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Human Reliability Analysis in Spaceflight Applications, Part 2: Modified CREAM for Spaceflight

Jessica Calhoun, Chris Savoie, Mary Randolph-Gips*† and Ipek Bozkurt

Human reliability analysis is a crucial for manned spaceflight success. Cognitive Reliability Error Analysis Model (CREAM) has been developed and used by the nuclear industry in predicting human error. Previously, the authors have calculated the probability error for an International Space Station ingress procedure using performance shaping factors (PSF). In this paper, the procedural risk under both ideal and common conditions using the new spaceflight specific PSFs is calculated. The risk was found to vary from the risk calculated using standard PSFs and to vary greatly depending on the spacecraft specific conditions. Under ideal conditions, the risk was found to be 1 in 88, but under common conditions, the risk was 1 in 3. Then, the new PSFs were used to analyze the impact of the three styles of training used at NASA under common conditions. Of skill-based training, task-based training, and knowledge-based training, the CREAM analysis using the new PSFs showed that skill-based training resulted in the most significant improvement in the risk of human error, from 1 in 3 to 1 in 11. Copyright © 2013 John Wiley & Sons, Ltd.

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1. Introduction

Modeling human error has always been a challenge especially when human performance data is 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. 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. The analysis in this paper will show the importance of updating and maintaining astronaut crew training and procedures in order to reduce the number of human errors performed on-orbit while executing intravehicular maintenance. An analysis of shuttle risk revealed 11 human actions during Shuttle re-entry 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, Heard, Presley, Burg, Mideen, Mongon, Hamlin, and Stewart[1]).

This paper examines training strategies for reducing risk during ISS procedures using the Cognitive Reliability Error Analysis Model (CREAM) analysis. (Hollnagel[2,3]) The CREAM analysis was originally developed by and for Nuclear Power Plant Applications and was adopted by NASA in the early 1990s (Swain,[4] Swain and Guttmann[5]).

The CREAM methodology involves the following steps (Hamlin and Stewart[6]). First, build or develop a list of the cognitive demands for each step of the task. Cognitive demands used for CREAM are observation, interpretation, planning, and execution. Second, identify the types of likely cognitive function failures (CFFs). Each CFF has a cognitive failure probability (CFP) calculated using data from the nuclear power industry. These are listed in Table IV from (Calhoun et al. [7]). Third, determine the specific action failure probability by taking the CFP and modifying it based on the nine common performance conditions (CPCs). An example of a CPC that can significantly affect the failure probability is whether enough time is available to perform the action.

Many of the unique challenges of spaceflight are inherent in the environment. Therefore, the CPCs from the nuclear power industry were examined to determine whether the risk of any of them could be mitigated by operational preparation. Of the nine original CPCs, two were determined to have the potential to be mitigated by operational preparation. The term *operational preparation* implies that the hardware has already been constructed but that the activity has not been completed. The two areas identified were adequacy of training and preparation and availability of procedures and plans. Additionally, an area that is important in spaceflight but not present in the nuclear power industry is the presence of ground support in mission control center. The flight control team serves as a second set of eyes and can also perform some actions remotely.

University of Houston Clear Lake, Houston, Texas, USA

**Correspondence to : Dr. Mary Randolph-Gips, University of Houston Clear Lake, Houston, Texas, USA.*
†E-mail: Randolph-Gips@uhcl.edu

In the previous paper in this series, the relevant spaceflight CFPs and their associated performance shaping factors (PSFs) were modified to better model human actions that are required for ISS mechanisms and maintenance tasks. CFPs use expert determined values to weight each of the four cognitive functions for each CPC. These values are then multiplied together and used to weight each task in a procedure. A detailed explanation of CREAM can be found in the first paper of this series (Calhoun et al.[7]).

Eleven modified spaceflight CPCs and PSFs were identified to more accurately describe and account for procedures, planning, and crew training; all of which play an enormous role in the proficiently and effectiveness of crew performance while performing a task on-orbit. The modified CPC/PSFs also help model safety and mission assurance by identifying weakness in procedural development, task analysis and planning, and crew training techniques. These new PSFs are multiplied along with the existing PSFs to create the weighting factor for each step in the procedure. This paper quantifies a new cognitive model by applying HRA methodologies and the CREAM analysis to determine a more accurate probability of human error.

2. Training, procedures, and ground support

There are three areas of importance in spaceflight that were not accounted for in the original CREAM analysis. The first is the NASA astronaut training regimen. NASA astronauts are extensively trained, but the inescapable fact is that training occurs in a different environment than in which the procedures will be ultimately performed; using flight hardware and in a microgravity environment. Additionally, all procedures cannot be exhaustively trained, and help is only available remotely.

Second, astronauts must perform a diverse list of tasks in a time critical atmosphere. The activities they are expected to perform are far more than can be safely memorized. Therefore there is a heavy on-orbit reliance on written procedures. Availability and adequacy of procedures can have a great impact on mission success.

The third important factor that the original CREAM PSFs did not qualitatively account for was ground support in MCC. The ground acts a redundant set of eyes and ears for the crew members on-board the ISS and significantly reduces human error as the ground has the ability to provide operational support and a two fault-tolerant level of functional redundancy. As the modified CREAM analysis will show, the modified PSFs highlight the importance of ground support, accurate procedures, and effective training as the crew member's task performance can suffer greatly and even result in a catastrophic event without proper consideration of the PSFs and correction if the PSFs are poorly considered.

2.1. Modified PSF weights

The modified PSFs identified in part 1 of this series must first be evaluated then weighted. The evaluation is used to define the PSF and identify a range of significance. Table I lists the modified PSFs, the definition, and their level of significance as it is applied to crew operational support and performance.

Each modified PSF for spaceflight is now weighted according to its significance level in comparison to the crew member's cognitive functions of observation, interpretation, planning, and execution. The factors range from 0.5 to 5 of which the higher the level of operational support and level of preparedness through training and procedures, the lower the weighting factor will be on human performance because the human will have a lesser chance of error though commission or omission. Table II lists the modified PSFs for spaceflight and their assigned weights. The modified PSFs will be combined with the original PSFs that were chosen to remain static and will be multiplied together for each task to yield an overall weighting factor for each task. The overall weighting factor will be applied in a similar manner as the CREAM analysis as it will be applied in step 4 to calculate the adjusted CFP both the mean and median for each task.

3. Maximum performance vs. common performance

In Part I, HRA methodologies and the CREAM analysis were used to determine the probability of human error for the HTV Vestibule Configure for Ingress on Node 2 Zenith using the old PSFs developed for the nuclear power industry. Results indicated that there was a 3.55E-02 or a 1 in 28 probability of human error and that this human error had a high likelihood of occurring while the crew was performing task 2 in which the crew needed to inspect the vestibule for condensation and take appropriate action to clean the area. Condensation on or around the vestibule may have a negative impact later in the procedure when the crew goes to install communication, data, and power lines. Other execution steps such as task 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 CFF potential.

The PSFs play a significant role in identifying the context of the analyzed task and what factors influence human performance. The PSFs can significantly reduce human error or significantly increase human error. In this section, the modified spaceflight PSFs were incorporated into the CREAM analysis to better predict human error as a result of spaceflight factors and constraints. This modified CREAM analysis identified and quantified a new set of basic human error probabilities based on spaceflight factors.

Two human performance scenarios were evaluated using the modified PSFs. The first maximizes the operational, training, procedural, and crew performance levels, and the second is a common median operational, training, procedural, and crew performance levels. To simulate a maximum performance level, the highest significant levels for each factor was selected. The maximum CREAM PSFS are listed in Table III. To simulate a common performance level for the analyzed task, the significant levels for each factor was determined for an average crew member based on an average knowledge level of the analyzed task and nominal training

Table I. Modified PSFs for spaceflight

PSF	Evaluation
Crew Offloading via Ground Support	The level of support and resources provided by the ground controllers for the task or work being performed. Very Efficient / Efficient / Inefficient / Deficient
Ground Failure Response	The ability and timeliness of ground response to off-nominal signatures. Very Efficient / Efficient / Inefficient / Deficient
Crew Workload Management	Level of allocation for crew tasking to maximize efficacy. Supportive / Adequate / Tolerable / Inappropriate
Consistency of Procedure Format	The familiarity of the procedural format for the crew member. Appropriate / Acceptable / Distracting / Deficient
Procedure Verification Quality	The quality and quantity of ground verification prior to on orbit execution of procedures. Supportive / Adequate / Tolerable / Inappropriate
Activity Intention	Was the procedure intended for used on-orbit or use in space? Direct / Indirect / Remote / Unintended
Procedure Quantity	How many procedures are needed to complete the given task? Are multiple procedures referenced in the tasked procedure? None / 1–2 Additional Procedures / 2 or more Additional Procedures / No procedures available
Crew Prior Experience	What is the experience level of the crew member to the specific hardware, software, procedure, ground team, and spaceflight maintenance activity? Every day / Recent or often / Minimal / Never
Applicability of Training	How close is the on-orbit procedure to the trained task? Are they any deltas or changes to the original trained procedure? Directly Applicable / Indirectly Applicable / Not Applicable / Contrary Training
Recency of Applicable Training	The level of training recency to the applicable training. Immediate / Recent / Distant Past / Never
Repetition of applicable Training	The level of repetition of the applicable training performed for the crew member on-orbit and on the ground. Supportive / Adequate / Tolerable / Unacceptable

preparation. The common CREAM PSFs for a common performance level are listed in Table IV. The modified PSFs for both human performance scenarios were combined with the original PSFs which remained static for each task of the HTV Vestibule Configure for Ingress on Node 2 Zenith procedure.

First, the maximum human performance scenario was evaluated. Each weighted factor was multiplied together for each task to yield an overall weighting factor for each task. Table V listed the overall weighting factors for each task. The new overall weighting factors was used to determine the mean adjusted CFP and the median adjusted CFP for each task as seen below in step 5 of the CREAM analysis.

Keeping the recovery action as task 20 as discussed in part 1, a complete dependency level, and a recovery action error factor of 10, the maximum mean adjusted CPF of 4.26E-03 was chosen from the maximum failure probability of each of the 21 tasks. Knowing the mean recovery action calculated previously in step 8, the overall failure probability is the product of the maximum failure probability of the activity and the mean recovery action. The adjusted CFP mean calculated for each step as

$$Adjusted\ \ CFP\ \ Mean\ (\alpha) = e^{\ln(CFP\ \ Median)+\frac{\left(\frac{\ln(error\ \ factor)}{1.645}\right)^2}{2}}$$

The recovery action for this procedure is completely dependent on all prior steps being completed correctly and was calculated in the previous paper as,

$$Recovery\ \ Action\ (mean) = e^{\ln(Mean\ \ Adjusted\ \ Recovery\ \ Action)+\frac{\left(\frac{\ln(error\ \ factor)}{1.645}\right)^2}{2}}$$

The max mean CFP is the maximum of the adjusted CFP means for each step. For this procedure, the max mean CFP occurs in step 2, Inspect Vestibule for Condensation

$$Overall\ \ Failure\ \ Probability = Max\ \ Mean\ \ CPF * Recovery\ \ Action\ (mean)$$

$$Overall\ \ Failure\ \ Probability_{Max\ \ Performance} = (4.26 \in -03) * 2.664 = 1.14 \in -02$$

Thus, the maximum human error probability for the HTV Vestibule Configure for Ingress on Node 2 Zenith task is 1.14E-02. This simply means there is a 1 in 88 probability that the crew will perform a human error while performing this task. This assumes the best possible crew performance, ground performance, and procedural development possible for this task.

Table II. Weighting factors for modified PSFs for spaceflight

Modified CREAM performance factors					
		Cognitive function			
Factor	**Level**	**Observation**	**Interpretation**	**Planning**	**execution**
Crew Offloading via Ground Support	Very Efficient	0.8	0.8	0.8	0.8
	Efficient	1.0	1.0	1.0	1.0
	Inefficient	2.0	2.0	2.0	2.0
	Deficient	5.0	5.0	5.0	5.0
Ground Failure Response	Very Efficient	0.8	0.8	0.8	0.8
	Efficient	1.0	1.0	1.0	1.0
	Inefficient	2.0	2.0	2.0	2.0
	Deficient	5.0	5.0	5.0	5.0
Crew Workload Management	Supportive	0.8	0.8	0.8	0.8
	Adequate	1.0	1.0	1.0	1.0
	Tolerable	2.0	2.0	2.0	2.0
	Inappropriate	5.0	5.0	5.0	5.0
Consistency of Procedure Format	Appropriate	0.8	0.8	0.8	0.8
	Acceptable	1.0	1.0	1.0	1.0
	Distracting	2.0	2.0	2.0	2.0
	Deficient	5.0	5.0	5.0	5.0
Procedure Verification Quality	Supportive	0.8	0.8	0.8	0.8
	Adequate	1.0	1.0	1.0	1.0
	Tolerable	2.0	2.0	2.0	2.0
	Inappropriate	5.0	5.0	5.0	5.0
Activity Intention	Direct	0.8	0.8	0.8	0.8
	Indirect	1.0	1.0	1.0	1.0
	Remote	2.0	2.0	2.0	2.0
	Unintended	5.0	5.0	5.0	5.0
Procedure Quantity	Single Procedure	0.8	0.8	0.8	0.8
	One to Two Additional Procedures	1.0	1.0	1.0	1.0
	Two or More Additional Procedures	2.0	2.0	2.0	2.0
	No Procedures Available	5.0	5.0	5.0	5.0
Crew Prior Experience	Everyday	0.8	0.8	0.8	0.8
	Recent or Often	1.0	1.0	1.0	1.0
	Minimal	2.0	2.0	2.0	2.0
	Never	5.0	5.0	5.0	5.0
Applicability of Training	Directly Applicable	0.8	0.8	0.8	0.8
	Indirectly Applicable	1.0	1.0	1.0	1.0
	Not Applicable	2.0	2.0	2.0	2.0
	Contrary Training	5.0	5.0	5.0	5.0
Recency of Applicable Training	Immediate	0.8	0.8	0.8	0.8
	Recent	1.0	1.0	1.0	1.0
	Distant Past	2.0	2.0	2.0	2.0
	Never	5.0	5.0	5.0	5.0
Repetition of Applicable Training	Supportive	0.8	0.8	0.8	0.8
	Adequate	1.0	1.0	1.0	1.0
	Tolerable	2.0	2.0	2.0	2.0
	Unacceptable	5.0	5.0	5.0	5.0

The same approach was used to determine the human error probability for the second scenario of a common median operational, training, procedural, and crew performance level. Table VI listed the overall weighting factors for each task.

Table III. Modified weighted factors for maximum performance

Maximum CREAM performance factors

Factor	**Level**	**Cognitive function**			
		Observation	**Interpretation**	**Planning**	**Execution**
Crew Offloading via Ground Support	Efficient	1.0	1.0	1.0	0.8
Ground Failure Response	Very Efficient	1.0	1.0	1.0	0.8
Crew Workload Management	Supportive	1.0	1.0	1.0	0.8
Consistency of Procedure Format	Appropriate	1.0	0.8	1.0	0.8
Procedure Verification Quality	Supportive	1.0	1.0	1.0	0.8
Activity Intention	Direct	1.0	1.0	1.0	0.8
Procedure Quantity	Single Procedure	1.0	0.8	1.0	0.8
Crew Prior Experience	Everyday	1.0	1.0	1.0	0.8
Applicability of Training	Directly Applicable	1.0	1.0	1.0	0.8
Recency of Applicable Training	Immediate	1.0	1.0	1.0	0.8
Repetition of Applicable Training	Supportive	1.0	1.0	1.0	0.8

Table IV. Modified weighted factors for common performance

HTV Ingress common CREAM performance factors

Factor	**Level**	**Cognitive function**			
		Observation	**Interpretation**	**Planning**	**Execution**
Crew Offloading via Ground Support	Inefficient	1.0	1.0	1.0	2.0
Ground Failure Response	Inefficient	1.0	1.0	1.0	2.0
Crew Workload Management	Tolerable	1.0	1.0	1.0	2.0
Consistency of Procedure Format	Acceptable	1.0	1.0	1.0	1.0
Procedure Verification Quality	Tolerable	1.0	1.0	1.0	2.0
Activity Intention	Direct	1.0	1.0	1.0	0.8
Procedure Quantity	One to Two Additional Procedures	1.0	1.0	1.0	1.0
Crew Prior Experience	Minimal	1.0	1.0	1.0	2.0
Applicability of Training	Indirectly Applicable	1.0	1.0	1.0	1.0
Recency of Applicable Training	Distant Past	1.0	1.0	1.0	2.0
Repetition of Applicable Training	Tolerable	1.0	1.0	1.0	2.0

The maximum mean adjusted CPF of 1.36E-01 was chosen as the maximum failure probability from each of the 21 tasks. Using the equation below for the overall failure probability, the maximum human error probability for common performance is 3.36E-01

$$Overall\ \ Failure\ \ Probability_{Common\ \ Performance} = (1.36 \in -01) * 2.664 = 3.63 \in -01$$

Thus, there is a 1 in 3 probability that the crew will perform an error in a space environment under average performance factors. This is in comparison to the 3.55E-02 or 1 in 28 probabilities calculated using the traditional CREAM analysis which did not account for space environment factors and operational constraints.

Applying the modified PSFs for spaceflight increased the likelihood of common human error but decreased the likelihood of an ideal human performance level. For the common human error, this resulted in a lower acceptable risk for the analyzed task. This is partly due to the fact that the analysis takes into account more factors influencing the crew member's performance that were not originally taken into account for using traditional PSFs. These modified factors are critical to crew performance and need to be maximize for efficiency, safety, and mission assurance.

Looking at the ideal scenario of a maximum performance level (1 in 88), the analyzed activity through crew offloading and the ground operators provides operational support while monitoring the crew's progress throughout the activity at a very efficient and efficient significance level. By adding redundancy in the form of crew offloading via ground support and crew workload management, the likelihood of a single crew operator failure is reduced. However, if the ground is ill-trained or inattentive during the task progression, an inefficient level results in a higher likelihood of crew error.

Ensuring the consistency of the procedure format and verifying the procedure quality help ensure that the appropriate procedure is being used and has been reviewed by system experts and safety representatives on the ground prior to use. Activity intention also ensures that the procedure(s) needed for the task are readily available and that the correct procedure needed to successfully

Table V. Overall weighting factors for maximum performance

Modified PSFs	Task	Overall weighting factor
Open Node 2 nadir hatch	1	0.011
Inspect vestibule for condensation	2	0.160
Report any condensation to MCC-H	3	0.011
Remove CBM center disk cover	4	0.011
Verify w/MCC-H power cable is safe	5	0.080
Connect power cable to HTV	6	0.011
Notify MCC-H 'Go for HTV power up'	7	0.011
Remove HTV hatch thermal blanket	8	0.011
Connect power cable (2) to HTV	9	0.011
Install Node 2 MPLM 1553 LB-B	10	0.011
Install Node 2 MPLM 1553 LB-A	11	0.011
Remove (4) CBM CPA	12	0.011
Inhibit HTV pressure relief	13	0.011
Equal HTV and ISS cabin pressure	14	0.011
Notify MCC-H of configuration	15	0.160
Install IMV supply jumper	16	0.011
Install ARS jumper	17	0.011
Open Node 2 deck ARS manual valve	18	0.011
Install radial port closeout	19	0.011
Notify MCC-H of task completion	20	0.011
Stow parts, materials, and tools	21	0.011

Table VI. Overall weighting factors for common performance

Modified PSFs	Task	Overall weighting factor
Open Node 2 nadir hatch	1	12.8
Inspect vestibule for condensation	2	0.25
Report any condensation to MCC-H	3	12.8
Remove CBM center disk cover	4	12.8
Verify w/MCC-H power cable is safe	5	0.125
Connect power cable to HTV	6	12.8
Notify MCC-H 'Go for HTV power up'	7	12.8
Remove HTV hatch thermal blanket	8	12.8
Connect power cable (2) to HTV	9	12.8
Install Node 2 MPLM 1553 LB-B	10	12.8
Install Node 2 MPLM 1553 LB-A	11	12.8
Remove (4) CBM CPA	12	12.8
Inhibit HTV pressure relief	13	12.8
Equal HTV and ISS cabin pressure	14	12.8
Notify MCC-H of configuration	15	0.25
Install IMV supply jumper	16	12.8
Install ARS jumper	17	12.8
Open Node 2 deck ARS manual valve	18	12.8
Install radial port closeout	19	12.8
Notify MCC-H of task completion	20	12.8
Stow parts, materials, and tools	21	12.8

complete the task is available. Acceptable, supportive, and direct yield the best human performance since the procedure provides the directions needed to successfully perform a task.

Crew prior experience and proficiency training ensure that the crew member(s) is adequately prepared for the task and has received the necessary instruction needed to successfully complete the analyzed task. While prior experience can often not be controlled, proficiency training done correctly can subsidize a crew member's lack of experience.

A considerable change can be seen by highlighting improvements in training and procedures and by incorporating the ground as a second level of redundancy. The modified spaceflight performance factors provide a unique process for analyzing human performance in spaceflight applications that ultimately yield a better representation of crew human error onboard the ISS.

4. Assessment of training strategies

The object of the modified CREAM analysis for the Spaceflight PSFs is to identify improvements that can be made, particularly in the training strategies. Some of the currently used training strategies are described below, along with how the PSFs and modified CREAM analysis suggest that those training strategies be used.

4.1. Skill-based training

The goal of skill-based training is to teach a base set of skills that can be applied across a variety of tasks, including those that are not specifically trained. In this training, a sample task that includes all of the skills required is often used, and then the skills learned in the task are expected to be performed in a variety of tasks that are not trained. The downside to this training is that the training often does not directly reflect the activity for which the training is created. For example, a cook may be trained to fry food using an egg, but required to fry a fish, a chicken, and a donut without additional training. The upside to this training strategy is that a relatively small amount of training may qualify the student for a large variety of tasks. In the above example, the thought is that if the student can successfully fry one type of food, they have learned the skill of frying and should be able to apply it to any food. This type of training is often used when either little time is available for training or the variety of tasks is such that the training could never accommodate all of the potential tasks.

4.2. Task-based training

The goal of task-based training is to teach the actual task that will be performed in a given activity. In this training, the student is not expected to extrapolate anything learned to additional tasks as in the skill-based training, but they are taught typically to memorize and perform a task in a specific way and will then perform the task exactly as instructed. The upside to this training is that the task that is trained tends to be performed with a very low probability of error. The downside to this training is that in practice, the training of the task often takes several times the amount of time required to perform the task, resulting in a low efficiency of training. This type of training is often used when there is an obvious task with high risk. This training can often be expensive in cost as well as time, as a high fidelity trainer must exist for the student to become well practiced at the task.

4.3. Knowledge-based training

The goal of knowledge-based training is to supply the student with the knowledge required to perform a given activity. The theory is that if the student understands the activity, they should be able to perform it successfully. The upside to this method of training is that the student may often study in their own time, the cost of supported equipment is low since little to no hardware is required for training, and understanding the task allows the student to react autonomously to issues that arise during the task. The downside to this strategy is that the student does not physically interact with hardware until the activity and therefore is unlikely to be familiar with the physical interfaces of the hardware. This can result in incorrect or slow manipulation of the hardware.

4.4. Mitigating error via training

Based on the descriptions of the different training strategies, they can be used to mitigate varieties of error. Task-based training assumes a perfect environment and hardware replication, so even a minor change to the activity may result in a large increase in the human error risk, and unexpected risks are exacerbated by this style of training. Task-based training can, however, mitigate issues in supporting materials, inexperience, and lack of repetition. Skill-based training by definition prevents the training from having completely direct applicability from most actual activities and therefore is designed to specifically add value in circumstances where the crew has to apply skills in an unexpected scenario. Knowledge-based training is likely to allow a crewmember to make up for deficiencies, but will not necessarily have complete applicability to activities performed. Table VII shows the assessed impact of each of the training strategies on the PSFs as the PSFs increase in their negative impact.

Using Table VII to affect the performance factors, values were determined for the HTV Ingress activity as affected by each of the different types of training. The new values are shown below in Table VIII, Table IX, and Table X. Table VIII shows the new values for the HTV Ingress with skill-based training, Table IX with task-based training, and Table X with knowledge-based training.

Based on the values determined for the skill, task, and knowledge-based training, the modified CREAM analysis was used to determine the new risk of human error for a crewmember performing the HTV Ingress activity in space. The assessment of the training strategies attempted to determine how the three most common types of training in human spaceflight would impact the risk of human error in the HTV ingress procedure. The results of the modified CREAM analysis for the training strategies are shown below in Table XI. Table XI also includes the risk of human error for the maximum operational and training support as well as the baseline risk of human error established earlier.

Based on these results, if one type of training must be chosen, the skill-based training offers the highest level of risk reduction, from 1 in 3 to 1 in 11. While this change is a far cry from the 1 in 88 risk level associated with an ideal environment for the activity, it is still the recommended training method based on the CREAM analysis. The second training strategy recommended is the task-based training, improving the risk from 1 in 3 to 1 in 9. This assessment did not take into consideration the potential for using multiple

Table VII. Training impact on PSF numbers

Factor	**Skill-based training**	**Task-based training**	**Knowledge-based training**
Crew Offloading via Ground Support	=	-	+
Ground Failure Response	=	-	+
Crew Workload Management	=	=	+
Consistency of Procedure Format	+	+	+
Procedure Verification Quality	+	+	+
Activity Intention	=	=	+
Procedure Quantity	=	+	=
Crew Prior Experience	+	+	=
Applicability of Training	+	-	=
Recency of Applicable Training	+	=	=
Repetition of Applicable Training	=	+	=

Table VIII. PSF numbers for HTV Ingress with skill-based training

Skill-based training CREAM performance factors					
		Cognitive function			
Factor	Level	Observation	Interpretation	Planning	Execution
Crew Offloading via Ground Support	Inefficient	1.0	1.0	1.0	2.0
Ground Failure Response	Inefficient	1.0	1.0	1.0	2.0
Crew Workload Management	Tolerable	1.0	1.0	1.0	2.0
Consistency of Procedure Format	Appropriate	1.0	1.0	1.0	0.8
Procedure Verification Quality	Adequate	1.0	1.0	1.0	1.0
Activity Intention	Direct	1.0	1.0	1.0	0.8
Procedure Quantity	One to Two Additional Procedures	1.0	1.0	1.0	1.0
Crew Prior Experience	Recent or Often	1.0	1.0	1.0	1.0
Applicability of Training	Directly Applicable	1.0	1.0	1.0	0.8
Recency of Applicable Training	Recent	1.0	1.0	1.0	1.0
Repetition of Applicable Training	Tolerable	1.0	1.0	1.0	2.0

Table IX. PSF numbers for HTV Ingress with task-based training

Task-ased training CREAM performance factors					
		Cognitive function			
Factor	**Level**	**Observation**	**Interpretation**	**Planning**	**Execution**
Crew Offloading via Ground Support	Efficient	1.0	1.0	1.0	1.0
Ground Failure Response	Very Efficient	1.0	1.0	1.0	0.8
Crew Workload Management	Tolerable	1.0	1.0	1.0	2.0
Consistency of Procedure Format	Appropriate	1.0	1.0	1.0	0.8
Procedure Verification Quality	Adequate	1.0	1.0	1.0	1.0
Activity Intention	Direct	1.0	1.0	1.0	0.8
Procedure Quantity	Single Procedure	1.0	1.0	1.0	0.8
Crew Prior Experience	Recent or Often	1.0	1.0	1.0	1.0
Applicability of Training	Not Applicable	1.0	1.0	1.0	2.0
Recency of Applicable Training	Distant Past	1.0	1.0	1.0	2.0
Repetition of Applicable Training	Adequate	1.0	1.0	1.0	1.0

Table X. PSF numbers for HTV Ingress with knowledge-based training

Knowledge-based training CREAM performance factors					
		Cognitive function			
Factor	**Level**	**Observation**	**Interpretation**	**Planning**	**Execution**
Crew Offloading via Ground Support	Efficient	1.0	1.0	1.0	1.0
Ground Failure Response	Efficient	1.0	1.0	1.0	1.0
Crew Workload Management	Adequate	1.0	1.0	1.0	1.0
Consistency of Procedure Format	Appropriate	1.0	1.0	1.0	0.8
Procedure Verification Quality	Adequate	1.0	1.0	1.0	1.0
Activity Intention	Direct	1.0	1.0	1.0	0.8
Procedure Quantity	One to Two Additional Procedures	1.0	1.0	1.0	1.0
Crew Prior Experience	Minimal	1.0	1.0	1.0	2.0
Applicability of Training	Indirectly Applicable	1.0	1.0	1.0	1.0
Recency of Applicable Training	Distant Past	1.0	1.0	1.0	2.0
Repetition of Applicable Training	Tolerable	1.0	1.0	1.0	2.0

Table XI. Risk of human error in spaceflight operations

CREAM performance factors	Human error probability	1 in X likelihood
Maximum Support and Training	1.14E-02	1 in 88
HTV Ingress Common	3.63E-01	1 in 3
Skilled-Based Training	9.44E-01	1 in 11
Task-Based Training	1.16E-01	1 in 9
Knowledge-Based Training	1.82E-01	1 in 6

training strategies for the same activity, but as shown in Table VII, the training strategies have different effects on different areas. It is possible that using a combination of them may result in further risk mitigation.

5. Conclusion

Modeling human error has always been a challenge in aerospace because performance data is not always readily available, and when data is available, it is often classified as sensitive. For spaceflight, the challenge is amplified because there are a small number of participants, limited amounts of performance data, and often a lack of definition of the unique factors influencing human performance in space. PSFs, in HRA terminology, are used in HRA modeling techniques to modify basic human error probabilities in order to capture the context of an analyzed task. Unfortunately, many human error modeling techniques were developed within the context of nuclear power plants, and therefore the methodologies do not address spaceflight factors and operational standards and practices for the space industry. In this paper, spaceflight specific PSFs were developed to reflect the unique conditions of spaceflight. They were used to assess risks in both an ideal and a common environment for an ISS HTV Ingress procedure. Using the new PSFs, the likelihood of error was calculated to be 1 in 88 for an ideal environment, and 1 in 3 for a common environment. The likelihood of error using standard PSFs was calculated to be 1 in 28. The great variance in the results highlights the importance of including spaceflight specific environmental factors in assessing the risks of spaceflight.

The type and quality of training are significant contributors to mission success. After the new PSFs were developed, common conditions were used to determine a baseline risk level for the subsequent assessment of potential training strategies. Of the three strategies considered, task, skill, and knowledge, skill-based training was found to have the lowest risk of 1 in 11. In tight budgetary times, being able to quantitatively justify high cost/high risk decisions such as training strategies is invaluable in assuring mission success.

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