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SAFETY ANALYSIS LOX-30 LIQUID OXYGEN GENERATOR.(U)

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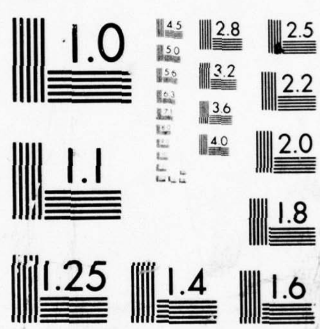
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NAVAL AIR ENGINEERING CENTER

LAKEHURST, N.J.
08733

SAFETY ANALYSIS LOX-30 LIQUID OXYGEN GENERATOR

Ground Support Equipment Department
Naval Air Engineering Center
Lakehurst, N.J. 08733

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SAFETY ANALYSIS LOX-30

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Safety of the LOX-30 Liquid Oxygen Generator was evaluated in accordance with MIL-STD-882. Thirteen safety/control devices and fifteen operational areas were extensively analyzed. Twenty-seven hazard classifications were assigned. Location of the storage vessel relief valve presents a severe personnel hazard. Incorporation of a shield around this relief valve to protect personnel would mitigate this hazard. No other significant safety hazards were identified.

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I. SUMMARY

A. The LOX-30 Liquid Oxygen Generator is an air transportable unit, comprised of five modules, which is capable of producing high purity liquid oxygen. Plant operation is essentially automatic subsequent to an initial start-up period of approximately six hours to reach steady state conditions. Safety devices are provided to prevent over-pressurization of the system plumbing and to initiate system shut down in event of component failure or malfunction. Data indicate that, with the exception of the cold box oxygen storage vessel relief valve location, the LOX-30 Liquid Oxygen Generator does not present a significant personnel hazard. The cryogenerator engine requires close tolerances and is vulnerable to deficiencies in operating and maintenance procedures and techniques.

B. The Safety Analysis includes a Fault Hazard Analysis of thirteen components selected from the Failure Mode and Effects Analysis. An Observed Hazard Analysis, based on plant operation during reliability and maintainability testing at the Naval Air Engineering Center, investigated fifteen potential operational safety hazards.

C. Twenty-seven hazard classifications were assigned. The Fault Hazard Analysis produced thirteen component hazard classifications: four Category II, Marginal and nine Category III, Critical. Fourteen hazard classifications resulted from the Observed Hazard Analysis: four Category I, Negligible; five Category II, Marginal; four Category III, Critical and one Category IV, Catastrophic. The Category IV hazard classification was assigned to the location of the product storage vessel relief valve. All hazard classifications can be reduced by minor system design changes, adherence to established safety precautions, compliance with operating and maintenance publications and posting warning/advisory placards within the LOX-30 facility spaces.

II. PREFACE

The LOX-30 Liquid Oxygen Generator is a modularized air transportable unit for the production of high purity liquid oxygen. The Safety Analysis was performed to identify and qualitatively evaluate operating characteristics and component failure modes which might present hazards to personnel or equipment. A Fault Hazard Analysis of thirteen potentially safety related components yielded thirteen component hazard classifications. An Observed Hazard Analysis of fifteen operational safety areas resulted in the assignment of fourteen hazard classifications. Minor system design changes, adherence to established operational and maintenance safety precautions, and proper compliance with maintenance requirements and technical publications will mitigate the hazards.

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V. SAFETY ANALYSIS

A. BACKGROUND. The LOX-30 Liquid Oxygen Generator is a modularized, air transportable unit designed to produce liquid oxygen used in servicing aircrew survival equipment, medical units and aviators' breathing oxygen systems. Units are planned for installation at overseas Naval Air Stations, to be co-located with the PLN-430 Liquid Nitrogen Generator.

B. PURPOSE. This analysis was performed to identify and qualitatively evaluate any LOX-30 Liquid Oxygen Generator operating characteristics which might present a hazard to personnel or equipment. The areas considered include operation and maintenance of the generating plant, training requirements, structural and operational limitations and technical publications adequacy.

C. DESCRIPTION OF EQUIPMENT.

1. OPERATION. The LOX-30 Liquid Oxygen Generator is a modularized equipment used to produce high purity liquid oxygen from ambient air, primarily for use in the aviators' breathing application. Subsequent to an initial start up period of about six hours to achieve steady state conditions from a warm plant, operation is essentially automatic with a nominal production rate of 25 liters per hour. The equipment is designed to operate unattended except for periodic monitoring of instruments and lubricant levels. Predicated on scheduled maintenance requirements, continuous operation for sixty days is achievable. Plant shut-down, for maintenance or other reasons, up to 24 hours, is permissible following which steady state operation is attained in about four hours. Shutdown for more than 24 hours require plant deriming and a complete start-up cycle. The equipment is electrically powered and water cooled. External utility requirements are approximately 110 KW of 460 volts, three phase, 60 Hz electrical power and 20 gpm of cooling water. Electric systems can be modified to accept 50 Hz power.

2. MODULE UNITS. Each plant consists of five module units, viz., air compressor, molecular sieve station, cryogenerator, cold box separation unit and system control panel.

a. The two stage piston air compressor, with air cooled intercooler, is driven by a 40 HP motor and delivers 140 cfm at 80 psig. Compressor discharge air is cleaned in the molecular sieve station then used as process input for subsequent separation into product liquid oxygen and tail gas nitrogen. The air compressor is provided with operation monitoring devices and safety devices to provide protection against over pressurization and inadequate lubrication. Details of monitoring and safety devices will be developed in subsequent paragraphs.

b. The molecular sieve station is comprised of a water cooled aftercooler, a cartridge filter water separator, an activated alumina oil separator, two molecular sieve adsorbers, an electric heater and associated plumbing, valves and controls. The molecular sieve adsorbers are alternately on line or undergoing regeneration at a 60-90 minute cycling interval. The purpose of the molecular sieve station is to remove moisture, oil, gaseous hydrocarbons and other impurities from the process air prior to liquefaction. Safety devices provide protection against over pressurization and failure of the adsorber regeneration gas electric heater.

c. The cryogenerator is a closed cycle, four cylinder engine driven by a 60 HP electric motor. The cryogenerator process uses the Stirling cycle with helium as the working medium. Cryogenic temperatures are achieved by alternate compression and expansion of the working medium, effected by an out-of-phase piston and displacer operating within each cylinder. Heat generated within the engine from friction and helium compression is removed by continuously flowing water. A condenser head encloses the upper cylinder area. The process air is directed from the molecular sieve station through the cold box heat exchanger to the condenser head where initial liquefaction occurs. Internal engine tolerances are extremely critical both to achieve the required cold temperatures and to avoid engine self-destruction. Safety devices are incorporated to effect automatic shut-down in event of insufficient cooling water, lubrication interruption, excessive electric current, unequal cylinder pressures and excessive helium working pressure.

d. The cold box is a cylindrical steel vessel within which the liquid air from the cryogenerator is separated into product liquid oxygen and tail gas nitrogen. Separation is effected by rectification (fractional distillation); nitrogen being the more volatile, the process fluid continues to enrich in oxygen attaining a purity of 99.5% or greater. Components within the cold box include a counterflow heat exchanger, rectification column, condenser, a seventy liter storage tank and associated control valves and plumbing. The cold box is filled with perlite to insulate the cold areas and thereby limit heat transfer with the environment. A 1 KW electric heater is used to build pressure in the storage tank to transfer product oxygen to a pressurized receptacle or prevent entry of impure liquid from the column during short shut-down periods. Acetylene concentration must be monitored, particularly during shut-down, because it has a higher boiling temperature than oxygen. Therefore, as liquid oxygen boils off the concentration of acetylene in the remaining fluid increases. Liquid oxygen levels in the storage tank and the column must not drop below 80% of the levels at plant shut-down because further evaporation could cause excessive acetylene contamination.

e. The system control panel contains indicating instruments, indicating/alarm lights, pushbutton switches and an elapsed time meter, all of which are used in manual and automatic control of the plant. Controls and monitoring instruments in the cold box, molecular sieve station and air compressor are also required for operating the plant and monitoring its performance. Figure 1, Appendix A, is a functional block diagram which depicts the functional interrelationships of the various system modules and subsystems.

3. INDICATING/MONITORING DEVICES. The LOX-30 is equipped with gauges and indicator lights which enable the operator to monitor plant performance and provide subsystem fault indication in event of automatic plant shut-down.

a. Air Compressor.

(1) Oil Pressure Gauge. Displays oil pressure in the air compressor. Normal indication is 21-35 psig.

(2) Intercooler Pressure Gauges. Indicates pressure in the intercooler between the low pressure and high pressure cylinders. Normal indication is 30 psig.

(3) Discharge Pressure Gauge. Indicates air compressor discharge working pressure. Normal indication is 70 psig.

(4) Crankcase Oil Dip Stick. Indicates the oil level in the compressor crankcase. A "max" level line is inscribed on the dip stick.

b. Molecular Sieve Station.

(1) Aftercooler Water Flow Indicator. A window in the air aftercooler which provides a cooling water flow indication.

(2) Gas Flowmeter. Provides an indication of the amount of regenerating gas flowing through the adsorbers. Normal indication is 110-130 on the flowmeter scale.

c. Cold Box.

(1) Inlet Air Pressure Gauge. Indicates the pressure of the inlet air from the cryogenerator. Normal indication approximately 61 psig.

(2) Column Pressure Gauge. Indicates the pressure at the bottom of the rectification column. Normal indication is 3.5 psig.

(3) Storage Vessel Pressure Gauge. Displays the pressure in the liquid product storage tank. Normal indication during plant operation is 2 psig. Maximum pressure when transferring liquid product is 29 psig.

(4) Hampsonmeter. The hampsonmeter is a manometer type instrument used for reading the liquid level in the rectification column (LI-1) and the storage tank (LI-2). Normal indication for LI-1 is 9 divisions. Indications for LI-2 are 28-32 divisions normal, 40 divisions maximum.

d. Cryogenerator.

(1) Oil Level Sight Gauge. Indicates cryogenerator crankcase oil level. Normal indication is halfway up the sight gauge.

(2) Temperature Indicators In/Out. Indicate the inlet and outlet temperatures of the cryogenerator cooling water.

(3) Helium Charge Gauge. Indicates the pressure of the cryogenerator helium charge. Normal pressure range is 200 psig minimum to 350 psig maximum.

e. System Control Panel.

(1) Helium Pressure Gauge (4 ea.). Displays helium pressure in each cylinder of the cryogenerator. Normal average working pressure is 325 psig.

(2) Cryogenerator Oil Pressure Gauge. Provides an indication of cryogenerator oil pressure. Normal indication is 39 psig.

(3) Ammeter. Indicates the current drawn by one winding in the cryogenerator drive motor. Normal indication is 60 amperes.

(4) Indicator Lights. Provide an indication of compressor and cryogenerator on and the subsystem responsible for an automatic plant shut-down.

(5) Elapsed Time Meter. Provides an indication of cryogenerator operating time. Reads to 9,999.9 hours then automatically resets to zero.

4. SAFETY DEVICES. Numerous safety devices are installed in the LOX-30 to provide protection of the plant. These devices are located in all modules of the plant.

a. Air Compressor. Three safety devices are installed.

(1) Intermediate Pressure Relief Valve. Protects the compressor against over-pressurization of the intercooler. Valve opens at 38-40 psig.

(2) Discharge Pressure Relief Valve. Protects the LOX-30 plant against over-pressurization. Valve opens at approximately 100 psig.

(3) Oil Pressure Switch. Protects compressor from damage caused by insufficient lubrication. Switch initiates automatic compressor shut-down if oil pressure drops below 7 psig.

b. Molecular Sieve Station. Five safety devices are installed at the molecular sieve station.

(1) Water Flow Sensing Thermostat. Provides protection against insufficient cooling of process input air. Initiates automatic system shut-down when aftercooler discharge water temperature reaches 115°F.

(2) Column Pressure Relief Valve (900). Limits rectification column pressure when plant is temporarily shut-down. Valve opens at 1 to 2 bar.

(3) Tail Gas Relief Valve (901). Limits column tail gas pressure when plant is in operation. Valve set to relieve at 2 bar.

(4) Thermal Safety Switch. Switch senses adsorber regenerating gas temperature during adsorber switching. Initiates system shut-down if regenerating gas temperature does not reach 200°C within four minutes after adsorber changeover.

(5) Temperature Control Relay. Senses regeneration gas temperature and controls electric heater operation. Turns off electric heater current when gas temperature reaches 300°C.

c. <u>Cold Box</u>.

Storage Vessel Relief Valve (911). Prevents over-pressurization of the liquid product storage tank when the plant is temporarily shut-down and while transferring liquid product to an external receptacle. Valve opens at 29 psig.

d. <u>Cryogenerator</u>.

(1) Oil Pressure Switch. Prevents cryogenerator damage due to inadequate lubrication. The switch initiates system shut-down if the cryogenerator oil pressure drops below 25 psig or exceeds 75 psig.

(2) Cryogenerator Cylinder Temperature Switch (4 each). Each cylinder of the cryogenerator is equipped with a temperature sensing switch to prevent damage due to overheating. System shut-down is initiated when cylinder temperature reaches 150°F.

(3) Cryogenerator Oil Temperature Switch. Senses the temperature of the cryogenerator lubricating oil to prevent engine damage due to insufficient lubrication caused by reduced oil viscosity. Initiates automatic system shut-down if oil overheats.

(4) Water Flow Sensing Switch. Provides protection against insufficient cooling water flow. Senses the cooling manifold outlet water flow. Initiates automatic system shut-down when the cryogenerator cooling water outlet pressure drops below 30 psig.

(5) Condenser Head Relief Valve. Provides protection against condenser over-pressurization due to working medium or process air leaking into the condenser head insulation space. Valve opens at 2 psig.

e. System Control Panel.

(1) Helium Pressure Limit Switch (4 each). The helium pressure limit switches are built into the helium pressure gauges. Protection of the cryogenerator against over/under pressurization is provided by high and low pressure limit contacts. System shut-down is initiated when helium working pressure exceeds 375 psig or drops below 200 psig. Attempts to start the compressor, when helium pressure is less than 200 psig, will result in compressor shut-down within ten seconds.

(2) Differential Pressure Switch (2 each). These switches are connected between the pressure gauges for cylinders 1 and 3 and cylinders 2 and 4 of the cryogenerator engine. The switches sense pressure differences between cylinders which have the piston and displacer unit in the same relative positions. System shut-down occurs when differential pressure is 15 psig.

(3) Excess Current Cutout. Protects the cryogenerator drive motor from continuous excessive current. Relay is adjusted to 5.8 times the nominal current consumption. Activation of the excess current relay necessitates resetting the magnetic line starters before attempting to restart the cryogenerator.

(4) Zero Voltage Safety Device. The star delta starting relays protect the cryogenerator drive motor from momentary interruptions of line power. A disruption of source voltage will shut-down the system. Restart must be accomplished by normal starting procedures.

D. PROCEDURE. The LOX-30 Liquid Oxygen Generator Safety Analysis was predicated on data gathered from a number of sources. The Failure Mode and Effects Analysis (FMEA) provided a broad area for safety analysis by identifying the reasonably conceivable failure modes of system module components. The FMEA provided sufficiently detailed information concerning system safety aspects to facilitate the formulation of a Fault Hazard Analysis. 3M data for the Model B Nitrogen Liquefier, submitted during the period June 70 through May 75, were examined. The similiarity of the cryogenerator in the LOX-30 and the Model B justified this data review. The Reliability and Maintainability testing of the LOX-30, performed at the Naval Air Engineering Center, provided information from which an Observed Hazard Analysis was developed. The objective of the observations, examinations and evaluations was to achieve qualitative results which were analytically substantiated whenever possible. This was accomplished to assign realistic hazard classifications to potential LOX-30 Liquid Oxygen Generator failures and operating conditions which have safety implications.

E. FAULT HAZARD ANALYSIS.

1. GENERAL. Fault Hazard Analysis (FHA) provides a systematic procedure for examining significant equipment/component failure modes, determining the subsequent effect on the system and identifying related system hazards. The LOX-30 Failure Mode and Effects Analysis was reviewed and those modes which had potential safety implications were made candidates for the FHA. Appendix B contains FHA and reflects those components whose failure could pose safety hazards to the equipment or to personnel.

2. HAZARD CLASSIFICATION. A hazard is defined as any real or potential condition that can cause injury or death to personnel or damage to equipment or property. The severity of the hazard is classified in accordance with "MIL-STD-882, Systems Safety Program for Systems and Associated Sub-systems and Equipment". Hazard Classifications are as follows:

a. Category I - Negligible. Condition(s) such that personnel error, environment, design characteristics, procedural deficiencies or subsystem/component failure or malfunction will not result in system damage or personnel injury.

b. Category II - Marginal. Condition(s) such that personnel error, environment, design characteristics, procedural deficiencies or subsystem/component failure or malfunction can be countered or controlled without injury to personnel or major system damage.

c. Category III - Critical. Condition(s) such that personnel error, environment, design characteristics, procedural deficiencies or subsystem/component failure or malfunction will cause personnel injury or major system damage, or will require immediate corrective action for personnel or system survival.

d. Category IV - Catastrophic. Condition(s) such that personnel error, environment, design characteristics, procedural deficiencies or subsystem/component failure or malfunction will cause death or severe injury to personnel or system loss.

3. COMPONENTS. Thirteen components contained in the Failure Mode and Effects Analysis, for which safety implications were indicated, were selected for Fault Hazard Analysis. Twenty-seven failure modes were evaluated; twenty-three hazard classifications were assigned. The Fault Hazard Analysis candidates, evaluation summaries, hazard classifications, and a discussion on resolution of hazards follows:

a. Valve, Regenerating Gas Heater (760). The regenerating gas heater valve (760) directs regenerating gas flow through the electric heater during the fifteen minute gas heating period. At the end of the heating time, the valve closes to by-pass the heater and route cool gas directly to the adsorber under regeneration. The valve can stick in either the heat or by-pass position. Should the valve stick in the heater position, regeneration gas will be continuously directed across the heater element. Since the heater is activated for only fifteen minutes of the adsorber regeneration cycle, cooling of the molecular sieve would occur, but at a slower rate until the heater elements had cooled to gas temperature. Reduced product purity could result. This hazard is mitigated by testing the output product for purity. A Category I, Negligible, hazard classification was assigned. Failure of the valve by sticking in the by-pass position prevents tail gas from being directed across the electrical heater element. Without this gas flow, the heating element will over-heat. Since the temperature control relay (TC-4) depends on gas flow for heat transfer from the heating element to the control relay thermal sensor, this failure can result in heater burn-out and possible gas plumbing damage. A Category III, Critical, hazard classification was assigned.

b. Thermostat, Temperature Control Relay (TC-4). The temperature control relay thermostat senses the temperature of the heated regenerating gas and provides the control signal to remove electric power from the heater when gas temperature reaches 300°C. The thermostat is subject to two failure modes; failure to open and failure to close. Failure of the thermostat switch to open would allow power to be constantly applied to the regenerating gas heating element. Excessively high regenerating gas temperature could result and the heating element could burn out. A Category III, Critical, hazard classification was assigned. Failure of the thermostat switch to close, after it has opened, would result in system shut-down within four minutes after the gas cools below 200°C due to the action of safety thermostat (TA-5) and the four minute time relay (T-1). A hazard classification was not assigned.

c. Thermostat, Safety (TA-5). The safety thermostat prevents operating the plant with unregenerated adsorbers. The thermostat causes automatic system shut-down in the event adsorber regenerating gas has not reached 200°C within four minutes after adsorber switching. The thermostat is subject to two failure modes; failure to open and failure to close. Failure to open would cause the plant to shut-down with a properly operating gas heater; a nuisance shut-down. No hazard classification was assigned. Failure of the thermostat to close, after it has opened, will disable the insufficient regenerating gas temperature time relay (T-1) which will allow plant operation with inadequately regenerated adsorber if the regeneration gas heater fails. Product purity will decrease. A Category II, Marginal, hazard classification was assigned.

d. Valve, Tail Gas Relief (901). The tail gas relief valve prevents over-pressurization of the column during plant operation. Two failure modes were analyzed; valve opens at higher than specified pressure and failure to close. Valve opening at higher than specified pressure causes an increased pressure in tail gas plumbing and the rectification column. A Category II, Marginal, hazard classification was awarded. Failure of the valve to close will continuously vent tail gas to the atmosphere. A Category II, Marginal, hazard classification was awarded. A failure of this valve would be associated with another system component failure or an operational procedure error which resulted in raising the rectification column pressure.

e. Valve, Column Pressure Relief (900). The column pressure relief valve prevents over-pressurization of the rectification column during periods of temporary plant shut-down. Two failure modes were analyzed, valve opens at higher than specified pressure and failure to close. Valve opening at higher than specified pressure would result in transfer of impure liquid from the column to the storage tank. The occurrence of this failure mode is considered unlikely, therefore, a Category II, Marginal, hazard classification was assigned. Failure of the valve to close would reduce column pressure and cause more rapid boil-off of column liquid. Contamination of the column liquid would result. This hazard can be mitigated by sampling the column liquid and deriming the plant before liquid purity approaches hazardous levels. A Category II, Marginal, hazard classification was assigned. Failures to this valve would be precipitated by another system failure which raised column pressure sufficiently to necessitate opening of the valve.

f. Valve, Float Controlled Column Inlet (120). The float controlled column inlet valve controls entry of process air into the rectification column. Air inlet is dependent on the condenser liquid level. Two failure modes, sticking open and sticking closed, were analyzed. Failure of the valve by sticking open permits process air to enter the column continuously and reduce the column temperature. Liquid product purity will decrease. A Category II, Marginal, hazard classification was assigned. Failure of the valve by sticking closed has more serious considerations. Process air cannot enter the column which will reduce the air flow through the cryogenerator and cause the condenser head to become excessively cold. With no input to the column, process fluid will drain from the column and reduce output product purity. When column liquid level has decreased sufficiently to close the float controlled transfer valve (236), gaseous oxygen will boil-off the liquid trapped in the column and possibly result in acetylene enrichment of the column fluid. A Category III, Critical, hazard classification was assigned.

g. Valve, Float Controlled Transfer (236). The float controlled transfer valve controls the rate at which liquid product is transferred to the storage tank. Additionally, this valve controls the liquid level in the column effecting product purity. Two failure modes were analyzed, sticking open and sticking closed. Should the valve fail in the open position liquid will be transferred too rapidly to the storage tank and product purity will decrease. A Category II, Marginal, hazard classification was assigned. Failure of the valve in the closed position prevents transfer of liquid product from the column to the storage tank. Liquid level in the rectification column and the condenser will increase until the float controlled column inlet valve (120) closes. Air flow through the cryogenerator will decrease and the cryogenerator will become excessively cold. A Category III, Critical, hazard classification was assigned.

h. Valve, Storage Tank Vent (281). The storage tank vent valve provides for venting gaseous oxygen from the storage tank during plant production, pressurizing the storage vessel to transfer product output to a pressurized receptacle and pressurizing the storage vessel to prevent column liquid transfer during temporary plant shut-down periods. Two failure modes, sticking open and sticking closed, were analyzed. Failure of the valve in the open position presents a nuisance factor if liquid product is to be transferred to a pressurized receptacle. Upon plant shut-down, column liquid will be transferred to the storage vessel until the float controlled transfer valve (236) closes. A Category I, Negligible, hazard classification was assigned. Failure of the valve in the closed position prevents transfer of liquid from the column if storage tank product transfer valve (240) is closed. Column liquid level will increase until process air to the column is shut off at which time the cryogenerator will become excessively cold due to reduced air flow. The hazard can be lessened by opening storage tank product transfer valve (240). A Category III, Critical, hazard classification was assigned.

i. Valve, Storage Tank Product Transfer (240). The storage tank product transfer valve controls outflow of liquid product from the plant storage vessel to an external storage receptacle. The failure modes sticking open and sticking closed were analyzed. Sticking in the open position prevents regulating product off-take. A Category II, Marginal, hazard classification was awarded. Sticking of the valve in the closed position prevents transfer of product from the storage tank which will cause the fluid level in the tank to rise until liquid oxygen is vented out the storage tank vent line. Correction requires deriming the plant. A Category III, Critical, hazard classification was assigned.

j. Valve, Storage Tank Relief (911). The storage tank relief valve prevents over-pressurization of the product storage tank during periods when the plant is temporarily shut-down or when transferring product liquid to a pressurized external receptacle. Two failure modes were analyzed; failure to open at specified valve and failure to close. Failure of the relief valve to open at prescribed pressure results in over-pressurization of the tank. Severe plumbing and structural damage can occur, however, the probability of this failure is low and the hazard can be mitigated by opening the storage vessel vent valve. A Category III, Critical, hazard classification was assigned to this failure mode. Failure of the relief valve to close will vent gaseous oxygen continuously from the storage vessel and reduce storage tank pressure. Liquid boil-off will be accelerated and liquid in the column may be transferred to the storage tank. Deriming the plant is required if storage tank liquid level drops to less than 80% of the level at plant shut-down. A Category III, Critical, hazard classification was awarded.

k. Switch, Cryogenerator Oil Pressure. The cryogenerator oil system can provide inadequate lubrication if pressure is below 25 psig. Should oil pressure rise above 75 psig, an oil by-pass opens to return a large portion of the oil to the crankcase to protect internal engine plumbing. The oil pressure switch initiates system shut-down to protect the cryogenerator engine from damage due to insufficient lubrication should either of these pressure limits be exceeded. Three failure modes were analyzed, failure of the switch to open above 25 psig, failure of the switch to close below 25 psig and failure of the switch to close above 75 psig. Failure of the switch to open above 25 psig will cause the system to shut-down as soon as the cryogenerator start button is released. No damage to the cryogenerator will result, however, the fault must be corrected before the plant can be operated. Evaluated as a nuisance shut-down, no hazard classification was assigned. Failure of the switch to close below 25 psig oil pressure will permit the cryogenerator to continue to run with inadequate flow of cooling and lubricating oil. The engine will overheat and possibly sustain internal damage. The hazard is lessened by the cylinder temperature switches, installed on each cylinder, which initiate engine shut-down when the external cylinder temperature reaches 150°F. A Category II, Marginal, hazard classification was awarded. Failure of the oil pressure switch to close at pressures above 75 psig allows the engine to run with reduced oil flow through the cylinder cooling jackets. The engine will overheat and possibly sustain internal damage. This hazard is mitigated by the cylinder external temperature switches, explained above. A Category II, Marginal, hazard classification was awarded due to the low probability of occurrence and the protection provided by the cylinder temperature switches. A failure in the cryogenerator oil system would be required to cause a failure of the oil pressure switch.

l. Switch, Helium Pressure Cutout. The helium pressure cutout switch is an integral part of the cryogenerator cylinder gauge(s). When cylinder average working pressure rises above 375 psig or drops below 200 psig the switch closes and initiates automatic system shut-down. Two failure modes which have safety implication, switch fails to close below 200 psig or above 375 psig, were analyzed. A third failure mode, switch fails to open above 200 psig, does not have safety connotations, but does result in nuisance shut-down of the plant. Failure of the switch to close below 200 psig cylinder working pressure will result in the plant producing little or no liquid output due to insufficient cryogenic action. The hazards of this failure are lessened by monitoring cylinder pressure gauges and the liquid level in the column and manually securing the plant. A Category II, Marginal, hazard classification was assigned. Failure of the switch to close at cylinder working pressure above 375 psig can result in severe internal damage to the cryogenerator. Engine temperature will rise due to heat of excessive compression, excessive current will be drawn by the cryogenerator drive motor and output product purity will decrease. The excess current cutout relay guards against excessive motor current and the cylinder temperature switches provide protection against engine overheating. Product purity decrease is detectable by sample testing of liquid output product. A Category III, Critical, hazard classification was assigned.

m. Switch, Differential Pressure (2 each). Differential pressure switches are connected between the output of cryogenerator cylinders which have the pistons in the same relative position at the same time. Switches are connected between cylinders 1 and 3 and cylinders 2 and 4. The switches close to initiate automatic system shut-down when the pressure differential between matching cylinders reaches 15 psig. Two failure modes were analyzed; switch closes at too low pressure differential and switch fails to close. Failure of the differential pressure switch to close will permit the engine to continue operating with internal failure such as a collapsed displacer dome, piston ring leakage or displacer ring leakage. Continued engine operation under these conditions can cause a relatively minor internal failure to degenerate into severe engine damage. The effect of differential switch failure to close can be lessened by monitoring cylinder pressure gauges and manually securing the plant. A Category III, Critical, hazard classification was assigned. Differential pressure switch closure at low pressure differentials will cause unnecessary automatic shut-down of the plant, however, damage to cryogenerator will not be sustained. A hazard classification was not assigned to this failure mode.

4. HAZARD CLASSIFICATIONS. Hazard classifications were assigned to all of the components selected for Fault Hazard Analysis. Multiple failure modes were evaluated for all components and, where appropriate, different hazard classifications were assigned to the individual failure modes. The hazard classification assigned to a component was the most severe classification awarded to any failure mode of that component. Category II, Marginal, hazard classification was assigned to four components; Category III, Critical, was assigned to nine components. The hazard classification assigned to each component is shown in Table 1.

TABLE I

COMPONENT HAZARD CLASSIFICATION

COMPONENT	HAZARD CLASSIFICATION
Thermostat, Safety (TA-5)	II
Valve, Tail Gas Relief (900)	II
Valve, Column Pressure Relief (901)	II
Switch, Cryogenerator Oil Pressure	II
Valve, Regenerating Gas Heater (760)	III
Thermostat, Control (TC-4)	III
Valve, Float Controlled Column Inlet (120)	III
Valve, Float Controlled Transfer (236)	III
Valve, Storage Tank Vent (281)	III
Valve, Storage Tank Product Outlet (240)	III
Valve, Storage Tank Relief (911)	III
Switch, Helium Pressure Cut-Out	III
Switch, Differential Pressure	III

5. Discussion and Resolution of Fault Hazards provided as attachment, Appendix D.

F. SHIPS 3M DATA.

1. Ships' 3M data for the Model B Nitrogen Liquefier were examined for information related to the cryogenerator. Data reviewed covered a reporting period from June 1970 to May 1975. The similiarity between the cryogenerators of the Model B and the LOX-30 justified this data review. Salient facts obtained from 3M data are as follows:

a. Technical Publicaticn. The complexity of the cryogenerator requires that the technical publication thoroughly expound on the theory of operation, contain explicit instructions for operating and maintaining the unit and include a comprehensive illustrated parts breakdown. 3M data contained twenty instances which specified inadequate publications or procedures as the cause of the difficulty; two requests for technical assistance to determine the cause of cryogenerator faults implied technical publication inadequacy. The technical publication for the Model B "NAVSHIPS 0923-004-9010 TECHNICAL MANUAL FOR MODEL B NITROGEN LIQUEFIER", while reported inadequate is far superior to the LOX-30 data package technical publication, "TECHNICAL MANUAL OPERATION AND MAINTENANCE INSTRUCTIONS LOX-30 PORTABLE LIQUID OXYGEN PLANT, July 1976".

b. Maintenance Training. The Stirling Cycle cryogenic process demands that close tolerances be used and adhered to in assembling and repairing the cryogenerator. 3M data indicated that repair or assembly deficiencies were a factor in eleven of the failures included in the data. Training courses for cryogenerator maintenance must fully acquaint maintenance personnel with the close tolerances involved and stress strict adherence to proper repair and assembly procedures.

2. Provided as attachment, Appendix E.

G. NAVAL AIR ENGINEERING CENTER

1. The Naval Air Engineering Center conducted reliability and maintainability testing of the LOX-30 from March to September 1977 and accumulated 1,620 plant operating hours. During this testing, attention was directed toward functional or environmental threats to either personnel or plant safety. The following potential hazards were made the subject of an Observed Hazard Analysis.

a. Electric Shock

b. High Temperature Surfaces

c. Low Temperature Surfaces

d. High Pressure Fluids and Gases

e. Static Generating Material

f. Toxic Material

g. Mechanical Vibration

h. Floor and Overhead Obstruction

i. Rotating Machinery

j. Equipment Physical Stability

k. Operating Control Accessibility

l. Atmospheric Contaminants

m. Noise

n. Proximity of Incompatible Systems/Components

o. Personnel Ingress/Egress

H. OBSERVED HAZARD ANALYSIS.

1. GENERAL. The Observed Hazard Analysis provides a procedure to evaluate hazardous conditions which are a result of equipment operation. The criteria for hazard classification are the same as those used for Fault Hazard Analysis. The Observed Hazard Analysis is contained in Appendix C.

2. SAFETY AREAS. Fifteen potential safety hazards which could arise during operation of the LOX-30 were studied. Fourteen hazard classifications were assigned. The Observed Hazard Analysis safety areas, evaluation summaries, hazard classifications and a discussion on resolution of hazards follows:

a. Electric Shock. The LOX-30 consumes approximately 110 KW of electrical power. Voltage present in the plant are 115V, 230V, and 380V or 460V. All voltage levels are potentially lethal. Electrical shock hazards can be significantly reduced when simple precautions are taken. All units of the plant should be electrically bonded and properly grounded. Rubber matting should be installed at all modules where operating and maintenance personnel will come in contact with the unit. Warning placards indicating the voltage levels present should be displayed. Placards providing shock treatment and resuscitation procedures should be posted in the plant. A Category III, Critical, hazard classification was assigned.

b. High Temperature Surfaces. The compressor discharge plumbing contains air which was heated to 252°F above ambient temperature by the compression process. Separation column tail gas which is used to regenerate the adsorbers is heated to 590°F. This hazard can be reduced by thermally insulating plumbing and plant units which have elevated external surface temperature. "Hot Spot" placards should be displayed at those locations where the installation of thermal insulation is not feasible. A Category II, Marginal, hazard classification was assigned.

c. Low Temperature Surfaces. The cryogenic process of the LOX-30 plant is contained within cryogenically insulated vessels and plumbing. The only low temperature fittings which are normally exposed are the liquid product discharge connection and the storage tank gaseous oxygen vent connection, both of which become extremely cold during plant operation. This hazard can be mitigated by the installation of low temperature warning placards and by ensuring that all operators wear required protective clothing. A Category I, Negligible, hazard classification was assigned.

d. High Pressure Fluids and Gases. The LOX-30 contains only low or medium pressure fluids and gases. Process air pressure from the compressor varies from 65-87 psig. Cooling water pressure is normally 58 psig. Cryogenerator working medium pressure varies from 200-375 psig and is contained within the cryogenerator engine. Little can be effectively done to reduce the presence of this hazard, however, placards advising the pressures present in the plant should be posted. A Category II, Marginal, hazard classification was assigned.

e. Static Generating Material. A potential for oxygen enrichment of the atmosphere in the LOX-30 plant exists. Synthetic and wool fabrics generate static electricity when relative humidity is low. Static electricity in an oxygen enriched atmosphere presents a fire hazard. A Category II, Marginal, hazard classification was awarded. This hazard can be reduced by ensuring that operating and maintenance personnel wear cotton clothing. Placards warning of the static electricity hazard from synthetic or wool fabrics should be displayed in the plant spaces.

f. Toxic Materials. The hampsonmeter is filled with S-TETRA-Bromoethane liquid, a poisonous compound. When combined with moisture it will hydrolyze to form an acid. During use of the hampsonmeter, the liquid can be vented from the top of the meter and sprayed on the operator. A Category III, Critical, hazard classification was assigned. This hazard can be reduced by placarding the cold box control panel to advise the use of extreme caution when using the hampsonmeter. A non-toxic fluid with the same physical properties should be investigated for use in the hampsonmeter.

g. Mechanical Vibration. The vibration level at the compressor discharge manifold is high. The compressor discharge line failed twice during LOX-30 reliability and maintenance testing due to vibration from the compressor. The studs used to connect the compressor discharge flange to the molecular sieve flexible line flange were too short to be properly gripped by the nuts. Mechanical vibration was awarded a Category III, Critical, hazard classification. This hazard can be countered by designing a bracket to support the compressor discharge line. Connecting flange studs should be replaced with machine bolts to permit insertion of longer bolts if securing nuts do not have sufficient grip. Properly torqued metal stop nuts should be used for plant plumbing connection to prevent loosening of nuts due to mechanical vibration.

h. Floor and Overhead Obstructions. The LOX-30 plant installation requires numerous plumbing and cable runs along the floor and overhead. These obstructions present a tripping and bumping hazard. A Category I, Negligible, hazard classification was assigned due to the ease of mitigating the hazard. Overhead plumbing should be at least seven feet above the floor. Installation of covers over floor level plumbing will significantly reduce the tripping hazard. Display placards warning of any tripping hazard.

i. Rotating Machinery. The cryogenerator drive motor is connected to the engine by a flexible coupling. The coupling is shielded by a cover mounted to the cryogenerator bed plate. The air compressor V-belt connection to the drive motor is shielded by a cover mounted on the compressor skid. A Category I, Negligible, hazard classification was assigned. Ensure that coupling and V-belt shields are in position prior to plant operation.

j. Equipment Physical Stability. The cold box, a cylinder 53 inches in diameter, 94 inches high and weighing 2,205 pounds, rests on three unattached leveling stands twelve inches tall. Vibration or severe bumping could cause the cold box to fall off the stands. Extensive damage to the plant or injury to personnel could result if the cold box slipped off the stands. A Category III, Critical, hazard classification was assigned. This hazard is considered unlikely and can easily be countered by bolting the cold box to the stands.

k. Operating Control Accessibility. The operating controls and indicators on the cold box control panel and the system control panel can be reached without stretching or reaching. The pressure gauges on the air compressor skid require only moderate bending to ensure accurate readings. No hazard classification was assigned.

l. Atmospheric Contaminants. The rectification column tail gas contains a high concentration of nitrogen which will not sustain life. Storage tank vent gas is pure oxygen which would cause oxygen enrichment in the immediate area of the vent discharge. Venting these gases into the plant enclosure space would result in a general increase in the nitrogen level of the space atmosphere. Such an increase would be hazardous to plant personnel. A Category II, Marginal, hazard classification was assigned. This hazard can be mitigated by ducting all plant vent gases to the outside of the plant enclosure. Ensure adequate plant ventilation from a source remote from plant gas discharge vents.

m. Noise. During reliability and maintainability testing, the compressor noise level was measured at 104 dbA with a SPL-103 Sound Level Meter. The maximum unprotected exposure to this sound level is one hour per day. Longer exposure can result in hearing loss. A Category II, Marginal, hazard classification was assigned to this safety area. The hazard can be countered by locating the compressor in a separate room from the rest of the plant or ensuring that personnel wear effective sound attenuators in the space which contains the air compressor. Display noise hazard area placards in the air compressor space.

n. Proximity of Incompatible Systems/Components. The liquid oxygen storage vessel pressure relief valve is mounted on the cold box above the instrument/control panel. When the relief valve opens, liquid oxygen, at -297°F, is sprayed in the control panel area. A Category IV, Catastrophic, hazard classification was assigned. This most serious hazard can be effectively countered by relocating the relief valve and installing vent piping to duct storage vessel blow-off oxygen to the atmosphere outside the plant enclosure.

o. Personnel Ingress/Egress. The LOX-30 requires access to all modules of the plant for scheduled and corrective maintenance. The cryogenerator winch is required for removal of the condenser head. A Category I, Negligible, hazard classification was assigned. Ensure that the plant installation provides sufficient clearance around all modules for personnel movement and equipment maintenance.

3. HAZARD CLASSIFICATION. The Observed Hazard Analysis yielded fourteen areas which exhibited potential safety problems. Four potential hazard areas were classified as Category I, Negligible; five were assigned Category II, Marginal; and four were assigned Category III, Critical. The safety area Proximity of Incompatible Systems/Components was assigned a Category IV, Catastrophic, hazard classification due to the location of the cold box liquid oxygen storage tank relief valve. The hazard classification assigned to each observed safety area is shown in Table II.

TABLE II

OBSERVED HAZARD CLASSIFICATION

OBSERVED AREA	HAZARD CLASSIFICATION
Operating Control Accessibility	--
Low Temperature Surfaces	I
Floor and Overhead Obstructions	I
Rotating Machinery	I
Personnel Ingress/Egress	I
Atmospheric Contaminants	II
High Pressure Fluids and Gases	II
Static Generating Material	II
High Temperature Surfaces	II
Noise	II

TABLE II (CONT.)

OBSERVED HAZARD CLASSIFICATION

OBSERVED AREA	HAZARD CLASSIFICATION
Electric Shock	III
Toxic Material	III
Mechanical Vibration	III
Equipment Physical Stability	III
Proximity of Incompatible Systems/Components	IV

4. Discussion and Resolution of observed hazards provided as attachment, Appendix F.

VI. CONCLUSIONS

A. The existing location of the LOX-30 liquid oxygen storage tank relief valve presents a severe safety hazard to operating personnel.

B. Except as noted above, the LOX-30 Liquid Oxygen Generator is functionally safe for producing liquid oxygen with minimal hazard to attending personnel.

C. The propensity of the air compressor and cryogenerator engine to sustain severe damage if not properly operated and maintained makes comprehensive maintenance training and complete, lucid technical manuals mandatory.

D. The Safety Analysis identified four Category I, Negligible, hazards; nine Category II, Marginal, hazards; thirteen Category III, Critical, hazards; and one Category IV, Catastrophic, hazard.

VII. RECOMMENDATIONS

A. Install shield around storage vessel relief valve to prevent spraying of liquid oxygen on operating personnel.

B. Develop a comprehensive LOX-30 maintenance training course.

C. Ensure the availability of complete, accurate technical publications covering maintenance and operating procedures.

D. Ensure that covers are installed over floor level plumbing and electrical cabling; ensure that conduit is installed on electrical cables.

E. Install vibration adsorber at the output of the air compressor.

F. Locate the air compressor to reduce the noise level in the cryogenic equipment space or ensure that sound attenuators are worn by operating personnel.

G. Ensure adequate ventilation of plant spaces to preclude atmospheric contamination by nitrogen and/or oxygen.

H. Replace plumbing connecting flange studs with machine bolts secured by metal stop nuts.

I. Securely attach cold box stands to the cold box.

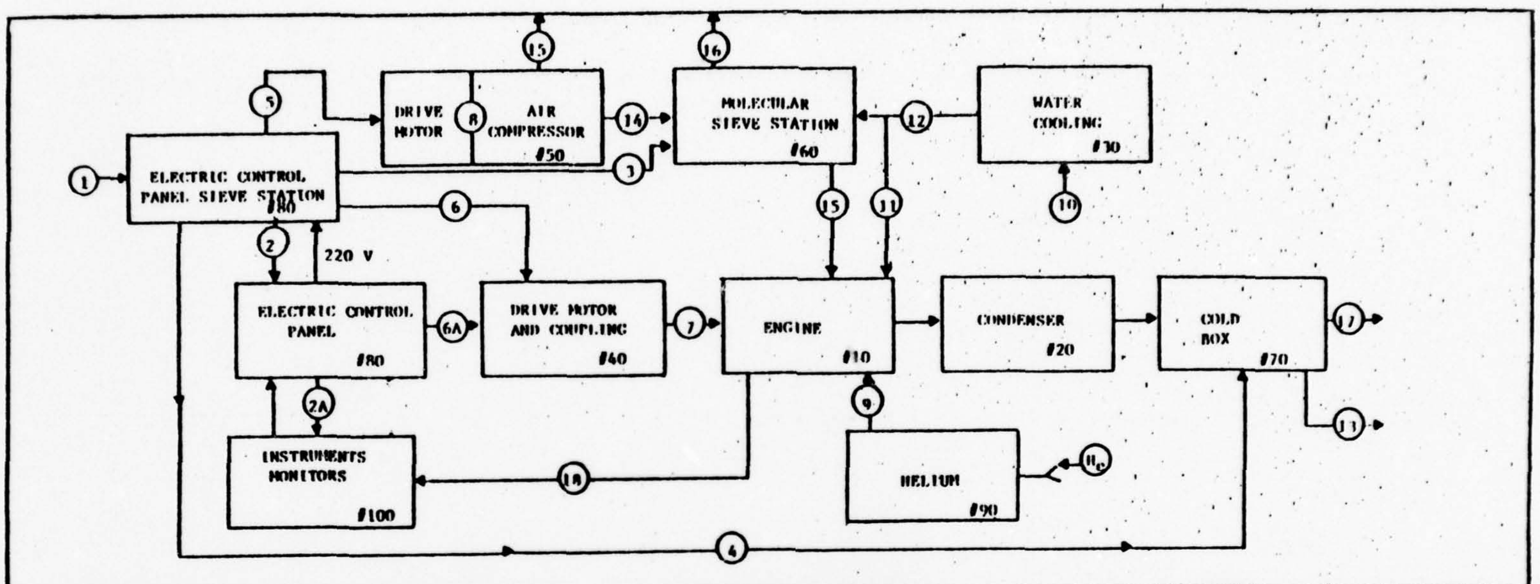
J. Ensure the use of protective clothing by plant operating personnel.

K. Display warning/advisory placards to indicate system pressures, voltages and high/low temperature areas as required in equipment operational spaces; include applicable first aid posters.

L. Install non-conducting rubber matting at all consoles and control stations.

M. Replace hampsonmeter with a differential pressure gauge on the cold box control panel.

APPENDIX A



CODE	FUNCTION	DESCRIPTION
1.	Line Power	380/460V, 3Ø 103KW, 50/60 Hz
2.	Control Power Cryo Panel	220V, 60 Hz
	A. Instrument Panel	115/220V
3.	Control Power Sieve Station	220V, 1Ø 60 Hz 380/460 3Ø 50/60 Hz
4.	Heater Power Column E1	220V 1Ø 50/60 Hz
5.	Drive Motor Power, Compressor	380/460V 50/60 Hz 3Ø, 30KW
6.	Drive Motor Power, Cryogenerator	460V, 60 Hz 3Ø 51KW
	A. Cryogenerator Safety Cutouts	220V
7.	Torque, Engine	Function of 3Ø Power Direct Drive Thomas Type Coupling
8.	Torque, Air Compressor	Function of 3Ø Power Belt and Sheave
9.	Helium Charge Line	Static Charge 230-240 psig
10.	Water Supply	20.0 gal/min
11.	Engine Water Supply	16 gal/min. 30 psig 59°F

CODE	FUNCTION	DESCRIPTION
12.	Sieve Station Water Supply	4.0 gal/min
13.	Liquid O_2 output	6.93 gal/hr, 0 psig
14.	Compressor Discharge Air	60 psig, 252°F.
15.	Compressor Safety Devices	
	A. Over Pressure	100 psig
16.	Molecular Sieve Station	
	A. Over Pressure Valve 901	2 bar
17.	Column	
	A. Storage Tank Relief Valve 911	3 bar
18.	Engine Sensor	
	A. Water Flow (gal/hr)	
	B. Cyl/Crankcase Temp	150°F
	C. Differential Pressure	15 psig
	D. Oil Pressure	25 to 75 psig
	E. Working Pressure	200-175 psig

FIGURE 1

FUNCTIONAL BLOCK DIAGRAM

APPENDIX B

LOX-30 LIQUID OXYGEN GENERATOR

FAULT HAZARD ANALYSIS

COMPONENT	FUNCTION	FAILURE MODE	OPERATIONAL MODE	FAILURE CAUSE	SECONDARY CAUSE	EFFECT ON SYSTEM	HAZ CLASS	SAFETY HAZARD DESCRIPTION
Valve, Regenerating Gas Heater (760)	Routes regenerating gas through electric heater or direct to adsorbers (A1) or (A2).	1. Sticks in Heater position.	Normally in bypass position, energized to heater position.	1. Material failure.	1. Failure of 15 minute time delay relay (3d6)	1. Regeneration gas will continue to pass through heater (EH-1) although heater power is off. Reduced cooling of adsorber molecular sieve mass.	II	Reduced product if operated for extended periods.
		2. Stick in bypass position.		1. Material failure.		1. Regeneration gas not routed through heater. Electric heater coil will overheat. Safety thermostat and temperature control relay operation depend on air flow, therefore, system may not shut down.	III	Electric heater can burn out. Excessive heat can damage plumbing.
Thermostat Control (TC4)	Controls temperature of adsorber regeneration gas.	1. Fails to open.	Normally closed.	1. Material failure.	---	Regeneration gas heater operates continuously during adsorber heating.	III	1. Heater element (EH-1) can burn out 2. System air plumbing can be damaged by excessive heat.
		2. Fails to close.		1. Material failure.	---	Regeneration gas heater inoperative.	--	1. Not a safety hazard. System will shut down 4 minutes after gas cools below 200°C.
Thermostat, Safety (TA-5)	Prevent system operation with inadequately regenerated adsorbers.	1. Fails to close.	Closed when regeneration gas temperature below 200°C.	1. Material failure.	---	System can operate with insufficient adsorber regeneration.	III	Output product contaminated.
		2. Fails to open.		1. Material failure.	---	System will shut down with properly operating regeneration heater.	--	Nuisance shut down.
Valve, Tailgas, Relief (900)	Prevents over-pressurization of column during plant operation.	1. Fails to open.	Normally closed.	1. Material failure.	---	Regeneration plumbing is overpressurized. Back pressure applied to column.	II	Product decreases.
		2. Fails to close.		1. Material failure.	---	Tail gas will vent to atmosphere. Inadequate adsorber regeneration.	II	Output product contaminated.

LOX-10 LIQUID OXYGEN GENERATOR

FAULT HAZARD ANALYSIS

COMPONENT	FUNCTION	FAILURE MODE	OPERATIONAL MODE	FAILURE CAUSE	SECONDARY CAUSE	EFFECT ON SYSTEM	HAZ CLASS	SAFETY HAZARD DESCRIPTION
Valve, column pressure relief (901)	Relieve column gas pressure during short term plant shut down.	1. Valve opens at higher than specified pressure.	Normally closed.	1. Material failure.	1. Improperly adjusted.	Gas pressure in rectification column higher than normal.	II	Impure liquid in column can be transferred to storage tank.
		2. Valve fails to close.		1. Material failure.	1. Contamination.	Rectification column will be at approximately atmospheric pressure.	II	Liquid product will boil off more rapidly than normal. Liquid becomes contaminated.
Valve, float controlled column (120) inlet	Control entry of process air into rectification column.	1. Valve sticks open.	Alternately open and closed.	1. Material failure.	---	Process air will expand into column continuously	II	Purity of liquid product is reduced.
		2. Valve sticks closed.		1. Material failure.	---	Process air cannot enter rectification column. Liquid product will be trapped in column.	III	Cryogenerator will become too cold. Liquid trapped in column may become acetylene enriched.
Valve, float controlled transfer (236)	Control liquid level in column; transfer liquid product.	1. Valve sticks open.	Alternately open and closed.	1. Material failure.	---	Liquid product will be transferred too rapidly to storage tank; liquid level in column will drop.	II	Liquid product is reduced.
		2. Valve sticks closed.		1. Material failure.	---	Liquid product will not be transferred to storage tank. Liquid level in storage tank will drop. Level is column will rise as liquid drains from column trays. Process air does not enter column.	III	Cryogenerator will become too cold.
Valve, storage tank vent (281)	Vent gas oxygen from storage vessel.	1. Valve sticks open.	Normally open.	1. Material failure.	---	1. Gas oxygen vents continuously. 2. Storage tank cannot be pressurized.	I	Liquid product in storage tank will quickly become contaminated. Derime required.
		2. Valve sticks closed.		1. Material failure.		1. Liquid product will not transfer from column; no production.	III	Cryogenerator will become too cold.

LOX-10 LIQUID OXYGEN GENERATOR

FAULT HAZARD ANALYSIS

COMPONENT	FUNCTION	FAILURE MODE	OPERATIONAL MODE	FAILURE CAUSE	SECONDARY CAUSE	EFFECT ON SYSTEM	HAZ CLASS	SAFETY HAZARD DESCRIPTION
Valve, storage tank product outlet (240)	Control liquid product transfer from storage vessel to external receptacle.	1. Valve sticks open.	Normally open during plant production.	1. Material failure.	---	1. Unable to pressurize storage vessel when plant is shut down.	II	Product from column will be transferred to storage tank.
		2. Valve sticks closed.		1. Material failure.	---	1. Unable to transfer liquid product to external receptacle. 2. Liquid level in storage tank will continue to rise.	III	Liquid product will flow out of storage tank vent line.
Valve, storage tank relief (911)	Relieve excess pressure from storage tank when tank vent valve is closed.	1. Valve fails to open.	Normally closed	1. Material failure.	Improperly adjusted.	Gas oxygen pressure is not relieved.	III	Storage tank will overpressurize.
		2. Valve fails to close.		1. Material failure.	Contamination.	Storage vessel is at atmospheric pressure. Oxygen boil-off rate increases.	III	Product in tank becomes contaminated, possible acetylene enrichment.
Switch, cryogenerator oil pressure	Protect cryogenerator engine. Initiates system shut down when oil pressure drops below 25 psig or rises above 75 psig.	1. Fails to open when oil pressure builds above 25 psig.	Normally open at operating pressure. Closes at 25 psig and at 75 psig.	1. Material failure.	Internal oil leak.	Cryogenerator will stop when starting cycle complete.	--	Nuisance.
		2. Fails to close when pressure drops to 25 psig.		1. Material failure.	---	Cryogenerator will overheat due to insufficient lubrication.	II	Internal damage to cryogenerator can result. Hazard is mitigated by cylinder temperature switches.
		3. Fails to close when pressure rises to 75 psig.		1. Material failure.	---	Cryogenerator will continue to run; overheats due to lack of cooling oil in cylinder jackets.	II	Possible damage to cryogenerator. Hazard mitigated by cylinder temperature switches.

LOX-30 LIQUID OXYGEN GENERATOR

FAULT HAZARD ANALYSIS

COMPONENT	FUNCTION	FAILURE MODE	OPERATIONAL MODE	FAILURE CAUSE	SECONDARY CAUSE	EFFECT ON SYSTEM	HAZ CLASS	SAFETY HAZARD DESCRIPTION
Switch, helium pressure cut out	Protect cryogenerator engine. Initiates system shut down when He pressure above 375 psig. Prevents engine start when pressure below 200 psig.	1. Switch fails to close - pressure below 200 psig.	Normally open.	1. Material failure.	Improper adjustment.	1. Engine continues to run at reduced working pressure.	II	1. Little or no product. Liquid oxygen in rectification column and storage tank will boil off resulting in high acetylene concentration.
		2. Switch fails to close-pressure above 375 psi.		1. Material failure.	Improper adjustment.	1. Engine continues to run at excessive working pressure.	III	1. Displacer piston domes may collapse. 2. Engine will overheat. 3. Product purity is reduced.
Switch, differential pressure	Protect cryogenerator actuates at cylinder differential pressure of 15 psig.	1. Switch fails to close.	Normally open.	1. Material failure.	---	1. Engine continues to operate with cylinder pressure differential.	III	1. Major engine damage can result.
		2. Switch closes at too low pressure.		1. Material failure.	---	1. Engine shut down unnecessarily.	--	1. Nuisance.

APPENDIX C

LOX-30 LIQUID OXYGEN GENERATOR
OBSERVED HAZARD ANALYSIS

HAZARD TYPE	CLASS	DISCUSSION	RECOMMENDATION
1. ELECTRIC SHOCK	III	1. The LOX-30 consumes approximately 110 KW of electrical power.	1. Ensure all components are electrically bonded and properly grounded.
		2. Voltages present in the generating plant range from 115V to 460V.	2. Install rubber matting at all units of plant installation.
			3. Display warning placards stating voltages present at each skid
			4. Display placards giving shock treatment and resuscitation procedures.
2. HIGH TEMPERATURE SURFACES	II	1. Compressor discharge air temperature is 252°F above ambient air temperature.	1. Install "HOT SPOTS" placards where thermal insulation cannot be installed.
		2. Adsorber regenerating gas is heated to 590°F.	
3. LOW TEMPERATURE SURFACES	I	1. Processing of liquid oxygen is accomplished within cryogenically insulated vessels and plumbing.	1. Display low temperature warning placards.
		2. Product liquid output connection and gaseous oxygen vent frost during plant operation.	2. Ensure plant operating personnel wear proper protective clothing during plant production.

LOX-30 LIQUID OXYGEN GENERATOR
OBSERVED HAZARD ANALYSIS

HAZARD		DISCUSSION	RECOMMENDATION
TYPE	CLASS		
4. HIGH PRESSURE FLUIDS AND GASES	II	1. Air compressor discharge pressure is 70 PSIG.	1. Display warning placards indicating fluid and gas operating pressures.
		2. Cryogenerator helium pressure varies between 200 PSIG and 375 PSIG.	
		3. Cooling water pressure is 58 PSIG.	
5. STATIC GENERATING MATERIAL	II	1. Synthetic and wool fabrics generate static electricity. The potential for oxygen enrichment of the plant enclosure atmosphere is high. Static electricity in an oxygen enriched atmosphere presents a fire hazard.	1. Ensure that operating personnel wear cotton clothing to reduce static electricity generation. 2. Display placards warning of static electricity from synthetic or wool fabrics.
6. TOXIC MATERIAL	III	1. The hampsonmeter is filled with S-TETRA-BROMOETHANE, a poisonous compound. When combined with moisture, it will hydrolyze and form acid.	1. Investigate the possible use of a non-toxic fluid with identical physical properties.
		2. During use of the hampsonmeter, fluid can be vented from the top of the meter and spray the operator.	2. Placard cold box instrument panel to exercise extreme caution when using hampsonmeter.

LOX-30 LIQUID OXYGEN GENERATOR
OBSERVED HAZARD ANALYSIS

HAZARD TYPE	CLASS	DISCUSSION	RECOMMENDATION
7. MECHANICAL VIBRATION	III	1. Compressor discharge line failed twice during reliability and maintainability testing. Failures resulted from air compressor vibration transmitted to discharge line.	1. Design support bracket for compressor discharge line.
		2. The studs used to connect compressor discharge flange to molecular sieve flexible line flange were too short to provide proper grip by nuts.	2. Ensure all coupling flange bolts are of adequate length.
			3. Use properly torqued metal stop nuts for connecting coupling flanges.
8. FLOOR AND OVERHEAD OBSTRUCTIONS	I	1. LOX-30 plant installation requires numerous air and water plumbing runs along the floor and overhead.	1. Install covers over floor plumbing to reduce tripping hazard.
			2. Display warning placards.
9. ROTATING MACHINERY	I	1. Cryogenerator engine and drive motor are connected by a flexible coupling. Coupling is shielded by a cover mounted on the cryogenerator bed plate.	1. Require protective covers to be in place when plant is operating.
		2. Air compressor is V-belt driven from an electric motor. V-belt is shielded by a cover on the compressor skid.	

LOX-30 LIQUID OXYGEN GENERATOR
OBSERVED HAZARD ANALYSIS

HAZARD TYPE	HAZARD CLASS	DISCUSSION	RECOMMENDATION
10. EQUIPMENT PHYSICAL STABILITY	III	1. The cold box, 53 inches in diameter, 94 inches high, weight 2,205 pounds, rests on three unattached stands 12 inches high. Shock vibration or bumping could cause cold box to fall off the stands with attendant damage to cold box, cryogenerator connecting plumbing and cryogenerator.	1. Bolt cold box to stands.
11. OPERATING CONTROL ACCESSIBILITY	---	1. Operating controls on cold box panel and system control panel require no excessive stretching or reaching.	1. NONE
		2. Instruments on compressor require operator to bend moderately to ensure accurate readings.	
12. ATMOSPHERIC CONTAMINANTS	II	1. Rectification column tail gas is impure nitrogen. Venting into plant space could hazard operating personnel due to oxygen deficiency.	1. Vent adsorber regeneration gas column tail gas and oxygen boil off gas to atmosphere outside LOX-30 building.
		2. Storage tank vent gas is pure oxygen. Venting into plant space will increase fire hazard due to atmosphere oxygen enrichment.	2. Ensure adequate plant ventilation.
13. NOISE	II	1. Air compressor noise was measured at 104DBA with a SPL-103 sound level meter. Maximum unprotected exposure at this level is 1 hour per day, longer exposure can result in hearing loss.	1. Relocate air compressor to separate room from rest of plant.
			2. Require personnel to wear sound attenuators if compressor is located in same space with rest of plant.
			3. Display noise hazard area placards in compressor space.

LOX-30 LIQUID OXYGEN GENERATOR

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HAZARD TYPE	CLASS	DISCUSSION	RECOMMENDATION
14. PROXIMITY OF INCOMPATIBLE SYSTEMS/ COMPONENTS	IV	1. Storage tank relief valve is mounted above the cold box instrument/control panel. When relief valve opens liquid oxygen, at $-297^{o}F$, is sprayed in the control panel area.	1. Incorporate shield around relief valve.
15. PERSONNEL INGRESS/EGRESS	I	1. The LOX-30 must be installed to permit accessibility to all modules. Cyrogenerator winch required for removal of condenser head.	1. Ensure plant installation provides sufficient clearance around all modules for personnel passage and equipment maintenance.

APPENDIX D

5. Discussion and Resolution of Fault Hazards

The following discussion is provided to present the actions anticipated to resolve the safety hazards reported in the Fault Hazard Analysis.

a. Prior to beginning reliability testing, a switch was installed in the heater circuit which is actuated by the operation of the Regenerating Gas Heater Valve (760). This switch prevented operation of the heater elements unless Valve (760) was in a position to direct the tail gas flow over the electric heater elements. This modification shall be incorporated on the production equipment and will negate the possibility of heater element burn out due to a failure of Valve (760). (See Paragraph E.3.a. for hazard.)

b. An over-temperature cutout switch should be installed in the electrical heater circuit to prevent heater element burn out in the event the thermostat switch (TC-4) fails to open at 300°C or regenerating gas flow is interrupted for any reason. The contractor will be requested to incorporate an over-temperature switch into the production design. (See Paragraph E.3.b. for hazard.)

c. Safety Thermostat (TA-5) is required to close only in the event of a regenerating gas heater failure. The switch system to be installed on the Regenerating Gas Heater Valve (see Paragraph 5.a.) will contain a "heater on" light to provide a visual indication that the heater elements are operative. This should eliminate the possibility of operating the equipment with unheated regenerating gas if the heater and safety thermostat fail. (See Paragraph E.5.c. for hazard.)

d. Tail Gas Relief Valve (901) - During plant operation Valve (901) and the Column Pressure Relief Valve (900) are protecting the same gas piping. If Valve (901) failed to open at the specified pressure, Valve (900) would act as a back-up relief and open before pressure in the plumbing and rectification column increased. In the event of a failure of Valve (901) to close after opening, any significant amount of gas (nitrogen in this case) venting to the atmosphere would cause a noticeable drop in regenerating gas flow which would be indicated on the regenerating gas flow meter. In addition, all safety relief valves are to be checked on a scheduled basis as listed in the equipment maintenance plan. In view of the above, it is considered unlikely that a failure of Valve (901) would develop into a hazardous situation and no further action is considered necessary at this time. (See Paragraph E.3.d. for hazard.)

e. Column Pressure Relief Valve (900) - During temporary shut-downs, Valve (900) and the Tail Gas Relief Valve (901) are protecting the same gas piping. If Valve (900) failed to open at the specified pressure, Valve (901) would act as a back-up relief and open before any excess pressure built up. In the event that a system failure during shut-down did cause Valve (900) to relieve and this valve did fail to close and boil-off of column liquid did occur, the liquid level gauge would indicate this drop in liquid level. Operating personnel are required to compare the existing liquid level to the level at initial plant shut-down before plant operation. If this comparison reveals that a minimum ratio has not been maintained, all liquids must be drained and the equipment must be derimed. In addition, all safety relief valves are to be checked on a scheduled basis as listed in the maintenance plan. In view of the above, it is considered unlikely that a failure of Valve (900) would develop into a hazardous situation and no further action is considered necessary at this time.

f. Float Controlled Column Inlet Valve (120) - If Valve (120) failed by sticking in the open position, a reduction in product purity would occur. This would be caused by the increased flow through the plant not allowing enough time for the rectification process to take place. The increased flow would also cause an increase in the storage tank and column liquid levels which would be indicated on the liquid level gauge. Eventually, if the operator has not corrected this situation, the increased flow would cause the cryogenerator helium pressure to rise to the high pressure cutout limit and shut-down the equipment. If Valve (120) failed by sticking in the closed position, there would be a reduction in the condenser head temperature due to a reduced air flow. This temperature reduction would cause a reduction in the column inlet pressure which would indicate on the inlet pressure gauge. Also, this condition would cause a reduction in the storage tank liquid level, regenerator tail gas flow and product purities which would all indicate on individual gauges. Even if the operator fails to take action, this equipment has operated in a reduced flow condition for two days without sustaining any damage. It is probable that a prolonged reduced flow situation could cause the cryogenerator helium pressure to reach the lower cutout limit and shut-down the equipment.

Due to the safety devices and numerous failure indications listed above, it is considered unlikely that the failure modes listed above would develop into a hazardous situation. Therefore, no further action is anticipated on this situation at this time. (See Paragraph E.3.f. for hazard.)

g. Float Controlled Transfer Valve (236) - If Valve (236) failed by sticking in the open position, flow from the column to the storage tank would increase and there would be insufficient time for the rectification process to take place. Therefore product purity would be reduced. This failure would cause abnormal readings on the column liquid level gauge, storage tank level gauge and purity monitor. This equipment will operate with reduced purity but without damage in this failure mode until corrections by operating personnel can be made. If Valve (236) failed by sticking in the closed position, the column liquid level would rise and provide a highly abnormal rise on the column level liquid gauge. Also, this failure would cause a closure of Valve (120). The results and indications caused by this occurrence are listed in the preceding paragraph. In view of the above, it is considered unlikely that a failure of Valve (236) would develop into a hazardous situation for equipment or personnel. Therefore, no further action is anticipated at this time. (See Paragraph E.3.g. for hazard.)

h. Storage Tank Vent Valve (281) and Storage Tank Production Transfer Valve (240) - Valves (281) and (240) are manual valves controlled by operating personnel. Failure of these valves to be opened or closed as required would cause abnormal readings on the storage tank liquid level and pressure gauges or be noticed by the operator's inability to move the valve handle. Operators can take immediate action to alleviate the situation by securing the equipment and repairing valves as required. Also, any excess pressure build-up caused by a failure of these valves would be relieved by Storage Tank Relief Valve (911), therefore possible equipment damage is considered unlikely. No action is being contemplated on these situations at this time. (See Paragraph E.3.h. and E.3.i. for hazards.)

i. Storage Tank Relief Valve (911) - If Valve (911) would fail to open during a short duration shut-down, either Relief Valve (901) or (900) would act as a back-up and relieve any excess pressure in the system. Transfer of liquid product to a pressurized external receptacle is a limited requirement and would require an operator to utilize Storage Tank Vent Valve (281) to control pressure in internal storage tank. In this instance, the operator must maintain constant surveillance of internal storage tank pressure and open Valve (281) before excess pressure can build and cause Valve (911) to open. (Note: Normal filling of storage tanks is not done under pressure.) If Valve (911) fails to close after opening any excessive liquid boil-off would be noticeable on the liquid level gauge and the procedures of comparison of liquid levels and deriming of the plant described in section e. above would apply. All Relief Valves are to be checked on a scheduled basis to ensure proper operation. In view of the above, it is considered unlikely that a failure of Valve (911) would develop into a hazardous situation and no further action is planned at this time.

j. Cryogenerator Oil Pressure Switch, Helium Pressure Cutout Switch and Differential Pressure Switch - These switches are safety devices which only activate in the event of failure of another system within the equipment. The switches are checked before every plant operation as part of the pre-start inspection as cited on the maintenance plan. In the event of a concurrent failure of the primary system and safety device, the hazard of equipment or personnel damage would be mitigated by other safety devices, operator surveillance, etc. as specified in the hazard classifications. No action is being contemplated on these situations at this time. (See Paragraph E.3.k., E.3.l. and E.3.m. for hazards.)

APPENDIX E

2. Current integrated logistic support planning includes development of improved operation and maintenance manuals for all levels of Naval personnel involved with this equipment. Also being planned is extensive operational and maintenance training of Naval instructors, depot level maintenance personnel, and all Naval operating personnel. Consult Integral Logistic Support Plan No. CGSE 0238:AA for any additional information which is required.

APPENDIX F

5. Discussion and Resolution of Observed Hazards

The following discussion is provided to present the actions anticipated to be taken to resolve the safety hazards reported in the Observed Hazard Analysis.

a. Electric Shock - All components of the LOX-30 system shall be inspected prior to initial operation in order to insure that the proper electrical grounding and bonding has been accomplished. The operating area shall also be inspected for appropriate voltage level and safety procedure placards. (See Paragraph H.2.a. for hazard.)

b. High Temperature Surfaces - All high temperature surfaces on this equipment are remote from the operator's area. Requirements for personnel to be in these hazard areas is limited and would be restricted to trained personnel who are familiar with the equipment design and operation. Considering these factors, personnel contact with high temperature surfaces is considered unlikely. In view of the above, no equipment modification is considered required on this observed hazard. Warning shall be incorporated in appropriate technical manuals. (See Paragraph H.2.b. for hazard.)

c. Low Temperature Surfaces - During operation of this equipment, operating personnel are not required to enter the area where low temperature surfaces are present. Operators must enter this area only when connection or disconnection of the liquid supply line is required. At this time, operators are required by NAVAIRINST to wear protective clothing for handling of liquid oxygen. This procedure would be carried out only by trained personnel who are familiar with this equipment design and operation. In addition, any hazardously cold surfaces would be self-indicating by development of a layer of frost or ice at the cold spot. In view of the above, and the low hazard classification, no equipment modification is considered required on this observed hazard. Warnings shall be incorporated in appropriate technical manuals. (See Paragraph H.2.c. for hazard.)

d. High Pressure Fluids and Gases - Medium and low pressure gages and fluids are required for proper operation of this equipment. This equipment will be operated by personnel trained in the system operation and design. These personnel will be familiar with the various fluid flows and pressures present in the plant. Considering the above and that only medium and low pressures are present, no equipment modification is considered required on this observed hazard. Warnings shall be incorporated in appropriate technical manuals. (See Paragraph H.2.d. for hazard.)

e. Static Generating Material - Numerous safety manuals and instruction at the Navy School of Cryogenics advocate operating and maintenance personnel wearing cotton clothing in the liquid oxygen generator environment. Protective clothing for handling of liquid oxygen is covered by

NAVAIR instruction. Warning placards can be placed in equipment operational area as required, but no equipment modification is considered necessary. (See Paragraph H.2.e. for hazard.)

f. Toxic Materials - Due to the toxic liquid required for operation of the hampsonmeter, a pressure differential gauge shall be utilized to replace the hampsonmeter on production units. (See Paragraph H.2.f. for hazard.)

g. Mechanical Vibration - An adequate vibration dampening system was not supplied with prototype unit at time of installation at NAVAIRENGCEN. A temporary vibration dampener system was utilized by this activity and it failed twice. An adequate dampening system was received subsequent to all testing and was delivered with equipment to NAF Sigonella. The proper dampening system will be provided with all production units. (See Paragraph H.2.g. for hazard.)

h. Floor and overhead obstructions were peculiar to NAVAIRENGCEN testing facility. Proper surveillance of facilities installation planning will prevent these obstructions reoccurring at the Fleet activities. (See Paragraph H.2.h. for hazard.)

i. Rotating Machinery - Cover shields on the cryogenerator drive motor and compressor drive belts are to be inspected on a scheduled basis as listed on the equipment maintenance plan. This will be included in appropriate technical publications. (See Paragraph H.2.i. for hazard.)

j. Equipment Physical Stability - Elevation stands are required on the LOX-30 liquid oxygen plant to allow a common base unit for the cryogenerator to be used on both the LOX-30 and PLN-430 liquid nitrogen plant. These stands will be securely attached to the cold box on production units. A requirement for alignment of the cryogenerator with the cold box precludes securing the leveling stands to the deck for additional stability. (See Paragraph H.2.j. for hazard.)

k. All installation planning will be reviewed to insure that proper ducting of vent gases is achieved. (See Paragraph H.2.l. for hazard.)

l. On all production units, a shield shall be placed around the storage vessel relief valve to prevent spillage of LOX on the operator if the relief valve opens. (See Paragraph H.2.n. for hazard.)

m. Activities installation drawings should be reviewed to insure that all modules have sufficient clearance for personnel movement and equipment maintenance. (See Paragraph H.2.o. for hazard.)

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