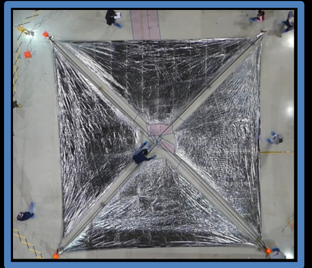
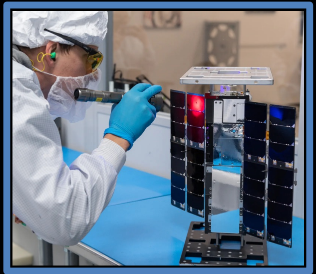




System Assembly, Integration and Test and Spacecraft Handling

January 24, 2024

Access to Space for All Systems Engineering Webinar Series

Elwood Agasid

Deputy Program Manager, Small Spacecraft Technology Program

Webinar Overview

This webinar will cover Systems Assembly, Integration and Test, and Spacecraft Handling as they relate to a small spacecraft project.

- What are the elements of system assembly, Integration and Test, and Spacecraft Handling?
- What are the various steps involved for each?
- Why is it important to a space mission?

This webinar will consist of examples of NASA based AI&T activities

System Assembly, Integration and Test, and Spacecraft Handling Description

Small spacecraft assembly, integration and test (AI&T) is a complex phase for small spacecraft with many different procedures, dependencies, operations, and tests occurring in parallel. Ensuring compliance with mission and science requirements, NASA utilizes best practices to implement planning, scheduling, and management of the small spacecraft AI&T flow.

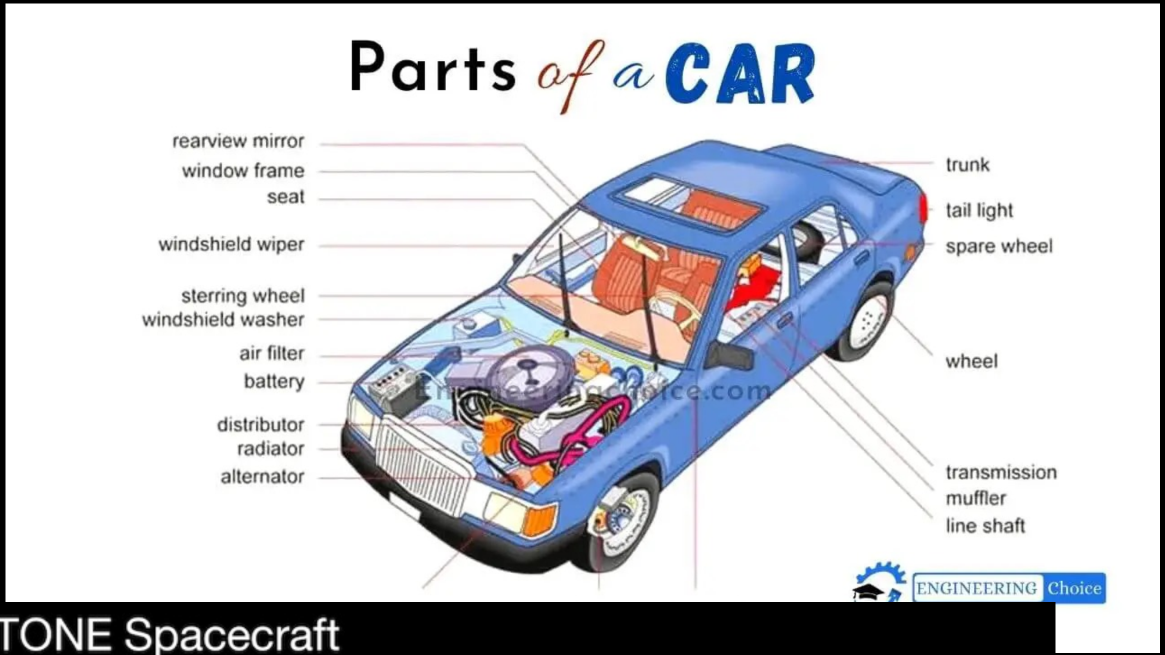
- Update documents developed and baselined in previous phases
- Monitor project progress against plans
- Identify and update risks
- Integrate/assemble components according to the integration plans
- Perform verification and validation on assemblies according to the V&V Plan and procedures
- Prepare and baseline relevant documentation
- Document lessons learned. Perform required Phase D technical activities from NPR 7120
- Satisfy Phase D reviews' entrance/success criteria from NPR 7123

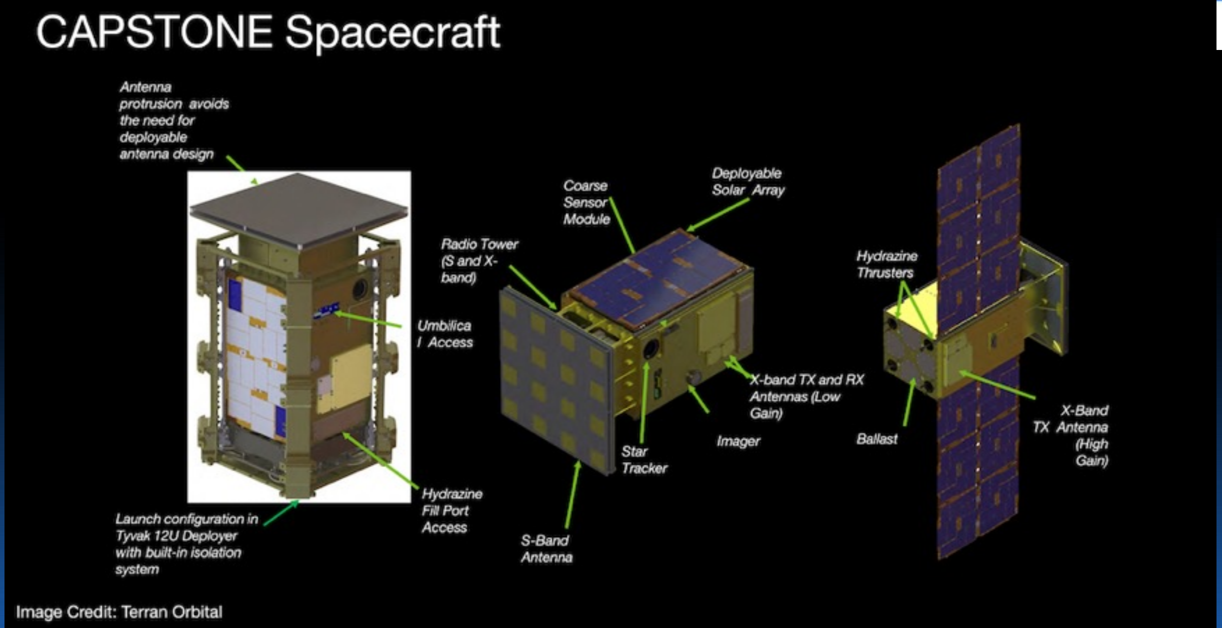
System Assembly

System assembly is a common element of numerous manufacturing and development industries and helps us:

- Put together various components to make a complete system
- Fully understand how each component plays a vital role in the finished product

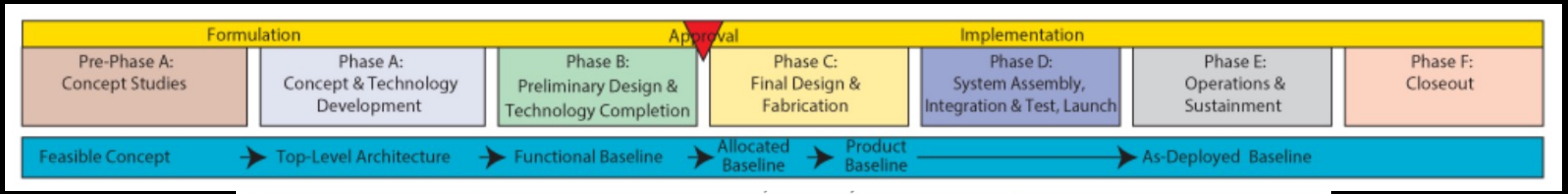
Spacecraft systems and components are often obtained from external vendors and internal organizations all of which should be assembled in a clear-cut, efficient, and cost-effective manner.





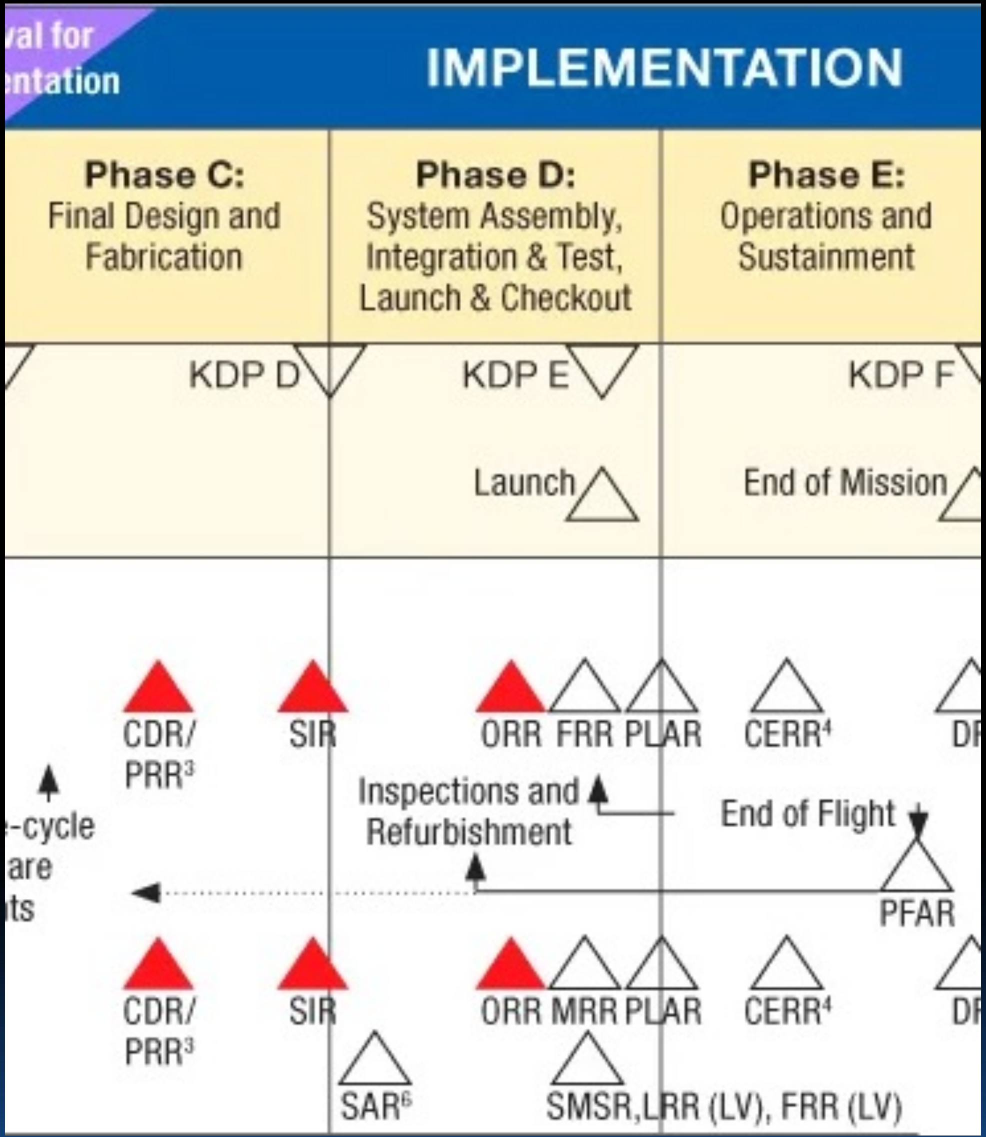
NASA PROJECT LIFE CYCLE

At NASA, projects and missions are managed around an established phased development process.



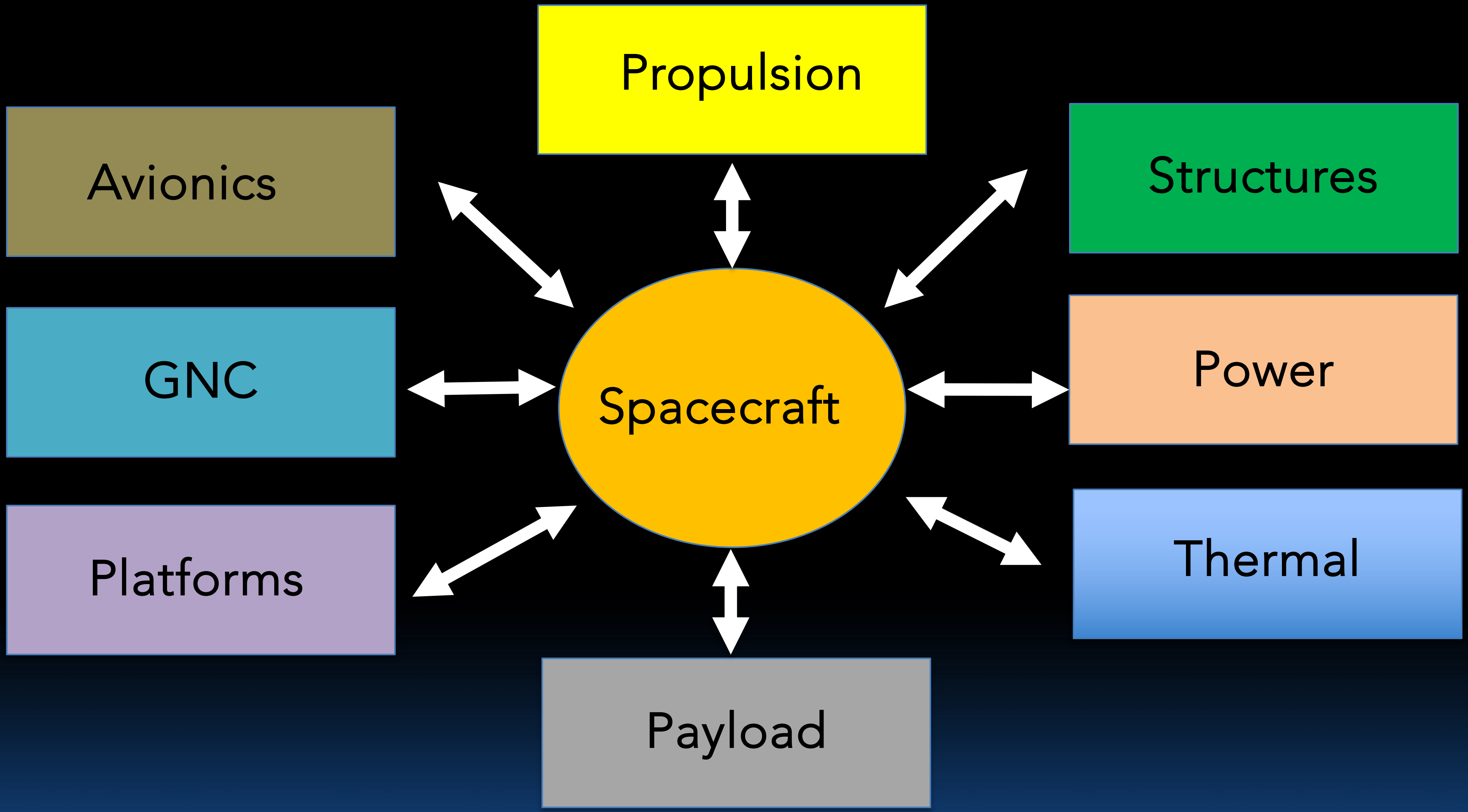
Phase		Purpose	Typical Outcomes
Pre-Formulation	**Pre-Phase A** Concept Studies	To produce a broad spectrum of ideas and alternatives for missions from which new programs/projects can be selected. Determine feasibility of desired system, develop mission concepts, draft system-level requirements, assess performance, cost, and schedule feasibility; identify potential technology needs, and scope.	Feasible system concepts in the form of simulations, analysis, study reports, models, and mock-ups
Formulation	**Phase A** Concept and Technology Development	To determine the feasibility and desirability of a suggested new system and establish an initial baseline compatibility with NASA's strategic plans. Develop final mission concept, system-level requirements, needed system technology developments, and program/project technical management plans.	System concept definition in the form of simulations, analysis, engineering models and mock-ups, and trade study definition
	Phase B Preliminary Design and Technology Completion	To define the project in enough detail to establish an initial baseline capable of meeting mission needs. Develop system structure end product (and enabling product) requirements and generate a preliminary design for each system structure end product.	End products in the form of mock-ups, trade study results, specification and interface documents, and prototypes
Implementation	**Phase C** Final Design and Fabrication	To complete the detailed design of the system (and its associated subsystems, including its operations systems), fabricate hardware, and code software. Generate final designs for each system structure end product.	End product detailed designs, end product component fabrication, and software development
	Phase D System Assembly, Integration and Test, Launch	To assemble and integrate the system (hardware, software, and humans), meanwhile developing confidence that it is able to meet the system requirements. Launch and prepare for operations. Perform system end product implementation, assembly, integration and test, and transition to use.	Operations-ready system end product with supporting related enabling products
	Phase E Operations and Sustainment	To conduct the mission and meet the initially identified need and maintain support for that need. Implement the mission operations plan.	Desired system
	Phase F Closeout	To implement the systems decommissioning/disposal plan developed in Phase E and perform analyses of the returned data and any returned samples.	Product closeout

Steps for System Assembly, Integration and Test, and Spacecraft Handling



- Phase D – System Assembly, Integration & Test, Launch & Checkout
- To assemble and integrate the system (hardware, software, and humans), meanwhile developing confidence that it is able to meet the system requirements. Launch and prepare for operations. Perform system end product implementation, assembly, integration and test, and transition to use.
- Key Reviews:
  - Test Readiness Reviews (TRRs)
  - System Acceptance Review (SAR) or pre-Ship Review
  - Operational Readiness Review (ORR)

Subsystem Components of a Small Spacecraft

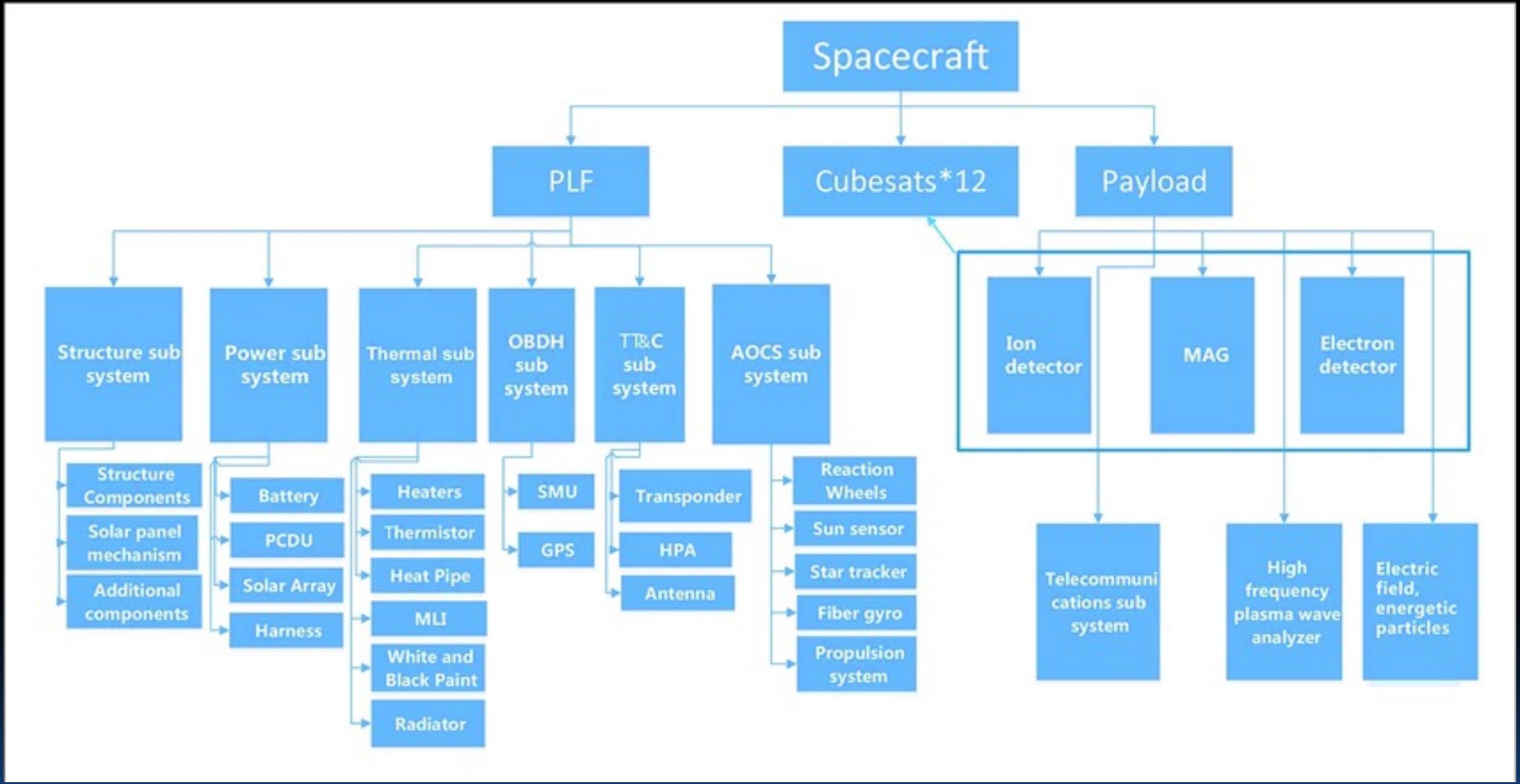


SYSTEM INTEGRATION REVIEW (SIR)

System Integration Review (SIR)	An SIR ensures segments, components, and subsystems are on schedule to be integrated into the system. Integration facilities, support personnel, and integration plans and procedures are on schedule to support integration.	SIR occurs at the end of the final design phase (Phase C) and before the systems assembly, integration, and test phase (Phase D) begins.	The entrance and success criteria for the SIR are defined in Table G-9 of NPR 7123.1.	As a result of successful completion of the SIR, the final as-built baseline and verification plans are approved. Approved drawings are released and authorized to support integration. All open issues should be resolved with closure actions and schedules. The subsystems/systems integration procedures, ground support equipment, facilities, logistical needs, and support personnel are planned for and are ready to support integration.

SIR is conducted prior to proceeding to the Assembly, Integration & Test Phase. This is done to ensure all spacecraft components and subsystem are available, all test plans and records are prepared, all personnel are available and trained, all assembly and test facilities are ready.

SPACECRAFT SYSTEM & SUBSYSTEM ELEMENTS



System Assembly, Integration and Test - Key Resources

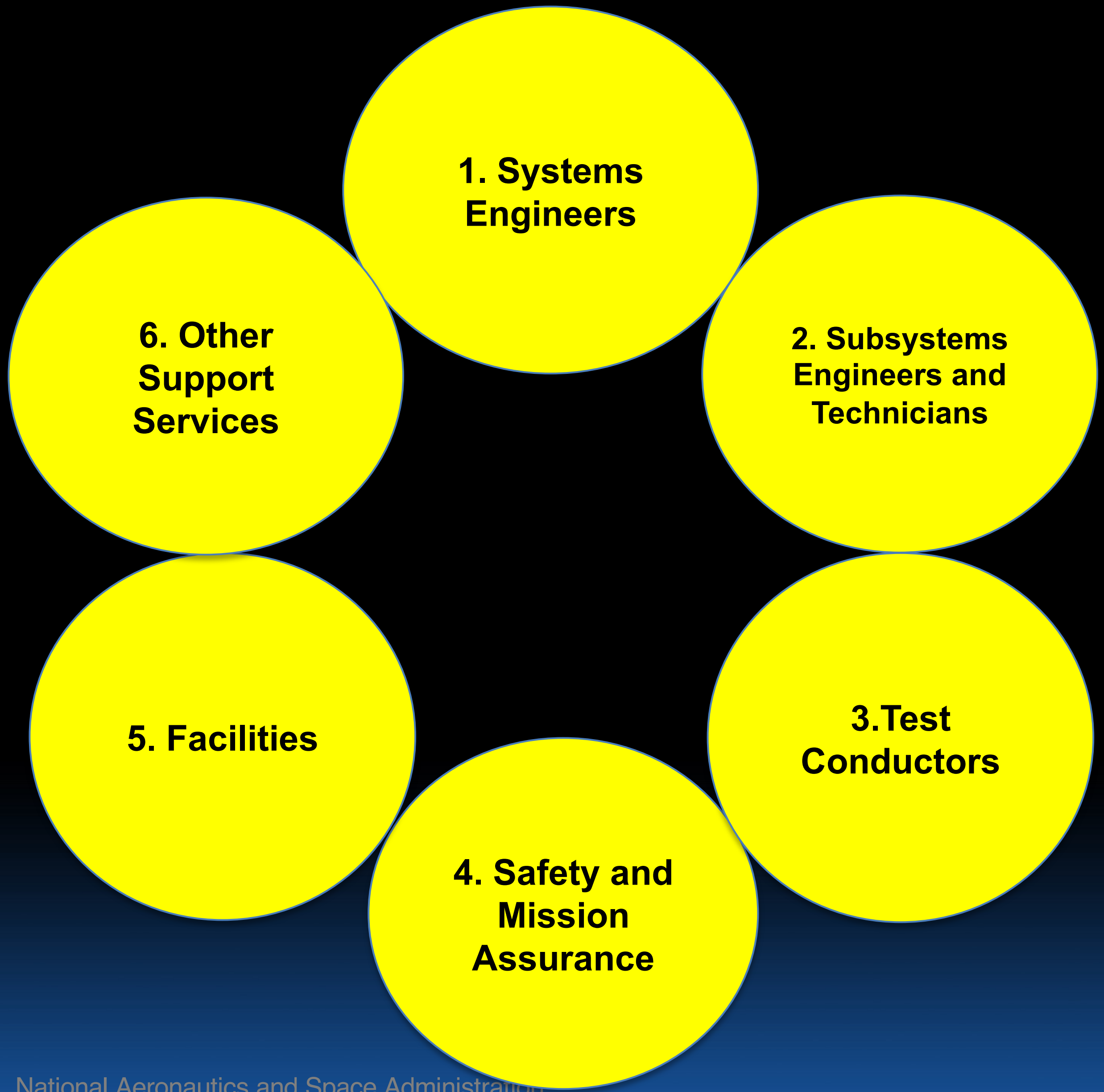
Planning and managing several resources are key to successful small spacecraft AIT efforts

- Facilities
- Personnel
- Ground Support Equipment

Requirements mapping for qualification tests along with verification and validation functions are also important planning elements.

CAPSTONE spacecraft assembly

Integration and Test Roles and Responsibilities Examples



1. Develop verification requirements, integrated test plans and procedures
2. Develop/deliver subsystem assemblies, subsystem I&T plans and procedures
3. Develop ground system displays and scripts for S/C control & monitoring
4. Provides safety and quality control oversight, problem/failure tracking
5. Make available facilities and infrastructure (e.g., cranes, power) required for I&T
6. Configuration management for documentation approvals and support

Integration and Test Key Personal

- I&T manager and engineers
- Systems engineers
- Subsystem/discipline engineers and technicians
  - Command and data handling
  - Electrical/power
  - Mechanical
  - Thermal
  - Propulsion
  - Optics
  - Instruments
- Test conductors
- Safety and mission assurance
- Facilities
- Configuration management
- Shipping, logistics

Handling of Fully Assembled Spacecraft

- Elements for handling fully assembled spacecraft during preparation for flight.

- Personal Protection Equipment
  - Electrostatic Discharge (ESD) straps
  - ESD clothing
  - Hairnets, ESD booties, gloves
- Facilities
  - Controlled access spaceflight rated clean rooms
  - Benches/tables with ESD mats
  - Grounding straps
  - ESD rated flooring
- Spacecraft Handling Fixtures
  - Fixtures aid in handling of spacecraft to protect critical components such as solar cells, etc.

Spacecraft Integration and Test

The physical hardware that attaches a small spacecraft and keeps it insulated from a rocket body include deployers, adapters, dispensers, and launchers. The hardware ejects the spacecraft safely into orbit.

The purpose of testing is to test philosophy for the environmental and other testing that is performed at higher-than-normal levels to ascertain margins and performance in worst-case scenarios.

Image Credit: NASA / Robert Markowitz

Image Credit: Massachusetts Institute of Technology

Integration and Test – Elements and Examples

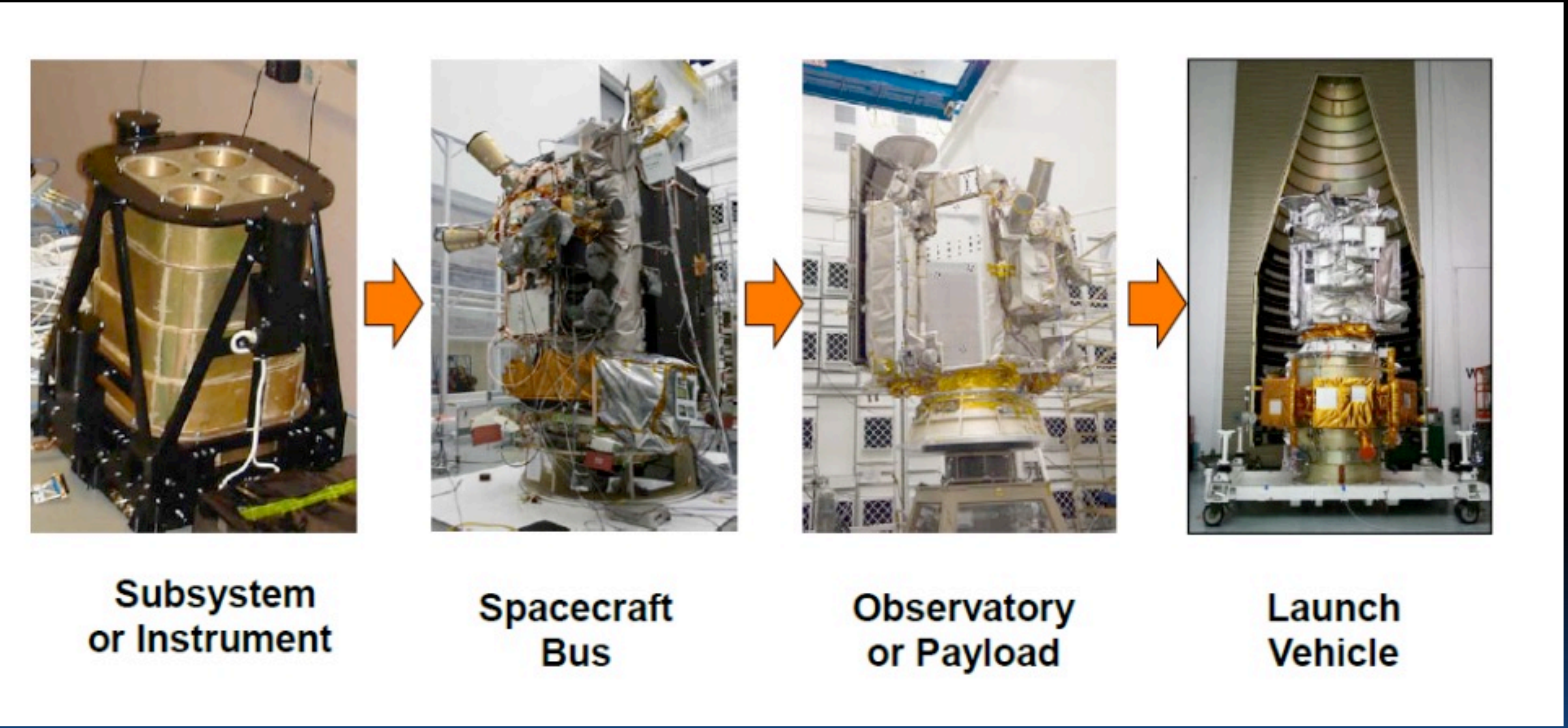
Integration Elements:

- Dispenser Integration (different types):
    - CubeSat Dispensers
    - Separation Systems
    - Secondary Payload Adapters
- Mass, volume and other performance margins
- Integration of electrical and mechanical subsystem elements

Types of Testing:

- Inspection
- Mass Properties
- Static Load Test
- Shock and Vibration
- Thermal Cycling
- Thermal Balance
- Thermal Vacuum

Various Integration Phases of a Spacecraft



Integration and Test Plans and Procedures

- Purpose
  - Ensure I&T approach and task are defined
  - Allow for required reviews and approval by stakeholders
  - Ensure adequate resources to completed the associated tasks
- Plans (Examples)
  - Integration and Test
  - Contamination Control
- Procedures (Examples)
  - Subsystem Integration
  - Thermal Vacuum Test
- Procedures should cover and hazards
  - Identify hazards, safety approvals
- Review, Approve, Release
  - Allow for sufficient time to perform required reviews and edit
  - Allow for adequate time for the team to become familiar and complete preparations

Test Readiness Review	
Entrance Criteria	**Success Criteria**
1. A preliminary TRR agenda, success criteria, and instructions to the review team have been agreed to by the technical team, project manager, and review chair prior to the TRR. 2. The objectives of the testing have been clearly defined and documented. 3. Approved test plans, test procedures, test environment, and configuration of the test item(s) that support test objectives are available. 4. All test interfaces have been placed under configuration control or have been defined in accordance with an agreed to plan, and version description document(s) for both test and support systems have been made available to TRR participants prior to the review. 5. All known system discrepancies have been identified and dispositioned in accordance with an agreed-upon plan. 6. All required test resourcesâ?"people (including a designated test director), facilities, test articles, test instrumentation, and other test-enabling productsâ?"have been identified and are available to support required tests. 7. Roles and responsibilities of all test participants are defined and agreed to. 8. Test safety planning has been accomplished, and all personnel have been trained. 9. Spectrum (radio frequency) considerations addressed. 10. As-built hardware and software documentation defining the configuration of the item under test are released and under configuration control.	1. Adequate test plans are completed and approved for the system under test. 2. Adequate identification and coordination of required test resources are completed. 3. The program/project has demonstrated compliance with applicable NASA and implementing Center requirements, standards, processes, and procedures. 4. TBD and TBR items are clearly identified with acceptable plans and schedule for their disposition. 5. Risks have been identified, credibly assessed, and appropriately mitigated. 6. Residual risk is accepted by program/project leadership as required. 7. Plans to capture any lessons learned from the test program are documented. 8. The objectives of the testing have been clearly defined and documented, and the review of all the test plans, as well as the procedures, environment, and configuration of the test item, provides a reasonable expectation that the objectives will be met. 9. The test cases have been analyzed and are consistent with the test plans and objectives. 10. Test personnel have received appropriate training in test operation and health and medical safety procedures.

Test Readiness Review (TRR)

- TRRs are conducted to ensure test plans have been prepared and teams are ready to conduct the test.

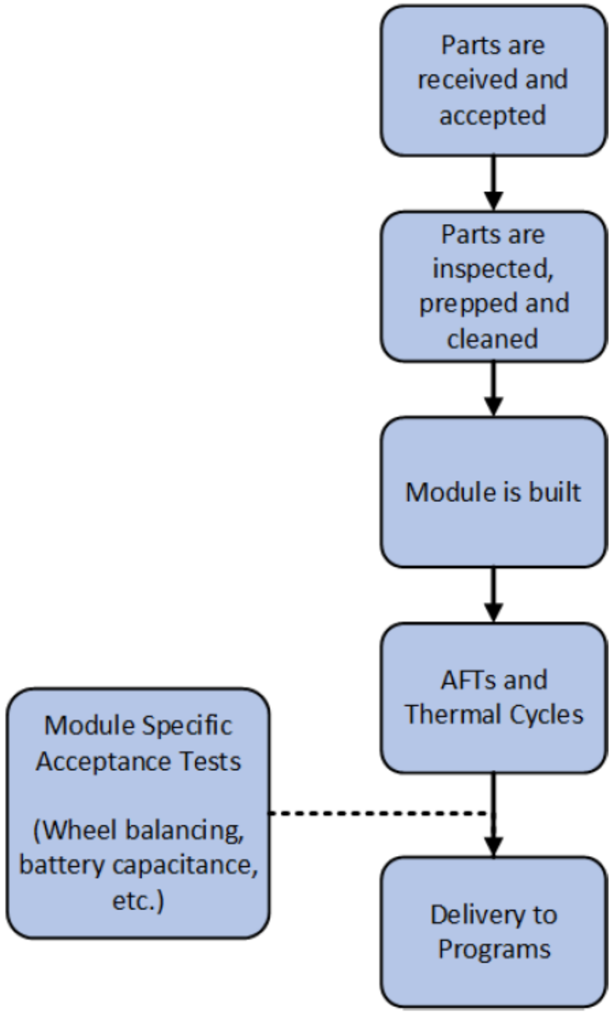
EXAMPLE OF COMPONENT SUBSYSTEM LEVEL TESTS

- Each module in house goes through the standard production flow before being delivered to the program

- Printed Circuit Boards
  - Boards are visually inspected, received, and inventoried
  - Automated Optical Inspection
  - HASS Testing
  - Automated Optical Inspection
  - X-Ray
  - Cleaning

- Flex cables
  - Visual Inspection
  - Thermal Cycling

- Modules
  - At the module level, the modules are first built following the procedure
  - Once built, each module goes through acceptance testing which includes Abbreviated Functional Tests and 12 thermal cycles
  - Some modules will also include module-specific tests during acceptance
  - Once the data is reviewed by the system RE, the module is delivered to the program



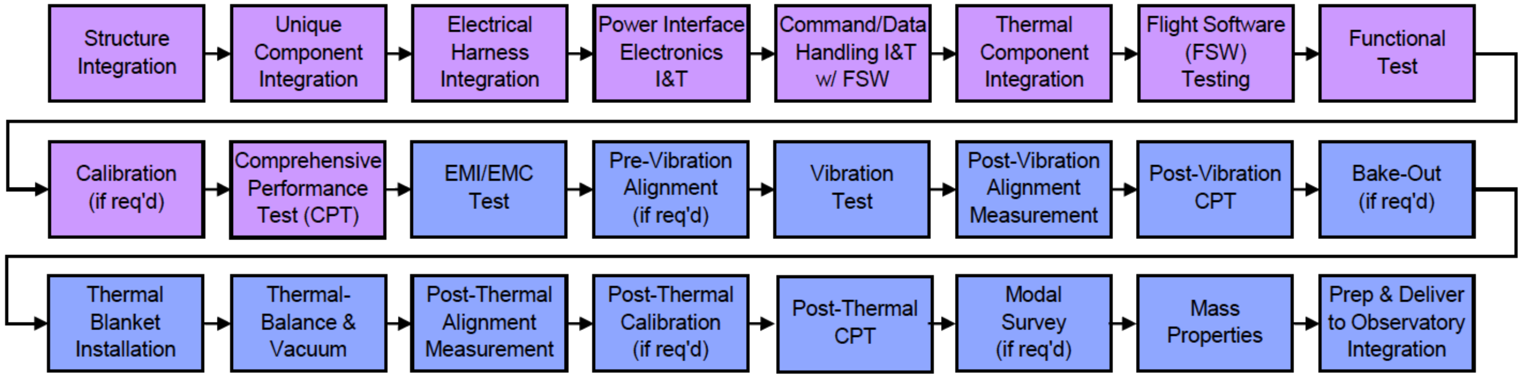
EXAMPLE SUBSYSTEM INTEGRATION & TEST FLOW

Flight Systems Integration & Test

Subsystem or Instrument I&T

- Includes tasks necessary for subsystem- or instrument-level I&T
  - Subsystem components: mechanical, electrical, thermal, unique (e.g., detector)
  - Functional and comprehensive performance tests (CPT's)
  - Subsystem- or instrument-specific tests (calibration, characterization, etc.)
- Environmental qualification testing
  - Electromagnetic interference/compatibility (EMI/EMC): radiated, conducted
  - Three-axis vibration: workmanship, random, sine-sweep
  - Thermal: balance, vacuum

Representative Subsystem/Instrument I&T Flow



Notes: - "I&T" includes: mechanical integration, electrical safe-to-mates, and/or functional testing
- Short functional tests performed following each vibration (axis) test
- Task sequence for reference only; some tasks may be performed in parallel (e.g., harness, thermal h/w)

Integration & functional testing
Environmental testing, pre-delivery

FUNCTIONAL AND COMPREHENSIVE TESTING OF FULLY INTEGRATED SPACECRAFT

Procedure	Description	Purpose	Test Article
Module Acceptance Testing	Testing used to screen bulk production of modules. Involves AFT, thermal cycles and module-specific tests.	Lot acceptance, workmanship	PCB, Module
Abbreviated Functional Test	Automated test to verify interconnectivity, power on, and basic software functionality of all components.	Interconnections, liveness, environments, workmanship	Module, Satellite
Ground Station Compatibility Test	Test RF compactivity with DSN ground station simulator.	Design verification, ground ops architecture	Module
Comprehensive Performance Test	Human-in-the-loop use of specialized ground support equipment. Comprehensive test of all software processes. Complete 'walk through' of expected mode and transitions.	Spacecraft build, environments, performance characterization, design verification, workmanship	Satellite
Electromagnetic Interference / Compatibility Test	Testing the internal EM compatibility of the vehicle in a RF isolated chamber.	Environments, design verification, RF characterization	Satellite
Vibration Test	Vibration tests per launch vehicle requirements.	Workmanship, design verification, LV survivability	Satellite
Thermal Vacuum Tests	Vacuum bake out and thermal cycles while under hard vacuum. Functional tests during each soak. Thermal balance test with subsequent thermal finishes to the bus.	Thermal model, design verification, vehicle cleanliness	Satellite
Mass Properties	Measurement of mass and CG at the vehicle level.	Characterization, GNC operations	Satellite
Day In The Life	Scripted long duration exercise of flight hardware. Test is conditional to mission risk posture.	Final software closeouts,	Satellite, HITL Testbed
Tip Off	Verifies the first 90 minutes of spacecraft operations in a plugs out fashion.	Final pre-shipment close out, Ground Ops architecture, Final sanity check	Flight

Components & subsystems are tested then integration process leading to a fully assembled spacecraft which is then tested for final launch preparation.

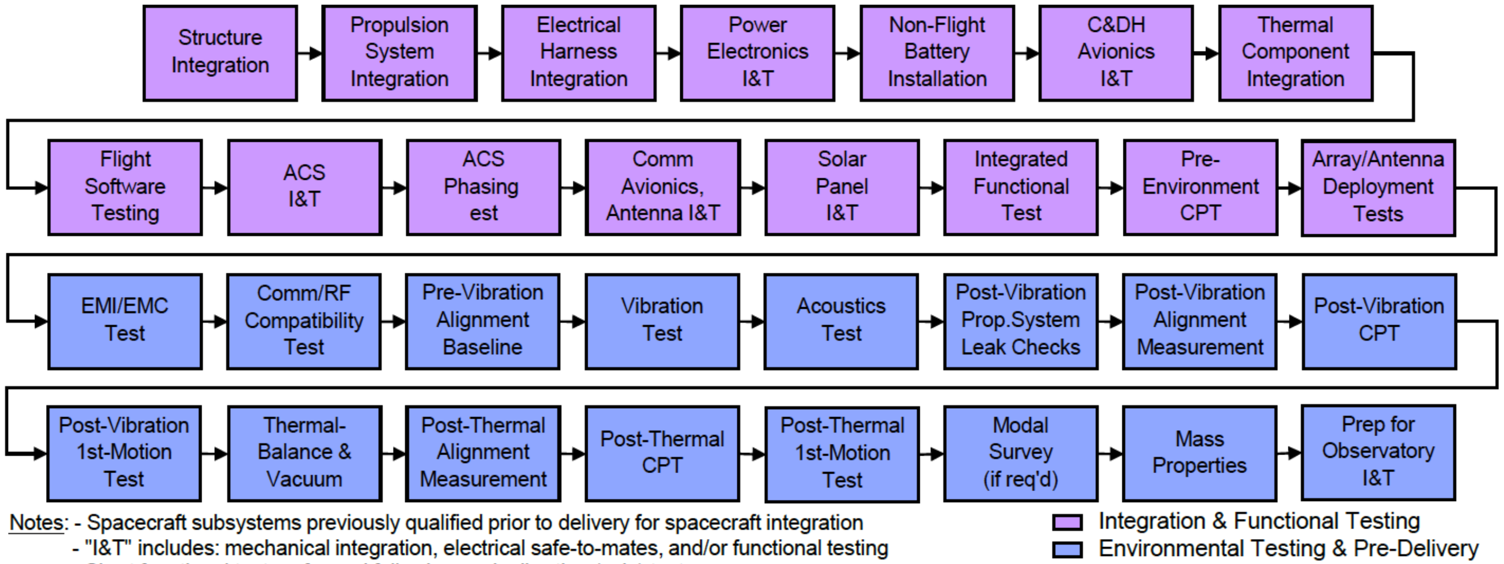
EXAMPLE SPACECRAFT BUS INTEGRATION & TEST FLOW

Flight Systems Integration & Test

Spacecraft Bus I&T

- Includes tasks necessary for spacecraft-level I&T
  - Subsystems: structures/mechanical, power, C&DH, thermal, ACS, prop, comm, FSW
  - Functional and comprehensive performance tests (CPT's)
- Environmental qualification testing
  - Electrical/Comm: EMI/EMC, radio-frequency (RF) compatibility test
  - Mechanical: random vibration, sine-sweep, acoustics, shock, modal survey (if req'd)
  - Thermal: balance, vacuum

Representative Spacecraft Bus I&T Flow



Notes: - Spacecraft subsystems previously qualified prior to delivery for spacecraft integration
- "I&T" includes: mechanical integration, electrical safe-to-mates, and/or functional testing
- Short functional test performed following each vibration (axis) test
- Task sequence for reference only; some tasks may be performed in parallel (e.g., harness, thermal h/w)

ENVIRONMENTAL TESTING OF FULLY INTEGRATED SPACECRAFT

Table 2.2-2
Test Factors/Durations

Test	Prototype Qualification	Protoflight Qualification	Acceptance
Structural Loads[1] Level Duration Centrifuge/Static Load[6] Sine Burst	 1.25 x Limit Load 1 minute 5 cycles @ full level per axis	 1.25 x Limit Load 30 seconds 5 cycles @ full level per axis	 1.0 x Limit Load 30 seconds 5 cycles @ full level per axis
Acoustics Level[2] Duration	Limit Level + 3dB 2 minutes	Limit Level + 3dB 1 minute	Limit Level 1 minute
Random Vibration Level[2] Duration	Limit Level + 3dB 2 minutes/axis	Limit Level + 3dB 1 minute/axis	Limit Level 1 minute/axis
Sine Vibration[3] Level Sweep Rate	1.25 x Limit Level 2 oct/min	1.25 x Limit Level 4 oct/min	Limit Level 4 oct/min
Mechanical Shock Actual Device Simulated	 2 actuations 1.4 x Limit Level 2 x Each Axis	 2 actuations 1.4 x Limit Level 1 x Each Axis	 1 actuations Limit Level 1 x Each Axis
Thermal-Vacuum	Max./min. predict. ± 10°C	Max./min. predict. ± 10°C	Max./min. predict. ± 5°C
Thermal Cycling[4,5]	Max./min. predict. ± 25°C	Max./min. predict. ± 25°C	Max./min. predict. ± 20°C
EMC & Magnetics	As Specified for Mission	Same	Same

ENVIROMENTAL TEST

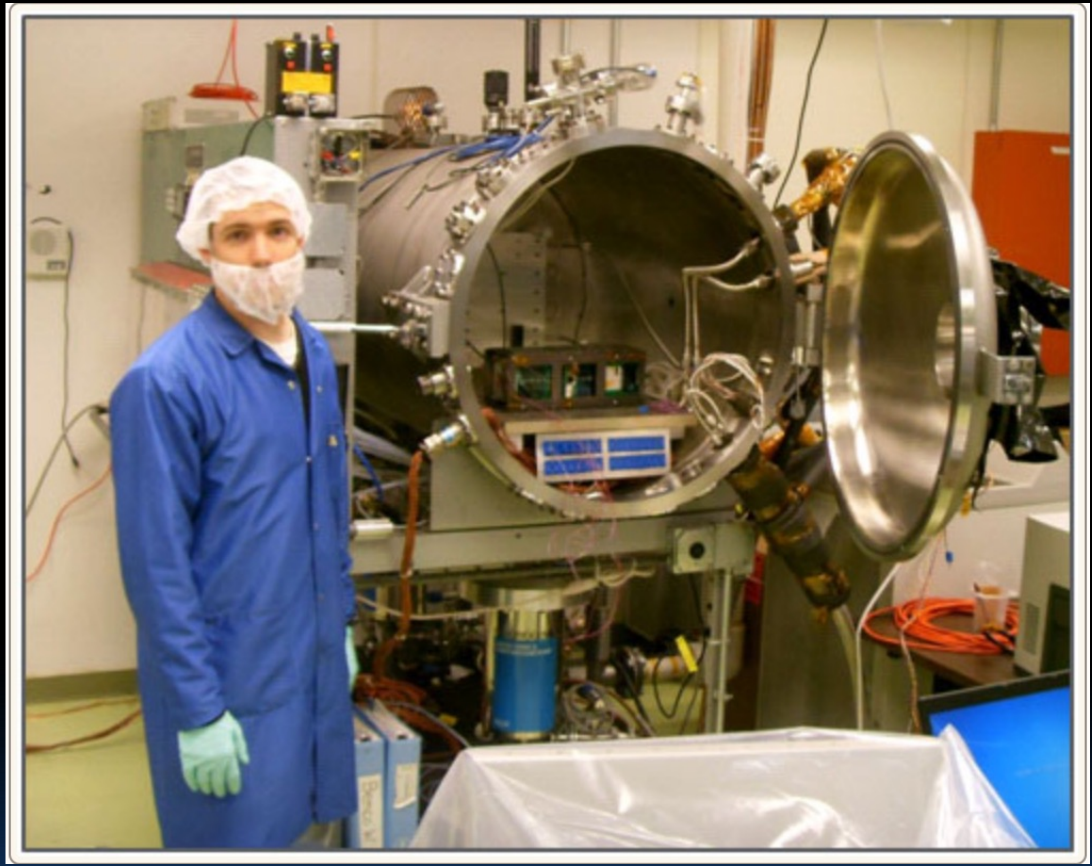
Tests to verify spacecraft will survive The launch and space environment

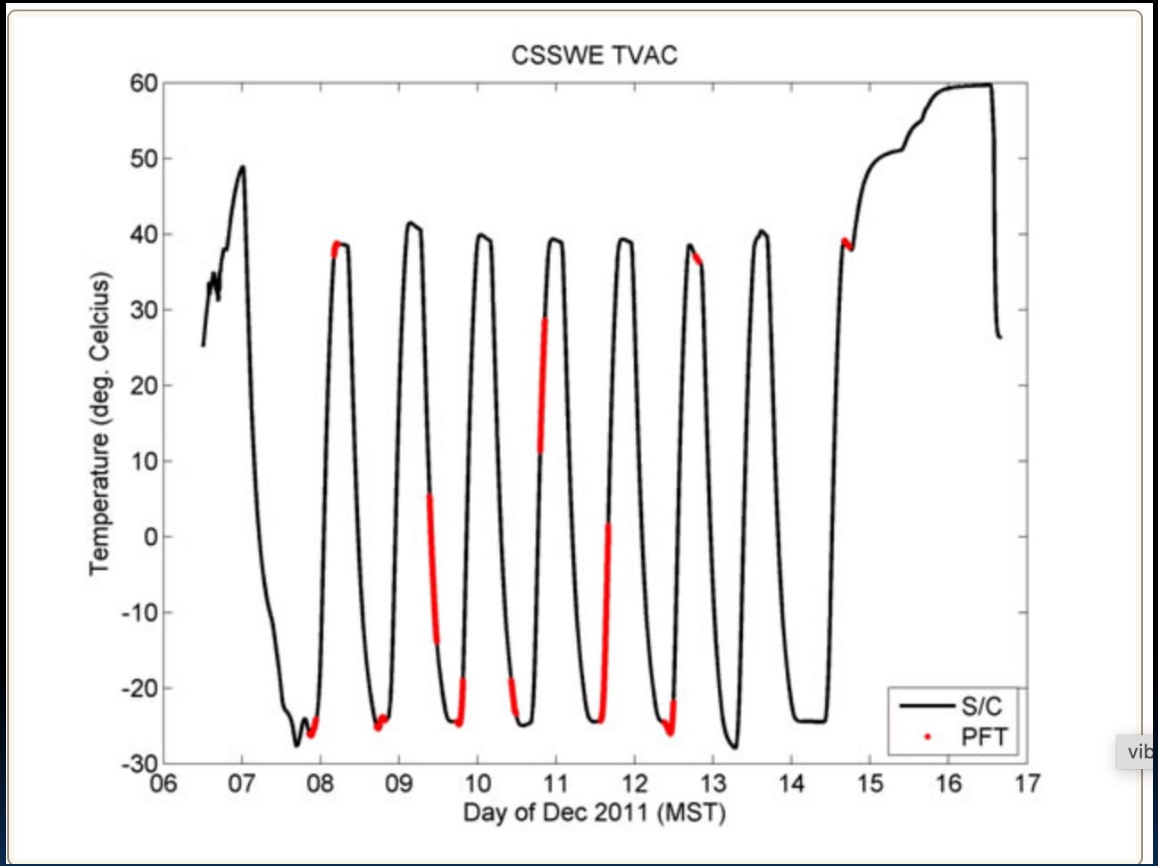
During environmental test, functional test are performed to ensure spacecraft is still functioning as desired.

Example of test profiles for space systems.

THERMAL VACUUM ENVIRONMENTAL TESTS

TVAC Tests to ensure the spacecraft can withstand the thermal environment of space.





VIBRATION ENVIRONMENTAL TEST

Table 2.4-3
Generalized Random Vibration Test Levels
Components (ELV)
22.7-kg (50-lb) or less

Frequency (Hz)	ASD Level (g^2/Hz)	
	Qualification	Acceptance
20	0.026	0.013
20-50	+6 dB/oct	+6 dB/oct
50-800	0.16	0.08
800-2000	-6 dB/oct	-6 dB/oct
2000	0.026	0.013
Overall	14.1 G_{rms}	10.0 G_{rms}

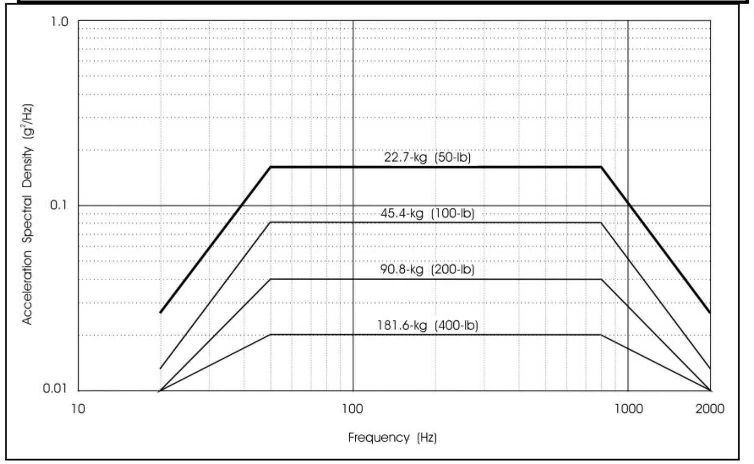
The acceleration spectral density level may be reduced for components weighing more than 22.7-kg (50 lb) according to:

	Weight in kg	Weight in lb	
dB reduction	= 10 log(W/22.7)	10 log(W/50)	
$ASD_{(50\text{-}800\ Hz)}$	= 0.16•(22.7/W)	0.16•(50/W)	for protoflight
$ASD_{(50\text{-}800\ Hz)}$	= 0.08•(22.7/W)	0.08•(50/W)	for acceptance

Where W = component weight.

The slopes shall be maintained at + and - 6dB/oct for components weighing up to 59-kg (130-lb). Above that weight, the slopes shall be adjusted to maintain an ASD level of 0.01 g^2/Hz at 20 and 2000 Hz.

For components weighing over 182-kg (400-lb), the test specification will be maintained at the level for 182-kg (400 pounds).



VIBRATION TEST TO ENSURE SPACECRAFT SURVIVE LAUNCH LOADS

Questions?

www.nasa.gov/smallsat-institute/

Upcoming Webinar: Introduction to the NASA Small Spacecraft Systems Virtual Institute (S3VI)

This webinar will focus on discussions and demonstrations of the S3VI tools; other webinar opportunities; and databases that could include:

- Small Satellite Reliability Initiative (SSRI) Knowledge Base Tool
- Community of Practice (CoP) Webinar Series
- Mission Design Tools
- Small Spacecraft Information Search
- State-of-the-Art (SoA) Small Spacecraft Report

Purpose

To provide attendees with information and knowledge of available resources and where to find them to support the design and development of their own small satellite missions.

References

NASA Procedural Requirements 7123.1D, Systems Engineering Processes and Requirements, Expiration Date: July 05, 2028
https://nodis3.gsfc.nasa.gov/displayDir.cfm?t=NPR&c=7123&s=1B

NASA Procedural Requirements 7120.8A, NASA Research and Technology Program and Project Management Requirements, Expiration Date: September 14, 2028
https://nodis3.gsfc.nasa.gov/displayDir.cfm?t=NPR&c=7120&s=8A

NASA Procedural Requirements 7120.5F, NASA Space Flight Program and Project Management Requirements, Expiration Date: August 3, 2026
https://nodis3.gsfc.nasa.gov/displayDir.cfm?t=NPR&c=7120&s=5E

NASA SP-2016-6105 Rev2, NASA Systems Engineering Handbook
https://lws.larc.nasa.gov/vfmo/pdf_files/[NASA-SP-2016-6105_Rev2_]nasa_systems_engineering_handbook_0.pdf

https://www.nasa.gov/reference/appendix-c-how-to-write-a-good-requirement/

Definitions

- NASA Procedural Requirements (NPR) 7120.5: NASA Spaceflight Program and Project Management Requirements
  - Establishes the requirements that NASA formulates and implements space flight programs and projects
- NASA Procedural Requirements (NPR) 7120.8: NASA Research and Technology Program and Project Management Requirements
  - Research and Technology typically using ground systems or sub-orbital vehicles, aircraft, sounding rockets, and balloons)
  - More recently CubeSats, SmallSats, ISS payloads have been included