Danish Space Research Institute

Danish Small Satellite Programme

DTU Satellite Systems and Design Course
Cubesat Thermal Design

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Thermal Design

- A satellite alone in the universe is a small world where conditions for “life” shall be maintained in the sense that electronics, batteries, solar cells etc. must not “die” before the mission is fulfilled.
- This requires that the temperature be within certain limits.
- The laws of nature will inevitably take care that an equilibrium is attained between the incident radiation from the sun, albedo from the Earth or some other body neraby and the infrared radiation to cold space.
- This is exactly the same as happens for the Earth on its position in the solar system
- Fortunately for us, the equilibrium here at Earth allows intelligent life.

- The discipline of obtaining a satisfactory thermal balance is called thermal design

Thermal Transport Mechanisms

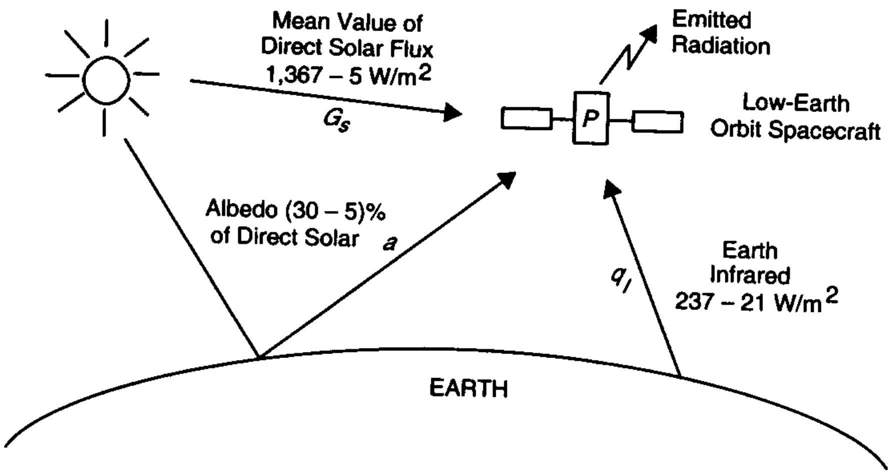
There are three mechanisms for transporting heat from one point to another

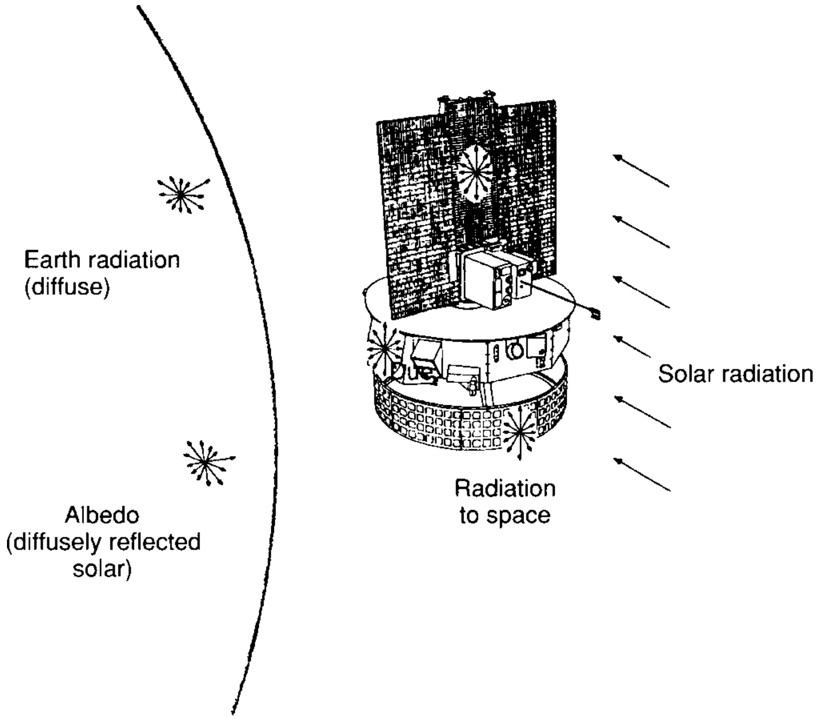
1. Conduction
   Metals are good conductors
   Plastics are poor conductors = good insulators

2. Radiation
   Black surfaces are good absorbers of radiation and good radiators (emitters) of heat to space
   Polished metal surfaces are poor radiators and absorbers
   We shall see later that the heat power radiated per unit surface is proportional to T^4, where T is the absolute temperature of the surface

3. Convection (Heat flow in a fluid or gas).
   This is not relevant in space except in liquid propulsion systems and special devices like heat pipes

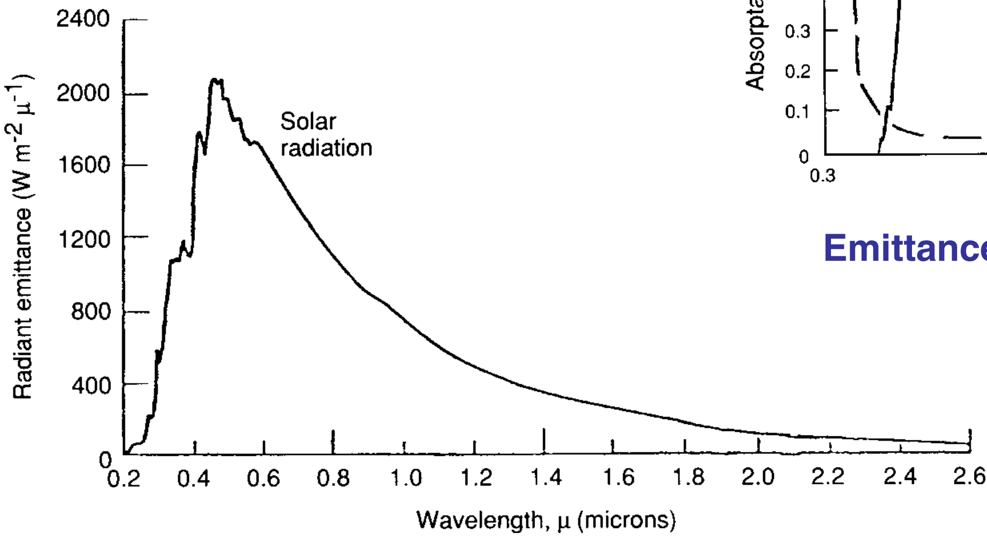
Thermal Environment - 1

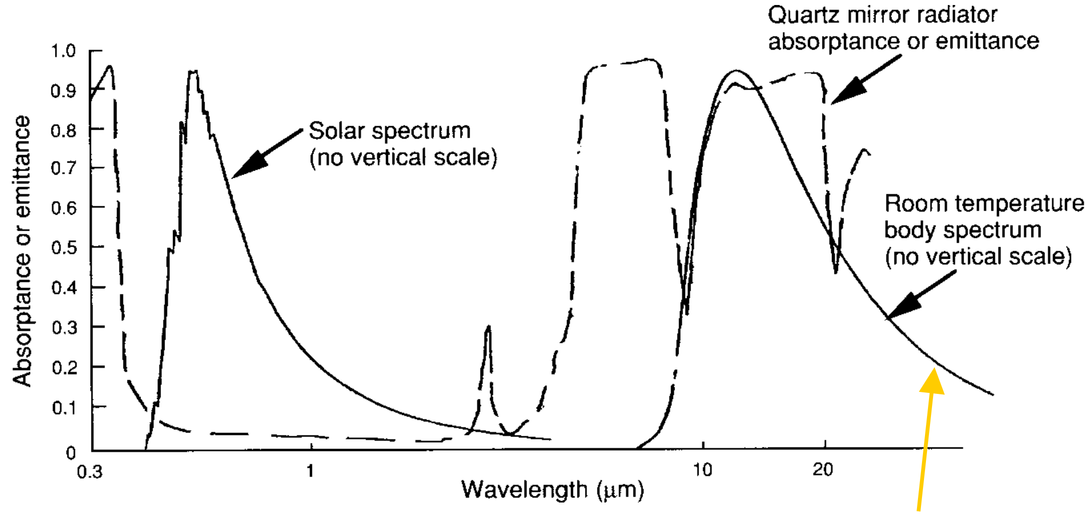




Thermal Environment - 2

Spectrum of Solar Radiation



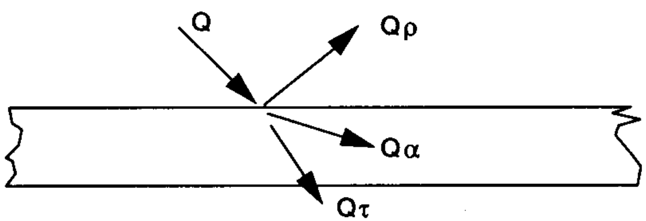


Emittance Spectrum of Room Temperature Body

Visible light: ≈0.4 µm - ≈0.76 µm (400 - 760 nm)

Thermal Characteristics of Materials - 1

What happens to Incident Solar Radiation ???



$$Q = Q\rho + Q\alpha + Q\tau$$

$$\rho + \alpha + \tau = 1$$

ρ = Reflectivity

α = Absorptivity

τ = Transmissivity

In addition we need to consider the cosine law:

$$Q_a = S_0 \cdot \alpha \cdot A \cdot \cos(\theta)$$ **, where:**

P_a is the absorbed power

S_0 is the solar constant: 1367 W/m^2

α is the absorbtivity

A is the area of the surface

θ is the angle of incidence, i.e. the angle between the surface normal and the direction to the sun

We need to consider four effects:

- Some of the power is reflected back into space (ρ)
- Some of the power is absorbed and heat the surface (α)
- Some of the power is transmitted into the body (τ)
- When the surface is warmer than absolute zero it emits long wavelength infrared radiation with an efficiency ε (emissivity) compared to a black body ($0 \leq \varepsilon \leq 1$)

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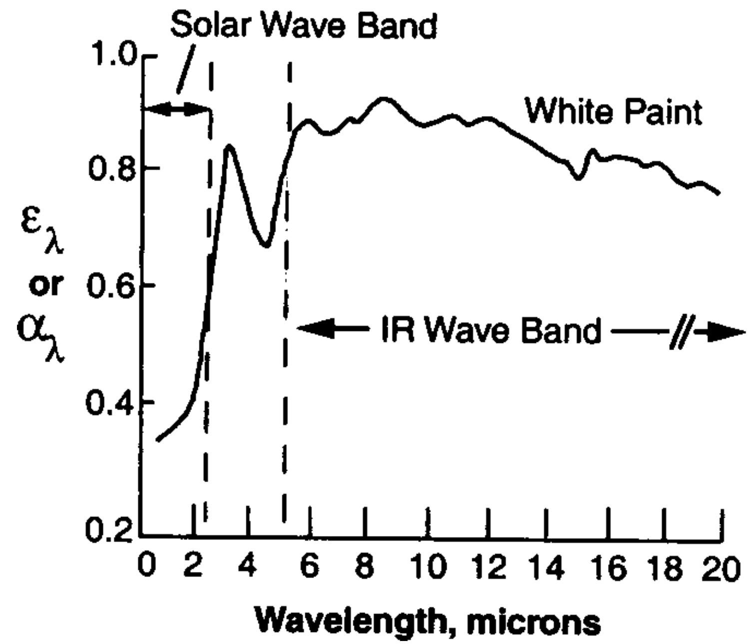
Thermal Characteristics of Materials - 2

How are the thermal characteristics in long wave IR compared to visible light ???
- or - how would surfaces look like if out eyes were tuned to the 10 - 20 μm range ???

First we should note that a surface emits long wave IR with an efficiency ε (emissivity) compared to a black body also absorbs radiation in the same wavelength range with an efficiency ε

This is important when we consider radiative heat exchange within the spacecraft body or within e.g. electronics compartnments.

Investigating the graph at right we realize that white = black, i.e. a paint that looks white to our eyes is actually black (almost) with long wavelength IR eyes.



Thermal Characteristics of Materials - 3

The combined absorbtivity/emissivity properties of a surface determines its characteristics:

- **If the α/ε ratio is high, the surface is “warm” as it is a good absorber but a poor radiator e.g. polished aluminium or gold**
- **If the α/ε ratio is low, the surface is “cold” as it is a poor absorber but a good radiator e.g. silvered or aluminized teflon**

No.	Material	Measurement Temp. (K)	Surface Condition	Solar Absorptivity, α	Infrared Emissivity ε	Absorptivity/Emissivity Ratio	Equilibrium Temp* (°C)
1	Aluminum (6061-T6)	294	As Received	0.379	0.0346	10.95	450
2	Aluminum (6061-T6)	422	As Received	0.379	0.0393	9.64	428
3	Aluminum (6061-T6)	294	Polished	0.2	0.031	6.45	361
4	Aluminum (6061-T6)	422	Polished	0.2	0.034	5.88	346
5	Gold	294	As Rolled	0.299	0.023	13.00	482
6	Steel (AM 350)	294	As Received	0.567	0.267	2.12	207
7	Steel (AM 350)	422	As Received	0.567	0.317	1.79	187
8	Steel (AM 350)	611	As Received	0.567	0.353	1.61	175
9	Steel (AM 350)	811	As Received	0.567	0.375	1.51	168
10	Steel (AM 350)	294	Polished	0.357	0.095	3.76	281
11	Steel (AM 350)	422	Polished	0.357	0.111	3.22	259
12	Steel (AM 350)	611	Polished	0.357	0.135	2.64	234
13	Steel (AM 350)	811	Polished	0.357	0.155	2.30	217
14	Titanium (6AL-4V)	294	As Received	0.766	0.472	1.62	176
15	Titanium (6AL-4V)	422	As Received	0.766	0.513	1.49	166
16	Titanium (6AL-4V)	294	Polished	0.448	0.129	3.47	270
17	Titanium (6AL-4V)	422	Polished	0.448	0.148	3.03	251
18	White Enamel	294	Al. Substrate	0.252	0.853	0.30	20
19	White Epoxy	294	Al. Substrate	0.248	0.924	0.27	13
20	White Epoxy	422	Al. Substrate	0.248	0.888	0.28	16
21	Black Paint	294	Al. Substrate	0.975	0.874	1.12	136
22	Silvered Teflon	295		0.08	0.66	0.12	–39
23	Aluminized Teflon	295		0.163	0.8	0.20	–6
24	OSR (Quartz Over Silver)	295		0.077	0.79	0.10	–51
25	Solar Cell-Fused Silica Cover			0.805	0.825	0.98	122

Thermal Characteristics of Materials - 4

Material	Absorbtivity α	Emissivity ε	α/ε
Aluminium (6061-T6 alloy) as supplied	0.379	0.0346	10.95
Aluminium (6061-T6 alloy) polished	0.2	0.031	6.45
Aluminium with Alodine 1200S Chromate Conversion Coating	0.08	0.15	0.53
Gold	0.299	0.023	13.00
White epoxy paint	0.248	0.924	0.27
Black paint	0.975	0.874	1.12
Silver coated Teflon	0.08	0.66	0.12
Aluminized Teflon (front surface)	0.163	0.80	0.20
Aluminized 25 μm Kapton (back surface)	0.36	0.61	0.59
Multi-Layer Insulation with aluminized 25 μm Kapton cover sheet, large areas without seams	0.36	e* = 0.002	180
Silicon solar cells (with cover glass)	0.75	0.83	0.90
Gallium-Arsenide solar cells (with cover glass)	0.75	0.83	0.90

Radiation into Cold Space

The infrared radiation in Watts into cold space from a surface (radiator) having the area A_r, the absolute temperature T_r and the emissivity ε is given by:

$$Q_e = \varepsilon \cdot \sigma \cdot A_r \cdot (T_r^4 - T_0^4)$$

where $\sigma = 5.6696 \cdot 10^{-8}$ $W \cdot m^{-2} \cdot K^{-4}$ is the Stephan-Boltzmann constant

and T_0 is the temperature of the cosmic background radiation, which closely matches the spectral properties of black-body radiation from a 2.7 K warm body. As the temperature is to the fourth power, a very good approximation is:

$$Q_e = \varepsilon \cdot \sigma \cdot A_r \cdot T_r^4$$

Temperature Equilibrium

An equilibrium will always be reached some time after the solar irradiation has begun. Assuming normal incidence ($\varphi = 0$) and a perfectly insulated back side, temperature will adjust until $Q_e = Q_a$.

This yields:

$$\varepsilon \cdot \sigma \cdot A_r \cdot T_r^4 = \alpha \cdot S_0 \cdot A_r$$

and

This is the background for the equilibrium temperatues shown ín the materials properties table and the reason for the importance of the α/ε ratio

Problem # 1 - Temperature Equilibrium

Imagine our Cubesat made from Alodine 1200S coated aluminium: $\alpha = 0.08$, $\varepsilon = 0.15$

8 GaAs solar cells 2 x 4 cm with cover glas on each of the 6 faces of the cube:
$\alpha = 0.75$, $\varepsilon = 0.83$, $\eta = 0.25$ (solar energy to electricity conversion efficiency)

The Cubesat is alone in the solar system far from the Earth.

The Cubesat is illuminated by the Sun at 1 AU distance with a flux of: $S_0 = 1367\ W/m^2$

The direction to the sun is parallel to the line between opposite corners of the cube.

1. Calculate the incidence angle of sunlight on the three sunlit faces
2. Calculate the electrical output from the solar cells
3. Calculate the equilibrium temperature of the Cubesat

Temperature equilibrium

Absorbed power: $Q_a = S_0 \cdot \alpha \cdot A \cdot \cos(\theta)$

Emitted power: $Q_e = \varepsilon \cdot \sigma \cdot A_r \cdot T_r^4$ (approx.)

Equilibrium condition: $Q_a = Q_a$

Stephan-Boltzmann constant:
$\sigma = 5.6696 \cdot 10^{-8}\ W \cdot m^{-2} \cdot K^{-4}$

Problem # 1 - Solution

1. The angle between a cube face and the farthest corner is calculated by:
   $\theta = \arctan(1/\sqrt{2}) = 35.26°$. The incidence angle is then: $\theta = 90° - 35.26° = 54.74°$

2. Three faces are illuminated at the same incidence angle: $\theta = 54.74°$
   There are 64 cm^2 of solar cell area on each of three faces: $A = 192\ cm^2 = 0.0192\ m^2$
   Output power: $P_o = S_0 \cdot A \cdot \eta \cdot \cos(\theta) = 1367 \cdot 0.0192 \cdot 0.25 \cdot 0.5774 = 3.79\ W$

3. The weighted average absorbtivity of a surface is: $\alpha' = (36 \cdot 0.08 + 64 \cdot 0.75)/100 = 0.5088$
   The weighted average emissivity of a surface is: $\varepsilon' = (36 \cdot 0.15 + 64 \cdot 0.83)/100 = 0.5312$

   The absorbed power on three sunlit faces is:
   $$Q_a = S_0 \cdot \alpha' \cdot A \cdot \cos(\theta) = 1367 \cdot 0.5088 \cdot 0.03 \cdot 0.5774 = 12.048\ W$$

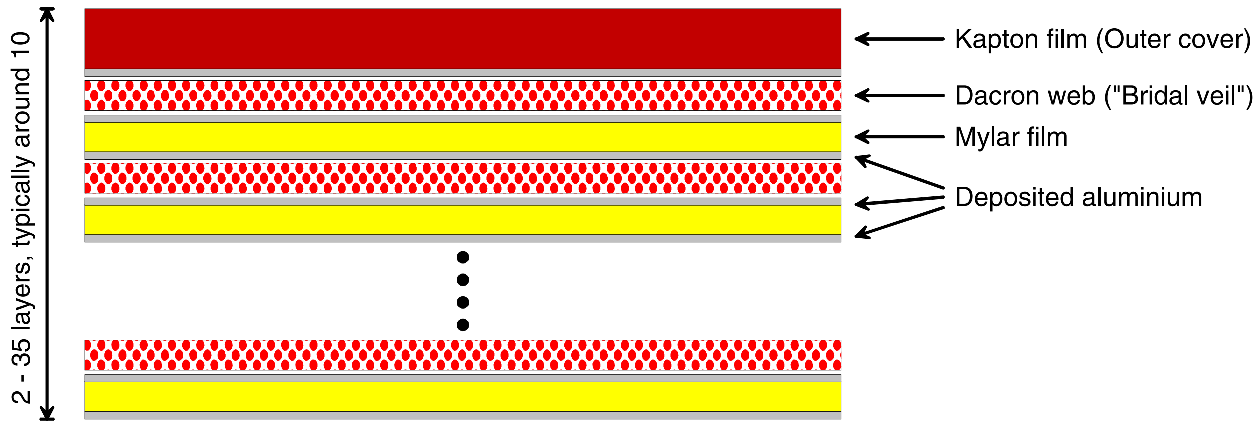
   The radiated power comes from all six faces of the cube:
   $$Q_e = \varepsilon' \cdot \sigma \cdot 2A \cdot T_r^4 = Q_a \text{ , for equilibrium}$$

   Solving for T yields: $T = 285.8\ K = 12.6\ °C$

Heat Insulation - 1

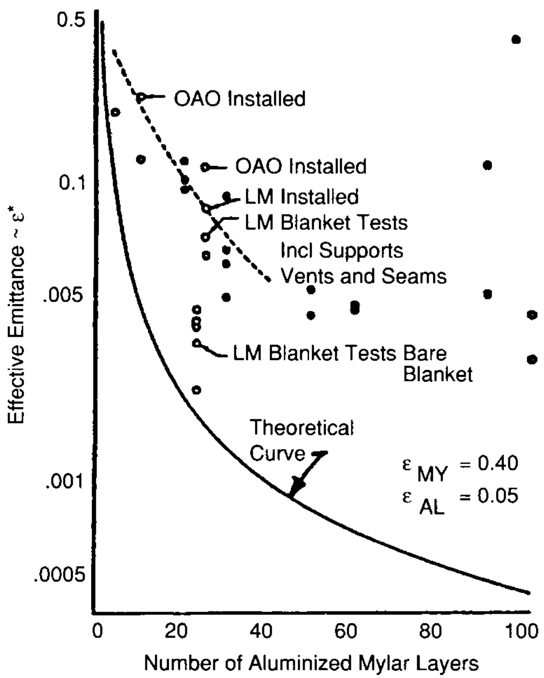
Often heat insulation is needed e.g. to keep an instrument sufficiently warm or the prevent heat from body-mounted solar panels from propagating into the spacecraft or for other reasons.

The material of choice is MLI (Multilayer Insulation)

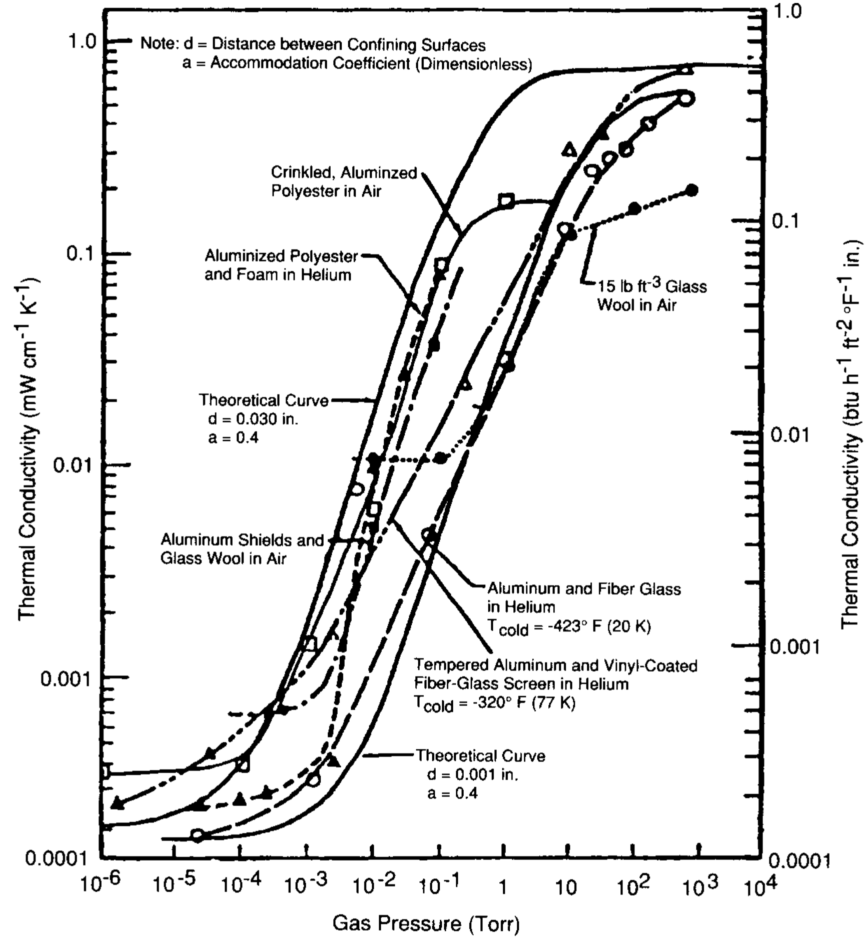


Heat Insulation - 2

MLI is most easily characterized by an effective emissivity: ε_{eff}



ε_{eff} **vs. Number of Layers**

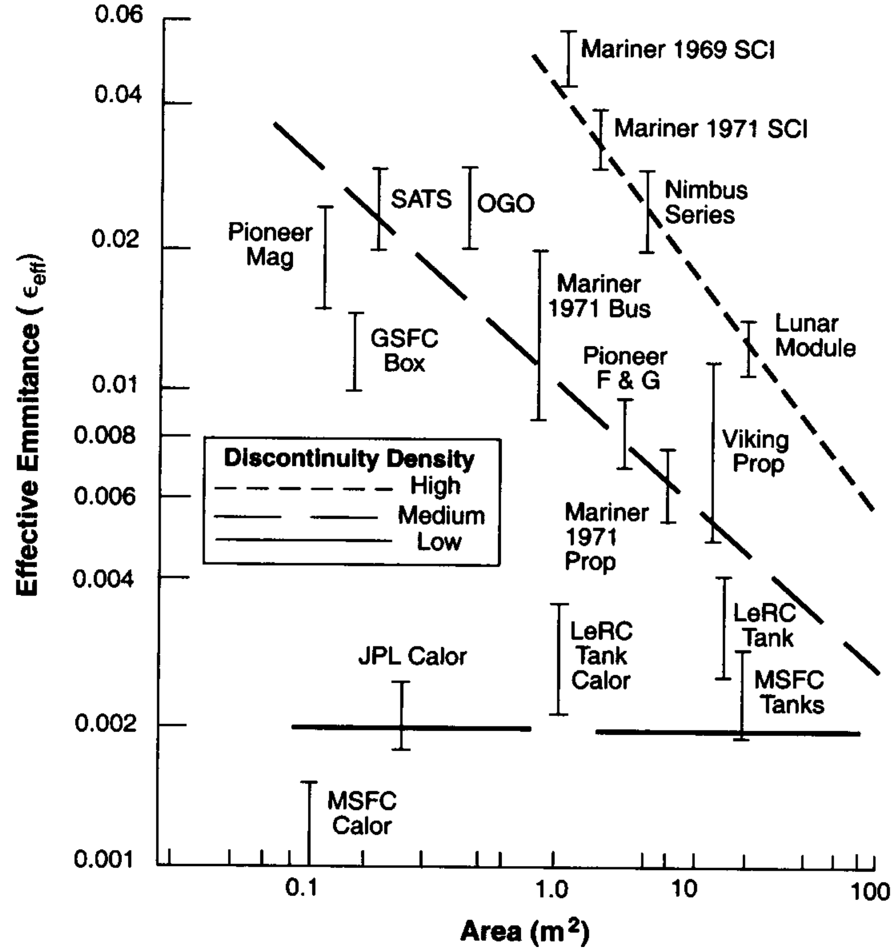


ε_{eff} **vs. Ambient Pressure**

Heat Insulation - 3

… but the efficiency of MLI is strongly dependent on the density of discontinuities created when sewing, welding, glueing or otherwize preparing the insulating blankets

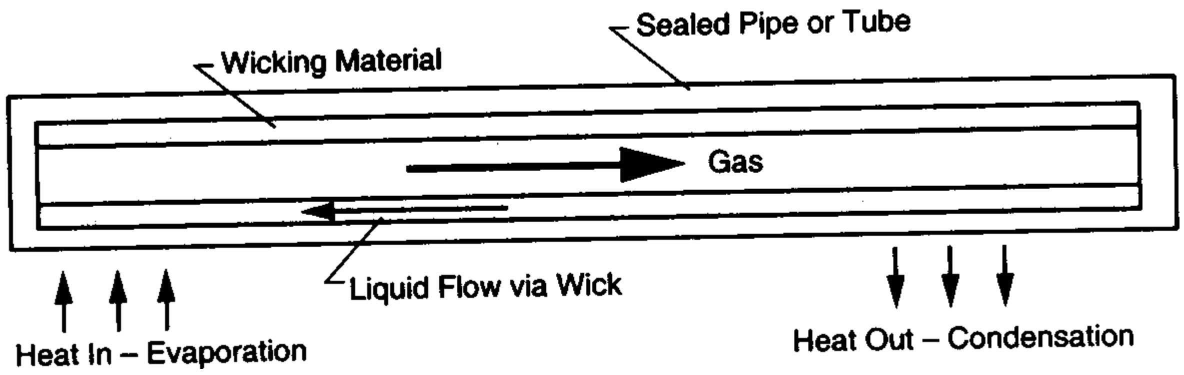
Good insulation is easier to obtain on a large cryogenic fuel tank than a small scientific instrument with a complex shape



Heat Pipes

Heat Pipes are simple and very efficient devices for transporting heat

Heat Pipes are passive and may be used both at cryogenic temperature, room temperature and elevated temperature depending on the working fluid selected



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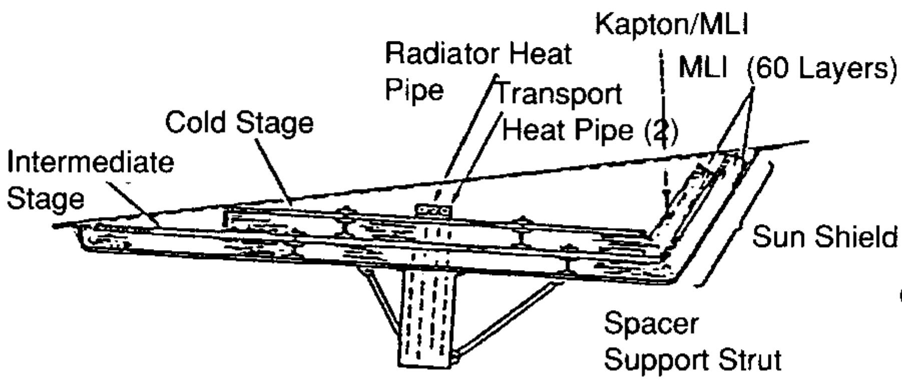
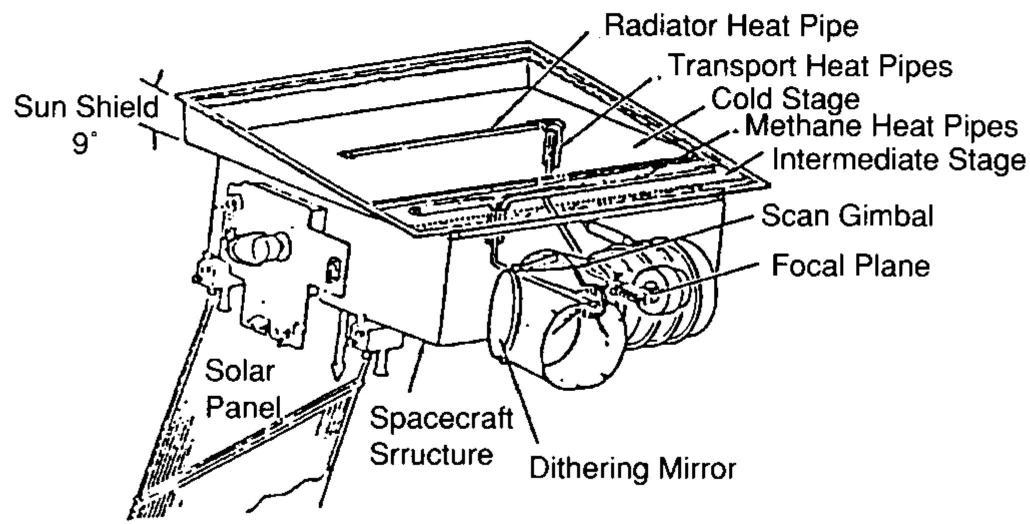
Example of Passive Cooling System for Cryo-Sensor

b) RADIATOR CROSS SECTION



c) SENSOR/RADITOR/SPACECRAFT INTEGRATION



The cold stage rejects 5 W heat at 70 K from a ≈1 m² surface

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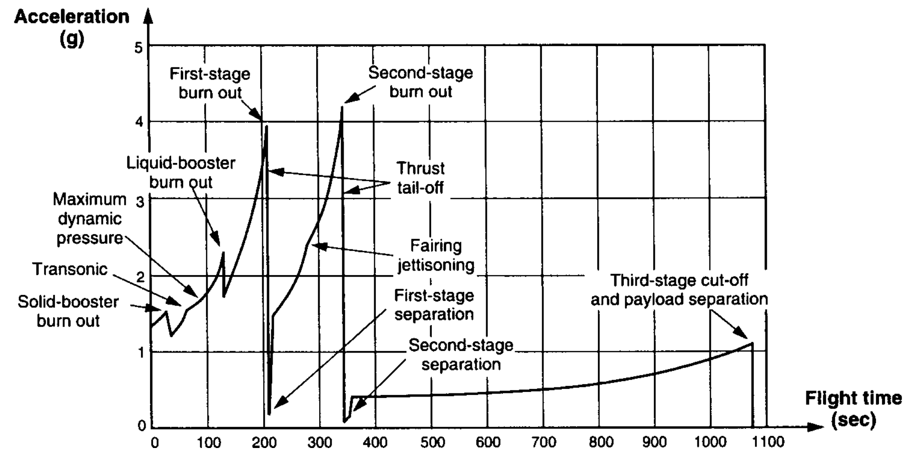
Structure

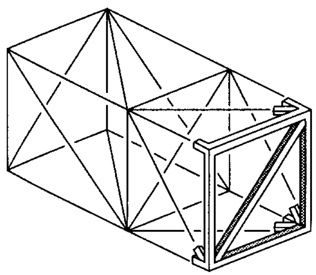
- The structure shall be strong and stiff in order to withstand the vibrations, quasi-static accelarations, shock and acoustic noise during launch
- The structure shall be thermally stable in order to withstand the temperature variations in orbit while maintaining instruments aligned
- The structure shall provide a common electrical grounding point
- The structure shall be lightweight
- The structure shall be designed for easy access to equipment and and for safe and easy handling during integration and transportation



Ariane 4 quasi-static acceleration profile during launch

Types of Structure - 1

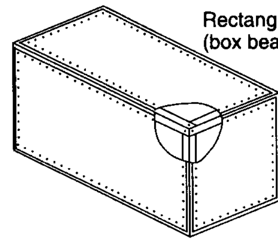
Trusses and Frames



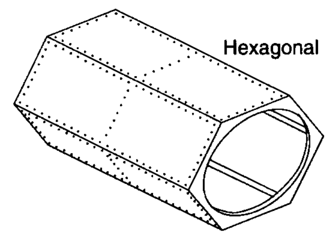
A *truss* is a structure that can withstand loads applied to its joints with its members loaded only axially (no shear and no moment). A stable truss is recognizable—the arrangement of its members forms triangles (see Sec. 15.6). Polygons of any other shape, such as a rectangle, usually imply instability, in which case we must make the structure a frame. A *frame* can carry shear and bending through its joints and members. In most cases, trusses are more efficient than frames. A statically determinate truss has no more members than are necessary for stability and to introduce and react loads. Note that if the ends of truss members are not pinned through the use of bearings or other devices, the members will carry shears and moments, which can greatly increase member stresses.

Forms of Construction:	• Extruded tubes (square or round) or open shapes • Separately machined members of open section (I, Z, channel, angle) • Truss sides integrally machined from plate-stock material • Members made of sheet metal formed into structural shapes • Laminated composite tubes with metallic end fittings
Typical Materials:	• Aluminum, magnesium, and titanium alloys; graphite/epoxy composite
Attachment Methods:	• Mechanical fastening (bolts or rivets), welding, or bonding, depending on the material (see Sec. 15.5)
Packaging and Access:	• Spacecraft components can be mounted internally or externally • Structure's interior is accessible for installing and wiring components
Other Design Considerations:	• Can be difficult to transfer loads from a truss to a cylindrical structure, such as a launch vehicle, without locally overloading the cylinder • Trusses are weight-efficient for structures of square, rectangular, or triangular cross section; they become less efficient as the cross section becomes more round (e.g., hexagonal) • Machining a full side of the truss from a single piece of metal is usually more economical than fabricating and assembling individual members; the cost of material and machining is typically offset by savings in labor

Skin-Frame Structures



Rectangular (box beam)



Hexagonal

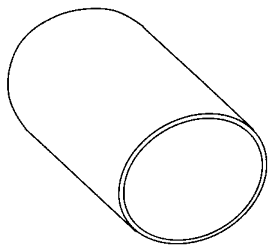
A *skin-frame structure* has *skin* (sheets or panels) surrounding a skeletal framework made of *stringers* (members oriented in the vehicle's axial direction) and lateral frames, which introduce shear into the skin. Intermediate frames are used to mount equipment or increase the buckling strength of the skin or stringers. Shown at left are two shapes; nearly any shape is possible. (The Manned Maneuvering Unit, shown in Fig. 17.5, has a skin-frame structure.) The skin can be allowed to buckle, in which case diagonal tension carries the shear (see Fig. 15.3); if it's designed not to buckle, it will help carry compressive loads.

To be stable, the ends of a skin-stringer structure must be closed with skin, be "triangularized" with diagonal members, or include radially deep frames, as shown for the hexagonal structure. Such frames stabilize the stringers and react radial components of load.

Forms of Construction:	• Frame members extruded, machined, or formed from sheet metal • Skin can be sheet metal, sandwich construction, or isogrid (see Fig. 15.4)
Typical Materials:	• Aluminum, magnesium, and titanium alloys
Attachment Methods:	• Mechanical fasteners (bolts or rivets)
Packaging and Access:	• Internal access can be difficult; may need removable panels • Sandwich and isogrid panels can be used to mount components (see FireSat example, Sec. 14.4)
Other Design Considerations:	• Versatile in shape • Closed structures require blind fasteners

Types of Structure - 2

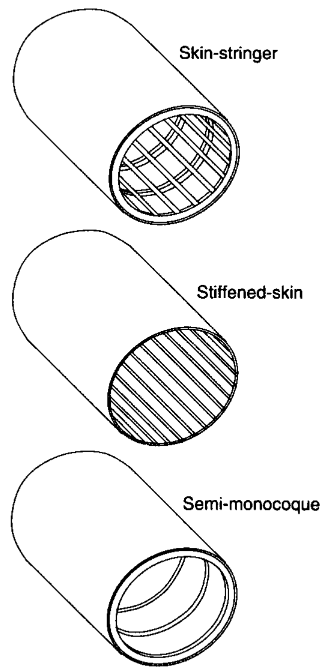
Monocoque Cylinder



A *monocoque cylinder* is an axi-symmetric shell without stiffeners or ring frames. Its strength is limited by its buckling stress. The shell buckling equations in Chap. 8 apply for unpressurized isotropic cylinders (identical properties in all directions). To be effective as a structure, a monocoque cylinder must have loads introduced uniformly over its cross section, with stress, f, following the relationship, $f = P/A + My/I$, where P is axial force, A is area, M is moment, y is distance from neutral axis, and I is area moment of inertia (see Chap. 6). Concentrated loads can cause local failure. To achieve a uniform load distribution, the mating structure must be either another monocoque cylinder or a stiff transition adapter.

Forms of Construction:	• Sheet metal or isogrid (see Fig. 15.4), with curvature formed by rolling • Sandwich construction (Fig. 15.4), with segments fabricated with curvature • Typically two or three segments used to form a cylinder
Typical Materials:	• Aluminum and magnesium alloys; graphite/epoxy composite is often used for sandwich face sheets
Attachment Methods:	• Mechanical fasteners (bolts or rivets) or welds for attaching segments
Packaging and Access:	• Difficult to mount components without overloading the shell. Decks often must be supported by ring frames. For wall mounting, we typically must provide ring frames and *intercostals*, which are short axial members that go between and attach to two frames. • Removable access panels may be required
Other Design Considerations:	• A solid-skin cylinder made of sheet or plate metal is the simplest and least expensive structure, but solid-skin cylinders are normally suitable only for stiffness-critical designs because of low buckling strength • Use of sandwich construction results in a light structure; isogrid shells can also be made at relatively low weight

Other Cylinder Structures



Each of these options for a cylindrical structure includes members that help carry loads and stabilize the skin.

In a *skin-stringer structure*, the skin is typically designed to buckle at relatively low loads and transfer shear and torsion by diagonal tension (see Fig. 15.3). The stringers carry most of the axial load and bending moment, and they and the ring frames must react the radial component of diagonal tension loads. The skin and members must be attached with closely spaced rivets or threaded fasteners in order to act together as a structure.

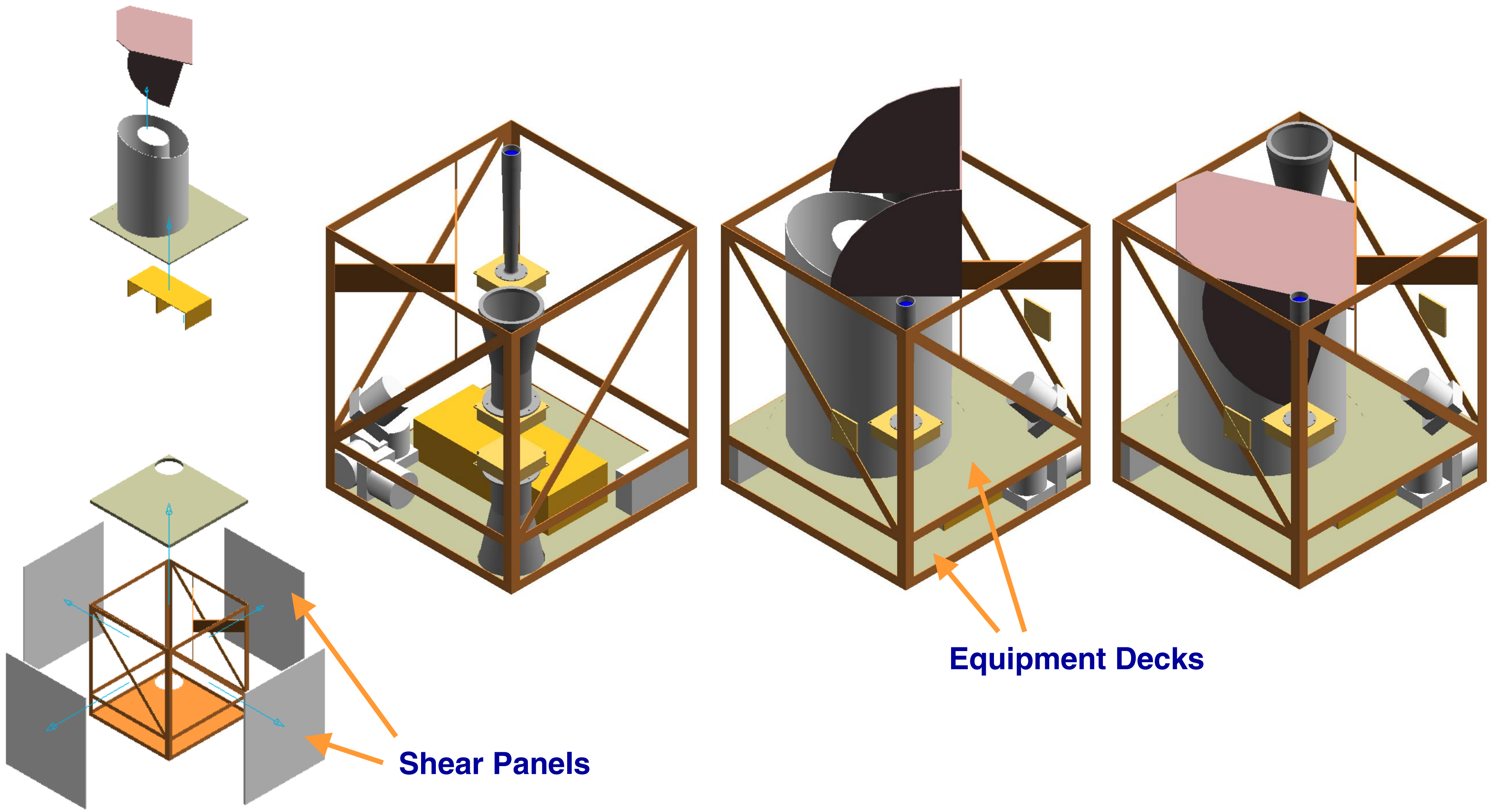
A *stiffened-skin cylinder* has a thin skin and light-weight, closely spaced stiffeners. *Stiffeners* are axial members intended to increase the buckling stress of the skin (as opposed to stringers, which carry most of the axial load). Intermediate ring frames are sometimes used to stabilize the stiffeners and thus reduce their size. The stiffeners and skin can be integrally machined from flat plate, which is then formed to have curvature between stiffeners.

A *semi-monocoque cylinder* has intermediate ring frames to increase the buckling stress of the skin, but no axial stiffeners or stringers.

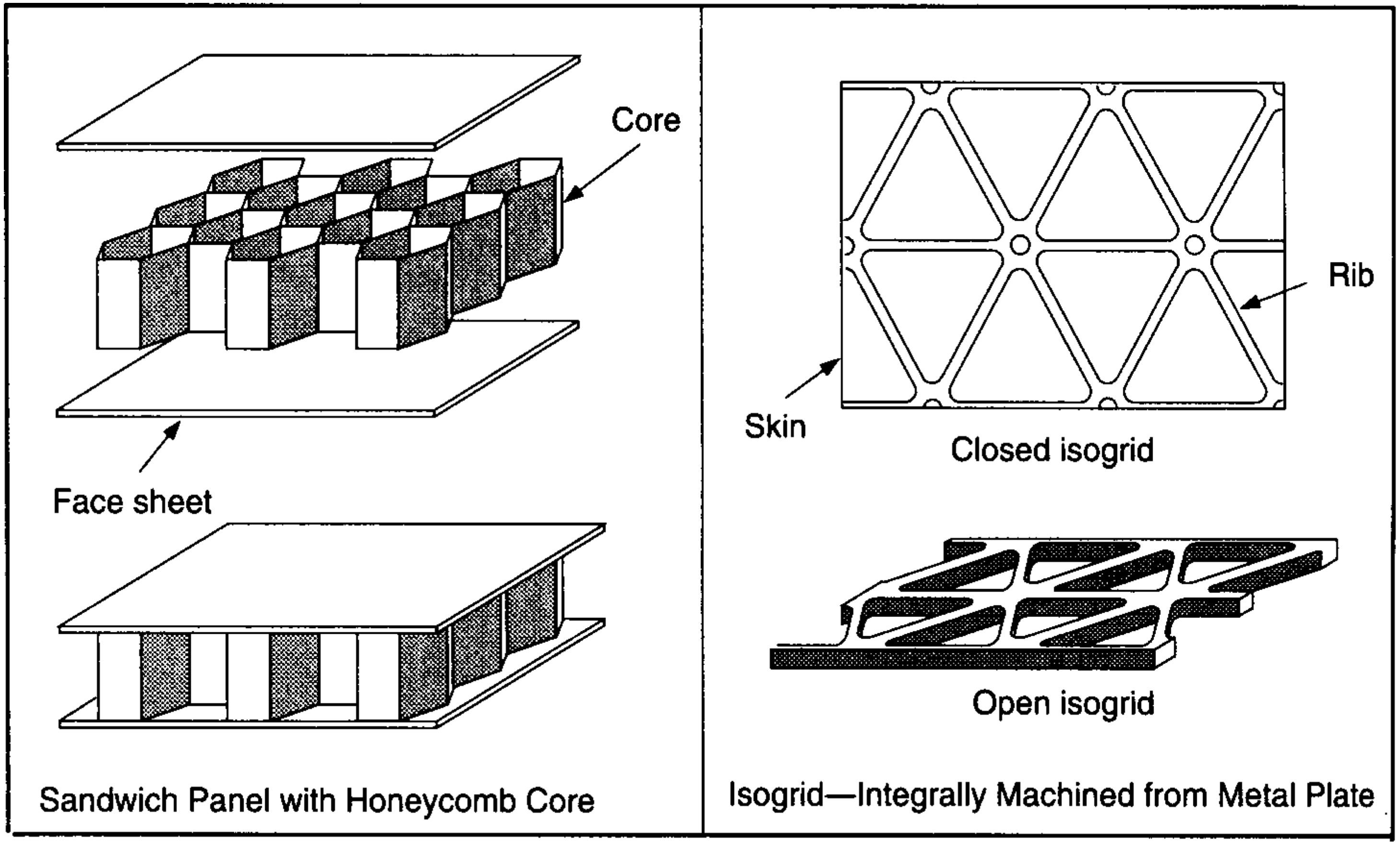
Of these, skin-stringer structures are most common. They have been used often for launch vehicles, booster adapters, and airplane fuselages. But these structures are not as economical as they used to be. The rising cost of labor during assembly usually makes skin-stringer structures less desirable than monocoque cylinders made of isogrid or sandwich construction (see Fig. 15.4).

Forms of Construction:	• Stringers and axial stiffeners extruded, machined, or formed from sheet metal; skin made of sheet metal • Ring frames machined from ring forgings • Skin and stiffeners integrally machined from a single flat plate, then formed.
Typical Materials:	• Aluminum alloys
Attachment Methods:	• Rivets or threaded fasteners
Packaging and Access:	• Internal access can be difficult; may need removable panels or framed cutouts
Other Design Considerations:	• The hard points provided by stringers make it easier to introduce loads from other types of structures than it is for monocoque cylinders

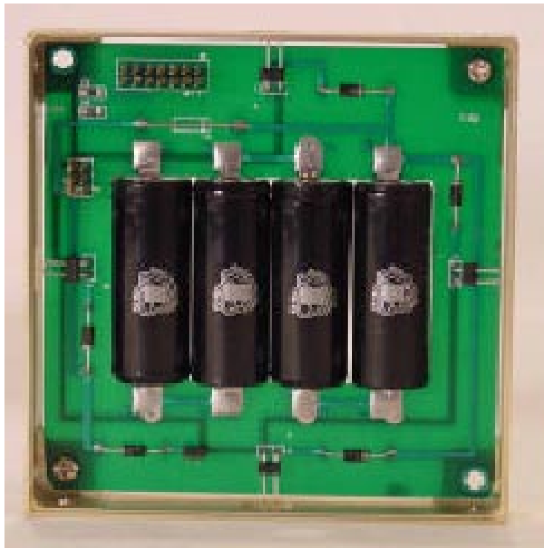
RØMER - Trusses and Frames Structure with Shear Panels



Honeycomb and Isogrid Panels



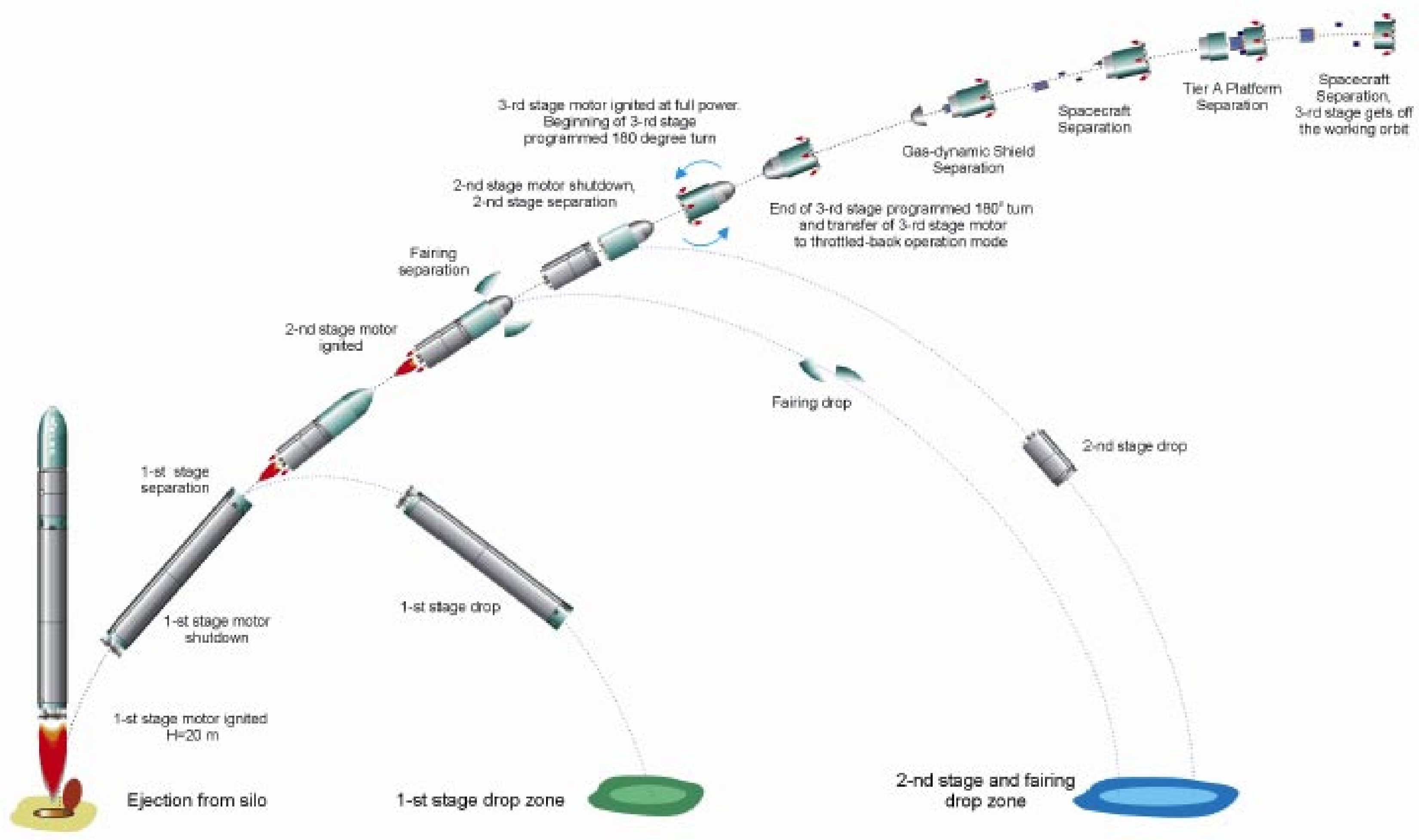
Cubesat Stackable Frame Structure



Specifications

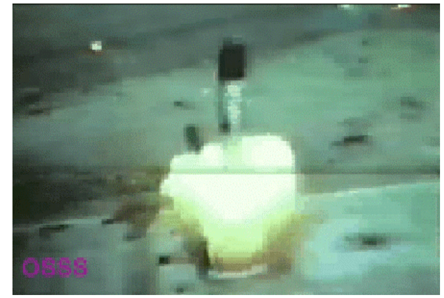
Feature	Data
Configuration	Vertical-stacking, independent compartments with standard connectors
Material	7071-T3 Aluminum
Dimensions	10cm x 10cm x 1.783 cm
Connectors	DB-9. DB-15, DB-25, DB-36, or NTSC

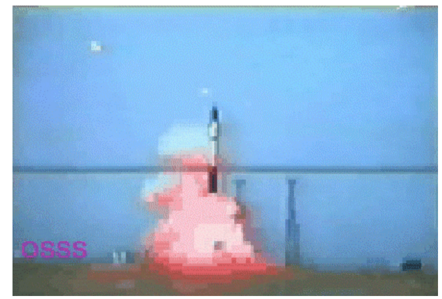
DNEPR Mission Profile for Launching Clusters of Small Spacecraft

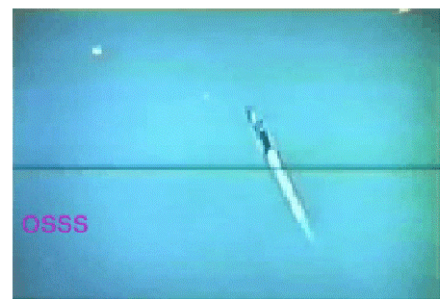


DNEPR Quasi-Static and Dynamic Loads

Load Source	Spacecraft/Launch Vehicle Interface	
	Axial g-load	Lateral g-load
Launch		
Movement inside the launch canister	2.4 ± 0.2	0.2 ± 0.3
After exit from the launch canister	0.0 ± 0.5	0.8 ± 0.3
First stage flight		
Maximum dynamic head	nx = 3.1 ± 0.3 at gmax	0.35 ± 0.2
Maximum axial g-load	nx max = 7.0 ± 0.5	0.1 ± 0.4
Second stage flight		
Maximum axial g-load	nx max = 7.7 ± 0.5	0.1
Third stage flight		
Maximum dynamic head	nx = -0.3…-0.5	







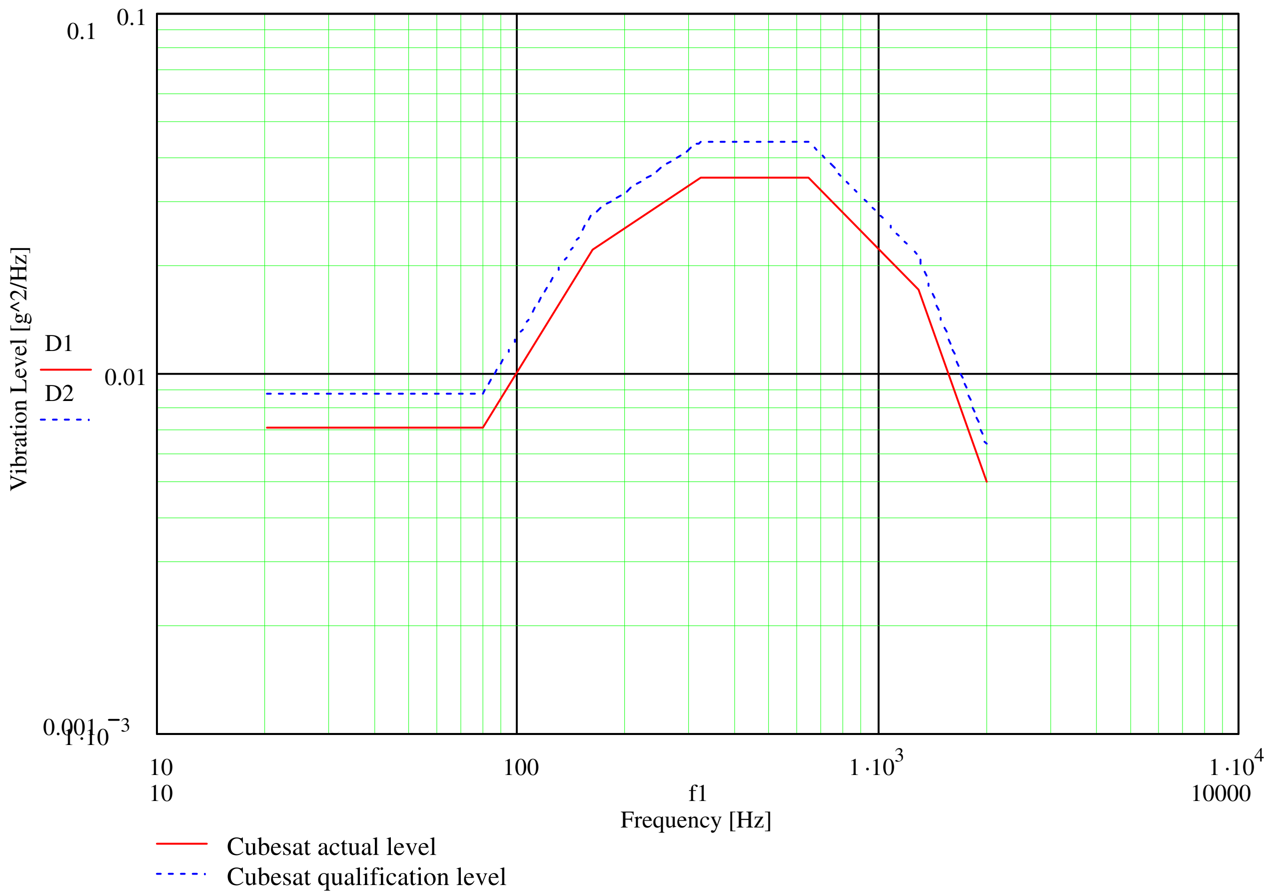
DNEPR Random Vibration Spectral Density

Actual vibration level experienced by Cubesat: 6.28 g rms

Cubesat qualification vibration level, 125% of actual: 7.85 g rms

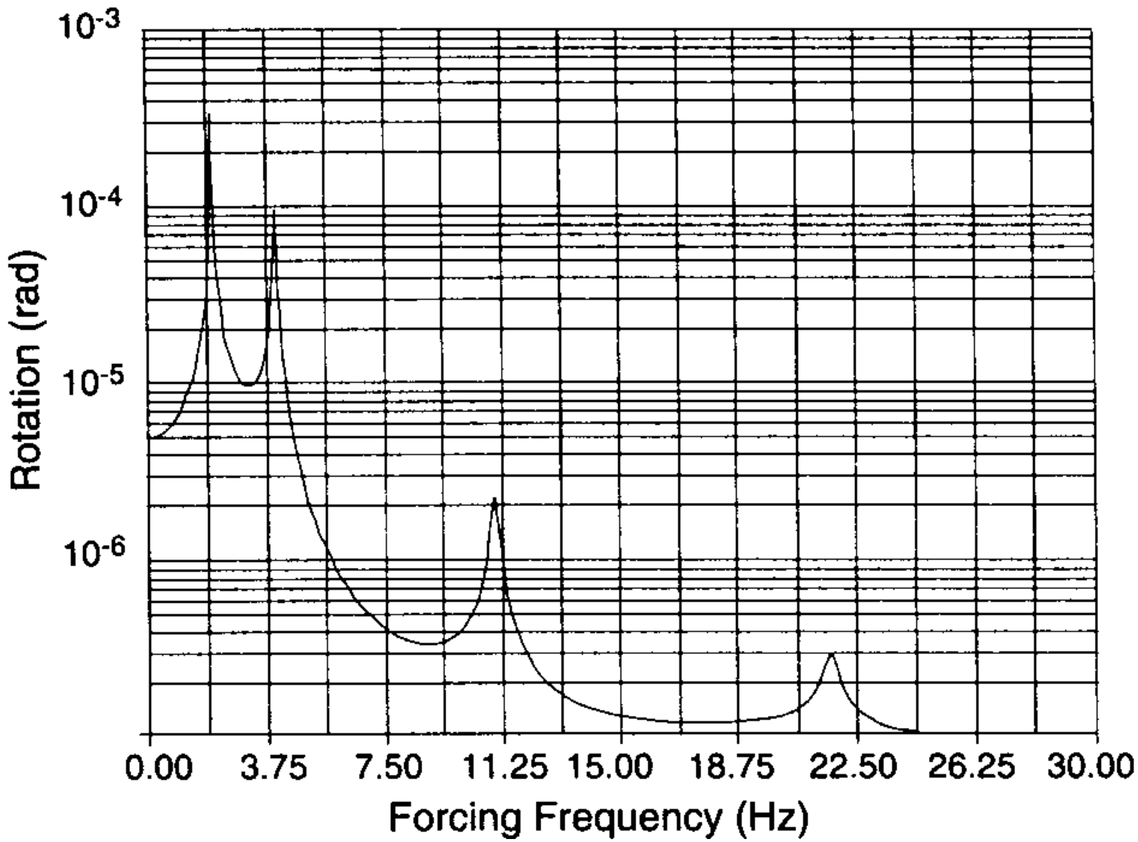
The RMS vibration level is obtained by integrating the vibration spectal density over the specified frequency band and taking the square root:

$$A1rms := \sqrt{\int_{20}^{2000} vsd(f,1)\, df}$$



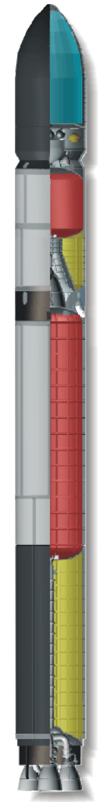
Duration: 90 sec.

Transfer Function for Unit Response to Sine Vibration



DNEPR Acoustic Loads under Fairing

Octave Frequency Band Mean Geometric Frequency Hz	Sound Pressure Level dB
31.5	125
63	132
125	135
250	134
500	132
1000	129
2000	126
4000	121
8000	115
Integral level of sound pressure dB	140
Duration sec	35



DNEPR Shock Spectrum