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COGNITIVE TASK ANALYSIS

Technical Basis and Guidance Development

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ABSTRACT

The staff of the U.S. Nuclear Regulatory Commission (NRC) uses the human factors engineering (HFE) guidance in NUREG-0711, Rev.3 to perform safety reviews of control room designs and technologies. Task analysis (TA) is one of the 12 review elements identified in NUREG-0711 as important to effective HFE in nuclear power plants. TA is the study of the work activities to be performed by teams or crews. With increasing automation, work activities are becoming increasingly cognitive, specifically, shifting away from easily observable physical actions to the domain of supervisory control. The current version of NUREG-0711 contains extensive information on methods and techniques for performing TA, however, only passing reference to cognitive task analysis (CTA) and cognitive work analysis is provided. As the operator tasks continue to move towards greater use of supervisory control via increasing automation, the use of the next generation of cognitive methodologies will aid in understanding the complexity of human-system, specifically human-automation interactions. CTA describes the broad class of cognitive methodologies aimed at describing the cognitive challenges associated with a particular task, and the knowledge and skills required to perform them proficiently. These methodologies are uniquely suited to documenting the decision making, information processing, and perceptual skills that cannot be easily observed, but play an important role in task performance. Thus, CTA is a necessary compliment to traditional TA. The objective of this report is to provide guidance to NRC staff during the review of licensee applications where CTA is included in submittals for new nuclear power plant designs and modifications. This guidance includes detailed summaries and use cases (appendix C) for all the CTA methods and techniques described in the document.

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ABBREVIATIONS AND ACRONYMS

ABWR	Advanced Boiling Water Reactor
ACTA	applied cognitive task analysis
ACWA	applied cognitive work analysis
AP600	Advanced Plant 600
AP1000	Advanced Plant 1000
APWR	Advanced Pressurized Water Reactor
CDM	critical decision method
CFO	cognitive field observations
CFR	Code of Federal Regulations
CM	concept mapping
COL	combined license
ConOps	concept of operations
COPMA	Computerized Operating Manuals
CTA	cognitive task analysis
CWA	cognitive work analysis
CWR	cognitive work requirements
DG	diesel generator
DI	design implementation
EDF	Electricite de France
EID	ecological interface design
EPR	Evolutionary Power Reactor
FAN	functional abstraction network
FITNESS	Functional Integrated Treatments for Novative Ecological Support System
FRA/FA	Functional Requirements Analysis and Function Allocation
FWC	feed water control
GDTA	goal directed task analysis
GOMS	Goals Operators Methods and Selection Rules
GVD	group view display
HED	human engineering discrepancy
HFE	human factors engineering
HPM	Human Performance Monitoring
HRA	human reliability analysis
HSI	human-system interface
HSID	HSI Design
HTA	hierarchal task analysis
I&C	instrumentation and control
IEC	Bureau Central de la Commission Electrotechnique Internationale
IEEE	Institute of Electrical and Electronics Engineers
IP	Implementation plan
M&T	methods and tools
NPP	nuclear power plant
NRC	Nuclear Regulatory Commission (U.S.)
OE	Operating Experience
OER	Operating Experience Review
OPAS	Operator Performance Assessment System
PD	Procedures Design
PIRT	Phenomena Identification and Ranking Table
RSR	Results Summary Report

S&Q	Staffing and Qualifications
SA	situation awareness
SAGAT	Situation Awareness Global Assessment Technique
SMR	small modular reactor
TA	task analysis
TIHA	Treatment of Important Human Actions
TMI	Three Mile Island
TPD	Training Program Development
VDU	Video Display Units
V&V	Verification and Validation
WDA	work domain analysis

1 INTRODUCTION

1.1 Background

Task analysis (TA) is the study of the activities that workers and crews must perform to accomplish their functions in a human-machine system. Its importance was recognized long before human factors engineering (HFE) became an established discipline. In the early 1900's, Frederick W. Taylor was one of the first researchers to scientifically and systematically study human performance in the work environment (Proctor & van Zandt, 1994). One of his major achievements was the development of a TA method based on time and motion studies of workers on a shop floor.

As HFE emerged during World War II as an important engineering discipline, TA became an integral part of the design of military systems (DoD, 2011). It addresses one of the four key considerations in system performance and safety (see Figure 1-1).

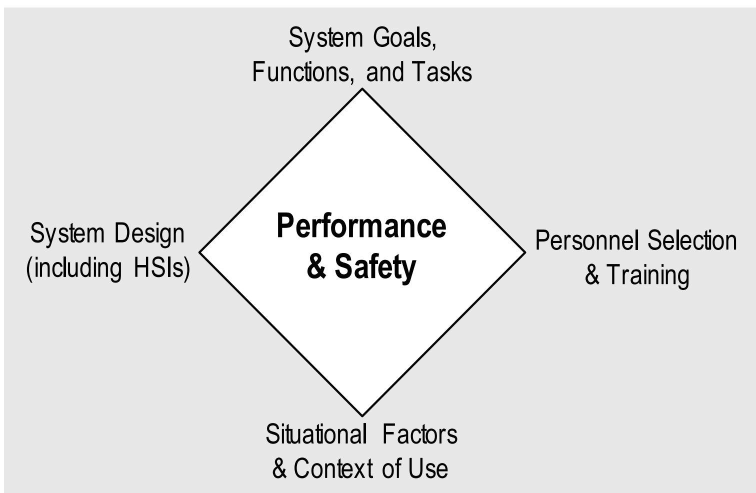

Figure 1-1 Key considerations in system performance and safety

In the commercial nuclear power industry, interest in TA rose considerably following the accident at Three Mile Island Nuclear Generating Station, Unit 2. One of the conclusions from investigations of the accident was that plant operators had difficulty understanding what was happening as the event unfolded (Kemeny, 1979; NRC, 1980). In response, the U.S. Nuclear Regulatory Commission (NRC) developed an action plan to improve operational safety at nuclear power plants (NPPs) across the U.S. (NRC, 1980, 1983). Facilitating the ability of crews to recognize and respond to events was one important aspect of the plan. One way to accomplish this goal was to improve the human-system interfaces (HSIs) used in the control room to monitor and manage the plant, especially when unanticipated events occur. One of the important means of improving HSIs is to ensure they are designed to support operator tasks during normal, abnormal, emergency, and severe accident conditions. Identifying task requirements is one of the main purposes of TA.

The NRC sponsored research to perform comprehensive analyses of a broad range of operator tasks (NRC, 1983) and plant-specific analyses were performed to support control room design improvements, as well as to provide input to improve training programs and procedures. The methodology chosen for many was "operational sequence analysis." This is a method that represents the operations associated with a task based on the order they are performed (Kirwan & Ainsworth, 1992). The flow of activity is often depicted graphically in operational sequence diagrams, which relate each operation to factors such as associated information, actions, decisions, and communications.

TA is still widely required and/or recommended as an integral part of complex system development in military (DoD, 2011) and industrial applications (IEEE, 2004). In fact, TA is considered "at the heart of the human factors contribution to system design" (Sanders & McCormick, 1993). For example, MIL-STD-46855A (DoD, 2011) states

> Human engineering principles and criteria shall be applied to analyses of tasks and workload, including cognitive task analysis if required. These analyses shall also be available for developing preliminary manning levels; equipment procedures; and skill, training, and communication requirements; and as integrated logistic support inputs, as applicable (Requirement 5.1.2, p. 10).

Given the instrumental role of TA in system design, it is not surprising that it is one of the key elements of the NRC's HFE safety review. TA is reviewed using the guidance provided in NUREG-0711, "Human Factors Engineering Program Review Model," Revision 3 (O'Hara, Higgins, Fleger & Pieringer, 2012). NUREG-0711 is based on the concept that the HFE aspects of NPPs should be developed, designed, and evaluated based on a structured systems analysis using accepted HFE principles at the same time other systems are being designed. The review addresses both the design process (i.e., function allocation and TA) and the HFE products of that process (i.e., the specification of personnel roles and responsibilities, HSIs, procedures, and training). Figure 1-2 shows all 12 elements of an HFE program review.

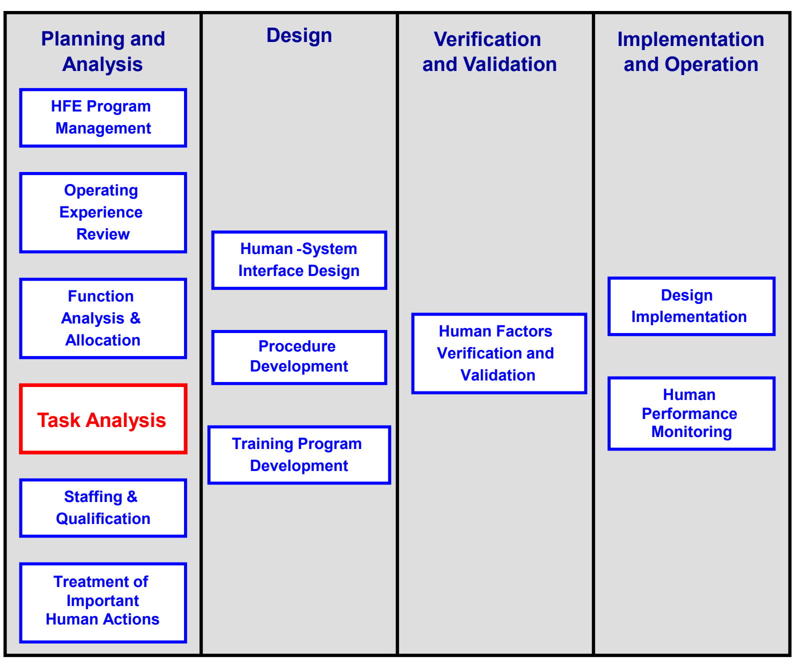

Figure 1-2 Elements of the NRC's HFE Program Review Model (NUREG-0711)

The objectives of the NUREG-0711 TA review are to verify that the applicant has performed analyses that:

- identify the specific tasks personnel perform to accomplish their functions
- identify the alarms, information, controls, and task support needed to perform those tasks

The NRC reviews an applicant's TA using ten criteria addressing the scope, task decomposition, task relationships, task characteristics (i.e., time and workload), and task requirements. Using this guidance, the NRC has performed design certification reviews of newer plant designs, such as General Electric's Advanced Boiling Water Reactor (ABWR: see GE, 2007), Westinghouse's Advanced Plant 1000 (AP1000), and NuScale Power LLC's Small Modular Reactor Plant Design (Houser, Young, & Rasmussen, 2013).

The NRC staff expect to begin reviewing the HFE programs of more advanced plant designs, such as non-LWRs. When compared with currently operating plants, non-LWRs have a very different concept of operations (ConOps) (O'Hara, Higgins & Pena, 2012). Examples of these differences include:

- Fewer required staff
- Individual operators may be managing multi-reactor units
- The configuration of units may be very different (e.g., moving reactor modules for servicing)
- High degree of automation in terms of process controls, as well as cognitive and decision support systems
- HSIs will incorporate many new design features and functions to accommodate the new ConOps

The NUREG-0711 review criteria are based on traditional approaches to TA, including operational sequence analysis and hierarchal TA (see Kirwan & Ainsworth, 1992, for a description of traditional TA methods). Traditional methods have their limitations when applied to both plant design and safety reviews. This report will discuss four of those limitations.

The first limitation is that most of the commonly used TA methods are focused on individual and crew *activity* (i.e., observable behaviors). However, as every aspect of plant operation becomes more automated, the role of personnel becomes less activity oriented and more cognition oriented. The role of personnel is evolving to that of a supervisory controller (i.e., setting goals, monitoring performance, making decisions, and adjusting operations as necessary). The tasks of a supervisory controller are much less "observable" than the shop floor movements of Taylor's workers or the operator's activity at control boards in a manually operated plant. The traditional TA methods are not as well suited to examining cognitive tasks and determining their requirements. It should be noted that many traditional methods consider cognitive aspects at a superficial level (e.g., what information is needed or that a decision must be made). They do not consider, for example, how decisions are made or the strategies personnel use.

The second limitation of traditional methods is that they tend to focus on the ways that tasks should be performed from the perspective of designers, procedure developers, and trainers. These perspectives do not always capture how work is performed under the demands of the actual environment or consider the knowledge and strategies personnel use to perform their tasks.

The third limitation of these methods is that they do not address what makes situations difficult, beyond relatively simple considerations, such as too little time available or too many concurrent activities to be performed. Because the focus is not on cognitive processes, the methods do only a coarse job of identifying aspects of operations that are likely to be difficult for operators. However, in real world settings, task difficulty is an important determinant of performance and safety.

The fourth limitation is that traditional methods are better suited to well-defined situations and planned activities where the steps required to perform the task and their order can be directly identified (e.g., switching the line-up of a system). They are less well-suited to analyzing unplanned and unanticipated situations, such as abnormal events that designers have not anticipated, and operations experts have not previously experienced – yet it is just these types of situations that can pose the greatest risk to safety.

Thus, although TA is an important element of an HFE program and many methods have evolved over the years, the recent trends toward supervisory control systems and reliance on cognitive rather than physical activities have revealed the weaknesses in traditional methods. Therefore, a family of methods, generically called "cognitive task analysis (CTA)," was developed to help address the four limitations discussed above. CTA methods are not intended to replace more traditional TA approaches; rather they are intended to supplement them to provide a means of understanding supervisory control and cognitive activities.

1.2 Research Objective

The objective of this research is to develop guidance for NRC staff to use when reviewing applications with CTA in their NPP design by applicants seeking certification and licensing by the NRC.

1.3 Organization of this Report

In Section 2 of this report, the overall methodology used to develop CTA review guidance is described. In Section 3, an overview of CTA techniques and their application to HFE programs is provided. This information provides the technical basis upon which review guidance can be developed. The CTA review guidance development included a review of NUREG-0711 elements and the relevance for CTA and is described in Section 4. As is discussed in Section 4, the review led to proposed modifications to NUREG-0711 elements on operating experience review (OER) and TA. Section 5 summarizes the research and provides overall conclusions. References to all cited publications are contained in Section 6.

The report also contains several appendices. Appendix A contains the revised OER element and Appendix B contains the revised TA element recommended for inclusion in a revision to NUREG-0711. Finally, Appendix C contains detailed descriptions of selected CTA methods.

2 OVERALL GUIDANCE METHODOLOGY

Figure 2-1 is an overview of the methodology used in developing guidance to address HFE issues (O'Hara et al., 2008a). Its objective is to provide a framework for establishing valid guidance. Validity is defined along two dimensions: internal and external validity. Internal validity is the degree to which the individual guidelines are linked to a clear, well founded, and traceable technical basis. External validity is the degree to which independent peer review supports the guidelines. Peer review is a good method of screening guidelines for conformance to generally accepted HFE practices, and to industry-specific considerations (i.e., for ensuring that they are appropriate based on practical operational experience in actual systems).

The first two steps in the framework for establishing valid guidance are addressed in the present document. The last two steps will be performed in the future.

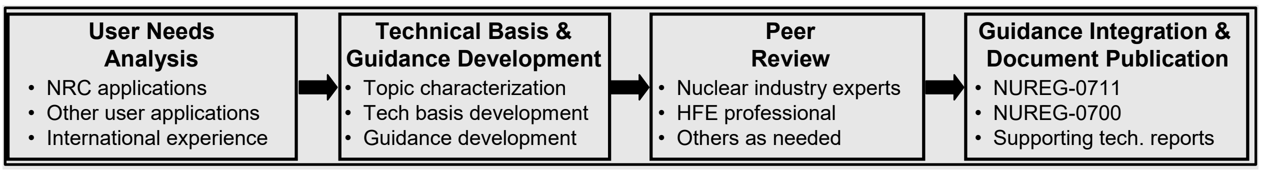

Figure 2-1 Major steps in developing the NRC's HFE guidance

2.1 User Needs Analysis

The first step of the methodology is the *User Needs Analysis,* which is broadly defined as a systematic effort to identify user goals, design constraints, and system functional specifications. As noted above, the NRC's human factors engineering (HFE) review process includes an evaluation of the methods and tools (M&Ts) used by applicants as part of their HFE program. The technology used to perform HFE activities has been rapidly evolving, reflecting changes in approaches to systems engineering in general. A new generation of M&Ts is available to support HFE practitioners. As these new M&Ts are adopted by the commercial nuclear industry, the NRC staff will need review guidance to determine that the M&Ts are being used appropriately. The availability of up-to-date review guidance helps to ensure that NPP personnel have the knowledge, information, capability, work processes, and working environment (both physical and organizational) to safely perform their tasks.

To help ensure that review guidance remains up-to-date, the NRC sponsored research to: identify potential human performance issues associated with emerging technology in the nuclear industry, prioritize these issues, and develop the technical bases needed to address issues of particular importance (O'Hara et al., 2008a; 2008b). These studies identified 64 issues which were organized into seven topic areas:

1. Role of Personnel and Automation

2. Staffing and Training

3. Normal Operations Management

4. Disturbance and Emergency Management

5. Maintenance and Change Management

6. Plant Design and Construction

7. HFE Methods and Tools

The issues were formally prioritized in a workshop by 14 subject matter experts (SMEs) into four categories using a Phenomena Identification and Ranking Table (PIRT) methodology (O'Hara et al., 2008a). The SMEs were knowledgeable in a variety of disciplines and included representatives of vendors, utilities, research organizations, and regulators. Of the 64 issues, twenty were categorized into the top priority category. Almost half of the top-priority issues belong to the HFE M&T topic. M&Ts are significant in the context of HFE safety reviews because, as noted above, the NRC evaluates the M&Ts used in the course of a plant design process. As HFE M&Ts evolve, modifications and improvements to the NRC's review methods and criteria may be necessary. The SMEs indicated that, for these reasons, the design process was of great importance for the safety of future plants.

The NRC's research findings regarding the importance of HFE M&Ts for safety is consistent with the conclusions of a National Research Council study. The Council identified the major reasons why systems fail. Of the reasons identified, most have to do with various aspects of the design process and the M&Ts used by HFE practitioners (Pew & Mavor, 2007). The authors concluded that advances in the M&Ts used by HFE professionals are revolutionizing the ways HFE programs are accomplished for complex systems.

Given the importance of HFE M&Ts to both design and safety evaluations, the NRC conducted an in-depth analysis of HFE M&T developments in the nuclear industry (see O'Hara et al., 2009 and O'Hara, 2010 & Higgins)[1]. Based on that work, 11 topics were identified for further consideration in guidance development for NRC safety reviews. These 11 topics were then prioritized, using a methodology based on a PIRT approach to identify topics of greater importance with respect to regulatory activities (Molino & O'Hara, 2010). The topics were evaluated by five SMEs along two dimensions: importance to regulatory review and the immediacy of the need for guidance on that topic. Using this methodology, three topics were rated highest priority. One was the *Analysis of Cognitive Tasks*. In the study by Molino and O'Hara, *Analysis of Cognitive Tasks* was described as follows:

> "Digital technology has changed plant [instrumentation and control] I&C systems to provide much more information processing and automation than was previously possible. The operator's role is increasingly moving to that of a supervisory controller who oversees plant automation, intelligent agents and operator support systems. This shift has led to an increased emphasis on analyzing cognitive tasks such as detection, situation assessment and decision making. As a result, a new suite of cognitive task analysis and cognitive engineering methodologies has emerged. However, there is no clear guidance to reviewers for determining what specific methods are appropriate for the analysis of particular NPP personnel tasks." p. 17.

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1 The reader is referred to the following reports for information on the *needs analysis*: Molino & O'Hara, 2010, O'Hara et al., 2008a & 2008b, 2009, 2012.

The in-depth analysis conducted in 2010 confirmed the 2008 findings regarding the importance of CTA. The review guidance in NUREG-0711 does not fully address the shift in the operator role to supervisory controller or the new generation of cognitive task methodologies used to understand it, and the cognitive complexities of interacting with highly automated systems. The NRC reviewers need improved guidance for reviewing applications using CTA methods.

2.2 Technical Basis and Guidance Development

The second major step, *Technical Basis and Guidance Development*, involves:

- Topic characterization
- Development of technical basis
- Development of guidance, and documentation

2.2.1 Topic Characterization

A topic is a human factors engineering (HFE) issue or a group of issues for which design-review guidance is being developed. The first step is to develop a topic characterization which defines the topic and identifies its key dimensions and considerations. The characterization will be discussed in Section 3 of this report.

2.2.2 Technical Basis Development

The next step is to analyze information about the topic to generate the technical basis upon which guidance can be developed and justified. Figure 2-2 illustrates the use of several sources of information in order of preference for this task. Following the flow chart downwards, the sources of technical basis change in three ways. First, the information sources near the top are already in the HFE guidance format, or close to it. Towards the bottom, individual research studies must be synthesized and HFE guidelines abstracted. Second, the information at the top already possesses a degree of validity, while towards the bottom it must be established as part of the development effort. Third, using the information at the bottom of the flow chart for developing guidance generally is more costly; thus, the preference is to use sources higher in the figure.

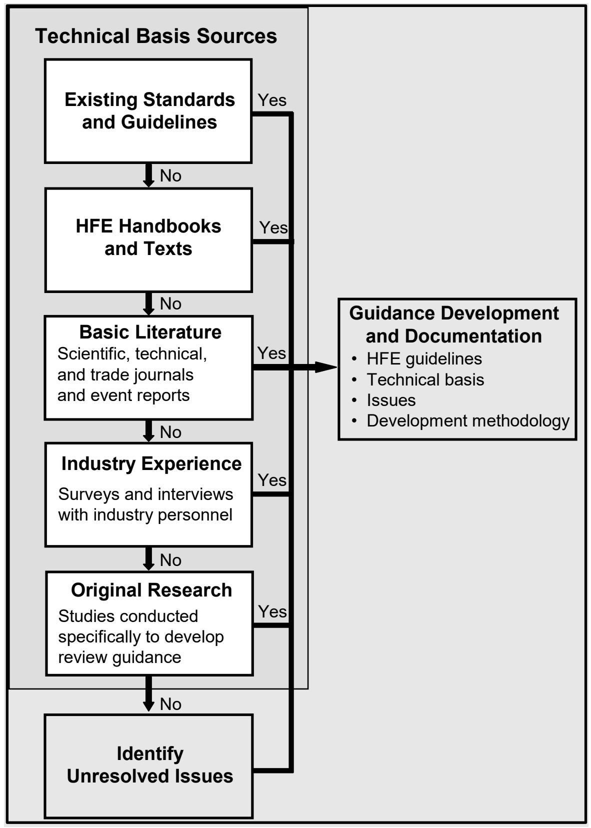

Figure 2-2 Technical-basis development, illustrating the sequential use of data sources

Existing HFE standards and guidance documents are considered first, for example, the standards developed by the U.S. military and organizations such as the American National Standards Institute (ANSI). The authors of such publications have established HFE guidelines using research data, operational experience, and their own knowledge/expertise. In addition, most existing standards and guidance documents have been peer-reviewed. Thus, the documents have internal validity, external validity, or both. Since the information already is in guideline form, it is easier to use than information from other sources. Unfortunately, there are not any known standards or guidance documents of this type addressing cognitive task analysis (CTA).

Next, documents providing good analyses and syntheses of existing literature were sought, such as handbooks. These documents are valuable because they constitute reviews of research and operational literature by knowledgeable experts. However, the information usually is not expressed in guidance form, so that guidance must be developed from it. There are excellent sources of this type for CTA. For example:

- The Oxford Handbook of Cognitive Engineering (Lee, Kirlik, & Dainnoff, 2013)

- The Handbook of Task Analysis for Human-Computer Interaction (Diaper & Stanton, 2004)

When those sources discussed above are insufficient by themselves to support the development of the needed guidance entirely, the basic literature is analyzed, such as technical reports, papers from professional journals, and papers from technical conferences. However, greater effort is required to translate the information into guidance than is involved in using the first two sources described earlier.

This report mainly employed information from HFE handbooks and texts, and basic literature. Industry experience and original research can also support developing a technical basis, although neither were used in this research, other than published reports of industry experience.

If the technical basis was inadequate to support guidance development for specific aspects of a topic, unresolved issues were identified. These topics can be addressed in the future.

2.2.3 Guidance Development

Having completed the steps described above, the technical basis was used to develop review guidance. The CTA guidance is in the format consistent with the NRC review guidance document (NUREG-0711) where it will be integrated. The use of the CTA technical basis and guidance development is described in Section 4 of this report.

2.3 Peer Review

Peer review typically occurs in two stages.

First, subject matter experts (SME)s from the NRC with expertise in human factors engineering (HFE) and Operations review the document. These reviewers evaluate:

- Scope
- Comprehensiveness
- Technical content
- Technical basis
- Usability

The reviewer evaluation will be used to make changes to the report.

During the second stage, the document is reviewed again by independent HFE SMEs. However, this part of the peer review will be accomplished together with other methods and tools (M&T) guidance developed in support of a future revision to NUREG-0711.

2.4 Guidance Integration and Document Publication

After the peer review process is complete, the document is developed into a technical basis report. Only the portions of the guidance necessary for reviewing an applicant's submittal (changes to review objectives or criteria) are integrated into NUREG-0711. NUREG-0711, in turn, will reference the technical basis report for readers interested in the development methodology and the technical basis. This task will be performed as part of a future revision to NUREG-0711.

3 COGNITIVE TASK ANALYSIS CHARACTERIZATION AND TECHNICAL BASIS

3.1 What is Cognitive Task Analysis (CTA)?

CTA describes the cognitive challenges associated with a particular task, and the knowledge, skills, and strategies that are needed to perform the task proficiently (Potter. Roth, Woods, & Elm, 2000; Schraagen, Chipman, & Shalin, 2000; Crandall & Hoffman, 2013). A CTA generally focuses on decisions, judgments, and perceptual skills; elements that cannot be observed directly, but nevertheless play an important role in task performance. For this reason, CTAs provide a useful complement to other forms of task analysis (TA) that focus more on the specific physical activities carried out while performing a task.

A CTA will typically specify:

- The aspects of a task and/or the context within which a task is being performed that are likely to pose cognitive challenges for individuals or teams (e.g., missing, or misleading information, lack of feedback, multiple conflicting goals, and need for tight coordination of activity)
- The knowledge, strategies, and skills that enable operators to perform a task well
- The kinds of errors that operators may make in performing a task and the factors that contribute to those errors (e.g., potentially confusing displays; high workload; and incomplete understanding of how the technology works)

A CTA can be performed on tasks that are currently conducted in existing plants, for example, activities associated with a plant start-up. In this case, the CTA analyst may have the opportunity to directly observe task performance in the actual work context or to interview operators who have performed that task. A CTA can also be performed to support the design of future, first-of-a-kind systems. This may involve analysis of tasks that are not currently being performed but will be in the new system (e.g., new tasks that may be needed to monitor or control multiple small modular reactors). In those cases, CTA methods can be used for deriving the likely cognitive demands and needed knowledge and strategies for performing effectively.

A CTA simultaneously examines the cognitive and collaborative challenges that work imposes and the knowledge and strategies operators have developed (or need to develop) to effectively address those challenges.

Typical objectives of CTA include:

- Identify complex situations - To identify complex situations and events that are likely to challenge cognitive or collaborative performance, and the characteristics that make them. This is useful as input to HSI design, training, and selection of scenarios for verification and validation (V&V).

- Identify complex task elements - To identify complex elements of a task that are likely to challenge cognitive and/or collaborative performance. This is useful as input to human reliability analysis (HRA) and identification of training or decision aiding requirements.

- Understand how complex tasks are accomplished - To gain a better understanding of how complex tasks are accomplished by operators; especially valuable for those tasks that require knowledge-based reasoning (i.e., tasks not proceduralized and rely on the skill and expertise of the operator). This is useful as input to training requirements.

- Capture expert knowledge - To capture and represent the operators' knowledge of the domain (i.e., how elements of the domain are related and determining operationally significant characteristics) for use in the design of training for future personnel or for the development of knowledge-based systems.

- Define the broader context of use - To define the broader context of use within which a new technology will be deployed. This includes identifying the range of contextual conditions, demands, and complexities that should be considered in designing and evaluating new technologies. It can thus play an important role as part of an operational experience review.

- Identify technology impacts - To identify how new technology is likely to impact operator performance both positively (e.g., by providing needed support) or negatively (e.g., by removing critical information that operators rely on for skilled performance).

- Identify design requirements - To develop design input, such as the requirements for HSI design, procedure design, and training program development to enable operators to perform at a high level, as input to future system design and upgrades.

CTAs are not limited to tasks that involve a single individual. They also can be used to examine the cognitive and collaborative demands of tasks that require coordinated activities of multiple individuals that may be together and/or distributed across time (i.e., multiple shifts) or space (i.e., operators in the control room coordinating with operators in the field). In those cases, requirements for communication, coordination, and collaboration (and the situational factors that may impose challenges on those activities) should be examined and documented. Aspects of both the work environment (e.g., information displays, shared planning systems, communication systems) and expert performance (e.g., coordination strategies; implicit and explicit communication methods) can be important contributors to successful communication and coordination.

CTAs can inform all aspects of human factors engineering (HFE), starting from early Operating Experience Review (OER) and requirements analysis through late-stage validation and monitoring performance in the field. The CTA results can be used to identify opportunities to improve performance, for example, through the introduction of systems that more effectively support cognitive performance (e.g., by integrating needed information in a single display that had previously been spread across multiple displays) or through training (e.g., to bring less experienced personnel to the level of experts). CTAs have also been used to guide other aspects of complex system analysis and design, including function-allocation decisions, or as input to workload analysis and HRA. The potential uses of CTA in the various HFE program elements are detailed in Section 3.4 of this report.

3.2 Review of Major Approaches to Cognitive Task Analysis (CTA)

There are a variety of CTA methods that have been developed to identify the demands associated with cognitive work and the knowledge and strategies that are needed for proficient task performance (Bisantz & Roth, 2008).

A CTA entails:

- Knowledge acquisition activities - to learn about the characteristics of the domain and associated complexities, and the knowledge and skill of operators that allow them to cope with the task demands.

- Analysis activities - to synthesize and draw conclusions based on what is learned.

- Representational forms - to present the results of the analysis. The output of a CTA can be represented in various forms including text descriptions, summary tables, graphic representations, and computer models.

Although all CTA methods require the steps listed above, they differ in the level of detailed guidance available to support these activities. For example, some CTA methods, such as the *Critical Decision Method* (Klein, Calderwood, & MacGregor, 1989) provides detailed guidance on how to perform the knowledge acquisition, and relatively less guidance on analysis and output representation. Other methods, such as *Cognitive Work Analysis* (CWA) (Rasmussen, 1986) specify what information should be gathered and the representational forms that should be used to support analysis and communication of results, but do not specify the knowledge acquisition method to use. Still, other methods, such as *Concept Mapping* (Crandall, Klein & Hoffman, 2006) provides guidance on both knowledge acquisition and the graphic representations used to support analysis and communication of results.

In this section, a broad overview of the types of methods available to support CTA knowledge acquisition and analysis activities are provided. The intent of this report is not to provide a detailed tutorial on how to perform a CTA, rather it is to introduce methods that have proved useful in nuclear power plants (NPPs) and process control applications, as well as other domains.[2]

Information for common CTA methods applied in NPPs and process control applications is provided in Appendix C. In addition, Section 3.5 of this document provides examples of CTA application in the commercial nuclear power industry.

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2 More in-depth reviews can be found in Bisantz and Roth (2008), Crandall and Hoffman (2013), and Roth and Bisantz (2013). Crandall, Klein and Hoffman (2006) provide a detailed practitioner's guide on how to perform a CTA.

3.2.1 Knowledge Acquisition Methods

The goal of the knowledge acquisition step in CTA is to understand the cognitive demands and challenges associated with task performance and the knowledge, skills, and strategies operators have developed that enable effective task performance. While it may be possible to derive some of this information from available documentation (e.g., system descriptions, procedures, risk assessments, or training documents), often the challenges associated with task performance (e.g., multiple competing demands on attention, missing or misleading information or a need to adapt the procedures to the situation) can only be obtained through interviews with experienced operators and/or observations of operators performing in the actual environment or under simulated task conditions.

A variety of specific techniques for CTA knowledge acquisition draws on basic principles and methods of cognitive psychology (Cooke, 1994; Ericsson and Simon, 1993; Hoffman, 1987; Potter et al., 2000). These include:

- Structured interview techniques, such as the *Applied Cognitive Task Analysis* (ACTA) method (Militello and Hutton, 1998) and the *Goal-Directed Task Analysis* (GDTA) method (Endsley, Bolte & Jones, 2003).

- Critical incident analysis methods, such as the *Critical Decision Method* that investigates actual incidents that have occurred in the past (Flanagan, 1954; Klein, Calderwood & MacGregor, 1989; Dekker; 2002).

- Field observation studies that examine performance in actual environments or in high fidelity simulators (Woods, 1993; Roth & Patterson, 2005; Chapter 5 of Woods & Hollnagel, 2006).

- 'Think aloud' protocol analysis methods where domain practitioners[3] are asked to report what they are thinking as they solve actual or simulated problems (e.g., Gray & Kirschenbaum, 2000).

- Simulated task methods where domain practitioners are observed as they solve problems under controlled conditions (e.g., Patterson, Roth & Woods, 2001).

- Document and database review methods that extract information on cognitive demands and performance challenges from analysis of descriptions of critical incidents. For example, a review of event reports and near-miss databases.

Three broad classes of methods for knowledge acquisition are summarized below:

- Methods that rely on interviews.

- Methods that rely on observations of individuals performing the task (or a close analog).

- Methods that rely on extracting information from review of available documentation or databases.

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3 "Domain practitioners" is a general term used to refer to the experts, such as operators, pilots, and surgeons, who perform the tasks CTA analysts' study.

3.2.1.1 Interview and Focus Group Methods

Interviews and focus groups are among the most common knowledge acquisition methods. These methods can range from unstructured to highly structured and formal. Unstructured interviews are free form, in which neither the content nor the sequence of the interview topics is predetermined (Cooke, 1994). They are most appropriate early in the knowledge acquisition process when the analyst is attempting to gain a broad overview of the domain. Typically, analysts will use a semi-structured interview approach. When using a semi-structured interview approach the analyst will generate a list of topics and candidate questions ahead of time, but the specific topics and the order in which they are covered is guided by the responses obtained (e.g., Mumaw, Roth, Vincente, & Burns, 2000; Roth, 2008). Structured interview techniques use a specific set of questions in a specific order.

Several semi-structured interview techniques have been developed to uncover the demands of complex cognitive work and the strategies that domain practitioners have developed to meet those demands. One technique is to ground the interviewees in an analysis of past critical incidents to understand what made them challenging and why the individuals who confronted the situation succeeded or failed (Flanagan 1954). The *Critical Decision Method* (CDM) is a structured interview technique that uses this approach (Hoffman, Crandall, & Shadbolt, 1998; Klein & Armstrong, 2004; Klein, Calderwood, & MacGregor, 1989).[4] Other structured interview methods include the GDTA method (Endsley et al., 2003) and *Concept Mapping* (Crandall et al., 2006).[5]

Interviews can be conducted with a single interviewees or multiple interviewees. Interviews conducted with multiple participants are usually referred to as focus groups (Krueger & Casey, 2009). In conducting focus groups, the analyst needs to consider: (1) the number of participants and (2) the range of backgrounds of the participants. General recommendations are to limit group size to 5 to 8 interviewees, so that everyone has an opportunity to provide input. The analyst also needs to consider the benefits and potential limitations of a group with either homogeneous or heterogeneous backgrounds. When participants have homogenous backgrounds, for example, all participants have the same level of experience and same position, the analyst can focus on understanding the work from that unique perspective. When participants have heterogeneous backgrounds, like different levels of experience or from the perspective of different positions, the analyst can uncover additional demands or sources of knowledge from the dialogue arising across the individuals.

3.2.1.2 Field Observation Methods

Observational studies in field settings are particularly useful for identifying mismatches between how work is depicted in formal processes and procedures, and how that work is actually performed. This can include identification of "home-grown" tools and workarounds that operators generate to cope with aspects of task complexity that are not well supported by the design (e.g., Mumaw, Roth, Vicente, & Burns, 2000). Differences between idealized descriptions of work and actual work practice can reveal opportunities to improve performance through more effective support. Observational studies can also be performed under simulated task conditions. For example, a high-fidelity simulator of a new control room design can be used to identify cognitive complexities associated with the new design, and emerging individual

4 Refer to Appendix C, Section C.4 for a detailed description of this method.
5 Refer to Appendix C, Sections C.3 and C.7, respectively, for a detailed description of these methods.

and team performance strategies for addressing those complexities (Roth & O'Hara, 2002). Simulated task environments offer the possibility of greater control over the task and the surrounding context. They also make it possible for methods such as the 'think aloud' protocol to understand the moment-by-moment thought process of the operator during task performance, which might not be practical to ask operators to provide in the actual work context.

Low-fidelity simulations, such descriptions of envisioned complex situations or mockups of future systems, can be used to understand the likely cognitive demands and emergent operator strategies early in the system design process (Dekker & Woods, 1999). A specific sub-type of field study that focuses on uncovering the cognitive and collaborative demands of a work environment, and the knowledge and skills operators develop to address those demands, is referred to as a *Cognitive Field Studies*.[6]

3.2.1.3 Documentation and Database Review Methods

While interviews of experienced operators and observations of actual work provide the most direct input on cognitive demands and operator skills and strategies, useful information also can be obtained through review of documents and databases. Document and database review, while not a CTA method per se, can provide a rich source of information to support a CTA. For example, review of engineering diagrams and documents can provide useful information on the tasks that operators are likely to be expected to perform and the information and controls that are likely to be available to them. Similarly, training documents and procedures can provide useful information on expected operator tasks. Another valuable source of information is reports or databases that document actual incidents or near misses that have occurred in the past (e.g., licensing event and accident investigation reports). These often provide important insights into the real-world complexities that operators face and the performance challenges and potential errors that occur as a result.

3.2.1.4 Guidance on Selection of Knowledge Acquisition Methods

In general, the specific knowledge acquisition method(s) selected will largely be dictated by the goals of the analysis and pragmatic considerations. If the goal of the analysis is to gain a broad overview of cognitive and collaborative requirements and challenges (e.g., identify opportunities for performance improvement through new training or decision support), then techniques such as field observations and structured interviews will be effective. If the goal is to develop a detailed inventory of knowledge required to perform a task, then methods that capture the detailed knowledge and skills that distinguish practitioners at different levels of proficiency can be particularly useful (focused groups, structured interviews, for example). Such a detailed knowledge inventory can be used to support the development of a training curriculum or evaluation metrics to establish practitioner proficiency or serve as inputs for cognitive modeling or workload analysis. In contrast, if the goal is to develop a fine-grained analysis of the mental processes involved in performing a task, then techniques that capture performance at a more detailed level, such as the 'think aloud' method might be most appropriate.

Pragmatic constraints, such as access to operators and the actual work environment also impact methods selection. For example, if access to the actual work environment is not possible, conducting field observations may not be possible. Then, structured interview techniques can be used. If experts cannot discuss actual cases (e.g., because the information is classified or proprietary) then analyses can be conducted using simulated scenarios or

6 Refer to Appendix C, Section C.5 for a detailed description of this method.

analogous problems. If access to domain experts is not possible, it may be possible to conduct CTA based on review of documented descriptions of past critical incidents (e.g., accident reports).

Whenever possible, multiple knowledge acquisition methods (e.g., observations and interviews) should be employed to ensure a more complete understanding of the complexities imposed by the task environment, and the knowledge and strategies of operators (Crandall & Hoffman, 2013; Roth & Patterson, 2005) to provide greater confidence in the results.

Typically, CTAs rely on individuals with current operational experience as the primary knowledge source. However, this is not always possible. For example, when designing 'first-of-a-kind' systems, there may be no current operational users to observe or interview. First-of-a-kind-systems represent a substantial leap from existing ones with respect to the technologies they employ and the ConOps they envision. They are sometimes referred to as "revolutionary" (as opposed to "evolutionary") systems. Examples include envisioned new systems with multi-mission capabilities (e.g., missions beyond power generation, such as hydrogen generation or other functions, see O'Hara, Higgins, & Pena, 2012; O'Hara, Fleger, Desaulniers, Seymour, D'Agostino, 2021) and dramatically reduced crew size such as navy ships (Bisantz et al., 2003), multiple heterogeneous unmanned vehicles intended to be supervised by a single operator (Nehme et al, 2006), and some small modular reactor (SMR) designs (O'Hara et al., 2012).

For these "first-of-a-kind" cases, engagements with stakeholders and system developers can provide insight into the goals, functions, and envisioned ConOps of the system (see Bisantz et al., 2003). Depending on the size of the leap forward, CTA analysts may also be able to draw insights by examining the cognitive demands associated with similar systems and operational environments (e.g., examining experiences in aviation to draw insights about future process control operations), as well as by examining the cognitive complexities that arise with current systems that are likely to apply to future systems (e.g., complexities that arise in current NPP operations that will continue to be relevant when new technologies are introduced).

Finally, while a particular CTA method may provide a recommended sequence of activities and sample questions (e.g., the CDM and ACTA methods include examples of typical probe questions), the analyst should tailor the specific question probes and sequence of analysis activities to the domain being investigated.

3.2.2 Methods for Analysis and Output Representation

The methods used to analyze and communicate the results of a CTA are an important aspect of the CTA process. Information that is gathered through CTA knowledge acquisition methods such as observations, interviews, and document analysis, must be processed and structured in a way that reveals the complexities of the task, and the knowledge and skills that are required for successful task performance.

The output of a CTA can take multiple forms. Bisantz and Roth (2008) provide numerous examples of types of tabular and graphic representations that have been used to communicate the output of a CTA:

- Narrative descriptions of critical incidents and the cognitive demands and strategies they reveal.

- Structured tables that catalogue the decision points that arise, why they are difficult, the knowledge and skill that enable experts to handle the situation, and the typical errors personnel may make.

- Concept maps that provide graphic depictions of the structure (i.e., relationships between knowledge) and content of knowledge of domain practitioners (i.e., both experts and less experienced individuals).

- Diagrams that illustrate the problem-solving strategies used by domain practitioners (e.g., contrasting expert vs. novice strategies).

- Formal, computer-based executable models.

Along with the development of knowledge acquisition methodologies, CTA analysts have also innovated around analytical methods for synthesizing insights, creating associated output representations, and deriving HFE requirements.

Analytical methods are also useful for the design of first-of-a-kind systems, for which experienced operators do not yet exist and, therefore, cannot be interviewed or observed to inform the CTA. In those cases, the analytic methods help define the information that should be collected as part of the design process, to aid in understanding the likely-to-be cognitively challenging aspects of the task and, thus, the needed HFE-related requirements for effective human performance.

These analytic methods generally fall into two classes:

- Methods that guide the analysis and characterization of the work demands inherent in a domain of practice (i.e., a model of the work domain).

- Methods that guide the analysis and characterization of the cognitive and collaborative activities that are required for task performance (i.e., a model of cognitive performance in the domain).

Below is a summarization of these two broad classes of analysis methods.

Work Domain Modeling

A function is a process or activity required to achieve a desired goal. Work domain modeling refers to methods that provide a functional description; one that focuses on the goals, means, and constraints of a work domain. The description can be used to define the work goals, tasks, and associated cognitive and collaborative challenges. Numerous functional analysis methods have been developed to characterize work domains.

These methods typically involve the generation of:

- Descriptions, which specify the major goals that the system must achieve

- Functions needed to achieve the goals

- Sub-systems available to achieve higher-level functions.

This description is called a “goal–means decomposition” (Rasmussen, 1986; Roth & Woods, 1988; Woods & Hollnagel, 1987; Woods & Roth, 1988; Hollnagel & Woods, 2005; Woods & Hollnagel, 2006).

CWA, introduced in Section 3.2 of this report, is the most fully developed CTA methodology that uses this approach (Rasmussen, 1986; Vicente, 1999). CWA includes five interlinked analyses:

- Work Domain Analysis (WDA)
- Control Task Analysis
- Strategies Analysis
- Social, Organizational, and Cooperation Analysis
- Worker Competencies Analysis

Each of these is discussed in greater detail in Section 3.2 and Appendix C.1. The discussion in the current section focuses on WDA, because it is a foundational methodology in several other cognitive task analysis techniques. A WDA represents the goals, means, and constraints in a domain that define the boundaries within which agents perform. In this context, the term "agents" refers to who (humans) or what (machines) is performing an activity (i.e., agents are entities that perform tasks). The results of this analysis provide the basis for identifying functions to be performed by humans (or machines) and the cognitive activities those entail. The remaining layers of the CWA build on the WDA foundation.[7]

Several useful variants of WDA have emerged, one particularly noteworthy method is the *Applied Cognitive Work Analysis* (ACWA), a comprehensive design methodology that incorporates a WDA (Elm, et al., 2008; Elm, Potter, Gualtieri, Roth, & Eastern, 2003). The output of ACWA is represented as a functional abstraction network (FAN) that specifies domain goals along with associated processes and system components that support those goals. The FAN is linked to, and provides the basis for, additional stages of analysis including the identification of information requirements and development of HSIs that represent the domain.[8]

The result of these types of analyses is a model of the work domain that provides representations that the analyst can use to identify the demands on the operators (see section 3.3 for an example CTA for a feedwater control during a startup task).

By providing a complete specification of the domain goals, functions, systems, and associated operator monitoring and control requirements, work domain models strive to capture the cognitive demands associated with monitoring and control of plant functions, and to identify the information and decision-support that is needed to enable plant operators to effectively monitor and control all plant functions and processes.

7 Refer to Appendix C, Section C.1 for a detailed description of this method.
8 Refer to Appendix C, Section C.2 for a detailed description of this method.

3.2.2.1 Cognitive Performance Modeling

CTA analytic frameworks include methods for identifying and representing the cognitive and collaborative activities required to perform a task. One method is the 'Decision Ladder' (Rasmussen et al., 1994), which provides a template for identifying the knowledge and cognitive activities necessary to make a decision or to achieve a goal (Rasmussen, 1983). Cognitive activities represented within a decision ladder include detection, state identification (i.e., situation assessment), goal selection, and planning and execution, which may include identifying and executing predefined procedures.[9]

As part of a CWA, analysts often use decision ladders to represent the outputs of control tasks and strategies analyses. Control task analysis identifies the cognitive functions needed to achieve domain goals without specifying what agent (person or machine) will perform the function. For example, in the case of supervisory control tasks, a human operator may be responsible for establishing goals to be achieved and monitoring goal achievement. Automated systems may take on the specific cognitive tasks required to achieve the goals, including detection, state identification, and response selection and execution. Analyses identify alternative detailed strategies that can be used to achieve the control tasks.

3.2.2.2 Decision Ladders

Decision ladders can be incorporated in CTAs to represent the cognitive activities associated with complex tasks (Nehme, Scott, Cummings, & Furusho, 2006). Nehme et al. (2006) used this approach to develop information and display requirements for future unmanned systems for which no current implementations exist. Decision ladders were used to map out the monitoring, planning, and decision-making activities that would be required of operators of these systems to specify information and display requirements that will support the corresponding cognitive activities. Smith, Cummings, Forest, and Kessler (2006) used decision ladders to represent the results of SME interviews, as well as communications transcripts. The authors used a decision ladder representation as the basis for defining future system requirements for lunar landing tasks. Macbeth, Cummings, Bertuccelli and Surana, (2012) similarly used a CTA method that included decision ladders to identify automation support requirements for an unmanned vehicle supervisory control task. Bisantz et al. (2003) used decision ladders to model monitoring and decision-making strategies used by operators identifying and tracking undersea objects. Multiple decision ladders were used to represent how differences in level of expertise and task demands resulted in different cognitive strategies. Decision ladders have been used to model decisions and provide design guidance across a variety of domains. Appendix C, and Figure C-3 provide a detailed example of using a decision ladder to represent a control task performed in a petrochemical plant (Jamieson et al., 2007).

3.2.2.3 Goal Directed Task Analysis (GDTA)

Another analytic method that defines cognitive activities required for task performance, and associated information and support requirements, is the Goal Directed Task Analysis (GDTA) method (Endsley, Bolte, & Jones, 2003). GDTA provides a framework for identifying and representing the situation awareness (SA) requirements of operators. This includes identifying the goals and decisions associated with a job, the SA requirements entailed, the information needed, and how it is combined to support the different levels of SA including perception,

9 Refer to Appendix C, Section C.1 for a detailed discussion of decision ladders.

comprehension, and projection into the future. GDTA is described in more detail in Appendix C, Section C.3.

3.2.2.4 Other Types of CTA Representations

Decision ladders and GDTA diagrams are examples of well-codified modeling frameworks that can be used by CTA analysts to identify and represent the cognitive activities associated with a particular task. CTA analysts may also develop tailored representations for communicating the cognitive activities that underlie task performance. For example, Vicente, Mumaw and Roth (2004) developed a model of the cognitive and decision-making activities associated with control room operator monitoring of normal operations that synthesized the results of observations and interviews of operators across multiple NPPs (see Figure C-8 in Appendix Section C.5, Cognitive Field Observations, for an example of a graphic depiction of these activities).

The results of a CTA also can be represented as formal, symbolic operation, cognitive models (e.g., Card, Moran, & Newell, 1983). These formal models often take the form of executable computer-based cognitive models. One of the simplest and most widely used example of this more formal modeling approach is the Goals, Operators, Methods and Selection (GOMS) family of models (John & Kieras, 1996 a&b), which decompose cognitive tasks into GOMS rules. Generally, these formal, computer-based modeling approaches, are best suited for simple, well-defined tasks that can be characterized as a sequence of discrete steps. They are less suited for cognitively more complex tasks, such as supervisory control of automated systems or complex emergency response where adaptive, knowledge-based performance is required (see Gray 2007 and Appendix C.6 for a more detailed review of computer-based modeling approaches, including GOMS).

3.2.3 Guidance on Selection of Analytic Frameworks and Representations

As in the case of knowledge acquisition, selection of an analytic framework to use and how to present the results of the CTA analysis (e.g., text descriptions; diagrams) will depend on the goals of the analysis. As discussed in Section 3.1, CTAs can have multiple objectives. They are useful for ensuring comprehensive analysis of the goals and functions of a system and the associated cognitive requirements (e.g., monitoring, choice, decision-making) and challenges (e.g., lack of needed information, goal-conflict situations) that the work imposes.

Cognitive performance modeling is useful for representing the knowledge and strategies of operators. This includes the strategies in use by current operators, as well as the idealized strategies that are required for effective performance. They are particularly useful for identifying an operator’s needs for information, decision-aiding, and training to support a given performance strategy.

There are additional analytic frameworks and output representations that are useful for communicating other aspects of individual or team performance. For example, concept maps are useful in documenting operator knowledge content and organization. Other graphic representations have been developed to depict team communication and collaboration requirements (e.g., Ashoori & Burns, 2010, 2013). Finally, as noted earlier, CTA analysts may find it useful to develop tailored output representations to highlight specific findings.

As in the case of knowledge acquisition methods, there are benefits in combining multiple analytic frameworks. For example, work domain modeling approaches can be used in combination with cognitive performance modeling approaches to provide a more complete understanding of the complexities imposed by the task environment and the knowledge and strategies of operators.

3.2.4 Strategies for Increasing Confidence in the Validity of CTA Results

The objective of a CTA is to draw conclusions about task demands and operator strategies that have broad validity across individuals and contexts, from what is necessarily a limited sample of observations, interviews, and/or critical incidents extracted from databases. Cognitive analysts have developed strategies to increase confidence in the validity of the generalizations drawn from limited samples (see Roth & Patterson, 2005 for relevant discussion). The following techniques can be used to increase the robustness of conclusions drawn from a CTA:

- Including a broad, and representative sample of practitioners. This could take the form of practitioners at multiple levels of expertise or sampling from multiple positions that may be involved in the task (such as reactor operators, balance of plant operators, shift supervisors) or sampling from practitioners from different plants or plant types.

- Including a broad and representative sample of environments and situations. For example, sampling from multiple shifts, multiple sites, or multiple locations within a facility.

- Including considerations of potential collateral tasks (e.g., communications) and distractions (e.g., alarms) that could affect performance of the main tasks.

- Including multiple observers/analysts who bring different types of knowledge and expertise to support the analysis (e.g., individuals who are knowledgeable with different types of CTAs).

- Using a multi-disciplinary team that includes not only individuals experienced in CTA, but also individuals that have subject matter expertise in performing the task (i.e., training instructors, or individuals who have held that position in the past), and individuals with engineering expertise (e.g., system designers with knowledge of the current plant or the planned design for the new plant).

- Using multiple techniques (e.g., field observations, structured interviews, questionnaires)

3.2.5 Use of Multiple Techniques Example

An approach is to combine formal work domain modeling with empirical CTA knowledge acquisition methods. Formal work domain modeling (e.g., a FAN used in ACWA, see Appendix Section C.2 Applied Cognitive Work Analysis for a description of functional abstraction networks) is used to characterize the work demands. Empirical CTA knowledge acquisition methods (e.g., field observations, critical decision method interviews) provide an effective means to obtain information on the knowledge and strategies that operators use to cope with these demands.

This approach was used by Roth and Woods (1988) to identify and document the cognitive and collaborative challenges associated with feedwater control during startup (see Section 3.3 for a more detailed description of this study). Among the advantages of such an approach is that the functional model provided an objective description of system goals, functions, and physical means available to achieve them, which can aid in the interpretation and evaluation of the results of operator interviews and observations. This specific combination of methods helps to guard against situations where operators may have incorrect or incomplete mental models of how systems works and/or suboptimal control strategies (Read, Salmon, & Lenné, 2012).

3.2.5.1 Example of Gathering Input from Observers and SMEs

A useful indicator of the validity of CTA results is that others who are knowledgeable about the domain and the nature of the work agree with the findings and interpretations. It is particularly important to get feedback from individuals who served as the knowledge sources in conducting the CTA (e.g., the operators and/or engineers who were interviewed and/or observed) on the accuracy and completeness of the results. A common practice in conducting a CTA is to present the results of the study to domain practitioners (i.e., either in the form of a report or a presentation) and solicit feedback on the accuracy of the base findings (i.e., the raw data collected during observations and interviews) as well as the conclusions drawn from the findings. The ultimate criterion in evaluating the validity of CTA results is to implement changes that have a positive impact on operator performance.

3.3 Cognitive Task Analysis (CTA) Links to Task Analysis (TA) Approaches

Traditional TA methods, such as operational sequence analysis and hierarchical task analysis (HTA), are generally organized around the steps required to perform a task. HTAs begin with the tasks personnel perform and analyze them in detail to define the task requirements (e.g., information needed, controls needed, and time needed). Often a task's workload demands can be estimated, and the knowledge and skills assessed. However, the primary focus is on activity (i.e., observable behavior). As such, these TA methods are well-suited for tasks that can be decomposed into a well-defined sequence of steps that are straightforward to execute.

In Section 1.1, four limitations to traditional TA methods were noted that make them poorly suited for tasks whose success depends on a more flexible cognitive and collaborative performance. These limitations include:

- A focus on activity
- A focus on idealized task performance
- Failure to address factors underlying difficult situations
- A focus on well-defined situations

Many tasks that operators perform do not entail a clear sequence of steps, and the cognitive processes and associated challenges required for task performance are not easily observable. Examples include:

- Supervisory control tasks where the main activities are monitoring automation processes
- Maintaining awareness of the overall status of the plant
- Recognizing/managing disturbances when they occur

CTAs are effective for identifying the cognitive and collaborative challenges and information and support requirements in those cases.

Further, CTAs are effective in identifying cognitive challenges and operator strategies in response to challenges that may not be apparent from a review of the steps required to perform a task. Thus, CTAs identify performance challenges and support requirements that might be missed by standard TA methods that focus narrowly on the information and control requirements associated with individual subtasks or steps in a procedure.

One example of the advantage of a CTA approach from the nuclear power industry was a CTA that identified the cognitive challenges associated with manual feedwater control during plant startup (Roth & Woods, 1988). Manual feedwater control during startup often led to automatic plant trips due to exceeding the steam generator (SG) water level trip setpoint. This resulted in costly delays in startup. The cognitive challenges associated with this process were not apparent from examination of the start-up procedure which specified a clear sequence of easily performed discrete steps, including steps for shifting from auxiliary feedwater to main feedwater as reactor power is gradually increased (e.g., place all main feedwater control and bypass valves in manual; start the main feedwater pumps, slowly close auxiliary feedwater pump discharge valves, observe that steam dump valves are opening, etc.). During their CTA, Roth and Woods observed and interviewed operators experienced in controlling feedwater during startup.

The CTA revealed several cognitive and collaborative challenges including:

- Complex, counter-intuitive dynamics (i.e., shrink and swell effects in the SGs) that made it difficult to predict and control SG level with changes in reactor power and feedwater

- Lack of accurate process state information (i.e., steamflow and feedflow at low power)

- Need for very close coordination and communication between the reactor operator, the feedwater control operator and the turbine operator because changes in reactor power and turbine power (the energy balance across the SG) both affect SG level

The feedwater operator needed to be cognizant of the intentions and activities of both the reactor and turbine operators to anticipate SG level behavior and take timely control actions. In addition to revealing the cognitive and collaborative demands of the feedwater control task during startup, the CTA identified a variety of communication, coordination, and control strategies operators used to reduce and compensate for SG level shrink and swell effects to avoid excessive SG level deviations as reactor power was increased. The results of the CTA were applied to training program design and the development of new engineered visualization concepts to better support manual feedwater control (Woods & Roth, 1988). The CTA also contributed to moves toward automatic feedwater control during startup.

In summary, CTAs are well suited for analyzing the requirements of tasks whose performance depends on cognitive processes such as monitoring, situation assessment, decision-making and response planning. Further, because they consider the broader work context, CTAs can identify cognitive and collaborative difficulties and challenges that personnel may face (e.g., demands on attention, communication, coordination). All these factors are things that might be missed by task analyses that focus narrowly on performance of an individual task in isolation.

CTA methods can provide a comprehensive analysis of both the well-defined activities and the more abstract activities inherent in supervisory control and disturbance management in situations that require flexible, adaptive response (e.g., unanticipated situations that are not fully covered by detailed procedures).

Several researchers have explicitly compared CTA methods (particularly work domain analysis methods) and more traditional TA approaches for identifying information requirements (Hajdukiewicz & Vicente, 2004; Laberge, Ward, Nakauskas & Creaser, 2007; Miller and Vicente, 2001; Jamieson et al., 2007b). Some of these studies will be discussed below, but the general finding is that while there is overlap in the task requirements revealed by the two approaches, there is also unique and complementary information revealed by each approach (see Miller and Vicente, 2001; Jamieson et al., 2007b).

Work domain analyses do a better job of:

- Uncovering the full set of constraints and capabilities inherent in a work domain
- Identifying requirements for monitoring, controlling and diagnosing a system (particularly in unanticipated situations for which predefined procedures have not been developed)
- Uncovering requirements that are independent of the specific current context (e.g., the specific displays, tools, processes and organizational structure that currently happen to exist)
- Uncovering information and support needs to enable domain practitioners to recognize the need to, and know how to, adapt procedures when confronted with unforeseen conditions

In contrast, more traditional task analytic approaches, such as hierarchical task analysis (HTA) are more effective for:

- Identifying priority, procedural, and temporal constraints
- Supporting development of efficient procedures for identified contingencies

Salmon, Jenkins, Stanton, and Walker (2010) compared the relative contribution of HTA to cognitive work analysis (CWA). HTA is a traditional method of TA and is a commonly used approach[10]. CWA is one of the more commonly used approaches to CTA. In this study, the authors conducted both HTA and CWA as part of their work to design a mission-planning tool for a military application. They compared the outputs of both methods and examined whether each provides unique inputs to the design process. Their overall conclusion was that HTA, and CWA produced different (non-overlapping) outputs. The results were generally complementary, with each providing unique and valuable input to the design. For example, at a high-level, CWA was able to specify what functions are necessary and how they can be performed at a strategic level. At a lower-level, HTA provided details as to how the strategies defined using CWA can be performed in a step-by-step fashion. Salmon et al. noted:

10 It is also one method upon which NUREG-0711 TA review guidance is based.

> "… the two can be used in a complementary fashion by applying them at either end of the system design life cycle. The formative nature of CWA means that it is better employed during the early stages of idea forming and concept design specification, whereas the normative nature of HTA means that it is likely to be more useful during the latter stages when there is an actual system or design concept present to evaluate and refine. This represents one level on which the two can be complementary: CWA as the design specification approach; HTA as the design concept evaluation and redesign approach. In this way, CWA acts as the front-end revolutionary design approach and HTA acts as the latter design phase evolutionary design approach." (p. 526)

The authors also commented that HTA is better suited to activities that are more structured and proceduralized, while CWA is better suited to more complex activities.

There is evidence that HSIs that have been developed based on the results of CWA particularly, work domain analysis that reveal higher level domain goals, constraints and affordances result in performance improvements relative to more traditionally designed interfaces. This advantage is particularly evident in abnormal situations requiring diagnosis or problem-solving (Bennett et al., 2008; Burns, Skraaning, Jamieson, Lau, Kwok, Welch, & Andresen, 2008; Jamieson, 2007; Roth, Lin, Kerch, Kenney, & Sugibayashi, 2001; Vicente, 2002).

There is also evidence of the need to integrate task-based information, derivable from traditional TA methods, with work-domain based displays (Jamieson, 2007; Burns et al., 2008). Work-domain based displays (see Figure C-2 in Appendix C.1, Cognitive Work Analysis, for an example) provide greater support for the full range of circumstances that the operator might encounter but are not optimized for supporting performance in anticipated situations for which common methods and standard procedures are available. As Jamieson (2007) points out, domain-based methods trade off efficiency (i.e., displays tailored to a specific situation) in favor of robustness (i.e., displays that are useful across multiple situations), whereas task-based approaches trade off robustness in favor of efficiency. Together, they provide a firm foundation upon which to develop effective designs.

3.4 Use of Cognitive Task Analysis (CTA) in Human Factors Engineering (HFE)

CTA methods are broadly applicable to several aspects of HFE, not just task analysis (TA). This section considers general applications of CTA to HFE programs. Section 3.5 describes how CTA has been applied in the commercial nuclear industry. Some of the applications and examples discussed in these two sections are discussed in greater detail in Appendix C.

Read et al. (2012) reviewed published design applications of cognitive work analysis (CWA) across a wide range of domains. The distribution of the applications is shown in Table 3-1. The most common CWA application was the design of HSIs. This is not surprising since CTA, like other types of TA, is an important source of design requirements. Table 3-1 lists many of the other applications identified by Read and colleagues.

Table 3-1 Applications of CWA in HFE Programs

HFE Activity	Number of Applications
Function Allocation	6
Job/Team Design	4

HSI Design	53
Procedures and Training Design	5
Workplace Design	1
Organizational Management	1

Note: Based on Read et al., (2012)

Following the conduct of CTAs for railway systems that were performed using a combination of field observations and structured interviews, Roth, Rosenhand, and Multer (2013) discussed the contribution of CTA to HFE programs using the same structured review elements contained in NUREG-0711 Rev. 3. This is important because, like nuclear power plants (NPPs), railways are complex systems operated by crews. The authors used the structure of NUREG-0711's HFE model to identify how CTA can contribute to each HFE element. The results are summarized in Table 3-2. Potential contributions for each element were listed as they were identified by the authors. Because they were evaluating a type of TA (i.e., CTA), separate contributions to the NUREG-0711 TA element were not considered. Note that the same contribution can be identified for multiple elements.

Table 3-2 Applications of CTA in HFE of Railway Systems from Roth et al., 2013 using the NUREG-0711 Structure

NUREG-0711 Rev. 3 HFE Elements and section numbers	Potential Contribution
Operating Experience Review (section 3)	• Explore implications of introduction of new technology • Identify opportunities for more effective support • Identify additional tasks (or changes to tasks) • Define the broader context of use within which a new technology will be deployed • Identify information and support requirements that can inform new technology design • Define the range of contextual conditions, demands, and complexities that need to be considered in designing and evaluating new technologies
Function Allocation (section 4)	• Explore implications of introduction of new technology • Identify or uncover additional issues and considerations • Identify additional tasks that would need to be supported as a result of introducing new technology • Identify information and support requirements that can inform design of the new technology
Staffing and Qualifications (section 6)	• Identify relevant aptitudes and experiences
Important Human Actions (section 7)	• Identify impact on system safety and health hazards • Explore implications of introduction of new technology • Identify unanticipated side effects and potential negative consequences
Human-System Interface (HSI) Design (section 8)	• Identify necessary information and support requirements for the new technology needs to meet • Explore implications of introduction of new technology • Identify unanticipated side effects and potential negative consequences • Identify areas where more focused investigation is required (via prototyping, simulation, or experiments)
Procedures Development (section 9)	• Identify procedure requirements resulting from new technology
Training Program Development (section 10)	• Identify knowledge, skill, and training requirements
Verification and Validation (V&V) (section 11)	• Specify range of representative situations and complicating factors that need to be embedded in evaluation scenarios and simulator-based tests
Design Implementation (section 12)	• Identify/uncover additional issues/considerations
Human Performance Monitoring (section 13)	• None identified

Note: Based on Roth, Rosenhand, and Multer (3013)

Following their analysis, the authors commented that one of the “striking findings” of the review of the railway worker CTAs was that it provided insight to many HFE elements.

Given the typical objectives of CTA (see Section 3.1), its useful to map how CTA methods can contribute to an HFE program. Using the NUREG-0711 elements as representative of an HFE program, Table 3-3 provides an overview of CTA objectives coverage of an inputs to HFE activities.

Table 3-3 Potential Contribution of CTA to HFE Program Elements

CTA Objective	NUREG-0711 HFE Element (see Note below)										
	OER	FRA / FA	TA	S&Q	TIHA	HSID	PD	TPD	V&V	DI	HPM
Identify complex situations	✓	✓	✓	✓	✓				✓		
Identify complex task elements	✓	✓	✓		✓						
Understand how complex tasks are accomplished	✓		✓			✓	✓	✓			
Capture expert knowledge	✓		✓			✓	✓	✓			
Define the broader context of use	✓		✓						✓		✓
Identify technology impacts	✓		✓						✓		
Identify design requirements			✓			✓	✓	✓			

Note: NUREG-0711 Rev. 3 Review Elements and their section numbers: OER - Operating Experience Review (section 3); FRA/FA – Functional Requirements Analysis and Function Allocation (section 4); S&Q - Staffing and Qualifications (section 6); TIHA – Treatment of Important Human Actions (section 7); HSID - HSI Design (section 8); PD - Procedures Development (section 9); TPD - Training Program Development (section 10); V&V - Verification and Validation (section 11); DI - Design Implementation (section 12); HPM - Human Performance Monitoring (section 13)

As the table indicates, CTA contributes to all HFE technical activities addressed in NUREG-0711, except design implementation. Within the NUREG-0711 HFE model, design implementation is mainly focused on verifying that the as-built design conforms to the design that was verified and validated. While CTAs have been used mainly in new design projects (Kaber et al., 2006), the methods should be equally applicable to design modifications, especially those using domain expert knowledge and experience.

Next, the specific contributions of CTA to the different HFE program elements will be considered. Appendix C contains a detailed description of several CTA methods. Each CTA description includes a discussion of the method’s contribution to HFE programs.

3.4.1 Operating Experience Review (OER)

An important objective of an OER is to examine the experience gained at a plant being modified or of predecessor design(s) for new plants to identify deficiencies that should be corrected, as well as to identify aspects of the design that support operator performance and should be implemented in the new design. While valuable OER information is available in documented sources, it is important to obtain information from operators and maintainers, as well. The reason is to better understand actual work practices, in part so the impact of changes or new designs on them can be evaluated. This is important because personnel often perform tasks and use HSIs in ways that are different from what is described in documentation and from designers' expectations of how they are used.

An example of the impact of the failure to understand actual work practices comes from early efforts to improve analog annunciator panels by replacing them with computer-based alarm systems using alarm message lists presented on video display units (VDUs) (O'Hara et al., 1994). The new alarm systems were unsuccessful because the designers failed to appreciate how much the old alarm system was used for high-level plant status assessment. Operators could quickly scan the alarm tiles and see which functions and systems were operating properly and which were not. This could not be accomplished with the message lists because only a small number of alarms could be seen at any one time (i.e., the message list had to be scrolled to see other alarms) and the alarm lists had no spatial dedication. Thus, the strong pattern recognition that operators had developed with the older alarm system was lost.

Another contribution of an OER is identification of deficiencies in an existing design. While conducting field observations and interviews with operators in a pressurized water reactor, O'Hara and Luckas (1993) identified numerous such issues. For example, operators indicated that the alarm system can be misleading during transients. For example, diesel generator (DG) trips are restricted during emergencies. If a non-emergency trip signal comes in, the DG will not trip, but the "DG TRIP" alarm still rings. This occurs because the DG TRIP alarm is set off by any of 17 trip signals; while, in emergencies, only 3 conditions will trip the diesel. Yet, if any of the remaining 14 signals occur, those trip alarms still come in. In this same study, the authors looked for workarounds as indicators of potential issues. In one case, the workaround was a "temporary" addition to the workplace made by personnel to provide a reminder to perform a needed task. One example related to manual isolation of the reactor coolant pump seal leak off return. When there was a loss of seal injection and thermal barrier cooling, operators are required to manually trip the reactor coolant pumps within one minute. This prompted personnel to place a large sign on the control panel to remind operators to take this action when indicated. Failure to do so could lead to seal degradation, potentially escalating the seal leak to a small loss of coolant accident. Due to the limited time available to respond, operators suggested that automation of the trip of the reactor coolant pumps seal isolation task should be explored.

CTA methods are excellent for conducting this aspect of an OER. Methods such as cognitive field observations and CDM can provide a structured means for identifying actual work practices. The studies on control room monitoring discussed in Section 3.3 provide other examples of this type of application.

Other ways in which CTA methods can be used to support more effective OER programs is to identify:

- Difficult and challenging situations where operators have to develop information about what makes them challenging, reveal undocumented strategies for coping with those demands, and develop suggestions for more effective support for managing such situations.

- The demands of the domain and the cues that operators use for situation assessment and decision-making.
- Information on work tempo and its impact (e.g., on workload).
- Communication and coordination demands and strategies.
- Errors and near-misses and the factors that contributed to those errors.
- Collateral duties and responsibilities that make key task performance more difficult.
- Opportunities for improving performance through improvements in practices, procedures, training and/or new kinds of decision-aids.
- The knowledge of domain experts about the characteristics of the current domain, including physical systems, procedures, work practices, and challenges.
- Information on the knowledge and skills operators have developed to cope with domain challenges, and limitations in knowledge and skills of less experienced practitioners.

This type of information can be documented in the OER and can subsequently provide inputs to many other HFE activities.

3.4.2 Functional Requirements Analysis and Functional Allocation

CTA, especially approaches such as CWA and ACWA, can identify the functions that need to be achieved, how they can be distributed across personnel and machine agents, and the implications of alternative function allocation for operator cognitive tasks and related information and support requirements (Roth & Mumaw, 1995). Roth and Bisantz (2013) discuss numerous studies using CWA's social, organization, and cooperation analysis to address the distribution of work across multiple agents, including personnel and automation.

Feigh and colleagues (Feigh and Pritchett, 2014; Pritchett, Kim and Feigh, 2014a and b) developed a framework for analyzing requirements for function allocation, as well as modeling and evaluating alternative function allocations across multiple agents. Their methodology provides an additional analytic framework for conducting a CTA that can inform function allocation.

Jenkins et al. (2010) conducted an interesting study using CWA to evaluate approaches to improve system flexibility. Work domain analysis was used to decompose functions using an abstraction hierarchy. Once the functional relationships were identified, a control task analysis (see Appendix C.1, Cognitive Work Analysis, for a discussion of this type of analysis) was performed to find situations where functions could not be accomplished. Using CWA's strategies analysis, design changes to the means to performing a given function were identified (see Section C.1 for a detailed description of the different types of analyses that make up CWA). Jenkins' use of CWA provided a means to explore how functions are accomplished and situations where function accomplishment is impeded. By designing changes to regain the functions in these situations, system flexibility and resilience can be improved.

3.4.3 Task Analysis

Like traditional methods, CTA can support identification of tasks that need to be performed and the requirements for efficient and reliable performance. However, CTA methods use different approaches to meet these objectives, thus providing complementary information (e.g., Salmon et al., 2010).

The unique contributions of CTA are mainly in their focus on the cognitive demands of task performance and on providing a means to understand the complexities, such as performance of multiple different types of tasks (e.g., monitoring levels on one gauge and shifting position on another valve) simultaneously or in quick succession, that arise in complex, dynamic systems. For example, the information gained from domain experts, like experienced operators, can provide information about complex task performance that cannot be derived from traditional methods. Such analyses provide a richer understanding of how tasks are performed, the requirements needed to address them, potential means for supporting that performance, and the necessary skills. The requirements can address important cognitive aspects of performance, such as situation assessment.

Further, CTA provides a means to understand task performance in the context of the constraints of the physical domain (e.g., understanding the implication of task performance failures on higher-level plant goals). For example, work domain modeling approaches that are organized around functions can be used to create an overall representation to show the relationships between: domain characteristics, overall practitioner goals, and the strategies, decisions, and steps required for successful task performance. These work domain modeling approaches enable a more comprehensive analysis of the set of capabilities and constraints in the work domain and provides a means to systematically identify the requirements for monitoring, controlling and diagnosing system functions and processes.

An important aspect of CTA is that it provides tools to analyze teamwork and organizational design. In NUREG-0711, teamwork is addressed as part of TA, but the scope is generally limited to the number of staff needed to perform a task and the coordination and communication needed between them. While this is likely sufficient for plants operated in conventional ways, it may not be for plant designs based on a different ConOps (e.g., crews managing multiple smaller units from one control room such as in some SMRs (O'Hara, Higgins, & Pena, 2012). New ConOps may necessitate the use of different tools to define the requirements for teams. Roth and Bisantz (2013) discuss numerous studies using CWA's social, organization, and cooperation analysis to define how work can be distributed across members of a team, both human and automation. Section 3.5 discusses one approach that was used in the nuclear industry. Ashoori and Burns (2013) have recently developed additional tools for use in CWA specifically to examine teamwork considerations. Thus, CTA provides a means to address an important aspect of plant operations that is not well addressed in NUREG-0711.

3.4.4 Staffing and Qualification

CTA provides a means of understanding the actual demands of the work and need for parallel tasks to provide input to decisions about staffing levels. CWA's social, organizational, and cooperation analysis supports HFE practitioners to evaluate the assignment of work with organizational structures, and the implication for communication and coordination requirements.

Worker competency analyses support the identification of the knowledge and skills that are required to efficiently and effectively perform the cognitive and collaborative functions identified through the prior analyses.

CTA also provides analytic methods to support workload analyses to ensure that work can be accomplished with the assumed staffing levels. For example, CTA can provide information on the various activities (documented and undocumented) performed across personnel in the current environment. This provides a baseline that can be used to ensure that new system designs that assume reduced staffing have considered all the activities currently being performed by each staff position in their analysis (i.e., all activities are accounted for either by eliminating its need, for example through automation, or by allocating the activity to a different staff position).

3.4.5 Treatment of Important Human Actions

CTA can be used to examine important human actions in detail to ensure designers have a full understanding of them. For example, GDTA can be used to identify the goals, decisions, and SA information requirements for effective performance of important human actions.

As another example, GOMS models can be used to represent the cognitive and physical activities required to perform important human actions and to estimate execution time (see Appendix C.6 for a detailed discussion of this model).

Additionally, CTA methods, like cognitive field studies and practitioner interviews, can be used to get a realistic assessment of the likely challenges and complicating situational factors that impact important human actions, and the types of human errors that can result. These techniques can serve as a useful complement to traditional task analyses by helping identify contextual situations where operators may fail to perform a task as required due to cognitive or collaborative challenges (e.g., missing cues that may cause operators to fail to realize that a task needs to be performed).

3.4.6 Human-System Interface Design

The primary contribution of CTA to HSI design is identification of task requirements based on a realistic assessment of tasks as they are performed, within the context of the demands and challenges operators face in the workplace. This helps ensure the cognitive requirements for task performance are accounted for and reflect operator input and observations of tasks as they are performed in the plant.

Methods such as CWA and ACWA have been shown to be useful for design of function-based displays intended to support cognitive performance under unanticipated conditions where procedural guidance may be limited (see Section 3.5 for a detailed discussion of this application). ACWA provides a streamlined approach for defining HSI requirements and providing traceable links to cognitive requirements for monitoring and controlling the plant. Once developed, concept maps can be used to identify important relationships between domain elements that the operator needs to understand and that should be depicted in the HSI.

CTA also provides a means to evaluate HSI designs. For example, GOMS models have been used to evaluate the adequacy of a user interface design, as well as to compare alternative designs (Kieras, 1997). Design aspects that can be checked with a GOMS model include whether there are methods available for all identified user goals, whether there are efficient methods to accomplish user goals that occur with high frequency, and whether the methods for achieving similar goals are accomplished in a consistent manner (Kieras, 1997; Endestad & Meyer, 1993).

Cognitive field observations in a high-fidelity simulator can be used to assess the impact of design changes on crew performance. They can support early identification of unanticipated consequences of the new HSI, such as new cognitive or collaborative demands, so that they can be addressed through changes in design, procedures, or training prior to actual system operations (e.g., Roth & O'Hara, 2002).

3.4.7 Procedure Development

CTA's contributions to procedure development include many of the same considerations as discussed in the HSI design section, specifically in terms of task requirements identification and evaluation. In addition, CTA provides tools specifically related to procedure design. For example, CWA's control task and strategies analysis can be used to identify effective methods for achieving practitioner goals. These analyses can be used as an input to procedure development. The functional abstraction network and cognitive work requirements outputs of ACWA can be used in combination to specify cognitive tasks and methods for achieving those tasks that can form the basis for procedure development.

CTA also provides methods to understand the cognitive complexity of procedure design and use which can be considerable. For example, some procedure designs require operators to:

- Make complex assessments to determine if a step is satisfied or not
- Perform multiple 'continuous action steps' while following the main procedure steps
- Consult fold-out pages in conjunction with the main steps
- Use multiple procedures in parallel (with go to and return steps between them)

These kinds of requirements can increase the cognitive demands associated with a procedure. CTA can be used to understand those procedure-associated demands and evaluate their complexity so that it can be reduced. Cognitive field observations in actual work settings and/or simulators are useful for this kind of understanding. These methods can be used to identify and correct mismatches between procedures and the actual demands of situations as they dynamically unfold. Endestad and Meyer (1993) used GOMS analysis to evaluate different computer-based procedures designs (see Appendix C.6 for a detailed discussion about the analysis).

3.4.8 Training

CTAs are used to provide input into training. Methods such as Concept Mapping can be used to define knowledge content and structure required for expert performance. Methods such as field observation studies and CDM can be used to understand domain challenges and the strategies that experienced operators have developed to perform tasks proficiently, and they can provide the basis for training development. CWA's strategies analysis and worker competencies analysis can be used to identify the knowledge, skills and strategies that should be included in training.

Methods such as GDTA can be used to identify the information that experienced practitioners use in maintaining SA. This can be used to develop training to enable trainees to achieve higher levels of SA.

In addition, CTAs can be used to support the design of training scenarios that capture the kinds of complexities and cognitive and collaborative demands that can arise to challenge performance. For example, CTA results can be used to train operators to handle unanticipated situations that require knowledge-based reasoning about how to recover plant functions when the standard prescribed methods for achieving plant goals are not available (Roth, Mumaw, & Lewis, 1994).

3.4.9 Human Factors Verification and Validation

CTA can contribute to the process of sampling operational conditions by providing one means to identify scenarios that can potentially challenge human performance. This is one of the key outputs of CTA that can inform the entire HFE program, especially the identification of validation scenarios.

The knowledge obtained from a CTA can be used to develop metrics to evaluate the ability of an HSI to support different levels of SA. For example, one measurement technique used to assess an operator's SA is called the "Situation Awareness Global Assessment Technique" (SAGAT) method. It uses probe questions to tap into the operator's awareness of important aspects of an ongoing scenario (Endsley, 2021). CTA can identify critical situations, statuses, and parameters that can be used to develop the questions.

Debriefings of operators following validation scenarios provide important information about:

- The determinants of crew behavior
- The crew's evaluation of aspects of the system such as automation, HSIs and procedures
- Recommendations for improvements to the design

Applicants can also use CTA to develop a structured and rigorous means to conduct post-validation scenario debriefings to obtain more in-depth information than might otherwise be obtained.

As part of the human engineering discrepancy (HED) resolution process, CTA can be used to analyze HEDs to identify root causes and potential solutions.

3.4.10 Design Implementation

As noted above, within the NUREG-0711 HFE program review model, design implementation is mainly focused on verifying that the as-built design conforms to the design that was verified and validated. Thus, CTA is not applicable.

3.4.11 Human Performance Monitoring

CTA methods, such as cognitive field observations, can be conducted periodically to ensure that conditions that may arise that challenge personnel performance are rapidly identified, mitigated, and potentially corrected. CTA can also be used to analyze issues that do arise. When used in this context, CTA can be an important tool in a licensee's corrective action program.

3.5 Use in the Nuclear Industry

This section reviews the use of cognitive task analysis (CTA) in the nuclear industry. The applications are organized into the following topics:

- Understanding the cognitive demands and challenges of control room operations
- Identifying task requirements and designing human-system interfaces (HSIs)
- Evaluating HSI designs
- Improving teamwork
- Capturing and representing the knowledge of experts

3.5.1 Understanding Cognitive Demands and Challenges of Control Room Operations

One important application of CTA is understanding the cognitive demands of work performed by operators (Militello & Hutton, 1998). Section 3.3 provides an example of the use of CTA to identify the cognitive challenges associated with manual feedwater control during plant startup (Roth & Woods, 1988). Another example is Vicente, Mumaw and Roth (2004) who aimed to understand the cognitive demands of nuclear power plant (NPP) monitoring (see also, Mumaw, Roth, Vicente, & Burns, 2000; Vicente, Roth, & Mumaw, 2001). Monitoring is an important cognitive activity of operators in a supervisory control role and in highly automated plants. The objective of Vicente's research was to understand how operators monitor complex, dynamic systems during normal operations for NPPs. The authors conducted a series of cognitive field observations of NPP control room operators to determine how monitoring is performed. Mumaw, Roth, Vicente, and Burns (2000) conducted cognitive field observations (CFOs) in control rooms at two plants using primarily analog displays. Vicente, Roth, and Mumaw (2001) made similar observations in a computer-based control room. Overall, they found operators use similar strategies in both types of control rooms. While operators did not find it difficult to identify abnormal situations (i.e., the HSIs are designed to support the identification of these situations), they did have difficulty monitoring information and trends that are potentially important during normal conditions. Therefore, operators used proactive strategies to support this type of monitoring.

The authors identified several factors that made monitoring difficult:

- System complexity and reliability – There are thousands of components which interact in different situations; making it difficult to understand the implications of each. Even though the number of components is large and highly reliable, at any one moment there are many that are out of service or malfunctioning. Operators must factor these considerations into their situation assessment.

- HSI design – Given the large number of parameter displays, it is often difficult to detect when an abnormal situation has occurred. First, interpretation of displayed parameter values is memory intensive. Displays may not give clear referent values and few aids are provided to support recall of recent values. Secondly, few emergent features[11] are presented to enable operators to rapidly identify higher-level information from the displays provided.

- Automation design – The operation of and feedback from automated systems may not be well represented in the display system. For example, the actual status of components being automatically controlled may not be displayed.

Vicente et al. identified several recommendations for improving the operators' monitoring capability. Based on these findings, Vicente, Mumaw and Roth (2004) built a model of the monitoring process. See Section C.5 of this report for additional information on these studies.

3.5.2 Identifying Task Requirements and Designing HSIs

Just as HSI design is a common application of CTA in the HFE community (Read et al., 2012), it is also perhaps the most common application in the nuclear industry. Most studies discuss HSI design in the context of identifying task requirements through CTA. Defining tasks and their requirements is one of the most important contributions of any task analysis (TA). As reflected in NUREG-0711's TA objective, these requirements help provide a basis for the design of HSIs and procedures as well as providing important inputs to training program development. CTA provides HFE practitioners with methods to identify task requirements not captured by traditional analyses.

Plant behavior is governed by a set of known relationships defined by the physical nature of plant equipment, the physical laws governing the process, and the purposes for which the system was designed. By analyzing requirements according to an abstraction-aggregation matrix (see Appendix C.1, Cognitive Work Analysis, for a discussion the abstraction-aggregation matrix), designers can represent these relationships in the HSI. CTA has been used to identify requirements through (1) functional modeling using a means-end hierarchical structure, and (2) work-domain analysis using an abstraction hierarchy. A means-end hierarchy links goals to be achieved (the "ends") with methods by which they can be achieved (the "means"). Examples of these approaches follow.

In support of Westinghouse's AP600 design, Roth used a combination of applied cognitive work analysis (ACWA) and a decision-making model based on Woods' modification to Rasmussen's classic model identifying tasks and their requirements (Roth, 1996, Roth & Mumaw, 1995). ACWA uses a work domain representation to specify the primary goals of the plant, the major plant functions that support those goals, and the plant processes available for performing the major engineered control functions available for achieving plant goals. At this level, designers can specify the manual and automatic control actions needed for goal achievement. The

11 An emergent feature is a high-level, global perceptual feature produced by the interactions among individual parts or graphical elements of a display (e.g., lines, contours, and shapes).

decision-making model provided a means to identify tasks and their requirements at the appropriate nodes of the functional decomposition.

Once requirements are identified, HSIs can be developed. In several of the studies described below, principles of ecological interface design (EID) were used. EID includes techniques such as integrated displays, emergent features, and placing data in a meaningful context (Duez & Jamieson, 2006).

Roth et al. (2001) used ACWA to support design of a first-of-a-kind group view display (GVD). The analysis was used to define and arrange critical information in the plant overview portion of the GVD. Using the ACWA means that a functional representation of the plant was used during the analysis. The functional representation supported operators in rapidly assessing whether major plant functions were being achieved and the state of active plant processes supporting those plant functions. In cases of plant disturbances, where one or more of the plant goals are violated, a functional representation allows the operators to assess what alternative means would be available for achieving the plant goals. One of the primary benefits of this type of representation is that it provides operators with the information needed to take action to restore plant functions without needing to fully diagnose the malfunction.

Liu, Nakata, and Furuta (2004) discussed display design for automatic control functions. To determine what information about the automatic system is needed for operators to properly monitor and understand it, they proposed employing functional modeling using a means-end hierarchical structure (Liu, Nakata & Furuta, 2004). At the top of the hierarchy are the system's goals, while its lower end describes the sub-functions used to accomplish them. Each function can be described by a functional primitive. Liu et al. proposed a set of functional primitives to model a system: generate, store, transport, transform, balance, barrier, and sink. They extended these basic concepts to control- and automation-systems (Liu, Nakata & Furuta, 2004). A set of control primitives were identified, including control, generate, transform, set, select, limit, calculate, and delay. Each of these primitives can be further divided into sub-items. For example, "control" can be "rate control," "closed-loop control," and so forth; each has a unique mathematical expression. Liu, Nakata, and Furuta (2004) noted that a good HSI display helps operators to develop an accurate understanding of how automation works. EID principles are aimed at supporting operator monitoring and situation assessment (at significantly less workload) by capitalizing on human perceptual capabilities. Accordingly, when HSIs designed using EID principles are organized into an abstraction hierarchy, the HSI conveys the functional and means-end relationships inherent in the automation system and its functional relationship to the aspects of the plant on which the automation is acting. This arrangement should support the operators' need for information at various levels (e.g., high-level for overall status monitoring and lower levels for more detailed interactions).

Dinadis and Vicente (1996) used CWA and EID principles to design prototype HSIs for a NPP's feedwater system. EID helps bridge the gap from task requirements to interface design. The CWA's work domain analysis used the abstraction-aggregation hierarchy to provide a framework to decompose the interface elements into functional units. An important aspect of such an approach is that the specification of task requirements is not dependent on the designer's ability to anticipate events that will impact plant functions, especially safety functions. Thus, a design based on a CWA will provide better support to operators when unanticipated events occur. Following the CWA, Dinadis and Vicente used EID in conjunction with other design principles to develop displays to support the CWA defined tasks. One of the interesting aspects of this approach is that the CWA identified the need for additional instrumentation (e.g., flow meters) beyond those in the original design.

A similar approach was applied by Itoh, Sakuma, and Monta (1995) to design boiling water reactor (BWR) startup displays. The authors defined display requirements using a work domain analysis based on an abstraction hierarchy. Once information needs at various levels of the hierarchy were identified, EID principles were used to develop an HSI.

Empirical support for the value of displays based on requirements derived from CWA and work domain analysis (WDA) came from a study that compared different types of displays of BWR secondary systems (Burns et al., 2008; Lau et al., 2008a & b).[12] The authors used a WDA similar to Dinadis and Vicente (1996) but applied it to the entire secondary side of the plant. The WDA identified task requirements which were developed into control room displays using EID principles. The CWA-EID displays were compared with traditional displays (consisting of plant mimics) and advanced displays (consisting of mimic plus additional features such as trend and configural graphics). Plant operators performed two-types of scenarios on the Halden simulator: procedurally supported scenarios and “knowledge-based” or beyond-design-bases scenarios (scenarios for which there were no procedures). The scenarios were divided into detection and mitigation phases. Dependent variables included task performance (as defined by Halden’s Operator Performance Assessment System, OPAS, measure) and SA. The results showed the CWA-EID displays significantly improved task performance during the detection phase of knowledge-based scenarios. The improved performance was attributed to CWA-EID style displays providing a higher level of support for monitoring events. SA for knowledge-based scenarios was also better than SA using the other types of displays. Thus, these studies demonstrated that HSIs that are developed based on requirements identified through a CWA and designed using EID principles led to improved operator performance during unanticipated situations. In a related study, Jamieson (2007) also showed performance improvements for EIDs when operators were confronted with unanticipated situations for which predefined procedures may be unavailable.

These studies show function-based work domain models help to provide a basis for designing displays and decision-support systems that will not only support operators in performing well-defined, pre-analyzed tasks, but will also enable operators to effectively monitor and control plant functions even under unanticipated conditions. When confronted with unanticipated conditions, the operator’s preferred means for achieving a plant function may be unavailable and they may need to rely on knowledge-based reasoning to identify alternative means for achieving the plant goal. This can happen in the case of severe accident conditions.

3.5.3 Evaluating HSI Designs

Endestad and Meyer (1993) compared two alternative NPP computerized procedure systems, called “Computerized Operating Manuals” (COPMA-1 and COPMA-2), using the Goals Operators Methods and Selection Rules (GOMS) models. GOMS models for each design were constructed for a reference scenario. The GOMS analysis was able to show that COPMA-2 was faster to use than COPMA-1 because of the availability of multiple, efficient methods of interaction that can be used.

12 While these studies were published as separate reports, they describe different aspects of the same study. For the purposes of showing an application of CTA, this report summarized them in a single integrated description.

3.5.4 Improving Teamwork

Klinger and Klein (1999) improved the emergency response performance at a U.S. NPP following the identification of several weaknesses by the NRC during the plant staff's handling of a minor event. The plant staff initially thought to address their issues with increased staffing and new technology. The analysts used a combination of critical decision method (CDM) and cognitive field observations (CFO) to study the organizational structure, individual roles and responsibilities, decision-making process, and communications in the technical support center. Based on their findings, the analysts recommended a reorganization of the team and a much more specific identification of roles and responsibilities. An interesting aspect of this study was that following the reorganization, the number of staff was reduced, as was the workload of the individuals involved.

In a related example, Costa et al., (2008) conducted an analysis of emergency planning during a simulated NPP emergency drill to identify strengths and weaknesses in the overall response. The authors used multiple CTA methods, including CDM and CFO. Costa et al., used a technique called protocol analysis, where participants were asked to "think aloud" while the exercise was video and audio recorded. The analysts then reviewed the recorded audio to identify the interactions that occurred and the problem solving and decision-making processes used. The protocol analysis classified participant statements into categories of behavior defined by a decision-making model. Interviews were also conducted to obtain a more in-depth understanding of the activities. The findings were represented in a variety of ways, including a timeline of activities and a graph depicting the interactions between individuals. Several strengths and weaknesses of the response to the emergency drill were identified.

Example weaknesses included:

- The high communication workload of the team coordinator which could become a bottleneck in the decision-making process
- The lack of visual and communication technology to support the sharing of the current situation among all participants.

Another approach was developed by Gualtieri, Roth and Eggleston (2000). They used the abstraction hierarchy of ACWA to examine the impact of task allocations between members of a nuclear plant team. The hierarchy was used to identify the cognitive demands (i.e., the need for information and to make decisions at each level). The analysis was expanded to identify dimensions needed to inform the allocation of tasks across members of the team.

Gualtieri et al. describe these dimensions as:

- Physical constraints impacting the distribution of cognitive work across (person and machine) agents.
- The temporal dynamics that influence the rhythm of activity (the ebb and flow of activity).
- The degree of interaction among functions that influence the extent to which agents can operate autonomously or must keep each other apprised of activities and coordinate their actions.

They also identified six strategies for allocating tasks:

1. Integrate related goals within a single team member
2. Minimize collaborative requirements between team members
3. Utilize multiple team members for concurrent problems
4. Allocate overlapping regions of responsibility to foster a common frame of reference
5. Provide mechanisms for transmitting goal structures among team members
6. Integrate team structure with organizational paradigm

The approach proposed by Gualtieri et al. (2000) is especially valuable in showing how teams shift task allocations, roles, and responsibilities to adapt to dynamic, changing situations.

3.5.6 Capturing and Representing the Knowledge of Experts

Hoffman and Moon (2010) conducted a project for the Electric Power Research Institute to address the loss of expertise from nuclear and other electric utilities. The goal was to develop a methodology that can be used by utility personnel to obtain valuable knowledge from experts within their organizations and represent that knowledge for future use. The authors used two CTA methods: concept mapping and CDM. Concept mapping uses detailed interviews of multiple experts to extract their knowledge which is then represented in concept maps that illustrate the relationships between concepts (see Appendix C.7 Figure C-11 for an example concept map).

CDM is used to drill down into difficult cases identified by experts that are not easily recalled. CDM provides a means to gain a better understanding of the information requirements and reasoning strategies (See Appendix C.4 for more details on the CDM method).

Using these methods, the Hoffman and Moon (2010) addressed a broad range of topics, including:

> "…the design of reactors and plants, nuclear plant construction and component manufacturing, reactor, plant and systems design, the nuclear fuel cycle, licensing and operation of complex nuclear facilities, regulation of nuclear facilities, similarities and differences among plants, telecommunication technology, utility relations with the Federal Communications Commission and Public Services Commissions, maintenance and overhaul of steam turbines, nuclear chemistry, environmental monitoring and testing, and power distribution and coordination." (p. 2118)

4 COGNITIVE TASK ANALYSIS (CTA) REVIEW GUIDANCE

While many contributions of CTA to design and evaluation were discussed, not all directly impact NUREG-0711 because:

- While the contributions of CTAs are useful, NUREG-0711 is only concerned with identifying the measures to be included, not how they should be obtained.

- There may be alternative methods to CTA that can achieve a satisfactory result.

Further, it is not the intent of this report to identify CTA as a method that applicants must use as part of a human factors engineering (HFE) program. The NRC review criteria for HFE program elements reflect a process approach. The review criteria focus primarily on inputs and outputs of a particular HFE activity (i.e., task analysis (TA)) and not on how the inputs are transformed to outputs (i.e., the specific methods applicants should use). Applicants use their own methods (subject to appropriate use considerations). For example, the TA review criteria identify the general characteristics of a good TA (e.g., the aspects of tasks that should be considered such as information requirements), the ways in which tasks are related (e.g., performed serially or in parallel), and the effects on personnel performance (e.g., time and workload). However, the criteria do not stipulate specific methods such as link analysis, operational sequence analysis, or HTA.

NUREG-0711 is not a design guideline; it is a design process assessment guideline similar to other HFE process assessment guidelines (e.g., ISO, 2010; ISO, 2000). Any process assessment guideline consists of a model of the subject process that is divided into key elements. For each element, a set of best practice indicators are identified that can be used to determine whether the HFE element is being comprehensively and appropriately performed. In the case of NUREG-0711 reviews, the indicators are review criteria that are used to assess the applicant's performance of the HFE process for a particular design.

In developing NUREG-0711 criteria related to CTA, two perspectives need to be considered:

1. What CTA contributions to system design should be reflected in NUREG-0711 to help ensure that an HFE program fully analyzes the work domain and personnel tasks so that the design supports safe performance?

2. What criteria do reviewers need to determine that an applicant's CTA is acceptably performed, beyond those criteria that are already in NUREG-0711?

Another consideration is where CTA can impact an HFE program. As discussed in Section 3.4, CTA is a TA method, it can contribute to many HFE program elements. However, its most significant impact is on the OER and TA elements. Proposed changes to these two NUREG-0711 elements are presented below.

4.1 <u>Operating Experience Review (OER)</u>

This section discusses proposed modifications to the OER element objectives and review criteria based on our review of CTA. The integration of these new objectives and review criteria in the OER element is shown in Appendix A (for existing criteria, see NUREG-0711, section 3).

4.1.2 Objectives

An expansion of the OER review objective is needed to ensure that applicants have a good understanding of actual work practices, which may differ from plant documentation. Understanding how work is actually performed is necessary to determine how changes to the design may impact performance and safety and also if there are undocumented problems with successful work performance.

The expansion also focuses on situations that are demanding and challenging to operators. This report makes a distinction between demanding and challenging situations. Demanding situations are those for which the crew knows what to do, but factors make managing the situation difficult. Some examples of factors making situations demanding are:

- High crew workload due to factors such as time limitations or need to perform parallel tasks
- Difficulty communicating due to a noisy environment
- Trouble coordinating operating crew members and support staff
- Unavailability of equipment

Challenging situations are those that are associated with potential failure of the operator's fundamental primary tasks of monitoring and detection, situation assessment, response planning, and response implementation.[13] Challenging situations are those that are:

- Very hard to detect (e.g., due to lack of needed instrumentation or human-system interfaces (HSIs)), where the indicators give misleading information, or where the pattern of indications suggest a different situation
- Difficult to assess and gain an understanding of what is going on (e.g., due to lack of training or experience with the situation)
- Difficult to decide what to do (e.g., because there are no procedures to support response planning)
- Difficult to take control of (e.g., because needed controls are not available)

Managing demanding nuclear power plant disturbances can be difficult even when they are anticipated, supported by training, governed by procedures, and needed HSIs (e.g., alarms, information, and controls) are readily available. However, managing disturbances that are challenging, beyond design basis situations can be difficult because they are not anticipated and the personnel's knowledge and coping strategies, HSIs, procedures, etc. may not be available.

The earlier in the design process these types of situations can be identified, the more comprehensively and effectively they can be addressed. That is, demanding and challenging situations should be identified and understood by the OER and addressed throughout the HFE program so that personnel can better manage them in new or modified plants. While this is more difficult in a new design, the effort to do so can be initiated in the OER and revisited as the design matures.

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13 These primary tasks are based on a simplified cognitive model used in much of the NRC's HFE guidance work (see O'Hara et al., 2008a). Other terms are often used in the literature.

This report proposes expanding the OER objectives from:

> The NRC staff uses the review criteria in this section to verify that the applicant has reviewed earlier designs similar to the one under review and has identified, analyzed and addressed HFE-related problems to ensure any negative features in the predecessor designs are avoided in the current design while also retaining the positive features.

to:

> The NRC staff uses the review criteria in this section to verify that the applicant has reviewed earlier designs similar to the one under review and has identified and analyzed:
>
> - Current work practices, so the potential impact of new technology or other planned changes can be assessed. If the proposed design is revolutionary or first of its kind, the NRC staff should review any consideration given by the applicant to predecessor designs[14], such as the avoidance of negative features while retaining positive features.
> - HFE-related problems with the operations or design that personnel experience, so they can be addressed during the design process
> - Demanding and challenging situations, so the difficulties can be better understood, and the new design can provide improved support to personnel
> - Positive features of the operations or design, so they can be retained, if possible, in the new design or design modification

4.1.3 Review Criteria

To meet the expanded OER objectives listed above, new criteria are proposed and presented in this section. Only the new review criteria are presented. Their integration into the OER element is shown in Appendix A.

CTA has shown the importance of gaining an understanding of work practices based on diverse information sources and methods. **Although all TA methods recognize the value of multiple sources of information, what distinguishes CTA from TA is the focus on the cognitive demands of the work environment.** This focus necessitates observing personnel in their work environment and obtaining information from them to understand their domain knowledge, strategies for task accomplishment, factors making work more difficult, and opportunities to support task performance. The studies discussed in the previous sections highlight some of the informal strategies and workarounds NPP operators have developed to facilitate monitoring (Mumaw, Roth, Vicente, & Burns, 2000; Vicente, Mumaw & Roth, 2004; Vicente, Roth &, Mumaw, 2001; see also, O'Hara et al, 1993, 1994) and illustrate the importance of information sources accessed during CTA to understanding operating experience. Thus, the following are new criteria for NUREG-0711's OER element (see NUREG-0711 Rev. 3, section 3.4 for existing criteria).

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14 For new plants, this may be the earlier designs on which the new one is based. For plant modifications, it may be the design of the systems being changed. The issues and lessons learned from operating experience provide a basis to improve the plant's design.

(a) The applicant's OER is based on:

- Information provided by personnel, such as through interviews or questionnaires

- Observations of personnel performing representative tasks in the workplace or in a training simulator

- Documentation, such as condition reports and corrective action information, event reports, and incident databases

Additional Information: To fully understand operating experience, multiple sources of data are needed. For example, relying only on documentation will fail to capture actual work practices and operator feedback and experience in situations that went wrong but failed to result in a reportable event. Ideally, the OER should be based on:

- A broad sample of predecessor sites (if available)

- A broad, and representative sample of personnel (e.g., at multiple levels of expertise and representing multiple positions that may be involved in the task such as reactor operators, balance of plant operators, shift supervisors)

- A broad and representative sample of situations (e.g., multiple shifts, multiple sites, multiple locations within a facility)

- Multiple observers/analysts who bring different types of knowledge and expertise to support the analysis (e.g., individuals that have subject-matter-expertise in the TA), task performance (such as training instructors, or individuals who have had that position in the past), and individuals with engineering expertise (e.g., system designers with knowledge of the current plant or the planned design for the new plant)

- A broad and representative sample of documents pertaining to plant design, operations, corrective actions, and event reports

OER review criterion 4 addresses "Issues Identified by Plant Personnel" (NUREG-0711, Rev. 3 Section 3.4 Operating Experience Review: Review Criteria). Criterion 4 contains two bullets: one identifying plant operations topics and another, focused on HFE design topics. Criterion 5 addresses important human actions (NUREG-0711, Rev. 3 Section 5.4 Task Analysis: Review Criteria. Between the two criteria, the range of topics addressed is comprehensive; however, these criteria do not address the information the applicant should identify beyond general personnel experience. Thus, this report proposes the following new criteria for NUREG-0711, Section 3.4.1, "Scope," as follows:

(b) The applicant should identify how experienced personnel perform their tasks using the HSIs and other resources for the range of topics covered in Criteria 4 and 5. They should identify:

- Normal work practices

- Knowledge, skills, and strategies that enable knowledgeable personnel to perform the tasks

- Factors that complicate task performance, e.g., duties personnel must perform at the same time as the tasks being analyzed

- Opportunities for improving performance through automation, teamwork, HSIs, procedures, training and/or new kinds of decision-aids

Additional Information: This activity provides applicants with an understanding of work practices so they can identify positive and negative features of the current design. Developing an understanding of how tasks are performed and how HSIs, procedures, etc. are used to support performance is important in determining the impact of new designs on work practices. Personnel often perform tasks and use HSIs in ways that are different from what is described in documentation and the way designers anticipated.

(c) The applicant should identify demanding and challenging scenarios applicable to the new design. Specifically:

- Factors that made each situation demanding and/or challenging, e.g., difficult to detect, difficult to understand events and/or context, difficult to know what to do, difficult to take appropriate actions, difficult to communicate, difficult to coordinate with teammates

- Any important human action involved (per criterion 5)

- The knowledge, skills, and strategies experienced personnel have developed to cope with challenging situations

- The impact on teamwork

- Opportunities for improving performance through improvements in automation, teamwork, HSIs, procedures, training and/or new kinds of decision-aids

Additional Information: Managing disturbances can be difficult even when they are anticipated, trained for, responses are governed by procedures, and needed HSIs (the alarms, information, and controls) are readily available. However, managing disturbances that are beyond design basis situations can be difficult because they are not anticipated and the HSIs, procedures, etc. may not be available to support determining what to do. The OER should identify such situations that operators have experienced and analyze them thoroughly to gain an understanding of what is needed to better manage them. For example, the OER analysts can use cognitive task analysis as one way to obtain such information. For new designs, such scenarios should be identified from a predecessor plant. For plant modifications, the plant’s own operating experience can be used.

4.2 Task Analysis

This section presents proposed modifications to the TA element objectives and review criteria based on our review of CTA. The integration of these new objectives and review criteria in the TA element is shown in Appendix B (for existing TA criteria see section 5.2 of NUREG-0711 Rev. 3).

Objectives

The rationale for expansion of the TA review objectives is the same as the OER. Thus, the objectives can be expanded from:

> The NRC staff uses the review criteria in this section to verify that the applicant has performed analyses that:
>
> - Identify the specific tasks personnel perform to accomplish their functions
> - Identify the alarms, information, controls, and task support needed to perform those tasks

to:

> The NRC staff uses the review criteria in this section to verify that the applicant has performed analyses that:
>
> - Identify the relationships between high-level functions and the tasks allocated to personnel
> - Identify all the specific tasks personnel perform to accomplish their functions, including supervisory control tasks
> - Identify how tasks are performed, including both the cognitive and physical aspects of skilled performance (i.e., knowledge and strategies employed by skilled personnel)
> - Identify the situations that are likely to cause the greatest demands and challenges to task performance and function accomplishment so that a thorough analysis of those situations can be performed
> - Identify the requirements for task performance including knowledge, skill, strategies, teamwork, alarms, information, controls, and task support needed to perform those tasks

4.2.1 Review Criteria

To meet the expanded TA objectives listed above, new criteria are proposed and presented in this section. Only the new review criteria are presented. Their integration into the TA element is shown in Appendix B. The new criteria are listed below (for existing criteria see NUREG-0711 Rev.3 Section 5.4).

(a) The scope of the applicant's TA should include supervisory control tasks, such as the monitoring and management of automation.

Additional Information: Supervisory control tasks include such activities as setting goals, monitoring performance, maintaining situation awareness, making decisions, and adjusting operations as necessary. Supervisory control tasks may be overlooked because they may not be associated with specific activities, such as performing a plant evolution, e.g., plant start-up, or event management (such as responding to a plant trip or a loss-of-coolant accident). Yet these are primary activities in highly automated tasks and important to overall performance and safety.

(b) The applicant's TA should be based on multiple sources of information, for example:

- Information provided by personnel, such as through interviews or questionnaires
- Observations of personnel in the workplace or in a simulator
- Documentation, such as procedures

Additional Information: To fully understand the tasks to be performed and their requirements, multiple sources of data are needed. Ideally, the TA is based on:

- Input from a broad, and representative sample of personnel (e.g., at multiple levels of expertise and representing multiple positions that may be involved in the task such as reactor operators, balance of plant operators, shift supervisors)
- A broad and representative sample of situations (e.g., multiple shifts, multiple sites, multiple locations within a facility)
- Multiple observers/analysts who bring different types of knowledge and expertise to support the analysis, e.g., individuals that have subject-matter expertise in performing the task that is the subject of the TA (such as training instructors, or individuals who have had that position in the past), and individuals with engineering expertise (e.g., system designers with knowledge of the current plant or the planned design for the new plant)
- A broad and representative sample of documents pertaining to plant design and operations, as well as the results of OER

(c) Generally, the type (and potentially the number) of TA methods used by the applicant should be sufficient to define both cognitive and physical tasks to be performed and their requirements.

Additional Information: Designers typically employ a combination of methods to accomplish TA objectives. For example, one applicant for design certification used a function-based TA to identify high-level tasks that need to be performed to accomplish plant functions and operational sequence analysis to identify the step-by-step task requirements. Both analytical methods and subject matter expertise can be used.

(d) The applicant's analysis should show the relationship between tasks and the higher-level functions they support.

Additional Information: Since the starting place for TA is the functions allocated to personnel, the analysis should show the relationship of tasks to those functions. This supports the understanding of a task's importance to function accomplishment and the analysis of the impact of task performance errors. As functions are decomposed to higher-level task descriptions and further into lower-level tasks, the relationship to functions should remain clear.

(e) The applicant's analysis should identify all tasks personnel have to perform to accomplish higher-level functions.

Additional Information: All of the lower-level tasks necessary to achieve the higher-level task or function should be described.

(f) The applicant should identify how experienced personnel will perform tasks. Specifically:

- Normal work practices, including both cognitive and physical aspects of skilled performance
- The knowledge, skills, and strategies that enable knowledgeable personnel to perform tasks
- The factors that complicate task performance, e.g., identify all duties personnel are to perform along with the main tasks being analyzed (including peripheral duties)
- The requirements for supporting skilled performance, including plant and I&C design, automation, HSIs, performance aids, procedures, teamwork, and training

Additional Information: The analysis should consider how tasks are performed, i.e., how operators use HSIs, procedures, etc. to perform their tasks. An understanding of how tasks are performed by operators will help the applicants in determining the impact of new designs on existing work practices. Personnel often perform tasks and use HSIs in ways that are different from what is described in documentation and the way designers anticipated.

(g) The applicant should identify demanding and challenging scenarios. Specifically:

- The factors that made each situation demanding or challenging
- The knowledge, skills, and strategies experienced personnel have developed to cope with these situations
- The requirements for supporting skilled performance, including plant and I&C design, automation, HSIs, performance aids, procedures, teamwork, and training

Additional Information: Demanding situations are those for which the crew knows what to do, but other factors make managing the situation difficult. Some examples of factors making situations demanding are:

- High crew workload due to such factors such as time limitations or the need to perform parallel tasks

- Difficulty communicating due to a noisy environment

- Trouble coordinating operating crew members and support staff

- Unavailability of equipment

Challenging situations are those that are associated with potential failure of the operator's fundamental primary tasks of monitoring and detection, situation assessment, response planning, and response implementation (see O'Hara, 1994).[15] Challenging situations are those that are:

- Hard to detect, potentially due to a lack of needed instrumentation or HSIs, or where indicators give misleading information, or the pattern of indications suggests a different situation

- Difficult to assess and gain an understanding of a situation due to factors such as lack of training or experience with the situation

- Difficult to decide on an action or response, potentially due to a lack of procedures to support response planning

- Difficult to take control of because the controls needed to perform control actions are not available

Managing disturbances can be difficult even when they are anticipated, trained for, responses are governed by procedures, and needed HSIs (including alarms, information, and controls) are readily available. However, managing disturbances that are beyond design basis situations (e.g., beyond-design-basis-events (BDBE)) can be very difficult because they are not anticipated and the HSIs, procedures, etc. may not be available to support determining what to do. In addition, the conditions for BDBEs are, by definition, unbounded and, thus, assumptions must sometimes be made regarding the cause and consequence. The TA should identify such situations for the new design and analyze them thoroughly to gain an understanding of what is needed to better manage them.

(h) The applicant should identify the errors personnel are likely to make and determine:

- The situational and performance shaping factors that may contribute to them

- The impact of errors in task performance on higher-level functions

(i) The applicant should have the results of the TA independently verified.

Additional Information: One way that applicants can check on the completeness of a TA is to have the analysis reviewed by operations and plant systems experts.

15 These primary tasks are based on a simplified cognitive model used in much of the NRC's HFE guidance work (see O'Hara et al., 2008a). Other terms are often used in the literature.

5 SUMMARY AND CONCLUSIONS

Task analysis (TA) is widely recognized as an important element of human factors engineering (HFE) programs for complex system design. Task analyses aim to identify tasks to be performed and the requirements to ensure those tasks are successfully completed. TAs serve as central inputs to workload assessment, staffing analysis, human-system interface (HSI) and procedure design, and training program development.

Given its importance to system design, TA is also an important element in the NRC's HFE safety reviews. Ensuring that applicants perform comprehensive TAs helps to ensure the overall design is based upon a sound understanding of the human's role and responsibilities in plant operation and safety.

While traditional TA methods have been used for over 100 years, they have some limitations when used to assess modern systems. These limitations include:

- They mainly focus on physical activity (observable behaviors). However, as modern plants become increasingly automated, the role of personnel becomes less activity oriented, and more cognition oriented. Traditional methods are limited in their ability to analyze cognitive, supervisory control tasks.

- Traditional methods tend to focus on the ways tasks should be performed from the perspective of designers, procedure developers, and trainers. These perspectives do not always capture how work is performed in the plant under the demands of the real work environment.

- Traditional methods do not address what makes situations demanding and challenging. However, in real world settings, task difficulty is an important determinant of performance and safety.

- Traditional methods are well-suited to clearly defined situations but fall short when analyzing unplanned and unanticipated situations, such as situations that have not been assessed by designers and not been experienced by operations experts. Yet, it is just these types of situations that can pose the greatest risks to safety.

The recent trends toward supervisory control systems and reliance on cognitive rather than physical activities have revealed weaknesses in traditional methods. To help address these weaknesses, a new family of methods, generically called "cognitive task analysis" (CTA), has been developed. Like traditional TA, there are many different CTA methods, each of which provides different approaches to addressing the limitations noted above.

CTAs provide major contributions to complex system design and evaluation. First and foremost is CTA's emphasis on cognition. Understanding the cognitive aspects of performance is essential to supervisory control operations, where many operator tasks may not be guided by procedures. An example is the monitoring and managing of automated systems. New plants are extensively automated, not just for process control, but also for task support (e.g., computer-based procedures) and HSI management (e.g., suggesting an appropriate display for a given situation). Understanding the cognitive requirements for effective supervisory control, the demands faced by operators, and the likely challenges supervisory control imposes will be very important to supporting human performance and plant safety, especially for new, more advanced designs.

Second, CTA has shown the importance of understanding how personnel actually perform their tasks in the complex work environment in contrast to traditional TA methods that examine isolated tasks in ideal conditions. CTA helps analysts to understand how personnel cope with the multiple demands of the work environment, how they coordinate and interact with each other, and how they compensate for design deficiencies through workarounds. We provided several examples of the types of insights gained by examining how work is actually performed in the work environment (Mumaw, Roth, Vicente, & Burns, 2000; Vicente, Mumaw & Roth, 2004; Vicente, Roth &, Mumaw, 2001; O'Hara et al, 1993, 1994). It is important to understand work strategies and the knowledge developed by personnel to manage the complexities posed by the real work environment in order to achieve successful performance and plant safety. The understanding of how tasks are performed also provides a basis to predict the types of errors personnel may make. CTA provides methods to understand these complexities and to acquire and represent the knowledge of expert personnel to inform the design of HSIs, procedures, and training programs.

A third major contribution of CTA is that it can be used to address challenging situations (i.e., those that are unanticipated, not planned for, and beyond the design basis). These situations do occur and, as analyses of major industrial accidents show, they pose significant threats to safety. As Vicente and Rasmussen (1992) noted, "The inescapable conclusion is that unanticipated events can and do happen in large-scale industrial systems. In fact, they are the major cause of life-threatening accidents" (p. 589). Research has shown that by focusing on personnel task and the relationship between personnel tasks and plant functions, CTA (in conjunction with HSI design techniques, such as EID) provides a means to design HSIs that can help operators manage demanding and/or challenging situations (Burns et al., 2008; Lau et al., 2008a, 2008b).

We reviewed the literature on the use of CTA in the design and evaluation of complex systems, including the commercial nuclear industry in particular. The review provided a technical basis to identify the contributions of CTA to HFE programs. CTA can and has contributed to many elements of a good HFE program. We then examined the review guidance in NUREG-0711 to identify opportunities to enhance the guidance. We concluded the main impact is on the OER and TA elements, and hence we developed new review criteria to address the important contributions outlined above. CTA provides tools applicants can use to conduct the HFE activities addressed by the element.

It is important to emphasize that CTA is not a substitute for more traditional TA methods. Instead, CTA methods are complementary; and together with traditional methods provide a rich set of tools to analyze and understand the requirements for human performance in complex systems.

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APPENDIX A REVISED OPERATING EXPERINCE REVIEW (OER)

A.1 Overview

In Section 4.1, we identified modifications to OER review objectives and additional review criteria. In this Appendix, the new guidance is integrated into the existing, NUREG-0711 Revision 3, OER element. The OER section consists of five subsections:

- 5.1 Background
- 5.2 Objective
- 5.3 Applicant Products and Submittals
- 5.4 Review Criteria
- 5.5 Bibliography

The integration process led to some changes to the organization of the NUREG 0711 Rev. 3 OER Section:

- Section 3.4.2, Issue Analysis, Tracking, and Review was divided into two sections:

  - 3.4.2 Issue Analysis
  - 3.4.3 Issue Tracking

- In Section 3.4.1, Scope, the Review Criterion 5 on important human actions was divided into two criteria. The first criterion was kept the same and remains in the scope section. The second criterion was moved to Section 3.4.2, Issue Analysis. The rationale is that this criterion was related to analysis and was the only criterion in the scope section that addressed more than scope.

- The headings were removed from guideline that occurred in sections other than in the scope section.

- Existing guidelines were renumbered to accommodate new guidelines.

- Some revisions to the Background and Applicant Submittal sections were made to accommodate the new guidelines.

A.2 Background

Applicants should provide the NRC staff with the administrative procedures that they will use for evaluating operating, design, and construction experience (referred to collectively as “operating experience”), and for ensuring that germane industry experiences will be provided in a timely manner to those designing and constructing the plant [10 CFR 50.34(f)(3)(i) and 52.47(a)(22)].

There are many reasons an applicant conducts an OER as part of the human factors engineering (HFE) program, for example identifying:

- HFE-related safety issues

- How personnel perform their tasks in the operational environment
- Coping strategies for demanding and challenging situations
- Positive and supportive aspects of the design and work practices

One source of OER information is past performance of predecessor designs. For new plants, these predecessors may be earlier designs upon which the new design is based. For modifications to plants, they may be the design of the systems being changed. The issues and lessons learned from operating experience offer a timely basis for improving the plant's design (i.e., at the beginning of the design process).

Considering an applicant's submittal for a new nuclear power plant (NPP), its predecessor designs are those plants, systems, human-system interfaces (HSIs), and operational approaches that are the basis for the new plant's design. The predecessor designs may include both non-nuclear and nuclear industry sources.

An applicant's NPP design may be an evolutionary one - based on changes to an existing design that was used for several operating plants for many years. Alternatively, an applicant's new NPP design may be an innovative break from past designs. A new design may employ new technologies or operational approaches to realize improvements in safety, performance, availability, or reliability. More likely, such a new plant fits somewhere on the continuum between a traditional evolutionary plant and a completely novel design. All plants on this continuum, likely include systems and HSIs elements similar to or evolved from existing operational plants.

Regardless of where on this succession the applicant's design lies, it is vital to identify those plants, systems, HSIs, and operational approaches that are precursors to, serve as the basis of, or act as a departure point for the new design. These operating experiences can be documented and evaluated to identify lessons learned.

The resolution of OER issues may involve changes in function allocation, automation, HSI equipment design, procedures, training, and so forth. Identifying and analyzing negative features from previous designs enable the applicant to avoid these features while retaining positive features in the development of a new design.

OER information contributes inputs to other review elements, for example, the OER can be used in selecting specific failure scenarios to incorporate in validation testing and as a basis for choosing specific performance measures to evaluate (e.g., to measure an aspect of human performance identified as problematic in the OER). See Table 3-1 for summary.

Table A-1 The Role of Operating Experience Review in the HFE Program

HFE Element	OER Contribution
Functional Requirements Analysis and Function Allocation	Basis for initial requirements
	Basis for initial allocations
	Identification of need for modifications
Task Analysis, Human Reliability Analysis, and Staffing/Qualifications	Important human actions and errors
	Problematic operations and tasks
	Instances of staffing shortfalls
Human-System Interface, Procedures, and Training Development	Trade study evaluations
	Potential design solutions
	Potential design issues
Human Factors Verification and Validation	Tasks to be evaluated
	Event and scenario selection
	Performance measure selection
	Issue resolution verification

A.3 Objective

The NRC staff uses the review criteria in this section to verify that the applicant has reviewed previous designs similar to the design under review and has identified and analyzed:

- Current work practices: assess the potential impact of new technology or other planned changes
- HFE-related problems that impact personnel experience with the operations or design, so they can be addressed
- Demanding and challenging situations, so the new design can provide improved support to personnel
- Positive features of the operations or design, so they can be retained, if possible, in the new design or design modification

A.4 Applicant Products and Submittals

The product of the applicant's OER consists of items identified during the review, together with their proposed solutions or mitigations that contribute to the resolutions of pertinent issues in the new design (see NUREG-0711 Rev 3. Section 3.3).

The applicant should provide either an Implementation Plan (IP) or a completed Results Summary Report (RSR). If the applicant submits an IP, it should describe the methodology for conducting the OER. The NRC will review it using the criteria set out in NUREG 0711 Rev. 3 Section 3.4 (see below). Then the applicant will submit the RSR when the work described by the IP is completed.

If the applicant submits a completed RSR, the NRC will verify the results using the criteria set out below. At a minimum, the RSR should include the following:

- Identification of predecessor/related plants and systems

- Methodology used to review the Operating Experience (OE) (may refer to an approved IP, if used)

- List of OE sources/documents reviewed and relevant findings

- Discussion of the conduct of the OER, and of the results of reviewing relevant HSI technology

- Description of, and findings from interviews with and observations of plant personnel or other users

- Listing of OER-identified issues incorporated into the design

- Enumeration of open issues still being tracked in the HFE issues-tracking system

Summaries may be used for any of the above items if references are given for more detailed documents. If the methodology was described in an IP that the NRC staff previously reviewed, the contents of the RSR should be consistent with the approved methodology and the applicant should discuss the rationale for any deviations from it.

In addition to evaluating the IP or RSR, the NRC staff reviewer may audit the issue-tracking system at the applicant's facility to determine how OER issues were resolved.

A.5 Review Criteria

A.5.1 Scope

(1) Predecessor/Related Plants and Systems – The applicant's OER should include information about human factors issues in the predecessor plant(s) or highly similar plants, systems, and HSIs, including the following:

  - Previous or predecessor design(s)/plant(s) used as part of the design basis for the plant being reviewed.

  - When there is more than one predecessor plant/design, the OER should define the relevance of each to the new design.

  - How the applicant identified and analyzed any HFE-related problems in the previous plants/designs, and how these issues are avoided in the new design.

  - How the applicant identified, evaluated, and incorporated or retained any positive features of previous plants/designs.

  - Descriptions of the predecessor plant(s) and systems, and an explanation of the relationship of each to the new design.

- For applicants proposing to use new technology or systems that were not used in the predecessor plants: the OER should review and describe the operating experience of any other facilities that already use that technology.

(2) Recognized Industry HFE Issues – The applicant should address the HFE issues identified in NUREG/CR-6400. The issues are organized into the following categories:

- Unresolved safety issues/generic safety issues (See 10 CFR 52.47(a)(21) and NUREG-0933)

- Three Mile Island (TMI) issues

- NRC generic letters and information notices

- Operating experience reports in the NUREG-1275 series, Vol. 1 through 14

- Low power and shut down operations

- Operating plant event reports

Additionally, the applicant should review and discuss all operating experience in the preceding categories that was published since NUREG/CR-6400 was published in 1996.

(3) Related HSI Technology – The applicant's OER should cover operating experience with the proposed HSI technology in the applicant's design.

Additional Information: For example, if a computer operated support system, a computerized procedures system, or advanced automation are planned, the OER should describe the HFE issues associated with using them.

(4) Issues Identified by Plant Personnel – The applicant's OER should discuss issues identified through interviews with plant personnel based on their operating experience with plants or systems applicable to the new design. As a minimum, the interviews should include the following topics:

- Plant Operations
  - Normal plant evolutions (e.g., startup, full power, and shutdown)
  - Failure modes and degraded conditions of the I&C systems, including, but not limited to: the sensor, monitoring, automation and control, and communications subsystems. For example, the safety-related system logic and control unit, fault tolerant controller (nuclear steam supply system), the local "field unit" for the multiplexer (MUX) system, the MUX controller (balance-of-plant), and a break in the MUX line failure modes
  - Degraded conditions of HSI resources (e.g., losses of video display units, of data processing, and of large overview display)
    - transients (e.g., turbine trip, loss of offsite power, station blackout, loss of all feedwater, loss of service water, loss of power to selected buses or MCR power supplies, and safety/relief valve transients)

        - accidents (e.g., main steam line break, positive reactivity addition, control rod insertion at power, control rod ejection, anticipated transients without scram, and various-sized loss-of-coolant accidents)
        - reactor shutdown and cooldown using the remote shutdown system

- HFE Design Topics
    - alarms and annunciation
    - displays
    - controls and automation
    - information processing and job aids
    - real-time communications with plant personnel and other organizations
    - procedures, training, staffing/qualifications, and job design

(5) Important Human Actions (HAs) – The applicant's OER should identify important HAs in the predecessor plants or systems (Section 7 defines important HAs) and determine whether they remain important in the applicant's design.

(6) The applicant should identify how experienced personnel perform their tasks using the HSIs and other resources for the range of topics covered in Criteria 4 and 5. They should identify:

- Normal work practices

- The knowledge, skills, and strategies that enable knowledgeable personnel to perform the tasks

- The factors that complicate task performance, e.g., duties personnel perform at the same time as the tasks being analyzed

- The opportunities for improving performance through improvements in automation, teamwork, HSIs, procedures, training, and/or new kinds of decision-aids

Additional Information: This activity provides applicants with an understanding of actual work practices so they can identify positive and negative features of the current design. Developing an understanding as to how tasks are performed and how HSIs, procedures, etc. are used to support performance is important in determining the impact of new designs on work practices. Personnel often perform tasks and use HSIs in ways that are different from what is described in documentation and the way designers anticipated.

(7) The applicant should identify demanding and challenging scenarios applicable to the new design. Specifically:

- The factors that make each situation demanding and challenging, e.g., the situation was:
    - difficult to detect
    - difficult to understand
    - difficult in knowing what to do

    - difficult to take appropriate actions
    - difficult to communicate
    - difficult to coordinate with teammates

- Any important human action involved (per criterion 5)

- The knowledge, skills, and strategies experienced personnel have developed to cope with challenging situations

- The impact on teamwork

- Opportunities for improving performance through improvements in automation, teamwork, HSIs, procedures, training and/or new kinds of decision-aids

Additional Information: Managing disturbances can be difficult even when they are anticipated, trained for, responses are governed by procedures, and needed HSIs (the alarms, information, and controls) are readily available. However, managing disturbances that are beyond design basis can be difficult because they are not anticipated and the HSIs, procedures, etc. may not be available to support determining how to act. The OER should identify such situations that operators have experienced and analyze them thoroughly to gain an understanding of what is needed to better manage them. For example, the OER analysts can use cognitive task analysis as one way to obtain such information. For new designs, such scenarios should be identified from a predecessor plant. For plant modifications, the plant's own operating experience can be used.

A.5.2 OER Process

(1) The applicant should discuss the administrative procedures for evaluating the operating, design, and construction experience, and for ensuring that applicable important industry experiences will be provided in a timely manner to those designing and constructing the plant.

Additional Information: 10 CFR 50.34(f)(3)(i) requires these administrative procedures.

(2) The applicant's OER is based on:

- Information provided by personnel through interviews, questionnaires, or other methods

- Observations of personnel performing representative tasks in the workplace or in a training simulator

- Documentation, such as condition reports and corrective action information, event reports, and incident databases

Additional Information: To fully understand operating experience, multiple sources of data are needed. For example, relying only on documentation will fail to capture operator feedback regarding actual work practices and experiences in situations that went wrong but failed to result in a reportable event. Ideally, the OER should be based on:

- A broad sample of predecessor sites (if available)

- A broad and representative sample of personnel (e.g., at multiple levels of expertise and representing multiple positions that may be involved in the task such as reactor operators, balance of plant operators, shift supervisors)

- A broad and representative sample of situations (e.g., multiple shifts, multiple sites, multiple locations within a facility)

- Multiple observers/analysts who bring different types of knowledge and expertise to support the analysis. Specifically, individuals that have subject-matter-expertise in the TA, task performance, (e.g., training instructors, or individuals who have had that position in the past), and individuals with engineering expertise (e.g., system designers with knowledge of the current plant or the planned design for the new plant)

- Broad and representative sample of documents pertaining to plant design, operations, corrective actions, event reports

(3) The applicant should analyze issues to identify:

- Human performance issues and sources of human error

- Design elements supporting and enhancing human performance

(4) The applicant should identify how experienced personnel perform their tasks using HSI and other resources for the range of topics covered in Criteria 4 and 5. They should identify:

- Normal work practices

- The knowledge, skills, and strategies that enable knowledgeable personnel to perform the tasks

- The factors that complicate task performance, e.g., duties personnel have to perform at the same time as the tasks being analyzed

- The opportunities for improving performance through improvements in automation, teamwork, HSIs, procedures, training and/or new kinds of decision-aids

Additional Information: This activity provides applicants with an understanding of current work practices so they can identify positive and negative features of the current design. Developing an understanding as to how tasks are performed and how HSIs, procedures, etc. are used to support performance is important in determining the impact of new designs on work practices. Personnel often perform tasks and use HSIs in ways that are different from what is described in documentation and the way designers anticipated.

(5) The applicant should identify demanding and challenging scenarios applicable to the new design. They should identify:

- The factors that made each situation demanding and challenging, specifically, the situation was:
    - difficult to detect
    - difficult to understand
    - difficult to know what to do
    - difficult to take appropriate actions
    - difficult to communicate and/or coordinate with teammates

- Any important human action involved (per Criterion 5)

- The knowledge, skills, and strategies experienced personnel have developed to cope with challenging situations

- The impact on teamwork

- Opportunities for improving performance through improvements in automation, teamwork, HSIs, procedures, training and/or new kinds of decision-aids

Additional Information: Managing disturbances can be difficult even when they are anticipated, trained for, responses are governed by procedures, and needed HSIs (the alarms, information, and controls) are readily available. However, managing disturbances that are beyond design basis can be difficult because they are not anticipated and the HSIs, procedures, etc. may not be available to support determining how to act. The OER should identify situations that operators have experienced and analyze them thoroughly to gain an understanding of what resources are needed to better manage such situations. For new designs, such scenarios should be identified from predecessor plants. For plant modifications, the plant's own operating experience can be used.

(8) Additional considerations for important human actions:

- The OER should identify the scenarios wherein actions are needed, and state whether they were needed and successfully completed. Those aspects of the design that helped ensure success should be identified.

- If errors occurred in the execution of important HAs, the applicant should identify insights to the needed improvements in human performance.

- When important HAs for the new plant are determined to differ from those of the predecessor plant, the OER should specify whether there is any operational experience with these different HAs.

A.5.3 Issue Tracking

(1) The applicant should document the analysis of operating experience.

(2) The applicant should document each issue determined to be relevant to the design, even if it is not yet addressed in the issue-tracking system (see NUREG-0711 Rev. 3 Section 2.4.4).

A.5.4 Plant Modifications

(1) Additional Considerations for Reviewing the HFE Aspects of Plant Modifications – In addition to any of the criteria above that relate to the modification being reviewed, the applicant should address the following considerations:

- The focus of the applicant's OER should be on the plant's systems, HSIs, procedures, or training that are being modified.

- The applicant's OER should account for the operating experience of the plant that will be modified, including experiences with the systems that will be changed and with technologies similar to those being considered.

Additional Information: Useful information may be found in the plant's corrective action program.

APPENDIX B REVISED TASK ANALYSIS (TA) REVIEW GUIDANCE

B.1 Overview

In Section 4.1, we identified modifications to TA review objectives and additional review criteria. In this Appendix, the new guidance is integrated into the existing NUREG-0700, Revision 3, Section 5, task analysis element.

The TA section consists of five subsections:

- 5.1 Background
- 5.2 Objective
- 5.3 Applicant Products and Submittals
- 5.4 Review Criteria
- 5.5 Bibliography

B.2 Background

As noted in Section 4, the functions allocated to personnel are human actions (HAs). Applicants further analyze HAs to identify the tasks that personnel must perform to accomplish them. Tasks are a group of related activities with a common objective. TA identifies the specific tasks needed to accomplish HAs and the information, control, and support required to complete those tasks. Accordingly, the results of task analyses are identified as inputs in many human factors engineering (HFE) activities, e.g., they form the basis for evaluating:

- Staffing and qualifications
- Human-system interfaces (HSIs), procedures, and training program design
- Task support verification (see Human Factors Verification and Validation (V&V) in Section 11 of NUREG-0711 Rev. 3)

B.3 Objective

The NRC staff uses the review criteria in this section to verify that the applicant has performed analyses that:

- Identify the relationships of high-level functions and the tasks allocated to personnel
- identify all the specific tasks personnel perform to accomplish their functions, including supervisory control tasks

- Identify how tasks are performed, including both the cognitive and physical aspects of skilled performance (e.g., knowledge and strategies employed by skilled personnel)

- identify the situations that are likely to cause the greatest demands and challenges to task performance and function accomplishment so that a thorough analysis of those situations can be performed

- Identify the requirements for task performance including knowledge, skill, strategies, teamwork, alarms, information, controls, and task support needed to perform those tasks

B.4 Applicant Products and Submittals

The product of the applicant's TA is a listing of the tasks to be undertaken and the requirements for performing each task. The TA generates inputs to other elements in the HFE process.

The applicant should provide either an implementation plan (IP) or a completed results summary report (RSR). If the applicant submits an IP, it should describe the methodology for conducting the TA. The NRC will review it using the criteria set out in Section 5.4 below. Then the applicant will submit the RSR when the work described by the IP is completed.

When the applicant submits a completed RSR, the NRC will verify the results using the criteria in Section 5.4 below. At a minimum, the RSR should include the following:

- The HAs to be addressed by TA

- A description of the TA methodology

- A description of:
    - personnel tasks including a narrative of the activities to be perform
    - the applicable aspects of the tasks (see Criterion 2 below)
    - the relationship between tasks
    - an estimate of the time needed to perform the tasks
    - estimated workload
    - a list of the alarms, information, controls, and task support identified by TA
    - an identification of the number of personnel needed to complete each task
    - a designation of the knowledge and abilities needed to perform each task

Summaries may be used for any of the above items if references are given for more detailed documents. If the methodology was described in an IP that the NRC staff previously reviewed, the contents of the RSR should be consistent with the approved methodology and the applicant should discuss the rationale for any deviations from it.

B.5 Review Criteria

(1) The scope of the applicant's TA should include:

- All important HAs as determined by probabilistic and deterministic means (see Section 7, Treatment of Important Human Actions, of this report)

- The applicant should select tasks for analysis that represent the full range of plant operating modes, including startup, normal operations, low-power and shutdown conditions, transient conditions, abnormal conditions, emergency conditions, and severe accident conditions. The chosen tasks should cover:
    - tasks that were not identified as “important HAs” but have negative consequences if performed incorrectly
    - tasks that are new compared to those in predecessor plants, such as ones related to new systems or procedures
    - tasks that, while not new, are performed significantly differently from predecessor plants
    - tasks related to monitoring of automated systems that are important to plant safety and the use of automated support aids for personnel, such as computer-based procedures
    - tasks related to identifying the failure or degradation of automation and implementing backup responses
    - tasks anticipated to impose high demands on personnel, e.g., little time or high workload (such as administrative tasks that contribute to workload and challenge ability to monitor the plant)
    - tasks important to plant safety that are undertaken during maintenance, tests, inspections, and surveillances
    - tasks with potential concerns for personnel safety (such as maintenance tasks performed in the containment)
    - supervisory control tasks, such as the monitoring and management of automation.

Additional Information: Supervisory control tasks include such activities as setting goals, monitoring performance, maintaining situation awareness, making decisions, and adjusting operations as necessary. Supervisory control tasks may be overlooked because they may not be associated with specific activities, such as performing a plant evolution, e.g., plant start-up, or event management (such as responding to a plant trip or a loss-of-coolant accident). Yet these are primary activities in highly automated tasks and important to overall performance and safety.

(2) The applicant should describe the screening methodology used to select the tasks for analysis, based on criteria specifically established to determine whether analyzing a particular task is necessary.

(6) The applicant’s TA should be based on multiple sources of information:

- Information provided by personnel, such as through interviews or questionnaires

- Observations of personnel in the workplace or in a simulator

- Documentation, such as procedures

Additional Information: To fully understand what tasks must be performed and their requirements, multiple sources of data are needed. Ideally, the TA is based on:

- Input from a broad and representative sample of personnel (e.g., at multiple levels of expertise and representing multiple positions that may be involved in the task such as reactor operators, balance of plant operators, shift supervisors)

- A broad and representative sample of situations (e.g., multiple shifts, multiple sites, multiple locations within a facility)

- Multiple observers/analysts who bring different types of knowledge and expertise to support the analysis, e.g., individuals that have subject-matter expertise in the TA, task performance (such as training instructors, or individuals who have had that position in the past), and individuals with engineering expertise (e.g., system designers with knowledge of the current plant or the planned design for the new plant)

- A broad and representative sample of documents pertaining to plant design and operations, as well as the results of OER

(4) The types (and potentially number) of TA methods used by the applicant should be sufficient to define the cognitive and physical tasks to be performed and their task requirements.

Additional Information: Designers typically employ a combination of methods to accomplish TA objectives. These methods can combine analytical approaches and subject matter expertise or may rely on multiple analytical methods. For example, one applicant for design certification used a function-based task analysis to identify high-level tasks that need to be performed to accomplish plant functions and operational sequence analysis to identify the step-by-step task requirements.

(5) The applicant's analysis should show the relationship between tasks and the higher-level functions they support.

Additional Information: Since the starting place for TA is the functions allocated to personnel, the analysis should show the relationship of tasks to those functions. This supports the understanding of a task's importance to function accomplishment and the analysis of the impact of task performance errors. As functions are decomposed to higher-level task descriptions and further into lower-level tasks, the relationship to functions should remain clear.

(6) The applicant's analysis should identify all tasks personnel have to perform to accomplish higher-level functions.

Additional Information: All of the lower-level tasks necessary to achieve the higher-level task or function should be described.

(7) The applicant should begin the TA with detailed narratives of what personnel have to do. The analysis should be sufficiently detailed to include definitions of the alarms, information, controls, and task support needed to accomplish the task. The detailed task descriptions should address (as applicable to the task) the topics listed in Table A-1.

Table B-1 Task Considerations

Topic	Example
Alerts	• alarms and warnings
Information	• parameters (units, precision, and accuracy) • feedback needed to indicate adequacy of actions taken
Decision-making	• decision type (relative, absolute, probabilistic) • evaluations to be performed
Response	• actions to be taken • task frequency and required accuracy • time available and temporal constraints (task ordering) • physical position (stand, sit, squat, etc.) • biomechanics - movements (lift, push, turn, pull, crank, etc.) - forces needed
Teamwork and Communication	• coordination needed between the team performing the work • personnel communication for monitoring information or taking control actions
Workload	• cognitive • physical • overlap of task requirements (serial vs. parallel task elements)
Task Support	• special and protective clothing • job aids, procedures, or reference materials needed • tools and equipment needed
Workplace Factors	• ingress and egress paths to the worksite • workspace needed to perform the task • typical environmental conditions (such as lighting, temp, noise)
Situational and Performance Shaping Factors	• stress • time pressure • extreme environmental conditions • reduced staffing
Hazard Identification	• identification of hazards involved, e.g., potential personal injury

(8) The applicant should identify the relationships among tasks.

Additional Information: For example, some tasks can be carried out in any order or in parallel while others must be performed in a linear sequence. The relationship between tasks can also be conditional, for example, if a given condition exists, perform task A. Some tasks may involve coordinated actions among crew members or control room crew members and local personnel.

(9) The applicant should identify how experienced personnel will perform tasks. Specifically:

- Normal work practices, including both the cognitive and physical aspects of skilled performance

- The knowledge, skills, and strategies that enable knowledgeable personnel to perform tasks

- The factors that complicate task performance, e.g., identify all the duties personnel are to perform along with the main tasks being analyzed (including peripheral duties)

- The requirements for supporting skilled performance, including plant and instruments and controls (I&C) design, automation, HSIs, performance aids, procedures, teamwork, and training

Additional Information: The analysis should consider how tasks are performed. An understanding of how tasks are actually performed by operators will help the applicant determine the impact of new designs on existing work practices. Personnel often perform tasks and use HSIs in ways that are different from what is described in documentation and the way designers anticipated.

(10) The applicant should identify demanding and challenging scenarios. Specifically:

- The factors that made each situation demanding or challenging

- The knowledge, skills, and strategies experienced personnel have developed to cope with these situations

- The requirements for supporting skilled performance, including plant and I&C design, automation, HSIs, performance aids, procedures, teamwork, and training

Additional Information: Demanding situations are those for which the crew knows what to do, but factors make managing the situation difficult. For example:

- High crew workload due to factors such as:
  - time limitations
  - need to perform parallel tasks

- Difficulty communicating due to a noisy environment

- Trouble coordinating operating crew members and support staff

- Unavailability of equipment

Challenging situations are those that are associated with potential failure of the operator's fundamental primary tasks of monitoring and detection, situation assessment, response planning, and response implementation.[17] Challenging situations are those that are:

- Hard to detect, due to:

17 These primary tasks are based on a simplified cognitive model used in much of the NRC's HFE guidance work (see O'Hara et al., 2008a). Other terms are often used in the literature.

    - lack of needed instrumentation or HSIs
    - indicators that give misleading information
    - the pattern of indications suggests a different situation
    - automation causing the human to be out-of-the-loop

- Difficult to assess and gain an understanding of what is going on, this can be due to lack of training or experience with the situation

- Difficult to decide what to do because there are no procedures to support response planning

- Difficult to take control of because the controls needed to perform control actions are not available

However, managing disturbances can be difficult even when they are anticipated, trained for, responses are governed by procedures, and needed HSIs (including alarms, information, and controls) are readily available. These beyond design basis disturbances can be difficult situations because they are not anticipated and the HSIs, procedures, etc. may not be available to support determining what to do. The TA should identify such situations for the new design and analyze them thoroughly to gain an understanding of what is needed to better manage them.

(11) The applicant should estimate the time required to perform each task.

(12) The applicant should identify the number of people required to perform each task.

(13) The applicant should identify the knowledge and abilities required to perform each task.

(14) The applicant should identify the errors personnel are likely to make and determine:

- The situational and performance shaping factors that may contribute to them

- The impact of errors in task performance on higher-level functions

(15) The applicant's TA should be iterative and updated as the design is better defined.

(16) Applicants should document and provide an analysis of the feasibility and reliability for important HAs that address the following:

- The analysis establishes the time available to perform given actions using an analysis method and acceptance criteria consistent with the regulatory guidance associated with those actions. The basis for the time available is documented.

  Additional information: The time available to perform the actions should be based on analysis of the plant response to the anticipated operational occurrence or accident. This analysis should reflect the guidance associated with the event.

- The analysis of the time required is based on a documented sequence of operator actions (based on TA, vendor-provided generic technical guidelines for emergency operating procedure development, or plant-specific EOPs, depending on the maturity of the design).

- Techniques to minimize bias are used when estimates of time required are derived using methods that are dependent on expert judgment. Uncertainties in the analysis of time required are identified and assessed.

- The sequence of actions uses only alarms, controls, and displays that would be available and operable during the assumed scenario(s).

- The estimated time for operators to complete the credited action is sufficient to allow successful execution of applicable steps in the EOPs.

  Additional Information: Acceptable methods for deriving analysis time estimates for individual task components include, but are not limited to:

  - Operator interviews and surveys
  - Operating experience reviews
  - Software models of human behavior, such as task network modeling
  - Use of control/display mockups
  - Expert panel elicitation (e. g., Kolaczkowski et al., 2007)

    - If credited manual actions require additional operators beyond the assumed staffing, a justification for timely availability of the additional staffing is provided and the estimate of time required includes any time needed for calling in additional personnel.

    - The analysis of the action sequence is conducted at a level of detail sufficient to identify individual task components, including cognitive elements such as diagnosis and selection of appropriate response.

  Additional information: The documented sequence of operator actions should be analyzed at a level of detail necessary to identify critical elements of the actions and performance shaping factors (e.g., workload, time pressure) that affect time required and likelihood of successful completion of the action sequence.

  The applicant should establish time estimates for individual task components (e.g., acknowledging an alarm, selecting a procedure, verifying that a valve is open, starting a pump) and the basis for those estimates through a method applicable to the HSI characteristics of digital computer-based I&C. The analysis identifies a time margin to be added to the time required and the basis for the adequacy of the margin.

(17) The applicant should have the results of the TA independently verified.

Additional Information: Review of a TA by operations and plant systems experts is one way the applicant can ensure the completeness of the analysis.

(18) Additional Considerations for Reviewing the HFE Aspects of Plant Modifications – In addition to the criteria above, if the modification under review will affect HAs previously identified as important, cause existing HAs to become important, or create new HAs of importance, the applicant should address the following:

- The existing TA should be revised and updated to reflect the modification.
  - If no pertinent TA exists, then consideration should be given to completing a new TA.
  - For maintenance, tests, inspections, and surveillances, attention should be given to new important human actions, or those supported by new technologies (e.g., new capabilities for on-line maintenance).

- The TA should identify the design characteristics of the existing HSIs supporting the performance of experienced personnel (e.g., support high levels of performance during demanding situations). Design features identified during the OER also should be carefully weighed in these analyses as well.

  Additional Information: The design characteristics may include:
  - the spatial arrangement of control and display devices
  - ease of adjusting controls and displays to deal with special tasks.

  The new design should have features performing similar functions as the previous design or should eliminate the need for those features if the functions are performed differently (e.g., by automating them).

  In addition, the TA should identify and examine any adjustments made to the previous HSIs by users, such as notes and external memory aids, suggesting that the previous design does not fully meet the users' needs. The new design requirements should adequately address all task demands.

APPENDIX C SELECTED CTA METHODS DESCRIPTIONS

C.1 Overview

This appendix contains detailed descriptions of a selection of CTA methods, including:

- Cognitive Work Analysis (CWA)
- Applied Cognitive Work Analysis (ACWA)
- Goal Directed Task Analysis (GDTA)
- Critical Decision Method (CDM)
- Cognitive Field Observations
- Goals Operators Methods and Selection Rules (GOMS) Model
- Concept Mapping

For each method, the following information is provided:

- The name of Related Methods
- The Goal of the analysis method
- The Most Appropriate Use of the analysis method
- A Method Description
- The type of Results to method produces
- The Resource Requirements needed to use the method
- Any Constrains and Limitations analysts have to deal with
- How the Results are Used in a human factors engineering (HFE) Program

The references to studies cited in the descriptions are in Section 6, References.

C.2 Cognitive Work Analysis

C.2.1 Related Methods

Applied Cognitive Work Analysis (see Appendix C.2) and Function-Based Task Analysis.

C.2.2 Goal

Cognitive Work Analysis (CWA) is used to identify and represent requirements, constraints, and opportunities, for cognitive and collaborative work in a domain, based on an analysis of the goals of the system, and the physical functions and processes available to meet those goals (Rasmussen, 1986; Vicente, 1999). The goal of CWA is to produce *formative models* that elucidate what it takes to do a job independently of the agent (person or machine) performing it or a specific event context. This contrasts with other approaches that are intended to provide *normative/prescriptive* models that specify how work *should* be accomplished or *descriptive models* that represent how work *is actually* accomplished.

C.2.3 Most Appropriate Use

CWA provides a set of inter-related analyses that support a broad range of HFE activities including function allocation, HFE design, and training. This makes it appropriate for comprehensive HFE applications. It is especially appropriate for design of first-of-a-kind-systems where there are no existing expert domain practitioners to interview, no current work environments to observe, and minimal prior experience that can be relied on to guide issues of human-system integration. It is also well suited for identifying information and support requirements to enable flexible and adaptive performance, particularly in the face of unanticipated situations for which preplanned procedures may not be available or may not fully apply.

C.2.4 Method Description

CWA encompasses five interrelated types of analyses that include:

- Work domain analysis – captures the physical characteristics and constraints in a domain
- Control task analysis - captures the work objectives and methods
- Strategies analysis -captures the specific strategies that can be used to accomplish identified control tasks
- Social, organizational, and cooperation analysis – captures the social and organizational influences
- Worker competencies analysis – captures the knowledge and skill requirements for effective performance

The grounding layer of a CWA is the work domain analysis (WDA). WDA uncovers and represents the goals, means, and constraints in a domain, which establishes the boundaries within which people must reason and act. This provides the basis for identifying functions to be performed by agents (humans or machines) and the cognitive activities those entail. The remaining layers of the CWA build on the WDA foundational base.

The control task analysis examines what work situations can arise in the domain and defines the functions required to achieve domain goals in those work situations, without specifying what agent (human or machine) will perform the functions.

Strategies analysis identifies the alternative strategies that can be used to perform the control tasks.

Social, organizational, and cooperation analysis explores how work can be distributed across multiple agents and organizational structures and the implication for communication and coordination requirements.

Finally, worker competencies analysis examines the knowledge and skills that are required to efficiently and effectively perform the cognitive and collaborative functions identified through the prior analyses.

CWA defines the types of information to gather in support of the analysis and how that information should be represented and used as input for further analysis and HFE activities. It does not specify what knowledge acquisition method to use.

Typically, a CWA is conducted based on review of engineering documents and interviews with design engineers to understand the goal-means functional relationship between the systems and the functions they are trying to achieve. If the systems are already in operation, then operational staff and trainers can also serve as a source of information.

Not all five CWA analysis types must be performed to the same level of depth, if at all. The CWA analyses selected will vary with the application. Because WDA is the foundational analysis, it is generally the most fully developed and widely used element of a CWA.

Commonly, a WDA (see Naikar, 2013 for a detailed introduction to WDA) is conducted by creating an Abstraction/Aggregation Hierarchy according to the principles outlined by Rasmussen (1986). The first dimension is the *level of abstraction*. A multi-level goal-means representation is generated with abstract system purposes at the top and concrete physical equipment that provides the specific means for achieving these system goals at the bottom. In many instances, the levels of the model include:

- Functional Purpose - a description of system purposes
- Abstract Function - a description of first principles and priorities
- Generalized Function - a description of processes
- Physical Function - a description of equipment capabilities
- Physical Form - a description of physical characteristics such as size, shape, color, and location

The second dimension is the *level of aggregation*. Aggregation reflects the degree of integration, from part to whole, toward which a domain practitioner's problem solving is directed. The level of aggregation could range from individual components to the entire system. For example, in a nuclear power plant this would include the plant as a whole, the systems that make up the plant, the equipment that makes up the systems, and the physical components of the equipment.

These two dimensions form a matrix describing the information needs of plant personnel, called the abstraction-aggregation (A-A) matrix (see Table C-1). That is, personnel need information along the levels of abstraction, e.g., from the physical form of functional purpose of the plant, systems, equipment, and components. The Lau et al. (2008a) study described below provides an example of the use of these levels of abstraction for identifying information needs and translating them into displays for operators.

Table C-1 Abstraction-Aggregation (A-A) Matrix

Level of Abstraction	Level of Aggregation			
	Plant	System	Equipment	Component
Functional Purpose				
Abstract Function				
Generalized Function				
Physical Function				
Physical Form				

An advantage of defining information needs using the A-A matrix is that normal plant behavior is dictated by a set of known relationships between plant parameters governed by constraints dictated by the physical nature of plant equipment, the physical laws governing the process, and the purposes for which the system was designed. Off-normal conditions are revealed when these constraints are violated. By analyzing information needs according to the A-A matrix, these constraints can be represented in the design of the information system.

CWA has primarily been applied to HSI design, especially the design of novel displays and decision support systems. CWA provides the theoretical and analytic foundation for "ecological interface design" (Burns & Hajdukiewicz, 2004; Vicente & Rasmussen, 1992; Vicente, 2002). It has been used in a several process control and nuclear power plant applications (e.g., Burns et al., 2008; Jamieson, 2007a, 2007b; Lau et al., 2008a, 2008b).
The framework is also applicable and has been successfully deployed in other aspects of HFE including:

- Function allocation
- Team structure design
- Training requirements specification

Naikar and colleagues provide additional details and examples in several reports (see, Naikar, 2009; Naikar, Pearce, Drumm, & Sanderson, 2003; Naikar & Sanderson, 1999; Naikar & Sanderson, 2001; Naikar & Saunders, 2003).

In summary, the A-A framework is particularly valuable for analysis and design of first-of-a-kind systems, especially for complex, dynamic, high-risk domains where the ability to understand and act adaptively in the face of unanticipated conditions is critical.

C.2.5 Results

The output of CWA analyses often takes the form of graphic representations with annotations, for example, the WDA abstraction hierarchy presented in Figure C-1.

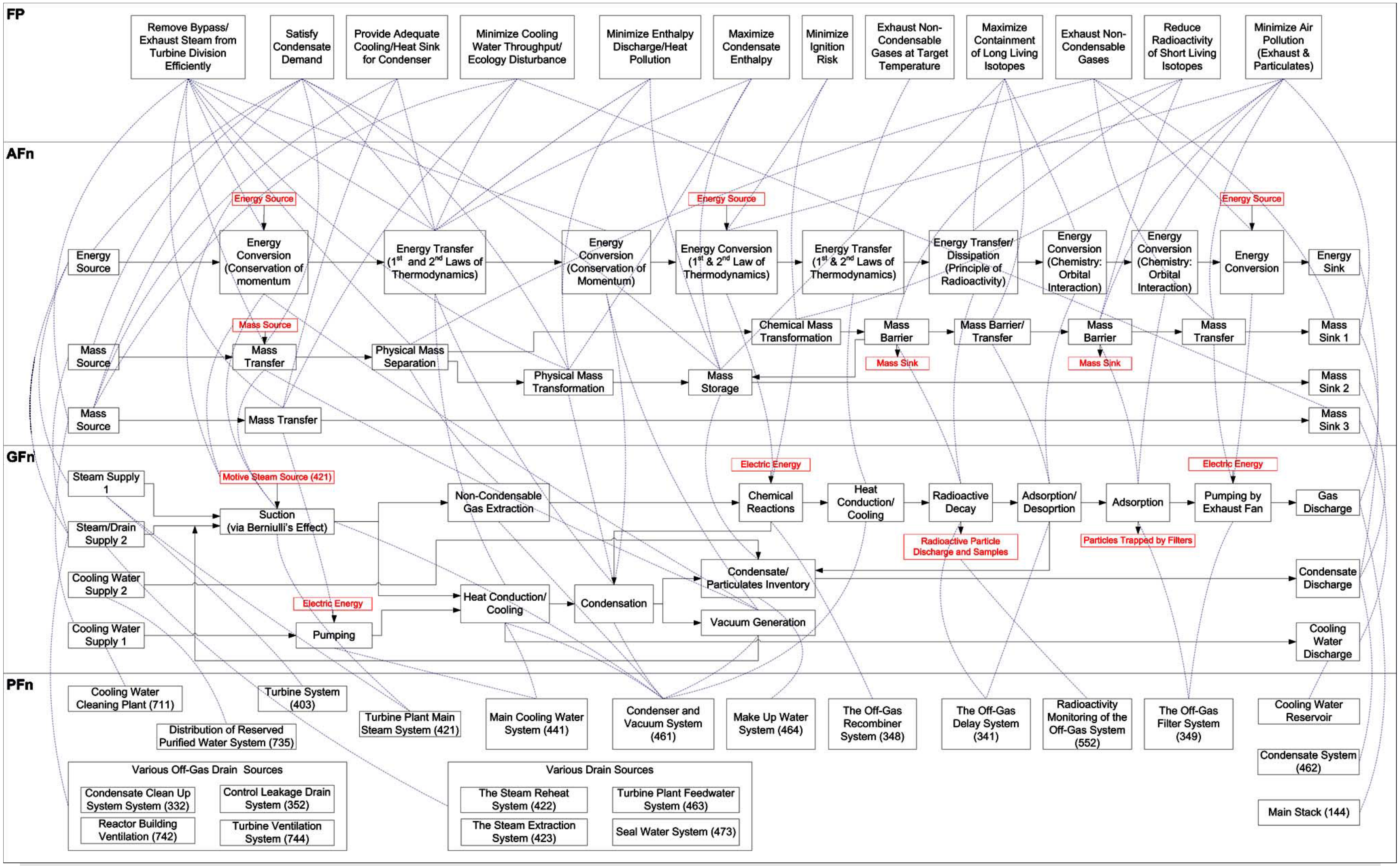

Figure C-1 Abstraction hierarchy model at the subsystem level of decomposition for a boiling water reactor secondary side condenser.

Shown are four levels of an abstraction hierarchy: functional purpose (FP), abstraction function (AFn), generalized function (GFn), and physical function (PFn). The dotted lines going from one level to another are means-ends links (see Lau et al, 2008a for a detailed explanation of the levels and links in the Figure), image sourced from Lau et al.

The abstraction hierarchy representations were used to guide the design of ecological displays that capitalize on perceptual processes to enable rapid assessment of the status of plant functions and processes (Lau et al., 2008a). Figure C-2 provides an example ecological display developed for the boiling water reactor secondary side condenser (see Figure C-1 for the WDA diagraming this system). In contrast to traditional physical mimic displays, this display includes graphical elements for monitoring the status of processes at a more abstract functional level, such as the status of mass and energy balances, and temperature pressure plots.

Ecological displays derived from WDA have been shown to enhance operator performance in complex simulated emergencies that involve unanticipated situations for which procedural guidance is unavailable (Lau et al., 2008b; Burns et al., 2008).

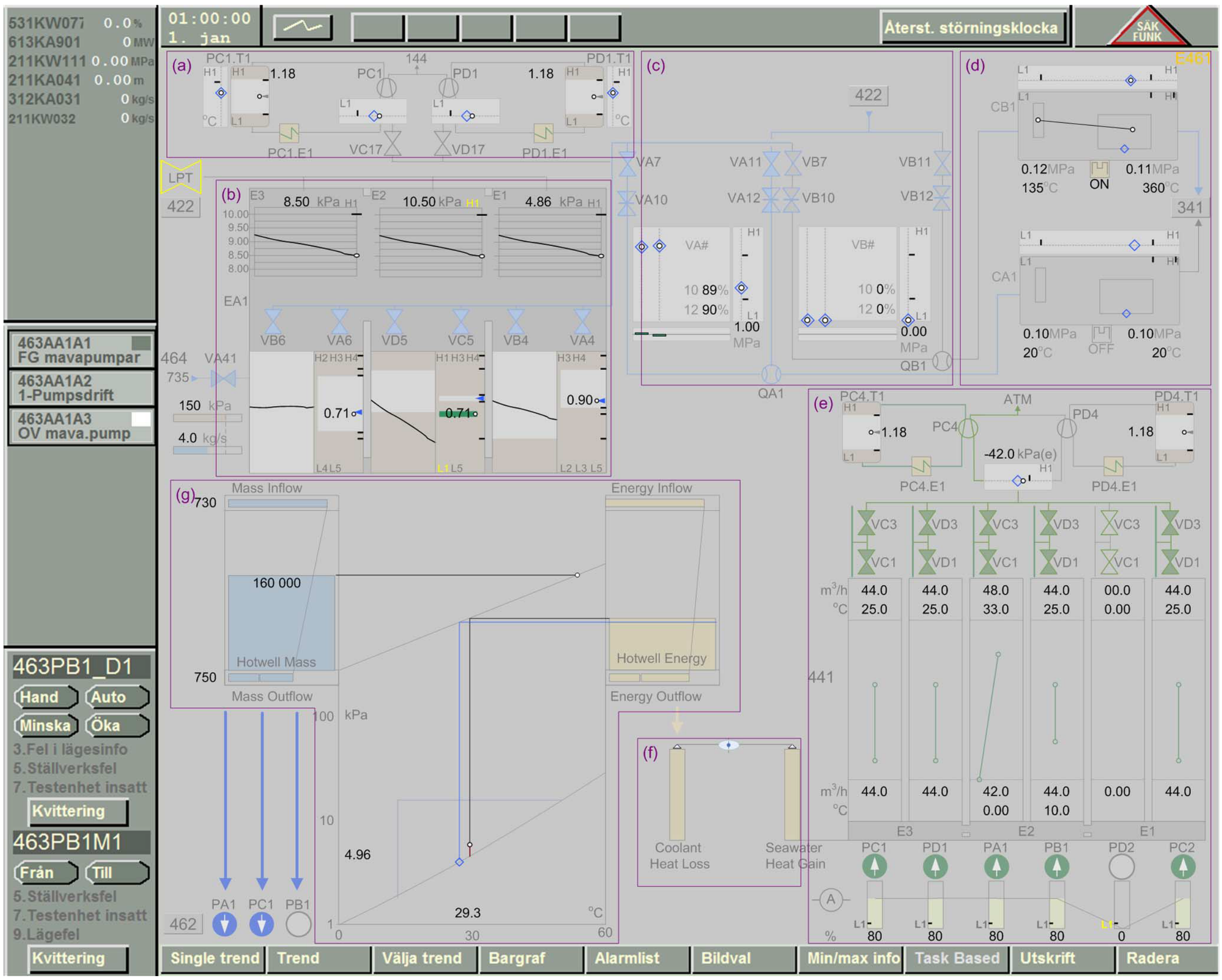

Figure C-2 Ecological display for a boiling water reactor secondary side condenser that was developed based on a WDA

(Source is Lau et al, 2008a)

Results of a control task analysis often take the form of a decision ladder that indicates the information processing activities required to accomplish a task. A decision ladder can be used to describe control tasks performed by people, machine agents or a combination of the two. An example of a decision ladder for an automated system is provided in Figure C-3. More information on control task analyses and associated output representations can be found in Naikar, Moylan and Pearce (2006).

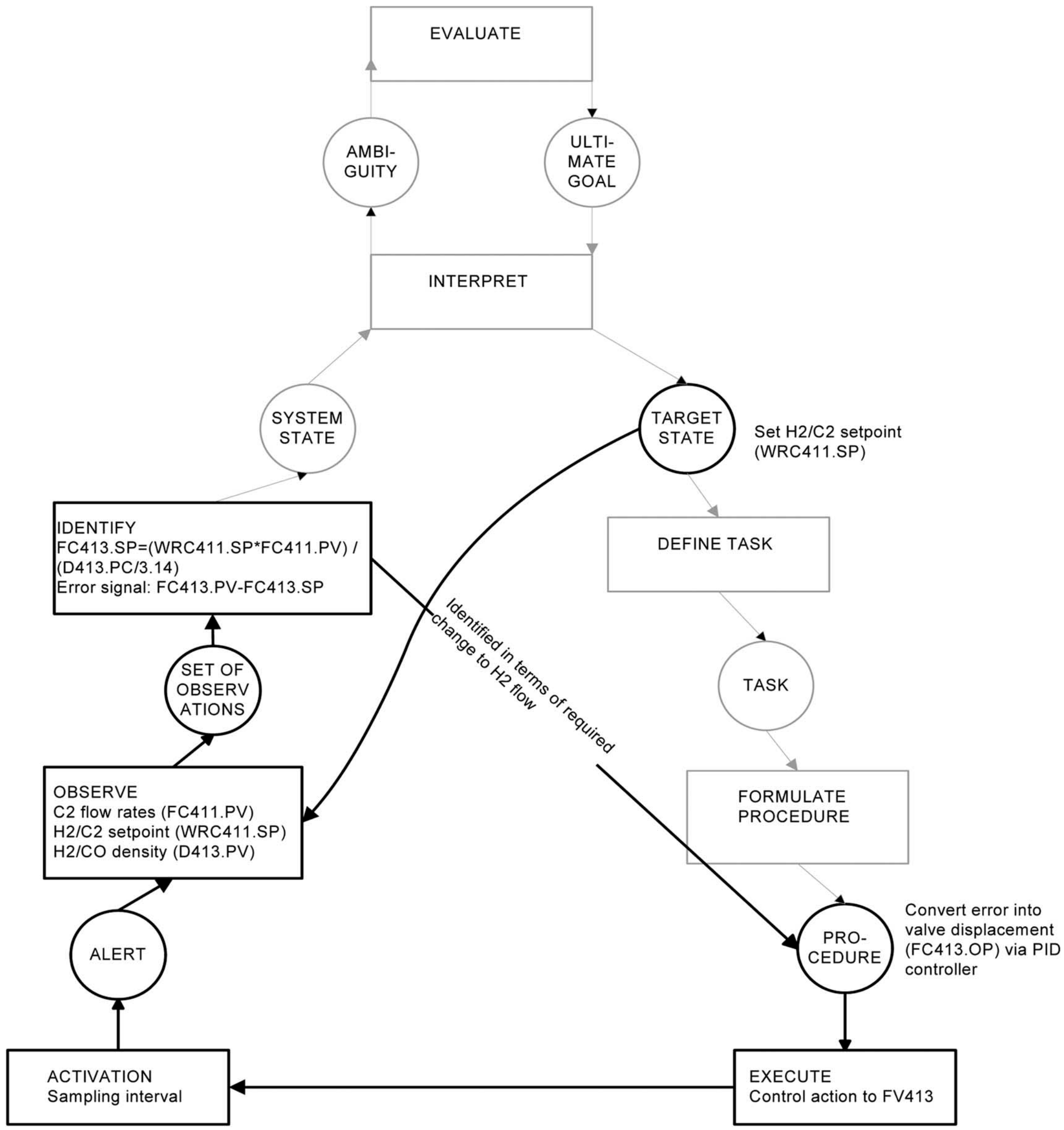

Figure C-3 A decision ladder for the control task analysis of the weight ratio automatic controller in a petrochemical production process.

The boxes are information processing stages and the circles are states of knowledge that serve as inputs and outputs. The process receives flow rate and chemical composition inputs from a "C2 stream" (defined as a stream consisting of ethane, ethylene, and various trace elements including acetylene, see Jamieson et al., for details), calculates a hydrogen flow rate to match a setpoint ratio, and outputs a control signal to a valve on the hydrogen stream to achieve that ratio. Diagram sourced from Jamieson et al., 2007b

The outputs of the other CWA analyses can take a variety of forms (see Roth and Bisantz, 2013 for examples of representative outputs, see also, Bisantz and Burns, 2009 for CWA applications in a variety of different domains).

C.2.6 Resource Requirements

Because CWA specifies *what* information needs to be collected rather than *how* it is to be collected, a CWA does not depend on the availability of experienced domain practitioners. A variety of sources can be used as input to a CWA. Inputs to a CWA can include:

- Documents such as manuals, procedures and engineering drawings
- Individuals with knowledge of the domain

Knowledge sources can include:

- System designers
- Engineers
- Experienced domain practitioners
- trainers

In the case of a system that is early in the design process, knowledge sources can also include those familiar with the design goals of the planned system capabilities, for example:

- Stakeholders
- System designers
- Domain practitioners familiar with legacy systems that the new system is intended to replace

C.2.7 Constraints and Limitations

A limitation of work domain analysis methods is that it can be resource intensive to exhaustively map the characteristics and constraints of a domain. However, as multiple projects have shown, it is not necessary to perform an exhaustive domain analysis to reap the benefits (see Bisantz, et al., 2003 for examples). A work domain analysis can be performed at different levels of detail, depending on the complexity of the system being analyzed and the phase of analysis. A preliminary, high-level work domain analysis can be performed early in the HSI design process to identify information needs, critical constraints, and informational relationships that are necessary for successful action and problem management within the domain. As the design evolves, the work domain analysis can be elaborated.

C.2.8 How the Results are used in an HFE Program

Functional Analysis and Allocation: CWA is particularly well suited to identifying the functions to be achieved, how they can be distributed across person(s) and/or machine agent(s), and the implications of alternative function allocation for the operator’s cognitive tasks and the associated information and support requirements (Roth & Mumaw, 1995).

- Task Analysis: CWA provides the basis for defining information and decision-support requirements that enable operators to perform their assigned cognitive tasks.

- Staffing Analysis: CWA's social, organizational, and cooperation analysis supports HFE practitioners to evaluate the assignment of work within organizational structures and the implications for communication and coordination requirements. Worker competencies analysis supports the identification of the knowledge and skills that are required to efficiently and effectively perform the cognitive and collaborative functions identified through the prior analyses.

- Human-System Interface Design: CWA has been shown to be particularly useful for design of function-based displays intended to support cognitive performance under unanticipated conditions where procedural guidance may be limited (Burns et al., 2008; Lau et al., 2008b).

- Procedure Development: Control task analysis and strategies analysis can be used to identify effective methods for achieving specific goals. These outputs can be used as an input to procedure development.

- Training Program Development: The outputs of CWA analyses, particularly WDA, strategies analysis and worker competencies analysis, can be used to identify the knowledge, skills, and strategies, that should be included in training. As the foundational element of CWA is a WDA the results can be used to train operators to handle unanticipated situations that require knowledge-based reasoning about how to recover plant functions when the standard prescribed methods for achieving plant goals are not available.

- Human Factors Verification and Validation: The results of CWA can be used to identify a range of cognitively and collaboratively challenging tasks to include in a final V&V.

C.3 Applied Cognitive Work Analysis

C.3.1 Related Methods

Cognitive Work Analysis (see Appendix C.1) and Function-based task analysis (Roth & Mumaw, 1995).

C.3.2 Goal

Applied Cognitive Work Analysis (ACWA) is used to provide traceable links from a function-based work domain analysis (WDA) to the cognitive performance requirements and related information and decision support that are needed to enable domain practitioners to perform effectively in both anticipated and unanticipated situations (Elm, Potter, Gualtieri, Roth & Eastern, 2003).

C.3.3 Most Appropriate Use

ACWA is especially appropriate for design of first-of-a-kind-systems where a principled approach is needed to identify information and support requirements based on a functional analysis of the goals of the designed system, the equipment and processes that are used to achieve safety and production goals, and the information and controls that operators need to monitor and control those equipment and processes. It is particularly useful for identifying information and control requirements for handling complex, unanticipated situations where more adaptive response is required.

C.3.4 Method Description

ACWA is a streamlined variant of CWA that is specifically focused on deriving information, display, and decision-support requirements (Elm, Potter, Gualtieri, Roth & Eastern, 2003).

ACWA is like CWA in that it uses a WDA as the foundation for deriving cognitive, information, and decision-support requirements. However, ACWA uses an alternative function-based goal-means decomposition to represent the work domain, called a functional abstraction network (FAN). FAN was developed originally as a functional modeling method for deriving cognitive work requirements for power plant applications (Roth & Mumaw, 1995), including the Westinghouse AP600 (Roth, 1996). Figure C-4, presented later in the section, graphically depicts a FAN.

A FAN uses interconnected node visualization to represent domain goals and the functions that must be available to satisfactorily achieve those goals. Higher-level functions are decomposed into more specific functions and processes. For example, in the case of engineered systems in a power plant, the FAN would include the purposes for which the engineered system has been designed and the means available for achieving those objectives (e.g., controls, information displays, etc.).

The result is a goal-means representation that specifies the goals to be accomplished, the relationships among goals (e.g., goal-subgoal relations, mutually constraining or conflicting goals), and the means available to achieve the goals (e.g., alternative methods available, pre-conditions, side-effects, preferred order). The representation enables the analyst to identify the information and display requirements to support operator monitoring and control of plant functions (Roth & Mumaw, 1995).

ACWA provides a step-by-step approach for performing the analysis and linking the results of a WDA to the development of visualizations and decision-aiding concepts (Elm, Potter, Gualtieri, Roth & Eastern, 2003). These include:

1. Using a FAN to capture domain characteristics that define the problem-space confronting domain practitioners

2. Overlaying Cognitive Work Requirements on the functional model as a way of identifying the cognitive demands / tasks / decisions that arise in the domain and require support

3. Identifying Information / Relationship Requirements needed to support the cognitive work identified in the previous step

4. Specifying Representation Design Requirements that define how the information/relationships should be represented to practitioner(s) to effectively support cognitive work

5. Developing Presentation Design Concepts that provide physical embodiments of the representations specified in the previous step (e.g., rapid prototypes that embody the display concepts)

Each design step produces a specific product. Collectively these products form a continuous design thread providing a traceable link from cognitive analysis to design (see Elm et al., 2004 for more details on the form and content of each product).

A unique aspect of the ACWA method is that it provides a principled way for defining the cognitive work requirements (CWRs) associated with monitoring and controlling the various plant functions and processes. The analyst answers a series of questions to identify the cognitive requirements associated with each plant function and process and the information and controls needed to support that CWR.

CWRs include:

- Monitoring requirements, including requirements for monitoring automated processes, as well as goal satisfaction (e.g., extent of function related goals that are satisfied under current plant conditions

- Situation assessment requirements

- Planning and decision-making requirements, including selecting among alternative means to achieve a goal

- Control requirements including controlling functional processes (initiating, tuning, and terminating) to achieve plant goals (Roth & Mumaw, 1995).

Representative lists of questions for deriving CWR and associated information and control needs can be found in Elm et al. (2003) and Roth and Mumaw (1995).

While traditional approaches to TA organize requirements around predefined task sequences, ACWA provides a method for visualizing operator cognitive requirements and the associated information and control requirements around the functions and processes in the FAN. ACWA ensures that the cognitive demands associated with monitoring and control of plant functions are comprehensively covered and that the information and decision-support that is needed to enable plant operators to effectively monitor and control all plant functions and processes are comprehensively identified. In this way ACWA ensures that the resultant displays and decision-support systems will (1) support operators in performing well-defined, pre-analyzed tasks, and (2) enable operators to effectively monitor and control plant functions under unanticipated conditions. In unanticipated conditions, the expected means by which to achieve a plant function may be unavailable and operators need to identify alternative means for achieving the plant goal.

ACWA does not specify a particular method for knowledge acquisition. Information can come from document reviews, interviews with designers and engineers, and/or interviews with experienced operators.

The main distinction of an ACWA knowledge-acquisition session is that it is focused on domain functions and implications for cognitive work requirements and associated information and control requirements. In this sense it differs from CTA methods that focus on specific critical past events, goals associated with particular roles, or knowledge that underlies expert performance. Bisantz et al., (2003) provide an example of how cognitive and collaborative requirements were derived for a next-generation Naval ship using this type of function-based knowledge-acquisition approach.

C.3.5 Results

ACWA generates a series of linked products that include:

- A FAN
- A specification of CWRs
- Information relationship requirements
- Representational design requirements that specify the information elements and their integration and design requirements to effectively support the cognitive work requirements.

These products provide the detailed requirements to support display design. More details on the form and content of these intermediate design products can be found in Elm et al., (2008) and Elm et al., (2003). Figure C-4 provides an example of a function-based work domain representation for a pressurized water reactor nuclear power plant.

This function-based representation was developed by Westinghouse (Roth & Mumaw, 1995) and is an early example of the FAN approach to work domain representation (Elm et al. 2003). The work domain representation specifies the primary goals of the plant (Generate Electricity and Prevent Radiation Release), the major plant functions in support of those goals (Level 2 functions) and the plant processes available for performing the plant functions (Levels 3 and 4). Level 4 specifies the major engineered control functions available for achieving plant goals. This is the level at which manual and automatic control actions can be specified to effect goal achievement. This WDA representation was used as the basis for advanced control room display design including design of a large wall panel display intended to support shared team situation awareness (Roth et al., 2001).

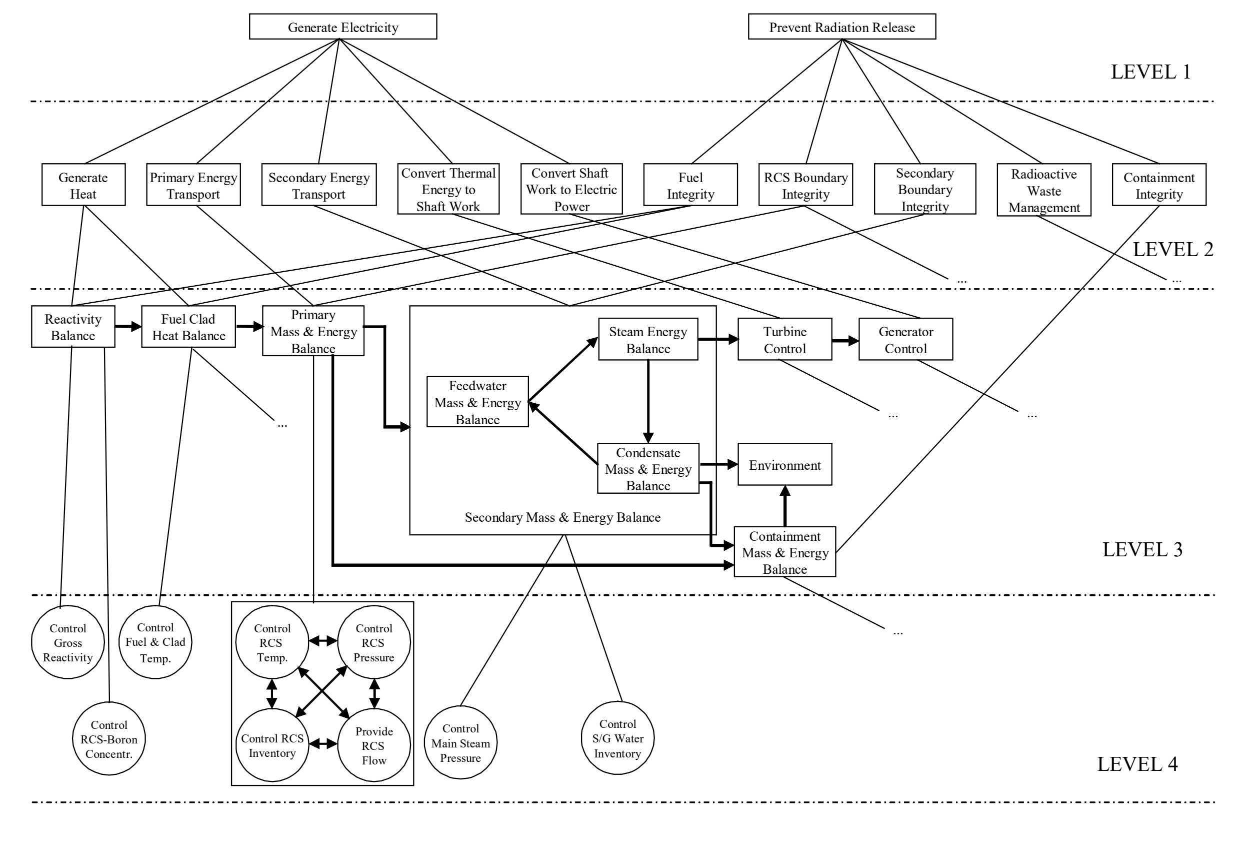

Figure C-4 Selected portions of a work domain representation for a pressurized water reactor nuclear power plant sourced from Roth et al., (2001).

This function-based representation was developed by Westinghouse (Roth & Mumaw, 1995) and is an early example of the FAN approach to work domain representation (Elm et al. 2003). The work domain representation specifies the primary goals of the plant (Generate Electricity and Prevent Radiation Release), the major plant functions in support of those goals (Level 2 functions) and the plant processes available for performing the plant functions (Levels 3 and 4). Level 4 specifies the major engineered control functions available for achieving plant goals. This is the level at which manual and automatic control actions can be specified to affect goal achievement. This WDA representation was used as the basis for advanced control room display design including design of a large wall panel display intended to support shared team situation awareness (Roth et al., 2001).

C.3.6 Resource Requirements

A variety of resources can be used to generate inputs to an ACWA. Knowledge sources can include system designers, engineers, experienced domain practitioners, and trainers. In the case of a system that is early in the design process, knowledge sources can include stakeholders and system designers familiar with the design goals and planned system capabilities. Domain practitioners familiar with legacy systems that the new system is intended to replace can also provide useful input.

C.3.7 Constraints and Limitations

ACWA requires development of a comprehensive WDA which can be labor intensive. However, since engineered systems generally require detailed function decomposition engineering documents, these can provide the foundation for the WDA, streamlining the process.

C.3.8 How the Results are used in an HFE Program

- Functional Analysis and Allocation - Because ACWA relies on a plant function decomposition, it is well suited to identifying the functions that need to be achieved, how they can be distributed across person and /or machine agent, and the implications of alternative function allocation for operator cognitive tasks and related information and support requirements (Roth & Mumaw, 1995).

- Task Analysis - ACWA provides a streamlined approach for defining human-system interface requirements and providing traceable links back to cognitive requirements for monitoring and controlling the plant.

- Human-System Interface Design - ACWA has been shown to be particularly useful for design of function-based displays intended to support cognitive performance under unanticipated conditions where procedural guidance may be limited. It provides a streamlined approach for defining human-system interface requirements and providing traceable links back to cognitive requirements for monitoring and controlling the plant.

- Procedure Development - The FAN and CWR outputs of ACWA can be used in combination to specify cognitive tasks and methods for achieving those tasks that can form the basis for procedure development.

- Training Program Development - The FAN and CWR outputs of ACWA can be used in combination to specify cognitive tasks and methods for accomplishing those tasks, which can form the basis for training. For example, because the foundational element of ACWA is a work domain analysis, the results can be used to train operators to handle unanticipated situations that require knowledge-based reasoning about how to recover plant functions when the standard prescribed methods for achieving plant goals are not available.

- Human Factors Verification and Validation (V&V) - The results of ACWA can be used to identify a range of cognitively and collaboratively challenging tasks to include in a final V&V.

C.4 <u>Goal Directed Task Analysis</u>

Related Methods

None identified.

C.4.1 Goal

Goal Directed Task Analysis (GDTA) is used to determine the situation assessment (SA) requirements of domain practitioners. This includes identifying the goals and decisions associated with a job, the SA requirements entailed, and the information needed and how it is combined to support the different levels of SA including perception, comprehension, and projection into the future (Endsley, Bolte & Jones, 2003).

C.4.2 Most Appropriate Use

Analysts use GDTA to identify the situational awareness (SA) requirements for job performance and to specify display and design requirements for more effective support of SA.

C.4.3 Method Description

GDTA is primarily a semi-structured interview method. Descriptions of GDTA and how to conduct it can be found in Endsley et al., (2003) and Hoffman, et al., (2008). Experienced domain practitioners are interviewed to identify the goals, decisions, and SA requirements associated with a job. Because SA is a dynamic process that involves processing of information in a non-linear fashion and shifting back and forth across multiple goals, GDTA interviews are organized around goals associated with a job rather than specific tasks or procedures.

GDTA interviews are typically conducted with a single domain practitioner at a time, using a semi-structured interview approach that focusses on identifying goals and then having the domain practitioner describe the decisions and information requirements associated with achieving the goals. To determine SA requirements, each decision is analyzed individually to identify all the information the domain practitioner needs to make that decision.

Typically, two interviewers are present so that one interviewer can continue with questions while the other interviewer quickly reviews and organizes notes or questions.

The results of these interviews are combined with information from other sources (e.g., documents, observations of actual or simulated operations) to create an initial set of GDTA diagrams that document goals, decisions, and SA requirements in a hierarchically organized manner (see Figure C-5). Goals are higher-order objectives essential to successful job performance. Main goals are typically decomposed into subgoals. Each goal and subgoal involves decisions that domain practitioners must make in order to achieve that goal. These decisions are represented as the questions the domain practitioner must answer. The final element of the GDTA involves the information needed to answer the questions that form the decisions. These information needs are the decision maker's situation awareness requirements. The GDTA documents the information relevant at each of three levels of SA:

- Level 1 SA entails the basic information that needs to be perceived
- Level 2 SA entails how information is combined to comprehend the current situation
- Level 3 SA entails how information is further combined to project how the situation is likely to change over time

The structure of the GDTA with respect to the number of goals and related sub-goals depends on the complexity of the domain and the goal being analyzed. One advantage of GDTA is that it is a flexible tool. The output format can be modified as needed to most accurately represent the relationship between the various goals, subgoals, decisions, and SA requirements essential to the domain under consideration.

Initial GDTA diagrams are more fully elaborated upon and validated through further interviews with additional experienced domain practitioners to ensure that it includes all relevant goals, decisions, and SA requirements.

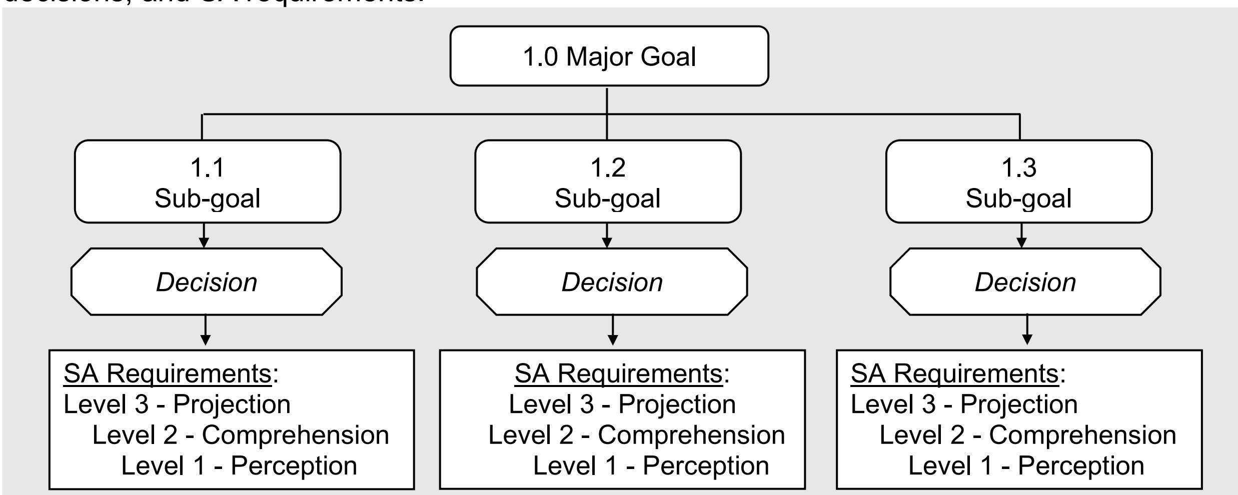

Figure C-5 An illustration of the hierarchically organized elements of a GDTA
(Source is Hoffman, Crandall, Klein, Jones, & Endsley, 2008)

C.4.4 Results

GDTA is a technology-independent CTA approach - it identifies the dynamic information domain practitioners need to know in order to make decisions without focusing on how the domain practitioner currently obtains that information. By focusing on what information is needed without regard to specifically how it is obtained given current technology, the output of a GDTA can support design of futuristic, first-of-a-kind systems that may provide different information or information in a different format.

The output of a GDTA is typically documented in two types of hierarchies: A *goal hierarchy* and a *relational hierarchy*. The goal hierarchy documents the hierarchical goal/subgoal structure of the job. Depending on the complexity of the work it may contain multiple levels of subgoals. The goal hierarchy is very similar in form to an HTA (see Figure C-6 for example).

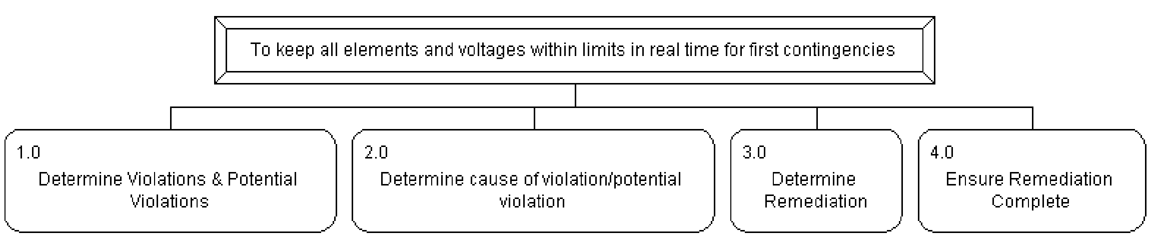

Figure C-6 A portion of a goal hierarchy representation for a reliability coordinator/system operator (RCSO) position for a power transmission and distribution center at a U.S. power plant
(Sourced from Connors, Endsley, & Jones, 2007)

The relational hierarchy documents the relationship between the goals, the subgoals, the decisions related to each subgoal, and the SA requirements relevant for each decision. Figure C-7 provides an example of a goal-decision-SA requirements relational hierarchy for the subgoal “Determine Remediation.” Immediately below the subgoal are the associated decisions presented in the form of questions. Below the decisions is the list of SA requirements needed to enable a domain practitioner to answer these questions. The indentation in the SA requirements list reflects the level of SA. Level 3 (projection) information is placed at the left side of the box, Level 2 (comprehension) is indented once, and Level 1 (perception) is indented twice. Indentation is also used to indicate that further indented elements, when integrated, provide answers to the less indented items presented immediately above.

C.4.5 Resource Requirements

The main requirement is access to experienced domain practitioners who are available to be interviewed in an office/conference room setting.

C.4.6 Constraints and Limitations

Success of the method depends on the ability of experienced domain practitioners to define the goals, decisions and information requirements associated with their position or job.

GDTA is less effective in situations where jobs and roles are likely to dramatically change over time or in roles that have not yet been created. For example, GDTA will be less useful in the case of first-of-a-kind systems that involve substantial changes from existing systems such as new or different functions to be achieved and/or new function allocation across individuals and/or automated systems.

C.4.7 How the Results are used in an HFE Program

- Task Analysis - GDTA can be used to identify the goals, decisions and information requirements associated with a job. It is similar to HTA, but with a particular emphasis on deriving the information requirements to support decisions and SA needs.

- Treatment of Important Human Actions - GDTA can be used to identify the goals, decisions, and SA information requirements for effective performance of important human actions.

- Human-System Interface and Procedure Design - The goals, decisions and information requirements identified through GDTA provide the basis for both the creation of new displays and support systems and the evaluation of current systems with respect to their ability to support job roles.

- Training - GDTA can be used to identify the information experienced practitioners use in maintaining SA, including SA levels 2 (comprehension) and 3 (projection into the future). This can be used to develop training to enable less experienced domain practitioners to achieve higher levels of SA.

- V&V - The knowledge obtained from a GDTA can be used to develop metrics to evaluate the ability of a new HSI to support different levels of SA.

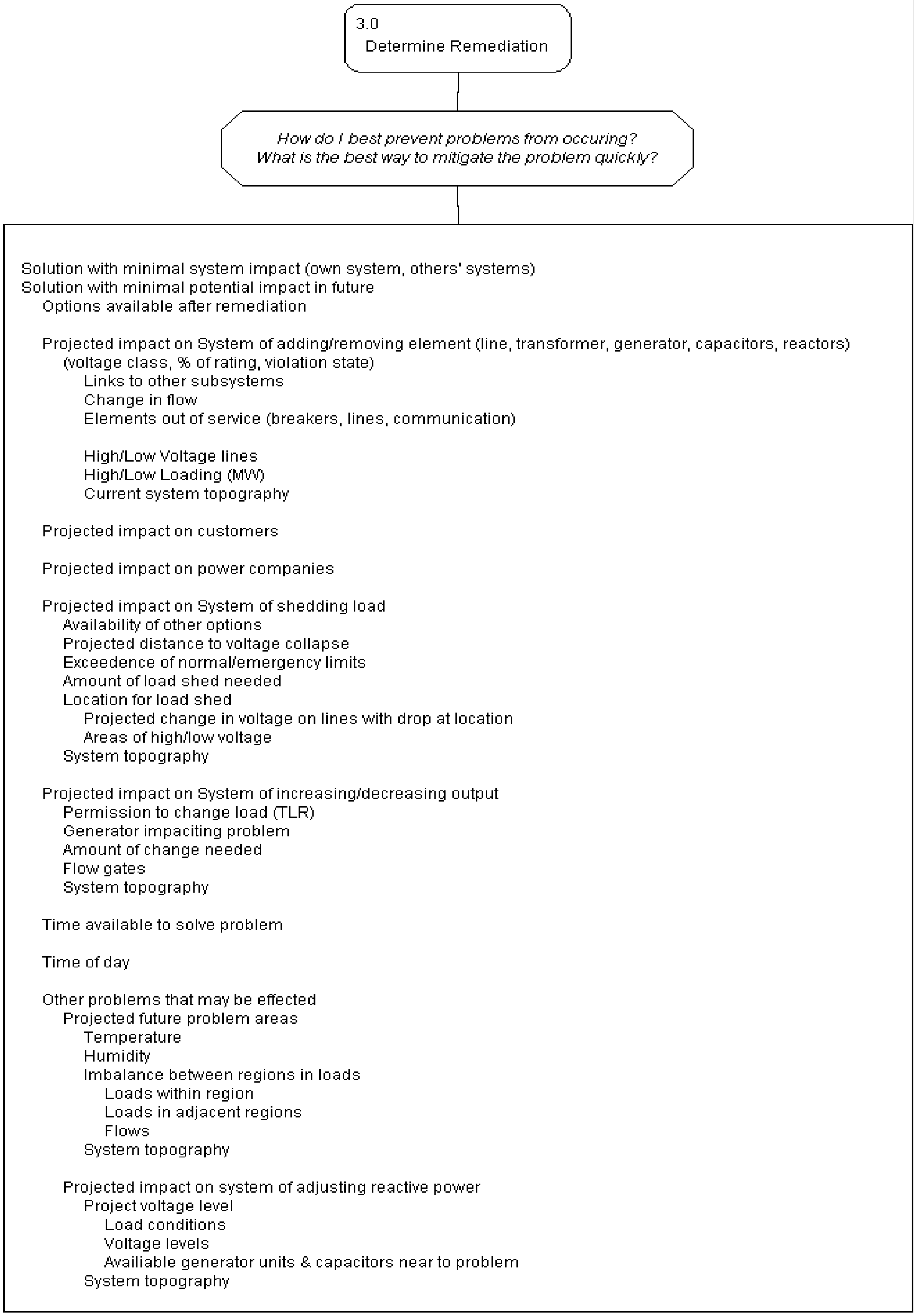

Figure C-7 An example of a goal-decision-SA requirements graph showing the decisions (in the form of questions) related to the goal 'Determine Remediation' for the RCSO position

(Sourced from Connors et al., 2007)

C.5 Critical Decision Method

C.5.1 Related Methods

Critical Incident Technique (Flanagan, 1954)

C.5.2 Goal

Critical Decision Method (CDM) is used to identify the knowledge and skills that underlie expert performance in real-world decision making and problem-solving situations (Klein, Calderwood & MacGregor, 1989.)

C.5.3 Most Appropriate Use

CDM is most appropriate for identifying training requirements as well as decision-support requirements (Militello & Klein, 2013).

C.5.4 Method Description

A detailed description of the CDM method can be found in Crandall, Klein & Hoffman (2006). In-depth semi-structured interviews are used to gather retrospective accounts of challenging incidents that the domain practitioner has personally experienced. A CDM session includes four interview phases or 'sweeps' that examine the incident in successively greater detail:

1. Identify a complex incident that has the potential to elicit information about the cognitive and collaborative demands of the domain and the basis of domain expertise.

2. Develop a detailed incident timeline that shows the sequence of events.

3. Examine key decision points more deeply by using a set of probe questions intended to understand what cues and factors the domain practitioner considered in deciding what to do (e.g., what were you noticing at that point? What was it about the situation that let you know what was going to happen? What were your overriding concerns at that point?).

4. Use additional probe questions to identify the variation in responses across domain practitioners and the knowledge, skill and situational factors that can contribute to different choices. These are often framed as 'what if' questions (e.g., what might have happened differently at this point? How might a novice have behaved differently?).

The set of probes are intended to uncover cognitive and decision-making challenges, as well as the knowledge and skills domain practitioners use to handle those challenges. The specific questions used will vary with application but will generally include asking about the presence or absence of salient cues, assessments made and the basis of those assessments, expectations generated about how the situation might evolve, the goals that factored in and the alternative options that were considered. Hoffman, Crandall, Klein, Jones and Endsley (2008) provide a list of typical topics and specific probe questions that can be used as a starting point.

C.5.5 Results

The CDM produces a collection of challenging, real-world cases and descriptions of the cues, knowledge, goals, expectations, and expert strategies domain practitioners use to handle cognitively challenging situations.

A representative way of depicting results may be a table identifying challenging decision points, what makes them difficult, the knowledge and skills that experts use, and what aids or training support could help. Table C-2 provides an example of CDM output documenting the decisions and challenges associated with AEGIS anti-air warfare (Kaempf et al., 1991). The last column provides recommendations for displays and decision-aids that can be used to facilitate operator performance on those decisions.

Table C-2 Example of CDM Results for Primary Decision Requirements for AEGIS Anti-Air Warfare

What Is the Decision?	Why Is It Difficult?	How Is It Made?	What Is the Aid, and How Does It Help?
Determining intent	Ambiguous data, requires memory of past and current events.	Story generation is used to assimilate cues; critical cues include course, range, and point of origin.	Trend data support judgment of track (speed, range, altitude) over time. Provides a mechanism to generate and evaluate hypotheses.
Recognizing a problem	A large number of tracks are monitored for changes in key parameters.	Must detect changes in track behavior; cues include course and radar emissions.	System monitors the key parameters; track violation message is sent to the operator.
Avoiding escalation	Operator must ensure self-defense, but avoid escalation.	Operator monitors the risk associated with a suspicious track; the most critical cue is range.	Operator can evaluate the level of risk associated with a track; can select appropriate intercept aircraft. System aids in decision timing.
Identifying a track	Many data fit with multiple hypotheses; missing data can be obscured by salient data.	Often involves feature-matching in the assessment of track identity; critical cues include speed, course, electronic emissions, and altitude.	System presents the most plausible hypothesis on track identity; displays non-matching as well as matching elements, to minimize confirmation bias.
Engaging a track	Need to ensure that no friendlies are at risk; may need to trade-off risk and weapon accuracy.	Must balance risk against the probability of a successful engagement; critical cues include range and course.	System allows operator to assess the level of risk associated with "holding off" from an engagement.

(Sourced from Hoffman, Crandall & Shadbolt, 1998)

C.5.6 Resource Requirements

The main requirement is access to experienced domain practitioners who are available to be interviewed in an office/conference room setting.

C.5.7 Constraints and Limitations

Success of the method depends on the ability of domain experts to describe specific challenging cases. It is most effective for identifying knowledge and skills that domain experts will be able to describe.

It is less useful for:

- Understanding implicit knowledge and automatic skills (e.g., perceptual skills) that are difficult for the expert to describe

- Identifying environment and contextual factors that domain experts may not be aware of or consider relevant enough to bring up during the interview

C.5.8 How the Results are used in an HFE Program

- Operating Experience Review - The results can be used to identify the demands of the domain and the ‘cues’ that experts use for situation assessment and decision-making. This can provide the basis for defining support requirements.

- Task Analysis - The results identify the requirements for addressing critical incidents, including the necessary skills.

- Treatment of Important Human Actions - The results can identify the factors that contribute to various types of human errors.

- Human-System Interface Design - The results can be used to identify the types of information, displays, and decision-aids, that could be provided to better support the complex decisions that the CDM analysis documented.

- Training - Examining the knowledge and skills of expert domain practitioners (rather than less experienced personnel), can provide the basis for defining training requirements and targets.

- V&V - The results can be used to identify challenging scenarios to be used in design of V&V scenarios.

C.6 Cognitive Field Observations

C.6.1 Related Methods

Ethnography (Nardi, 1997) and Contextual Inquiry (Beyer & Holtzblatt, 1998)

C.6.2 Goal

Cognitive field studies are used to identify cognitive and collaborative activities and challenges associated with task performance in actual work environments (Roth and Patterson, 2005).

C.6.3 Most Appropriate Use

Cognitive field studies are particularly appropriate to identify the *actual* cognitive and collaborative demands of the work that can only be learned through first-hand observation. They are also useful for uncovering the often undocumented, ad hoc methods or strategies that domain practitioners develop to deal with demanding situations.

C.6.5 Method Description

One or more cognitive analysts observe domain practitioners as they perform their work in the actual workplace or under highly realistic, dynamic work conditions such as in a dynamic high-fidelity simulator. The analyst should attempt to sample from a broadly representative set of sites, practitioners, and situations. Ideally observations are as unobtrusive as possible so as not to slow down or otherwise interfere with the ability of the domain practitioners to do their work.

Typically, the observer(s) will sit or stand in a location that allows him or her to see and hear what the domain practitioner is doing without getting in the way of the work. If feasible the observer will shadow the domain practitioner as they move about the environment and interact with different people. They may also ask questions during low workload periods (if it is acceptable to do so).

Observations and interview questions are guided by a prepared checklist of topics to be covered. Typical checklist items include:

- Job roles and responsibilities
- Standard practice and procedures
- Human-system interfaces
- Challenging aspects of the work and factors in the environment that contribute to complexity, for example, situations that create high workload, complicate situational assessment, response planning, and/or decision making
- Strategies that domain practitioners have developed to cope with complexity
- User-created artifacts that allow users to “work around” or compensate for deficiencies in user interfaces, policies, or procedures
- Deviations/exceptions from standard practice
- Opportunities for error/contributors to error
- Critical incidents/illustrative cases: Example situations that are observed or described that provide concrete illustration of cognitive or collaborative challenges and the strategies that domain practitioners have developed to cope with complexity

It is important to know that the items on the checklist should be used as a guide and adapted to the specific context rather than as questions asked verbatim in a rigid order.

Particular attention is placed on documenting illustrative incidents that provide concrete examples of the kinds of complexities that can arise in the environment, the kinds of cognitive and collaborative strategies and facilitating activities that domain practitioners use to handle these situations, and how existing artifacts are tailored to meet situation demands. These illustrative incidents may be examples of practitioner performance in routine situations that arise often, or they may represent a response to a relatively rare occurrence (e.g., equipment malfunction, accident) that arises during the observational study.

While field observations are typically conducted in the actual workplace, they may also be conducted using dynamic, high-fidelity simulators that enable analysts to observe performance under realistic conditions.

C.6.6 Results

Observing work settings can provide important insights that would not be easy to obtain otherwise. Of particular note is the potential for field observations to generate insights around aspects of the work environment or practices that practitioners would not highlight when asked directly outside of the specific working context. For examples, physical aspects of the environment (e.g., constrained workspaces or high noise levels), problems with user interfaces or work processes, and informal practices or expert strategies developed to compensate for limitations in interfaces, processes, or procedures.

The output of field observations can take multiple forms ranging from textual descriptions of illustrative cases, to diagrams of the physical environment, to graphics that depict expert strategies (see Figure C-8 for example).

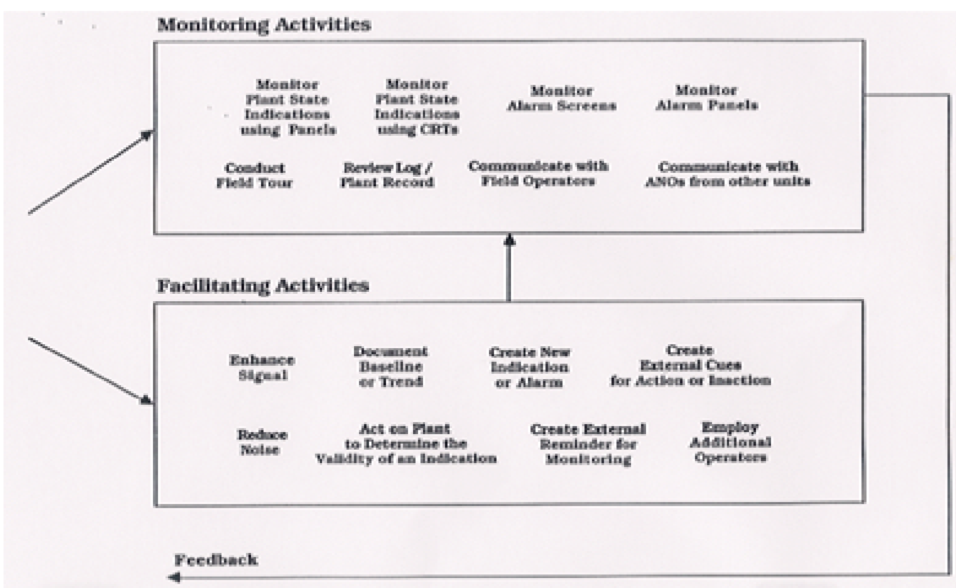

Figure C-8 Example graphical representation used to communicate the informal strategies that NPP operators have developed to facilitate monitoring of a NPP control board during normal operations (Mumaw, Roth, Vicente, & Burns, 2000; Vicente, Mumaw & Roth, 2004; Vicente, Roth &, Mumaw, 2001).

The graphic depicts the active strategies that NPP control room operators use to extract information during monitoring of control board alarms and displays during normal operations. (Sourced from Vicente, Mumaw & Roth, 2004)

C.6.7 Resource Requirements

The primary requirement is access to the actual work environment and/or to high fidelity simulators where domain practitioners can be observed under naturalistic conditions. If feasible, performance may be videotaped for later analysis but that is not a critical requirement.

Another requirement is that the observers should have sufficient domain knowledge to be able to appropriately interpret observations without the need to ask intrusive questions. Consequently, field observations are often conducted by pairs of observers, one having human factors expertise and the other having domain expertise so that, in combination, they are able to appropriately interpret observations and their implications for opportunities to improve performance.

C.6.8 Constraints and Limitations

Cognitive field studies depend on the availability of an established work environment and experienced domain practitioners. As such, they have limited applicability to first-of-a-kind systems that have yet to be designed. The primary use of cognitive field studies in the design of first-of-a-kind systems is to analyze predecessor systems as part of an operating experience review.

A related limitation is the need to have access to the work environment or to a high-fidelity simulator. In some cases, access to the work environment may not be possible (e.g., due to security or safety concerns) or may be highly restricted.

Also, observations can be time consuming and often only generate a limited sample of domain practitioners and/or work situations. This limitation generally results in field observations being conducted in conjunction with structured interview techniques with a broader set of domain practitioners to confirm and expand upon the conclusions drawn from the limited field observations.

Finally, field observations are most suited for open work environments where practitioners naturally reveal their thought processes as they communicate with each other. Nuclear power plant control rooms and other command and control centers are examples of work environments that are particularly well suited for field observations because the active communication that goes on among operators enables observers to readily follow the reasoning and decision-making process.

C.6.9 How the Results are used in an HFE Program

Operating Experience Review: Field observations can provide a rich source of input to operating experience review including:

- Providing an overview of work domain demands that cannot be obtained from other sources (e.g., design documents, training manuals, procedures, interviews conducted out of context)
- Identifying (undocumented) strategies for coping with work domain demands
- Understanding work tempo and its impact (e.g., on workload)

- Observing communication and coordination demands and strategies

- Documenting deficiencies in current HSIs, practices, procedures, and training

- Documenting errors and near-misses and the factors that contributed to those errors

- Documenting features of the existing environment that are important to effective performance and should be preserved or otherwise reproduced to provide equivalent or better support

- Identifying opportunities for improving performance through improvements in practices, procedures, training, and/or new kinds of decision-aids

The results can then feed into all subsequent elements of the HFE program.

- Task Analysis - Can be used to identify how work is actually performed, the challenges associated with performing a task (e.g., complex dynamics, missing or delayed information that can complicate diagnosis or response, goal conflicts), the crew member roles and responsibilities, and the strengths/limitations of the design to support work.

- Staffing and Qualification - Can provide information on the various activities (documented and undocumented) performed across personnel in the current environment. This provides a baseline that can be used to ensure that new system designs that assume reduced staffing have considered all the activities currently being performed by each staff position in their analysis (i.e., that all activities are accounted for either by eliminating its need, for example, through automation or by allocating the activity to a different staff position).

- Treatment of Important Human Actions - The method can uncover the types of human errors that can arise and the factors that contribute to human error.

- Human-System Interface Design - Observations in a high-fidelity simulator can be used to assess the impact of design changes on crew performance. Observation can identify unanticipated consequences (such as new cognitive or collaborative demands) of a new HSI early so that they can be addressed through changes in design, procedures, or training prior to system fielding (e.g., Roth & O'Hara, 2002).

- Procedure Development - Field observations in work settings and/or simulators can be used to identify and correct mismatches between procedures and the actual demands of a situation as it dynamically unfolds.

- Training - Examining the knowledge and skills of expert domain practitioners (rather than less experienced personnel) can provide the basis for defining training requirements and targets.

- V&V - The method can be used to establish a corpus of challenging scenarios to be used in design of V&V scenarios.

- Human Performance Monitoring - Field observations can continue to be conducted periodically to ensure that emerging conditions that challenge performance are rapidly identified and corrected.

C.7 Goals Operators Methods and Selection Rules (GOMS) Model

C.7.1 Related Methods

Keystroke Level Model (KLM)

C.7.2 Goal

GOMS is a family of methods intended to provide simplified engineering models that represent the cognitive and physical activities required to perform well-practiced, routine tasks with well-defined steps (Card, Moran & Newell, 1983; John & Kieras, 1996a & b).

C.7.3 Most Appropriate Use

GOMS models provide quantitative predictions of task execution time for routine procedural tasks (i.e., tasks with well-defined steps). They have been widely used for design and evaluation of human-computer interaction.

C.7.4 Method Description

A GOMS analysis is performed by specifying the Goals, Operators, Methods, and Selection Rules for a set of tasks using a formal (often computer executable) language. Tasks are decomposed into:

- Goals – the user's purpose or intention
- Operators – discrete, elemental cognitive and physical acts such as: retrieve a piece of information from memory or pressing a key on a keyboard
- Methods – combinations or sequences of operators that can be used to accomplish the goals
- Selection Rules – rules that specify which method to use for a particular situation

Multiple versions of GOMS models have been developed that vary in style and level of detail in the cognitive model (John & Kieras, 1996 a & b). The simplest form of a GOMS model is the Keystroke-Level Model which models the detailed keystroke-level actions required to perform tasks (e.g., moving a cursor, pressing a key). Other GOMS modeling approaches model cognitive and physical tasks as a hierarchical goal-means decomposition similar to an HTA. Most GOMS models assume that operators are performed serially (one after the other). Some versions of GOMS enable modeling of tasks that might be performed in parallel (e.g., moving a cursor with the hand as the eyes move toward a location on the screen), but these tend to be more complex computer simulation models (John & Kieras, 1996b).

Detailed guidance for performing a GOMS analysis can be found in Kieras (2006). The first step in a GOMS analysis is to conduct a traditional TA to identify the goals the user is trying to achieve and the specific computer interactions that are required to achieve those goals. This is accomplished using observations of users and interview techniques. In cases where the computer system is still under development, the analyst can develop a GOMS model of the ideal method for interacting with the computer to accomplish goals as specified by the computer system developers. The analyst then represents the set of cognitive and physical actions required to perform the task using the GOMS formalism. Time estimates for elemental-level cognitive and physical activities (operators) are specified. Card, Moran and Newell (1983) provide typical time estimates for simple, standard, computer interaction tasks such as pressing a key or button as well as equations for estimating times for computer actions such as moving a mouse to a target on a display (e.g., the time to point varies with distance and target size according to Fitts's Law, [see Fitts, 1951]). Later research continued to expand upon and refine available time estimates and methods for computing them (e.g., Olson & Olson, 1995). In general, cognitive, and physical tasks that go beyond very basic, keystroke-level operators (identified by Moran and Newell) require that the analyst generate task specific time estimates (e.g., through direct task observation and measurement).

In many cases complex cognitive processes such as deciding what action to take or reading a procedure step are too complex to explicitly represent in a GOMS model. These are currently handled by simply including a 'dummy' or 'place holder' operator for these cognitively complex activities. While this allows the modeling to proceed and enables comparison across designs that include identical 'dummy' operators, it means that the contributors of these more complex cognitive processes to variability in execution time and possibility of error are not addressed by the GOMS analysis.

In cases where system response to an operator action is not instantaneous, time estimates are also required for system response time (e.g., the time for a valve to open in response to an operator action).

Once the GOMS model of the task (with time estimates) is developed, the model can be used to estimate total task time. For example, for a simple keystroke-level model, execution time is predicted by summing the times for the component keystroke-level actions and the associated mental activities required to perform the task.

Often, analysts will use bracketing techniques to generate a range of time estimates by constructing two GOMS models of a task, one representing using the system as fast as possible and another representing the slowest reasonable model. These two models will provide a 'high' and 'low' estimate that bracket how actual users are likely to perform.

Some versions of GOMS models have also been used to estimate learning time (John & Kieras, 1996b) under the assumption that learning time will be a linear function of the complexity of the methods required to accomplish goals. GOMS models also highlight opportunity for positive transfer of training under the assumption that similar methods do not have to be learned twice.

We note that the learning time estimates assume that the users already are well trained on the individual GOMS operators (e.g., moving a cursor with a mouse) and, thus, they do not take into account the time to learn new actions (e.g., selecting an object with an eye-movement tracker). GOMS learning time estimates also do not account for the time required to learn the broader task context (e.g., to develop a mental model of how the system works and develop efficient strategies for performing a control task). Consequently, the general recommendation is that learning time predictions should be used with caution and preferably only in making relative comparisons across alternative designs (John & Kieras, 1996b).

C.7.5 Results

Figure C-9 provides a sample output of a GOMS analysis for a simple manuscript editing task. In this version of GOMS (CMN-GOMS described in Card, Moran & Newell, 1983), the representation resembles programming code. The top-level goal (edit-manuscript) is decomposed into lower-level goals (e.g., Modify text), which are then decomposed further into subgoals (e.g., delete phrase), which are then decomposed into low-level operators (e.g., move cursor to beginning, click mouse button, move cursor to end). These low-level operators are simple computer interactions that have associated estimated execution times. The estimated execution times of component tasks are then used to estimate the time to complete higher level tasks such cutting and pasting a string of text.

```
GOAL: EDIT-MANUSCRIPT
.  GOAL: EDIT-UNIT-TASK ...repeat until no more unit tasks

 .  .  GOAL: ACQUIRE UNIT-TASK ...if task not remembered
 .  .  .  GOAL: TURN-PAGE ...if at end of manuscript page
 .  .  .  GOAL: GET-FROM-MANUSCRIPT
 .  .  GOAL:EXECUTE-UNIT-TASK ...if a unit task was found
 .  .  .  GOAL: MODIFY-TEXT
 .  .  .  .  [select: GOAL:  MOVE-TEXT* ...if text is to be moved
 .  .  .  .           GOAL:  DELETE-PHRASE ...if a phrase is to be deleted
 .  .  .  .           GOAL:  INSERT-WORD] ...if a word is to be inserted
 .  .  .  .    VERIFY-EDIT

*Expansion of MOVE-TEXT goal
GOAL: MOVE-TEXT
.  GOAL: CUT-TEXT
.  .  GOAL: HIGHLIGHT-TEXT
.  .  .  [select**:  GOAL: HIGHLIGHT-WORD
.  .  .              .  MOVE-CURSOR-TO-WORD
.  .  .              .  DOUBLE-CLICK-MOUSE-BUTTON
.  .  .              .  VERIFY-HIGHLIGHT
.  .  .              GOAL: HIGHLIGHT-ARBITRARY-TEXT
.  .  .              .  MOVE-CURSOR-TO-BEGINNING                 1.10
.  .  .              .  CLICK-MOUSE-BUTTON                       0.20
.  .  .              .  MOVE-CURSOR-TO-END                       1.10
.  .  .              .  SHIFT-CLICK-MOUSE-BUTTON                 0.48
.  .  .              .  VERIFY-HIGHLIGHT]                        1.35
.  .  GOAL: ISSUE-CUT-COMMAND
.  .  .  MOVE-CURSOR-TO-EDIT-MENU                                1.10
.  .  .  PRESS-MOUSE-BUTTON                                      0.10
.  .  .  MOVE-MOUSE-TO-CUT-ITEM                                  1.10
.  .  .  VERIFY-HIGHLIGHT                                        1.35
.  .  .  RELEASE-MOUSE-BUTTON                                    0.10
.  GOAL: PASTE-TEXT
.  .  GOAL: POSITION-CURSOR-AT-INSERTION-POINT
.  .  .  MOVE-CURSOR-TO-INSERTION-POINT                          1.10
.  .  .  CLICK-MOUSE-BUTTON                                      0.20
.  .  .  VERIFY-POSITION                                         1.35
.  .  GOAL: ISSUE-PASTE-COMMAND
.  .  .  MOVE-CURSOR-TO-EDIT-MENU                                1.10
.  .  .  PRESS-MOUSE-BUTTON                                      0.10
.  .  .  MOVE-MOUSE-TO-PASTE-ITEM                                1.10
.  .  .  VERIFY-HIGHLIGHT                                        1.35
.  .  .  RELEASE-MOUSE-BUTTON                                    0.10
```

```
                                    TOTAL TIME PREDICTED (SEC)  14.38

**Selection Rule for GOAL: HIGHLIGHT-TEXT:
  If the text to be highlighted is a single word, use the
  HIGHLIGHT-WORD method, else use the HIGHLIGHT-ARBITRARY-TEXT method.
```

Figure C-9 Example of CMN-GOMS text-editing methods
(Sourced from John & Kieras, 1996a).

The results of GOMS models can also be represented as a network structure (See Figure C-10). This representation can be useful when comparing alternative designs. Endestad and Meyer (1993) used a network structure to compare two alternative computerized procedure systems for NPP application (COPMA-1 and COPMA-2). COPMA-1 existed as a prototype. COPMA-2 was still in the concept specification stage. GOMS models were developed of the methods available for the two computerized procedure designs and compared. As shown in Figure C-10, COPMA-2 provided multiple alternative methods for searching for a procedure to use, whereas COPMA-1 provided only one way to search for a procedure. Note that “Layer 1” in the figure corresponds to the user’s goals and “Layer 2” corresponds to information processing and decision-making strategies. COPMA-2 also provided methods for entering a procedure in the middle as well as at the start whereas COPMA-1 only allowed procedures to be entered at the beginning. The GOMS analysis was able to show that COPMA-2 was faster to use than COPMA-1 because of the availability of multiple, efficient methods, but for the same reason (multiple methods to accomplish a given goal) COMPA-2 was more complicated to learn and use.

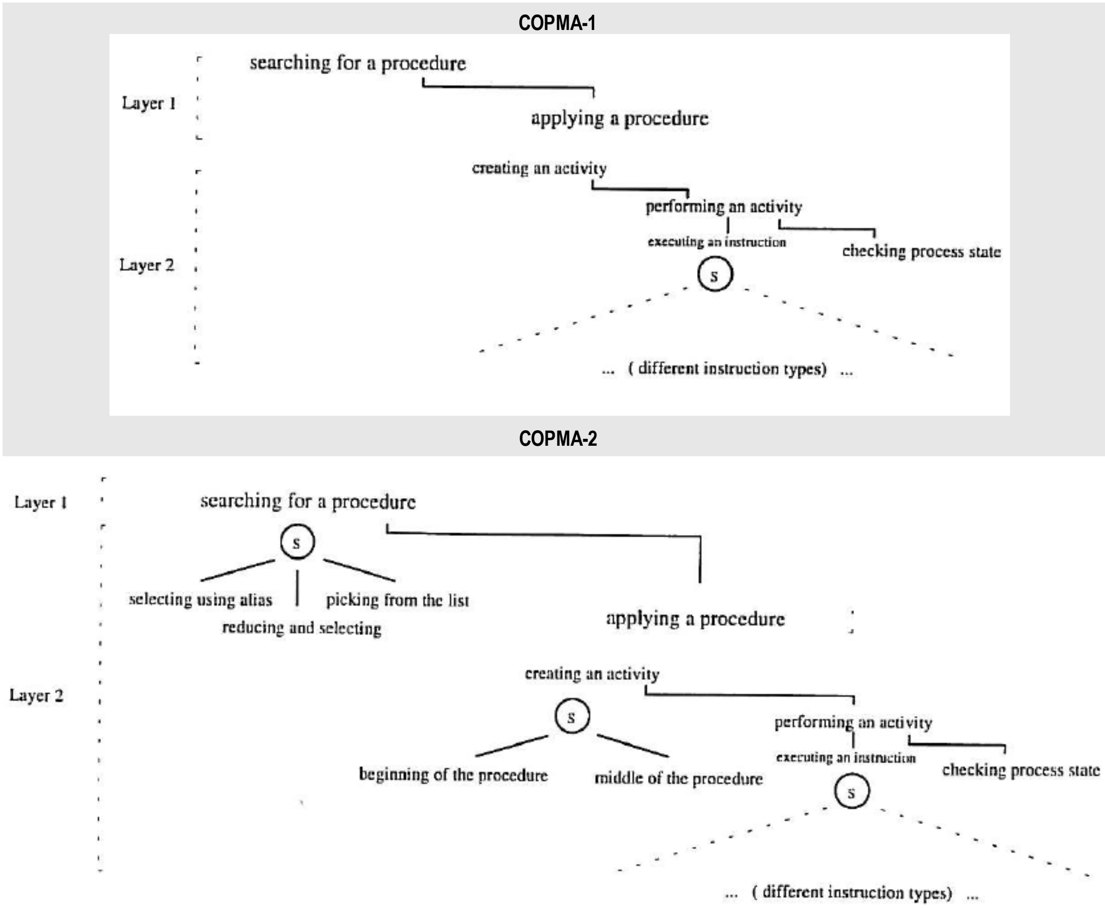

Figure C-10 GOMS models for NPP computerized procedure systems
(Source is Endestad & Meyer, 1993)

C.7.6 Resource Requirements

The primary requirement is access to the results of a standard TA that identifies the goals, specific cognitive and physical actions required to perform a task, and reliable time estimates for the cognitive and physical operators included in the GOMS analysis. Some GOMS methods are supported by software tools. For example, GOMSL (GOMAS Language) is processed and executed by a GOMS model simulation tool (Kieras, 2004).

C.7.7 Constraints and Limitations

GOMS models are primarily appropriate for tasks where the methods for accomplishing user goals are tightly constrained by the design of the interface. There are other important aspects of a task and the work environment that are not related to the procedures entailed by the interface design. These include low-level perceptual factors such as the legibility of items on the display and higher-level issues such as the ability to use the interface successfully within the broader context of the work (e.g., when having to perform multiple tasks simultaneously under dynamic conditions). Consequently, the GOMS method would not be able to identify interface deficiencies at the perceptual level (e.g., small fonts that limit readability), nor would it be able to identify the impact of more cognitively complex processes on execution time and error.

For these reasons GOMS modeling does not replace the need to perform a detailed TA to understand the work context, including the cognitive and physical challenges posed by the work and the user’s goals and strategies for accomplishing the work (Kieras, 2004). It serves as a complement to other TA and CTA methods rather than a substitute.

Further, appropriate application of GOMS models is limited to well-defined and well-practiced procedural tasks, such as human-computer interaction tasks (Kieras, 2004). It is not suitable for application to tasks that require complex cognitive activity such as situation assessment, problem-solving, or decision-making. It is also not appropriate for dynamic control tasks that require active monitoring and process control, or activities that require active attention shift across multiple tasks.

When applied to tasks other than very simple computer interaction tasks, time estimates for the basic perception, cognition and motor elements included in the model will need to be obtained using traditional TA methods (e.g., observation and measurement).

C.7.8 How the Results are used in an HFE Program

- Task Analysis - GOMS can be used to represent the results of a TA for routine procedural tasks and to provide high-level task time estimates derived from a detailed analysis of low-level task operators. It can be used early in the conceptual design phase to describe goals and methods at a high level and then iteratively refined by adding details as to how the methods are accomplished as the design matures (Kieras, 1997).

- Treatment of Important Human Actions - GOMS models can be used to represent the cognitive and physical activities required to perform important human actions and to estimate execution time. However, for the reasons provided above, GOMS-derived execution time estimates are only likely to be accurate under very narrow conditions. Specifically, GOMS analyses are only likely to apply under circumstances where the tasks are routine, well-practiced, and involve simple, well-defined steps that are executed serially. It does not account for tasks that require more complex cognitive activities, nor does it apply to tasks, such as process control tasks, where control requirements and system responses are likely to be complex and variable.

- Human-System Interface Design - GOMS models have been used to evaluate the adequacy of a user interface design, as well as to compare alternative designs (Kieras, 1998). Design aspects that can be checked with a GOMS model include whether there are methods available for all identified user goals, whether there are efficient methods to accomplish user goals that occur with high frequency, and whether the methods for achieving similar goals are accomplished in a consistent manner (Kieras, 1998; Endestad & Meyer, 1993).

- Training - GOMS analyses can be used to guide training by providing an explicit specification of user goals and the methods available to achieve those goals. This can provide the basis for presenting to users what methods are available to achieve typical goals as well as guidance as to which methods are likely to be most efficient. This can lead to an improved understanding of 'how to' knowledge among users and enable instructors to foster more uniformity across users in how they use the system to accomplish tasks.

C.8 Concept Mapping

C.8.1 Related Methods

Conceptual Graph Analysis (Gordon & Gill, 1992)

C.8.2 Goal

Concept Mapping is used to identify and represent information about a work domain as well information about knowledge and strategies used by domain experts (Crandall, Klein & Hoffman, 2006).

C.8.3 Most Appropriate Use

Concept mapping is particularly useful for eliciting the unique knowledge of expert practitioners.

C.8.4 Method Description

Concept maps are diagrams made up of concept nodes connected by labeled links (directed arrows). They are used to capture the content and structure of domain knowledge experts employ in solving problems and making decisions. This includes descriptions of physical systems and processes, events, procedures, and reasoning strategies.

In concept mapping knowledge acquisition, the analyst helps experts create a representation of their knowledge and strategies using concept map diagrams. Concept mapping is typically conducted in group sessions that include multiple domain practitioners (e.g., three to five) and two facilitators. One facilitator provides support in the form of suggestions and probe questions, and the second facilitator creates the concept map based on the participants' comments for all to review and modify (e.g., by displaying the concept map on a large projector screen). Concept mapping can also be conducted in one-on-one sessions with a single domain practitioner.

Concept mapping sessions are often complemented by other interview and observation techniques to enable domain experts to communicate their knowledge and strategies used in the work environment (such as providing examples of informally developed 'cheat sheets' or demonstrating how they perform a task). Concept mapping techniques are also often coupled with other CTA methods such as the critical-decision method to elicit more automated aspects of expertise that domain practitioners are not able to explicitly access and articulate. The information derived from these other sources can then be added to the concept map.

A good introduction to concept mapping can be found in Crandall, Klein and Hoffman (2006).

C.8.5 Results

The output of concept mapping is sets of interlinked concept maps that document expert domain knowledge. The concept maps can be large and multi-layered, including hyperlinks to documents, images, and other concept maps. A set of linked concept maps is referred to as a concept map knowledge model. These concept map models can be simple, consisting of a dozen or so concept maps, or they can be complex, consisting of hundreds of concept maps.

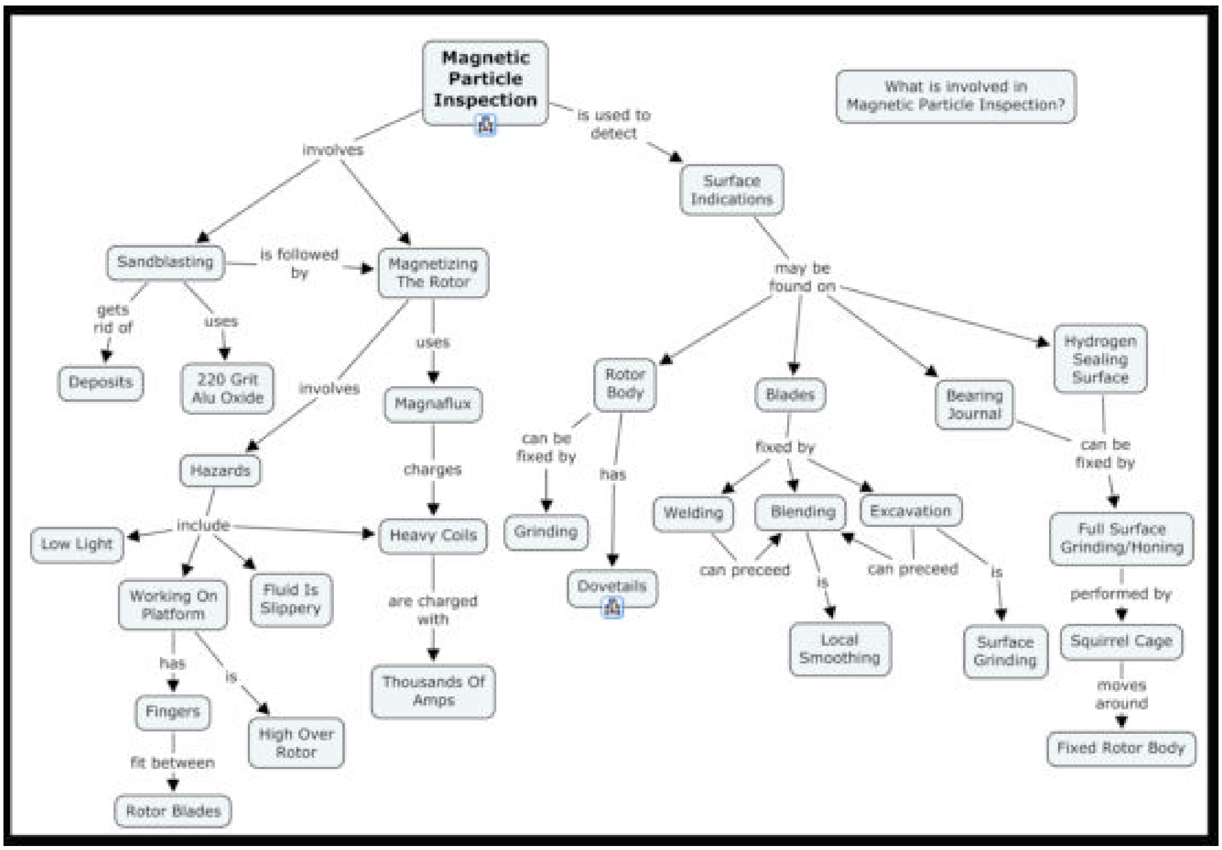

Figure C-11 Example concept map representing knowledge of a magnetic particle inspection process.

This concept map captures knowledge about how to complete a magnetic particle inspection. The knowledge ranges from factual knowledge that could be obtained from manuals (e.g., equipment tolerances) to ‘how to’ knowledge that is gained from experience. (Source is Hoffman & Moon, 2010)

C.8.6 Resource Requirements

The main requirement is access to articulate, experienced experts to be interviewed in an office/conference room setting. Concept maps can be drawn on a white board, with paper and pencil or on a computer. A number of software diagraming tools are available, including Cmap (concept map) Tools, which is available as a free download from The Institute for Human & Machine Cognition (www.ihms.us).

C.8.7 Constraints and Limitations

Success of the method depends on access to articulate domain practitioners willing to share the basis of their expertise. It is most effective for uncovering factual knowledge as well as knowledge and skills that domain experts are able to describe.

It is less useful for understanding automated knowledge and skills (e.g., perceptual skills) that are difficult to describe. Also, it is less useful for uncovering environmental and contextual factors that domain experts may not think to mention. For this reason, concept mapping techniques are often coupled with other CTA methods such as the critical decision method.

C.8.8 How the Results are used in an HFE Program

- Operating Experience Review - Because the results are based on the experience of domain experts, they can be used to understand the characteristics of the current domain, including physical systems, practices and procedures, and challenges. It can provide information on the knowledge and skills experts have developed to cope with domain challenges and limitations in knowledge and skills of less experienced practitioners.

- Task Analysis - The results can be used to create an overall representation of a knowledge domain that shows the relationships between the characteristics of the domain and the overall goals of the practitioner and to identify the strategies, decisions, and steps that are required to successfully perform tasks.

- HSI Design - The results can be used to identify important relationships between domain elements that the operator needs to understand and that should be depicted in the HSI.

- Procedure Development - The results can be used to identify effective procedures that expert practitioners have developed that can then be codified in formal procedures.

- Training - The results can be used to develop training by examining the knowledge and skills of expert domain practitioners in contrast to less experienced personnel, to provide the basis for defining training requirements and targets.