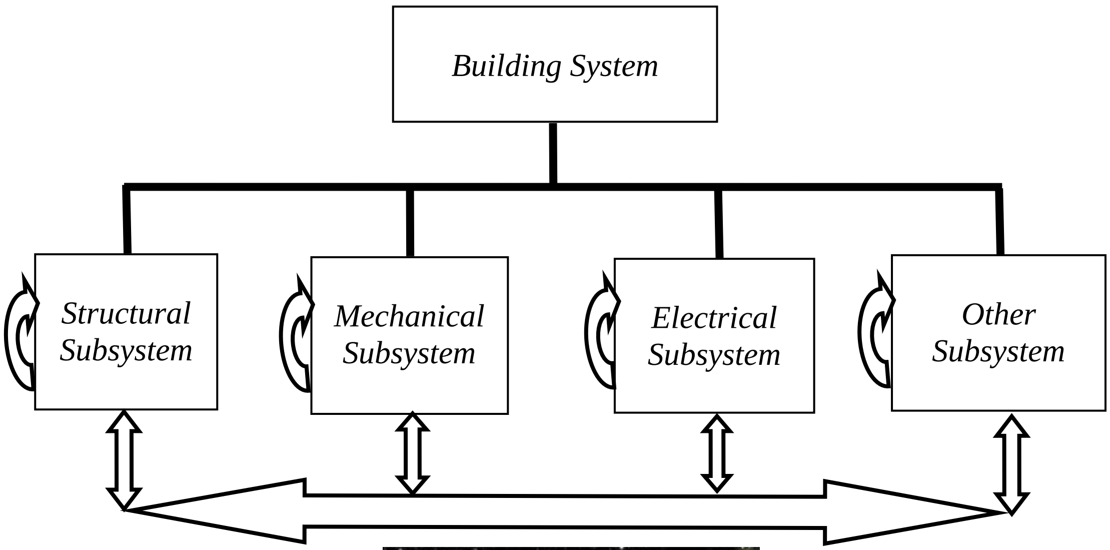
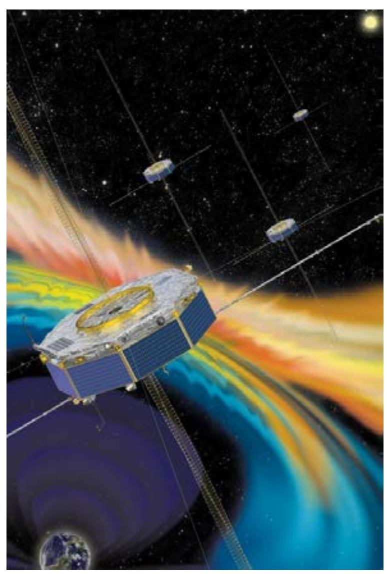
A SunCam online continuing education course

What Every Engineer Should Know About Systems Engineering





by

Michael A. Benoist, P.E., CSEP

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1. Introduction

Every engineer should know that their discipline can be modeled as a system, where design decisions can hinder the operation of other systems, therefore impacting the overall system. Realizing there are many other consulting engineering disciplines of equal importance, general and specialized, such as: fire protection, lighting, telecommunications, security, civil, plumbing, and environmental – structural, mechanical, and electrical disciplines will be covered in order to help streamline and simplify this short course.

As depicted in the following figure, a building can be modeled as one engineering system composed of multiple engineering subsystems for each discipline. The successful function of each system (or subsystem) is of critical importance in order for the building system to also function successfully. The concept of intradiscipline and interdiscipline systems engineering can be applied to all disciplines. This means how your design decisions can affect systems within your own discipline and other disciplines as depicted by the arrows.

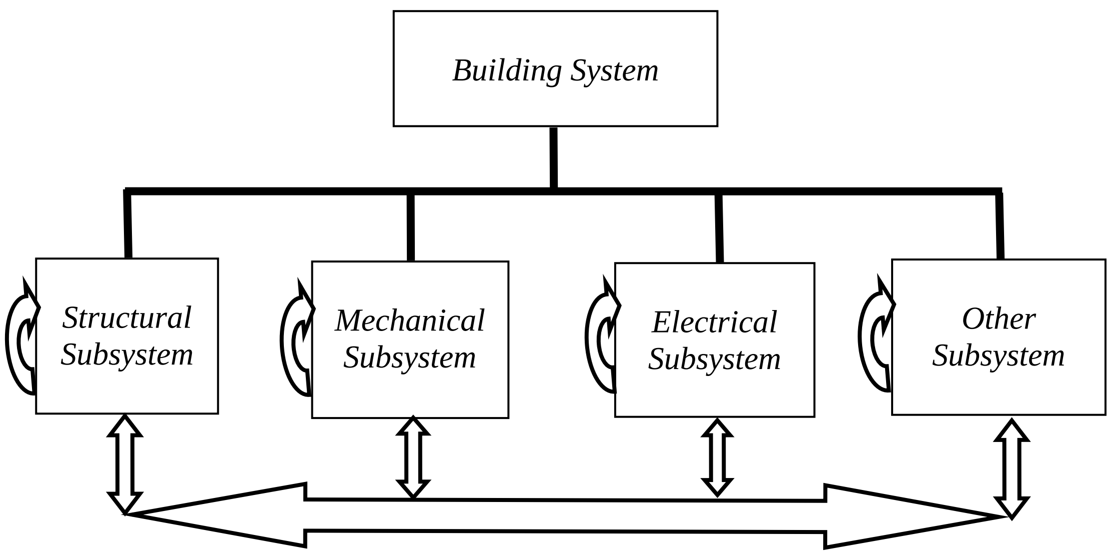

Figure 1.1: Systems Impacting Other Systems

Whether you know it or not, you are most likely performing some level of systems engineering if you are engineering a building system as described by the previous figure. So what is systems engineering? Systems engineering as defined by the International Council on Systems Engineering (INCOSE) website [ref. 1]:

> *"Systems Engineering is an interdisciplinary approach and means to enable the realization of successful systems. It focuses on defining customer needs and required functionality early in the development cycle, documenting requirements, then proceeding with design synthesis and system validation while considering the complete problem: Operations, Performance, Test, Manufacturing, Cost & Schedule, Training & Support, Disposal. Systems Engineering integrates all the disciplines and specialty groups into a team effort forming a structured development process that proceeds from concept to production to operation. Systems Engineering considers both the business and the technical needs of all customers with the goal of providing a quality product that meets the user needs."*

My Case Study – Electrical Interferes with Sound

When I began working at a consulting engineer firm as a telecommunications engineer in the late 1990's, one of my first tasks was to try to solve an existing noise problem in a newly installed school auditorium sound system. New to the company, I had no background knowledge of the project. I was starting fresh, which can be a good thing sometimes.

My boss provided me with all the engineering drawings, specifications, and manufacturers documentation. I recall laying out everything on an old drafting table to study. Also, my boss and I made a trip to the job site to perform a site survey, where we met with the sound system contractors. They proposed that it was a ground loop problem.

After the site visit, I looked at all the engineering documentation again and noticed that the power for the sound system was being fed by the auditorium lighting dimmer system. Lighting dimmer systems can be a source of electronic noise. With this knowledge, I realized that this noise can be injected into the sound system if there is insufficient filtering. I confirmed this lack of filtering after verifying the engineering documentation and calling the manufacturer of the lighting dimmer system. The ***systems engineering*** problem was identified, the lighting dimmer system which fed power to the auditorium sound system was not filtered, allowing noise to enter the sound system, and output to its speakers.

After presenting my findings of the problem to my boss, to solve the problem, we made the decision to simply move the power feeding the sound system from the lighting dimmer system to be fed elsewhere. After creating engineering change drawings detailing the solution and meeting with the electrical contractor on-site, the change was implemented – the ***systems engineering*** problem was solved, no more noisy sound system! At this time, I never even heard of systems engineering.

2. Systems Impacting Systems

In this section you will see how other domains such as spacecraft, have similar problems of systems impacting other systems as in the consulting engineering domain. The following will be presented:

- The forces from other systems the spacecraft structure must be designed to withstand.
- A spacecraft structure's thermal design can impact the mechanical system (e.g. orientation) as experienced by the Polar BEAR spacecraft.
- An electrical design decision impacts mechanical as experienced by the Apollo 13 mission.

Structural Impacted by Launch Systems

Spacecraft structures, like the Magnetospheric Multiscale (MMS) presented in this section, must account for forces created by other systems, such as those encountered during launch from the heat shield, rocket stages, main engine, and pyrotechnic.

Launched March 12, 2015 the MMS mission consists of four identical spacecraft, with their mission to explore the interactions between the Sun's and the Earth's magnetic fields, focusing on energy transfer during their magnetic field connects and disconnects. With all four stacked one on top of the other in their launch configuration, they utilize low shock systems (similar to those used to separate launch vehicle stages) to separate the upper three spacecraft from the stack. Shock refers to an event of short duration.

The following is an artist's illustration of the four MMS spacecraft passing through the Earth's magnetic field. In this depiction, you can clearly see the following:

- two deployed boom electric field sensors extending from the thrust tube in the center
- long boom which contains the magnetic field sensors
- side solar panels for power (4 are shown, 8 total)

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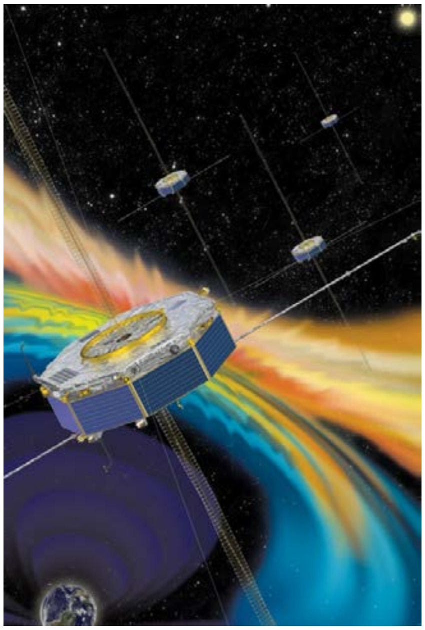

Figure 2.1: MMS Spacecraft in Orbit – Artist rendering
[Reprint from source: nasa.gov]

The following page includes two pictures of an MMS spacecraft, showing the progression from structure in the first photo to the integration of the subsystems (e.g. electrical, mechanical, payload) in the second photo. The first picture shows an MMS spacecraft structure ready for alignment testing, with the struts attaching the upper instrument deck and the lower spacecraft deck. The second picture shows the MMS spacecraft structure with payload instruments installed on the upper deck and bus (e.g. electrical, mechanical) subsystems installed on the lower deck. Note, the black tube in the center contains the propulsion subsystem, including the fuel tank, which for this spacecraft is known as the thrust tube.

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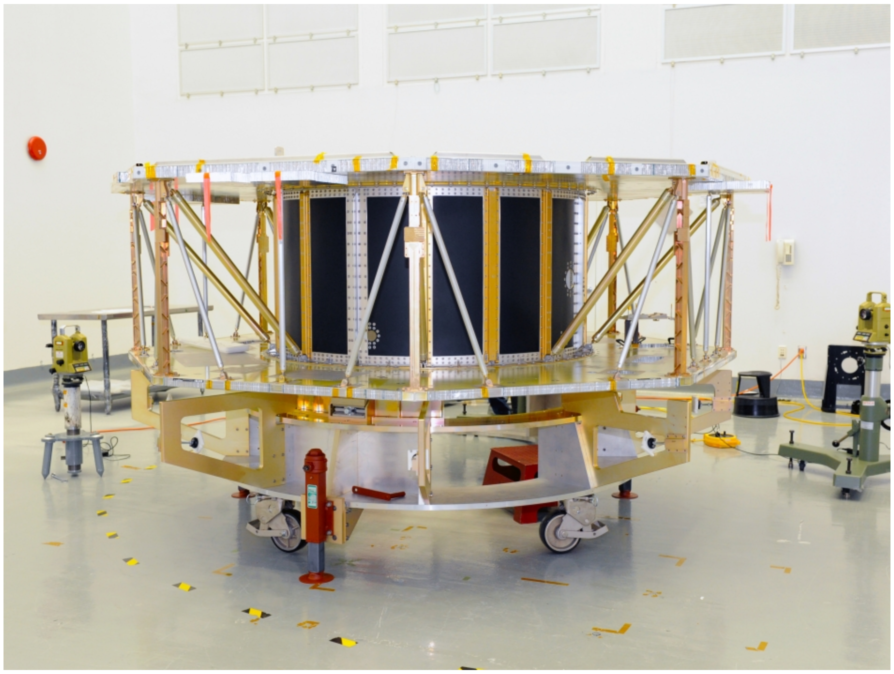

Figure 2.2: MMS Spacecraft Structure – BEFORE Subsystem Integration
[Reprint from source: nasa.gov]

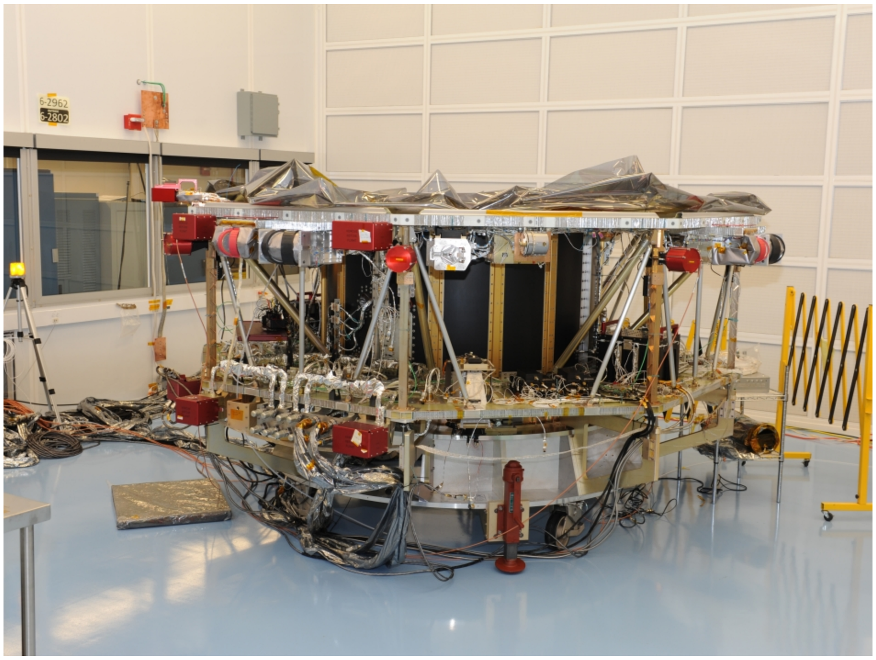

Figure 2.3: MMS Spacecraft Structure – AFTER Subsystem Integration
[Reprint from source: nasa.gov]

Structural spacecraft designs such as in the MMS must take into account all loading conditions the spacecraft will experience during its entire lifecycle (i.e. not just in space), especially launch forces which are most dominant.

Violent Launch Forces

Spacecraft loading conditions are most intense during the launch sequence. Since most spacecraft launch vehicles have the same sequence (aka launch profile), similar loading conditions are experienced by most spacecraft. The following figure captures the liftoff of Apollo 13 on a Saturn V rocket, April 11, 1970, initially a lunar mission changing to a heroic rescue of the astronauts after an explosion of one of its oxygen tanks.

Figure 2.4: Apollo 13's Launch Vehicle – Saturn V Rocket
[Reprint from source: NASA @ nasa.gov]

Launch event sequences during ascent into space are:

1. Liftoff
2. Maximum Winds & Transonic Buffeting
3. Staging
4. Heat Shield/Fairing Separation
5. Spin Stabilization
6. Separation

The spacecraft structural design must consider all loading condition and effects the spacecraft will experience during each launch event sequence as described in the following table. The effects are on the spacecraft structure unless otherwise noted.

Launch Event Sequence	**Loading Condition**	**Loading Definition/ Explanation**	**Loading Effect On Spacecraft**
1	Acoustic	Sound pressure (dB) caused by reflected waves from the ground generated by the launch vehicle's main engine	Random vibrations
1	Ignition	Due to engine ignition transients	Vibrations
2	Maximum Winds	Structural loading caused by higher altitude winds	Mostly impacting the heat shield, reduces the clearance between the heat shield and the spacecraft
2	Transonic Buffeting	Shock waves directed at heat shield because of change in speeds from subsonic to sonic	
3	Maximum Sustained Acceleration	Peaks at each stage separation, and is most dominant loading condition at this event sequence	Gravitational forces
3	Vibration Transients	Mechanical shock transferred from the separated stage	Small amounts of variations about the maximum sustained acceleration
4	Mechanical Shock	Caused by physical separation of the heat shield (payload fairing)	Generates lower frequencies

Launch Event Sequence	Loading Condition	Loading Definition/ Explanation	Loading Effect On Spacecraft
4	Pyrotechnic Shock	Caused by explosive mechanisms that activate heat shield (payload fairing) separation	Generates higher frequencies more damaging to spacecraft electronic components
5	Upper Stage	Often uses spin stabilization for attitude control during transfer of satellite to its correct higher orbit (e.g. geosynchronous)	Tangential and centripetal accelerations (±)
6	Pyrotechnic Shock	Caused by firing explosive devices to cut hardware (e.g. bolts, straps), freeing the spacecraft from the launch vehicle's upper stage	Generates higher frequencies more damaging to spacecraft electronic components

Structural Impacts Mechanical – Polar BEAR Case Study

Thermal Stress

Thermal stress pertains to mechanical stresses induced by temperature gradients (i.e. changes). Because of these gradients, it is best to interface structural members using similar materials that are thermally compatible, this is, they have similar thermal response characteristics. If dissimilar, they are more prone to thermal stress.

Stresses at joined members, (e.g. a beam constrained between two deck plates), if ΔT is large, deformation can occur which translates to strain, subsequently resulting in stress in the structural beam which can be described by the following equations:

$$\delta_T = \alpha L(\Delta T)$$

$$\varepsilon = \delta_T \div L = \alpha L(\Delta T) \div L = \alpha \Delta T$$

..and using Hooke's Law to obtain stress is:

$$\sigma = E\varepsilon = E\alpha\Delta T$$

...where each variable is defined as:
δ_T...........thermal deformation
α............coefficient of linear thermal expansion*

L............beam length(before stress)
ΔT..........change in temperature
ε.............strain
E.............modulus of elasticity (aka Young's modulus)*
σ.............stress
**a material characteristic*

To further complicate matters, if thermal stresses are imposed on a spacecraft's structural appendage such as a gravity gradient boom, the spacecraft's attitude (orientation) can become greatly degraded due to boom deformations or oscillations.

Gravity Gradient [ref. 2]
The gravity gradient stabilization method utilizes the differences in the earth's gravity gradients (i.e. gravitational forces) as a function of altitude by changing the inertia tensor of the spacecraft. The inertia tensor of a spacecraft can be increased by extending a long boom where a typical length might be 8m. The gravity gradient torques acting on the spacecraft are increased by placing a mass at the end of the boom to counteract the forces acting on the spacecraft mass in order to keep the spacecraft earth pointing (i.e. control attitude). Gravity gradient stabilization is a passive closed loop control system (like a basic mass-spring-damper) with no sensor feedback in the loop. Therefore, the restoring torque generated by the controller is based on error size and will be proportional to the attitude error.

Gravity gradient control of spacecraft is limited by altitude as can be seen in the following figure, where to be effective, its altitude needs to be much lower than geosynchronous and above 600km. The boom and two masses (m_1 and m_2) produce the inertias required to maintain nadir (z-axis) pointing toward earth.

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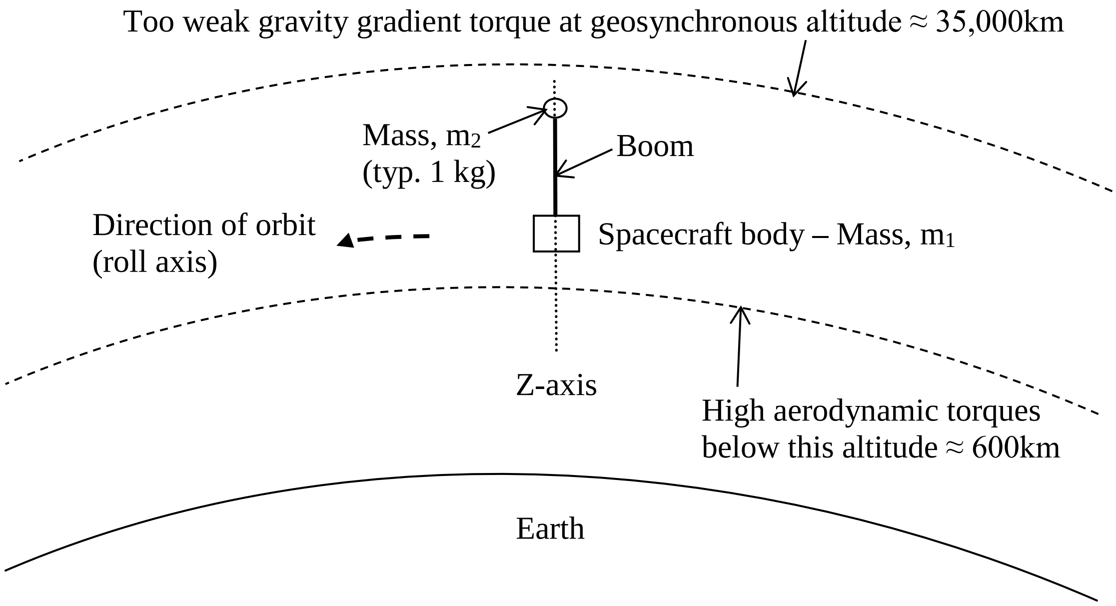

Figure 2.5: Gravity Gradient Stabilization

Suppose a gravity gradient controlled satellite is tilted about the pitch axis by θ degrees; how will the mass forces (F) interact as depicted in the following figure? The two masses are displaced by boom of length (L), where the force interaction between the two masses cause the spacecraft to act like a pendulum. The difference in forces between the two masses cause a stabilizing (restoring) torque; returning the spacecraft (both masses) to the desired local vertical axis position ($\theta = 0°$). This position is an equilibrium state of a rigid pendulum; hence, also for a satellite.

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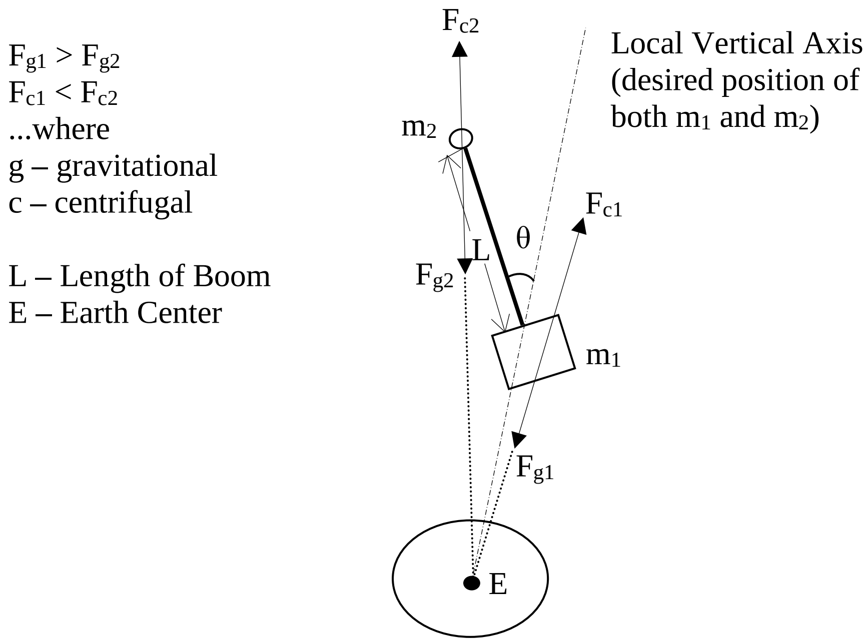

Figure 2.6: Gravity Gradient Forces

Bending or deformation (aka thermal flexing) of a spacecraft's gravity gradient boom can cause destabilizing torques which reduce pointing accuracy and can lead to attitude inversion (i.e. the satellite is upside down). Therefore, before employing this method, risk should be considered and boom thermal properties chosen to minimize flexing. The thermal flexing modes which need mitigation are:

- Dynamic – snapping of boom as satellite crosses from earth shadow into sunlight
- Static – steady state offset of the boom on which the sun shines (i.e. thermal difference between cold side and hot side)

<u>Orbital Characteristics [ref. 3]</u>

Most satellite orbits have a cyclical characteristic where the spacecraft goes from light (i.e. the sun is present) to dark (i.e. cannot "see" the sun). Sometimes, the spacecraft may be in sunlight or darkness for extended periods of time – worst cases are known as 100% sun or minimum sun respectively. Percent sun refers to the amount of sun present during each orbit. For example, in 100% sun, the spacecraft is exposed to the sun the entire duration of each orbit, where the sun vector is normal (orthogonal) to the orbital plane, and Sat #2 (in the following figure) will "feel" this as its temperatures rise. Occurring over several days, this has a warming effect on a spacecraft as expected.

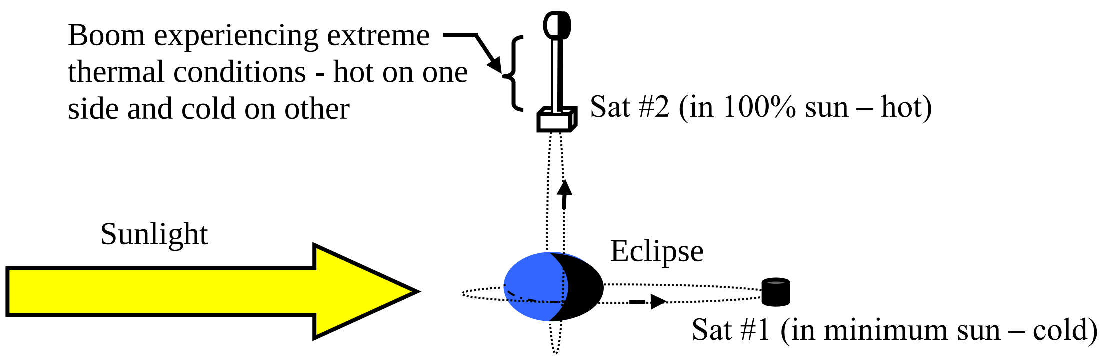

Figure 2.7: Sun vs Eclipse
[Reprint from source: ref. 3]

<u>Polar BEAR Case Study [ref. 2]</u>
Polar BEAR (Beacon Experiment and Auroral Research) was a gravity gradient stabilized spacecraft consisting of a single boom with tip mass. In 1987, as the spacecraft entered first period of full (100%) sun orbit, the attitude became degraded substantially and then the spacecraft inverted. The probable cause was believed to be thermal deformation of the boom due to the differences between cold side and hot side. It used momentum wheel spin/despin to provide enough torque to reinvert the spacecraft (i.e. get it back upright). This spacecraft was built from the Transit-O 17 navigational satellite, where it had been on display in the Smithsonian's National Air & Space Museum for eight years.

Electrical Impacts Mechanical – Apollo 13 Case Study

A single design change can have serious impacts to a building or spacecraft system. One well known example of this is in the Apollo 13 mission, where an electrical design change impacted the operation of the oxygen tank heaters. The following includes these events and others leading up to the oxygen tank explosion.

<u>Apollo 13 Sequence of Events [ref. 3]:</u>
<u>Pre-Flight</u>

1. O_2 tank 2 was damaged during removal for modification from Apollo 10
2. Design change (voltage) to oxygen tank heaters
3. Did not change thermostatic switches to accommodate for the voltage change
4. Attempt to normalize liquid O_2 level in O_2 tank 2 to 50% did not work using gaseous O_2
5. Normalized liquid O_2 level in tank 2 to 50% using heaters – an atypical method
6. O_2 tank 2 fan motor wiring insulation damaged by excess heater on time

<u>In-Flight</u>

7. Astronaut stirs O_2 tanks in routine housekeeping task
8. Current applied to O_2 tank 2 fan motor
9. Electrical short circuit occurs in fan motor wiring with arcing
10. O_2 tank 2 exploded

See the following figure for oxygen tank locations located in the service module.

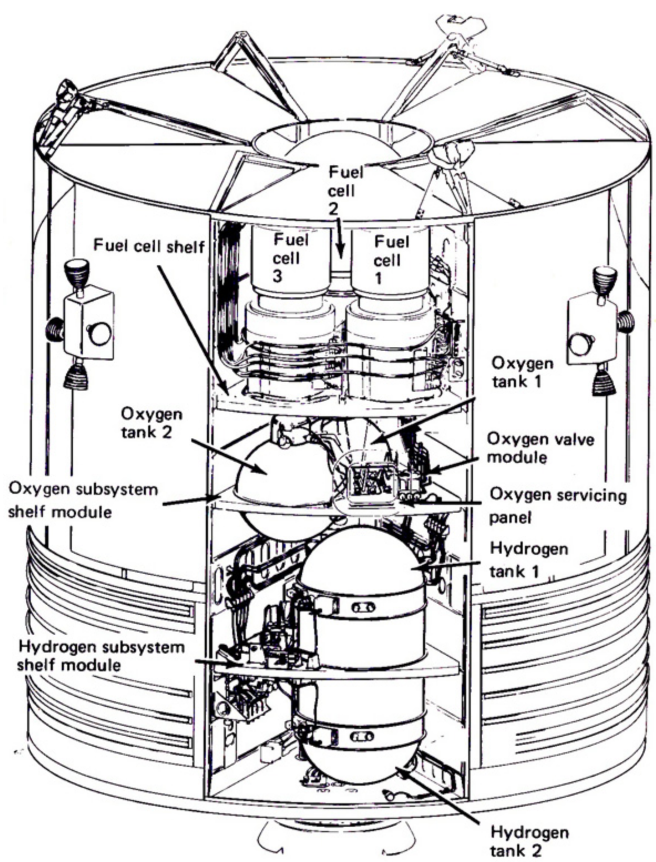

Figure 2.8: Apollo Oxygen Tanks
[Reprint from source: NASA @ nasa.gov]

The root cause of the explosion was due to thermostatic switches not being modified for the voltage change to oxygen tank heaters from 28VDC to 65VDC (sequence 3). This allowed the heaters to be on too long during normalization of liquid oxygen levels (sequence 5), thus damaging wiring insulation near the heaters by exposing the wiring to temperatures of 1000°F (sequence 6). Since tank 1 was normalized successfully (sequence 4) it's fan wiring was not exposed to excessive heater usage.

3. Recommendations For You

Design Checklist

If I recall correctly, I used a design checklist to ensure a complete telecommunication design, about a 20 item checklist. I recommend adding the following to your checklist:

- ✓ Is my design creating problems to other systems within my engineering discipline?
- ✓ Is my design creating problems to other engineering discipline systems?
- ✓ Have all identified design problems (intradiscipline or interdiscipline) been resolved?

This checklist should be visited weekly and not just near the end of the project. This will allow time to resolve any systems engineer problems identified.

Examine Your Case Study

In addition to the checklist, if you have your own case study similar to what I presented in the introduction of this course, I encourage you to do your own case study analysis and create a checklist item unique to your discipline and/or the problem you experienced.

References

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