Human Reliability in Spacecraft Development:
Assessing and Mitigating Human Error in Electronics Assembly

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1.0 Introduction

Integral to the proper functioning and reliability of any spacecraft are the proper design, fabrication, assembly, and integration of its electrical and electronic systems. A critical look at the composition of such spacecraft systems reveals a preponderance of circuits built on printed wiring assemblies (PWA). Considering the highly complex process of spacecraft development and the stringent reliability and performance requirements imposed on operational spacecraft, it is apparent that human reliability during the development process is a factor in the quantification of overall spacecraft system reliability.

This paper presents the development and application of Human Reliability Analysis (HRA) methods to specifically analyze the human error associated with the task of applying a polymeric coat onto a printed wiring assembly, a process also known as conformal coating. The polymeric coat serves to protect electronic circuitry against moisture, chemical contaminants and corrosion, extremes of temperature, and dust particles. The conformal coating is typically specified to protect against the particular space environment to which the spacecraft will be subjected. Subsequently, improper application potentially leads to loss of electro-electrical functionality.

Yet a closer look at the development process shows the high degree of interface and contact between the human fabricator and the system in development however, traditional system reliability analysis does not address the issue of human error introduced during the manufacturing and integration phase. It is assumed that quality assurance and quality control standards and processes will eliminate these workmanship-related defects. Acknowledging that no system or process is perfectly capable of arresting quality escapes in manufacturing, fabrication, and integration, how then can one account for human error in the absence of more modern and precise machine controlled processes?

In the context of polymeric application, we will need to establish the boundaries of human error by defining the scope and then decide on the methods and tools relevant to analysis of human error. Human error in this process shall be defined as an action, or omission of action, by a technician, which detracts from reaching a specific target end state; in this case, the perfect application of the appropriate polymeric coat on a PWA.

2.0 HRA Overview

HRA[1] is the process of modeling the likelihood and consequence of human error and the subsequent impact on the reliability of a system. These methods were divided into first and second generation methods, discussed in subsequent sections.

2.1 First Generation Methods

Early methods of HRA, often referred to as the First Generation Methods (FGMs) developed in the 1980s, were based on modeling the human operator as a component within the system,

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whereby the failure of the "human component" and the effects of its consequence on the system could be traced through a fault tree [2]. FGMs treated human error in a similar fashion as component failures in fault tree analysis. Error probabilities could then be assigned to these human errors. An attribute of FGMs is the decomposition of errors in to two basic types; errors of omission, a case where an operator fails to respond to an event, and errors of commission, a case where a human performed an unintended action.

FGMs in HRA include; Technique for Human Error Rate Prediction (THERP)[1], Success Likelihood Index Method (SLIM)[3], Standardized Plant Analysis Risk-Human Reliability Analysis (SPAR-H)[4], Human Cognitive Reliability Method (HCR)[5], and Human Error Assessment and Reduction Technique (HEART)[6].

2.2   Second Generation Methods
FGMs proved insufficient for characterizing the effects cognitive and human behavioral processes. Another limitation of the first generation methods is the inability to account for dependence of human errors on the dynamic evolution of incidents [7].
The solutions to these limitations represented a breakthrough and resulted in the development of second generation methods [7]. Some of these methods include; A Technique for Human Event Analysis (ATHEANA)[8], Assessment Method for the Performance of Safety Operation ("Méthode d'Evaluation de la Réalisation des Missions Opérateurs pour la Sûreté ") MERMOS [9], and Cognitive Reliability and Error Analysis Model (CREAM)[10]. These methods were based on four main components: 1) a cognitive model of human behavior; 2) a taxonomy or classification; 3) a database; and 4) a formal application method [7].

2.3   Application of HRA in Space Industry
HRA methods have been applied to the NASA and the Space Industry. Most recently, probabilistic risk assessment (PRA) performed on the Space Shuttle included a Space Shuttle HRA. Also the International Space Station PRA[11] included an HRA. The NASA Shuttle PRA used the Technique for Human Error Rate Prediction (THERP) as a screening tool and evaluated pre-initiating events (Shuttle ground processing errors), initiating events (crew errors), and post initiating events (crew errors) using CREAM. The International Space Station program, chose to identify human errors in their accident scenarios rather than explicitly quantifying the contribution of human error to risk [12].

3.0   Method Development
HRA utilizes a set of tools to estimate the probability of human error in the context of a PRA. An HRA methodology must include a procedure for generating qualitative and quantitative results. It must also be based on a causal model of human response rooted in cognitive and behavioral sciences. Finally, it must be detailed enough to support data collection, and empirical and theoretical validation.

The method presented in this paper is based on a task analysis, which identifies and lists potential unsafe acts. Performance Shaping Factors (PSFs) that contribute to the unsafe acts are also identified and cross-linked with the unsafe acts. Existing HRA methods were then evaluated for use by comparing each method's responsiveness to a set of assessment questions.

3.1   Task Analysis

Several task analysis methods were considered, such Hierarchical Task Analysis, Cognitive Task Analysis, and Procedural Task Analysis (PTA). A Procedural Task Analysis (PTA), based on NASA Workmanship Standards[13], was selected due to its relevance in addressing the cognitive and physical actions required of the human to successfully complete the primary task A description of the human-system interface is used to provide the requisite contextual basis to guide the proposed HRA.

The PTA was performed using a series of task flow diagrams. The first step in the PTA was to decompose the primary task into a four secondary tasks that could still be further discretized depending on the desired fidelity of the HRA. The benefit of this approach is that the essential framework for the HRA can then be applied to all levels of tasks in the polymeric application process.

The four secondary tasks are each assigned a unique identifier for ease of reference and for place keeping. They are listed as follows; Surface Preparation, Chemical Preparation, Chemical Application, and Curing and Demasking. Each secondary task is further decomposed into a set of discrete task steps. These discrete task steps are also assigned unique identifiers that link them back to their parent secondary task. These task flow diagrams aided in the identification of purely cognitive task steps and physical task steps.

3.2 Unsafe Acts

After completion of the PTA, another decision tool was introduced – a comprehensive list of Unsafe Acts (UA), grouped according to the pertinent secondary task, Table 3-1. Each UA was assigned a unique identifier for reference and place keeping. The completed PTA facilitated identification of the UAs by allowing an assessment of what could go wrong at each step in the four task flow diagrams. Recognizing that each task flow step fit into one or two categories of human action; cognitive or physical, it is then possible to evaluate potential behavioral theories and models from these two broader human factors areas that would apply to the each UA.

Table 3-1 Sample Unsafe Acts List

Identifier	Unsafe Acts for Surface Preparation Task
1	Inadequate surface cleaning
2	Improper execution of Ionic Contamination Test
7	Incorrect application of masking
8	Application of masking in areas not specified by engineering specifications

3.3 Performance Shaping Factors

PSFs are used in HRA to characterize the dimensions – cognitive, social, emotional, and physical – of human response. They aid in understanding why human error occurs and are classified as social, personal, organizational, and or technological. A natural consequence of developing the list of UAs is the ability to document a set of PSFs and link the UAs to the top-level categories of PSFs; social, personal, organizational, and technological.

3.4 Method Evaluation

The evaluation of existing HRA methods for this application was performed by addressing a set of 11 questions, which allowed for a cross-method comparison of the essential elements of any HRA. The evaluation allows for identification of deficiencies in any single method that can be compensated for by adopting a particular aspect of another method.

Table 3-2 HRA Method Evaluation Questions

3.4.1.1.1.1.1	1. Are generic or context/operator-specific tasks required?	3.4.1.1.1.1.2	7. Are task and PSF dependencies necessary?
2. Are generic or context/operator-specific PSFs required?		8. Is consideration of error recovery a necessary component?	
3. Is a screening method required?		9. Do uncertainty bounds need to be estimated?	
4. What type of HEP source is appropriate (analysis or method)?		10. What knowledge level is required for HRA implementation?	
5. Is current data available (type, source)?		11. Is a software implementation tool available?	
6. Has this method been validated for the context in question?			

The 11 questions were structured to highlight the suitability of each of the essential elements of an HRA. Figure 3-1 illustrates assessment of HRA methods against Question 9. The elements addressed were: task decomposition; number of PSFs; human factors coverage; source of Human Error Probability (HEP); error mode-specific HEPs; treatment of task/error dependencies and recovery; uncertainty bounds estimation; required knowledge level for use; industry applicability or experience base; and software implementation availability. Comparing the method-specific task decomposition – typically presented as a set of generic tasks – with the polymeric application task analysis ensures that each method is vetted for suitability. Also, the link between task, unsafe act, and PSF, combined with the cross-method comparison to aid in the method selection.

Figure 3-1 HRA Method Assessment Example

Method	Screening	Primary Source for HEP Estimates		HEPs for Specific Error Modes	Explicit Treatment of		Uncertainty Bounds Estimation
		Number provided by method	Number produced by analyst		Task/Error Dependencies	Recovery (includes actions with feedback)	
THERP	√	√		Detailed and many	√	√	√
NARA		√		None specified			
SPAR-H		√		Diagnosis & Action	√	√	√
ASEP	√	√		Diagnosis & Action	√	√	√
SLIM			√	None specified			
HEART		√		None specified			
ATHEANA			√	Expert judgment	√	√	√
CREAM	√	√		13 error modes			√

The use of the decision tools resulted in the selection of the combination of CREAM and the HEART.

Eric Hollnagel developed CREAM in 1998 after an analysis of HRA existing methods and based on the Contextual Control Model [14]. The method is applicable to retrospective analysis as well as to performance prediction. It is based on a distinction between competence and control, utilizing a classification scheme that separates causes and manifestations, also referred to as genotypes and phenotypes respectively [15].

CREAM method identifies 9 Common Performance Conditions CPCs, which are individually assessed for an Expected Effect on Performance Reliability (EEPR) based on a possible CPC state. CPCs are assumed to exist in various possible states depending on the particular CPC. Similarly, the EEPRs are assumed to have potential impacts on an operator's performance

ranging from; Improved, Not Significant, and Reduced. Each EEPR is associated with a CPC State. A description of EEPR and CPC is available in the literature [10]. The pertinent Control Mode identifies the differing levels of control that an operator has in a given context and the characteristics which highlight the occurrence of distinct conditions [2]. The control modes are available in the literature. CREAM applies a set of CPCs to a particular setting in order to establish the applicable control mode. The applicable control mode is then indicative of the expected level of reliability in the given setting. This is possible because each control mode is assigned a predetermined reliability interval as shown in the Table 3-3 below.

Table 3-3 CREAM Control Modes and HEP [10]

Control Mode	Reliability Interval (probability of failure)
Strategic	$0.5E-5 < p < 1.0E-2$
Tactical	$1.0E-3 < p < 1.0E-1$
Opportunistic	$1.0E-2 < p < 0.5E-0$
Scrambled	$1.0E-1 < p < 1.0E-0$

CREAM in its current state does not provide for explicit treatment of Error Dependencies nor Error Recovery (Reduction), this is made evident in the method evaluation by addressing Question 8 for the HRA methods in the same manner as Question 9 (figure 3-1); given these two limitations one can adopt the error reduction techniques proffered by the HEART method to address the latter. However, task or error dependency methods as presented in other HRA methods are largely subjective and do not offer a viable solution. These dependency factors are similar to common cause factors in system reliability analysis, however they have not been validated for cross-context implementation in HRA.

HEART is an HRA method based on the premise that human reliability is dependent upon the nature of the task to be performed. The method also supposes that this level of reliability will be consistently achieved within uncertainty limits given perfect conditions. Given these two premises, the method also assumes that in the absence of perfect conditions, human reliability degrades as a function of the applicability of Error Producing Conditions (EPCs)[6].

To facilitate combining both methods in order to eliminate the error reduction deficiency in the CREAM, a comparison of the 9 CPCs used in CREAM and the 38 EPCs [6] used in HEART was conducted. This PSF comparison provided the relationship between both methods and served to link the error reduction techniques given for the HEART EPCs to the CREAM CPCs.

Combining aspects of CREAM and HEART results in Cognitive Reliability and Error Analysis Method with Error Reduction Techniques (CREAM+RT), adopted based on a contextual task analysis and satisfactory responsiveness to the essential characteristics of a complete HRA method. This new composite method, CREAM+RT, still lacks a method for addressing error dependency, however, the introduction of this component could potentially introduce another layer of analyst subjectivity to the method thereby decreasing the confidence level in the method.

A key motivator for the selection of the CREAM as the foundational method is rooted in the method's ability to address basic types of human functions – cognitive, physical, and social. The method discretizes human function into four areas: observation, interpretation, planning, and execution. Each of these can be used to describe the individual steps outlined in the PTA.

3.5   CREAM+RT Overview

CREAM+RT is a composite HRA method that is based entirely on the SGM CREAM albeit with a slight modification which allows for incorporating reduction techniques derived from the HEART. This modification, as discussed in the preceding section, is the inclusion of the reduction techniques presented in the HEART method by evaluation of similar PSFs of both methods.

A detailed description of the task to be analyzed is developed to allow decomposition into subtask. This is usually performed as a task analysis. The subtasks can be matched to one of the method-specified cognitive activities. CREAM specifies 15 cognitive activities available in the literature [12]. The next step is the identification of the applicable cognitive activity for each subtask identified in the task analysis. The third step is to identify the associated human function for each subtask. As earlier stated, CREAM prescribes for human functions; observation, interpretation, planning, and execution.

In the next quantitative step, the basic human error probability (BHEP) for each subtask is determined. This is achieved by determining failure modes that result from human functions and then, associating them with a BHEP and CREAM-specified uncertainty bounds.
Following their initial quantification, adjustments due to CPC effects are made to the BHEP of the subtasks. CREAM specifies adjustment factors based on the CPC states [12]. The final step is to calculate the task HEP based on the adjusted BHEP of the subtasks. Utilizing the reduction techniques adapted from HEART, mitigation and control strategies can then be proposed in order to buy down the risk or error probability identified through the CREAM process.

The advantages of the proposed CREAM+RT include the following: allows for direct quantification of HEP, allows for contextual tailoring that explicitly fits the situation under assessment, results are readily adaptable to overall system reliability and safety analysis, allows for retrospective and predictive analysis, provides a concise, structured, and highly repeatable process, provides a set of error reduction techniques, and allows for assessment of the impact of error reduction techniques

The limitations of the proposed CREAM+RT method include the following: it is resource intensive, it may be time intensive depending on the level of analysis; and it requires a level of expertise in the field of human factors. The time intensiveness can be mitigated by the repeatability of the process, hence once a suitable framework is established for a large HRA effort, the process becomes more streamlined.

3.6   HRA Method Classification

Any analysis method must refer to a consistent classification scheme that is relevant for the domain under investigation [10]. Furthermore, the classification scheme must refer to a set of supporting theoretical principles; these principles are collectively referred to as the model. The classification scheme employed in defining the categories of effects and causes should be clearly traceable to the applicable model. The CREAM+RT method classification scheme is identical to CREAM classification and based on delineation between causes or genotypes and manifestations or phenotypes.

Genotypes are divided into three categories (individual, technological, organization). The first, **individual**, contains those causes that have a link to behavior such as personality and emotional state. The second category, **technological**, contains factors that are related to the human-system interface and interaction. The third category, **organizational**, includes those that are dictated by

the organization such as local environment [2]. These three genotypes are fully described in the literature[16]:

Phenotypes are manifestations that result due to operator actions or omissions of actions. There are eight basic error modes or phenotypes that are divided into four sub-groups. The sub groups and error modes are also available in the literature[16].

The advantages of this classification scheme include the ability to predict and then describe how an error would occur. It also allows one to define the links between the genotypes and the phenotypes pertinent to the analysis. The classification scheme allows coverage of the three aspects of human function ensuring an exhaustive look at the task and potential sources of error.

3.7 Model Theory Development

Cognitive theories guide the CREAM+RT model. The foundational method of CREAM+RT, CREAM, is based on the Contextual Control Model (COCOM) [14]. The COCOM is discussed in below, however the basic concept posits that the degree of control an operator holds determines the reliability of their performance [16] as a consequence operator control is directly proportional to reliability of their performance

The COCOM is a model of human behavior that advocates the study of how a person's ability to maintain control of a situation enables effective control of a process or system on which they are working. This model is a deviation from the traditional study of human cognition which tends to focus on the cognition of the individual [17].

The PTA results show the criticality of cognitive ability to several key steps in the process. Additionally the UAs identified via the PTA direct the model selection towards a model that is largely based on cognitive theories. These cognitive theory principles range from perceptual principles, to principles of detection and understanding. A survey of the UAs listed for this task reveals several instances of correlation between an act and a cognitive theory. An example is the unsafe act "Underestimation of amount of Precipitate in Part A". This UA is clearly contrary to the first Perceptual Principle; "Avoid judging the level of a variable (e.g. loudness, color, size) which contains more than 5 to 7 possible levels.

The theoretical model of CREAM+RT also incorporates other elements of human behavioral modeling. These include information processing, type of response, human capacity and tendency, social and organizational influences.

The relevance of these additional dimensions of human behavior modeling to the CREAM+RT model is demonstrated here in relation to the UAs. Looking specifically at a single UA and its consequence, the applicability of social and behavioral models to the human error is shown.

Investigation of the failure of an electronic board in the power distribution unit of a spacecraft during testing revealed that the failure mechanism was a short circuit of the electronic board. The root cause has been identified as conductive debris on the printed circuit board (PCB) during the conformal coating process. The specific human error that led to this failure has been identified as: Improper surface preparation of the PCB before spraying of the conformal coating material.

To identify the appropriate theory for evaluating this error, an assumption is made that all steps in the conformal coating process where executed. A resultant concern is performance of each step. It is noteworthy that in the polymeric process, which includes staking and bonding of components, conformal coating is the last step prior to delivery for thermal bake-out and integration. Schedule

pressure may become a valid PSF, which would directly impact the thoroughness of each executed step.

The Theory of Planned Behavior (TPB) posits that *behavior may not always be under volitional control.* TPB also proposes that behavioral control represents the perceived ease or difficulty of performing the behavior. The theory further states that behavioral control is impacted by knowledge of relevant skills, experience, emotions, and external circumstances. The TPB is based on the Theory of Reasoned Action (TRA), which states that intent to perform is a critical determinant of behavior. TRA further states that intention is influenced by attitude towards the action, behavioral expectations of the individual's social network, and motivation to comply with others' wishes.

Evaluating the applicability of these theories to the human error study at hand requires some understanding of the social structure in the organization. Technicians who rank much lower in the organization than design engineers perform PWA tasks in accordance with engineering design specifications and industry workmanship standards. The design engineers are usually under management pressure to deliver products on schedule and on budget. These pressures are communicated to technicians.

The following is a one-to-one mapping of the elements of the applicable theories to the Human Error incident.

Table 3-4 Theory Element Manifestation

Theory Element	Possible Manifestation
TRB: behavioral control represents the perceived ease or difficulty of performing the behavior	Technician is very conversant with process of spraying-cleaning a board and may or may not regard it as trivial
TRB: behavioral control is impacted by knowledge of relevant skills, experience, emotions, and external circumstances	Technician is under pressure to complete the conformal coating
TRA: intention is influenced by attitude towards the action	Technician is performing a cleaning action and assumes that debris cannot be generated but removed
TRA: intention is influenced by behavioral expectations of the individual's social network	Technician is expected to perform the task without questioning engineering decisions
TRA: intention is influenced by motivation to comply with others' wishes.	The technician ranks lower than the engineer in the organizational hierarchy and relies on engineering documents for guidance

From the aforementioned it is apparent that a theoretical model that addresses cognitive, social, and behavioral effects on human performance is desired. Understanding the attributes, specifically the CPCs and cognitive activities, antecedents and consequences, and error modes, of the foundational CREAM on which CREAM+RT is based allows a wider appreciation of the encompassing nature of its underlying model.

3.8 Data Collection

Any analysis is only as reliable as the data on which it is based. However before embarking on the pursuit of reliable data, we must first define data as pertains to the polymeric application process. There are two main categories of data that are potentially applicable in this context–objective data and subjective data. Objective data is a measurable representation of facts while subjective data contains a level of personal interpretation of the facts. The pertinent data in this case includes the number of instances of human error during conformal coating resulting in either

a test or operational anomaly. This type of data is clearly objective and will be truncated to exclude errors and defects found during the post-process inspection of the PWA as these errors are remediated by reworking the PWA. Subjective data is also required but more so in establishing the contextual details of the conformal coating process. The subjective data supports the development of an accurate task analysis and the crosslinking of unsafe acts to personal performance shaping factors.

A list of data necessary for such analysis is provided below:

- Number of electronics failures attributed to human error during conformal coating
- Root cause information on actual error that caused the board failure
- Instantiation of the various root causes (a count of occurrence of an unsafe act that resulted in a failure)
- Number of conformal coated PWA boards
- Number of conformal coated PWA per electronics box – box level
- Time duration of performing the conformal coating task
- Contextual information

Given the data required to quantify the HEP in conformal coating, it is apparent that a record of anomalous events is required and would prove a satisfactory resource for the analysis. Such data support retrospective statistical analysis of such anomalous events and can serve as the validation of the predictive abilities of the HRA method used.

Spacecraft development processes and standards require collection of anomaly and problem failure data starting from the acceptance and qualification testing phase [18]. Most space system development efforts require a centralized closed-loop tracking system tracking system for documentation of anomalies, problems, and test failures. This centralized database system is essential for root cause documentation in addition to failure investigation. The data collection process for performing the proposed analysis will entail review of the spacecraft developer's anomaly and problem database and identifying each instance of component failure attributed to human error during conformal coating.

3.9   Data Analysis
This section documents the CREAM+RT analysis performed on the conformal coating process. An overview of the HEP calculation steps has been provided in Section 3.1.

From the PTA, the four secondary tasks are further decomposed in to discrete subtask steps. The secondary task and the number of associated subtask step are listed below.

1. Surface Preparation – 12 subtask steps
2. Chemical Preparation – 19 subtask steps
3. Chemical Application – 17 subtask steps
4. Curing and De-masking – 5 subtask steps

There are 53 total subtasks identified for the process.

3.9.1   HEP Calculation using CREAM+RT
Below is the list of all the subtasks in the Surface Preparation Secondary Task with their attendant identifier. Note that only error-inducing tasks are steps are included. Steps such as "return to engineering" are not considered since they do not induce error. The preceding numbers are included as the subtask identifiers.

1. Surface Preparation
   - 1.1. Is conformal coating with Arathane 5750 A/B specified?
   - 1.2. Clean the surface with Isopropyl Alcohol (IPA)
   - 1.3. Record Time of Cleaning
   - 1.4. Perform Ionic Contamination Test per ICT process
   - 1.5. Did surface pass the ICT?
   - 1.6. Record Oven Time-In (OTI)
   - 1.7. Bake-out PWA per Bake-out Process
   - 1.8. Record Oven Time-Out (OTO)
   - 1.9. Is present time within 8 hours of OTO?
   - 1.10. Apply masking in areas specified in engineering drawing
   - 1.11. Is present time within 8hrs of OTO?
   - 1.12. Apply Arathane 5750 per Chemical Application Process

The next step is to identify the type of cognitive activity associated with each subtask from the 15 activities specified by the CREAM+RT method. The following table, Table 3-5, is an extract of a matrix that links the steps to the cognitive task.

Table 3-5 Subtask-to-Activity Linking

Cognitive Activity	Description	Subtask #
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, etc.	1.1
Compare	Examine the qualities of two or more entities (measurements) with the aim of discovering similarities or differences. The comparison may require calculation.	1.9 1.11

The next step is to identify the type of human function associated with each subtask and the HEPs. The error modes, based on CREAM error modes, within each of the four types of human function are as follows:

- Observation (O1 – Wrong Object observed, O2 – Wrong Identification, O3 – Observation not made)
- Interpretation (I1 – Faulty Diagnosis, 12 – Decision Error, 13 – Delayed Interpretation),
- Planning (P1 – Priority Error, P2 – Inadequate Plan)
- Execution (E1 – Action of Wrong Type, E2 – Action at Wrong Time, E3 – Action on Wrong Object, E4 – Action of Sequence, E5 – Miss Action).

The UAs associated with the Surface Preparation Task are:
1. Inadequate surface cleaning
2. Improper execution of Ionic Contamination Test (ICT)
3. Misreading of ICT Data
4. Misinterpretation of Engineering Bake out Data (data includes temperature and time for the PWA)
5. Error in recording Oven Time In (OTI) and/ or Oven Time Out (OTO)
6. Error in assessing length of time since OTO
7. Incorrect application of masking

8. Application of masking in areas not specified by engineering specifications

CREAM+RT specified error modes are assigned to the unsafe acts as follows:

1. Inadequate surface cleaning with IPA → E5
2. Improper execution of Ionic Contamination Test (ICT) →E5
3. Misreading of ICT Data →O2
4. Misinterpretation of Engineering Bake out Data (data includes temperature and time for the PWA) →O2
5. Error in recording Oven Time In (OTI) and/ or Oven Time Out (OTO) →E1
6. Error in assessing length of time since OTO →I1
7. Incorrect application of masking →E5
8. Application of masking in areas not specified by engineering specifications →E3

The "X"s in Table 3-6 correspond to the specific error mode ascribed to the UAs associated with the task. For example, there are three separate E5 errors.

Table 3-6 Error-Specific HEP Determination Matrix[12]

Type of Functional Failure BHEP Type of HSI Activity	Type of Human Function												
	Observation			Interpretation			Planning		Execution				
	O1	O2	O3	I1	I2	I3	P1	P2	E1	E2	E3	E4	E5
	1E-3	3E-3	3E-3	2E-1	1E-2	1E-2	1E-2	1E-2	3E-3	3E-3	5E-4	3E-3	3E-2
Coordinate													
Communicate													
Compare													
Diagnose					x								
Evaluate													
Execute											x		x x x
Identify		x x											
Maintain													
Monitor													
Observe													
Plan													
Record									x				
Regulate													
Scan													
Verify													

The next step is to adjust the basic HEPS with the CPC coefficients. For simplicity, we will assume that all CPC states are optimal. The CPC states should in reality be determined by collected contextual and objective data.

The most likely HEP is the final task HEP, calculated from the following equation:

$$Final\ HEP = Prob(Most\ Likely\ Error\ Mode|Activity\ Type)$$
$$\times \prod_{i-1}^{9} Adjustment\ Coefficient\ of\ CPCs$$

The calculated Final HEP is 0.0201 and is representative of performance reliability in the Strategic Control Mode. It is important to note, however, that the HEP calculation assumed the most positive CPC states.

4.0 Conclusion

The contextual control model informs the risk assessment process given that it is the basis for the HRA method. Increasing the operators' proficiency in the four CREAM+RT cognitive functions, but specifically the execution function, will improve operator performance reliability. The results support the fact that a large contribution of human error in this process can be attributed to the higher level Personal PSF that is related physical and cognitive ability.

Given availability of resources, a suitable risk mitigation strategy would address all three unsafe acts. However, a higher fidelity analysis may be required to fully discriminate amongst the three and select the most likely contributor. This higher fidelity analysis would necessitate collection of more contextual and personal data.

The proposed HRA method leverages the attributes of existing HRA techniques and is extremely implementable given the existence of policies, procedures, and organizational resources currently in place. These policies and procedures -- such as the NASA Workmanship Standards, IPC J-Standards, NASA Handbook for Program Managers and Program Management of Problems, Nonconformance, and Anomalies, organizational plans, procedures, tools and databases for implementation of NASA and industry standards -- all can serve to facilitate implementation of this method.

To implement this method, spacecraft development organizations would need to establish a framework to periodically analyze the anomaly, problem, and failure reporting system data. The data would directly inform the HRA and alert program management of risk areas associated with the human element in the development process. Spacecraft requirements include system reliability analysis; these requirements could be expanded to require, at a minimum, a preliminary HRA based on the CREAM+RT. Analysis results that are indicative of unacceptable HEPs (based on the control modes) would trigger risk mitigation activities and in light of cost benefit analyses, stakeholder acceptance would be anticipated.

A limitation of the CREAM+RT is that it does not account for task or error dependency, although dependency is implicitly accounted for in the treatment of the genotypes and phenotypes. As was stated earlier, this dependency modeling is structurally similar to common cause modeling in system reliability analysis. Common cause failure modes are identified and then modeled explicitly for their contribution to overall system failure; as a consequence, component-specific failure modes are then adjusted to account for the common cause failures. Such a practice has been proven and validated for system and component reliability, however in the realm of HRA, it only serves to introduce additional analyst subjectivity. Decisions on how to assign weighting or adjustment factors on error-specific HEPs for cross-context tasks by analysts would devolve into arbitrary guesses since no validated method exists. It is in light of this that CREAM+RT is presented without error dependency. Investigating improvements on this deficiency could benefit from using the common cause failure modeling as a starting point.

The far-reaching impacts of human error during the fabrication phase of spacecraft require that a structured and methodical yet easily implementable approach be adopted for identifying and arresting these consequences. It is in consideration of this circumstance that the CREAM+RT HRA method is proposed. The *a priori* and a *posteriori* knowledge of cause and effect as related to human error would significantly improve system reliability for the high cost yet indispensable technological marvels known as spacecraft.

5.0 References

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