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R. Shikiar
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June 1982

Prepared for the U.S. Department of Energy
under Contract DE-AC06-76RLO 1830

Pacific Northwest Laboratory
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APPLICATIONS OF HUMAN FACTORS ENGINEERING TO LNG RELEASE PREVENTION AND CONTROL

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Seattle, Washington

June 1982

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the U.S. Department of Energy Office of
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FOREWORD

This report is one of a series prepared by Pacific Northwest Laboratory (PNL) to communicate results of the Liquefied Gaseous Fuels (LGF) Safety Studies Project, being performed for the U.S. Department of Energy, Office of Environmental Protection, Safety and Emergency Preparedness (DOE/EP). The DOE/EP Office of Operational Safety, Environmental and Safety Engineering Division (ESED), is conducting the DOE Liquefied Gaseous Fuels Safety and Environmental Control Assessment Program. The LGF Safety Studies project contributes research, technical surveillance and program development information in support of the ESED Assessment Program. This study of applictions of human factors engineering to LNG release prevention and control benefited from the technical direction and guidance provided by Dr. John M. Cece and Dr. Henry F. Walter of ESED.

Completed effort in other tasks of the PNL project are reported in

1. Assessment of Research and Development (R&D) Needs in LPG Safety and Environmental Control (PNL-3991)
2. Assessment of Research and Development (R&D) Needs in Ammonia Safety and Environmental Control (PNL-4006)
3. An Overview Study of LNG Release Prevention and Control Systems (PNL-4014)
4. Analysis of LNG Import Terminal Release Prevention Systems (PNL-4152)
5. Analysis of LNG Peakshaving Facility Release Prevention Systems (PNL-4153)

Work in progress includes more detailed studies of topics identified in the LNG facility overview study as being worthy of further investigation. Other reports of this series are in preparation on the following subjects:

- Storage Tank Analysis
- Fire Prevention and Control Assessment

ABSTRACT

The results of an investigation of human factors engineering and human reliability applications to LNG release prevention and control are reported. The report includes a discussion of possible human error contributions to previous LNG accidents and incidents, and a discussion of generic HF considerations for peakshaving plants. More specific recommendations for improving HF practices at peakshaving plants are offered based on visits to six facilities.

The HF aspects of the recently promulgated DOT regulations are reviewed, and recommendations are made concerning how these regulations can be implemented utilizing standard HF practices. Finally, the integration of HF considerations into overall system safety is illustrated by a presentation of human error probabilities applicable to LNG operations and by an expanded fault tree analysis which explicitly recognizes man-machine interfaces.

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Finally, Marlene Hale at PNL and Maureen Braun at HARC contributed their word processing skills in the preparation of the final manuscript.

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1.0 SUMMARY

The results of an investigation of human factors (HF) engineering and human reliability applications to LNG release prevention and control are reported. The report includes a brief description of the discipline of human factors engineering and its applications to LNG system safety analysis. Possible human error contributions to previous LNG accidents and incidents are reviewed in an attempt to assess the potential contributions of HF to LNG safety. This review indicates that such applications may exist.

To provide an example of HF applications to LNG release prevention and control, an assessment of systems and components normally found in LNG peakshaving plants is used as the point of departure for examining such applications. Specifically, important human interfaces with the systems or components are analyzed in terms of HF considerations. General HF recommendations for potentially improving system safety are given. More specific recommendations are made on control panel designs based on systematic observations of six peakshaving plants.

An important impetus for HF applications in the LNG industry is the recently promulgated DOT regulations. These regulations are analyzed in this report in terms of the HF implications, and methods of implementing the requirements with solid HF bases are discussed.

The literature on human error probabilities is reviewed and applications to the LNG industry are discussed. In addition, applications of HF to potential accidental LNG release scenarios are explored by examining selected fault trees taken from a system safety analysis prepared for LNG import terminals. These fault tree analyses are expanded to include a consideration of potential human errors. Such analyses allow for a systematic examination of potential mitigating strategies.

Future research should start with further examination of the extent to which HF principles are currently applied in the LNG industry, especially for facilities in addition to peakshaving plants. Improvements in HF practices

having an impact on overall system safety should be addressed. Successful applications of HF principles in other industries can serve as a model for the LNG industry.

2.0 INTRODUCTION

Human factors (HF) engineering is a multifaceted discipline that attempts to optimize the man-machine interface in complex systems.(a) Human factor considerations were first developed by the military and aerospace industries where errors could have fatal consequences. These industries presently lead the way in the application of HF principles as exemplified by the fact that human factor criteria are included in military procurement orders.(b)

In general, the degree to which HF principles have been applied outside these areas has not been as great, probably because the possibility for loss of human life is not as great. However, as technologies used by society become more complex and hazardous, HF applications have become more prevalent. Current examples include the use of HF principles to help develop man-machine interfaces in the chemical processing industry and the automobile industry. Also, the perceived need for greater use of HF principles in the nuclear power industry has been raised, mostly as a result of the accident at the Three Mile Island (TMI) nuclear power plant. Analyses of that accident have identified HF deficiencies at TMI.(c)

The LNG industry has had a very good safety record over the past two decades. The only major accident involving large releases of LNG and subsequent conflagration occurred in Cleveland in 1944, resulting in the loss of 128 lives. The accident was attributed to inadequate cryogenic properties of the steel from which the storage tank was constructed. The accident resulted in a complete halt to the use of LNG in the United States for nearly twenty years. During that time advances in cryogenic technology were made that allowed for the safe handling of LNG during processing, storage, and distribution. In fact, safety complacency as a result of the good safety

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(a) See Appendix A for a brief overview of HF.

(b) See Appendix B for a brief overview of HF applications in the military and aerospace industries.

(c) See Appendix C for a brief overview of HF studies in the nuclear industry.

record since the resurgence of the LNG industry has been cited as a reason for concern. In their analysis of the benefits and risks in LNG shipping and storage, Katz and West (1975) discuss methods for combating the potential for safety complacency as one of the preferred methods for reducing risks. Or, as stated by the Accident Prevention Committee of the American Gas Association, "Plant operation for ten years or more is still no guarantee that it will always operate safely" (AGA 1973). The committee urged a continuing training program as a means of assuring a good safety program.

This recommendation could be expanded to include consideration of the impact that additional HF applications might have on maintaining or improving LNG safety. For example, it may be worthwhile to examine the extent to which LNG processing, storage, and distribution have been viewed as complex man-machine systems in which the design, operation, and maintenance of equipment and procedures for the selection and training of personnel have been integrated to optimize safe and efficient operation of the entire system. This systems approach, with HF an integral part of the system, has been beneficially adopted in the military and aerospace industries, and more recently in the nuclear power industry. Such an approach to LNG safety, generally, and release prevention and control, specifically, could reasonably be expected to result in increased system safety.

2.1 RESEARCH GOALS

The overall goal of this research was to analyze the need for the application of HF principles to LNG facilities. More specifically, this study focused on HF needs with regard to the release prevention and control systems used in the LNG industry. This goal was accomplished by focusing on four objectives:

1. identify applications of HF in other industries that might have a bearing on possible applications in the LNG industry
2. identify systematically the extent of current HF applications in the LNG industry

3. identify general research needs and gaps in knowledge in the application of HF to the LNG industry
4. investigate further the potential human error contributions to LNG release scenarios.

During the course of the research, the authors made a total of eight site visits to six different LNG peakshaving facilities, spoke to numerous individuals in the LNG industry, and visited with a HF engineering group at an aerospace company. In addition, an extensive search of the LNG literature and a selective search of the HF literature were undertaken.

2.2 OUTLINE OF THE REPORT

The remainder of this report consists of seven chapters and six appendices. Chapter 3 is a review of the possible contributory role of human error in previous LNG industry incidents. This task was undertaken to assess potential HF applications in the LNG industry. Chapter 4 is a discussion of generic HF considerations for a generic LNG peakshaving plant. This includes a description of a reference peakshaving facility, examination of potential hazard conditions in that facility, and delineation of potential release events that are representative of those expected at that facility. The understanding of peakshaving plant conditions resulting from this work, actual observations made at operating peakshaving plants, and knowledge of HF practices in other industries formed the bases for identifying and describing potential HF applications in the LNG industry. Chapter 5 represents a more systematic attempt to assess HF practices in the LNG industry using empirical data gathering efforts, assisted greatly by an HF checklist for peakshaving facilities developed specifically for this purpose.

A major impact on HF practices in the LNG industry are the recently promulgated Federal Regulations (DOT 1980a, b, and c). Chapter 6 describes the HF aspects of these regulations and demonstrates how HF input could be of great value in implementing the regulations.

One potential use of HF information is in probabilistic risk assessment. Knowledge of the probability of various operator actions (as well as the likely range of these probabilities) can serve as input into fault tree analysis in which the points of human interaction in the man-machine system have been identified. Chapter 7 summarizes much of the literature on human error probabilities that is appropriate to the LNG industry. Chapter 8 illustrates how the human interaction portion of a fault-tree analysis could be expanded to examine various causes for inappropriate operator response. This, in turn, can be instructive for determining methods of reducing the probability of operator error (e.g., improved training and better instrumentation).

Chapter 9 presents a summary of this report and recommendations for future courses of action. The recommendations tend to be broad-based, and in some cases, represent a call for research in areas that were not included in the present research.

Finally, Appendix A discusses basic considerations in HF, Appendix B discusses military and aerospace applications of HF, Appendix C reviews the literature in HF applications to nuclear power plants, and Appendix D is the HF checklist used for site visits to peakshaving plants, Appendix E is the checklist developed for LNG facility site visits, and Appendix F is an LNG telephone interview protocol.

3.0 PREVIOUS INCIDENTS IN THE LNG INDUSTRY: THE POTENTIAL CONTRIBUTORY ROLE OF HUMAN ERROR

Determination of the potential contribution of human error to LNG system safety might begin via analysis of accident or event reports from LNG facilities. Unfortunately, a comprehensive body of such reports does not exist. In the absence of such reports, this effort focused on published reports of LNG accidents. Several comments are in order concerning the analysis of these reports. First, the incidents reported here, especially the truck and shipboard accidents, have generally resulted neither in harm to human life nor in very large releases of LNG. This is likely a result of the safety features that have been designed into LNG facilities and LNG transport trucks and ships. Nonetheless, as has been stated in the preamble to the new Department of Transportation (DOT) regulations concerning LNG (DOT 1980a), the potential catastrophic nature of a large scale LNG release dictates that extreme caution be taken when analyzing the potential for release. In the present instance, this indicates that concern should focus on how attention to HF principles can result in a reduction of the incidence of even small releases of LNG, since the mechanisms used for reducing the frequency of small releases may also reduce the likelihood of a larger release. Second, it should be noted that the list of incidents from which these were chosen is not comprehensive. It generally excludes foreign accidents. Moreover, it is likely that not all incidents, especially very minor ones, have been reported. Similarly, while the analysis of "near misses" has been found to be an effective method for detecting problems in the aerospace industry, no mechanism exists for doing such an analysis at present in the LNG industry. Finally, it should be noted that many of the reports are only very sketchy as to details, making the already speculative venture of attributing fault to human error even more so.

3.1 SHIPBOARD INCIDENTS

The following incidents were reported in a General Accounting Office (GAO) report (1978), which in turn relied upon the Welker et al. (1976) report to the U.S. Coast Guard. They all are possibly indicative of an HF related problem.

1. Methane Progress, May 1, 1976. LNG spilled from the ship's crossover line during disconnection of loading arms. A piece of failed valve facing was stuck between the valve disc and valve seat, allowing LNG spillage. The LNG thermally shocked the deck plating that it contacted and a minor crack developed. This problem is indicative of a possible maintenance or inspection error.
2. Jules Verne, May, 1976. The cargo tank gauges malfunctioned during loading, due to a foreign object jammed in the float track. This resulted in an overflow of LNG, causing fracture in the tank cover and a deck stringer plate. This indicates a possible maintenance/inspection error as well as an HF design error, since a redundant liquid level indication was not available.
3. Polar Alaska, December 13, 1979. The space between the primary and secondary barriers was inadvertantly pressurized with nitrogen by the crew. This resulted in distortion of the primary barrier, which required removal of the damaged tank from service. This indicates a possible deficiency in nonroutine procedures, since the nitrogen pressurization was being performed as the result of previous leakage in the primary barrier.
4. Methane Princess, May 30, 1971. The liquid nitrogen loading line opened, spilling liquid nitrogen onto the deck. Some cracking of the deck plating resulted. The cause was a relief valve, which had been improperly reset at the annual survey, indicating an operational error and perhaps a procedural deficiency.
5. Methane Progress, October 31, 1971. A liquid nitrogen storage tank was inadvertantly overfilled, resulting in cracking of the main and second deck plating. This indicates a potential deficiency in instrumentation, warning systems, and/or procedural operations.

6. Massachusetts, June 4, 1974. A coupling cracked, resulting in a ten-gallon spill of liquid nitrogen. The probable cause was the repeated attempts to seal the coupling by hammering at it, indicating a deficiency in procedures and possibly in training.

7. Massachusetts, July 15, 1974. A nitrogen purge valve was overpressurized during cargo loading due to a momentary electrical power interruption after generator switchover, resulting in a spill of about 40 gallons of LNG. This indicates a potential procedural error regarding when a generator switchover should occur.

The following incident was also reported in the open literature (Davis 1978; Lloyds Register of Shipping 1977).

8. Hilli, May 14, 1977. Bolts and metal pieces were discovered in the discharge line during the initial unloading operation, resulting in a one month delay before the cargo could be unloaded. This indicates a possible failure in shakedown procedures and preloading inspection.

In addition to the above, there have been several incidents involving groundings or collisions, none of which resulted in LNG spills.

3.2 TRUCK ACCIDENTS

Twelve accidents involving LNG road tankers are cited by GAO (1978). Details of most of these accidents were obtained via interviews with LNG trucking industry officials.

It should be recognized that road accidents in general involve a large component of human error. Only those with a high likelihood of driver error are reported here:

1. August 28, 1971. A tanker was driven off the road, rolled over, and landed on its wheels. A small LNG leak resulted. A Department of Transportation accident investigation found that the driver had been driving about 11 hours at the time of the accident and had falsified

his driver's log. Other drivers were also found who engaged in this same practice.

2. October, 1973. An LNG truck sideswiped a parked car. The truck's brakes locked and the trailer overturned.
3. 1973. A driver was unable to negotiate a turnoff. The truck overturned, thus demonstrating the driver's failure to deal with the high center of gravity on LNG tanker trucks.
4. February 21, 1974. A loose valve on an LNG tanker leaked during a transfer operation. This indicated a possible maintenance or inspection error.
5. March or April, 1977. A parked LNG truck with a flat tire was hit by a tow-truck. This indicated a possible lack of safety precautions.

In general, the road accidents, both those listed above as well as others, attest to the soundness of the design of the LNG tankers. Some truck accidents have been severe, (e.g., in November, 1975, a driver swerved to avoid a pedestrian, causing the tanker to crash through the guard rail and roll over and down an 80-ft embankment), yet there has been only one case of a large loss of LNG (8 cubic meters in Waterburg, Vermont, on June 25, 1971) and no instance of an LNG fire or explosion.

3.3 LAND-BASED ACCIDENTS

There have been a few reported accidents at LNG peakshaving plants and import terminals, the most notable of which was the 1944 Cleveland accident. However, only one of the accidents had a high likelihood of human error involvement, although human error may have played an undetermined part in several of the other accidents.

1. January 27, 1972. Five workers were injured in a fire in the control room of an LNG plant in Montreal, Canada. The apparent cause was that a valve on a nitrogen line was inadvertently left

open after a deriming cycle, resulting in seepage of natural gas into the control room. An explosion occurred when a worker lit a cigarette. This accident is indicative of several HF shortcomings, including inadequate procedural checks, lack of a feedback system to indicate the valves were left open, and inadequate warning devices in the control room (Fire Journal, 1972).

2. October 6, 1979. One worker was killed and one worker was seriously injured in an explosion in an electrical substation at the Cove Point, Maryland, LNG import terminal. The probable cause of the accident was LNG, which leaked through an inadequately tightened LNG pump seal, vaporized, and migrated through a 3-inch conduit into an electrical substation building (National Transportation Safety Board, 1980). There the vaporized LNG-air mixture was ignited by the arcing contacts of a circuit breaker interlock. The accident report also stated that the absence of any combustible gas indicators in the substation to detect and warn personnel of the presence of flammable vapors in the building contributed to the accident. In addition, combustible gas detectors in the pump house, which had not been recalibrated for 17 months, failed to detect a gas-air mixture even though large quantities of LNG were leaking into the pump house. Finally, the report stated that facility operators were inadequately trained to carry out the plant emergency plan for such an accident.

A final instance of human error with fatal consequences was cited in Wolf (1978). According to this report, an Algerian liquefaction plant worker inadvertantly opened a wrong valve. This action released a stream of LNG, in which the worker froze to death. Without greater knowledge of the specific details of this incident, it is impossible to determine the extent to which valve labeling, operational procedures, or personnel training were at fault.

3.4 CONCLUSIONS

What conclusions can be drawn from this review of incidents at LNG facilities? First, human error does seem to be a factor in these incidents. Because of the sketchy details in some of the reports, we can only speculate that deficiencies may exist in the various procedures (both operational and maintenance/inspection), in the feedback systems (i.e., gauges, meters, warning systems, and recorders), and possibly in the use of HF considerations in the design of various subsystems. Visits to several LNG facilities have indicated great variability in several of these factors. Alternatively, the problems depicted above may have resulted from inadequate training, especially in the use of procedures for abnormal events.

In the future it may prove worthwhile to review actual incident reports, as was done by Finnegan et al. (1979) and Seminara et al. (1976) for electric power generating stations, rather than to rely on secondary reports of the incidents, as was done in the present report. However, such an analysis assumes a comprehensive accounting of all such incidents. The DOT regulations (Federal Register 1980) call for an investigation of "each operational error or failure or malfunction of a component which results in (1) death or injury requiring hospitalization, or (2) property damage exceeding $10,000." This type of proposed analysis should be carried out after enough data have been accumulated to make such an endeavor meaningful.

Information about HF related errors can also be obtained from interviews with plant operators as was done by Seminara et al. (1976). The interviews can be used both to supplement the analysis of incident reports, or, in absence of these reports, to serve as substitutes for such an analysis.

4.0 GENERIC HF CONSIDERATIONS FOR A PEAKSHAVING PLANT

This chapter uses an analysis of a peakshaving plant to describe potential HFL applications in the LNG industry (Pelto et al. 1982a). It deals with possible HF applications at a broad level, beginning with the types of human interactions listed in the peakshaving plant analysis. Included are descriptions of potential hazard conditions for components of the gas treatment system, the liquifaction system, the storage system, the vaporization system, and the transportation and transfer system. Approximately 120 component/operating mode permutations and associated potential hazard conditions are discussed. A majority of these list some HF consideration as an existing prevention or control mechanism. The most frequently mentioned HF consideration is the maintenance and inspection procedure. Other HF considerations are "operator expertise," "operator attention," various types of instrumentation, and various alarms. Rather than discussing each instance of potential human error contributions to a given hazard scenario, the present discussion will focus on generic HF issues that are applicable to release prevention and control at a peakshaving plant.

4.1 OPERATING PROCEDURES

Operator expertise is recognized as a prevention and control mechanism at several points in the peakshaving plant analysis. Operator expertise depends on the adequacy of the operating procedures that operators use. The major HF issue is the usability of these procedures. Usability involves several criteria:

1. difficulty, clarity, and precision of the written materials
2. inclusion of detailed step-by-step instructions with appropriate checkoff lists and indications of what the system response should be to each step
3. use of indexing and tabbing to facilitate the location of the correct procedures

4. correspondence of the language in the procedures to the language used in the specific plant, and more importantly, to the labels used on controls and displays in the plant
5. actual physical accessability of the procedures and adequate workspace to use them.

4.2 MAINTENANCE AND INSPECTION PROCEDURES

Maintenance and inspection were the most frequently mentioned human-related prevention and control mechanisms in the peakshaving plant analysis. Regularly scheduled maintenance and inspection checks should be performed on all appropriate components. Such checks are facilitated by use of checklists and step-by-step instructions. For crucial components, an inspection team in which one person inspects and the other person records the data can result in somewhat better compliance with procedures than having a single person doing all the work. The maintenance schedules should be based both on operating history and manufacturer's recommendations.

4.3 ALARMS AND WARNINGS

Operator attention is considered to be a key prevention and control mechanism. One method for assuring operator attention for an abnormal occurrence is to have a highly noticeable alarm and annunciator system. Ideally, the alarms should be prioritized and should indicate the nature, extent and location of the problem.

Another area related to operator attention is a vigilance problem. Especially during steady-state operations, it may be difficult for an operator to maintain vigilance because of boredom or drowsiness. Techniques for maintaining operator motivation and attention from organizational psychology, such as job rotation and job enhancement, represent some possible mitigating strategies. While alarm systems are designed to assure operator attention if something is amiss, continuous operator attention might be able to prevent the alarm condition in the first place.

4.4 CONTROLS AND DISPLAYS

Displays should convey concise, meaningful, error-free information to the operator and should enhance the operator's ability to respond correctly via appropriate manipulation of controls. HF has a long tradition of research and guidelines concerning appropriate control and display instrumentation. Primary concerns include:

1. placement of displays in the visual field
2. appropriate labeling of displays and scale points
3. general ease of viewing and freedom from distortion (e.g., glare, parallax, reflection)
4. use of markers for high and low set point indications
5. completeness and accuracy of the information
6. timeliness of the indications
7. layout of the displays so as to minimize scanning time and misidentification (e.g., use of either functionally grouped or "mimic" displays)
8. consistency in the use of colors, lights, and other coding devices
9. consistency between the array of display instrumentation and control instrumentation.

Important HF criteria for controls include:

1. maximum discriminability (using such coding devices as color, size, and shape)
2. labeling that is readable, meaningful, and consistent with terminology on the display panels and in the procedural manuals
3. ease of access, especially for the most important controls
4. Safeguards against accidental actuation.

4.5 OPERATOR SELECTION, TRAINING, AND STAFFING

Operator expertise depends partially on the methods for selection and training. Increasingly, this function is coming under government regulation. Nonetheless, there still remains a great deal of flexibility in actual selection and training procedures. Ideally, selection and training should be based on a thorough understanding of the job requirements for the position in question. This understanding is traditionally obtained by means of a detailed task analysis, which specifies the behaviors (as well as the abilities and skills necessary to perform these behaviors) necessary to perform adequately all important aspects of the job. Once the prerequisite abilities and skills are determined, selection and training can be based on these. Porricelli et al. (1976) have conducted job analyses for LNG barges and ships; the research team has not uncovered similar analyses for peakshaving plants. To be effective, analysis of requirements and development of training programs should be done on a site by site basis.

Emphasis should be placed on training for emergency conditions because an actual emergency can result in very high stress levels on operators. It has been demonstrated that extreme stress can preclude or delay appropriate human performance. Repeated training in simulated emergency conditions can result in decreased stress in an actual emergency and thereby increase the likelihood of acceptable responses in such a situation.

5.0 CURRENT HUMAN FACTOR ENGINEERING PRACTICES AT LNG PEAKSHAVING PLANTS

Two methods were used to gain information about HF considerations at the control rooms of LNG peakshaving facilities. First, telephone interviews were held with representatives of architect/engineering (A/E) and construction firms that design and build LNG facilities in order to determine the extent to which HF principles are employed in the design and construction phases of an LNG facility. Second, site visits were made to LNG peakshaving plants to evaluate actual HF control room applications. The findings from these two data collection tasks are reported below. In addition, recommendations about optimizing HF considerations in the control room are presented.

In general, there are three types of HF recommendations, with the resulting changes, that could be made with regard to existing control room setting. The first are recommendations that involve changes that could be made on a backfit basis while the plant remains in operation. The second are recommendations that involve changes that could be made during a planned shutdown. The third are recommendations that require changes that cannot be made on the above retrofit bases. They must be made over a more extended period of time or must be viewed as recommendations for the design of new facilities.

However, it is clear that the three situations discussed above are more clear-cut for other industrial processes than for LNG peakshaving operations. For example, a utility company would like to keep its base-load, coal-fired electricity-generating facility under continual operation, except for a short period of planned down time for such things as preventive maintenance. Thus, changes that could be made during normal operations could somewhat easily be effected, while changes that require down time are possible but not necessarily attainable during a short period of down time. Changes that required extensive operational down time could not be carried out.

At an LNG peakshaving facility, however, the different processes at the plant are carried out during different parts of the year. Thus, for example, the tank (almost) always contains LNG after the initial filling, liquefaction is likely to occur during a period lasting anywhere from just a few months to almost year around, and vaporization is likely to occur only two to five months of the year. Thus, at peakshaving facilities, some parts of the control panel could be changed during a period of several months without affecting operations.

5.1 HF CONSIDERATIONS IN DESIGN AND CONSTRUCTION

One method of trying to determine the current state of HF practices in the LNG industry involved several telephone interviews with selected individuals in firms that design and/or build LNG facilities. While the telephone interviews were judged to be of some value, this aspect of the study was discontinued for two reasons after several calls. First, the firms were involved in construction of a variety of LNG operations. This diversity made it difficult to draw general conclusions on the basis of discussions with a limited number of individuals. Second, it became apparent that the information obtained from telephone interviews about a completely unfamiliar facility was of limited value.

While conclusions could not be drawn on the basis of the limited number of telephone interviews, a few premises were uncovered that warrant further study. First, it would be worthwhile to investigate how HF considerations are included in the design of LNG facilities. None of the interviewees hired HF analysts per se. Some relied on input from operations people; others relied on the customer to supply the operations input; and others used a detailed mock-up to check for operability features. Second, it would be of interest to examine the nature and extent of interaction between the customer and the contractor with regard to HF considerations, including layout and design, training of customer personnel, and development of operating and emergency procedures. Construction and A/E firms might vary widely in how hard they promote HF considerations to the customer. Finally, it would be of value to explore the "feedback loop" that exists between operators and designers. Do operational problems, especially of a HF variety, get back to the designers? Does a mechanism exist for doing so? These are all points worthy of determination when data of this sort are systematically obtained from construction and A/E firms.

5.2 HF EVALUATION OF REPRESENTATIVE PEAKSHAVING FACILITIES

The purpose of this task was to determine the extent to which HF considerations have been applied to the construction and upgrading of existing LNG peakshaving facilities. Most of the task was directed at an HF evaluation of the control panel and of operator training. However, some analysis of control panels outside of the control room, such as in the compressor building, was also carried out.

To standardize the evaluations of different facilities, an HF checklist was developed for safety-related features of LNG operations. The checklist was directed at eight general areas of interest: 1) specific system safety devices, including gas detectors, flame detectors, the emergency shutdown system (ESD), and other safety indicators; 2) labels; 3) displays; 4) controls; 5) workspace; 6) measures; 7) procedures; and 8) operators.

Over the course of the research, the checklist (see Appendix D), or an earlier version of it, was used to evaluate six different peakshaving facilities, and included eight separate site visits to these facilities. The facilities were chosen to be representative of the range of sizes and ages of peakshaving facilities. They were not selected using any statistical sampling technique. Facilities both from the West Coast and the East Coast were visited.

The facilities were selected to represent a range of LNG peakshaving facilities, based mainly on age of facility and size of facility. The oldest facility that we visited was built in 1968 and the newest facility visited was built in 1977. The size of the tanks, which was used as a general measure of facility size, ranged from 175,000 gallons of LNG to over 12,000,000 gallons of LNG. Two of the facilities had two large tanks each with the combined capacity of approximately 20,000,000 gallons of LNG.

5.3 SPECIFIC SYSTEM SAFETY DEVICES

One aspect of the evaluation was to look at the HF considerations for specific system safety devices such as gas detectors, flame detectors, and the emergency shutdown system (ESD). These are discussed below.

5.3.1 Gas Detectors

All of the facilities had gas detection devices that were displayed in the control room. The number of detectors ranged from 3 to 56. One facility did not have gas detection devices around the tank or the vaporization equipment, which was not located in a building. The remainder of the facilities had gas detection devices around the liquefaction equipment, the main tank(s), the vaporization equipment, the gas cleaning equipment, and the compressor building. All but one of the facilities had a gas detector in the control room.

The displays for the gas detectors were always grouped together in some portion of the control room. They typically had a meter that indicated what percent of the lower flammable limit had been reached. In addition each display typically had four lights to indicate: 1) correct functioning of the equipment (green); 2) known malfunction in the equipment (yellow); 3) 20 percent of lower flammable limit detected (red); and 4) 40-50 percent of lower flammable limit detected (flashing red). Also, when any gas is detected, an audible alarm is set off that is detectable in the control room and throughout the grounds.

Gas detection equipment had been retrofitted at most of the facilities. Consequently, the gas detection displays were not always optimally located on the control panel. A set of the grouped displays at one site was located approximately 12 to 18 inches off the floor, and at a second site the grouped displays were located around a corner from one of the two operator work stations. Other sets of gas detection displays have been integrated quite nicely within the layout constraints of the existing control panels.

Most of the gas detectors experience false positive signals, typically because of dust. The number of false positive signals ranged from one or two per month to one or two per year, depending mostly on the dust storm frequency in the area. Generally once a signal is received in a control room that gas has been detected, the operator will reset the device to see if the signal was a false one. If the device then resignals, the operator would then send someone to investigate. Inspection for proper functioning ranged from monthly at most of the sites to yearly at one site.

5.3.2 Flame Detectors

All facilities had flame detection devices that were displayed in the control room. The number of detectors ranged from 2 to 25. One facility did not have flame detectors in the tank area or in the vaporization area. All of the other facilities had flame detectors covering the liquefaction equipment, the main tank, the vaporization equipment, the gas cleaning equipment, and the compressor building.

As with the gas detectors, the displays for the flame detectors were always grouped together in some part of the control room. The advanced flame detectors differentiated between a flame of less than five seconds duration and those of longer duration with two separate warning lights on the display. This system significantly reduced the number of false positives from such things as lightning. Other detectors indicated that a flame of any duration had been detected. Both types of systems also used an audible alarm, which was distinct from the audible alarm connected to the gas detection equipment, to indicate that a flame had been detected.

Flame detection equipment has also been added to most of the facilities since the control room had been built. Since the gas detection displays and the flame detection displays were usually mounted next to each other at the facilities, placement on the control was not always optimal.

Through experience, most of the flame detectors have been calibrated by plant personnel to minimize false positive signals. Some plants have experienced no false positive signals from their flame detectors over the past year, while several plants experienced one or two. Whenever the flame detection signal is sounded, the operator first tries to reset the detector to see if the signal was a false positive. If the device signals that a flame has been detected a second time, a staff member is sent to investigate. The flame detectors are examined for proper functioning monthly at most facilities and yearly at one facility.

5.3.3 Emergency Shutdown System (ESD)

All of the plants had some form of ESD, but what equipment is shut down, whether it is automatically or manually shutdown, and what causes the shut down, varied from plant to plant. The plants were about equally split as to whether the ESD actuation was automatic or manual. The ESD was automatically actuated at one plant if one of five conditions existed: 1) a flame was detected, 2) a high tank level was reached, 3) a power failure occurred, 4) the nitrogen pressure got too low, or 5) there was a loss of pressure in the pneumatic instrumentation lines. At other plants, fewer conditions are typically programmed to actuate the ESD or to actuate a signal that indicates that the ESD should be manually activated. In the manual activation situation, the operator typically receives a signal that the ESD should be activated and then the operator makes a judgment as to whether the ESD activation should actually occur. Typically this involves a check to see if the signal is a false positive. If it cannot quickly be determined that the signal is false, all of the operators have been trained to activate the ESD at that point.

One of the facilities had emergency operating procedures that specified operator actions after an automatic actuation of the ESD. The procedures tell the operators which valves to check for proper closure and which systems to check for deactivation. These types of procedures are not available at most facilities. The operators at other facilities indicated that they quickly scan the control panel after an ESD actuation, but no specific pattern of operator responses was learned. From two to six controls were available at the facilities to actuate the ESD manually. One is in the control room and the other(s) are out on the grounds. The manual activation control was usually clearly marked and quite different from other nearby controls. At one facility, however, the controls were painted the same color as nearby controls and no other special labeling distinguished the control's function.

5.3.4 Other Specific Safety Considerations

In addition to the three systems discussed above, tank safety indicators, vaporization equipment safety indicators, and several general control room considerations were evaluated. With regard to tank safety indicators, all but one facility had a tank liquid level gauge and a tank high-level alarm in the control room. All facilities had alarms for off-normal tank vapor pressure. All facilities that had tanks built on the ground had temperature indicators for the tank foundation to warn about frost heave. All but one facility displayed the temperature indication in the control room, while at that one facility temperature readings were taken and recorded each shift at the tank and then written down on a recording sheet in the control room. All but one facility had a method of reading LNG temperatures at various levels in the tank from the control panel, while that one facility could take such readings at the tank. Typically the facilities did not display the tank temperature indications continuously, so temperatures had to be called up on a temperature selection panel and read one at a time.

With regard to vaporization equipment safety indicators, all facilities had indicators in the control room that displayed the temperature of the LNG going into the vaporization equipment and the outlet temperature of the natural gas as it left the vaporization equipment. At about half the facilities the outlet pressure of the natural gas is displayed only at the pipeline, while at the other facilities it is displayed both at the pipeline and in the control room.

With regard to general control room safety considerations, all facilities are able to operate the ESD from the control room. Some of the control rooms were located a reasonable distance from plant equipment that might be involved in gas release or fire. Other control rooms were located close to some of the equipment, such as the vaporizers.

Presently, the control centers typically do not have someone in continual attendance. During the day shift, at least one operator is always on duty in the control room. During the graveyard shift, the operator often splits his duties between the control room and the plant. All facilities had phone communication between the control center and the remote control centers located on the grounds. All but one facility also had a set of hand-carried two-way radios that could be used in a controllable emergency situation. Some of the control centers had an unrestricted view of the grounds and equipment. Other facilities had little to no view of the grounds.

5.3.5 Recommendations

Several recommendations can be made about increasing the safety of operations through changes in the interface between the operator and specific system safety devices. First, flame detectors and gas detectors should be installed so that all of the major plant processes are monitored for gas leaks and fires. There should also be a gas detector in the control room. Second, the gas and flame detector indicators should be placed so they can be viewed from all operating positions in the control room. Third, if the panel were to be completely changed or if a panel is now in the design stages, it is recommended that the gas and flame detection indicators be arranged so an operator can determine immediately what area of the plant is experiencing the difficulty. This could be done in several ways. For instance, the gas and flame detector indicators could be located on the same physical portion of the panel as the controls and displays for the part of the processing monitored. Or, the indicators could be appropriately located on a "top down" schematic of the plant. If a computer system were used with the gas and flame detectors, the computer could immediately provide information about the affected area.

Some safety improvements could also be made on the ESD system. First, the ESD manual activation control(s) located on the grounds should be clearly marked, so that they can be located as easily as possible during a controllable emergency. Second, in the case where the ESD is signalled, but requires manual operation by the operator, the operator should be carefully trained as to how to make the decision whether to activate the ESD. Third, careful training and/or written procedures should be given to operators with regard to appropriate operator actions following an ESD. The training/procedures would specify that the operator verify the correct activation of the ESD (e.g., proper valves shut and processes deactivated) and would provide directions for further mitigating actions on the part of the operator.

5.4 LABELING, MIMICKING, AND DEMARCATION OF PANEL ELEMENTS

To differentiate quickly between different elements of the control panel, it is important that the various processes that are monitored/controlled from the panel be clearly demarcated. To quickly and correctly determine the functions of the various displays and controls, proper labeling is necessary. In addition, the use of mimics can greatly facilitate the selection of correct displays and controls. The checklist was used to make general determinations about the extent to which good HF practices were employed on panel labeling, the use of mimics, and the demarcation of panel elements at the LNG peakshaving facilities.

5.4.1 Labeling

There was a great variation in the labeling used at the different facilities. Some facilities had most of the displays and controls clearly and uniformly labeled. At other facilities, the labels were sometimes located below or above a display or control. All of the facilities had at least a few hand punched labels that were made by the operators. At several facilities, these nonpermanent, operator-made labels were used frequently. Operator-made labels that were yellow with white punch letters were especially hard to read.

5.4.2 Mimics

A mimic is a symbolic or graphic representation of the system of interest, e.g., the various system functions at an LNG peakshaving plant. For simple systems, it is often easy to represent symbolically the process on the control panel and to place the displays and controls physically within the mimic, which makes it easier for the operator to control the system. For more complex processes, the mimics become more complex and the ability to incorporate the displays and controls in the mimic is restricted. In these cases, the mimics often include references to the respective controls and displays.

The control rooms visited included a wide variety of mimics. None of the panels included displays and controls within the mimic, but most of them had mimics that referenced the respective displays/controls. At some plants all of the various LNG systems were mimicked. The level of detail of the mimics varied from plant to plant.

5.4.3 Demarcation of Functionally-Related Panel Elements

All of the facilities grouped functionally-related displays and controls on the panels to some extent. That is, vaporizer displays and controls are typically located in one place on the panel, liquefaction displays and controls are located in a second area on the panel, etc. However, clear lines of demarcation, such as black lines, are not provided on the panels to differentiate between the different process displays and controls. In addition, large labels are typically not used to distinguish between functionally-related panel elements.

5.4.4 Recommendations

Labels should be located consistently throughout the displays and controls. They should be sharp in contrast and visible from the operator's work position. Nonpermanent labels should be replaced with permanent labels. The control panels should make more use of graduated label sizes to indicate varying levels of processes (e.g., "Tank Systems" in two inch letters, "Tank 1" and "Tank 2" in one inch letters, and "Temperature" and "Pressure" in one-half inch letters). Facilities may also want to consider using special label coding practices, such as using red labels with white letters for critical controls and displays and black labels with white letters for less critical controls and displays.

Mimics have great potential in LNG peakshaving operations. LNG processes are simple enough so that system mimics would not be so complex as to inhibit their usefulness. To some extent, it is possible for mimics to be placed on existing control panels. Companies planning new facilities or companies planning to remodel old control rooms should carefully incorporate the use of mimics in control panel design.

In addition to using graduated label sizes, lines of demarcation should be placed on the panels to make it easier for operators to distinguish between controls and displays for one system (e.g., liquefaction system) from controls and displays for another system (e.g., vaporization system). Such lines, which can be painted onto the panel, could also be used to separate subsystems (e.g., tank 1 controls from tank 2 controls). Labeling changes and the addition of demarcation lines are inexpensive and can be accomplished during normal operations. Additional mimics can also be incorporated on some of the existing control panels. These changes improve operational safety by enhancing the operator's information gathering abilities both during normal and emergency conditions, and they also facilitate operator training. Making such changes in consultation with the operators will guarantee a better final panel configuration and more effective operators.

5.5 DISPLAYS

There are two major types of displays used in control rooms--quantitative displays, such as a pressure and temperature indicators, and qualitative displays, such as the annunciator panels and the audible alarms. These two types of displays are discussed separately below.

5.5.1 Quantitative Displays

Quantitative displays are used in LNG peakshaving facility control rooms to provide information on temperatures, pressures, flow rates, and liquid levels. Except for LNG tank temperatures, which are often provided by a digital readout, most of the readings are provided by vertical meters with a fixed face and a movable triangular pointer. Often, several of these meters are mounted side-by-side, each having a different numerical progression. The meters typically did not contain a scale coding approach to indicate normal, marginal, and out-of-limit conditions. If the meters fail, there is typically no specific indication of a failure. The pointer failed to zero at many of the facilities and to an intermediate scale position at one of the facilities. There were no major glare problems regarding the display faces. Parallax did exist in the display faces, but not enough to critically affect display readings. Almost all of the displays lacked a written unit of measurement written on the display face (e.g., psig, °F, or scfm). The unit of measurement usually had to be inferred from the display label.

5.5.2 Qualitative Displays

Qualitative displays include indicator lights, annunciator panels, and audible alarms. All of the control rooms had distinct audible alarms for gas detection, for flame detection, and for other important out-of-limit conditions.

All of the control rooms used indicator lights to signal certain types of conditions, e.g., whether a valve is closed or open. All of the facilities had valve indicator lights that signaled the status of the valve, not the status of the control. This is a highly desirable situation. All but one facility used two different colored lights (red and green) to signal valve status. One facility used the "lights-out" condition with single bulb indicators to signal a closed valve.

The use of green, amber, solid red, and flashing red qualitative indicators is not consistent throughout the industry. Most of the facilities attached consistent meanings to the four light conditions within a control room, although this was not the case for two of the facilities.

All of the peakshaving plants used annunciator panels to signify out-of-limit conditions for the more important systems and processes. The number of annunciators ranged from twenty-four to over two hundred. Most of the plants used red and white annunciator lights to prioritize the severity of the problem. One plant used green lights on the annunciator panel to signify that a critical system was running.

5.5.3 Recommendations

Several recommendations can be made regarding control room displays. The displays should have the unit of measurement printed on the display face (e.g., psig or °F). Indications for normal, marginal, and out-of-limit conditions should be placed directly on the display scales, if possible, or at least on the display covers.

Consistent use of colored indicator lights should be achieved. The following guidance is recommended: 1) GREEN to indicate that monitored equipment is in tolerance or that a state of readiness exists; 2) YELLOW to indicate a marginal condition or to alert the operator to situations of caution, recheck, or delay; 3) SOLID RED to indicate that a system or one of its parts is inoperative or that some corrective action is needed; and 4) FLASHING RED to indicate the need for immediate operator attention to avoid personnel injury and/or equipment damage. Finally, the use of a "lights-out" condition to signal system status is not recommended, since a burned out bulb in the display would give an incorrect signal.

5.6 CONTROLS

The major types of controls used in the peakshaving plant control rooms were pushbutton controls and dial selector controls. In general, the controls usually met most of the HF criteria (see the checklist in Appendix D). Several points are worth noting, however. One facility used a square pushbutton control that was back lit separately in the four quadrants to signal "on," "off," or two caution conditions. Below this row of pushbutton controls, a similar row of pushbutton controls was used simply as an indicator for the position of an adjacent two-position toggle switch. The use of identical controls with two different functions--control and display in one case and display only in the second case--could cause confusion on the part of the operator, especially during an emergency situation. A more general finding was that most of the facilities have pushbutton controls that are susceptible to inadvertent actuation. Many of these controls are located from knee to shoulder level and are not guarded or recessed.

It is recommended that the facilities investigate which controls are susceptible to inadvertent actuation and whether such actuation could cause a safety-related incident. If such is deemed to be the case, the control should be protected in some physical manner. Also, controls should be used in a consistent manner on the control panel (i.e., not as a display/control and a display only).

5.7 WORKSPACE

At all of the facilities visited, the workspace was more than adequate to provide sufficient space around control room desks and between the desks and the control panel to allow for efficient traffic flow. Lighting was adequate and glare was only a minor problem at one of the facilities. All of the control rooms had a desk that was the operator's nominal work station. The desk is usually too far from the control panel for the quantitative indicators to be read to the desired degree of accuracy, so the operators spend much of their time standing closer to the control panel. Some of the control rooms did not have adequate space for procedure manual storage, and standing operators usually did not have a place provided to support manuals during use except on the desk behind them.

Because the work space for operators was of adequate size at all the facilities, few recommendations are necessary. One recommendation, however, is that adequate space be provided for the procedures both during storage and use. In addition, the operator's work station should be clearly specified so that decisions about future placement of displays and controls can be made to insure optimum visibility and usability.

5.8 MEASURES

Measures refer to the units of measurement on displays and includes the lines that are marked on the display face and the numbers on the display face. The measures used at the plants visited allowed the displays to be read at the desired accuracy. Although measures on the displays did not meet many of the HF requirements of the military, this was judged not to be a problem for LNG operations. The measures on displays required a viewing distance of approximately one to three feet. Many of the displays did not indicate what parameter was being measured.

When displays are being changed at facilities, it is recommended that new displays, which meet more of the military standards, be used. It is also recommended that the unit of measurement for the displays be printed on the display face.

5.9 PROCEDURES

The use of procedures at the facilities differed greatly. Of interest in this evaluation were normal operating procedures, emergency operating procedures, and maintenance procedures. All of the facilities had some form of operating procedures. The procedures were used very little at some plants but almost continuously at one plant that was using a CRT display to monitor and control part of the operations. One of the plants had fairly extensive emergency procedures to assist the operators in making alerting phone calls to authorities (fire department, police department, etc.) and in carrying out required operator responses to the emergency. Other plants' emergency procedures were simply lists of people to notify in case of an accident. Maintenance procedures were available at some plants and not at others. The procedures could be placed on the operators' desks, but there was no good place to set the procedures while standing at the control panel at most of the facilities.

Most of the plants had a place to store the procedures so that they were easily accessed by the operators. The procedures were all legible and bound in some way. There was little use of tabbing or color coding in the procedures.

The use of procedures in LNG operations is recommended. Normal operating procedures and maintenance procedures can help to prevent accidents, and emergency operating procedures can help to mitigate accidents. In addition, detailed written procedures facilitate training. The procedures should be within easy reach of the operators. The emergency operating procedures should be easily distinguishable from the other procedures. The emergency procedures, especially, should be tabbed for easy access to subprocedures.

5.10 OPERATORS

The facilities visited differed in terms of selection criteria and some aspects of training for operators and maintenance personnel. However, the one mode that was common to all facilities was the use of a training regimen not unlike an apprenticeship. Specifically, the person being considered for a starting operations or maintenance position works alongside an experienced job incumbent for some time period before he is permitted to assume sole responsibility for the position himself. During this time the job aspirant learns about his job and about plant operations in general. The length of this "apprenticeship" varied among facilities, from about three months to about two years or more. This was affected in part by the number and frequency of job openings at the particular facilities. Passage into job incumbency was made when the "apprentice" was able to demonstrate, to the satisfaction of one or more of his superiors, that he was capable of taking on the responsibilities of the position. In addition, personnel at one of the facilities had to pass a licensing exam administered by the municipal fire department.

In addition to this apprenticeship type of arrangement, training was supplemented in different ways at the different facilities. Training films were used by a few of the facilities, formal classroom instruction was used in one of the facilities, and all facilities tried to have "hands-on" fire prevention and control training. The latter most often involved sending personnel to a regionally located school specializing in fire fighting.

Selection procedures (i.e., those occurring before the "apprenticeship") varied among the facilities. One of the facilities used a written selection test on LNG operations, others looked for backgrounds in steam operations or electronics, others emphasized mechanical aptitude (although no formal testing procedure was used), and others did not seek any special skills or backgrounds.

Career paths were company specific. At one site, the career path went from assistant to operator to maintenance to supervisory, whereas in other facilities maintenance preceded operations, and in others maintenance and operations were almost completely separate career paths. Also, at several of the plants, career progression involved moving from one type of facility (e.g., pipeline compressor station) to another (e.g., peakshaving plant). Part of the differences in career paths are attributable to the pattern of union membership among maintenance and operations personnel. If one is unionized and the other is not, it is not likely to have one be part of a career path for another.

Continuing education efforts also varied among facilities. One facility required attendance at periodically held classroom instructions. At another facility the plant supervisor would fill slow periods by developing various scenarios to which the operations personnel would respond. This seemed a particularly efficient method of keeping personnel in a state of readiness in case of an emergency.

The variability among gas companies and LNG facilities in personnel practices is indicative of the fact that some facilities have developed practices in a given area (e.g., selection) that might be of value to other facilities. Some mechanism should be instituted, perhaps through the auspices of the American Gas Association, to delineate and validate more fully the various personnel practices now being used at LNG facilities than was possible in the present study. This information can then be used to develop model programs for selection, training, promotion, and career progression that can be tailored to fit the site-specific requirements of a facility. For example, development of a standard curriculum about the properties and behavior of LNG and other liquid fuels would be supplemented at a given site by instruction in operations at the given site. Similarly, delineation of desired background characteristics for LNG operations can be used in a selection regimen for a given facility.

6.0 HUMAN FACTOR ASPECTS OF DEPARTMENT OF TRANSPORTATION REGULATIONS

Recently promulgated DOT regulations (DOT, 1980a, b, and c) address several aspects of HF practices, including equipment design, procedures, and personnel selection and training. The purpose of this section is to describe how HF practices in the LNG industry will be affected by these regulations. Much of the change will occur by 1982, when many of the regulations dealing with both existing and new facilities become effective.

The DOT standards address LNG safety issues in general and not just HF considerations. The standards are a legal document; they are neither guidelines for standard HF practices nor are they an HF checklist. However, included throughout the standards is a rough outline for HF practices. Any detailed HF applications in the LNG industry will be made within the context of this outline. Therefore, a description of the HF aspects of the regulations is an integral part of the present chapter. The purpose of this section is to describe the effect the standards will have on LNG operations in terms of HF practices. However, it is important to examine both those aspects of standard HF practices that are covered by the standards and those aspects that are not. The latter is especially instructive, since it may include additional areas in which the LNG industry may be able to improve overall system safety by using HF methods that have been shown to be related to safety and productivity in other industries.

6.1 BACKGROUND

The current DOT regulations represent a significant change over the 1972 Federal Standards governing LNG facilities. The latter involved use of the National Fire Protection Association (NFPA) Standard 59A plus some additional standards. The 1972 Standards were an interim measure until regulations more applicable to LNG could be formulated, revised, and adopted. In 1977 the Materials Transportation Bureau (MTB) of the DOT invited public participation via an Advanced Notice of Proposed Rulemaking (ANPRM) concerning safety standards for the design, siting, construction, operation, and maintenance of LNG facilities. On the basis of the comments to the ANPRM, MTB issued two Notices of Proposed Rulemaking (NPRM):

1. In February of 1979, the MTB issued an NPRM for standards concerning the design, siting, and contruction of new LNG facilities or for existing facilities that were undergoing significant changes. These standards were adopted in February of 1980 and are applicable to all new facilities covered by the standards.[a]
2. In February of 1980, the MTB issued an NPRM for standards concerning operations, maintenance, fire protection, personnel qualifications and training, and security for <u>all</u> existing and planned LNG facilities. These standards were adopted in October of 1980, and became effective November of 1980, with the exception that many of the HF related standards were made effective on July 23, 1981, while others are effective as of January 1, 1982.

Most of the HF related sections are contained in the second set of the standards. Specifically, within the ten subparts of Part 193, Code of Federal Regulations (49CFR178.0, 1980), all of sections F (Operations) and H (Personnel Qualifications and Training), as well as major portions of E (Equipment) have to do with HF consideration. Other HF considerations are scattered throughout the remaining subparts: A (General), B (Siting Requirements), C (Design), D (Construction), G (Maintenance), I (Fire Protection), and J (Security). Contrary to the organization of the regulations themselves, the following discussion of the DOT regulations is arranged by type of HF consideration.

In reviewing the DOT regulations, a paragraph was considered to be "HF relevant" if it directly mentioned human interaction or response or if such interaction or response was strongly implied by the paragraph. Thus, training requirements are included because they directly involve plant personnel. Instrumentation requirements are generally included if there is the strong implication that plant personnel will have to monitor the output of the

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(a) See paragraphs 2001, 2003, and 2005 of the standards for concise definitions of applicability.

instrumentation. This requires some very fine distinctions to be made. As a specific example, paragraph 2413[a] requires that air intakes to vaporizers be equipped with sensing devices to detect the induction of a flammable vapor. This paragraph is not included in the following discussion, since it neither mentions nor strongly implies the nature of the human interaction. However, paragraph 2819, which addresses gas detectors throughout the facility, is discussed, since it also addresses the need for alarms that are visible and audible (assumedly to plant operators) to be linked to the detectors. Similarly, other paragraphs that require or imply that it is plant personnel who are primarily responsible for continuously or intermittently monitoring the status of some system for equipment are also considered to be "HF relevant."

In the next subsection, DOT standards pertinent to equipment design are discussed. While it is recognized that equipment design traditionally includes such issues as training of personnel on the use of the equipment and the written procedures for operating the equipment (e.g., Van Cott & Kincade 1972), a more circumscribed view of equipment design is taken in the present chapter. The subsection on equipment design addresses issues specific to the equipment itself (e.g., controls, displays, etc). Procedures, training and selection, and other HF aspects are discussed in subsequent subsections.

6.2 EQUIPMENT DESIGN

There are three paragraphs that address separate aspects of equipment design: warnings and alarms; instrumentation, including indicators and monitoring devices requiring either periodic or continual attendance of plant personnel; and operability of the equipment. Each of these aspects will be discussed in turn. Table 6.1 lists the paragraphs in the regulations that are pertinent to HF aspects of equipment design.

(a) For ease of presentation, the first three digits in the paragraph number--193--referring to the part of the Code of Federal Regulations in which the DOT standards are found are omitted in the present report. Thus, 2413 refers to paragraph 193.2413 in the standards.

TABLE 6.1. DOT Regulations Addressing HF Aspects of Equipment Design

Paragraph Number (193.----)	Description	Applicability
	A. Warnings and Alarms	
2169	Gas Detection in Impoundment System	1
2205	Heating System Under Tank	1
2209	Storage Tank-Abnormal Level, Vapor Pressure, and Temperature Alarms	1
2433	Sensing Devices for Gas and Flame; General	1
2435	Warning Devices Linked to Sensing Devices	1
2819	Gas Detection	2
2821	Flame Detection	2
	B. Instrumentation, Indicators and Monitoring Devices	
2209	Storage Tank Level, Vapor Pressure, Temperature, and Rotational Movement Indicators	1
2407	Vaporizer LNG Pressure, Vapor Pressure and Temperature Indicators	1
2421	Monitor or Detect Natural Gas Concentration in the Cold Box	1
2433	Monitoring Device for Component Malfunction	1
2437	Signal Light Showing On/Off Status of Pump or Compressor	1
2507	Monitoring for Alarms; General	2
	C. Equipment Operability	
2231	Cargo Transfer Area Designed to Minimize Truck Maneuvering	1
2233	Power Operability of Transfer System Shutoff Valve at Valve and at Least 50 Feet Away	1
2409	Operability of Vaporizer Valves During A Controllable Emergency	1
2429	Provide Manual Method of Relieving Pressure and Vacuum in an Emergency	1
2437	Provide Local and Remote Shutdown of Pump or Compressor	
2439	1. ESD Operable at Control Center 2. Delay for Manual Response Permitted Before Automatic ESD	1
2441	Control Center for Operations and Monitoring	1
2443	Fail Safe Control	1

1. Applicable to new facilities

2. Applicable to all facilties, effective July 23, 1981.

6.2.1 Warnings and Alarms

Standard HF practice with respect to warnings and alarms (Deatherage, 1972) suggests that:

1. The warning signal should alert the attention of the operator without overly startling him.
2. The warning signal should indicate the nature and direction of the problem.
3. There should be some method of prioritizing the alarms, if there are several alarms, to allow the operator to respond to the most important problem or to the primary causal problem.
4. There should be manual shutoff of alarms when appropriate.
5. There should be visual and auditory presentation corresponding to the nature of the information and the operator requirements.

The paragraphs dealing with warnings and alarms will result in conformity to some of the HF standard practices just mentioned. The most important paragraphs relevant to this area are 2819 (Gas Detection) and 2821 (Fire Detection), which relate to existing facilities as well as new facilities. Together, these paragraphs require sensing devices to detect fire or combustible gas in two types of circumstances: 1) fire or combustible gas (at not less than 25 percent lower flammability limit) in areas that have the potential for the presence of flammable fluids (in accordance with NFPA 70); and 2) combustible gas in all enclosed buildings. Fire or gas detected in circumstance (1) must be linked to warning devices that will produce visual and audible alarm in the control center and an audible alarm in the area of detection. Gas detected in circumstance (2) must be linked to a warning system that provides a visible or audible alarm outside the enclosed building

Paragraphs 2433 and 2435 cover the same areas but in more detail than paragraphs 2819 and 2821, but they are only relevant to new facilities. For example, in addition to the verbal and audible warnings stipulated in paragraphs 2819 and 2821, paragraphs 2433 and 2435 also stipulate that the warnings in the control center should indicate the nature and location of the problem. In addition, these paragraphs also stipulate that sensing devices should be placed to detect component malfunctions, which, if not corrected, could result in a hazardous condition.

Thus, the regulations require modal redundancy (i.e., visual and auditory) for the gas and flame alarms in all existing plants. New facilities will be required to have alarms and provide the operator with information on the nature and location of the problem. In addition, new facilities must have various out-of-limit storage tank indications, as required in paragraphs 2205 and 2209. However, the modality of these alarms is not specified.

In summary, the DOT regulations address a very important HF concern by specifying that the most hazardous conditions, especially gas and flame detection, be linked to alarms. An alarm is the best way to assure that an operator is alerted to a problem. In addition, the regulations touch upon other HF considerations with respect to warnings and alarms by specifying redundancy in modalities (visual and auditory) for the most important alarms. The detailed aspects of alarms, such as prioritization strategies, consistent color coding, and placement within the operator's visual field, are left to individual plant operators to determine with the assistance of HF input.

6.2.2 Indicators and Monitoring Devices Requiring Operator Attention

This section deals with displays that require periodic or continuous attention of designated plant personnel. Alarms that "make themselves known" to the operator were discussed in the previous section. They tend to be discrete--either they signal an alarm or they do not. The instrumentation of interest in this section is of a more continuous nature (e.g., pressure indicators, temperature indicators, and flow indicators). They may or may not be linked to an alarm at specified set points. If they are linked to alarms, the pertinent paragraph would appear in the previous section as well.

The most omnibus paragraph regarding monitoring is 2507. This requires that warning alarms tied to the detection of hazardous conditions of components be monitored either by observation at an attended control center or by inspection or testing of the component at intervals specified in the operating procedures. The other paragraphs relevant to this section deal with the need for displays for various storage tank, liquefaction, and vaporizer parameters, such as pressure, temperature and level.

Thus, a minimum of displays are required by the regulations. In fact, as discussed in other sections of this report, site visits revealed that LNG peakshaving plants have many more displays and monitoring devices that require operator attention.

Much of the field of HF has concerned itself with displays. Examples of this concern include: placement within the visual field; appropriate and consistent labeling; freedom from parallax; the layout of the set of displays and controls; consistency between display and controls; and consistent use of color, size, and shape codings. The checklist used during site visits exemplifies many of these principles (see Appendix D). In meeting the requirements of the regulations, the individual facilities have the discretion to design the display system in different manners, all of which can meet standard HF practices.

6.2.3 Equipment Operability

Although the design of a facility in terms of human operability of equipment is generally left to the discretion of the facility operator, there are several paragraphs in the DOT standards, most of which are related to operation during emergencies, that specify operational standards. Probably the most important is paragraph 2441, which specifies that an LNG facility must have a control center that is operational during a controllable emergency and from which specified remotely actuated shutdowns and automatic shutdowns must be operable. This includes the ESD and various relief devices. Paragraphs 2233 and 2409 also pertain to the operability of valves during emergencies. Other paragraphs are concerned with the ability to isolate or shut various components during emergencies.

Whereas the regulations are concerned at a general level with operability of equipment during emergencies, human factors input into LNG facility design can assist in operability issues at a very specific level. Much of HF applications has concerned operability of equipment from an anthropometric viewpoint as well as from the viewpoint of minimizing errors of operation. Again, the reader is referred to the LNG site checklist in Appendix B as an example of the types of concerns with which human factors engineers deal. These vary from design of controls to guard against accidental actuation to the labeling of controls.

6.3 STANDARDS FOR PERSONNEL QUALIFICATIONS AND TRAINING

The standards regarding personnel selection and training at LNG facilities are contained in subpart H of the DOT standards. This subpart, which is pertinent to all LNG facilities, took effect July 23, 1980.(a) Paragraphs 2707-2719 of the subpart calls for plant personnel to be trained according to a written plan of instruction. All maintenance and operational personnel must be trained via this plan in the following:

- characteristics of LNG and other flammable fluids used at facility
- potential hazards involved in operating and maintenance activities
- operating, maintenance, and emergency procedures related to the personnel's assigned function
- first-aid administration
- fire protection procedures, including fire prevention, knowledge of potential causes and areas of fire, behavior of fires and of different types, and fire fighting techniques per their assigned responsibility.

In addition, operational and appropriate supervisory personnel must be trained in facility operations, including controls, functions, operating procedures and transfer procedures. Also, a written plan for continuing instruction of operational and maintenance personnel is required, and it is also required that such training take place at least every two years.

(a) The exception is paragraph 2701-2705, which deals with personnel involved in design, fabrication, construction, installation, inspection, and testing of new facilities. These took effect in February 1980, and are only relevant to new facilities.

In terms of qualifications for a given operations or maintenance position, the standards call for an individual to have completed successfully the course of training, to have experience related to the given position, and to demonstrate acceptable performance on a proficiency test relevant to the position. If a person does not meet all three requirements, he can only perform the job if accompanied and directed by a person who does meet the requirements.

Other aspects of subpart H include: 1) training for security personnel (they must be trained according to a written plan of instruction and be retrained at intervals not to exceed two years according to a written program of continuing instruction); 2) personnel health (the operator must follow a written plan to verify that personnel do not have physical disabilities that would impair performance of assigned duties); and 3) corrosion control procedures (which must be carried out by individuals qualified in corrosion control technology).

This subpart of the standards addresses a number of important points concerning personnel qualifications. It specifies minimal training objectives and specifies the steps a person must take before he can hold an operations or maintenance position. Finally, the standards stipulate that training programs must be in accordance with a written plan.

There are at least seven issues that a facility operator may want to address in integrating the provisions of this subpart into his operations. First, the written plan of training should specify detailed training objectives at a task and subtask level. The objectives should consist of the specific job related behaviors in which the person should be proficient. The objectives may also include aspects less tied to specific aspects of any one task, such as "safety consciousness." Second, the plan should specify the training methods for each part of the training program. Third, the training program should allow for as much supervised practice as feasible to allow "hands-on" experience. Fourth, methods for determining achievement of training goals should be specified. Fifth, periodic evaluation of the training program itself should be carried out. Sixth, determination of the definition of "acceptable performance" on the proficiency test required by the standards should be made. Although the standards do not specify the format of the proficiency test, the supplementary information appears to imply a written test (Federal Register 1980). Seventh, a determination of the job-relatedness (i.e., validity) of the proficiency test should be made. The more valid a test is, the more useful it is in making personnel decisions.

Most of the considerations mentioned above are best accomplished by performing a detailed job analysis of each of the maintenance, operational, and supervisory positions. A thorough knowledge of the various aspects of each job, obtained via a job analysis, will facilitate detailed specification of training objectives and can form a sound basis for constructing valid proficiency tests. It is also instrumental in determining methods to appraise the performance of personnel.

6.4 PROCEDURES

The design of equipment to optimize the man-machine interaction and even the selection and training of competent personnel can be for naught if the procedures that the employee must follow are poorly conceived or written. While it is true that rigorous training, even on poor procedures, can overcome many shortcomings of the procedures, superior HF practices involve having procedures that are well written and technically accurate. It is especially important to have such procedures when the operator is using them in a high stress situation, such as during a controllable emergency. Specifically, procedures should be precise, easy to read, accessible, and unambiguous. In addition, the procedures should be written to correspond to the displays and the controls and should contain check-off lists when appropriate.

The DOT regulations call for written procedures in several paragraphs, as shown in Table 6.2. In general, the paragraphs on procedures specify the content of the particular procedure. For example, paragraph 2503, for operating procedures, specify that the procedures must include:

- monitoring components or buildings
- startup and shutdown

- recognizing abnormal operating conditions
- maintaining vaporization rate, temperature and pressure within design limits for vaporization operations
- maintaining temperatures, pressures, pressure differentials and flow rates within design limits during liquefaction for: boilers; turbines; pumps, compressors, and expanders purification and regeneration equipment; and cold box equipment
- cooldown of components
- compliance with the fire protection plan.

TABLE 6.2. DOT Standards for Written Procedures

Paragraph Number	Issue	Applicability
2305	Procedures for Construction, Installation, Inspection, or Testing	(a)
2503	Operating Procedures	(b)
2509	Emergency Procedures (Except for Fires)	(b)
2513	Procedures for Transfer Operations	(b)
2605	Maintenance Procedures	(b)
2903	Security Procedures	(b)

(a) Applicable to new facilities.
(b) Applicable to all facilities, effective July 23, 1981.

Most of the other paragraphs dealing with procedures are at about the same level of detail with respect to the content.

As implied above, the HF perspective of procedures lies more with the format and presentation than the technical content. Technical content is considered to be an engineering concern. Thus, in meeting the requirements of the DOT standards in terms of content of procedures, a facility should consider utilizing HF principles in writing the procedures.

6.5 OTHER HF CONSIDERATIONS

There are several other HF considerations spread throughout the regulations. Several of them (paragraphs 2619, 2621, and 2635) set maximum intervals between inspection of various components, such as transfer hoses, control systems, and relief valves and for corrosion control. A whole subpart is devoted to plant security, and several other paragraphs are devoted to record keeping requirements. Both of these areas, while dealing with the human systems at facilities, are not within the primary domain of HF.

Finally, one other paragraph (2515) deals with investigation of all accidents resulting in injury or damage greater than $10,000. A facility operator may choose to have a person with HF training, along with a safety engineer, be involved in the investigation. These individuals should be well equipped to determine primary as well as secondary causes of the accident. Often accidents are attributed to equipment failure when the initial cause is human error.

6.6 SUMMARY

As discussed in the introduction to this section, the DOT standards address several HF areas of concern. However, these are addressed at a general level of specification. Compliance with the HF-relevant parts of the regulations affords the utilities the opportunity to adopt detailed HF practices in the operation of its LNG facilities. The regulations provide the framework around which accepted HF practices, which have been shown in other industries to be related to safety and productivity, can be implemented.

7.0 HUMAN ERROR PROBABILITIES

One potential use of HF information is in probability risk assessment. Knowledge of the probability of incorrectly carrying out various operator actions (as well as the likely range of these probabilities) can serve as input into a probability risk assessment. The basic unit of measurement in this area is a "human error probability" (HEP), which is discussed in detail below.

7.1 BACKGROUND ON HUMAN ERROR PROBABILITIES

HEPs are numerical values assigned to specific actions to indicate the probability that an action will be performed incorrectly. For example, an HEP of .05 for dialing a telephone number indicates an estimate that, on the average, a person will misdial a telephone number 5 times out of 100. This does not mean that the mistake will not be corrected by hanging up and redialing. It simply means that performance will likely deviate from perfect a specified proportion of the time. Usually associated with an HEP are error bounds. Error bounds indicate the range of values that the estimated value may actually take, usually 95 percent of the time. The HEP of .05 for telephone number dialing might have an error bound from .01 to .25, indicating that the actual HEP will lie between those values 95 percent of the time. The circumstances of the dialing (say in a noisy or quiet room) and uncertainty as to the "correct" value, due to the nature of the supporting research, require that relatively large error bounds accompany HEPs.

Because of the limited research in the field of HEPs, in general, and the lack of HF research that specifically addresses LNG facilities, data from other areas must be used. The major available publication that catalogs HEPs in detail for tasks and equipment similar to LNG plants is by Swain and Guttman (1980). Most of the HEPs presented here have been adapted from this publication.

Establishing HEPs for activities central to the operation of any facility is a difficult task requiring a synthesis of data from widely divergent settings. Field studies of error rates in job performance that are applicable to the industrial LNG setting are few. Ideally, data would be derived from personnel performing the LNG operations of interest on the job. No such studies have been reported, and it is unlikely that any will be completed. In order to collect such data it would be necessary to monitor equipment and personnel continuously for extended periods of time. Not only would this type of procedure be expensive and potentially cumbersome to the operation of the plant, it would also affect the data. Although it is possible that simulators could be designed for some specific components of the operations to be studied, this too is an excessively expensive and time consuming alternative.

The data that are available from industrial settings are primarily from the chemical and nuclear industries; documentation is more complete in these areas than most. These studies do more to emphasize the importance of the human error component than to specify error likelihoods. Joos et al. (1979), for example, reviewed 25 months of nuclear power plant operations providing actuarial data on gross operator error rates. Values in this study were based on complete tasks (as opposed to subtasks, such as turning a specific control on or off) in which there were failures that led to reportable occurrences. The study reported 401 human errors from 3 plants over the 25-month period. Operator errors and administrative procedural errors were the most frequent (accounting for 53.1 percent of all errors), although frequencies of error types varied significantly between plants. It was concluded that HF engineering could be helpful in error rate reduction, especially in areas involving equipment manipulation (e.g., closing a valve). These data are important in identifying human error as a problem area, but underestimate the actual number of errors, since it is unknown how many errors go unreported after being corrected or do not lead to reportable occurrences.

The data used for estimating HEPs for specific tasks are derived primarily from laboratory studies and modified somewhat for the specific application. Where data are not available, expert opinion (often based on industrial experience) is used for the estimation. Of crucial importance in laboratory studies is the degree to which the circumstances of the study are similar to those in the situation to which it is generalized. There are, of course, inherent differences between virtually any laboratory study and the applied setting; it is both inefficient and impossible to mimic a worker going through a daily routine in order to collect data. The differences between laboratory and applied settings can be minimized by using subjects and stimuli that resemble those found in the anticipated application.

A variety of circumstances and factors that affect any HEP based on laboratory data must be considered when these estimates are actually applied. A fundamental consideration when evaluating any error rate estimate is the speed at which the task must be, or is likely to be, performed. As might be expected, the more rapidly a task is performed, the higher the error rate; i.e., there is a speed/accuracy tradeoff. For example when subjects are instructed to read scales as accurately as possible they are slower yet more accurate than when instructed to read as accurately and rapidly as possible (Kappauf et al. 1947). It would be a mistake to assume that in any setting (including LNG facilities) that task performance is never speeded. Aside from emergency situations in which time is a factor, more subtle factors affecting attention and performance, such as a break or the end of a shift, will have an effect on the speed-accuracy tradeoff. Lighting, comfort, and other distractions are environmental circumstances that may affect error rate in a way that is difficult to anticipate when interpreting laboratory studies.

The error ranges associated with specific error rates tend to be very broad, with limits separated by at least a factor of 10. These broad limits are necessary because of the nature of the estimates. As noted above, a host of local factors such as temperature, noise, time pressure, or even the time of day will affect the error rate. Personnel factors will also have an important impact on error rates. There are considerable individual differences in error rates for any given task; these differences are noted in most laboratory studies. Familiarity with the task and time spent on the task figure into any given error rate as does training. The differences noted by Joos (1979) between plants also suggests that differences in the physical facilities, system design, and HF considerations will also play important roles in error rate variability. Equipment and hardware design are very important factors in determining error rates. For example, the design of a simple dial indicator has a large effect on its readability. The apparent size of the dial and scale spacing (Murell et al. 1958), scale divisions (Kappauf and Smith 1948; Williams and Grether, 1947), reflectivity, zero point location, readability of numerals (Kappauf et al. 1947), pointer clearance (Churchill 1956), and other factors can significantly influence error rates in reading and reporting a single dial indication. Differences between dials when many are being monitored will also affect overall readability (Vernon, 1946). Clearly, an HEP must have fairly wide bounds in order to accommodate differences in plant and equipment design.

The error bounds also take into account genuine uncertainty as to the "correct" HEP value. Even when good data are available when constructing HEPs, wide differences are often found between studies measuring error rates from similar tasks. A range of uncertainty is also introduced in the circumstance that no data pertaining to a particular task are available and expert judgment must be used in adapting error rates from similar tasks.

7.2 HUMAN ERROR PROBABILITIES RELEVANT TO LNG OPERATIONS

The major available source in which there has been a complete listing of HEPs and associated limits for an industrial setting is by Swain and Guttman (1980). Although their report emphasizes applications to the nuclear power industry, most of their data sources come from nonnuclear applications, which are believed to be generally applicable to any industrial process. Thus, many of the task specific HEPs from this document may be adapted to LNG facilities without much risk of overgeneralization.

Five tables of HEPs adapted from Swain and Guttman (1980) have been developed for this report. The tables have the most relevance to LNG applications. In some cases, the HEPs and their ranges have been modified, as suggested by Swain and Guttman (1980), based on knowledge of the LNG industry. In the remainder of this chapter HEPs and their relationship to site visit findings are discussed.

7.2.1 Actuation of Manual Controls

Table 7.1 lists HEPs regarding the actuation of manual controls. Note that most of the HEPs have a mean value of around 10^{-3}. The HEP for selecting an incorrect control from among similar controls is .003 (.001 to .01). However, this is reduced by a factor of 3 if the controls are

TABLE 7.1. Human Error Probabilities for Actuation of Manual Controls

Error	HEP	(Range)
Selecting a wrong control:		
Among similar controls	.003	(.001 to .01)
With functional grouping	.001	(.0005 to .005)
With clear mimic lines	.0005	(.0001 to .001)
Turning a control in the wrong direction:		
No violation of strong population stereotype	.0005	(.0001 to .001)
Violation of a strong population stereotype	.05	(.01 to .1)
--and under high stress	.5	(.1 to .9)
Setting a multiposition switch to wrong setting:	.001	(.0001 to .1)
Selecting an incorrect manual valve from a group of similar valves	.005	(.002 to .02)

NOTE: This table is adapted from Swain and Guttman (1980, Table 20-13).

functionally grouped and by nearly a factor of 10 if the controls are clearly mimicked. Thus, these HEPs indicate the benefits of following the recommendations regarding functional grouping and the use of mimics.

A control is rarely manipulated incorrectly (.0005) if it is consistent with population stereotypes (e.g., turn clockwise to increase), but the HEP is increased by two magnitudes if the control is to be manipulated the opposite of the population stereotype. In an emergency situation, these types of controls can be expected to be used incorrectly half of the time. Obviously, it is important to follow population stereotypes for controls.

7.2.2 Check Reading Displays

Table 7.2 lists HEPs related to check reading displays, i.e., reading relevant displays to determine whether their values are within acceptable limits. An operator is likely to make an error reading an analog meter at the

TABLE 7.2 Human Error Probabilities for Check Reading Displays

Error	HEP	(Range)
Read digital indicators incorrectly	.005	(.0005 to .01)(a)
Read analog meters incorrectly:		
With easy to see limit marks	.005	(.0005 to .01)(a)
With hard to see limit marks	.01	(.002 to .04)(a)
Without limit marks	.015	(.001 to .06)(a)
Checking the wrong indicator lamp in an array of lamps.	.003	(.001 to .01)
Misinterpret the indication on indicator lamps	.001	(.0005 to .005)
Read analog chart recorder incorrectly	.006	(.002 to .02)
Read graph incorrectly	.001	(.005 to .05)
Read cluttered printing recorder incorrectly (.01 to .2)		.05
Failure to record reading correctly when more than 3 digits	.001	(.0005 to .005)

(a) These HEPs have been adjusted from those tabled in Swain and Guttman 1980).

NOTE: This table is adapted from Swain and Guttman (1980).

rate of .015 (.001 to .06), but if easily seen limit marks are placed on the meter, this HEP is reduced by a factor of three to .005 (.0005 to .01). It is then comparable to the HEP of .005 (.0005 to .01) for reading a digital display incorrectly. Thus, digital displays are generally easier to read than analog displays, and analog displays should have limit marks. Most of the other HEPs are in the range of 10^{-3}, except for the HEP related to reading a cluttered printing recorder, which is .05 (.01 to .2).

7.2.3 Inspection Tasks

Table 7.3 lists HEPs for inspection tasks that occur at a shift change or at a comparable plant walkthrough inspection. The main point to be made from this table involves the use of a checklist to conduct the walkthrough to determine whether the system is operating normally. If no checklist is used, the HEP is .5 (.1 to .99). However, if a checklist is used and is used correctly, the HEP is .005 (.002 to .05). Unfortunately, this does not mean

TABLE 7.3. Human Error Probabilities for Inspection Tasks that Occur on a Change of Shift or Comparable Walk Through Plant Inspection

Error	HEP	(Range)
Fail to recognize incorrect status:		
With checklist used correctly	.005	(.002 to .05)*
With checklist used incorrectly	.05	(.01 to .5)*
Without checklist	.5	(.1 to .99)*
Use checklist incorrectly	.5	(.1 to .99)
Fail to detect deviant meter:		
With limit marks	.05	(.01 to .1)
Without limit marks	.15	(.03 to .3)
Fail to detect annunciator light requiring attention which is not annunciating	.9	(.8 to .98)
Fail to detect incorrect status of a legend light other than an annunciator light	.98	(.96 to .996)
Fail to detect incorrect status of an indicator lamp	.99	(.98 to .o98)
Fail to follow established policies or procedures	.01	(.003 to .03)

(a) These values were adjusted from Swain and Guttman (1980) to account for circumstances specific to LNG facilities.

NOTE: This table has been adapted from Swain and Guttman (1980), Tables 20-9, 20-10.

that a checklist is a panacea for reducing operator error, since the HEP is .5 (.1 to .99) that the checklist, if available, will be used incorrectly. Yet, using a checklist incorrectly still results in better performance than not using a checklist at all. It is very likely that an operator will not detect an annunciator light that is lit but not flashing, the incorrect status of a legend light, or the incorrect status of an indicator lamp at a shift change over.

7.2.4 Completion of Tasks

Table 7.4 lists the HEPs for incorrectly completing a set of 1 to 10 tasks and 11 or more tasks with and without a checklist. For 1 to 10 tasks, the HEP is .3 (.01 to .99) when no list is used to remind the operator of the tasks and the order of the tasks. This decreases by two magnitudes to .003 (.001 to .01) if a list is used and to .001 (.0005 to .005) if the list contains checkoff provisions. With 11 or more tasks and no list, the operator is almost certain to make an error. Thus, a list of the tasks is especially important when 11 or more tasks are involved.

TABLE 7.4. Human Error Probabilities for Correctly Completing a Set of Multiple Tasks

Number of Tasks	Lists/Checkoffs Used	HEP	(Range)
1-10	No list	.3	(.01 to .99)(a)
	List used without checkoff provisions	.003	(.001 to .01)
	List used with checkoff provision	.001	(.0005 to .005)
11 or more	No list	.99	(.9 to .999)(a)
	List used without checkoff provision	.01	(.005 to .05)
	List used with checkoff provision	.003	(.001 to .01)

(a) Estimate based on memory span data.

NOTE: This table is adapted from Swain and Guttman (1980, Tables 20-18 and 20-20).

Table 7.5 lists HEPs regarding responding to annunciated legend lights. When an annunciator panel is activated, several things happen. First, at least one annunciator panel window light begins to blink and an audible alarm is sounded. However, since many of the systems are interrelated, usually several lights begin to blink at the same time. Additionally, many of the panels often already have several windows solidly lit because of a known and accepted plant condition. Second, when the panel is activated, an operator usually quickly glances at the panel to see which lights are blinking and then depresses the "acknowledge" button, which cancels the audible signal and causes the blinking lights to go solid. In other cases, a "silence" button cancels the audible signal and the "acknowledge" buttons causes the blinking

TABLE 7.5. Human Error Probabilities for Responding to Annunciated Legend Lights

Error		HEP	(Range)
Failure to respond to one of many lights:			
No. of lights	1	.0001	(.00005 to .001)
	2-4	.001	(.00006 to .02)
	5-7	.006	(.0003 to .09)
	8-10	.033	(.002 to .5)
	11-15	.10	(.01 to .999)
	16-40	.175	(.015 to .999)
	more than 40	.25	(.025 to .999)
Reading the wrong message		.001	(.0005 to .005)
Resume attention to a legend light within one minute after an interruption (sound and blinking cancelled before interruption)		.001	(.0001 to .01)
Resume attention to a legend light if more than one minute elapses after an interruption)		.75	(.9 to .99)

NOTE: These values are adapted from Swain and Guttman (1980), Tables 20-3 and 20-4.

light to go solid. An error can result, then, when the operator does not respond to all of the warning lights that are lit, and the probability of the error increases as the number of lights increases.

Thus, the HEP for not responding correctly to one annunciated light when it is the only one lit is only .0001 (.00005 to .001). However, if more than 40 lights are lit, the HEP for not responding correctly to any one of them is .25 (.025 to .999). This emphasizes the importance for a prioritization scheme for the annunciator panel. The operator is unlikely to read the wrong message off of the legend, but if the operator is distracted from responding to a given light for over a minute, the operator is likely never to respond to that light.

7.3 SUMMARY

HEPs are estimates of the likelihood that an operator will make an error performing a specific task, such as reading a display or controlling a valve. Some HEPs are based on laboratory data and others are based on expert technical judgment. Very few are based on actual plant experience. Because of this and because local environmental conditions (e.g., lighting, temperature, and time constraints) can influence the likelihood of error, a range of uncertainty is associated with the best estimate for an HEP.

A listing of HEPs has been developed by Swain and Guttman (1980) for application to the nuclear industry. The estimates were typically based on nonnuclear applications, but were thought to be adapted to most industrial applications. Thus, for this study many of their estimates were adapted for use in the LNG industry.

The HEPs that were presented lead to several general conclusions. First, the use of functional grouping of controls with its related displays or the use of mimic lines can greatly reduce the likelihood of an operator selecting the wrong control. Second, the use of limit marks on displays greatly increases the likelihood that an operator will notice an out-of-limit condition when scanning the displays. Third, the likelihood that any out-of-limit condition will be noticed is enhanced if an operator uses a checklist when monitoring system status. Fourth, the use of a list of tasks decreases HEP's involved with currently completing the set of tasks, especially if 11 or more tasks are involved. Fifth, if numerous annunciator lights are often activated at the same time, some scheme of prioritization is needed to insure that the most critical conditions are responded to promptly.

8.0 FAULT TREE ANALYSES

In this chapter the human aspect in potential LNG accident scenarios using LNG import terminals as a basis for analysis is examined. The purpose of this exercise is illustrative: to show how the human interaction portion of a fault tree analysis could be expanded to examine various causes for inappropriate operator response. This, in turn, can be instructive for determining methods of reducing the probability of operator error. Finally, the exercise also illustrates how HF considerations are an integral part of the total systems analysis.

Work by Baker (1982) and ongoing work at PNL have outlined parts of possible release scenarios. Some fault tree analyses have been completed (Pelto et al. 1982b) regarding the failure of the emergency shutdown system and the overfilling of the LNG storage tank. Portions of these fault tree analyses have been adopted and expanded in this chapter to include more detailed consideration of the human component. These fault trees will be discussed and lessons learned from the military and from the nuclear power field and information gained from site visits to LNG plants will be included.

8.1 EMERGENCY SHUTDOWN SYSTEM FAILURE

An emergency shutdown system at an LNG import terminal consists of three elements: detection, activation, and isolation. Emergency situations are detected by process instrumentation (flow, temperature, pressure, and level sensors), emergency instrumentation (combustible gas, fire, and low temperature detectors), and the plant operators. The emergency shutdown system (ESD) is activated either automatically by the controllers or limit switches, or manually by the operator in response to an alarm or visual recognition of the emergency.

Figure 8.1 presents one branch of a fault tree describing the failure of the emergency shutdown system. The operator could fail to activate the ESD either because he failed to perceive the release or because he failed to perceive indications of abnormal functioning on the temperature, pressure, or flow displays (if they existed). The operator might not see the leak either

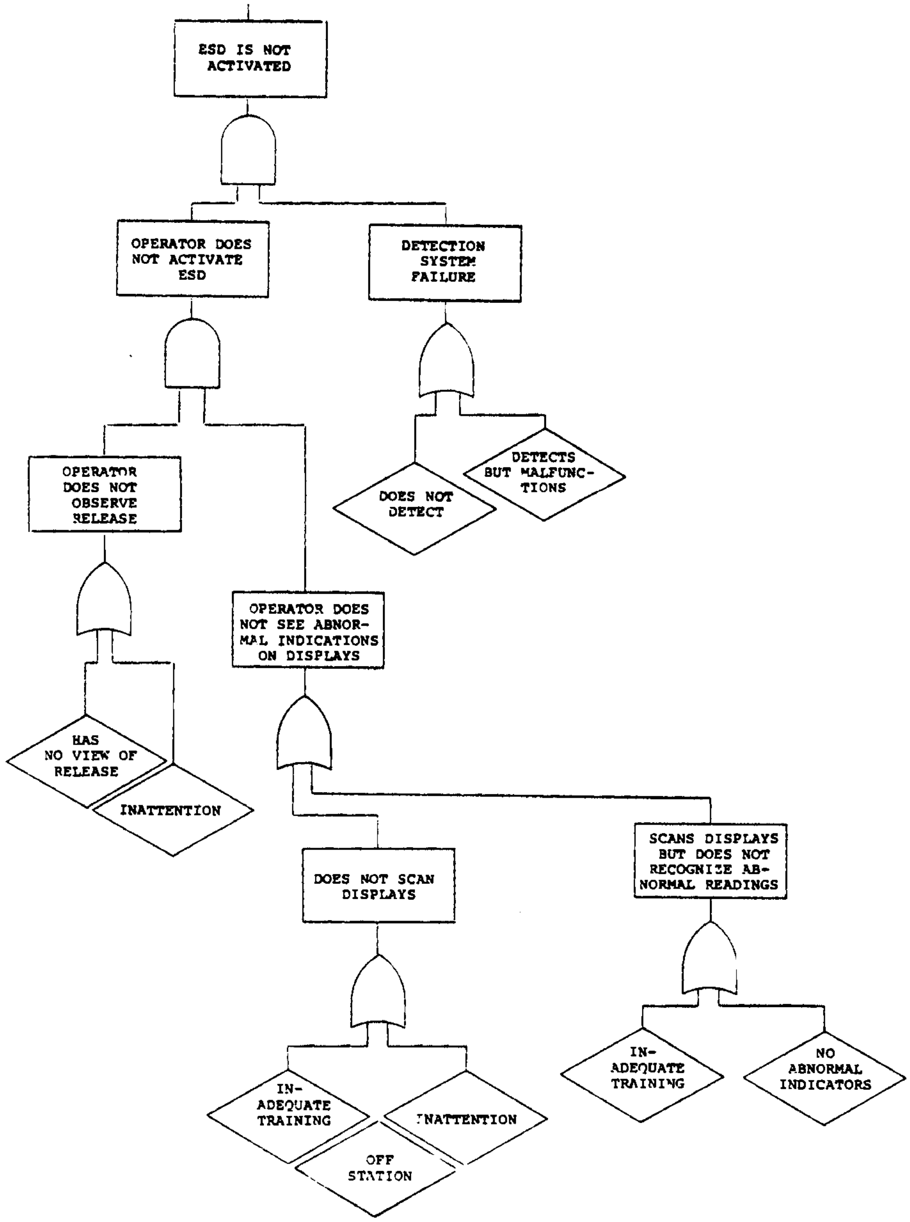

FIGURE 8.1. Preliminary Fault Tree of An Emergency Shutdown Failure

because he has no view of the area in which the leak occurs or, if such a view existed, because he was not scanning the grounds for a leak. Regardless, the operators likely spend little time visually scanning the grounds while working in the control room, so it is to be expected that the operators will likely not see releases of LNG. However, maintenance personnel and others who patrol the grounds are more likely to see a release.

The operator would also not activate the ESD if he did not notice any abnormal indications on the displays. He might not notice abnormal readings either because he does not scan the displays or, if he does scan the displays, because he does not recognize that the displays are indicating an abnormal condition. The operator may not scan the displays because he is off-station or because of inadequate training or because of inattention. The more interesting case is when the operator is attending to the displays, but does not recognize abnormal indications. This could be due to inadequate training as to what an abnormal indication is. For instance, the operators at TMI did not deduce that a relief valve had stuck open, even when the temperature indications in the piping outside the valve were above normal. The operators did not have adequate training regarding normal temperatures for this valve, especially for the unique conditions in which they found themselves.

The operator might also fail to recognize abnormalities if the controls and displays lack indications of normal and abnormal ranges. These indicators could be qualitative, as with annunciators or flashing lights, or quantitative, as with temperature and pressure indicators that had, for instance, red lines on them to indicate conditions outside the normal range. As noted earlier regarding the TMI accident, lack of abnormal indicators on a temperature read-out contributed to the seriousness of the accident.

In summary, the operator may fail to actuate the ESD manually if he does not observe the release or does not observe indications of abnormal conditions on the control panel. Lack of abnormal indicators is likely to be the more important event here. Further investigation is needed to determine whether enough abnormal condition indicators are present at LNG facilities for release prevention and control purposes.

8.2 STORAGE TANK OVERFILL

Figure 8.2 is a fault tree for the event in which the storage tank is overfilled. The causes for human error in this fault tree deal with inadequate training, operator inattention, the operator being off-station, past experience with erroneous signals, and operator distraction due to too many alarms being set off in the control room. In this example only operator distraction will be discussed in more detail.

It is possible that numerous devices signaling an abnormal condition could lead to confusion and perhaps an erroneous action on the part of the operator. Such has been the case in some nuclear power plants, for instance, due to the fact that several thousand annunciators are located in the control room. Also in a nuclear power plant control room, there are often several annunciators solidly lit because of known and accepted reasons. This condition could add to confusion during emergency situations. In severe situations, such as in the TMI accident, tens to hundreds of these qualitative warnings go off simultaneously with no prioritization. This situation can cause confusion on the part of the operator. However, because LNG plants have many fewer qualitative warning systems than nuclear plants, less confusion is likely to result from abnormal event indicators in LNG plants.

We should note that this fault tree was constructed assuming that two high level alarms, two high high level alarms, and a level detector with automatic shut-off were built into the system. While these devices are required at new LNG facilities by DOT regulations, they may not be standard for all existing facilities.

While only portions of two fault tree analyses were discussed in this chapter, numerous other events could occur at an LNG plant, and these events should also be analyzed using fault tree analysis. For example, Baker (1982) did a preliminary hazards analysis for an LNG import terminal. He analyzed, among other things, components that might be involved in an LNG release and the existing preventive or control measures for such a release for the marine terminal, the storage system, the vaporizer system, and the pump and compressor system. What is important from a human factors standpoint is that

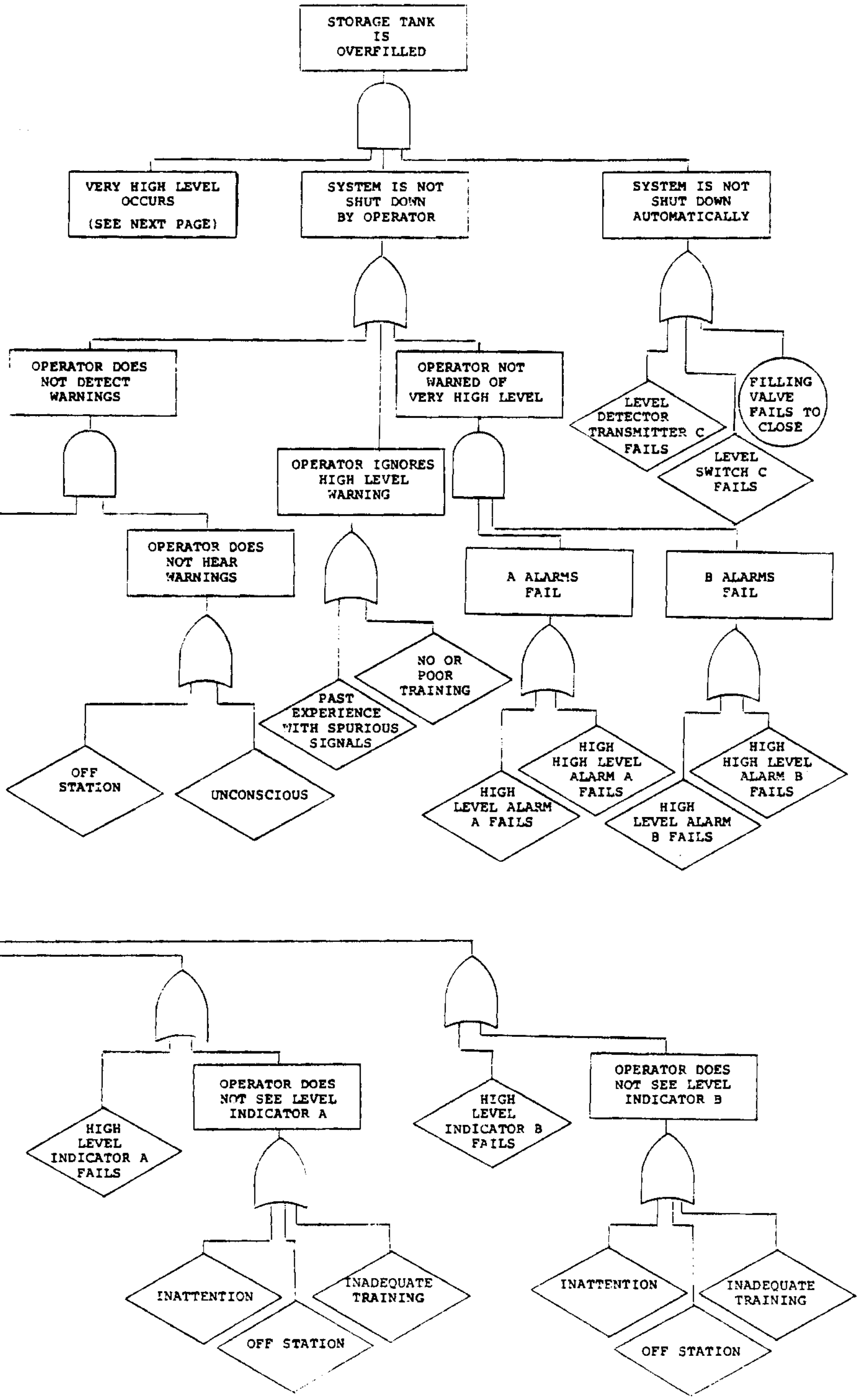

FIGURE 8.2. Preliminary Fault Tree of Storage Tank Overfilling

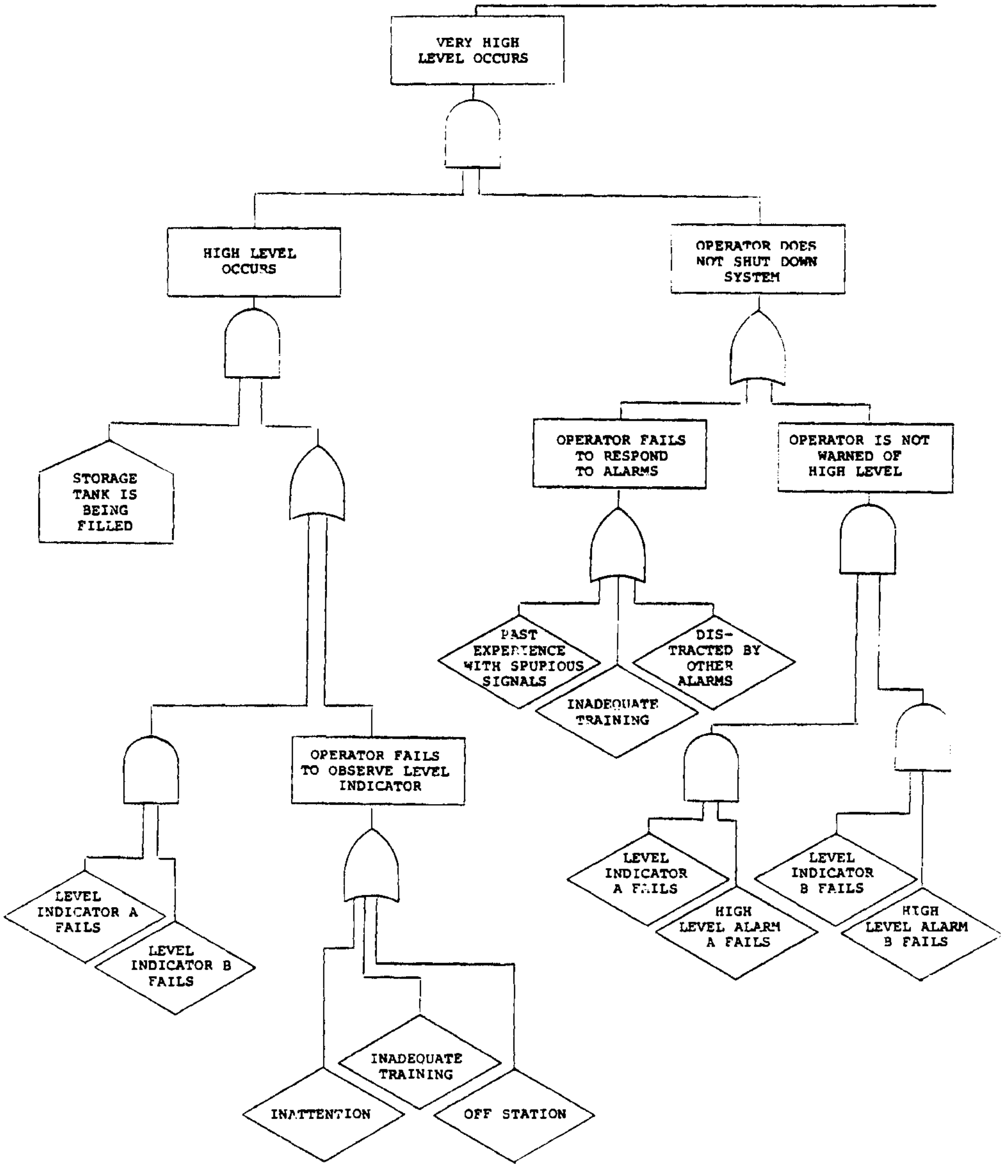

FIGURE 8.2. (Contd)

over half of the release control measures discussed involved some sort of operator action. Thus, their analysis points strongly to the need for operator training.

In summary, fault tree analyses of two events--emergency shutdown system failure and overfilling of an LNG tank--were considered in order to look at the human component in the fault events. Human errors could occur for several reasons. The most important reasons, from a release prevention and control perspective, deal with inadequate operator training, operator inattention, past experience with incorrect warning signals, and lack of quantitative and qualitative abnormal indicators or complete lack of relevant instrumentation. Analogies were drawn from the TMI incident indicating how these fault events have been involved in a nuclear power plant accident sequence. Although experience gained from site visits to LNG peakshaving plants indicate that LNG control rooms may have some of the same problems as do nuclear power plant control rooms, further research is necessary to determine the likely probability and the likely impact of these fault events.

9.0 SUMMARY AND RECOMMENDATIONS

This investigation of HF applications to LNG release prevention and control had four objectives: 1) to identify applications of HF in other industries that may bear upon potential applications in the LNG industry; 2) to determine the extent of current HF applications in the LNG industry; 3) to identify research needs in HF applications in the LNG industry; and 4) to investigate further the possible role of human error contributions to LNG release scenarios. This work focused on peakshaving facilities.

9.1 SUMMARY

There are numerous examples of HF applications outside of the LNG industry. The military/aerospace industry, the electrical generation industry, and the chemical processing industry, especially, have applied HF principles in the areas of design, construction, operation, and maintenance that have potential application in the LNG industry. The analysis of LNG accidents found that "human error" was a possible cause in several of the accidents, which indicates a need for HF application. Site visits to several peakshaving facilities also found that the potential for HF improvements at LNG facilities exists, especially with regard to the control room. The application of human error probabilities (HEPs) to fault tree analysis demonstrated another use of HF to the LNG industry.

9.2 RECOMMENDATIONS

Based on the above analyses, the following recommendations are made:

1. The work discussed in this report represents a first step. More peakshaving plants should be visited and HF considerations at other types of LNG facilities should be investigated.
2. Research should be conducted to determine the extent to which HF principles have been applied in the design and construction of LNG facilities. The present effort represented a start, but was limited by lack of familiarity with various types of facilities. This can

be accomplished by extensively interviewing the architect/engineering firms that were involved in the design and construction of the facilities to ascertain their HF approach, if any, in designing and constructing the facilities.

3. Additional work is needed to move specific recommendations concerning control panel improvements discussed in Chapter 5.0 into general guidelines for the incorporation of important human factors principles in the development of new or modified control panels at LNG facilities. As part of this effort, the role of the computer in the control room should be explored. As new facilities rely increasingly on computers, the issue of smooth transition of this type of control technology becomes more important. The LNG industry might benefit from the experiences of other industries or occupations that have recently converted to computer technology (e.g., FAA).
4. As discussed in Section 3 of this report, it is important to begin a more in-depth analysis of the human error contributions to previous LNG accidents. This can be approached in several ways. Recent past accidents should be investigated thoroughly from a HF perspective. Also, personnel intimately involved in the operation of LNG facilities should be interviewed to gain their insights regarding human error in operation and maintenance. In addition, incident records that LNG facilities keep should be collected and analyzed to determine the extent to which human error is contributing to the events. Finally, it is important for the industry to develop feedback and rapid dissemination methods to allow the industry to learn quickly about potential hazards, whether HF related or not.
5. To allow for more extensive fault tree analyses which incorporate the human component of the man-machine systems, LNG release events need to be more thoroughly analyzed for man-machine interaction. Specifically, personnel response to various potential release events should be articulated. The information needs of personnel to

respond appropriately to these situations, in terms of display and control requirements, can then be thoroughly assessed. The traditional method for doing this is to conduct detailed task analyses for both normal and abnormal conditions.

6. To facilitate the inclusion of the human component in fault tree analyses, the assessment of error rates for different types of operator actions discussed in Section 7 should be expanded and continually updated. This might involve a computerized search of the literature to determine recent advances in the state-of-the-art, as well as consultation and solicitation of expert judgments from professionals in the practice of HF.

7. A closely related area of research would be to evaluate thoroughly the procedure manuals for ease of use, readability, comprehensiveness, etc., especially for procedures pertinent to the release events deemed to have a relatively high likelihood of occurrence on the basis of preliminary hazard analyses.

8. The LNG industry should consider developing model programs for the selection, training, promotion, and career progression for operators and other personnel at the LNG facilities. These model programs might include such things as core training curricula and delineation of selection practices that have been shown to be related to good job performance. The model programs would then be tailored for site specific applications. Generic job task analyses would form an appropriate basis for developing such programs. As part of this program, the potential vigilance problems involved in operations, especially during graveyard shifts, might be investigated and mitigating strategies for overcoming the problems, if any, should be devised.

9. Finally, one area which has not been the subject of investigation in this effort but which should be explored in the future is the adequacy of the whole emergency response system in responding to an

LNG accident. The need for such response capabilities, which include local emergency response personnel, as well as facility personnel, should be explored. Lack of adequate attention to this point can result in ineffective system response in the event of an actual emergency.

10.0 REFERENCES

Accident Prevention Committee of the Operating Section of the American Gas Association. 1973. Introduction to LNG for Personnel Safety. Arlington, Virginia.

Allan, D., S. Atallah, E. Drake, R. Hinetley, and S. Mathias. 1974. Technology and Current Practices for Processing, Transferring and Storing LNG. PB-241 048, prepared for Department of Transportation, by Arthur D. Little, Inc.

Askren, W. B., ed. 1967. Symposium on Reliability of Human Performance in Space. Wright Air Development Center, Wright-Patterson Air Force Base, Aerospace Medical Research Center Laboratory.

Baker, C., ed. 1965. Visual Capabilities in the Space Environment. Pergammon Press, New York.

Baker, E.G. 1982. Analysis of LNG Import Terminal Release Prevention Systems. PNL-4152, Pacific Northwest Laboratory, Richland, Washington.

Beatty, D. 1969. The Human Factor in Aircraft Accidents. Stein and Day, New York.

Berkun, M. M. 1964. "Performance Decrement Under Psychological Stress." Human Factors, 6:21-30.

Brush, J. M., R. W. Douglass III, F. R. Williamson. 1974. In A Guide for Performing System Safety Analysis. Report (NASA-TM-x-64799) N74-13689, Martin C. Dorman, ed. A NASA Technical Memorandum from the George C. Marshall Space Flight Center, Alabama.

Chapanis, A. 1976. "Engineering Psychology." In Handbook of Industrial and Organizational Psychology, M. Dunnett, ed. Rand McNally, Chicago, Illinois.

Christensen, J. M., and R. G. Mills. 1967. "What Does the Operator Do in Complex Systems?" Human Factors, 9(4):329-340.

Churchill, A. V. 1956. "The Effect of Scale Interval Length and Pointer Clearance on Speed and Accuracy of Interpolation." Journal of Applied Psychology, 40(6).

Churchill, E., W. Thornton, J. Annis, J. McConville, L. Laubach, H. Reynolds, and H. Stoudt. 1978. Anthropometric Source Book Volume I: Anthropometry for Designers. NASA Reference Publication 1024.

Curry, R., D. Kleinman, and W. Hoffman. 1977. "A Design for Control/Display Systems." Human Factors, 19(5):421-436.

Davis, L. N. 1979. *Frozen Fire: Where Will It Happen Next?* Friends of the Earth, San Francisco, California.

Deatherage, B. H. 1972. "Auditory and Other Sensory Forms of Information Presentation." In Van Cott, H. P., and R. G. Kinkaide, eds., *Human Engineering Guide to Equipment Design*. McGraw-Hill, New York.

Department of Transportation. 1980a. *49CFR Part 193, Liquified Natural Gas Facilities; New Federal Safety Standards*. Part II, February 11.

Department of Transportation. 1980b. *49CFR Part 193, Liquified Natural Gas Facilities; Reconsideration of Safety Standards for Siting, Design, and Construction*. August 28.

Department of Transportation. 1980c. *49CFR Parts 192 and 193, Liquified Natural Gas Facilities; Federal Safety Standards*. Part III, October 23.

Federal Register. 1980. "Liquified Natural Gas Facilities; Federal Safety Standards, Final Rule and Proposed Rulemaking," 45(29):9184-9237.

Finlayson, F. C., T. A. Hassman Jr., K. R. Smith Jr., R. L. Crolius, and W. W. Willis. 1977. *Human Engineering of Nuclear Power Plant Control Rooms and Its Effects on Operator Performance*. ATR-77(2915)-1, The Aerospace Corporation, El Segundo, California.

Finnegan, J. P., T. W. Rettig, and C. A. Rau Jr. 1979. *The Role of Personnel Errors in Power Plant Equipment Reliability*. Electric Power Research Institute, Palo Alto, California.

Fire Journal. 1972. "LNG Plant Explosion," pp. 38-39.

Fitts, D. M. 1951. Engineering Psychology and Equipment Design. In S. S. Stevens, ed. *Handbook of Experimental Psychology*, pp. 1287-1340, Wiley, New York.

Fitts, D. M., and R. E. Jones. 1947. *Psychological Aspects of Instrument Display. I: Analysis of 270 "Pilot Error" Experiences in Reading and Interpreting Aircraft Instruments*. Report ISEAA-694-12A; Aero Medical Laboratory, Air Material Command, Dayton, Ohio.

Gagne, R. M., ed. 1962. *Psychological Principles in System Development*. Rinehart & Winston, New York.

General Accounting Office. 1978. *Liquified Energy Gases Safety*. EMD-78-28, Vol. I-III. Report to the Congress of the United States by the General Accounting Office.

Harris, D. H., and F. B. Chaney. 1969. *Human Factors in Quality Assurance*. John Wiley & Sons, Inc., New York.

Hopkins, V. David. 1970. *Human Factors in the Ground Control of Aircraft*. AGARD-AG-142-70, North Atlantic Treaty Organization, Advisory Group for Aerospace Research and Development, London.

Hornyak, S. J. 1967. *Effectiveness of Display Subsystem Measurement and Prediction Techniques*. Report RADC-TR-67-292, Rome Air Development Center, Griffiss AFB, New York.

Joos, D. W., Z. A. Sabri, and A. A. Husseiny. 1979. "Analysis of Gross Error Rates in Operation of Commercial Nuclear Power Stations." *Nuclear Engineering and Design*, 52:265-300.

Kappauf, W. E. and W. M. Smith. 1948. *Design of Instrument Dials for Maximum Legibility--II, A Preliminary Experiment on Dial Size and Graduation*. MCREXD-694-IN, Air Material Command, Wright-Patterson Air Force Base, Ohio.

Kappauf, W. E., W. M. Smith, and C. M. Bray. 1947. *Design of Instrument Dials for Maximum Legibility: I. Development of Methodology and Some Preliminary Results*. Memorandum Report T5EAA-694-IE, Army Air Forces, Air Material Command.

Katz, D. L., and H. H. West. 1975. "The Overall Problem - Risk/Benefit for LNG Shipping and Storage." In D. Okrent, ed., *Risk-Benefit Methodology and Application: Some Papers Presented at the Engineering Foundation Workshop, September 22-26, 1975, Asilomar, California*. UCLA School of Engineering and Applied Science, Los Angeles, California.

Keeney, R., R. Kulkarni, and K. Nair. 1979. "A Risk Analysis of an LNG Terminal." *OMEGA*, 7(3):191-205.

Lewis, H. W., R. J. Budnitz, W. D. Rowe, H. J. C. Kouts, F. von Hippel, W. B. Loewenstein, and F. Zachariasen. 1978. *Risk Assessment Review Group Report to the U.S. Nuclear Regulatory Commission*. NUREG/CR-0400.

Lloyd's Register of Shipping. 1977. Lloyds, London, p. 3.

Loftus, G., V. Dark, and D. Williams. 1979. "Short Term Memory Factors in Ground Controller/Pilot Communication." *Human Factors*, 21(2):169-181.

Malone, T. B., M. Kirkpatrick, K. Mallory, D. Eike, J. H. Johnson, and R. W. Walker. 1980. *Human Factors Evaluation of Control Room Design and Operator Performance at Three Mile Island-2*. NUREG/CR-1270, U.S. Nuclear Regulatory Commission, Washington, D.C.

McCormick, E. J. 1964. *Human Factors Engineering*. 2nd Ed., McGraw-Hill Company, New York.

Meister, D. 1971. Human Factors: Theory and Practice. John Wiley and Sons, New York.

Merren, G. T., R. G. Esterling, and A. D. Swain. 1975. Uses of Reliability Techniques in Evaluation of Nuclear Power Plants. SAND76-0325 (NUREG-76/6504), Sandia National Laboratories (available only in U.S. Nuclear Regulatory Commission Reading Room).

Morgan, D., J. Cook, A. Chapanis, and M. Lund, eds. 1972. Human Engineering Guide to Equipment Design. McGraw-Hill, New York.

Murrell, K. F. H., W. D. Laurie, and C. McCarthy. 1958. "The Relationship Between Dial Size, Reading Distance, and Reading Accuracy." Ergonomics, 1:182-190.

Mott, M. 1975. LNG Terminal Risk Assessment Study for Los Angeles, CA. SAI-75-614-LJ, prepared for Western LNG Company by Science Applications, Inc.

National Transportation Safety Boards. 1980. Pipeline Accident Report: Columbia Liquified Natural Gas Corporation Explosion and Fire, Cove Point, Maryland, October 6, 1979. NTSB-PAR-80-2, Bureau of Accident Investigation, Washington, D.C.

Pelto, P. J., E. G. Baker, T. B. Powers, A. M. Schreiber, J. M. Hobbs, and P. M. Daling. 1982a. Analysis of LNG Peakshaving Facility Release Prevention Systems. PNL-4153, Pacific Northwest Laboratory, Richland Washington.

Pelto, P. J., E. G. Baker, G. M. Holter, and T. B. Powers. 1982b. An Overview Study of LNG Release Prevention and Control Systems. PNL-4014, Pacific Northwest Laboratory, Richland, Washington.

Porricelli, J. D., V. E. Keith, and B. Paramore, eds. 1976. Recommendations for Qualification of Liquified Natural Gas Cargo Personnel, Volume II, Appendix C: Functional Job Analysis of Tasks for Cargo Operations of a Liquified Natural Gas Cargo Ship. NTIS No. AD-A-026 109, Operations Research, Inc., Silver Springs, Maryland, and Engineering Computer Optecnomics, Inc., Arnold, Maryland.

Porricelli, J. D., V. E. Keith, and B. Paramore, eds. 1976. Recommendations for Qualifications of Liquified Natural Gas Cargo Personnel, Volume III, Appendix D: Functional Job Analysis of Tasks for Cargo Operations of an Unmanned Liquified Natural Gas Barge. NTIS No. AD-A026 110, Operations Research, Inc., Silver Springs, Maryland, and Engineering Computer Optecnomics, Inc., Arnold, Maryland.

Rabideau, G. F., J. I. Cooper, and C. Bates. 1961. A Guide to the Use of Function and Task Analysis as a Weapon System Development Tool. Report NB-60-161, Northrup Corporation, Hawthorne, California, 1961.

Rogovin Commission Report. 1980. Three Mile Island: A Report to the Commissioners and to the Public. Volume I, Nuclear Regulatory Commission Special Inquiry Group, Washington, D.C.

Ronan, W. W. 1953. Training for Emergency Procedures in Multi-engine Aircraft. IAR-153-53-FR-44, American Institutes for Research, Pittsburgh, Pennsylvania.

Roscoe, S. 1979. "When the Day is Done and Shadows Fall, We Miss the Airport Most of All." Human Factors, 21(6):721-731.

Rouse, W. 1979. "Problem Solving Performance of Maintenance Trainees in a Fault Diagnosis Task." Human Factors, 21(2):195-203.

Sells, S. B., and C. A. Berry, eds. 1961. Human Factors in Jet and Space Travel: A Medical-Psychological Analysis. The Ronald Press Company, New York.

Seminara, J. L., W. R. Gonzalez, and S. O. Parsons. 1976. Human Factors Review of Nuclear Power Plant Control Room Design. EPRI NP-309 and EPRI NP-309-2Y (Summary), Lockheed Missiles & Space Company for the Electric Power Research Institute.

Seminara, J. L., S. K. Eckert, S. Seidenstein, W. R. Gonzalez, R. L. Stempson, and S. O. Parsons. 1979. Human Factors Methods for Nuclear Control Room Design. EPRI Report NP-1118 (3 volumes), Palo Alto, California.

Swain, A. D. 1969. Human Reliability Assessment in Nuclear Reactor Plants. SCR-69-1236.

Swain, A. D. 1975. Preliminary Human Factors Analysis of Zion Nuclear Power Plant. NUREG-76/6503, (available only in U.S. Nuclear Regulatory Commission Reading Room).

Swain, A. D., and H. E. Guttman. 1974. Human Reliability Analysis Applied to Nuclear Power. SAND74-5379, Sandia National Laboratories, Albuquerque, New Mexico.

Swain, A. D., and H. E. Guttman. 1980. Handbook of Human Reliability Analysis with Emphasis on Nuclear Power Plant Applications. NUREG 1Cr-1278, Sandia National Laboratories, Albuquerque, New Mexico.

Teel, K. S. 1971. "Is Human Factors Engineering Worth the Investment?" Human Factors, 13(1):17-21.

The Human Factor in Metals Plant Operations and Design. 1976. Proceedings of a conference organized by The Metals Society in association with The Ergonomics Society, London, England, December 1-2.

Van Cott, H., and R. Kinkade, eds. 1972. Human Engineering Guide to Equipment Design. McGraw Hill, New York.

Vernon, M. D. 1946. Scale and Dial Reading. A.P.U. 49, Medical Research Council Unit in Applied Psychology, The Psychological Laboratory, Cambridge, England.

WASH-1400 (NUREG-75/014). 1975. Reactor Safety Study--An Assessment of Accident Risks in U.S. Commercial Nuclear Power Plants. U.S. Nuclear Regulatory Commission, Washington, D.C.

Weiner, E. L. 1977. "Controlled Flight into Terrain Accidents; System Induced Errors." Human Factors, 19(2):171-181.

Welker, J. R., L. E. Brown, J. N. Ice, W. E. Martinson, and H. H. West. 1979. Fire Safety Aboard LNG Vessels. Report No. CG-D-94-76 (NTIS No. AD-A030619). Final report submitted to the Department of Transportation by the U.S. Coast Guard, Office of Research and Development, Washington, D.C.

Williams, A. C., and W. F. Grether. 1947. Speed and Accuracy of Dial Reading as a Function of Dial Diameter and Spacing of Scale Divisions. Memorandum Report TSEAA-694-IE, Army Air Forces, Air Material Command.

Wolf, S. M. 1978. "Liquified Natural Gas." Bulletin of the Atomic Scientists, 34(10):20-25.

APPENDIX A

HUMAN FACTORS: BASIC CONSIDERATIONS

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HUMAN FACTORS: BASIC CONSIDERATIONS

Human factors (HF) engineering is best understood from a systems perspective. HF is that discipline which has as its major concern the interface between humans and machines in man-machine systems. When the man-machine interface is a very important aspect of the system, as it is for a jet-fighter pilot, for instance, HF should be involved in the design, test, operation, evaluation, and maintenance of the system. Prerequisite knowledge for performing HF analyses includes information concerning typical human performance, as well as human performance capabilities and limitations, especially under a full range of conditions (e.g., from highly stressful to completely non-stimulating). In addition, the HF analyst should be intimately familiar with the design features of the machine and know what design features are likely to result in optimal human performance. Finally the HF analyst should be knowledgeable about "human resources," including appropriate selection, training, and staffing for the human part of the man-machine system. Chapanis (1976) indicates that HF draws from the following areas of specialization: engineering, anatomy, anthropometry, applied physiology, engineering psychology, environmental medicine, sociology, toxicology, operations research, and industrial design. All of these functions make HF sound like a superhuman job, but it must be emphasized that, in line with a systems approach, the HF analyst is part of a research team working on the development, design, and testing of the given man-machine system.

The specification of a man-machine system is a delineation of a set of components whose purpose is to perform a certain function. These components consist not only of the machinery and equipment needed to perform the function, but also the humans who must interact with that machinery. It is true that many operations once performed by humans may now be done by machines, yet these machines must be built, maintained, operated and evaluated by humans. In order for HF considerations to have their greatest impact, they should be included from the initial stages of system design through the final stages of operation and maintenance. Although there is no rigid format to which all human factors engineers conform, a summary of the steps generally taken in human factors design is outlined in the following paragraphs. This description of the discipline is based principally on sources such as Meister (1971); Brush, Douglass, and Williamson (1974); Van Cott and Kinkade (1972) and Gagné (1962).

A.1 SYSTEM ANALYSIS

To conduct almost any version of a system analysis, it is first necessary to state explicitly what the purposes or goals of the system are to be. Generally, the analyst will work from broad goals (e.g., safely processing LNG) to more specific goals (e.g., safely loading LNG into a tanker truck). Once a sufficient amount of detail has been obtained in describing the inputs and functions required to achieve the desired system outputs, the specific functions must then be assigned to either machines or men. The decision to allocate a given set of functions either to a man or to a machine is based on the differential capabilities of men and machines (see Fitts 1951). Humans are capable of performing a wider variety of tasks and are far more adaptable to modification and circumstance than are machines, yet machines may perform a task with much less variability in performance and may also be designed to perform functions of which humans are not physically capable (Gagné 1972). With these and other considerations in mind, the HF analyst may devise a set of alternative man-machine configurations for a specific set of tasks. The decision between these configurations is based on the relative weights of various factors such as cost, safety, reliability, maintainability, etc. (Meister 1971).

After the man-machine configurations have been specified, the HF must describe and analyze each human-performed task in detail. First, the higher order tasks are listed, and they in turn are broken down into corresponding subtasks (see Rabideau, Cooper and Bates 1961; Christensen and Mills 1967). The purpose of this taxonomy is to determine the optimal operational sequence and to suggest what equipment characteristics are required by each task.

A.2 EQUIPMENT DESIGN AND PROCEDURES

Wherever the man-machine system contains equipment operated by humans, the HF analyst attempts to design the equipment to decrease the probability of an error in task performance. Selection of these control/display components is based on state-of-the-art information as to the reliability of various controls and displays for certain tasks. Standards for human engineering criteria applicable to the military are available in many publications such as MIL-STD 1472, Van Cott and Kinkade (1972), Morgan et al. (1972), and Churchill et al. (1978). Once the type of control is specified, other engineering criteria such as reliability and maintainablity may dictate which specific piece of hardware will be used. The controls themselves also have an optimum layout configuration, and so does the location and arrangement of the control/display panels. Despite the vast amount of information available on equipment design and operation, any particular project is very likely to require some unique procedures and equipment. In these cases the HF analyst is equipped to determine experimentally the reliability and human factors considerations through mock-up procedures and data collection for important tasks.

Procedures and instructions for operation are largely derived from previous design considerations. Most, but not all, procedures are determined by equipment considerations. Where this is not the case, procedures are designed with other human factors considerations in mind such as ease of operation, time of operation, etc. Of utmost importance in the design of procedures is the elimination of conditions which impose excessive demands on personnel and consequently lead to errors in that or later steps of operation.

A.3 SYSTEM SAFETY ANALYSES

As described by Brush et al. (1974), in the context of the NASA mission, a first step in a system safety analysis is the development of a functional hazard analysis. This analysis is a broad statement of potentially hazardous events associated with system operation (e.g., major LNG tank fire). The purpose is to provide a general idea of what events pose a serious threat to safety and with what part of the operational system they are associated.

The information from a functional hazard analysis is used as a basis for a fault hazard analysis. The intent of the fault hazard analysis is to identify under precisely what conditions system failures can occur which would endanger safety. The HF analyst is particularly interested in procedural discrepancies, errors in operator behavior, and parameters of tasks, operation, and maintenance that could lead to system failure. These considerations are fundamental to a fault hazard analysis. Potential predisposing conditions for such human-related failures include task difficulty, environmental stress, poor human factors design (especially controls), unskilled personnel operating dangerous equipment, and lack of appropriate training.

If the HF team identifies areas that are potentially hazardous as a consequence of human error, it is then desirable to obtain an estimate of the probability of occurrence of such an event for purposes of comparison. This may be done either by reference to one of the many manuals designed for this purpose (e.g., Morgan et al. 1972; Hornyak 1967), or, preferably, by a statistical estimation based on data collected on site. Human factors considerations are then employed in the effort to redesign the system to eliminate those conditions that have been identified as contributors to the probability of an undesired event. In many cases redesign may be achieved through minor changes such as interlocks, procedure changes, use of appropriate reference manuals or training.

A.4 SUMMARY

The HF analyst attempts to either build or revise a system to exploit the capabilities of its human components, or remove conditions which predispose humans to poor performance. This may be done with respect to specific goals, such as maximizing system safety or system efficiency. The achievement of such goals requires an explicit statement of human functions and tasks and decisions on how equipment should be designed to match these activities.

APPENDIX B

HUMAN FACTORS APPLICATIONS IN THE MILITARY AND AEROSPACE

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HUMAN FACTORS APPLICATIONS IN THE MILITARY AND AEROSPACE

Human factors engineering has its longest history in the military and aerospace industries. This approach has been an integral part of equipment design and operation in these fields since World War II (Meister 1971). The importance of HF in military and aerospace is a consequence of the low tolerance for inefficiency or error in equipment operation for these industries. For much of the private sector individual errors may be of little consequence to overall system performance. Even so, HF applications have been demonstrated to be effective in improving production quality (Harris and Chaney 1969) and is pertinent to worker reliability (Askren 1967) even when many human errors must be eliminated in order to achieve a significant improvement in system performance. In the military and aerospace fields, human error may have far more serious consequences; a missile off target or a circuit breaker left open may constitute not only a mission failure, but a danger to life as well. Thus, it is not surprising that HF is well established in applications for which a single operator-initiated error may endanger many lives.

To separate out the contributions and applications of human factors from aerospace and the military is an impossibility. Both these industries have a special interest in minimizing human errors since these types of failings are both frequent and serious. An entire book, The Human Factor in Aircraft Accidents (Beatty 1969) is devoted to accounts of serious aircraft accidents and typical scenarios in which human error nearly, or in fact did, lead to catastrophe. Beatty estimates that roughly half of all serious aircraft accidents are attributable to pilot error. These are also claimed to represent a disproportionately large percentage of accidents resulting in fatalities. Pilot error is not limited to civilian aircraft, nor are the serious consequences of human error limited to civilian systems. As long ago as 1947, Fitts and Jones analyzed 270 pilot error experiences, concluding that most of these errors were a result of poor HF applications. The types of errors analyzed included misreading instruments (altimeter, tachometer, air speed, etc.), and misinterpreting direction of bank, pitch, etc. Similarly, Meister (1971), has listed examples of human initiated failures in missile launch systems which endangered not only the mission, but the lives of crew members and civilians. In one case the inadvertent flip of a switch resulted in a missile falling miles short of its target; in another, improper sequencing of operations resulted in a missile flying erratically and nearly crashing into a populated area. The number of such errors occurring in the military and aerospace industries is not estimable, as many such events go either unnoticed or unreported. Clearly though, the application of HF principles to these industries is most appropriate since human errors are common, and their consequences serious.

That a pilot, or operator of some system, is likely to make errors does not imply that the propensity for error is inherent to that individual or humans in general. Rather, it suggests that there are components of the system which predispose it to malfunction. In the case of piloting an aircraft, a pilot error may simply be the end result of a poor communications system, control design, or other inadequate system component. Indeed, Weiner (1977) points out that:

> . . . errors [are] generated by a complex air traffic control system with ample opportunities for system induced errors. Problem areas [include] pilot-controller communications, flightdeck workload, noise abatement procedures . . . etc. (p. 171)

Weiner ascribes much of these problems to inadequate human engineering in the air traffic control area. This is very much in agreement with the observation of Jones and Fitts thirty years earlier--that pilot error is often a result of poor design. The point here is that human error is avoidable. The HF discipline assumes that human errors are a result of poor system design. That is, the tasks assigned to humans are either inappropriate to human capacities, or the tools and information provided to complete those tasks are inadequate. The military and aerospace industries are far ahead of other areas in locating the sources of human errors. Aside from the studies already mentioned there is considerable data available as to the loci of human errors in the military and aerospace. For example, Roscoe (1979) has classified serious pilot errors resulting from illusions and misjudgments when flying over water and breaking out of clouds. An informed pilot can use this information to his/her advantage, as can the aircraft designer. Loftus et al. (1979) have also reported data that indicate that humans' inherent limitations in short term memory should be taken into account when planning ground controller/pilot communication systems. Any communication system which ignores the limitations of human memory and attention will likely prove ineffective in conveying information to and from humans. When one exceeds the capacities of the human information processing system, the additional information is lost. If that information is important, its loss will likely lead to error(s).

Up to this point emphasis has been placed on the operator of a system in operation. While this source of human error is indeed important, it is at least as important to design equipment and tasks so as to facilitate maintenance. Military, aerospace, and private industry have all emphasized the importance of maintenance and inspection on overall system operation. Maintenance procedures, among other things, generally are dependent on inspection and troubleshooting. The available data indicate that the quality of maintenance depends both on aspects of the equipment to be maintained (Harris and Chaney, 1969) and the procedures used in maintenance (Rouse, 1979). Many systems (LNG processing notwithstanding) rely on proper maintenance to function efficiently and safely. If maintenance is inadequate as a result of poor design or maintenance procedures, system operation will suffer accordingly.

Perhaps the most significant contribution the military has made to the human factors discipline has been the development of standards for HF applications. Without such a reference guide a unified approach to any analysis would be difficult. Whether one wishes to analyze a system in operation or to use HF as a guide to system design, these standards are an invaluable source. The Human Engineering Guide to Equipment Design, first edited by Morgan et al. (1963) and subsequently revised by Van Cott and Kinkade (1972), is also a standard reference for HF considerations.

However well developed the HF discipline might be, it is of considerable interest whether this type of analysis actually pays off in the long run. Although sources of human error may be expounded upon at great length, the cost effectiveness of eliminating such errors is a separate question. The value of a safe system is difficult to quantify, and it is probably sufficient to note that the empirical approach of the HF discipline allows a relatively unbiased estimate of the ability of a given design to conform to system standards. This issue has not gone unresearched. Teel (1971) conducted three separate evaluations of the cost effectiveness of HF applications for a military contractor. One study evaluated the effects of using visual aids designed to improve the performance of machined-parts inspection. As is often the case with inspection tasks, performance before any redesigning took place was poor (about 40% effective). The HF improvement significantly enhanced the performance of the inspectors; the average percent improvement was 42%. This improvement resulted in a savings of four times the cost of the research over a three year period. Electronic assembly work was reviewed by an HF analyst and an industrial engineer who designed job aids to improve performance. Workers using job aids were both faster and less likely to make errors than when they worked without the aids (64% less time, 75% fewer errors). This improvement resulted in a net savings to the company. Similarly, a study designed to verify the audibility of a toxic propellant warning system in a missile launch facility prevented the purchase of an expensive alternative system. Other research has shown significant improvement of inspecting with HF applications, (e.g., Harris and Chaney 1969).

Human factors engineering is an integral part of the military and aerospace industries. The discipline has made contributions in system design in these areas with respect to operator performance, reliability, equipment design and maintainability. Equally as important, these industries have used the empirical approach of HF for system and component evaluation. HF applications have proven, in these industries, to be a cost effective method of assuring efficient and safe system operation.

APPENDIX C

HUMAN FACTORS APPLICATIONS IN NUCLEAR POWER PLANTS

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HUMAN FACTORS APPLICATIONS IN NUCLEAR POWER PLANTS

This appendix briefly summarizes much of the HF work in the nuclear power industry. The first major use of HF in the industry was in the Rasmussen Report, which used human error probabilities in estimating reactor safety. This report is summarized. It is followed by a summary of research, conducted by Seminara et al. and Finlayson et al., which were HF reviews of nuclear power plants. Finally, information about the HF implications of the TMI accident from Malone et al. and from the Rogovin Commission Report is summarized.

C.1 THE RASMUSSEN REPORT

One major use of HF in the nuclear industry was employed in the WASH-1400 Reactor Safety Study (1975, Appendix III, p. III-59ff). Data or "best estimates" regarding human reliability were used to estimate the influence of human errors on the unavailability of different reactor safety systems. Most of the error rates used were based on the judgment of HF analysts who were familiar with reactor systems. A second data source was error rate data from military weapons production, maintenance, and testing. These estimates were then modified by independent judgments of two human reliability experts after they reviewed information on operator skill levels, operator job history, operating procedures, and the design of controls, displays, and other equipment read or manipulated by the operator.

The modifications were based on seven criteria: level of presumed psychological stress, quality of human engineering of controls and displays, quality of training and practice, presence and quality of written instructions and methods of use, coupling of human actions, type of display feedback, and personnel redundancy. These factors are discussed in more detail below.

C.1.1 Stress.

WASH-1400 attempted to estimate human errors following a large loss of coolant accident (LOCA), which was considered to be a highly stressful situation, by extrapolation from two classic studies in the field of HF. The first study (Ronan 1953) related stress and error rates to frequencies of errors that were reported by World War II bomber crews after successful completion of a mission that involved an in-flight emergency. The critical incident error rate was 0.16. That is, 16% of the time the critical actions of the crew either made things worse, or, at best, did not alleviate the situation. In the second study (Berkun 1964), new Army recruits were subjected to simulated emergencies in such a way that they were lead to believe that the situation was real (e.g., an increasing proximity of falling mortar shells). Nearly one third of the new recruits fled in panic rather than perform their assigned task. These studies were used as a basis for assuming that error rates following a highly stressful situation, such as a LOCA, would range from 0.2 to 0.3. In general, the relationship of stress to human error was considered in WASH-1400 to be curvilinear. That is, at very low stress levels, where the task is so dull that operators would not be expected to perform at optimal levels, and at very high stress levels, the error rate is assumed to be highest, with the error rate approaching 1.0 as the stress increases. The lowest error rates were assumed for medium stress levels. These assumptions were later challenged by Finlayson et al. (1977), who felt that the relationship of stress to performance was too complex and not yet understood well enough for WASH-1400 to assume the specific curvilinear relationship that was used. Also, studies of the TMI accident have concluded that stress did not seem to affect operator actions during the accident (see Rogovin Commission Report 1980).

C.1.2 Controls.

Higher error rates were assigned to operator actions that were dependent upon potentially confusing displays and controls. In many cases, error rates taken from military sources were raised by the independent judges, since it was their opinion that the design of controls and displays deviated from the

HF standardized practices developed for the military. Later HF analyses of nuclear power plant control rooms agreed with this opinion.

C.1.3 Training.

On the basis of interviews, observation, visits to training centers, and a review of training materials, the level of training for control room operators was judged to be outstanding for normal operations. However, training for emergency situations was judged to be inadequate, so that presumed error rates were assumed to be fairly high for emergency situations.

C.1.4 Written Instructions.

The quality of written procedures was analyzed by examining such factors as: the ease with which emergency procedures could be located, the extent to which the format would facilitate operator performance, and the likely ease of understanding nonroutine instructions. The experts concluded that the instructions were poorly written, the quality of printing was poor, there was no distinctive binder or location for emergency procedures, there was a lack of tabs and other indexing aids which made it difficult to find specific procedures, and the procedures were poorly formatted.

C.1.5 Coupling of Actions.

The coupling of human actions refers to the extent to which performance of one action depends on performance of a second action. Coupling ranges from complete independence to complete dependence. An example of tight coupling is the calibration of several displays, which are located together and which are to be calibrated to the same reading. Thus, if maintenance personnel miscalibrate the first display, they are likely to do so on the others. In many cases, tight or complete coupling of important information sources were found to exist in control rooms.

C.1.6 Display Feedback.

The type of display feedback dealt with whether data was presented to the operator directly (e.g., on a dial or through the use of an annunciator) or whether the operator had to infer information (e.g., inference based on a slow change in a meter reading or the difference between two meter readings). Some important parameters in a nuclear power plant must be inferred, and therefore are more likely than others to contribute to a reactor accident.

C.1.7 Personnel Redundancy.

Finally, the amount of personnel redundancy (use of second person to verify performance of first) for operation and maintenance functions was examined. In general, the WASH-1400 HF analysts found that there was a high degree of personnel redundancy for calibration operations, a lower degree of personnel redundancy for operator tasks such as manipulating motor operated valves (for which good feedback instrumentation is rarely available to operators), and the lowest degree of personnel redundancy for maintenance tasks.

All of the above considerations were used by the HF experts to make estimates or to change existing estimates of human error probabilities. These estimates were then incorporated with failure rates for equipment to make overall probability estimates for the likelihood of reactor accidents.

C.1.8 Comments on the Rasmussen Report

The use of HF to make error rate estimates was not without its critics, however. The Risk Assessment Review Group Report to the U.S. Nuclear Regulatory Commission (NUREG/CR-0400), (Lewis et al. 1978) found several limitations regarding WASH-1400. First, the data base was weak and relied extensively on expert judgment (readily admitted by WASH-1400 authors). Second, time dependent information about operator responses were not incorporated into WASH-1400. Third, operators and other personnel might make matters better or worse in ways that are hard to analyze. Thus, fourth, there may be a great amount of uncertainty as to the role that control room operators and other personnel should play during an accident. (This point was realized during the TMI accident, when operators had to decide when to move from a monitoring status--i.e., watching the plant's safety system work automatically--to an operating status--i.e., taking over from the automatic status by shutting off the high pressure injection system.) With no quantitative basis for their belief, Lewis et al. (1978) also stated that they felt that WASH-1400 underrated human problem-solving abilities during accident conditions, but that some event trees where human error might have severe consequences might have been overlooked. The latter point has oft been repeated by antinuclear groups.

Finlayson et al. (1977) also offered comments about the HF applications in WASH-1400. Besides their criticisms about the effect of stress on performance, which was discussed earlier in this section, they also questioned the accuracy and utility of exact error estimates. Instead, they stressed the comparative use of error estimates (e.g., which of two dials is more easily read). Finlayson et al. (1977) did not argue against research to determine absolute human error levels. They simply felt that precise enough data did not yet exist for WASH-1400 to make absolute error judgments. (Research for determining error rates has been and is still being carried out by Swain and his coworkers at Sandia Laboratory [e.g., Swain 1969, 1975; Swain and Guttman 1975; Merren, Esterling, and Swain 1975]).

WASH-1400 strongly suggested that HF applications had been neglected, to the detriment of operator performance, by the nuclear industry. Studies in the mid-1970s by Seminara et al. (1976) and Finlayson et al. (1977) strongly confirmed these suggestions. These studies will be discussed in some detail below, because of the importance of their findings and because of their relevance of HF to the LNG industry.

C.2 THE SEMINARA ET AL. STUDIES

The EPRI sponsored Seminara et al. (1976) study reviewed the HF aspects of five control room simulators and their corresponding operational plants, which became operational in the mid-1970s. Their general purpose was to evaluate nuclear power plants, with special emphasis on the control room, relative to industries where HF has played a significant role and to estimate the significance of any differences that were uncovered in terms of the effects on reactor safety and plant reliability.

C.2.1 Study Design

Seminara et al. (1976) evaluated the five control rooms and five control room simulators using several different methods of data collection. First, using military standards, they devised a 111-page checklist containing HF evaluation criteria pertinent to control board design, anthropometrics, controls, indicator lights, meters, chart recorders, annunciator-warning systems, coding of displays and controls, and labeling. Second, control room dimensions, illumination levels, and actuation force requirements were measured, and a photographic record was made. Third, a 51-question structured interview (averaging 2.5 hours) was carried out on 53 operators and trainers. Fourth, direct observations were made of operators' behaviors. Fifth, selected operator tasks and procedures were analyzed using task analysis. Finally, records of operational errors at the five operating plants were analyzed. The results are summarized below.

C.2.2 Control Room Design

With regard to control room design, Seminara et al. (1976) concluded that insufficient attention had been given to the abilities and limitations of reactor operators. A 59% majority of those surveyed felt that the control room was too large. All of the plants had relegated some instrumentation and controls to the back panel area, where they were not easily accessed. Four of the five plants did not have a place to rest procedural manuals when they were being used. Control room illumination was generally inadequate (lights were often lowered to reduce the glare on the instrumentation), and there were complaints voiced by the survey repondents regarding lack of an adequate air conditioning/heating system and the smell of diesel fumes. Subjectively, the research team evaluated the control rooms as rather drab and dingy.

C.2.3 Control Board Design

Control board design was in need of improvement. Control boards were too big, requiring too great a visual span and control span for the operators. Control board design was not optimized for minimum manning requirements. There was a lack of functionally segregated control panel areas, which could cause operator confusion. The large number of identical components compounded this problem. Functionally related controls and displays were often separated in space, such that two-person operations became necessary. Finally, one control room had mirror image control panels, which grossly violates psychological principles regarding transfer-of-training and memory interference.

In general, the designers of reactor control rooms have segregated the components into three groupings: the controls are on bench boards, quantitative displays (meters, etc.) are on a vertical wall immediately above the benchboard, and qualitative displays (annunciators and warning lights) are located higher still. This segregation does not allow functional grouping. Since most operators have a preference for functional grouping, the operators have often used crude methods (e.g., tape) to provide for some functional grouping. Finally, Seminara et al. (1976) noted that control panels outside the main control room revealed an even more serious lack of HF application.

With regard to the components proper, large and cumbersome selector switches were often used where smaller switches would serve better. Some control pointers had pointing and nonpointing ends that could be confused, and some control configurations were placed too high, resulting in parallax problems. Neglect of shape-coding for switches resulted in greater than necessary accidental operation of the wrong control (some operators had retrofitted some control levers to provide for shape coding).

With regard to indicator lights, the research team found a significant number of burned out, single lamp indicators. This is especially a problem because of the use of "negative indicators" (the absence of an indication is supposed to convey information) in the nuclear industry. Also, the use of negative indicators violates a basic HF principle. The meters were found to be in need of HF improvements. The most seriously noted problem was that meters did not differentiate between normal, marginal and out-of-limit conditions. Meters were neither coded nor labeled well. There was improper use of minor, intermediate, and major scale markings, and some scale numeral progressions were hard to interpret. Some meters suffered from parallax, glare, and reflection problems. Finally, some of the meters failed with the pointer indicating normal operating mode. Too many channels of information were printed out on the chart recorders.

C.2.4 Annunciator System

The annunciator warning system was too complex in nuclear power plant control rooms. Besides being functionally separate from related indicator lights and controls, there were an excessive number of annunciators. When an emergency occurs, the great number of blinking lights and blaring horns could overload the perceptual/attentional capacity of the operator and make the situation worse, not better. Also, none of the five control rooms had fully resolved the problem of false alarms or the problem of annunciators that are continually on because of the particular status of the system at that time.

C.2.5 Coding

The coding of displays and controls was often not done well, which could result in misidentification of control and display elements. An 89% majority of those interviewed said that they had problems distinguishing between identical controls located in close proximity. Also, present coding conventions indicate component status, but not whether it is the correct status. Labels were not consistently placed above or below components being identified, and operators felt compelled to provide their own labels to make up for labeling inadequacies. Thus, many aspects of control panel design were found not to meet current military standards for HF applications.

C.2.6 Procedures

Another aspect of the Seminara et al. (1976) study was to look at operating procedures and operational practices and training. As mentioned earlier, four out of five of the control rooms did not have a table or shelf to hold the manuals while in use. Otherwise, using their 55-item checklist, the researchers found that the procedure manuals complied on 74% of the evaluation criteria. The main problems that were found included: lack of clarity of written material; inconsistencies between unit measurements in the manuals and unit measurements on the displays; and a lack of correspondence between training practices and procedures. The research team also found that the operators were more satisfied with the written procedures if they had helped to establish them and that a majority of the operators and trainers interviewed felt that it was important to upgrade and rely upon procedures.

C.2.7 Operational Practices and Training

Operational practices were analyzed by reviewing shift crew changeover procedures, shift crew composition, adaptation to shift changes, operator morale, overtime practices, and boredom and stress factors. Seminara et al. (1976) found that it took up to 30 minutes of unpaid overtime for shift changeover. Coupled with the shortage of control room operators, the fact that most operators already work large amounts of overtime, and the fact that the NRC is likely to increase the number of operators required in the control room, these factors point to a potential morale problem, as well as performance problems resulting from fatigue and sleep deprivation. Training courses were often taken on overtime. Shift crew composition was found to be a problem when choice of shift was determined by seniority. In these cases, senior staff typically worked together and inexperienced staff worked together. A 70% majority of trainers and operators felt that the operator's job contained a large boredom component. Suggestions for breaking up the long shift stretches included walks through the plant, training, and preparation or upgrading of procedures. Stress, though infrequent, was at times intense when new events were encountered. This could best be alleviated by more hands-on experience on simulators, which is a suggestion made by others also (Finlayson et al. 1977; Malone et al. 1980). Operators also suggested a de-emphasis on training in formal subject matter.

C.2.8 Operator Errors

Finally, Seminara et al. (1976) analyzed operator errors through interviews with operators and trainers and through analysis of reported operational error. They found that the largest reason for operator error was due to the absence of timely, attention-getting information. [Perhaps it is more than coincidental, then, that the TMI accident was largely a result of the fact that a power operated relief valve failed to close as it was to automatically have done, and there was no direct indication of this failed condition on the control room panel.] The second most common error was incorrect line-up of valves. Also, lack of control coding and shift turnover procedures contributed to operator error. When questioned, the operators and trainers offered three areas where HF could greatly improve operations.

First, unclear, illogical, overly complex, and mirror-imaged control panels needed to be changed. Second, control coding and separation of identical controls needed to be effected. Third, inadequate information display formats, e.g., overlapping information channels on chart recorders, needed to be changed.

C.2.9 Conclusions and Follow-up

Seminara et al. (1976) concluded their report by suggesting several important lines of research. First, control boards should be configured using HF principles, and a comparison of operator performance on the engineered panels should be compared to operator performance on existing control panels. As a corollary, the use of advanced, computer-based control board concepts should be investigated. Second, new warning-annunciator approaches should be explored. Third, decision-aiding techniques should be explored that could help the operator process disparate bits of information. Fourth, auxiliary operators' tasks, procedures, and control panels should be thoroughly evaluated. Fifth, nuclear power plant communications systems should be evaluated and upgraded. And, sixth, the ease and adequacy of maintenance, along with maintenance personnel selection and training, should be evaluated.

In a follow-up study, Seminara et al. (1979) were able to act on some of their recommendations from their previous study in terms of developing and evaluating control board design concepts for three subsystems: reactor control, steam generator feedwater control, and the turbine generator. On the basis of an analysis of control and display requirements, they were able to show how existing control boards could be updated to improve HF design aspects of the board. They also developed a new control board design from scratch which incorporated substantially more HF principles than was possible in upgrading the present control board. THe HF-designed board was very positively evaluated both by nuclear power plant operator trainers and by equipment designers. They also recommended alternative warning system approaches and methods of integrating these into the new control board design.

Seminara et al. (1979) also investigated the use of advanced, computer-based cathode-ray tube (CRT) control room approaches. They suggested possible HF applications to these systems (e.g., greater reliance on color coding in the CRTs), and discussed the notion of "hybrid" systems consisting of the integration of CRT capability with conventional control board design. Finally, interviews with architect-engineers and control board designers resulted in the following conclusions: 1) at present, there is a lack of an integrated human factors approach to control room design; 2) there is a lack of and need for HF guidelines specifically focused on the industry; 3) there tends to be an overreliance on operator input in terms of designing control boards, at the cost of obtaining professional HF input; 4) there is underutilization of mock-ups and simulators in design evalution, and 5) there is a lack of feedback to designers concerning design deficiencies.

C.3 THE FINLAYSON ET AL. (1977) STUDY

The purpose of the Finlayson et al. (1977) study was to conduct an appraisal of desired nuclear power plant operator performance and the nuclear power plant control room features that enhance operator performance.

C.3.1 Research Design

In order to meet the above objectives, site visits were made to six operational nuclear power plants, three nuclear power plants in various stages of construction, three nuclear power plant simulators, one fossil fired plant, two Federal Aviation Administration (FAA) approach control centers, one FAA air route traffic control center, and one U.S. Air Force satellite test center. The non-nuclear sites were visited for comparison purposes. Control board design, data acquisition procedures, operating procedures, and operator training were the main focus of the site visits.

C.3.2 Research Findings

Finlayson et al. (1977) did not provide as detailed a set of comments as Seminara et al. (1976). Yet many of their general conclusions were the same. Control rooms on the most recently built reactors were considered to be possibly too large, although a trend toward smaller control rooms was noted. However, the reseachers believed that control boards should be reduced in size, either through use of smaller components or through the use of cathode ray tube/computer systems, preferably the latter.

There was a need found for better color coding and tactile coding of controls in order to make operator responses both more accurate and more timely. The researchers also found that while nearly one-third of the control devices were related to critical safety functions, less than one-tenth of the displays provided data about these functions. Thus, not enough information about safety systems is presented to the control room operators. This was also true regarding the automatically invoked engineered safety features of the plant, for which the operators often did not have indicators to determine whether certain aspects of the system were, indeed, functioning correctly.

Finlayson et al. (1977), like Seminara et al. (1976), noted the lack of system mimics on the control panel. They also suggested more use of mimics, and noted that many operators had often made their own system mimics with colored tape. The research team also found that annunciator alarm displays were not placed next to the controls and displays with which they were associated. They strongly suggested contiguous location of these components, as opposed to the use of banks of annunciators along the highest row of the control panels as is present practice.

With regard to operator training, the research team concluded that there was insufficient use of simulation in training. Too few simulators with too many trainees had meant that simulators were used for demonstration, not hands-on learning, purposes. In general, however, they believed that operators were generally well-qualified for their work.

Emergency operating procedures were also seen as inadequate. Although voluminous in size, they were not indexed properly for rapid use. Thus, the procedures would likely not be useful in time-critical circumstances. Finlayson et al. (1977) suggested that the operators may have to rely on their memory (not written procedures) during time-critical events. However, they appeared not to have considered the implications of this suggestion from a learning and memory perspective--i.e., how much material would have to be memorized (stored) and how much of it would be remembered (retrieved) during the specific emergency condition. This should be investigated.

The study team also compared the control rooms of nuclear power plants with FAA controls rooms and an Air Force Satellite Tracking Center. In general, they did not feel that the HF quality was different among the utility, FAA, and Air Force installations, especially in terms of such variables as glare, noise, acoustics, seating height, panel height, control panel orientations, etc. The nuclear power control rooms did appear to be a bit more dated, largely because of the use of older, larger components.

This difference was likely due to the fact that the FAA and Air Force control rooms had gone through numerous panel design arrangements. Numerous changes would mean that more modern (and usually smaller) components are used and might also indicate that superior HF considerations had not been the case for the original control room, as was often claimed by others (e.g., WASH-1400; Seminara et al. 1976). Finlayson et al. (1977), however, also noted that the FAA and Air Force facilities were used to gather information, to make decisions, and then to have others outside the control room make the responses (e.g., pilots). In contrast, nuclear power plant control rooms must not only have displays to provide information but also controls so that operator decisions can be carried out. Thus, by their nature, nuclear power control rooms were more complex than the non-nuclear control rooms that they visited.

C.3.3 Recommendations

Finlayson et al. (1977) had three major recommendations to make. First, they suggested that regulatory guides, with enough specificity to be useful, should be developed, using military HF guides as an example. Second, they suggested that Licensee Event Reports should be thoroughly analyzed with regard to personnel errors and their relationship to other factors at the time of the event such as plant licensing status; operational power levels; specific equipment, displays, and controls involved in the event; significance of the event; radioactivity release; and operator training and experience. Third, they suggested that a thorough analysis be conducted of human errors in responding to programmed accidents on training simulators. This research could be used to serve as the basis for making judgments about operator competence for safety, as well as licensing, purposes.

C.4 The Malone, et al. (1980) Analysis of TMI.

TMI, often called the most serious nuclear power plant accident ever to have occurred, has provided perhaps the best "data point" ever for researching such things as nuclear power safety systems and reactor core integrity. Part of the research effort (Malone et al. 1980) was a thorough analysis of the human factors component of the accident, in conjunction with a standard HF analysis of the TMI control room and two other nuclear power plant control rooms. The authors concluded that, "Human engineering planning in TMI-2 was virtually nonexistent" (Volume I, p. 65). Lack of such planning was all too apparent during the first 150 minutes of the TMI accident. This accident is described in more detail below. Hopefully, it will become obvious that much of the "human error" was preventable.

C.4.1 Analysis of the Accident

In analyzing operator performance during the accident, Malone et al. (1980) focussed on operator actions/inactions during four operational sequences: delay in isolating the stuck open power-operated relief valve (PORV); bypassing the engineered safety features injection system by throttling the high pressure injection system (HPI); inadequate management of the steam generator levels; and lack of control over the reactor coolant pumps disallowing natural circulation. Below, we will describe in some detail one of these sequences--delay in isolating the PORV--and the extent to which this was operator error.

The accident at TMI started when a malfunction in the condensate booster pumps caused the turbines to trip. This raised the pressure and temperature in the reactor coolant system (RCS), which caused the PORV on the pressurizer to open. After the pressure had reduced, the valve failed to close as it should have. When the pressure dropped below normal, high pressure injection of water into the RCS began. When the pressurizer level exceeded its nominal high setpoint level, it is assumed that the operator checked the status of the PORV indicator, which indicated that the valve had been ordered to close (interpreted as "had closed" by the operators), dismissed the PORV as the problem, and proceeded to throttle HPI and a makeup pump in order to avoid going water solid in the pressurizer. Was this operator error? Malone, et al. (1980) noted the following design, training, and procedural problems that contributed to the operators' responses.

Design inadequacies seemed to have contributed significantly to the event. First, the PORV status indicator is a red light that goes on when a signal is sent for the PORV to open and goes out when a signal is sent for the PORV to close. This violates two basic HF principles from MIL-STD-1472B, paragraph 5.2.2.1.4. The first is that the extinguishment of an indicator light is not supposed to be used to signal a completion condition (a bulb could burn out, for example). Second, changes in display status are supposed to signify changes in functional status and not just the results of control actuation alone. If this second principle had not been violated the TMI accident would probably not have occurred.

Other design problems were found during the investigation. For example, there is no direct indicator on the control panel for flow through the PORV discharge line. Flow had to be inferred from temperature changes in the discharge line--another very poor practice from a HF point of view. Also, although the emergency operating procedure states that reactor coolant drain tank pressure and temperature are the main indicators of a failed PORV, these indicators were located on a control panel outside the main area of the control room. Labelling of the PORV indicators was also inadequate.

Training and procedure problems also contributed to the accident. First, operators were trained to avoid a water solid pressurizer. Thus, they throttled the HPI and attended almost completely to pressurizer level and neglected RCS pressure. Second, the operators believed that the drop in RCS pressure was due to loss of the air bubble in the pressurizer, which was an event they had never experienced on a simulator. Third, emergency procedures for a LOCA give symptoms as loss of pressure and level, and operators were trained to believe that a RCS leak must be followed by a reduction in level. Fourth, the operators were trained to believe that if they had coolant in the pressurizer, then the core was covered. Fifth, the operators were trained to believe that the absence of the illumination of the PORV status indicator meant that the valve was closed, not just that the signal to close the valve had been sent. Finally, the operators had expected higher than normal temperatures in the PORV discharge line for two reasons--the pressurizer had been leaking earlier and the PORV had opened at three seconds into the accident allowing hot water to flow out the discharge line. In addition, the operators had no training regarding how hot the discharge line should be after opening and then closing and no training regarding how great a difference was tolerable between the PORV discharge line temperature and the code safety temperature. As noted by Malone et al. (1980), "This is an example of the phenomenon of prior experience serving to establish expectancies in the absence of adequate training" (Volume I, p. 11).

In their final analysis of the PORV sequence of the accident--synthesizing operator action/inaction, design problems, and training and procedure problems--the authors concluded that, "In retrospect, however, it is apparent that the operator performance was driven by a conception of plant status which was based on inadequate and erroneous information" (Volume II, p. 15). Furthermore, after similar careful analysis of operator action/inaction, design problems, and procedure and training problems for the other three major event sequences--inadequate management of steam generator levels, throttling HPI and thereby bypassing the engineered safety features, and failure to control the reactor coolant pumps in order to start natural circulation--the research team reached a similar final conclusion:

> The overall conclusions are: 1) operators did commit a number of errors which certainly had a contributory if not causal influence in the events of the accident; and 2) these errors resulted from grossly inadequate control room design, procedures, and training rather from inherent deficiences on the part of the operators. (Volume I, p. 27).

In order to determine whether these problems were somewhat unique to the specific incident at a specific plant, Malone, et al. (1980) then fully analyzed control room design, control room development, procedures, and training for TMI and two other nuclear power plants.

C.4.2 Conclusions

From this analysis, they formed seven general conclusions. First, TMI was built without a concept or philosophy about man-machine interface, but this was not so much the case for the other two reactors. Second, this lack of a man-machine concept resulted in a lack of a fully defined role for the operators during an emergency situation--i.e., are they merely to watch the emergency safety features work automatically or are they to insert themselves into the control process. Third, because there had not been an analysis of information requirements as a function of operator tasks at TMI, some critical information was not displayed at all, some was not immediately available because of location outside the control room, and much unnecessary information was displayed. Fourth, the control room design at TMI, more so than at the other two reactors, violated a number of HF principles, which resulted in excessive operator motion, excessive workload, increased error probability, and increased response time. Fifth, the TMI emergency operating procedures were of little use to the operators during the emergency largely because they failed to provide a systematic method for diagnosing the problem. Sixth, operator training was quite deficient with regard to assisting the operators during the incident and would likely be deficient in other emergency situations. And, seventh, the conflicting implications from indicators, training, and procedures precluded timely and effective operator response.

C.5 ROGOVIN COMMISSION REPORT (1980)

Following the TMI accident, the Nuclear Regulatory Commission set up a Special Inquiry Group to independently investigate the accident. Mitchell Rogovin, Esq., headed the Special Inquiry Group, so the report will be preferred to as the Rogovin Commission Report (1980). The Commission gathered its data on the accident using formal depositions under oath, transcripts of interviews and depositions taken by other investigations, and consultant expertise. The Commission's conclusions and recommendations regarding HF applications at TMI are quite similar to the conclusions reached by HF analysts before TMI (Seminara et al. 1976, 1979; and Finlayson et al. 1977) and after TMI (Malone et al. 1980), so they are just briefly presented below.

In general, the Rogovin Commission Report (1980) concluded that the HF problems were not so much that instrumentation did not exist to help the operators, but that the information was not obtained or displayed in a useful and timely fashion. For example, soon after the accident began, the computer that was used for information display got so far behind in printing information that information had to be dumped during the accident, because the incore thermocouples were giving off-scale readings, temperatures had to be determined by hand-held electrical meters snapped onto wires located in a cabinet one floor below the control room; temperature indications that the pressurizer relief valve had stuck open were available, but temperature was not easily determined to be too high because of lack of abnormal indicators on the temperature readout; and the indicator on the control panel only signalled that the pressurizer relief valve had been instructed to close and did not give the actual status of the valve. However, two important pieces of information were not available to the operators: level of reactor coolant in the main reactor vessel and a visual alarm to show that the emergency feedwater system was blocked off. In addition, the report concluded that the operators were inadequately trained for emergency conditions and, because of inadequate training, they repeatedly ignored warnings that the pressurizer relief valve was stuck open.

C.6 SUMMARY

HF applications in the nuclear industry research literature have dealt with the use of human error probabilities (HEPs) in estimating reactor safety and the analysis of control rooms with the intent of recommending improvements. The applications of HEPs has been limited. However, several control room reviews have been carried out and have pointed to many areas where the HF applications could be improved. These include, for instance, improvements in labelling practices and the use of lines of demarcation, arrangement of controls and displays, annunciator systems, procedures, and training. The analysis of the TMI accident confirmed that nonoptimal use of HF principles in the design, construction operation, and maintenance of at least one nuclear power plant was partially responsible for the accident.

APPENDIX D

CHECKLIST FOR LNG PEAKSHAVING PLANT SITE VISIT

APPENDIX D

CHECKLIST FOR LNG PEAKSHAVING PLANT SITE VISIT

(Original)

YES NO N/A

I. STORAGE TANK

A. Gas Leak Detection

1. Are there gas leak detectors and warning devices around the tank?
2. Where is the warning signal heard?

B. Instrumentation

1. Are the redundant liquid level guages and recorders with high level alarms, and a minimum of one independent high level alarm?
2. Are there redundant guages and recorders with high and low vapor pressure alarms for monitoring vapor pressure in the tank?
3. Are there temperature indicators and recording devices with alarms for critical points in the foundation to warn about frost heave?
4. Are there temperature recorders for the temperature of contained liquid at various vertical levels in the tank? If so, how are they spaced?
5. Are there thermocouples with recorders located at various critical points to monitor abnormal temperatures in the tank structure?
6. Are there linear and rotational movement indicators located between inner container and outer shell with recorders to measure excessive relative movement of inner container and outer shell?

YES NO N/A

II. CARGO TRANSFER SYSTEM

A. Is there a signal light at each control location or remotely located pumps or compressors used for transfer which indicates whether the pump or the compressor is off or is in operation?

B. Communication

1. Is there a means of commnication between the loading/unloading area and other areas (such as the control room) in which personnel are associated with the transfer operations?

2. Could the communication system be used in an emergency situation, or is it subject to possible malfunction as a result of the accident?

C. Emergency Shutdown

1. Are the transfer system shut-off valves that are designated for use in the emergency procedures manually operable at the valve and at a remote location at least 50 feet from the valve?

2. Is there an automatic emergency shutdown control system for the transfer system?

III. VAPORIZATION EQUIPMENT

A. Monitoring Devices

1. Is there a device to monitor the inlet temperature of the LNG?

2. Is there a device to monitor the outlet temperature of the vaporized gas?

3. Is there a device to monitor the outlet pressure of the vaporized gas?

4. Is there a device to monitor the inlet pressure of the heating medium fluids?

YES NO N/A

B. Emergency Shutdown

1. If the vaporizer is installed in a building, is the shut-off valve located outside the building?

2. Is there an automatic emergency shutdown system for the vaporization system?

C. Are the combustion air intakes to the vaporizers equipped with sensing devices to detect the induction of a flammable vapor?

IV. CONTROL SYSTEMS

A. Pump and Compressor Control

1. Is there a control system to shut down the pump or compressor in a controllable emergency that can be operated locally and remotely?

   Can it be inspected and tested and maintained?

2. Is there a signal light at the local and at the remote control locations that indicates whether the pump is in operation or is off?

   Can it be inspected and tested and maintained?

B. Emergency Shutdown Control

1. Is there an automatic emergency shutdown control system

   a. for the liquefaction system;

   b. for the storage tank?

2. When do the automatic emergency shutdown control systems actuate?

   a. When temperatures of the component exceed design specifications.

   b. When pressures in the system are above or below design specifications.

   c. When liquid in the receiving vessels reaches the design maximum liquid level.

YES NO N/A

  d. When gas concentrations in the area of the system exceed 40% of the lower flammable limit.

  e. When there is a sudden excessive pressure change (or other condition) which indicates a potentially dangerous condition.

  f. When there is a fire present in the area of the system or component.

3. Can, are, and how are each of the above systems regularly inspected, tested, and maintained?

4. If any of the above monitoring devices detects an abnormal condition, is the warning that is given

  a. both audible and visual, and

  b. does the warning indicate the nature and extent of the hazard?

5. Is there a time delay between the warning that there is an abnormal condition and the automated shutdown in order to provide for a manual response (override)?

   Under what conditions would you manually override an automated shutdown?

6. Are the above automated systems operable both at the system site and in the control room?

C. <u>Control Center</u>

1. Is the control center located apart or protected from other LNG facilities so that it can be operational during a controllable emergency?

2. Are all the control systems and automatic shutdown systems operable from the control center?

3. Does the control center have someone in continual attendance? How Many? Who?

YES NO N/A

4. Is there a means of communication between the main control center and the remote control centers?

5. Does the control center have a means of warning about hazardous conditions to other locations in the plant frequented by personnel?

D. Do the control systems have a fail-safe design?

E. Do the following have at least two sources of power?

1. Electrical control systems;

2. Means of communication;

3. Emergency lighting; and

4. Firefighting equipment.

5. If auxiliary generators are used for back-up power, is it

   a. located apart or protected from components so that they are not unusable during a controllable emergency?

   b. Is the fuel supply protected from hazards?

F. Control System Testing

1. Are relief valves inspected and tested for verification of the valve seat lifting and reseating pressures at least once a year?

2. How often are the following control systems inspected?

   Pump and compressor automatic control system

   Vaporizer automatic control system

   Liquefaction automatic control system

   Storage tank automatic control system

   Transfer automatic control system

YES NO N/A

Emergency automatic shutdown system

Relief valves

3. Is the vaporization control equipment inspected and tested before seasonal use?

4. Are fire control systems and equipment tested at least every six months?

V. Operating Procedures

A. Normal Operation

1. Are there written operating procedures? Do they include

   a. inspections and tests of components;

   b. initial startup;

   c. normal operations?

2. Are the procedures easily accessible?

3. Is there a place for the procedures to be placed for easy use?

4. Are the procedures

   a. indexed;

   b. tabbed;

   c. well-organized;

   d. legible?

5. Do you have occasion to use the operating procedures? Do you find them useful?

B. Emergency Situations

1. Are there procedures for what to do if temperatures are outside of design limits?

2. Are there procedures for what to do if pressures are outside of design limits?

YES NO N/A

C. Are there written procedures for maintenance?
Are there maintenance checklists?

VI. PERSONNEL

A. Are there written job descriptions for the following personnel

control room operators;

maintenance personnel;

supervisory personnel.

B. What kind of training (other than high school degree) are control room operators required to have for getting a control room job?

None, on-the-job-training given.

Required to have worked in control room of energy-related plant (coal, oil, etc.).

Required to have worked previously in control room of LNG plant.

C. What kind of outside training (i.e., not on-the-job) do the following personnel receive over the course of their employment?

Control room operators:

LNG in general

Firefighting

Classroom instruction on plant operation under normal conditions

Classroom instruction on plant operation under abnormal conditions

Maintenance personnel:

LNG in general

Firefighting

YES NO N/A

Equipment testing

Equipment maintenance

Supervisory personnel:

LNG in general

Firefighting

Plant operation

Supervision/administration

D. Are licenses required for the:

Control room operator?

Maintenance personnel?

Supervisory personnel?

VII. OFF-SITE EMERGENCY RESPONSE INTERACTIONS

A. What kind of interactions do you have with off-site emergency response personnel?

Local law enforcement?

Local firefighting units?

Local medical?

State Department of Emergency Services?

B. Warning Surrounding Population

1. Is there any plan for warning the surrounding population in case of an emergency situation?
2. How would the public probably be warned?

APPENDIX E

CHECKLIST FOR LNG FACILITY SITE VISIT

APPENDIX E

CHECKLIST FOR LNG FACILITY SITE VISIT

(Revised)

I. SPECIFIC SYSTEM SAFETY DEVICES

Detailed Design Considerations	Yes	No	N/A	Comments
A. Gas Detectors				
1. How many gas detectors are there?				
2. Is there a gas detector covering the				
a. Liquefaction equipment?				
b. Main tank?				
c. Vaporization equipment?				
d. Gas cleaning equipment?				
e. Compressor building?				
f. Other?				
3. a. If gas is detected, is an audible alarm set off in the control room?				
b. If yes, is there a way to determine which detector?				
4. a. Have the gas detectors given false positives in the past two years?				
b. If yes, how often?				
5. Are they inspected for proper functioning? If yes, how often?				
B. Flame Detectors				
1. How many flame detectors are there?				

Detailed Design Considerations	Yes	No	N/A	Comments
2. Is there a flame detector covering the				
a. Liquefaction equipment?				
b. Main tank?				
c. Vaporization equipment?				
d. Gas cleaning equipment?				
e. Compressor building?				
f. Other?				
3. a. If a flame is detected, is an audible alarm set off in the control room?				
b. If yes, is there any way to determine which detector?				
4. a. Have the flame detectors given false positives in the past two years?				
b. If yes, how often?				
5. a. Are they inspected for proper functioning?				
b. If yes, how often?				
C. Emergency Shutdown System				
1. a. Is the ESD actuated automatically?				
b. What conditions cause automatic actuation?				
c. If automatically actuated, describe the operator's actions immediately following actuation. (Make sure and determine if an how the operator checks to see that all valves have closed properly and that pumps have shut down.)				

Detailed Design Considerations	Yes	No	N/A	Comments
2. a. If manually operated, what goes into the decision whether or not to actuate the ESD?				
b. Describe the operator's actions immediately following the actuation. (Make sure and determine if and how the operator checks to see that all valves have closed properly and that pumps have shut down.)				
c. How many places on the site can the ESD be manually actuated?				
D. Tank Safety Indicators in Control Room				
1. Are there tank liquid level gauges?				
2. Are there tank high-level alarms?				
3. Are there alarms for off-normal tank vapor pressure?				
4. Are there temperature indicators and warning devices for the tank's foundation to warn of frost heave?				
5. Are there temperature indicators for various levels in the tank?				
E. Vaporization Equipment Safety Indicators in Control Room				
1. Is there a device to measure inlet temperature of LNG?				
2. Is there a device to measure outlet temperature of the gas?				
3. Is there a device to measure outlet pressure of the gas?				

Detailed Design Considerations	Yes	No	N/A	Comments
F. Control Center - General				
1. Is the control center located apart or protected from other LNG facilities so that it can be operational during a controllable emergency?				
2. Are all control systems and automatic shutdown systems operable from the control center?				
3. Does the control center have someone in continued attendance? How many? Who?				
4. Is there a means of communication between the control center and the remote control centers?				

II. LABELS, MANUALS, MARKINGS

Detailed Design Considerations	Yes	No	N/A	Comments
1. Controls and displays are clearly marked and labeled.				
2. Labels are on or near the item to be identified.				
3. Labels do not cover any other information and are not located behind controls. They can be seen easily by the operator and are not obscured by the operator's hand activating a control.				
4. Labels are located in the same manner throughout the equipment and system.				
5. Labels are not covered by other equipment.				
6. Labels are mounted so that they cannot be accidentally damaged or removed.				
7. Labels are graduated in size. Group label characters are at least 25% larger than those of individual controls and displays.				
8. Abbreviations are capital letters, periods being omitted except when there is a possibility of misinterpretation.				
9. Labels are easily read at operational reading distances with vibration/motion and lighting levels taken into consideration.				
10. Labels are sharp with high contrast.				
11. Markings and tags are as permanent as the equipment to which applied and able to withstand environmental and cleaning conditions.				

Detailed Design Considerations	Yes	No	N/A	Comments
12. Labels are accessible and visible during maintenance.				
13. Roman numerals are not used, if possible.				
14. Vertical labels are used only when the labels are not critical for personal safety and performance, and space is limited.				
15. Warning placards are well illuminated.				
16. Warning notices are clear and direct. Characters are 25% larger than any following instructions.				
17. Trade names and other irrelevant information do not appear on labeling.				
18. Labels are concise with a minimum of repetitive information.				
19. An abstract symbol is used only if meaningful.				
20. Each indicator or control is labeled with a visible and meaningful name, number, and symbol.				
21. Printed information is directly useable with a minimum of decoding and interpolation.				

III. CONTROLS

Detailed Design Considerations	Yes	No	N/A	Comments
1. Control relationship to its display is apparent, through mimic.				
2. Functionally related controls and displays are grouped together.				
3. Control groups, sequential operations have left-to-right order of use or top-to-bottom order of use.				
4. Controls in functional groups are located in accordance with operational sequence and/or function.				
5. Controls are located so that they cannot be accidentially moved.				
6. Groups with similar functions are similar throughout the system.				
7. Controls are marked to indicate in which direction to operate the control.				
8. Control/display groups used only for maintenance are not located in prime operating space.				
9. Controls used most often are located in the best position for ease of reaching and grasping.				
10. Sensitive adjustments are located or guarded to prevent accidental activation.				
11. Adequate control response feedback is provided.				
12. Control movement conforms with corresponding related display.				
13. Rotary controls turn to the right (clockwise) to increase, and left (counterclockwise) to decrease.				

Detailed Design Considerations	Yes	No	N/A	Comments
14. Stops are provided at the beginning and end of the control movement travel.				
15. In right-hand operations knobs are placed below or to the right of displays.				
16. For left-hand operations knobs are placed below or to the left of displays.				
17. Controls meant to have a limited degree of motion have adequate mechanical stops.				
18. Controls are labeled as to function and method of operation by means of arrows and appropriate legends.				
19. Range of control action does not interfere with other controls.				
20. Coding is uniform throughout the system.				
21. Controls are useable in the time required despite inadvertent operation protection (guards).				
22. Control motion is minimized, not cycled through ON/OFF unnecessarily.				
23. Minimum use made of horizontal or 3 position toggle switches.				
24. Critical controls are designed and located so that they are not susceptible to being moved accidentally.				
25. If there is a possibility of inadvertent activation causing a hazardous condition, controls are recessed or shielded by a physical barrier.				
26. Controls are black or gray.				

Detailed Design Considerations	Yes	No	N/A	Comments
27. Controls are labeled with basic information, utilization, actuation, or manipulation of the element.				
28. Mimics are used wherever possible.				
29. Adjustment controls are easy to set and lock.				
30. All controls have appropriate scales or indexing.				

IV. DISPLAYS

Detailed Design Considerations	Yes	No	N/A	Comments
1. Relationship between the display and its associated controls is unmistakable in terms of:				
a. The proper control to use.				
b. Direction of movement of the control.				
c. Rate and limits of movement of the control.				
2. Controls are located adjacent to (either under or to right of) associated displays.				
3. Functionally related units are grouped together and are similar from panel to panel.				
4. Displays in groups are located from left-to-right and/or top-to-bottom order of use.				
5. Displays used in system checkout are located so they can be observed from one position.				
6. All displays are arranged in the sequence in which they are used.				
7. Meters, dials, and instruments are so sized/arranged that they can be read from the normal operating position.				
8. In standing positions, the most frequently used displays are located approximately at the eye level of the operator.				
9. Frequently used displays are grouped together.				
10. Displays are located where they can be read to the required degree of accuracy.				

Detailed Design Considerations	Yes	No	N/A	Comments
11. If on separate panels, positions of related controls and displays correspond and the panels do not face each other.				
12. Control display groups for maintenance use only are not located in prime operating space.				
13. Display arrangement is consistent from one situation to another.				
14. Unusual aids such as ladders, extra lighting, etc. are not needed to read or gain access to a display.				
15. Display scales are limited to only information needed to make a decision or take action. All needed information is presented.				
16. Information is presented in such form that no interpretation or decoding is necessary.				
17. Failure in the unit is clearly shown or the operator is otherwise warned.				
18. The displays include special markings to indicate "off-normal" conditions.				
19. Trademarks, company names, and other unnecessary information are not on the panel face.				
20. The display pointer extends to but does not obscure the index mark width.				
21. Display pointer is mounted as close as possible to dial face to eliminate parallax and shadows.				
22. Counters and flags are mounted close to the panel surface.				
23. Illumination is uniform.				

Detailed Design Considerations	Yes	No	N/A	Comments
35. Material in printer is easily changed and indicates remaining supply of printing materials.				
36. Failure of a display circuit is immediately apparent.				
37. Most important displays are placed in the optimum visual zone.				
38. A signal absence does not denote "go ahead," "ready," etc., only a power off condition.				
39. Transilluminated, LED and incandescent displays conform to the following color code, except that training equipment colors can be approximate:				
a. Flashing red denotes only emergency conditions which require operator action without undue delay to avert personnel injury and/or equipment damage.				
b. Red alerts an operator that a system or any of its parts is inoperative or that a successful mission is not possible unless corrective action is taken.				
c. Yellow advises an operator of a marginal condition or alerts him to situations of caution, recheck or unexpected delay.				
d. Green indicates that monitored equipment is in tolerance or that a state of readiness exists.				
40. Flashing lights are used only to call the operator's attention to a condition requiring action.				
41. Audio signal action specifies the nature of the problem (maintenance emergency, health hazard).				

Detailed Design Considerations	Yes	No	N/A	Comments
42. Audio signals denoting emergencies are notably different from routine signals.				
43. The height to width ratio of all labeling is acceptable for fast and accurate reading.				
44. Counters are horizontally positioned.				
45. The same numerical progression is used on all scales of combined displays.				
46. In sequential displays, the sequence progresses from left to right.				
47. Scale values and their indexes are consistent in directions of increase or decrease.				
48. The display can be read quickly in the manner desired (quantitative, qualitative, or check reading).				

V. WORKSPACE

Detailed Design Considerations	Yes	No	N/A	Comments
1. Design and sizing insures accommodation, compatibility, operability and maintainability by at least 90 percent of the user population.				
2. Consoles have at least 4 feet (1.220 m) of free floor space in front whenever feasible.				
3. Display reading location is identified.				
4. Instrument reflection is avoided.				
5. If possible there is a direct view of the grounds.				
6. The acoustical environment does not degrade system effectiveness.				
7. Hazard alerting devices are provided.				
8. Illumination is adequate and glare is reduced.				
9. Adequate and suitable storage is provided for manuals, worksheets, etc.				
10. Standees have work surfaces provided to support manuals, etc.				
11. Controls (switches, knobs, etc.) are easily reached from the working position.				
12. Controls are located so that physical interference among operators working on the same areas is lessened.				
13. The lines of sight to a display are not obsured by poor arangement of people or equipment.				

Detailed Design Considerations	Yes	No	N/A	Comments
14. Traffic flow between areas is efficient.				
15. Auditory alerting and warning signals are loud enough to be heard above environmental noise.				

VI. MEASURES

Detailed Design Considerations	Yes	No	N/A	Comments
1. Displays are located so they can be read to the required accuracy.				
2. Display arrangement is consistent from one application to another				
3. Display viewing distance: 13-28".				
4. Scales: linear, start at 0, use whole numbers, 2 pointers max, numerals oriented upright.				
5. Information is directly useable.				
6. Measures clearly detailed.				

VII. PROCEDURES

Detailed Design Considerations	Yes	No	N/A	Comments
1. Are there written procedures for				
a. Maintenance?				
b. Initial start-up?				
c. Normal operations?				
d. Emergencies?				
2. Are the procedures easily accessible?				
3. Is there a place for the procedures to be placed for easy use?				
4. Are the procedures				
a. Indexed?				
b. Tabbed?				
c. Well-organized?				
d. Legible?				
e. Readable?				
5. Other comments.				

VIII. OPERATORS

Detailed Design Considerations	Yes	No	N/A	Comments
1. Are there written job descriptions for				
a. Control room operators?				
b. Maintenance personnel?				
c. Supervisory personnel?				
2. Are control room operators trained? If so, how?				
3. Are maintenance personnel trained? If so, how?				

APPENDIX F

LNG TELEPHONE INTERVIEW PROTOCOL

APPENDIX F

LNG TELEPHONE INTEVIEW PROTOCOL

1. (Introduction). I am ______________________________, from the Battelle Human Affairs Research Centers.

   We are working on a DOE funded study to examine the extent to which human factors and the potential for human error are taken into consideration in the design, planning, and operation of LNG facilities.

   The objective of this research is to asure that the LNG industry continues to operate at a high level of system safety.

2. Can you answer, or can you direct me to someone who can answer, a few questions concerning applications of human factors and the extent to which the potential for human error is accommodated in the LNG industry.

   For referral: Name ______________________________

   Telephone No. ______________________________

   Organization ______________________________

   Position in Organization ______________________________

3. What type of LNG facility were you involved with?

   Peakshaving plant ____________________

   Satellite facility ____________________

   Import terminal ____________________

   Other ____________________

4. Were human factors considered in the design of:

   a. Control room?

      If yes, how? Was an HFE employed? Were operators included? Was use made of behavioral stereotypes? What considerations went into the types of displays and dials/switches that were used?

   b. Locations of valves, controls, switches, etc., outside of the control room?

      If yes, how?

    c. Warning systems?

       If yes, how?

    d. Emergency equipment--fire prevention, etc.?

       If yes, how?

    e. Maintenance of equipment?

       If yes, how?

    f. Emergency and normal operating procedures?

       If yes, how?

5. What is the relationship between your organization and the customer in terms of designing for human effects?

    a. Who makes the decision about actual equipment?

    b. Are people with operational experience included for evaluating designs?

    c. How much does your firm get involved with training the operational personnel?

    d. Do you ever get feedback from the customer concerning the compatibility of equipment with human capabilities? Is this information solicited by you?

6. Are mock-ups used of equipment and control boards which will be heavily used by personnel?

7. Any other ways in which human effects are considered by your organization?

8. Is there someone else, either in your organization or elsewhere (e.g., subcontractors), who might be of help to us on this project?

Name ____________________________

Telephone No. ________________

Organization __________________

Thank you for your help. If we can be of help to you, please let us know. We would be happy to give you a report summarizing what we find.

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16. Abstract

The results of an investigation of human factors engineering and human reliability applications to LNG release prevention and control are reported. The report includes a discussion of possible human error contributions to previous LNG accidents and incidents, and a discussion of generic HF considerations for peakshaving plants. More specific recommendations for improving HF practices at peakshaving plants are offered based on visits to six facilities.

The HF aspects of the recently promulgated DOT regulations are reviewed, and recommendations are made concerning how these regulations can be implemented utilizing standard HF practices. Finally, the integration of HF considerations into overall system safety is illustrated by a presentation of human error probabilities applicable to LNG operations and by an expanded fault tree analysis which explicitly recognizes man-machine interfaces.

17. Key Words ● Liquefied Natural Gas (LNG) ● Human Factors ● Human Factors Engineering ● LNG Release Prevention and Control ● Human Error ● Fault Trees	**18. Distribution Statement** Release Unlimited

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