

Rapid Satellite Deployment of a Consumer Electronics Payload

Marit E. Meyer
Graduate Student

Dr. Michael Swartout
Faculty Advisor

Washington University in St. Louis, MO 63130

Currently, launching a satellite into orbit is plausible only for organizations with multi-million dollar budgets and requires three or more years for development and qualification. Small satellites traveling as secondary payloads on regularly scheduled launches provide access to space at a fraction of the cost and in a fraction of the time. However, a modular adaptable satellite container can significantly reduce cost and development schedule. By sealing and pressurizing the container to maintain an earthlike environment in orbit, a payload of unmodified terrestrial electronics can be integrated and launched in a matter of weeks. Such a container, SCUTE (Sealed Container for Universal Terrestrial Equipment), can provide a ride to space for K-12 educational experiments, research projects or electronic sensing and communication equipment. SCUTE can also enable military surveillance missions to be accomplished in a timely manner. A conceptual design investigation for SCUTE has been performed including benchmark designs and preliminary structural, thermal, and pressure loss analyses. This paper presents multiple design concepts for four different SCUTE attributes. The leading concept selected for thermal management is a forced air convection thermal switch (FACTS). Other SCUTE attributes selected for simplicity and compatibility with FACTS are the box configuration, an adjustable payload mounting shelf, and the use of air as the working fluid. These selected concepts are recommended for a preliminary design phase and more detailed analysis to make SCUTE a viable option for rapid and inexpensive access to space.

Introduction: Small Satellite Industry

At present, small satellites launched as secondary payloads provide the best access to space for many worthy endeavors. While this method is faster than the traditional large satellite paradigm, many industries and organizations still cannot benefit from the current small satellite industry. Secondary school science experiments and academic research projects may lack the budget or program longevity to reach orbit this way. Furthermore, the U.S. Department of Defense's goal of operationally responsive space (ORS) is to provide timely solutions to strategic space needs for the purpose of national security.¹ Communication and surveillance missions cannot be accomplished in a timely manner if space-qualified hardware must be designed and built for each individual mission. A modular container able to accommodate an unspecified payload of terrestrial electronics within a short integration time would make space more accessible for these and many other missions. Such a container, SCUTE (Sealed Container for Universal Terrestrial Equipment), has been developed and analyzed as a preliminary design concept. SCUTE maintains an interior earthlike environment for up to one year in low earth orbit (LEO). With further detailed design, analysis, and testing, SCUTE can potentially take a mission from

concept to orbit in weeks, once regular launch opportunities are established. An inventory of SCUTE modules can be kept available, and with only moderate engineering to adapt consumer electronic components to common interfaces, the payload will be provided with power and a thermal control system. Since SCUTE is pressurized, most unmodified terrestrial electronics will operate normally in this environment. Thus, the two major obstacles to reaching orbit—cost and engineering schedule—are greatly reduced with SCUTE.

Requirements/Design Constraints

The launch platform for SCUTE is the Evolved Expendable Launch Vehicle (EELV) Secondary Payload Adapter (ESPA). This is the United States Air Force sponsored secondary payload transportation system for up to six secondary satellites per EELV launch. The launch conditions and size constraints for ESPA² have determined the allowable payload and many design criteria for SCUTE. Reasonable figures for payload power consumption and weight were chosen for a 'typical mission' of a small satellite. The resulting design constraints and attributes for SCUTE are in Table 1. The weight of SCUTE and its payload must not exceed 250 kg, and its overall size must be smaller

than the maximum secondary satellite dimensions on ESPA to allow for a range of spacecraft bus types. The maximum dimension of 60 cm is allowed, provided that the center of gravity of the fully integrated SCUTE is within the ESPA guidelines.

Table 1: SCUTE and Payload Design Constraints

SCUTE Attribute	Constraints
Weight	50 kg
Size	50 cm x 50 cm x 50 (or 60) cm
Internal Environment	Earthlike
Temperature	0° to 40° C for PEMs
Pressure	101.3 ± 10 kPa
EMI sealing	yes
Orbit	700 km, LEO
Lifetime	max 1 yr ground, 1 yr orbit
Payload Attribute	
Weight	up to 200 kg
Power Consumption	100 W
Consumer Electronics	Low power dissipation, good thermal packaging (low θ_{jc})
Thermal Design	
Vibration Resistance/ Packaging	Sensitive components ruggedized when possible

This dimension is reduced to 50 cm if this requirement cannot be met. The internal environment of SCUTE simulates earth, where consumer electronics operate at atmospheric pressure and in a temperature range from 0° to 40° C. The sealing method used to maintain atmospheric pressure should also incorporate an electro-magnetic interference (EMI) barrier.³ SCUTE is designed for a 700 km LEO with a maximum 2-year lifetime, consisting of up to 1 year ground storage after integration and up to 1 year in orbit. The payload can consume at most 100 W of power, but to protect against thermal failure and improve reliability, the plastic encapsulated microcircuits (PEMs) in the terrestrial electronics must not dissipate excessive waste heat. This can be managed by performing a thermal analysis of the payload electronics and avoiding PEM packages with a high junction-to-case resistance (θ_{jc}). Choosing ruggedized equipment when possible improves launch survival of sensitive components. Components can also be ruggedized during integration. Circuit card assemblies (CCAs) should be conformal coated with parylene to improve PEM reliability.⁴

The following ‘user needs’ outline the fundamental design objectives for SCUTE:

1. Structure shall survive launch
2. Temperature shall be controlled within allowable range
3. Atmospheric pressure shall be maintained
4. Interior layout shall be adaptable for integration of varying payloads

5. Sealing method shall allow for re-work and repair

The first three objectives are evaluated in three preliminary analyses: structural, thermal and pressure loss. The remaining objectives are explored with different design concepts. An unspecified payload adds complexity, particularly for integration and thermal control. Ease of integration depends on a mounting scheme that can accommodate many or few components in a range of sizes. The thermal control system must also be adaptable for varying quantities of consumer electronic components with different geometries and power dissipations. Additionally, in the event of a qualification test failure before launch, SCUTE must be easily opened for repair or re-work.

Benchmarks

Sealing and pressurizing a satellite is not a new idea. An informative step in the design process is to research existing hardware that meets objectives similar to those of SCUTE. Comparing these as benchmark designs sheds light on the objectives and requirements for SCUTE (Table 2). All benchmarks are containers that hold electronics comparable to a SCUTE payload, including one pressurized vehicle not designed for space. Evaluation of benchmarks is somewhat subjective and based on whether they meet user needs and can be launched on the ESPA (Table 3). The requirements are weighted according to attributes that make SCUTE a satellite solution for ORS. A score of 1.0 indicates that all requirements are met perfectly. Resulting ranks of the benchmark designs and their weighted scores are as follows:

- | | |
|-----------------|------|
| 1. GeneSat | 0.59 |
| 2. BIRD | 0.57 |
| 3. GAS Canister | 0.56 |
| 4. ROV | 0.45 |
| 5. Sputnik 1 | 0.27 |

Benchmarks scored the lowest against the following SCUTE requirements: maximize space available for unspecified payload, maintain temperature and pressure for one year, and integration of the terrestrial electronics payload within days. This indicates that SCUTE will uniquely meet a need not currently satisfied in the realm of documented small satellite designs. Note that some low scores result from shorter mission durations of benchmarks, and it is assumed that the sealing was engineered for significantly less than 1-year in orbit.

Table 2: Benchmark Descriptions

Benchmark	Description	Country & Year	Duration	Payload	Ref
GeneSat	Gene experiment initiated in orbit, data downlinked from autonomous satellite that supported microorganism growth and monitored gene expression	USA 2006	21 day mission, 96 hour experiment	Autonomous E. coli experiment: fluidics, optical sensors, support equipment, transceivers	5
ROV Comex Super Achille (Remotely Operated Underwater Vehicle)	The SUPER ACHILLE is a pressurized underwater vehicle equipped with a TV camera	France, ongoing	N/A	Color TV camera, electronics control unit	6
BIRD Satellite (Bi-Spectral Infrared Detection)	The micro satellite BIRD contains a compact infra-red push-broom sensor system	Germany 2001	1 year expected lifespan, useful life over 4 years	Camera, IR sensor, payload data handling w/ mass memory, neural network classifier	7
GAS canister G-056 (Get Away Special)	The G-056 experiment is designed to detect gamma-ray bursts from celestial sources	USA 1996	8 days on shuttle	Gamma-ray detector, camera, data system, charged particle detector, photo-diodes, data storage	8
Sputnik 1	The world's first artificial satellite	Russia 1957	Functioned 21 days, orbited 3 months	Antennas, radio signal transmitter	9

Table 3: Weighted Evaluation of Benchmarks

Requirements	Weight	GeneSat	ROV	BIRD	GAS Can.	Sputnik
Space available for unspecified payload	0.10	0.3	0.1	0.2	0.3	0
Max 50 kg without payload & bus	0.05	0.25	0.05	0.25	0.25	0.05
Suitable for space environment	0.15	0.75	0	0.75	0.75	0.75
Survive launch conditions	0.05	0.25	0	0.25	0.25	0.25
Maintain atm pressure for 1 yr	0.15	0.3	0.6	0	0.15	0.3
Maintain temp range for 1 year	0.20	0.4	0.2	1	0.2	0
Ease of re-work	0.10	0.3	0.5	0.2	0.5	0
Integrate terrestrial payload within days	0.20	0.4	0.8	0.2	0.4	0
Total	1.00	0.59	0.45	0.57	0.56	0.27

Preliminary Structural Analysis

Analyses for preliminary sizing of an aluminum SCUTE structure are based on three approximations. The first analysis assumes SCUTE is a flat plate with the entire launch load applied laterally. The second analysis uses preliminary sizing formulas for spacecraft structural members, which consider a vertical cylindrical spacecraft structure constrained as a cantilever.¹⁰ The last analysis assumes SCUTE is a thin-walled cylindrical pressure vessel with flat heads. Wall thicknesses resulting from these analyses are shown in Table 4, and vary by three orders of magnitude. For each analysis, the assumptions underlying the applied formulas are examined to determine the applicability of these simplifications to SCUTE. Material properties are

for Al 7076-T6,¹¹ and load factors are based on the EELV Secondary Payload Adapter (ESPA) launch conditions.² In the axial and lateral directions, SCUTE must withstand 10.6 g's, which includes a 1.25 factor of safety. During launch, SCUTE will be oriented horizontally as a cantilever from the launch vehicle. For all calculations, both the ultimate strength and load are used as well as the yield strength and load, but only the largest resulting thickness is reported. Loads are not applied simultaneously in two directions at this preliminary stage. The only safety factor in these calculations is the 1.25 that is included in the secondary payload load factor. Many formulas are independent of cross-sectional geometry; however, when cylindrical cross-sectional area appears in a formula, SCUTE is considered to be a cylinder with internal volume equal to the box configuration. Future analyses will determine the final length of SCUTE based on center of gravity; however in this analysis, it is assumed to be 60 cm.

Flat Plate. In order to approximate SCUTE as a flat plate, it is assumed to be a very short straight beam of relatively great width. For this approximation, an effective width is substituted in place of the actual width, which accounts for the non-uniform fiber-stress distribution and deflection that occur in wider beams. This effective width is determined based on the method of support and loading, as well as the breadth-to-span ratio. In order for a simply supported wide short beam to not fail under the yield load applied at a point in the beam center, a thickness of approximately 20 mm is necessary. If the load is uniformly distributed across the plate, a thickness of 27.6 mm is required. The other flat plate

Table 4: SCUTE Wall Thickness from Preliminary Analyses

Approximation	Support	Dimensions	Analysis	SCUTE Wall Thickness, mm	Loading Conditions	Ref
Flat Plate	Simply Supported	50 x 60 cm ² (plate area)	Lateral load	20.0	Point load in center	12
	Simply Supported		Lateral load	27.6	Uniformly distributed	
	Cantilever		Lateral load	12.2	In center of infinitely wide cantilever	
Cyl Spacecraft Spring Beam Column	Cantilever	L=60cm r_equiv=28 cm	Stiffness/Rigidity	0.022	Axial load	10
			Stiffness/Rigidity	0.038	Lateral load	
			Tensile Strength	0.11	Axial load	
			Stability/Compr Strgth	0.91	Axial load	
Cyl Pressure Vessel		L=60cm r_equiv=28 cm	Thin-walled Cylinder	0.073	1 atm int pressure	13,
			Flat Lid Thickness	5.09	1 atm int pressure	14

configuration analyzed is a concentrated load on a cantilever slab, considered to be of infinite width but having the length of SCUTE. Results vary according to the location of the load and the point at which the stress is calculated. For a concentrated load at the center of the SCUTE plate, the maximum bending stress occurs in the mid-plane of the cantilever (normal to the load), which requires a thickness of 12 mm in order to not fail.

Each flat plate calculation results in a very large thickness due to the gross geometric simplification of SCUTE. Although coefficients and effective width formulas for the SCUTE span-width ratio accompany the formulas,¹² it can be argued that SCUTE is not 'long in proportion to its depth', a stated assumption preceding all beam formulas. Nevertheless, with these very conservative calculations, the dimensions result in a structural mass of 10 to 23 kg for an aluminum SCUTE, which is well within the 50 kg allowance. This calculation and comparison have merit as they indicate that an aluminum beam-like structure subjected to the launch load will not violate the weight requirement.

Cantilevered Spacecraft: Beam, Spring, and Column. The second analysis is based on preliminary structural sizing formulas for a spacecraft that is approximated as an upright cylindrical cantilever.¹⁰ This orientation is considered because the launch configuration is that of a primary payload. Since SCUTE is a secondary payload, it is oriented perpendicular to the direction of launch; however the load factors are the same in the lateral and axial directions so the analysis is applicable.

The stability of the spacecraft is analyzed to determine the minimum wall thickness that meets specific natural frequency requirements. The requirement for SCUTE is that the fundamental

frequency of a secondary payload shall be greater than 35 Hz.² The total mass of SCUTE is assumed to be 250 kg, which includes structure, thermal control system and payload. Although ultimately the spacecraft will be analyzed with a finite element model, it is possible to estimate the fundamental frequency by treating the spacecraft as a beam with equivalent mass properties and stiffness. For the lateral rigidity calculation, SCUTE is approximated as a beam with uniform cross-section having a uniform load per unit length. For the axial rigidity calculation, it is considered to be a uniform bar or spring vibrating along its longitudinal axis. The width or radius of the spacecraft does not appear explicitly in these calculations, only the length and area or area moment of inertia. When the required frequency is used, the wall thickness for a cylindrical shell or box can be obtained from the resulting value of area or moment of inertia. For axial rigidity, the required thickness of SCUTE is 0.022 mm, and for lateral rigidity, the required thickness is 0.038 mm.

Sizing the simplified spacecraft for tensile and compressive strength involves the application of an equivalent axial load, which combines the axial, lateral and bending loads. This is valid for square and circular cross sections, and is based on the maximum bending stress at the extreme fibers of the member (farthest from the neutral axis). This equivalent load is significantly larger than the limit load, but is not considered overly conservative because bending loads due to wind or drag will act on the spacecraft from any direction. These loads cause a peak stress that must be withstood by the entire cross section of the spacecraft. The equivalent axial load applies this peak stress uniformly on the cylinder or box.

For tensile strength, no special assumptions apply, and the axial stress equals the equivalent axial load

divided by the cross-sectional area. For SCUTE, a box wall-thickness of 0.011 mm was obtained from the area required to withstand this load. For the compressive strength calculation, certain assumptions must be fulfilled. First, the spacecraft is approximated as an Euler column in the elastic region. The Euler buckling load is the critical load which will cause a long column in compression to fail by bending. Columns loaded above this critical load violate Hooke's law, since excessive deflection occurs that is not proportional to the applied load. The slenderness ratio of a column, λ , defined as the effective length divided by the least radius of gyration, determines whether a column is considered short or long.

SCUTE can be classified as a short column when mounted as a cantilever and has a slenderness ratio of 5 to 10, depending on the thickness used in the radius of gyration calculation. Caution must be exercised when applying Euler's formula to short columns. As a rule-of-thumb,¹² the length should not approach the radius of gyration. Since SCUTE is not a long column, it will fail when the compressive yield strength is exceeded; therefore Euler's formula does not apply. Another approach that confirms this conclusion is to apply the yield strength of aluminum to the critical stress formula. Solving for effective length gives the minimum slenderness ratio for which Euler's equation is valid (in the elastic region). The slenderness ratio for SCUTE violates this requirement, therefore Euler's equation is not applicable. The result of the improperly applied Euler's equation is a thickness of 0.91 mm, which is larger than the thickness required for rigidity or tensile strength, but still significantly smaller than the flat plate calculations. This figure confirms the rule-of-thumb that shorter spacecraft are dominated by strength concerns rather than stiffness requirements.

Cylindrical Pressure Vessel with Flat Head. First order pressure vessel calculations apply only to spherical and cylindrical geometry. Square geometry introduces numerous complications that are best solved numerically; therefore in this preliminary analysis, SCUTE is assumed to be a cylinder with an internal volume equal to the box configuration. Pressure vessel design manuals provide equations to calculate average stresses for a ductile, thin-walled, cylindrical pressure vessel with a maximum allowable working pressure.^{13,14} To qualify as thin-walled, the ratio of the outer radius to the inner radius must be less than 1.1. This condition would be violated only if the wall-thickness were 28 mm (which is still larger than the worst flat plate approximation). There will be areas of stress

concentration that are significantly higher than the average stresses, and these should be investigated in a more detailed model in the next design phase.

The internal pressure for SCUTE is 1 atmosphere at 25° C and varies with temperature. A thickness is calculated for a cylindrical SCUTE based on the maximum allowable hoop stress. The minimum wall thickness that meets the yield strength requirement of the material is 0.073 mm. For an assumed maximum temperature of 100° C, the required thickness is 0.092 mm. This temperature is assumed to be the hottest exterior temperature encountered by SCUTE during pre-launch activities and in space, based on similarly scaled satellites. The lid thickness is determined from formulas for flat, circular end-closures, which account for a bending moment that occurs in bolted lids. The resulting lid thicknesses for this geometry are 5.09 mm at 25° C and 5.69 mm at 100° C. The increases in thickness due to higher pressure at elevated temperatures are not significant. Launch loads are not applied in these pressure vessel calculations.

Structural Analysis Conclusion. Results of the preliminary structural analysis provide insight for the SCUTE initial design phase. The flat plate approximation resulted in very large thickness, but also indicated that the structure alone would not violate the weight requirement. The spacecraft calculations address rigidity and natural frequency, indicating that a very small wall thickness will satisfy these requirements. Also, given the compact shape of SCUTE, stability will not be a concern. The very thin wall thickness from the pressure vessel calculations was of the same order of magnitude as the spacecraft calculations. The conclusion of these analyses is that the ground handling conditions will dictate the wall thickness of SCUTE. A very thin shell would not be robust enough to withstand a typical manufacturing and integration environment for aerospace vehicles. A reasonable value for the SCUTE wall thickness is 5 mm, but ultimately, a finite element model will determine this parameter.

Preliminary Thermal Analysis

Preliminary thermal analyses for SCUTE are based on two approximations. The first analysis approximates SCUTE as a flat plate and applies orbital average values of environmental fluxes at a LEO altitude of 700 km. The second analysis approximates SCUTE as a sphere with surface area equivalent to the box configuration and considers only the worst-case incident environmental fluxes on

Table 5: SCUTE Thermal Analysis Input Parameters

Parameter	Symbol	Value	Units	Reference
Max power dissipated	Q_{Dmax}	100	W	SCUTE requirements
Min power dissipated	Q_{Dmin}	20	W	estimate
Solar flux	G_s	1358 ± 5	W/m^2	10
Albedo	a	30 ± 5	%	10
Earth IR	q_{IR}	237 ± 21	W/m^2	10
Solar absorptivity	α	0.3	-	10
IR emissivity	ϵ	0.8	-	10
Stefan-Boltzmann const	σ	5.67E-08	$W/m^2 \cdot K^4$	10
LEO Altitude	h	700	km	10
Flat Plate Analysis				
Orbital average solar flux	q_s	110.3	W/m^2	16
Orbital average albedo	q_a	34.1	W/m^2	16
Orbital average Earth IR	q_E	95.8	W/m^2	16
Sphere Analysis				
SCUTE surface area	A	1.7	m^2	calculated
Earth radius	R_E	6378	km	10
Angular radius of Earth	ρ	1.12	radians	calculated from h & R_E
Albedo correction factor	K_a	0.993	-	calculated from ρ
Angle between surface normal & solar vector	β	0°	degrees	worst-case cold
		90°	degrees	worst-case hot

the spherical surface. Both analyses provide first-order estimates of the steady-state thermal performance of SCUTE based on the energy balance between external and internal heat sources. Input parameters for the analyses are given in Table 5. Launch thermal conditions play no role in these steady-state analyses since the orbit duration is on the order of months (maximum one year), whereas the launch conditions last only minutes. Thermal launch conditions are given in the Secondary Payload Planner’s Guide.² Best practice analysis assumes that the worst-case power dissipation equals the maximum power consumption (100 W)¹⁵ and the minimum dissipation is assumed to be 20 W for the cold case. Values for α and ϵ are chosen to represent white epoxy paint that undergoes degradation due to UV radiation over the mission duration. Since the maximum time in orbit for SCUTE is one year, these values are considered to be constant for all analyses, so the beginning of life (BOL) condition of the surface equals the end of life (EOL) condition. For the purposes of analyzing general thermal performance, the SCUTE preliminary thermal analysis temperature limits are from 0° C and 40° C . Margin will be added to these limits in future detailed thermal models.

Flat Plate. A spacecraft can be represented as an isothermal plate which maintains a uniform temperature even while localized heating takes place.¹⁶ This idealized assumption is valid if the thermal control system is deliberately designed to

reduce local hot spots due to high dissipating electronic components. The other assumption for this analysis is that SCUTE has a relatively high thermal capacitance, so over time its response to transient heat sources is roughly the same as its response to an orbital average temperature. Transient heating is due to variations in solar and albedo flux during an orbital period, as well as the duty cycle of the power supplied to the payload. This assumption is valid if SCUTE is sufficiently massive and can absorb heat during the hot portion of the orbital period without a significant bulk temperature rise before the cold portion of orbit begins. Similarly, during the cold portion of orbit, temperature will drop slowly due to the thermal inertia of SCUTE. With a total mass of 250 kg and an orbital period of about 90 minutes, SCUTE satisfies this assumption. This assumption is not valid for lighter weight appendages on a satellite, such as antennas and solar arrays, because they have small mass and large surface area, causing the bulk temperature to increase rapidly when subjected to heat fluxes.

Orbital average fluxes are calculated by multiplying the maximum heat fluxes of the orbit by the percentage of the orbit period that the spacecraft is subjected to the maximum, with an adjustment for the angle of the heat source or the view factor. The orbital average values used for this analysis are from a communications and data handling system on NASA’s Explorer Platform in LEO,¹⁰ with hot and

cold case averages based on an Earth-oriented inclined orbit at 700 km altitude.

An energy balance calculation using the average orbital fluxes and electronics power dissipation in Table 5 requires a radiator area of 0.32 m² for SCUTE to remain at 40° C when the internal heat dissipation is 100 W. This is easily achievable since the box configuration of SCUTE has 1.7 m² surface area, with the surface area of one side measuring roughly 0.3 m². Assuming a radiator covers one side of SCUTE, the orbital average radiator temperature can be calculated as a function of power dissipation for a hot case and a cold case. Results of this analysis can be used to determine whether active thermal control hardware is required. The values for hot case and cold case fluxes are estimated by multiplying orbital averages by a ratio of the tolerances of the fluxes. For example, the orbital average albedo would be multiplied by the ratio of the maximum and minimum values in Table 5. Since albedo is 30 ± 5%, the orbital average would be multiplied by 35/25 for the hot case or multiplied by 25/35 for the cold case.

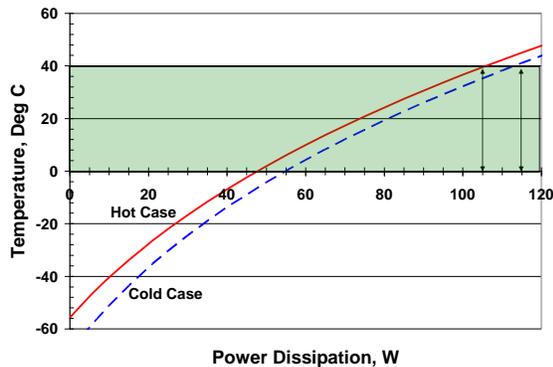


Figure 1: Orbital Average Radiator Temperature for Flat Plate Approximation, Radiator Area = 0.317 m²

The hot and cold cases for the flat plate approximation are evaluated parametrically for power dissipations ranging from 0 W to 120 W. Figure 1 shows little difference between the hot and cold case results. This first-order steady state analysis indicates that an equipment temperature between 0° C and 40° C can be achieved when the ratio of maximum to minimum power dissipated is approximately 2:1. For example, the temperature is in the desired range when the power is between 115 W and 55 W for the cold case (115/55 ~ 2:1). The power ratio is similar for the hot case since the slopes of the temperatures are nearly constant in that region. A power ratio of 2:1 indicates that a passive thermal control system will be sufficient to maintain SCUTE

within the required temperature range.¹⁶ If the ratio is 4:1 or higher, then active thermal control hardware is required. It is also significant that at the maximum power dissipation of 100 W, the maximum allowable equipment temperature is not exceeded. However, the lower range of power dissipation indicates that survival heaters will likely be necessary to maintain the lower equipment temperature at 0° C. Additional power for these heaters must be accounted for in future thermal analyses.

Sphere. The next preliminary thermal analysis assumes SCUTE is an isothermal sphere with any internal energy dissipation generated uniformly at the surface. First order estimates of maximum and minimum surface temperatures and radiator area are calculated for absolute worst-case conditions for both hot and cold at 700 km LEO.¹⁰ The resulting steady-state surface temperatures give an indication of the type of thermal control system that will be required.

The energy balance for worst-case hot conditions accounts for absorbed solar energy, Earth IR emission, albedo, and worst-case power dissipation from SCUTE while it is directly overhead at high noon. For this scenario, $\beta = 0^\circ$ and the sun position is on the right in Figure 2. The worst-case cold conditions omit the solar flux and albedo while SCUTE is in solar eclipse (the sun position on the left in Figure 2). In this condition, SCUTE is in the Earth's shadow and is not exposed to any part of the Earth's surface that is lit by the sun. The only sources of heat are the Earth's IR emission and the power dissipation from the electronics.

Resulting surface temperatures of the two steady-state energy balances are 2° C for the worst-case hot condition and -52° C for the worst-case cold condition. The hot surface temperature is well below 40° C, which indicates that an active thermal control system is probably not necessary. The paint color and finish on SCUTE's outer surface can be adjusted to achieve values of α and ϵ which bring the hot and cold temperatures closer to the allowable limits. The necessity of surface heaters for the cold case will be evaluated in the future thermal finite element model.

The next calculation for the sphere is independent of the previous surface temperature results. The radiator area necessary to eliminate the excess heat in the worst-case hot conditions is calculated using the maximum dissipated power for a radiator temperature of 40° C (the upper limit for SCUTE electronics). The required area is 0.23 m², which easily fits on one side of SCUTE. Using this size, the radiator temperature for worst-case cold conditions can be

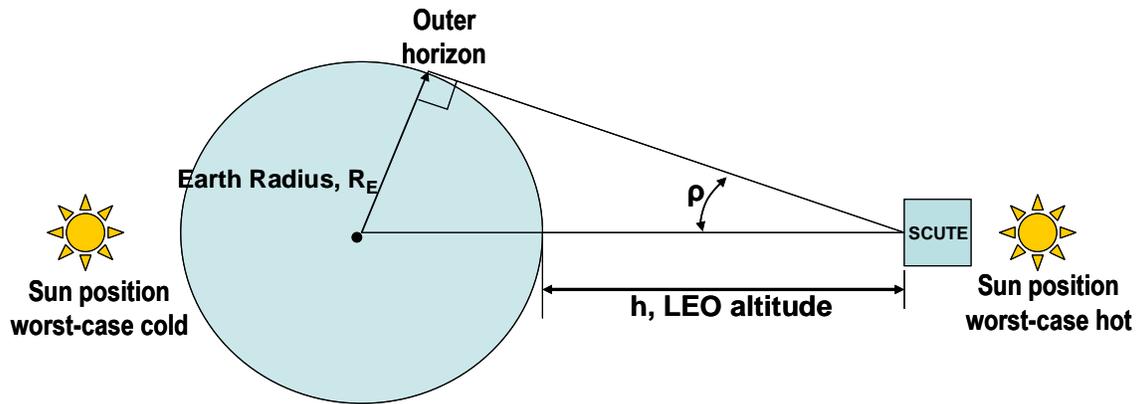


Figure 2: Definitions of SCUTE Worst-Case Conditions--Hot Condition with Right Sun Only; Cold Condition with Left Sun Only; Earth Angular Radius, ρ

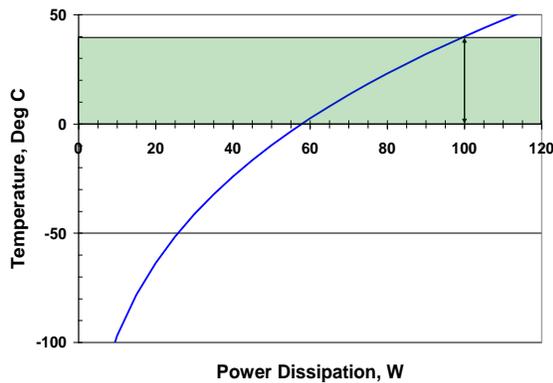


Figure 3: Cold Case Radiator Temperature for Sphere Approximation, Radiator Area = 0.23 m²

calculated as a function of power dissipation. Results are shown in Figure 3. The power dissipation ratio for the allowable equipment temperature range is less than 2:1 (~100:58). This also indicates that a passive thermal control system will be sufficient to manage SCUTE temperatures. Results for both geometries are given in Table 6.

Table 6: Preliminary Thermal Analysis Results

Analysis Results	Flat Plate	Sphere
Radiator area, m ²	0.32	0.23
Max surface temperature, °C		2
Min surface temperature, °C		-52
Ratio of max & min power dissipation for 0° - 40° C limits	2 to 1	2 to 1

To make first-order thermal predictions for SCUTE, the two steady-state preliminary analyses apply different approaches to environmental conditions. The flat plate analysis used orbital averages, which give a general idea of the thermal performance of the

system during the mission. Maximum and minimum surface temperatures are not as meaningful with this approach. The sphere analysis considers the extreme hot and cold conditions, and the results are considered conservative. Future detailed thermal analyses for SCUTE will systematically consider many different scenarios for LEO since the exact orbit is unspecified.

The maximum surface temperature for the sphere indicates that high electronics power dissipation for equipment consuming up to 100 W is compatible with SCUTE's size and with LEO. Estimated radiator areas for both geometries are reasonably close, considering the vastly differing approaches to environmental fluxes. At most, two sides of SCUTE will be designated for radiators to eliminate waste heat. Also, the power dissipation ratios for the allowable temperature range are the same for both analyses. Thus, there is reasonable confidence in the conclusion that an active thermal control system is not absolutely necessary for SCUTE.

The underlying assumption for both analyses is that SCUTE is isothermal. This is an idealization for any payload consisting of electronics equipment, particularly those with high-dissipating processors. However, designing SCUTE to be isothermal is essential for the requirement of integrating an unspecified payload within days. In spite of the preliminary analysis indicating that a passive thermal control system is sufficient, it is possible for some active thermal elements to be included if necessary, for the specific purpose of making the contents of SCUTE as isothermal as possible.

Pressure Loss Analysis

In order to maintain an earth-like environment for the duration of SCUTE's orbit, the design must include provisions to maintain pressure, minimizing loss of the working fluid to space due to permeation and leakage. Permeation is the activated diffusion of a molecular penetrant through a solid barrier and is dictated by the solubility of the penetrant in the barrier material and its concentration gradient across the barrier. This is independent of pneumatic leakage, which is the free flow of molecules through pinholes, cracks or porosities in the barrier materials and interfaces. Both of these physical processes can be modeled to predict the pressure loss SCUTE will experience during one year of orbit.¹⁷ A spreadsheet analysis is suitable for SCUTE since the external environment in space is constant. The ground handling phase is not included in the calculation since the internal pressure is atmospheric, with possible minor fluctuations due to temperature changes. A controlled environment is recommended during ground handling in order to protect the payload from possible condensation of water vapor inside SCUTE. Aerospace hardware is typically subjected to leak testing since a low leak rate is an indication of workmanship quality and seal integrity. Typically a maximum allowable leak rate requirement is imposed.

The goal of this analysis is to determine a reasonable air leak rate that will maintain internal pressure to within 10% of atmospheric (requirement in Table 1). Other analysis parameters are SCUTE's internal free air volume, seal material permeation coefficients for each constituent of air,¹⁸ and o-ring dimensions and percent compression. Five o-ring seals are modeled at 20% compression with a cumulative length of 2.4 m: the main seal, camera window seal, leak check port o-ring and two DB-25 connector o-rings. These connectors must be high quality 'near hermetic' connectors which are manufactured to have a lower leak rate due to superior sealing at the glass/pin interface. The formula for predicting permeation of gases out of SCUTE is based on the laws of Henry and Fick (governing solubility and diffusion), and the formula for molecular leakage is based on the Knudsen equation.¹⁹ The assumption is that SCUTE hardware will be of such quality that the mode of leakage is molecular (narrow leak paths) rather than viscous, which is associated with larger leak paths. These equations use the partial pressures of the constituent gases in air, with N₂, O₂ and Ar modeled. Based on the analysis results, a maximum leak rate of 8×10^{-5} std atm cc air/sec at 0.5 atm differential is recommended. With this leak rate, SCUTE will lose

0.053 atm (5.4 kPa) in one year. As a comparison, if the leak rate is increased to 8×10^{-4} std atm cc air/sec at 0.5 atm differential, SCUTE will lose 0.42 atm (42.3 kPa) in one year (higher by a factor of 8). The recommended leak rate is reasonable for aerospace hardware, and can be achieved by following design best practices, such as minimizing the number of openings, having double seals (both environmental and EMI seals in series [not included in this analysis]), and through proper gland design.³ This analysis should be repeated in subsequent SCUTE design phases since it is based on estimates of seal dimensions and a payload that takes up 75% of the interior volume of SCUTE. Permeation coefficients are temperature-dependent, with higher diffusion at elevated temperatures. Since this analysis uses material properties at 30° C, permeation results are considered conservative.

Design Concepts

The following four challenging aspects of SCUTE design have been explored conceptually: shell/structural configuration, payload integration method/interior layout, thermal management and working fluid. The goal of the design investigation is to generate at least three concepts for each category, including one unconventional concept. These concepts are not investigated at any significant level of technical detail since they are the result of brainstorming to facilitate innovative design solutions. Of all the ideas presented, one concept from each category is selected for further research. Some concepts represent a solution for more than one category, and not all concepts are compatible with one another, which restricts the final choice of concepts somewhat. Concepts are portrayed in the accompanying figures with a 'typical' payload consisting of a camera, a data recorder and two CCAs.

Shell and Structural Configuration. SCUTE is most naturally expected to be a box, due to the allowable rectangular dimensions given in the design constraints. The first concept is a simple aluminum box. This material is favored in aerospace applications for its weight, strength and thermal properties. Another concept is a composite box, which would reduce the weight without sacrificing strength. For ease of ground handling, the box would either open from the top or have a clamshell design. In order to facilitate opening and closing for ground testing and re-work, the box could be sealed with a bolted flange, shown in Figure 4, or a clamped flange. Both designs incorporate o-rings to seal the working fluid inside SCUTE.

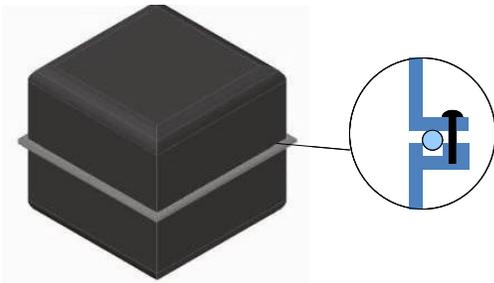


Figure 4: Clamshell Design with Detail of Bolted Flange and O-ring²⁰

In order to maximize interior space for payload and working fluid, an innovative shell concept for SCUTE is an inflatable structure. Kevlar[®] is desirable in this application for its strength and low weight, but should be combined with a less permeable material in order to reduce loss of the working fluid to outer space. A Kevlar[®]-Teflon[®] composite has been successfully used for military inflatable shelters²¹ and could be used for SCUTE. The payload components and a compressed gas bottle of the working fluid are closely packed in the Kevlar[®] material, which is folded much like a parachute. Once SCUTE reaches its orbit, the bottle will inflate the bubble, and the payload components will be separated from one another as in Figure 5. Obviously, extensive testing would be necessary to prove and refine this concept.

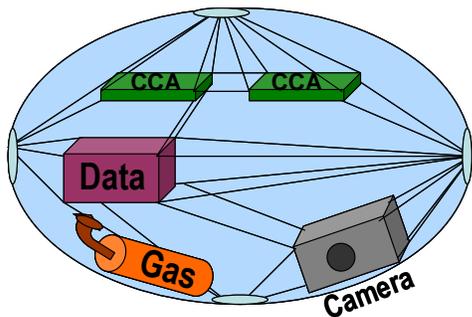


Figure 5: Kevlar[®]-Teflon[®] Inflatable SCUTE Shell

Payload Integration Method. For an unspecified payload, the integration method must be flexible to accommodate different volumes and shapes of terrestrial electronics. There may be many small items to be mounted and interconnected, or there may be just a few larger pieces. Individual components should be readily installed or extracted in case one should require testing or replacement during integration. The simplest integration method for a SCUTE box configuration is an adjustable payload shelf. Payload components are bolted to both sides of the shelf as in Figure 6, and can be optimally

arranged with regard to the thermal characteristics of each item. If larger consumer electronic components make up the payload, the shelf can be mounted at a lower level or removed altogether. In the absence of a mounting shelf, the interior walls of SCUTE can be lined with a peg-board-type substrate, and payload components can be attached with cable ties or Velcro[®] straps. The substrate can be relatively thick and thermally conductive, or it can be a grate that maximizes working fluid circulation around the components. An innovative method of integrating the payload is to rigidly pack tiny spheres into SCUTE, with payload components spaced and layered between spheres throughout the volume.

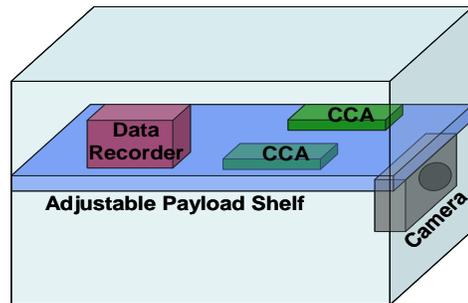


Figure 6: SCUTE Payload on Adjustable Shelf

For optimal thermal control, the spheres should be highly conductive, so that in spite of small contact area between the spheres themselves and between the spheres and the payload components, heat will be transferred quickly away from hotter components. All spheres will reach a thermal equilibrium or quasi-steady-state even during intense power duty cycles. In this sense, the spheres can be viewed as a working fluid for SCUTE. If re-work is necessary, the spheres can be scooped out and payload components can be removed layer-by-layer. Re-packing the spheres and payload can be done as many times as necessary to thermally optimize the location of hotter components, based on testing. This integration concept covers three categories of design concepts and provides the added benefit of ruggedizing SCUTE contents. The allowable weight of SCUTE and its contents is 250 kg, so the sphere size and material should be chosen with this requirement in mind.

Thermal Management. Choosing a thermal management system for an unspecified payload is difficult because parameters that would define the system are unknown. The ultimate goal of the SCUTE thermal control system is to make the entire payload isothermal and then regulate the bulk temperature with radiators and surface finish. Based on the preliminary thermal analysis, an active thermal control system is not necessary, but some active

elements can be incorporated during the integration period. One concept that has been explored is a forced air convection thermal switch (FACTS).¹⁵ The original FACTS involved hermetically sealing each satellite subsystem in enclosures attached to a base plate. Some enclosures are passively controlled through conduction to the base plate while others are controlled by a DC axial fan inside the enclosure. The temperature is regulated as the heat transfer coefficient is determined by the fan. Application of the FACTS concept to SCUTE involves using fans to make the payload components isothermal by forced air convection without exposing the circulating working fluid to the radiators. When a temperature sensor detects that the bulk temperature has reached a threshold, the 'switch' creates a physical opening or channel which will allow circulating air to flow adjacent to the radiators and thus eliminate heat. Figure 7 depicts two fans circulating air throughout SCUTE and through switch openings so SCUTE air is in contact with the radiator (the thermal switches are 'on').

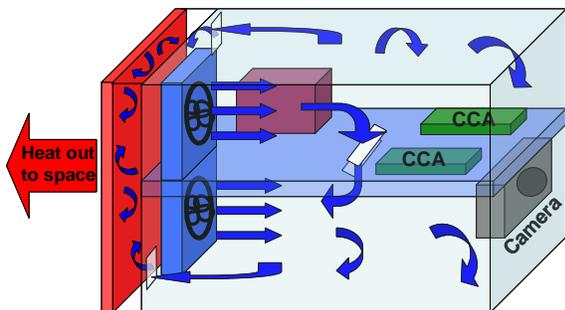


Figure 7: FACTS with Air Flowing Through Switch Openings to Adjacent Radiator Section

With this approach, thermal interfaces between payload components and the mounting shelf are unimportant since the surface area of the components exposed to the working fluid determines the amount of heat transferred. For a high-dissipating processor on a CCA, the board can be mounted on stand-offs to allow circulation of the working fluid both above and below the printed wiring board. Another thermal management approach for SCUTE is the incorporation of heat pipes on the payload mounting shelf, which itself is made of a highly conductive material. The placement of the heat pipes will likely vary from payload to payload, depending on the location of the hottest components. The end of the heat pipe is mounted on the radiator side of SCUTE to eliminate heat into space. Alternately, the payload mounting shelf could contain a phase change material to remove heat from the hottest components. This concept may be incorporated with the FACTS

method and would create a more uniform bulk temperature, making the thermal switch more effective.

Working Fluid. Air and nitrogen are the most obvious working fluids. Either one is effective with the FACTS system. Both fluids will permeate and leak out into space, but air presents less complexity during the ground handling phase. Sealing and pressurizing with N₂ is an additional process that would have to be repeated every time SCUTE is opened for re-work. Nitrogen would provide a short-term benefit for moisture management, particularly if the hardware is subjected to diurnal temperature cycles with night temperatures below the internal dew point. However, the cost and schedule for SCUTE integration can be improved by using dry atmospheric air as the working fluid. An innovative concept would be to fill SCUTE with R134 or another refrigerant. Such direct liquid cooling would result in a much higher heat transfer coefficient, so the payload would become isothermal in a shorter period of time. However, testing would be required to ensure compatibility with electronics, and some components might need to be sealed individually against the fluid. The design for sealing the SCUTE structure to hold liquid and the re-work process would be more complex.

Summary of Selected Designs. The innovative design concepts provide unique alternative solutions that would require extensive research, analysis and testing. At this time, however, in the interest of providing a low cost satellite which enables ORS, conventional concepts are recommended for further research. The selected thermal management system is FACTS. This concept is the most promising for achieving an isothermal SCUTE because it is not necessary to assess and improve unknown thermal interfaces which will vary from payload to payload. The clamshell box configuration with air as the working fluid simplifies the re-work and repair process, and the adjustable payload shelf is a compatible integration method that creates two connected sections for forced air circulation. These concepts chosen for further development all meet SCUTE user needs and requirements and can provide a pressurized and thermally controlled environment for terrestrial electronics in orbit.

Conclusions

Based on the benchmark investigation, preliminary analyses, and possible design concepts, SCUTE is considered a viable solution to achieve ORS and provide timely and inexpensive access to space for

small educational and commercial projects. Of the design concepts proposed, the FACTS system is selected for further investigation. This choice is compatible with the adjustable payload shelf and will use air as the working fluid. The next steps for SCUTE development include preliminary mechanical design, detailed thermal and structural finite element analyses, and developing preliminary cost estimates. More frequent launch opportunities for secondary payloads are an objective actively pursued by the small satellite community. As progress is made on that front, the further development of SCUTE will provide a valuable deployment option.

References

¹ Sega, R.M. and Cartwright, J.E., Plan for Operationally Responsive Space, A Report to Congressional Defense Committees, http://www.responsivespace.com/ors/reference/ORS_Plan.pdf, March 2008.

² DoD Space Test Program Secondary Payload Planner's Guide for Use on the EELV Secondary Payload Adapter http://eng.usna.navy.mil/~midstar/downloads/structures/ESPA_Payload_Planners_Guide.pdf, March 2008.

³ Parker O-ring Handbook Catalog ORD 5700A/US www.parker.com, July 2007.

⁴ Pecht, M.G. et al, *Plastic-Encapsulated Microcircuits, Materials, Processes, Quality, Reliability and Applications*, Wiley Interscience 1995.

⁵ Kitts, C. et al, "The GeneSat-1 Microsatellite Mission: A Challenge in Small Satellite Design," *Proceedings of the 20th AIAA/USU Conference on Small Satellites*, Logan, UT, August 2006.

⁶http://www.comex.fr/suite/dom/media/PDF/ROV_SUPER_ACHILLE.en.pdf, March 2008.

⁷ Walter, L. et al., "BIRD – Microsatellite for Hot Spot Detection," *Proceedings of the 13th AIAA/USU Conference on Small Satellites*, Logan, UT, August 1999.

⁸ McCall, B.J. et al. NASA Small Self-Contained Payload Program Get Away Special G-056 Phase III Safety Data Package, http://bjm.scs.uiuc.edu/pubs/G056_SDP.pdf, June 2007.

⁹ Garber, S., "Sputnik and the Dawn of the Space Age," <http://history.nasa.gov/sputnik/>, March 2008.

¹⁰ Wertz, J.R. and Larson, W.J., eds., *Space Mission Analysis and Design*, 3rd Edition, Space Technology Library, Kluwer 1999.

¹¹ MatWeb Material Property Data, <http://www.matweb.com/>, July 2007.

¹² Young, W.C. and Budynas, R.G., *Roark's Formulas for Stress and Strain*, 7th ed., McGraw-Hill 2002.

¹³ EH&S Manual: *Pressure Vessel and System Design*, Lawrence Livermore National Laboratory, Document 18.2, http://www.llnl.gov/es_and_hhsm/doc_18.02/doc18-02.html, July 2007.

¹⁴ *2004 ASME Boiler and Pressure Vessel Code*, American Society of Mechanical Engineers, 2004.

¹⁵ Williams, A.D., "Robust Satellite Thermal Control Using Forced Air Convection Thermal Switches for Responsive Space Missions," (M.S. Thesis, University of Colorado), November 2005.

¹⁶ Karam, R.D., *Satellite Thermal Control for Systems Engineers*, Progress in Astronautics and Aeronautics, Volume 181, AIAA, 1998.

¹⁷ Myers, D.G., "Humidity Control Simulation for Electronics Packaging," *Proc. International Electronic Packaging Technical Conference and Exhibition*, American Society of Mechanical Engineers, New York, 2003.

¹⁸ van Amerongen, G.J., "The Permeability of Different Rubbers to Gases and Its Relation to Diffusivity and Solubility," *Journal of Applied Physics*, **17**, p. 973 (1946).

¹⁹ Dushman, S., *Scientific Foundations of Vacuum Technique*, 2nd ed., John Wiley & Sons, New York, 1962.

²⁰ Figure 4 SCUTE box courtesy of E. B. Meyer.

²¹ Donahue, K., "Chemical and Biological Barrier Materials for Collective Protection Shelters" http://nsrdec.natick.army.mil/jocotas/ColPro_Papers/Donahue.pdf, April 2008.