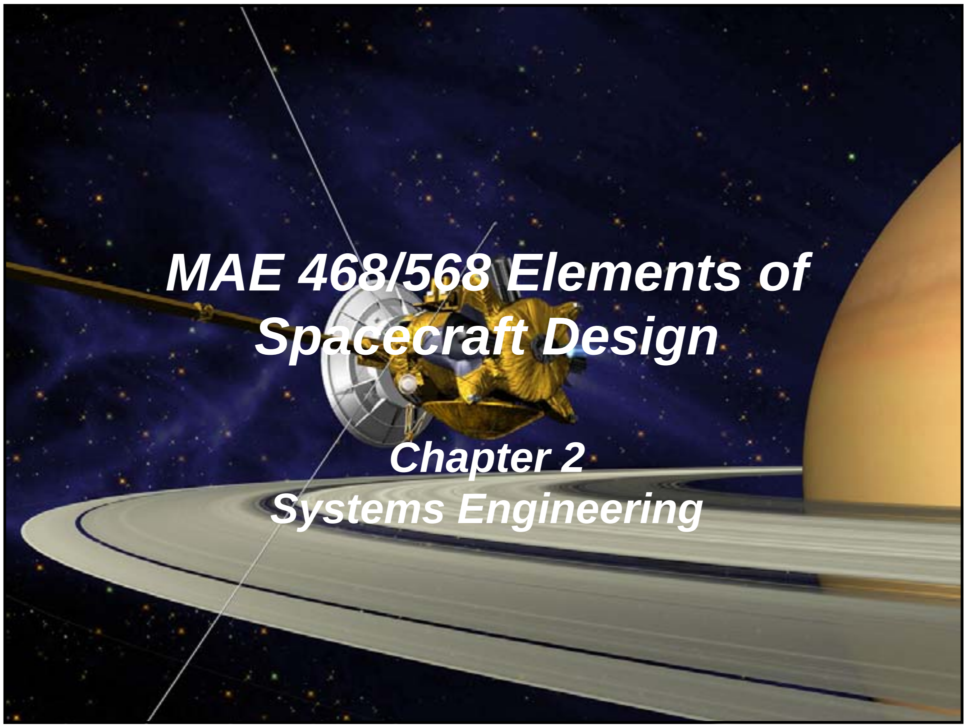

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Class Agenda

- Ch. 2 - System Engineering
  - – Anatomy of a Spacecraft
  - – Mass Properties
  - – Power
  - – Other Margins
  - – Redundancy
  - – Launch Vehicle

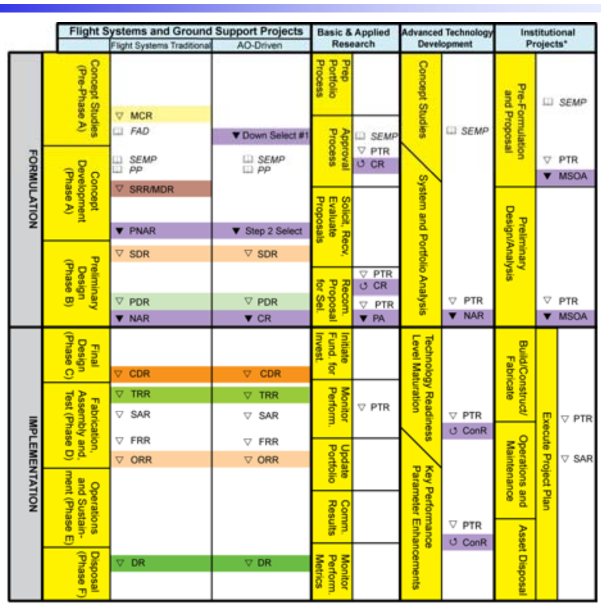
2

Spacecraft Programs

- Discovery
  - 3 year development time
  - $425M ($FY03) cost cap
- New Frontiers
  - 4 to 5 year development time
  - $700M ($FY03) cost cap
- Flagship Missions
  - Multi-year programs (decades)
  - Multi-national programs
  - $1B+ budgets

3

Spacecraft Life Cycle



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Spacecraft Life Cycle

- Phase A – Preliminary analysis
  - Studies done by several organizations
    - Government & contractor
  - Primary questions
    - What is a reasonable spacecraft configuration that will do the mission?
    - Are there any "tall poles" in the development?
    - What major trade studies should be made?
    - About what is it going to cost?
    - About how long will it take?
  - Conceptual design
    - Meets mission statement
    - No technical flaws
    - Internally consistent

5

Spacecraft Life Cycle

- Phase B – Definition
  - Awarded competitively to two contractors
  - Not necessarily phase A contractors
  - Questions answered
    - What is the best spacecraft design for the mission?
    - What are the risks involved?
    - What is your implementation plan?
    - What is your company's cost estimate?
    - How much time would it take your company?
    - Are any long-lead actions necessary to protect schedule?
  - Technical and business baselines are defined

6

Spacecraft Life Cycle

- Phase C/D – Full-scale development
  - Winner awarded full-scale development contract
  - Winner conducts delta-Phase B – revised design requirements
  - Preliminary Design
    - Requirements and performance are defined – drawings can be made
    - Engineering emphasis
      - Functional performance
      - Requirements definition
      - Interface definition

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Spacecraft Life Cycle

- Phase C/D, cont'd
    - Phase ends with Preliminary Design Review (PDR)
    - PDR – formal customer review to evaluate adequacy of design and requirements compliance
    - Post PDR – design partially frozen – change control in effect on specifications
  - Design phase
    - Build drawings are made and software is coded
    - Subcontracts are initiated
    - Subsystem-level build and test is started
    - Phase ends with Critical Design Review (CDR)
    - CDR – formal customer review to evaluate the adequacy of the design and the interface definitions
    - CDR usually occurs at 80% design complete
    - If CDR successful – hardware is fabricated

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Spacecraft Life Cycle

- Assembly, test, and launch operations
  - Flight-qualified subassemblies are available
  - Qualification units – now protoflight units
- System level tests
  - Functional test of each mission phase
    - Repeated between environmental tests
  - Thermal vacuum tests
  - Acoustics – simulate launch environment
  - End-to-end communications
  - Mission simulations and environmental tests
- Phase ends with pre-ship review

Spacecraft Life Cycle

- Launch phase
  - Reassembly after shipment
  - Launch site retesting
  - Phase ends with Flight Readiness Review (FRR)
- Phase E – Mission operations
  - Starts immediately after launch
  - Team trained for months before
    - Can be large or small – depends on spacecraft

Spacecraft Life Cycle

- Reviews
  - CoDR – Conceptual design review
  - PDR – Preliminary design review
  - CDR – Critical design review
  - PRR – Preshipment readiness review
  - FRR – Flight readiness review
  - New ones
    - SDR – System definition review
    - TRR – Test readiness review

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Commercial Procurement

- Spacecraft life cycle described – Government
- Commercial procurement different
  - Design driven by financial concerns
  - Approval chain extends to B of D
  - Single customer engineering POC
  - Minimal customer oversight
  - Legal and regulatory impact on design

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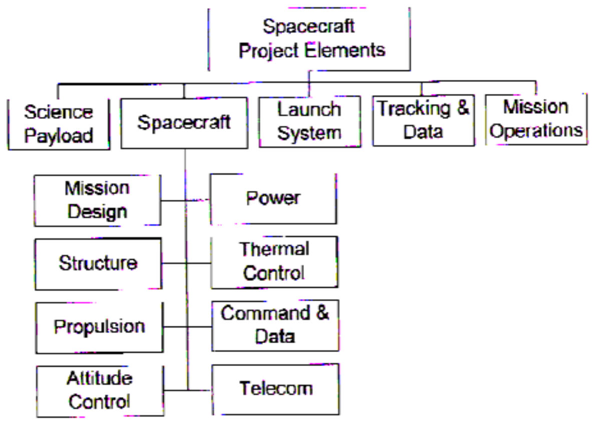
Project Elements

- Five elements to a spacecraft project



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Project Elements

- Science payload
  - Set of instruments that perform the mission
  - Can be 1 instrument or 12 instruments
  - Usually comes from a different organization than spacecraft
  - Interfaces with spacecraft
    - Power
    - Data management
    - Command
    - Thermal
    - Mechanical
    - Field of view
  - Sometimes come with built-in data collection and formatting capability

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Project Elements

- Launch system
  - Vehicle and support elements
  - Major energy source to orbit Earth or escape trajectory to a planet
  - Primary interface
    - Structural design loads
    - Shroud determines maximum spacecraft dimensions
      - Launch configuration to mission configuration
    - Power, command, telecommunication, and command and data systems

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Project Elements

- Launch vehicle, cont'd
  - Two methods
    - Expendable Launch Vehicle (ELV)
      - Delta
      - Atlas
      - Pegasus
    - Space shuttle

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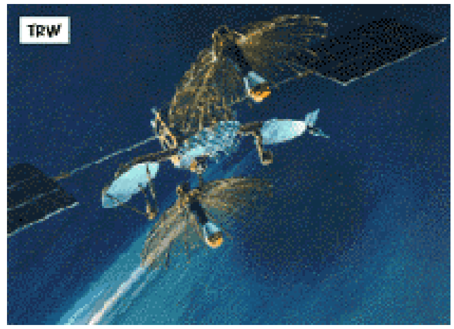
Project Elements

- Tracking and data systems
  - Link to spacecraft
    - Receive spacecraft downlink and relay it to mission operations
    - Uplink commands to the spacecraft
  - Use radio link to provide range, azimuth, and elevation



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Project Elements

- Mission operations
  - After liftoff hand-off occurs
  - Launch team – Cape Canaveral
  - Planetary team – Jet Propulsion Laboratory (JPL)
  - MOS team provides analysis of spacecraft performance from downlink and sends commands in uplink
  - Uplink commands are pretested before being sent to spacecraft
    - Can have simulator to test commands

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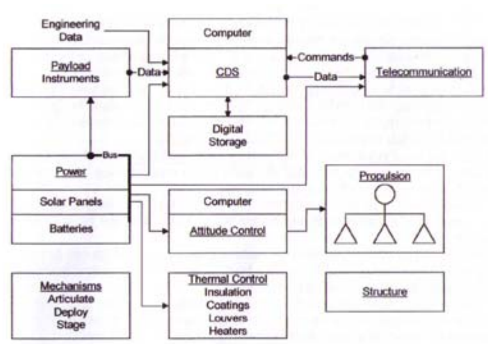
Project Elements

- Mission operations, cont'd
  - Planetary MOS complicated by time delay
    - Mars/Venus – 15-30 minutes
    - Jupiter – 1 hr.
  - On board fault protection system
    - Significant failures result in spacecraft going into "safe mode"

Spacecraft Subsystems

- Eight subsystems
  - Orbital mechanics
  - Propulsion
  - Attitude control
  - Power
  - Thermal control
  - Command and data handling
  - Telecommunications
  - Structure and mechanisms

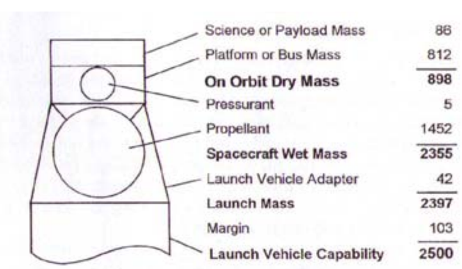


Mass Properties

- Three types to control
  - Spacecraft moments of inertia
  - Spacecraft mass
  - Center of mass
- Each calculated, controlled, and current
  - Launch mode
  - Cruise mode
  - Mission mode
- Mass always an issue
  - Mass increases as design matures

Mass Definitions

- Science (payload) mass – science instruments mass + all equipment used in direct support of instruments (mounting structure, cabling, engineering instrumentation, thermal control heaters, blankets, radiators)
- Bus (platform) mass – total, on-orbit dry mass of spacecraft – science, propellants, and gases are not included
- Launch vehicle adapter mass – mass of structure, separation devices, cabling, thermal control equipment necessary to adapt spacecraft to launch vehicle



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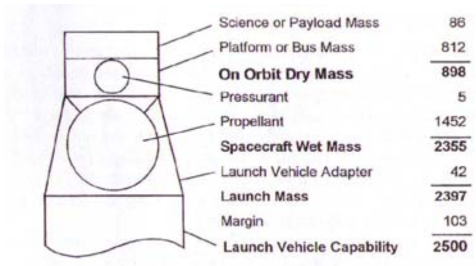
Mass Definitions

- Injected mass – planetary spacecraft mass that is accelerated to Earth departure velocity
- Launch mass – total mass of spacecraft as it rests on the launch vehicle
- Cruise mass – wet or dry mass in interplanetary cruise configuration – launch mass minus adapter mass
- On-orbit dry mass
  - Science instruments
  - Platform/bus



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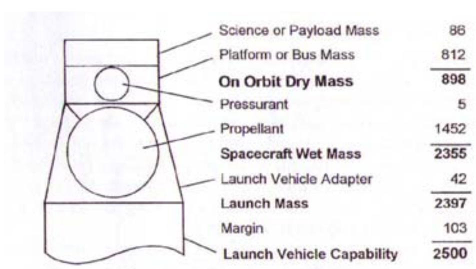
Mass Definitions

- Burn-out mass – mass after shutdown from propulsion event – spacecraft + gas + remaining propellant
- Mass uncertainty – mass growth estimate from a given time to launch
- Mass maturity – degrees of maturity
  - Estimated - history
  - Calculated – engineering calculation
  - Actual – weight measurement
- Mass margin – difference between spacecraft estimate and launch vehicle capability



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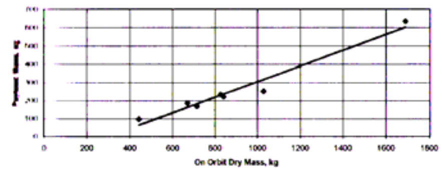
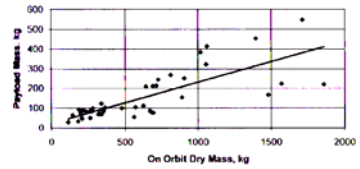
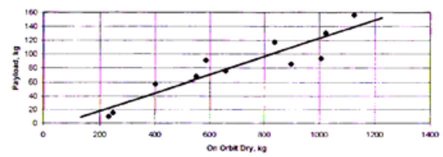
Preliminary Estimates

- Statistics from prior spacecraft
- Geosynchronous communication satellites
  - On-orbit dry mass to be 3.6 times payload mass
- JPL study
  - On-orbit dry mass to be between 3 and 7 times payload mass
- Planetary spacecraft
  - On-orbit dry mass to be 7.5 times payload mass







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Mass Growth

- Spacecraft continues to increase during design
  - Even after all equipment is weighed – more mass is added
- Historical data shows 27% mass growth

Program	Span, months	ATP mass, kg	Launch mass, kg	% Growth
Pioneer Venus	52	292	374	28
Scatha	25	360	396	10
FLTSATCOM	50	645	840	30
Magellan	72	830	1032	25
HEAO-2	60	2223	3016	36
HEAO-3	60	2313	2722	18
Mars Observer	71	827	1125	36
Average				27

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Mass Growth

- U.S. Air Force study
  - CD&H shows most erratic mass history

Program	Structure, %	Power, %	CDS, %	ACS, %	COM, %
1	8	3	12	42	16
2	11	27	-50	-3	82
3	24	4	11	16	44
4	10	15	-28	43	25
5	57	3	8	-7	82
6	29	14	-1	8	NA
7	28	9	10	-23	NA
8	29	7	-4	43	4
9	105	66	4	46	NA
10	65	8	58	9	47
11	50	-27	42	62	69
Average	37.5	11.7	3.6	21.5	46.1

Why Mass Increase?

- Improved understanding
  - Increased understanding of actual spacecraft design
    - Electrical cable weights
    - Propellant/pressurant feed lines
- Make-play changes
  - Structural test failure – add weight
  - Supplier going out of business
- Improvement changes
  - As design progresses better ideas occur

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Recommended Mass Margin

- Mass margin
  - Margin = Total capability – Current best estimate

$$\%\textbf{\textit{margin}} = \frac{\textbf{\textit{margin}}}{\textbf{\textit{capability}}} x100$$

- Classes
  - 1 – new spacecraft
  - 2 – next-generation spacecraft based on previously development family
  - 3 – production-level development on an existing design

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Recommended Mass Margin

Category	Bid			CoDR		
	Class			Class		
	1	2	3	1	2	3
AW 0-50 kg	50	30	4	35	25	3
BW 50-500 kg	35	25	4	30	20	3
CW 500-2500 kg	30	20	2	25	15	1
DW 2500+ kg	28	18	1	22	12	0.8

Recommended Mass Margin

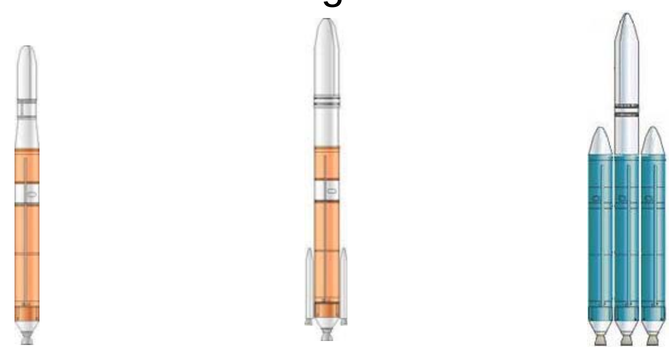
Category	PDR			CDR		
	Class			Class		
	1	2	3	1	2	3
AW 0-50 kg	25	20	2	15	12	1
BW 50-500 kg	20	15	2	10	10	1
CW 500-2500 kg	20	10	0.8	10	5	0.5
DW 2500+ kg	15	10	0.6	10	5	0.5

Allocating Subsystem Dry Mass

1. Determine maximum spacecraft launch mass from mission
2. Deduct launch vehicle adapter mass from launch mass
3. Determine propellants and pressurants required for mission
4. Determine total allowable on-orbit dry mass
5. Establish total allowable payload weight
6. Evaluate mass margin to be set aside
7. Allocate mass budgets to each subsystem

Maximum Spacecraft Launch Mass

- Derived from launch vehicle capability
- Function of mission design



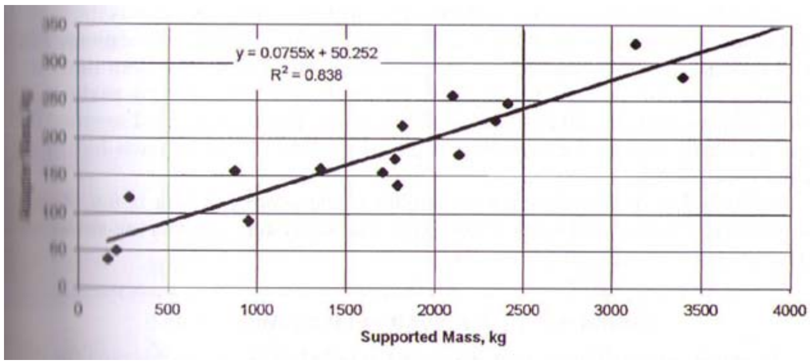
Rocket	Delta-IV Medium	Delta-IV Medium (4,2)	Delta-IV Medium (5,2)	Delta-IV Medium (5,4)	Delta-IV Heavy
TLI Mass (kg)	3,132	4,445	3,623	4,858	9,956

Launch Vehicle Adapter

- Adapts the launch vehicle structure to the spacecraft structure
- Provides for spacecraft separation
- Designed by spacecraft team
- Left with launch vehicle after separation
- Adapter mass comes from spacecraft budget
- Strong function of spacecraft mass

Launch Vehicle Adapter

LVA = 0.0755LM + 50



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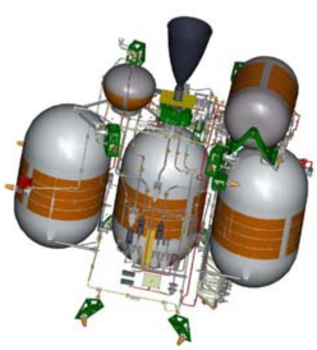
Propellant and Pressurant

- Spacecraft performs any velocity change maneuvers – will require propulsion



$$M_P = M_O\left(1 - e^{\frac{-\Delta v}{g_O Isp}}\right)$$

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Total Allowable Subsystem On-Orbit Dry Mass

- Total allowable dry weight for spacecraft subsystems = LM – LVA – Margin – Payload mass – Propellant mass – Pressurant mass

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Allocating Subsystem Mass Budgets

- Subsystem on-orbit dry mass allocation guide
- 2 conditions
  - Payload supplied by spacecraft team
  - Customer-supplied payload

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Allocating Subsystem Mass Budgets

Subsystem	Comsats		Metsats		Planetary		Other	
	with P/L	GFE P/L	with P/L	GFE P/L	with P/L	GFE P/L	with P/L	GFE P/L
Structure	21	29	20	29	26	29	21	30
Thermal	4	6	3	4	3	3	3	4
ACS	7	10	9	13	9	10	8	11
Power	26	35	16	23	19	21	21	29
Cabling	3	4	8	12	7	8	5	7
Propulsion	7	10	5	7	13	15	5	7
Telecom	-	-	4	6	6	7	4	6
CDS	4	6	4	6	6	7	4	6
Payload	28	-	31	-	11	-	29	-

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Launch Mass Prediction Algorithm

- Design process started
  - Changes from budget allocation to monitoring progress
  - Estimating actual launch weight
  - Customary to tabulate detailed weights
- Classes
  - Estimated - algorithm
  - Calculated - designed
  - Actual - built

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Launch Mass Prediction Algorithm

- Monthly statements
  - Current spacecraft weight estimate
  - Estimate of weight at launch
  - Percentage of total weight in each maturity category
  - Report card on weight status of each subsystem

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Launch Mass Prediction Algorithm

- Structure LM = 1.25(Est Stru) + 1.046(Calc Stru) + 1.026(Actual Stru)
- Propulsion LM = 1.05(Est Prop) + 1.046(Calc Prop) + 1.026(Actual Prop)
- Electronics LM = 1.15(Est Elect) + 1.032(Calc Elect) + 1.012(Actual Elect)
- Cabling LM = 1.50(Est Cable) + 1.05(Calc Cable) + 1.012(Actual Cable)
- Projected dry mass is sum of all

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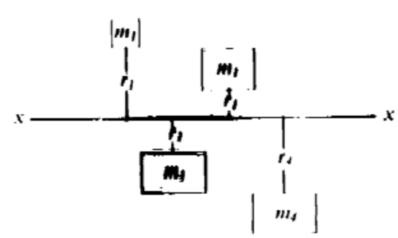
Moments of Inertia

- Important
  - Propellant required to maintain stability or to make rotational maneuvers is proportional to moment of inertia
  - Spin axis of spinning spacecraft must be the axis of highest moment of inertia or spacecraft is unstable
- Must be actively controlled to maintain spin stability

Moments of Inertia

- Sum of elemental masses times distances from axis

$$I_X = \sum mr^2$$



- As design progresses, detailed MoI are calculated
- Figure 2.11 – MoI for different shapes

Estimating Power

- Second most critical resource – next to mass
- Start with payload requirements
  - Total spacecraft power strong function of payload required power
  - See following chart
- Add contingency

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Estimating Power

- Communications

$$P_t = 1.1568 P_{PL} + 55.497$$

- Meteorology

$$P_t = 602.18 \ln(P_{PL}) - 2761.4$$

- Planetary

$$P_t = 332.93 \ln(P_{PL}) - 1046.6$$

- Other missions

$$P_t = 210 + 1.3 P_{PL}$$

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Payload Heaters

- Replacement heaters
  - Used for thermal control reasons
  - Equipment turned off – heater turned on
  - Power usually slightly lower than replacement
  - High enough for thermal protection – but low for power consumption
  - Do not add replacement heater power to equipment maximum power

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Payload Heaters

- Bake-out heaters
  - Used with optical instruments to bake out volatiles in elastomers, coatings, insulations, and other organics
  - Make sure volatiles do not condense on lenses
  - Done early in flight – can take many days
    - Instrument ready for use when mission starts\
  - Free to power system – solar panels are new
    - BOL greater than EOL power
      - EOL power is design point
    - Power very plentiful – make sure radiators are large enough to dump excess heat
  - Not included in establishing power requirements

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Power Allocation

- Guide for initial allocation of power for each subsystem
  - Statistical analysis

Subsystem	Comsats	Metsats	Planetary	Other
Thermal Control	30	48	28	33
Attitude Control	28	19	20	11
Power	16	5	10	2
CDS	19	13	17	15
Communications	0	15	23	30
Propulsion	7	0	1	4
Mechanisms	0	0	1	5

Propulsion Margin

- Based on
  - Maximum possible spacecraft mass
  - Minimum engine specific impulse
  - Maximum possible mission ΔV requirement
- More margin – better chances for extended mission
- Propellant temperatures >10°C above freezing temperature
- Upper temperature controlled with substantial margin

Power Margin

- Margin = Total capability – Current best estimate

$$\%\textbf{margin} = \frac{\textbf{margin}}{\textbf{capability}} x100$$

- Total capability – total power capability of power system – maximum output of power source
- Solar powered planetary mission
  - Power at Earth different from planet
  - Capability decreases with age of panel
- RTG mission
  - Power decreases with time as isotope decays

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Power Margin

Category	Bid			CoDR			PDR		
	Class			Class			Class		
	1	2	3	1	2	3	1	2	3
AP 0-500 W	90	40	13	75	25	12	45	20	9
BP 500-1500 W	80	35	13	65	22	12	40	15	9
CP 1500-5000 W	70	30	13	60	20	12	30	15	9
DP 5000+ W	40	25	13	35	20	11	20	15	9

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Computer Resource

- Memory, CPU speed, throughput
  - Computer selection – 400%
  - Start of phase C/D – 60%
  - Launch – 20%

- Processing time and data bus usage
  - Less than 50% of computer capacity at computer selection

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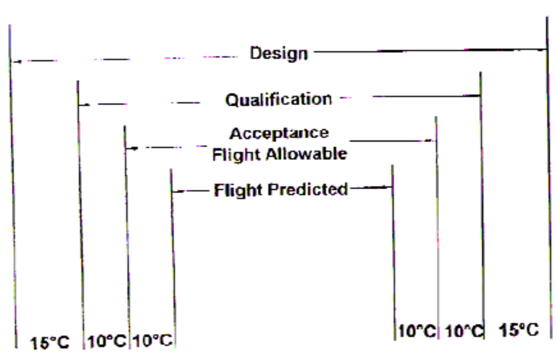
Thermal Margin

- Kept at component level
  - Inside component design, qualification, and flight acceptance limits



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Other Margins

- Battery
  - 40% at Phase C/D start
- Force/Torque
  - Mission-critical deployments and separations require a 100% margin under worst-case conditions
- Electronics minimum operating time
  - 1000 hr at system level prior to launch

Schedule Margin

- Period of time when there are no scheduled activities

Phase	Margin, months
Phase C/D start to ATLO Start	1 month/year
ATLO start to ship to launch site	2 months/year
Arrival at launch site to launch	1 week/month

Redundancy Techniques

- Most common method of increasing failure tolerance of spacecraft
- Electronics
  - Piece part level
  - Circuit level
  - Box level
- Fluid systems
  - Component level
- Requires additional weight and cost
  - Cost – more than cost of additional units; analysis and testing of redundant system more time consuming and expensive

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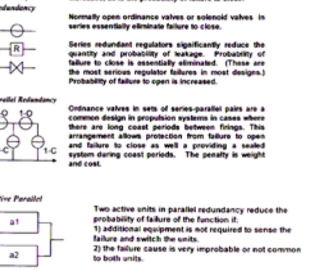
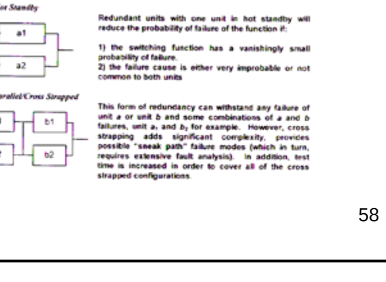
Redundancy Techniques

- Propulsion and fluid systems



- Electronic systems



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Launch Vehicle Interface

- Most critical interface with spacecraft
- Usually decided by customer early in design process
- Critical technical interfaces
  - Launch mass capability
  - Fairing dynamic envelope
- As design matures, interfaces become increasingly complex

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Launch Vehicle Interface

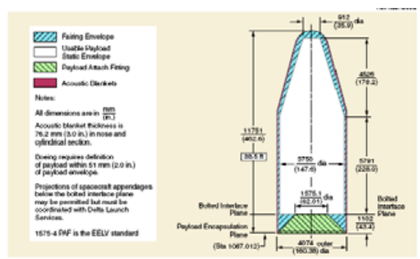

Figure 3-2. Payload Envelope, 4-m-dia Composite Fairing—1575-4 PAF

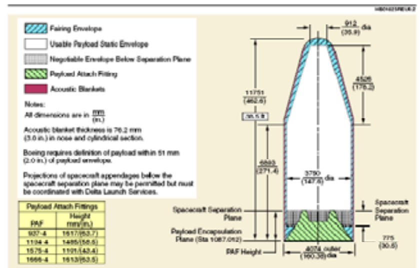

Figure 3-3. Payload Envelope, 4-m-dia Composite Fairing

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