System Engineering the International Space Station

by

L. Dale Thomas, Ph.D., P.E.
Manager, Vehicle Analysis & Integration Team
NASA Space Station Program Office

ABSTRACT

The International Space Station (ISS) development includes substantial challenges in the arena of system engineering. The system development is time-phased, geographically dispersed, and integrated in the field. This paper will discuss the process employed to system engineer and integrate this unique spacecraft. A background briefly presents the vehicle architecture, including an overview of ISS Program participating nations' contributions, and gives and overview of the novel engineering documentation scheme utilized to define and control the baseline design. The System Engineering and Integration (SE&I) process is then described in the context of development of the SE&I products required to enable appropriate Certificate of Flight Readiness endorsements for a given ISS assembly flight. These products are developed in one or more constituent SE&I processes including the Design Analysis Cycle and Stage Assessments; a brief description of these processes is then given. Finally, metrics developed to measure SE&I process performance for the Incremental Design Review are briefly discussed.

1. Background

Development of the International Space Station (ISS) is currently proceeding around the world. Participating nations building elements of the orbiting station, or Vehicle, include the United States, Russia, Canada, Japan, Italy, and the member nations of the European Space Agency. The elements comprising ISS Vehicle are shown in Figure 1, including the development responsibilities of the individual program participants. The United States has development responsibility for a core portion of the station, which is collectively referred to as the United States On-orbit Segment (USOS); multiple flight elements -- such as the United States Laboratory module -- are integrated as components to form the USOS. Likewise, the Russian Segment is also comprised of multiple flight elements, including the FGB Tug and the Service Module.

In addition to development responsibility for the USOS, the United States is providing the system engineering and integration (SE&I) for the overall ISS Program. In total, the six international partners are building 87 flight elements which must be integrated to form the ISS over the course of 44 assembly flights during a five year time frame [1,2] -- a formidable SE&I task. Fortunately, the classical SE&I methods developed since W.W.II offer powerful mechanisms to deal with system complexity. [3,4,5,6,7] Although the classical system engineering methods work well, their application to any system development must be

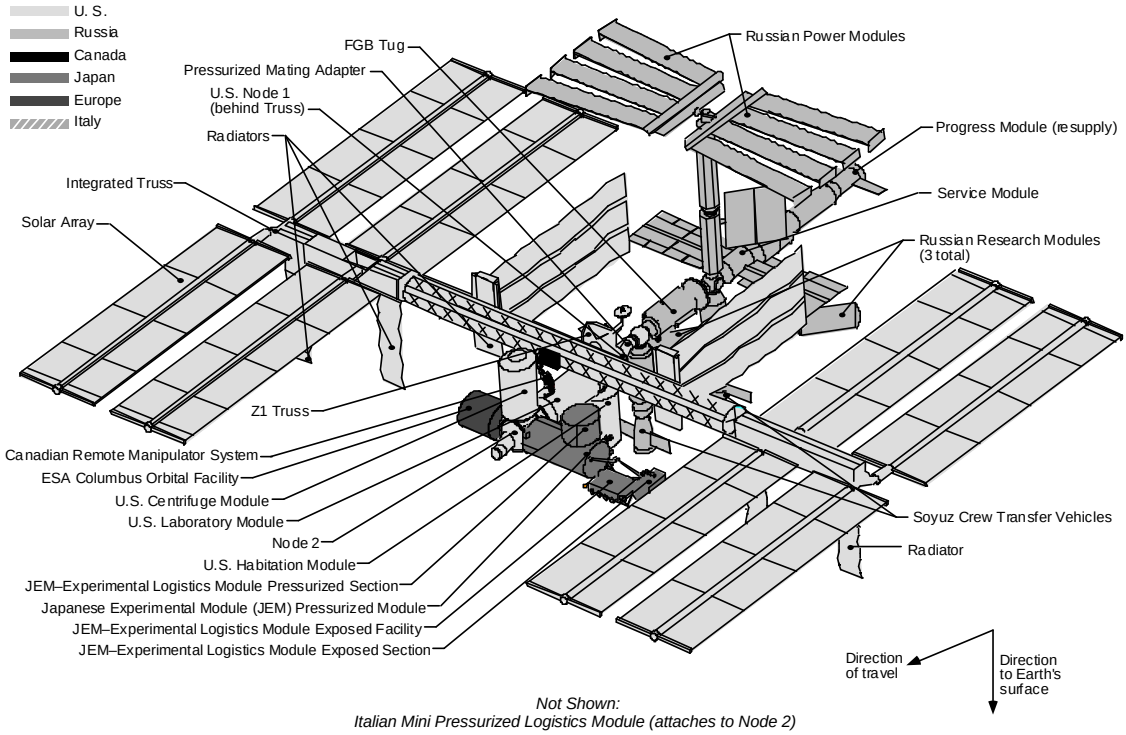

Figure 1. The International Space Station Configuration

tailored; the ISS system engineering process is no exception. The ISS system engineering approach is based on the classical textbook model as adapted in four respects:

(1) The ISS Vehicle is a time-phased development -- the build schedules for the ISS components are driven by the launch schedule, which is spread over a five year period.

(2) The ISS Vehicle is physically integrated "in the field" -- the ISS is assembled on orbit from its' 87 major component items.

(3) The ISS Vehicle is literally built "around the world" -- major component items are being built in the United States, Europe, Japan, Canada, and Russia, each of whose engineering methods and cultures differ significantly.

(4) The ISS Vehicle must function as a spacecraft during its assembly -- crew will inhabit the ISS beginning with the third assembly flight, both to aid in assembly and conduct scientific research.

While each factor cited above represents a unique challenge individually, the second order effects which result from taking them together present the real challenges. For instance, factors 1 and 3 combine to make integrated test planning a very challenging task, one with which the ISS Program is currently struggling. The discussion which follows will briefly discuss the ISS system engineering approach, concentrating primarily on the manner in which these four factors are being accommodated.

2. System Engineering & Integration Process

The ISS Program System Engineering & Integration (SE&I) process may be most easily understood within the context of two principle objectives: (1) Vehicle SE&I, the SE&I of the of all the flight elements of ISS Vehicle with each other, and (2) Launch Package SE&I, the SE&I of the individual ISS Vehicle flight elements with the other constituents of an assembly mission, such as launch vehicle integration. Certainly, there are ingredients of both SE&I objectives which may satisfied based on successful completion of a single process; indeed, one example is the Stage Assessment, which will be briefly discussed subsequently. Still, in general, this partition is valid and will serve as the context for describing the ISS Program SE&I process. The discussion which follows will address the Vehicle SE&I process in some detail; since the Launch Package SE&I process is largely a collection of well established integration processes, it will be briefly discussed with detailed treatment available in cited references.

2.1 Vehicle System Engineering & Integration

"System engineering translates a customer's stated need into a set of requirements and specifications for a systems' performance and configuration." [8] All to often, system engineering preoccupies itself with requirements definition for a product. Requirements definition is a means, not an end. For this reason, this section explicitly includes *integration* in the title. Indeed, within the scope of this paper, system engineering includes the development of a valid and cogent set of requirements *and* the verification of the as built design against those requirements. Hence, system engineering must provide assurance that the product as designed and built meets the customer's stated need; this is the integration half of the process.

The system engineering and integration process is commonly depicted using the "V" model. [9] This model captures very overtly the concept of "rolling down requirements and rolling up verification." Figure 3 depicts a modified "V" model in which the architectural development and analysis process which bridges the two legs of the "V" is shown explicitly rather than implicitly; the reason for this variation will hopefully become evident in subsequent discussion.

The design activity in aerospace systems is typically subdivided into discipline areas, or subsystems; typical subsystems groupings include avionics, structures and mechanisms, etc. The scale of the ISS and NASA culture have led to a finer granularity of subsystems classification, with the design comprised of twelve subsystems:

Command & Data Handling	Electrical Power	Extravehicular Activity
Communications & Tracking	Structures & Mechanisms	Crew Health Care
Guidance, Navigation, & Control	Thermal Control	Flight Crew Systems
Propulsion	Extravehicular Robotics	Life Support

Table 1. ISS Vehicle Subsystems

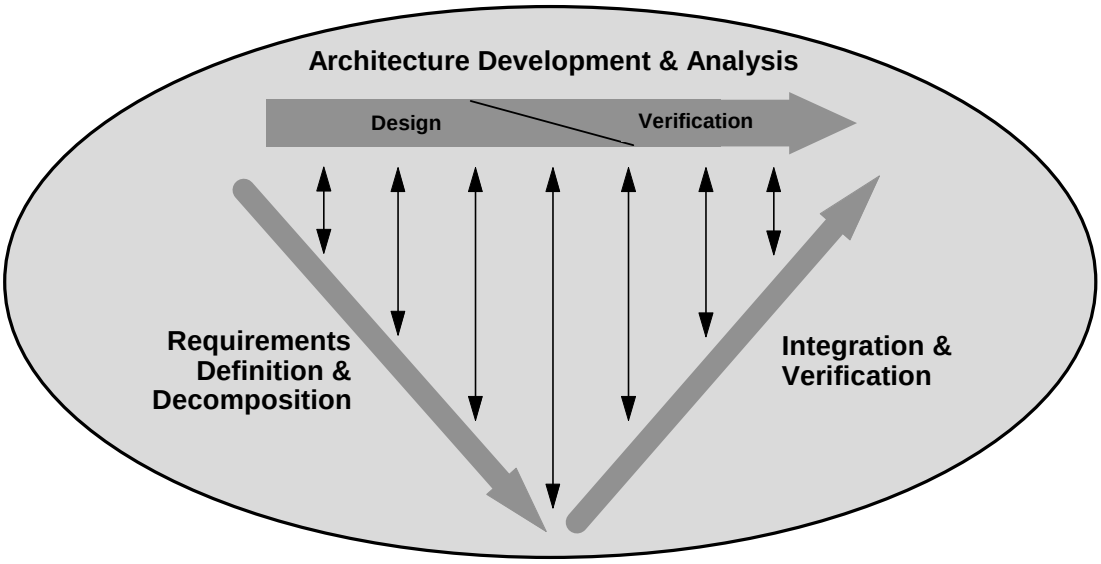

Figure 2. ISS Vehicle System Engineering “V”

Every nut, bolt, and line of code is within the purview of one of these subsystems. Each subsystem team develops the "end-to-end" vehicle architecture for their particular subsystem -- from one end of the ISS Vehicle to the other, including International Partner elements.

This subsystem architecture "end-to-end" responsibility entails assurance that the subsystem architecture functions appropriately during each stage of the ISS Vehicle assembly. This assurance drives the analysis and integration activities, since, for instance, the ability of the Life Support subsystem to control the relative humidity in the cabin atmosphere is dependent on the performance of the Thermal Control subsystem; likewise, both require electrical power from the Electrical Power Subsystem, and so on. Hence, although the subsystem teams design their subsystems to meet the respective performance requirements during each stage of the ISS Vehicle assembly, the integrated performance of all subsystems at each stage of the ISS Vehicle assembly mutually determine mission success.

The on-orbit integration of the ISS Vehicle in a series of stages represents the fundamental difference between the ISS Vehicle and NASA’s previous major programs. Each stage must be a viable spacecraft, capable of meeting stage mission requirements and capable of survival until the next assembly stage. In some cases, this leads to “stage unique” design requirements above and beyond those defined for the final configuration. For example, Node 1 must function without active thermal control during stages 2A and 3A of the assembly; this in turn widens (decreases the lower bound and increases the upper bound) the thermal design environment for components inside the Node 1 beyond those they will be required to function in for stage 4A and subsequently. Thus, the stage unique thermal environment must be included in the Node 1 specification as a design requirement for it to survive stages 2A and 3A during the assembly.

The design requirements for each subsystem are developed by the subsystem teams and flowed down through a classical spec tree. However, since the ISS Vehicle flies in 44 configurations during the assembly phase, the development of a spec tree is not straightforward. One option is to develop 44 ISS Vehicle specification trees, one for each flight configuration. Those with experience in spec maintenance will recognize the near impossibility of keeping this quantity of overlapping specifications in synchronization in the

face of routine design change activity. Another option is to develop a single spec tree for the final configuration, and include any stage-unique requirements. This approach is viable since the next tier of specification below the segments are the flight element specifications, or PIDSs (Prime Item Development Specifications); the added functionality of the appropriate flight elements approximates the jump in stage functionality for an assembly mission. This approach is clearly more efficient if the quantity of stage unique requirements is small relative to final configuration design requirements. Since this is the case for the ISS Vehicle, the latter approach was implemented, with the Stage Unique Requirements Report (SURR) serving as the single repository for those stage unique requirements "above and beyond" the final configuration design requirements. This approach is depicted in Figure 3.

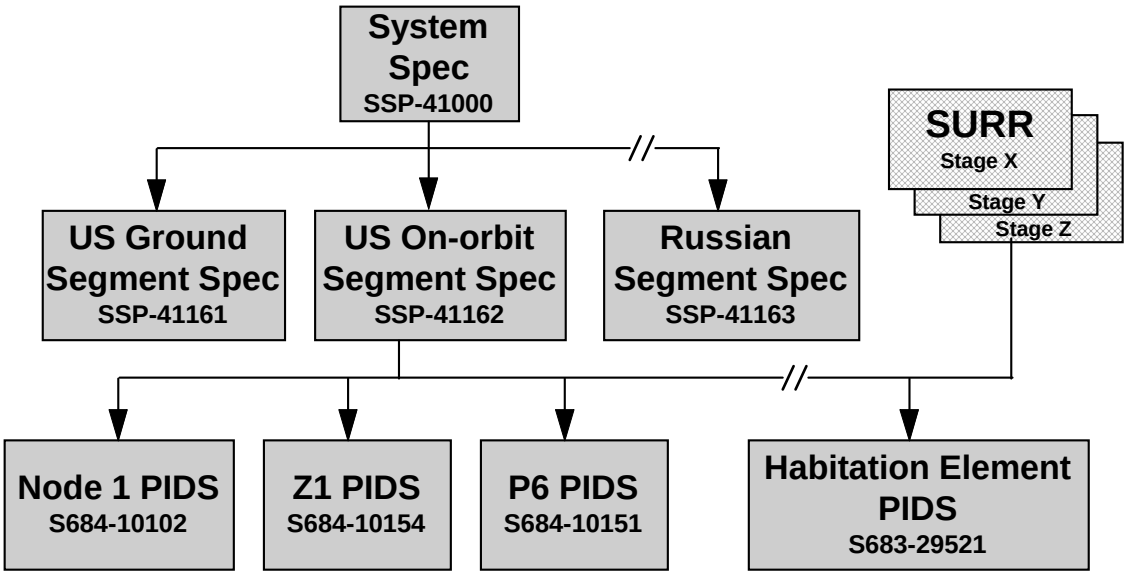

Figure 3. ISS Specification Structure

While the preceding paragraph addressed the mechanism for inclusion of stage-unique design requirements in the requirements documentation, it did not address the method for assuring that the "necessary and sufficient" stage unique design requirements are identified. The Design Analysis Cycle (DAC) is an attempt to integrate the ongoing program design/analyses tasks to ensure that each stage of the current design of the ISS Vehicle can perform the intended mission objectives. The intent of the DACs is to integrate stage oriented, "horizontal" design assessments. DAC analyses assess the integrated vehicle performance in the technical areas/disciplines listed in Table 2. The DAC process is a structured iterative approach to conducting analyses and assessments of the evolving Space Station design. The process supports the progressive definition and baselining of the design of each spacecraft (i.e., each stage of assembly), and the characterization of that design through analysis of the functionality, resource utilization, and performance capability. [11]

Altitude Strategy	Command & Data Handling	Structures & Mechanisms
EVA	Environments	Resupply/Return
Electrical Power Loads	Electrical Power Generation	Active Thermal

Flight Crew Support	Robotics	Passive Thermal
Loads & Dynamics	Proximity Operations	Propellant Requirements
AR&D	Mating	Contamination
Micro-gravity	Shuttle Performance	Traffic Model
Communications & Tracking	Environmental Control and Life Support System	Guidance, Navigation & Control

Table 2. Design Analysis Cycle Disciplines

A second cross-disciplinary review process which addresses the adequacy of the ISS Vehicle design on a staged basis is the Stage Assessment process. This review assesses the adequacy of stage unique design requirements indirectly by reviewing the flight configuration and planning products. While the DAC is focused on the integrated performance of the ISS Vehicle design over a series of stages, the Stage Assessment puts a single assembly mission under a microscope. The Stage Assessment reviews the planned Shuttle manifest for an assembly mission, the operations planning products, and command and telemetry capabilities to ensure that the assembly mission objectives -- typically assembly and activation of the flight element -- can be accomplished. This review also provides output products to support the Launch Package SE&I process discussed in the next section.

Together, the DAC and Stage Assessment provide a powerful forcing function for the identification of the necessary and sufficient set of design requirements for the ISS Vehicle. However, before the assembly mission is launched, the design must be *verified* against these requirements. A disciplined verification process has been implemented in which verification logic networks are constructed to link the design requirements and verification logic flow for each stage. These networks form the basis for detailed verification planning, including specification of the appropriate method of verification for each requirement -- inspection, analysis, demonstration, or test. [12]

Although the ISS Program verification philosophy is to “integrate and test on the ground what we fly before we fly,” the build schedules are paced by launch dates. As a result, the primary method used to verify Segment and System Specification level requirements is analysis. A Verification Analysis Cycle, a stage particular set of integrated analyses which resemble a DAC in content and method, is conducted with certified analytical models using flight element qualification data to verify the stage requirements prior to stage acceptance. The risk of this approach is exacerbated by the fact that the station is initially integrated “in the field.” The “Element-to-Element Systems Interface Integrity” (EESII, pronounced “easy” for those who appreciate irony) process has been implemented as a risk mitigation strategy. The EESII process includes several constituent processes. Principle among these are Quantitative Functional Analysis, where each element interface is assessed in terms of relative complexity and inherited lower-level testing, facilitating identification of the most critical or highest-risk element level interfaces. Given these element interface relative complexities, steps have been taken to facilitate integration-level testing at the factory, including the provision of master cabling and the utilization of “digital preassembly” to assess physical interfaces; it should be noted that the digital preassembly technology, while new to NASA, was used very successfully in the Boeing 777 development. [13] Although these mitigation strategies cannot equal an actual integrated test in the eyes of most engineers, they represent adequate risk mitigation given the cost, schedule, and geographical constraints on integrated testing.

The cultural diversity of ISS Program participants been very evident in the SE&I process. Because each International Partner has an unique engineering culture, a “meets or exceeds” process has been implemented to allow each partner to use their own process standards rather than trying to force adoption of NASA’s process standards. From the system of units and measures (metric versus English) to welding processes, equivalence of process standards has been examined to ensure a cogent set of design requirements for the entire ISS Vehicle. As would be expected, the cultural difference was largest between the American and Russian cultures owing to the significant manned spaceflight heritage of each; the meets or exceeds process was successfully completed allowing Russian flight hardware, built using Russian methods, to be integrated and verified with American flight hardware built using American methods. [14] Details concerning joint verification planning between NASA and each International Partner are contained in Bilateral Integration and Verification Plans; these plans are currently under development between NASA and each International Partner to specifically address the methods and procedures for joint verification activities.

2.2 Launch Package System Engineering & Integration

The Launch Package SE&I process concentrates more on the right hand side of the "V" than the left. The justification is straightforward -- most of the requirements are already defined, and the process is principally one of integration only. For instance, the shuttle has been flying almost twenty years. If one wishes to fly cargo, such as an ISS Vehicle flight element, on the shuttle, the interface and requirements documentation are readily available. [10] Hence, the Launch Package SE&I process is largely one of invoking these requirements -- which can be done via applicable documents in specifications -- and instituting a process for their verification. However, the Launch Package SE&I constituent processes are constantly evolving under the guise of continuous improvement, and this serves as one source of requirements development work; another source is performance enhancements being implemented by the shuttle to increase the cargo mass to orbit. Thus, while the Launch Package SE&I process is largely focused on integration, that certainly does not comprise the entire scope of work.

The culmination of the Launch Package SE&I process is certification of flight readiness for the flight element(s) comprising a particular assembly flight. The process for development of the Certificate of Flight Readiness (CoFR) “certifies the successful completion of program activities that are required to ensure safety and operational readiness of Space Station Program hardware and software, facilities, and personnel that support pre-launch activity, launch/return, on-orbit assembly, operation, and utilization.” [14] A CoFR includes multiple endorsement statements, such as “‘As built’ flight article satisfies the functional and performance requirements in ‘design-to’ specifications and system specifications; any departures from requirements have been documented” and “Flight hardware is within time, cycle, age, life, and maintenance.” The products resulting from completion of the ISS Vehicle verification process, such as stage verification compliance notices, and from other processes such as the ISS Vehicle Safety Review and the Shuttle Payload Integration, provide the basis for senior ISS Program managers’ approval of the CoFR. Completion of the CoFR is the last step for the ISS Program preceding launch.

2.3. Incremental Design Reviews

As stated previously, the ISS Vehicle flies in 44 configurations during the assembly phase, and is comprised of approximately twice that many flight elements. A typical design review approach would entail multiple parallel efforts to support design review activities for each flight. Instead, the ISS Program holds a consolidated Incremental Design Review (IDR) annually to review of the current status of all ISS Program hardware and software. This status is taken as a metric relative to where in the development cycle the hardware and software needs to be to support flight schedules -- in other words, where are the pieces of the ISS Program on the road to their respective CoFRs? The IDR closure criteria define this "where" in some detail, specifying which analyses must be complete, which fabrication tasks must be complete, etc., in terms of lead time away from CoFR, as depicted in Figure 4.

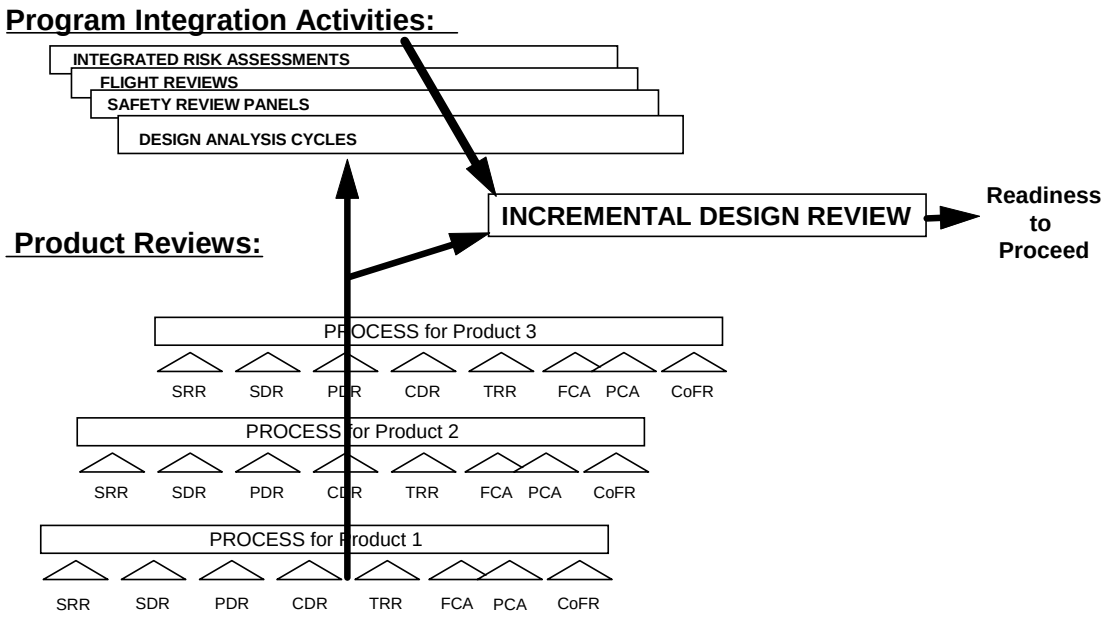

Figure 4. Incremental Design Review Content

For the ISS Vehicle, these closure criteria are established by Launch Package and by integrated subsystem; for the integrated subsystem, the closure criteria are also established by stage. This "lead time away from CoFR" paradigm is applied to the other portions of the ISS Program as well. The detailed closure criteria for the ISS Vehicle, Operations and Utilization, Safety and Mission Assurance, and Risk Management are contained in the appendices of the *IDR Plan*. [16] The IDR product is approval by the ISS Program Manager of "readiness to proceed" for each subsystem and launch package for the ISS Vehicle, and as appropriate for other components of the ISS Program, given either (1) satisfaction of closure criteria or (2) an acceptable recovery plan for each closure criteria not met.

3. Remarks

The foregoing discussion has presented a brief overview of the ISS Program SE&I process. This process has as its basis the tried and true system engineering methods. The ISS Vehicle development presents four primary wrinkles to a smooth implementation of a textbook SE&I approach. The foregoing discussion has also addressed how these complications are being dealt with. In summary:

(1) The ISS is a time-phased development -- addressed by the IDR approach and the EESII verification risk mitigations.

(2) The ISS is physically integrated "in the field" -- addressed by the DAC and Stage Assessments and by the EESII verification risk mitigations.

(3) The ISS is literally built "around the world" -- addressed by developing joint specifications and standards via a "meets or exceeds" process which allows spacecraft flight elements built using different yet equivalent engineering practices to be integrated and verified.

(4) The ISS must function as a spacecraft during its assembly -- addressed by architecture design and analysis processes such as the DAC and Stage Assessment, which drive out stage unique requirements captured in SURRs.

One notes from the preceding four statements that multiple strategies, such as the DAC and EESII verification risk mitigations, address multiple SE&I complications. Killing two birds with one stone becomes more important as one has fewer stones; given the cost and schedule constraints within which the ISS Program must perform, working efficiently is a requirement. To the extent that these strategies are successful in addressing these complications, they will serve as the basis for new chapters in the System Engineering and Integration textbook.

4. References

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