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ANALYZING HUMAN ERRORS IN FLIGHT MISSION OPERATIONS

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Abstract

A long-term program is in progress at JPL to reduce cost and risk of flight mission operations through a defect prevention/error management program. The main thrust of this program is to create an environment in which the performance of the total system, both the human operator and the computer system, is optimized. To this end, 1580 Incident Surprise Anomaly reports (ISAs) from 1977-1991 were analyzed from the Voyager and Magellan projects. A Pareto analysis revealed that 38% of the errors were classified as human errors. A preliminary cluster analysis based on the Magellan human errors (204 ISAs) is presented here. The resulting clusters described the underlying relationships among the ISAs. Initial models of human error in flight mission operations are presented. Next, the Voyager ISAs will be scored and included in the analysis. Eventually, these relationships will be used to derive a theoretically motivated and empirically validated model of human error in flight mission operations. Ultimately, this analysis will be used to make continuous process improvements to end-user applications and training requirements. This Total Quality Management approach will enable the management and prevention of errors in the future.

Introduction

A long-term program is in progress at JPL to reduce cost and risk of flight mission operations through a defect prevention/error management program. Flight mission operations require systems that place human operators in a demanding, high risk environment. This applies not only to the mission controllers in the "dark room", but also to the mission planners and flight teams developing sequences, to the Deep Space Network (DSN) operators configuring and monitoring the DSN, and to the engineering teams who must analyze spacecraft performance. This environment generally requires operators to make rapid, critical decisions and solve problems based on limited information, while following standard procedures closely. The mission operations environment is, therefore, inherently risky because each decision that a human operator makes is potentially mission critical, and in a high-demand environment, human errors occur frequently. Given the high risk in such an environment, these human errors can have grave financial (e.g., the Soviet loss of PHOBOS) or loss-of-life (in manned space flight) consequences.

To contain this risk at JPL, flight mission operations procedures include intensive human reviews. In addition, when an error does occur, rapid rework is required to ensure mission success. This strategy has worked well to reduce risk and has ensured the success of JPL missions. However, the large human labor investment in these reviews and rework has contributed substantially to the cost of flight mission operations. Prevention of such errors would reduce both cost and risk of flight projects. The motivation of this program is that risk can be contained more cost effectively by preventing human errors rather than reworking them. The goal of this program is the management, reduction and prevention of errors. The key facet of this program is to create an environment in which the performance of both the human operator and the computer system is optimized. Systems must be designed to enhance normal human performance (e.g., as described in Card, Moran, & Newell, 1983); training programs must be designed to alleviate likely errors; and functions that are human-error prone should be automated. Thus, to design and implement a successful defect/error prevention program requires a theoretically motivated model of human problem solving and decision making based on current theories of knowledge representation, the structure of memory, schemas, and mental models (e.g., Anderson & Bower, 1973; Norman, 1988). further, such a model must be data-validated to ensure its ultimate applicability to the flight mission operations environment. Principles of cognitive psychology, human-computer interaction, and Total Quality Management (TQM) are used to analyze past errors and make changes to end-user applications and training requirements and task policies and procedures to prevent or manage these errors in the future.

Method and Results

The process developed for this program can be viewed as a continuos process improvement loop consisting of five steps:

1. Institute the Mission Operations and Command Assurance (MO&CA) function on JPL flight projects.
2. Analyze Incident Surprise Anomaly (ISA) data for causes of errors and patterns of causes.
3. Develop a prototype of a human process model of the underlying factors causing cognitive errors during flight operations based on the ISA data.
4. Develop a defect prevention/error management methodology based on the flight operations human process model.
5. Insert the methodology into Flight Mission Operations system development and training via system requirements and training prototypes and into policies and procedures via MO&CA.

Thus far in the program Step 1 has been successfully completed. MO&CA teams have been installed on flight projects to help reduce cost and risk. The main benefits of these teams are realized from collecting and analyzing error data in the form of ISA Reports. Based on these reports MO&CA teams make recommendations for subsequent changes to flight operations procedures, and work with the flight mission operations teams to incorporate the recommendations. The work of these teams is ongoing on several projects. The current work, reported in this paper, consists of extended analysis of error data (ISAs) to determine patterns of causes and develop a prototype human process model (Steps 2 and 3). Currently, error data with cause codes is available for three flight projects over a 14 year period.

The goal of Step 2 was to reduce the data to a meaningful subset of the most frequent causes of errors based on the TQM principle of investigating the most prevalent problems first in a defect prevention/error management program. ISA reports from two projects, Voyager and Magellan, were classified in one of 12 cause code categories. Each project used a slightly different taxonomy of detailed cause categories within the high-level cause. Thus, the detailed analysis entailed developing a composite cause category taxonomy of data for both projects making the detailed cause category analysis equivalent. The categories used were developed by MO&CA teams based on major functions in the flight mission operations environment. An early Pareto analysis was performed to determine the most frequent high-level causes of errors. The analysis showed that, of the 1580 ISA reports recorded, the three cause categories of Human (38%), Software (20%), and Documentation (10%) accounted for 68% of the errors (Figure 1).

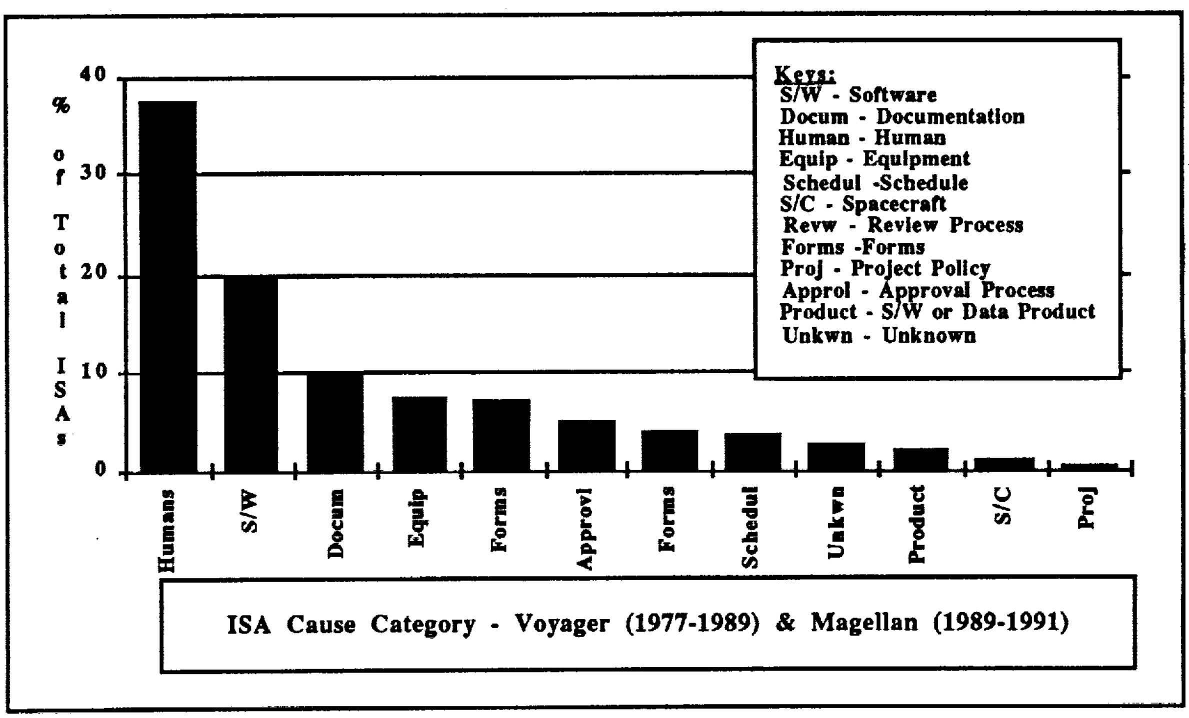

Figure 1
Voyager and Magellan ISAs - By Cause Code

Based on the high number of human errors, subsequent analysis of more specific cause codes was restricted to ISA reports for the Magellan project that were classified as Human Error. The taxonomy of cause codes was then used to score the 204 Magellan Human ISAs. Each ISA was read by a team of 2 investigators who assigned as many cause codes as was appropriate. In addition, each cause code was assigned a value of 0, 1, or 2. These values were assigned as follows: "2" was assigned if this cause alone caused the anomaly to occur and the ISA to be written; a "1" was assigned if this cause was an ancillary cause which contributed to the anomaly, but would not by itself have caused it; a "0" was assigned if this cause did not apply to the ISA. Thus, for the 204 Magellan Human Error ISAs examined, 269 cause codes were assigned.

Next, the Magellan human error data was subjected to a cluster analysis to identify clusters of cause code patterns. Interpretation of these clusters was expected to reveal the underlying factors causing cognitive errors. BMDP's cluster analysis, a multidimensional scaling technique, was used. The program groups the pair of cases (in this case ISAs), with the shortest Euclidean distance (the square root of the sum of squares of the difference between the values of the variables for two cases). In a step-wise manner, two cases or clusters are grouped such that initially each case is an individual cluster and at the end all cases are in one cluster. In the present analysis, 25 clusters were formed first at distance 0. Thus the internal distance among ISAs in each of those 25 clusters was 0; that is, the ISAs were scored identically. Figure 2 shows a Pareto chart of the size of the first 25 clusters. The 4 largest clusters contained 25, 21, 19, and 15 ISAs respectively, followed by a gap. The next cluster, of size 9, was the cluster of ISAs of unknown cause. Thus, only the 4 largest clusters were selected for interpretation. These 4 clusters consisted of ISAs with only one cause rated "2". They were Oversight (12%), Lack of Communication (10%), Edit Error in Product (9%), and Omission of Action (7%), respectively, and accounted for 39% of the 204 ISAs (Figure 3). At the next major level of clustering, distance 3.3, these 4 clusters joined, along with others, to account for 52% of the total ISAs. Finally, at the third major level of clustering, distance 6.6 , 95% of the ISAs joined. The final 5% of the ISAs did not join until distance 14.8 and these errors were rare, dissimilar cases.

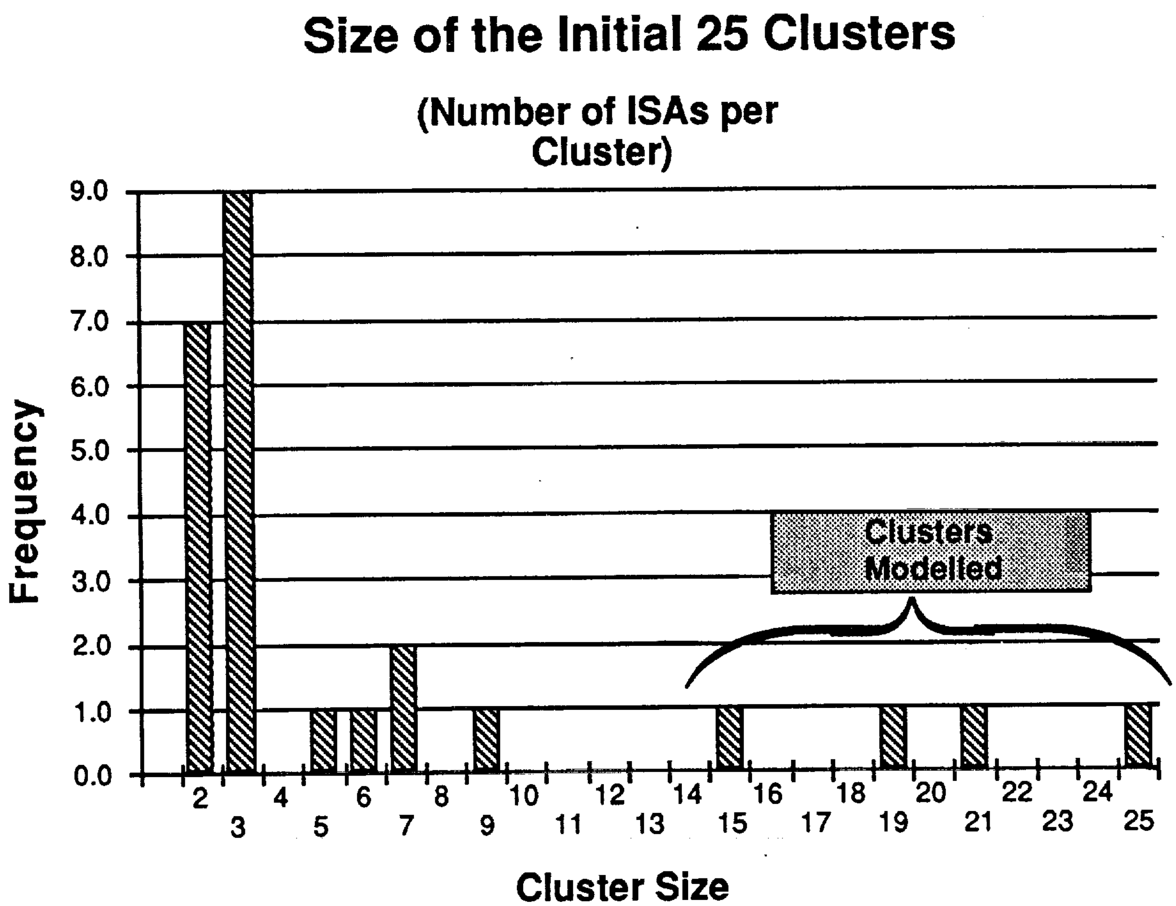

Figure 2
Magellan Human Error ISAs - By Cause Code

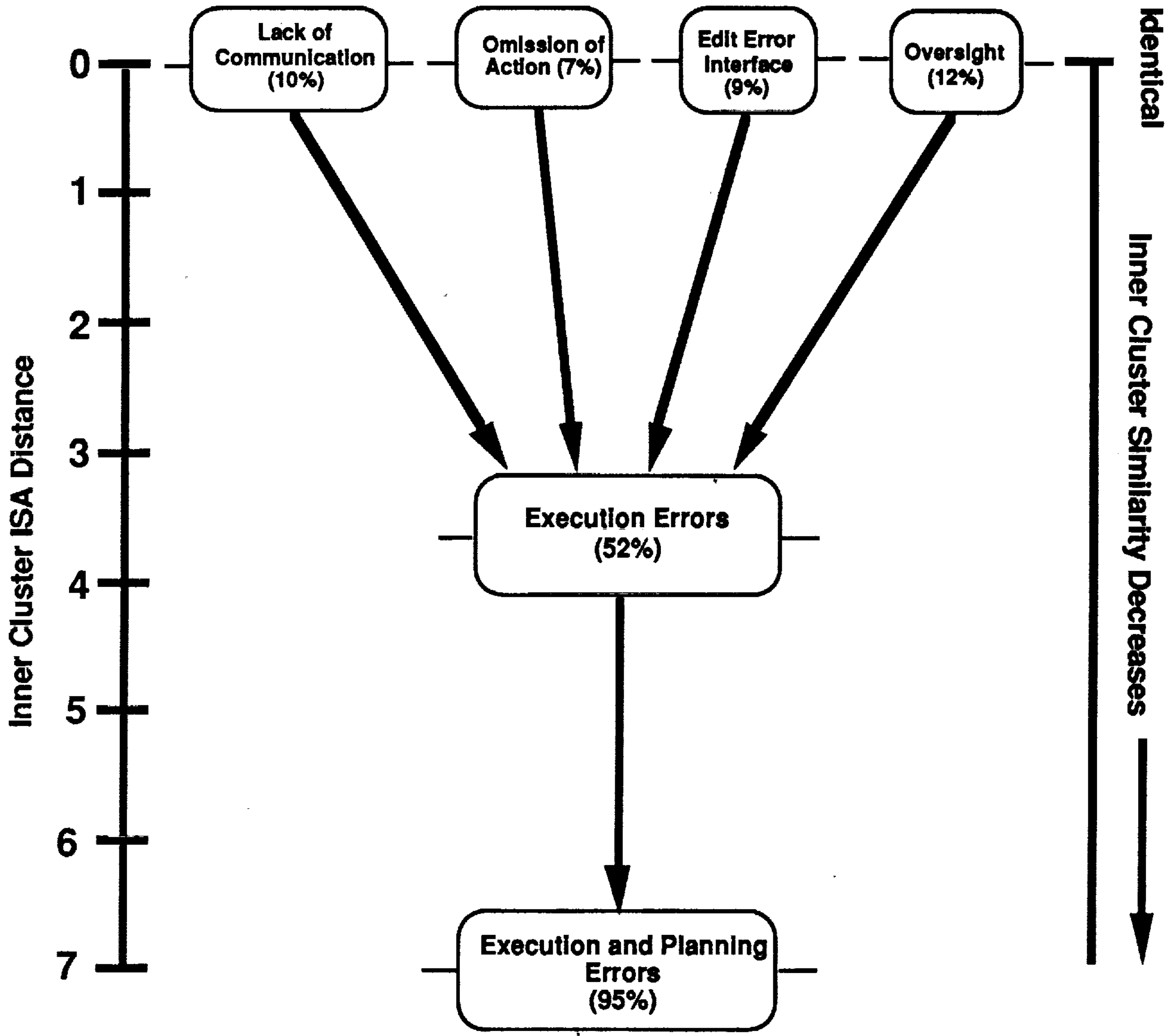

Figure 3
Magellan Human Error ISA Cluster Analysis

In order to model the underlying causes of the ISAs within the four initial clusters, each ISA within a cluster was reexamined for its specific characteristics. Characteristics common to all ISAs in the cluster were compared to known cognitive phenomena, particularly with human error theory. Several taxonomies of human error have been proposed (e.g., Norman, 1981, 1983; Reason, 1990). However, there is no general agreement on a single taxonomy. Thus, it has been suggested that a taxonomy must be tailored to a given environment (Senders & Moray, 1991). The taxonomy adopted here, in Appendix A, is tailored and simplified from Reason (1990). Figure 4 shows the cognitive mechanisms in the taxonomy. Tasks are divided into a planning and an execution component. The error types are Oversight (generally known as a slip), Omission of Action (generally known as a lapse), a mistake, and a violation. This general taxonomy was then used to model the common characteristics within each cluster. The four highest frequency clusters that joined at distance 3.3 exhibited at least two common cognitive elements, omission of action and oversight. In omission of action, a goal was acquired, but a subgoal was not executed for some reason, typically cognitive capture or a distraction. Cognitive capture generally refers to a psychological phenomenon in which a well-rehearsed action takes control of a less familiar action. This is particularly true when attention is drawn elsewhere. For example, one ISA (8508) documented a case in which DSN station operators did not notice for three days a special condition in the Sequence of Events (SOE) during Magellan support. The problem was caused by the fact that Magellan support had become routine and the SOE rarely changed. Thus, this routine support "captured" the processing of the changed SOE so that some new steps were omitted. This error

Error Type	Task Type	
	Planning	**Execution**
Oversight (slip)	OK	Followed plan, but performed a wrong action
Omission of Action (lapse)	OK	Followed plan, but skipped an action
Mistake	Faulty Plan	Followed faulty plan
Violation	OK	Intentionally deviated from plan

Figure 4
Human Error

resulted in a loss of data. The second common cognitive element in this cluster was oversight, in which the status of the task is not evident at any given point in time. Thus, an incorrect action (i.e., inappropriate at this point in the task) may be performed, or an incorrect object may be used. For example, another ISA (1973) documented an error in which a file was created using an old version of the required software. The problem was traced to the fact that, as new versions of the file generation software became available, they were simply installed on the appropriate machines. As time passed, multiple versions of the software were available. To the operator generating the file, it was not clear which was the correct version of the software. Thus, the task status was not evident, and a wrong object (the old software) was used. The lack of distinction between the current software and previous releases generated a description error. There were no salient attributes to facilitate the use of the correct software release. This error resulted in loss of time, since the problem had to be researched and the file regenerated, thus increasing operations costs. In addition, risk increased since an incorrect file was generated.

As these common cognitive elements were uncovered, it became clear that the single common element underlying this cluster was that all the ISAs were execution errors. Thus, this cluster, at distance 3.3, was labeled "Execution Errors"(Figure 3). Finally, at the third major level of clustering, at distance 6.6, planning errors joined the execution errors, thus suggesting a label of "Execution and Planning Errors."

Preliminary Conclusions

Although this defect prevention and error management program is in its infancy, some preliminary conclusions can be drawn from the initial analysis.

1. Flight mission operations human error data is amenable to interpretation via human error theory. JPL currently has a large volume of ISA data. While this data may be locally analyzed within a project during operations, particularly during a major anomaly, the analysis is typically ad hoc and localized to that one project. This preliminary work demonstrates that by modeling error data, underlying causes can be investigated in a systematic way, and classes of errors in this environment (such as execution errors) can be uncovered. In addition, this general information can then be shared across projects.

2. In JPL flight mission operations, a significant portion of human ISAs are errors in executing a task. The results of this study showed that 52% of the 204 Magellan human errors analyzed were execution errors. This provides a focus for possible solutions on execution problems. It is also speculated that execution errors will be found to be preventable or manageable.

3. System requirements, policies and procedures can be written to prevent known cognitive errors. As was previously mentioned, through this systematic analysis, classes of errors will be uncovered. In this way, solutions to manage errors that do occur, or solutions to prevent them from occurring can be generated. For example, to prevent errors like the one documented in ISA 8508, special conditions in a file can be highlighted to avoid capture in routine tasks. To avoid errors such as ISA 1973, proper configuration management policies and procedures should be written and enforced in operations. In this case, archiving old versions of the file-generation software off-line would eliminate operator confusion about which software to use in generating files and thus prevent this oversight or slip.

In summary, a method for analyzing human errors in flight mission operations has been presented. Although in a preliminary phase, it is clear that such a method in which error data is subjected to a cluster analysis, the resulting clusters are examined for common cognitive elements, and these elements are modeled using cognitive psychological theory, can lead to an understanding of the causes of errors and typical classes of errors. Using TQM principles, these findings can then be used at the beginning of a project's life cycle to improve system requirements, project policies and procedures, and operator training to manage errors that do occur, or prevent them from occurring at all. It is only through such a systematic analysis method that cost and risk can be reduced in flight mission operations. Finally, it is clear that this analysis has wide applicability to other errors. It is currently planned that this program will eventually expand to include analysis of other errors in Figure 1 such as software and documentation, and to other environments such as the DSN and system development.

Acknowledgement

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References

Anderson, J. R. & Bower, G. H., Human Associative Memory, V. H. Winston, Washington, D.C., 1973.

Card, S., Moran, T., & Newell, A., The psychology of human-computer interaction, Erlbaum Associates, Hillsdale, N.J., 1983.

Norman, D. A., "Categorization of action slips," Psychological Review, 88, 1981, 1-15.

Norman, D. A., "Design rules based on analyses of human error, " Communications of the ACM, 26 (4), 1983, 254-258.

Norman, D. A., The design of everyday things, Doubleday, New York, 1988.

Reason, J., Human error, Cambridge University Press, New York, 1990.

Senders, J. W. and Moray, N. P., Human Error, Lawrence Erlbaum Associates, Hillsdale, N.J., 1991.

APPENDIX A

Taxonomy of Human Error Cause Codes

HUMANS

HUM		
HUM1	Inadequate Knowledge/ Inexperience	Error made due to inexperience or lack of knowledge if person is experienced.
-1	Procedures	
-2	Policies/guidelines/ requirements	
-3	S/C characteristics	
-4	Command procedures	
-5	Ground Operations	
-6	S/C Status	
-7	Constraints	
-8	Schedule change	
-9	Anticipated command effect	
-10	S/W Flight	
-11	S/W Ground	
HUM2	Violation of Rule/ Constraint/Procedure	Error made due to an intentional deviation from plan
-1	Procedures	
-2	Policies	
-3	Guidelines	
-4	Flight / Mission Rules	
-5	S/C Compatibility	
-6	Ground Operations - Compatibility	
-7	Operational Requirement	
HUM4	Error	Error made due to an unintentional deviation from plan
-1	Wrong Plan - Mistake	Plan is wrong, but was executed correctly
-2	Plan OK - Error Unknown	Plan is correct, error is unknown
-3	Plan OK - Omission of Action	Plan is correct, but an action was omitted during execution
-4	Plan OK - Oversight	Plan is correct, but an action during execution was wrong.
HUM5	Product Interface	Error made while producing a product
-1	Error in Copying	
-2	Error in calculation	
-3	Data entry error	Error in original data entry
-4	Edit Error	Error in editing an existing product
HUM6	Communication	
-1	Lack of communication	
-2	Miscommunication	

Session H3: HUMAN PERFORMANCE MEASUREMENT III— OPERATION SIMULATION

Session Chair: Capt. James Whiteley