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# Extending ISS Life Beyond 2030

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**Abstract**

This paper presents an overview of the International Space Station life extension project, focusing on the analytical approach used to assess its primary structure. Also addressed are life extension approaches for other affected sub-systems, including secondary structure, materials, Environmental Control and Life Support Systems (ECLSS), Electrical Power System (EPS), and Logistics and Maintenance (L&M).

The United States On-orbit Segment (USOS) of the International Space Station (ISS) was initially designed for a 15-year on-orbit life, but with the realization of its continued importance, efforts were made to extend its operations through 2030. This paper discusses the various analyses conducted, including future operations planning, load simulation, material degradation studies, thermal analyses, and fracture analyses. The results demonstrate the feasibility and achievability of extending the ISS's life, ensuring its on-going role as a hub for scientific research, international cooperation, and educational endeavors. With the life extension process in place, continuous operations beyond 2030 are possible to maintain an uninterrupted human presence in Low Earth Orbit, facilitating the testing of new technologies, and allow for a seamless transition to new commercially owned and operated destinations.

**Keywords:** ISS, Fracture, Life Extension, Sustaining, Boeing, NASA

**Nomenclature**

a = Crack depth in thickness or diametral direction
N = Number of applied fatigue cycles
$\Delta K$ = Stress intensity factor range
$da/dN$ vs. $\Delta K$ = Crack Growth Rate curve

**Acronyms/Abbreviation**

Alpha Joint Interface Structure (AJIS)
Beta Gimbal Assembly (BGA)
Common Berthing Mechanism (CBM)
Contractor Furnished Equipment (CFE)
Covered Interconnected Cell (CIC)
Crew Space Transportation (CST)
Electrical Power System (EPS)
Environmental Control and Life Support (ECLS)
Environmental Control and Life Support System (ECLSS)
Express Logistics Carrier (ELC)
External Stowage Platform (ESP)
Extra Vehicular Activity (EVA)
Failure Analysis and Spares Assessment (FASA)
Finplate (FP)
functional Availability Simulation Tool Enhanced Release (fASTER)
Government Furnished Equipment (GFE)
Heat Rejection Subsystem (HRS)
High Transfer Vehicle (HTV)
Integrated Equipment Assembly truss (IEA)
Intermediate Level (I-Level )
Intra Vehicular Activity (IVA)
ISS Roll Out Solar Array (IROSA)
Life Extension (LE)
Logistics and Maintenance (L&M)
Long Spacer (LS)
Low Earth Orbit (LEO)
Material Information and Usage List (MIUL)
Material Usage Agreement (MUA)
Mean Time Between Failure (MTBF)
Mobile Transporter (MT)
Modified Rocketdyne Truss Attachment System (M/RTAS)
Module-to-Truss Structure (MTS)
National Aeronautics and Space Administration (NASA)
Orbital Replacement Unit (ORU)
Oxygen Generator System (OGS)
PhotoVoltaic Radiator (PVR)
Portable Breathing Apparatus/Prebreathe Hose Assembly (PBA/PHA)
Pressurized Mating Adapter (PMA)
Probability of Sufficiency (POS)
Reliability and Maintainability (R&M)
Run to Failure (RtF)
Science Power Module (SPM)
Segment-to-Segment Attach System (SSAS)
Short Spacer (SS)

Solar Array Wing (SAW)
Thermal Radiator Rotary Joint (TRRJ)
United States On-orbit Segment (USOS)
Water Recovery Management (WRM)

## 1. Introduction

The International Space Station is a multinational space station that serves as a laboratory for scientific research and a platform for international cooperation in space exploration. It is a joint project involving space agencies from the United States, Russia, Europe, Japan, and Canada. The Boeing Company has been the primary contractor for the USOS since before the on-orbit construction of the ISS began in 1998. The first ISS module, a Russian element named Zarya, was launched into space in 1998. It was followed closely by the US Node-1 Unity module which docked to form the beginning of the integrated ISS. Since then, numerous modules and components have been added, making it the largest human-made structure in space.

The ISS has a mass of approximately 420,000 kilograms (925,000 pounds) and spans an area roughly equivalent to the size of a football field (Fig. 1). The ISS is a complex structure, consisting of many complex mechanisms which must operate under varying dynamic loading and extreme thermal conditions.


Fig. 1. International Space Station Size Comparison [1]

The National Aeronautics and Space Administration (NASA) and its international partners have maintained a continuous and productive human presence aboard the ISS for more than 23 years. The ISS primary structure was designed to meet a 15-year on-orbit life. Since the first hardware was launched in late 1998, the ISS would have reached its end of life in 2013. With the realization that the ISS would be needed well into the next decade, and beyond, a multi-disciplinary effort was undertaken to extend the ISS' life through 2028 and to show that further extension to 2040 and beyond is not only feasible but achievable. Currently, NASA and the ISS international partners have agreed to extend its operations through 2030. This collaborative effort ensures that the ISS will continue to serve as a hub for scientific research, international cooperation, and educational endeavors for the next decade. Maintaining a continuous human presence in LEO is desirable for testing new LEO, lunar, and deep-space technologies; conducting scientific research in micro-gravity for the benefit of life on Earth; and enabling a seamless transition of capabilities to one or more commercially owned and operated destinations.

The multi-disciplinary Life Extension (LE) approach includes aspects such as logistics resupply, electrical power systems, environmental control and life support systems, limited-life materials, and primary and secondary structure fatigue and fracture. This paper focuses primarily on the analytical approach used to extend the life of the USOS primary structure, but also touches briefly on the other disciplines. This analytical approach includes future operations planning, critical location screening, on-orbit mechanical loads analysis, on-orbit optical property degradation studies, on-orbit thermal-structural loads analyses, spectra generation, crack model idealization, fracture analyses, and post processing. Structural life results and identification of the most critical on-orbit events are presented. The USOS approach outlined here was also heavily utilized in extending the life of the international partner structures, in addition to performing some ground testing of Russian elements.

Also addressed are life extension approaches for other affected sub-systems and functions, including:

- Secondary Structure, which attaches to and is supported by the primary structure. A screening process was developed to determine which secondary structure needed fracture analysis.
- Non-structural fracture critical hardware, such as flex hoses, valves, fittings, and pressure vessels.
- Materials and processes: Evaluations consider environmental exposure to atomic oxygen, ionizing and gamma radiation, fluids, etc. Life limited materials, wear, and usage effects are also considered.
- Logistic and maintenance: Analyses are performed to determine critical spares required to maintain functionality.
- Electrical Power System: Power generation and balance analyses are performed considering hardware degradation and increasing power demand.
- Environment Control and life support system: Evaluations are performed to determine which hardware can be run to failure and which are assessed for life extension.

The successful life extension results have built confidence to safely operate, maintain and enhance the ISS well beyond the current decade. Extending the operational life of the ISS maintains an international presence in LEO and serves to avoid a gap in a capability necessary to fulfill the exploration and research needs of NASA, international partners, and industry without interruption until a commercial space station is operational

## 2. ISS USOS Primary Structures Approach and Status

The ISS USOS LE project is a multiyear on-going project involving several phases. The project was divided into different phases depending on the hardware's launch date. The first hardware to launch would reach its end of life limit first and was therefore prioritized. A list of all hardware that went through the LE process and which phase it was performed in is listed in Table 1. The LE project Phase I started in November 2009 with a goal of extending ISS USOS Phase I hardware life through December 2028. Subsequent phases began in a stair-step fashion as prior phases ended, all with a goal of extending primary structure life through 2028. All phases of the analysis, some of which were repeated to accommodate updated assumptions, were completed by the close of 2019. All ISS USOS primary structure had successfully achieved the end of life goal of December 2028.

Table 1 ISS USOS hardware by LE phases

| LE Phases | | | |
|---|---|---|---|
| I | II | III | IV |
| Node-1 | ESPs (1, 2) | M/RTASs | ELCs |
| CBMs | S0 Truss | IEAs (P4, S4, S6) | |
| Hatches | MTS Struts | IEA FPs (P4, S4, S6) | |
| PMAs | P1 Truss | SAWs (P4, S4, S6) | |
| Z1 Truss | S1 Truss | BGAs (P4, S4, S6) | |
| RTAS | TRRJs | PVRs (P4, S4, S6) | |
| LS (P6) | HRS | ESP-3 | |
| IEA (P6) | MT | AJISs | |
| IEA FP (P6) | SSASs | LS (S6) | |
| SAW (P6) | | P3 Truss | |
| BGA (P6) | | S3 Truss | |
| PVR (P6) | | SARJs | |
| US Lab | | P5 Truss | |
| US Airlock | | S5 Truss | |

Following US Congressional approval of ISS Extension to 2030, NASA directed the Boeing Company to start a new ISS LE effort to extend the ISS to 2038. The new ISS USOS Life Extension project kicked off in January 2023 with a goal of further extending hardware life through the end of 2038.

The ISS primary structure LE approach includes the following major steps:

- ISS future flight plan and assumptions
- Critical fracture location screening of hardware
- Optical properties studies
- On-orbital thermal analysis
- On-orbit mechanical analysis
- Load and stress spectra generation
- Fracture model idealization
- Fracture analysis and post processing.

The flow charts for ISS primary structure can be found below in Fig. 2:

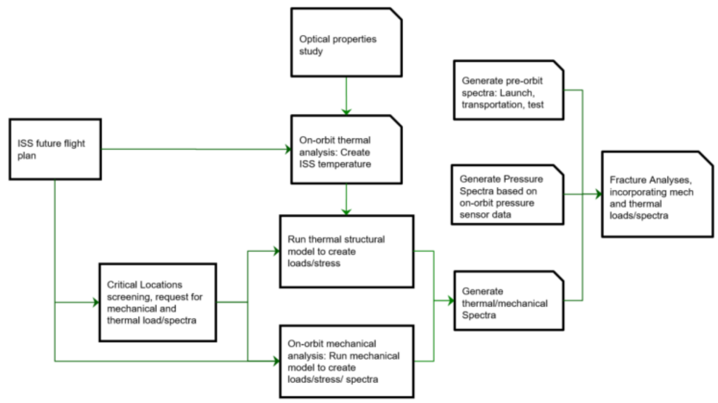


Fig. 2. Process Flow of ISS USOS Primary Structure Life Extension

Details about each step can be found in subsequent sections.

### *2.1. ISS Projected Future Flight Plan and Assumptions*

The ISS LE project takes reconstructed load/stress spectra and projected load/stress spectra as input for fracture analyses. The reconstructed spectra consist of pre-orbit events including ground test, ground transportation, and launch, along with past on-orbit events including thermal, mechanical, and pressure loads. The projected spectra are developed based on an ISS future flight plan and usage assumptions which were provided by NASA in collaboration with Boeing teams.

The ISS future flight plan that is being used for the current ISS life extension effort to 2038 covers calendar years 2021 through 2038. It includes the following major categories:

- ISS configuration changes
  Major ISS configuration changes include the installation of the IROSAs on outboard trusses, the addition of a Russian SPM, and the arrival of Axiom Commercial Segment modules. Fig. 3 shows the ISS future configuration.

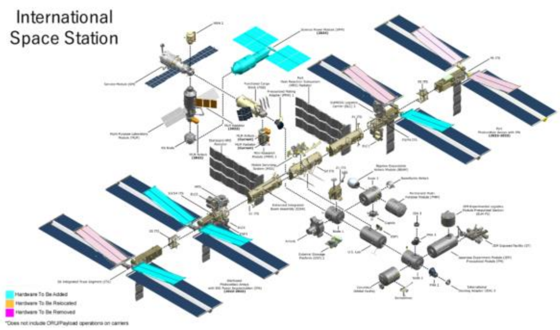


Fig. 3. The International Space Station future configuration (without Axiom) [2]

- ISS Vehicle Traffic Assumptions
  ISS vehicle traffic assumptions include the types of vehicles, number of annual docking events, and usage of the various docking ports. Fig. 4 shows a representation of six spaceships parked at the space station including Japan's High Transfer Vehicle (HTV) cargo transfer spacecraft, the SpaceX Dragon spacecraft, Northrop Grumman's Cygnus space freighter, the Soyuz MS-25 crew ship, and the Progress 87 and 88 resupply ships. Additionally, the Boeing CST-100 Starliner can dock to the Node-2 module and the Sierra Space DreamChaser cargo resupply vehicle is planned to berth to Node-1.

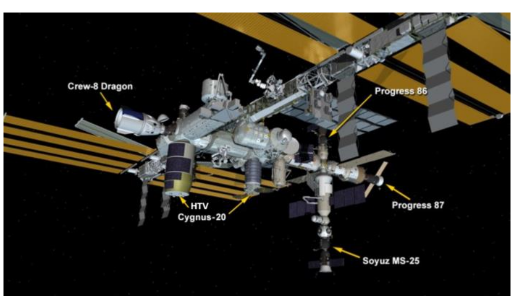


Fig. 4. ISS Vehicle Examples and Docking Ports [2]

- Thruster events - Thruster events include Reboosts, Debris Avoidance Maneuvers, Attitude hold, desaturation of the control moment gyroscopes, and vehicle dockings and un-dockings, among others.
- Flight Attitudes and Solar Beta angles assumptions - flight attitude and solar beta angles during different on-orbit events.
- Extra Vehicular Activity (EVA) and Robotics plans
  Number of USOS EVA, Russian EVAs, and Axiom EVAs per year, and number of annual on-orbit operations that utilize Robotic arms.
- Payload plan - Future payload configurations on ESPs, ELCs, other pallets and racks

## 2.2. *Critical Location Screening*

A set of critical locations for each ISS hardware was chosen for fracture analysis rather than a complete reanalysis of each hardware element. Critical location selection was made on the basis of low life areas in the design analysis, knowledge of the ISS future usage plan, and engineering judgment.

The ISS LE project uses the fracture analysis software program NASGRO, which is maintained by Southwest Research Institute. Since the time of the pre-flight design analysis of the first USOS hardware dating back to the 1990s, NASGRO has been through several upgrades, including advancements in fracture theory and additional material test data, among other improvements. The ISS LE project must include the impact of the NASGRO upgrades in its critical location selection process. A comprehensive version change study was performed, which included comparisons of material property da/dN vs. ΔK curves and assessment of the impact of fracture methodology changes. The study results show that under the same cyclic loads, later versions of the fracture tool generally predicted faster crack growth than the original version for most materials, particularly in the low stress intensity factor threshold regime. Thus, the 'low life areas in the design analysis' criterion had to be adjusted accordingly. Fig. 5 is a version change study example for the case of a surface crack of a typical aluminum used on the ISS.

| Design Spectra | |
|---|---|
| # of life in Flagro 2.03 | # of life in Nasgro 6.0 |
| 21 | 10 |

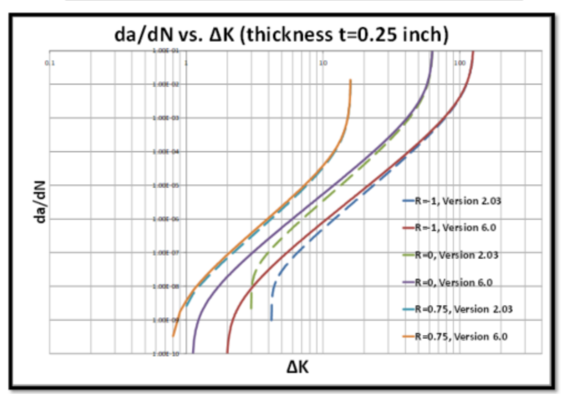


Fig. 5. Fracture Tool Version Change Study

Records of manufacturing discrepancies and on-orbit hardware anomalies/modifications were also reviewed and taken into consideration when choosing critical locations.

### *2.3. On-Orbit Mechanical Analysis*

The intent of reconstruction of loads and spectra induced on the ISS is to reproduce as closely as possible on-orbit conditions and activities. This is best achieved with the use of models and forcing functions that were correlated with on-orbit-measured data. For each reconstructed flight, data collected during flights were employed to correlate forcing functions and integrated finite element models.

For the projected time period, analysis was performed for all on-orbit loading conditions defined in the ISS future flight plan. The projected mechanical analysis uses new forcing functions and models to produce a more realistic estimate of on-orbit loads and spectra.

The validated loads models were generated using finite element modeling techniques. MSC/NASTRAN is the primary tool used in the development of the models. The integrated on-orbit system model of a given ISS stage configuration is generated from collections of validated component models. Fig. 6 shows an example of mode shape validation. Integrated on-orbit system models are also validated using on-orbit data which was collected for various ISS configurations using a variety of instrumentation systems, see Fig. 7. This data was measured during nominal Russian and Space Shuttle vehicle docking and undocking events, ISS attitude maneuvers, Station Detailed Test Objectives, and ISS reboosts. Several other on-orbit data takes were recorded for various configurations. The test/model correlation effort continues on an on-going basis as the ISS configuration changes and new crew and cargo vehicles arrive and depart.

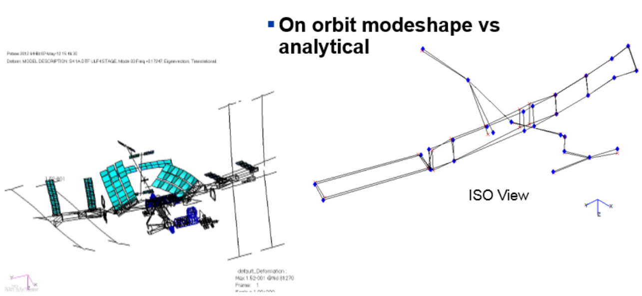


Fig. 6. Integrated on-orbit system model validation: mode shape vs analytical

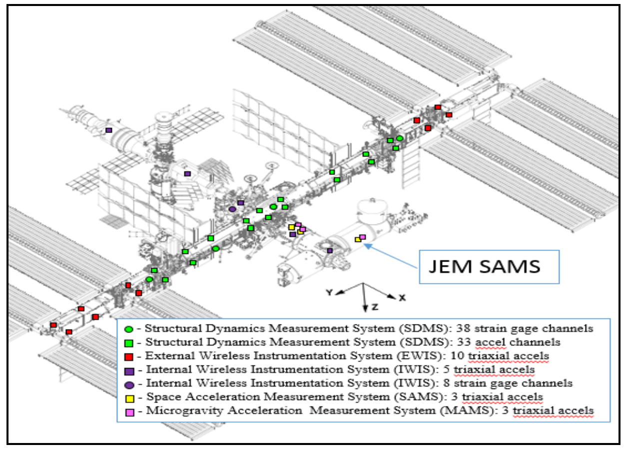


Fig. 7. On-orbit Measurement systems

Forcing functions are used to simulate the forces imparted by operational events on the ISS. Analysis for projected events uses a sufficient number of forcing functions to envelop anticipated variability in the operational event criteria. The peak loads for each hardware interface from each event were selected to identify the highest loads that could potentially be experienced during any given event. For reconstructed analysis, available on-orbit data was employed to reproduce and refine the forcing function criteria. Whenever available, data collected during the actual on-orbit occurrence of the events were used to develop a forcing function that closely simulated the forces imparted on the ISS. Such supporting data eliminated the need to account for potential variability in the operational criteria since they could be reproduced to a high level of confidence.

### *2.4. Optical Property*

The ISS's beginning of life optical property value is the basis for the initial absorbance, and the subsequent optical property degradation is calculated from this starting value.

Fig. 8 shows an example of P6 truss beginning of life solar absorbance. Fig. 9 was the P6 truss end of life absorbance value predicted at the ISS design phase and shows that the values are generally larger and, thus, are typically conservative, when compared to the solar absorbance with degraded optical property as predicted in LE (see Fig. 10).

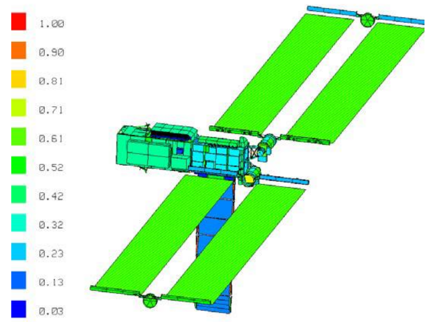

Fig. 8. P6 Truss with beginning of life Solar Absorbance

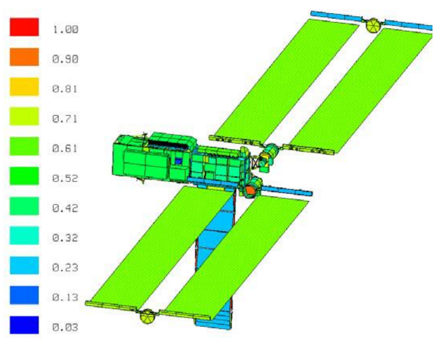

Fig. 9. P6 Truss with Design End of Life Solar Absorbance

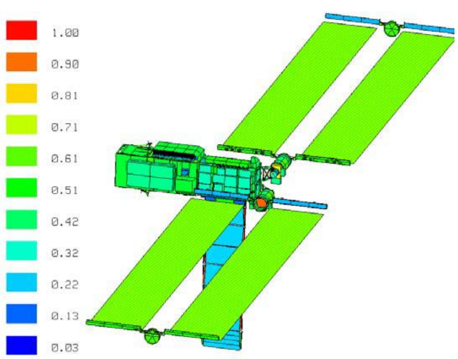

Fig. 10. P6 Truss with Degraded 2028 Solar Absorbance

Optical degradation (i.e., the increase of solar absorbance) modeling of optically sensitive and thermal control surfaces due to the combined effects of atomic oxygen, molecular contamination, and ultraviolet radiation is critical in establishing a realistic thermal environment and estimating the operational lifetimes of hardware.

Optical degradation models are developed from flight data, as well as from laboratory testing. For molecular contamination and polymeric based coatings or surfaces, the model is expressed in terms of a rate of reaction of the contaminant layer and underlying substrate due to ultraviolet radiation. The model determines the amount of optical property degradation and solar absorbance at discrete time intervals, for the different materials and thermal control coatings found on the ISS. These values were then incorporated into the thermal models.

### *2.5. Thermal Analysis*

The thermal analysis performed for the ISS LE project was run as quasi-steady state. The goal of thermal analysis is to determine the temperature contour on ISS structure at different stage/time intervals as influenced by several analytical parameters, including flight orientation, altitude, stage configuration, orbital inclination (i.e., beta angle), etc. Fig. 11 shows analytical parameters used in the thermal analysis.

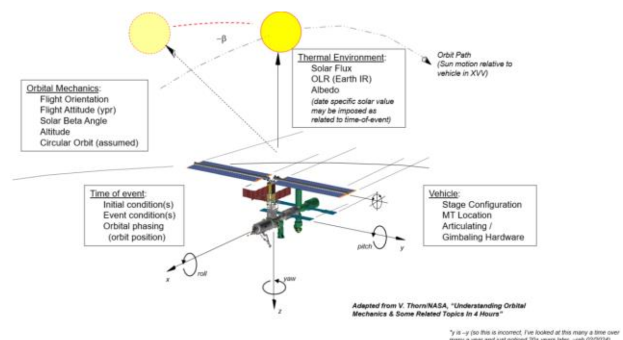

Fig. 11. Analytical Parameters for Thermal Analysis

The temperature data from thermal analyses are mapped onto thermal-structural finite element models. Fig. 12 shows how temperatures on a thermal coarse model on the left are mapped to a finer thermal-structural model on the right.

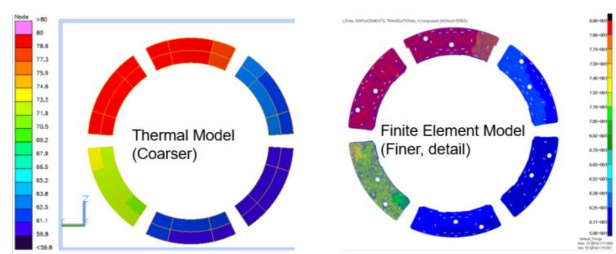

Fig. 12. Temperature Mapping on Structural Model

### *2.6. Spectra Generation*

ISS LE analyses implement the generalized rainflow algorithm from ASTM E1049-85 for spectra generation/cycle counting. Fig. 13 shows an example of cycle counting using rainflow algorithm.

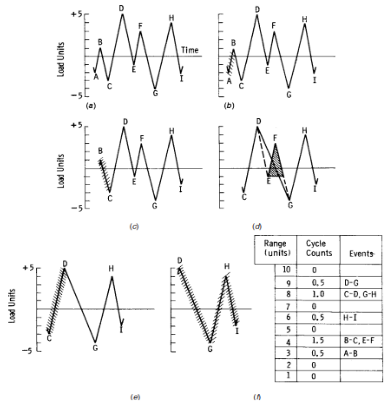


Fig. 13. Rainflow counting example [3]

Spectra are organized in blocks, where each block represents one type of on-orbit event during a flight or a period of time. The organization of the spectra allows for later identification of the major life driving events during post-processing. The following is an example of spectra organization where the letter and number designation in the reconstructed section reflect the corresponding Space Shuttle flight number:

| Reconstructed | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Block 1 | Block 2 | Block3 | Block 4 | Block 5 | Block 6 | Block 7 | Block 8 | Block 9 | Block 10 | Block 11 |
| Ground Operations | Mech | Thermal | Mech | Thermal | Mech | Thermal | Mech | Thermal | Mech | Thermal |
| Test | 12A | 12A | 10A | 10A | 1J | 1J | 15A | 15A | 20A -12/2020 | 19A |
| Transport | 12A.1 | 12A1 | 1E | 1E | ULF2 | ULF2 | 2 J/A | 2JA | | ULF4 |
| Launch | 13A | 13A | 1 J/A | 1JA | Reboost Anomaly | | 17A | 17A | | ULF5 |
| | 13A.1 | 13A1 | | | | | ULF3 | ULF3 | | ULF6 |
| | | | | | | | | 20A | | ULF7 |
| | | | | | | | | | | ULF7-12/2020 |

| Projected (2021-2028) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Block 12 | Block 13 | Block 14 | Block 15 | Block 16 | Block 17 | Block 18 | Block 19 | Block 20 | Block 21 | Block 22 |
| Mech Proj. | Mech Proj. | Mech Proj. | Mech Proj. | Mech Proj. | Mech Proj. | Mech Proj. | Mech Proj. | Mech Proj. | Mech Proj. | Mech Proj. |
| Event 1 CMG DESAT | Event 2 OPM to/from +/- XVV | Event 3 USTO MMO 0 | Event 4 RS MCS - Nadir Roll | Event 5 RS MCS - Zenith Roll | Event 6 Reboost/DAM | Event 7 TV Prox Ops - HTV-Class | Event 8 Space-X Dragon Dock/Sep | Event 9 USTV Prox Ops - Orbital-Class | Event 10 Russian Dock/ Undock | Event 11 CST-100 Dock/Undock |
| Block 23 | Block 24 | Block 25 | Block 26 | Block 27 | Block 28 | Block 29 | Block 30 | Block 31 | Block 32 | Block 33 |
| Mech Proj. | Mech Proj. | Mech Proj. | Mech Proj. | Mech Proj. | Mech Proj. | Thm. Proj. | Thm. Proj. | Thm. Proj. | Pressure | EVA |
| Event 12 EVA APFR | Event 13 EVA non-APFR | Event 14 IVA Pushoff/ landing | Event 15 T2 | Event 16 BD2 | Event 17 Exersise - Other | Event 18 Mechanisms | 2021-2024 | 2025-2028 | BOL-EOL | BOL-EOL |

Fig. 14. ISS LE Spectra Organization Example

There are up to four different types of on-orbit load blocks: pressure, thermal, mechanical, and EVA. The following load combinations were used for the different load blocks:

- Pressure blocks: Pressure spectra generated by cycle counting on-orbit pressure sensor data
- Thermal blocks: Thermal spectra generated from time history of thermal loads/stresses, and build on to the maximum pressure loads/stresses
- Mechanical blocks: Mechanical spectra cycle counted from event-based mechanical loads/stresses, and build on to the maximum pressure loads/stresses and maximum thermal loads/stresses
- EVA blocks: cyclic EVA loads build on to the maximum pressure loads/stresses and maximum thermal loads/stresses

### 2.7. *Crack Model Idealization*

The fracture analysis tool NASGRO used in ISS LE has a list of pre-defined fracture models grouped in several categories. The ISS LE project utilized the following three general classes

- Through cracks:

  Two of these crack model types are often used: the through crack at edge of plate (TC02) and the through crack at a hole in plate (TC03) as shown in Fig. 15.

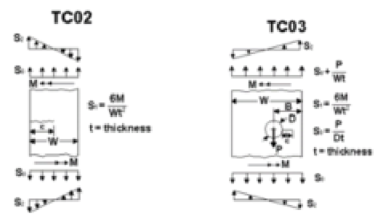


Fig. 15. NASGRO Through Crack Models Used in ISS LE Analyses [4]

- Corner cracks

  Two corner crack models are often used: the quarter elliptical corner crack in plate (CC01) and the corner crack at hole (CC16), as shown in Fig. 16.

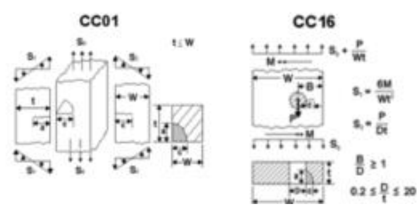


Fig. 16. NASGRO Corner Crack Models Used in ISS LE Analyses [4]

- Surface cracks

  Three surface crack models are often used: the semi-elliptical surface crack in plate (SC01), the semi-elliptical surface crack in solid cylinder (SC07) and the semi-elliptical surface crack in threaded solid cylinder (SC08), as shown in Fig. 17.

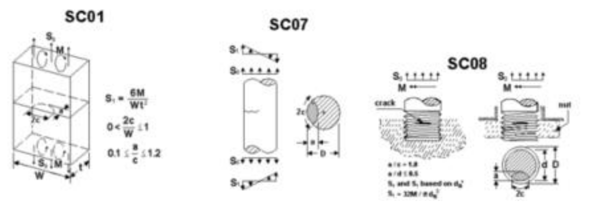

Fig. 17. NASGRO Surface Crack Models Used in ISS LE Analyses [4]

Since the primary structure of the ISS includes a large variety of geometries with different dimensions, under different loading conditions, care must be given in selecting representative crack models for each fracture analysis. Fig. 18 shows some sample critical locations on different parts of the ISS, represented by different crack models.

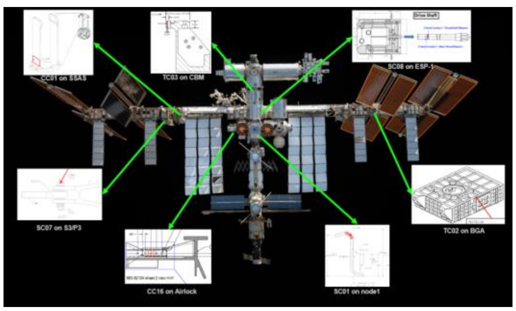

Fig. 18. Sample Crack Models on ISS

## 2.8. *Fracture Analyses*

As mentioned previously, NASGRO is the fracture mechanics software tool used in the ISS LE project. The primary capability of the program is to calculate crack growth and crack instability of cyclically loaded structures that contain an initial crack-like defect. [1].

The basic steps of NASGRO utilization include

- Crack model selection and geometric dimensions inputs
- Material selection
- Loads/Stress spectra and schedule building

## 2.9. *Post Processing and Conclusion*

The NASGRO output file contains information about the crack length at every spectra block, the number of lives the hardware achieves before failing, and the failure mode. Mitigation methods can be applied by the analyst to remove conservatism if an unfavorable result is initially obtained.

The output file is post-processed using Boeing in-house build software to determine the major event(s) that drove the crack growth. The following two examples are the post-processed results of a location on the HRS Radiators, Fig. 19 and a location on the P6 Truss, Fig. 20, respectively:

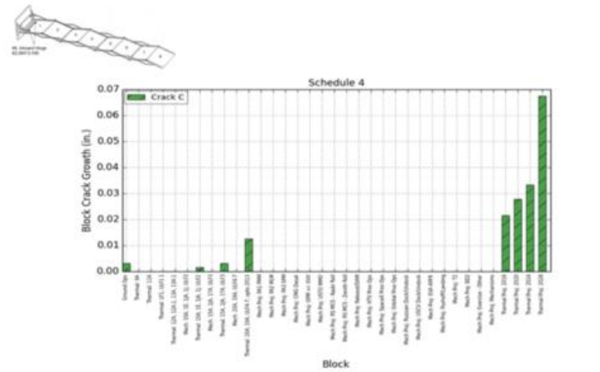

Fig. 19. HRS radiator critical location crack growth per event

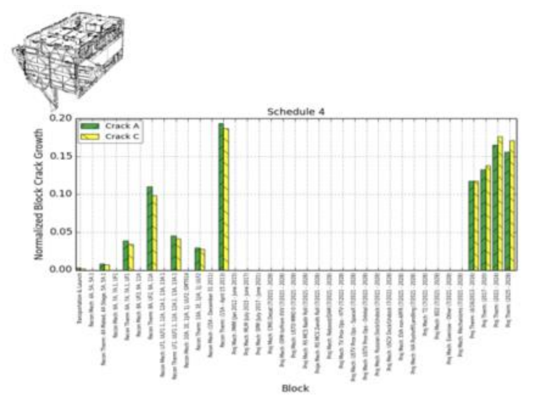

Fig. 20. IEA critical location crack growth per event

All USOS hardware meets the minimum requirement of 4 lives to the end of 2028. Table 2 identifies the most critical events that drive crack growth for USOS primary structures in Phases I and II.

Table 2. Critical Events Driving ISS USOS Primary Structure Life for Phase I & II Hardware

**X** Locations with 4 lives   X Locations with 5 or 6 lives

| Event | Node-1 | CBMs | Hatches | PMA-1 | PMA-2 | PMA-3 | Z1 Truss | P6/Z1 RTAS | P6 Long Spacer | P6 IEA | P6 IEA finplates | P6 PVAs | P6 BGAs | P6 PVRs | US Lab | US Airlock | S0 Truss | MTS Struts | S1 Truss | P1 Truss | SSASs | TRRJs | HRS Radiators | Mobile Transporter | ESP-1 | ESP-2 ESPAD |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Projected Thermal | | | | | X | **X** | | | **X** | **X** | **X** | | | | | X | **X** | | X | **X** | X | **X** | **X** | | | |
| Reconstructed Thermal | | | | | | | **X** | | | **X** | | | | | | **X** | | | | | | **X** | | | | |
| RS MCS Zenith Roll | | | | | | | | | | | | **X** | X | | | | | | | | | | | | | X |
| USTO MMO 0 | | | | | | | | | | | | | X | | | | | | | | | | **X** | | | |
| Projected Mech (07/2017-06/2021) | | | | | | | | | | | | | | | | | | | X | | X | | | | | |
| Reconstructed Mech | | | | | | | | | | | | **X** | X | | **X** | | | | **X** | | | | | | | |
| Pressure Cycles | | | | | | | | | | | | | | | | X | | | | | | | | | | |

## 3. Secondary Structure Process and Results

Secondary structure is defined as an internal or external structure which is used to attach small components, provide storage, and make either an internal volume or external surface usable.

On-orbit secondary structure does not sustain significant applied on-orbit loads. The following flow chart, Fig. 21, depicts the ISS secondary structure LE screening process.

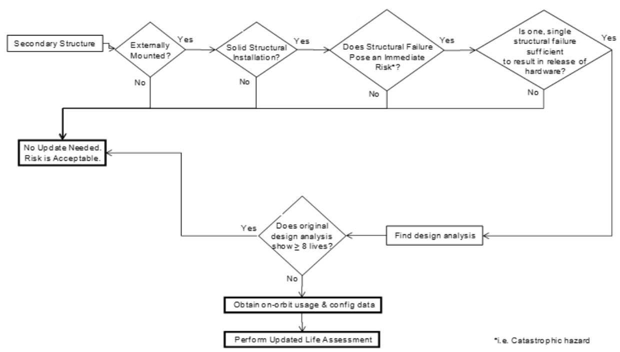


Fig. 21. ISS secondary structure LE screening process

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## 4. Non-Structural Fracture Critical Hardware

Non-replaceable, non-structural fracture critical hardware falls into the following two categories:

- No analysis required fracture critical components (Table 3)
- Analysis required fracture critical components (Table 4)

Table 3 No-Analysis Required Non-Replaceable Fracture Critical Components

| Component | Discussion | Comment |
|---|---|---|
| **Flexible Metallic Lines (Flex Hoses)** | Low working stress (<25% $F_{tu}$), typically below fatigue endurance limit | Good through 2028 (1) |
| **Hard Lines < 1.5 inch Dia.** | Low working stress (<25% $F_{tu}$), typically below fatigue endurance limit | |
| **Valves** | • Typically more robust than connecting lines<br>• Stronger link in the chain<br>• Low fatigue impact by design | |
| **Quick Disconnects (QD)** | | |
| **Fittings** | | |
| **Switches** | | |

*(1) As long as original design and operational parameters/limitation are maintained*

Table 4 Analysis Required Non-Replaceable Fracture Critical Components

| Component | Discussion | Comment |
|---|---|---|
| Hard Lines ≥ 1.5 inch Dia. | Working stress ~ 50% Ftu Typically designed to 10 yr. operation life | • Analysis required using Actual + Projected usage spectra<br>• Fatigue or Fracture analysis |
| Bellows (1) | Several design approaches (welded, formed, etc.) | Lifetime extension requires analysis on a case by case basis |
| Pressure Vessels(1) | Designed per MIL-STD-1522(a)<br>Similar considerations as primary structure | Lifetime extension requires rigorous analysis on a case by case basis |

*(1) Limited number of components*

Hardware requiring analysis included the following:

- 35 hardlines with a diameter greater than 1.5" were found to have a minimum of 76 service lives (where 15 years is one service life) using fracture analysis with initial crack size of 0.5t
- 1 Accumulator: Venting of accumulators was rejected based on low level of risk
- 2 Antenna Booms were found to have more than 100 service lives (where 15 years is one service life)

The results of the analysis of the non-replaceable fracture critical hardware show a large number of service lives assuming the original 15-year design life. Extending the design life well beyond 15 years still allows the components to maintain more than the required 4 service lives.

## 5. Materials and Processes

Materials and Processes Engineering evaluates materials for potential aging degradation primarily related to environmental exposures and whether that additional degradation during the proposed additional life allow the component to continue to function properly. Only selected components are evaluated. Component evaluation is requested by the hardware sustainers and is typically done for critical hardware or for hardware with spare availability challenges. A component is not considered if it is easily replaced.

For EVA (space vacuum) areas the causes of degradation include atomic oxygen erosion, ionizing radiation, ultraviolet radiation, existing mirco meteoroid/orbital debris impacts or arc-tracking, visiting vehicle contamination, and temperature exposure. For IVA (internal habitable volumes) degradation effects to be considered include corrosion, wear, and natural aging of non-metallic materials. Non-metallics are generally the materials that warrant the majority of the focus for LE evaluations. Typical non-metallics include cable insulation, elastomer seals, fabrics, and tapes.

Material Information and Usage Lists contain a list of materials used in each piece of delivered hardware. These can be reviewed to identify materials that may be susceptible to degradation in their given environment. The assembly is reviewed to determine what type and how much exposure to potential degradation various components may have.

Material Usage Agreements (MUAs) are documents that during the design of the hardware provide rationale as to why a component or material may acceptably not meet a Materials and Processes requirement. All MUAs are reviewed to assure that the noncompliance is not a condition that would be susceptible to unacceptable degradation in the LE analysis.

Invaluable data and information were obtained from multiple studies during the Space Shuttle Orbiter Life Extension program. This data came from material testing and evaluation of orbit flown hardware. Material testing for aging requires accelerated exposures. Additionally, experience with and knowledge of the materials, degradation rates caused by different environmental conditions, and on-orbit exposures allows the Materials and Processes engineer to determine the acceptability of life extensions.

## 6. Logistics and Maintenance

### *6.1.* Systems Analysis

Systems teams review various hardware failure data and on-orbit performance. The teams evaluate re-design options, trades and workarounds. The Boeing Reliability and Maintainability team updates the Mean Time Between Failures (MTBF) data through the Bayesian analysis process. This Bayesian process provides a projected MTBF for the Orbital Replacement Units (ORUs) based on operational run-time and failure history. The Bayes' Theorem begins with a statement of knowledge prior to performing the experiment. For ISS ORU MTBF updates, the Bayesian process combines prior knowledge, such as a predicted MTBF, and new information, such as operational run-time and total number of random failures, to calculate an operational MTBF. This data is then used to calculate an ORU failure rate which is utilized as modelling parameters in simulated spares demand modelling tools:

- fASTER
  A Monte Carlo simulation tool that assists the Program with determining logistics support resources by simulating operational scenarios of the ISS configuration that allows for the impacts of complex program resources including crew maintenance time, carrier up-mass capability, and sparing postulate. fASTER is applied to ISS functions where hardware interdependencies exist where the goal of the simulation is to project sufficient spares required to achieve a 90% average of functional availability.
- Probability of Sufficiency (POS)
  For standalone ORUs (e.g. Portable Fire Extinguisher), the probability of being available (or not available) can be calculated as a function of time using the POS methodology. POS uses a Lognormal distribution to allow for various levels of confidences in the ORU failure rate as the further out in time means more uncertainty in the failure rate estimates. Through POS, ORU spares demand is assessed with the goal to have at least a 90% probability that a spare will be available to support every failure. The L&M team looks at top level spares recommended in the past, vendor availability, ORU and parts availability, and repair status to mitigate sparing risk. This input data is coordinated with system teams.

Assumptions and ground rules are documented as well as risk level definitions and criticality considerations. The functional availability analysis is performed and identifies potential sparing shortfalls. Items are categorized by low, moderate, or high risk from a supportability perspective. Quantity recommendations are provided for varying levels of support. All sparing mitigation actions are annually approved by Vehicle and Program management.

### *6.2. I-Level Maintenance*

The standard maintenance approach for the ISS is the replace ORUs and return the failed ORUs to the ground for refurbishment and reflight. This requires a ready fleet of spares on orbit and/or on ground to react to failures on ISS. While this is a more efficient use of crew time resources to recover from failures it can result in a large stowage footprint and up-mass and down-mass issues to maintain the logistics train. An alternative option is to perform I-level maintenance in which some subcomponents of the ORUs are able to be removed and replaced from the ORU to recover system functionality. While this option can reduce the required on-orbit stowage footprint, it does typically require additional crew time to recover from a failure as the failed ORU is typically uninstalled from ISS and taken to a work station on ISS to perform the I-level maintenance before begin reinstalled. The other downside to I-level maintenance is that typically the full suite of diagnostic tools/test equipment is not available to the crew to perform post repair validation and typically the only validation of a successful crew repair is when the ORU is reinstalled and activated. Ideally the best time to perform an analysis of an ORU on the feasibility of I- level maintenance would be when the ORU was being designed such that interfaces on/within the ORU would aid any I-level maintenance activity. With the switch from launching spares on the Shuttle to commercial providers, many ORUs that were not originally designed and reviewed for I-level maintenance have been reviewed for I-level feasibility and in some cases, Boeing ISS teams have been able to provide this additional maintenance level option to maintain ISS while lowering the stowage requirements for spares. As part of the I-level capability review for each of the ORUs, the ORU is reviewed to ensure that the failure can be isolated to the subcomponent that is being proposed to be made an I-level candidate, that the component can be uninstalled and reinstalled by the crew using the standard tools allocated on the ISS or if new tools need to be developed and/or flown to ISS and what post-test capability is available and required prior reinstallation of the removed ORU.

## 7. Electrical Power System (EPS)

The EPS consists of power generation, storage, distribution, and regulation hardware. The EPS hardware was evaluated and cleared to operate through 2030 and dispositioned as Run-to-Failure. The majority of the EPS hardware sparing posture is monitored to ensure that the ISS power system is operational and does not impact mission readiness. The ISS EPS has spare modules, on-orbit and/or on the ground to support the station beyond 2030. In addition, repair capabilities have been developed for some of the modules. The solar arrays and battery capabilities are monitored in more detail. These two components gradually degrade over time reducing the power generation and storage capability, therefore the EPS team periodically tests these subsystems to measure the degradation rate, track current and predict future performance.

The ISS has eight independent power channels, powered by eight solar arrays that originally generated more that 30kW each of electrical power. These solar arrays, even though they have outperformed their original design capabilities, have degraded over their decades of service and required an upgrade to support the life extension and future growth of the ISS. To increase the power generation capability of the legacy arrays, with minimum ISS design changes and with a cost-effective approach, the ISS team incorporated a smaller set of arrays that mounted on the legacy array structure, and deployed over the existing legacy arrays. The new arrays used the latest Roll Out Solar Array (ROSA) deployment technology from Redwire, for reduction in weight, volume and complexity, and high-performance triple junction CICs from Spectrolab, for higher power density per square meter. The new arrays replaced almost 60% of the legacy solar array strings (48 out of 82 strings were replaced) and the rest of the legacy array strings are still in operation providing power to the ISS. The replacement of the legacy strings boosted the array power from an average of 18.6kW per channel to 26.8kW. In addition to the increased power per channel, the new triple junction CICs have a slower degradation rate than the legacy silicone solar cells.

A second EPS subsystem that was upgraded was the energy storage sub-system. The ISS was originally equipped with six Nickel-Hydrogen (Ni-$H_2$) batteries per channel. As the legacy Ni-$H_2$ batteries reached their end of life and the ISS program was planning to extend the life of the ISS, the ISS program approved the replacement of the Ni-$H_2$ batteries with new Li-Ion batteries. The Li-Ion batteries have a higher energy density than the legacy Ni-$H_2$ and therefore only three batteries were needed per channel, instead of the six Ni-$H_2$. The replacement of the Ni-$H_2$ batteries for Li-Ion increased the energy storage capability from 192kWh to 357kWh. In addition, the Li-Ion batteries are not being used in their full capacity, and as they degrade, the charge profile can be modified to extend the life of the batteries.

## 8. Environmental Control & Life Support Systems (ECLSS)

### *8.1. ECLSS ORUs*

ISS ECLSS ORUs and components have been assessed for life extension. A summary of the Environmental Control and Life Support Systems are listed below:

- Atmosphere Control & Supply hardware
- Temperature & Humidity Control hardware
- Common Cabin Air Assembly hardware
- Fire Detection & Suppression subsystem hardware
- CO2 Removal Assembly hardware
- Major Constituent Analyzer hardware
- Sample Delivery System hardware
- Trace Contaminant Control Subassembly hardware
- Vacuum System hardware
- Permanent Multi-purpose Module hardware

### *8.2. Government Furnished Equipment (GFE)*

The ECLSS GFE hardware has been reviewed through Assembly Complete. The following hardware are evaluated:

- Ammonia Measurement Kit
- Ammonia Respirator
- Ammonia Cartridge

- Fire Cartridge

All of this hardware is NRtf (Not Run to Failure) due to its nature of being emergency response equipment. It is regularly changed out to be certain of its performance if the need arises.

### *8.3. Regenerative ECLSS Hardware*

Most Regenerative ECLSS Hardware are Run to Failure (RtF) and are assessed annually as part of the Failure Analysis and Spares Assessment (FASA) process and support ISS Lifetime Extension through 2028.

Regenerative ECLSS GFE evaluated the following Urine Processor Assembly hardware:

- Wastewater Storage Tank Assembly
- Distillation Assembly
- Fluids Control & Pump Assembly
- Pressure Control & Pump Assembly
- Separator Plumbing Assembly
- Firmware Controller Assembly
- Oxygen Generator Assembly hardware
- Water Recovery & Management hardware
- Water Processor Assembly hardware
- Water Storage System hardware
- Urine Transfer System hardware
- Urine Processor Assembly associated hardware
- Waste Hygiene Compartment hardware

With sparing based on life cycle test results, all the above hardware could be supported indefinitely.

## 9. Conclusion

The ISS LE effort is a long and complex endeavor, but the dedicated team has successfully demonstrated the capability to maintain and operate the ISS well beyond its original design life. With the life extension process in place, the ISS can continue to function as a beacon of international cooperation, a platform for technology demonstrations and research, and inspiration through 2030 and beyond. Extending the operational life of the ISS maintains an international presence in LEO and serves to avoid a gap in a capability necessary to fulfill the exploration and research needs of NASA, international partners, and industry without interruption until a commercial space station is operational.

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