MSFC-008-

Risk Assessment Challenges in the Ares I Upper Stage

James E. Stott[(1)], Robert W. Ring[(2)], Hassan A. Elrada[(2)], & Frank Hark[(2)]

[(1)]NASA Marshall Space Flight Center Safety and Mission Assurance Directorate QD10, MSFC, AL USA, Email: James.E.Stott@NASA.gov

[(2)]Hernandez Engineering Inc., NASA Marshall Space Flight Center HEI, MSFC, AL USA, Email: Robert.W.Ring@NASA.gov, Hassan.A.Elrada@NASA.gov, *and* Frank.Hark-1@NASA.gov

ABSTRACT [1]

NASA Marshall Space Flight Center (MSFC) is currently at work developing hardware and systems for the Ares I rocket that will send future astronauts into orbit. Built on cutting-edge launch technologies, evolved powerful Apollo and Space Shuttle propulsion elements, and decades of NASA spaceflight experience, Ares I is the essential core of a safe, reliable, cost-effective space transportation system -- one that will carry crewed missions back to the moon, on to Mars and out into the solar system.

Ares I is an in-line, two-stage rocket configuration topped by the Orion crew vehicle and its launch abort system. In addition to the vehicle's primary mission -- carrying crews of four to six astronauts to Earth orbit -- Ares I may also use its 25-ton payload capacity to deliver resources and supplies to the International Space Station, or to "park" payloads in orbit for retrieval by other spacecraft bound for the moon or other destinations. Crew transportation to the International Space Station is planned to begin no later than 2014. The first lunar excursion is scheduled for the 2020 timeframe.

This paper presents the challenges in designing the Ares I upper stage for reliability and safety while minimizing weight and maximizing performance.

1. INTRODUCTION [1]

NASA is currently designing, testing, and evaluating hardware for the Ares I Crew Launch Vehicle (CLV) (Fig. 1.1), the next generation vehicle that will carry humans into Earth's orbit and beyond. Ares I is an in-line, two-stage rocket configuration topped by the Orion crew exploration vehicle, its service module and a launch abort system. The Ares I CLV is separated into several element teams led by NASA Marshall Space Flight Center in Huntsville, Alabama. These element teams are the First Stage (FS), the Upper Stage Engine (USE), and the Upper Stage (US). This section presents an overview of these CLV elements.

Figure 1.1 Concept Launch of Ares I

1.1 First Stage

The FS Element is a single, five-segment reusable solid rocket booster derived from the Space Shuttle Program. It has a Reusable Solid Rocket Motor (RSRM) that burns a solid propellant called PolyButadiene AcryloNitrile (PBAN). A newly designed forward adapter will mate the FS to the US, and the US interstage will be equipped with booster separation motors to disconnect the stages during ascent. During the first 2.5 minutes of flight, the first stage booster powers the vehicle to an altitude of about 200,000 feet and a speed of Mach 6.1.

ATK Thiokol of Brigham City, Utah, is the prime contractor for the first stage.

1.2 Upper Stage Engine

The Upper Stage Engine, the J-2X (Fig. 1.2), is an evolved variation of the J-2 engine that propelled the Saturn 1B/Saturn V, and the J-2S (the J-2S was a simplified version of the J-2 developed and tested in the early 1970s but never flown). After the FS separates, the J-2X engine ignites and powers the Orion to an altitude of about 63 miles.

Pratt & Whitney Rocketdyne in Canoga Park, Calif., is the prime contractor for the CLV upper stage engine.

Figure 1.2 Concept Image of the J-2X

1.3 Upper Stage

The function of the Upper Stage is to complete the second portion of the ascent phase after the First Stage separates from the vehicle.

The CLV Upper Stage (US) is the portion of the CLV extending from the first stage forward frustum to the Crew Exploration Vehicle (CEV) adapter. The Upper Stage consists of three major structural sections: the Instrument Unit, the Core Stage, and the Interstage. The Main Propulsion System provides LOX/LH2 fuel tanks, pressure system, and feedlines to the Upper Stage J2-X engine. The Roll Control System (RoCS) performs roll stabilization control of the vehicle prior to FS separation, and the Upper Stage Reaction Control System (RCS) provides attitude control to the vehicle during Upper Stage flight. The Upper Stage also provides Thrust Vector Control (TVC) to the Upper Stage Engine. The Upper Stage also provides control electronics for the entire CLV launch stack, as well as the separation systems required to perform first stage separation [2].

The Upper Stage of the Ares I Crew Launch Vehicle is primarily an in-house NASA design being led at Marshall Space Flight Center in Huntsville, Alabama. The following section presents a synopsis of the Risk Assessment process within the Upper Stage element.

2. UPPER STAGE RISK ASSESSMENT PROCESS

2.1 Organization

The Upper Stage Element organization (Fig. 2.1) is led by an Upper Stage Office and each substructure under the US Office is an Integrated Product Team (IPT). The Upper Stage Safety and Mission Assurance (S&MA) organization operates adjunctively to the Upper Stage Office and is responsible for safety, reliability, quality, software assurance, and other mission assurance functions.

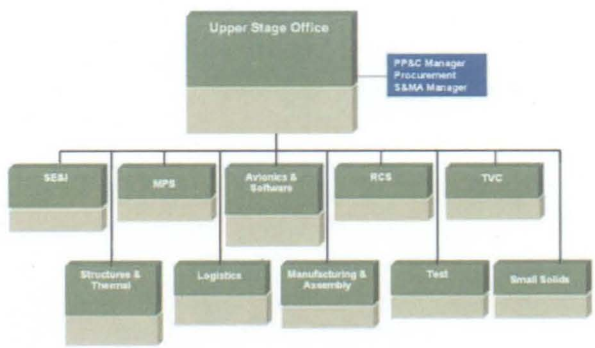

Figure 2.1Upper Stage Organization

The adjunctivity of the US S&MA organization and the nature of the IPT process requires reliability, safety, and quality engineers to be represented in each IPT. The IPT process then ensures that safety, reliability, and quality are designed into the system.

2.2 Integrated Reliability, Maintainability, and Supportability (RMS) Analysis Process

The RMS Analysis Process consists of three sub-processes, the Reliability Analysis Process, the Maintainability Analysis Process, and the Supportability Analysis Process (Fig. 2.2).

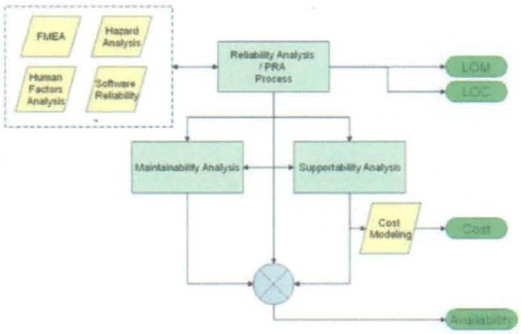

Figure 2.2 Integrated RMS Process

2.2.1 The Reliability Analysis Process

The Reliability Analysis (RA) Process starts with inputs from the Failure Modes and Effects Analyses (FMEA), Hazard Analyses (HA), and Human Factors/Software Reliability Analyses when available. This information, along with the information obtained during system familiarization within the IPT Process (i.e. system schematics) prompts the IPT reliability analyst to begin a baseline logic model of the system. In parallel with the logic model development, the reliability analyst collects available data and begins to quantify the reliability logic model. The model is further refined within the IPT process, and ultimately generates estimates for Loss of Mission (LOM) and Loss of Crew (LOC). A flow diagram of the Reliability Analysis process is shown in Fig. 2.3.

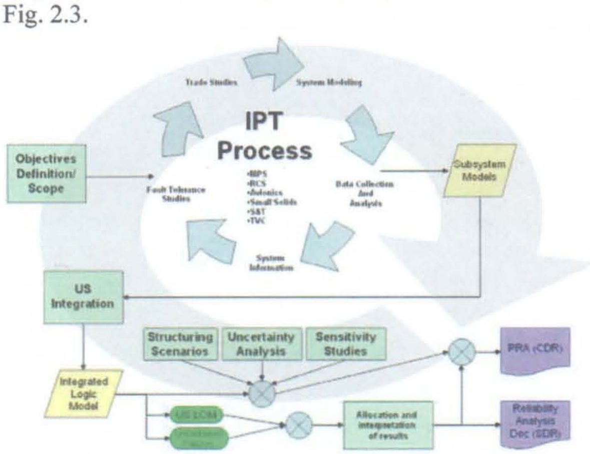

Figure 2.3 Reliability Analysis Process

Once the process of developing the logic models has begun within the IPT framework, the subsystem models are simultaneously integrated into a complete Upper Stage model. The integrated model is then analyzed for failures across subsystems. Sensitivity studies, uncertainty analysis, and scenario modeling will also be conducted within the integrated model and also at the lower level system models.

2.2.1.1 Development of Reliability Models within the IPT

The reliability analysis within each IPT is of primary importance not only to the development of the models, but also for the feedback the analysis provides to the system designers. This feedback facilitates the process of influencing the design to make the system safer and more reliable. Thus, it can be said that the real goal of the reliability analysis is to improve design by identifying high probability failure modes and accident sequences, and mitigating those risks through system redesign.

A flowchart representing the Reliability Analysis process within each IPT is shown in Fig. 2.4. The process begins with system familiarization and review of the current FMEAs, HAs, system schematics, available data, etc. Groundrules and assumptions of the modeling and the interpretation of system failures are then constructed and a preliminary model is developed. The system logic model, goundrules and assumptions, and data are then reviewed with the design engineers. The model is subsequently updated and reiterated until the model has IPT concurrence. To demonstrate concurrence, the IPT lead will sign a statement formally declaring that the Reliability Analysis model has been concurred with within the IPT.

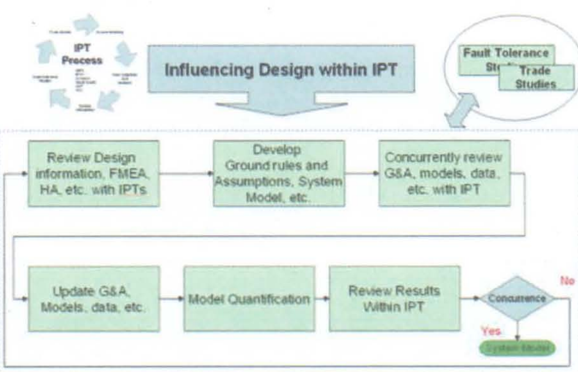

Figure 2.4 Reliability Analysis process within the IPT

It should also be mentioned that, parallel to the development of the reliability logic model, reliability analyses are performed during trade and fault tolerance studies specific to that IPT. Depending upon the outcome of these studies, the subsequent analyses are potentially used as part of the system model.

2.2.2 The Maintainability Analysis Process

The inputs to the Maintainability Process consist of outputs from the Reliability Analysis Process (i.e. Mean Time To Failure (MTTF)), and information garnered from the Supportability Analysis Process regarding scheduled and unscheduled maintenance events. The process performs maintenance analysis to define the maintenance activity flow. Outputs of this task include Mean Time To Repair (MTTR), maintenance task definition, maintainability assessments, and maintenance characteristics.

2.2.3 Supportability Analysis Process

Supportability analysis is performed by the Logistics Support Integration (LSI) IPT. The MTTF, MTTR, and other related information garnered from the Reliability and Maintainability Analyses feed the Supportability Analysis Process. The Supportability Analyses will provide for the dynamic flow of interactions between the flight hardware, ground support equipment, processing personnel, and facilities.

The combination of the outputs of all three processes within the RMS Analysis will subsequently generate system Availability estimates.

3. INTEGRATED CREW LAUNCH VEHICLE PROBABILISTIC RISK ASSESSMENT (PRA)

The Upper Stage PRA, in conjunction with the FS and USE PRAs, will be integrated by the S&MA Vehicle Integration Team. The Vehicle Integration (VI) PRA team performs a top-down analysis which includes analyses of ascent risk scenarios, abort modeling, and a thorough review of relevant historical failures. The VI PRA team then relays this information to the element Reliability Analysis/PRA teams and the models and analyses will incorporate this data and feed up to the VI team. The subsequent PRA models will then merge into an integrated PRA model for the Ares I launch vehicle. This analysis, combined with the PRA analysis of the Orion Crew Exploration Vehicle (CEV), integrate to form an integrated Crew Launch Vehicle (CLV) stack PRA. A flowchart of the CLV Integrated PRA approach is shown in Fig. 3.1.

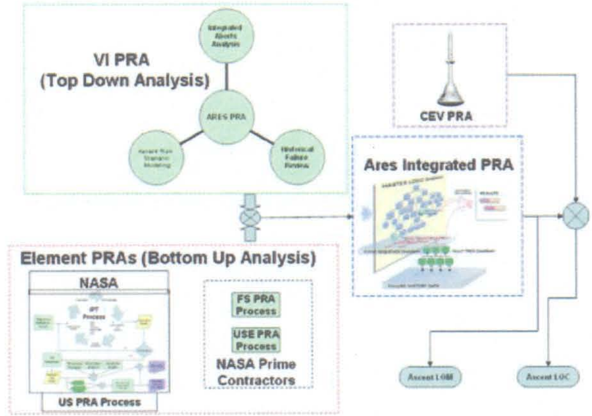

Figure 3.1 Integrated CLV PRA Approach

4. CHALLENGES AND OPPORTUNITIES

4.1 Challenge I: Being the Prime

Not since the Apollo Program in the 1960's has NASA been so influential in the design of a space transportation system. The Space Shuttle and other attempts at next generation space transportation (Space Launch Initiative (SLI), Orbital Space Plane (OSP), etc.) relied on an open trade space and the Request For Proposal (RFP) process. The FS and the USE have Prime contractors, which make sense in this context due to the continuity of the contractors with the Shuttle/Saturn derived hardware. The Upper Stage however, is unique in the sense that NASA is functioning as the 'Prime' contractor.

By taking the lead in the design of the Upper Stage for Ares I, NASA is providing a unique opportunity to its design team and to the Safety and Reliability engineers within S&MA. The Upper Stage Project has partnered with S&MA to integrate both qualitative and quantitative reliability and risk assessment with the subsystem IPTs responsible for Upper Stage design through concurrent engineering. This approach has already produced demonstrated benefits by influencing the design for improved reliability for several subsystems. In addition, it offers potential long-term benefits to NASA because future project managers will be selected from today's engineers who are getting the hands-on design experience necessary to successfully manage the development of future space exploration systems.

In-house design presents challenges as well as opportunities. The learning curve is very steep for the Upper Stage designers and systems engineers. Management needs to take this into consideration or else the projected budget and workforce have the potential of being underestimated.

4.2 Challenge II: Tight Schedule

On May 25, 1961, President Kennedy announced:

"I believe that this nation should commit itself to achieving the goal, before this decade is out, of landing a man on the Moon and returning him safely to the Earth. No single space project in this period will be more impressive to mankind, or more important in the long-range exploration of space; and none will be so difficult or expensive to accomplish..."[3]

The first manned launch occurred in December 1968, carrying the Apollo 8 circumlunar mission.

Similarly, on January 14^{th}, 2004 President Bush announced the "Vision for Space Exploration" with one of the goals being to develop and fly the Crew Exploration Vehicle (CEV) by 2012, but no later than 2014.

If the goal of 2012 is to be achieved, this would be comparable to the schedule of the development of the Saturn V. The evidence has shown that NASA has successfully overcome this schedule challenge in the past. We therefore have the confidence in overcoming this challenge today.

4.3 Challenge III: Communication, Coordination, and Integration

A third challenge is maintaining adequate communication and coordination within the IPTs and among the several layers of the Constellation organizational infrastructure. An approximate breakdown of the current NASA structure in supporting the Vision for Space Exploration in relation to the Upper Stage Organization is as follows:

- Level 0
  – Vision for Space Exploration
- Level 1
  – Exploration Systems Mission Directorate
- Level 2
  – Constellation Program
- Level 3
  – Ares I, Orion, etc.
- Level 4
  – Upper Stage, First Stage, etc.
- Level 5
  – MPS, RCS, etc.

The challenge from an Upper Stage viewpoint is to integrate the level 5 system PRAs into an overall integrated Upper Stage PRA, while attempting to maintain consistency with the higher level Ares I integrated PRA at Level 3. Assuring consistency of PRA methodology within the Upper Stage will not be a driving issue because it is being developed in house with a single team of analysts. However, NASA learned from its development of the Space Shuttle PRA that it can be challenging to ensure consistent methodology across multiple contractors. This is particularly true regarding the data analysis used in quantification of basic events, such as combining prior data sources, discounting failures, assessing the applicability of failures, and the consistent failure-rate analysis of similar components across subsystems. Since the PRA will be used by the Cx Program to support risk-informed decision making and to allocate resources for risk mitigation across the program, it is imperative that risk be comparable.

5. CONCLUSION

Designing the Ares I Upper Stage for reliability and safety while minimizing weight and maximizing performance is indeed challenging. The reliability/ risk analysis process described in this paper has been adopted and employed in all aspects of the preliminary design phase to improve the reliability of the CLV and reduce the risk of loss of mission and loss of crew. This process will iterate and evolve throughout the program's life cycle from design, development, testing and operation of the CLV. The process has already proven valuable in identifying preliminary design weaknesses that resulted in design improvements and higher reliability.

6. ACRONYMS

CEV	Crew Exploration Vehicle
CLV	Crew Launch Vehicle
FMEA	Failure Modes and Effects Analyses
FS	First Stage
HA	Hazard Analysis
HEI	Hernandez Engineering Incorporated
IPT	Integrated Product Team
LH2	Liquid Hydrogen
LOC	Loss of Crew
LOM	Loss of Mission
LOX	Liquid Oxygen
LSI	Logistics Support Integration
MTTF	Mean Time To Failure
MTTR	Mean Time To Repair
MSFC	Marshall Space Flight Center
NASA	National Aeronautics and Space Administration
OSP	Orbital Space Plane
PBAN	PolyButadiene AcryloNitrile
PRA	Probabilistic Risk Assessment
RA	Reliability Analysis
RCS	Reaction Control System
RoCS	Roll Control System
RFP	Request For Proposal
RMS	Reliability Maintainability and Supportability
RSRM	Reusable Solid Rocket Motor
SLI	Space Launch Initiative
S&MA	Safety and Mission Assurance
TVC	Thrust Vector Control
US	Upper Stage
USE	Upper Stage Engine
VI	Vehicle Integration

7. REFERENCES

1. "NASA Constellation Program: America's Fleet of Next-Generation Launch Vehicles the Ares I Crew Launch Vehicle", NASA MSFC, FS-2006-07-85-MSFC Pub 8-40598, July 2006.
2. Upper Stage (US) Design Analysis Cycle (DAC)-1C Design Definitions Document (DDD).
3. John F. Kennedy, "Special Message to the Congress on Urgent National Needs", May 25th, 1961.