Design for Maintenance

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Design Influence Considerations

- Design influence is accomplished through inclusion of Reliability, Maintainability, and Supportability (RMS) as part of the system's design characteristics from program/project inception to ensure the system(s) can be supported and maintained throughout the life cycle.
- Design influence is best applied early in the design and development life cycle phase and optimally between System Design Review (SDR) and Preliminary Design Review (PDR).
- Design influence criteria should be established to aid designers to ensure hardware and software supportability, sustainment, operational availability, and affordability.
  - Criteria examples: Modularity, autonomy, commonality, standardization, interoperability, maintainability, accessibility, testability, habitability, transportability, fault detection, diagnostics, and robotic interfaces.

Integrated Logistics / Product Support (ILS / IPS)

- Apply ILS / IPS techniques and methodologies in design influence.
- ILS / IPS is a disciplined, unified and iterative approach to the management and technical activities necessary to:
  - <u>develop</u> support requirements that are related consistently to readiness objectives, to design, and to each other,
  - <u>influence</u> hardware design,
  - <u>integrate</u> support considerations into system and equipment design,

DDT&E

  - <u>acquire</u> the required support; and

SUSTAINMENT

  - <u>provide</u> the required support during the operational phase at affordable cost.

Supportability

- Defined: The degree to which system design characteristics and planned logistics resources meet system requirements.
  - Supportability is the capability of a total system design to support operations and readiness needs throughout the system's life cycle at an affordable cost
- Supportability relates to the degree to which a system can be supported, both in terms of the inherent design characteristics of the components of the system such as standardization, commonality, interchangeability, accessibility…
  - …and the characteristics of the various elements of support capabilities such as spares, maintenance and repair processes, tools, diagnostics, and management of related information.
- In a broad context, Supportability draws on the interrelationship of design characteristics of a system, such as reliability, maintainability, human factors, and the application of ILS / IPS.

RMS Activities Influencing Product Design

Systems Engineering	Engineering
❖ Requirements: Mission, Performance, RMS, Availability, Safety, Quality ❖ Verification / Validation of Performance Measures	❖ Hardware & Software Design ❖ Reliability, Safety and Quality consideration and trades during design ❖ Human Rating considerations ❖ Design Trade Studies ❖ Integrated Design Strategy

System Design

Higher Safety, Reliability at Optimum Life Cycle Cost

Reliability (R)

- ***Reliability must be designed in***
- ***Reliability Modeling and Reliability Prediction***
- *Reliability Trade Studies*
- ***FMEA and related analyses***
- ***Design Reviews (Safety/Reliability)***
- *Design Qualification & Development Testing*
- *Verification / Validation of reliability models and analysis*
- ***Subcontractor and Vendor Controls***
- *Closed Loop FRACAS (including failure analysis & trending)*

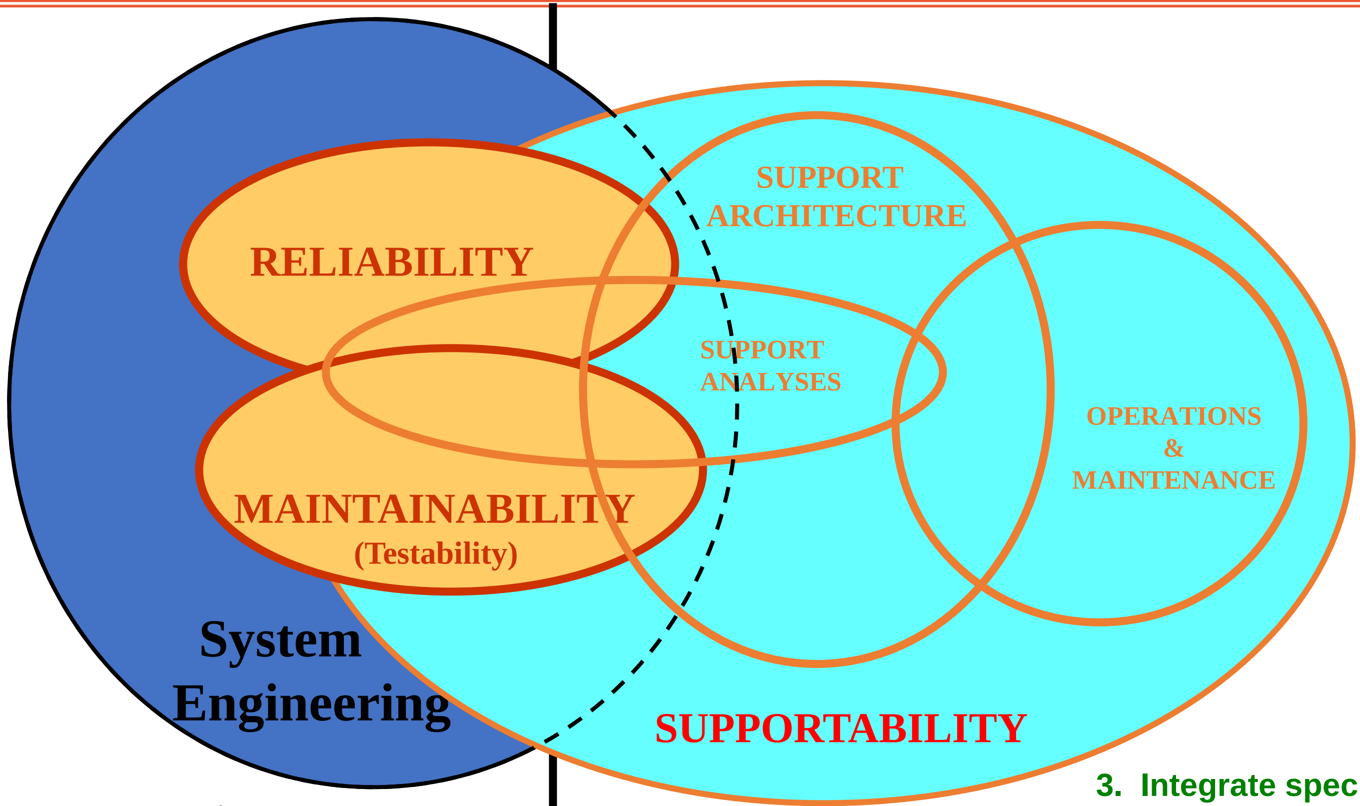
Maintainability (M)

- Maintainability must be designed in
- Design must be simple, robust and modular with easy LRU accessibility
- Use IVHM and/or Prognostics and Testability Analysis based on function criticality and value enhancement analysis
- **Measure of the ease and rapidity with which a system or equipment can be restored to operational status following a failure**

Supportability (S)

- Supportability must be designed in
- Optimize Levels of Maintenance
- Optimize Logistics support infrastructure
- Include Supportability in system requirements
- Strive for Performance Based Supportability
- Utilize tailored ILS / IPS engineering concepts / techniques

Supportability Integration Role



1. Translate operational needs into verifiable system performance parameters.

2. Integrate & optimize technical parameters and ensure compatibility of physical, functional and program interfaces .

3. Integrate specialties into total design process (R&M, ILS / IPS, Cost, Safety, Producibility, Human Factors, Stress / Dynamics, etc.)

Design & Development Phase
(Product Effectiveness)

Operations and Support Phase *(Support Efficiency)*

TOTAL COST OF OWNERSHIP →

Supportability and the "ilities"

❖ **Supportability is concerned with many "ilities"**

- Reliability
- Maintainability
- Affordability
- Availability
- Commonality
- Accessibility
- Habitability
- Producibility
- Criticality
- Compatibility
- Dependability
- Testability
- Transportability
- Visibility
- Feasibility
- Usability
- Durability
- Interchangeability
- Disposability
- Sustainability
- Interoperability

Related Space Shuttle Lessons Learned
(NASA/TP-2006-214203,)

- **Design for maintenance** is a primary consideration in reducing the logistics footprint. Smaller parts may be possible for repairs, consistent with the ability to test the sufficiency of the repair and the tools and training provided to the crew. An optimization is preferable, taking into account tools, time, packaging, stowage, and lifecycle cost.
- **Commonality** is a prime consideration for all vehicles, systems, components, and software in order to minimize training requirements, optimize maintainability, reduce development and sparing costs, and increase operational flexibility. Failure to do this increases the logistics footprint.

Space Station Logistics Lessons Learned

(Bill Robbins/JSC/ISS – original source,
see Back-Up charts for additional details)

- Establish ILS early as a systems engineering discipline.
  - Putting Logistics in Operations tempts deferring Logistics budget and products.
- Need ILS to be an integral part of the design development effort.
  - Hold design teams accountable for logistics supportability.
  - Give designers incentive for <u>designing supportability into their systems.</u>
  - Create a partnership between logistics & designer, instead of an adversarial relationship.
  - Make Life Cycle Cost model a part of the design process.
    - First thing thrown out of Station program when budget got tight.
  - Ensure requirements for <u>supportability, maintainability and reliability start with the highest level program document and flow down to the lowest level specification.</u>

Space Station Logistics Lessons Learned

(Bill Robbins/JSC/ISS – original source, see Back-Up charts for additional details)

- Treat ILS as an integrated product support function.

- Program ILS or Supportability Manager Position.
  - No more than two levels below the Program Manager
  - Equal to or reporting to the system engineering manager.
  - <u>Integrate reliability and maintainability into logistics supportability.</u>
  - Logistics was buried in Space Station Freedom organization, resulting in a lack of Program visibility and lack of access to Program management.

- Establish a requirement for Operational Availability.

- Standardize!

Recommendations

- Establish and implement Reliability, Maintainability and Operational Availability requirements.
- Include Supportability and Maintainability as system design characteristics.
- Apply ILS / IPS management and engineering techniques to ensure supportable and affordable systems.
- Comply with NASA Policy Directive 7500.1D, Program and Project Life-Cycle Logistics Support Policy.
- Design for maintenance to meet reliability, maintainability and operational availability requirements.

Back-Up Charts

International Space Station Supportability Lessons Learned

William W. Robbins
Space Station Program Office
Johnson Space Center

Acquisition Logistics and Life Cycle Cost

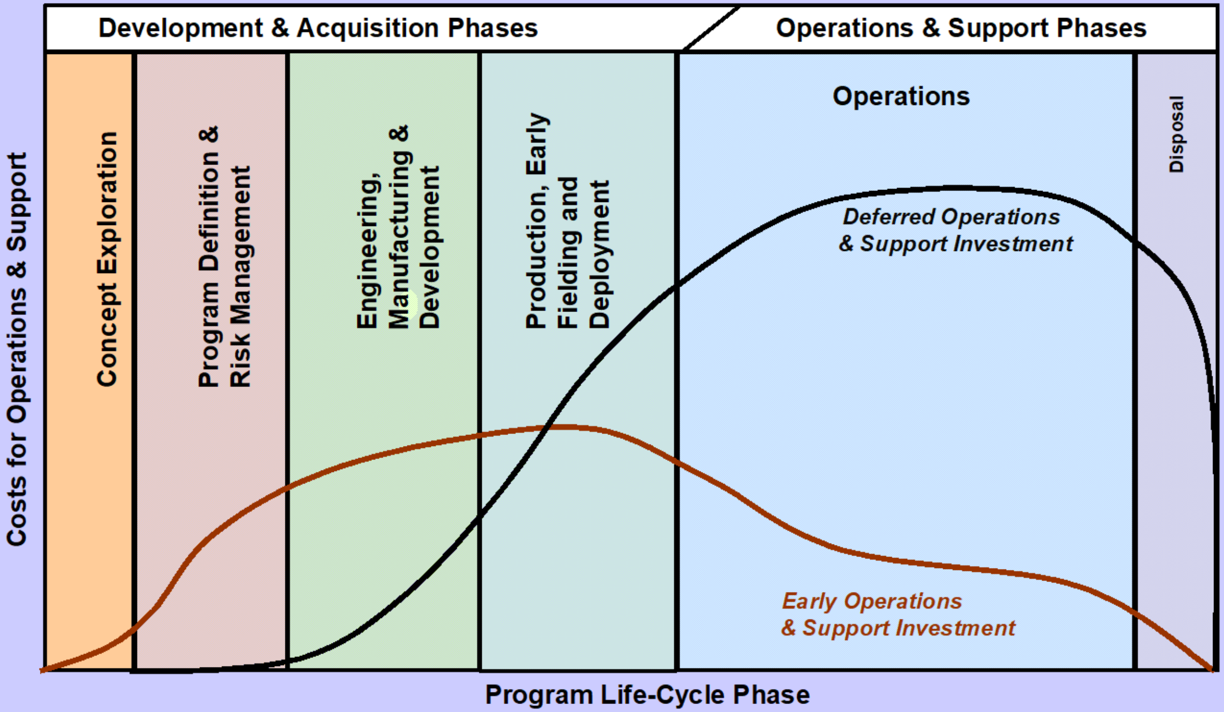


FIGURE 1. Early investments in Supportability (Inherent Hardware Designs and the Support Infrastructure) reduces the "Total Cost of Ownership".

Programmatic Lessons

- **Supportability advocates must work with both design and operations.**
  - –Organization must be structured accordingly.
  - –Must integrate supportability experts into design teams, systems integration teams and operations teams.
- **Supportability planning must analyze design regarding spares, maintenance planning, technical data, shipping, warehousing, facilities, automation, etc.**
- **Must have authority early in the program to embed supportability into the design.**
  - –Starts with design requirements and continues through detailed design.
- **Put the supportability manager at the "Vice Presidential" level, or as a direct report to Systems Engineering Manager.**
  - –May move to the Operations organization as design is completed.
  - –Must keep a close association with engineering.

Programmatic Lessons

Hold design teams accountable for supportability.

- **Give designers incentive for designing supportability into their systems.**
- **Create a partnership between supportability & designer, not an adversarial relationship.**
  - Embed supportability experts in design teams as a contributor to design, not a reviewer.
- **Make Life Cycle Cost model a part of the design process.**
  - Use to help managers make design trade decisions that adequately consider the long term cost implications.
  - First thing thrown out of Station program when budget got tight.
- **Ensure requirements for supportability, maintainability and reliability start with the highest level program document and flow down to the lowest level specification.**
  - Ensure requirements are verifiable.
  - Track requirements to completion.
- **Functional Availability requirements integrate the inherent reliability of the design with the planned support resources.**
  - Helps the Program trade design requirements against support infrastructure.
  - Requirements against one parameter (Maintenance Man Hours/Year) do not constrain other elements of support (upmass and storage volume).

Government Furnished Equipment (GFE)

- **ISS Program removed content from Prime Contractor and tasked institutional organizations to provide hardware and products.**
  - GFE used different requirements and standards than Prime
  - GFE providers are not be held to the same degree of accountability as Prime
  - Result has been that GFE has often been built without adequate reliability/maintainability performance.
  - Initial cost savings were greatly overcome by re-design, re-work and operational workarounds.
- **Lesson 1: To determine whether to use a GFE provider, the Program Office must require the same fidelity basis of estimate as the Prime, including Life Cycle Cost.**
- **Lesson 2: The GFE provider must accept the same requirements for reliability/maintainability/availability, as well as deliver the same support products, as the Prime**

As-Designed, As-Built, As-Flown

- **As-Designed, As-Built, and As-Flown will be different**
  - –Different groups are responsible for design, build and configuration for flight
  - –Maintenance and Operations must know what the As-Flown configuration is in order to support the crew
- **Verification of maintainability by analysis does nothing to verify As-Built and As-Flown configuration.**
  - –Situation is exacerbated by frequent necessity to use draft engineering for maintainability verification (schedule driven)
  - –Requiring maintainability to be verified by demonstration increases cost, but greatly reduces errors discovered after launch
- **Make the Program Office/Prime Contractor responsible for verification by demonstration**
  - –Gives the design organization the incentive to include operations organization in their processes to assist with verification
  - –Operations organization must therefore be staffed adequately to support design, build, integration and test phases

Predictive Modeling

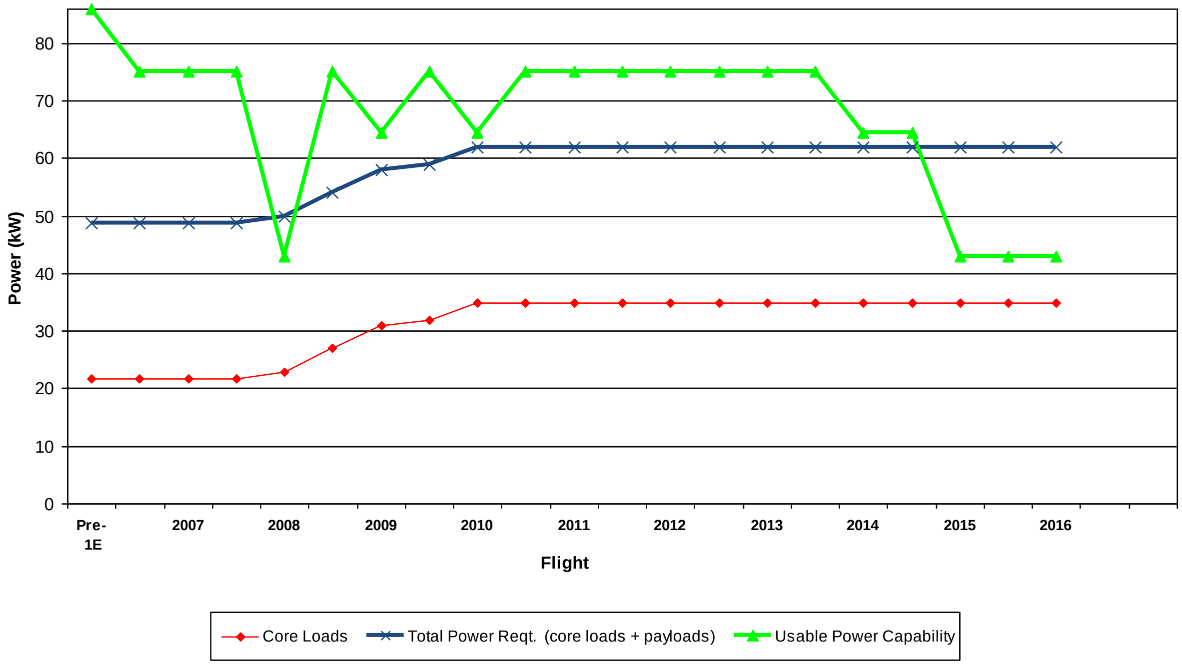
- **Functional Availability Assessment – Enhanced Release (FASTER) Tool**
  - Provides measure of availability of functions over time
  - Functional architecture consists of combinations of systems hardware that provide a necessary function
    - Example is the Usable Power function which is made up of electrical power, thermal rejection and mechanical hardware
  - User can constrain upmass, crew time and spares to gauge impact on any of 32 ISS functions

Reliability/Maintainability Predictive Data

- **FASTER uses predictive data as inputs**
  - Analyses/Reports
    - Failure Modes & Effects Analysis
    - Hazard Reports
    - Reliability Block Diagrams
  - Key predictive data elements
    - Mean Time Between Failures (MTBF)
    - Mean Time Between Preventive Maintenance Actions (MTBPMA)
    - Mean Time To Repair (MTTR)
- **Predictions are developed concurrent with design**
  - R&M Engineers analyze developing design
  - System designers consulted on hardware operation/performance
  - Historical performance tables in MIL-HNBK-217 used to create tabular predictions
- **Program must get predictive tools early, and use or create early representative data in order to conduct trades between different design options**
  - Program must understand the relative cost/benefits of design options in terms of reliability, resource requirements and life cycle cost

Functional Availability - Example

Model output shows the correlation between changes in FA and availability of resources.



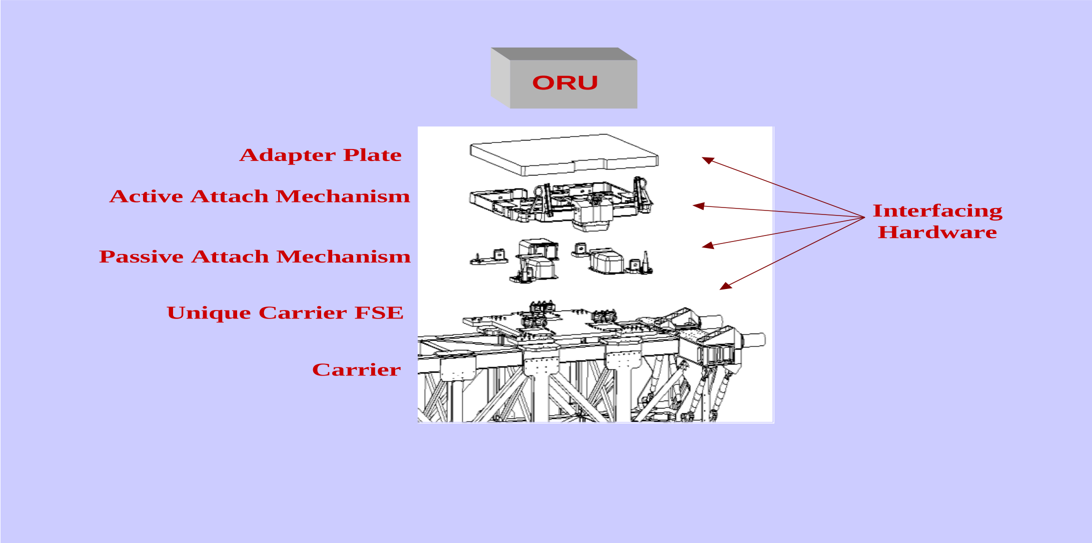
Predicted and Measured Functional Availability

Top-Ten Functions	Predicted Availability (End of Assembly)	Cumulative Measured Availability	Measured Availability for October 04
Vehicle Power	82%	**100%**	**100%**
CO2 Removal	99%	**70%**	**100%**
Intramodule Thermal	96%	**96%**	**100%**
Heat Transfer	97%	**89%**	**100%**
Command/Telemetry	99%	**100%**	**100%**
Robotics	98%	**99%**	**100%**
P/L Data Downlink	88%	**100%**	**100%**
Command & Control	99%	**99%**	**100%**
EVA Maintenance	98%	**100%**	**100%**
Fire Det/Suppression	99%	**98%**	**100%**

• CO2 Removal Availability was impacted by early failures in the Carbon Dioxide Removal Assembly (CDRA). Redundancy in US and Russian CO2 Removal systems allowed on-orbit operations to continue without interruption.

Source: Boeing, Station Availability Reporting Tool (StART)

When Supportability is Absent From Design…



- Orbital Replacement Units (ORU) were designed only for their intended installation, not for resupply.
- Result is that heavy, expensive adapter hardware has to be used to resupply hardware.
- A standard interface footprint requirement would have had long term cost savings.

Design Lessons

- **Define the interface between cargo carriers and cargo and levy this as a design requirement.**
  - Large, non-standard ORUs require unique, expensive resupply accommodations.
    - Unique Flight Support Equipment
    - Multiple cargo carrier configurations
    - Detailed loads analysis
  - Small, standardized ORUs allow use of simple, common cargo carriers.
- **Drive design to allow maintenance at lower levels of hardware indenture.**
  - Allow the crew to repair or replace circuit cards instead of boxes.
  - Standardize the configuration of cards so they can be carried in a standard type carrier.
  - Utilize Reconfigurable Hardware
    - Single hardware type which can perform different functions.
    - Example is circuit cards which can be programmed to work in multiple systems.

Design Lessons

- **Establish requirements to make designers consider the ORU as a maintenance and resupply item.**
  - ISS requirements only had some human factors and crew time constraints on ORUs.
  - Sizing and configuration for resupply not considered in design requirements.
- **Impacts:**
  - Many ORUs are too large and cumbersome to ship, launch and handle on-orbit without extensive, expensive packaging and handling equipment.
  - Engineering and certification documentation addressed ORUs as they were configured for initial launch, not for individual resupply.
    - Pre-launch servicing requirements not defined.
    - No engineering documentation of how to configure ORU for launch – additional effort/cost required to develop drawings defining launch configuration.

Design Lessons

- **Standardization of interfaces, parts and materials must be mandatory early in requirements development.**
  - Almost no standardization requirements were levied, as they were considered a constraint on design.
  - Each manufacturer used parts and materials that met their performance and cost requirements.
  - Now ISS has a proliferation of parts and material types, as well as ORU interfaces.
    - Drives parts costs.
    - Drives packaging & handling costs.
    - Drives cost of design documentation.
- **High use mechanical hardware, such as exercise equipment must have stringent reliability and maintainability requirements.**
  - Need a robust design to stand up to heavy use
  - Development should include life testing to ensure its performance is understood prior to launch

Design Lessons

- **Modularity requirements early in design pay off in life cycle cost.**
  - Modularity of design increases initial launch weight, but reduces resupply weight.
  - Critical over time due to the high cost of launching hardware to space.
  - Pump Module: Manages the Ammonia pressure on the External Thermal Control System
    - Original design of six ORUs that weighed 150-200 pounds each were combined into one ORU of 860 pounds
    - Saved about 250 pounds at initial launch.
  - However, this ORU is predicted to fail every two years.
    - Original modular design would have had an annual resupply weight of 75 pounds.
    - Non-modular design requires 430 pounds annual resupply weight.

Design Lessons

- **Require commonality and standardization across architecture elements.**
  - Architecture will include multiple elements such as crew transport vehicles, cargo vehicles, habitats and laboratories.
  - Standardize interfaces and hardware at all levels (ORU, Subassembly, Component)
  - Simplifies spares provisioning, reduces the number of unique tools and enables substitution across elements.
  - Positive examples on ISS are the Lamp Housing Assemblies and the Smoke Detectors.
    - Used in US and International Partner modules.
    - Costs reduced due to common hardware and interfaces.

Design Lessons

- **Make automated inventory management part of the design throughout cargo handling.**
  - –Automatic inventory readers on the ground, in the cargo vehicle, and in the living/work area.
  - –Have a single inventory management system on-orbit and on-ground to track item usage and movement.
  - –Inventory system should be transparent to the crew and require no manual inputs.
  - –Example: RF Tags on cargo items with automatic readers on a network.
  - –Example2: Self ID and configuration data embedded in electronics units
- **Recycle Waste Products**
  - –Design should include features to preclude accumulating waste
  - –Enhances mass efficiency, storage
  - –Recycle and reuse packaging and failed hardware

Design Lessons

- **Delivery of Engineering data “just in time” impacts logistics products.**
  - Clean up and delivery of engineering drawings, etc., close to hardware launch was driven by performing hardware qualification and acceptance in parallel
  - Logistics products are needed in advance of hardware launch to allow operations organizations to prepare for planned or potential maintenance
  - Result is that initial operations products rely on logistics products that are based on draft engineering data
    - Potential for errors due to changes in final engineering
  - Burden is then on Logistics organization to go back and review all delivered products and reconcile with delivered engineering
    - Process can go on for years
  - The solution is adequate schedule margin to deliver engineering data in advance of qualification, acceptance and hardware delivery.
    - Not always possible due to technical and budgetary challenges

Procurement Management

- **Space Station is a very low quantity spares program, but…**
  - –Many manufacturers/vendors
  - –Each spare is a high dollar item.
- **Statistical analysis methods used on large production programs do not give good results.**
- **Analysis must be on each individual ORU type, focusing on:**
  - –Duty Cycle
  - –Failure Effect
  - –Resupply Opportunities
- **Procurement timing is critical and is compressed by concurrent Qualification Testing, Acceptance Testing and Fabrication.**
- **Desire to procure spares at the end of the production run, but must balance against the operational need for spares.**
- **Detailed production schedules from manufacturers is a must.**
  - –ISS was able to mitigate need for dedicated spares by accepting manufacturing diversion if needed.

Operational Maintenance Lessons

- **Failure Rates**
  - Actual failure rates have occurred at about 50% of predictions.
  - Failure rates of individual ORUs have varied significantly.
  - Early failure leads to engineering & management concern.
    - Design change, additional spares procurements?
  - Must caution against over-reacting to one failure.
  - As the Program matures, predictions can be balanced with actual hardware performance to determine the need for additional spares procurements.
- **Software Effect on Maintenance**
  - Hardware failure predictions did not consider that failure could be overcome by software change.
    - Hardware maintenance not required for these cases.
  - Part of the mitigation of upmass and crew-time for maintenance.

Operational Maintenance Lessons

- **Management Evolution**
  - –Early in assembly, every failure was "core drilled."
  - –Station grew, so did maintenance.
  - –Management was forced to prioritize failures based on impact to station.
  - –Management had to learn to be comfortable with carrying a "maintenance backlog."
- **Resource Allocation**
  - –Crew Time & Weight to Orbit are critical operational resources.
  - –Strict prioritization required.
  - –Maintenance competes with all other resource users.
  - –Logistics partnership with Engineering is essential to successfully defining and defending resource requirements.

Operational Maintenance Lessons

- **Integration of International Partners**
  - Essential to major human space projects
    - Cost
    - Scope
    - Expertise
  - Different cultures, political objectives, ideals and work processes.
  - Integrate through negotiation of requirements.
  - Example: US and Russian partnership
    - No Russian word for “logistics”
    - US has a centralized group to integrate maintenance planning and logistics operations.
    - Russian process is to hold each system manager responsible for all logistics and maintenance functions.
    - Establishing integrated maintenance planning processes took years.

Conclusions

- Space Station supportability is a success, but it wasn't easy.
- Where supportability wasn't designed in, the penalty is increased life cycle cost.
- Supportability/availability must be measured to have an impact on design and operations.
- Management structure must facilitate integrating supportability into design engineering.
- Unique, complex hardware with very low quantities requires innovative techniques to support in a cost effective manner.
- Detailed production schedules, hardware standardization, and hardware modularity are key tools to controlling support cost.
- Must help management to understand impact of failures and maintenance requirements.