International Space Station End-of-Life Probabilistic Risk Assessment

Gary Duncan*

ARES Technical Services, Houston, TX, USA

Abstract: Although there are ongoing efforts to extend the ISS life cycle through 2028, the International Space Station (ISS) end-of-life (EOL) cycle is currently scheduled for 2020. The EOL for the ISS will require de-orbiting the ISS. This will be the largest manmade object ever to be de-orbited, therefore safely de-orbiting the station will be a very complex problem. This process is being planned by NASA and its international partners. Numerous factors will need to be considered to accomplish this such as target corridors, orbits, altitude, drag, maneuvering capabilities, debris mapping etc. The ISS EOL Probabilistic Risk Assessment (PRA) will play a part in this process by estimating the reliability of the hardware supplying the maneuvering capabilities. The PRA will model the probability of failure of the systems supplying and controlling the thrust needed to aid in the de-orbit maneuvering.

Keywords: PRA, ESD, ISS, Footprint, End State

1. INTRODUCTION

When the ISS is de-orbited it will be the largest manmade object to ever reenter the earth's atmosphere. This presents numerous technical challenges as well as logistical problems to the ISS international partners. The target risk to the ground population is less than 1 in 10,000 for a single Progress option. (Note that the estimated energy for a loss of life incident is an impact to a person of about the energy of a baseball pitched by a major league pitcher or about 130 joules). This paper presents the structure of planned re-entry using a single Russian Progress M cargo vehicle and the ISS Service Module (SM) for re-entry maneuvering. This plan is being reevaluated and will probably be revised to use three Progress M vehicles to supply re-entry maneuvering; however, the structure and methodology will be similar. Because of the sensitive nature of the material, quantitative values will not be presented here.

There are many driving factors that will play into the successful re-entry of the ISS. These include vehicle inclination, altitude at start of re-entry sequence, first interface with atmosphere, and breakup sequence. Experiments are being performed to collect data on these parameters. Because of these factors there will be uncertainty in the plan even if the hardware functions nominally. The PRA team's role in this process is to model the probability that the hardware will successfully provide the thrust necessary to support the planned re-entry.

2. RE-ENTRY PLAN

The re-entry plan is still in a preliminary planning stage. The current plan is outlined below:

- Planned ISS EOL will begin with natural drag from 400km to final operations starting at 200km. This phase will last over a year with only phasing burns to nearly 200km with a circular orbit.
- ISS will be reduced to a 3-man crew.
- Two decision points in the final week will allow holds, if needed, with the same intended ground track available 4 days and 1 day later than first planned.
- Numerous consecutive-orbit preparatory burns will shape the final orbit using Progress rendezvous and docking (R&D) thrusters.

- Ballistic/altitude plan leading into the final burn will support an optimized combination of abort capability and projected footprint that is completely contained in the ocean.
- Final burn will be a combination of (up to) three Progress M vehicles, and propulsion enhancements selected below. This analysis considers a single Progress case.
  - SM main engine
  - Cross-flow of aft Progress resupply tanks to aft Progress main engine
  - Burn time extension of Progress R&D engines
- ISS will be in an aerodynamically-trimmed configuration with its center of pressure behind the center of drag, and minimum exposure of solar arrays to RAM pressures.

3. APPROACH

Industry standard event tree and fault tree methodology will be used to model the hardware systems required for successful ISS re-entry. Although many of the systems required are already modeled in the ISS PRA Progress R&D and ISS SM models, there are still modeling challenges ahead. Some of the hardware, such as thrusters, may be required to operate outside of their design parameters. In these cases, the use of the current failure rate data, developed for nominal operations, will need to be reassessed. Test data could help fill in the gaps between data acquired for nominal cases and data to evaluate a system challenged beyond its design constraints.

4. ANALYSIS

Figure 1: ISS EOL Re-entry Burn Sequence, Single Progress Option
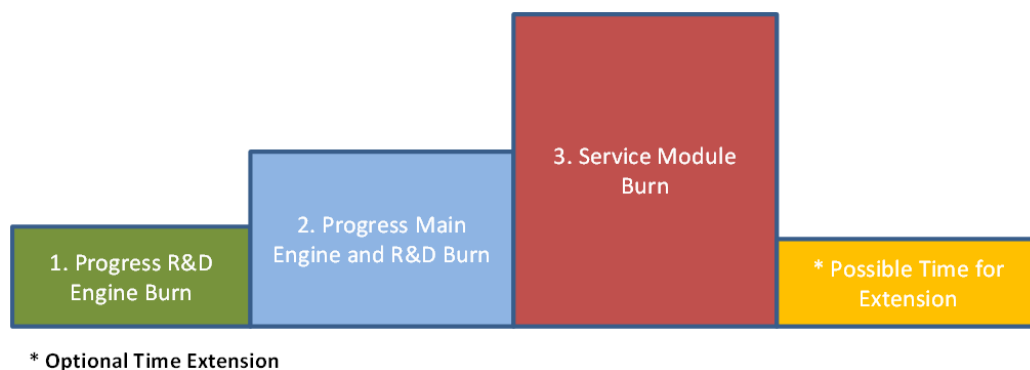
Burn 1 utilizes Progress R&D Engines, Burn 2 utilizes Progress R&D and Main Engines, Burn 3 uses the ISS SM engines, and Burn 4 is a contingency burn which could be used to make up failures that occur during the first three burns. Event Sequence Diagrams (ESDs) (Figures 2 through 8) were developed for the planned re-entry scenarios.

The single Progress planned re-entry will rely on the burn sequence presented in Figure 1. This plan, once initiated, can accommodate up to two abort/restart sequences as needed on subsequent orbits. The ESDs could result in the five possible end states listed below:

- P_n = Nominal Re-entry
- P_r = Random Re-entry
- P_p = Pseudo Random
- P_l = Large Under-Burn
- P_s = Small Under-Burn
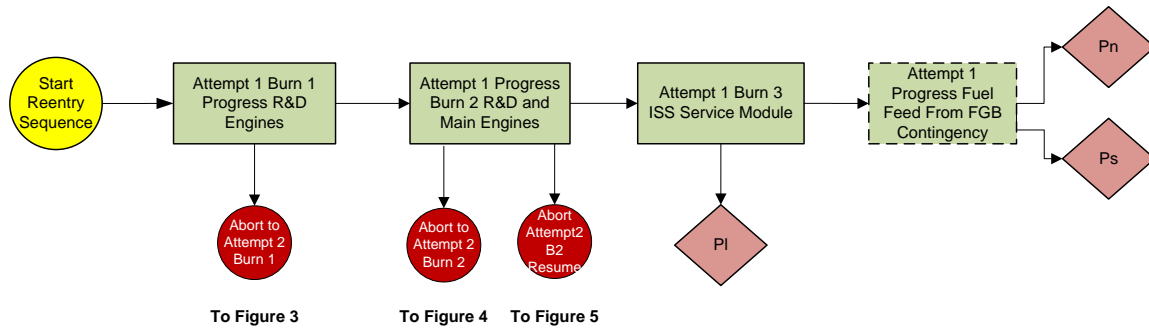
Figure 2: ISS EOL ESD De-Orbit Attempt 1

Figure 2 presents the initial re-entry attempt. There are 3 paths that result in re-entry: Nominal, Small Under-Burn, and Large Under-Burn. Three abort paths are included: abort to Attempt 2 with a restart at Burn 1, abort to Attempt 2 with a restart at Burn 2, and abort to Attempt 2 by resuming Burn 2.
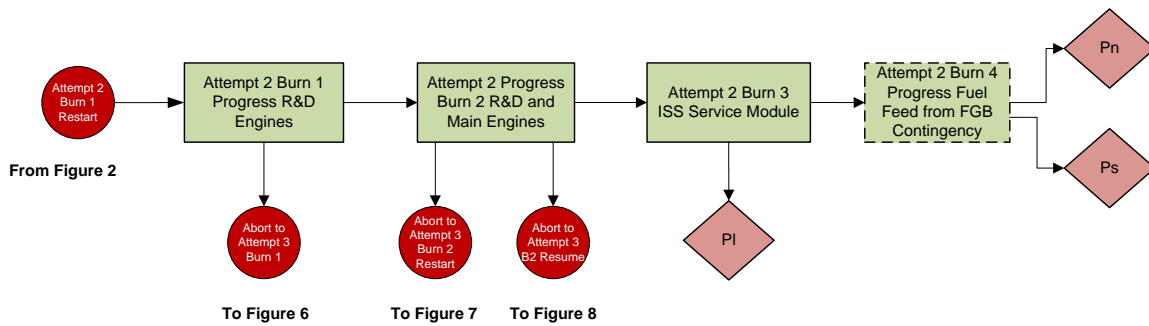
Figure 3: ISS EOL ESD Attempt 2 Restart Burn 1

Figure 3 is the first of three abort trees from Attempt 1; this tree assumes the burn sequence will restart from the beginning. There are 3 paths that result in re-entry: Nominal, Small Under-Burn, and Large Under-Burn. Three abort paths are included: abort to Attempt 3 with a restart at Burn 1, abort to Attempt 3 with a restart Burn 2, and abort to Attempt 3 by resuming Burn 2.

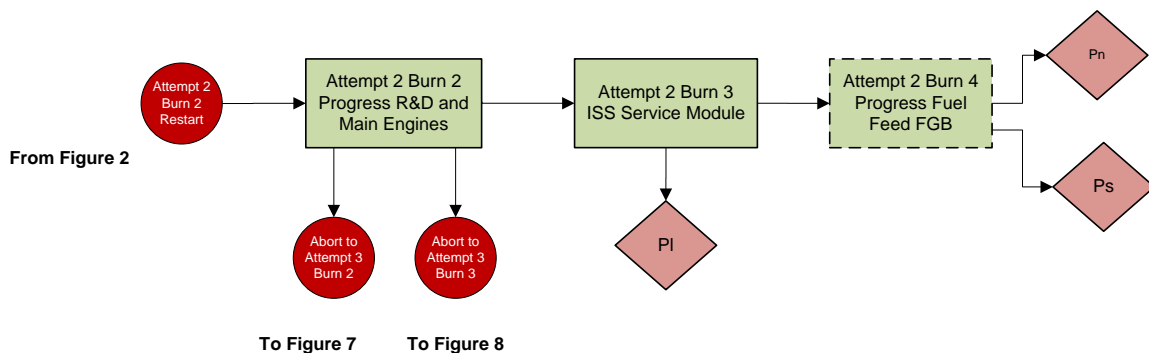**Figure 4: ISS EOL ESD Attempt 2 Resume Burn 2**

Figure 4 is the second of the aborts possible from Attempt 1 and assumes Burn 1 completed and so this burn will restart from the beginning of Burn 2. There are 3 paths that result in re-entry: Nominal, Small Under-Burn, and Large Under-Burn. Two abort paths are possible: abort to Attempt 3 with a restart at Burn 2, and abort to Attempt 3 with a restart at Burn 3.

Figure 5: ISS EOL ESD Attempt 3 Resume Burn 2

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Attempt 2        Attempt 2 Burn 2        Attempt 2 Burn 3        Attempt 2 Burn 4              Pn
Burn 2    ───►   Progress R&D and  ───►  ISS Service Module ───► Progress Fuel   ───┬──►
Resume           Main Engines                                    Feed FGB            │
                                                                                     └──►    Ps
From Figure 2          │        │                 │
                       ▼        ▼                 ▼
                   Abort to   Abort to            Pl
                   Attempt 3  Attempt 3
                   Burn 2     Burn 3

                  To Figure 7   To Figure 8
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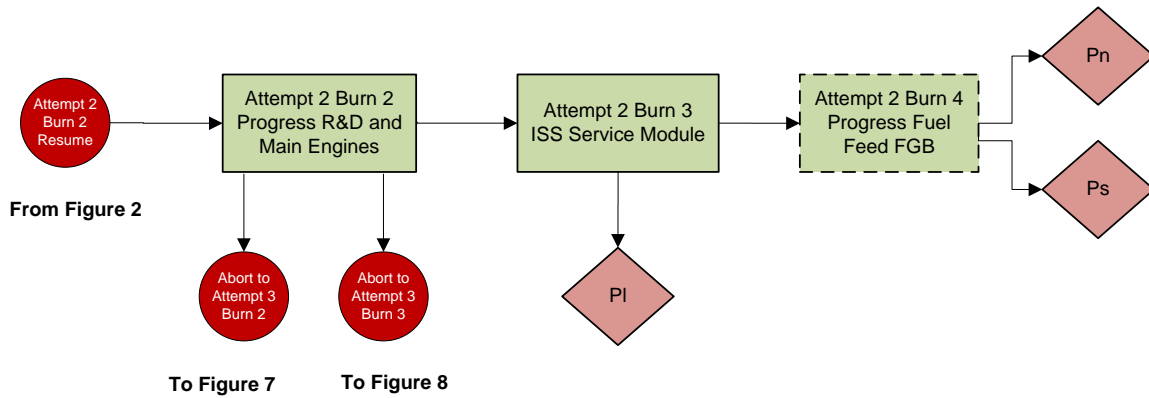
Figure 5 is the third of the aborts possible from Attempt 1 and assumes Burn 2 was aborted while in progress. There are 3 paths that result in re-entry: Nominal, Small Under-Burn, and Large Under-Burn. Two abort paths are possible: abort to Attempt 3 with a restart at Burn 2, and abort to Attempt 3 by resuming Burn 2.

Figures 6, 7, and 8 model Attempt 3, which is the final attempt to complete the process – there are no abort paths possible. At this point Nominal Re-entry can still be achieved.

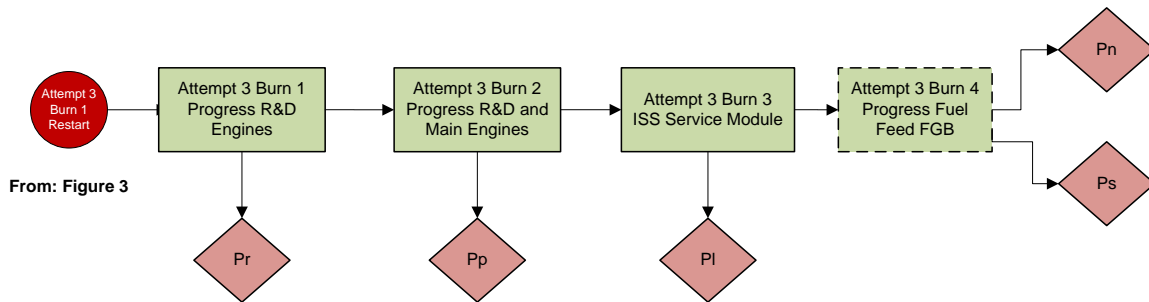**Figure 6 – Attempt 3 ISS EOL ESD Restart Burn 1**

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Attempt 3    Attempt 3 Burn 1    Attempt 3 Burn 2    Attempt 3 Burn 3    Attempt 3 Burn 4         Pn
Burn 1  ──►  Progress R&D   ──►  Progress R&D and──► ISS Service Module► Progress Fuel  ──┬──►
Restart      Engines             Main Engines                           Feed FGB           │
                                                                                           └──►  Ps
From: Figure 3    │                   │                    │
                  ▼                   ▼                    ▼
                  Pr                  Pp                   Pl
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Figure 7 – ISS EOL ESD Attempt 3 Restart Burn 2

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Attempt 3         Attempt 3 Burn 2        Attempt 3 Burn 3        Attempt 3 Burn 4             Pn
Burn 2    ───►    Progress R&D and  ───►  ISS Service Module ───► Progress Fuel   ───┬──►
Restart           Main Engines                                    Feed FGB            │
                                                                                      └──►    Ps
From Figure 4 or 5      │                       │
                        ▼                       ▼
                        Pp                      Pl
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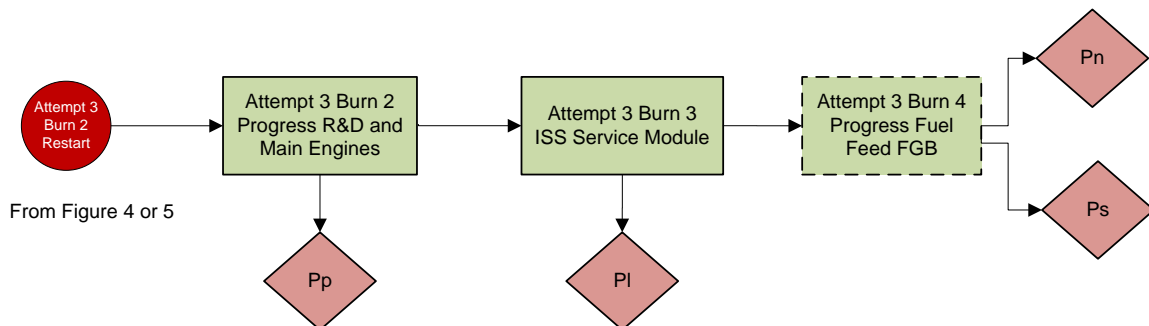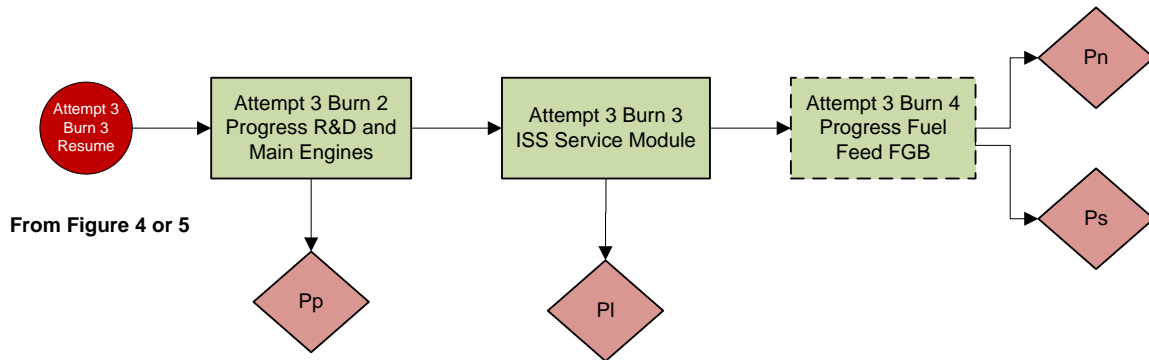
Figure 8 – ISS EOL ESD Attempt 3 Restart Burn 3

The end states from the model are P_n (Nominal Re-entry), P_r (Random Re-entry), P_p (Pseudo Random), P_l (Large Under-Burn) and P_s (Small Under-Burn), and will be binned into the following Footprints.

- Nominal Footprint
- Ocean Footprint
- Populated Footprint

Figure 9 shows the potential footprints for the start of the re-entry process.

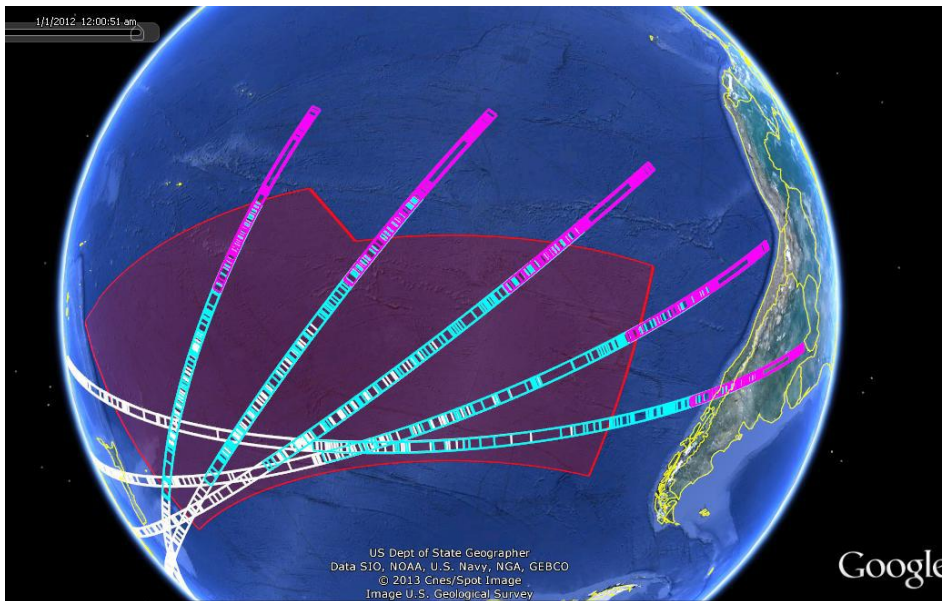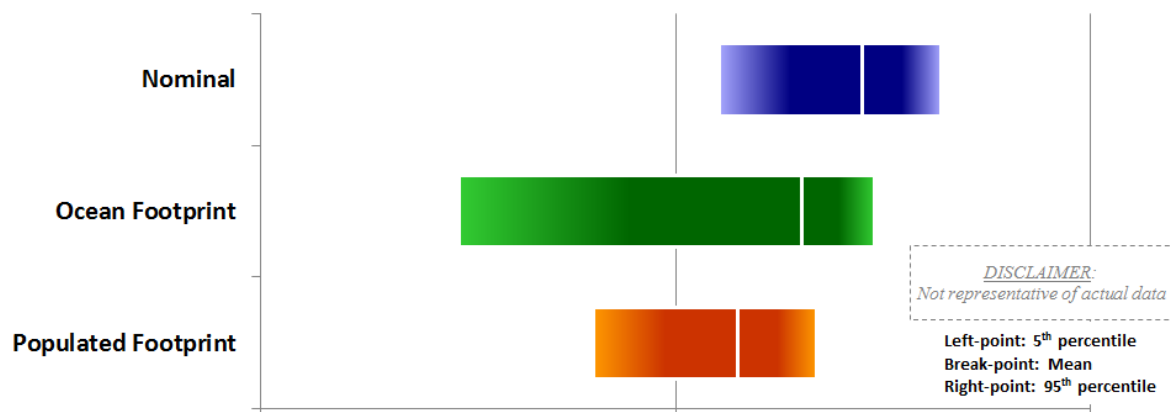**Figure 9 – ISS Re-entry Footprints**

Figure 10 is the type of chart that will be used to present the PRA results, once completed.

Figure 10 – Example: Probability of ISS Re-entry Footprints

5. METHODOLOGY

ISS PRA will utilize event tree/fault tree methodology. Some of the challenges facing the ISS PRA team are discussed in this section.

Any analyst that has attempted to model common cause using Multiple Greek Letter or Alpha Models knows it gets convoluted after about four components. The Progress has 28 thrusters and the ISS SM has 32 thrusters, whose redundancy and similar design make them susceptible to common cause failures. The Global Alpha Model (as described in NUREG/CR-5485) [1] can be used to represent the system common cause contribution, but NUREG/CR-5496 [2] supplies global alpha parameters for groups only up to size six. Because of the large number of redundant thrusters on each vehicle, regression is used to determine parameter values for groups of size larger than six. An additional challenge is that thruster failures must occur in specific combinations in order to fail the propulsion system; not all failure groups of a certain size are critical. The calculation of common cause will become even more complicated if the ISS program opts to use the thrusters on three Progress vehicles in addition to the SM to de-orbit the ISS vehicle. The methodology that will be used to model common cause failures of the thrusters required to de-orbit the ISS has already been used to model common cause failure of thrusters on the ISS Visiting Vehicles and is described in "*Modeling Common Cause Failures of Thrusters on ISS Visiting Vehicles*" [3].

Fault trees are based on Boolean algebra failures and therefore failures are generally bounded as failed or operational – this makes modeling difficult in an area where reduced performance issues can occur. The challenge is mapping thrusters under performance issues into bins and establishing how these under-performance issues will stack up if they occur in sequence. There is also difficulty in dealing with hard thruster failures in cases where the thruster vectoring can be equaled or approximated by other thruster combinations.

There are current Progress models accounting for functional failures during R&D operations; however, these models focus on motion control and include propulsion and supporting control systems and power systems. The current models are in the process of being refined for this re-entry analysis. The command and control of the overall de-orbit vehicle configuration, whichever configuration is selected (single Progress with SM or three Progress) will also pose a challenge. Once the burn sequence begins, the de-orbit maneuver becomes software-dependent, and the current model does not account for software reliability.

6. CONCLUSION

The ISS EOL and resulting vehicle de-orbit will be a highly publicized event involving many nations – those invested in the safe completion of the ISS Program, and those potentially affected by the footprint of the ISS debris following re-entry. The ISS EOL PRA will contribute to the planning and safe execution of this event by capturing the probability of hardware failures associated with ISS EOL. The PRA will be used as one of the components of the overall plan, to assist in ISS Program decisions regarding vehicle configuration as measured against the likelihood of success. The ISS EOL PRA package will be integrated into the overall risk plan for ISS EOL re-entry, and may be used by the agency to accept any residual risk (complete with uncertainty bounds) to the general population.

References

[1]   U.S. Nuclear Regulatory Commission, *Guidelines on Modeling Common-Cause Failures in Probabilistic Risk Assessment, NUREG/CR-5485*, November 1998.

[2]   U.S. Nuclear Regulatory Commission, *CCF Parameter Estimations, 2009 Update to NUREG/CR-5496*, January 2011.

[3]   Haught, Megan, *Modeling Common Cause Failures of Thrusters on ISS Visiting Vehicles*, Probabilistic Safety Assessment and Management (PSAM), Honolulu, Hawaii, June 2014.