USABILITY OF PAPER-BASED INDUSTRIAL OPERATING PROCEDURES

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ABSTRACT

Procedures are standardized instructions designating a safe and accepted way of accomplishing a task. As with any other human-system interface, procedures have an aspect of usability. This study sought to develop and compare the usability of paper-based industrial operating procedures. An internal audit at a uranium conversion facility cited operating procedures as a common cause of several incidents. Two procedures were redesigned with evidence-based guidelines and human factors input. Operators rated the new procedures significantly or moderately better in terms of their efficiency, effectiveness, and subjective satisfaction. Experienced and inexperienced operators reported similar satisfaction ratings across both procedure types. Future studies should attempt to discern particular changes in the procedures that contributed most to increased usability, and whether operator experience correlates with the usability ratings.

Key Words: procedure, usability, human factors, chemical processing

1 INTRODUCTION

The accident at Three Mile Island sparked a realization amongst industry experts that procedures require design consideration and analysis from many perspectives [1]–[5]. Procedures in safety-critical domains have difficult-to-describe physical actions and phenomena, and must be written with an appropriate level of detail. These concerns are not minor ones, as it has been reported that procedural faults are a factor in 69% of nuclear plant incidents [6]. Clearly, failure to follow procedures can have disastrous consequences if executed incorrectly.

Several guidelines for the design of procedures in the nuclear industry have been developed in an attempt to alleviate some of these concerns. They include items such as having multidisciplinary writing teams, being willing to rely on operator's knowledge, and using writing guides to keep procedure format and language consistent [5], [7]. Additionally, human factors-specific guidelines have been suggested to improve the usability of written procedures, such as treating each page as a display, keeping information in small blocks, and using the learned expectations of the operators as the template for the procedure [8].

Since procedures can be thought of as information displays, they can also be considered to have usability characteristics. ISO-9241 defines usability as the "…extent to which a product can be used by specified users to achieve specified goals with effectiveness, efficiency, and satisfaction" [9]. If operators perceive their procedures to be ineffective, inefficient, or unsatisfactory, they are less likely to use them. Procedure writers must have solid evidence that human factors input can increase usability and that it should be integrated into the procedure development process. This is particularly true for procedures that are used under normal conditions; as they are used frequently, errors in their implementation or use might cause abnormal operating conditions [10].

Although some plants may be migrating to computer-based procedures, most still use paper [11]. Thus, it seems peculiar that at the time of writing this paper, despite the existence of HF guidelines for procedure design, and despite the fact that usability comparisons have been performed between computer-based procedures and paper-based procedures ([12], [13], [14], no usability comparison of paper-based operating procedures has been completed (to the author's knowledge).

This paper directly compares the usability of existing paper industrial operating procedures with versions that were redesigned with the input of evidence-based document design principles and human factors processes.

2 PROCEDURE REDESIGN

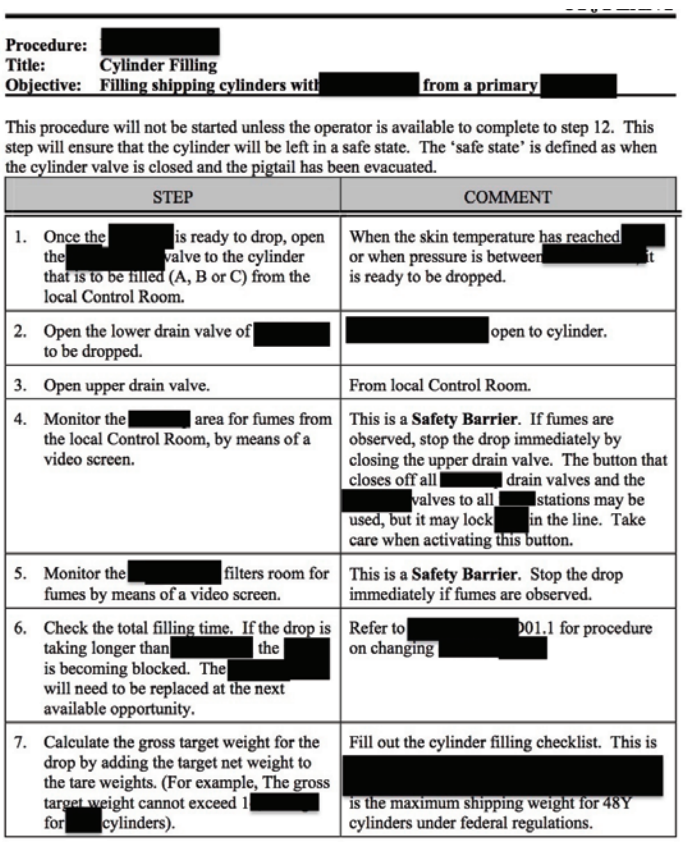
This comparison of paper industrial operating procedures was performed at a chemical processing facility. The majority of the operations in this facility are carried out in the field.

Incident reviews in 2009 cited operating procedures as contributing causal factors for several reportable incidents. This prompted management to request an internal audit to review the status of operating procedures. The audit resulted in several recommendations, including the creation of a procedure style guide and the updating of the plant's procedures.

As will be discussed below, we created a new style guide and procedure format. Thereafter we conducted an operating experience review, function analysis, and task analysis for each procedure.

2.1 Motivation for Procedure Redesign

The existing format of the procedures was a two-column step-comment format. Figure 1 shows an example of a page from an old procedure.



Procedure: [redacted]
Title: Cylinder Filling
Objective: Filling shipping cylinders with [redacted] from a primary [redacted]

This procedure will not be started unless the operator is available to complete to step 12. This step will ensure that the cylinder will be left in a safe state. The 'safe state' is defined as when the cylinder valve is closed and the pigtail has been evacuated.

STEP	COMMENT
1. Once the [redacted] is ready to drop, open the [redacted]alve to the cylinder that is to be filled (A, B or C) from the local Control Room.	When the skin temperature has reached [redacted] or when pressure is between [redacted]t is ready to be dropped.
2. Open the lower drain valve of [redacted] to be dropped.	[redacted] open to cylinder.
3. Open upper drain valve.	From local Control Room.
4. Monitor the [redacted] area for fumes from the local Control Room, by means of a video screen.	This is a **Safety Barrier**. If fumes are observed, stop the drop immediately by closing the upper drain valve. The button that closes off all [redacted] drain valves and the [redacted] valves to all [redacted] stations may be used, but it may lock [redacted] in the line. Take care when activating this button.
5. Monitor the [redacted] filters room for fumes by means of a video screen.	This is a **Safety Barrier**. Stop the drop immediately if fumes are observed.
6. Check the total filling time. If the drop is taking longer than [redacted] the [redacted] is becoming blocked. The [redacted] will need to be replaced at the next available opportunity.	Refer to [redacted]01.1 for procedure on changing [redacted]
7. Calculate the gross target weight for the drop by adding the target net weight to the tare weights. (For example, The gross target weight cannot exceed 1[redacted] for [redacted] cylinders).	Fill out the cylinder filling checklist. This is [redacted] is the maximum shipping weight for 48Y cylinders under federal regulations.

Figure 1 - Sample of an old procedure (proprietary information redacted)

Although the existing procedures were familiar to the operators and relatively short (i.e., typically 3-5 pages), the internal audit revealed several weaknesses that may have contributed to the reportable incidents:

1. The procedure format was inconsistent,
2. Procedures were not being used consistently,
3. Relevant information was missing, and
4. Procedures were not easily accessible.

This project addressed the first three items on the list.

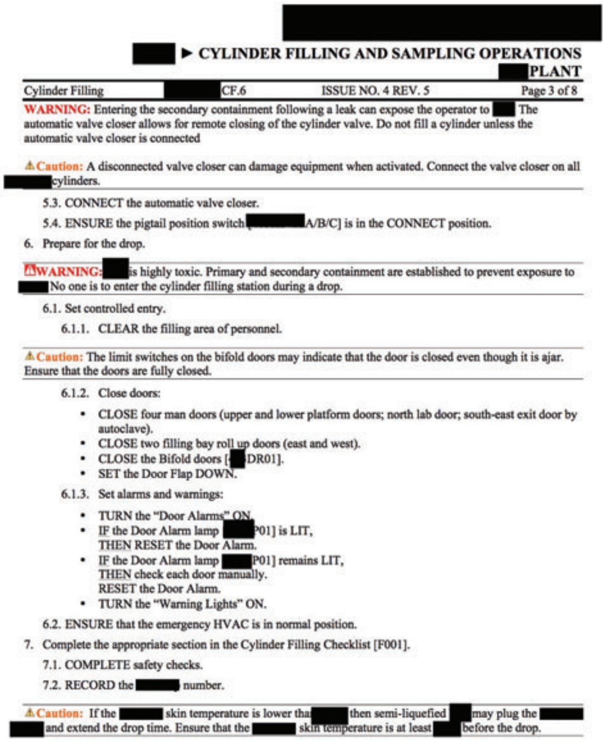
2.2 Redesign Process and Results

A review of the literature yielded few obviously evidence-based guidelines for constructing a procedure template. To create a new style guide and format for the procedures, we consulted the sources that did have evidence-based guidelines: an industry-standard book on procedure writing [15], the Nuclear Energy Institute's procedure writers' manual [16], and the Institute of Nuclear Power Operations (INPO) guide to procedure use and adherence [17]. Additionally, we consulted subject matter experts, used human factors heuristics and professional judgment, and incorporated (where appropriate) operator feedback.

Once the style guide and new format were developed, we followed a human factors program plan [18] to develop each new operation procedure. First, an operating experience review included a review of incident reports and interviews with operators. Next, a function analysis defined the system capabilities. Then we performed a task analysis by completing heuristic and experienced-based reviews of the existing procedure, shadowing operators, and interviewing the area engineers. We conducted operational walkthroughs of the task with operators on multiple crews, asking them to speak aloud, explain their actions and tell us when they thought a step was missing or inaccurate. We placed all of this information in task analysis tables, and held iterative discussions with operating staff and area engineers to resolve apparent discrepancies.

Next, we organized the task analysis into the proposed procedure sequence. Shift supervisors and area engineers reviewed the proposed action sequence to identify steps that were missing, placed in the wrong order, or had excessive (or insufficient) detail. We then transposed the task into a draft procedure in the new format. After final reviews by the crews, engineers and managers, the procedures were introduced into service.

Figure 2 shows a representative page in the new procedure format. The new procedures contain more of the steps that operators perform; are structured in local groups of hierarchical actions; are based on a style guide that enforces consistent vocabulary and formatting; and contain new, relevant information in the form of clearly demarcated details, notes, warnings, and cautions. The length of the procedures also increased markedly (e.g., the example procedure expanded from 3 to 14 pages).


[redacted]

[redacted] ► **CYLINDER FILLING AND SAMPLING OPERATIONS**
[redacted]**PLANT**

Cylinder Filling [redacted]CF.6 ISSUE NO. 4 REV. 5 Page 3 of 8

WARNING: Entering the secondary containment following a leak can expose the operator to [redacted] The automatic valve closer allows for remote closing of the cylinder valve. Do not fill a cylinder unless the automatic valve closer is connected

⚠**Caution:** A disconnected valve closer can damage equipment when activated. Connect the valve closer on all [redacted]cylinders.

5.3. CONNECT the automatic valve closer.

5.4. ENSURE the pigtail position switch[redacted]A/B/C] is in the CONNECT position.

6. Prepare for the drop.

⚠**WARNING:**[redacted]is highly toxic. Primary and secondary containment are established to prevent exposure to [redacted]No one is to enter the cylinder filling station during a drop.

6.1. Set controlled entry.

6.1.1. CLEAR the filling area of personnel.

⚠**Caution:** The limit switches on the bifold doors may indicate that the door is closed even though it is ajar. Ensure that the doors are fully closed.

6.1.2. Close doors:

- CLOSE four man doors (upper and lower platform doors; north lab door; south-east exit door by autoclave).
- CLOSE two filling bay roll up doors (east and west).
- CLOSE the Bifold doors [[redacted]DR01].
- SET the Door Flap DOWN.

6.1.3. Set alarms and warnings:

- TURN the "Door Alarms" ON.
- IF the Door Alarm lamp [redacted]P01] is LIT,
  THEN RESET the Door Alarm.
- IF the Door Alarm lamp [redacted]P01] remains LIT,
  THEN check each door manually.
  RESET the Door Alarm.
- TURN the "Warning Lights" ON.

6.2. ENSURE that the emergency HVAC is in normal position.

7. Complete the appropriate section in the Cylinder Filling Checklist [F001].

7.1. COMPLETE safety checks.

7.2. RECORD the [redacted] number.

⚠**Caution:** If the [redacted] skin temperature is lower tha[redacted] then semi-liquefied [redacted] may plug the [redacted] [redacted] and extend the drop time. Ensure that the [redacted] skin temperature is at least [redacted] before the drop.

Figure 2 - Sample of a new procedure

Table 1, below, compares the characteristics of the old and new procedures.

Table 1 - Differences in characteristics of old and new procedures

Old procedures	New procedures
Equipment is identified by functional name only.	Equipment is identified by both functional names and device identifiers.
Two-column, step-detail format; not sub-divided into logical groupings of actions.	No columns; use a numbering scheme and allows for visual separation via local groupings of actions.
Steps written in paragraphs including actions, notes, cautions and warnings.	Steps written in concise action-object structure. Highlighting of warnings and cautions consistent with ANSI guidelines.
Inconsistent step structure and terminology.	Action-object step structure; lowest-level actions selected from defined action list and printed in capital letters.
Rarely contained explanations for actions.	Often contains explanations for actions in notes, cautions, and warnings.

3 METHOD

We wanted to evaluate whether the operators would rate the usability of the new procedures higher than the old procedures. We compared old and revised procedures from two areas of the plant (flame reactor and cold trap area (FR), and the cylinder filling (CF) area.

16 operators were selected for the study to reflect a range of experience and qualifications (see Table 2. Operators are classified by ascending qualification levels between 0 and 3 in each area of the plant based on the number of supervised hours worked in the area and the amount of training they have undergone. Four operators were qualified as L3 operators in the CF area and at least two other areas (with the exclusion of FR); four were L3 operators in FR and at least two other areas (with the exclusion of CF); and eight operators were less than or equivalent to L0 in the CF and FR areas (and L3 in one other area or less). For reference, the first group will be referred to as "Experienced CF", the second group as "Experienced FR", and the third group as "Inexperienced".

Table 2 - Summary of operator selection

Operator	Cylinder Filling	Flame Reactor	Other areas
Operators 1-4 (Experienced CF)	L3	< L0	L3 in ≥ 2 areas
Operators 5-8 (Experienced FR)	< L0	L3	L3 in ≥ 2 areas
Operators 9-16 (Inexperienced)	≤L0	≤L0	L3 in ≤ 1 area

3.1 Independent Variables

The independent variables were the procedure type (new or old), the procedure area (CF or FR), and operator experience level (experienced in either CF or FR, and inexperienced).

3.2 Dependent Variables

A review of 180 usability studies published in HCI journals classified measures according to three categories: effectiveness, efficiency and satisfaction [19]. ISO-9241 defines these categories as follows:

Effectiveness: "accuracy and completeness with which users achieve specified goals"

Efficiency: "resources expended in relation to the accuracy and completeness with which users achieve goals"

Satisfaction: "freedom from discomfort, and positive attitudes towards the user of the product".

We selected one measure from each category. For "effectiveness", a users' assessment was chosen; for efficiency, a modified NASA Task Load Index (NASA TLX) questionnaire; and for satisfaction, a questionnaire that included several Likert-type scale-questions and open-ended questions.

For the "effectiveness" measure, the operators were asked to read through the procedures and identify any inaccuracies or confusing points that they found. These were tallied for each procedure. The operators were asked to count only the inaccuracies that, if the procedure was followed precisely, would result in damage to equipment, harm to themselves or others, or an inability to complete the task.

For the "efficiency" measure, the NASA TLX questionnaire was chosen. The published version of the NASA Task Load Index contains the six dimensions of mental demands, physical demands, temporal demands, own performance, effort, and frustration. However, given that the item being tested here were the usability of documents, the subscale for "physical demands" was removed.

To assess "satisfaction" two questionnaires were adapted: the Questionnaire for User Interface Satisfaction (QUIS) [20], and a questionnaire based on the consumer information rating form that measured the perception of usability [21].

Also assessing satisfaction, 5-point Likert questions were included asking the operator about the following qualities for each of the procedures:

- Well-organized
- Ease-of-reading

- Written accurately enough in order to be able to achieve the specified goal completely
- Written in a way that lets you achieve the specified goal safely
- Written with the appropriate amount of detail
- Overall satisfaction with the procedure

Additionally, there was an open-ended question regarding the level of detail that was included in the procedure. The final question asked the operator whether they preferred the new or the old procedures overall and why.

3.3 Test Design

A within-subjects counterbalanced design was used for this study. The orders of procedure (old or revised) and area (FR or CF) were counterbalanced for each of the crews and qualification levels.

3.4 Hypotheses

We expected that the new procedures would have a positive usability impact. The type of procedure (old versus new) was predicted to directly affect all three usability categories: effectiveness, efficiency, and satisfaction. Relative to the old procedures, the new procedures were predicted to have lower inaccuracy and confusion counts; lower NASA TLX scores; and higher subjective ratings of satisfaction.

We predicted that these positive impacts of the new procedures would hold across both of the procedure areas and that the operators would prefer the new procedures to the old ones.

3.5 Testing Protocol

The tests were run in a meeting room close to the process areas. During the test, the operators were seated at a table, with copies of the procedures in front of them.

The NASA-TLX workload assessment was explained to the operator, and they were given one practice run with the assessment to ensure the scales were understood. The operator was then told to read the first procedure and to note anything that confused them or that seemed inaccurate.

After reading each procedure, the operator filled out the questionnaire and the modified NASA-TLX workload assessments. Operators took a 5-minute break after the first and third procedures and a 20-minute break after the second procedure (i.e., when switching between different areas in the plant).

After the operator completed the read-through of the two procedures in the first area (and their accompanying questionnaires and NASA-TLX scales), they were asked to complete their subjective weightings of the NASA-TLX factors. After all of the procedures had been read through, the operator was asked whether they had an overall preference for the new procedures or the old ones, and whether they had any overall comments.

4 RESULTS

The data were tested for normality before statistical tests were run. Where the assumption of normality was violated, an appropriate non-parametric test was used.

4.1 Demographics

Table 3 summarizes the demographic data collected from the operator participants. Most of the participants were between the ages of 31-50, and most had been working at the plant for between 5 and 10 years.

Table 3 - Participating operator demographics

	Years as operator				
Ages	10 years or more	5-10 years	2-5 years	Less than 2 years	Grand Total
18-30	0.00%	0.00%	0.00%	12.50% (2)	12.50% (2)
31-50	12.50% (2)	25.00% (4)	6.25% (1)	18.75% (3)	62.50% (10)
51 or older	6.25% (1)	12.50% (2)	6.25% (1)	0.00%	25.00% (4)
Grand Total	18.75% (3)	37.50% (6)	12.50% (2)	31.25% (5)	100.00% (16)

4.2 Usability Measures

Table 4 summarizes the effectiveness, efficiency, and satisfaction[1] measures. Bolded numbers indicate the better value.

Table 4 - Summary of usability measure scores

Usability category	Measure	New CF Mean (StDev)	Old CF Mean (StDev)	New FR Mean (StDev)	Old FR Mean (StDev)
Effectiveness	Confusion	**0.94** (0.28)	1.06 (0.32)	**0.69** (0.28)	1.81 (0.28)
	Inaccuracy	**0.50** (0.27)	2.94 (0.8)	**0.75** (0.25)	1.69 (0.25)
Efficiency	Workload	**7.40** (1.05)	10.04 (1.12)	**8.60** (1.02)	9.40 (1.3)
Satisfaction	Organization	**4.12** (0.24)	3.13 (0.28)	**4.25** (0.21)	2.93 (0.28)
	Ease of reading	**3.81** (0.22)	3.44 (0.25)	**3.94** (0.23)	3.19 (0.29)
	Accuracy	**4.25** (0.19)	2.89 (0.27)	**3.81** (0.27)	2.81 (0.29)
	Safety	**4.25** (0.17)	2.69 (0.25)	**3.81** (0.3)	2.75 (0.29)
	Appropriate Detail	**4.06** (0.23)	2.81 (0.28)	**3.81** (0.23)	2.75 (0.29)
	Satisfaction	**4.00** (0.20)	2.88 (0.27)	**3.88** (0.22)	2.81 (0.30)

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[1] The surveys for the new procedures had a Cronbach's alpha of 0.894, and the surveys for the old procedures had a Cronbach's alpha of 0.915. Thus, it can be said that the operator questionnaire questions were relatively internally consistent and all measured the same variable.

4.3 Operator Preferences

13 of 16 operators stated a preference for the new procedures. Most operators noted that this was because the new procedures have more detail and information. Of the three that did not prefer the new procedures (one experienced; two inexperienced), all stated that the old procedures were more direct and had fewer steps.

4.4 Statistical Test Summary

Table 5 summarizes the statistical test results. Significant p-values ($p \leq 0.05$) have asterisks. Values that indicate moderate or moderately strong evidence of an effect ($p \leq 0.1$) are bolded.

Table 5 - Summary of statistical test results

	New vs. Old	New CF vs. Old CF	New FR vs. Old FR
Confusion (Wilcoxon)	0.037*	0.751	0.027*
Inaccuracy (Wilcoxon)	0.001*	0.005*	**0.07**
Subjective Workload (t-test)	**0.055**	0.02*	0.27
Satisfaction[2] (Wilcoxon)	<0.001*	0.003*	0.007*

5 DISCUSSION

5.1 Effect of New Procedures

Operators rated paper-based procedures redesigned with human factors input and evidence-based guidelines as more usable than their original versions. Consistent with the hypotheses, strong or moderate evidence of differences between the new and the old procedures were shown in the results across all of the usability categories tested. Of the nine metrics that were collected for each procedure (two for effectiveness, one for efficiency, and six for satisfaction), all of them displayed better mean values for the new procedures (overall) than for the old procedures: three were significantly better, and one (subjective workload) was moderately better.

The new CF procedure was reported to be more effective, more efficient, and had higher subjective ratings of satisfaction than the old one. Of the four statistical tests that were run between the new and old CF procedures, all but one of them (confusion count) showed strong evidence of statistically significant differences; the new CF procedures were shown to be significantly better than the old. Similarly, the new

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[2] Satisfaction scores were compared by calculating the mean of the sum of each procedure's Likert questions.

FR procedure was reported to be more effective, more efficient, and had higher subjective ratings of satisfaction than their old counterpart. Of the four statistical tests that were run between the new and old FR procedures, two of them showed strong evidence of a statistically significant difference, one showed moderate evidence of an effect (inaccuracy count), and one showed no evidence of a significant effect (subjective workload); all were in favour of the new FR procedure.

The lack of evidence for a significant difference in subjective workload between the FR procedures may be attributable to two operators who gave unexpectedly low subjective workload ratings to the old FR procedure. One factor that could have impacted their ratings could have been their familiarity with the old procedure. Also, subjective workload ratings may have been influenced by the old procedure being only two pages in length while the new procedure was eight pages. Despite this, the evidence supports the conclusion that the new FR procedures had higher usability.

Finally, operators rated the new procedures to have a higher overall subjective satisfaction and preferred them over the old ones. The operators found the new procedures to be better organized, more accurate, more conducive to safe work practices, more appropriately detailed, and more satisfactory than the old procedures. The lack of a clear advantage for the new FC procedure in the "ease of reading" category may be due to its length; three operators commented on how long it was relative to the old procedure, was less direct, and how that made it more difficult to get through. However, this did not affect the overall conclusion, as 13 of the 16 operators tested (approximately 81%) stated a preference for the new procedures.

5.2 Limitations

A key limitation on the study was the fact that the procedures were not evaluated in the context of a real commercial process operation. Multiple anticipated and unanticipated shutdowns constrained the selection of research methods and ultimately resulted in the tests being performed outside of the process environment. The removal of environmental cues from the task context may have affected the operators' ability to count inaccuracies or to accurately judge their subjective workload.

This study was carried out with an industrial operator population with mixed experience using paper-based field operation procedures. Generalizability to other operating contexts and operator populations is difficult to assess. The literature review indicates that computer-based and paper-based procedures seem to share some design guidelines. Although the sample size for this study was small, the results may be generalizable to other paper-based and computer-based procedures in other plants with similar operator populations.

Finally, although it would have been insightful to determine which of the particular changes in format or content contributed the most to usability, the immediate goal was to determine whether a human factors engineering process would yield more usable procedures.

6 CONCLUSION AND FUTURE WORK

To our knowledge, this is the first usability comparison of paper-based industrial procedures for normal operating conditions. As predicted, the procedures developed using a human factors engineering process were rated more usable by operators across the categories of efficiency, effectiveness, and satisfaction. These findings suggest that paper-based procedures processes would benefit from the inclusion of human factors input.

A follow-up to this study should attempt to identify which particular changes in the procedures contributed most to the perceived usability differences. Ideally, future studies of procedure usability would either have access to a simulator or the actual plant (for walkthroughs) so that more reliable effectiveness measures could be employed (e.g., number of errors committed, time completed, etc.). Additionally, although we could not test the hypothesis with inferential statistics here, determining whether the experience level of operators statistically significantly impacts their usability ratings of the procedures would aid in determining whether differently experienced operators would benefit from different procedure formats and content.

7 ACKNOWLEDGMENTS

This research was supported through funding from a MITACS Accelerate internship. My gratitude goes out to the operators, managers, and engineers who I worked with at the plant in order to get this work completed.

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