USING THE RAG TO ASSESS INTERNATIONAL SPACE STATION ORGANIZATIONAL RESILIENCE

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Abstract

Understanding high risk work settings from the viewpoint of resilience engineering (RE) requires methods that enable the researcher to successfully collect and analyze data, then provide well-founded findings and recommendations. We report on our experience using one RE method, the Resilience Analysis Grid (RAG) to assess the organizational resilience of the role the U.S. National Aeronautics and Space Administration (NASA) plays as a partner in the International Space Station (ISS) Program. In 2013, a potentially dangerous amount of water was observed to accumulate in an astronaut's helmet during a spacewalk. After an investigation of this mishap, the assessment team leader selected the RAG to analyse NASA performance in routine ISS operations. The team used the four RAG cornerstones (anticipate, monitor, respond, learn) to structure data collection, analyses, and findings. We reflect on the application of the RAG to study a complex, high risk work setting and share our experience with introducing team members to RE in general, as well as the RAG in particular.

1. INTRODUCTION

The National Aeronautics and Space Administration (NASA) has supported the US mission to achieve human space flight since 1958 through the Mercury, Gemini, Apollo, Space Shuttle and International Space Station (ISS) programs. NASA's many accomplishments, including lunar landings, have demonstrated remarkable success in accomplishing high risk ventures. NASA's history, however, has also demonstrated how failure to learn from past events and manage risks can threaten future missions.

1.1 Shuttle Mishaps

On January 28, 1986, the space shuttle Challenger broke apart 73 seconds after the liftoff of Shuttle orbiter mission STS-51-L. The Rogers Commission report (Rogers Report, 1986) cited multiple contributors: flawed decision making (from communication failures, incomplete and misleading information, poor management judgement), missed warning signs (accepting unsafe flight risks), a silent safety culture, production pressures (compressed training schedules, focus on short term resource shortages) and overconfidence in past success. NASA responded by creating the Office of Safety & Mission Assurance.

On February 1, 2003, the space shuttle Columbia disintegrated upon reentering the Earth's atmosphere. The Investigation Board report (CAIB, 2003) cited multiple causes including normalization of deviance, shuttle program complacency, and a broken safety culture. NASA responded by creating the NASA Engineering and Safety Center (NESC) as an independently funded program composed of technical experts to fill the need for an independent resource to provide an alternative perspectives on complex technical issues.

1.2 The International Space Station

The ISS is a habitable artificial satellite within a multifaceted, international sociotechnical system that is partly run by the NASA ISS Program. Crew members have inhabited and continuously operated the ISS in low space orbit altitude (249 mi) since late 2000. Members of the ground control staff are based in Johnson Space Center, in Houston, TX.

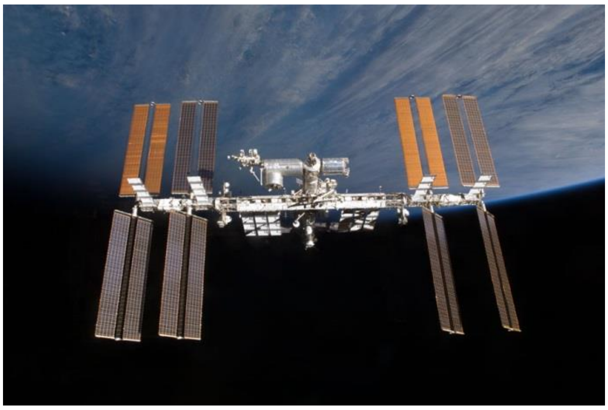

Figure 1 : *The International Space Station (NASA 2017)*

Figure 2. *Water in helmet* of *EVA23 astronaut (MIB 2013)*

1.3 Extravehicular Activity (EVA) 23

On July 16, 2013, two US crew members performed maintenance tasks outside of the ISS during Extravehicular Activity (EVA) 23. Forty-four minutes into the EVA, a crew member reported water from an unidentified source inside of his helmet at the back of his head. The crew member continued working, but the amount of water increased and moved to his face, creating a potential suffocation hazard. The EVA was terminated and the crew members returned to the ISS.

The post-EVA debrief revealed that the water covering his eyes, nose and ears had impaired the crew member's visibility and breathing. A Mishap Investigation Board (MIB) later identified what caused the situation and made 19 recommendations that NASA could implement to prevent future similar mishaps. ISS program management approached the NESC after the MIB to provide an objective engineering and safety assessment of the ISS organization in the wake of the EVA 23 incident. The assessment project lead saw the use of resilience engineering as an opportunity to obtain insights into the issue beyond what conventional risk management approaches would normally offer.

1.4 Scope and value

Even though resilience engineering research has identified resilient performance for years in a number of high-risk sectors (Nemeth & Herrera, 2015), few methods such as the Functional Resonance Analysis Method (Hollnagel 2012) and the Resilience Analysis Grid (RAG) (Hollnagel 2011) are specific to resilience engineering (RE). The RAG's simplicity and relatively recent introduction provided the team with the opportunity to use it to study an aerospace application and to try it with team members who were unfamiliar with RE. Results from team member experience using the RAG would provide insights into the method's strengths and any potential opportunities to enrich it.

2 RESEARCH DESIGN AND METHODS

2.1 Preparation

NASA has developed extensive flight rules and procedures through the decades to manage high risk operations, yet the accumulation of water during EVA 23, as well as during EVA 22 shortly before, fell outside of ISS procedures. The Mishap Investigation Board (MIB) Chair asked during a briefing on EVA 23 (Hansen, 2013) "…why do we keep having these tragedies and not learning the lessons they are teaching us?" In addition, an experienced assessment team member mentioned that the EVA 23 report was like many other mishap reports, suggesting that NASA does not always change what it does even after evidence from near-misses that threats to mission performance have occurred. The team member drew the comparison to "plan continuation errors", which are decisions to continue with a plan despite cues in the environment that suggest changing the course of action (e.g., Orasanu, Martin, & Davison, 2001).

This assessment study sought to look beyond simple adaptation to learn "…how well can a system handle disruptions and variations that fall outside of the base mechanisms/model for being adaptive as defined in that system" (Woods, 2012). Our understanding of the issues that the ISS organization confronted during EVA 22 and 23 led us to identify two research questions to guide our study:

- How does ISS handle weak signals that indicate potential safety threats?
- How does ISS balance ongoing resource constraints with production pressures?

We used the four RAG cornerstones to detail how we would seek the data. Table 1 shows an example of how the cornerstone «anticipate» was used to structure inquiry.

Table 1: Use of RAG Cornerstone

	Issue Number/Issue	Research Query	Source
Anticipate	M2a Who is watching what? Is there a monitoring plan?	What constitutes a signal that a potential threat to safety exists?	Interview
	M2b How does ISS allocate attention? Reallocate attention?	What is a "weak" safety signal? Who is responsible for safety signals?	Interview Artifact, Interview

Interview Guide

Development and use of a guide ensured that interviews would collect data consistently across participants and provide answers to the research questions. Rather than limiting inquiry, the guide's structure ensured a consistent approach among the interviews so that the team could identify and tabulate patterns during the analysis phase. One team member conducted a pilot interview with a NASA contractor to demonstrate how to perform an interview using the guide.

2.2 Data Collection

The assessment team collected data in 3 ways: 1) structured interviews with ISS staff members, 2) direct observation of real-time ISS operations, and 3) analysis of ISS documents, presentations, and meeting transcripts.

Structured Interviews

Assessment team members conducted structured interviews with 17 NASA staff members who directly supported ISS in one of 8 roles: Flight Crew, Flight Director, Increment Manager, Mission Evaluation Room (MER) Manager, Operations Planner, Safety, Engineering, and Training. To identify interview candidates, the team lead sent email requests to ISS Branch leads at JSC in Houston. The request included the study's purpose, the expected length of the interview (90 minutes), and a request for contact information for up to 3 Branch members who might be available to participate. All interviews took place during 1 of 3 week-long assessment team visits to JSC. Once the team lead received contact information, he arranged a 90-minute block of time with each participant during one of the team's site visits.

Team members conducted individual interviews with all participants. One team member performed as lead interviewer, accompanied by one or more note takers who used word processing software on laptop computers to record interview questions and responses in real time. Notes included a mix of verbatim and paraphrased participant responses. Across the 17 interviews, all assessment team members served in both roles. Before each interview began, the lead interviewer briefed the participant on the study's purpose and introduced other assessment team members who were present. Participants were assured that they would not be identified personally in our analysis, and they were free to withdraw or end the interview at any time.

Observations

Over the course of the project, assessment team members observed four Extra-Vehicular Activities (EVAs) and one visiting-vehicle event (cargo vehicle berth) from two locations within the Mission Control Center at JSC: the observation room overlooking the Mission Control "floor," and a conference room inside the MER, station-to-ground voice loops were also available in both locations. Assessment team members also attended an EVA readiness review, and a post-EVA debrief in the MER. These observations helped the assessment team to better understand the flow and pace of real-time ISS operations. Notes team members took during these observations were available to supplement, support, and interpret interview data.

Artifact Analysis

The team also considered archival data ISS staff members had produced. These included the EVA 23 Mishap Investigation Board report (NASA, 2013), the Corrective Action Plan detailing ISS Program responses to the EVA 23 MIB Recommendations, and an audio recording of the ISS Mission Management Team (IMMT) EVA 23 go/no-go meeting. As with real-time observations, analysis of these archival data was available to supplement, support, and interpret data from the structured interviews.

2.3 Data Analysis

Analysis of data from the team's collection efforts translated observed phenomena into findings that describe the ISS organization. The team used thematic analysis, which is "… a method for identifying, analysing, and reporting patterns (themes) within data. It minimally organises and describes your data set in (rich) detail" (Braun & Clarke 2006). The following analysis phases ensured that the process was rigorous and maintained continuity from data, through analysis, to themes, findings, and recommendations.

Systematic data review and coding

We copied content from each team member who took notes during an interview into a common file for each interviewee, identifying which of the two research questions and which of the four cornerstones the data point addresses. We sorted notes from each team member according to interview topics, organized along the same lines as the interview guide. We then identified, from among all of the team member notes for a particular topic, what went well, as well as instances that affected ISS ability to adapt. Using the thematic categories developed during the team working session, we coded interview sections according to their relevance to one or more themes.

Review and interpretation of coded data

With a consensus set of themes, each research team member was assigned a subset of the data excerpts to review and interpret. Analyses coded data according to the research question(s) it addressed, and which RAG cornerstones it related to. We then collected the key data points into a common file of all subjects who have the same role (e.g., flight director).

Synthesis and integration

With all data assembled according to roles, team members were then assigned separate sets to review and write insights: summary statements that drew from the data to address the research questions. Some of the data points could apply to more than one insight. In the final phase of analysis, insights from all team members were clustered into 52 sets with similar meanings, and their similarity was confirmed by being able to represent them with an "integrated insights" statement.

Findings

Two team members then reviewed all insights, merged them into 26 groups according to the research questions and RAG, and wrote findings statements. Statements noted resilient performance, needs for improvement, and implications that pointed toward recommendations. These conclusions into the actual nature of NASA and ISS performance were based on the above analyses, which included data drawn from artifacts and interviews. Recommendations were couched in terms of RE, and nature and implications of NASA/ISS ability to adapt and how that affects ISS ability to anticipate, monitor, respond to, and learn from unanticipated challenges.

3 DISCUSSION

Except for two consultants, members of the assessment team were initially unfamiliar with resilience engineering. This provided us with the opportunity to introduce team members to RE as a concept, and the RAG as an RE method.

3.1 RAG Strengths

Our experience using the RAG revealed a number of aspects that served the team well through the study.

Simplicity

The RAG concept can be expressed in one chapter, using four essential aspects to understand a complex high-hazard system. Team members were able to start to use the RAG soon after learning about it.

Accessibility

The use of plain language terms for each cornerstone made it possible for less experienced team members to understand how to use them.

Veracity

The four cornerstones enabled team members to accurately call out aspects of, and impediments to, resilient performance without the need to create additional terms or workarounds.

Support for qualitative and quantitative inquiry

The RAG can support both quantitative as well as qualitative system analyses. Hollnagel (2015) describes how Likert-style ratings can be used to develop value estimates of the required abilities. The values can be used to construct representations, such as polar diagrams or "radar charts." The assessment team for this project relied on verbal descriptions to elicit ISS organization nuances and complexities, then produced the data-insights-findings-recommendations structure it has been asked to provide.

3.2 RAG Opportunities

There were a few aspects of the RAG that the study team found challenging, and might provide an opportunity for further development.

Tacit Knowledge

While team member backgrounds included cognitive science, psychology, or human factors, some members found it necessary to know more about RE than what the cornerstones alone represented. Team members who had more experience with RE were able to provide context on RE. Members reviewed several articles that described fundamental concepts of RE, and the RE consultants shared examples and described resilience and brittleness as opportunities arose. Future publication on RE might provide deeper explanations so that those who are new to the RAG might absorb it more readily.

Examples

Team members who were new to RE found it a challenge to get the "big picture" of how to use the RAG. Examples of performance or behavior or practices that are specific to the domain being studied could be used to describe each RAG cornerstone in terms of whether or not it facilitates resilience. Providing this kind of structure early in a project could enable team members who are not familiar with RE to be better informed when planning data collection and analysis. Applications such as this study and future studies can provide examples for others who may be unfamiliar with the RAG to use the method.

Software support

The team successfully used Microsoft Excel to manually manage data analysis. Commercially available qualitative analysis software programs that are designed to support thematic analysis (e.g. Dedoose, www.dedoose.com) can facilitate the coding, tracking, and management process from data to themes, insights, findings, and recommendations.

3.3 Team Use of RAG

Prior studies such as Aaen-Stockdale (2014) and Ljunberg & Lundh (2013) have used the RAG to understand clearly bounded systems or processes with questions that were designed for use in a survey with quantitative data results depicted in polar diagrams. For example, questions related to "monitor" ask how indicators have been defined, how often revised, how many in the design of are leading or lagging, etc. By contrast, our team used a more open-ended approach, using the RAG cornerstones to organize the interview guide to answer the 2 research questions (RQ). Table 2 compares the two approaches using the RAG.

Table 2: Prior RAG Studies and NASA Study Comparison

Prior RAG Studies	*ISS study*
RAG process structured with detailed questions, possibly applied in survey format.	RAG process shaped a flexible interview process. Analysis was deliberately unstructured to benefit from the diversity of team member backgrounds and avoid biasing outcomes.
Boundaries well defined, process focused	Boundary / scope of project was broad and loosely defined

Investigative, quantitative	Explorative, qualitative

Table 3 shows how the ISS study interview guide spelled out questions ("Interviewer asks") the interviewer would use to elicit a response form the participant, and how responses could be used to inform the research question ("Interviewer listens for"), and which RQ and RAG cornerstone were pertinent.

Table 3: Interview Guide Structure

General Topic	*Interviewer asks*	*Interviewer listens for*	*Relevant to RQ 1*	*Relevant to RQ 2*	*RAG*
Roles and Responsibilities	Please briefly describe your role on the ISS team and how it relates to mission safety.	How do new/diverse team members participate in ISS operations?	X		M

Unique Contribution of RE

We found several similarities in observations when we compared our study's findings to the lesson learned presentation for the NASA EVA 23 water incursion (Hansen, 2013), which indicated it was difficult to define corrective actions for findings that were related to "human nature." We believe RE can add unique value beyond existing risk management approaches by offering innovative practices to learn, collaborate, prepare for surprise, and notice and respond to the unexpected. Table 4 compares a resilience engineering approach in comparison with traditional risk management.

Table 4: Comparison between Traditional and Resilience Engineering Approaches

Type of finding	*Traditional Risk Management*	*Resilience Engineering*
Share lessons learned from failures "in a way that people take them to heart and can find them faster."	Document lessons in databases. Require staff to periodically read and study.	Learn from what goes well. Find similar events where things went well, ask "*why* did this go well?"
Informal pressure and deference to rank inhibit speaking up.	Encourage front line workers to speak-up (e.g., "If you see something, say something.")	Practices that increase speaking up and collaboration: change format of meetings such that leaders speak last, round robin, train leaders to ask open ended questions, invite cross-checks, leave rank at the door.
Failure in responding to unexpected situation.	Create rules to specify expected response.	Develop drill and simulation scenarios that include surprising branches, subtle cues. Assess how collaboration, social influences, affect response to weak signals.

4 CONCLUSIONS

Resilience engineering enables those who study and work in complex high risk settings such as the ISS to become sensitive to, and manage, potential threats to mission success. The Resilience Analysis Grid offers an efficient, accessible means to study complex socio-technical systems, supporting both quantitative and qualitative inquiry. The RAG is simple, accessible, and gets at the true nature of the system under consideration. At the same time, its simplicity makes it necessary for those who are new to the method to learn more about how to use it. Thematic analysis of data using the RAG will benefit from the use of software that has been developed for this purpose. Those who use the RAG in the future, particularly those who are new to the method, may benefit from interactive orientation and training such as case studies, drills and simulation.

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