10 Promising Applications

As explained in the 6 chapters of Part II, the TACOM measure was developed to evaluate the complexity of proceduralized tasks by quantifying complexity factors pertaining to the performance of a process control task. To this end, each action to be performed by qualified operators has been analyzed from the point of view of an *OBJECT*, an *ACTION VERB,* and action specifications that can be subdivided into a *MEANS*, an *ACCEPTANCE CRITERION*, a *CONSTRAINT,* and a *peculiarity*. This strongly indicates that the TACOM measure is a verbatim probe evaluating the complexity of proceduralized tasks as written. In other words, the TACOM measure provides not a subjective but an objective value representing the *verbatim complexity* of proceduralized tasks that is to be loaded on qualified operators who have diverse individualities, such as aptitude, capability, cognitive style, motivation, self confidence, etc.

For example, washing both hands is a very easy task for many people. However, for some people, this task could be more complicated than it seems if they worried about the fact that many actions must be done simultaneously within a very short time: (1) turn on the water, (2) get soap, (3) rub soap on hands, (4) put the soap down, (5) rub both hands, (6) submerge both hands under water, (7) rub both hands, and (8) turn off the water. In an extreme case, someone might become more anxious about this task because the number of actions would vary from person to person. This means that the levels of a task's complexity felt by qualified operators would be widely dispersed, even though they performed the same task. Accordingly, it is very difficult to develop an effective strategy by which the countermeasures to reduce the possibility of human error (or to enhance the performance of qualified operators) can be identified. However, since the TACOM measure quantifies the complexity of proceduralized tasks based on a task description, it is reasonable to expect that useful guidelines or insights to support qualified operators can be identified from an analysis of TACOM scores.

10.1 Providing HRA Inputs

From the point of view of engineering, the most popular approach to coping with human error is to develop a method that can be used not only to quantify the possibility of human error but also to identify crucial factors causing human error.

This approach is widely known as HRA (human reliability analysis or human reliability assessment). In order to conduct HRA, many kinds of information should be provided to HRA practitioners. Typical information includes the following (Cooper et al. 1996; Hollnagel 1993b; IAEA 1990; IEEE 1997; Kirwan 1994; Kirwan and Ainsworth 1992; Sträter and Bubb 1999; Swain and Guttmann 1983):

- Description of the tasks to be performed
- List of available (or to be used) procedures
- The experience level of qualified operators (or teams) who have to perform the required tasks
- The dependence among the required tasks
- An allowable time window by which the required tasks should be completed
- The time needed to perform the required tasks (i.e., task performance time)

Of these, time-related information (i.e., the available time as well as the task performance time) is essential. Briefly, the available time is the difference between an allowable time and a task performance time, as illustrated in Fig. 10.1.

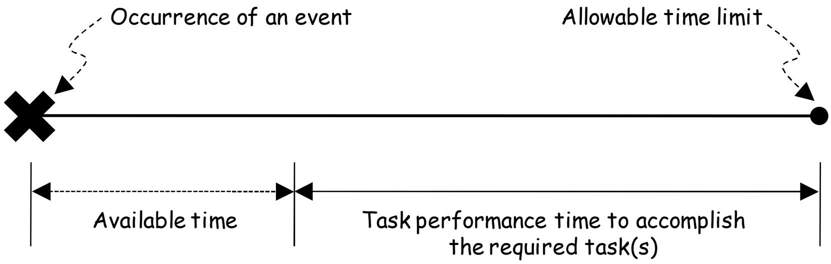


Fig. 10.1 Allowable time, task performance time, and available time

For example, when an SGTR has occurred, it is strongly recommended that qualified operators should successfully isolate a ruptured SG within about 30 min by following a set of proceduralized tasks described in an SGTR procedure. In this case, if qualified operators need at least 20 min to complete the required tasks, then 10 min are available to correctly recognize the occurrence of the SGTR. This implies that qualified operators are likely to make a mistake in recognizing the occurrence as well as the nature of an ongoing situation because 10 min does not seem to be enough time. In addition, if qualified operators fail to recognize the situation within 10 min, then they are apt to make an additional mistake in the course of performing the required tasks because they have to accomplish what should be done more quickly (i.e., time pressure). Accordingly, the possibility of human error increases as the decrease of the available time (Hollnagel 1993b; Kozine 2007; Woods et al. 1984; Williams 1988).

Here, since the allowable time can be estimated by deterministic approaches (e.g., a thermohydraulic experiment or a theoretical analysis), it is possible to say that the available time is a function of the task performance time. However, it is very difficult to gather a sufficient amount of task performance time data based on operating experience because of the infrequency of occurrence of an emergency event. For this reason, although several divergences from a real-life situation (i.e., a fidelity problem) still make it possible to dispute the use of simulators (Stanton 1996; O'Hara and Hall 1992; Hollnagel 2000; IAEA 2004), it is apparent that the use of simulators has been regarded as the most cost- and effort-effective way in collecting task performance time data, especially in an emergency situation (Stanton 1996; Rasmussen and Jensen 1974; IAEA 2004). Nevertheless, the use of simulators is still problematic, because a huge amount of resources (e.g., manpower, time, and cost) is generally required to simulate emergency events.

In light of these concerns, the TACOM measure seems to be a practicable solution because there is a strong correlation between TACOM scores and task performance time data. That is, as depicted in Figs. 8.7 and 9.3, the TACOM measure should be able to estimate task performance time data with an upper as well as a lower prediction limit when the TACOM scores of the required tasks are given. Actually, Chi and Chung (1996) and Hamilton and Clarke (2005) have independently shown that task performance time data predicted by a theoretical model are directly comparable to those which are actually observed. This means that, from the point of view of HRA, estimating the possibility of human error based on the predicted task performance time (or the available time) is a viable approach.

However, although HRA is a useful tool to cope with human errors, a more straightforward way would be the management of complicated tasks that challenge the cognitive ability of qualified operators. That is, if we recall that a significant portion of human error are caused by complicated tasks that force qualified operators to use a lot of cognitive resources exceeding their cognitive ability, the identification of complicated tasks that are likely to place an excessive workload on qualified operators seems to be indispensable.

10.2 Identifying Complicated Tasks Demanding an Excessive Workload

As stated at the end of Chap. 2, the complexity of proceduralized tasks should be managed because the complexity increases the possibility of human error by placing an excessive workload on qualified operators. Accordingly, we at least have to answer one crucial question – *how can we identify a complicated task demanding an excessive workload of qualified operators*?

In this regard, it is very interesting to point out that a complicated task increases the possibility of violations by making qualified operators look for more effective shortcuts. That is, as depicted in Fig. 2.4, qualified operators are likely to deviate from a procedure if they believe that there is a better way to accomplish a complicated task demanding an undue workload. Therefore, scrutinizing the characteristics of procedure deviations along with changes in TACOM scores would provide us with an important clue regarding the identification of complicated tasks. For this reason, the behavior types of SROs who must shoulder most of the burden arising from the performance of emergency tasks are worth investigating.

10.2.1 Three Kinds of Behavior Types in Conducting Procedural Steps

The audiovisual records of retraining sessions, which were the data sources of the OPERA database, have been meticulously analyzed in order to observe how SROs have carried out emergency tasks included in EOPs. In particular, these observations have focused on the performance of procedural steps because they are the minimal unit of emergency tasks (i.e., each emergency task consists of one or more procedural steps). Consequently, as summarized in Table 10.1, three types of distinctive behaviors are identified from SROs' activities.

Table 10.1 SROs' behaviors pertaining to the performance of procedural steps included in EOPs

Type		Meaning
A	Strict adherence	SROs strictly follow all the required actions as written
B	Skipping redundant actions	SROs skip an action that is identical to one that already carried out in the previous procedural step
		SROs perform the same action based on previously known information
C	Modifying the sequence of actions	SROs carry out a procedural step using a modified sequence of actions that is different from the predefined sequence of actions

From Table 10.1, *Type A (strict adherence)* means that SROs have conducted all the required actions along with the predefined sequence of actions (i.e. compliance behavior). In contrast, both *Type B (skipping redundant actions)* and *Type C (modifying the sequence of actions)* imply typical noncompliance behaviors related to finding an effective shortcut. In order to understand the characteristics of noncompliance behaviors, let us consider Fig. 10.2, which shows three arbitrary procedural steps included in EOPs.

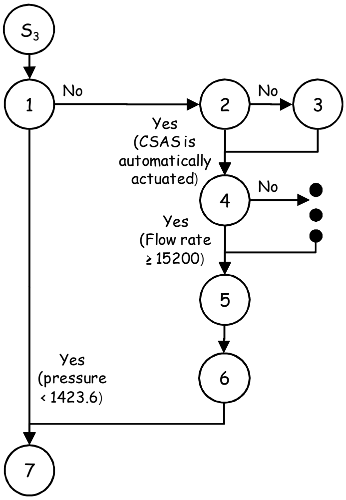
First, *Type B* denotes that SROs conduct all the required actions included in a procedural step to be performed, excluding redundant actions that were already conducted in the previous procedural step (i.e., prior actions). For example, as can be seen from Fig. 10.2, *verify containment pressure is less than 70* cmH_2O action is commonly included in both *Steps 1* and *2*. In this case, it has been frequently observed that SROs did not check the current value of containment pressure in the course of performing *Step 2*, since they already checked it in *Step 1*. In addition, instead of skipping this action, several SROs performed this action by themselves (i.e., without communicating with board operators) based on the old value of the containment pressure obtained in the course of performing *Step 1*.

	Instructions	Contingency Actions
Step 1	Determine the containment isolation acceptance criteria are met by performing **ALL** of the following: a. Verify containment pressure is less than 70 cmH_2O. b. Verify **NO** containment area radiation alarms or unexplained rise in radiation has occurred. c. Verify **NO** steam plant radiation alarms or unexplained rise in radiation has occurred.	a. **IF** containment pressure is greater than 133.1 cmH_2O, **THEN** ensure CIAS is actuated. b. **IF** there is steam plant radiation alarm or unexplained rise in radiation, **THEN** sample SG activity.
Step 2	Determine containment temperature and pressure acceptance criteria are met by performing **BOTH** of the following: a. Verify containment temperature is less than 49°C. b. Verify containment pressure is less than 70cmH_2O.	a. Ensure all required containment normal cooling and ventilation systems are in operation: ***… (rest of actions)***
Step 3	**IF** containment pressure is greater than 1423.6 kg/cm^2, **THEN** perform **ALL** of the following: a. Verify CSAS (containment spray actuation signal) is actuated automatically. b. Verify all CS (containment spray) pumps are delivering at least 15,200 LPM (liter per minute) c. Close RCP (reactor coolant pump) seal leak-off isolation valves. d. Stop all RCPs.	a. **IF** CSAS has **NOT** been initiated automatically **THEN** manually actuate CSAS. • EF-HS-101A/101B/101C/101D. b. **IF ANY** CS pumps **CANNOT** deliver 15,200 LPM **THEN** perform **ANY** of the following: ***… (rest of actions)***

Fig. 10.2 Three arbitrary procedural steps to explain *Type B* and *Type C* behavior (Park and Jung 2003, © Elsevier)

Second, *Type C* indicates that SROs carry out the required actions based on a modified sequence of actions. It has been frequently observed that SROs seem to try to change the predefined sequence of actions into another one in order to perform a procedural step more easily. It is to be noted that the main difference between *Type B* and *Type C* is the existence of *prior actions*, since *Type C* automatically includes the behavior of skipping actions due to the modified sequence of actions. Let us consider Fig. 10.3, which depicts the ACG of *Step 3*.

First, when SROs start to perform *Step 3*, they have to verify whether the containment pressure is greater than 1423.6 kg/cm^2 or not (refer to the first action in Fig.10.3). If the result is *yes*, then SROs have to perform either *verify all containment spray (CS) pumps are delivering at least 15200 LPM* action or *manually actuate containment spray actuation signal (CSAS)* action based on the results of *verify CSAS is actuated automatically* action. However, several SROs accomplished this procedural step using a modified action sequence, as illustrated in Fig. 10.4.



ID	Action description
S_3	Perform Step 3
1	Verify containment pressure is greater than 1423.6 kg/cm^2
2	Verify CSAS is actuated automatically
3	Manually actuate CSAS
4	Verify all CS pumps are delivering at least 15200 LPM
5	Close RCP seal leak-off isolation valves
6	Stop all RCPs
7	Go to the next procedural step

Fig. 10.3 ACG of *Step 3* (Park and Jung 2003, © Elsevier)

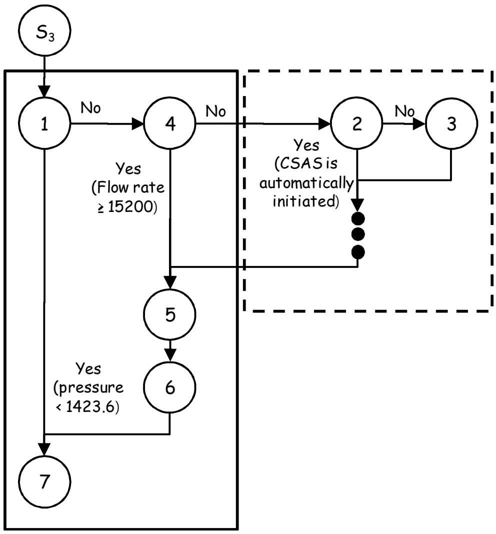


Fig. 10.4 Modified sequence of actions about *Step 3* (Park and Jung 2003, © Elsevier)

As shown in Fig. 10.4, SROs carried out *verify all CS pumps are delivering at least 15200 LPM* action before conducting *verify CSAS is actuated automatically* action. This sequence of actions is the deviation from the predefined one depicted in Fig. 10.3. Nevertheless, the fruit of this modification seems to be attractive – *reducing the number of actions to be conducted by SROs*. This is because SROs do not need to consider the several actions enclosed by dotted lines when the flow rate of CS pumps is greater than 15200 LPM.

From the above examples, thus, the meaning of prior actions could become obvious, since the only way to discriminate *Type B* from *Type C* is to check the existence of identical actions. It is to be noted that there will be many different types of noncompliance behaviors that can be observed in the course of performing procedural steps. Unfortunately, it is very difficult to detect other types of noncompliance behaviors because most of them have occurred in the mental processes of SROs. Accordingly, for the sake of simplicity, it is assumed that all the noncompliance behaviors belong to either *Type B* or *Type C*.

10.2.2 The Meaning of Noncompliance Behaviors

It seems that there is a plausible explanation why SROs adopt these types of noncompliance behaviors. As one of the training instructors working in the reference NPPs stated:

> When the containment pressure is high, SROs ultimately want to know whether a sufficient CS flow is delivered or not. In addition, most SROs already recognize that, when the CSAS is actuated, CS pumps and the associated valves are automatically aligned in order to deliver sufficient CS flow. Thus, the adoption of Type C is understandable, because they are able to reduce the number of the required actions by checking flow rate from CS pumps before anything else.

At the same time, however, the training instructor also noted that both *Type B* and *Type C* might be risky, because these noncompliance behaviors can directly result in an unanticipated consequence. For example, licensee event reports (LERs) issued in the U.S.A have revealed that a significant portion of incidents was caused by a noncompliance behavior such as *an operator's decision upon a course of action based on what information he had* (Brune and Weinstein 1981). In addition, Macwan and Mosleh (1994) stated that *memory of recent actions* is one of the causes resulting in a procedure-related human error. That is, when qualified operators are asked to verify the flow rate, they are apt to omit verifying the current value of the flow if they have recently verified that the status of the associated pump is running.

Nevertheless, the above explanations clearly show that both *Type B* and *Type C* are not malicious but a kind of optimized response to satisfactorily perform the required tasks under a given constraint. This means that the comparison between noncompliance behaviors and TACOM scores would be meaningful because qualified operators will try to reduce the amount of undue workload by adopting a more effective way to perform procedural steps.

10.2.3 Comparing the Occurrence of Noncompliance Behaviors with the Associated TACOM Scores

In order to compare noncompliance behaviors with the associated TACOM scores, the OPERA database has been meticulously examined. As a result, Table 10.2 summarizes a profile about the number of compliance as well as noncompliance behaviors, which is grouped so that the distribution of observations is fit to a normal distribution with respect to TACOM scores (Kolmogorov-Smirnov test passed, $p > 0.2$).

Table 10.2 Profile of compliance as well as noncompliance behaviors

TACOM score (bin size = 0.6)	Number of observations			
	Type A	Type B	Type C	Total
1.401 ~ 2.000	28	0	1	29
2.001 ~ 2.600	143	20	37	200
2.601 ~ 3.200	332	32	139	503
3.201 ~ 3.800	175	3	55	233
3.801 ~ 4.400	104	7	19	130

In order to clarify whether the occurrences of noncompliance behaviors are influenced by the associated TACOM scores, the χ^2 test is conducted as summarized in Table 10.3.

Table 10.3 Results of χ^2 test

TACOM score		The number of observations			The number of expectations		
Range	Representative	Type A	Type B	Type C	Type A	Type B	Type C
1.401 ~ 2.000	1.700	28	0	1	20.7	1.6	6.6
2.001 ~ 2.600	2.300	143	20	37	142.8	11.3	45.8
2.601 ~ 3.200	2.900	332	32	139	359.2	28.5	115.3
3.201 ~ 3.800	3.500	175	3	55	166.4	13.2	53.4
3.801 ~ 4.400	4.100	104	7	19	92.8	7.4	29.8

$\chi^2 = 38.4$, df (degrees of freedom) = 8, $p < 10^{-3}$; rejection criterion = $\chi^2_{0.05}(8) = 15.5$

As a result, it seems that the occurrences of compliance behaviors are able to be explained by TACOM scores since the χ^2 value is greater than the rejection criterion for the null hypothesis (e.g., $\chi^2 = 32.1 > \chi^2_{0.05}(8) = 15.5$). This means that qualified operators are likely to change their behaviors with respect to the complexity of procedural steps. If we adopt this expectation, then it is meaningful to compare the effect of TACOM scores on the percentage of compliance behaviors (Fig. 10.5).

From Fig. 10.5, it is observed that many SROs seem to adopt noncompliance behaviors more frequently when they have to conduct procedural steps whose TACOM scores range from 2.300 to 3.500 (based on representative values). In contrast, when SROs are faced with procedural steps whose TACOM scores are either relatively low (i.e., less than 2.300) or relatively high (i.e., greater than 3.500), they seem to try to follow procedural steps as written.

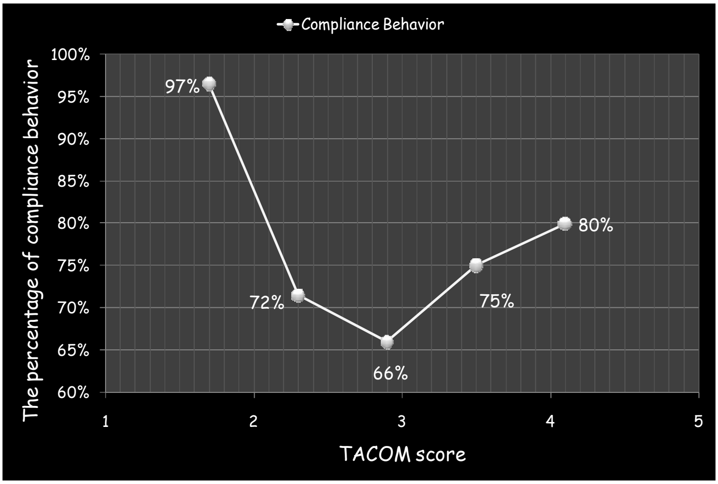


Fig. 10.5 Comparing the percentage of compliance behaviors with the associated TACOM scores

10.2.4 Criterion for Complicated Tasks

As can be seen from Fig. 10.5, the relation between compliance behaviors and TACOM scores shows a large U shape (or an inverted-U shape for noncompliance behaviors). In this regard, it is possible to assume that we are able to establish a criterion for complicated procedural steps demanding an excessive workload. To this end, let us consider Fig. 10.6.

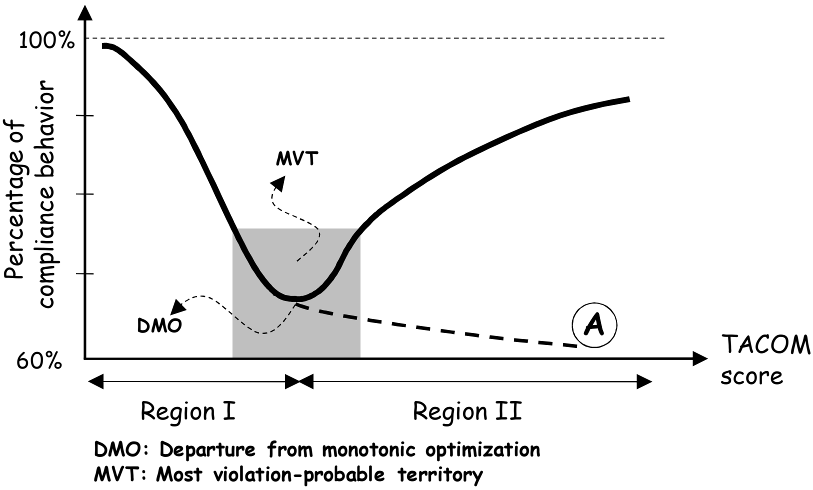


Fig. 10.6 Hypothetical tendency of compliance behaviors with respect to an increase in TACOM scores

In *Region I*, SROs show an expected tendency to frequently adopt noncompliance behaviors (i.e., searching for a shortcut) accompanied by an increase in TACOM scores. If this tendency continues, the percentage of noncompliance behaviors will follow a hypothetical line that is monotonically falling such as Ⓐ in Fig. 10.6. However, in *Region II*, observed data show that SROs seem to less frequently adopt noncompliance behaviors when they exceed a certain value of the TACOM measure. In other words, SROs seem to try to carry out the required actions as written even if they have to accomplish more complicated procedural steps. This contradictory tendency can be understood if we consider two assumptions from the point of view of optimization behavior.

First, when SROs are faced with a procedural step that consists of a few actions with a simple action sequence, they will likely to carry it out as written. This is because the procedural step is so easy that SROs do not need to consider noncompliance behaviors to reduce an undue workload. Meanwhile, in the case of a complicated procedural step, it is assumed that SROs might feel a burden in adopting noncompliance behaviors because there is no benefit to reducing an undue workload. That is, customizing a complicated procedural step through adopting noncompliance behaviors is not favorable since SROs may use a considerable amount of cognitive resources dealing with various kinds of causalities, such as the automatic running of CS pumps due to the actuation of the CSAS, in the course of searching for a shortcut. For this reason, the inflection point from which the percentage of compliance behaviors starts to increase can be referred to as the departure from monotonic optimization (DMO). According to Fig. 10.5, in the case of qualified operators working in the reference NPPs, it is expected that the DMO will be located somewhere in the range 2.300 to 3.500. Here, we are able to refer to this territory as the most violation-probable territory (MVT), because the chance of an unintended violation is relatively high in an unstable environment.

Fortunately, these assumptions appear to be reasonable because it is anticipated that SROs will just try to trade off noncompliance behaviors with the complexity of procedural steps (i.e., cost-benefit trade-offs) (Reason 2008). For example, Amalberti (2001) pointed out that “Fundamentally, an operator does not regulate the risk of error, he regulates a high performance objective at the lowest possible execution cost. In the human mind, error is a necessary component of this optimized performance result (p. 118).” Similarly, Leplat (1998) stated that “These studies, for example, have shown that when the demands or the complexity of the work increase, one process for reducing complexity is to change work method (p. 110).”

And Vicente (1999) explained:

> At one plant, operators would not always follow the written procedures when they went to the simulator for recertification. They deviated from them for one of two reasons. In some cases, operators achieved the same goal using a different, but equally safe and efficient, set of actions. … In other cases, the operators would deviate from the procedures because the desired goal would not be achieved if the procedures were followed. It is very difficult to write a procedure to encompass all possible situations (p. xiii).

Therefore, the percentage of noncompliance behaviors will be proportional to the amount of benefits that are seen as outweighing the possible costs if SROs believe that they will not result in bad consequences (Dien et al. 1992; Maurino et al. 1995; Vessey 1994; Visciola et al. 1992; Lawton 1998). This strongly suggests that SROs are apt to adopt noncompliance behaviors when they have to perform procedural steps whose complexity is within a certain tolerable range. Subsequently, it is presumed that qualified operators are able to accomplish procedural steps whose TACOM scores are less than the DMO, with an acceptable workload. In contrast, qualified operators are likely to feel an excessive workload when they have to accomplish procedural steps whose TACOM scores are greater than the DMO. Here, if we assume that the value of the DMO is the best representative value of the MVT (i.e., 3.500), then 4.100 (i.e., the central value between 3.801 and 4.400) should be a representative value distinguishing a procedural step that might place an excessive workload on SROs. Consequently, it is highly expected that the possibility of procedure-related human errors (i.e., distraction-due-to-workload) will increase when qualified operators need to accomplish a proceduralized task that consists of a series of procedural steps whose TACOM scores are greater than this value. This implies that we might have a decisive clue for answering one of the pending issues in cognitive engineering: *In many hazardous technologies, the important issue is not whether to violate but when to violate* (see p. 291 of Reason et al. 1998).

Although a great amount of additional effort should be spent in advance to justify the aforementioned assumptions and expectations, it is hoped that the TACOM measure would contribute greatly to the identification of effective countermeasures to support qualified operators if we are able to establish a firm criterion regarding a complicated proceduralized task. In this vein, one of the typical contributions will be the provision of necessary inputs in the early phases of a human-machine interface (HMI) design process.

10.3 Providing Design Inputs on Effective HMIs

In general, it has been widely recognized that one of the key processes in the design of HMIs is task analysis. For example, as stated by Kirwan and Ainsworth (1992):

> Task analysis involves the study of what an operator (or team of operators) is required to do to achieve a system goal. The primary purpose of task analysis is to compare the demands of the system on the operator with the capabilities of the operator, and if necessary, to alter those demands, thereby reducing error and achieving successful performance (p. 15).

To this end, at least, it is essential to identify what kinds of information and activities are necessary to achieve the required tasks (Kirwan 1994; Kirwan and Ainsworth 1992; IEEE 1997). In this regard, Fig. 10.7 shows the typical results of a task analysis about the HMI design of NPPs (Lee et al. 1994).

Function	Regulating RCS inventory
Task	Increasing the rate of charging flow
Purpose	Increasing the rate of charging flow in order to compensate for expected condensations due to the cooling of RCS
Action	1. Switch the controller of charging flow to manual position. 2. Control the rate of charging flow until the water level of pressurizer reaches 70%. 3. If necessary, close BG-HV-1 and BG-HV-2. 4. Control the rate of charging flow less than 27 m^3/h. 5. If necessary, stop all remaining RCPs except one.
Indicator	1. CVCS (chemical and volume control system) charging flow indicator • BG-FI-122 (0-50m^3/h) 2. Pressurizer level: indicators • BB-LI-459A (0-100%) • BB-LI-460 (0-100%) • BB-LI-461 (0-100%) 3. Pressurizer level: trend recorder • LR-459 (0-100%)
Controller	1. CVCS charging flow controller • BG-FK-122 (manual: 0-100%, modulate) 2. CVCS letdown orifice valve switches • BG-HS-1 (Open, Close) • BG-HS-2 (Open, Close) 3. RCP controllers (Start, Stop)

Fig. 10.7 Typical results of a task analysis

It should be emphasized that the TACOM score of a task being considered can be directly quantified from the results of a task analysis because Fig. 10.7 contains all kinds of information for quantifying the five submeasures. This implies that more detailed as well as helpful functional specifications can be extracted in the early stages of an HMI design process. For example, Table 10.4 summarizes the TACOM score of *increasing the rate of charging flow* task.

Table 10.4 TACOM score of *increasing the rate of charging flow* task

SIC	SLC	SSC	AHC	EDC	TS	TR	TU	TACOM
3.640	2.000	3.000	4.564	4.736	3.458	2.279	4.736	3.436

It is to be noted that this task seems to be violation-probable, because the TACOM score shown in Table 10.4 belongs to a range in which qualified operators might adopt a noncompliance behavior more frequently. Due to this concern, we have to do something to reduce the possibility of an unintended violation about this task. Fortunately, the scores of the five submeasures provide diagnostic information by which an appropriate countermeasure can be figured out.

For example, it is anticipated that the EDC will be a primary contributor since its score is greater than those of the other submeasures. Actually, this anticipation seems to be reasonable because qualified operators have to conduct a couple of equally acceptable actions, such as *If necessary, close BG-HV-1 and BG-HV-2*, or *If necessary, stop all the remaining RCPs except one*. This means that it is indispensable for qualified operators to additionally provide either clearer task descriptions or more helpful information to support the selection of a proper action. However, as already explained at the end of Sect. 5.4, it is very difficult (or almost impossible) to describe detailed actions that accurately cover every situation it would be better to come up with the design of effective HMIs that provide supportive information to qualified operators. From this standpoint, it is expected that the TACOM measure can contribute to the design of effective HMIs in the following ways.

10.3.1 Clarifying the Types of Information Displays

The results of existing studies have revealed that the performance of qualified operators vary dramatically varied with respect to the appropriateness of information displays (Bennett et al. 1997; Goodstein 1981; Ham and Yoon 2001; Ham et al. 2008; Vicente 1999; Vicente and Rasmussen 1990; Wickens 1992; Woods 1991). In short, conventional information displays seem to be inappropriate for supporting the completion of required tasks that demand a high level of cognitive activities, such as searching for necessary information, interpreting information, and inferring information, etc. As a result, conventional information displays are likely to put a great cognitive burden on qualified operators who are working in a large and safety-critical process control system. Therefore, the provision of effective information displays is very important for enhancing the performance of qualified operators as well as, to some extent, for reducing the possibility of human errors.

In this regard, one of the essential questions is *what types of information displays are necessary to provide supportive information*? In other words, we need to clarify what kind of task-related information is necessary to decrease the amount of cognitive burden (or workload) to be placed on qualified operators. From this point of view, Vicente and Rasmussen (1992) suggested the framework of an ecological interface design (EID). Ham et al. (2008) summarized the features of the EID framework as follows:

> EID aims to systematically represent the identified work domain constraints in displays in order to support the adaptive, goal-directed human behavior. Two most important ingredients of the EID approach are identifying invariant constraints of work domains by employing AH (abstraction hierarchy) and designing information display to capitalize the human's powerful pattern recognition ability. The use of AH, a multilevel knowledge representation framework for describing the goal–means structure of work domains, allows designers to build a work domain model that makes human operators have a right mental model of the work domain. Up to now, there have been several studies proving the validity and effectiveness of the EID framework in diverse work domains. Collectively,

> these studies claimed that EID could lead to better performance than traditional displays. Cognitively complex tasks seemed to be more benefited from EID, compared to simple tasks; however, there were no harmful effects of EID under simple tasks (p. 255).

Here, it should be emphasized that the EID framework is effective for *cognitively complex tasks*. This strongly implies that the application of the EID framework should be selective for complicated tasks, because considerable time and effort are necessary to appy the EID framework to a large-scale problem (Vicente 2002). That is, in order to practically apply the EID framework to a large and safety-critical process control system, it should be combined with a kind of additional framework that can identify a complicated task challenging the cognitive ability of qualified operators (Jenkins et al. 2009). From this concern, it is expected that the TACOM measure could play an important role, because TACOM scores can identify complicated tasks that are likely to place an excessive workload on qualified operators. Consequently, one could say that the concurrent use of both the EID framework and the TACOM measure is a very promising approach to providing effective information displays.

10.3.2 Specifying Information Requirements for CBPs

From the point of view of providing supportive information, the use of a systematic framework to determine proper information displays in the early stages of an HMI design is an ideal solution. For example, the EID framework can be applied in the early stages of HMI design processes if a list of complicated tasks could be identified from the results of a task analysis. However, this solution is only available to a system to be constructed or being constructed. This means that we are able to come up with an alternative solution that can be applied to an operating system, such as NPPs. In this regard, a plausible solution would be to use a computer-based procedure (CBP), which is comparable to a paper-based procedure (PBP).

O'Hara et al. (2002) summarized the characteristics of both PBPs and CBPs as follows:

> PBPs also impose tasks on the operator that are not directly related to controlling the plant. To make transitions between procedure steps and documents, and maintain awareness of the status of procedures that are in progress, operators must handle, arrange, scan, and read PBPs in parallel with monitoring and control tasks. CBPs are being developed to support procedure management. CBPs have a range of capabilities that may support operators in controlling the plant and reduce the demands associated with PBPs. In the simplest form, CBPs show the same information via computer-driven video display units (VDUs). More advanced CBPs may include features to support managing procedures (e.g., making transitions between steps and documents, and maintaining awareness of procedures in progress), detecting and monitoring the plant's state and parameters, interpreting its status, and selecting actions and executing them (p. 1-1).

In sum, static PBPs have inherent drawbacks in supporting transitions among multiple procedures as well as a high level of cognitive activities that will dynamically vary with respect to an ongoing situation (such as interpreting process information or selecting appropriate actions). Therefore, CBPs have been developed for not only new NPPs but also existing NPPs with advanced computer and information technologies (Jung et al. 2004; Kontogiannis 1999a; Lipner and Kerch 1994; Pirus and Chambon 1997; Reynes and Beltranda 1990; Spurgin et al. 1988; Spurgin et al. 1993).

However, CBPs have not been widely used as expected because (1) there are still many unresolved issues and (2) practical guidance for their design is still insufficient (Kontogiannis 1999a; O'Hara et al. 2002; Niwa et al. 1996; Niwa and Hollnagel 2002). For example, one of the important design issues is the provision of supportive information to reduce *general cognitive workload* resulting from the high demand of cognitive activities, such as monitoring or decision making (O'Hara et al. 2002). Unfortunately, instead of practical guidelines that allow the designer of CBPs to identify what kind of information should be provided, only a list of high-level functional requirements is currently available.

In this regard, it is expected that another contribution of the TACOM measure could be the specification of design requirements for CBPs. In order to clarify this expectation, let us recall *verify the water level of Tank 1 is abnormally decreasing* action. As explained in Sect. 7.5, qualified operators probably need to check the water level of Tank 1 in parallel with the status of surrounding components to find out whether there is a good explanation for the decrease in the water level. If there is no evident cause, then qualified operators will suspect an abnormal decrease due to other factors, such as a break in a pipe. This implies that CBPs should support qualified operators by providing additional information, such as the status of related components or equipment, which is helpful for reducing the amount of cognitive resources to deal with an action description including an ambiguous *ACCEPTANCE CRITERION* (i.e., abnormally decreasing). Similarly, in the case of *align all the valves to transfer a coolant from Tank A to Tank B* action, CBPs should support qualified operators by providing the associated valves that are necessary to make a flow line to two tanks, because there is no specification about *MEANS*. In this way, it is possible to systematically articulate information requirements for CBPs.

References

Amalberti R (2001) The paradoxes of almost totally safe transportation systems. Saf Sci 37:109–126

Bennett KB, Nagy AL, Flach JM (1997) Visual displays. In: Salvendy G (ed) Handbook of Human Factors and Ergonomics, Wiley, New York, pp.659–696

Brune RL, Weinstein M (1981) Development of a checklist for evaluating emergency operating procedures used in nuclear power plants. NUREG/CR-1970, Washington, DC

Chi C, Chung K (1996) Task analysis for computer-aided design (CAD) at a keystroke level. Appl Ergonom 27(4): 255–265

Cooper SE, Ramey-Smith AM, Wreathall J, Parry GW, Bley DC, Luckas WJ, Taylor JH, Barriere MT (1996) A technique for human error analysis (ATHEANA) – technical basis and method description. NUREG/CR-6350, Washington, DC

Dien Y, Llory M, Montmayeul R (1992) Operators' knowledge, skill and know-how during the use of emergency procedures: design, training and cultural aspects. In: Proceedings of the 5th IEEE Conference on Human Factors in Power Plants, Monterey, CA, pp.178–181
Goodstein LP (1981) Discriminative display support for process operators. In: Rasmussen J, Rouse WB (eds) Human Detection and Diagnosis of System Failure, Plenum, New York, pp.433–449
Ham DH, Yoon WC (2001) The effects of presenting functionality abstracted information in fault diagnosis tasks. Reliabil Eng Syst Saf 73:103–119
Ham DH, Yoon WC, Han BT (2008) Experimental study on the effects of visualized functionality abstracted information on process control tasks. Reliabil Eng Syst Saf 93:254–270
Hamilton WL, Clarke T (2005) Driver performance modelling and its practical application to railway safety. Appl Ergonom 36:661–670
Hollnagel E (1993b) Human Reliability Analysis: Context and Control. Academic, London
Hollnagel E (2000) Looking for errors of omission and commission or the hunting of the Snark revisited. Reliabil Eng Syst Saf 68:135–145
IEEE (1997) IEEE guide for incorporating human action reliability analysis for nuclear power generating stations. IEEE Std 1082-1997, Piscataway
IAEA (1990) Human error classification and data collection. IAEA-TECDOC-538, Vienna
IAEA (2004) Use of control room simulators for training of nuclear power plant personnel. IAEA-TECDOC-1411, Vienna
Jenkins DP, Stanton NA, Salmon PM, Walker GH (2009) Cognitive Work Analysis: Coping with Complexity. Ashgate, London
Jung Y, Seong PH, Kim MC (2004) A model for computerized procedures based on flowcharts and success logic tree. Reliabil Eng Syst Saf 26:351–362
Kirwan B (1994) A guide to Practical Human Reliability Assessment. Taylor and Francis, London
Kirwan B, Ainsworth LK (1992) A Guide to Task Analysis. Taylor and Francis, London
Kontogiannis T (1999a) Applying information technology to the presentation of emergency operating procedures: implication for usability criteria. Behav Inf Technol 18(4):261–276
Kozine I (2007) Simulation of human performance in time-pressured scenarios. J Risk Reliabil 221:141–151
Lawton R (1998) Not working to rule: understanding procedural violations at work. Saf Sci 28(2):77–95
Lee YH, Cheon SW, Suh SM, Lee JW (1994) A survey on the task analysis methods and techniques for nuclear power plants operators. KAERI/AR-402, Daejeon, South Korea
Lee JW, Park JC, Lee YH, Oh IS, Lee HC, Jang TI, Kim DH, Hwang SH, Park JK, Kim JS (2008) Development of the digital reactor safety system. KAERI/RR-2909, Daejeon, South Korea
Leplat J (1998) Task complexity in work situations. In: Goodstein LP, Anderson HB, Olsen SE (eds) Tasks, Errors and Mental Models, Taylor and Francis, London, pp.105–115
Lipner MH, Kerch SP (1994) Operational benefits of an advanced computerized procedures system. In: Nuclear Science Symposium and Medical Imaging Conference, Norfolk, VA, vol 3, pp.1068–1072
Macwan A, Mosleh A (1994) A methodology for modeling operator errors of commission in probabilistic risk assessment. Reliabil Eng Syst Saf 45:139–157
Maurino DE, Reason J, Johnston N, Lee RB (1995) Beyond Aviation Human Factors – Safety in High Technology System. Ashgate, Aldershot, UK
Niwa Y, Hollnagel E (2002) Integrated computerization of operating procedures. Nuclear Eng Des 213:289–301
Niwa Y, Hollnagel E, Green M (1996) Guidelines for computerized presentation of emergency operating procedures. Nuclear Eng Des 167:113–127
O'Hara JM, Hall RE (1992) Advanced control rooms and crew performance issues: implications for human reliability. IEEE Trans Nuclear Sci 39(4):919–923
O'Hara JM, Higgins JC, Stubler WF, Kramer J (2002) Computer-based procedure systems: tech-

nical basis and human factors review guidance. NUREG/CR-6634, Washington, DC
Pirus D, Chambon Y (1997) The computerized procedures for the French N4 series. In: Proceedings of the 6th IEEE Conference on Human Factors and Power Plants, 3-9 June 1997, Orlando, FL.
Rasmussen J, Jensen A (1974) Mental procedures in real-life tasks: a case study of electronic trouble shooting. Ergonomics 17(3):293–307
Reason J (2008) The human Contribution: Unsafe Acts, Accidents and Heroic Recoveries. Ashgate, London
Reason J, Parker D, Lawton R (1998) Organizational controls and safety: The varieties of rule-related behavior. J Occupat Organizat Psychol 71:289–304
Reynes L, Beltranda GA (1990) Computerized control room to improve nuclear power plant operation and safety. Nuclear Saf 31(4):504–513
Spurgin AJ, Orvis DD, Cain DG, Yau CC (1988) Testing an expert system: Testing the emergency operating procedures tracking system. In: Proceedings of 4th IEEE Conference on Human Factors and Power Plants, Monterey, CA, pp.137–140
Spurgin AJ, Wachtel J, Moieni P (1993) The state of practice of computerized operating procedures in the commercial nuclear power industry. In: Proceedings on Human Factors and Ergonomics Society (HFES) Annual Meeting, Santa Monica, CA, pp.1014–1017
Stanton N (1996) Simulators: a review of research and practice. In: Stanton N (ed) Human Factors in Nuclear Safety, Taylor and Francis, London, pp.117–140
Sträter O, Bubb H (1999) Assessment of human reliability based on evaluation of plant experience: requirements and implementation. Reliabil Eng Syst Saf 63:199–219
Swain AD, Guttmann HE (1983) Handbook of human reliability analysis with emphasis on nuclear power plant applications. NUREG/CR-1278, Washington DC
Vessey I (1994) The effect of information presentation on decision making: a cost-benefit analysis. Inf Manage 27:103–119
Vicente KJ (2002) Ecological interface design: progress and challenges. Hum Factors 44(1):62–78
Vicente KJ (1999) Cognitive Work Analysis: Toward Safe, Productive and Healthy Computer-based Work. Erlbaum, Mahwah, NJ
Vicente KJ, Rasmussen J (1990) The ecology of human-machine systems II: Mediating direct perception in complex work domains. Ecol Psychol 2(3):207–249
Vicente KJ, Rasmussen J (1992) Ecological interface design: theoretical foundations. IEEE Trans Syst Man Cybern 22(4):589–606
Visciola M, Armando A, Bagnara S (1992) Communication patterns and errors in flight simulation. Reliabil Eng Syst Saf 36:253–259
Wickens CD (1992) Engineering Psychology and Human Performance, 2nd edn. Harper Collins, New York
Williams JC (1988) A data-based method for assessing and reducing human error to improve operational performance. In: Proceedings of the 4th IEEE Conference on Human Factors in Power Plants, Monterey, CA, pp.436–450
Woods DD (1991) The cognitive engineering of problem representations. In: Weir G, Alty JL (eds) Human-computer Interaction and Complex Systems, Academic, New York, pp.169–188
Woods DD, Rumancik JA, Hitchler MJ (1984) Issues in cognitive reliability. In: Lassahn PL, Majumdar D, Brockett GF (eds) Anticipated and Abnormal Plant Transients in Light Water Reactors, vol 2, Plenum, New York, pp.1127–1140,