberate tactical decision to bypass certain enemy elements thereby leaving them behind the Forward Edge of the Battle Area (FEBA), and in part due to advances in the mobility of tactical assets, in improved logistics support, and in digitized Command and Control (C2). This remarkable development in sustained troop mobility has been accompanied by a shift in Command and Control (C2) technology from paper maps and thumbtacks to digitized graphical displays and instant chat two-way communication. While military logistic support, battle maneuver, and C2 methodology have advanced, the deployable structures that house C2 assets have not. Much effort has been made to improve C2 shelters, and improve they have. Yet, it currently takes six times as long (average of three hours) to deploy a Command Post (CP) as it did eight years ago (average of one-half hour). This decline in performance comes at a time when the battlefield is the least forgiving of sluggishness. Retarded employment of command assets increases the distance between the command structure and the maneuvering elements that require fire-support and decision making capabilities from the CP. This increase in distance strains the ability of current communications thereby making linkage failure more likely. Additionally, slow deployment increases the hazard posed by the enemy contingent not neutralized by the forward military elements.

Each individual component of the CP is highly functioning and modernized; however, the primary reason CP structures are so slow to deploy is that many of the required elements of the command structure are designed separately to fulfill separate functions. Apart, they are quick and innovative. Together, they are cumbersome and labor intensive. The command structure must be viewed as a system that requires an encompassing solution. The functional elements of a CP must be analyzed and a comprehensive deployment structure designed to enhance the speed of Command Post establishment. The proposed design of this thesis, termed the Automated Command Post (ACP), is capable of a five minute deployment with ten additional minutes required to establish communication links. This is accomplished with an airflow rate of 1,200 cubic feet per minute an airflow rate 80 times less than that designed for in order to sustain air pressure in the event of a 21 square foot sidewall rupture.

The ACP establishes Command and Control in a mere fifteen minutes from start to finish; this is a 92% improvement over existing Command Post structures. The ACP is an air-supported structure that requires only ½ gallon of extra fuel per day to stay inflated, which at an average cost of $17.5 per gallon results in a daily cost of just $9.68 per day to maintain. The ACP also possesses the robustness required to withstand many rips, tears, and holes prior to needing repair. When the ACP requires repair, repair of the ACP is simple. Most holes and tears can be patched with a simple self-sealing patch. Larger tears can be fixed utilizing ready to apply sealant to a piece of extra repair fabric.

The recommended ACP layout as shown in figure 42 was constructed from an analysis of current command post layouts and an application of network theory in order to maximize the potential usefulness of the command structure with appropriately placed physical space. Many elements of the command post structure such as wiring, camouflage netting, and climate control are automatically integrated into the ACP, and the individual elements of the ACP are modular allowing for multiple configurations in addition to the recommended setup.

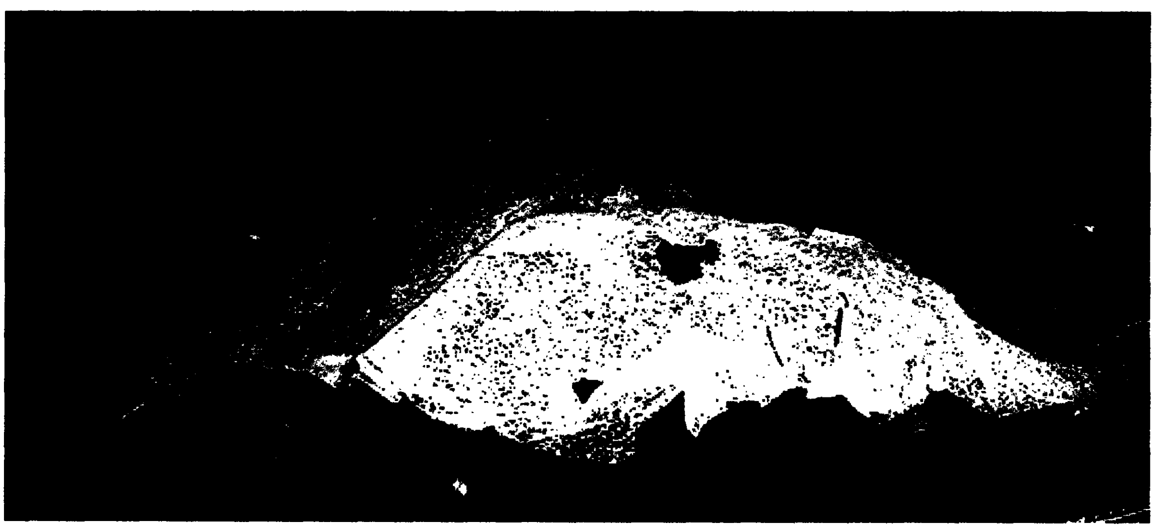

Figure 41: Model of the ACP with camouflage netting. View is of the plans cell (foremost left) with the main module (high peak to the right and below).

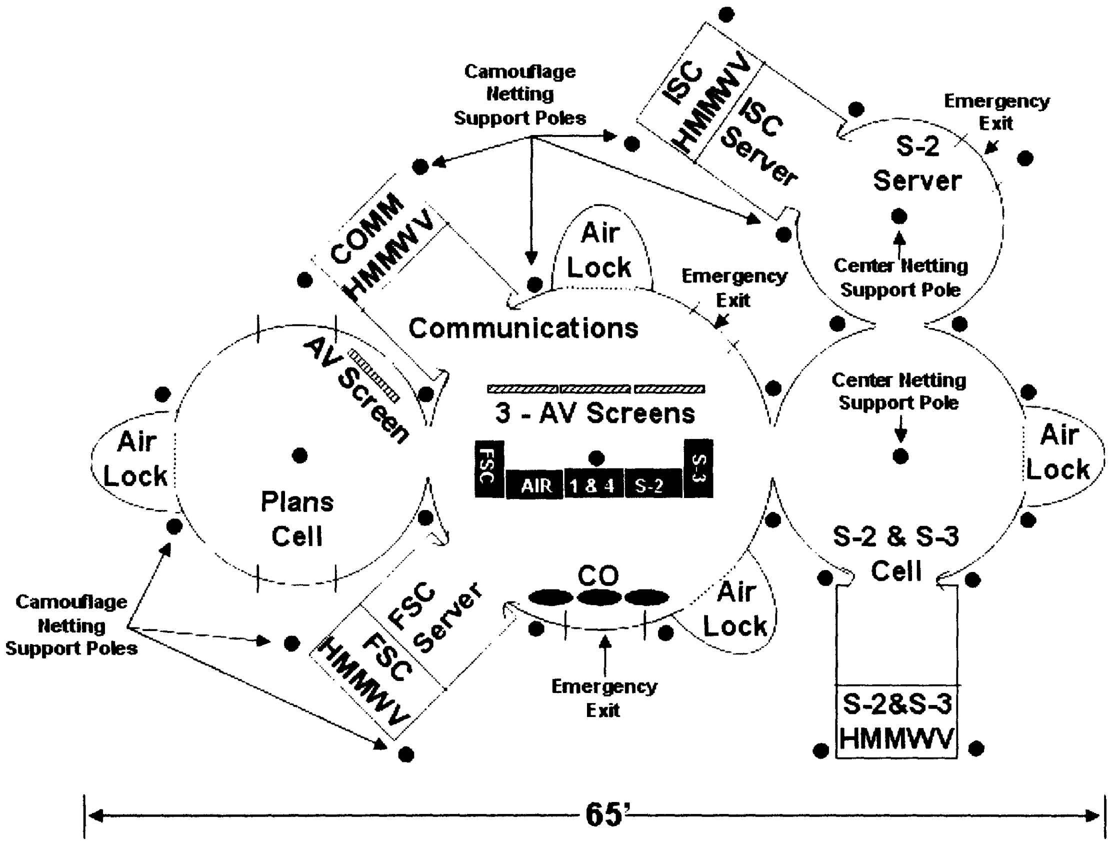

Figure 42: Layout of the Automated Command Post.

Figure 43: Side view of the ACP model with a cutaway view under the camouflage netting

Fabric stresses within the ACP were compared to the test value of most impermeable tent fabric and various load bearing calculations performed. With a nominal internal pressure of 0.0036 psi the ACP can be expected to withstand up to 75 mph winds without difficulty. The highest equivalent stress calculated was 9×10^5 N/m^2. Since many fabrics available for use as the membrane of the ACP possess an ultimate tensile strength of 1.5×10^8 N/m^2, the current ACP shape configuration is flexible and capable of higher internal pressures in order to withstand higher wind values and other modifications as necessary.

The ACP has significant anchorage requirements which are calculated at 300 lbs per foot for winds up to 75 mph. This anchorage is created through a catenary cable and ground anchor system with additional anchorage provided by fabric flaps and sandbag ballast. The ACP also has fire retardant fabric and very robust capability to sustain in spite of individual component mishap.

The Automated Command Post is the only Command Post structure designed with an integrated camouflage netting to ease setup and reduce the thermal signature of the CP facility. The integrated netting provides excellent visual camouflage as well by breaking up the outline and rouging out the texture of the ACP. With an internal gauge pressure of only 0.036 psi, the ACP is unnoticeably pressurized and climate controlled to enhance the operation of computerized assets. The future of Command and Control facilities is in rapidly deployable air supported structures like the ACP.

Figure 44: Overhead view of the Automated Command Post model with cutaway camouflage netting.

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