Type B Investigation of Electrical Fault in 351 Substation, December 4, 1994

H. L. Debban
C. A. Shearer
R. M. Boger
G. P. McDonald
ICF Kaiser Hanford Company

L. E. Eyre
L. D. Dell
D. S. Kelly
Westinghouse Hanford Company

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**Westinghouse
Hanford Company**

P.O. Box 1970
Richland, Washington

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APPROVALS

H. L. Debban, Chairman
Type B Accident Investigation Board
ICF Kaiser Hanford Company

2-1-95
Date

W. S. Chin, Board Liaison
U.S. Department of Energy
Richland Operations Office

2/1/95
Date

L. D. Dell, Accident Investigator
Westinghouse Hanford Company

1-31-95
Date

L. E. Eyre, Conduct of Operations
Westinghouse Hanford Company

2/1/95
Date

R. M. Boger, Electrical Engineering
ICF Kaiser Hanford Company

2/1/95
Date

G. P. McDonald, Chief Electrical Engineer
ICF Kaiser Hanford Company

1-31-95
Date

D. S. Kelly, Construction Projects
Westinghouse Hanford Company

1-31-95
Date

C. A. Shearer, Industrial Safety
ICF Kaiser Hanford Company

1/31/95
Date

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**TYPE B INVESTIGATION OF ELECTRICAL FAULT IN 351 SUBSTATION
DECEMBER 4, 1994**

1. SCOPE

Mr. J. D. Wagoner, Manager, U.S. Department of Energy (DOE), Richland Operations Office (RL) commissioned this Type B Accident Investigation to examine the causes of a fault in a 13.8kV line, in an underground vault, at the 351 Substation, at the Hanford Site (Appendix A).

This final report provides results of the "Type B Investigation of Electrical Fault in 351 Substation, December 4, 1994." It contains the investigation scope, executive summary, relevant facts, analysis, and conclusions. DOE Order 5484.1, "Environmental Protection, Safety and Health Protection Information Reporting Requirements," was followed in preparation of the report.

Because of fire damage to Vault R122V and three 13.8kV lines which passed through it, the Accident Investigation Board determined that involvement by a team of experts with expertise in similar accidents would be necessary to determine the direct cause of the fault. This phase of the investigation included:

- o Inspection and extensive photography of the event site,
- o Research and selection of consultants with extensive electrical fault and accident reconstruction experience,
- o Preparation of a vault entry and analysis plan which assured qualified personnel would perform a systematic evaluation of evidence,
- o Videotaping and still photography of the vault excavation process and reassembly,
- o Determination of direct cause of the fault.

After determining the location of the fault, the board evaluated the circumstances which led to it. Also evaluated were the post accident emergency response actions. This phase of the investigation included:

- o Performance of extensive interviews,
- o Review of procedures, drawings, specifications, instructions, standards, critiques, and audio recordings,
- o Preparation of scale models,

- o Preparation of three-dimensional, computer-generated models,
- o Examination of the Occurrence Notification System for similar events,
- o Development of a detailed event timeline,
- o Analysis of the events,
- o Identification of contributing and root causes for identified deficiencies,
- o Identification of the actions needed to prevent recurrence.

2. EXECUTIVE SUMMARY

2.1. INTRODUCTION

On December 4, 1994, at 2132:10 hours, an electrical failure of a cable-tapping splice resulted in a fire in the 300 Area of the DOE Hanford Site. The fire occurred in the yard of Substation 351 in electrical Vault R122V, where the cable-tapping splice was located (see Figure 3-1). The fire incinerated all cables passing to and through the vault causing them to fail. The failure of the cables resulted in a power outage to twenty customers in the 300 Area. The vault was electrically isolated, and power was restored to the electrical distribution system at 2311 hours.

The fire was declared out at 2321 hours.

2.2. ACCIDENT SCENARIO

At the time of the failure, the Operating Contractor, Electrical Utilities (EU), was in the process of energizing 13.8kV Circuit C3L2 which had been recently modified. The modification consisted of installation of three T-splices, one for each phase of Line C3L2. Splices were installed in the existing vault.

When the circuit was energized and load applied, a faulty connection caused heating and arcing to occur. Subsequently, the heating caused the splice to fail, resulting in a cable fault to ground. Protective relays operated causing circuit breakers to trip, thus, isolating the fault.

2.3 DIRECT CAUSE

The Accident Investigation Board determined that the direct cause of the fault and resulting fire was a compression lug on one of the conductors that had not been bolted into place when the splice was assembled. When electrical load was applied, the faulty connection overheated and ignited cable insulating materials.

2.4 ROOT AND CONTRIBUTING CAUSES

Root cause and contributing causes were determined using the results of change analysis, barrier analysis, events and causal factors analysis, and MORT Based Root Cause Analysis. Figure 2-1 displays summaries of the probable causes from the analysis techniques. It also provides a consolidation of the probable causes and the root cause. Findings, Judgements of Need, and Recommendations were derived through the analysis results.

2.4.1 Root Cause

Work was not properly integrated; management failed to ensure roles and responsibilities of all participants were clear, and failed to ensure implementation of a clear process for controlling transfer of responsibilities of the interfacing organizations.

**FIGURE 2-1
PROBABLE AND ROOT CAUSES**

PROBABLE CAUSES	CONTRIBUTING CAUSES	ROOT CAUSE
Supervision Between Companies/Departments Less Than Adequate Supervision Less Than Adequate Planned Change Control Less Than Adequate Deviation from Planned Activities Calibration Between Instruments Less Than Adequate OTP, Checklists, and Recovery Modes Definition Less Than Adequate Communications Less Than Adequate on Job Turnover Planning and Change Control Less Than Adequate Technical Information Less Than Adequate Inspection/Test Planning Less Than Adequate Test/Inspection Less Than Adequate Technical Information Relevant to Work Flow Process Inadequate Operational Test Specification Implementation Less Than Adequate Monitoring and Control of the Job Less Than Adequate Project Integration Less Than Adequate Policy Implementation Less Than Adequate	Operational control necessary to ensure clearly understood expectations and sequencing of testing, assembly, acceptance inspection, re-energization, and system performance checks were inadequate. Project participants roles and responsibilities were not clearly defined. Application of Conduct of Operations was not recognized as being necessary for project integration.	Work was not properly integrated; management failed to ensure roles and responsibilities of all participants were clear, and failed to ensure implementation of a clear process for controlling transfer of responsibilities of the interfacing organizations.
Task Performance Error Attention to Detail Less Than Adequate Safety Hazard Recognition Less Than Adequate Self-test and Measurements Less Than Adequate	Inattention to detail during assembly. Assembly procedure and work package did not include effective self-check.	
Risk Assessment System Less Than Adequate Human Factors Review Less Than Adequate Design of Splice Environment Less Than Adequate	Design of the installation which used a very small pull box for the splice. Conformance to NESC and construction specification was very difficult if not impossible. Assembly procedure and work package did not use self-checks.	
Failure to Provide a Work Environment Conducive to Task Performance Did Not Specify Personnel Environment Job Safety Analysis Less Than Adequate Work Environment Less Than Adequate	Human factors were not adequately considered in design prejob planning. Lack of recognition of factors which contribute to diminished work performance of individuals.	

2.4.2 Probable Causes

- o Operational controls necessary to ensure clearly understood expectations and sequencing of testing, assembly, acceptance inspection, re-energization, and system performance checks were inadequate.
- o Project participants roles and responsibilities were not clearly defined.
- o Application of Conduct of Operations was not recognized as being necessary for project integration.
- o Inattention to detail resulted in a faulty assembly.
- o Assembly procedure did not include effective assembly self check.
- o Design of the installation did not adequately consider constructability. Conformance to National Electric Safety Code (NESC) and to construction specification was very difficult, if not impossible.
- o Human Factors were not adequately considered in design, prejob planning or post event activities.
- o Lack of recognition of factors which contribute to diminished work performance of individuals.

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3. FACTS

The purpose of this section is to provide facts relevant to the event. It describes facts surrounding organizational structure, design of the installation, event evolution, and post events.

3.1 EVENT CHRONOLOGY

A detailed chronology of the events is contained in Appendix B. The facts supporting this listing were obtained from various sources, including log books, documentation records, audio tapes, personnel interviews, and work packages. Additional detail is found in this appendix.

3.2 BACKGROUND

Power to the 300 Area is supplied from Substation 351, a 115-13.8kV substation. There are three, 115-13.8kV transformers in the station connected to the Bonneville Power Administration (BPA) 115kV transmission system grid. One of the transformers is normally in a standby configuration, and the other two feed two separate 13.8kV busses (front and rear bus arrangement). Within the control house, 15kV indoor circuit breakers are installed, and general area feeders are provided which distribute 13.8kV power throughout the 300 Area.

Project 92L-GFL-047, "300 Area Electrical Distribution Conversion and Safety Improvements Phase II," (L-047) is an ongoing project in the 300 Area, and was funded as part of a safety and infrastructure upgrade. The design for the project was completed in April 1993. The construction contract was awarded to a fixed price contractor (the contractor) in November 1993.

On the weekend of December 4 and 5, 1994, crews from the contractor and EU performed scheduled work as part of Project L-047. This involved the installation of three, 600 Ampere, dead break T-splices, in Vault R122V. The 1.2 m x 1.2 m x 1.5 m deep (4 ft x 4 ft x 5 ft deep) vault is located approximately 15 m (50 ft) east of the 351 Substation. Three of the existing 13.8kV, 380 mm² (750 MCM) underground feeders, designated C3L2, C3L3, and C3L5, were routed from the control house through Vault R122V, and continued on to connect to aerial lines for distribution throughout the 300 Area. The new T-splices were connected to existing Line C3L2, to provide a 13.8kV, 4/0 AWG feeder to a recently-installed pad mounted switch located adjacent to Vault R122V.

3.3 ORGANIZATIONAL STRUCTURE

Project L-047 involved multiple participants from both ICF Kaiser Hanford Company (ICF KH) and the fixed price construction contractor.

The L-047 project is funded through RL. ICF KH was contracted by RL, through their contract with Westinghouse Hanford Company (WHC), RL's Operating Contractor, to perform the integrating lead role in the L-047 project management (PM). The PM enlisted the support of ICF KH Construction Management (CM) to manage the construction contractor interface and field coordination. An offsite Architect Engineer (A-E), Black and Veatch, was

contracted to perform the design. The PM coordinated the formal design review. Power City Electric, a fixed price contractor, performed the construction. ICF KH Acceptance Inspection (AI) provided acceptance of construction activities for the government. ICF KH EU, which was the eventual owner and operator for the electrical distribution system being modified by the project, performed the cable testing, final connection of components, phase testing, and energization of the new installation. They did not perform an acceptance inspection for all work completed.

Emergency response involved multiple companies and organizations (e.g., Hanford Fire Department, Hanford Patrol, etc.) as described in Section 3.9, Post Events.

The project-specific Project Management Plan was approved December 22, 1992 and outlined intended roles and responsibilities at the time of issuance.

See Appendix C for a chart of the "Vault R122V Fire Demonstrated Roles and Responsibilities Summary."

3.4 DESIGN

3.4.1 Existing Conditions and Intended Modification

3.4.1.1 Existing Vault R122V

Vault R122V, in which the event occurred, was existing from a previous modification to the 300 Area electrical distribution system. It is a standard 1.2 m x 1.2 m x 1.5 m deep (4 ft x 4 ft x 5 ft deep) concrete box. Hinged metal covers allow full access to the vault from the top. The vault was used for the routing of three 13.8kV circuits, C3L2, C3L3, and C3L5, as shown in Figure 3-1. Each of the three circuits comprised three 380 mm² (750 MCM), 5 mil tape shielded, 15kV power cables. Measured diameter of the cable was between 48.26 mm and 50.80 mm (1.9 and 2.0 in). Figure 3-2 shows the location of the cables as existing prior to modification by Project L-047.

3.4.1.2 Existing Installation Did Not Meet National Electric Safety Code (NESC)

The minimum bend radius for the existing shielded cable is 12 times the diameter of the cable. By inspection, the orientation of the first 3 cables which loop through the vault caused the cables to be installed with a permanent bend radius less than the minimum 584.20 mm (23 in) required for a cable with a diameter of 48.26 mm (1.9 in). The cables installed in the center conduit opening could meet the minimum bend radius, although with very little margin. These cables were modified with splices. The third set of cables had the largest bend radius and easily met the minimum bend radius. Therefore, the existing installation did not meet the National Electric Safety Code (NESC), as the permanent bend radius of at least three cables was less than the required minimum.

3.4.1.3 Dead-Break T-Splices To Be Installed

The modification required installation of T-splices in existing three-phase Line C3L2 per Drawing H-3-300059, Sheet 3, Note 9. The splices would

FIGURE 3-1
LOCATION OF VAULT R122V

FIGURE 3-2
VAULT R122V CABLE ARRANGEMENT PRIOR TO PROJECT L-047 MODIFICATION

allow power to be supplied to the new Switch SW111. Conductors to the new switch were specified as 4/0 AWG, copper, ethylene-propylene rubber insulated, shielded, with full bare concentric neutral, and polyvinyl chloride jacket.

3.4.2 Design Package

The A-E was required to provide a complete design package including technical information necessary to properly install and verify correct installation of the design. In addition to drawings, this included preparing the Construction Specification, V-L047-0001 Rev. 1, and Acceptance Inspection Plan, WHC-SD-L047-IP-0001 Rev 0. The normal design process specified for a project was followed. DOE Order 6430.1A, "General Design Criteria," was required as a design criteria.

Extensive field walk-downs were conducted by the A-E in preparation of project design. Design reviews were conducted with the proper participants including EU. No objections were raised during the design review regarding vault size.

The design media specifically called for splicing into the existing circuit in the vault. The T-splices were specified as 15kV, 600 ampere, molded dead-break (non-loadbreak) elbow connector type.

The Construction Specification, V-L047-0001 Rev 1, contains several requirements pertinent to installation, testing, and turnover of completed work. The responsibilities and technical requirements are paraphrased below:

3.4.2.1 T-Splices to be Installed per Manufacturers Instructions

Install the splices in accordance with the manufacturer's recommended procedures (V-L047-0001 Rev. 1, Sec 16120, para S.4, V.2, and W.1, page 16120-15,16).

3.4.2.2 Cable Supports to be Installed

Support cables with permanent racks or trays so that there are no short bends, excessive sags, and the cable is not permitted to lie on the manhole floor (V-L047-0001 Rev. 1, Sec 16120, para 3.1.C, page 16120-9).

3.4.2.3 Cable Bend Radius Specified

Use extreme care during the placement of all cable to prevent tension and bending conditions in excess of the manufacturer's recommendations. The permanent radius of bends after cable installation shall be in accordance with the cable manufacturer's recommendations (V-L047-0001 Rev. 1, Sec 16120, para 3.1.L, page 16120-12). This requirement of the construction specification repeats the similar requirement of the NESC, ANSI C2, one of the industry standards required by DOE Order 6430.1A.

3.4.2.4. Arcproofing Required

Arcproof the cable where it occupies an enclosure such as a pullbox or manhole (V-L047-0001 Rev. 1, Sec 16120, para 3.1.R, page 16120-14).

3.4.2.5 Torquing of Bolted Connections to be Done Per Manufacturer's Instructions

The contractor is to certify that the tightness of each bolt in all bolted electrical connections, factory or field, is in accordance with the manufacturer's recommendations (Sec 16010, Para 1.17, page 16010-6).

3.4.2.6 Testing Specified

The contractor is to furnish the necessary experienced personnel, material, equipment not furnished by ICF KH, and apparatus necessary for adjustment and testing of electrical equipment connected or installed and connected under these specifications (V-L047-0001 Rev. 1, Sec 16010, para 3.1.E, page 16010-11).

All insulated conductors shall be electrically tested after placement. All circuits shall be tested with the circuit complete except for connections to equipment. All splices, terminators, connectors and attachments on shielded cable, shall be complete prior to testing. Equipment and labor required for testing shall be provided by the contractor (V-L047-0001 Rev. 1, Sec 16120, para 3.2.A, page 16120-17).

After installation and prior to energizing, the Operating Contractor (OC) will perform cable tests to verify acceptability of installation (V-L047-0001 Rev. 1, Sec 16120, para 3.2.B, page 16120-18).

Insulated conductors will be tested for continuity to confirm that each conductor is continuous throughout its entire length (V-L047-0001 Rev. 1, Sec 16120, para 3.2.C, page 16120-18).

Conductors with insulation rated over 5kV will be given a "field dc insulation test" (V-L047-0001 Rev. 1, Sec 16120, para 3.2.D(1), page 16120-18). It further states: "After installation and prior to energizing, the OC will perform dc overpotential [D.C. Hy-Pot] tests on cable to verify acceptability of installation" (V-L047-0001 Rev. 1, Sec 16120, para 3.2.D(2), page 16120-19).

3.4.2.7 Final Connection to be Performed by Electrical Utilities

Final connection to electrical equipment after acceptance testing and system energization will be made by the OC site utility organization (V-L047-0001 Rev. 1, Sec 16010, para 3.1.G, page 16010-11).

3.4.2.8 Lockout/Tagout Coordination is Responsibility of ICF KH

KEH (now ICF KH) will coordinate the system of lockout/tagout as the permanent plant equipment and systems are completed and capable of energization. The system will consist of placing appropriate tags on each item of equipment and each system component indicating its current status and requiring mandatory clearances from designated personnel to operate, energize, or remove from service the equipment or systems. KEH will coordinate the

procedures and details of the operation control system. Notifications of status and requests for clearances for operations shall be made to KEH (V-L047-0001 Rev. 1, Sec 16010, para 3.1.F, page 16010-11).

3.4.2.9 Vault Size Not Questioned During Design

No objections were raised during the design reviews regarding the vault size. It was stated by participants of the design review that there was no discussion of anticipated difficulty in carrying out the job. Vault size of the existing vault was not specified on the design drawings.

3.4.3 Splice Orientation Alternatives

In interviews with installing contractor personnel, it was determined that the intended orientation of the splices was vertical. As is typical, this orientation was not documented in design media. Figures 3-3 and 3-4 show a concept of the orientation of the splices as intended by the installing contractor.

3.5 INSTALLATION

3.5.1 Initial Installation Performed by Contractor Personnel

3.5.1.1 Lines Were De-Energized on Friday

On December 2, 1994, at 1839 hours, Lines C3L2, C3L3, and C3L5 were de-energized.

3.5.1.2 Work Started on Saturday

The contractor crew picked up their clearance for work on C3L2 from the EU dispatcher on December 3, 1994, at 0700 hours. No clearance was issued for C3L3 and C3L5. Chapter 296-45, Section WAC 296-45-65005, Item (14) of the Washington Administrative Code (WAC), "Safety Standards for Electrical Workers," defines a clearance as:

"Clearance (operating power lines and equipment). The certification by the proper authority that a specified line or piece of equipment is de-energized, that the proper precautionary measures have been taken and the line or piece of equipment is being turned over to the employee."

The air temperature was -5 degrees C (23 degrees F) at 0700 hours and never rose above 1.7 degrees C (35 degrees F) all day Saturday. Power outages were scheduled in order to connect facilities into the new circuits. A limited time window was available to complete the task without impacting facility outages scheduled for Monday.

The contractor identified Line C3L2 and grounded the circuit. They then accessed the vault and cut into the three cables that make up C3L2. In cutting the cables, the contractor purposely cut close to the end going to Substation 351 as there was slack available from that direction and there was no slack available on the cables going north to the next vault. The contractor pulled the new 4/0 AWG cable from Switch SW111 to the vault and installed the #2 ground conductor.

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FIGURE 3-3

CONTRACTOR'S INTENDED SPLICE ORIENTATION - NORTHWEST VIEW

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FIGURE 3-4

CONTRACTOR'S INTENDED SPLICE ORIENTATION - SOUTHWEST VIEW

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The contractor placed the vault ends of the new cable above ground to prepare the cables for termination. The contractor installation crew indicated this would be easier outside of the vault due to the limited space. There was insufficient slack in the existing cables to do the same. Therefore, one man completed terminations in the vault and one man completed terminations at the ground level outside of the vault.

To prepare the cables for termination, it was necessary to strip cable jacket, insulation, and semi-conductor layers down to a specified length (see Figure 3-5). This proved to be a difficult task on the existing cable due to three conditions: 1) the cable was oval-shaped and, thus, electric stripping tools could not be used; 2) the semi-conductor layer was embedded in the copper; and 3) the cable had memory and wanted to lie in a specific plane and shape. Therefore, stripping of the existing cables was done by hand.

Construction specifications instruct the installers, in this case the contractor, to follow manufacturer's instructions. The instructions were taped to the vault wall. The cables were terminated by installing a cable adapter, crimping the compression lugs onto the cable, and sliding the adapter and lug into the T-body (see Figure 3-6). A piece of tape is placed onto the cable prior to insertion into the T-body as part of the visual inspection to ensure the cable adapter and lug are seated in the T-body. The instructions clearly state to remove the tape after inserting the lug into the T-body prior to final assembly. The contractors followed this instruction.

To ensure mechanical continuity and proper phase identification, the contractor pulled the cables, and used cable phones to verify continuity from the substation, the new switch, and the aerial switch, and color-coded each cable phase to aid in correct assembly during the final connection. The installation took fifteen hours. CM, when asked, said this type of job normally takes five hours. Because of anticipated difficulty caused by tight working space, the work was scheduled to take ten hours.

Throughout the day, the AI inspector made routine inspections. He witnessed the cable pulling (this is a witness point in the AI plan) and the phase taping of the cables (this is a hold point). The AI inspector left the site at 2030 hours. The contractors left close to midnight (approximately 2400 hours).

3.5.1.3 Work Continued on Sunday

The contractor returned at 0700 hours on Sunday December 4, 1994, to finish their tasks. The contractor superintendent talked with the lead worker of the EU test crew (EU supervision was not present) with regard to completing assembly of the splices at this time. EU stated that they were anxious to begin testing and had expected to do so at 0700 hours. The assembly would take an additional one to two hours; it was about -11 degrees C (12 degrees F); there was pressure to commence testing and the test crew would disassemble the splice almost immediately. The plan was to have the contractor assemble the splice. Then, the test crew would disassemble the splice and perform testing. The EU assembly crew would make final connection after testing. In this event, the contractor and EU agreed that the contractor would not complete assembly of the splice. The racking, supporting, and arcproofing of the cables and splices was not done as required by the

FIGURE 3-5

380 mm² (750 MCM) CABLE LAYERS

FIGURE 3-6

380 mm² (750 MEM) TERMINATED CABLE

specifications. An Engineering Change Notice (ECN) was not issued for deviation from the construction specification for omitting cable supports and arcproofing.

The contractor removed grounds from C3L2 and released clearance at 1009 hours.

The Job Safety Analysis (JSA) mentioned the hazard of working in tight quarters with regard to "bumping heads," but did not address how workmanship would be affected.

3.5.1.4 Cable Testing by Electrical Utilities

EU picked up their clearance on C3L2 at 1030 hours. There was no other acceptance documentation other than releasing the clearance. Over the next 8 1/2 hours, they carried out their tests. The D.C. Hy-Pot test was witnessed by the AI inspector, this is a scheduled hold point on the AI plan. The AI observed the EU truck by the vault. If he had not observed the EU truck by the vault, he would not have known testing was being performed. No formal notification to the AI was made that testing was being performed. This test measures leakage current and determines insulation integrity. The cable tests were satisfactory. Testing was not performed on the completed splice assembly. Testing was completed at 1800 hours.

3.5.1.5 AI Expressed Concerns to Contractor

Between 1400 hours and 1430 hours, the AI inspector told the contractors that he had the following concerns regarding this task:

- o The constructability of the splices in the vault
- o The bend radius of the cables meeting code
- o The ability to support the cables and splices as specified

The AI inspector instructed the contractor to provide the support materials to the crew making the final assembly to the existing circuit. He explained that EU did not have the required supports.

The AI inspector left at about 1730 hours. The AI inspector said he was told by the contractor that the new system would be energized Monday morning. The inspector planned to inspect the vault prior to energization on Monday to satisfy his concerns over this task. He also intended to inspect Switch SW111 which had a hold point on his AI plan.

3.5.1.6 Final Assembly is Improper

After D.C. Hy-Pot testing, EU craftsmen performed final assembly of the T-splice connectors. One electrician from the test crew and one lineman formed the team that carried out the splice assembly. The lineman had been working on other projects throughout the day. The lineman had worked 73.1 hours during the week leading up to and including Sunday, the day of the event, and 26.6 hours within the last 48-hour time frame. The "ICF KH Environmental, Safety, and Health Program Manual," Procedure IS 11, limits employee work hours to 24 hours in a 48-hour period.

The EU craftsmen did not know that the installation crew had intended a vertical T-splice configuration be used, and were unaware of AI concerns.

The EU crew performing the final assembly felt that the task was very difficult, however, they also felt that it was constructable. They chose a configuration based on cable lengths, cable memory, and position of the lugs in relation to the cable orientation. Their configuration was different from the contractors (see Figures 3-3 and 3-4). The EU configuration had the T-body splices angled and tipped slightly down instead of vertical and cascaded (see Figures 3-7 and 3-8). They received the material for supporting the cables and splices but decided it was impossible to install them. An ECN was not obtained for this design change.

To make the final splice assembly required both men to enter the vault. One man supported one cable and T-body while the other man installed the end connector through the lug, sighted down the T-body, and threaded the female connector over the bolt. Once one cable was connected, one man supported the connected cable, the second cable and the two T-bodies while, again, the second man sighted the second lug's position and installed the next female connector. The third cable was connected into the splice in a similar fashion. This procedure was performed three times resulting in three sets of splices each with three cables, two 380 mm² (750 MCM) and one 4/0 AWG cable. A tent and heater were available, but the heater was not used.

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FIGURE 3-7

AS ASSEMBLED SPLICE ORIENTATION - NORTHWEST VIEW

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FIGURE 3-8
AS ASSEMBLED SPLICE ORIENTATION - SOUTHWEST VIEW

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The crew performed a visual check of their work. They checked the position of the cable adapter in relation to the T-body per the manufacturers instructions. They could not check cable position in the T-body as tape was removed during initial installation as instructed.

The test crew leader and the two men who did the final assembly stood together on the ground outside of the vault and visually inspected the splices prior to closing and latching the vault doors. They detected no anomalies. Continuity testing was not done on the completed splice assemblies.

The craftsmen stated that this particular task was rated for difficulty as an 8 to 9 on a scale of 1 to 10, 10 being the most difficult. They indicated that this task was challenging due to cable memory, normal difficulty in assembling the splices (because of the back pressure on connector module interfaces, and tight fits) and the need for both craftsmen to work in the vault, along with the large stiff cables and T-bodies in a small space. They completed the final connection at 1930 hours.

The results left the center A Phase lug improperly connected outside of the bolt inside a T-body. Figure 3-9 illustrates two properly assembled connected lugs and the center lug improperly connected. Note that the external orientation of the cable adapter to the T-body of the splice is similar.

Clearance was released on C3L2 at 2000 hours. The hold point on the AI plan for final inspection on Switch SW111 was not communicated to EU.

3.6 DESCRIPTION OF ACCIDENT and VAULT R122V

3.6.1 Accident

3.6.1.1 Phase Checks of New Installation Did Not Identify Discrepancy

At 2011 hours, on December 4, 1994, the electrical system dispatcher issued a switching order (S9400908, step 15 and subsequent steps) to electrically isolate and establish lock and tag protection to the load side of Switching Station C3-28 (see Figure 3-10). The dispatcher then executed a switching order to close Breaker C3X2 to prepare for phase checks at aerial Switch C3X21. The phase check was required to ensure that after modification to the existing C3L2 Circuit, correct phase orientation had been maintained (i.e. "A" to "A", "B" to "B" and "C" to "C"). At this time, voltage was applied to Circuit C3L2 splice in Vault R122V but load was not applied since C3X21 was open. Linemen at aerial Switch C3X21 performed a "nine-point" phase check from bucket trucks. The linemen reported the phase checks were acceptable. After completion of phase checks, the dispatcher opened Breaker C3X2. This allowed Aerial Switch C3X21 to be closed without load being applied, and permitted C3L2 load to initially be picked up by Breaker C3X2 which is a common EU switching practice. This switching arrangement provided breaker protection when energizing the new splice installation and provided additional safety protection to the linemen. Aerial Switch C3X21 was then closed.

**FIGURE 3-9
CONNECTOR LUG ASSEMBLY COMPARISON**

FIGURE 3-10
300 AREA ONE-LINE SWITCHING SKETCH

3.6.1.2 Load Applied to New Installation

At 2118 hours, the electrical system dispatcher closed Breaker C3X2. When Breaker C3X2 was closed, load was applied for the first time after splice installation (i.e., the beginning of the arcing fault). While the dispatcher was on the telephone with the substation operator, the dispatcher noted a Supervisory Control and Data Acquisition (SCADA) reading of three amperes on Breaker C3X2 at the control panel ammeter. The dispatcher asked the substation operator to check the ampere readings on Breaker C3X2. The substation operator reported readings of 0 amperes on A Phase and 40 amperes on B and C Phases. Within one minute, the dispatcher stated to the substation operator; "I now have 34 amps on C3X2." The dispatcher continued with switching orders and closed Breaker C3X3. The dispatcher then requested the substation operator to take readings on Breakers C3X2 and C3X3. The substation operator reported a little deflection on A Phase on Breaker C3X3 and a little imbalance on Breaker C3X2. The readings on Breaker C3X2 dropped to a minimal amount (i.e., "17 to 18 amps") due to the closure of Breaker C3X3. Since the readings had appeared to balance out on Breaker C3X2, the dispatcher continued with his switching orders. System readings were not recorded before de-energizing. Expected system readings after re-energizing were not calculated or included in restart procedures. The dispatcher issued switching orders to the linemen to remove temporary mechanical jumpers across Circuits C3L2 and C3L5. The location of the temporary mechanical jumpers was on the west side of Stevens Drive, approximately 400 m (one-fourth mile) from the 351 Substation. The jumpers had been installed earlier to provide an alternate source of power to the Fast Flux Test Facility.

3.6.1.3 First Indication of Fault is Electrical System Alarm

While the linemen were removing jumpers, SCADA reported a "Station Service #1 Momentary Failure" alarm at 2132:07 hours from Substation C3S4. Substation C3S4 was connected to Circuit C3L2 via Breaker C3X138.

3.6.1.4 Multi-Circuit Fault Causes Breaker Trip

Seconds later, a multi-circuit fault developed. The three circuit fault caused Breakers C3X300 front and rear, C3X2, C3X3 and C3X5 to trip by relay action at 2132:10 hours. Since the fault was still being fed from C3S4 Substation via Breakers C3X138 and C3X139, Breakers C3X91 front and C3X92 front at C3-3 switching station tripped by relay action to clear the fault at 2132:34.

The linemen had only removed the C Phase jumper when the above event took place.

3.7 POST EVENTS

This section outlines the problem identification process, emergency response actions, Emergency Control Center (ECC) activation, and restoration of power. Several groups of people were required to respond to the emergency. The process involved the Hanford Fire Department (HFD) that had its notification protocol, the Occurrence Notification Center (ONC) and its notification protocol, the 300 Area ECC, and the Unified Dose Assessment Center (UDAC).

3.7.1 Post Event Response

3.7.1.1 Problem Identification

The EU substation operator was on the phone with the dispatcher, located 25 miles to the north, when the breakers for Lines C3L2, C3L3, and C3L5 tripped open. The substation operator immediately went into the switchgear room to assess annunciator panels and relay targets on individual breakers. EU linemen who were in the process of removing jumpers between Lines C3L2 and C3L5 stopped their activity, having only removed the jumper on C Phase, and returned to the 351 Substation.

A smokey odor had been noticed in the substation building.

After conferring with the EU dispatcher, the two linemen and the substation operator went to investigate Vault R122V. The vault lids were still closed, and personnel noted smoke coming out and around the edges of the vault lids. They took immediate action to remove a test truck and propane bottle which had been used for the construction tent heater. The truck had extension cords still connected to the 351 Substation. These cords were used to power the test equipment in the truck and the engine block heater. The truck had been parked for the night and was not going to be removed until the following morning. After moving combustibles from around the vault, the substation operator ran back to the 351 Substation and pulled the fire alarm. He then called 911. At the 351 Substation, the Radio Fire Alarm Receiver (RFAR) tripped at the HFD.

The HFD had responded to multiple fire alarms in the 300 Area from the facilities affected by the unplanned electrical outage and were attempting to understand what had taken place.

3.7.1.2 Hanford Fire Department Response

The HFD redirected units responding to the multiple fire alarms to the 351 Substation. They were on the scene at 2158 Hours. It was unknown at this time whether or not the vault had been de-energized. Therefore, charged personnel exposure lines (fire hoses) with fog nozzles were deployed to Vault R122V and the north door of the 351 Substation. The firemen also placed a ventilation blower at the 351 Substation in the back of Cubicle C3X5 to blow products of combustion toward the vault and prevent the fire from extending. At 2225 hours, the HFD opened the vault lids to reduce pressure within the vault and to avoid forcing fire products into the 351 Substation.

3.7.1.3 Knowledge of Vault Isolation Delayed

The EU dispatcher first reported Vault R122V was isolated at 2208 hours, but rescinded that 4 minutes later with the recognition that Lines C3L3 and C3L5 were also routed through the vault.

The dispatcher had to deal with more than one task (divided attention) as well as multiple sources of information (selected attention). The tasks were:

- o Assessing the problem
- o Isolating the vault

- o Restoring power
- o Directing personnel
- o Providing information to outside agencies, such as the HFD

In each of these tasks, decisions were made based on information coming in, as well as deciding which task had priority. The multiple sources of information were:

- o SCADA, which was providing equipment status on a monitor
- o Radio communications
- o Several telephone lines (20 telephone calls in 40 minutes)
- o SCADA data logger

None of these systems prioritized information, and SCADA gave indication of the time that the information was received, but did not give the time of the actual event. EU dispatch did not recognize the HFD dispatch as a source of information since he was in communication with HFD at the scene through the substation operator.

The dispatcher confirmed vault isolation at 2232 hours.

When the EU Operations Manager arrived, at 2230 hours, the vault was on fire. After conferring with the HFD captain, agreement was reached to let the fire burn itself out and avoid exposure of any personnel to the fumes. The fire was reported out at 2321 Hours.

3.7.1.4 Emergency Control Center Activation Delayed

The HFD captain was concerned for freeze protection for facilities affected by the outage. He requested activation of the ECC and that various building managers be contacted to determine if other problems existed.

The ONC procedure does not authorize the HFD to activate the ECC. As a result, a chain of six telephone calls was required to obtain authorization from the Building Emergency Director (EU Operations Manager). The ECC became operational at 2328 hours. A delay in activation was also caused by the ONC duty officer calling the Primary Job phone list which was for day-shift notification. The alternate duty officer discovered the error and called the correct Alternate Job (off-shift) phone list.

3.7.1.5 Unified Dose Assessment Center (UDAC) Activation

The Unified Dose Assessment Center (UDAC) was operational at 2335 hours and immediately conducted assessments for PCB's and the presence of radiological materials at the vault. The results confirmed that neither was present.

3.7.1.6 Power Restored in 1 Hour and 39 Minutes

The EU dispatcher, after ensuring the vault was isolated, began re-configuring the electrical distribution system to restore power to the 20 buildings affected by the unplanned outage. The 300 Area distribution system was restored at 2311 hours, and all affected buildings were restored at

0150 hours. The ECC terminated operations at 0215 Hours. The vault was cordoned off pending investigation.

3.8 OTHER FACTORS

The following factors were relevant to the investigation, but were not easily grouped into the previous Fact Section.

3.8.1 No Similar Events Were Found

A review of the Occurrence Reporting and Publication System was conducted to determine if there were any similar events. No other events of electrical fires involving 13.8kV cable splices were found. Consultants hired to assist in determining the direct cause of the fire were not aware of a similarly caused fault. Manufacturers stated they did not know of similar occurrences. The U.S. Corps of Engineers had a fire in a similar sized vault near Lyons Ferry, Washington, approximately four years ago. This event was traced to a manufacturer's defect in a wall-mount, load-break elbow assembly.

3.8.2 Standards, Policies and Procedures

3.8.2.1 Existing Procedures Govern Actions

Existing procedures govern participant interfaces and actions:

	<u>Topic</u>	<u>Manual</u>		
o	Acceptance of Completed Work (ACW) phased turnover	WHC-CM-6-2	PM21	3.0 and 5.2
		QS10.16		
		QS10.4		
		CM 10-A		
		CM 10-B		
		PD 1.28		
o	Acceptance Test Procedures to ensure design requirements are met	WHC-CM-6-2	PM21	3.0
o	Operations test procedures to verify that functional, operational and design requirements are met.	WHC-CM-6-2 WHC-SP-0708	PM21	3.0
o	Acceptance inspections to verify installation	WHC-CM-6-2	2.0	5.4
		PS-PMP		
		PD 1.28		
		QS 10.4		
		QS 10.16		
		CM 10		
		QS 9-0		
		CON 3-4		

o	Change control of Design	WHC-CM-6-2	2.0	5.4
		WHC-SP-0708		
o	Integration of Subcontractors	WHC-CM-6-2	2.0	5.4
o	Pre-start Checklist (Conduct of operations)	WHC-SP-0708	8	

3.8.2.2 Human Factors are not Included in Existing Procedures

- o DOE Order 6430.1a, Division 13 on human factors engineering did not apply to this non safety class job (designated a Safety Class 4)
- o ICF-KH IH 11, "Occupational Ergonomics," applies to prevention of injuries, but prevention of incidents is not addressed.

3.8.3 Experience Levels Were Satisfactory

As part of the investigation, experience levels of personnel performing work for Project L-047 were researched. Experience of ICF KH PM, Power City Electric (the contractor), ICF KH CM, Black and Veatch (the A-E), the Acceptance Inspector, and ICF KH EU were reviewed.

The experience level of all personnel investigated was satisfactory. Appendix E displays experience levels for each project function.

3.8.4 Industrial Safety

The WHC and ICF KH Safety Programs require that all employees accept responsibility for working safely. Interviews with participants verified that the employees understood their safety responsibility. All, including the contract employee, understood that they could shut down a job for safety reasons. They all indicated that they believed that there would be no adverse ramifications if they took that action. All stated that they felt the job was difficult but not unsafe.

3.8.5 Integration of Project Participants

The definition of each participant's role was provided in the Project Management Plan at a macro level, with each organization focusing on the micro details of their work only.

The Acceptance of Completed Work (ACW) form is the established project process to lead phased turnover and was not utilized. Using the ACW process, the project participants mutually define and agree on system turnover boundaries, condition, testing and inspection status. CM did not utilize the ACW form; EU did not include the ACW form in the JCS work package; and PM did not recognize the lack of use of ACW form.

The AI role to perform inspection is defined in the Project Management Plan but is not included in EU work packages. The review of the JCS work package did not identify AI hold points. The AI plan was not reviewed and acknowledged by EU. The project AI plan did not clearly identify which

organization was performing which test. EU did not recognize AI responsibilities and, thus, did not notify AI of when testing or energizing would take place.

The EU crew was not familiar with the construction specification. Construction specifications are not incorporated into the JCS work package. Information such as splice configuration and the importance of racking and supporting cables and splices was not passed on from CM to EU.

The contractor did not communicate the intended splice configuration to EU. The AI did not express his concerns with regard to constructability to EU. The AI also did not tell EU of intended final inspection of the vault prior to energization of the hold point on the new pad mounted Switch SW111. The contractor did not pass on the AI's concerns about bend radius, cable supports, or constructability to EU. AI was also not informed by EU of when energization would take place. The AI was told by the contractor that energization would take place on Monday morning.

There was no field supervision of crews on project turnover. Dispatch orders do not require confirmation of all required project tasks prior to energization.

3.8.6 Prejob Planning

Work Package 99-6B-94-00908 was prepared for this task. A Job Safety Analysis (JSA) and prejob briefing were held. A walk-down of the task was performed and a checklist was completed. Hold points for construction were not included. The work package did not analyze for human factors nor did the work package instructions require a human factors analysis.

3.9 PIT EXCAVATION AND COMPONENT REMOVAL

The Type B Accident Investigation Board met on December 7, 1994. After observing the condition of Vault R122V, the board decided that participation by personnel with experience in assessing the condition of similar events was necessary. Contracts were placed with Clapp Research Associates, and Accident Reconstruction Analysis for this assistance. Clapp Research Associates have investigated 400 fault-related fires. Accident Reconstruction Analysis participated in analysis of the Challenger disaster among many other similar tasks.

A vault investigation team, led by R. M. Boger and G. P. McDonald, was formed. A Vault Entry Plan was prepared for safe, systematic excavation of the pit (see Appendix F). The plan included video taping and still photography of each step of the process. All items were labeled as they were removed.

Figure 3-11 shows the vault condition after the event.

Upon excavation, it was found that a cable connecting lug on A Phase of C3L2 was not connected into the middle position of the splice assembly.

Figure 3-12 shows a connecting lug in a splice assembly.

Figure 3-13 shows the splice with the missing connecting lug held in position. Arc burns on the splice and the lug match. All other lugs were in position.

Additionally, it was noted that the grounding conductor on Line C3L2 was separated by an arc burn.

Consultants reports are located in Appendix H.

FIGURE 3-11
VAULT R122V AFTER FIRE

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CONNECTING LUG PROPERLY INSTALLED IN SPLICE ASSEMBLY

Note that aluminum splice connector has melted.

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FIGURE 3-13
SPLICE WITH MISSING CONNECTING LUG

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4. ANALYSIS

The Analysis Section of the report was developed in accordance with the requirements of DOE Order 5484.1, "Environmental Protection, Safety, and Health Protection Information Reporting Requirements." It consists of the investigators reasoning pertaining to factual information, which supports the conclusions. Additionally, the analysis was developed by the Board to illustrate the interpretation of facts, conditions, circumstances, and inferences which support the findings, probable causes, and judgements of need. When conflicting information emerged during personnel interviews, the Board collaborated the facts by multiple means.

The Board employed change analysis, barrier analysis, events and causal factors analysis, and Management Oversight and Risk Tree Based Root Cause Analysis techniques to develop findings, contributing causes, and root cause.

This section will present results of an analysis of electrical data and the fault/fire scenario; an events and causal factors line; integration of project participants; change analysis; barrier analysis; and Management Oversight and Risk Tree Analysis. From the analytical procedures, a root cause and contributing causes were developed. The analysis techniques were used to validate the conclusions of other techniques and to look for discrepancies or deficiencies in the analysis process. Appendix G provides additional electrical analysis detail. Figure 4-1 displays the less than adequate conditions and root causes from the analysis techniques.

4.1 Analysis of Electrical Data and Fault and Fire Scenario

Load current (3 Amperes on A Phase) was first applied to C3X2 at 2118:06 hours. At that time, the initial heating and arcing due to the faulty connection began within the splice module. The poor electrical connection between the energized connecting lug on the cable and the bushing inserts created heating due partially to high current densities across limited contact area, and was compounded by extremely high temperatures involved in the electric arc across the air gap between the connecting lug and the bushing stud. Since Circuit C3L4 was loaded, and C3L2 was unable to pass current through the connection, a resulting arc voltage of several hundred volts was present across the air gap within the connector. This voltage was sufficient to start and sustain an arc, which continued until the splice module failed. Additionally, the actual current passing through the faulty connection increased with time, and reached 34 Amperes at 2119 hours.

Accident Reconstruction Analysis (see Appendix H) reviewed the materials associated with the T-splice, including the cable insulation and other dielectric materials. It is calculated that the amount of energy needed to fail these materials is 2700-3000kW-seconds. This correlates with the observed failure time.

At approximately 2132:07 hours, the heat (and probable fire) in the splice caused the insulating materials to fail. When this occurred, the energized conductor associated with A Phase on Circuit C3L2 broke away from the insulating materials and contacted ground. Shortly thereafter, heat and fire

**FIGURE 4-1
LESS THAN ADEQUATE CONDITIONS BY ANALYSIS TECHNIQUE**

CHANGE ANALYSIS	BARRIER ANALYSIS	EVENTS AND CAUSAL FACTORS	MORT BASED ROOT CAUSE ANALYSIS	CONSOLIDATED ROOT AND CONTRIBUTING CAUSES
			ROOT CAUSE	
			Less than adequate policy implementation for project integration. Integration of project and operations participants did not ensure clear understanding of roles and responsibilities; ensure effective communications; and ensure effective self-check, inspection, and testing were performed prior to placing the splice in service.	Work was not properly integrated; management failed to ensure roles and responsibilities of all participants were clear, and failed to ensure implementation of a clear process for controlling transfer of responsibilities of the interfacing organizations.
CONTRIBUTING CAUSES				
Communications on Job Turnover Supervision Planned Change Control Attention to Detail Test and Inspection	Policy Implementation Technical Information Monitoring and Control Project Integration Deviation from Planned Activities Job Safety Analysis Safety Hazards Recognition Self-Test and Measurements Operational Test Procedures	Operational Controls Work Integration Attention to Detail	Technical Information Relevant to Work Flow Risk Assessment Task Performance Error Inspection/Test Planning Supervision Between Companies/ Departments Operational Test Specification Implementation	Operational control necessary to ensure clearly understood expectations and sequencing of testing, assembly, acceptance inspection, re-energization, and system performance checks were inadequate. Project participants roles and responsibilities were not clearly defined. Application of Conduct of Operations was not recognized as being necessary for project integration. Inattention to detail during assembly. Assembly procedure and work package did not include effective self-check.
Design of Splice Environment Human Factors Review Did Not Specify Personnel Environment	Planning and Change Control Work Environment Correlation between Instruments	Human Factors	Work Environment	Design of the installation which used a very small pull box for the splice. Conformance to NESC and construction specification was very difficult if not impossible. Human factors were not adequately considered in design prejob planning. Lack of recognition of factors which contribute to diminished work performance of individuals.

engulfed the vault, and conductors associated with Circuits C3L3 and C3L5 also failed and contacted ground. At 2132:10, five circuit breakers (C3X2, C3X3, C3X5, C3X300F and C3X300R) tripped by relay operation.

Since the relay settings indicate a fault of this magnitude should be cleared in .39 seconds and it actually took 24 seconds, it is believed the actual fault current was much less due to a high fault impedance, typically seen in arcing type faults. It was at this time that the protective relays had completely isolated the faults. Based on this analysis, the relays worked as designed.

4.2 Events and Causal Factors Analysis

Events and causal factors analysis (see Appendix B) analyzes a chronological ordering of events and the reasons the events occurred. In the analysis process, an event line was constructed and then conditions were added. Event sequences and conditions were validated through operations logs, interviews, document reviews, and must-occur-next logic. Causal factors were developed from less than adequate conditions displayed on the chart and as a result of change, barrier, and MORT analyses.

Four causal factors emerged as the primary drivers for this event. These were: work was not adequately integrated; human factors were not adequately considered; operational controls were less than adequate; and attention to detail was less than adequate. A summary of these causal factors follows.

Work was not adequately integrated. The scope of this causal factor is evident from design to system re-energization. Project participants roles and responsibilities were either not clear or not specified.

In the design phase, EU was not adequately involved in the development of the inspection test plan. When a change occurred down-stream, such as not installing supports for cables and splices, they were not aware of the requirement for acceptance of the modified system. Additionally, a hold point was missed and inspection of the assembled splices was not done by the AI inspector.

Other areas exhibiting a lack of integration include job turnover by crews performing sequential tasks. Initial configuration of splices, AI concerns, expected time of energization, and intended acceptance inspections were not shared. The project inspection plan did not specify performing organizations; expectations for review of the EU work package by construction management was not clear; changes were made without authorized approval; testing and phased turnover was unclear; and AI's role to perform inspection of EU work was not well defined or understood by EU.

Human factors were not adequately considered. Human factors considerations span from design to emergency notification and response. Design of the splice assemblies did not include adequate consideration of human factors. Placement of the assemblies in the existing vault made work harder than previous tasks. One phase took 15 hours instead of the normal 5 hours. The use of overtime exceeded company guidelines and contributed to work stress as did inadequate equipment for stripping the existing cables.

Dispatch's multi-tasking and multiple sources of information without prioritization aids slowed down data analysis and possibly interfered with judgement skills. The effects of inadequate human factors consideration also caused the wrong call list to be used by ONC when activating the ECC. Labeling on the ECC call list console was interpreted incorrectly because of labeling terminology. The day-shift phones were called rather than the off-shift phones.

Operational controls were less than adequate. Operational control inadequacies span installation and event evolution and include turnover and operational readiness. Also, phased turnover of the system was done without an adequate review. This had the effect of not knowing system configuration before re-energization. (WHC-CM-6-2, Operational Test Procedure, PM-21, Punchlist Walk-through Requirements of CP 23 Open Items List; QS 10.4, Project Punchlist; and CM 10-A, Final Checklist. Requirements for phased acceptance are found in WHC-CM-6-2, Project Management, Section PM-21; CP 23 Open Items List; QS10.4, Project Punchlist; CM 10-A Final Checklist; and CM 10-B, Work Acceptance.)

The Operations organization did not ensure that the electrical system was ready for operation prior to re-energization or specify expected system parameters or mitigating actions following re-energization. This had the effect of energizing a system before all hold points and inspections were completed allowing the event to evolve. (Turnover checklist guidelines contained in DOE Order 5480.19, "Conduct of Operations Requirements for DOE Facilities;" and WHC-SP-0708, Rev. 1, Chapter 8, "Control of Equipment and System Status," was not satisfied.)

Attention to detail was less than adequate. This factor is evident in the assembly of the splices and led to a connecting lug being installed incorrectly, the direct cause of the event. This factor is tied to the human factors inadequacies described previously.

4.2.1 Integration of Project Participants

The system turnover roles and responsibilities were not adequately defined. There is a failure to integrate EU as a project participant during the assembly and testing phases of the project. Without a clear definition of roles, there were differing expectations of EU responsibilities. (WHC-CM-6-2, PM-21, Section 6.0; and PD 1.24, "Management of Architect-Engineer Subcontractors," Section 3.1.)

The definition of each participant's role was made in the PMP at a macro level, with each organization focusing on the micro details of their work only. Less-than-adequate integration of these detailed plans caused redundant requirements and omissions.

The ACW form, is the established project process to lead the phased turnover. Using the ACW process, the project participants mutually define and agree on system turnover boundaries, condition, testing and inspection status. This is essential to ensure safe and adequate definition and performance of lock and tag, operational testing, turnover, operation, and maintenance responsibilities. A system should not be turned over, nor energized without this type of Conduct of Operations control (WHC-CM-6-2, PM21, 6.2.2).

Integration deficiencies are as follow.

4.2.1.1 Roles and Responsibilities Were Unclear

Coordination of project participants including EU was not effective. Although the Project Management Plan identified responsibilities, there was inadequate integration to assure that participants interfaced thus, ensuring a quality product. Construction crews work to construction specifications, drawings, and instructions. EU crews work to JCS work packages. The instructions were not adequately integrated.

CM is given a role to interface between the contractor, and other organizations, but little definition of the role is given. The project-specific PMP does not adequately define the role of CM to provide integration between the contractor and EU, nor does it require CM to review EU JCS packages for conformance to the design and other project documents. In this event, there was not a clear understanding of what the CM role was in cross-checking the JCS packages for conformance to project requirements.

Roles and responsibilities were unclear as demonstrated by the lack of understanding by multiple crews as to who was accountable for completion of each phase and turnover to the next crew. In addition, the system was energized prior to completion of all inspections.

The AI role to perform inspection is defined in the PMP (PD 1.28, "Project Acceptance/Closeout;" QS 10.4, "Project Punchlist;" QS 10.16, "Official Acceptance of Construction and Acceptance of Completed Work;" and CM 10, "Contractor Closeout;" QS 9-0, "Quality Planning"). However, AI's authority is not understood in regard to inspection of EU work. The project review of the JCS work package was inadequate. There was a failure to clearly confirm communication of AI roles. The AI plan was not adequately reviewed and acknowledged by EU. The JCS work package did not incorporate construction specifications or AI hold points for EU work. The project AI plan did not clearly identify which organization was performing which task. Since EU did not recognize AI responsibilities, they did not notify AI of when testing or energizing would take place.

4.2.1.2 Project Participants Were Working in Unfamiliar Roles and Responsibilities

Project participants were working in unfamiliar roles and responsibilities. The EU crew was unfamiliar with the construction specification and, thus, did not consider the importance of deciding not to install a support system for the cables and splices.

The construction specification contained conflicting information. One portion was written as if the contractor would perform all work. When work allocation was made to several crews, the specification was not adequately changed. This increased the likelihood of confusion over roles and responsibilities. This may have been caused by "boiler-plating" specifications from the commercial world. In such cases, the A-E would specify that the contractor do testing and final assembly.

4.2.1.3 Turnover Between Organizations was Deficient

Turnover between organizations was deficient because the contractors did not communicate the intended splice configuration to EU. The AI did not express his concerns with regard to constructability to EU. The AI also did not tell EU of intended final inspection of the vault prior to energization or of the hold point on the new pad mounted Switch SW111. The contractor did not pass on the AI's concerns to EU. AI was also not informed by EU of when energization would take place. The contractor was misinformed as the AI was told that energization would take place on Monday morning.

4.2.1.4 Acceptance of Completed Work (ACW) Form Not Utilized

The ACW Form was not utilized. This form would have facilitated turnover communications. For instance, there would have been acknowledgement of inspection completion and a punchlist of incomplete work. EU did not include turnover acceptance checks in the JCS work package, and PM did not recognize this lack of phase turnover (WHC-CM-6-2, PM 21, 6.2.2, CM-10).

4.2.1.5 Incomplete Turnover Between Crews

There was incomplete turnover between crews as information such as splice configuration and the importance of racking and supporting cables and splices was not passed on.

There was a failure of EU to include field supervision of the crew on project turnover. Dispatch orders do not require confirmation of completion of all required tasks prior to energization. There was insufficient CM and contractor representation during final assembly and energization.

4.2.2 Design

4.2.2.1 Direct Cause

The direct cause of the electrical fault and resulting fire was failure to properly assemble a 13.8kV cable splice located in Vault R122V. The terminating compression lug on one cable of A Phase of Line C3L2 was not bolted into the splice module. When electrical load was applied, the faulty connection overheated and caused cable and splice electrical insulating materials to ignite and fail. The compression lug eye was found intact (unbroken circumference), and the splice modules were found still physically connected. Thus, the bolt of the splice module connector was not assembled through the compression lug eye as designed (see Figure 3-9). Additionally, the dimension between properly assembled splice module connectors is nominally 12.95 mm (0.51 in), the width of the lug eye. The same measurement of the as-found assembly was 9.65 mm (0.38 in). For comparison, two splice modules were hand tightened without a lug in between resulting in a space of 9.91 mm (.39 in) between the connectors. Conclusively, the lug was not properly assembled in the splice. The connector was probably assembled with partial but minimal contact between the metal parts of the lug and the splice module connectors. Electrical tests required by the construction specification are typical for the installation scope. The specified tests will not detect an improperly assembled connection in which partial contact is present.

4.2.2.2 Contributing Design Factors

The existing installation prior to Project L-047 did not conform to the NESC. The bend radius for at least three cables was less than the minimum required. However, three cables which did not meet the bend radius requirement were not involved in the L-047 modification other than by their proximity to the work on the other cables in the vault.

A conceptual representation of the intended orientation of the splices as stated by the contractor is shown in Figures 3-3 and 3-4. The installation appears to allow conforming to the minimum bend radius requirement. However, support for the cables is required by the construction specification. Training of the nine cable shield ends and their termination and grounding in the vault add interference in an already very restricted work space.

Considering the physical space occupied by the splices and the working space necessary to train the cables, assemble the cable and splice components, and torque the threaded splice components, completing the work in the vault in conformance to all design requirements including NESC and the construction specification was very difficult, if not impossible.

The construction specification makes numerous assignments of responsibilities for testing and assembly of the cable and splice hardware. It is not clear whether duplicate testing is intended or whether some testing by EU would substitute for the testing required of the contractor. Similarly, it is not clear how contractor requirements for ensuring proper tightening of all bolted electrical connections are carried out for the assembly of splices. These detailed work breakdown and task assignments should be specified in project documents.

The report by Accident Reconstruction Analysis, Inc., Appendix H, suggested that the ground connector used to ground the ends of the concentric neutral of the 4/0 AWG cables entering the splice may be undersized. The ground conductor was #2 AWG copper. The report also notes that the ground conductor was melted in two with an appearance indicative of a point arc contact rather than by overload heating. The size of this ground conductor was not a factor in the initiation of the fault. Considering the physical evidence, it is unlikely that the size of ground conductor contributed to the severity of the fault. Nonetheless, an engineering evaluation should be performed to determine if a larger size ground conductor is needed based on available fault current.

In attempting to determine whether the intended design met the requirements of the NESC, the Board needed a functioning and appointed Interpretive Authority for the NESC. This is chartered but is not functioning within the structure of the Hanford Electrical Safety Committee.

4.2.2.3 Installation

Schedule pressure existed because this work had to be completed prior to planned outages to facilities the next day. The existing cable's oval shape extended the length of time to complete the installation because it had to be

hand stripped. The existing cable was also difficult to strip because of the semi-conductor's adhesiveness to the copper conductor. This also added to the installation time.

Splice assembly or "dry fit" was not completed by the contractor in the initial installation because it would have added one to two hours to the installation time. Because of this, final assembled connections were not in the configuration intended by the contractors doing the initial installation. Also, constructability of the splice was not tested.

Cable and splice supports were not installed by contractors. Cables retained the prior curved shape and cable tension increased. In the final configuration, the cable was twisted and again cable tension was increased. Angled T-bodies required more handling and more lifting and restraining by the craftsmen.

Racks and supports were not installed, thus, there was no mechanical assistance holding the cables in place while assembling. Unsecured splices made the assembly more difficult.

The manufacturer and work package instructions for the T-body splice were inadequate due to the orientation tape being removed prior to final connection. The recommended self-check was the position of the cable adapter relevant to the T-body. This does not consider the force required to install the splice and thus, cause the adapter to slide up the cable. This would create the impression that the lug is properly seated.

4.2.3. Human Factors

A number of aspects were not considered or acted on in the human factors arena. The small working space within the vault was not adequate considering what was put in it. Two large men along with fifteen large, stiff conductors; and three sets of splices consisting of three T-bodies each created a tight working space. Additional factors were cold weather conditions, considerable continuous hours worked, including overtime, long hours completing the tasks due to tools being inadequate for stripping the existing cables and the memory of the existing cables, and time of day work was performed. Because of these stressors, there was a reduction in accuracy, a shift from conservative thought processes to risky ones, a regression to well known learned habits, and considerations of fewer alternatives such as re-orientation of the splices.

The DOE Order 6430.1a, Division 13 human factors engineering requirements did not apply to this non-safety class job (was Safety Class 4). ICF KH IH 11, "Occupational Ergonomics," addresses industrial safety but not event reduction or quality issues. Human factors elements should be included in applicable procedures.

4.2.4 Conduct of Operations

The lack of project oversight by management and failure to clearly define roles and responsibilities between the two organizations performing construction work contributed to the event. There is inadequate coordination between these two work control systems.

There is no turnover documentation used that follows the development of the project to provide turnover status between performing organizations and the work control system. EU does not have a quality control organization nor are there quality control checks within the Job Control System work package. The effects of these changes and the lack of proper job oversight and field authority allowed the project to proceed without full understanding of the final configuration of the T-splice assembly or system readiness.

EU accepted this portion of the 300 Area, Line C3L2 work, without performing acceptance testing, job walk-down, or check of all documentation to ensure all actions were completed. This resulted in the re-energization of Switch SW111 without having been inspected by the AI.

The effort required by the dispatcher to understand the impact of an unplanned electrical outage on system configuration is laborious and time consuming. The amount of information required to gain understanding combined with multiple nonessential calls contributed to information overload and delayed the dispatcher's assessment of the electrical energy isolation to the vault and the subsequent system recovery action required (WHC-SP-0708 Rev. 1, "Westinghouse Hanford Company Conduct of Operations Manual").

4.2.5 Behavior

The safety program at ICF KH and WHC requires that all employees accept personal accountability for working safely. This is contained in company policies and training and is understood by most employees.

The direct cause of the electrical fault was failure to properly install the connector in a T-splice. The craftsmen who improperly installed the connector were experienced in this work (one had installed "hundreds" and the other "tens").

To understand why a motivated experienced crew failed to assemble the splice without error, the board analyzed the event using two models. WHC/ICF KH Behavior Based Safety Training teaches that Total Safety Culture requires continual attention to three factors - Person, Environment, and Behavior. Using this model and the study "Why People Perform Unsafe Behaviors" (see Appendix D) allowed the Board to place the three safety factors in perspective (see Figure 4-2). Environmental factors, time of day, size of vault, overtime used in prior 48 hours and schedule pressure were stressors on the person. According to Management Systems Laboratories (MSL), author of "Why People Perform Unsafe Behaviors," the effects of stress on performance are:

- o Reduction in accuracy
- o Shift from conservative to risky performance
- o Consideration of fewer alternatives
- o Regression to well learned habits
- o Persevering with inappropriate strategies
- o Attention narrowing

These performance detractors coupled with the lack of recognition of risk and an insufficient self check method (length of insertion) resulted in installation of a lug not in place. When difficult jobs are conducted with

FIGURE 4-2

A TOTAL SAFETY CULTURE REQUIRES CONTINUAL ATTENTION TO THREE FACTORS

performance detractors present, additional means must be put in place to assure safe and quality work. The means can include close supervision, more detailed procedures and instructions, and additional quality tests and inspection.

4.2.6 Post Event Response

Communication between personnel in the 351 Substation and the EU dispatcher and the HFD dispatcher failed to pass on information vital to an early understanding of the event. The HFD does not have authority to activate the ECC. They are typically the first to arrive on the scene on back shifts (as much as 35 to 40 minutes before off-shift management arrive). This puts them in a better position to assess the impact of an event and activate the ECC if necessary. The wrong call list was activated by the ONC Specialist, causing a 30-minute delay in manning the ECC. The effect was a delay in response time.

4.3 Management Oversight and Risk Tree Analysis

Management Oversight and Risk Tree analysis was performed using four findings. The findings were design, installation (including human factors), system restoration, and post event actions. Information gained from the events and causal factors charting, barrier analysis, and change analysis were used to answer questions posed by MORT and to validate the conclusion from each analysis process.

4.3.1 MORT Based Root Cause Analysis

Less than adequate policy implementation for project integration. Integration of project and operations participants did not ensure clear understanding of roles and responsibilities; ensure effective communications; and ensure effective self-check, inspection, and testing were performed prior to placing the splice in service.

4.3.2 Contributing Factors

4.3.2.1 Task Performance Error

The direct cause of the event was determined to be that a compression lug on one of the conductors had not been bolted into place when the splice was assembled.

4.3.2.2 Risk Assessment System is Less Than Adequate

Failure to give adequate consideration to human factors in the design of the splice installation environment.

4.3.2.3 Failure to Provide a Work Environment Conducive to Task Performance

The work environment plays an important role in successful task completion. Vault size was not adequate to install splice assemblies with two personnel in the vault. Another factor that may have led to inadequate task performance was the number of continuous hours of work by personnel installing

the splice assembly. Temperature was also a factor considered in the work environment. Temperatures during installation were below freezing. Schedule pressure existed because this work had to be completed prior to the planned outages to facilities the next day.

Taken separately, these factors may not have contributed to task errors. When combined, they had an impact on successful task completion.

4.3.2.4 Operational Test Specification Implementation is Less Than Adequate

Operational test specifications help to ensure facility functional operability. In this situation, a "dry-fit" or demonstration of the splice assembly to ensure associated hardware fit and needed adjustments for final installation of the splice assembly was not performed as had been previously done on other projects.

4.3.2.5 Supervision Between Companies/Departments was Less Than Adequate

In a complex work-flow process, supervision's roles and responsibilities need adequate definition to ensure project completion. Supervision in all departments/companies did not function together as an integrated team. Rather, each entity performed their task and left the job to the next crew in line.

Supervision did not ensure that job task turnover was completed, communicating technical information, intended configurations, problems encountered, or possible schedule problems.

Planned splice configuration was not communicated to down-stream crews for splice installation.

A valid system re-energization schedule was not communicated to AI personnel. The reason for this is that there is no project documentation that travels from one task entity to another ensuring that all work including test and inspection is completed before the next task is done. In this case, a hold point was missed.

4.3.2.6 Inspection/Test Planning was Less Than Adequate

The inspection program does not identify the condition of all work processes, equipment, environment, and personnel. Inspection planning does not provide adequate measurement of splice dimensions for proper assembly.

The inspection test plan did not transcend organizational boundaries. This allowed hold points to be missed and premature system re-energization.

A startup checklist does not exist for electrical system restoration that adequately describes the steps necessary to recognize anomalous conditions.

AI of pad mounted switchgear was not complete prior to energization. While not contributing directly to the event, this is symptom of inadequate project integration and control.

4.3.2.7 Technical Information Relevant to Work Flow Process was Inadequate

The effect of not having adequate technical information in the operations and installations process taken separately may not have been enough to allow the event to occur. In this case, system status was not known by Operations nor was the status of the installed splice known. Lack of adequate technical information about the work flow process by Operations contributed to the event.

4.4 Change Analysis

Change analysis looks at what is different and was used as a quick entry into the event. Change analysis efforts evolved around installation and event evolution. During these two phases of the event, multiple changes occurred that if adequately controlled may have prevented or mitigated the event.

The first major change occurred when it was decided that instead of the contractor assembling the splice configuration in a "dry fit," an EU crew would perform testing and installation without a "dry fit." This was done to save time. There was schedule pressure to get the system re-energized as soon as possible. The second change occurred when splice supports were not used. They were not used because given the size of the splice environment and the number of cables and splice assemblies, there was not adequate room.

The third factor of change involved lack of expected system readings on re-energization or a startup checklist with expected system readings on restart. Lack of having expected test results left Operations personnel without a thorough understanding of abnormal condition definitions and recovery modes.

The first change had the effect of not communicating the intended splice configuration to the crew performing installation of the splice assemblies and not testing constructability. The second change had the effect of not having mechanical assistance in holding the cables which would have helped in assembly. The third change had the effect of missing an opportunity for early detection.

Listed below are finding and probable causes. Figure 4-3 displays a change analysis worksheet used for the change analysis.

4.4.1 Finding

Direct cause is a compression lug on one of the conductors not being bolted into place when the splice was assembled.

4.4.2 Probable Causes

Attention to Detail Less Than Adequate
 Test/Inspection Less Than Adequate
 Design of Splice Environment Less Than Adequate
 Did Not Specify Personnel Environment
 Human Factors Review Less Than Adequate
 Supervision Less Than Adequate
 Planned Change Control Less Than Adequate
 Communications on Job Turnover Less Than Adequate

**FIGURE 4-3
CHANGE ANALYSIS**

Event	Non-Event	Differences	Effect	Probable Cause
<u>What</u> T-Splice Fault	Other T-splices have been successfully installed. Possible rack/wall mount configurations.	None with the T-Splice. Rack/wall mount configuration is easier to align.	NONE Easier alignment methods would help to ensure proper fit-up and torquing.	DIRECT CAUSE IS TERMINATION END NOT CONNECTED (BOLTED) IN T-SPLICE. TASK PERFORMANCE ERROR
<u>How</u> Inattention to Detail during difficult task.	Careful attention is given to detail during abnormally difficult task.	Difficult tasks require extra means to ensure completion. In this case, adequate detail was not given to insertion of lug into assembly with additional self checks.	The effects of inadequate attention to detail and self checks lead to a lug not being fully inserted into the splice assembly.	Inadequate work environment and design of installation.
<u>Where</u> 351 Substation Vault R122V	Other vaults or manholes.	This vault was smaller than other areas where splices were made. On a scale of 1 to 10 with 1 the easiest and 10 the hardest, personnel said this would be an 8 or a 9 for installation.	The effect of the tight working space is that it was extremely difficult to assemble the splice and to check for lug engagement prior to torquing.	Environment Less Than Adequate, MB3.b12 D/N Specify Personnel Environment. MB3.c34.d19
<u>When</u> In Time: 12/04/94, 21:32-10, late at night, cold weather conditions, extended work shift. In Process: While re-energizing 13.8kv line.	During normal 40 hour shift.	The difference is that it occurred during extended work hours during an outage.	Outage work occurs on a semi frequent basis. Extended work hours effect task performance and may contribute to errors.	Human factors were Less Than Adequate. Lead worker had exceeded the number of hours consecutively worked. Supervision Less Than Adequate.
<u>Who</u> Workers: Power City Electric constructors made terminations. ICF KH Electric Utilities Testers/Installers did testing and assembly of T-splice.	Contractor makes terminations and dry-fits splice assembly. EU personnel disassemble dry- fit, test, and re-assemble splice.	Normal procedure is to have the contractor make terminations and dry-fit the splice assembly. In this incident, a decision was made to have EU personnel test and assemble the splice. Termination by contractors w/o dry-fit.	Dry fit helps to ensure that splice can be installed. Intended splice configuration is known by tester/installers. In this case the intended splice configuration was not known and the splice was installed in a different configuration than intended by the contractor who made up the terminations.	Planned Change control Less Than Adequate. SD1.a4.b18 Communications Less Than Adequate on job turnover. SD1.b2
<u>Working Conditions</u> Environment: Splice make-up started at 18:00 hours, in a 4 ft x 4 ft x 5 ft vault. It was dark, temperature was 20s/10s. Multiple (6) 380 mm2 (750 MCM) cables were in the vault. Cramped conditions existed. Overtime: Personnel making up the splice had worked 13.2 and 32.6 hours respectively of overtime the last three days. Schedule: Schedule pressure existed to get the system back on line by 12/05/94. Delays: Existing cable oval shaped, semi-conductor in copper.	Lighting is sufficient to ensure proper alignment for splice installation. Work place is not excessively cramped. Smaller cable size and/or not as many cables. Larger vault. Routine splice operation without facilities waiting for system being back on line. Cable new or not deformed.	Work environment is not conducive to task. Size of vault. Large cable made assembly difficult. Schedule pressure adds psychological stress to an already difficult task. Delays in stripping/cable preparation.	The compound effects of darkness, cramped work space, and large cable sizing had the effect of making a tough job tougher. Extreme pressure was exerted on cables (twisting and pulling) to connect T-Splice components. Twisting cable ends can cause terminations to rotate out of alignment. There was inadequate room to ensure that cable terminations were properly fitted. Psychological and physiological stressors contributed to task errors.	Design of Splice Environment Less Than Adequate. Human Factors Review Less Than Adequate. Supervision Less Than Adequate.
<u>Managerial Controls</u> Work Site Supervision present from time to time. Monitoring: Detection Plans, Logs Schematics, Change Review not adequate. Energization took place Sunday, December 4, 1994, 2118.08	Present all of the time. OTP, checklist, etc. Energization to take place Monday, December 5, 1994.	Supervision unavailable for decision-making or decisions made by others. Technical information not available. Energization was earlier than anticipated by the Acceptance Inspector (AI)	Risk decision not elevated to appropriate level for decision. Decision made based on marginal information. Early energization did not give AI an opportunity to inspect splice installation prior to energization.	Supervision Less Than Adequate. Planned Change control Less Than Adequate. SD1.a4.b18 Communication Less Than Adequate.

4.5 Barrier Analysis

Barrier analysis activities focused on three topical areas as targets. These were implementation of design of the installation, installation of the T-splice assemblies, and system re-energization activities. Conclusions drawn from the analysis validate findings from change analysis and were used to answer question asked by the MORT Based Root Cause Analysis lines of inquiry. They were also used as a basis for root cause and contributing factors formulation. Both administrative and engineered barriers were analyzed for their adequacy and subsequent effect on the event. The following summarizes the analysis results. More detail is given in Figure 4-4.

Barriers found inadequate in the implementation of design are, detailed design of the splice assembly and environment; human factors as part of design and design review; and the vault size or splice environment. The probable cause of the inadequacies are technical information and job task analysis being less than adequate. These factors contributed to the failure to implement the design for the splice assemblies.

To ensure adequate installation of the T-splice assemblies, multiple barriers need to be in place. These include attention to detail, measurement and testing, inspections, job task turnover, human factors analysis, and problem recognition, supervision, and project integration. Inadequacies existed in monitoring and control of the job, project integration, policy implementation, safety hazard recognition, the work environment, planning and change control, self-test and measurements, and deviation from planned activities.

During system re-energization activities, deficiencies noted included calibration of SCADA and field instrumentation and procedures for re-energization. SCADA and field instrumentation vary significantly. Procedures for re-energization do not include readings before and after. Both contributed to not knowing system status and difficulties in trouble shooting. Procedures also do not direct operations to go back to the last known safe condition. The following is a summary of findings and probable causes.

4.5.1 Finding

Failure to implement design.

4.5.2 Probable Causes

Technical information less than adequate; Job Safety Analysis less than adequate.

4.5.3 Finding

Improper assembly of T-splice.

**FIGURE 4-4
BARRIER ANALYSIS**

TARGET	UNWANTED ACTIVITY	BARRIER	ANALYSIS	PROBABLE CAUSE
Design	Failure to Implement Design	Detail Design of Splice Assembly	A detailed design of the splice assembly in the vault was not performed. Thus, adequate information for hazards analysis was not available.	Technical Information Less Than Adequate
		Human Factors as Part of Design/Design Review	Human factors analysis was not performed and results used in-design consideration resulting in inadequate task environment for job completion.	Technical Information Less Than Adequate
		Vault Size/Splice Environment	The vault size was relatively small and made it relatively difficult to work. Conformance to NESC and construction specifications was very difficult if not impossible.	Job Task Analysis Less Than Adequate
Installation	Improperly Assembled Splice Assemblies	Human Factors Analysis/JSA	A human factors analysis was not performed describing the interaction between man and machine either separately or in the JSA. The number of consecutive work hours was not monitored and acted on allowing personnel to work more than requirements allowed.	Inadequate Hazards Analysis Process; Inadequate Monitoring and Control
		Job/Task Turnover/ Intended Splice Assembly Configuration	Job/task turnover between the contractor and the test and installation crews did not include a written description of the intended configuration of the splice assembly. Also, the contractor/installation/operations interface did not relay AI hold points that were not fulfilled.	Inadequate Project Integration
		Manufacturers Instructions	The manufacturer instructions provided self checks for adapter installation and overall longitudinal measurement. The latter not catching a partially inserted connector lug. Tape markings on cables would help provide an adequate indication of proper assembly.	Inadequate Thought to Marginal Assembly Environments
		Attention to Detail	Attention to detail was not adequate. Splicing activity similar to this one had been done numerous times. the size of the vault, number of splices, continuous hours worked, schedule pressure, time of day, and weather contributed to less than adequate attention to detail.	Inadequate Work Environment; Human Factors Analysis
		Project Work Instructions	Project work instructions did not transcend organizational/company boundaries nor adequately specify roles and responsibilities. Examples include who follows the project from start to finish; transfer and acknowledgement of hold point before re-energization; and EU test/inspection points.	Inadequate Technical Information; Inadequate Policy Implementation

**FIGURE 4-4 (CONTINUED)
BARRIER ANALYSIS**

TARGET	UNWANTED ACTIVITY	BARRIER	ANALYSIS	PROBABLE CAUSE
Installation	Improperly Assembled Splice Assemblies	Overall Work Planning/Plan Implementation (Construction Specification, etc.)	Deviations in following construction specifications had an impact on the event. Construction Specification calls for the use of support for splices. Knowing they were required to be used but were not because of vault size may have caused a re-design if elevated to a sufficient level. Full system test was also required prior to system turnover. This was not completed. Work plan did not supply overall project coordination/integration responsibilities.	Inadequate Policy/Procedure Implementation
		Project Integration/Coordination	Project coordination and integration was not adequate between construction crew and EU test/installation/operations personnel. System status was not known by those who needed to know, EU Operations; Re-energization schedule not communicated; test plan requirements not recognized/known by project participants.	Inadequate Policy/Procedure Implementation
		Dry-fit	Dry-fit of splice assemblies was not performed as previously done by construction personnel. Because of this, the intended splice assembly configuration was not communicated to test and installation crews. This contributed to the event.	Deviation from Plan; Schedule Pressure
		Problem Recognition	Throughout the project, indicators of a problem were noted and not acted on. During construction, oval cables made use of stripping tools impossible; cable supports were not used as specifications required; crimping task took considerably longer than expected.	Potential Hazard Not Recognized
		Test Procedures Verification	While continuity testing of individual components was done as well as required D.C. Hy-Pot, test procedures did not require continuity testing of the entire system. X-raying of completed splice assemblies was not done. Cost considerations and history of successful installation deferred this action.	Assumed Risk; Not Thought Needed
		Tape/gauge to monitor splice	Tape marking was removed per manufacturers instructions after alignment of cable adapter. Gauge measurement of longitudinal axis would not catch mis-assembly if connector lug was butted against splice stud and not fully inserted.	Tape Marking/Gauge Not Considered Needed; Assumed Risk
		Re-energization Hold Points	Hold points were described in the AI plan. These did not cross organizational boundaries. The AI did not inspect EU work nor was his checklist recognized by EU. As such, when a change was made directing EU personnel to install T-splices without a dry-fit, the AI plan was circumvented.	Inadequate Project Integration

FIGURE 4-4 (CONTINUED)
BARRIER ANALYSIS

TARGET	UNWANTED ACTIVITY	BARRIER	ANALYSIS	PROBABLE CAUSE
Installation	Improperly Assembled Splice Assemblies	EU Test Procedures; Standardized Phase Testing (Nine-Point); Test Data Sheets	A nine-point phase test was performed on this installation and indications pointed to proper phasing. Phase testing is not a continuity test but could reveal problems if cables were not connected. Actual voltage readings are not looked for, but rather meter deflection. Test data sheets are not used for recording actual readings. Thus, information baselines are not established. EU test procedures do not include before-readings, after-readings, or requirements to return to the last known safe condition. This has the effect of possible exasperation of an event.	Not Thought Needed; Assumed Risk; Inadequate Technical Information
		Inspection Plan	The inspection plan included witness and hold point for splice construction, testing, and inspection. It did not cross organizational boundaries and was not effectively communicated. When changes in construction process implemented, down-stream effects were not adequately identified.	Planning and Change Control Inadequate
System Re-energization	EU Failure to Successfully Re-energize	SCADA Correlation with Field Instruments	Readings between SCADA and field instrumentation vary. This can cause confusion for Operations personnel especially when anomalous conditions occur. Inaccurate or misleading instrument readings can exasperate an event. In this event, an operator was in the 351 Substation building to help with instrument readings. This is not the normal case.	Not Thought Required; Assumed Risk
		Multi-Phased SCADA Analog Points	Multi-phased SCADA analog points (ampere indication on A, B, C Phases at SCADA points) have not been used in the past. In this event, their use may have enabled Operations personnel to assess the event sooner or provided indications an event would occur if re-energization continued.	Budget Constraints Would Not Allow Multi-phased SCADA Analog Points
		Remote Observance of Splice	Remote observation of the splice was not completed or required. This may have been done if splice integrity was in question after tests and inspection. In this event, splice integrity was not in question by crews who assembled.	Not Normally Done; Not Thought Required; Assumed Risk
		OTP/Checklist Recovery Modes	Clearance procedure signifies when all work is completed and switching can take place. In this event, readings were not taken before de-energization for use when work was complete and re-energization occurred. It was not required. When anomalies occur, Operations personnel are instructed to troubleshoot the problem which does not include returning the system back to its last known safe condition.	Procedure Inadequate

4.5.4 Probable Causes

Monitoring and control of the job, project integration, policy implementation, safety hazard recognition, work environment, planning and change control, self-test and measurements, deviation from planned activities.

4.5.5 Finding

EU failed to successfully re-energize.

4.5.6 Probable Causes

Calibration Between Instruments; Operations Startup Checklist (OSC), checklists, and recovery modes does not validate splice assembly.

4.6 Root and Contributing Causes

Root cause and contributing causes were determined using the results of change, barrier, events and causal factors analysis, and MORT Based Root Cause Analysis. Figure 4-1 displays summaries of the probable causes from the analysis techniques. It also provides a consolidation of the probable causes and the root cause. Findings, Judgements of Need, and Recommendations were derived from these analysis results.

4.6.1 Root Cause

Work was not properly integrated; management failed to ensure roles and responsibilities of all participants were clear, and failed to ensure implementation of a clear process for controlling transfer of responsibilities of the interfacing organizations.

4.6.2 Contributing Causes

Operational control necessary to ensure clearly understood expectations and sequencing of testing, assembly, acceptance inspection, re-energization, and system performance checks were inadequate.

Application of Conduct of Operations was not recognized as being necessary for project integration.

Project participants roles and responsibilities were not clearly defined.

Inattention to detail resulted in a faulty assembly.

Assembly package and work package did not include an effective self check.

Design of the installation which used a very small vault for the splice. Conformance to NESC and construction specification was very difficult if not impossible.

Human factors were not adequately considered in design prejob planning.

Lack of recognition of factors which contribute to diminished work performance of individuals.

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5. CONCLUSIONS

This Conclusions section presents findings, probable causes and judgements of needs. For continuity they have been grouped into Operations Control, Project Participant Roles, Conduct of Operations, Behavior, Assembly Procedures, Design, Human Factors, and Post Event Response.

5.1 OPERATIONS CONTROL

5.1.1 Finding 1

EU did not adequately ensure that the electrical system was ready for operation prior to energizing or specify the expected system parameters or mitigating actions following energization.

5.1.2 Finding 2

EU accepted a phased turnover of project work without adequate review. CM failed to initiate a proper phased turnover. EU failed to recognize the lack of a proper phased turnover.

5.1.3 Probable Cause

Operational roles and responsibilities necessary to ensure clearly understood expectations and sequencing of assembly testing, acceptance, inspection, and re-energization were not defined or were unclear.

5.1.4 Judgement of Need

EU needs to define the requirements for acceptance of project work involving phased turnovers and ensure integration with project procedures. EU should ensure that systems are acceptable prior to energization by use of an Operational Start-up Checklist for system energization. The list should include checks that assure system readiness, including electrical continuity, assurance that hold points are satisfied, expected post energization parameters are established, field monitoring is in place to assist the dispatcher and recovery modes are established if the parameters are not met. An EU person in charge of EU project interface work and acceptance needs to be appointed.

5.2 PROJECT PARTICIPANT ROLES

5.2.1 Finding

Project participant roles were not adequately specified or were unclear.

- o AI role to perform inspection of EU work was not fully understood by EU.
- o Expectations for review of the EU work package by construction management were not clear.
- o AI plan was not incorporated in EU work package.
- o Project inspection plan did not specify performing organization.

- o Expectations of system turnover were unclear.
- o Turnover of crews performing sequential tasks was not specified.
- o Testing and acceptance of phased turnover unclear.
- o Changes were made without authorized approval.

5.2.2 Cause

Project participant roles and responsibilities were not understood. The customer-supplier relationship with EU caused confusion in all parties.

5.2.3 Judgement of Need

Project management needs to include integration of clear roles and responsibilities of all project participants:

- o Integrate EU into project planning and procedures.
- o Integrate work control elements across all project participants (hold points, pre-energization checklist, project turnover documentation, field change control for spec changes and work assignments).
- o Clear and normal means of control of sequential activities and task-to-task turnover practices defined.
- o A designated person should be in charge of field activities of all participants until formal acceptance by the end user.

5.3 HUMAN FACTORS

5.3.1 Finding

Human factors were not adequately considered during design, pre-job planning and installation.

- o Design did not adequately consider difficulty of construction.
- o Overtime was used which exceeds Company guidelines.
- o Environmental items such as, time of day and temperature impacted performance.

5.3.2 Probable Cause

Human factors elements are not stressed during design, constructability reviews, prejob planning, or work assignments.

5.3.3 Judgement of Need

Human factors elements need to be included in design, constructability reviews, and pre-job planning and work assignments. Personnel performing

these functions need to be trained in basic human factors. Applicable procedures need to be modified to include human factor elements.

An Error Cause Removal program needs to be developed to implement human factors/human error training (see Appendix I).

5.4 CONDUCT OF OPERATIONS

5.4.1 Finding

There is incomplete implementation of Conduct of Operations.

- o There was no formal turnover between the construction crew and the EU crew on the intended in-vault configuration of the T-splice assemblies.
- o There was no approval or documentation on deviation from the construction plan, i.e., not to rack mount the cables in the vault and not to have the T-splice assembled by the contractor.
- o There was no integration on a detail level between construction and EU.
- o Clearly defined roles and responsibilities between departmental interfaces do not exist.
- o Lines C3L3 and C3L5 were de-energized, but clearances were not issued.
- o The controlling organization for the project does not review/approve all project related work packages, namely the JCS work package.
- o EU did not perform an acceptance inspection for all work to be completed, documented, etc., prior to energization.
- o Communication among all parties involved in the construction, testing, and subsequent response during the event was less than adequate.

5.4.2 Probable Causes

Application of Conduct of Operations was not recognized as being necessary for project integration.

5.4.3 Judgement of Need

See Judgement of Need, Operations Control and Project Participant Roles.

Turnover, communications, shift routines, operating practices, lock and tag and equipment status control need to be emphasized.

5.5 BEHAVIOR

5.5.1 Finding

Performance of the EU work crew did not result in a proper installation.

5.5.2 Probable Cause

o Inattention to Detail

Procedures and techniques utilized for this job have been successfully employed many times in the past, but failed in this instance. Slippage or misalignment of components was not noticed.

o Human Factors

Lack of recognition of factors which contribute to diminished work performance in individuals. There were numerous factors which should have been recognized as leading to diminished work performance.

5.5.3 Judgement of Need

Provide training to all personnel that enables people to understand work stressors and how they can adversely impact performance. Incorporate training into refresher safety training.

5.6 ASSEMBLY PROCEDURES

5.6.1 Finding

The manufacturer's instructions did not include adequate self-check, and no other self-check was specified to indicate that final assembly was proper.

- o** Manufacturer's instructions specify removal of the position marking tape from the cable after positioning of the cable adapter into the T-body and prior to the assembly of components.
- o** The cable adapter can slide on the cable giving a faulty position indication of final assembly.

5.6.2 Probable Cause

Self-check is not a rigorous part of the manufacturer's instructions. Procedure did not anticipate use of the force needed for this installation of splice connectors.

5.6.3 Judgement of Need

An accepted means of self-check needs to be incorporated into an integrated work package. For example: construction specification needs to specify use of a brightly colored (not red, blue or yellow) position tape on the cable. The tape should not be removed until after final testing and assembly. Inspector should authorize removal of the tape after verifying that the position is correct. Other methods of self check may be acceptable.

5.7 DESIGN

5.7.1 Finding

Design contributed to the event:

- o An existing 1.2 m x 1.2 m x 1.5 m deep (4 ft x 4 ft x 5 ft deep) vault was used for the splice.
- o Vault size was marginal for 3 splices with 9 cables, 6 additional existing cables, racks and supports, and a 2-man assembly crew.
- o Testing requirements were not specified which fully demonstrated assembled system integrity.
- o In performing the analysis, the Board needed an Interpretive Authority for NESC.

5.7.2 Probable Cause

Design did not adequately consider constructability of the design and means to verify the finished assembly.

5.7.3 Judgement of Need

- o Greater emphasis needs to be placed on constructability and verification testing of assembled systems.
- o A 1.2 m x 1.2 m x 1.5 m deep (4 ft x 4 ft x 5 ft deep) vault should not be used for splices of this size. Free-standing splice modules should be avoided if an alternate design is practical.
- o Although not contributing to the cause of this event, an engineering analysis needs to be completed to determine if a larger ground conductor is needed based on calculated ground faults.
- o An interpretive authority needs to be functional for NESC in the Hanford Electrical Safety Committee.

5.8 POST EVENT RESPONSE

5.8.1 Finding

Post event response, although implemented well, has some areas for improvement.

- o HFD response was excellent.
- o EU dispatcher received non-essential communication that delayed his assessment of the actual electrical distribution configuration in the 300 Area.
- o The on-scene HFD command post does not have authority to activate support agencies, namely, the ECC.

- o EU supervisory systems did not allow timely assessment of electrical distribution.
- o Occurrence Notification system activated the day shift call list when the event occurred in the evening, thus, delaying response.

5.8.2 Probable Cause

Human factors has not been adequately considered in post event activities.

5.8.3 Judgement of Need

- o A phone screening device needs to be installed to aid the dispatcher in post event situations.
- o The HFD needs to have the authority to activate the ECC.
- o The ONC needs to review its function to assure that human factors has been incorporated so as to minimize errors in post event actions.
- o EU needs to complete the upgrade to the SCADA system to provide the dispatcher with prioritized, adequate, and timely information of system status and configuration.

5.9 INDUSTRIAL SAFETY AWARENESS

5.9.1 Finding

Industrial safety awareness is high:

- o All workers interviewed understand that they could stop a job for safety reasons.
- o All workers felt that there would be no repercussions for stopping a job for safety.
- o All interviewed placed a strong emphasis on performing work safely.

5.9.2 Probable Cause

There is a strong sense of ownership for industrial safety among employees. Behavior Based Safety Training, management commitment to safety, employee involvement, JSA, and prejob briefings were apparent.

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WHC-MR-0487

APPENDIX A
APPOINTMENT LETTER

Department of Energy

Richland Operations Office
P.O. Box 550
Richland, Washington 99352

9407537 B

DEC 9 1994

Dr. A. L. Trego, President
Westinghouse Hanford Company
Richland, Washington

DEC 22 1994

H. L. DEBBAN

Dear Dr. Trego:

TYPE B INVESTIGATION BOARD APPOINTMENT

I am appointing an intercontractor investigative board to investigate the Electrical Fault in 13.8 kV Cable at the 351A Substation which occurred on December 4, 1994. The event should be thoroughly investigated and a report prepared in a manner consistent with DOE Order 5484.1, "Environmental Protection, Safety and Health Protection Information Reporting Requirements."

The following employees have been selected to serve on the board:

Herb Debban, Chairman, Steam/Electrical Recovery Project, ICF KH
Larry Eyre, Conduct of Operations, WHC
Dave Kelly, Projects, WHC
Mike Boger, Electrical Engineering, WHC
TBD, Accident Investigator

Wu Chin of the Project Management Division has been appointed to serve as DOE Liaison to the Board. Additional key resources to work with the board are Bob Fritz and Bill Johnson of ICF KH Electrical Utilities. Additionally, you are authorized to draw upon the resources of RL and contractor staff for a thorough and expeditious investigation of this problem.

Your final report is to be documented and submitted to me by January 23, 1995.

Sincerely,

John B. Wagoner
Manager

cc: H. L. Debban, ICF KH
R. E. Tiller, ICF KH

WHC-MR-0487

APPENDIX B

EVENTS AND CAUSAL FACTORS CHART

EVENTS AND CAUSAL FACTOR CHART - DESIGN

B-1

EVENTS AND CAUSAL FACTOR CHART - INSTALLATION

B-2

EVENTS AND CAUSAL FACTOR CHART - INSTALLATION

B-3

EVENTS AND CAUSAL FACTOR CHART - INSTALLATION

B-4

EVENTS AND CAUSAL FACTOR CHART - EVENT

B-5

B-6

B-7

EVENTS AND CAUSAL FACTOR CHART - POST EVENT

B-8

EVENTS AND CAUSAL FACTOR CHART - POST EVENT

B-9

B-10

EVENTS AND CAUSAL FACTOR CHART - POST EVENT

B-11

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APPENDIX C

VAULT R122V FIRE - DEMONSTRATED ROLES AND RESPONSIBILITIES

APPENDIX C

VAULT R122V FIRE - DEMONSTRATED ROLES AND RESPONSIBILITIES SUMMARY

Party	Design	Installation	Testing	Tie-in	Event Response
PM	Coordinate Design Review and Overall Project Coordination	Permits, etc. Submittal Review			
CM		Submittal Coordination Coordination of Contractor work			
AI	AI Plan Coordination	Witness of Contractor Cable Pulling and Continuity Testing	Witness of EU D.C. Hy-Pot Testing		
Off-site A-E	Design AI Inspection Plan	Submittal Review			
Fixed Price Contractor		Material Testing, Initial Cable Identification Initial Cable Installation and Connector Make-up (Crimp Connectors) Released Clearance	Foreman Coordinated with EU		
EU Engineering	Reviewed Design Media	JCS Package Preparation			
EU Test Crew			D.C. Hy-Pot Testing		
EU Craftsman			Picked up EU Clearance	Final Labeling and Landing of Connections (T-splice/ Aerial Disconnect) Final Phase Check Removed EU Clearance	Removal of Jumpers Status from Substation Opened Aerial Disconnects
EU Dispatcher		Clearance Coordination Line Outage Switching	Clearance Coordination	Clearance Coordination Switching Activities	System Restoration

VAULT R122V FIRE - DEMONSTRATED ROLES AND RESPONSIBILITIES SUMMARY

Party	Design	Installation	Testing	Tie-in	Event Response
Fire Department					RFAR, Pullbox, 911 Fire Response Requested Activation of ECC
EU Operations Manager					Contacts Command Post Authorized ECC Activation Categorized Event
ONC					Activated ECC
Patrol					Notified RL SAS (No Special Access Control Needed)
ECC					Monitored Event and Provided Assistance (Notifications, etc.)
UDAC					Performed Hazard Assessment
EDO					Provided assistance to the Building Warden
WHC Presidents Office					Notified Manager of RL
WHC/ICF KH Other (Safety, etc.)	Planning Design Review	Planning and Overview			Supported Next-Day Fire Investigation
RL (Assistant Manager, Environmental Waste Management Monitor, etc.)					Arrived on Scene to Provide Monitoring and Support

WHC-MR-0487

APPENDIX D

**"WHY PEOPLE PERFORM UNSAFE BEHAVIORS" REPORT
MANAGEMENT SYSTEMS LABORATORIES (MSL)
VIRGINIA POLYTECHNIC INSTITUTE AND STATE UNIVERSITY**

Why Do People Perform Unsafe Behaviors?

A Review of the Scientific Literature Concerning Underlying Factors Affecting the Performance of Unsafe Acts in the Workplace

**Final Report
P. O. # MSJ-SRV-287290**

**Submitted to
Westinghouse Hanford Company**

March 22, 1994

**Prepared by
Management Systems Laboratories
Department of Industrial and Systems Engineering
Virginia Polytechnic Institute and State University
1900 Kraft Drive
Blacksburg, VA 24060
(703) 231-3501
Fax: (703) 231-3538**

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Abstract

Abstract

A large portion of industrial as well as other accidents can be attributed at least in part to "human error." In a variety of situations, people are known to perform behaviors which directly lead to accidents, often resulting in human injuries. Individuals may simply not be aware of the likely consequences of their actions. In some cases, however, it is also not uncommon for people to engage in behaviors they know (or should know) to be unsafe.

To understand why such situations occur and to truly affect change in people's behaviors and hence safety in the workplace, one must acknowledge that individuals' behavior is influenced to a considerable extent by factors within the system that individuals work. As a result, efforts to change individuals' behaviors without addressing the underlying system-level factors affecting those behaviors is akin to treating the symptoms of a disease without fighting the cause. Small, temporary improvements may be made. However, if the root of the problem is not addressed, significant, lasting change can not be realized. Numerous factors influence an individual's behavior in a sociotechnical system, many of which often play a role in accidents attributable to human error. Among the most prevalent are:

System of Reinforcement

The current reward structure within an organization may (or may be perceived to) reward behaviors other than those which are most safe when other factors must be compromised. For example, when trade-offs are necessary between safety and schedule or cost goals, individuals may perceive that a greater emphasis is placed on the latter. Even when formal reward structures emphasize safety, vicarious reinforcement of unsafe practices may exist (e.g., seeing other people perform unsafe practices, thus excelling in meeting schedule goals, and receiving superior performance evaluations as a result). Social reinforcement among peer groups may also encourage individuals to use less-than-safe practices.

Perceptions of Risk

Research suggests that individuals naturally underestimate some risks and overestimate others. To further exacerbate this problem, reinforcement of risky behaviors can affect our estimates of future risk. When an individual performs an unsafe behavior and fails to receive a (naturally-occurring) negative consequence, s/he is more likely to further underestimate the risk associated with that behavior in the future.

Training

Training individuals in the correct, safe manner to perform an action is, of course, a necessary precondition to expecting them to perform that action safely. However, the design of that training in terms of content, process, and follow-through can dramatically affect the transfer of knowledge and behavior to the workplace. For example, training which fails to operationalize concepts through hands-on experience or high-fidelity simulations may not achieve the desired behavior change in many applications. Training which focuses on the "what to do" without explaining the "why" is less effective. Additionally, employee attitudes towards the training will naturally affect the knowledge they gain and the degree to which that knowledge is transferred to the work environment.

Learned Helplessness

Learned helplessness can play an important role in the suppression of safe practices. Learned helplessness is a phenomenon in which people conclude they are powerless to influence their own lives or their surroundings. Over time, people can learn to believe that what they do does not make a difference, their efforts and successes are unappreciated, and what happens is more a matter of luck than human effort. Individuals developing learned helplessness are much less likely to take the initiative to correct unsafe conditions, or even exert the effort necessary to perform a task safely. Research shows learned helplessness varies among individuals. Because the phenomenon is learned, it may also be unlearned. Understanding the extent to which learned helplessness operates in a particular setting is important for thorough assessment and for designing corrective action.

Task Demands

Demanding task conditions may cause individuals to perform unsafe acts which they otherwise would not. In simpler contexts, the individual may be able to perform the behavior safely. However, as the situation becomes more complex, more and more demands are on the individual's finite resources. High mental workload (resulting from concurrent information processing, time constraints, etc.) may invite unsafe behaviors which would otherwise not be performed. People can become "task focused" and simply can not think about all the factors that must be considered. In addition, personal states such as fatigue or boredom, and other responses to stressors, such as emergency conditions or rotating shift schedules, temporarily reduce the individual's physical, perceptual, and/or cognitive (attention, vigilance, short-term memory, etc.) capacities. Where such conditions are unavoidable, measures above merely training the individual must be taken to prompt/ elicit the correct, safe response.

Environment/Equipment Design

The environment and/or equipment design often drives behavior. Therefore, the design of the human-machine interface of equipment and/or environment must consider the resulting behavioral implications and must be considered in a systems context. Complex technical systems often demand perceptual, cognitive or physical performance beyond a human's reasonable capabilities, particularly where conditions of high task demands are present. Measures to design the environment so that it augments rather than conflicts with human capabilities and limitations can often be easily made. Design guidelines for incorporating human engineering principles into the design of systems and system components are available (e.g., DOE 6430.1A, 1989; EPRI NP-3659, 1984; MIL-STD-1472C, 1981; Van Cott and Kinkade, 1972; as well as numerous reports by the U.S. Nuclear Regulatory Commission). However, to assess and alleviate human engineering problems requires the full participation of skilled operators familiar with the system in question. Even exemplary operator motivation and performance cannot compensate for inadequate design.

These are several of the prevailing factors that may adversely affect human performance in a complex system, resulting in the performance of an unsafe behavior, and ultimately, in many cases, an accident and even human injury. Each is discussed in some detail in Chapters 2-6 of this report, which contain an overview of the scientific literature regarding each of these topic areas. Throughout each chapter, concepts and theories from the scientific literature are illustrated by providing pertinent examples from the Hanford site. These examples were gathered through our

formal and informal interactions with Hanford employees who attended workshops associated with both the current project (OSS Mentor Project) as well as a second project in which MSL team members are currently involved (i.e., "Achieving a Total Safety Culture Through Employee Involvement").

The sample of employees with whom we spoke included representatives from all levels of the organization (i.e., bargaining unit, non-exempt, exempt/professional, and management), and from several divisions (TWRS, OSS, Facility Operations, and Restoration and Remediation). Much of the information came from structured exercises which were designed specifically to elicit this type of information. Other information was gathered via informal conversations with employees over the past six month time period; and because of our impartiality, we believe employees have been candidly honest in sharing their thoughts and feelings. Hence, we believe the information we have obtained provides a unique insight into the 'state of affairs' at Hanford regarding each of the underlying influences of human behavior. Finally, we conclude this report (Chapter 7) by offering recommendations for further addressing the behavior-based aspects of workplace safety through continual attention to the system-level factors that may be playing a role in the performance of unsafe behaviors at Hanford.

Chapter 1: Background: The Role of Human Behavior in Accident Causation

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A nuclear facility is an extremely complex technical system. While much attention is traditionally paid to the safety aspects of hardware components, the larger system in which the technical system exists is often overlooked. Humans work within and interact with the technical components of a system as well as with one another. Their behavior plays a significant role in the safe operation of the system. Therefore, a much wider perspective must be taken in defining the system boundaries. The facility must be viewed not as a technical system in isolation, but as a sociotechnical system: a combination of plant hardware whose operation is governed by physical laws, humans whose individual behaviors are governed by the laws of biology and psychology, and the interactions of individuals which are governed by the pressures and influences of social forces (Moray and Huey, 1988).

When insufficient attention is paid to the human behavioral aspects of system performance, safety is often compromised, sometimes resulting in catastrophic or near catastrophic results (e.g., the Three Mile Island accident). Sociotechnical systems must consider the human element, including the physical and cognitive capabilities and limitations, morale, and attitude in the design of the total system. In many cases where these factors have not been adequately considered, "human errors" should be termed instead "system-induced human errors," because underlying system factors contribute to the individual's unsafe behavior. This philosophy doesn't relieve the individual from responsibility but shifts the emphasis from trying to "fix" the people to trying to "fix" the system; to determine and resolve the underlying cause for an individual's unsafe act. According to the experiences of one professional in the field of human performance in the nuclear industry, about 90% of events attributed to human performance deficiencies have root causes in the system, whereas only about 10% of events have unknown causes or were caused by willfully negligent behavior on the part of personnel in the system (Paradies, 1991).

As Margolis and Kroes (1975) clearly state, "For many years, this 'uncontrollable' human element has been a source of frustration. If people would only work like machines, we could engineer out most of the accident potential. But people are not machines and strictly engineering solutions to human problems are too limited to be fully successful. Engineers will continue to be frustrated in their attempts to minimize industrial accidents as long as the large number of psychological factors which bear on the worker and affect his accident potential are not effectively taken into account."

They continue, "The psychological factor in human accidents is complex, having many elements and forms. It is seen in the motivation of a worker to perform safely; it is part of the day-to-day work habits a worker develops by observing his peers or supervisor; it is his attitude toward himself and the people around him; it is the skills a worker brings to his job; it is the state of alertness, boredom or fatigue arising from a task or the length of work time and hours or schedules of work. All these factors and more are part of the human element."

In the history of technological disasters, the unsinkable ships, the indestructible bridges, the perfect flying machines were not undone by the obvious failure everyone had planned for, but by the unexpected lineup of details.

Gray, M. and Rosen, I. (1982). *The warning: accident at three mile island*. New York: W. W. Norton.

The Prevalence of Accidents Attributable to Unsafe Behaviors

The percentage of accidents that are attributable to unsafe behavior is difficult to determine. Reports vary considerably, some citing figures as high as 85 to 95%, others as low as 30 to 50%. The discrepancy comes from how far back in the chain of events the investigators go in determining the “source” of the accident. Traditionally, human error has been used to describe operator error, or errors of the injured employee. However, further up the “event chain” may be the errors of other humans such as managers, system designers, maintainers, coworkers, etc. When a broader perspective is considered, some conclude that “human error is the basic cause behind all accidents” (Sanders and McCormick, 1993).

Another factor that influences the proportion of accidents attributed to human error is the “source list” for blame. In the simplest model, accidents are categorized as being attributable to either unsafe acts of persons or to unsafe conditions. The major emphasis of accident investigations tends to be on describing the individual who was injured and the injury-producing events rather than on finding the aspects of the situation that contributed to the accident or that disposed the individual to have the accident.

This leads to a tendency to direct attention to the fault of the person and unsafe act of the person. Shealy (1979) suggests four reasons why this tends to happen:

1. it is human nature to blame what appears to be the active operator when something goes wrong;
2. our legal system is geared toward the determination of responsibility, fault, and blame;
3. it is easier *for management* to blame the worker than to accept the fact that the workplace, procedures, or environment might need improving; and
4. the forms that we fill out when we investigate accidents are usually modeled after the “unsafe act—unsafe conditions” dichotomy.

Regardless of the specific number, a staggeringly large proportion of all accidents can be attributed, at least in part, to the unsafe behavior of the operator. Justification certainly exists for directing significant effort to improve the underlying system-level factors that influence the performance of unsafe behaviors. As Margolis and Kroes (1975) point out, “The responsibility for safety does not lie with the worker alone. The physical environment in which the individual works, the social environment of the workplace, the expectations of one’s superiors and the overall organizational milieu have substantial effects on worker behavior. The worker may be the one to put his hand in the works of a machine or fall off a ladder, but it involves management-employee teamwork to arrive at the catastrophe. This same teamwork can be applied toward preventing a catastrophe.”

Thus, to truly affect change in people’s behaviors and hence safety in the workplace, one must acknowledge that individuals’ behavior is influenced to a considerable extent by factors within the system that individuals work. Among the most important of these factors are: perceived reward systems, learned helplessness, risk perception, training, and task demands/equipment design. Each of these topic areas will be discussed in remaining chapters of this report.

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Chapter 2: Perceived Reward Systems

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RELATIONSHIP BETWEEN PERCEIVED REWARDS AND INDUSTRIAL SAFETY

One of the most important reasons why safety programs fail is often behaving unsafely has naturally occurring positive consequences. For example, performing quickly and haphazardly may get the work completed sooner and with less effort. Workers may be significantly motivated by such consequences and unwilling to give up the benefits afforded by them.

		Consequence		
		Natural	Artificial	
			Old	New
Behavior	Safe	Time consuming More difficult (Self-approval)		Praise Feedback Incentives
	Unsafe	Time saving Easy (Injury - rare)	Reprimand Punishment	Feedback

Figure 2.1

Figure 2.1 shows a matrix of behaviors (safe versus unsafe) and consequences (natural versus artificial). Nested within artificial consequences are both old and new consequences. As the figure indicates, performing safely often takes more time and is more difficult than performing unsafely. On the other hand, behaving unsafely gets the job done quickly and with less difficulty and discomfort. Organizations can intervene to change behaviors by adding artificial consequences. Typical attempts to deal with unsafe behaviors by adding artificial consequences rely on reprimands and punishment. To encourage safe behaviors, it is often better to introduce new artificial consequences such as praise, feedback, and rewards to counteract the naturally occurring consequences for working unsafely. For unsafe behaviors, we suggest introducing corrective (constructive) feedback. Interventions are often necessary to introduce artificial positive consequences for people who perform safely.

In addition, both at the systems level and the individual level, organizational reward systems often discourage safe behaviors. Many managers think they are fostering safe behaviors in their workplaces, when their systems actually work against safety. Hanford is no different. Time and

again at Hanford, workers have told us that they perceive the system to actually discourage safe practices. Understanding how to establish a safety-reinforcing reward system requires attention on several fronts.

HOW ATTENDING TO PERCEIVED REWARD SYSTEMS CAN IMPROVE SAFETY

Reward systems are either company-wide, division wide, group wide, or dyadic (between subordinate and supervisor). They can also be administered by peers one-on-one. Reinforcement may be formal (e.g., pay, bonuses, leave days, formal recognition, formal feedback) or informal (e.g., approval, praise, positive feedback). Several principles underlie the effective use of reward systems in industrial settings and warrant attention at Hanford.

Principle 1: Safety must be a value, not just a priority. Many organizations consider safety a priority. Some organizations, including contractors at Hanford, even refer to safety as their top priority. This prioritization is well-intended. However, the prioritization is actually dangerous because priorities change. Along with shifting priorities can come a de-emphasis on safety. Safety must be a value, not just a priority that can get shuffled at the first sign of a new “brushfire” (Geller, 1993a). On the other hand, a value guides everything we do. It is associated with every priority (Geller, 1993a). The idea of safety needing to be a value is one of the most widely misunderstood notions we see at work at Hanford. An organization’s formal and informal reward systems must reinforce safety as an organizational value.

Principle 2: A total safety effort focuses not just on outcome but also on process. Focus on the process for safe behaviors (Krause, 1990). Much has been said about the dangers of strictly outcome-based education, organizational change programs, and safety programs. One of the main problems with outcome-oriented programs is they focus on the ends, not the means. To understand how the system is set up to discourage safety, one need look no further than the Total Recordable Injury Rate or TRIR (Geller, 1993b). A TRIR-based safety program is outcome based. TRIR is important because it provides one overall look at how an organization is doing injury-wise. And, it’s important to recognize that organizations are required by law to keep TRIR data because OSHA monitors it. But a zero TRIR rate is our purpose, not our goal. It can’t be our goal because it doesn’t specify what we are to do, how often, or by when. Five major shortcomings are involved in using the TRIR as a basis for rewarding employees.

First, it is contaminated. Although the TRIR is intended to be a measure of safety, it’s subject to what is called criterion contamination. That is, other things besides safety can creep into the measure. For example, unsafe behaviors people get away with, unsafe conditions, employee and supervisor honesty in reporting, and the doctor’s decision to report or not report an injury may affect the accuracy of the TRIR. Second, it is not a measure of safe behaviors. People don’t know from the measure what specifically they are expected to do to improve. They feel no personal control over the means to improve the number. Third, it’s focused on failure, not accomplishment. Research consistently shows humans are more motivated when they’re working to achieve a goal, rather than working to avoid failure. Fourth, a TRIR emphasis is negative, not positive. Indeed, recent work at Hanford by Virginia Tech revealed most employees agreed “In my work group, more attention is given to unsafe rather than safe acts” (mean=3.8 on a five-point scale). Fifth, it doesn’t incorporate specific, achievable goals against which to measure progress. To be effective, goals must be moderately difficult, but achievable, and specific (Locke, 1968; Locke & Latham, 1984; 1990). People

need to know what specifically they must do to be safer (Latham, Cummings & Mitchell, 1987). To improve safety, they must ask "By what process? By what method?" (Deming, 1986; Krause, 1990). Otherwise, workers may ignore behaviors leading to the outcomes, fail to redesign faulty processes, fudge, blame others, and fail to address human factors engineering issues. Therefore, the focus of our attention needs to be on safe behaviors, how safe practices are encouraged, and strategies to increase their appearance. One answer lies in effective reward systems, based on rewarding safe work practices rather than outcome measures.

Principle 3: The system of reinforcement must be compatible with the desired change. There may be congruence between the business strategy and the reward system (Lawler, 1987). McIntire and White (1975) say that the reason people do what they do is what happens after the behavior. What happens next is **consequences**. If positive consequences follow unsafe practices, unsafe practices are reinforced. Therefore, if good outcomes happen for paying attention to speed rather than safety, cost rather than safety, loyalty rather than whistle blowing, people are simply more likely to repeat unsafe acts. These are classic examples of what Steven Kerr (1975) calls "reinforcing A while hoping for B." Inadvertent reinforcement of the wrong thing is a serious problem in organizations because in so doing, organizations fail to design processes reinforcing behaviors they want, but also make undesirable behaviors much more difficult to change. Care must be taken to identify specific behaviors workers must perform and reinforce only those. Participants in our workshops indicated that "reinforcing A while hoping for B" is pervasive at Hanford. Issues such as cost savings, manpower, deadlines, and procedures all tend to work against safety if allowed to do so. Conscious effort on the part of the management must be made to avoid giving employees the perception that other outcomes are more important than safety.

Principle 4: There are generally two kinds of outcomes and you must use each wisely. A reinforcing consequence is anything making a behavior more likely. Punishment is applying unpleasant consequences or removing pleasant ones to reduce unwanted behavior. In general, research consistently shows that positive reinforcement works best to modify behaviors. While punishment is occasionally warranted, consequences should ordinarily be positive. Consequences need to be not only positive, but also soon and certain (Geller, 1993a).

The effects of punishment are usually short-term (McIntire & White, 1975). For example, a supervisor who punishes for non-use of personal protective equipment (PPE) will probably create a situation where the employee wears PPE in the supervisor's presence, but takes it off after the supervisor leaves. Also, punishment conveys information about what is unacceptable, but not always or directly what is acceptable behavior (McIntire & White, 1975). However, because of possible catastrophic consequences of some unsafe acts, punishment can't be ruled out. If punishment is used, it should be applied fairly and consistently to those who have committed significant unsafe behaviors. This requires avoidance of attributional errors and biases (discussed in the next chapter) when trying to understand why safe events occur. People are more likely to blame people for safety problems than they are likely to look at how the person interacts with his or her environment. Special care should be taken so that it is not unintentionally applied to those who had no part in unsafe practices. Punishment should fit the incident. That is, it should be matched to the severity of the offense. Possible negative side effects of punishment include emotional reactions, escape/avoidance, aggression, and perpetuation of the use of punishment by the punisher (Kazdin, 1989). Moreover, even if punishment is used, it is still necessary to positively reinforce the desired response.

Principle 5: There's vicarious reinforcement of unsafe practices. Sometimes, employees learn unsafe practices by observation. This can occur in two major ways. First, they can see others reinforced for unsafe practices (e.g., seeing other people get away with unsafe practices and get good performance reviews anyway or seeing someone who fudges on safety getting a promotion). Second, people can learn safe behaviors by observing them (Bandura, 1986; Kazdin, 1989). People imitate others. Modeling is a primary way to teach by example (Bandura, 1986; Manz & Sims, 1987; Mazur, 1986), but modeling is not as simple as it seems at first glance. It's a primary means to "transmit, values, knowledge, and skills" (Bandura, 1986, p. 163). Whether or not people follow good or poor example is a complex issue, including how the model is reinforced, characteristics of the model, the observer, and the nature of the behavior.

Mischel (1971) summarized several characteristics of models, learners, and learning contexts that are worth noting. For example, learners are more likely to imitate when models demonstrate "rewardingness," nurturance, power, and dominance. Interestingly, dominant learners are more likely to imitate others. Situations uncertain and moderate in task difficulty are more likely to induce imitation.

Models influence observers' behavior by influencing expectations (Sims & Lorenzi, 1992). Two kinds of expectations arise: self-efficacy expectations and outcome expectations (Sims & Lorenzi, 1992). Self-efficacy (SE) is self-mastery of a task (Bandura, 1986; Gist & Mitchell, 1992). SE is the state in which a person possesses confidence to confront his or her responsibilities. They know what's expected of them and they are confident they can carry out the task. Outcome expectations are formed by the observer observing consequences of a model's behavior.

Principle 6: Reinforcement is often in the eye of the beholder. Rewards may be material, symbolic, social, or task-related (Sims & Lorenzi, 1992). Material rewards include direct rewards (i.e., cash, wages, bonuses, piece-rate pay). Indirect rewards include fringe benefits, such as health plans, vacations, and passes to sports events. Direct or indirect rewards need to be behavior-linked to enhance safety. However, not all people respond to direct, contingent rewards (Sims and Lorenzi, 1992). Although money can be a powerful reward, most day-to-day work behaviors are influenced by judgements, comments, tokens, and other symbolic rewards (Sims and Lorenzi, 1992). The nature of the task can provide powerful rewards. For many, doing what they enjoy or find meaningful is significantly rewarding. One way people can be reinforced for performance is to redesign the job with desirable responsibilities or tasks. What one person finds reinforcing, another does not. For example, at Hanford, many items on the list of things one group of people find reinforcing showed up on another list of things people do not find reinforcing! This shows vast individual differences in what will work. Therefore, it's important to tailor reward systems. If you want to know what the workers want, ask them (Skinner, 1973). What is known is that praise consistently works. However, if workers sense that management is either "cheap" in its use of tangible rewards or insincere in its use of praise, then praise can backfire, actually undermining the entire effort.

When asked for examples of what people find rewarding, Hanford workers have cited such divergent examples as shown in Figure 2.2.

Individual Incentives

- freedom from injury
- continued employment
- prizes
- peer recognition
- intrinsic reward
- career advancement
- pat on the back
- more than a pat on the back
- certificates
- small gifts or trinkets (shirts, caps, pens)
- earning points toward catalogue items
- comp time
- cash, gift certificates
- jewelry
- trips
- context prizes for safety ideas
- extra hour of vacation
- US Savings bonds
- 2 chips each day to give to peer for safe act
- donation to charity
- "atta-bucks"
- published recognition

Group Incentives

- donation in group's name
- group gifts
- pizza feed
- cafeteria
- reward upper management for fixing 80% of problems within a particular time

Figure 2.2

Of course, for most items listed, there are individuals who would not care for the item as a reward. Though not requested to do so, some groups mentioned specific items to avoid:

- more seminars
- \$25 gifts with company logo
- pens, belt buckles, penlights
- ridicule
- trinkets

Naturally, there are economic limitations. For example, someone at Hanford informed us that DOE places a \$25 limit per employee on prizes or bonuses that can be awarded during the year. Managers are allowed to decide how the total amount (Total= (\$25x number in the group)) may be divvied up. This puts some significant limits on the flexibility of managers to set incentives. However, based on employee comments, employees are fully aware and appreciative of those constraints. It should be noted that positive feedback is readily available, regardless of monetary limits. Although feedback shouldn't be used to the exclusion of other incentives, many times participants told us they simply want knowledge of results—they want to know how they're doing and want to know they are recognized and appreciated for what they do right, not just criticized for what they do

wrong. They want to do their best. They want to believe their suggestions for improvement are accepted and appreciated.

Principle 7: How you deliver reinforcement is important. Making rewards long after the safe practice is less effective than when they occur soon after the behavior. Consequences must follow soon after behavior. Delaying consequences reduces the probability of their effectiveness (McIntire & White, 1975; Geller, 1993a). This is not to say that larger rewards for extended effort cannot be effective. However, small rewards for (especially praise and recognition) should reinforce the "small wins." In general you need to reinforce consistently to develop new behaviors and partially to maintain already-learned behaviors.

Principle 8: Shape behavior. Ordinarily, don't expect workers to perform perfectly the first time. Complex sequences of behavior can't realistically all be learned at once. Break complex tasks into approximations of the correct response. Shape behavior. As improvement occurs, continue to reinforce with praise or other rewards. Overlearning may also be necessary for some safety-related behaviors to assure those behaviors will occur under stressful conditions. An example of this is emergency procedures.

Principle 9: Inappropriate social reinforcement (encouragement from others to use less-than safe practices or to hurry up at the cost of safety). Social reinforcers are positive consequences associated with being around others. They include attention, approval, facial expressions, praise, belonging to the group, group cohesiveness, etc. Social reinforcers are powerful. Reactions of peers act as powerful social consequences following either safe or unsafe acts. Social consequences fostered by an actively caring approach (Geller, 1993a) need to be focused toward increasing safety. Establishing a support system in which workers help each other be more safe can be one of the most effective strategies in safety improvement efforts.

Principle 10: Risk-taking behavior is more reinforcing to some people (risk takers) than others. Some individuals depend upon more stimulation in their environments than others. This can lead some individuals to accept greater risk than others. This phenomenon can be explained by individual reinforcement histories. We discuss risk and perception of risk more fully in Chapter 4. Special care must be taken to substitute other reinforcers for these individuals.

Principle 11: Design effective activators. Consequences are more effective when activators (those things coming before and directing or cueing behavior) are selected carefully and designed well. Activators include signs, procedures, decisions, incentives (positive consequences we know about or expect in advance), and goal setting.

Principle 12: Feedback mechanisms must be effective. Dozens of studies have underscored the importance of feedback in safety improvement (McAfee & Winn, 1989). Simply, people need knowledge of results to know how they're doing, to know how to improve. However, use of feedback isn't always effective (Kazdin, 1989). It matters how feedback is delivered. Feedback can be formal or informal. Although either can be effective, informal feedback carefully administered usually has the advantage of being more immediate. Feedback should also be specific, positive (or constructive if a correction must be made), and process-oriented (Kilbourn, 1990). Feedback should be conducted with an actively caring approach (Geller, 1993a). Feedback should also be conducted

in private. Research shows managers can be trained in feedback and that this training translates into reduced attributional bias (inappropriately blaming) and more collaborate functioning (Lawrence, 1992).

Principle 13: Employees must feel they are a vital part of achieving the organization's mission. Employees must believe they are a vital part of achieving the organization's mission. In recent years, the mission of DOE and it's contractors has changed. Workers were once thought of as cold war warriors. They felt a part of the vital mission of defending our country. Much the same as returning Vietnam vets, many now feel they aren't appreciated. The media criticizes them. Their management criticizes them. They don't feel they are vital to the organization's achieving its mission. They don't feel valued. As such, efforts to reward employees and ensure that they realize their efforts are appreciated are especially important.

Principle 14: Extinguish unsafe behaviors by eliminating the reinforcers that support those behaviors. Getting rid of unsafe practices requires you identify what employees should be doing and design a reinforcement system to support correct behaviors. However, it's also necessary to carefully examine response contingencies for unsafe behaviors to determine if unsafe practices are inadvertently being reinforced. Remember, however, that "Failure to respond to behavior has reinforcing consequences" (Hamner & Hamner, 1976). It's also crucial to address extinguishing vicarious and social reinforcement, as discussed above, that runs counter to safe practices. Those reinforcers must be withdrawn. It's probably too simplistic to believe that punishment will never be necessary.

Principle 15: Make consequences equitable. Equal means the same; equitable means according to one's relative inputs. Ordinarily, consequences must be equitable, not equal (Hamner & Hamner, 1976). Otherwise, consequences will not be effective. However, there may be times when positive consequences may be delivered to group members equally. One example is the reinforcement of equal group member efforts to improve housekeeping on site. Efforts of all group members are needed. Care must be taken to assure that "free riders" don't get rewards, however. In our focus groups, participants pointed to the ineffectiveness of reward systems that suggest anyone gets a reward just by being a member of the group (i.e., without having to do anything). Not only will such systems not motivate the desired behavior, but they will also result in participants purposefully undermining the system.

Principle 16: Let people know what behaviors you expect and try to meet trainees' expectations. Expectancies often lead to their realization (Rosenthal & Jacobson, 1968; Eden, 1988). In training contexts, such as industrial training, often meeting trainee expectations result in greater commitment, self-efficacy, and motivation to change (Tannenbaum, Mthieu, Salas, & Cannon-Bowers, 1991). These constructs are precursors to improved trainee performance.

STRATEGIES FOR ORGANIZATIONAL IMPROVEMENT

Implied in each principle above is a strategy or strategies for improving the effectiveness of existing reward systems. Specifically, organizations should ensure recognition is given for performing safe behaviors rather than the typical approach of recognizing only unsafe behaviors. Managers must reward the desirable behaviors to reinforce their occurrence in addition to providing feedback to discourage unsafe behaviors. It is also important to determine if and when unsafe behaviors may be inadvertently rewarded so as to eliminate those reinforcers.

One-on-one feedback is a strong reinforcer of behavior. When providing constructive feedback, it is important to use sound interpersonal communication skills such as doing so in private. Praise and recognition, on the other hand, should be shared publicly when appropriate. In addition to informal feedback, organization sub-systems should have formal mechanisms in place to recognize employees and allow them an opportunity to improve the reward system. This can be implemented through the use of programs such as the Mentor Program, Management Tours, the formal and informal employee concerns program, and through implementing behavior-based safety training.

It is also critical that employees have a clear understanding of what is expected of them and what behaviors they will be rewarded for. This, of course, requires employee involvement and open communications. This can be fostered through the practice of 'management by walking around,' participative goal setting, all-employee meetings, and in general, welcoming employee input.

Essentially, the organization must convey the message that safety is a value, not a priority that can be rearranged when necessary to meet cost, schedule, or manpower needs. Employees must believe they will be recognized and rewarded for safe behaviors that follow from internalizing the concepts of the behavior-based safety training.

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Chapter 3: Learned Helplessness

Chapter 3: Learned Helplessness

RELATIONSHIP BETWEEN LEARNED HELPLESSNESS AND INDUSTRIAL SAFETY

Those who've ever submitted a suggestion only to find it ignored or those who believe it's no use trying know the feelings of helplessness and hopelessness that can occur in the workplace. People learn to believe they can't make a difference. When they believe that, self- (and other-) defeating behaviors can follow. So also can depression and illness (Seligman, 1975; 1990). Decrements in actively caring about safety will not be far behind (Geller, 1993). Actively caring (Geller, 1993), taking the initiative to look out for others' safety, is a necessary ingredient to achieving safety.

Unfortunately, work environments are often structured to foster helplessness. When people make an effort to improve, only to be repeatedly "shot down," they are not likely to try again. They give up. These are ways the environment can contribute to helplessness. People may not believe it matters what they think. Real events can also cause feelings of helplessness (Peterson, 1990). The extent of such feelings may depend on the extent and duration of frustrating experiences. We emphasize the importance of principles and strategies outlined for recognizing employee contributions in Chapter 2. Adhering to those principles and employing those strategies can substantially reduce helplessness and hopelessness. But helplessness isn't learned just from experience in the environment. There are also individual differences in susceptibility to helplessness because of how people think about causes of events. Thus, helplessness arises from reciprocal influences of person, environment, and behavior (Bandura, 1978; 1986).

LEARNED HELPLESSNESS IN ORGANIZATIONS

Learned helplessness (Maier & Seligman, 1976; Seligman, 1975; 1990; Seligman & Maier, 1967) is a person's feeling of powerless to do anything about events and is an important phenomenon in the suppression of safe practices. The concept of learned helplessness was formed when Seligman observed that under certain conditions both humans and animals give up. Seligman coined the term learned helplessness after observing that dogs exposed to inescapable shock would give up—even when they could finally escape. He also observed his father act helpless following a stroke. He dedicated his career to identifying the presence of learned helplessness in animals and humans, in the laboratory and in the field. His work has received a lifetime achievement award from the American Psychological Association, the most prestigious award a psychologist can receive from his or her peers.

Initially, Seligman thought the root cause of learned helplessness was inescapable stress. Later research revealed that human helplessness was more complicated than earlier thought (Miller & Norman, 1979). Abramson, Seligman, and Teasdale (1978) amended helplessness theory to include human cognitive behaviors (thought patterns). Research has since revealed that learned helplessness can arise from inescapable stress, ongoing frustration, inappropriate reinforcement, and even people's thought patterns.

Still later research (Peterson & Seligman, 1984) found thought patterns may be important contributors to helplessness. When trying to explain events, people decide whether a cause is internal or external to the person, stable or unstable, and global or specific. Internal explanations include ability and effort, while external explanations include the situation or luck. Stable explanations refer to consistencies in behaviors across time, while unstable explanations refer to causes that change. Global explanations involve everything the individual does, while specific explanations refer to a specific case or tasks. The direction these explanations take tends toward either optimism or pessimism. That is, when a bad event happens, pessimists blame themselves, while optimists do not. When good events happen, pessimists take no credit, while optimists tend to do so.

Let's look at how these explanations arise. When events, including bad events, happen, people naturally try to figure out why. Although situations partially determine our explanations, often vast individual differences in interpretations are a result. People develop characteristic patterns of explaining and reacting to events (Peterson & Seligman, 1984). We call this characteristic way of explaining events explanatory style (ES). In particular, ES is the way people tend to explain bad events. As a person variable, ES is important because it's a pre-cursor to perceptions of efficacy (Bandura, 1986; Gist & Mitchell, 1992) and it sets the boundary conditions for learned helplessness (Peterson, 1990). ES can affect how individuals tend to explain themselves, evaluate others, set expectations, react pessimistically or optimistically, get depressed or not, stay healthy or get sick, perform well or poorly, and perform safely or unsafely. Peoples' causal explanations can affect their perceptions of efficacy and their ability to get the job done (Bandura, 1986). Causal explanations may also determine the effectiveness of training (Gist & Mitchell, 1992). ES is more than an attitude. It's a process of understanding and judging the reasons why things happen the way they do. Therefore, they serve as a major obstacle to appropriate responsibility. When making explanatory errors, people can shift blame or accept inappropriate blame. Neither of these alternatives moves people to change what they are doing. In one case, people don't see the role their own actions play in workplace safety. In another, people feel so dejected over their inability to "do anything right" they cannot function effectively.

ES has its roots in "common sense psychology" (Heider, 1958; Wegner & Vallacher, 1981) and locus of control research (Rotter, 1966). According to these lines of research, people naturally try to understand why people do what they do and who's in control. People are therefore "common sense psychologists" (Kelley, 1992). When individuals explain safety violations, incidents, and accidents, they may use at least three dimensions, illustrated by the following set of questions. Common sense psychologists seek to match their causal explanations with the evidence (Kelley, 1972; 1992; Weiner, 1990; Weiner, Frieze, Kukla, Reed, Rest, & Rosenbaum, 1987): Where does the cause seem to reside? Do others agree with me? Does this person do this in more than one kind of situation? Locus of control research found that people perceive the extent to which they have control over events in their lives and react to these perceptions. People tend to attribute control either to internal or external loci.

When it Comes to Safety, Our Explanations Can Get Us into Trouble

Explanations Can Be Biased. Explanations people give for events can also be biased. For example, research shows that people often blame individuals rather than the system when sometimes blaming the latter is appropriate. This bias is called the fundamental attribution error and was coined by Ross (1977).

Some research has explored explanatory style in the assessment of people's risky behaviors and in their explanations of major disasters. However, more research is needed to explore the operation of explanatory style in reactions to training interventions (Gist & Mitchell, 1992; Steiner, Dobbins, & Trahan, 1991). Wilkins & Patterson (1987) identified attributional biases in the explanation of major disasters (e.g., Bhopal & Chernobyl). Another study (Baxter, Macrae, & Manstead, 1990) identified attributional bias as a factor in assignment of cause to one's own risky behavior. Folkes (1990) contends differences exist between consumer and provider attributions, particularly when products fail. So, for example, when an accident at a nuclear electric generating plant occurs, different explanations will probably originate from consumers, industry officials, and government regulators. Such differences can lead to seeming intransigence by the public in public outreach contexts. But more than likely, the parties operate from different attributional frameworks. One problem is that the parties' focus of attention is ordinarily directed outward (Bem, 1972). Hence, explanations for events are typically directed outward toward the environment or toward others. People often don't see how their own behaviors are linked to unsafe practices and accidents. The problem with these errors is that they fail to address system concerns, don't lead to appropriate responsibility, don't lead to constructive solutions, promote learned helplessness, and prevent actively caring.

Explanations can be dysfunctional. Biases can lead people to abdicate their shared responsibility. When this happens, improvement can't occur. For example, sometimes people demonstrate self-serving bias. That is they don't take responsibility for their behavior when they should. This is not to say one should blame people for accidents. Accidents occur in a system and thus to the extent there is personal responsibility, it is usually shared with other system factors, such as equipment, plant, and design features. However, explanatory biases can prevent one from taking constructive actions to improve.

Explanations can lead to pessimism rather than optimism. Optimism is often cited as an antidote to pessimism. We concur. *However, it's not that simple where safety is concerned.* Appropriate optimism is preferable. Workers need to be able to assess what they can change versus what they cannot change and to take appropriate corrective action when their effort can make a difference. In other words, where safety is concerned a healthy dose of realism must temper optimism. How do we know if optimism is appropriate? Seligman (1990) says to consider

- the field of work,
- the nature of the context (time and place), and
- the appropriate amount (or degree) of optimism.

Fields requiring more optimism than pessimism include sales, brokering, public relations, presenting and acting, fund raising, creative jobs, highly competitive jobs, high-burnout jobs (Seligman, 1990). Fields requiring realism include design and safety engineering, technical cost estimating, financial control/accounting, law (except litigation), business administration, statistics, technical writing (Seligman, 1990). What's the time and place for optimism? Some degree of pessimism is appropriate when:

- it causes people to think twice,
- it serves as a reality check,
- planning a high-risk uncertain environment,

- counseling others with a dim future (initially at least),
- establishing empathy during active listening,
- the cost of failure is high,
- balancing unrealistic optimism,
- bringing real concerns to light,
- increasing thoughtfulness of planning, problem solving, and decision making,
- preventing disasters,
- accounting for resources,
- a pilot decides whether to de-ice a plane,
- a partier who's been drinking decides whether to drive, and
- what you can do can affect others.

Some degree of optimism is appropriate when:

- there's an achievement situation,
- feelings are important,
- there's a long-lasting situation when health could suffer (i.e., on-again, off-again downsizing),
- one wants to lead or inspire others,
- the cost of failure is low,
- one needs to build small successes, and
- to foster innovation and constructive change.

The amount or extent of optimism is also important. Overconfidence can result from too much optimism. Research shows inappropriate optimism can lead to optimism bias on the part of male college student drivers. These drivers tend to be overconfident in their ability and to underestimate their risk (De Joy, 1992). Another study (De Joy, 1989) showed perceived control predicted optimism and that age and experience also predicted optimism. This research emphasized the need for efforts to improve appropriate optimism while fostering appropriate realism where safety is concerned.

Despite the upbeat message of attribution theory, that message can be undercut by the tendency to blame the victim. We ought not blame "those kinds of people for how they think" (Peterson, 1990). Nor do we underestimate the extent to which environments play a part in the onset of learned helplessness of workers. However, because there are vast individual differences in the onset of learned helplessness, it is logical to question how those who experience LH can benefit from approaches taken by those who seem not to experience it. Again, we emphasize the importance of appropriate optimism.

Evidence of Learned Helplessness at Hanford

To identify the presence or absence of helplessness at Hanford, we examined results from a large multiple-choice survey sampling 537 Hanford employees by the Virginia Tech team during workshops. We also used open-ended surveys, observed and took notes at workshop exercises, and used facilitated discussion with workshop participants.

The multiple-choice survey of Hanford employees revealed little evidence for personal, generalized helplessness. For example, using a five-point response scale, ranging from 1=highly disagree to 5=highly agree, most responded in the direction of optimism. For example, most either disagreed or highly disagreed with the statement "things never work out the way I want them to" (mean=1.95). Most either disagreed or highly disagreed with the statement, "It's only a matter of time until I get hurt in a work-related accident" (mean=2.18). Most either disagree or highly disagree that "I hardly ever expect things to go my way" (mean=2.31). Most either disagree or highly disagree that "I rarely count on good things happening to me" (mean=2.28). Most either disagreed or highly disagreed, "If anything can go wrong, it probably will" (mean=2.0). However, while reasonably optimistic personally, Hanford employees revealed rather extreme pessimism specific to changing the way things are done "around here" and improving safety. Overwhelmingly, employees seem motivated to do their jobs well and safely. They believe many systems are in place to discourage safety however. Workshop participants defined learned helplessness as when "the systems, environment, peers, in fact the entire culture conspires to 'Hanfordize' and discourage innovation." Participants estimated that 90% to 100% of individuals experienced this situational helplessness. Participants concluded that in such a culture improvements are not even suggested and risk factors increase as attitudes deteriorate.

When asked to list events or situations leading to learned helplessness, workshop participants generated the following:

- The common response of: "We can't afford to do that."
- "In-box ice age" —the excessive time required to do anything due to the wealth of necessary paperwork
- "They won't listen anyway."
- "Hanford is politically incorrect."
- "Peer pressure" —Pressure to not excel, otherwise others will be expected to do so.
- "Lack of closing loop on communication" (on both good and bad ideas)
- "Shooting the messenger"
- "Patronizing attitudes"
- "The open door swings only one way—and it's out."
- "Team self-esteem is gone."

In discussion groups elsewhere at Hanford, employees also frequently mentioned repeated re-organization which interfered with getting anything done and prevented making progress on safety and other matters. The good news is that in the absence widespread personal or cognitive helplessness, establishing reinforcement systems, as indicated in the previous section, for safe behaviors will improve the situation throughout.

Hanford employees surveyed across all levels have identified many appropriate ways they personally can improve optimism in the workplace. Here are some of their ideas:

- Believe in the individual.
- Give positive feedback, reinforcement.
- Encourage and compliment.
- Have a clear understanding of goals.

- Appreciate small as well as large accomplishments.
- Be consistent.
- Have reasonable work expectations.
- Train when (and only when) necessary.
- Train effectively.
- Encourage to look on the bright side.
- Foster appropriate (not “blind”) optimism.
- Build self-esteem.
- Build self-efficacy.
- Maintain a sense of humor.
- Recognize job importance.
- Give people tools they need to do their jobs.
- Encourage team comraderie.
- Turn failures into successes.
- Sequence steps to an end goal
- Take ownership
- Make sure employees feel involved.
- Assure appropriate feedback mechanisms.

STRATEGIES FOR ORGANIZATIONAL IMPROVEMENT

To reduce employees' feelings of learned helplessness, managers and supervisors must be aware of the prevalence of such an attitude at Hanford and make a conscious effort to apply strategies, such as those learned in the behavior based safety training, to help their employees overcome these feelings. Such strategies include recognizing small successes and building upon them, following through on employee suggestions, and focusing on what can be done as opposed to what seems impossible. When barriers exist to implementing change, the manager must work with employees to help overcome the barriers and develop in them a 'questioning attitude.' Employees must have visible signs that their concerns and ideas are appreciated and that action will be taken if and when possible. When their ideas or concerns cannot be addressed, it is important for them to understand why. Positive reinforcement, encouragement, and compliments, as discussed previously, can help an individual realize that his/her efforts are appreciated. Strategies for building individuals' feelings of self-esteem and empowerment, also taught in the behavior-based safety training, can help overcome feelings of learned helplessness when applied regularly. For cases of extreme learned helplessness, supervisors should encourage employees to take advantage of the Employee Assistance Program.

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Chapter 4: Risk Perception

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RELATIONSHIP BETWEEN PERCEIVED RISK AND INDUSTRIAL SAFETY

"Workplace safety relies on the ability of workers to recognize hazards that may result in personal injury and to take action removing or minimizing these dangers" (Harrell, 1990, p. 1351). Working safely requires accurate perception of hazards, taking corrective action to remediate hazards, and performing other activities in the direction of safety. Thus risk perception plays a part in unsafe behaviors. An individual must have an awareness of potential risk to correct unsafe situations or to avoid risk-taking behavior. The greater the perceived risk a person has of an action the more likely s/he is to take pre-cautionary behaviors. On the other hand, perception of little or no risk won't lend to efforts to address safety problems. With enough time to act, people who think the high risk behavior is dangerous tend to take precautions (Weinstein & Nicolich, 1993).

The purpose of this chapter is to describe some of the factors which influence an individual's perception of risk as related to unsafe behaviors. An understanding of these factors will provide supervisors and operators with a basis for modifying their own awareness of risk relating to performing unsafe behaviors. In this section, the following are discussed in relationship to risk perception and unsafe behaviors: risk, risk perception, risk perception influences, and risk communication. Before we discuss the factors which influence risk perception, we provide some operational definitions for the major topics to be discussed: risk, risk behavior (unsafe behavior), risk perception, perceived risk, and risk acceptability.

Defining Risk

Risk can be viewed from a number of perspectives; there is no single definition (e.g., Yates, 1992; Sjoberg & Drottz-Sjoberg, 1991; Wagenaar, 1992). Risk is typically viewed from the perspective of expert assessment as the potential for loss. This definition of risk focuses on two components. The first is the probability of a loss, or undesired event. How likely is it that a negative consequence will happen under the present conditions? The size of the loss or negative consequence is the second component of risk. A qualitative description of the definition of risk, as combining both the probability of the loss and the size of the possible loss, is shown in Figure 4.1.

Using this combined definition of risk, perceived risk can be considered as the content of possible negative consequences combined with the probability of the negative event. Risk perception is a process of identifying hazards and estimating their effects. It can be considered as the estimation of possible negative consequences of actions, and the assessment of whether or not the negative consequences will occur (Slovic, Fischhoff, & Lichtenstein, 1977). One workshop participant defined risk perception as the personal interpretation of hazards as opposed to the reality of those hazards. However, there is a great deal of evidence that a nonexperts sense of risk depends on more than the probability and magnitude of the loss (Pitz, 1992).

Risk perception, perceived risk, and risk acceptability influence our choice of behavior. Risk acceptability is the level of risk an individual is willing to subject herself/himself to and is influenced by the perceived benefit of the action. The greater the perceived risk compared to the risk acceptability level, the greater the tendency to take precautionary action (Weinstein & Nicolich, 1993).

One implication of the combined definition of risk is that people may over-compensate or under-compensate for a risk if the probability is low and the size of the loss is high or the probability is high but the size of the loss is low. For example, in siting nuclear facilities the probability of a nuclear accident is low but the negative impact could be severe. This interaction of low probability with the high consequences leads to concern because the high consequences overshadow the low probability. Moreover, people are notoriously poor judges of probability (Bazerman, 1990).

		Size of Loss	
		Low	High
Probability	Low	Low	Medium
	High	Medium	High

Figure 4.1

Risk Perception Processes

An unsafe behavior is an action involving some chance of loss. When confronted with an event represented by a set of stimuli describing the state-of-the-world, we process information to select an action to respond to the environment (Beyth-Marom, et. al., 1993). Sometimes the information processing and action selection involves a conscious choice among alternative courses of action. Often, however, the processing and action selection is more automatic with little conscious consideration of the risks involved. In this chapter we focus on factors that influence our more conscious decision-making process. Taking the perspective of normative decision theory, the risk perception process can be characterized as an estimation of the extent of the possible consequences (negative and positive) and the probability of each consequence occurring. Figure 4.2 displays the important components of information processing for risk and unsafe behaviors. In choosing a behavior, we weigh, or balance, the perceived risk versus the perceived benefit, (i.e., weigh the costs versus the benefits (Holtgrave & Weber, 1993)). Sometimes we choose a behavior because of perceived rewards or we rationalize the risk away. We may lower our dread of a risk if we receive a benefit from the action that we really want. For example, the negative consequences of running a red stop light could be to get a ticket or get into an accident, whereas the benefits might be to make up for lost time.

At one Hanford workshop we asked participants to describe the tradeoffs involved in performing a risky or unsafe behavior. These are listed in Figure 4.3.

Uncertainty in the risk-perception process is due to the lack of knowledge about 1) what consequences are possible, 2) the magnitude of the consequence, and 3) how likely it is the consequence will occur (Beyth-Marom, et. al., 1993). To compensate for uncertainty, people form estimates using information such as the following:

- severity of consequences and the ease of risk reduction;
- immediacy of consequences: immediate, future, chronic;
- extent of exposure: self, family, co-workers, organization, community, environment;
- physical effect: minor injury, irritation, death;
- organizational consequences: equipment, production time, material;
- known to science; and
- observable effects (Gregory & Mendelsohn, 1993; Holtgrave & Weber, 1993).

Figure 4.2

Figure 4.3

We can represent the risk perception process in a flow chart as displayed in Figure 4.4. The risk perception process begins with the identification (ID) of the state of the world. From this description of the world, we identify the alternative behaviors and the associated consequences and probabilities. The risk is assessed producing the perceived risk. If the perceived risk is greater than the risk a person is willing to accept, then a precautionary action is taken. For our discussion, if the perceived risk is less than risk acceptability, then the “unsafe behavior” may be performed.

When people consider unsafe behaviors, the important information used in processing are:

- what is the state of the world or conditions under which we take unsafe behaviors?
- what are the perceived consequences of unsafe behavior?
- what is the level of risk acceptability?
- what pre-cautionary actions are taken? and
- what influences the answers to the above questions in the work environment?

Figure 4.4

SOME FACTORS AFFECTING RISK PERCEPTION

There are many factors that contribute to risk perception (e.g., see Yates, 1992; Sitkin & Pablo, 1992). In this section we provide a brief synopsis of some of those factors. In addition, Chapter 6 provides a further discussion of task demands and equipment factors. The principles of reinforcement discussed in Chapter 2, provide a more in-depth discussion of behavioral issues related to safety.

Beliefs about risk are learned through: experience, training, and familiarity with equipment, task, or accidents (Honkasalo, 1992). Experience can increase confidence in choices and actions to take under a given situation. Learning can also strengthen beliefs about the actions to be taken under a set of conditions. Prior success lends to predictions of future success. However, from a risk perspective, this could be good or bad. If we perform an unsafe behavior and no negative consequences occurred due to the probabilistic nature of events, then we may perceive the action is safe when in fact it is unsafe. Risk perception combines with reinforcement and experience to affect unsafe behavior. Chapter 3 provides discussion on the effect a person's reinforcement history and experience has on unsafe behaviors. Chapter 5 provides a discussion on training.

Situational factors. Different situational variables may combine with our perception of risk and lead us to act safely or not due to our perceptions of risk (Stasson & Fishbein, 1990). Hanford Site employees described some environmental contributors to unsafe behaviors:

- (perceived) emergencies,
- time constraints,
- no one is watching,
- inconvenient to be safe,
- employee is distracted by emotions or personal problems,
- employees are trained to act in an unsafe manner, i.e., "have always done it this way" or it is an acceptable practice to be unsafe, and
- management inadvertently reinforces unsafe practices.

Harrell (1990) has found perceptions of risk are greater for:

- workers exposed to many hazards,
- workers lacking control over their work pace,
- workers who think their work is repetitive and fast paced, and
- workers without the freedom to control their own work.

However, one can't assume workers exposed to many hazards perceive greater risk and act more safely. They may adapt by ignoring risks. We discuss this under "Familiarity."

Situations affect people's estimates of the negative and positive consequences and the probabilities of accidents. For example, a firefighter and a non-firefighter have different risk perceptions when confronting a burning house. Each will behave differently because the firefighter is trained to deal with emergencies, whereas the lay person is not. In an emergency, the risk acceptability threshold may go up, which means a person is more willing to accept risk for the task because the larger risks of the emergency change the consequences. For example, Honkasalo (1992) found that divers take more risks if a diving partner is in an emergency situation compared to if the dive is normal.

Knowledge of Risks. Knowledge of risks is an important variable in an individual's perception of risk. The greater the knowledge, the greater the potential to accurately perceive risk. For example, if a person doesn't know anything about the risks, then the risks cannot be part of the risk perception process (Sjoberg & Drottz-Sjoberg, 1991). However, knowledge and experience with risk doesn't necessarily translate into greater caution. Other variables may determine precautionary behavior.

Familiarity. Familiarity describes the level of experience the person has with the risk, that is, whether the risk is novel or familiar. Often, workers exposed to many hazards by the nature of the work are more aware of the risks. This can translate into greater safety. However, they may have adapted to higher levels of risk and hence adopted higher levels of risk acceptability. This can work against safety. When work is fast and repetitive, workers believe risk is part of the job because they may not have the time to identify a risky situation or have time to take preventative measures when a risky situation is identified. Vaughan (1993) has found that people have greater risk perceptions when there has been past harm, future harm is likely, precautions are not effective, and risks are unavoidable.

Perceived Control. Perceived control affects employees' willingness to react to risk. Harrell (1990) has found those exercising the greatest control over their work perceive the least risk of accidental injury. Control of work is defined in terms of: how a job should be done, when to take breaks, and control of the speed of performing the task. When workers feel they have more control, they are more likely to take appropriate actions. For example, Honkasalo (1992) found divers were afraid of getting a "bad" supervisor because the workers could not control the task and may be put in a situation of increased risk. When the workers feel they are in control of a task, they believe they are responsible for their own safety. The results of our Safety Climate Evaluation show the majority of Hanford employees believe they are in control of their safety. When responding on a five point scale (1= highly disagree to 5=highly agree) respondents overwhelmingly agreed or highly agreed with the statement "It is the responsibility of each employee to seek out opportunities to prevent injury."

Furthermore, people are more likely to take self-protective actions or behavior when they have greater perceptions of control over the occupational situation, view precautionary methods as effective, and receive risk information (Vaughan, 1993). Hanford employees do believe precautionary methods are effective. In response to the question on the Safety Climate Evaluation "If people follow safe life practices, they can avoid many unnecessary injuries," employees overwhelmingly agreed or highly agreed.

Individual Risk Taking. Some research suggests people have different tendencies towards risks. The trait approach to risk assumes there is cross-situational consistency of risk. According to this view, people tend towards either: risk taking and risk aversion (Sitkin & Pablo, 1992). Trait theorists see risk-taking people as more prone to take risks whereas risk-averse people avoid situations in which they place themselves at risk. Other theorists believe personality traits interact with situations in determining how risk taking will be played out (Mischel, 1979). However, risk seeking is predictive of safe behaviors only within a narrow range of situations (Bromley & Curley, 1992). Bromley and Curley found pronounced situational specificity for personal risk seeking as a predictor of unsafe behavior. Inappropriate optimism can also lead to reduced risk perception (Weinstein, 1984) and an increased likelihood of risk-taking behavior. We discussed this issue in Chapter 3.

Misconception of Chance. People are notoriously poor judges of probabilities (Bazerman, 1990) in part because they often misunderstand the notion of chance. "Individuals expect that a sequence of data generated by a random process will look 'random,' even when the sequence is too short for those expectations to be statistically valid" (Bazerman, 1990, p. 40). People think low probability means impossibility. People also perceive probabilities very differently depending on the frame (positive or negative). For example, Kahneman and Tversky (1982) presented subjects with identical probabilistic statements stated either positively or negatively. Subjects tended to select the option stated positively. Thus, people seem to treat the concept of gain differently than the concept of loss (Bazerman & Neale, 1983).

Confirmation Trap. The confirmation trap is sometimes called self-confirming bias. "Individuals tend to seek confirmatory information for what they think is true and neglect the search for disconfirmatory evidence" (Bazerman, 1990, p. 41). We need to provide and ensure the employee correctly seeks and understands both types of information. For example, we may use only one indicator in determining the status of an operation when we should use multiple indicators. Chapter 6 discusses equipment design.

Insensitivity to Base Rates. Heuristics and biases affect our probabilistic estimates and therefore our perception of risk (Chaiken, 1987; Kahneman & Tversky, 1982; Slovic, Fischhoff, & Lichtenstein, 1982; Tversky & Kahneman, 1974). Biases are systematic errors in cognitive processes that can lead to systematic errors and poor decisions (Tversky & Kahneman, 1982). Heuristics are shortcuts or "rules of thumb" people use in the course of informal reasoning. These shortcuts, while often helpful, can result in biased estimates of the likelihood of events. These biases can influence how we process information and how we select a behavior (Bazerman, 1990; Slovic, Fischhoff, & Lichtenstein, 1982). When judging the likelihood of an event, one could draw on the base rate (how common some pattern is in the population). Often, however, logical information is not used and subjective or qualitative judgements are made from descriptive information. In fact, people rarely use base-rate information. This failure is referred to as the base-rate fallacy. Base-rate insensitivity can work either for or against safety. Those who believe they are even more likely to be hurt than population data suggest, may take additional precautions. For example, people often overestimate their risk of being a victim of violent crime. These individuals may then take precautions (e.g., stay in at night, avoid dark places) and therefore be more safe. On the other hand, a particular mechanical malfunction could be expected at estimated intervals, because of wear and tear on parts. If a maintenance employee ignores the base rate because "he's never had a problem with that part before," necessary maintenance or parts replacement won't be conducted.

Retrievability. Availability is the ease with which occurrences can be brought to mind (Tversky & Kahneman, 1974). Relying on availability, people tend to make estimates based on easily retrieved information. Based upon vividness or recency, people judge events to be more likely than other equally likely events. "Individuals are biased in their assessments of the frequency of events based on how their memory structures affect the search process" (Bazerman, 1990, p.40). People need to address more than just the most visible cases of unsafe behavior. They need to recognize the other more probable risks as well as the most severe or the most recent risk receiving national attention. For example, people believe incorrectly that flying in a plane is riskier than driving because airplane crashes are frequently shown on the television, whereas car crashes are not. Also, in performance appraisals we inadvertently weigh the last three months more heavily than the previous nine months. Memory processes affect the search for information. How we structure and organize information, especially that relating to risk, can affect how we perceive risk. The structure of indicators and equipment design will be discussed in Chapter 6.

In summary, the way we think affects our risk perception. The following represents some of the cognitive influences on the risk perception process:

- Focusing on easily recalled items
- Inability to trade-off probabilistic characteristics of different events
- Over-estimate low probability events
- Under-estimate high probability events
- Overconfidence of judgments
- My answer is right.
- It won't happen to me.

Biases can affect one's decision-making process—selection of a course of action—and the perceived risk level. How workers process the information may lead to risky or unsafe behaviors. Biases can be either good or bad. They let one process information more easily. However, by taking these "shortcuts" we could be losing relevant information.

COMMUNICATION OF RISK

The way risk information is communicated to workers affects the processing of this information. Sometimes, the communication doesn't inform the workers of the risks in a way they can understand (Viscusi & Magat, 1987). For example, we ignore the information, not enough information is given to accurately describe the risks, or the information is too complex to be effective (Geller, 1993).

Risk communication must convey new information in a convincing way. Both the content and format of the information is crucial. The characteristics of the content include:

- making set of hazards more specific,
- making potential risks more vivid,
- describing the negative and positive consequences of risky behavior, and
- describing the magnitude of the consequences (Roth, et al., 1990).

Guidelines for the format or information portrayal include:

- using a standardized format,
- using a common set of concepts,
- organizing knowledge into related clusters, and
- making it easy to locate and encode the relevant information (Viscusi & Magat, 1987).

Professionalism, rules, instructions, checklists, operating procedures, and operating aids can be used to give the right information in a complete risk communication program (Colas, 1992).

In their study of risk communication, Viscusi & Magat (1987) found workers respond to new risk information and take precautionary behavior. Hanford employees do use safety and risk information. In response to the question "When a safety regulation is issued, I try to follow it as best I can," the employees overwhelmingly agreed or highly agreed. However, "we need to do further research on the relationship between how to mobilize employees to learn on their own and risk communication" (Harrell, 1990, p. 1359).

What are the risk communication issues at WHC?

- conflicting instructions, information and procedures;
- risk communication, expectations, and rigor of are not being reinforced;
- over-reaction (crying wolf, not in balance);
- lack of consistency;
- don't know when to transfer to the task at hand (may need job aids which help describe the task, the procedures, and the associated risks); and
- instructions and procedures are not being implemented.

STRATEGIES FOR ORGANIZATIONAL IMPROVEMENT

Perceptions of risk naturally vary from individual to individual. Therefore, it is critical that the organization provide information regarding the risks involved in each and every job. Organizations must provide effective, timely risk communication to "debias" individuals' natural assessment of the hazards associated with a given job. Procedures must spell out specifically the hazards of a job and methods to mitigate those risks. Pre-job briefs must address the hazards associated with the job and the precautions to be taken. Individuals must feel empowered to not perform a job that they feel is

unsafe. And the reward system must recognize individuals for demonstrating the proper concern for safety when they take the initiative to stop a job. Individuals must be encouraged to take responsibility for the safety of their co-workers as well as themselves, as discussed in the behavior-based safety training. The application of these strategies must be consistent across managerial lines and across jobs. Otherwise, employee perceptions about management's commitment to safety are negatively influenced.

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Chapter 5: Training

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RELATIONSHIP BETWEEN TRAINING AND SAFETY

Training is, of course, a necessary precursor to expecting personnel to perform a task correctly and safely. An individual must acquire the necessary skills, knowledge, concepts and attitudes to allow him/her to perform the task in the manner specified. Initial learning in the training program is important because the material must be well learned if it is expected to be used in the field. However, initial learning during training does not guarantee that the lessons will be applied on the job, performance will improve, or behavior change will occur. Effective training must also support the worker in transferring the new skills and knowledge to the job and maintaining them after initial training. The organizational training system must include more than simply the formal or on-the-job instructional components; equal attention must be paid to the organizational infrastructure supporting the instructional components in order to encourage transfer of training to the work environment.

In addition, training serves a second, equally important role in organizations; one of establishing clearly-defined expectations of personnel. Effective training programs define for the participants the expected behaviors and levels of performance considered necessary by the organization for successful job performance. As discussed previously in Chapter 4, individuals' assessments of risk differ greatly among one another. As a result, individual perceptions of what constitutes reasonably safe behavior differ as well. Effective training programs that are fully supported on the job clearly define for all involved the organization's expectations regarding safe job performance.

On the other hand, poorly designed and implemented training programs and those which are not visibly supported throughout the organization can have a negative impact on safety. If safe work practices are not well learned, they are less likely to be performed correctly, especially under demanding task conditions such as emergency situations. (See Chapter 6 for more details on this topic). If safety training is not perceived to be supported fully by the organization, conflicting messages will be sent to the employees, undermining the success of even the best designed program.

The following chapter describes an overview of some of the key principles from the education and training literature that apply to the design of effective training programs. Included are principles which apply to the design of the instructional training program, as well as principles which apply to the design of a training system—the organizational structure that supports training programs.

EFFECTIVE ORGANIZATIONAL TRAINING

Despite the vast amount of resources typically allocated by an organization to training, an astonishingly large portion of such training is considered only marginally effective or ineffective. Training at Hanford is no exception. For the most part, the employees with whom we came in contact over the previous six months have been fairly critical of the training programs they've experienced as part of their jobs. For example, during workshops at Hanford, participants perform an exercise in which they brainstorm what they believe are the leading barriers to performing safely

on the worksite at Hanford. Training is *consistently* named as one of the top barriers. Participants in other workshops echoed this thought. To illustrate, one workshop participant suggested that as much as 75% of "Hanford's problems" are attributable to inadequate training systems.

There are a number of reasons why training may be ineffective and as a result be considered as a barrier to safety. By studying the problems related to why training fails to produce expected results, we can understand the sources of the problems better, and in turn be better able to determine an appropriate solution(s). The following topics are frequently cited in the training and development literature as critical components influencing the effectiveness of training, and are those which are most often overlooked by organizations. In most cases, they also relate directly to the criticisms expressed by Hanford employees regarding Hanford's training systems.

Transfer

The purpose of any training program is to provide an environment for the acquisition of attitudes, knowledge, or skills so that newly acquired behaviors may be transferred to the job setting. After all, learning in the training environment is only important if it leads to enhanced performance in the work setting. The transfer process is, therefore, the most important factor in the design of training programs. Transfer may actually be positive, none, or even negative (Goldstein, 1986; Camp, et al., 1986). No transfer refers to the condition where the training has no impact on performance in the workplace; positive transfer occurs when learning from training positively affects performance in the work place. Negative transfer, on the other hand, occurs when learning from training negatively affects performance in the work place and performance in the work place is actually lower than expected as a result of training. Trainers often make assumptions regarding trainees' likelihood to transfer their newly acquired skills or knowledge based on some measure of learning at the end of the training session. That is, trainees' performance on a quiz, test, or some other performance indicator administered immediately after a training session is assumed to be a predictor of their likelihood to use what they have learned back on the job. However, satisfactory performance on these evaluations does not necessarily predict trainees' likelihood to transfer to the work setting what they learned (Goldstein, 1986). Students may successfully acquire skills or knowledge during training but have difficulty applying them when they return to the job, despite the effective instruction.

Two common strategies trainers may use to increase the likelihood of positive transfer include identical elements and transfer through principles (Goldstein, 1986; Camp et al., 1986). Identical elements involves making the training environment as similar as possible to the actual work environment. A nuclear facility control room simulator is an example of how the identical elements strategy is successfully applied. The control room simulator is identical in nearly every respect to the actual control room, including the lights and sounds that are activated under varying conditions. Because the physical fidelity of the training conditions is so high, trainees are more likely to demonstrate a high degree of positive transfer (Camp et al., 1986). However, it is difficult to make all conditions in the training and the work environment identical. For example, although the physical conditions can be re-created in a control room simulator, it is difficult to simulate the stress that operators experience in their jobs. The psychological fidelity is the "extent to which the training environment simulates in the trainee the feelings and emotions that would be experienced on the job"

(Camp et al., 1986). This is particularly true when the potential consequences for poor performance in training are much less severe than poor performance on the job.

The training environment cannot always be made identical to the work environment, but positive transfer may be expected just the same. In most cases, the training environment and the work environment are different, but the responses required of the trainee are the same in both situations. For example, in an automobile repair course, trainees may learn to repair cars using a 1973 Chevelle, an American car with a large engine and parts that are easily accessible. When trainees begin work in auto repair shops, they are more likely to encounter much smaller cars and, in addition, many of these cars will be foreign. Although the cars repaired at work are different than the car employees may have learned on, the symptoms indicating a problem in one kind of car typically call for the same type of repairs as in other types of cars. Although the training conditions and the work conditions are different, the response required of the trainees in both conditions are very similar, usually resulting in positive transfer. To further increase the likelihood of transfer, instructors should discuss the similarities and differences during training and follow-up training on the job (which will be discussed in a later section) should highlight those differences. The principle of identical elements relates to a commonly cited problem with the training programs at Hanford, that is the lack of 'tailored' or customized training programs. Without specifically addressing similarities and differences between the instructional material and work applications, transfer can not be maximized.

In a case where the training environment and the work environment are different and the responses required of the trainee in both environments are different, we can often expect negative transfer. Fortunately, these conditions are rare in even the most mediocre training programs. However, they are not so rare in informal training situations. As will be discussed subsequently, organizations often rely on on-the-job training in place of, or to augment formal training programs. Particularly in these situations, it is not uncommon for an individual to train on one piece of equipment or machinery and then switch to another, or to train on a task with one set of procedures and then switch to a similar task with subtle differences in appropriate actions. In these situations, the response required of the operator is different than that taught during training, and negative transfer can be expected. As will be discussed again in Chapter 6, subtle differences in equipment design, task requirements, or procedures between otherwise similar situations often induce human error due to negative transfer. Workshop participants could easily identify where such conditions are common, and many were able to recount instances where negative transfer occurred, resulting in an error.

A second strategy trainers should use to increase the likelihood of transfer is teaching the basic principles behind the subject matter (Goldstein, 1986; Camp et al., 1986). When trainees understand the concepts or principles involved in a given task, they are more likely to perform the task correctly than when they simply are taught the rules or the steps to follow. For example, once the trainee understands the principles behind how a diesel engine operates, then he or she should be able to work on many different kinds of diesel engines (e.g., car, boat, and truck engines). Similarly, if one understands the principles behind a safety rule, s/he is more likely to comply with the rule. One problem associated with this strategy is that applying the principles to real examples must be demonstrated during training, which can sometimes be difficult to do. Training that neglects application examples and focuses solely on principles is not likely to result in positive transfer. Other empirical studies have suggested that an important condition for transfer is that the students be

allowed to establish general principles for themselves, rather than having the principles simply told to them. Hence, transfer is not an automatic process, students must be given practice in both tasks and the transfer process if they are expected to transfer newly acquired behavior to the job (Goldstein, 1986). Again, Hanford employees easily identified past training experiences where rules were taught but no principles or explanations were given.

Although only two popular strategies to increase the likelihood of transfer have been discussed here, there are other approaches that may also be appropriate to incorporate into a training program to enhance its effectiveness. For example, allowing for sufficient practice during training may also increase the likelihood of transfer. Trainees should attain some minimum skill level before returning to the work place. Learning the skill on the job, without the benefit of feedback from the instructor, may result in learning to do the skill incorrectly. Also, presenting the information in different contexts or having trainees use the information in different contexts helps trainees see a variety of ways to apply training. For example, when learning to use a new tool, learning to use the tool for many purposes stimulates the trainee to find additional uses for the tool. Finally, pointing out situational cues indicating when a particular response is required of an employee is appropriate when problem solving skills are targeted during training. Highlighting important features of a task also helps trainees recognize the appropriate conditions on the worksite for using that task.

Training System

The training system refers to the system-wide components of an organization supporting the instructional components, and as mentioned previously, can have a major affect on the success of the training program (Goldstein, 1986). Well-developed and administered instructional components may be followed by no transfer to the work environment if careful attention is not paid to the training system as a whole. There are many organizational elements affecting the training system that exists within an organization. Understanding these elements and how they affect the success of training is necessary in order for the organization to find ways to improve the current training system. A formal organizational assessment will lead to a thorough understanding of the training system in place. However, for managers and supervisors, an informal assessment of the organization may be done quickly by asking the following questions (Goldstein, 1986):

- Are the organizational goals reflected in the training objectives?
- Are various levels in the organization committed to the training objectives?
- Will trainees be rewarded on the job for showing or using what was learned in training?
- Is training being used by the organization as a cure-all for its problems?
- Is management willing to commit the necessary resources to maintain the work group while individuals are being trained?

Training programs must have goals in line with those of the organization (Camp et al., 1986). When training programs and the organization have conflicting goals the employee ultimately suffers. When conflict exists among individuals regarding the work to be done and the goals to be achieved, the employee does not know how to proceed properly in his or her job, and is likely to become confused and frustrated. Also, the employee acquires new knowledge, skills and attitudes in training (based on the goals of the training program) that can not be used on the job because of conflicting organizational goals. Statements such as "I wish my boss had been exposed to this training

program" indicate real differences between the approach or values of the training program and those of upper-level supervisors (Goldstein, 1986). Virtually without exception, workshop participants agreed that conflicting goals was a prevalent problem at Hanford. Many suggested that training programs which have no support upon returning to the work environment are more common than those that do.

A reward structure which rewards employees for using information learned in training must be in place. This reward structure may be formal or informal. Formal reward systems include, of course, performance appraisals. An organization should not train employees to perform in one manner and evaluate job performance using another set of criteria. Assuming training objectives are on target with organizational goals, performance appraisal systems should be evaluated to ensure that they support the knowledge, skills, and attitudes employees learn in training. Performance appraisal systems that are not in line with organizational goals and subsequent training send conflicting messages to the employees and do not encourage employees to apply to their jobs what they learned in training. Other formal rewards may be in the form of incentive programs for implementing suggestions that employees make based on what they learned in training. Some informal rewards may consist of recognition from upper-level management, or peer approval.

In the same manner, managers must be rewarded not only for transferring what they learn in their own training, but must also be rewarded for actively supporting the training programs of their employees. Salinger (1973) found that managers who were not rewarded for supporting the implementation of a training program failed to plan or budget for future training. Also, if upper-level management does not appreciate the need for a training program and does not visibly support it, then employees down the line will not be supported when they try to implement what they learned in training. Baumgartel and Jeanpierre (1972) found managers used only those skills developed in training when the organizational climate was favorable for the application of those skills. The researchers concluded a favorable organizational climate consisted of management's willingness to devote resources to training, good communication among managers, and the expressed desire of the organization for managers to use what they learned in management courses. There are other organizational factors affecting the success of training, discussed below, particularly concerning conflicts between the organization's expectations and training objectives.

Appropriate resources must be committed to a training program if it is to be effective. Skilled and prepared trainers, well-designed materials, and adequate employee time must be devoted to each training program. Not only is the learning process heavily dependent on having the necessary resources committed, but employee attitudes (which will be discussed subsequently) toward the program will be influenced. If the program is not perceived by the employees as being fully supported by the organization, then their motivation to learn will be compromised. Hanford employees again felt that inadequate resources were generally committed to training initiatives. Complaints about inexperienced, unprepared trainers, inadequate training facilities, and insufficient time allocations were often followed by comments regarding management's true commitment to the training program. Employees perceived management to merely be fulfilling a training requirement (i.e., 'check the box' training).

Employee Attitudes

The impact of employee attitudes on the success of a training program has been well documented (Mager, 1968; Laird, 1985; Gagné, Briggs, & Wager, 1988). Attitudes amplify employees' positive or negative reactions towards training. Trainees with positive attitudes toward the training program are more willing to acquire new knowledge, whereas trainees with negative attitudes towards the training program are much less likely to benefit from the training.

There are many factors that influence employee's attitudes towards training. These factors and potential solutions can be more systematically approached through the organization's training system. The organization's training system has a great deal of influence over employee attitudes towards training. As discussed above, the training system includes all organization components affecting the success of the training program. If the components of a training system fail to support the training program, then employees are not likely to demonstrate support for the training program. Furthermore, one component of the system affects many other training system components, making it difficult to pinpoint one cause of poor attitudes towards training. Ensuring that a strong training system is in place will do much to improve employee attitudes towards training. There are a number of ways to improve a training system so as to address employee attitudes. The following suggestions are only a sample of the possibilities. A thorough examination of an organization's training system will reveal more specific solutions to the problem of poor employee attitudes towards training.

There are a number of ways organizations can begin to improve their training systems to turn around poor attitudes towards training. Poorly delivered training is one component of the training system contributing to poor attitudes. When using in-house trainers, the organization must make sure trainers are prepared to deliver a quality training program. Trainers must thoroughly understand the content, and should have good basic presentation skills. If trainers are not prepared to give training, then the training should be delayed until the trainers can practice delivery and receive coaching from qualified subject matter experts. The time lost waiting for trainers to prepare themselves is more than made up in the quality of the training and improved attitudes of the participants. The same principle applies to on-the-job trainers as well. Being a master of a skill is not a sufficient qualification for training the skill; on-the-job trainers must know some basic training principles as well.

Visible buy-in from supervisors and managers is another component of the training system impacting employee attitudes towards training. When employees hear management berate a training program as being unnecessary or a waste of time, then employees are not likely to have a positive attitude toward the training program. When supervisors and managers understand the need for training, they can communicate this need to employees. To do so, supervisors and managers need information. A pre-training session or meeting, or a detailed memo outlining information on the training program may be enough to prepare supervisors and managers to discuss the need and purpose of the training program.

In addition, employees also need to understand the purpose of the training program. Although this too should be obvious, it is a detail that is often overlooked, especially in planning large training programs. For example, during the workshops, many employees indicated that they were told the previous day they would be attending safety training. No explanation was given to them regarding the content or purpose of the safety training. Without understanding why they were attending

training and the level of support the training would receive from management, they were skeptical that this training program would make a difference in their jobs. Many participants thought the training simply represented the safety training “flavor of the month.” Poor attitudes towards a training program can result in part from poor preparation of the participants.

The organization must demonstrate support for training by allocating sufficient resources for employees to attend training. This includes release time, and making sure someone is available to cover the employee’s job while he or she attends training. The organization must also go beyond supporting training attendance by demonstrating a commitment to implement what is learned during training. When employees understand that management is serious about implementation, employees see that training makes a difference in their jobs. When training is perceived as not being a waste of time, then attitudes toward training are positively influenced.

Most WHC employees in the workshops agreed that attitudes toward safety training are a definite deterrent to safety at WHC. Workshop participants also identified attitudes as one barrier to successful safety training. An assessment of these attitudes to determine their intensity and source may help WHC understand how to address them in future training.

Training as the Wrong Solution to a Performance Problem

Often times, training is used as a solution to a performance problem that is not a result of inadequate knowledge or skills. A training need exists when an employee lacks the knowledge or skill to perform an assigned work task satisfactorily (Laird, 1985). During a training needs assessment, a performance deficiency is examined to identify the problem and determine if training is the appropriate solution. When training is used as a solution for a performance problem attributable to something other than employees’ lack of knowledge or skills, the organization will not get the performance results they expect, and the training will undoubtedly be deemed unsuccessful. This is unfortunate because the training program may actually be well planned and executed, but if it isn’t the appropriate solution, then no amount of effort will make the training program produce improved performance.

An unsystematic approach to determining training requirements can lead the organization to make incorrect decisions regarding training needs. It can also prevent the organization from getting the expected results. However, performing an adequate training needs assessment requires a significant amount of time and can be expensive. Organizations rarely commit the resources to conduct a proper training needs assessment (Reiss & Morley, 1993). Decisions to provide training are often based on opinions or intuition.

Training is quite commonly used inappropriately because it is often considered a “safe” solution. That is, responding to a performance problem by requiring training suggests the problem lies within the employees, and not the organization. If employee training is deemed the solution, then employees must be the source of the problem. While the organization may be obligated to provide training, it is ultimately the employees’ responsibility to learn how to perform more safely, regardless of the system factors that may be in place causing the employee to perform unsafely. Workshop participants’ comments clearly indicated that they perceive training to be a ‘catch all’ solution to safety at Hanford. Regardless of the true problem, employees are “herded” through training classes—giving the perception that management is attributing every problem that arises to

unskilled, unmotivated employees. They also spoke often of 'disciplinary safety training'. Many perceive that safety training is used as a punitive action. Given this perception, employees will certainly not be motivated to learn, and their attitudes toward future safety training (which will be discussed subsequently) will naturally be affected.

Training Objectives

If the training needs assessment identifies training as the appropriate solution, and training still fails to deliver the expected results, then the training objectives may be targeting the wrong topics. All training programs should have performance objectives guiding the design, development, delivery and evaluation of the training program. If these objectives are off-target or non-existent, then training is not likely to be successful. Despite the seeming simplicity of this idea, inadequate or even nonexistent training objectives are often the norm rather than the exception in many organizations. Bob Mager, well-known for his criteria for performance objectives says, "If you're not sure where you're going, your liable to end up someplace else—and not even know it" (Mager, 1984).

There are a few basic criteria for writing or evaluating performance objectives. Performance objectives should target the performance problem (Camp et al., 1986). If employees need to learn to operate a crane, then the performance objectives should target the skills required for employees to operate a crane. Good performance objectives also should tell trainees what they need to do to successfully complete the course. Performance objectives should be written in behavioral terms. That is, the verb in the objective should be observable and measurable. The conditions under which the objective will be tested and the criteria for successful completion of the objective must also be stated, when appropriate. The performance objective should be written so trainees know exactly what is expected of them (Mager, 1984).

Lastly, good performance objectives should be achievable as a result of the training (Mager, 1984). If the training program is designed and developed using the performance objectives as guides, then this should not be a problem. However, if a training program is designed and developed without considering the objectives, then it is possible that the objectives will not be achieved through participation in the training program.

Trainee Evaluation

Once good performance objectives have been written, and employees have participated in the training program, employees should be evaluated against the performance objectives. Assuming the objectives are related to the performance problem and are targeted in the training program, then employees must meet those objectives if performance is expected to improve back on the job. If training is not producing the expected results, it may be because employees are leaving the training program without meeting the performance objectives.

Trainee evaluations may be formal, such as a test or quiz, or informal, such as observation and feedback during training. The form of evaluation will depend on the training program, how the objectives were written, and any laws or regulations affecting training. If some form of evaluation is not done, the organization cannot be certain that employees will leave the training with the expected knowledge or skills. They may return to the workplace no better skilled than when they

left for training. Training evaluations also offer a means to motivate student participation. Naturally, participants will be more motivated to learn the material presented if there is to be a formal evaluation at the completion of the training that will impact their job in some way. However, even informal evaluations such as classroom discussions will increase employee motivation to participate and learn. Most humans enjoy the opportunity to demonstrate their knowledge to others. In addition to motivating participant learning, training evaluations can help continually improve the training content and format.

Follow-up Training

Regardless of whether trainees meet the objectives as determined in the trainee evaluation, some form of follow-up training is often desirable (Camp et al., 1986). Mastery of skills and retention of knowledge gained during training cannot be expected unless skills are practiced, feedback is given, and knowledge is used. Even when skills are mastered at a minimal level during training, employees are still fine-tuning skills when they return to the work place. They need the time and the proper feedback to hone those skills and to determine the most appropriate way to apply (or transfer) the skills to the work environment. Unfortunately this component of a training program is often neglected because of the added effort and cost of formal follow-up training, like additional classroom training or formal coaching sessions back on the job. However, follow-up training may also be as simple as a memo reminding employees what they learned in training, or a job aid, supporting what was learned. Informal follow-up training may also be appropriate, such as coaching by a supervisor, other employees, or an informal visit by the instructor. The formation of implementation teams which will plan how to carryout the new ideas within the work environment can be considered a form of follow-up training. Safety-related training, for example, should be followed by group discussions during safety meetings of the principles taught.

Follow-up training is important for a second reason as well. Not only does it allow the employee additional opportunities to master and apply the new skills and knowledge, but it reinforces the importance of the training to the organization. Follow-up efforts send visible signs to the employee that the organization supports the training and expects (and will reward) performance in accordance with what was taught during the training. Of all of the criticisms voiced regarding training at Hanford, lack of management support and follow-up training are probably the most common. Many employees suggested that they learned and were excited to apply new skills and knowledge, only to find no follow-up support for the training once they returned to the job.

ADDITIONAL RECOMMENDATIONS

Embedded in the above discussion are principles for an effective training program and training system design. In addition to these, there are several other recommended practices and techniques to increase the effectiveness of an organization's training efforts. This section discusses several of these. This certainly is not an exhaustive list of solutions, but a summary of some common solutions in the field of training and development. In some cases, a combination of solutions may be appropriate responses to a performance problem. The solutions discussed here are only a beginning to understanding the many possible solutions managers and supervisors may implement to support training on the work site.

Needs Assessment

The process of a training needs assessment results in identifying a problem and a possible solution. If a performance problem related to safety arises, one response might be to do a training needs assessment to first determine if training is the appropriate response, and if so, to determine the appropriate content for the training. The results of the assessment may indicate safety training is not the solution to a problem and other solutions are more appropriate (Laird, 1985).

Essentially, the training needs assessment is carried out by first determining the requirements of a job (e.g., standards, specific duties, and the knowledge and skill requirements). Second, assess the person holding the job to determine if he or she meets the standards and possesses the necessary knowledge and skills to do the job. The work environment may also be examined to determine if there are any barriers keeping an employee from performing the job well (e.g., poor materials and equipment to work with, excessive time pressures to perform a job quickly, and poor motivation among all employees) (Goldstein, 1986). (These issues will be discussed in some detail in Chapter 6.) Once the source of the performance problem is determined, a solution may be identified and implemented.

There are a number of ways to gather the data for a training needs assessment, both formal and informal (Goldstein, 1986; Camp et al., 1986). These include observation, interviews, proficiency tests, organizational records, and work samples. There are advantages and disadvantages associated with each alternative. The data collection method(s) chosen will depend on each individual work situation. There is no one best way to determine the cause of a performance problem. However, understanding the variety of options allows organizations to select the most appropriate for individual situations. Once data concerning the performance problem has been collected, it must be analyzed to determine the precise cause of the problem. Generally, the data should be analyzed to determine if the cause of the problem is attributable to a lack of knowledge, skill, ability, or a poor attitude. One item that is often overlooked in a training needs assessment is literacy. Adult illiteracy is a serious problem facing America's workforce and is increasingly gaining attention in the training and development literature. This is not to suggest America's workforce is unable to read, but there are different levels of reading ability. Most safety materials are currently written at a tenth grade reading level and the average working American reads at a seventh grade level (Fried, 1994). In addition, there is a growing number of workers who do not speak fluent English. These workers may also have difficulty reading directions or warning signs. Supervisors managing workers in positions where reading skills may have an impact on the workers' ability to do their jobs safely need to be aware of this potential problem. This can be a sensitive issue with some adults and should be approached with much care, but when the safety of an individual, or those who work with that individual, are at stake, this potential source of a performance problem must be considered and literacy training offered as a solution.

On-the-Job Training

On-the-job training occurs on the work site as a result of interaction between co-workers, supervisors, subordinates, or professional instructors, and accompanying feedback (whether positive or negative) (McCord, 1987). On-the-job training may be formal, with planned, structured learning activities such as an apprenticeship program, or informal, where an employee simply "picks it up" from a more experienced co-worker.

On-the-job training is extremely common in organizations today. In fact, research shows employees spend three to six times more time on informal on-the-job training than in structured classroom training (Carnevale & Gainer, 1989). Furthermore, in a survey of employees from large (5,000+ employees) manufacturing, transportation, and communication organizations Rothwell and Kazanas (1990) found that when there is no formal, structured on-the-job training in place, employees most often turn to co-workers for advice on doing a job. Consulting procedure manuals and watching fellow workers perform were also popular strategies. On-the-job training is also common even when formal training programs are available. Rothwell and Kazanas also found that 60% of all training occurs on the job despite the large portion of a 'Human Resources' budget that is spent on off-the-job training programs. In their study, on-the-job training was reported as the most frequently used training method across most jobs, including skilled and semi-skilled industrial, sales, and supervisory-managerial positions.

On-the-job training is a training alternative that is easy and convenient for managers and supervisors to take advantage of. Not only can on-the-job training have the potential to reduce breaking-in periods for newly hired, promoted, or transferred employees, but can also supplement or serve as follow-up training to formal, classroom training (Rothwell & Kazanas, 1990). Continually pulling workers away from their jobs so they can attend classroom training may be a problem on the worksite. On-the-job training allows workers to remain on the job and receive follow-up training at the same time. In addition, because learning takes place on the job, the likelihood of positive transfer is very high because the training environment is the same as the job environment (applying the identical elements approach to training). Ideally, workers practice their skills right away and receive immediate feedback, reducing the time between learning and applying what they learned, and the likelihood of forgetting the steps. Because workers receive immediate feedback about what they are doing, and because they are performing their job as they train, less time is required to train workers. And finally, the worker remains the focus of the training. Workers receive individual attention and can ask questions and receive answers almost immediately. On-the-job training is usually done one-on-one, or at least in small groups, ensuring workers receive the attention they need.

Despite the advantages, on-the-job training is often ineffective. Because on-the-job training is usually less formal, it often does not receive adequate attention and planning (Jacobs, 1992). As with all training, a strong training system must be in place, which includes the support of management. Also, experienced people must be available to provide training. These employees should demonstrate exemplary performance, have good interpersonal skills, have a predisposition to share job knowledge, and be a volunteer. In addition, the trainer must be given the time to provide enough attention to the learner to make the experience work. The daily work schedule must support on-the-job training and must allow the worker receiving the training access to the experienced co-worker. There must be opportunities for the trainer and trainee to interact and work together without frequent interruptions in order for successful on-the-job training to occur. Although experienced workers are not often trained to perform on-the-job training, they do need some instruction regarding how people learn, and clarification regarding their responsibility to see that the trainee is trained.

Rothwell and Kazanas (1990) also recommend supplementing on-the-job training programs with written materials. Written materials ensure employees are getting the same information. For example, if there is a procedure that employees are expected to follow, then having the procedure documented on paper and available to employees will ensure that all employees at least have access

to the proper procedure. Furthermore, these written materials may serve as job aids after training is complete, or as self-study materials when the trainer is not available.

Managers and supervisors need to understand the process and benefits of on-the-job training so they devote the necessary resources, making sure on-the-job training is a positive and successful experience for everyone involved. Workshop participants' comments regarding on-the-job training were again somewhat critical. Often, there is no purposeful attention given to on-the-job training, rather it is left to an employee to ask for help when needed. When trainers are assigned to assist trainees, they are often given inadequate time and no instruction on training techniques (such as those discussed below). Rather, they are left to their own accord to determine how best to transfer skills to the employee. The result is often poorly-trained and frustrated trainees.

On-the-job training is often used in conditions where it should not (Jacobs, 1992). In some cases the work schedule cannot be interrupted so quality on-the-job training can occur. In any situation where an untrained employee could be seriously injured, it is not appropriate to conduct on-the-job training until some minimal level of performance has been established through other training means. If the work site has many hazards, such as moving heavy equipment, and employees need to know what is occurring around them for safety reasons, on-the-job training may not be appropriate because the trainer and trainee could be temporarily distracted, putting them both in danger.

In addition to the concerns discussed above, there are some classic steps the trainer should be familiar with in order to make on-the-job training successful (McCord, 1987). Basically, the trainer first demonstrates the whole task, explaining in detail what the trainer does during the task and why. Second, the trainer breaks the task into parts, allowing the trainee to master each part by practicing the sub-task under the supervision of the trainer and receiving feedback for his or her performance. Once the sub-tasks are mastered, the trainee performs the whole task, under the supervision of the trainer. After some level of proficiency, the worker is left to perform the task without supervision.

As discussed previously, poorly designed and implemented on-the-job training can result in no performance improvement, and can also negatively influence the employee's attitude toward training and his perception of organizational commitment, which could foster the feeling of learned helplessness, as discussed in Chapter 3.

Coaching

Coaching is an additional form of on-the-job training and is often an appropriate solution when formal training programs have failed to produce the expected results. Typically, coaching focuses on the immediate improvement of performance and the development of skills (Parsloe, 1992). Much like a sports coach, coaches are concerned with helping employees maximize their current performance. Through coaching, employees are able to improve work skills, generate results, and be empowered by the results they generate.

In a recent workshop conducted by Virginia Tech, participants discussed the behaviors and characteristics of a good coach. Figure 5.1 contains the results of that discussion. In general, good communication skills were stressed by all as an important coaching skill. Knowing how and when to give feedback is essential for the success of a coach and the employees s/he coaches. The need to understand the employees being coached was also stressed over and over again by coaches attending the workshop. What works with one employee may not work with every employee. Coaching is

also an effective informal means to show visible support for training by management, and to positively reinforce employees when they successfully demonstrate their new skills in the work environment. Workshop participants consistently mention the poor coaching skills of their supervisors. In many cases, little or performance feedback is given informally through coaching, and that which is usually centers on negative performance rather than acknowledging positive performance. Participants agree that they need to receive and actually want 'corrective feedback' from their supervisors, but suggest many supervisors need to acquire better interpersonal communication skills to make the exchange a more positive experience for both parties.

STRATEGIES FOR ORGANIZATIONAL IMPROVEMENT

The majority of the comments gathered regarding training at Hanford clearly indicate fairly strong employee dissatisfaction with Hanford's training systems. Of the comments voiced regarding training at Hanford, the misapplication of training, lack of visible support by management, and little or no opportunity to transfer training to the work environment were the most common. Criticisms regarding the quality of training programs were also common. Objectives that are off-target, inexperienced or unprepared trainers, attitudes of trainees, and a lack of customized training were cited as specifics. In one exercise, workshop participants were asked to describe reasons when safety training does not produce expected results. The participants' responses are provided in Figure

Behaviors and Characteristics of a Good Coach:	
• Be a good listener.	• Be highly motivated.
• Make sure you are understood.	• Delegate.
• Put yourself in their shoes.	• Focus on behavior, not on people.
• Set a good example by modeling.	• Be consistent (among SAs).
• Be honest.	• Be flexible and recognize responsibility.
• Recognize others' accomplishments.	• Stress the positive.
• Make lemonade from lemons.	• Give negative feedback in private.
• Be sincere.	• Give praise in public.
• Give timely feedback.	• Stress open, two-way communication.
• Be sure to follow up.	• Set intermediate goals.
• Get to <i>know</i> the people you're working with.	• Don't avoid confrontation.
• Seek a common understanding.	• Suspend prejudice.
• Show the benefits of common sense.	

Figure 5.1

5.2. Again, one of the most frequent responses was the lack of support for employees trying to apply training on the worksite. A poor training *system* will hamper the efforts of the best training *program*.

Participants were also asked to consider the results of poor safety training and brainstorm some ways poor safety training affects the work site. The one result considered most detrimental was that employees learn safety training is not important. Attitudes toward safety training (management and employees) become negative, affecting the effectiveness of future safety training programs. Learned helplessness was discussed as another result of poor safety training. Employees learn to feel that safety training is done to fulfill a requirement and nothing will change back on their worksite, regardless of what they learn in a safety training program, or what they try to bring back to their own jobs.

Workshop Participants response to the question "When does training fail to produce expected results?"

- no follow-up training is provided
- no viable route to apply training back on the work site
- no practical examples are provided during training, decreasing participants' ability to apply
- training used as a punitive action - that is, employees get safety training when they perform unsafely
- training is provided simply to fulfill a requirement (check the box)
- a poor attitude on the part of the trainee
- inexperienced, unprepared trainers
- use of canned training without customization
- training is too generic, misses target (doesn't address what is really wrong)
- answer does not lie in training
- trainers preach versus train
- during implementation, it is discovered the problem is lack of equipment
- environment is not conducive to implementation
- training materials do not match job task

Figure 5.2

In order for training to be effectively transferred to the workplace, all levels of management must visibly support the training system. They must encourage employee participation, provide opportunities and mechanisms for applying new knowledge and skills, provide feedback on resulting performance, and ensure reward systems recognize those who apply what they learn to their jobs. Employees must perceive that the training will help to increase the safety of the workplace, as opposed to increasing efficiency alone. To further increase employee attitudes toward training, the employees must be involved in decisions regarding the training they will receive. Employee involvement also ensures that the training is relevant to their specific jobs. Training materials must be kept up-to-date and must incorporate the concepts from the procedures that guide the associated jobs. This can be further accomplished by including the training department in the review cycle for procedures. On-the-job training can be improved by providing training for those who will serve as OJT trainers.

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Chapter 6. Task Demands and Equipment Design

Chapter 6. Task Demands and Equipment Design

THE RELATIONSHIP BETWEEN TASK DEMANDS AND EQUIPMENT DESIGN AND INDUSTRIAL SAFETY

Human error takes many forms and has been identified as one of (if not the single) leading cause of accidents in a variety of work environments. The performance of human errors, however, does not take place in a vacuum. Rather, the characteristics of the work environment create “error-producing conditions” that play an important role in shaping the forms and probabilities of unsafe acts (Wreathall and Reason, 1992). Characteristics of the task and the demands that a task places on an operator can increase the probability of human error. In addition, the design of the physical workspaces, including tools, equipment, procedures, and environments can be instrumental in influencing the behavior of individuals; either increasing or decreasing the likelihood that an operator error occurs. Carefully designed systems, in which human factors principles are applied to the design of tasks and work environments, elicit the correct behavior and inhibit the performance of unsafe behaviors.

Improving workplace safety through the application of human factors principles involves the systematic use of relevant information about human capabilities, limitations, characteristics, behavior, and motivation in the design of the things people use and the environments in which they use them. Human factors focuses on human beings and their interaction with tools, equipment, facilities, procedures, and environments. The emphasis is on human beings and how the design of things influences people. Human factors, then, seeks to change the things people use and the environments in which they use these things to better match the capabilities, limitations, and needs of people. The objectives of the human factors discipline include: enhancing operator effectiveness and efficiency, increasing productivity, reducing fatigue and stress, increasing comfort, increasing user acceptance, and increasing job satisfaction. But foremost among the goals is to minimize the potential for operator error and thereby increase workplace safety (Sanders and McCormick, 1993).

Because humans must work within and interact with the technical components of a system, the design of human-machine systems *must* take into account the cognitive, perceptual, and physical strengths and weaknesses of humans. The notion of designing jobs within the capabilities of humans is, of course, not new. We do not require operators to manually lift and move 400 lb. objects; this would clearly exceed the *physical* capabilities of human beings. We don't require operators to differentiate 100 different auditory alarms; this would not be within the *perceptual* capabilities of humans. Similarly, we do not require operators to quickly multiply (2) 6-digit numbers without the aid of pen and paper or a calculator; this would exceed the *cognitive* capabilities of humans. There are countless, less obvious situations, however, where task requirements are made which exceed human capabilities. Most often, these situations fall within the “gray region,” where the requirements may be within the “skirts” of human abilities. Under ideal, or even normal conditions, operators can fulfill the requirements. However, when other stressors are present (high workload, fatigue, time constraints, relaxation of vigilance, inadequate training, etc.), operator error often results.

As Grether (1975) points out, “workers can and do successfully adapt to a wide variety of tasks and situations; but it is an unrealistic organizational practice to require them to compensate for

engineering design deficiencies in equipment and work operations without a corresponding increase in errors and accidents." As countless high-profile accidents demonstrate (e.g., the incident at Three Mile Island, the release of methyl isocyanate from Bhopal, the downing of an Iranian airliner by the USS Vincennes, the accident at Chernobyl, the sinking of the passenger ferry *Herald of Free Enterprise*), the design of operator tasks and equipment can often be a primary determinant of human response (Malone, 1990; Wiener, 1989; Casey, 1993). As the above examples illustrate, human errors resulting from inattention to human factors design of the task and workspace can have serious or even catastrophic implications regarding safety.

As such, human error can often be attributable to a mismatch between the task demands of the situation and the capacity of the operator. In other situations, the mismatch occurs between the design of the physical working environment and the capabilities and limitations of the operator. However, in the overwhelming majority of cases of design-induced human error, the combined effect of the task demands and the environment and equipment with which the operator works determine the operator's unsafe behavior. Before discussing the role of task demands and equipment design in accident causation, it is first useful to consider in some detail the nature and types of human error.

In the following sections we present an overview of the scientific literature on the role of "design-induced" human error in the performance of unsafe acts. The first section, Human Performance & Human Error, presents a framework for understanding how errors arise from the natural capabilities and limitations of humans as systems which pick up information from their environments to guide their actions. By understanding the various ways in which the human system can produce error, we will be in a better position to anticipate error likely situations and to take steps to minimize the potential for conditions in which error leads to unsafe acts and ultimately to accidents.

The second section, Task Demands and Stress, summarizes the role task and environment related stress plays in increasing the likelihood of human error. How does mental and physical workload affect performance? By understanding the effects of stress on the human operator as information processing system, we will be able to identify probable changes in task performance and potential error-inducing task requirements and procedures.

The third section, Equipment and Design, summarizes and illustrates how equipment interfaces affect the match between human capabilities and task requirements. How does control and display compatibility affect human performance? The system design can put the user in a situation in which a high probability of success cannot be expected.

The fourth section, Incorporating Human Factors Principles in the Workplace, provides an operational strategy for identifying error-likely situations and developing error and safety conscious operators.

HUMAN PERFORMANCE AND HUMAN ERROR

Introduction

Our ability to predict errors depends on how much we know about the factors that cause or influence errors. Behavioral scientists are interested in developing strategies to predict the conditions under which an error will occur and the form it will take. Understanding the sources of error and the influences on performance are the first steps to designing a strategy for reducing unsafe acts.

Figure 6.1
(Adapted from Chapanis, 1951 in Reason, 1990)

For example, consider the three targets shown in Figure 6.1. Targets A and B illustrate the difference between variable, therefore relatively unpredictable, and constant, therefore more predictable, error (from Reason, 1990). The pattern of shots in A indicates no constant error but large variable errors. The pattern of shots in B shows a large constant error with no variable error. These errors differ in their degree of predictability. We can predict fairly accurately where B's next shots will fall; the error is constant. We cannot, however, predict where A's next shots will fall, the error is variable. The reason we can predict B's error is because we know more about the factors that cause or influence the error. B is an expert with misaligned sights. A, on the other hand, is unsteady. A's errors vary considerably. Perhaps we can attribute A's errors to lack of training or practice, or perhaps A is competent, but operating under stressful conditions.

When this graphic was presented at one of the workshops conducted at Hanford, it initiated discussion about the current situation with regard to predictability of errors. That discussion can best be summarized by referring to the target of marksman C. C's pattern of errors illustrates both constant and variable error. The perception of the workshop participants was that there was so much variability in performance, it was difficult to separate the predictable from the unpredictable. Much of this variability is perceived to be due to differences in knowledge and skill, and to differences in

attitude towards following procedures. The perception of the participants is that until everyone is operating with the same procedures it will be difficult to separate the pattern of errors in C into its variable (as in A) and constant (as in B) components.

There is, however, a strategy for identifying predictable sources of error in the workplace. By considering the natural or built-in limitations of the human operator as a complex component in a complex system, we can analyze the work environment for situations where: 1) if an error occurs, it can lead to unsafe consequences; 2) demands in the task environment may drive the human component too close to safe operating limitations, or impose more restrictive limitations on the operator; 3) safe operating procedures are not facilitated and reinforced by the characteristics of the task environment itself, and therefore encourage circumvention; and 4) the interfaces through which the human operator interacts with the work environment and equipment are more likely to increase, rather than reduce, the occurrence of errors. Identifying situations with the potential to negatively influence human performance is a first step in a strategy for reducing unsafe acts due to task and/or equipment design.

Before beginning the survey of the literature, we offer this perspective taken from Kletz (1993). Kletz is a chemical engineer and well known throughout the process industries as an expert on process safety.

"However impartial we try to be—and we do not always try—our views are affected by our background and responsibilities; our first reaction, when there has been an accident, is to think of all the things that other people might have done to prevent it taking place. The following account shows how different people might react to the same accident.

The liquid in a pair of pumps (one working, one spare) decomposed on standing with the production of gas. To prevent damage to the seal the plant instructions said that the pumps should be isolated and drained when they were not in use, and the drain valve left open in case the isolation valves were leaking. Before starting up a pump, operators should close the drain valve. This was pointed out to new operators during their training.

One day the operator on duty—a young, enthusiastic man who had completed his training only a few months earlier—started up a pump without closing the drain valve. He was hit on the leg by liquid that came out of the drain valve and splashed off the baseplate. The liquid was corrosive and burnt his leg; he was absent from work for two days. The supervisor's comments are directly from his report, the other comments are examples of how different people with different perspectives might react.)

FOREMAN

The accident was entirely due to the carelessness of the injured man who failed to follow instructions. He has been told to do so in the future. No further action is necessary.

SUPERVISOR

...it was carelessness which led him to open liquors to the pump with the vent open...Labels will be provided to remind operators that certain pumps may be left with open vents. Process supervisors will be told to ensure that all operators, and particularly those with limited experience, are fully aware of the elementary precautions they are expected to take in carrying out their duties.

INJURED MAN

I forgot, but it's easy to forget that there is something special about a particular pump when you are busy and trying to do everything at once. If the manager spent more time on the plant (including a few night shifts) and less time in his office, he might understand this.

UNION REPRESENTATIVE

Blame the working man, as usual. There should be an interlock to prevent the isolation valves being opened before the drain is closed.

SAFETY OFFICER

It is inevitable that sooner or later someone will forget that there is something special about certain pumps and start them up in the usual way. The labels will help but will soon become part of the scene and may not be noticed. Interlocks would be expensive. Can a relief valve be fitted to the pump and can the drain be moved so that it will not splash the operator?

DESIGN ENGINEER

No-one told me that the drain valve on this pump had to be left open. If I had known I might have arranged it differently. According to our Engineering Standards relief valves are fitted only on positive pumps, not on centrifugal ones."

(From Kletz, 1993, pp. 138-139).

The following review takes the perspective of the 'injured man' in the above account, that is, the perspective of the average operator.

Sources of Human Error

One of the consequences of the accident at Three Mile Island on March 28, 1979 was a review of the human factors environment, including procedures, training, and the human-machine interface (Wreathall and Reason, 1992). Additionally, the accident served as the impetus for research into the sources of human error. A framework for classifying human error was developed based on a compilation of the root causes of significant events in nuclear power plants (Rasmussen, 1982). Rasmussen's framework is built on a distinction between three levels of activity involved in human performance. These levels correspond to performance based on skilled control of actions, rules and formal procedures, and problem solving based on an understanding of system causal structure (Rasmussen, 1983; 1986). This framework has become a common standard with scientists and practitioners who study human reliability and human error in complex work environments. The skill-rule-knowledge distinction is a principal component of Reason's (1990) generic error modeling system (GEMS) which is one of the most comprehensive strategies in the scientific literature for understanding the sources of human error. The approach outlined in this section draws heavily on elements of the work of Rasmussen and Reason. It also draws on research and theories common to the scientific communities involved in the study of human performance (e.g., see Proctor and Van Zandt, 1994; Wickens, 1992).

Figure 6.2 shows a simplified and modified version of Rasmussen's framework for understanding the sources of error. Typically an accident analysis process will trace an accident to a set of root causes, one or more of which will be classified as human error. These are the observable behaviors or unsafe acts in the "result" column of Figure 6.2. In the "where?" column, the observable error is identified as a malfunction of some internal component of the human information processing system. Was information not detected or not detected on time? Was information identified incorrectly? Was information forgotten or distorted? Was there a miscommunication? In the "how?" column, three different levels of behavior are identified. Each of these levels is associated with a characteristic way of processing and acting on information, and consequently, with characteristic types of errors. Also included at this level is the selection of the right level of control over behavior. Each level has its advantages and disadvantages and each is appropriate under different sets of conditions. The "why?" column includes the factors that influence or shape performance. These are the many factors in the environment that contribute to, support, or induce human error and consequently unsafe acts. The characteristics of the ergonomic environment are

important in shaping the forms that unsafe acts will take and the probabilities of their occurrence. We have dealt with the social environment and training factors in previous chapters. In later sections of the this chapter we discuss the effects of task demands and stress, and equipment and work environment. In this section we summarize typical error mechanisms, the “how” component, and sources of error in the human information processing system, the “where” component.

Figure 6.2
(Adapted from Rasmussen, 1982)

First, however, let's return to our strategy for identifying error-likely situations in the workplace. In the final section of this chapter we lay out a set of analysis procedures. The procedures provide a strategy for working from an analysis of work tasks through the columns of Figure 6.2 from causes to results. For a given task the operator considers general environmental factors (e.g., glare, noise, distractions, social pressure, stress, workload etc.) and task specific factors (equipment design, availability of information, ease of use of controls, and other task demands) that can influence task performance; the level of behavior at which the operator is likely to engage these task situations (operational, tactical, strategic); the detailed level perceiving, thinking, and acting steps involved in the task where errors might occur; and the observable action that is classified as an unsafe act. Participants in workshops conducted at Hanford selected work tasks to analyze. They listed observable errors that can occur when performing these tasks. Many of those listed are the kinds of errors that we will be discussing throughout this chapter. Some examples include: improperly leaving a valve open or closed, errors that involve not following procedures, misreading or misinterpretation of indicators, and communication errors.

Human Information Processing

The human is a 'fallible' machine (Reason, 1990). This fallibility is one consequence of the adaptive capabilities of the human processing system. We have limited capacities for perceiving, attending, remembering, calculating, manipulating, etc. Errors are more likely to occur when the task requirements exceed these capacity limitations. Figure 6.3 illustrates the cycle of activity from perceiving, or picking up information from the environment, through processing that information with respect to current goals to planning and executing actions which in turn alters the environment and reorients the attentional processes to provide new information back to the perceiving end of the system. There is more information in an environment than is picked up by sensory systems. Sensory systems have built in limitations. Action systems also have obvious built in limitations (e.g., speed, strength, flexibility). The complex set of processes we have grouped under the label "thinking" in Figure 6.2, also have built in limitations. These limitations are more subtle than sensory and action limitations but are equally important. They are more likely to be overlooked in equipment and task design and are more susceptible to stress and task demands. They, therefore, play an important role in human error.

Humans are goal-directed systems. At any given moment an individual's behavior may be directed by a complex hierarchy of goals, some of which are task and job specific, others are personal, social or biological. Goals are not always conscious or discrete. For example, stable personality characteristics such as need for acceptance vs. need for achievement define goals. Attitudes towards work, safety, and risk influence the goals people set. The organizational objectives and culture influence goals. Individuals will accept or take risks to achieve goals. Short-term and long-term goals often conflict. For example, when performing a task or operating a system, the goal of 'getting the job done' may conflict with the goal of avoiding compromises in safety. If safety devices get in the way of efficient performance they are more likely to be circumvented.

Figure 6.3

We can think of the structure of our long-term knowledge base as organized around goals and attitudes. We classify and store information as standard examples, episodes, models, sets of rules, action plans, etc. As Figure 6.3 illustrates, the structure and content of what we have called a long-term knowledge base defines our expectations about the world. Expectations are derived from our standard model or image of a situation that has been built up from experience over our lifetimes, and lets us filter out much of the detailed information and operate with a standard model or set of expectations about a situation. Expectations are an essential part of skilled operation, they let us “preprogram” actions to make skilled tasks more efficient and effective.

We select from the flow of information what is important and relevant to achieving the current goals and focus our attention or concentration on that, perhaps very task specific, information. We can think of attention as a kind of filter process that determines how and when we sample the environment for information, as well as what kind of information we pick up and what we don't. Referring to Figure 6.3, goals and expectations serve to direct how and when we sample the environment for information. We can use what we expect to happen to set our attention “filters” so they are very sensitive to the slightest indication that the event we expect has occurred. We are then preset to respond and do so faster than normal. However, we are also prone to information that only roughly resembles our expectations.

Working memory can be thought of as the mental space where conscious thinking and planning is accomplished. It is closely associated with the limited processing resources of the cognitive system. This limited capacity lets us essentially do one thing at a time while keeping a small number of things in memory. It makes it difficult to manipulate and consider many factors or conditions at the same time and therefore requires individuals to use various simplifying strategies. Many of the characteristic strategies and shortcuts employed during the course of demanding activities are devices to ease the burden of working memory or processing resources. These adaptive strategies required to accomplish a task can often be a source of human error.

Levels of Performance

Rasmussen's three levels of performance correspond to decreasing levels of familiarity with the environment or task (Reason, 1990). At the *skill-based level*, performance is thought to be governed by preprogrammed action sequences which are activated and coordinated by specific spatio-temporal information picked up from the task environment. This type of performance is typical of well-practiced tasks carried out in familiar surroundings by skilled operators. At the *rule-based level*, performance is based on applying known rules (if (condition) then (action)) in familiar situations. At the *knowledge-based level*, performance involves conscious analysis and problem solving based on a mental model or representation of the system or task situation. This level comes into play in unfamiliar situations which require evaluation and planning. While skill-based performance is typically associated with more expertise in a task, all three levels can be operating at the same time.

A similar distinction between levels of operation in behavior has been applied to behavior involved in driving an automobile (Van der Molen & Boetticher, 1988). The *operational level* accounts for the ongoing perception-action behavior during driving; the *tactical level* involves rule-based decisions such as passing and stopping; the *strategic level* involves longer-term decisions such as planning the route. These two strategies for distinguishing levels of organization of behavior are analogous and can be combined (Wagenaar, 1992).

Recognizing a task or situation as a set of conditions for which a behavioral response pattern is appropriate occurs at the tactical or rule level. Execution of the fixed response pattern occurs at the operational or skill level. Adapting responses to new changes or new situations occurs at the strategic or knowledge level. Control shifts between the three levels of operation (Reason, 1990; Rasmussen, 1986). If, while performing routine activities in a familiar situation, attentional monitoring detects information that suggests a deviation from the expected conditions, then the operator would switch from skill- to rule-based processing. The operator would scan local information, identify the conditions, find an appropriate rule and apply the rule. If an appropriate rule can be found, then the operator switches back to the operational level. If an appropriate rule is not found quickly, then the operator switches to knowledge or model based behavior. This may involve a number of different strategies, such as thinking of an analogous situation and trying the rules associated with the analogous situation to see if they apply to the current situation. If analogous situations cannot be found, then cause and effect reasoning based on the operators mental model of system operation would be applied. Since this highly conscious mode is slow, difficult, and limited, people usually try to find interpretations of the situation that will let them switch back to the application of known rules.

An Example. The application of this approach to the workplace is supported by examples from workshops conducted at Hanford. Participants considered the different levels of behavior that come into play in the task they selected to analyze. They considered where operational level skill-based behavior was likely to be used and where it was appropriate. They considered where tactical-level rule or procedure-based behavior would be used. And they considered what conditions might warrant the use of strategic knowledge-based behavior. Clearly, all three levels are involved in most tasks. However, often only the rule-based level is considered because it is most accessible. Even experts initially have difficulty recalling skill-based and knowledge-based performance. We asked the participants to consider where the operator might switch between these levels of performance during the task. A simple but informative example is the task of opening a valve. The task can be approached from the operational skill, tactical rule, or strategic knowledge level of performance. Ideally, different components of the task involve different performance levels and the operator will switch back and forth between the levels where appropriate. However, if this was a familiar valve, an operator (operator 1) might engage the task in a primarily skill based mode. The operator's conscious planning might involve primarily spatio-temporal images about the location of the valve and the actions required for operating it. We might say that this operator's intention was to engage in the physical task of opening the valve, and the operator's internal model of the task is based primarily on representations of the task based on location, shape, application of force, etc. Operator 2 may be functioning in a primarily rule based mode. This operator's intention may be to engage a set of procedures required for opening a valve, and the operator's model would be primarily, procedural. And perhaps operator 3 is functioning primarily at the strategic knowledge mode. This operator's intention would then be to engage the entire system or process that the valve interfaces. Operator 3's behavior would be based on a model of the plant process and the role that the valve plays in regulating that process. Clearly each of the three operators will attend to different information in the environment since they are each approaching the task in a different way.

Unsafe Acts & Human Error

Reason's (Reason, 1990; Wreathall & Reason, 1992) summary of the psychological varieties of unsafe acts is presented in Figure 6.4. The classification breaks unsafe acts into those that are unintended and those that are intended. This distinction between intended and unintended actions refers to the differences between actions that are part of an operational-level skilled routine and those that are consciously planned. Unintended actions refer to the failure of actions to go as intended. These are classified as slips and lapses. The failure of intended actions to achieve desired consequences are classified as mistakes. Circumventions are intended actions that are not mistakes. They are deliberate but usually not malicious departures from rules. Often, if not usually, they achieve the intended short-term objective. The following section is a synopsis of Reason's error classification.

Slips and Lapses

Slips are errors that occur when a situation is correctly interpreted and a correct action is planned, but the wrong action is accidentally triggered. They are execution failures. Two conditions are required for a slip, the operator is performing a largely automatic task in familiar surroundings, and some degree of attention is captured by something other than the job at hand.

Figure 6.4
(From Wreathall & Reason, 1992)

A common class of slips are attention capture errors. These occur when you are performing some well-practiced activity in familiar surroundings, but you intend to depart from your usual routine. At the moment when you should monitor your actions to make the necessary departure from custom, your attentional resources are claimed either by some internal preoccupation or by an external distracter. The strongest set of expectations available (your usual routine) takes over the action. This scenario can lead to a number of different kinds of slips. A strong habit may intrude during the moment of inattention and result in a wrong action, or a strong habit may result in an omission of an action. Perceptual confusions are slips which result from over reliance on expectations during routine actions. We reduce our attentional resources and rely on rough approximations of the object as criteria for recognition. A typical workplace example is grabbing the wrong control when two controls are located together and they look and feel very similar.

Overattention or mistimed monitoring can also lead to slips. These slips involve making an attentional check at an inappropriate moment during a routine action sequence. These types of errors often occur when monitoring continuous action sequences like typing, playing the piano or playing sports. In the workplace they are most likely to occur when, after a period of inattention to the task at hand, you are not sure if you performed a necessary action. Your attentional focus interrupts an action sequence and causes an error. Mistimed monitoring errors are typical when learning a new skill.

Lapses represent failures to carry out actions because of failures of memory. These are the common lapses of everyday activity rather than mistakes due to memory overload which will be covered later. These may be caused by forgetfulness or interruptions and can result in omitting planned items, losing ones place in a sequence of activities, or forgetting one's intentions. Another type of error that is often due to a type of memory failure are mode errors in which you forget the context you are in and perform an inappropriate action (Norman, 1981). Mode errors are a potential problem in any system of multimode switches and displays (Wickens, 1992).

Rule-based Mistakes

Mistakes are inappropriate plans or intentions which will not achieve the desired goal or consequence. They are failures in judgment or interpretation involved in selecting an objective or in the means to achieve it. Mistakes can occur because of limitations of perception, memory, and cognitive processing. Mistakes are harder to detect than attention slips. We are tuned to picking up departures of action from intention but mistakes often go unnoticed or are not considered mistakes at the time. Mistakes, therefore, are often more dangerous than slips.

Rule-based mistakes occur when operators believe they understand the current situation and they develop a rule or plan of action to deal with it. The selection of an appropriate rule follows an "if-then" logic. Information in the environment is picked up which suggests that a certain set of conditions exist and these conditions match the "if" side of a particular rule, or, a rule that has often been used successfully seems to be a match for some of the "if" conditions of the current situation. The "then" side of the rule is activated.

Reason (1990) suggests two general possibilities why rules might fail. The first is misapplication of a good rule. A good general purpose rule may be misapplied when the "if" conditions that activate it do not actually exist in the current situation or there are other conditions

that contraindicate application of the rule. Reason refers to these as “strong-but-wrong” rules. This mistake often occurs as exceptions to rules are learned. The rule usually is successful but some subtle difference in the environment or some difference in the state of the system indicates that it is not appropriate.

Misapplication of a good rule can occur because there is not enough information to suggest an exception to the rule or because there is too much information and the natural selectivity of attentional processes will limit information pick-up to information that matches strong rules. Information that suggests that the situation calls for an exception to a general rule may not be obvious, may be misinterpreted, or may be argued away because they do not agree with the current ‘mental model’. Too much information confronting the problem solver is the other side of this problem. Only a limited number of cues may be attended to and these may match the conditionals for several rules. Therefore the strong rule (the one that has been successful most often) becomes the best bet. Misapplication of a good rule can also occur because of what Reason calls “failures of expertise.” This is the “It’s always worked before.” situation. Again, a strong and often successful plan or problem solution is applied inappropriately.

The second way rule-based mistakes occur is through applying a “bad rule.” The action component of a rule may simply be wrong; achieve its objectives, but in an inefficient or clumsy way; or it may be inadvisable or risky. A risky rule is one that achieves its objective most of the time but can occasionally lead to avoidable accidents. Often people use risky rules due to conflicting goals, such as getting the job done quickly or saving money and maintaining safety. Inadvisable rules can be due to risk handling—using risky rules because you know from experience you can handle the situation. You know the risks involved, and you know the safest option, but you try to find a compromise between the two that will reduce risks to those that can be handled (Yates, 1992).

Knowledge-based Mistakes

Knowledge-based mistakes are similar to the kinds of errors made in decision making. Incorrect plans of action are made because the situation is not fully understood. Knowledge-based mistakes are often due to a relatively low level of experience with a situation. The operator does not have an off-the-shelf routine and must generate a plan from whatever relevant knowledge the person has. Knowledge-based performance uses working memory capacity to think through the situation, compare alternatives and come up with a solution. Errors usually originate from a) the limitations of working memory and the conceptual resources available for processing information, and b) an incomplete or inaccurate mental representation of the problem. The individual’s knowledge relative to the system being operated may be large, however, due to the limitations of conscious processing and working memory, only a small amount of that knowledge can be applied at any moment. Problem situations are not always static, the situation may change as a result of the problem solvers actions or due to independent factors of the situation or both. Complex dynamic problems are common in today’s complex work environments. Often, the situation is changing faster than one’s ability to collect and interpret information. The system is in one state, but the problem solvers think it is in another state. In cases like this, the problem solvers are operating with the wrong mental model (Carnino, Nicolet, & Wanner, 1990).

Carnino et. al. (1990) provide some examples of this type of error that apparently occurred during the Three Mile Island incident. First, the operators did not have information about the closed isolation valves and were therefore operating with a model of the situation that was different from the real state of the system. Second, information that the pressure relief valve had received a signal to close was apparently interpreted as indicating that it was closed.

Reasoning errors are also a type of knowledge- or model-based error. These can be due to a number of factors. Many of these factors have to do with the adaptive strategies or short cuts we use to overcome the limitations of our reasoning and memory capabilities. Some of these were discussed in Chapter 4, as decision-making heuristics and biases.

As the simplified model (Figure 6.3) and discussion of the human perceiving-thinking-acting cycle illustrated, humans are selective information processors. While selective information sampling is a useful and adaptive strategy for coping with information overload, mistakes occur during selective processing of task information if attention given to the wrong (perhaps the most obvious) features or cues or not given to right features.

Another aspect of selectivity is the tendency to give undue weight to facts that come readily to mind and ignores those that are not readily present, or as Reason (1990) puts it “out of sight out of mind.” Common experience and a large body of research evidence (e.g., Kahneman et al., 1982) support the existence of this “availability heuristic.” Another strategy we use to overcome processing limitations is confirmation bias. Once you favor a particular interpretation, this interpretation will interfere with your processing of later information and you will tend to selectively try to confirm your hypothesis (e.g., Nisbett & Ross, 1980). Another common reasoning error is poor knowledge of the consequences of an action (Carnino et. al., 1990). This is usually due to inexperience with some facet of system operation which leads to an incomplete system model. Finally, reasoning errors occur due to refusal of reality (Carnino et. al., 1990). This can take many forms, from “it can’t happen to me” to ignoring alarms and error messages.

Complex dynamic situations create additional types of reasoning errors as individuals try to cope with a constantly changing situation and many sources of information. Problems with complexity can include: the inability to hold information about many different factors in working memory at once; the inability to form a predictive model of the situation due to delay of feedback; focusing on the current situation instead of how the system arrived at that situation and where it might be going next; and underestimating the effects of rates of change of variables. Another source of error when dealing with complex situations is over-simplifying cause and effect relations. We have a tendency to see things in linear, causal sequences. We are sensitive to the effects of our actions on the immediate path to a goal but are not aware of side effects on the rest of the system. Therefore, fewer contingencies plans are made.

Circumvention of Procedures or Rules

Circumventions is perhaps the category of unsafe act that gets the most attention in safety training. The focus is on how to get people to conform to rules and procedures they often view as unnecessary or conflicting with other goals. Often circumventions are a result of reinforcing unsafe habits. Figures 6.5 and 6.6 (from Burkhardt, Schubert & Schubert, 1970; cited from Kuhlmann, 1986) illustrate the learning process involved in the development of safe and unsafe behaviors.

Figure 6.5
(From Kuhlmann, 1986)

Figure 6.6
(From Kuhlmann, 1986)

Carnino et. al., (1990) describe the Chernobyl accident as one which involved a number of circumventions of operating procedure. The authors use this example to illustrate one of the situations that may lead to circumventing procedures. They refer to an "illusion of system stability." This may occur after a long period when there are no severe malfunctions. For months and years the operators and organizations see the system run at normal levels. Incidents are rare and everyone starts to think of the system as stable. This is related to a second potential cause, the expert paradox. The best operators are often the most vulnerable to error—they push the risk envelop. Many of the published accidents involved experienced pilots and operators. A third, and perhaps more common, way rules are circumvented is the 'simplification' of procedures over time. Redundant safety checks are omitted and under normal conditions there are no consequences and thus these simplifications are rewarded.

TASK DEMANDS AND STRESS

Human Reliability

A number of efforts have been directed towards applying engineering reliability analysis to the human operator in an attempt to predict human error. The best known of these is the Technique for Human Error Rate Prediction (THERP) developed by Swain and his associates (Miller & Swain, 1987; Swain, 1990). The THERP process has the following components: (1) Conduct a task analysis for the task or procedure. (2) Establish the probability of a human error for each subtask. The human error probability is expressed as the ratio of the number of errors made on a particular subtask to number of opportunities for error. If data from human performance data bases are not available, the values for number of errors and opportunities for error are estimated by experts. (3) Compute the combined error probability of all subtasks; considering subtasks that are completed in series and those that have some parallel overlap. (4) Consider the effect of performance shaping factors. Performance shaping factors are multipliers which can increase or reduce the probabilities for error. For example, as illustrated in Figure 6.7, degree of expertise or stress level modify the probabilities for error in a task (Miller & Swain, 1987). Other performance shaping factors that have been considered in the THERP methodology include: the format and content of procedures, adherence to administrative rules, layout and style of displays, item labeling and tagging, unfamiliarity, time pressure, signal to noise ratio, no means of reversing actions, and others (Wreathall & Reason, 1992; Williams, 1988). These performance shaping factors can increase the probability of error in a task by factors of 10 or 11 (signal to noise ratio, time pressure) or even 17 (unfamiliarity) (Williams, 1988).

Performance Shaping Factors		
<u>Stress Level</u>	<u>Increase in error probability</u>	
	<u>Skilled</u>	<u>Novice</u>
Very Low	X2	X2
Moderate	X1	X1
Moderately high	X2	X4
Extremely high	X5	X10

Figure 6.7
(From D. Miller & A. Swain, 1987)

Referring back to Figure 6.2, titled “Sources of Error”, recall that the first column, which we labeled “Why?” listed causes or influences on error. We can see from the error estimates derived from human reliability analysis methods that this influence can be quite substantial. In the first section of this chapter we considered in some detail the mechanics of how errors are produced by the human component of complex systems. In this section we consider the influence of task demands and environmental stressors on human error. We refer to task demands as involving both the general aspects of the work environment that might influence the accident process, and the way in which specific task requirements are designed to be compatible with the capabilities and limitations of human operators. While operators can and do successfully adapt to a wide variety of tasks and situations, they cannot be expected to consistently perform under conditions of high task demand without increasing the likelihood of error. Susceptibility to the influence of a large range of factors which can affect performance is part of the cost of adaptability.

Mental Workload

How much mental effort is required? How difficult are the tasks? What additional tasks can the operator handle? How fast will the operator respond to uncertain events? How much time pressure does the operator feel? Over the past twenty years the concept of mental workload has emerged as an important indicator of the demand a task imposes on the operator’s limited resources (Wickens, 1992). Workload is usually defined by the relationship between resource supply and task demand as illustrated in Figure 6.8.

Figure 6.8
(Adapted from Wickens, 1992)

Increased task demand does not necessarily correspond with decreased performance. Let’s assume that, under normal working conditions, the relationship between the task demands and the resources supplied by the operator remains relatively stable between points A and B. Performance remains stable, the operator has a reserve resource capacity, and workload is acceptable. As task demands increase, the operator can increase the resources applied to the task and maintain adequate performance up until some workload level at point C. Beyond that point task performance will start

to decrease. From this perspective, changes in workload can result not only from the task demands for resources but from changes in the operator's capacity to supply resources. This relationship is one reason why the concept of mental workload is central to understanding human error. As mental workload increases beyond some limit, the probability of error increases. And mental workload can be increased by the demands of the task or other stresses on the operator that reduce the operator's ability to supply attentional resources to the task.

Workload Measures

Workload measures can be used to assess the demands of different tasks and equipment configurations. This kind of assessment is used to identify potential bottlenecks where resource demands might momentarily exceed supply resulting in reduced performance and an increase in the probability for error. It can also be used to assess differences in the resource capacity available to operators. Workload can be measured in a number of different ways. Performance methods measure the actual decrement in performance on a primary task as other tasks are added. Physiological techniques use changes in nervous system activity as indicators of mental activity and workload. Subjective workload measures assess the effort required to perform a task from the perspective of the operator. They reflect two factors: (1) the perceived effort that must be invested into performance of a task, and (2) the number of tasks that must time shared (Wickens, 1992). Figure 6.9 is a commonly used multidimensional scaling technique to assess operator's perceptions of mental workload associated with a task.

NASA-TLX Rating Scale	
1. Mental Demand	How much mental and perceptual activity was required (e.g., thinking, deciding, calculating, remembering, looking, searching, etc.)? Was the task easy or demanding, simple or complex, exacting or forgiving?
2. Physical Demand	How much physical activity was required (e.g., pushing, pulling, turning, controlling, activating, etc.)? Was the task easy or demanding, slow or brisk, slack or strenuous, restful or laborious?
3. Temporal Demand	How much time pressure did you feel due to the rate or pace at which the tasks or task elements occurred? Was the pace slow and leisurely or rapid and frantic?
4. Performance	How successful do you think you were in accomplishing the goals of the task? How satisfied were you with your performance in accomplishing these goals?
5. Effort	How hard did you have to work (mentally and physically) to accomplish your level of performance?
6. Frustration Level	How insecure, discouraged, irritated, stressed, and annoyed versus secure, gratified, content, relaxed, and complacent did you feel during the task?

Figure 6.9
(From Hart & Staveland in Hancock & Meshkati (Eds.), 1988)

Attention & Time-Sharing

In the discussion of Figure 6.2 the concept of attention was described as operating as a kind of filtering mechanism, the parameters of which could be set by goals and expectations. The concept of working memory was associated with conscious attentional control. Working memory was said to be a system with limited capacity that essentially allowed us to do one thing at a time while keeping a small number of things in memory. Attentional control was said to be slow, effortful, sequential and difficult to sustain. However, we often seem to be able to accomplish more than one thing at a time and human operators of complex systems are often called upon to time share between different tasks. The concept of processing resources is often used to understand time sharing, task interference and workload. When performing any task different mental operations (perceiving, thinking, acting) must be carried out and performance of each requires some of the operator's limited processing resources. Two activities will demand more resources than one activity, and since resources are limited there will be a greater difference between supply and demand. Some activities may require resources that are different than other resources. There would then be less competition between these activities and perhaps better time sharing.

Successful time sharing between tasks is accomplished by effective scheduling of subtask activities and efficient switching between those activities (Wickens, 1992). In addition we often engage in concurrent processing. We may be picking up information about and planning a future task, interpreting information from a previous task, and performing some action on the present task in parallel. The effectiveness of multi-task performance will be influenced by the similarity of task components and task difficulty, where difficulty refers to the amount of processing resources required. A good example is driving in heavy traffic vs. driving on an open highway. In heavy traffic, we sample the environment for information more often and pay more attention to our control actions.

Research supports the idea that efficient time sharing is skill that individuals develop as they become expert in a task environment. Efficient time sharing results from more automatic performance of the component tasks, and from knowing when and where to sample for information, when and where to make responses, and how to integrate the flow of information and action between the tasks (Wickens, 1992). Research on attention and time-sharing has important applications to predicting the effectiveness of multiple task performance in many technology related areas such as process control and power plant operation. For example task and equipment designers need to know if two tasks will interfere with each other under normal conditions and as task demands and time pressures increase.

Time-line Analysis

Time-line analysis procedures are used to develop predictions about the distribution of workload over time of an operator in a task environment. In a time-line analysis workload is assumed to be proportional to the ratio of the time occupied performing tasks to the time available. The total time for the selected set of tasks is broken down into appropriate time units. And the number of subtasks performed during each unit is recorded. The time-line analysis process must be sensitive to both the internal (detecting information, planning, rehearsing) and external activities required. While time-line analysis is typically used to inform task design decisions, it can also be an effective method to

identify potential situations where time sharing between tasks may be required of an operator. Since effective time-sharing takes training and experience, the combination of periods of high task demands and less experienced operators is a recipe for increasing the probability of error.

Relationship Between Stress Level and Performance

Stress is one of the consequences of high levels of mental workload, especially if those levels must be sustained for a long period of time. Stress in turn produces changes in the functioning of many of the internal information processing components of the human operator with consequent effects on performance. Stress and errors seem to go together. Errors, when we are aware of them, cause stress; stress, at high levels, increases the likelihood of errors.

The influence of stressors on the human operator is manifested by: (1) psychological changes—feelings or experience of frustration or increased arousal or anxiety; (2) physiological change— increased heart rate or other long term effects; and, (3) changes in the efficiency of information processing. But changes in information processing do not necessarily lead to decreased performance. Many stressors seem to influence performance through a concept referred to in the scientific literature as arousal. Arousal can be thought of as similar to alertness or energy level. As Figure 6.10 illustrates, performance is best when arousal (stress) level is neither too low nor too high. Both very low cognitive demands and excessively high mental strain will have a negative effect on efficiency and performance.

This relationship has been demonstrated in many experiments and for many different tasks (e.g., Easterbrook, 1959; Kennedy & Coulter, 1975). The increase in performance as arousal moves from low to moderate levels can be thought of as due to an “energizing” function that allows the operator to increase the amount of reserve resources available (e.g., see Figure 6.8) (Wickens, 1992). The decrease in performance is thought to be due to the effect of arousal level on the focus of attention—people become more narrowly focused and don’t think about all the factors that should be considered. As Figure 6.10 shows, high levels of stress are more detrimental to complex tasks than to simple tasks. Complex tasks typically require attention to more diverse sources of information. Research also supports the common experience that the negative effects of stress are reduced by higher levels of knowledge and skill. Using the classification of performance discussed in the previous section, individuals with more expertise in a task environment can conduct more of the task at the skill or rule based level thereby allowing more working memory resources for problem solving. The task is therefore less complex for the expert than the novice.

Excessively low levels of arousal lead to boredom. Monotony is a concern under conditions that involve: minimum task difficulty, narrow fields of perception and prolonged uninterrupted activity (Kuhlmann, 1986). Monotony leads to effects somewhat similar to mental fatigue. Where mental fatigue interferes with the ability to perform, monotony interferes with the readiness to perform. Vigilance tasks, which are common to process control monitoring, can lead to monotony. Studies have shown that after about 30 minutes of uninterrupted monitoring attentiveness decreases and the percentage of errors (e.g., missed signals) increases significantly.

Figure 6.10
(Adapted from Proctor & Van Zandt, 1994)

Types of Stressors

We have discussed the relationship between mental workload, stress and performance. Clearly, the relationship between stress and workload is a complex one, high mental workload is one source of stress and sources of stress external to the immediate task take some of the attentional resources away from the task thereby increasing the perceived workload. Figure 6.11 lists some of the common classes of stressors. Each of these stressors can be viewed as influences on arousal, or activation level. We discussed some of the psychological influences on performance in Chapters 2 & 3. The effects of drugs and alcohol are beyond the scope of this report. In this section we briefly summarize effects of environmental stressors, fatigue and cyclical changes on operator performance.

Environmental factors. The important environmental factors in the workplace include lighting, noise, vibrations, temperature and chemical substances. At extreme levels environmental factors are obviously detrimental to health and safety. However, even within “safe” ranges environmental factors such as lighting and noise effect performance. Lighting level influences performance, mood, and attitude. Stronger lighting enhances activity, vigilance, and the ability to concentrate and reduces feelings of fatigue. A number of studies have related improper lighting to increased error and accident frequency (Kuhlmann, 1986). In general, glare, extreme contrasts, shadows and flickering light sources should be minimized. An additional lighting related factor that can contribute to error is light-dark adaptation. The time required for an operator’s eyes to adapt to a dark environment can vary from 5 to 45 minutes. The effects of noise on performance varies in accordance with the arousal curve presented in Figure 6.10. In general, lower levels of noise increases attentiveness and has a positive effect on performance. Higher noise levels result in more

hyperactivity and decreases performance. Higher noise levels are more distracting for more difficult tasks. As noise levels approach the 85 dB level they may interfere with concentration and attentiveness and increase error.

Figure 6.11

Fatigue. Fatigue, due to working too long without rest or due to working at times when body mechanisms are functioning less efficiently also acts as a stressor and can lead to errors and unsafe performance. Muscle fatigue can be due to static loading to maintain posture or repetitive or awkward dynamic loading. General mental fatigue due to prolonged high workload is characterized by an increase in the length and variability of reaction time, increase in errors, and a tendency to neglect peripheral aspects of a task such as checking routines. These effects can be demonstrated in most tasks after periods of uninterrupted working of between 10 and 50 minutes depending on task load. Both mental and physical fatigue can arise from inadequate work-rest cycles. Higher levels of fatigue take proportionally longer to recover from than lower levels. Therefore frequent short rest periods are most effective. Research supports common sense in demonstrating that adequate rest periods increase performance, decrease variability, and decrease error (Margolis & Kroes, 1975).

Fatigue can also be a result of the distribution of working hours. Circadian rhythm mechanisms follow cyclic variation in activity linked to the 24 hour light-dark cycle. On average task performance will vary with the diurnal rhythm with performance on different tasks being best at different times of day. The difference in performance between the high and low periods is about 10% - which is as significant as the degradation in performance caused by the loss of two hours sleep the night before (Ridley, 1986). The sleep cycle is usually coordinated with the light-dark cycle, for night shift workers adjustments begin in about 2-3 days and is reasonably stable after about two weeks, provided the individual continues to live on a night schedule on the weekends.

Stress Effects

Wickens (1992) presents a summary of some of the effects of various stressors on the human operator's information processing performance. Some of these effects are listed in Figure 6.12.

Stress Effects

Attentional narrowing

Reduction in rate of work

Shifting from accurate to fast but error prone performance

Shifting from conservative to risky performance

Reduced Working Memory capacity

Regression to well learned habits

Persevering with inappropriate strategies

Considering fewer alternatives

Figure 6.12

Attentional narrowing. Stressors such as perceived danger, anxiety or noise often leads to a perceptual “tunneling” effect whereby attention is focused only on information and tasks of high subjective importance (e.g., Baddeley, 1972). The consequence of attentional narrowing can be positive or negative, depending on the degree to which the subjectively important information is the actually important information.

Reduced working memory capacity. Research (e.g., Poulton, 1976; Stokes & Raby, 1989) shows that stress reduces the capacity of both verbal and spatial working memory. This in turn will effect problem solving that requires visualization and tasks that require maintaining information in memory. It also effects learning efficiency since it reduces the transfer of information from working memory to the longer term knowledge base.

Shifts in performance strategies. Research (e.g., Hockey, 1986) shows that stress results in a shift in the speed-accuracy trade-off from accurate to fast but error prone responding. This problem has been cited as a concern in operator response to complex failures in nuclear power control rooms (Wickens, 1992). Another shift in strategies that is associated with stress is the shift from conservative to risky information processing.

Decision making. Research shows that decision making degrades in predictable ways under stress. Individuals tend to persevere with inappropriate strategies (Cowen, 1952), they consider fewer alternatives, and become unsystematic in their allocation of attention.

Long term memory. Stress restricts the ability to acquire new information but does not seem to disrupt the retrieval of information that is well learned from long term memory. However, research (e.g., Allnut, 1987) supports the common experience that stress restricts retrieval to well learned response patterns.

Based on these specific effects, tasks that are especially susceptible to the effect of stressors would include vigilance, tracking (e.g., driving), visual search, memory tasks, complex tasks susceptible to speed accuracy trade-offs, and problem solving tasks.

Minimizing the Effects of Stress on Performance

Design. Some of the error inducing effects of stress can be minimized by attention to task and equipment design: increasing the organization of information displays, reducing unnecessary information, minimizing requirements on working memory, making emergency procedures—since they will be used under conditions of reduced working memory—very clear, any procedures should be clearly phrased in terms of the specific actions to take (Wickens, 1992). The role of design implications will be discussed in more detail in the following section of this chapter.

Training. An important mediating effect of stress is training. Well-learned skills will be less likely to degrade under stress. In addition, successful experience in a stressful situation reduces the anxiety associated with that experience. Both of these factors argue for the importance of training for emergency conditions. In fact, some experts make the case that training for emergency conditions should be given more priority than training for routine operations (Wickens, 1992). Under conditions of stress, it is the well learned habits that are easily retrieved from long term memory that we rely on. By encouraging operators to actively analyze the tasks they perform, they will be more likely to discover potential sources of error that can occur under stressful conditions. This will allow operators to consider and rehearse the actions they might take under stressful or emergency conditions.

EQUIPMENT DESIGN

As mentioned previously, deficiencies in the design of a system's human-machine interface are often the root causes of human performance difficulties and human errors. During the design of many complex systems, little attention is given to the role of the human operator. As an illustration, see Figure 6.13, which is a synopsis of a conversation between a design engineer and a human performance specialist. Were it not based on the actual experiences of the source author, it would actually be comical! However, the result is often a situation which virtually "invites" the wrong behavior on the part of the human operator.

Many human errors can be traced to basic error-inducing designs such as non-standard controls, non-communicative displays, needlessly complex interfaces, illogical relationships, etc. Such difficulties can often be magnified under adverse environmental conditions (e.g., extreme temperatures, low illumination, usage of personal protective equipment) and demanding task requirements (e.g., time constraints, emergency conditions, highly repetitive operations, physically or mentally taxing job requirements). Such design inadequacies have been colorfully described by one author as "resident pathogens, buried within systems, patiently awaiting their chance to make mischief" (Reason, in Wiener, 1989). Reason argues that, in the majority of situations, such design

flaws should have been predictable, and hence preventable, and thus lays the blame with management.

It is not uncommon for little attention to be given to the role of the human operator during the design of many systems. Illustrated below is a synopsis of a conversation between a human factors professional and two engineers responsible for designing the console of a nuclear power plant:

Engineers: These are the six XYZ concentrate indicators.

Consultant: What is the operator's task here? Does the operator have to read a specific value, compare values between indicators, or use these indicators while manipulating controls?

Engineers: We really don't know - that's Operations' responsibility.

Engineers: This is a digital readout that directs the operator's sequence of actions.

Consultant: How does the operator use that? What displays and controls are referred to by the readout? How much time does the operator have to respond to the display?

Engineers: We don't know - that's Operation's responsibility.

Consultant: (now becoming a little irritated) Exactly what did the two of you have to do with this console anyway?

Engineers: We designed it! Each of us started at a different end, and we laid out the displays going across.

Consultant: I think I need a cup of coffee.

Figure 6.13
(From Sanders & McCormick, 1987)

In each of the high-profile incidents of human error mentioned earlier in this chapter (Three Mile Island, Bhopal, USS Vincennes, Chernobyl, Herald of Free Enterprise), the event was, in part, caused by inadequate design of the human-machine interface. At TMI, one contributing factor was a misleading indicator. The indicator did not display the actual state of a valve (as would be expected), but merely the fact that a signal had been sent to the valve. In this case, the indicator showed that the signal had been sent commanding the valve to close; the operators misinterpreted the display's message to mean that the valve was in fact closed. The valve was, however, actually stuck in the open position. Based partly on this wrong information, the operators were unable to diagnose the underlying problem with the system. In the Vincennes incident, poorly designed displays were misread, indicating that an approaching Iranian aircraft was descending. This information was taken as an indication that the aircraft was diving for an attack, further confirming the operator's assessment that the aircraft was an Iranian F-14 Tomcat. The aircraft (actually a passenger plane carrying 290 persons), which was in fact ascending at the time, was shot down by the USS Vincennes killing everyone onboard. In each of these incidents, operator stress also played a role, but as Malone (1990) points out, much of the stress encountered was the direct result of the inadequate human-machine interface design. The interface impeded optimal performance and added significantly to operators' mental workload.

In these and countless other examples, the accident was, to a significant degree, due to the poor design of the human-machine interface. These examples should serve to represent the magnitude of the potential consequences of inattention to human factors issues in interface design. Although operator errors rarely result in the catastrophic consequences demonstrated in these examples, the occurrence of everyday incidents which result in comparably minor, nonetheless serious, consequences, are countless. It is actually quite difficult to estimate the proportion of times that

interface design deficiencies contribute to an event. Typical investigative procedures for non-catastrophic events rarely go beyond assigning human error as a contributing cause to discover what (if any) underlying problems influenced the individual's performance of the error. Therefore, the potential human factors contributions to many accidents and injuries are never explored. As an illustration, consider the Type A investigation of the U-2 steam pit valve failure which led to the establishment of this project. The section of the accident report entitled "Human Factors" describes primarily the skill and competence levels of those involved; not the true "human factors" issues which may have played a role in the accident. If such factors were investigated, the results were not documented in the final report. As the incidents discussed above point out, it may be impossible to predict when a seemingly small human error will be the catalyst to an accident of significant consequence. This, combined with the ease with which improvements can often be made, strongly argues that least some attention to interface design be given in any effort to improve workplace safety.

A human factors approach to increasing safety in the workplace places an emphasis on designing the environment to discourage or prevent unsafe behaviors from occurring. Essentially, where possible the environment should be designed to encourage/ elicit the intended operator response and discourage unsafe alternatives (or human errors). Where this is not possible, the next most acceptable alternative is to remove humans from the error-producing or hazardous situation. In addition to, or when neither of these alternatives are feasible, one should look to guarding the worker using engineering guards, personal protective equipment, etc. Warnings should be used in addition to the first three measures, or when none of the first three are available. Finally, operators should be trained to recognize and work within the error-producing or hazardous conditions. While training is always an alternative, it should not be used *alone* if other means are feasible. As the example in Figure 6.14 illustrates, the probability of human error increases as the approach moves from top to bottom. Also, as Sanders and McCormick (1987) note, "designing to reduce errors or their consequences can often be the most cost-effective approach to the problem of human error. A system need be designed [or redesigned] only once, while selection and training must be repeated as new people become part of a system. In essence, it is easier to bend metal than to twist arms." It is important to note, also, that by the term "design," we do not only mean the initial design of the equipment or environmental considerations. A wealth of strategies exist to redesign, modify, or aid an existing work environment to increase its ease of use from a human factors perspective.

Among the many human factors considerations of the work environment are the design of information displays and manually activated controls, and the location and arrangement of controls and displays. These three factors will be expanded on herein, not because they alone are responsible for human error, but as a means to illustrate at some level of detail, the consideration of the physical environment that is necessary in order to determine potential error-producing conditions. Other features which also play a role include, but are not limited to, the design of tools, operating procedures, communication systems, performance aids, physical environment (illumination, noise, temperature, etc.), and training systems.

Human Factors Design Priorities for Safety (Manhole Example)

1. Design	(Put a cover on the manhole.)
2. Remove	(Don't require workers to be in the area while the manhole is open.)
3. Guard	(Place barricades around the open hole preventing individuals from stepping into the hole.)
4. Warn	(Post placards alerting people of the presence of an open hole.)
5. Train	(Instruct people to walk around the open hole.)

Figure 6.14

Display Design

Effective display design supports reliable information gathering from the environment. There is much more to designing a good visual display than merely making it visible. The displayed information must be easily understandable so that correct decisions or control actions can be made without unacceptable delays. The design of a display should consider the way each item on the display will be used, its importance, when it will be used, and specific characteristics of users, such as visual acuity or skill level. Different uses of the same display during normal operation versus an emergency situation must also be considered, as should the physical environment within which it is to be used. An acceptable display must therefore convey the appropriate information to the user, require as little reliance on inference as possible, and have minimal chance of misinterpretation. Errors attributable to poor display design may occur not only by misreading a displayed value, but can also occur by misinterpreting a display, confusing displays and reading the wrong display, not attending to changes in displayed information, or not being able to read and/or interpret the display quickly enough. Samples of specific errors related to display design are shown in Figure 6.15. These items, taken from NUREG/CR-1580, are illustrative of the types of errors which may occur because of poor display design. The complete list of design features influencing human errors from NUREG/CR-1580 is shown in the supplement to Appendix D. This is one of many taxonomies of human error resulting from inadequate equipment design.

On the other hand, detailed design guidelines are available to assist an evaluator/designer in [re]designing the visual information portrayals in a workplace (e.g., EPRI NP-3659, 1984; MIL-STD-1472C, 1981; Van Cott and Kinkade, 1972). These guidelines, which are not presented here due to their complexity and length, are based on simple principles that enhance the effectiveness of visual displays, as shown in Figure 6.16.

Not all information is conveyed to the operator via the visual channel. Auditory information is often presented, especially warnings/alarms and speech. When designing these forms of information portrayal, special consideration must be given to masking by ambient noise, masking by barriers, and distortion of the acoustic signal. Other factors that must be considered include the effects of age-related or noise-induced hearing loss and the use of personal hearing protection on the audibility, discriminability, and intelligibility of acoustically presented information.

Sample Design Features of Displays Influencing Human Errors

Viewing distance makes reading difficult
Display located such that the operator's view is obscured
Displays difficult to read due to poor brightness contrast
Display readability impaired by glare
Scale increment size makes reading difficult
Pointer parallax increases likelihood of reading errors
Process controls display demand only, not actual value
Display not easily differentiable from adjacent displays
Display labeling not readily readable
Display not adequately illuminated
Direction of display motion not conventional or stereotypical
Failure of a meter is not readily detectable

Figure 6.15
(From NUREG/CR-1580)

Principles for Enhancing the Effectiveness of Visual Displays

Conspicuity: The display must draw the user's attention when necessary.
Visibility: The display should be visible under all anticipated conditions.
Legibility: The display must be easily readable under all anticipated conditions.
Intelligibility: The operator must be able to reliably and quickly translate the displayed data into usable information.
Emphasis: The display should emphasize only the needed information.
Consistency: The display design should be consistent with respect to both operator expectations and the design of similar displays.

Figure 6.16
(Adapted from Woodson and Conover, 1964)

Control Design

The types of systems people control in their jobs vary tremendously, from light switches to complex industrial machinery. However, the basic human functions involved in the control process are the same. The human receives information, processes it, selects an action, and executes the action. The action taken serves as the control input to the system, and in most cases some form of feedback is provided to the operator regarding the effects of the action taken. Types of errors which may result from poor human factors design of manual controls include: inadvertent actuation (accidental activation of a control), substitution errors (selection of the wrong control), activation errors (selecting wrong position/setting on the right control), and temporal errors (taking too much time to locate, acquire, and activate a control). Such errors may result from being unable to quickly

and easily distinguish one control from another, being unable to quickly discern the manner in which the control should be operated, failing to receive feedback as to whether the intended input was accepted by the system, etc. Samples of specific errors related to control design are shown in Figure 6.17. Again, these items, taken from NUREG/CR-1580, illustrate of the types of errors which may occur because of a lack of detailed concern for the role and capabilities of the human operator in the specification and design of a system's controls.

Sample Design Features of Controls Influencing Human Behavior

- No guards or barriers - may lead to inadvertent actuation
- Too little force required to activate - may lead to inadvertent actuation
- Type of motion required to activate makes accidental activation likely
- Direction of motion does not follow accepted stereotypes or conventions
- Direction of motion is not consistent for similar types of controls
- Direction of motion is not labeled
- No feedback of control activation
- Control position/setting not readily discernable
- Control shape/size/color/position not readily distinguishable from other controls
- Control label obscured by the control itself or by the operator's hand
- Control label not readily readable
- Labeling of control positions is difficult to read
- The associated display is not located with the control
- The motion of the associated display with respect to control motion does not follow convention
- Force required to activate the control is excessive

Figure 6.17
(From NUREG/CR-1580)

In addition, one must consider all of the conditions under which the controls are to be used, for example, extreme temperatures limit tactile feedback and impair dexterity, personal protective equipment (e.g., gloves) impairs manual dexterity and increases the probability of missettings and/or inadvertent activation.

Layout of Controls and Displays

In some situations, a display panel will be a complex arrangement of many dials and annunciators. In such situations, one needs to be sensitive to the factors that influence the perceptibility of information within each of the individual displays as well as to the overall organization of the display. Operators must be able to quickly discern the value of an individual display, as well as make comparisons between displays, assess the overall system status, etc. The same is true for controls—they are often situated in an arrangement with other controls and with displays associated with the controls. In these conditions, errors are likely because of design characteristics of individual items, but of the layout and arrangement of the combinations. Samples of specific errors related to display/control layout are shown in Figure 6.18. Again, these items, taken from NUREG/CR-1580, are illustrative of the types of errors which may occur because of poor design of display/control combinations.

Sample Design Features of Control and Display Arrangements Influencing Human Behavior

- Display not located within visual access from viewing position
- Display not located within visual access from corresponding or associated control
- Display arrangement is illogical or inconsistent
- Displays not functionally grouped
- Display not located adjacent to an associated display
- Location of a control with respect to the operator's body may lead to inadvertent actuation
- Location of a control with respect to operator's hand while controlling other controls may lead to inadvertent actuation (e.g., there is not enough spatial separation of different controls)
- Control located in a string of other controls of the same shape
- No consideration given to the sequence of control use
- Control is located such that operator reach can result in mis-settings
- Control is located or oriented such that selection of some positions is difficult
- Control position arrangement is not consistent across different controls
- Access to the control requires excessive travel on the part of the operator

Figure 6.18
(From NUREG/CR-1580)

During the half-day portion of the workshop dealing equipment design, the participants were encouraged to think about these types of potential errors as they might apply to their own work environment. Although this is a very difficult task (it is quite difficult to recall such specific details when not situated within the actual work environment - an approach to conducting a workplace assessment will be discussed in a following section of this chapter), the participants were surprisingly quick to recall specific examples of numerous potential error-producing conditions in their own worksite. Simple examples include valves which open in directions contrary to stereotypes, poor display and label legibility due to discoloration and damage, and numerous examples of inconsistencies in display and/or control design and layout between otherwise similar pieces of equipment.

INCORPORATING HUMAN FACTORS PRINCIPLES IN THE WORKPLACE

Although ideally human factors design principles should be incorporated throughout the development lifecycle of a technical system, the majority of the more complex systems in existence today were not designed in such a manner. Substantial improvements, however, can be made to existing systems. Similarly, job requirements and job safety analyses seldom study the task requirements in sufficient detail to recognize the subtle, nonetheless critical, contributors to human error. By recognizing potential problem areas, the potential for human error can be minimized. In some cases, redesign can eliminate the problem area; in other cases a retrofit can be designed to effectively eliminate the problem. Where environmental or equipment modifications are impractical or job redesign is not feasible, aids can often minimize the potential for human error. And at a minimum, by making the operator aware of any potential problem areas, s/he may be able to compensate for the increased potential for error when necessary.

Since humans are fallible systems, we cannot eliminate error, but we can modify the probability of error occurring and focus on reducing error under conditions in which error is likely to result in accidents. If it is possible to specify the conditions under which human errors or circumventions are likely to occur and the conditions under which they are likely to result in accidents, then we can focus efforts on implementing safe guards to defend against errors and training which focuses on conditions under which vigilance should be increased.

An approach to decreasing the occurrence of unsafe acts is to train all operators to be active problem solvers in their work environments. In order to be effective, training in active problem solving should be a continuous process. The problem solving process, in which conditions, existing or potential, which could result in an accident are identified, takes considerable mental effort and can be a time consuming process. However, the payoff is operators that are more knowledgeable about the systems they operate, more aware of the potential for error in interacting with those systems, and more likely to maintain safer attitudes in the work environment.

Getting people to change their behaviors requires implementing a strategy that will provide them with tools and methods to look “with an eye for detail” at their task environment and how they operate within it. In other words provide them with tools and methods to observe their operational and tactical levels of performance from a strategic perspective. This is the mode of performance we refer to as active problem solving. In this section we outline the components of a formal human factors engineering task, error and equipment analysis process and summarize a strategy for training operators and other employees to study their own jobs at this level of detail.

Task/Error Analysis

Task analysis has become a generic term which is applied to the analysis of human performance in a work environment for any number of reasons. Strictly speaking task analysis involves the analytic procedures used to breakdown human work in terms of tasks and subtasks. It is typically the first step of a broader or more detailed analysis that is aimed at some aspect of human performance. In the first section of this chapter, we outlined what is essentially a cognitive analysis process - an analysis that breaks tasks down to the detailed level internal and external behaviors from the perspective of the operator. In the next section, we provided the foundation for a detailed error analysis and discussed human reliability analysis. We also discussed various methods for operator workload analysis. Finally, we discussed ergonomic analysis methods. We use the term task analysis here to represent a broader and more detailed system analysis process that includes aspects of cognitive analysis, error analysis, workload analysis, and ergonomic analysis. The objective of this detailed analysis is similar to that of an error analysis or safety analysis. We detailed these objectives earlier in this chapter and repeat them here. By considering the natural or built-in limitations of the human operator as a complex component in a complex system we can analyze the work environment for situations where: (1) if an error occurs, it can lead to unsafe consequences, (2) demands in the task environment may drive the human component too close to safe operating limitations, or impose more restrictive limitations on the operator, (3) safe operating procedures are not facilitated and reinforced by the characteristics of the task environment itself, and therefore encourage circumvention, and (4) the interfaces through which the human operator interacts with the work environment and equipment are more likely to increase rather than reduce the occurrence of errors. The typical steps of a task analysis are described below. As indicated, the task is broken

into its lowest level of steps, where each step can be expressed in behavioral terms. Figure 6.19 describes one behavior taxonomy that is a useful aid in performing a detailed task analysis. In addition, Figure 6.20 provides a list of questions that are also useful in referring to when conducting a task analysis at this level.

Task Analysis Steps

The detailed task analysis process consists of the following steps:

1. Determine the objective of the task to be analyzed.
2. Determine task requirements. Include:
 - (a) criterion for successful performance
 - (b) physical requirements
 - (c) knowledge and skill requirements
 - (d) performance time restrictions
3. Breakdown the task into its lowest level steps (see Figure 7.26).
4. Develop a detailed, sequential description of each task step.
Include:
 - (a) all equipment the operator will interact with
 - (b) all operator behaviors required (external & internal)
 - (c) all information required to perform the step correctly
 - (d) feedback - indicators of correct or incorrect action
5. Determine task time line.
6. Determine factors that may limit performance
(e.g., protective clothing etc.)
7. Determine safety considerations
8. Consider equipment layout for task requirements.
9. Estimate workload
10. Determine potential sources for error
11. Consider any unusual conditions that might occur, especially interruption of machine function, distractions, changes of state of the system, etc. Work through the task analysis for each of these to determine if any of the factors change significantly.

Additionally, more detailed checklists are provided in Appendix D. Additionally, design guidelines for incorporating human engineering principles into the design of systems are available (e.g., DOE 6430.1A, EPRI NP-3659, MIL-STD-1472C, Van Cott and Kinkade, 1972, as well as numerous reports by the U.S. Nuclear Regulatory Commission).

Behavior Classification for Task Analysis		
Processes	Activities	Specific Behaviors
Perceptual processes	Searching for and receiving information	<ul style="list-style-type: none"> Detect Inspect Observe Read Receive Scan
	Identifying objects, actions, and events	<ul style="list-style-type: none"> Survey Discriminate Identify Locate
Mediational processes	Information processing	<ul style="list-style-type: none"> Categorize Calculate Encode Compute Interpolate Itemize Tabulate Translate
	Problem solving and decision making	<ul style="list-style-type: none"> Analyze Calculate Choose Compare Compute Estimate Predict Plan
Communication processes		<ul style="list-style-type: none"> Advise Answer Communicate Direct Indicate Inform Instruct Request Transmit
Motor processes	Simple, discrete tasks	<ul style="list-style-type: none"> Activate Close Connect Disconnect Join Move Press Set Raise Lower
	Complex, continuous tasks	<ul style="list-style-type: none"> Hold Adjust Align Regulate Synchronize Track Transport

Figure 6.19
(Adapted from Berliner, et al., 1964)

Questions to Ask in Performing a Task Analysis

1. Functions/Tasks
 - A. Are functions/tasks to be performed within operator capability?
Consider requirements in the following functions:
 1. Sensory/perceptual,
 2. Motor,
 3. Decision making, and
 4. Communication.
 - B. Do task characteristics impose excessive demands?
 1. task duration (possible fatigue effects?)
 2. frequency of task performance (possible fatigue effects?)
 3. information feedback (insufficient operator guidance?)
 4. accuracy (too demanding?)
 5. error probability (too high?)
 6. error criticality (effect on task performance?)
 7. multitask requirements (effect of one task on another?)
2. Environment
 - A. Events requiring operator response
 1. speed of occurrence (too fast?)
 2. number (too many?)
 3. persistence (too short lived?)
 4. movement (excessive?)
 5. intensity (too weak to perceive?)
 6. patterning (unpredictable?)
 - B. Physical Effects
 1. temperature, humidity, noise, vibration (excessive?)
 2. lighting (substandard?)
 3. safety (potential problems?)
 - C. Mission conditions
 1. potential emergencies (can operator recognize and overcome rapidly?)
 2. Event criticality (effect on error probability?)
 3. Equipment
 - A. Display information requirements
 1. too much to assimilate?
 2. difficult to perceive/discriminate/track?
 3. require excessively fast operator response?
 4. too much memory required?
 - B. Control requirements
 1. excessively fine manipulations required?
 2. too much force required?
 3. must be responded to rapidly?
 4. too many to perform in sequence?

Figure 6.20
(Adapted from Meister, 1971)

STRATEGIES FOR ORGANIZATIONAL IMPROVEMENT

To best address the human factors concerns in the workplace, employees should become involved in searching for and correcting situations in the workplace that may promote human error. This can be accomplished by forming and training cross function teams to review the worksite and job requirements for areas warranting human factors improvements. The teams must then be empowered to make any modifications where feasible. For example, the team may assess the adequacy of a variety of data forms and documents, revise them accordingly, and submit for approval. They can ensure that a logical approach to repetitive tasks, such as surveillance tours and roundsheet tour inspections, is taken. Other suggestions include ensuring the labeling program is being implemented, shift turnover is conducted properly, and logsheets are completed as required. A casualty drill program can help increase the likelihood that individuals are able to perform as required under adverse conditions.

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Chapter 7: Recommendations and Conclusions

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OBSERVATIONS AND RECOMMENDATIONS

Through our interaction with workshop participants (both in the workshops related to this project as well as the Total Safety Culture workshops), we have gained some insight as to the prevalence of each of the six system-level factors considered during this project. Again, it must be noted that these observations and resulting recommendations have been detailed throughout this report, but some will be briefly summarized here as well.

Without question, the overwhelming majority of employees at Hanford appear to be experiencing a strong feeling of learned helplessness with respect to their jobs. The feeling is certainly prevalent at the operator level, but is also found at mid and probably upper level management as well. To illustrate, employees have coined the term "Hanfordize" to mean the acquisition of this attitude by new, eager employees. As described previously, the political climate and change in mission of the organization certainly contribute, as do the restrictions on and lengthy process associated with making improvements in such a large and controlled environment. These influences cannot be changed easily, or in some cases, at all. However, there are many strategies that individuals, especially those in supervisory roles, can use to help overcome the organizational-level limitations. Many of these were discussed throughout this report. There does, however, need to be an organizational level commitment to instructing and rewarding supervisors for their effort in these areas. In addition, organizational level improvements in each of the other five factors should offer encouragement to employees that change is possible, and that management is committed to improving the safety of their work environment, rather than their current perception that management lays the blame for any mishap at the employee level.

A problem of this magnitude will take significant time and effort to resolve. Not only must we "eat the elephant one bite at a time," but we must be sure to take visible bites and publicize every small success. Managers at all levels must make a conscious effort to do these things, otherwise, like so many other good ideas, they will fall through the cracks as we go about our primary tasks of the day. After all, most of the strategies for combatting learned helplessness in the workplace make common sense; they are the things that a good supervisor or manager should be doing anyway. But unless the organization visibly values these efforts, what appears to be the "little things" often get lost in the shuffle.

With respect to the perceived reward systems, there is clearly an impression on the part of many that the organization as a whole emphasizes meeting production schedules and cost estimates over safety when such choices must be made. The employees refer to 'convenient compliance' as management's approach to safety; safety is a priority when it's convenient. There is also the perception that management believes the workers use safety as an excuse to avoid work. Despite the organization's voiced commitment to safety, there appears to be strong social and vicarious reinforcement of unsafe work practices. One workshop participant shared the experience with us of seeing a questionable job handed-off four times before the supervisor found someone who was willing to take the risk without questioning the safety of the job. That employee was rewarded for his willingness to accept the 'tough assignments.' Other employees have raised the issue that they are uncertain exactly what their supervisor's expectations of them are, and thus they're not certain what they should be doing in order to be rewarded.

Again, to alleviate a problem of this magnitude will require significant effort. However, effort must be expended not only on removing the rewards for compromising safety, but also on making expectations clear and emphasizing rewards for safe behaviors. Westinghouse and Kaiser have both made important strides in this regard by committing to the Total Safety Culture approach in which employees themselves design reinforcement strategies for performing safe behaviors. To be successful, visible commitment on the part of all levels of management must be made. Supervisors must not only support the formal processes that are put in place, but they must take the lead in implementing the informal processes of rewarding peers and co-workers for performing work safely. It is all too common for safety to be recognized only when it is negative (i.e., an accident or injury). Positive, safe behaviors must be recognized and rewarded.

Many employees appear to be rather dissatisfied with the training they receive at Hanford. Some complain that they cannot get the additional training they need to do their jobs well, others complain that they are routinely required to attend training that is irrelevant to their jobs or that is poorly conducted. Most agree that the level of follow-up to most training is inadequate. Supplemental training is often needed but not offered, and most importantly, there is no support for implementing new knowledge and skills gained from training when the employee returns to the worksite. There is rarely any structured implementation plan, and there is little or no 'reward' (e.g., supervisor approval) offered for applying their new knowledge. Inadequate formal attention is paid to on-the-job training; insufficient time is allocated, trainers are sometimes unprepared, etc. So despite the effort of the trainers and trainees, the value of the training program is limited. Again, this information is based strictly on employee perceptions, not an objective assessment of the training system at Hanford, however, as has been said time and again throughout this report, worker's perceptions influence their behaviors as much as, if not more than, the actual state of affairs.

Opinions as to the employees' accuracy in assessing risks are strongly mixed. Many feel that employees do not understand the risk involved in their jobs or have been desensitized to appreciate the level of risk involved. Others feel that most employees have a realistic appreciation for the risk involved and make every attempt to act accordingly, but other system-level factors often influence their behaviors. Regardless, continual attention to effective risk communication is probably warranted in an environment such as Hanford's. The literature contains countless recommendations for improving risk communication, in both formal and informal modes. Supervisors need to be able to recognize individuals who are likely to be more prone to take unnecessary risks and be equipped with strategies (other than punishment) to curb those tendencies.

Finally, Hanford's environment is naturally a hazardous one. However, many of the hazards are not found solely in the aging facilities and hazardous materials. The complex tasks involved place heavy demands on the operators, and the physical equipment, much of which was designed before the realization of the importance of human-machine interface design, often conflicts with the limitations of human beings. With only a brief introduction to these topics, workshop participants were able to quickly and easily begin identifying areas where human error is likely and improvements could be made. Although Westinghouse apparently has a set of guidelines concerning human factors design of work environments, there has evidently not been a concerted effort to apply those at Hanford to date. In addition, it does not appear that the potential human factors contributions to accidents and near-misses are investigated systematically, which is unfortunate because lessons learned in this regard could have a positive impact on improving safety within the workplace.

As discussed in Chapter 6, a detailed assessment of the task demands and equipment/environment could offer two benefits. First, many of the poorly designed features of the work environment could be easily identified and corrected. But secondly, and perhaps equally important, such an analysis has been shown to be an excellent tool for involving the operator in assessing his/her job and environment and initiating a 'problem-solving' mentality where the operator thinks beyond the merely following the steps s/he has been told to follow. However, such an approach can only be effective if sufficient time and resources are committed, and suggestions for change are genuinely considered.

CONCLUSIONS

Unsafe behaviors undoubtedly play as prominent a role in accident causation at Hanford as they do in other organizations. Although it is often easier to deal with tangible problems than human behavior with all of its inherent unpredictability, significant improvements in safety cannot be realized without considering the human element. But, it must also be remembered that human behavior does not occur in a vacuum. Human behavior is heavily influenced by the physical and social forces resulting from the system within which people work. As a result, efforts directed specifically at modifying behaviors can only be marginally successful if system-level factors are acting against such change. There appears to be numerous areas in which management can direct attention and consequently realize measurable improvements in employee compliance with safe work practices. Many sample strategies have been briefly discussed in this report, but careful thought must be given in each situation to determine the most effective and efficient approach.

However, a word of caution regarding expected results from such efforts is necessary. Change with respect to these issues will require a coordinated effort by all, but may require a significant paradigm shift for many. Upon hearing the message depicted herein, most could not help but agree that underlying system factors do heavily influence employee behavior, and that an organization must address these factors if genuine change in safety is to be realized. But, like so many other 'management philosophies', actually changing the way individuals think, and hence their everyday approach to improving safety, is far from easy. Society as a whole tends to focus on attributing blame when individuals' behaviors contribute to an accident; it is inherent in our culture in general, and even more strongly inherent in many subcultures where individuals are held completely accountable for their behavior virtually regardless of the influences that contribute to that behavior. So despite their agreement with the concepts, when an accident or near-miss actually occurs, individuals often have difficulty acknowledging that any unsafe behaviors were a result of more than the performance of "stupid, lazy people"—a message we have heard frequently from supervisor-level employees. When we consider the behavior of others, we often find it difficult to acknowledge the importance of external influences; we either fail to acknowledge their existence or assume the individual should have been immune to the influences. Thus, when addressing the root causes of human behavior, many managers have difficulty accepting the fact that concerted effort should be expended to address the system-level factors, rather than merely threatening and disciplining the individuals involved. However, if system-level factors are negatively influencing behavior, disciplinary actions toward a given individual may fix the symptom, but certainly not cure the problem.

Finally, the issues raised in this report are extremely complex in general, and those complexities are magnified at Hanford given its size, history, and controlled environment. Many of the prevailing conditions negatively influencing people's attitudes have been in existence for years. For many,

substantial change will be required to significantly influence their attitudes and behaviors. Patience and persistence will be required by everyone, and must be modeled in exemplary fashion by those in supervisory positions if the same is to be expected from others.

Summary

In summary, why do people perform unsafe behaviors? They do so in many cases because there are system-level factors influencing their behavior. Reward systems are not perceived by employees to recognize people for performing a job in a safe manner. Over a length of time, people develop a feeling of learned helplessness, which significantly hinders efforts to empower individuals and have them accept and welcome individual responsibility. People's perceptions of risk are often biased. When people do not acknowledge the hazard associated with a job, they are less likely to take precautionary measures. Training is too often viewed as a means to meet qualification requirements rather than as a means to give employees new knowledge and skills that can be transferred to the work environment. And finally, many work environments have failed to adequately incorporate human factors considerations into the design of equipment, environments, and task designs.

Organizations can address these issues by examining the formal and informal reward systems in place. They need to work on empowering people to take control of their work and develop a sense of "learned optimism." Continual reinforcement of appropriate assessments of risk is needed, stressing a conservative approach where safety is concerned. Management must support and reinforce training by setting clear expectations that transferring training to the workplace is not only expected, but will be rewarded. And finally, management must encourage employees to examine their jobs with a "problem-solving mentality" to determine in advance the probable sources of error.

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APPENDIX E

EXPERIENCE LEVEL MATRIX

APPENDIX E
FUNCTION EXPERIENCE MATRIX

Function	Experience
Project Management	Project Manager had 20 years experience in electrical engineering and 7 years experience with Utilities Projects.
Construction Management	Construction Manager had 14 years experience in construction including civil, mechanical, and electrical.
Acceptance Inspection	<p>Level II civil inspector from 1980 to present at various locations.</p> <p>Level II electrical inspector from 1989 to 1992, Idaho Falls, Idaho, ICF KH.</p> <p>Level II electrical inspector from 1992 to present at Hanford Site, ICF KH</p> <p>Level II liquid penetrant inspector from 1989 to present, Idaho Falls, Idaho, and Hanford Site.</p>
Power City Electric	Linemen had 20 and 30 years experience respectively. Both served in an apprenticeship program and were union journeyman linemen.
Black and Veatch	Personnel from Black and Veatch had experience of at least 21 years in electrical power system design.
Electric Utilities	<p>Personnel experience ranged from 6 to 34 years.</p> <p>Lineman Supervisor - 11 years, prior journeyman</p> <p>Substation Electrician - 34 years, prior journeyman; instructor; 5 years college</p> <p>Lineman - 10 years, journeyman</p> <p>Lineman - 9 years, journeyman; state licensed</p> <p>Working Foreman - 28 years</p> <p>Dispatcher - 6 years, 3 months</p> <p>Substation Operator, 7 years 10 months</p>

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APPENDIX F
VAULT ENTRY PLAN

**APPENDIX F
VAULT ENTRY PLAN**

I. PRE-STAGED EQUIPMENT CHECKLIST

- Tent for covered work area
- Tables for layout of recovered pieces
- Heat sufficient for 4-6 hours work
- Light sufficient for work and videotaping
- 120 VAC convenience outlets
- Tags suitable for labeling pieces in vault
 - tags with wire ties
 - masking tape
 - permanent marker
- Cable cutters for taking conductor samples (cable cutter, bolt cutter, porta band saw)
- Sample containers; rust resistant steel ~1/2 liter, 8 oz. or pint or glass
- Coveralls
- Ladder, not required if access can be done using existing steps and handholds
- Come-along for movement of pieces in vault
- Plastic wrapping or sleeving for preserving cable and conductor samples
- 2 face masks for in vault work; for particulate; paper or HEPA
- Stereo-microscope
- Vacuum cleaner with hose long enough to reach the vault floor from outside tent
- Gloves
- Eye Protection
- Hard Hat

II. PRE-REQUISITES FOR ENTRY TO VAULT

- Vault investigators shall be escorted while in the 351A Substation and yard
- Pre-stage equipment checklist reviewed for acceptability
- Investigation board approval obtained
- Photographer standing by, including normal still photography and macro lens
- Videotaping capability ready
- Entry requirements for confined space satisfied, if any
- Job Safety Analysis reviewed
- Grounds established on disconnected lines involved in the vault and isolation reviewed to satisfaction of investigators

III. GENERAL INSTRUCTIONS FOR VAULT ENTRY AND MATERIAL RETRIEVAL

1. Vault entries will only be made by experienced investigator.
2. To the extent possible, all pieces shall be labeled in a manner which preserves knowledge of their relationship to other pieces.

GENERAL INSTRUCTION cont.

3. A log will be kept of all labels applied with a description of the piece to which it was applied.
4. The phase and line number of all cables, conductors, and splice pieces shall be clearly marked on the cable/conductor in large enough lettering to be readable in photographs.
5. Videotaping will be performed at the direction of the accident investigators or by the vault investigation leads, R. M. Boger or G. P. McDonald.

As a minimum, videotaping will be done when labeling any pieces or when moving any pieces.

6. Still pictures will be taken at anytime per the direction of the investigators or leads.
7. When directed by the vault investigator leads, cables may be pulled back out of the conduits. Samples of the cable/conductors shall be labeled when cut to indicate the line, phase and sequence of the sample.

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APPENDIX G

ELECTRICAL DATA AND FAULT/FIRE SCENARIO

APPENDIX G
ELECTRICAL DATA AND FAULT/FIRE SCENARIO

The configuration of the electrical distribution system after final cable testing is shown in Diagram G-1. Since Circuits C3L2, C3L3 and C3L5 were de-energized, the majority of the loads normally supplied by the rear bus were being supplied by Circuit C3L4. This circuit was back-fed into Switch C3X21 via Switching Station C3-3 and Substation 351 in order to provide an energized source to perform phasing checks. At 2033:22 hours, switching orders were issued (see Diagram G-2) to close Breaker C3X2, and phase across aerial Switch C3X21. Phase checks were performed by the OC's lineman, and included phase-to-phase checks across all three phases of Switch C3X21, as well as phase-to-ground checks on all phases on each side of C3X21 (nine-point phase check). All indications based on phase readings were normal.

Based on normal phase readings, switching orders proceeded at 2118:08 hours to energize and apply load to Circuit C3L2 (see Diagram G-3). When Breaker C3X2 was closed, SCADA had indicated that the load current on C3L2 was 3 amperes. The dispatcher had anticipated a higher value of current based on prior historical readings on Circuit C3L4 since the load was now shared by C3L2 and C3L4. Since SCADA indicates A Phase current only, the dispatcher ordered the operator to go to the panel meter on C3L2 and report all three phase readings based on the analog meter installed on the switchgear cubicle.

The following readings were reported back to the dispatcher:

C3X2

A Phase - 0 Amperes
B Phase - 40 Amperes
C Phase - 40 Amperes

The panel ammeters used to indicate amperes are analog meters, using a scale from 0-600 Amperes (see Diagram G-4). In the low end of the scale, meter graduations are in 20 Ampere increments. Since the current readings were so low, there was concern about the accuracy of the readings both from the SCADA and from the panel meters.

In an effort to troubleshoot the system and determine a possible cause for the current imbalance, the dispatcher proceeded with switching, and at 2121:19 hours closed Breaker C3X3 and at 2121:49 hours closed C3X5 (see Diagrams G-5 and G-6). The following readings were reported by SCADA after this switching:

C3X2 - A Phase - 18 Amperes
C3X3 - A Phase - 80 Amperes
C3X5 - A Phase - 1 Ampere

Load current (3 Amperes on A Phase) was first applied to C3X2 at 2118:06 hours. At that time, the initial heating and arcing due to the faulty connection began within the splice module. The poor electrical connection between the energized connecting lug on the cable and the bushing inserts created heating due partially to high current densities across limited contact area, and was compounded by extremely high temperatures involved in the electric arc across the air gap between the connecting lug and the bushing stud. Since Circuit C3L4 was loaded, and C3L2 was unable to pass current

TEMPORARY MECHANICAL JUMPERS

DATE: 12/04/94

TIME: 2052

CONFIGURATION TO CHECK PHASING
ACROSS C3X21 ON LINE C3L2.

- Energized
- De-energized
- Circuit Breaker
- ⎓ Aerial Switch
- * Fault on Circuit

DIAGRAM - G-2

TIME: 2118:08

¹L2 PHASE

A = 0 AMPS
B = 40 AMPS
C = 40 AMPS

L4

A = 125 AMPS *

* CALCULATED

13.8KV FRONT BUS

OL351003

DIAGRAM G-3

DIAGRAM G-4

C3X2 AMPERE METER

DATE: 12/ 14

TIME: 2121:19

LOAD SHIFT AFTER C3X3 CLOSED.

I L2 PHASE

A = 0 AMPS * Some Deflection Noted
B = 10 AMPS *
C = 10 AMPS *

I L4

A = 30 AMPS *
B = 30 AMPS *
C = 30 AMPS *

I L3

A = 58 AMPS *
B = 58 AMPS *
C = 58 AMPS *

DIAGRAM G-5

* CALCULATED

NOTE: NO LOAD ON C3L5 LINE DUE TO THE LINE IS A STANDBY LINE.

A = 0 AMPS *

B = 10 AMPS *

C = 10 AMPS *

A = 30 AMPS *

B = 30 AMPS *

C = 30 AMPS *

A = 58 AMPS *

B = 58 AMPS *

C = 58 AMPS *

A = 0 AMPS *

B = 0 AMPS *

C = 0 AMPS *

TEMPORARY MECHANICAL JUMPERS

DIAGRAM G-6

OL351005

' ALICULATE

through the connection, a resulting arc voltage of several hundred volts was present across the air gap within the connector. This voltage was sufficient to start and sustain an arc, which continued until the splice module failed. Additionally, the actual current passing through the faulty connection increased with time, and reached 34 Amperes at 2119 hours.

Accident Reconstruction Analysis (see Appendix E) reviewed the materials associated with the T-splice, including the cable insulation and other dielectric materials. It is calculated that the amount of energy needed to fail these materials is 2700-3000kW-seconds. It is also assumed that the relationship between current and time (based on arc voltage) is basically linear.

At approximately 2132:07 hours, the heat (and probable fire) in the splice caused the insulating materials to fail. When this occurred, the energized conductor associated with A Phase on Circuit C3L2 broke away from the insulating materials and contacted ground. Shortly thereafter, heat and fire engulfed the vault, and conductors associated with Circuits C3L3 and C3L5 also failed and contacted ground.

Station transformers at B3S4 are connected in a delta-wye configuration, with a solid connection to ground from the neutral of the transformer secondary. Based on a model of the power system in its configuration during the fault, the total single-line-to-ground fault was calculated at approximately 13,387 Amperes. Approximately 12,935 Amperes was being supplied through C3L2, and 469 Amperes was being supplied by C3L4. The overcurrent relays for Breakers C3X300F/R and C3X2 saw a ground fault of 12,935 Amperes and the relays for C3X100F/R saw a ground fault of 6667 Amperes (see Diagram G-7).

When all three feeders (C3L2, C3L3 and C3L5) faulted to ground, the total ground fault current was approximately 13,571 Amperes. Each of the three feeders shared the total fault current as shown in Diagram G-8.

At 2132:10, five circuit breakers (C3X2, C3X3, C3X5, C3X300F and C3X300R) tripped by relay operation (see Diagram G-9). Breaker C3X2 tripped due to an operation of the 51N time overcurrent ground relay. Breaker C3X3 tripped due to an operation of the 51N time overcurrent ground relay. Breaker C3X5 tripped due to an operation of the 50 A Phase instantaneous and 50N ground instantaneous relays. Incoming Breakers C3X300F and C3X300R tripped due to an operation of the 51N time overcurrent ground relay.

Based on relay settings, the coordination time between the ground relay settings on C3X2 and incoming Lines C3X300F/R for the initial single-line-to-ground fault of 12,935 Amperes is .120 seconds. For the multiple circuit faults, the coordination time between ground relay settings on breakers C3X2, C3X3, C3X5 and incoming line C3L300 is also .120 seconds. For both fault conditions, coordination was achieved.

If the fault initiated on Circuit C3X2, and quickly involved the other adjacent circuits as believed, the coordination time between incoming breakers and feeder breakers would be effectively reduced. During the initial fault, the overcurrent relay disks for C3X300F/R began to operate at the same time as those on Circuit C3X2. When relays on C3X2 timed out and tripped Circuit

TIME: 2132:07

Energized
De-energized
Circuit Breaker
Aerial Switch
Fault on Circuit

* CALCULATED

DATE: 12/04/94

TIME: 2132:09 *

FAULT OCCURS AT SPLICE CONNECTIONS
ON C3L2, C3L3 AND C3L5.

* CALCULATED

TIME: 2132:10

RELAY OPERATION TRIPS C3X300F, C3X300R, C3X2, C3X3 AND C3X5. FAULT CONTINUES TO BE FED FROM C3L4 THROUGH C3X138 AND C3X91F.

• CALCULATED

OL351008

Breaker C3X2, relays on C3X300 began to reset. However, when the second fault sequence started, if relays for C3X300F/R had not had time to reset, overall coordination time was reduced.

After Breakers C3X2, C3X3, C3X5 and C3X300 front and rear tripped, the fault contribution from the front bus at B3S4 was removed. However, since Circuit C3L4 was still connected to the rear bus, the fault had not been isolated. At this point, the maximum three-phase-fault contribution via the rear bus on Circuit C3L4 was approximately 5169 Amperes. This value is for a solidly bolted fault. At 2132:34 hours, Circuit Breaker C3X91 front tripped due to an operation of 51 C Phase time overcurrent relay, and Circuit Breaker C3X92 front tripped due to an operation of the 51 C Phase time overcurrent relay (see Diagram G-10). Since the relay settings indicate a fault of this magnitude should be cleared in .39 seconds and it actually took 24 seconds, it is believed the actual fault current was much less due to a high fault impedance, typically seen in arcing type faults. It was at this time that the protective relays had completely isolated the faults. Based on this analysis, the relays worked as designed.

At 23:11, the fault was isolated and area distribution power was restored (see Diagram G-11).

FAULT CLEARED BY RELAY OPERATION OF
C3X91F AND C3X92F.

* CALCULATED

TIME: 23:11

FAULT ISOLATED AND AREA DISTRIBUTION
POWER WAS RESTORED.

WHC-MR-0487

APPENDIX H
CONSULTANT REPORTS

**Clapp Research
Associates, P.C.**
Consulting Engineers

3540 McNeely Drive, Suite 201
Raleigh, NC 27612
(919) 782-7745 tel
(919) 881-2147 fax

December 22, 1994

P.O. Box 30189
Raleigh, NC 27622-0189

Mr. R. Michael Boger
Manager
Electrical Power Systems Engineering
Engineering Services
Westinghouse Hanford Company
P.O. Box 1970, L4-90
Richland, Washington 99352

Re: Report on Utility Vault Fire

Dear Mr. Boger:

Attached is my preliminary report. I am faxing a copy to your attention and will forward a regular copy by mail. Please call if you have any questions or want to discuss the report.

Although I have not yet received the photographs, videos, or additional information that I discussed with Greg, I wanted to go ahead and get this report to you. The receipt of the above information should not change my overall findings and recommendations.

Sincerely,

John Dagenhart, P.E.

Enclosure

RECEIVED

DEC 22 1994

R. M. BOGER

REPORT ON UTILITY VAULT FIRE
HANFORD FACILITY
AREA 300 DISTRIBUTION FACILITY
DECEMBER 4, 1994
PURCHASE ORDER MGK-SVV-409386

Johnny B. Dagenhart

Johnny B. Dagenhart
December 22, 1994
Clapp Research Associates, P.C.
5540 McNeely Dr., Suite 201
Raleigh, N.C. 27612

Requested by:
Westinghouse Hanford Company
P.O. Box 1970
Richland, Washington 99352

Executive Summary

This report examines the cause of a fire in an electric utility vault in the 300 Area of the Hanford Facility occurring on December 9, 1994. The cause of the fire was a fault condition originating at new splices installed on circuit C3X2, extending a new underground circuit to supply an overhead line.

The fault occurred because of an improperly assembled splice. This report recommends that the type splices used for this project be avoided if alternate designs permit. If the same type splices are to continue to be used for such installations, more care should be taken in assembly.

This report also recommends considering the following additional design and operating considerations:

- Adequately sized manholes.
- Avoidance of unfused taps, whether overhead or underground.
- Racking of cables in manhole walls and not lying on each other.
- Fireproofing cables and splices within manholes.
- Using arc blankets on new splices during testing.
- Closer monitoring of loads for abnormal conditions during switching procedures.
- Stopping switching procedures when an abnormal condition is suspected.

Purpose of Report

Our office was contact on December 9, 1994 by representatives of Westinghouse Hanford Company to discover and evaluate evidence at the scene of a utility vault fire at Hanford. The purpose of this investigation is to determine the most likely cause and advise on methods to prevent recurrence of this type of incident. This is a preliminary report and will be revised upon the receipt and review of new information.

Description of Incident

On December 9, 1994, at the 300 Area Substation B3-S4 of the Hanford Facility, a new underground circuit was being installed to supply a nearby overhead circuit. In a vault near the substation, the 15 kV underground 750 kcmil cables for circuit C3X2 were tapped to supply the overhead circuit. 4/0 15 kV cables were tapped to the existing 750 kcmil cables utilizing Cooper 600 A, nonloadbreak, insulated connector modules, sometimes called "hammerhead splices." The 4/0 cables exited the vault and ran a short distance to a padmounted switching cabinet. The 4/0 cables were terminated with 600 A nonloadbreak elbows in the switching cabinet. Cables leaving the switching cabinet were terminated with 200 A loadbreak elbows in the switching cabinet and were terminated on a nearby pole for the overhead circuit. **See Diagram A** for a schematic.

A crew from Power Engineers apparently cut the 750 cables, made up the lugs for the 4/0 and 750 cables and inserted the lugs into the splicing modules. **See Diagram B** for how the cables were left by Power Engineers. A crew from Kaiser Engineering tested the individual sections of the splicing modules with a hi-pot test and assembled the modules. They then energized the modules for phasing testing by closing overhead circuit switch C3X21. Once the phasing was determined to be correct they proceeded with switching procedures to return the circuits in the 300 Area to normal operation.

When the overhead switch C3X21 was closed, no load had yet been placed on the splices. When the circuit breaker for circuit C3X2 was closed, some load current began to flow through the new splices. Breaker C3X2 was closed at 21:18.08 hours. Although no load current was seen to be flowing on phase A but was seen on phases B and C, the switching procedure was

continued. During the switching procedure the crew removing jumpers to the circuit supplying FFTF heard a loud noise sometime around 21:27 or 21:30 hours. The fault was over at 21:32.54 hours. Therefore, the new splices were carrying load for only about 9-12 minutes. The actual fire within the vault probably lasted only a few minutes.

Examination of Damaged Components in the Manhole

The examination of the contents of the manhole took place on Monday, December 12, 1994. All splicing modules, cables connected to the splicing modules, compression connectors and other recoverable items in the vault were photographed in place, documented, labeled, and removed from the vault. In some cases, the parts were again photographed. A videotape of the examination and removal of the parts was also made. Unique markings and melting patterns on the compression connectors, eye-type lugs, and conductors were noted in order to reconstruct the orientation of the cables within the vault.

The insulating materials of the splicing modules for the newly tapped circuit were heat damaged to the extent that they fell apart on handling except for the internal metal parts. All compression connectors for the 4/0 conductors had melted off the 4/0 conductors with only the eye-type connectors remaining attached to the splicing modules. Only two out of three eye-type connector lugs for the 4/0 cables remained connected to the splicing module determined to be for phase A of circuit C3X2. The third eye-type connector was found on the floor of the vault.

All but one of the 750 cables that had been attached to the splicing modules had separated from the splicing module. Some of the connectors for the 750 kcmil conductors were destroyed in the fire with only one remaining intact and attached to the splice modules. One 750 kcmil conductor on phase C was damaged on its end, with small pieces of copper stranding separated from the main conductor body.

For the portion of the other circuit cables in the vault, the insulation for conductors for circuits C3X5 and C3X3 were almost completely burned away in the vault fire. It is not clear whether any fireproofing was applied to the splicing modules or cables after the splices were completed. No evidence of such material could be found in the vault.

Examination of Phase A Splicing Module and Compression Connectors

Upon examining the splicing module for phase A, along with the eye-type connector that did not remain intact with the splicing module, it was concluded that the compression connector had never been properly connected within the splicing module. Apparently, the eye end of the compression lug was clamped between the two inserts on the module, without the threaded portions of the two inserts actually passing through the eye of the connector. This resulted in only a small area of metal to metal contact to exist within the module. **See Diagram C** for an illustration of how this connection probably existed within the splicing module prior to failure.

The improper connection within the module would have allowed the phasing test (which did not show anything wrong) to indicate correct phasing without indicating an improperly made connection. The connection overheated when load current passed through the splicing and failed minutes after being subjected to load current.

Conclusion

The fire within the vault near substation B3-S4 was caused by an improperly assembled splicing module. The small metal-to-metal contact within the splicing module allowed the phasing test conducted on the splice after assembly to indicate a normal condition. However, the connection could not sustain load current and failed shortly after being subjected to load current during switching procedures to place the circuits back in normal operation.

It is fortunate that no one was in close proximity to the manhole when the fault occurred. It is not clear whether this is a standard procedure or if it was just good luck.

The splicing module threaded portions intended to pass through the eye of the connector can be tightened so that it appears the connection has been properly made. No exterior reference marks on the module or other obvious indications show that the splice is improperly assembled. Even if the two inserts are completely tightened without any portion of the lug in between, the two pieces become tight only a small distance (about .12 inches) beyond the point at which they would be if the lug was properly placed between the two parts. **See Diagram C.**

The vault in which the splices were assembled was not very large, making it difficult to work; 750 kcmil cable is extremely difficult to bend and shape in a small area. This may have made it difficult to align and assemble the modules; the improperly connected cable may have shifted during this procedure.

A different design of the installation could have made the use of "hammerhead" splicing modules unnecessary. New 750 cables could have been attached to the existing cables with in-line splices in the vault, extending the 750 cables to the switching cabinet. Then the 4/0 cable could be fused appropriately at the switching cabinet location. **See Diagram D.** (It is not clear as to whether the existing switching cabinet can utilize fuses.) The in-line splices would have been much easier to install and there would have been less likelihood of such a connection error as happened with the "hammerhead" modules.

Recommendations

Obviously, more care should be taken when assembling these types of splicing modules. No amount of redesign of the splicing module can replace taking appropriate care in the module assembly. An easy check would be to insert the connecting plug with the male threaded end first, making sure this is passing through the eye-type lug before inserting the other side. One crew member should cross-check the other before final assembly is made.

A review may be necessary on whether or not the use of two separate crews to complete this job was a factor in the incorrect module assembly.

It is also recommended that, in the future, more consideration be given to the design, to determine whether the design is logical, does not impose installation problems, maintains high reliability, and maintains the full capacity of the system. Such design considerations should include:

- Adequately sized manholes.
- Avoidance of unfused taps, whether overhead or underground.
- Avoidance of "hammerhead" splicing modules, if an alternate design is practical.
- Racking of cables in manhole walls and not lying on each other.

- Fireproofing cables and splices within manholes.

A determination should be made as to whether someone familiar with the normal conditions and expected loads could have detected an abnormal condition during the switching procedure. During switching procedures, if something does not appear normal, stop the switching procedure until the problem is resolved.

Also, unless it is a standard procedure to have all personnel stand well clear of manholes when new facilities are energized, this should be done. Also, give consideration to temporarily wrapping new splices with a special blanket designed to contain arcs when energizing and testing new splices. The blanket is removed after it has been determined the splice will hold. In this way, the blanket contains the arc and limits the damage to other cables within the vault.

[illegible]

TU 400 AREA (FFTF)

Diagram B

Diagram C

Diagram D

Accident Reconstruction Analysis, Inc.

SPLICE VAULT FIRE EXAMINATION AND RECONSTRUCTION

to

WESTINGHOUSE
HANFORD COMPANY
Post Office Box 1970
Richland, Washington 99352
Attention: Mr. Chuck Manasmith

Purchase Order MGK-SVV-409387

from

ACCIDENT RECONSTRUCTION ANALYSIS, INC.
5801 Lease Lane
Raleigh, North Carolina 27613

Prepared by: Richard T. Edwards, B.S.Mat.E., P.E.

December 21, 1994

The following report details the results of a splice vault electrical fire which occurred at 9:32 p.m. on December 4, 1994 in vault R122V in the 8354 substation yard. The fire burned for about two hours before extinguishment was verified. No personnel injuries were incurred. The switch and electrical actions were well documented by utility system recorders. The purpose of the examination was to determine the direct cause of the electrical system failure and the physical contributing factors, if feasible.

Prior to detailed examination of the splice vault, a temporary shelter was set up with lighting and heat available. The metal covers to the vault had been damaged by the explosion during the fire. The door latch and prop mechanisms were tied off in a safe position to prevent inadvertent closure. The vault's contents were scrupulously documented by still photograph and video camera prior to excavation.

Excavation of the vault contents was performed from the top layer downward. Intact metallic debris was removed and labeled if identifiable in nature. The splice bar assemblies were numbered 1, 2, and 3 in the order in which they were removed. Afterwards, pattern matching of the copper lugs and their associated aluminum crimp connectors allowed matching of conductors to their respective splices. During the course of the examination it was determined that phases A, B, and C corresponded to splices 1, 2, and 3. In

addition phases A, B, and C are alternatively referred to as red, yellow, and blue respectively.

Nuggets of fire melted aluminum were retrieved from the vault floor. For purposes of analysis, the nugget positions were assumed to coincide with the horizontal positions of individual crimp connectors since the molten metal would gravity-drip directly downwards to the vault's cement floor.

Prior to removal of parts from the vault, it was noted that splice 1 which eventually corresponded with A phase was missing the center lug from the cable end which came out of the vault's east wall. The vault walls which had cable conduits were the north and east walls.

It was determined that the new 4/0 conductors which were spliced into the line occupied the top lug positions on the splice modules. The north wall cable leads were bolted into the center lug positions and the east wall cable leads were bolted into the bottom lug position. The east wall cable crimp connectors and lugs were, for the most part, intact. The middle positions were occupied by cable leads from the north wall where the crimp connectors were completely melted away by the fires heat.

Splice number one was connected to the following cable leads:

- a) North wall, center bottom opening, west conductor at the center lug position.

- b) East wall, center bottom opening, center cable at the bottom lug position.

Splice number two was connected to the following cable leads:

- a) North wall, center bottom opening, east bottom cable at the center lug position.
- b) East wall, center bottom opening, top south cable at the bottom lug position.

Splice number three was connected to the following cable leads:

- a) North wall, center bottom opening, top cable or conductor at the center lug position.
- b) East wall, center bottom openings, bottom conductor at the bottom lug position.

The center lug connections were matched by phase checking of the cable leads and matching the phases of the known bottom lug cables to the unknown center lug cables.

The A phase, (splice one) center lug cable, once determined, exhibited a deep red oxide coloration of the crimp connector end and burn through of individual outer layer copper strands at approximately 3-7/8 inches from the cable end, a distance correspondent with the crimp connector insertion depth. The red oxide coloration is consistent with an elevated temperature in excess of 1300 degrees Fahrenheit. This oxide formation was not observed in any of the other cable leads.

The C phase (splice three) center lug cable exhibited a two axis compound curvature unlike the other cable ends and a splayed

end giving the appearance of unraveling. At first look, this splayed or unraveled appearance suggests arcing of sufficient intensity to cause explosive disruption of the cable strands by rapid heating of the air. This was not the case. The unraveled end, when taken in conjunction with the uncharacteristic compound bend of its respective cable end, was caused by longitudinal compression in the cable within the confines of the splice vault. When the cable end was freed by the melting of the aluminum crimp connector, the cable end was pressed into the splice module or whatever object was in its way causing the now-unbound end to splay and unravel. Areas of arcing were found on both the A phase and C phase cable ends caused by contacting the mounds of grounded aluminum on the vault floor or from touching other phases. These areas of arcing considered are considered to be strictly secondary and unrelated to the cause of the fire.

Phase to ground checks performed previous to the fire indicated that all phase to ground voltages were normal. At very close distances it has been suggested that capacitive coupling could have produced normal readings with minimal circuit connection. SCADA and current meter readings indicated that approximately 3 amps was crossing the A phase middle lug/splice bar gap before the relay trip was recorded. A first order approximation of the splice lug-gap arc energy absorption found

energy levels across the gap on the order of 36-38 KVA. An estimate of the time required to cause circuit disruption based on specific heats and heats of fusion for the materials involved found that approximately 2-5 minutes would be required to cause a phase or phase of phase to ground fault.

A review of operations from tape transcripts shows some key events in the ten minutes prior to the relay fault at 21:32:10. For instance, switch CX3 was closed at time 21:21:19 shifting load from CX2 cabling (increased impedance in splice gap), a loud noise was heard about 21:22 to 21:23, and jumpers were removed from 21:27 to 21:30 which may have caused minor change in load distribution. Following heating of the A phase splice module the weakened crimp connectors would have softened or melted enough to allow a major fault to occur. Up until this fault occurred, a fire was already in progress within the confines of the splice vault. After the fault occurred and the splice was de-energized, the insulation materials inside the vault had been sufficiently degraded to continue burning and maintain the fires intensity. The tape log of C3X2 panel readings indicates decreasing current readings on the C3X2 circuit. Part of this decrease was caused by closing C3X3 with the expected load shift and the gradual decrease was caused by the increasing impedance on the C3X2 A phase created by a slowly enlarging arc gap. The 4/0 line that comprised the necessity for

the splice was not loaded and did not contribute to the failure.

CONCLUSIONS

The conclusions listed below are based upon the foregoing report and are the opinion of the undersigned.

1. The direct cause of the fire was a failure to properly bolt in a connector lug within the splice module casing on A phase of the C3X2 circuit.
2. Contributing factors to the cause of the fault include a lack of procedural check to physically ensure connection, small splice vault size, a "handoff" of a incompletely assembled splice module from one corporate entity to another and splice module design that does not require positive connection for complete assembly.
3. The ground cable on the 4/0 side of the splice may have been underdesigned for connection to a splice of this size without an interruptive protective device. The confines of the splice vault would have made installment of a protective device difficult and probably impractical. At any rate, the ground lead was melted in two with an appearance indicative of a point arc contact rather than general overload heating based on the visual appearance of the melted ground lead, there is no basis for mandatory use of protective devices. An engineering analysis of the ground lead performance should be performed to determine if a more capable ground is needed.

Respectfully submitted,

ACCIDENT RECONSTRUCTION ANALYSIS, INC.

Handwritten signature of Richard Thomas Edwards in cursive script.

Richard Thomas Edwards, B.S.Mat.E., P.E.

Handwritten signature of Charles R. Manning, III in cursive script.

Charles R. Manning, III, M.S., P.E.

Handwritten signature of Charles R. Manning, Jr. in cursive script.

Charles R. Manning, Jr., Ph.D., P.E.

WHC-MR-0487

APPENDIX I

S. P. CASALI, Ph.D. - RECOMMENDATIONS

Telefacsimile Transmittal Lead Sheet

Fax: (703) 231-3538

standard G3; auto-receive

Sherry Perdue Casali, Ph.D.
Virginia Polytechnic Institute and State University
1900 Kraft Drive
Blacksburg, VA 24060
(703) 231-4460 (D)
(703) 552-8449 (E)
Date: January 18, 1995

MSEC Project Code: 5MK
Number of pages:

To: Herb Debban
(509) 376-7750

Dear Herb,

I was thinking about the information you sent me, especially your conclusion for doing some employee training in the area of human factors and human error. I fully agree that such a training program would go a long way to improve workplace safety (not to mention quality and productivity). In addition, however, you may want to take your recommendation a small step further by suggesting not only training, but also some sort of employee involvement program to implement the training on an ongoing basis. It may not be a real formal program, but essentially what you'd need is some way of getting employees to actually use the information they get in the training. I've attached a few page from an article that describes one approach. They call it an Error Cause Removal (ECR) Program, but essentially all they're doing is using a team structure to implement the human factors/human error training. In some cases, it may lead to implementing design solutions, but more commonly, it will get the employees to identify, on an ongoing basis, "error-likely situations" so that they can compensate by simply "being more careful".

Hope this info is helpful. I'll talk to you again soon!

Sincerely,

Sherry Perdue Casali, Ph.D.

6.2.5 METHODS OF REDUCING THE POTENTIAL FOR ERROR

Two Approaches

Two different, but related, approaches to improving the quality of industrial production exist. The traditional approach emphasizes changing the worker. The work situation approach emphasizes design of the production setting to support the worker. In the latter approach the emphasis is on human engineering the work situation so that the demands it creates are compatible with the capabilities, limitations, and needs of the worker.

The two approaches are not incompatible; the difference between them is a matter of emphasis. Both should be utilized as appropriate, but emphasis is given here to the work situation methodology because selection and training are usually one-shot affairs, and the options they present are either to fire the worker or to retrain him or her. The work situation methodology may be used in setting up the production job and repeatedly thereafter to dispose of error situations if they recur.

The most effective strategy is to prevent the occurrence of error by designing the work situation so that the potential for error is minimized. It is relatively inexpensive to make design changes when planning a system compared to making them in later stages. After the production system is operational, remedial changes are usually restricted to changes in work procedures and methods and to minor changes in fixtures and handling equipment.

It would take far more space than is available in this chapter to describe in detail the method required to anticipate and avoid error during the design of the production process. That method involves a man-machine system analysis in which jobs and tasks are analyzed to discover error-likely situations (ELS), and design changes are then recommended to avoid the errors. The reader is advised to consult Chapter 6.8 of this handbook, which describes man-machine system analysis in general.

Although avoidance of ELS by proper design of the production system is the most desirable strategy, realistically the industrial engineer must expect to be faced most often with the task of reducing excessive error in an already designed production area. The following material describes what Swain¹ terms an "error-cause removal" (ECR) program, which is somewhat idealistic because it depends on management-worker cooperation, which is not easily achieved.

The ECR Program

One of the main characteristics of the ECR program is its emphasis on preventive, rather than merely remedial, action. Therefore the identification and analysis of ELS is at least as important as the identification and analysis of errors that have occurred.

A requirement of an effective ECR program is the direct participation of production workers (inspectors, assemblers, suppliers, handlers, machinists, maintenance personnel, etc.) in the data collection, analysis, and design recommendation aspects of the program. The most effective program will be one that these production personnel see as their own.

The ECR program consists of teams of production workers with appropriate team coordinators, who might be supervisors or workers with special technical and group skills. The role of the coordinator is to keep the group's activities goal directed. The group should consist of no more than 8 or 12 people, and these should be people who work together.

Reports of errors and ELS are made by individual workers at periodic meetings of an ECR team. These reports are discussed, and suggestions are made for preventive or remedial measures. Each team presents its own proposals, through the team coordinator, to management for appropriate evaluation and implementation. Human factors specialists and others are available to assist each team and also to help management evaluate proposed design solutions.

The ECR program should be restricted to identifying work situations that require redesign in order to reduce the potential for error. It should not be contaminated by tacking on other goals, such as increasing production quantity. An attempt to expand the program might well raise workers' suspicions that the program was merely a speedup ploy.

ECR Elements

The elements of the ECR program are:

1. Everyone involved is educated about the value of an ECR program.
2. Workers and team coordinators are trained in the data collection and analysis techniques to be employed.
3. Workers report errors and ELS; they analyze the reports to determine causes of errors and develop proposed design solutions to remove these causes.

4. Specialists and management evaluate the proposed design solutions in terms of worth and cost and implement the best of these or develop alternative solutions.

5. Management recognizes appropriately the efforts of production personnel in each ECR program.

6. Specialists evaluate the effects of redesign changes to the production process, aided by continuing inputs from the ECR program.

This last point is most important. The effects of instituting a remedial program for ELS must be evaluated, and the ECR program itself must be thought of as a continuing one.

The primary function of the ECR team coordinator is to stimulate participation. If the program is perceived by the members of any team as being threatening, coercive, or "another management gimmick," that team will not function well. The program is not another "cost savings" effort, and no monetary worth is assigned to any design solutions suggested and accepted. Management must make it clear that, even if a design solution cannot be accepted because of technical or cost considerations, the identification of a production problem that did or could lead to errors is a valuable input.

Workers should be allowed to set up their own teams. However, participation in the program must be mandatory because, although all workers will not be equally enthusiastic about it, those participating cannot be made to feel that they are performing an additional duty from which others are excused.

ECR Analysis

The data to be collected in the ECR program consist of errors, ELS, and accident-prone situations (APS). The latter are important because most accidents are the result of some work situation that encourages errors leading to accidents.

Most errors in an industrial setting will be related to defects, accidents, and near accidents. Identification of defects presents few problems in production operations where quality standards of the product are clearly defined. Disagreement among members of the ECR team as to whether or not a product is defective indicates a need for more careful definition of tolerance limits.

Errors are important even when no severe consequences have resulted. This is because the error may indicate a deficiency in the work process that could lead to a much more serious error later. This point should be emphasized to workers because their natural tendency will be to ignore what they consider nonconsequential errors. The same logic applies also to reports of accidents and near accidents.

The essence of an ELS and APS analysis is the recognition that certain characteristics of the situation are undesirable and make excessive demands on the worker. Questions to be asked include the following: Is the task within the worker's capability? Is there anything about the task that does or could cause the worker fatigue or discomfort? Is there sufficient information feedback? Does the task make demands that require too much precision or too many movements? Is the physical environment (temperature, noise, lighting) adequate? Questions should be asked about each of the situational PSFs listed in Exhibit 6.2.3.

Each ECR team should meet periodically (without management participation) and evaluate the reports turned in. The team would then comment on the suggestions made, and some consensus would be reached. This consensus would be added to the error, ELS, or APS report sent to management for evaluation. Every report must be passed upward; even if the suggestions for improvement are unworkable, at least a problem has been identified.

ECR Evaluation

Each suggestion made by the ECR team for a redesign of the work situation should be evaluated by a committee of specialists in terms of:

1. **Technical Worth.** Will the redesign really reduce errors and by what amount?
2. **Nontechnical Worth.** Will the redesign result in other improvements, such as greater job satisfaction? Some of these nontechnical factors are intangibles to which it is difficult to assign a monetary value. Nevertheless, they may reduce turnover, absenteeism, and grievances.
3. **Cost-Effectiveness.** Will the cost of the redesign be paid for by the presumed reduction in errors or by other considerations of worth?

For management to make an appropriate evaluation of errors, ELS, or APS, their importance must be ascertained. Importance is determined by three factors: consequences in terms of money and/or customer loss, likelihood of error occurrence, and cost of corrective action. Each factor can be rated on the following scales (from Swain,¹ as modified by the author):

1. Potential ELS Consequences:
 - a. >\$100,000 scrap and 1000 customers lost.
 - b. >\$10,000 scrap and 100 customers lost.
 - c. >\$1000 scrap and 10 customers lost.
 - d. >\$100 scrap and 1 customer lost.
 - e. Negligible.
2. Likelihood of Uncorrected Error:
 - a. Several times a month.
 - b. Once a month.
 - c. Several times a year.
 - d. Once a year.
 - e. Less than once a year.
3. Cost of Corrective Action:
 - a. Less than \$100.
 - b. \$100 to \$1000.
 - c. \$1001 to \$10,000.
 - d. \$10,001 to \$100,000.
 - e. More than \$100,000.

Admittedly these scales are quite crude, and the resulting values cannot be combined; however, they present a means of semiquantifying the ELS that management must deal with. Obviously, an ELS or APS rated E on each scale could be dismissed, but one rated A on each scale should be seriously considered.

Quality Control Circles

A variation of the ECR approach is the concept of quality control (QC) circles, developed in Japan in 1963 and since then highly successful in that country in solving quality control problems. The essence of QC circles is participative problem solving. Groups of 8 to 10 people (e.g., supervisors, workers, production engineers) performing similar or interrelated work form a circle on a voluntary basis. They are given special training in statistical quality control techniques, training that, in the United States, is usually reserved for quality control engineers. The training includes use of Pareto diagrams to isolate the major problems producing a defect, cause-effect diagrams (something like a fault tree diagram), histograms, graphs, control charts, stratification, and binomial probability.

Meetings are held at least once a month, usually on a paid basis. With the help of a facilitator who may be a supervisor, the group selects a problem that is responsible for product defects and that appears amenable to solution. Using Pareto diagrams,^{9,10} the circle analyzes the factors responsible for the greatest percentage of the defects found. The group then develops a cause-effect diagram to determine the specific cause of the problem. After establishing goals for reducing the defect rate, the circle recommends potential solutions, such as improved procedures or changes in design, and attempts to implement the solution. All of this is done with the active cooperation of management.

Certain elements of the ECR team and the QC circle are much the same, for example, the problem solving orientation, the concept of participative democracy, and the crossover among levels of management, engineering, and production. The QC circle differs from the ECR team in the emphasis on training in statistical quality control techniques, although the training is practical rather than academic; the formal way in which problems are investigated (i.e., through the use of Pareto and cause-effect diagrams); and, most particularly, the emphasis on teamwork, pride, and identification with the company, an emphasis that is viewed by American management as being peculiarly Japanese.

QC Circle Analytic Aids

The two major analytic aids used in training in the QC circle methodology are the Pareto and the cause-effect diagrams.

Pareto Analysis. The technique of arranging data according to priority or importance and tying them to a problem solving framework is called Pareto analysis. The following discussion is taken from the American Society for Quality Control's training manual for QC circles.¹¹

The Pareto distribution is based on the order-of-measurement value for each element considered rather than on the quantitative value of the element. The steps involved are:

Exhibit 6.2.4

1. List all the elements of interest.
2. Measure the elements, using the same unit of measurement for each element.
3. Order the elements according to their measure, not their classification.
4. Create a cumulative distribution for the number of items and elements measured.

For example:

Type of Defect	Number of Elements	Percentage of Elements	Total Dollars	Percentage of Dollars
A	1	14.29	5865	79.58
B	2	28.57	6736	91.40
C	3	42.86	7005	95.05
D	4	57.14	7181	97.44
E	5	71.43	7275	98.71
F	6	85.71	7330	99.46
G	7	100.00	7370	100.00

The preceding distribution can be plotted as a curve, with one axis being percentage of value, and the other, percentage of items. This enables one to see that a few elements account for a disproportionate sum of all measurements and should therefore be the elements to attack. In the example given, it is obvious that defect type A is responsible for 80% of the problem and that major attention should therefore be given to that defect.

Cause-Effect Diagrams. The cause-effect diagram developed by Ishikawa in 1950 consists of defining an occurrence (effect) and then reducing it to its contributing factors (causes). The relationships among the contributing factors are illustrated in a "fishbone" arrangement, as shown in Exhibit 6.2.4.

In developing this diagram the principal factors or causes are first listed in terms of four categories (manpower, machine, methods, and material) and then iteratively reduced to their sub-causes. The process is continued until all possible causes are listed. The factors are then critically analyzed in terms of their probable contribution to the effect or the problem.

The major objection voiced to the QC circle concept is that the procedures employed cannot be utilized in a non-Japanese society; in other words, it would be difficult to gain the necessary co-operation, teamwork, and motivation from westernized workers. The QC circle method has been applied primarily in Japan (where it has been enormously successful), and has been tried out in a number of American plants with positive results. Because of resistance on the part of American industrial management, however, the method has not been tried out on a large scale in this country.

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WHC-MR-0487

APPENDIX J
RESUMES OF BOARD MEMBERS

HERB L. DEBBAN

Manager, Operations Standards, ICF Kaiser Hanford Company

Work Experience: Mr. Debban managed the recovery activities after a fatality in a Hanford steam plant. Concurrently, he managed implementation of Electrical Safety Upgrades for the Hanford Site. From 1987 to 1993, he was Plant Manager of the N Reactor. Prior to 1987, he was Director of Reactor Services and Director of Projects and Programs for UNC Nuclear Industries, at Hanford. He has led numerous task group activities including the Westinghouse GOCO Operations Council (all Westinghouse GOCO sites), the Westinghouse Hanford Operations Excellence Council, and the Alarm Task Force. He has chaired several accident investigations.

Education: BS - Engineering - University of North Dakota
MBA - University of Washington

Certificates: Registered Professional Engineer, Washington

LARRY E. EYRE

Executive Manager, Westinghouse Hanford Company

Work Experience: Directed the Conduct of Operations recovery activities after a fatality in a Hanford steam plant. From 1992 to 1994, he was Manager of Conduct of Operations for the Hanford Tank Farms. Prior to 1992, he was the Manager of the West Tank Farms in the Hanford area. Larry was certified as a Shift Manager at the N Reactor and served as point-of-contact from 1980 to 1986 with the Institute of Nuclear Power Operations. He is also certified as an instructor for a Cause Analysis Course. He participated in numerous task groups in implementing Conduct of Operation practices including conducting critiques. He has participated in several accident investigations.

Education: AA - Management - Columbia Basin College

Certificates: Instructor for Zenger-Miller Supervisor Course
Instructor for ALAMO Cause Analysis
Shift Manager/Control Room Supervisor - N Reactor
Course Completion of Kepner-Trego Cause Analysis

DAVID S. KELLY - PMP

Lead, Systems, Innovations & Improvements, WHC Construction Projects

Work Experience: Senior Engineer for Westinghouse Hanford Company, who serves as a Project Engineer for special projects and provides internal project management consulting to the Construction Project organization. His construction management and project management job experience spans various facets of the nuclear industry from power generation, chemical processing, and tank farm construction. He most recently coordinated the WHC response to the RL Class B Investigation of the Project C-018H 13.8kV Cable Excavation Event.

Education: BS - Construction Management - Washington State University

Certificates: Certified Project Management Professional through the Project Management Institute

GREGORY P. MCDONALD

Chief Electrical Engineer, ICF Kaiser Hanford Company

Work Experience: Mr. McDonald currently manages the Electrical Engineering group within the Engineering Services Division at ICF KH, and as Chief Electrical Engineer he is technically responsible for all electrical and control systems engineering within the company. Prior to his management position, he performed lead electrical design engineering duties from 1985 to 1990 for the onsite A-E. From 1981 to 1985, he worked in the Utilities Engineering group at Hanford for the Operating Contractor. From 1976 to 1981, he worked for Minnesota Power & Light Co., an investor-owned utility, in the distribution engineering group.

Education: BS Electrical Engineering - North Dakota State University

Certificates: Registered Professional Engineer - Washington

R. M. (MIKE) BOGER

Manager, Electrical Engineering and Code Compliance, Westinghouse Hanford Co.

Work Experience: Mr. Boger has 25 years experience in engineering design and management, startup testing, power plant operation, and maintenance of nuclear power plants and support facilities. He currently manages a group which provides electrical engineering services across the Hanford Site. He has led a site-wide effort to initiate an effective National Electrical Code Compliance program. Previously, he led WHC's Site Electrical Task Group, responsible for performing a WHC site-wide assessment of electrical system conditions.

Education: BSEE - University of Notre Dame
MBA - University of Washington

LARRY D. DELL

Principal Engineer, Quality Compliance Assurance, Westinghouse Hanford Company

Work Experience: Mr. Dell has over 15 years in the quality assurance and assessment fields including program planning. He is co-author of ROOT CAUSE ANALYSIS, A TOOL FOR QUALITY MANAGEMENT Quality Press, 1992. He has provided instruction to hundreds of individuals in root cause analysis philosophy and application as well as led and participated in root cause analysis activities for the Department of Energy. He also has a background in trend analysis and risk evaluation. In his current position, he is a Quality Assurance Lead Auditor for Westinghouse Hanford Company.

Education: BS, Business Administration, Management Science Specialty
BS, Economics, Business Economics Specialty
Central Washington University

MBA, NOVA Southeastern University, April 1995

Certificates: Certified Accident Investigator, Management Oversight and Risk Tree/Accident Investigation (MORT/AI), Safety Systems Development Center, EG&G Idaho.

Certified Quality Auditor, American Society for Quality

Control

Certified Quality Assurance Lead Auditor,
Westinghouse Hanford Company

CAROL A. SHEARER

Safety Specialist, Industrial Safety and Health, ICF Kaiser Hanford Company

Work Experience: Researched, developed, and implemented corporate safety, health, and environmental program for GEO-CENTERS, INC., a diverse research and development company. Duties included: accident investigation; writing and implementing hazardous waste management operations procedures; setting up medical surveillance program; and advising and monitoring safety issues for off-site personnel located in federal facilities.

Previous experiences included: electrical design engineering; field engineering for surveys detecting buried unexploded ordnance and waste drums; nursing on orthopedic and general medical/surgical floors; and setting up operations and managing a nursing agency.

Education: B.Sc. Electrical Engineering - Northeastern University
Boston, MA

R.N. - Westminster Hospital, Wolfson School of Nursing,
London, England

Certificates: Certificate of Professional Achievement: Hazardous Waste
Management - Northeastern University, Dedham, MA

40 Hour Hazardous Waste Safety and Health Training;
8 Hour Supervisory Training - University of Massachusetts,
Lowell, MA

LIST OF ACRONYMS

ACW	Acceptance of Completed Work
BPA	Bonneville Power Administration
CM	Construction Management
DOE	Department of Energy
ECC	Emergency Control Center
ECN	Engineering Change Notice
EM	Environmental Restoration and Waste Management
EU	Electrical Utilities
HFD	Hanford Fire Department
JCS	Job Control System
JSA	Job Safety Analysis
KEH	Prior acronym of Kaiser Engineers Hanford, now known as ICF Kaiser Hanford Company (ICF KH)
NESC	National Electric Safety Code
OC	Operating Contractor
ONC	Occurrence Notification Center
OSC	Operation Startup Checklist
PCE	Power City Electric
PM	Project Management
PMP	Project Management Plan
POC	Patrol Operations Center
RFAR	Radio Fire Alarm Receiver
RL	U.S. Department of Energy, Richland Operations Office
SCADA	Supervisory Control and Data Acquisition
UDAC	Unified Dose Assessment Center

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