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Fire Hazard Study of the Coolidge, Arizona, Solar-Powered Irrigation Facility

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ABSTRACT

A fault tree analysis of the Coolidge, Arizona, solar powered irrigation facility has been performed to study the causes and probability of fire. The analysis identifies the component malfunctions and the events which contribute to fires while quantifying the fire probabilities. Uncertainties are identified and recommendations for reducing the probability of fire are specified.

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INTRODUCTION

The Coolidge, Arizona, solar-powered irrigation facility, which is operated jointly by Sandia and the University of Arizona, converts solar energy into electrical energy which is used to power irrigation pumps. The heat transfer fluids used in the facility operate at temperatures well above their fire points creating a potential fire hazard from leaks. The possibility of fire was demonstrated at a similar solar facility in Willard, New Mexico, where the heated collector fluid leaked onto a dried weed which ignited resulting in damage to part of the collector field. At Coolidge, a pump caught fire and had to be manually extinguished. Leaks of the heat transfer fluids are common at the Coolidge facility and under certain conditions, a major fire is possible.

The objective of this study was to identify and quantify the component malfunctions and accompanying factors which could result in a fire at the Coolidge facility. Recommendations for reducing the probability of fire were formulated and are presented along with the analysis conclusions.

Facility Description

The Coolidge, Arizona, solar-powered irrigation facility is a 150 KW_e plant involving three heat transfer loops. A schematic drawing of the facility is provided in Figure 1.

The first loop extracts a stable high temperature oil, Caloria HT-43, from the bottom of a 30,000 gallon thermal storage tank, circulates it through the collector field and returns it at 550°F to the top of the thermal storage tank. The caloria used has a flash point of approximately 350°F, a fire point of approximately 380°F, and an auto-ignition temperature of about 700°F.

The collector field consists of eight flow loops, each one being made up of six collector groups as illustrated in Figure 2. A group consists of six single, parabolic trough shaped solar collectors which run north-south and rotate as a group to follow the sun as it moves throughout the day. Each trough is about six feet across by 10 feet long and has an aluminum reflective surface. The Caloria HT-43 is circulated through a pipe located at the solar collector focus. The sun's energy, concentrated about 35 times by the reflectors, is absorbed by the oil and heats it to an operating temperature of 550°F. The groups are connected to each other by flexible hoses and interconnecting piping. Each group has its own tracker and drive mechanism. The flow loop may be isolated from the system piping by manual valves near the interfaces with the supply and return

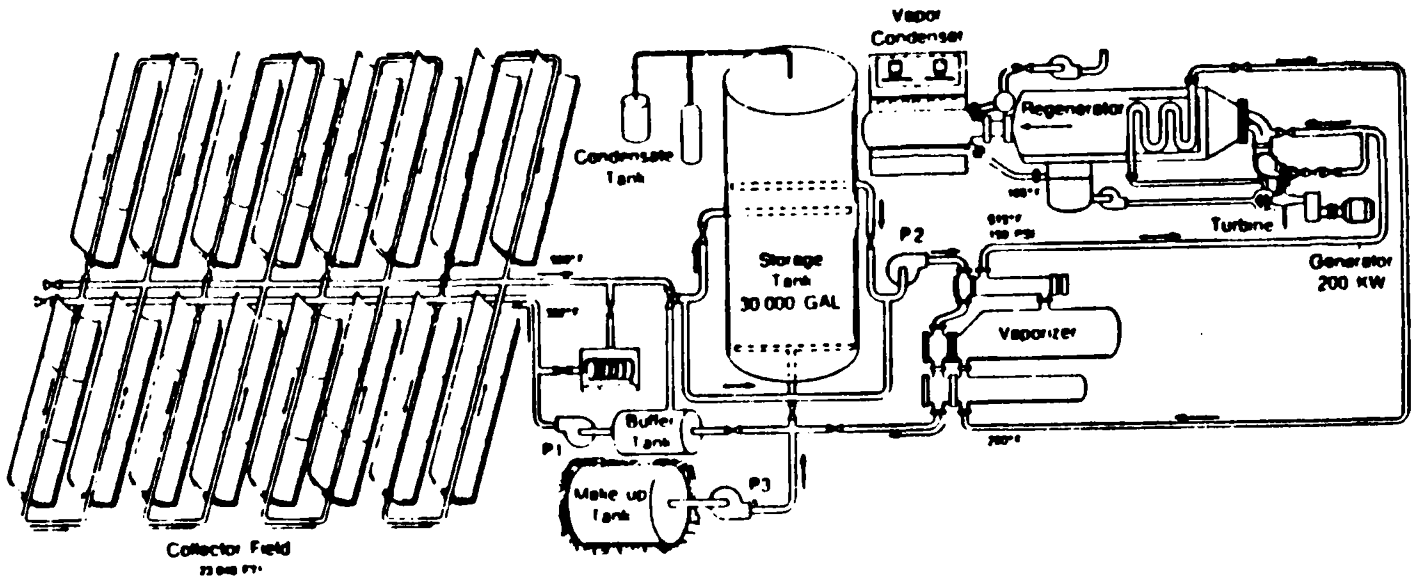

Figure 1. 150 kW Solar-Powered Irrigation Facility Flow Diagram.

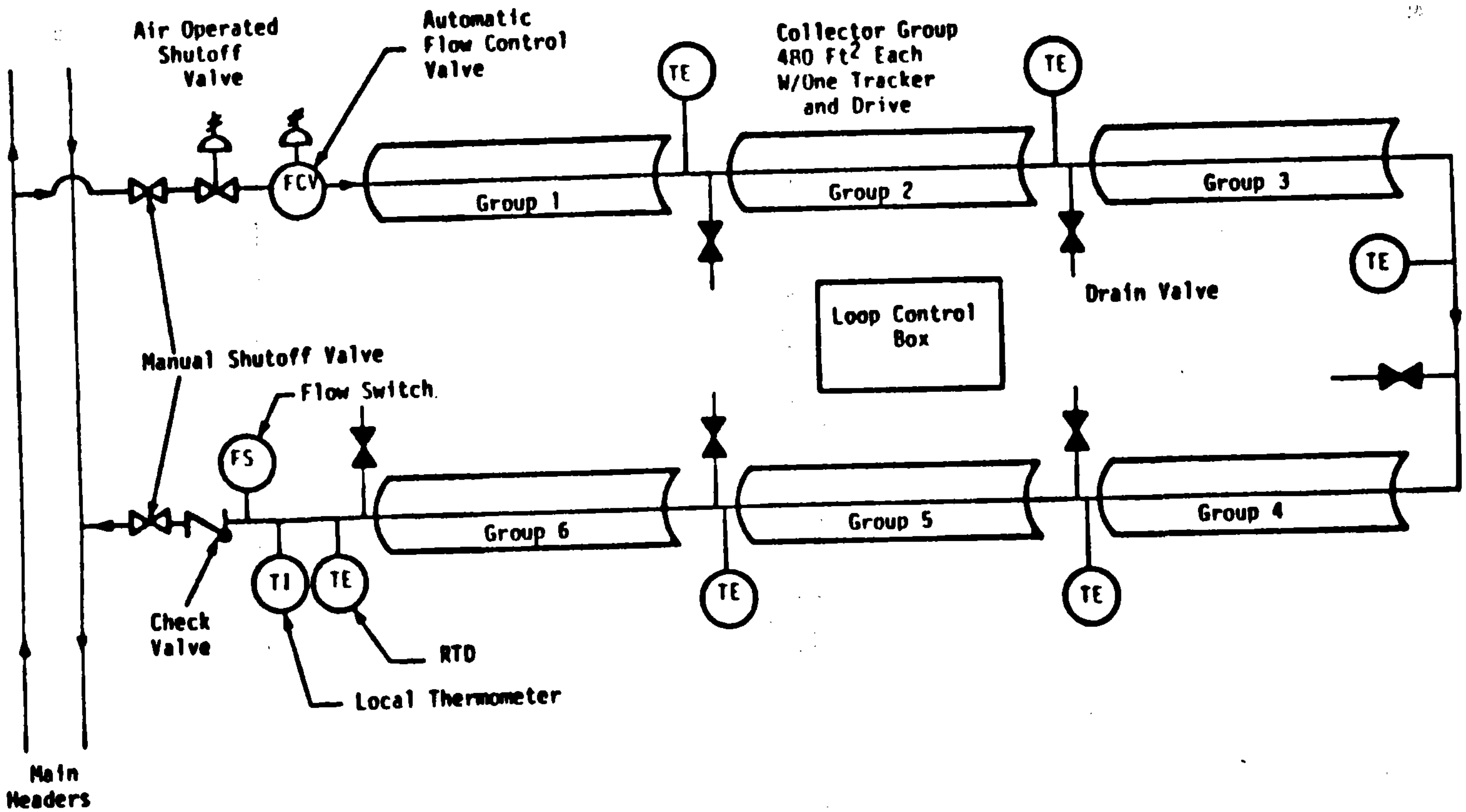

Figure 2. Collector Field Control.

headers. The loop may also be isolated from the system by the air operated shutoff valve, which can be actuated from the control room, in conjunction with the check valve. The flow control valve regulates the HT-43 flow rate through the loop. Resistance temperature detectors (RTD's) are located at the outlet of each collector group to sense any over-temperature condition and to relay information to the flow control valve. The flow switch is a safety interlock in the control system which prohibits tracking of the collectors until flow has been established in the collector loop. The heated oil is stored in the 30,000 gallon tank to permit operation for up to five hours after the sun goes down.

The second heat transfer loop extracts hot oil from the top of the storage tank and circulates it through a vaporizer heat exchange unit where it heats the second fluid, an organic fluid called toluene, to 515°F. The vaporizer assembly consists of three sections shown in Figure 3; the preheater, vaporizer, and superheater. The hot HT-43 from the storage tank is pumped through the superheater section, the vaporizer section, and the preheater sections before being pumped back through the solar collectors. At the same time, toluene is pumped into the preheater, through the vaporizer and superheater sections, transferring the heat from the HT-43 to the toluene. This heat transfer vaporizes the toluene which is then expanded through the turbine on the Power Conversion Module (PCM), seen in Figure 4, to extract the energy for electrical power generation, thus forming the third heat transfer loop. A toluene level sensor in the vaporizer section is provided to signal the level control valve on the PCM to open or close as needed to regulate the amount of toluene entering the vaporizer assembly. The remainder of the toluene cycle is composed of additional heat exchangers (regenerator and cooling tower) which give up some heat and then convert the fluid from a gas back to a liquid in preparation for absorption of thermal energy and another working cycle.

The control system monitors and controls the collection and storage of solar energy, the supply of hot fluid to the power generation subsystem, and the generation and supply of electric power. In addition, it protects against system-related anomalies such as high temperatures or low flow in the collector field, as well as natural events such as high gusty winds. These safety interlocks monitor critical parameters and automatically shut the system down and prohibit automatic restart if these parameters are beyond safety limits.

The control system is also equipped with manual override options for all control functions to enable greater flexibility for tests and experiments. To aid in these tests, an auxiliary heater fired by natural gas was added to the system

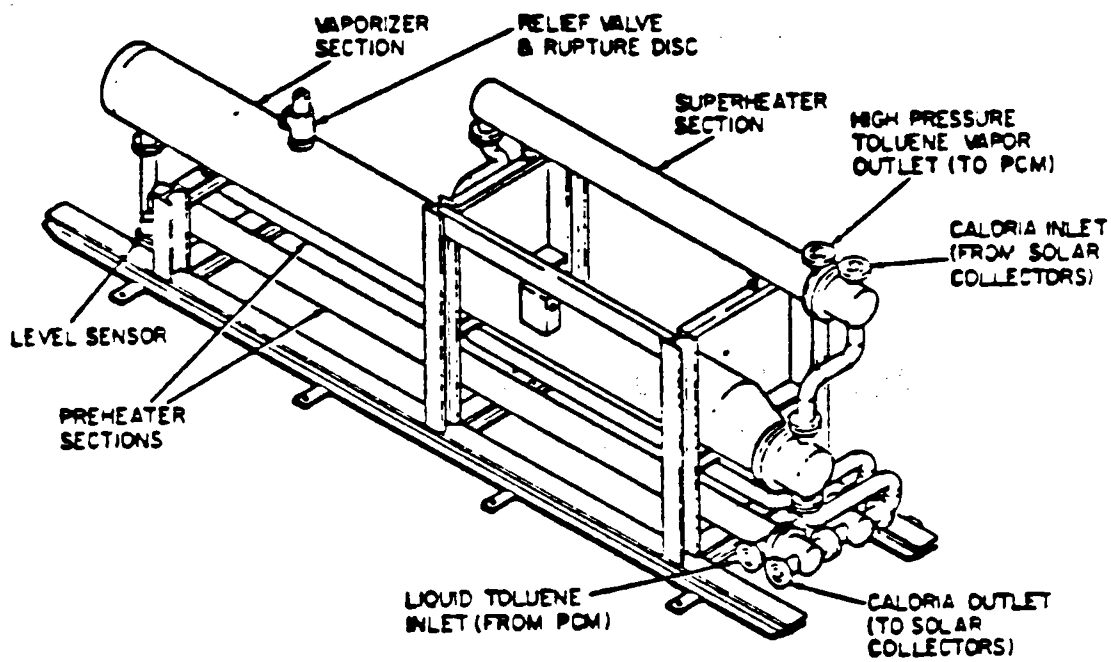

Figure 3. Vaporizer Assembly.

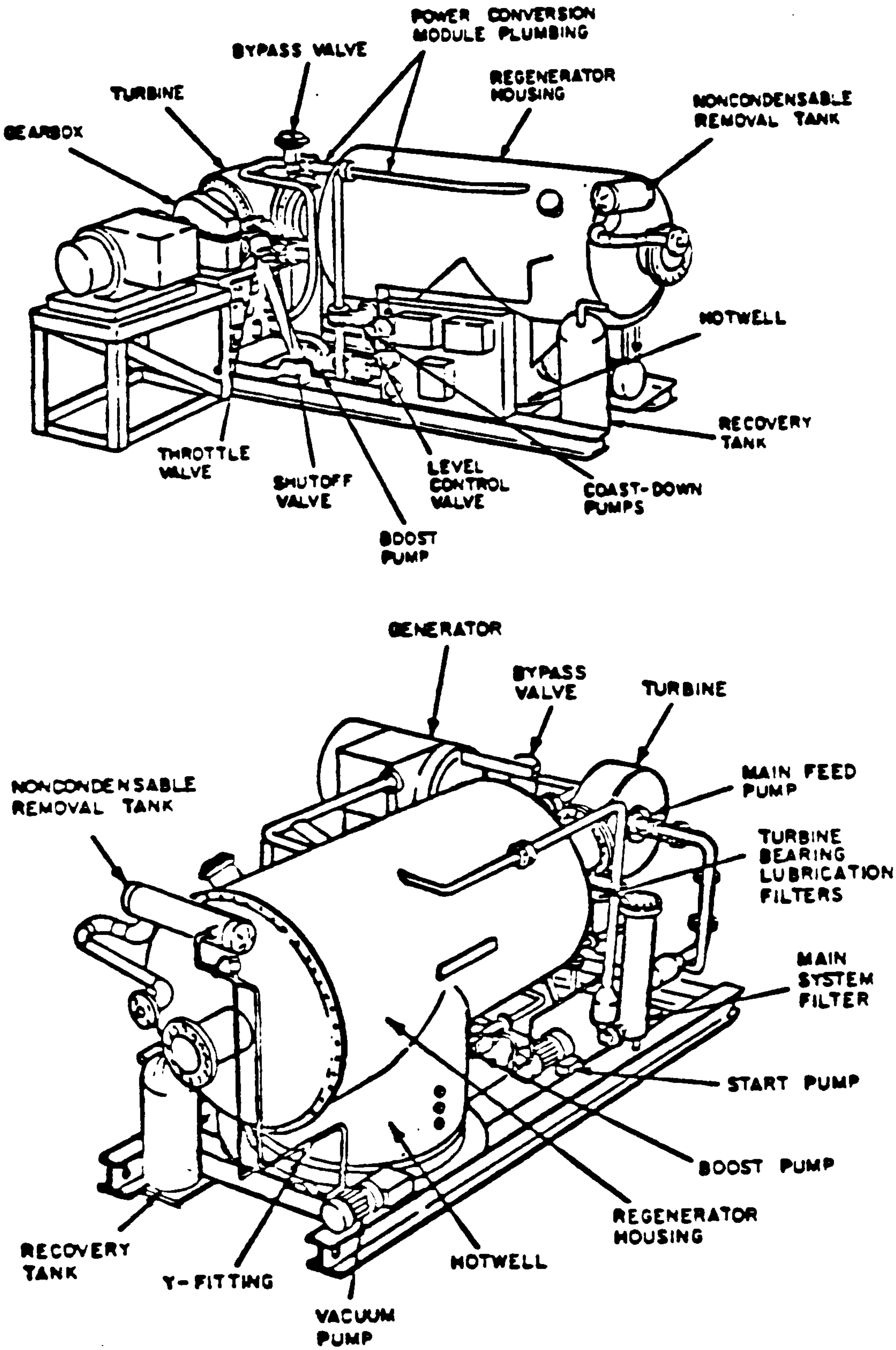

Figure 4. Power Conversion Module.

in the storage tank area. The purpose of the heater is to allow experiments which require thermal input equivalent to the output of a larger collector field. The heater also enables tests and experiments to be performed on the storage and power generation subsystems at times when the insolation level is inadequate for operation of the collector field.

Study Approach

To study the possibility of fire, the facility was divided into three physical areas where a fire could occur. The first area is the collector field which is surrounded by a trench fitted with wells to catch a Caloria HT-43 spill. The second area is the thermal storage tank area which is surrounded by an earth wall with a large pit to contain a Caloria leak in this area. The vaporizer and PCM constitute the third area. This area has a danger of toluene being ignited into a power conversion platform fire.

To study the system leaks, a tour was made of the Coolidge facility to visually examine the plant for areas of weakness and to consult with operators to obtain their insights. The analysis continued with a complete review of: 1) the Willard fire; 2) the Coolidge daily maintenance reports from the first day of operation in September 1979 through January 1981; 3) all plant log books, 4) the Collector Operation and Maintenance Manual; and 5) the monthly reports published by the University of Arizona. Periodic consultations were held with Sandia solar engineers to review the findings and to discuss ongoing safety improvement programs at Coolidge.

The accumulated information concerning possible fires was developed into three fault trees with the top events being fire in each of the three facility sections described earlier. Leroy Torkelson and Earl Rush of Sandia Solar Energy Projects Department II added their knowledge of the Coolidge facility and used their engineering judgment and experience at Coolidge to assign frequencies to the events. Frequencies for leaks were converted to probabilities by assuming that a component would leak for two days before being repaired. Thus, if six valves were predicted to leak in a year and each would leak for two days, the probability for a valve leak is (six leaks/year x two days/leak) ÷ 365 days/year = 0.0329. The probabilities were used in the fault tree analysis as cut sets were generated. All numbers are based upon estimates and engineering judgment and should not be construed as exact or used as reference for future analysis without this acknowledgement.

The primary events of the fault trees are assumed to be statistically independent. The probability of occurrence of the top event of the fault tree was approximated by computing the rare event approximation. This approximation is acceptable when all of the primary events have a small probability of occurrence. More importantly, from a risk perspective, the approximation is conservative, i.e., it is an upper bound on the true probability of occurrence of the top event of the fault tree. In this paper, the usage of the term "total probability" should be interpreted as a conservative approximation to the true total probability.

STUDY RESULTS

Fire Probability in the Collector Field

1. Discussion of the Collector Field Fault Tree

Diagrams 1A through 1F show the fault tree logic for an oil fire in the collector field. The diagrams show that a collector field fire can result from either an oil spill from a leak igniting or from high pressure and temperature conditions causing a component rupture which auto-ignites.

In the case of the high pressure and temperature causing a component rupture and auto ignition, the system must exceed the design conditions in conjunction with a failure of safety systems to trip at the limiting temperature (550°F), pressure, or flow rate. The failure to trip may result from several system malfunctions. The interlock which detects insufficient flow rates may fail, the resistance temperature detectors could allow the oil temperatures to rise beyond design criteria, or the high pressure safety valve could stick shut. In addition to these malfunctions, the operator could override the low flow or temperature interlocks and prevent a trip of the system.

Excessive temperatures and pressure may be the direct result of an inadequate oil flow due to pipes or valves being plugged, the pumps not running efficiently, or the air operated valves or manual shutoff valves not being full opened. The three-way valve could also stick in a position causing hot oil to circulate back to the collector field instead of to the storage tank and could result in pressures and temperatures which, if not checked by the interlocks, would rupture a component and pose a collector field fire hazard.

Oil spills can occur from the high pressure relief valve, crossover pipes, flexible tubes or their attachments, receiver tubes, receiver tube compression fittings, air operated shutoff valves, or the manual shutoff valves.

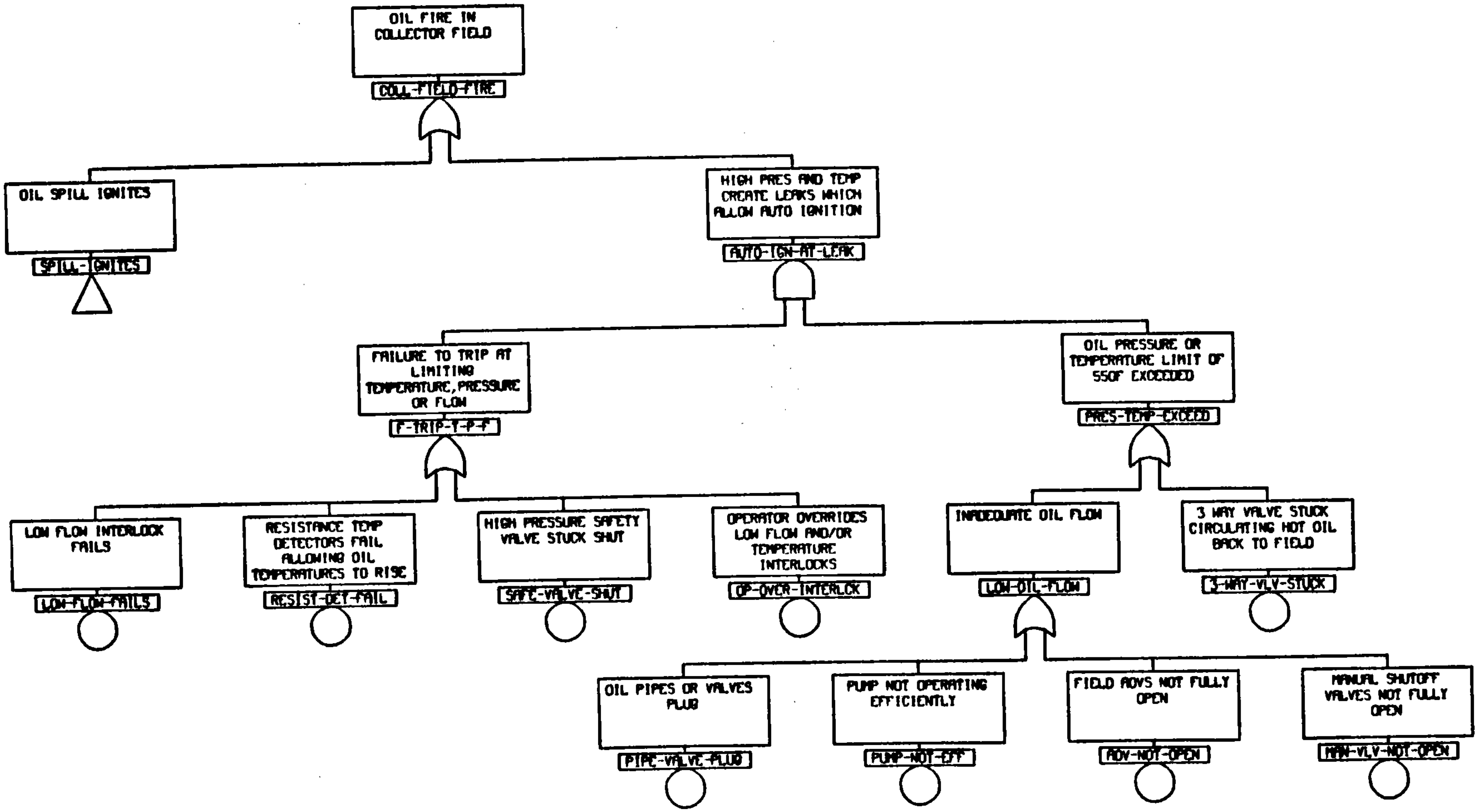

Diagram 1A. Fault Tree Logic for Collector Field Fire.

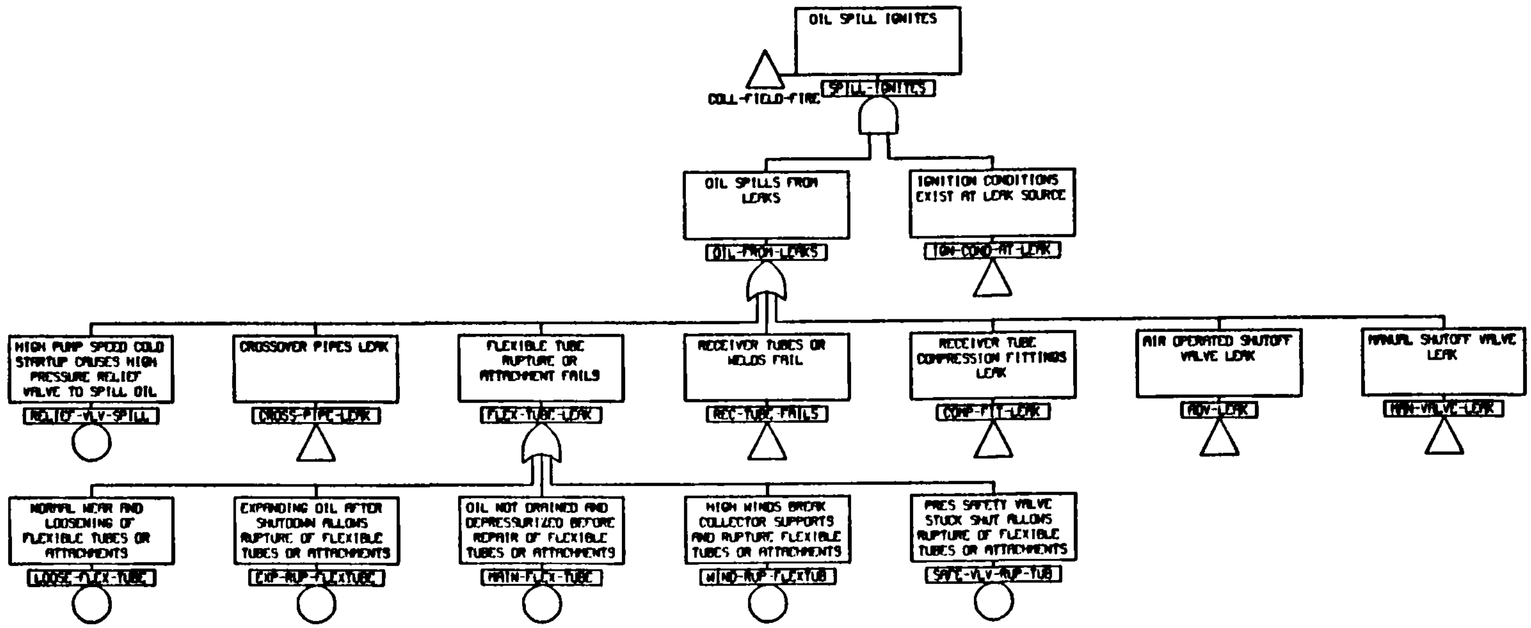

Diagram 1B. Fault Tree Logic for Collector Field Fire.

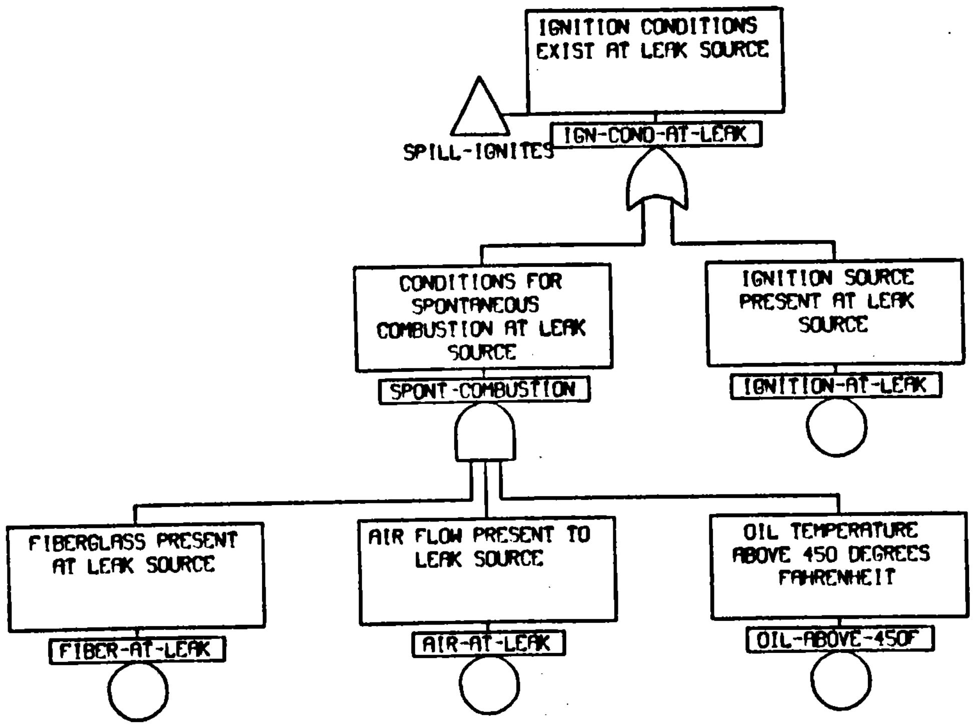

Diagram 1C. Fault Tree Logic for Collector Field Fire.

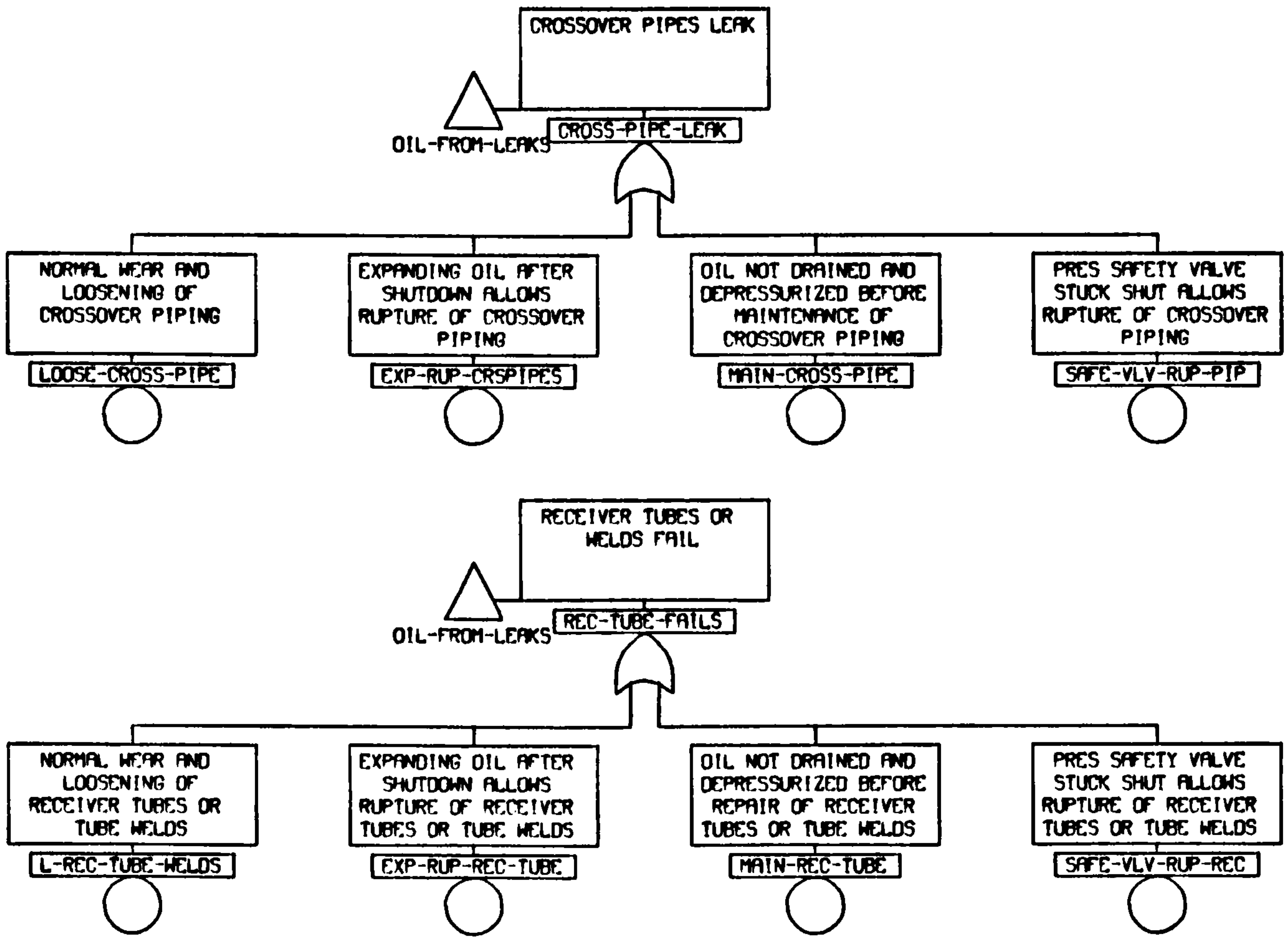

Diagram 1D. Fault Tree Logic for Collector Field Fire.

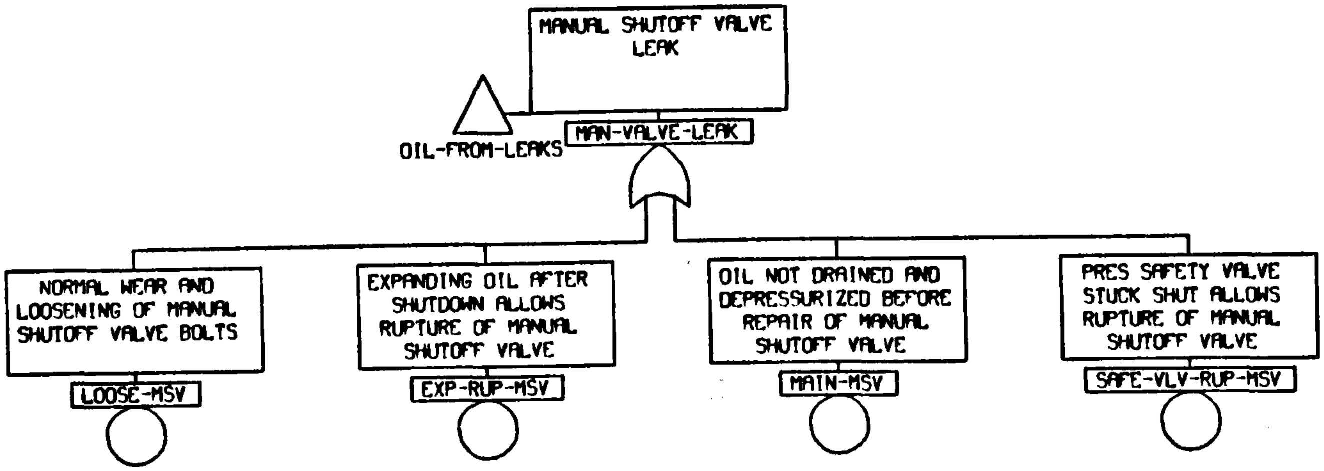

Diagram 1E. Fault Tree Logic for Collector Field Fire.

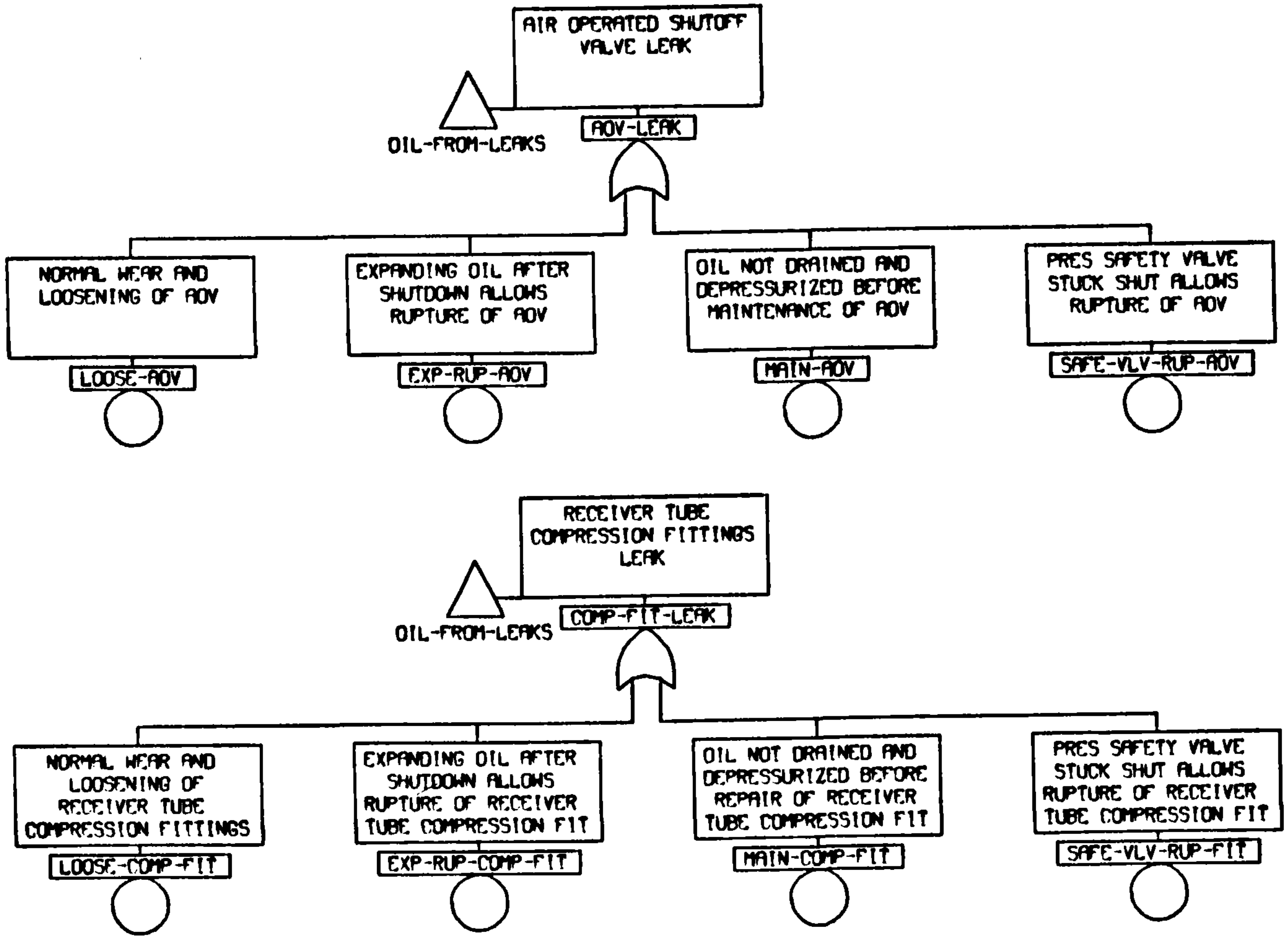

Diagram 1F. Fault Tree Logic for Collector Field Fire.

All of these components may leak as a result of any one of four scenarios. The first scenario involves simple wear and loosening of a component or its attachments allowing an oil leak which is assumed to persist for two days. The second scenario involves a technician not depressurizing and draining the oil prior to maintenance work. A third scenario resulting in collector field oil spills begins with a long term shutdown of the collector system without draining the oil. A startup will then allow the expanding oil to rupture one of the components listed above and result in an oil spill. The fourth scenario involves the high pressure safety valve which is located just downstream from the collector field pump. During a cold, high-pump-speed startup, the thick oil moves slowly and is under a great deal of pressure. If the pressure is above design specifications, the safety valve should open and spill Caloria HT-43 onto the ground. However, should the valve stick shut, any collector component may be forced to rupture with the flexible hoses between collector groups being most likely to do so. These flexible hoses have an additional scenario involving high speed winds breaking the collector panels from their supports resulting in major ruptures of the flexible tubes and their attachments.

All of these component leaks will spill oil, but ignition conditions must be present to start a fire. As seen in Diagram 1C, there are two ways that ignition conditions could exist at the leak point: there could be an external source or spontaneous combustion. The conditions for spontaneous combustion include there being fiberglass present at the leak along with a sufficient air flow and oil temperatures above 450°F. Ignition sources at a leak include such things as cigarettes, welding sparks, or sparks from the gas fired heater.

2. <u>Quantification of the Collector Field Fault Tree</u>

Listed in Table 1 are the component failures, human errors, and natural phenomena which constitute the basic events in the fault tree leading to a collector field fire. The estimates of the frequencies per year with which these events are expected to occur are also presented.

The total probability for an oil fire in the collector field was determined to be 1.92×10^{-2} per year, i.e., one fire every 52.2 years. The probability for fire was dominated by the sequences involving spontaneous combustion from leaks of the air operated and manual shutoff valves. These spontaneous combustion sequences had a total probability of 8.22×10^{-3}, while a leak

Table 1

Event	Frequency/Year
- Low flow interlock fails	.01
- Resistance temperature detectors fail	.01
- High pressure safety valve stuck shut	.02
- Operator overrides low flow or temperature interlocks	2
- Oil pipes or valves plug	1
- Pump not operating efficiently	3
- Air operated valves not fully open	2
- Manual shutoff valves not fully open	2
- High pump speed, cold startup causes high pressure relief valve to spill oil	2
- Wear and loosening of flexible tubes or attachments	6
- Expanding oil after shutdown ruptures flexible tubes or attachments	.005
- Oil not drained or depressurized before repair of flexible tubes or attachments	.05
- High winds break collector supports and rupture flexible tubes or attachments	.01
- High pressure safety valve stuck shut forces rupture of flexible tubes or attachments	.01
- Fiberglass present at leak source	6

Table 1 (Cont.)

Event	Frequency/Year
- Air flow present at leak source	always
- Oil temperatures above 450°F	25% of the time
- Normal wear and loosening of crossover pipes	.05
- Expanding oil after shutdown allows rupture of crossover pipes	.005
- Oil not drained or depressurized before repairing crossover pipes	.05
- High pressure safety valve stuck shut causes rupture of crossover pipes	.0001
- Normal wear and loosening of receiver tubes or welds	.1
- Expanding oil after shutdown allows rupture of receiver tubes or tube welds	.005
- Oil not drained and depressurized before repair of receiver tubes or tube welds	.05
- High pressure safety valve stuck shut allows rupture of receiver tubes or tube welds	.001
- Normal wear and loosening of manual shutoff valve bolts	always
- Expanding oil after shutdown allows rupture of manual shutoff valves	.0001
- Oil not drained and depressurized before repair of manual shutoff valve	.01
- High pressure safety valve stuck shut allows rupture of normal shutoff valve	.0001

Table 1 (Cont.)

Event	Frequency/Year
- Normal wear and loosening of air operated valves (AOVs)	always
- Expanding oil after shutdown allows rupture of AOVs	.0001
- Oil not drained and depressurized before repair of AOVs	.05
- High pressure safety valve stuck shut allows rupture of AOVs	.0001
- Normal wear and loosening of receiver tube compression fittings	6
- Expanding oil after shutdown allows rupture of receiver tube compression fittings	.005
- Oil not drained and depressurized before repair of receiver tube compression fittings	.05
- High pressure safety valve stuck shut allows rupture of receiver tube compression fittings	.001

of these valves being ignited by an ignition source had a total probability of 5.48×10^{-3}. The operator overriding of safety valves was the third most probable sequence resulting in fire for a total probability of 4.94×10^{-3} per year. The spontaneous combustion of leaks from loose flexible tubes or receiver tube compression fittings have a probability of 2.70×10^{-4}, while fires from ignition sources at these same leaks have a probability of 1.80×10^{-4} per collector year. The other 59 sequences which could result in fire have a total probability of only 6.38×10^{-5}, i.e., 0.33% of the total probability for collector field fire.

Fire Probability in the Pit Area

1. Discussion of the Pit Area Fault Tree

Diagrams 2A through 2E present the fault tree logic for an oil fire in the pit area. The diagrams show that an oil fire in the pit area can be the result of either a pipe fire or a pump fire. In either case, both an oil supply from leaks and the proper ignition conditions at the leak are necessary for a fire to occur.

In the case of a pipe fire, the ignition conditions are the same as those presented in the collector field fault tree, i.e., either an ignition source may be present or spontaneous combustion conditions are available. The flames from the gas-fired heater constitute the major ignition source since it is in operation about 10 percent of the year.

The ignition conditions for a pump fire were displayed by the past pump fire at Coolidge. The fire was caused by worn bearings and rotating mechanical seals generating sufficient friction to ignite the oil. To prevent ignition, CO_2 is currently blown over the outer seal faces to restrict oxygen supply. Should the CO_2 supply fail while the bearings generate sufficient friction or there exists another ignition source at the pumps, the ignition conditions at the pump will be met.

Diagram 2C shows that the oil supply from pipe and valve leaks in the pit area of the solar facility could come from the boiler pressure gauge line, boiler outlet pipe, oil piping, vaporizer loop vapor bypass line shutoff valve, three-way valve, or the three storage tank flanges. The vaporizer loop vapor bypass line shutoff valve and the storage tank flanges would be expected to leak only due to normal wear and loosening. The other components listed above are subject

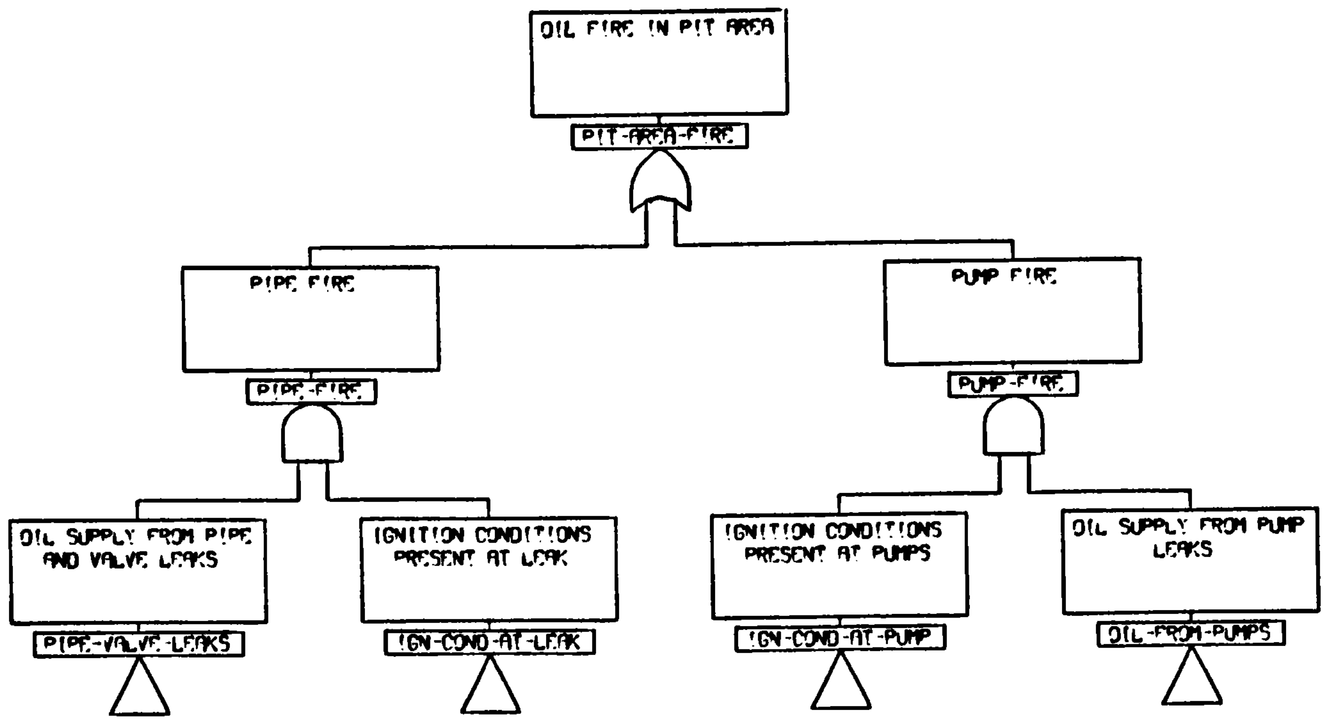

Diagram 2A. Fault Tree Logic for Pit Area Fire.

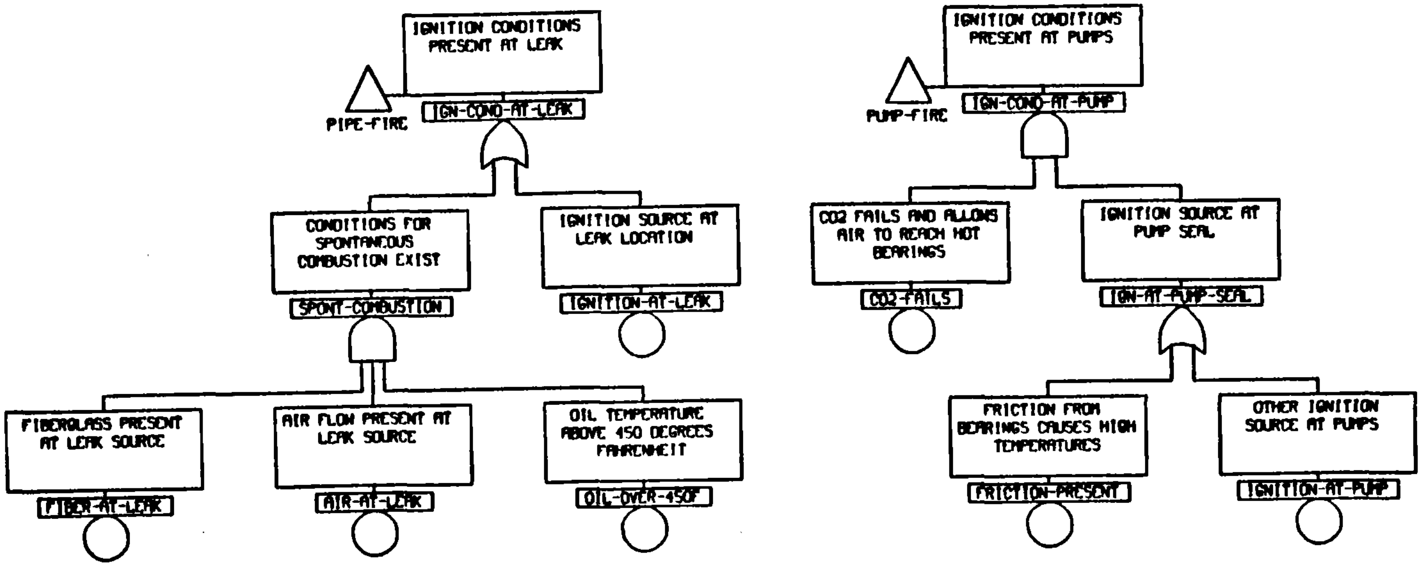

Diagram 2B. Fault Tree Logic for Pit Area Fire.

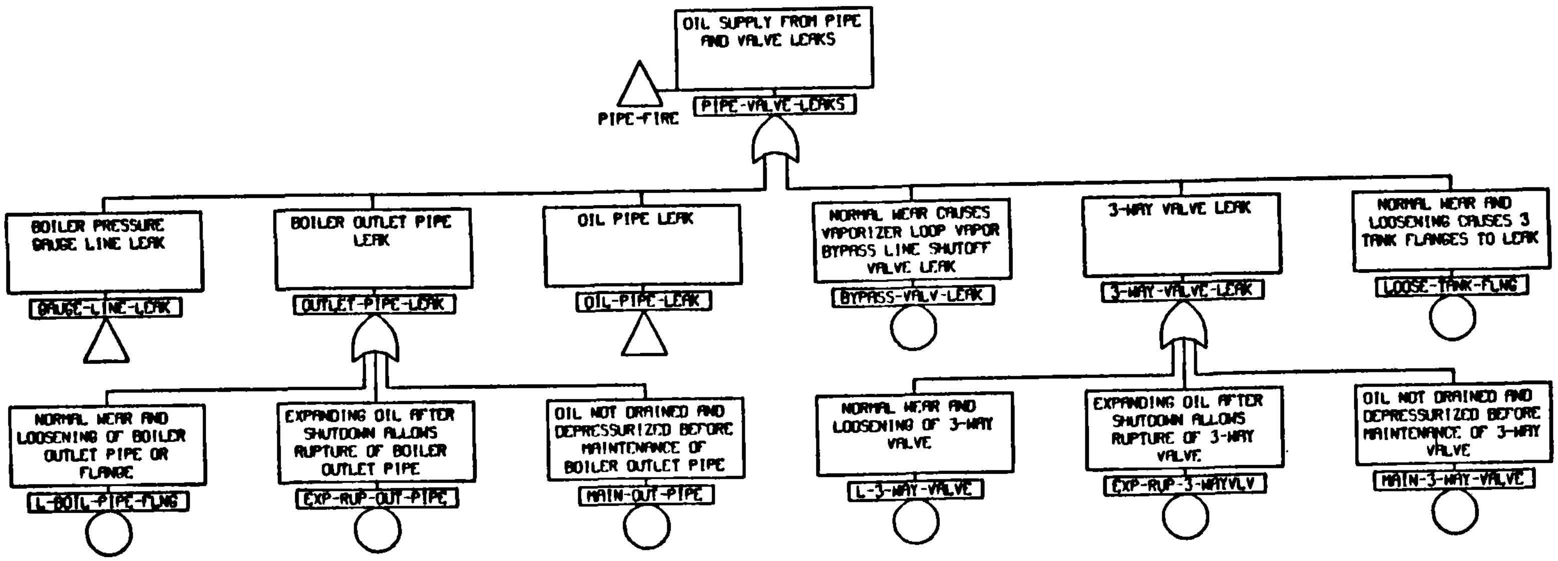

Diagram 2C. Fault Tree Logic for Pit Area Fire.

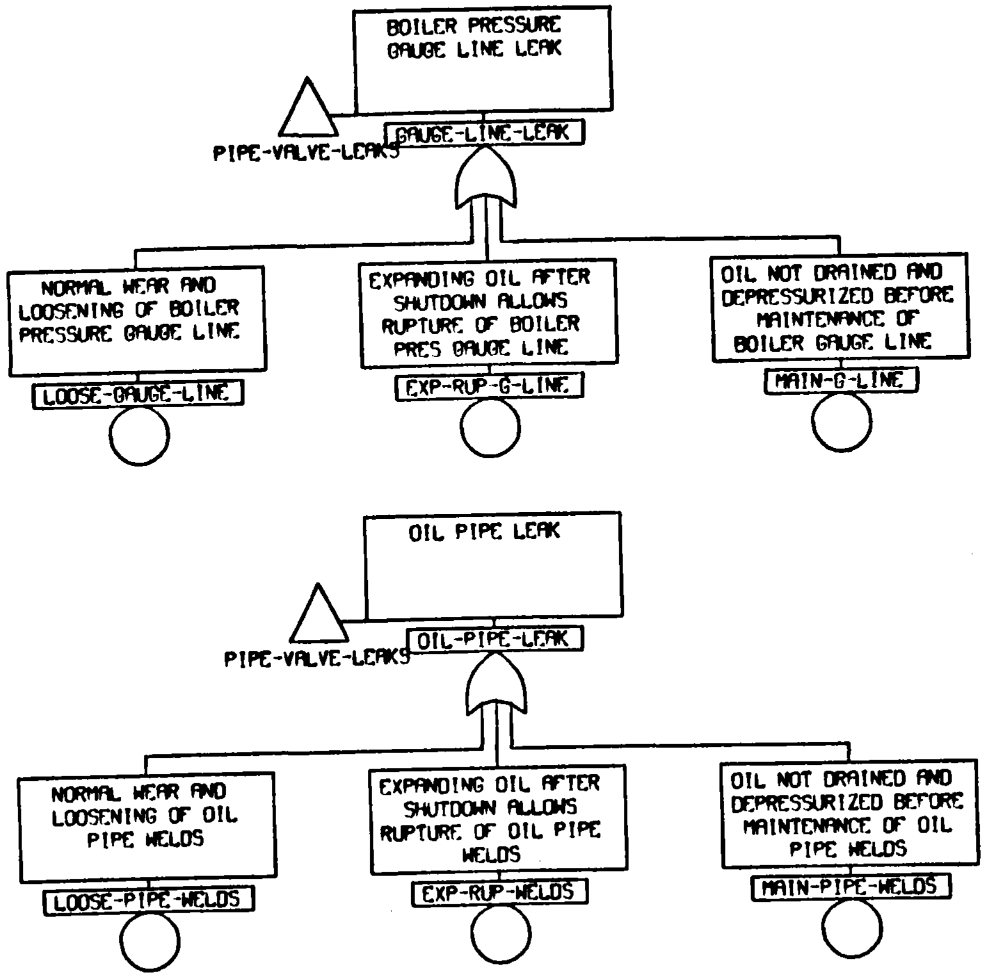

Diagram 2D. Fault Tree Logic for Pit Area Fire.

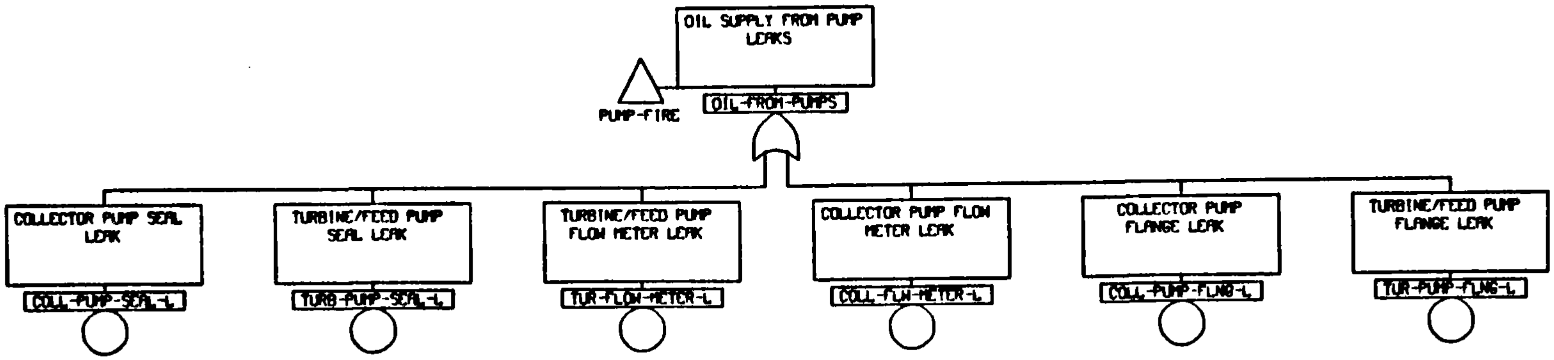

Diagram 2E. Fault Tree Logic for Pit Area Fire.

not only to normal wear and loosening, but also to rupture by expanding oil after a longterm shutdown without draining oil and to spills when the oil is not drained and depressurized before maintenance work begins.

The oil supply for a pump fire may be due to a collector-pump seal leak, a turbine/feed-pump seal leak, a turbine-feed-pump flow meter leak, a collector-pump flow meter leak, or a flange leak on either pump.

2. Quantification of the Pit Area Fault Tree

Listed in Table 2 are the component failures and human errors which constitute the basic events in the fault tree leading to a pit area fire. The estimates of the frequencies per year with which these events are expected to occur are also presented.

The total probability for fire in the pit area calculated from these expected frequencies is 1.52×10^{-3}, i.e., one fire every 656.2 years. The dominant sequences include the ignition of oil leaks from wear or loosening of the thermally flexed storage tank flanges (probability of 6.98×10^{-4} per year) as well as loosening of the three-way valve, the gas-fired heater's outlet flange and gauge line, or the pipe welds; each of which has a probability of 1.40×10^{-4}. Maintenance without draining oil had a total probability for resulting in fire of 3.14×10^{-4} while ignition of the vaporizer loop vapor bypass line leak was found to have a 6.98×10^{-5} probability. The other 30 sequences had a total probability of 5.34×10^{-5}, i.e., 3.5% of the fire probability in the pit area.

Fire Probability on the Power Conversion Platform

1. Discussion of the Power Conversion Platform Fault Tree

Diagrams 3A through 3C present the fault tree logic for a toluene fire on the power conversion platform. It is evident that such a fire may result from either a leak or rupture of toluene coming in contact with an ignition source, or from a power outage while the back-up lubrication system is plugged allowing the turbine bearings to burnout on spindown and ignite the turbine oil present.

The danger from leaks and ruptures stems from the regenerator or the vaporizer burst discs, component joint leaks, and organic Rankine cycle lubrication system leaks. The regenerator burst disc may rupture if the condenser pumps fail thus causing the regenerator to overpressurize or if a faulty toluene level sensor

Table 2

Event	Frequency/Year
- Fiberglass present at leak source	1
- Air flow present at leak source	always
- Oil temperature above 450°F	25% of time
- Ignition source at leak location	10
- CO_2 fails and allows air to reach hot bearings	10
- Friction from bearings causes high temperatures	2
- Ignition source present at pumps	.1
- Normal wear and loosening of boiler outlet pipe or flange	.2
- Expanding oil after shutdown allows ruptuer of boiler outlet pipe	.001
- Oil not drained and depressurized before maintenance of boiler outlet pipe	.1
- Normal wear of vaporizer loop vapor bypass line shutoff valve	.1
- Normal wear and loosening of three-way valve	.2
- Expanding oil after shutdown allows rupture of three-way valve	.001
- Oil not drained and depressurized before maintenance of three-way valve	.1
- Normal wear and loosening of three storage tank flanges	1
- Normal wear and loosening of boiler pressure gauge line	.2

Table 2 (Cont.)

Event	Frequency/Year
- Expanding oil after shutdown allows rupture of boiler pressure gauge line	.001
- Oil not drained and depressurized before maintenance of boiler pressure gauge line	.1
- Normal wear and loosening of oil pipe welds	.1
- Expanding oil after shutdown allows rupture of oil pipe welds	.001
- Oil not drained and depressurized before maintenance of oil pipe welds	.05
- Collector-pump seal leak	1
- Turbine/feed-pump seal leak	1
- Turbine/feed-pump flow meter leak	.2
- Collector-pump flow meter leak	.4
- Collector-pump flange leak	.2
- Turbine/feed-pump flange leak	.2

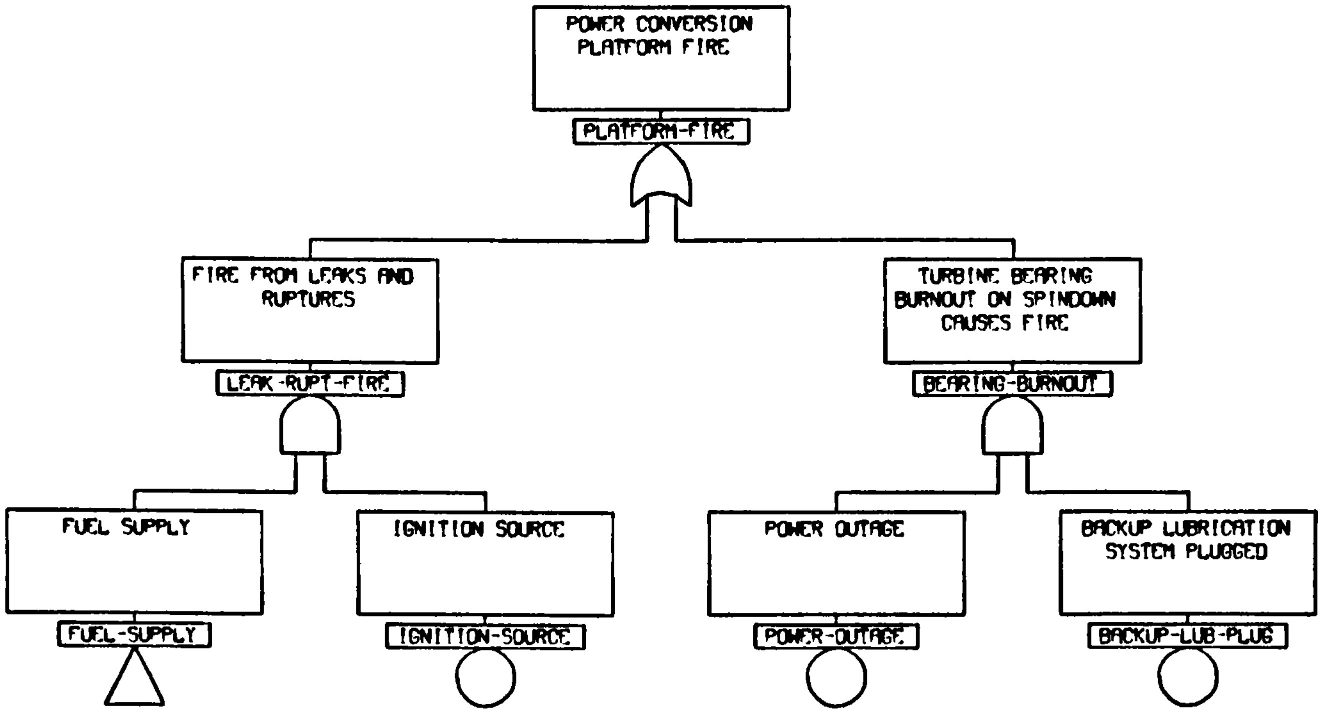

Diagram 3A. Fault Tree Logic for Power Conversion Platform Fire.

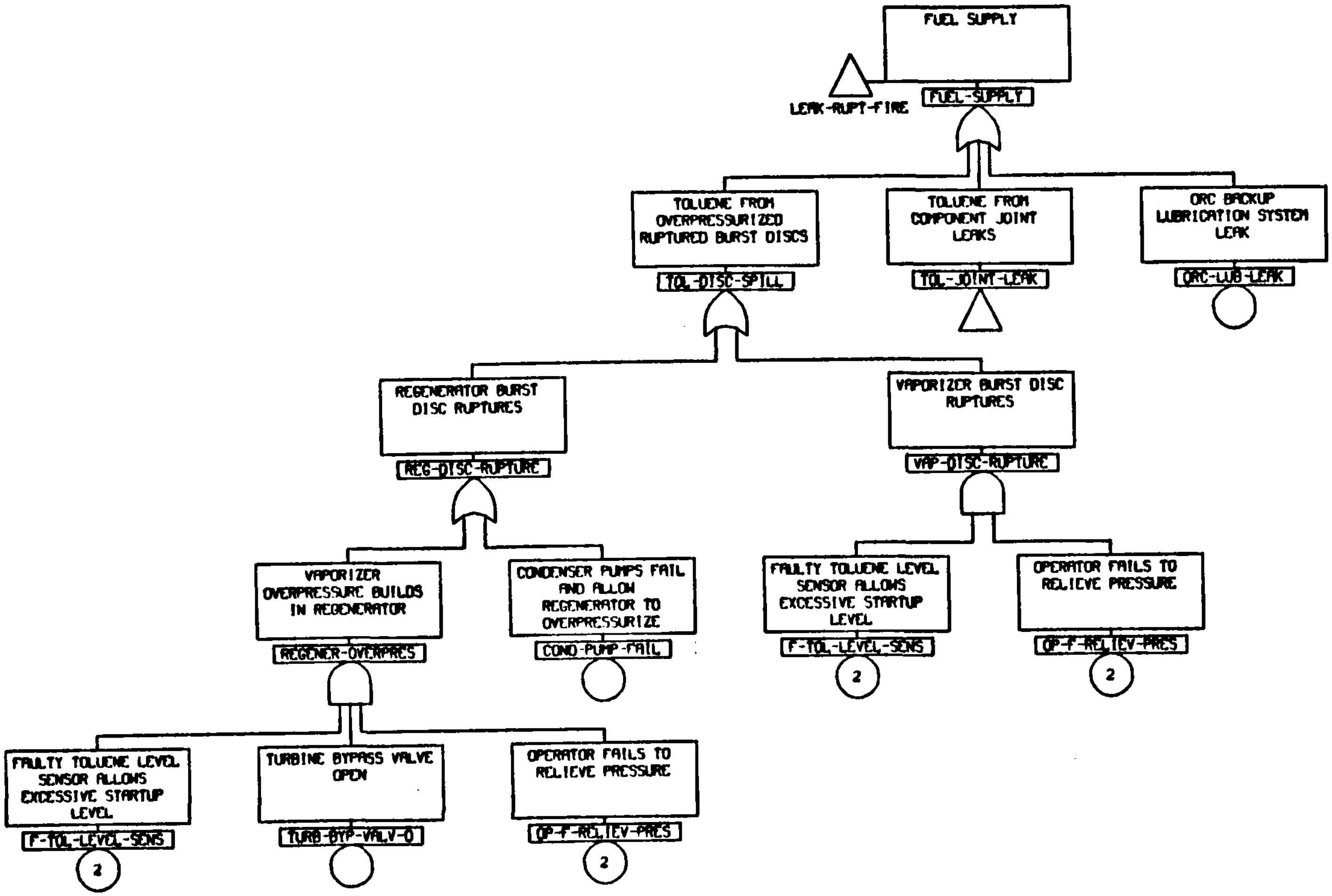

Diagram 3B. Fault Tree Logic for Power Conversion Platform Fire.

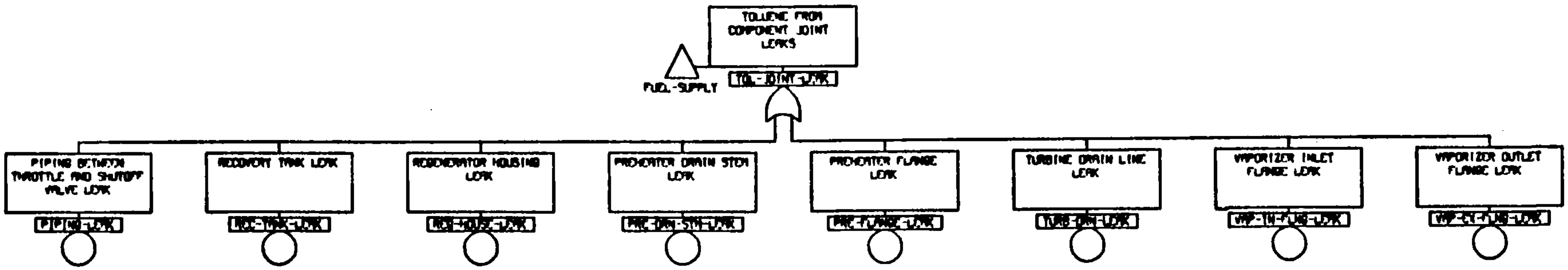

Diagram 3C. Fault Tree Logic for Power Conversion Platform Fire.

allows an excessive startup level while the turbine bypass valve is open and the operator fails to relieve the pressure. The vaporizer burst disc may rupture if the faulty toluene level sensor allows an excessive startup level while the turbine bypass line is closed and the operator fails to relieve the pressure.

Toluene from component joint leaks include the piping between the throttle and shutoff valve, the recovery tank, the regenerator housing, the preheater drain stem, the preheater flange, the turbine drain line, the vaporizer inlet flange, and the vaporizer outlet flange.

2. <u>Quantification of the Power Conversion Platform Fault Tree</u>

Listed in Table 3 are the component failures and human errors which constitute the basic events in the fault tree leading to a power conversion platform fire. The estimates of the frequencies per year with which these events are expected to occur are also presented.

The total probability for fire on the power conversion platform each year is 1.26×10^{-3}, i.e., one fire every 793 years. The major chance of fire is due to the faulty toluene sensor causing a burst disc rupture which is then ignited. This sequence has a probability of 3.75×10^{-4}. Ignition of the toluene spilled from the regenerator burst disc due to condenser pump failure has a probability of 1.50×10^{-4} while ignition of a regenerator housing leak has a 3.00×10^{-4} probability per year. The turbine bearing burnout after a power outage, ignition of toluene leaks from the vaporizer inlet and exit flanges, and ignition of toluene from the preheater flange leak each have a 7.51×10^{-5} probability. Ignition of leaks from the turbine drain line, backup lubrication system, preheater drain stem, and recovery tank each have a 3.00×10^{-5} probability each year. The final sequence is ignition of the piping leak between the turbine throttle and shutoff valve which has a probability of 1.50×10^{-5}.

SUMMARY

The total probability of fire at the Coolidge, Arizona, solar-powered irrigation facility is estimated to be 2.2×10^{-2} per year which corresponds to one fire every 45 years. The major source of fire probability was found to be in the collector field as a result of either spontaneous combustion or ignition of the constantly leaking manual and air-operated shutoff valves. If the manual and air-operated shutoff

Table 3

Event	Frequency/Year
- Power outage at facility	50
- Backup lubrication system plugged	.2
- Ignition source present at toluene leak	10
- Condenser pumps fail	2
- Faulty toluene level sensor allows excessive startup level	10
- Turbine bypass valve open	2
- Operator fails to relieve pressure	5
- Organic Rankine cycle backup lubrication system leaks	.2
- Piping between throttle and shutoff valve leaks	.1
- Recovery tank leak	.2
- Regenerator housing leak	2
- Preheater drain stem leak	.2
- Preheater flange leak	.5
- Turbine drain line leak	.2
- Vaporizer inlet flange leak	.5
- Vaporizer outlet flange leak	.5

valves were made leak free, the total probability of fire at the Coolidge facility would drop to 8.23×10^{-3} per year which corresponds to one fire every 122 years. Operator override of the safety interlocks during a component failure were the second major contributor to fire probability, while ignition of the loose storage tank flange leaks was third. Spontaneous combustion or ignition of the flexible hose or receiver tube compression fitting leaks, ignition of a burst disc rupture, and ignition of a regenerator housing leak were the next significant fire probability contributors.

From these observations, the following recommendations can be made for reducing fire probability:

1. Improve the design of both the manual and air-operated shutoff valves to prevent the high incidence of leaks.

2. Insure that the operator is properly trained in the safety interlock features of the collector field as well as the response to a malfunction of a faulty toluene level sensor on the vaporizer.

3. Eliminate the use of fiberglass or other wick-like materials to insulate potentially leaky components.

4. Attempt to eliminate storage tank flange and regenerator housing leaks.

5. Improve the performance of the flexible hoses and their attachments in the collector field.

6. Insure the proper fit of all receiver tube compression fittings.

These improvements, combined with attention to the normal wear and loosening of all components, will significantly reduce the probability of fire at the Coolidge solar facility. An ongoing data acquisition program aimed at the specific events presented in the fault trees is also highly recommended for future analysis.

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