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# Human Reliability Analysis in Spaceflight Applications

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**Predicting and mitigating human error in manned spaceflight can be the difference between mission success and lost vehicle or crewmember. The National Aeronautics and Space Administration (NASA) has used the Cognitive Reliability Error Analysis Model analysis developed by the nuclear industry during the last 30 years of manned spaceflight to predict human error. Although the analysis has proven to be reliable, it does not take into account operations specific for long duration spaceflight such as crew training and ground support. This article first explains the principles of the Cognitive Reliability Error Analysis Model and how it is used at NASA. Then, the probability for error for an International Space Station ingress procedure is calculated using standard performance shaping factors developed for the nuclear power industry. Lastly, the environmental and operational constraints of space flight are used to develop new performance shaping factors specific to a NASA-operated spacecraft. Copyright © 2012 John Wiley & Sons, Ltd.**

**Keywords:** reliability; CREAM; spaceflight; performance shaping factors; NASA

## 1. Introduction

The purpose of this article is to incorporate system engineering techniques such as human reliability analysis (HRA) and probabilistic risk assessment (PRA) to the application and implementation of crew training and operations onboard the International Space Station (ISS). The goal is to show the importance of updating and maintaining astronaut crew training and procedures to reduce the number of human errors performed on orbit while executing intravehicular maintenance.

Errors in performing tasks can lead to decreased safety and efficiency. Many human performance errors during spaceflight operations are directly caused by poor, insufficient, or untimely training. Poor training is often a result of the lack of integration and consideration of the human throughout the operational process. Evidence for the risk associated with crew error due to poor task training is related to both manual and automated tasks. In addition, if roles and responsibilities for accomplishing tasks are not clearly defined for the crew, the potential risk of omission or commission errors could occur. Crew performance of tasks onboard the ISS such as extravehicular activities, intravehicular activities, maintenance, and medical tasks relies heavily on the provision of adequate procedures and ultimately a strongly defined operational concept. Examples of existing and potential human error events include the following:[1]

- failures of omission
  - failure to issue a command
  - failure to repair an orbital replacement unit successfully
  - failure to close a hatch properly
  - robotic arm operator fails to notice signs of imminent collision
- failures of commission
  - incorrect interpretation of visual data
  - failure to hook up or operate safer correctly
  - extravehicular crewmembers in keep-out zone during thruster firing
  - items jettisoned during extravehicular activities without previous analysis

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## 2. Human reliability analysis

### 2.1. Overview

HRA is used to calculate the probability of a system-required human action, task, or job that will be completed successfully within the allocated period and will have no extraneous human actions detrimental to system performance. Results of HRAs are often used to model human actions in a PRA, which analyze the reliability of entire systems by decomposing the system into constituent components, including hardware, software, and human operators. Results from space shuttle PRAs revealed that HRA was useful by showing the importance of maintaining crew training at its current level despite budgets reductions and layoffs that threatened training levels. An example of the benefit of HRA was seen in the years leading up to the space shuttle's retirement.

One of the shuttle mission phases addressed by HRA was entry, the time interval starting at shuttle de-orbit to wheel stop on the runaway. During entry and landing, there are several critical tasks the space shuttle's commander and pilot must train for to ensure a successful landing. A shuttle PRA revealed 11 human actions that could potentially lead to a loss of crew and vehicle end state if not properly trained for. This information was useful in leading an initiative to retain the critical workforce responsible for crew training until the end of the shuttle program (for more information, see Chandler *et al.*[2]).

Modeling human error has always been a challenge especially when human performance data are not readily available. For spaceflight operations, the challenge is greater because there have only been a small number of participants, limited performance data, and an unclear definition of the human performance factors that influence operations in space.

### 2.2. CREAM approach

The approach to modeling human action is an iterative process. Dominant human errors are evaluated using the Cognitive Reliability Error Analysis Model (CREAM) analysis. The CREAM analysis was originally developed for nuclear power plant applications and was adopted by the National Aeronautics and Space Administration (NASA) in the early 1990s. Several methods were analyzed to provide an approximation of human error, but the CREAM method provided the closest approximation (for more information, see Hollnagel[3,4]). A recent study conducted by Lee *et al.*[5] has used CREAM as the basis for a communication error analysis method (CEAM), in which the communication errors causing incidents and accidents in the nuclear industry have been analyzed quantitatively and qualitatively. To provide a simplified quantification process for CREAM, He et al.[6] have used the basic method for the purposes of previous screening of human actions by looking at overall performance reliability. Following this, they presented the extended method of CREAM to provide an additional level of analysis for human interactions. Following up on the work conducted by Konstandinidou *et al.*[7] on fuzzy modeling application of CREAM for HRA, Marseguerra *et al.*[8] have proposed a systematic procedure for calculating probabilities of operator action failure in CREAM. The importance of integrating approaches such as fuzzy modeling to the use of HRA is also stated by Sharma *et al.*[9]

The CREAM methodology involves the following steps (Hamlin and Stewart[10]):

- build or develop a list of the cognitive demands of the task
- identify the likely cognitive function failures
- determine the specific action failure probability

The specific action failure probability is calculated by taking a nominal value and modifying it based on nine common performance conditions (CPCs). An example of a CPC that can significantly affect the failure probability is the time available to perform the action. Failure probabilities are expressed as medians. Means are calculated by first assigning an error factor, based on either the original distributions in CREAM if the action is a nominal action, or based on guidelines provided in NUREG/CR-1278[11] if the action is in response to a failure. When recoveries to human actions are considered, dependencies among crewmembers and Mission Control Center (MCC) are addressed using equations from NUREG/CR-1278.[11]

#### 2.2.1. Cognitive demands

The first step to performing the CREAM analysis is to build or develop a list of tasks needed to accomplish a specific objective or activity and to determine the associated cognitive demand of each task. This first involves describing the activity to be analyzed and identifying the cognitive activities for each task or step. The list of the cognitive activities and the general definition associated with each cognitive activity is provided in Table I. The cognitive activities are verbs used to describe the actions the human must take to perform the task. These verbs include coordinate, communicate, compare, diagnose, evaluate, execute, identify, maintain, monitor, observe, plan, record, regulate, scan, and verify.

The cognitive demand or break down of the cognitive activity into its cognitive functions can be found for each cognitive activity identified by using Table II. The underlying principle behind Table II is that there are four basic cognitive functions: observation, interpretation, planning, and execution. The analyst can describe each typical cognitive activity in terms of the combination of the four basic cognitive functions. The cognitive demand is a function of the cognitive activity chosen and cannot be adjusted.

#### 2.2.2. Cognitive function failures

The second step in the CREAM method is to identify the likely cognitive function failures. The list of potential cognitive function failures associated with the four cognitive functions is given in Table III. Considering the task as a whole, the object is to identify what cognitive function failure or failure mode is expected to be committed by the human operator for each task.

**Table I.** List of critical cognitive activities (human factors process failure modes and effects analysis[15])

| Cognitive activity | General definition |
|---|---|
| Coordinate | Bring system states and/or control configurations into the specific relation required to carry out a task or task step. Allocate or select resources in preparation for a task/job, calibrate equipment, and so on. |
| Communicate | Pass on or receive person-to-person information needed for system operation by verbal, electronic, or mechanical means. Communication is an essential part of management. |
| Compare | Examine the qualities of two or more entities (measurements) with the aim of discovering similarities or differences. The comparison may require calculation. |
| Diagnose | Recognize or determine the nature or cause of a condition using reasoning about signs or symptoms or by the performance of appropriate tests. “Diagnose” is more thorough than “identify.” |
| Evaluate | Appraise or assess an actual or hypothetical situation based on available information without requiring special operations. Related terms are “inspect” and “check.” |
| Execute | Perform a previously specified action or plan. Execution comprises actions such as open/close, start/stop, fill/drain, and so on. |
| Identify | Establish the identity of the vehicle state or **sub**system (component) state. This may involve specific operations to retrieve information and investigate details. “Identify” is more thorough than “evaluate.” |
| Maintain | Sustain a specific operational state. (This is different from maintenance, which is generally an offline activity.) |
| Monitor | Keep track of system states over time, or follow the development of a set of parameters. |
| Observe | Look for or read specific measurement values or system indications. |
| Plan | Formulate or organize a set of actions by which a goal will be successfully achieved. Plans may be short term or long term. |
| Record | Write down or log system events, measurements, and so on. |
| Regulate | Alter speed or direction of a control (system) to attain a goal. Adjust or position components or subsystems to reach a target state. |
| Scan | Quick or speedy review of displays or other information source(s) to obtain a general impression of the state of a system/subsystem. |
| Verify | Confirm the correctness of a system condition or measurement, either by inspection or test. This also includes checking the feedback from previous operations. |

**Table II.** Generic cognitive activity by cognitive demand (human factors process failure modes and effects analysis[15])

| | Cognitive demand | | | |
|---|---|---|---|---|
| Cognitive activity | Observation | Interpretation | Planning | Execution |
| Coordinate | | | • | • |
| Communicate | | | | • |
| Compare | | • | | |
| Diagnose | | • | • | |
| Evaluate | | • | • | |
| Execute | | | | • |
| Identify | | • | | |
| Maintain | | | • | • |
| Monitor | • | • | | |
| Observe | • | | | |
| Plan | | | • | |
| Record | | • | | • |
| Regulate | • | | | • |
| Scan | • | | | |
| Verify | • | • | | |

*2.2.3. Failure probability* The final step in performing CREAM is to determine the failure probability. Once the cognitive function and potential cognitive function failures have been assigned for each task, it is possible to assess the probability of failure for each cognitive failure type. This is known as the cognitive failure probability (CFP). The parameters used in CREAM, such as the nominal values and uncertainty bounds for cognitive failures, are derived from four other HRA methods[11–14] and expert judgment. Thus,

**Table III.** Generic cognitive function failures (human factors process failure modes and effects analysis[15])

| Cognitive function | | Potential cognitive function failure |
|---|---|---|
| Observation errors | O1 | Observation of wrong object (response is given to the wrong stimulus or event). |
| | O2 | Wrong identification made (a mistaken cue or partial identification). |
| | O3 | Observation not made (omission, overlooking a signal or a measurement). |
| Interpretation errors | I1 | Faulty diagnosis (either a wrong diagnosis or an incomplete diagnosis). |
| | I2 | Decision error (either not making a decision or making a wrong or incomplete decision). |
| | I3 | Delayed interpretation (not made in time). |
| Planning errors | P1 | Priority error (as in selecting the wrong goal, intention). |
| | P2 | Inadequate plan formulated (when the plan is either incomplete or directly wrong). |
| Execution errors | E1 | Execution of wrong type performed (with regard to force, distance, speed, or direction). |
| | E2 | Action performed at wrong time (either too early or too late). |
| | E3 | Action on wrong object (neighbor, similar or unrelated). |
| | E4 | Action performed out of sequence (repetitions, jumps, and reversals). |
| | E5 | Action missed, not performed (omission), including the omission of the last actions in a series (“undershoot”). |

the validity of CREAM is strongly dependent on the credibility of those HRA methods and the quality of judgments made in their selection. No known empirical validation of the qualitative and quantitative results of CREAM has been conducted.

There are three steps to quantifying the CFP:[10]

Step 1: Determine the nominal CFP for each of the potential cognitive function failures (using Table IV) by picking a generic failure type.

Step 2: Assess the effects of the CPC on the nominal CFP values (using Tables V and VI) by multiplying the total weighting factor by the nominal CFP value. The total weighting factor is the product of the individual CPC weighting factors.

Step 3: Calculate the overall failure probability of the human action being evaluated. This calculation varies according to the human action being modeled, and therefore the equations used are shown on a case-by-case basis. It involves conversion from a median value to a mean value.

The overall failure probability depends on the most dominant CFP, the CFP with the highest probability of failure. If the task involves a series of actions that all have to be performed, that is, if any one fails, the task fails, the overall failure probability is the maximum CFP. However, if the task involves two or more possible success paths, the product of the success path CFPs is taken to get the overall failure probability.

**Table IV.** Nominal CFP values (human factors process failure modes and effects analysis[15])

| | | CREAM nominal values and uncertainty bounds for cognitive failures | | | | Calculated EF |
|---|---|---|---|---|---|---|
| Cognitive function | | Generic failure type | 5% Lower bound | Median | 95% Upper bound | Square Root (95th/5th) |
| Observation | O1 | Wrong object observed | 3.0E − 04 | 1.0E − 03 | 3.0E − 03 | 3.16E + 00 |
| | O2 | Wrong identification | 1.0E − 03 | 3.0E − 03 | 9.0E − 03 | 3.00E + 00 |
| | O3 | Observation not made | 1.0E − 03 | 3.0E − 03 | 9.0E − 03 | 3.00E + 00 |
| Interpretation | I1 | Faulty diagnosis | 9.0E − 02 | 2.0E − 01 | 6.0E − 01 | 2.58E + 00 |
| | I2 | Decision error | 1.0E − 03 | 1.0E − 02 | 1.0E − 01 | 1.00E + 01 |
| | I3 | Delayed interpretation | 1.0E − 03 | 1.0E − 02 | 1.0E − 01 | 1.00E + 01 |
| Planning | P1 | Priority error | 1.0E − 03 | 1.0E − 02 | 1.0E − 01 | 1.00E + 01 |
| | P2 | Inadequate plan | 1.0E − 03 | 1.0E − 02 | 1.0E − 01 | 1.00E + 01 |
| Execution | E1 | Action of wrong type | 1.0E − 03 | 3.0E − 03 | 9.0E − 03 | 3.00E + 00 |
| | E2 | Action at Wrong Time | 1.0E − 03 | 3.0E − 03 | 9.0E − 03 | 3.00E + 00 |
| | E3 | Action on wrong object | 5.0E − 05 | 5.0E − 04 | 5.0E − 03 | 1.00E + 01 |
| | E4 | Action out of sequence | 1.0E − 03 | 3.0E − 03 | 9.0E − 03 | 3.00E + 00 |
| | E5 | Missed action | 2.5E − 02 | 3.0E − 02 | 4.0E − 02 | 1.26E + 00 |

**Table V.** CPCs (human factors process failure modes and effects analysis[15])

| CPC name | Evaluation |
|---|---|
| **Adequacy of organization** | The quality of the support and resources provided by the organization for the task or work being performed. |
| Descriptors | Very efficient/efficient/inefficient/deficient |
| **Working conditions** | The conditions under which the work takes place |
| Descriptors | Advantageous/compatible/incompatible |
| **Adequacy of man–machine interface (MMI) and operational support** | The quality of the MMI and/or specific operational support provided for the crew |
| Descriptors | Supportive/adequate/tolerable/inappropriate |
| **Availability of procedures/plans** | The availability of prepared guidance for the work to be carried out, including operating/emergency procedures, routines, and familiar responses |
| Descriptors | Appropriate/acceptable/inappropriate |
| **Number simultaneous goals** | The number of simultaneous goals that the crew must attend. Because the number of goals is variable, this CPC applies to what is typical or characteristic for a situation |
| Descriptors | Fewer than capacity/matching current capacity/more than capacity |
| **Available time** | The time available to complete the work or the general level of time pressure for the task and the situation type |
| Descriptors | Adequate/temporarily inadequate/continuously inadequate |
| **Time of day (circadian rhythm)** | The time at which the task is carried out, in particular, whether a person is adjusted to the current time |
| Descriptors | Daytime (adjusted)/nighttime (unadjusted) |
| **Adequacy of training and preparation** | The level of readiness for the work as provided (by the organization) through training and previous instruction |
| Descriptors | Adequate, high experience/adequate, limited experience/inadequate |
| **Crew collaboration quality** | The quality of the collaboration among crewmembers, including the overlap between the official and the unofficial structure, the level of trust, and the general social climate among crew members |
| Descriptors | Very efficient/efficient/inefficient/deficient |

## 3. Applying CREAM to spaceflight

HRA and the CREAM analysis can be applied to NASA mission operations onboard the ISS as a way to evaluate the interaction between the crew member and the ISS systems. Knowing how human actions affect the overall system reliability and its contribution to risk must be well understood and managed. Crew members daily interact with systems onboard the ISS and thus the potential for human error through commission and/or omission exist. In-flight maintenance (IFM) is a frequent crew task in which the crew member performs routine or corrective procedures for preventative system maintenance or in response to a system anomaly. These IFMs typically involve numerous crew callouts and human actions, in which the crew member will naturally apply the four basic cognitive functions: observation, interpretation, planning, and execution.

One of these procedures is the HTV Vestibule Configure for Ingress on Node 2 Zenith. This procedure prepares the Node 2 Module Hatch and the HTV Cargo Vehicle Hatch for opening after the HTV has docked to the ISS. The crew must supply internal power from the ISS to the HTV vehicle and install communication lines.

The first step in the CREAM analysis is to list each subtask of the activity in sequential order and identify the cognitive activity associated with each task (Table I). The HTV Vestibule Configure for Ingress on Node 2 Zenith procedure requires 21 major crew actions. Each cognitive activity is associated with a cognitive demand as seen in Table II. The cognitive demand is used in step 2 to identify the cognitive function failures or failure mode. Table VII contains a brief description of the procedure's activities, the order of the tasks, the tasks associated cognitive activity, and the cognitive demand for the HTV Vestibule Configure crew activity.

The next step is to identify the potential cognitive function failure for each cognitive function identified in step 1. The CREAM method identifies error modes of the four information processing phases: observation, interpretation, planning, and execution. The specific error modes within each of these four generic failure types are seen in Table VIII. Each specific error mode has a classification and a median failure rate. The median is the basic human error probability (HEP) of failure for the classification determine by expert elicitation. Several generic failure types or failure modes are identified, and each median is associated with a basic HEP and uncertainty bonds. The associated median failure rate for each task based on the cognitive function classification can be seen in Table IX.

**Table VI.** Weighting factors for CPCs (human factors process failure modes and effects analysis[15])

CREAM performance factors

| | | Cognitive function | | | |
|---|---|---|---|---|---|
| Factor | Level | Observation | Interpretation | Planning | Execution |
| Adequacy of organization | Very efficient | 1.0 | 1.0 | 0.8 | 0.8 |
| | Efficient | 1.0 | 1.0 | 1.0 | 1.0 |
| | Inefficient | 1.0 | 1.0 | 1.2 | 1.2 |
| | Deficient | 1.0 | 1.0 | 2.0 | 2.0 |
| Working conditions | Advantageous | 0.8 | 0.8 | 1.0 | 0.8 |
| | Compatible | 1.0 | 1.0 | 1.0 | 1.0 |
| | Incompatible | 2.0 | 2.0 | 1.0 | 2.0 |
| Adequacy of man machine interface | Supportive | 0.5 | 1.0 | 1.0 | 0.5 |
| | Adequate | 1.0 | 1.0 | 1.0 | 1.0 |
| | Tolerable | 1.0 | 1.0 | 1.0 | 1.0 |
| | Inappropriate | 5.0 | 1.0 | 1.0 | 5.0 |
| Availability of procedures | Appropriate | 0.8 | 1.0 | 0.5 | 0.8 |
| | Acceptable | 1.0 | 1.0 | 1.0 | 1.0 |
| | Inappropriate | 2.0 | 1.0 | 5.0 | 2.0 |
| No. simultaneous goals | Fewer than capacity | 1.0 | 1.0 | 1.0 | 1.0 |
| | Matching capacity | 1.0 | 1.0 | 1.0 | 1.0 |
| | More than capacity | 2.0 | 2.0 | 5.0 | 2.0 |
| Available time | Adequate | 0.5 | 0.5 | 0.5 | 0.5 |
| | Temporarily inadequate | 1.0 | 1.0 | 1.0 | 1.0 |
| | Continuously inadequate | 5.0 | 5.0 | 5.0 | 5.0 |
| Time of day | Daytime | 1.0 | 1.0 | 1.0 | 1.0 |
| | Nighttime | 1.2 | 1.2 | 1.2 | 1.2 |
| Adequacy of training/preparation | Adequate, high experience | 0.8 | 0.5 | 0.5 | 0.8 |
| | Adequate, low experience | 1.0 | 1.0 | 1.0 | 1.0 |
| | Inadequate | 2.0 | 5.0 | 5.0 | 2.0 |
| Crew collaboration quality | Very efficient | 0.5 | 0.5 | 0.5 | 0.5 |
| | Efficient | 1.0 | 1.0 | 1.0 | 1.0 |
| | Inefficient | 1.0 | 1.0 | 1.0 | 1.0 |
| | Deficient | 2.0 | 2.0 | 2.0 | 5.0 |

Step 3 is to identify the CREAM performance shaping factors (PSFs), which are used to determine the situational influence on the operator's performance. As seen in Table V, there are nine types of CPCs, and each CPC is associated with a weighting factor based on the PSF state. The PSFs weights are derived by expert judgment. On the basis of known inputs to the activity, the expected effect on performance reliability is estimated. For example, if the crew member has been trained on a particular activity on the ground and is considered proficient, but has never performed this activity on orbit, the PSF state for the CPC type of training and preparation made will be considered adequate and low experience and will be assigned a weighting factor of 1.0.

Table X lists the PSFs and weights selected for each task based on the known conditions of the work environment, crew training received, operational and ground support available, and the willingness and cooperation of the crew. Each weighting factor for each task is multiplied together yielding an overall weighting factor for each task, for a total of 21 weighting factors. These overall weighting factors will be used in step 4 to calculate the adjusted CPC or CPC mean for each task.

In step 4, the adjusted CFPs for both the median and the mean are calculated for each task. This is performed by taking the nominal CFP/median-specific error mode determined in step 2 for each task and multiplying it by the overall weighting factor determine in step 3 for each task (Equation (1)). The product is the adjusted CFP (median) for each task:

$$\text{Adjusted CFP(median)} = \text{nominal CFP} \times \text{overall weighting factor} \tag{1}$$

Next, an error factor is determined using Table 20-20 of NUREG1278.[7] The error factor is based on the estimated HEP and is used to calculate a mean given a median to specify a mean log-normal distribution. The guidelines for picking error factor are based on the task's step-by-step procedure conducted under routine circumstances (e.g. test, maintenance, or calibration task, and the crew member's stress level is deemed optimal for the task). Under these HEP guidelines, the estimated HEP and error factor can be selected for the ranges as follows:

**Table VII.** Cognitive activity matrix for HTV vestibule

| | | | Cognitive demand | | | |
|---|---|---|---|---|---|---|
| Brief description of activity | Task | Cognitive activity | Observation | Interpretation | Planning | Execution |
| Open Node 2 nadir hatch | 1 | Execute | 0 | 0 | 0 | 1 |
| inspect vestibule for condensation | 2 | Evaluate | 0 | 1 | 1 | 0 |
| Report any condensation to MCC | 3 | Communicate | 0 | 0 | 0 | 1 |
| Remove CBM center disk cover | 4 | Execute | 0 | 0 | 0 | 1 |
| Verify w/MCC-H power cable is safe | 5 | Verify | 1 | 1 | 0 | 1 |
| Connect power cable to HTV | 6 | Execute | 0 | 0 | 0 | 1 |
| Notify MCC-H "go for HTV power up" | 7 | Communicate | 0 | 0 | 0 | 1 |
| Remove HTV hatch thermal blanket | 8 | Execute | 0 | 0 | 0 | 1 |
| Connect power cable (2) to HTV | 9 | Execute | 0 | 0 | 0 | 1 |
| Install Node 2 MPLM 1553 LB-B | 10 | Execute | 0 | 0 | 0 | 1 |
| Install Node 2 MPLM 1553 LB-A | 11 | Execute | 0 | 0 | 0 | 1 |
| Remove (4) CBM CPA | 12 | Execute | 0 | 0 | 0 | 1 |
| Inhibit HTV pressure relief | 13 | Execute | 0 | 0 | 0 | 1 |
| Equal HTV and ISS cabin pressure | 14 | Execute | 0 | 0 | 0 | 1 |
| Notify MCC-H of configuration | 15 | Compare | 0 | 1 | 0 | 0 |
| Install IMV supply jumper | 16 | Execute | 0 | 0 | 0 | 1 |
| Install ARS jumper | 17 | Execute | 0 | 0 | 0 | 1 |
| Open Node 2 Deck ARS Manual Valve | 18 | Execute | 0 | 0 | 0 | 1 |
| Install radial port closeout | 19 | Execute | 0 | 0 | 0 | 1 |
| Notify MCC-H of task completion | 20 | Communicate | 0 | 0 | 0 | 1 |
| Stow parts, materials, and tools | 21 | Execute | 0 | 0 | 0 | 1 |

**Table VIII.** Specific error modes (NUREG-CR1278)

| Specific error modes | | |
|---|---|---|
| Classification | Median | Description |
| O1 | 1E − 03 | Observation of wrong object |
| O2 | 3E − 03 | Wrong identification made |
| O3 | 3E − 03 | Observation not made |
| I1 | 2E − 01 | Faulty diagnosis |
| I2 | 1E − 02 | Decision error |
| I3 | 1E − 02 | Delayed interpretation |
| P1 | 1E − 02 | Priority error |
| P2 | 1E − 02 | Inadequate plan formulated |
| E1 | 3E − 03 | Execution of wrong type performed |
| E2 | 3E − 03 | Action performed at wrong time |
| E3 | 5E − 04 | Action on wrong object |
| E4 | 3E − 03 | Action performed out of sequence |
| E5 | 3E − 02 | Action missed, not performed |

1. Estimated HEP $< 0.001$: error factor = 10.
2. Estimated HEP 0.001 to 0.01: error factor = 3.
3. Estimated HEP $> 0.01$: error factor = 5.

For the purposes of this activity, 10 was chosen as the error factor because the estimated HEP for this task is considered to be less than 0.001. A mean log-normal distribution is used to derive the adjusted CFP (mean) equation. This equation uses the error factor and the adjusted CPF (median) from the previous step to determine the adjusted CPF (mean). The following sets of equations (Equations (2)–(5)) are used to determine the adjusted CFP (mean) (Equation (6)):

**Table IX.** Task versus cognitive function for HTV vestibule

| Cognitive Function | | Task | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 |
| Observation Errors | O1 | | | | | | | | | | | | | | | | | | | | | |
| | O2 | | | | | ■ | | | | | | | | | | | | | | | | |
| | O3 | | | | | | | | | | | | | | | | | | | | | |
| Interpretation Errors | I1 | | | | | | | | | | | | | | | | | | | | | |
| | I2 | | ■ | | | | | | | | | | | | | ■ | | | | | | |
| | I3 | | | | | ■ | | | | | | | | | | | | | | | | |
| Planning Errors | P1 | | | | | | | | | | | | | | | | | | | | | |
| | P2 | | ■ | | | | | | | | | | | | | | | | | | | |
| Execution Errors | E1 | ■ | | | ■ | | | | ■ | | | | | | | | | | | | | |
| | E2 | | | | | | | | | | | | | | ■ | | | | | | | |
| | E3 | | | | | | | | | | | | | | | | | | | | | |
| | E4 | | | | | | ■ | | | ■ | ■ | ■ | ■ | ■ | | | ■ | ■ | ■ | ■ | | |
| | E5 | | | ■ | | | | ■ | | | | | | | | | | | | | ■ | ■ |

$$\text{Mean}(\propto) = e^{\mu + \frac{\sigma^2}{2}} \tag{2}$$

$$\text{Log mean}(\mu) = \ln(x), x = \text{CFP median} \tag{3}$$

$$\sigma = \frac{\ln(\text{error factor})}{\vartheta^{-1}(0.95)}, \text{error factor} \tag{4}$$

$$\vartheta^{-1}(0.95) \approx 1.645,\ \text{95th normal percentile} \tag{5}$$

$$\text{Adjusted CFP mean } (\alpha) = e^{\ln(\text{CFP median}) + \frac{\left(\frac{\ln(\text{error factor})}{1.645}\right)^2}{2}} \tag{6}$$

Tables XI and XII listed the task order, nominal CFP (median), adjusted CFP (median) (Equation (1)), error factor, and adjusted CPF (mean) (Equation (6)) for each task.

Table XI shows the nominal CFPs for each step in the procedure. The greatest likelihood for error occurs in task 2 in which the crew inspects the vestibule for condensation and takes appropriate action to clean the area. Condensation on or around the vestibule may have a negative effect later in the procedure when the crew goes to install communication, data, and power lines. Other execution steps such as tasks 3, 5, 7, 15, and 21 had the next highest likelihood of yielding a human error. The steps required the crew member to communicate, evaluate, and execute task with high cognitive demand and thus a higher cognitive function failure potential.

In step 5, the dependence of the recovery action or *N* valve is determined based on the last available crew checkout and verification point during the activity. For this task, this recovery action occurs during task 20 in which the crew has the options to verify the completion of a successful task through ground or MCC verification. This allows the crew to receive input from the ground operators to recover any missed step, action, or unfinished task before the procedure or activity is complete. As seen in Table XII, the recovery action (task 20) has an "R" in the failure/recovery row. The adjusted CPF (mean) is not calculated for recovery actions until step 6,

$$N = \text{recovery action} \tag{7}$$

Step 6 determines the dependence of the recovery action and calculates a median adjusted recovery action (MARA). The dependence options range from zero, low, moderate, high, or complete dependence, and each dependence has an associated calculated MARA. The dependence options are used to weight and determine the importance of the recovery action. For example, if the successful completion of the procedure is highly dependent on the recovery action, the likelihood of human error and the likelihood of a nonsuccessful task are increased in comparison with a zero, low, or moderate dependent recovery action. In this case, the successful completion of this task requires that all steps are completed correctly and the recovery action is needed to ensure all steps in the procedure have been accounted for. A median adjusted CFP of 1 was selected for this procedure because it has complete dependence on the overall completeness of this activity. Equations (8)–(12) are used to determine the MARA for each dependence and where determined by expert judgment:

$$\text{MARA (zero dependence)} = N \tag{8}$$

$$\text{MARA (low dependence)} = \frac{(1 + 19 \times N)}{20} \tag{9}$$

**Table X.** PSFs for HTV vestibule

| CREAM PSFs | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Task | | | | | | | | | | | | | | | | | | | | |
| CPC name | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 |
| Type | E | I | E | E | O | E | E | E | E | E | E | E | E | E | I | E | E | E | E | R | E |
| | 4 | 2 | 4 | 4 | 1 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 2 | 4 | 4 | 4 | 4 | 4 | 4 |
| Adequacy of organization | 0.8 | 1 | 1 | 1 | 1 | 0.8 | 1 | 1 | 1 | 1 | 1 | 1 | 0.8 | 0.8 | 1 | 1 | 1 | 0.8 | 1 | 1 | 1 |
| Working conditions | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Adequacy of MMI | 0.5 | 1 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 1 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 |
| Procedures/ plans | 0.8 | 1 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 1 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 |
| No. goals | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Available time | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 |
| Time of day | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Training and preparation | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Crew collaboration | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 |
| Overall weighting factor | 0.08 | 0.25 | 0.1 | 0.1 | 0.1 | 0.08 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.08 | 0.08 | 0.25 | 0.1 | 0.1 | 0.08 | 0.1 | 0.1 | 0.1 |

**Table XI.** Nominal CFPs for HTV vestibule—Part 1

| Task | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|---|
| Failure/recovery | F | F | F | F | F | F | F | F | F |
| Nominal CFP (median) | 3.0E − 03 | 2.0E − 02 | 3.0E − 02 | 3.0E − 03 | 1.3E − 02 | 3.0E − 03 | 3.0E − 02 | 3.0E − 03 | 3.0E − 03 |
| Adjusted CFP (median) | 2.4E − 04 | 5.0E − 03 | 3.0E − 03 | 3.0E − 04 | 1.3E − 03 | 2.4E − 04 | 3.0E − 03 | 3.0E − 04 | 3.0E − 04 |
| Error Factor | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 |
| Adjusted CPF (mean) | 6.4E − 04 | 1.3E − 02 | 7.9E − 03 | 7.9E − 04 | 3.5E − 03 | 6.4E − 04 | 7.9E − 03 | 7.9E − 04 | 7.9E − 04 |

**Table XII.** Nominal CFPs for HTV vestibule—part 2

| 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| F | F | F | F | F | F | F | F | F | F | R | F |
| 3.0E − 03 | 3.0E − 03 | 3.0E − 03 | 3.0E − 03 | 3.0E − 03 | 1.0E − 02 | 3.0E − 03 | 3.0E − 03 | 3.0E − 03 | 3.0E − 03 | 3.0E − 02 | 3.0E − 02 |
| 3.0E − 04 | 3.0E − 04 | 3.0E − 04 | 2.4E − 04 | 2.4E − 04 | 2.5E − 03 | 3.0E − 04 | 3.0E − 04 | 2.4E − 04 | 3.0E − 04 | 3.0E − 03 | 3.0E − 03 |
| 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 |
| 7.9E − 04 | 7.9E − 04 | 7.9E − 04 | 6.4E − 04 | 6.4E − 04 | 6.6E − 03 | 7.9E − 04 | 7.9E − 04 | 6.4E − 04 | 7.9E − 04 | 7.9E − 03 | 7.9E − 03 |
| 7.9E − 04 | 7.9E − 04 | 7.9E − 04 | 6.4E − 04 | 6.4E − 04 | 6.6E − 03 | 7.9E − 04 | 7.9E − 04 | 6.4E − 04 | 7.9E − 04 | 0.0E+00 | 7.9E − 03 |

$$\text{MARA (moderate dependancy)} = \frac{(1 + 6 \times N)}{7} \tag{10}$$

$$\text{MARA (high dependence)} = \frac{(1 + N)}{2} \tag{11}$$

$$\text{MARA (complete dependence)} = 1 \tag{12}$$

Step 7 uses the same error factor determined by Table 20-20 of NUREG1278[7] (error factor = 10) to determined the mean recovery action probability of failure (step 8). The mean recovery action is calculated using the MARA based on the dependence chosen in step 6, Table XIII, and the mean adjusted CFP (recovery action/*N*), chosen in step 4. Equation 13 calculates the mean recovery action and is derived using a mean log-normal distribution.

$$\text{Recovery action (mean)} = e^{\ln(\text{MARA}) + \frac{\left(\frac{\ln(\text{error factor})}{1.645}\right)^{\wedge}2}{2}} \tag{13}$$

$$\text{Recovery action (mean)} = 2.664 = e^{\ln(1) + \frac{\left(\frac{\ln(10)}{1.645}\right)^{\wedge}2}{2}}$$

To determine the overall failure probability of human error by a crew member, the maximum or most likely failure rate from all tasks is chosen. Looking at Tables XI and XII, the maximum mean adjusted CPF for the first possible failure occurs during task 2 with a maximum failure probability of 1.33E−02. The overall failure probability is the product of the maximum failure probability of the activity and the mean recovery action,

$$\text{Overall failure probability} = \text{max mean CPF} \times \text{recovery action (mean)}(1.33 \in -02) \times 2.664 = 3.55 \in -02 \tag{14}$$

Thus, the overall failure probability for the HTV Vestibule Configure for Ingress on Node 2 Zenith task is 3.55E−02, or there is a 1 in 28 probability that the crew will perform a human error.

## 3. Spaceflight PSFs

PSFs like the ones seen in Table V are the factors or operational constraints that influence human performance and human reliability. These are generic factors that were developed for the nuclear power industry and are not optimized for spaceflight. Human activities are required for nominal operations and maintenance onboard the ISS. Each human onboard the ISS must perceive information about the state of the system through the portable computer system displays, digital displays, and written and/or oral instructions. They must process that information, determine what course of action to take, and execute it. Human PSFs are used to determine the human behavior of an activity based on a set of known factors. The factors are multiplied together to yield a total weighting factor, which is used to estimate human error probabilities.

The PSFs can be divided into two primary sets: factors where risk can be mitigated with operational preparation and factors where risk cannot. The term *operational preparation* implies that the hardware has already been constructed but that the activity has not been completed. A listing of the factors, whether they can be mitigated, and a brief explanation of why they are in the chosen category are shown in Table XIV.

The four factors that are within the control of the operational team are the adequacy of the organization, the availability of procedures and plans, the adequacy of training and preparation, and the crew collaboration quality. Taking a closer look at each will help narrow down which of these factors offer the maximum ability to maximize or minimize the risk in a given maintenance activity.

### *3.1. Adequacy of spaceflight organizations*

To date, all human spaceflight organizations have been government entities. The only entities to successfully send humans into space have been the China National Space Administration, the Russian Space Agency and the NASA. As government agencies, these organizations have vast resources, high safety margins, and well-established support structures for their spaceflight operations. Particularly at this point in history, the Russian Soyuz spacecraft, the American space shuttle, and the ISS all have years of historical data from which to base decisions, procedures, processes, and ground support training to ensure that the organizations maintain high quality support. Therefore, although operational preparation may mitigate the risk associated with the adequacy of spaceflight operations, it is unlikely that significant improvement can be made in this category to minimize the risk of an error. It should be noted that this factor will likely become a more scrutinized factor as private companies establish a presence in the human spaceflight industry.

### *3.2. Availability of procedures and plans*

The availability of procedures and plans is almost exclusively the domain of the operations team in support of a given spaceflight activity. Although a few procedures and plans may be developed well before an activity, rarely is an activity in human spaceflight actually performed exactly as intended by the designers of the hardware or software. More often than not, unique accessing, performance, or timing requires the operational team to take a given set of objectives and develop a procedure and plan to execute. In addition to activities that are planned or known well in advance, many human spaceflight activities are performed in reaction to a failure or unexpected circumstance. Although some of these circumstances, such as the known emergencies of fire, rapid pressure loss, and release of toxic materials, have predefined, vetted procedures for crewmembers to follow, many of those unexpected failures or circumstances do not have such procedures. Often, the more hazardous and time critical a failure scenario is, the less time for vetting and verification of procedures is possible. The result is that the availability of procedures and plans to mitigate risk can be inversely proportional to the hazard and risk that the activities themselves involve.

### *3.3. Adequacy of training and preparation*

The adequacy of training and preparation is one of the primary areas that can vary widely by task, crewmember, and subject area. As noted in the previous section, some tasks performed in human spaceflight are known well in advance, some are well planned for contingencies that are hoped to never happen, and others may be unexpected and unplanned. Many of the executed activities actually fall within the gray areas between these three categories. In addition to the tasks, the backgrounds of the crewmembers vary just as widely. Astronauts have backgrounds as doctors, test pilots, scientists, mechanics, and many other professions. With such variety of starting points, vastly different training may be required to achieve the minimum adequate level of training and preparation for spaceflight. Assessing their background and amount of training required to ensure adequate preparation can often be as difficult as accomplishing the training and preparation itself. For any of these backgrounds or circumstances, the adequacy of training and preparation for the types of activities and the environment can be the difference between success and failure for a given task.

### *3.4. Crew collaboration quality*

In any team environment, the ability of the team members to collaborate successfully can determine the success of the team. Human spaceflight is no different when activities are being performed by multiple crewmembers. However, most activities in human spaceflight are performed individually. Even when activities are performed collaboratively, it is difficult to take a team of people that have difficulty working together and improve their collaboration. Often, the only path that an operations team has to prevent collaborative issues from causing task failure is to simply replace one or more team members to improve the chemistry of the team. The evaluation of team performance is important to be able to verify, particularly to determine whether the quality of collaboration might cause the failure of a given task. However, because not many changes can be made to significantly improve crew collaboration quality, it is not a PSF that may range greatly in its risk to an activity.

### *3.5. PSF assessment*

From the previously mentioned description, the two areas that seem likely candidates for performing a more detailed analysis of the PSF to assess different ways to improve the likelihood of success are availability of procedures and plans and the adequacy of training and preparation. For both of these PSFs, it is not feasible to expect every task and contingency circumstance to be 100% considered, planned, and trained. When the need arises for a given task to be performed, there are a relatively simple set of decisions to construct a plan and build procedures to execute the activity, and the more manpower and time that is given to that procedure, the higher the

**Table XIII.** Dependence factor for HTV vestibule (NUREG-CR1278)

| Dependence | MARA | Choose dependence |
|---|---|---|
| Zero dependence | 7.99E − 03 | 0 |
| Low dependence | 0.05759102 | 0 |
| Moderate dependence | 0.149706183 | 0 |
| High dependence | 0.503995273 | 0 |
| Complete dependence | 1 | 1 |

**Table XIV.** CPC factors versus operational preparation

| CPC name | Mitigate by operational preparation | |
|---|---|---|
| Adequacy of organization | Yes | The supporting organization is a direct result of adequate training, technical preparation, and attention to the job at hand. |
| Working conditions | No | Human spaceflight conditions are always some of the most challenging that human beings have encountered, and it is nearly impossible to minimize the hazard and difficulty of the conditions. |
| Adequacy of man–machine interface (MMI) and operational support | No | The physical interfaces for spaceflight hardware are typically designed many years before when they are actually used and the challenges of operating in the harsh environment of space often trumps human factors in the design decisions. |
| Availability of procedures/plans | Yes | The availability and quality of procedures is directly controlled by the operational community in the build up to the execution of the event. |
| Number of simultaneous goals | No | The number of simultaneous goals in human spaceflight is typically driven more by the needs of the vehicle to ensure survivability than by the operational team. |
| Available time | No | The availability of time in human spaceflight is largely controlled by consumables and activities required to ensure survivability than by the operational team. |
| Time of day (circadian rhythm) | No | In space, a day can vary from extremely short (on the order of 40 min) to weeks or days for extraorbital flight. By necessity, the circadian rhythm is nearly continuously disrupted in spaceflight. |
| Adequacy of training and preparation | Yes | The time spent and quality of training is determined by the operational team and can be verified through testing before flight. |
| Crew collaboration quality | Yes | This factor can only be evaluated as part of operational preparation. However, the quality of the collaboration may often be out of the control of the operational preparation. |

quality often is. Because training has to by definition be performed well in advance and once a crew member is in remote space, training is often not an option. Therefore, the training that was given, whether directly or indirectly related, becomes a significant factor in whether the activity will be successful.

An additional area that is relevant to NASA operations is the ability to offload some of the on-orbit work to the ground flight control team. NASA Mission Control has teams of flight controllers to support each major discipline, including operations support and operations planning. The operations support officer is responsible for training and planning of IFM procedures. The operations planner develops crew work schedules and operations plans. So, for example, if an unscheduled IFM needed to be performed on the air revitalization system, the operations support officer will coordinate with the operations planner and the Environmental Control and Life Support System officer to develop or modify procedures and schedule the procedure at an appropriate time considering constraints such as daylight cycle, crew workload constraints, and downlink availability. If there is a problem, whole teams of flight controllers can help troubleshoot. It is evident that the support of the ground team will greatly enhance the performance of the procedure compared with the nuclear power industry standard with no outside support.

### *3.6. Modified PSFs*

The proposed procedural modified PSFs are the consistency of procedure format, the procedure verification quality, the activity intention, and the procedure quantity. Procedures can be developed in different organizations within NASA and without. The organizations

**Table XV.** PSFs within procedures, planning, and training

| PSF name | Description |
|---|---|
| Consistency of procedure format | Maximizing the familiarity of procedural format minimizes the risk of procedural misinterpretation. |
| Procedure verification quality | The quality and quantity of ground verification before on-orbit execution of procedures impacts the risk involved in the execution. |
| Activity intention | If a procedure was intended to be performed on spaceflight hardware, the risk is lower than if the hardware was not intended to be used in the way that the procedure requires. |
| Procedure quantity | The more procedures involved in an individual task, the higher the risk of confusion or wrong procedure selection for a given step in an activity. |
| Applicability of training | The closer an on-orbit procedure is to a directly trained task, the lower the risk of error. |
| Recency of applicable training | The more recent the applicable training, the more likely that training is to mitigate risk of error. |
| Repetition of applicable training | The more times applicable training has been performed, the more likely that training is to mitigate the risk of error. |
| Crew prior experience | The more experience the crew has with the specific hardware, software, procedure, ground team, and spaceflight maintenance in general, the less risk is involved in a given maintenance activity. |
| Crew offloading via ground support | If ground commanding, inspection, or verification can replace crew time, risk of crew error is mitigated, although crew situational awareness may drop. |
| Ground failure response | The ability and timeliness of ground response to off-nominal signatures or configurations in maintenance can mitigate risk of erroneous actions. |
| Crew workload management | The appropriate allocation of crew tasking to maximize efficacy can impact the risk of error involved. |

may have different and possibly confusing formats that may not consider the standards of NASA training or operations. Therefore, the consistency of format is an important consideration. The verification of procedures is an issue as it is impossible to verify all possible procedures on the ground to the same degree due to resource constraints and the constraints, or lack of constraints, of microgravity. The activity intention refers to whether the activity was originally intended to be performed on spaceflight hardware. An activity that was not developed to be performed in space may carry higher risk. Procedure quantity can be a problematic with complex systems such as the ISS. For example, malfunction procedure flow charts can be several pages long and link to procedures elsewhere in the same or even different documents. This multitude of procedures increases the risk for confusion or wrong procedure selection.

Astronauts and cosmonauts are highly trained, but even that level of training cannot account for all potential activities. The proposed training-modified PSFs are applicability of training, recency of training, repetition of applicable training, and crew prior experience. The closer, or more applicable, the on-orbit procedure is to a directly trained task, the lower the risk. Risk is also lower for more recently trained tasks. The repetition of applicable training can reduce risk. Crew prior experience reduces risk and includes not only experience during official training but also experience during simulations and spaceflight itself.

A mitigating factor for both procedures and training is the presence of microgravity. Procedures cannot be verified preflight in microgravity conditions, nor can training be performed in microgravity. However, microgravity has a profound effect on operations. Tools may float away unless secured, and the “ceiling” may be a viable workspace. Microgravity can be approximated by NASA KC-135 “vomit comet” or by the Neutral Buoyancy Laboratory for critical tasks, but for most tasks, standard 1-G conditions prevail for crew training and procedure development.

Ground support can mitigate some of the difficulties of spaceflight. The proposed ground support PSFs are crew offloading via ground support, ground failure response, and crew workload management. Some of the work that may normally be performed by the crew can be offloaded to the ground. Ground support teams can send commands and monitor and verify data to reduce crew workload. Flight controllers can aid in malfunction procedures and even form “Tiger Teams” to deal with unforeseen circumstances. The management of crew time by the ground can improve efficiency and reduce crew fatigue. The ground team can consider things such as conflicts over downlink priority for different experiments, crew constraints such as prebreathing requirements before extra-vehicular activity, and other hazard mitigation requirements that would be burdensome to the crew, thus reducing risks.

To more fully understand what aspects of procedures, planning, and training can have the greatest impact in mitigating risk, the subcategories of each are defined in Table XV as modified PFSs. All of these proposed PSFs have the potential to modify risk in ways that are not included in the standard CREAM.

## 4. Conclusion

Spaceflight is extremely expensive, and procedures, training, and planning are optimized by the flight control and training teams to maximize efficiency and mission success. In addition to generic and mission specific training, procedures are worked and reworked to maximize clarity and efficiency. Timelines of crew workload are intricately choreographed to account for crew constraints and experiment and equipment requirements. Finally, probably the most significant difference is the ability to offload some of the work to the flight controllers on the ground and the independent monitoring the flight controllers provide.

HRA identifies, models, and quantifies human error to assess the impact of human actions on a system or task. Human interactions with space hardware and equipment occur during all phases of flight: launch and orbit insertion, nominal on-orbit operations, and in response to anomalous events. Human interactions with equipment on board the ISS can cause catastrophic events through improper actions. With proper training and instruction, the crew may prevent catastrophic events through recovery and control actions. Humans have the ability to deal with complex situations and system interactions beyond the capability of machines. HRA is a method used to assess, qualitatively and quantitatively, the occurrence of human failures in the operation of complex machines that affect availability and reliability. Modeling human actions with their corresponding failure in a PRA provides a more complete picture of the risk and risk contributions. A high-quality HRA can provide valuable information on potential areas for improvement, including training, procedural tasks, and equipment design.

This article performed an HRA CREAM analysis on an ISS HTV Vestibule Configure for Ingress on Node 2 Zenith procedure using standard PSFs. The probability of error using the standard CREAM PSFs was calculated to be 1 in 28. New PSFs specific to the NASA ISS spaceflight environment were identified and justified. PSFs that can be mitigated operationally are identified for further examination. Future research includes using the new PSFs to determine the effects of ideal and common environments and also to identify the type of training that will result in the greatest reduction of error.

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