IV. ENGINEERING CONTROLS

Introduction

Engineering controls combined with good work practices will minimize worker exposure in coal liquefaction plants. Such controls pertain to erosion, seal and instrument failures, maintainability, reliability, and sample withdrawal systems. Additional engineering controls for specific equipment or systems are also identified in the following paragraphs.

Engineering controls to protect worker health and safety include (1) modification of design layout and specifications, (2) modification of operating conditions, or (3) add-on control devices to contain liquids, gases, or solids produced in the process and/or to minimize physical hazards. Modifying operating conditions or adding control devices may require retrofitting equipment or components after plant startup. Such modifications may necessitate system or plant shutdown.

Throughout this chapter, modification of plant design and specifications is emphasized. Engineering controls based on this methodology may minimize maintenance and retrofitting requirements. Engineering controls involving design include system safety analyses, containment integrity, equipment segregation, redundancy of safety controls, and fail-safe design. The application of these engineering controls, as discussed in the following sections, will minimize the need to modify operating conditions or to add control devices.

Plant Layout and Design

Plant layout and design features to ensure a safe work environment include system safety programs and analyses, pressure vessel codes, control room location and design, equipment layout, insulation of hot surfaces, noise abatement, instrumentation, emergency power supplies, redundancy, and fail-safe features.

(a) System Safety

Identification of hazards and necessary controls is important in the design of a safe operating plant. Hazards and controls should be determined during the design phases of the plant and whenever a change in process design occurs. For example, after recognizing the hazards associated with high-pressure vessels, one plant installed protective barriers around its bench-scale coal liquefaction process [1]. An explosion did occur in this system, but because of the barriers no workers were injured. Incidents in other industries have resulted in fatalities when initial design and/or design changes were inadequately reviewed for potential safety problems [82-84].

Review and analysis of design, identification of hazards and potential accidents, and specification of controls for minimizing accidents and their consequences should be performed during plant design, construction, and operation. Review and analysis should include, but not be limited to, procedures for startup, normal operations, shutdown, maintenance, and emergencies. This review process should be performed by knowledgeable health and safety personnel working with the engineering, maintenance, and management staff who are cognizant of the initial design and/or process design changes. To provide this interaction, a formal program should be developed and documented. At a minimum, it should include review and analysis requirements, assignment of responsibilities, methods of analyses to be performed, and necessary documentation and certification requirements. All of these elements are necessary in order to review the design, identify hazards, and specify solutions, and would be included in a well-documented, formalized system safety program.

The system safety concept has been used in the aerospace and nuclear industries [85] to control hazards associated with systems or products, from initial design to final operation. This concept is also being applied in other industries, eg, the chemical industry [82].

Fault-tree analysis is one method of system safety evaluation that has been applied in coal gasification pilot plants [86], and it is used in the world's oldest and largest coal liquefaction plant to help engineers with the design and construction of new facilities [21]. In the coal gasification criteria document [16], NIOSH recommended that fault-tree systems analysis, failure-mode evaluation, or equivalent safety analysis be performed during the design of coal gasification plants or during the design of major modifications of existing plants.

A system safety program that incorporates design reviews, hazard identification and control, organization, and fault-tree analysis should also be used during the design of coal liquefaction plants and during any design modifications of operating plants. This program would provide a disciplined approach to involving all responsible departments in design decisions that will affect employee protection. Appendix VII lists several references on system safety.

(b) Pressure Vessels

Because most liquefaction plants operate at high pressures ranging from 400 to 4,000 psi (2.8 to 28 MPa) and at temperatures ranging from 800 to 932°F (427 to 500°C) [33], it is essential that pressure vessels be properly designed. Rupture of a pressure vessel containing flammable solvent or other flammable materials could be catastrophic [87]. Pressure vessels at existing plants are designed in accordance with the applicable American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Codes to ensure vessel design adequacy [1,88]. Quality control measures should be formulated and performed to ensure the necessary reliability of the vessel integrity [1]. A quality assurance (QA) program should be established prior to plant and equipment design. The program should document formalized quality control measures for design, construction, and operation. It should also document the requirements of functions such as audits, inspections, and tests. The program should be modeled after the ASME QA programs and the American National Standards Institute (ANSI) QA standards.

Pressure safety and relief valves should be installed where appropriate, as determined by well-established engineering practice [1,88]. If the discharge of these valves is a toxic or potentially dangerous material, it should be collected and treated in an acceptable manner. Flaring should be restricted to gaseous discharges; any liquid discharges should be contained by appropriate knockout drums. Pressure safety valves on steam drums and other vessels that do not contain toxic or dangerous materials should be vented in accordance with standard safety practices. These valves should be designed or located so that they will not become plugged with condensed coal products.

(c) Control Room Design

The control room for plant operation should be designed to provide a safe environment for operating personnel and to remain functional in the event of an accident and/or the release of hazardous materials within the plant. For example, at one site, reinforced concrete walls were provided between the liquefaction system and the operating control room to protect the operating personnel from possible explosions [1]. An explosion did occur, but control room personnel were not injured, and control equipment was not damaged. As a result, the operators were able to shut down the operation to prevent additional occurrences, such as intense fire resulting from the uncontrolled flow of hydrogen. The control room was structurally designed to withstand the forces generated by anticipated accidents.

Air supplied to the control room should not be contaminated with hazardous materials. In the event of an accident or the release of hazardous materials (such as hydrogen sulfide) within the plant, operators must be able to respond effectively.

(d) Separation of Systems or Equipment

System safety analyses can identify those systems, unit processes, and unit operations that should be separated from one another by design or location. In one coal liquefaction pilot plant, a fire resulting from a pump seal failure contacted an adjacent pump and caused it to fail [1].

Experience with hydrocrackers used in petroleum refineries for producing gasoline from heavier hydrocarbons has led the Oil Insurance Association to recommend that these units be remotely located within the plant perimeter [89]. Hydrocrackers operate at pressures of up to 3,200 psi (22 MPa) and at temperatures of up to 1,800°F (980°C) [89], similar to the hydrotreatment units used in coal liquefaction. When a hydrocracker fails, flammable material is released over a larger area than with lower-pressure units. Based on experience with hydrocrackers [89], the hydrotreater unit should also be remotely located within the plant to minimize the impact that its failure might have on other equipment. A systems safety analysis can identify the types of multiple failures that could occur in a specific plant design. Unit processes and operations should be designed or located to prevent a single failure from initiating subsequent failures.

(e) Location of Relief Valves

Relief valves discharging directly to the atmosphere should be located so that operating personnel are not exposed to releases. These valves should not be located near stairways or below walking platforms [1].

Design Considerations

The systems in coal liquefaction plants are closed because flammable and other hazardous materials are handled at high pressures and temperatures. However, workers can be exposed to the process materials when these systems are opened. The opening of the system may be intentional, as is the case during maintenance. On the other hand, poor connections, seal failures, or line failures due to erosion or corrosion can result in leaks that may release process materials into the work environment. Minimizing maintenance activities, limiting the amount of process material present during maintenance, and preventing leaks will reduce the potential for worker exposure. Design factors requiring engineering controls for systems, unit operations, and unit processes include maintainability, seals, erosion/corrosion in systems handling fluids that contain solids, hot surfaces, noise, instrumentation, emergency power, redundancy of controls, fail-safe design, and sampling.

(a) Maintainability

Maintenance activities are the most frequent cause of worker exposure to the process materials in coal liquefaction plants. Coal liquefaction plants should be designed to ensure that systems, unit processes, and unit operations handling hazardous materials can be maintained with minimum employee exposure. Prior to maintenance, the equipment should be isolated from the process stream by blinds and isolation valves [1,90,91]. The equipment should also be depressurized if necessary, flushed, and then purged, where practicable, with steam or an inert gas (nitrogen or carbon dioxide). Cleaning solvent, water, or other suitable material may be used for flushing equipment that handles liquids and solids. Flushing and purging are necessary to minimize residual process materials in equipment requiring maintenance or removal.

Decontamination of equipment in place requires appropriate systems with adequate flush and purge capacity as well as adequate storage capacity for the materials flushed out of the system. The contaminated flushing material should be contained, treated, and disposed of properly if it is not recycled [1,92]. At one plant, the inert gas purge is sent to a flare header system and then to a flare stack [88]. Decontamination at another plant is performed after the equipment has been removed from the process system and prior to maintenance activities [1]. In other cases, equipment is removed first, decontaminated, and checked for contamination using a UV light prior to any maintenance [1]. However, UV light was ineffective in fluorescing thick layers of coal-derived materials [1]. Decontamination of equipment after removal from the system increases the potential for worker exposure to residual material in the equipment. However, if the equipment is decontaminated prior to removal from the system, the amount of residual material would be minimal.

Employee exposure during maintenance should be minimized by providing redundant equipment. If an entire system must be shut down to repair one piece of equipment, workers will sometimes be instructed to postpone maintenance and continue operating with marginal equipment until extensive maintenance is necessary. Redundant equipment permits maintenance activities to be performed without interrupting normal operations [88]. Isolation and decontamination capabilities should also be available for equipment requiring frequent maintenance.

Maintenance activities may result in process material spills. All spills should be contained and collected to control the release of the material. Dikes with chemical sewer drains are sometimes used to contain and collect spills [1]. For example, one plant was built on a diked concrete pad that drained into a chemical sewer arrangement [1]. Adequate ventilation should be provided where flammable liquids are collected to reduce the flammable vapor concentration to less than its lower explosive limit.

(b) Systems Handling Fluids Containing Solids

Minimizing leaks will reduce employee exposures. Good engineering practices should minimize leakage from loose flange bolts, connections, or improper welds.

(1) Seals

In systems that handle fluids containing solids, abrasive particles may enter the seal cavity and cause rapid seal failure, resulting in the release of hazardous materials [1,88,93-95]. To reduce the frequency of leaks and minimize personnel exposure, pumps, compressors, and other equipment with rotating shafts should be designed so that seals are compatible with the fluid environment.

(2) Erosion/Corrosion

Where erosion occurs in a corrosive environment, base metals are more susceptible to corrosion. The term "erosion/corrosion" is used throughout this document to indicate erosion, corrosion, or a combination of both. Erosion/corrosion often causes leakage problems in systems, unit processes, and unit operations that handle gases with entrained solids and slurries. Where practicable, slurry transport pipes should be designed to minimize sharp elbows and turbulent flows, which increase the severity of erosion [1,93,96-98]. Severe erosion has also been observed where there is poor alignment at flanged joints on piping and at slip joints of inner tubes inserted to minimize erosion. Erosion is enhanced by the flow turbulence at these discontinuities [98].

Periodic ultrasonic tests may be performed to indicate locations of excessive erosion [1,88]. Other methods that have been used include dye-checking for cracks, special metallographic examinations, and X-rays to identify affected areas [88]. The location and frequency of monitoring for erosion/corrosion should be established prior to plant operation and revised as necessary.

Valve internals should also be designed to minimize erosion/corrosion. Considerable erosion/corrosion has been observed in high-pressure letdown valves in coal liquefaction plants [88,93,96,99,100]. However, improved designs and materials, such as multiple letdown valves in series and tungsten carbide trim, have minimized erosion effects [88,94,96]. Other valves used in slurry service have also shown signs of erosion/corrosion [96,100]. Considerable research has been and is being conducted on methods to minimize valve erosion/corrosion [32,88,96,98,101]. A hard surface metal to be applied to the valve internals is currently being developed [1,94]. However, a major problem to date has been effecting an adequate bond between the protective coating metal and the base metal [1,94]. In addition, extra care needs to be exercised during construction and maintenance to avoid chipping any protective coatings [94]. Valves used in systems handling fluids that contain solids should also be designed to close properly, because problems have occurred when suspended solids have prevented proper valve closure [1]. Where these valves are needed for control purposes, redundant valves should be included in the plant design.

Pump casings, particularly centrifugal pumps, should also be designed to minimize erosion. Centrifugal pumps have been designed with hard coatings to provide abrasion resistance in slurry service [94], and pumps operating at temperatures below 150°F (66°C) were relatively successful. However, poor coating adherence to the base metal was noted with pumps that handle slurries at temperatures above 150°F (66°C).

Although one plant experienced erosion problems in its centrifugal pumps [94], another plant had favorable experience using Ni-Hard casings for its centrifugal pumps [88].

Other material problems in coal liquefaction systems include hydrogen embrittlement, particularly in hydrogenation processes and hydrotreater units, and stress-corrosion cracking, particularly around welds. These problems have been investigated [32,88,96,98,101], and research is being conducted in an effort to solve or minimize them [102,103].

Erosion/corrosion is also a problem in pyrolysis and hydrocarbonization processes. Erosion in these processes is due to entrained solids in gas and vapor streams at high velocities. These problems are analogous to those experienced in coal gasification processes where solids become entrained in gas and vapor streams.

(c) Hot Surfaces

Equipment operated at elevated temperatures should be designed to minimize personnel burn potential and heat stress. One method for accomplishing this is to insulate all hot surfaces. However, experience has shown that there is a fire potential if the process solvent contacts and reacts with certain insulation materials. One example of this occurred in a small development unit when hot process materials came into contact with porous magnesium oxide insulation, causing a minor fire [1,88]. Therefore, insulation used to protect personnel from hot surfaces should be nonreactive with the material being handled.

(d) Noise

Noise abatement should be considered during facility design. Noise exposures occur in the coal handling and preparation system, around pumps and compressors, and near systems with high-velocity flow lines [38]. Where practical, noise levels in the plant should be minimized by means of equipment selection, isolation, or acoustic barriers. The noise levels to which employees may be exposed should not exceed the NIOSH-recommended 85 dBA level, calculated as an 8-hour TWA, or equivalent dose levels for shorter periods [104].

(e) Instrumentation

Instrumentation necessary to ensure the safe operation of the coal liquefaction plant should be designed to remain functional in the most severe operating environment. Instrument lines can become plugged with materials in the process stream [1] and should be purged where needed with a suitable material to prevent plugging. For process liquid streams, instrument lines are normally purged with clean process solvent [1], while instrument lines in gas systems are usually purged with inert gases such as nitrogen or carbon dioxide [1]. The purge material selected should be compatible with the process stream. Because of small flowrates used in pilot plant operations, the purge material may dilute the process stream.

Radioactive sources and detectors are used in some coal liquefaction plants to monitor the liquid level inside vessels and, in some cases, to perform density analyses by neutron activation [1]. Sufficient shielding is needed to minimize the radiation levels to which workers are exposed in areas in and around the radioactive source location. The use of radioactive materials also requires comprehensive health physics procedures and monitoring, particularly when maintenance is to be performed on equipment in which radioactive materials are normally present. Anyone using radioactive materials must comply with the regulations in 29 CFR 1910.96. Combining engineering controls and work practices should prevent radiation exposures in excess of those specified.

(f) Emergency Power Supplies

Instrumentation and plant equipment that must remain functional to ensure safe operation and shutdown of the plant should have emergency power supplies. For example, pumps used for emptying equipment such as catalytic reactors of all material that might coke or solidify and inert gas purge systems necessary for shutdown need an emergency power supply. Without an inert gas purge or blanket during shutdown, the potential for a fire or an explosion increases [1]. Emergency power supplies should be remote from areas in which accidents identified in the system safety analysis are likely to occur.

(g) Redundancy of Controls Needed for Safety

Throughout the coal liquefaction plant, equipment, instruments, and systems needed to perform a safety function should be identified by the system safety analysis. These safety functions should be redundant. For example, pressure relief valves are provided to prevent overpressurization and vessel rupture. Where necesary, parallel relief valves, rupture disks, or safety valves should be provided for an added degree of safety so that in the event that one fails to function when needed, another is present. Redundant pressure relief systems are used in the petroleum industry [91] and in coal liquefaction operations [1].

(h) Fail-Safe Design

The failure of any safety component identified in the system safety analysis should always result in a safe or nonhazardous situation [1,105]. For example, fail-safe features include spring returns to safe positions on electrical relays, which deenergize the system [106]. All pneumatically actuated valves should fail into a safe or nonhazardous position upon the loss of the pneumatic system [105]. The safe position, open or closed, of a valve depends on the valve function.

(i) Process Sampling

A common source of worker exposure to hazardous materials in the petroleum industry is process stream sampling [107]. This source of exposure also exists in coal liquefaction plants. In addition, process streams containing flammable liquids or gases present fire and explosion hazards [1]. To minimize the potential for fires, explosions, or personnel exposures, sampling systems should be designed to remove flammable or toxic material from the lines by flushing and purging prior to removal of the sampling bomb. Flushing and purging also minimize the potential for some process materials to solidify in the lines if allowed to cool to near-ambient temperatures [1,88,95]. A number of sampling systems have been developed and are shown in Figure XVIII-3. The system shown as "best" in this figure does not permit removal of the material between the isolation valves prior to removal of the bomb. The sampling system shown in Figure XVIII-4 allows removal of material contained between the two isolation valves on each side of the bomb [1]. When the operator removes the bomb, the potential for fire, explosion, or worker exposure to residual process material is minimized. Further protection from exposure would be afforded if a flush and purge system were provided to remove the material from the sampling lines but not from the bomb. The flush and purge system could also be used to enhance depressurization of high-pressure sampling systems. For gas sampling systems, the bleed lines should discharge to a gas collection system for cleanup and disposal.

Systems Operations

Another safety aspect in plant design involves evaluating systems, their hazards and engineering problems, and the necessary engineering controls.

(a) Coal Preparation and Handling

The coal preparation and handling system receives, crushes, grinds, sizes, dries, and mixes the pulverized coal with process solvent, and preheats the coal slurry. Slurry mixing and preheating may not be required for the pyrolysis and hydrocarbonization processes, but the other operations are needed for all coal liquefaction processes. Instead of slurry pumps, pyrolysis and hydrocarbonization processes generally have lockhoppers, which provide a gravity feed of the coal into the liquefaction reactor [70]. NIOSH's coal gasification criteria document [16] discussed and recommended standards for lockhopper design.

Noise, coal dust, hot solvents, flammable materials, and inert gas purging are factors that contribute to potential health and safety hazards. For example, coal dust presents inhalation, fire, and explosion hazards. Inhalation hazards should be minimized by using enclosed systems for transporting the coal fines, by using an inert gas stream [1,88], or by using proper work practices [1]. Vacuum and water spray systems have been suggested as methods for cleaning up coal dust resulting from fugitive emissions [92]. To minimize the fire and explosion potential, standards should be applied such as the National Fire Protection Association (NFPA) Standard 653, "Prevention of Dust Explosions in Coal Preparation Plants"; NFPA Standard 91, "Blower and Exhaust

Systems, Dust, Stock, and Vapor Removal or Conveying"; NFPA Standard 85F, "Pulverized Fuel Systems"; NFPA Standard 85E, "Prevention of Furnace Explosions in Pulverized Coal-Fired Multiple Burner Boiler-Furnaces"; and NFPA Standard 69, "Explosion Prevention Systems." Pressure relief valves are used to prevent overpressurization and equipment failure resulting from fires in the coal handling system [1]. Equipment in the coal handling and preparation system has been identified as a major noise source [38]. This equipment includes the pulverizer (90-95 dBA), preheater charge pump (95-100 dBA), gravimetric feeder (90-95 dBA), and vibrator (110 dBA) [38]. When selecting such equipment, priority should be given to equipment designed to attain noise levels that are within the NIOSH-recommended limits [104]. If this equipment design is impractical, acoustical barriers and personal protective equipment (see Chapter V) should be used.

Certain operations, such as coal pulverizing and drying, should be performed in a relatively oxygen-free atmosphere to minimize the potential for fires or explosions. At various plants, the oxygen concentration level during startup, shutdown, and routine and emergency operations is maintained at <5% by volume using nitrogen as the inert purge gas [1,106,108]. At one plant, the baghouse used to collect coal dust and the coal storage bins are blanketed with an inert gas, ie, nitrogen [1,108]. At one bench-scale hydrocarbonization unit [106], nitrogen purge is used to remove hydrogen during shutdown. The oxygen concentration level, which minimizes or eliminates the fire and explosion potential, varies with the type of purge and blanketing gas and the type of coal being used [109]. If carbon dioxide is used as the inert gas, the oxygen concentration should be less than 15-17% by volume, depending on the type of coal used, to prevent ignition of coal dust clouds [109]. When the inert gas is nitrogen, the oxygen concentration should be lower [109]. The maximum oxygen concentration in the coal preparation and handling system should be determined by the type of inert gas and the type of coal used. Oxygen levels should be continuously monitored during plant operations [1,106,108]. In addition, redundancy in oxygen monitoring should be provided because the oxygen concentration is an important parameter in assuring a safe system operation.

Purge and vent gases for all systems handling coal-derived materials in a coal liquefaction plant should be collected, treated, recycled, or flared [1,92]. An emergency backup purge system (storage of carbon dioxide or nitrogen) with sufficient capacity should be provided for emergency shutdown and extended purging periods. Inert gas purging presents an asphyxiation hazard if it accumulates in areas where worker entry is required. Plant designs that include enclosed or low-lying areas should be avoided to minimize the potential for such accumulation. Where carbon dioxide generators are used, monitoring should be performed to detect increases in carbon monoxide concentrations resulting from incomplete combustion [38].

Coking and solidification of the process stream can occur in the preheater tubes and in the piping to the liquefaction system [1,88,108]. One factor that contributes to coking is improper heating of the slurry. To minimize coking and subsequent maintenance, controls and instrumentation should be provided to ensure the proper heating of the slurry. If the tubes cannot be decoked in place by combustion with steam and air, they must be removed and decoked by mechanical means such as chipping [108]. Worker exposure to process materials, particulates, vapors, and trapped gases should be minimized during the decoking of the lines. Where practicable, prior to the performance of maintenance activities, the material that has not coked should be removed. Worker exposure can be minimized if adequate ventilation and/or personal protective equipment such as respirators are provided (see Chapter V). However, adequate ventilation may not always be possible because of difficulties in obtaining capture velocities in outdoor locations where there are high winds, and difficulties in locating the exhaust on portable ventilation units so as not to discharge vapors into another worker's area. Where adequate ventilation is not possible, work practices and personal protective equipment should be relied upon to minimize worker exposure during decoking activities.

The process stream can also solidify and plug the preheater tubes and the transfer lines beyond the preheater if the slurry temperature approaches ambient temperature [1,88,108]. At one plant, the pour point of the process solvent used for slurrying ranged from 25 to 45°F (-4 to 7°C) [108]; the process solvent was semisolid at room temperature [1]. Until the pour point of the material is lowered by hydrocracking to a temperature less than the anticipated ambient temperatures, the potential exists for the material to solidify or become too viscous for transporting. Solidification in the lines is possible from the preheater to the liquefaction system in all coal liquefaction processes except pyrolysis and hydrocarbonization. Plugging can be minimized by heat-tracing the lines to maintain the necessary temperature during startup, routine operations, shutdown, and emergency operations [1]. Plugging due to the settling of solids can be minimized by avoiding dead-leg piping configurations and by connecting into the top of process piping [1].

Even when pipes are heat-traced and properly designed, there will be occasions when plugging occurs and maintenance is required [1]. Lines must be removed from the system if the obstruction cannot be flushed out under pressure [1]. Where practicable, prior to removal of the plugged lines or equipment, residual, nonsolidified process material should be removed to avoid worker exposures. If the material has completely solidified, the line or equipment may be cleared by hydroblasting [1], which is a method of dislodging solids using a low-volume, high-pressure (10,000 psi or 70 MPa), high-velocity stream of water [1]. During the hydroblasting process, workers may be exposed to particulates, aerosols, and process materials, but this exposure has been reported to be low [1]. Portable local exhaust ventilation should be used, wherever possible, to control inhalation exposures. The exhaust from portable ventilation should be directed to areas that are not routinely occupied. Water contaminated with process material should be collected, treated, and recycled, or disposed of. If the material plugging the line is semisolid, the line can be cleared using mechanical means, eg, a scraper or rod [1]. During the removal of semisolids, generation of particulates is minimal. However, hydrocarbon vapors or gases may be present [1], and local exhaust ventilation, if practical, should be used to minimize worker inhalation of these materials. Where local exhaust ventilation is not practical, personal protective equipment should be provided.

(b) Liquefaction

In pyrolysis/hydrocarbonization processes, solid coal from the coal preparation and handling system is transferred to the liquefaction system. In the hydrogenation and solvent extraction processes, the coal is first slurried with a solvent, and erosion/corrosion and seal failure may occur because of solid particles suspended in the slurry [1,88]. Erosion can also occur in pyrolysis/hydrocarbonization processes because of solids entrained in the gas-vapor stream leaving the reactor. Pressure letdown valves in the liquefaction system are another area where considerable erosion occurs [1,88,99,108]. Erosion/corrosion and seal failure problems can result in releases of process material into the worker environment, and these releases may present a fire hazard [1].

Plugging caused by solidification of the process material can occur in the hydrogenation and solvent extraction liquefaction systems, particularly in transfer lines [1,88]. Major problems with agglomeration may be encountered in pyrolysis reactors when strongly caking coals are used [2]. If agglomeration occurs, maintenance must be performed to unplug the equipment or lines. Unplugging may expose workers to aerosols, particulates, toxic and/or flammable vapors, and residual process material.

During the startup of a coal liquefaction plant, inspections should be performed to detect potential leaks at welds, flanges, and seals. Leaks, when found, should be repaired as soon as is practicable. Systems throughout the plant should be pressure tested prior to startup using materials such as demineralized water and nitrogen [88] to locate and eliminate leaks, thereby reducing the potential for worker exposure.

The liquefaction system of all coal liquefaction processes should be flushed and purged when the plant shuts down to minimize process material solidification and/or plugging due to solids settling. A flush and purge capacity equal to or greater than the capacity of the liquefaction system should be available. Storage vessel capacity should be equal to the flush capacity so that all materials flushed from the system can be collected and contained. During shutdown, as well as during startup, the purge material (carbon dioxide, nitrogen, etc) may contain flammable hydrocarbon vapors and should be collected, cleaned, and recycled, or collected and sent to a flare system to be incinerated.

Other health and safety hazards associated with the liquefaction system for all liquefaction processes are thermal burns and exposure to hazardous liquids, vapors, and gases during operation and maintenance.

(c) Separation

The separation system separates the mixtures of materials produced in the liquefaction system. Table XVIII-1 lists the separation methods used for coal liquefaction processes. Materials found in separation systems include solvents, unreacted coal, minerals, water containing compounds such as ammonia, tars, and phenols, and vapors containing compounds such as hydrocarbons, hydrogen sulfide, ammonia, and particulates [31]. Workers may be exposed to these materials during maintenance activities and when releases occur because of leaks, erosion/corrosion, and seal failures. Steam is sometimes used to clean equipment that has been used to separate solids from hot oil fractions [31]. Steam discharges from blowdown systems and ejection jets on vacuum systems have been identified as sources of airborne materials that fluoresce under UV lighting [31]. Engineering controls should be provided to minimize these discharges. Steam should be discharged into a collection system where it is condensed, treated, and/or recycled.

Plugging and coking may be a problem in separation systems for all coal liquefaction processes. For instance, plugging has occurred in the nozzles inside the filtration unit [88]. Material remaining in the nozzle may react chemically and solidify at the filter temperature. Coking in the wash solvent heaters also produces solids that plug the nozzles downstream. Nozzles should be cleaned during each filter outage and should be aimed downward when not in use to permit adequate drainage of material. Coking has also occurred in the mineral residue dryer downstream from the filter [88]. However, the use of mineral residue dryers has been observed at only one plant [1]. These dryers may not be used in larger plants where the solids from the separation unit may be sent to a gasifier [26,27]. The dry mineral residue itself presents problems because of its pyrophoric nature [100].

The separation methods discussed are those currently used in coal liquefaction pilot plants. As new separation technology is developed, the present separation systems and their related problems may no longer be relevant. For example, solvent de-ashing processes have been developed and will be tested at two coal liquefaction pilot plants [1,28,29,110]. Data on these new units are limited because of proprietary information [1,110]. As new technology is developed, the health and safety hazards associated with the new units should be identified, and controls should be specified to minimize risks to worker health and safety. A system safety program would perform this function by reviewing hazards and determining necessary control modifications.

(d) Upgrading

The upgrading system receives the liquid products from the separation system. Upgrading is achieved by using methods such as distillation and hydrogenation. Process solvents, filtered coal solution, catalysts, hydrocarbon vapors, hydrogen, and other gases may be present in the fractionator and the hydrotreater. Maintenance activities present a significant potential for worker exposure to these materials. Plugging resulting from solidification of the process stream is a problem in solvent extraction and noncatalytic and catalytic hydrogenation processes [1].

Severe corrosion has occurred in the distillation system at one plant, particularly in the wash solvent column [88,111]. The design of the distillation system and of all systems susceptible to corrosion should minimize corrosive effects. This may be accomplished by developing and/or using more suitable construction materials (eg, 316 Stainless Steel and alloys such as Incoloy 825 [88]).

The hydrotreater presents a significant potential for fire or explosion hazards because of high pressure, high temperature, and the presence of hydrogen and flammable liquids and vapors. Vessel integrity should be ensured to reduce this potential. Proper metallurgy should be used in hydrotreater design to minimize hydrogen attack and other corrosion problems [1].

(e) Gas Purification and Upgrading

The process gases are purified using an acid-gas removal system to remove hydrogen sulfide and carbon monoxide from the hydrogen and hydrocarbon gases such as methane. Methanation may be used to upgrade the hydrogen with carbon monoxide to form pipeline quality gas, or the hydrogen may be recycled within the plant for hydrogenation.

Potential safety and health hazards to workers in this system include hot surfaces and exposure to hazardous materials during maintenance. NIOSH has previously made recommendations [16] on engineering controls for nickel carbonyl formation, hydrogen embrittlement monitoring, catalyst regeneration gases, and other safety and health hazards associated with this system.

Nickel carbonyl formation in the methanation unit is a major hazard associated with this system. As the methanation unit cools during shutdown, carbon monoxide reacts with the nickel catalyst to form highly toxic nickel carbonyl. In the coal gasification criteria document [16], NIOSH recommended that an interlock system, or its equivalent, be used to dispose of any gas containing nickel carbonyl where nickel catalysts are used. Formation of nickel carbonyl can be eliminated during startup and shutdown of methanation units if carbon monoxide is not permitted to contact the catalyst once the catalyst temperature is below 260°C (500°F) [1,16].

(f) Product Storage and Handling

Pilot plants operate in batch modes, and batch operations require personnel to handle products frequently. Product storage and handling equipment should be designed to minimize, to the extent possible, employee exposure to coal-derived liquids, vapors, and solids during routine and maintenance operations.

Specific engineering controls should be developed as problems are identified. For example, dust in the solid product handling system at one plant presented an inhalation hazard [88]. A baghouse and collection system were installed to minimize this hazard. A dust collection and filter system should be provided for product storage and handling areas in all coal liquefaction plants where an inhalation hazard is found to be present.

Liquid and gas are stored in closed systems, thus minimizing the potential for worker exposure under normal conditions. However, workers may be exposed to these materials during maintenance. Exposures can be minimized by emptying the equipment prior to maintenance. During filling operations, vapors inside tanks will be displaced. Vapors and gases from liquid and gas storage should be collected and recycled, or flared.

(g) Waste Treatment Facilities, Storage, and Disposal

Waste treatment facilities concentrate waste products that may contain potentially hazardous materials. Because of the presence of concentrated waste materials, ventilation systems and/or personal protective equipment should be provided during waste treatment equipment maintenance. Similar precautions need to be taken during the handling and disposing of wastes such as spent carbon, ash, contaminated sludge from ponds, and contaminated catalysts. Where possible, waste products should be contained when handled or transported, using appropriate methods. One method could involve packaging and sealing contaminated wastes in drums under controlled conditions prior to handling or transporting.

Where provisions are made for pumping or spraying liquids into liquid retention ponds, engineering controls such as louvered windbreaks should be provided to limit the dispersal of water droplets from the spray. An industrial hygiene study at a Charleston, West Virginia, pilot plant revealed that the airborne water droplets originating in the aeration pond contained material that was fluorescent under UV lighting. A louvered windbreak was installed adjacent to the pond in an attempt to confine the water droplets [37]. Whenever possible, liquids should be pumped into the bottom of the pond to minimize the generation and dispersal of contaminated sprays.