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Thomas J. Altenbach
Sandra J. Brereton

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Risk from a Compressed Toxic Gas System: Part I - Dispersal Probability

by
Thomas J. Altenbach
Risk Assessment and Nuclear Engineering Group
Applied Research Engineering Division
Fission Energy and System Safety Program
and
Sandra J. Brereton
Hazards Control Department
Lawrence Livermore National Laboratory
University of California
7000 East Ave., P.O. Box 808, Livermore, CA 94550 L-196
Phone 510-422-1285, Fax 510-424-5489

I ABSTRACT

At the Lawrence Livermore National Laboratory, we have prepared a Safety Analysis Report for the Department of Energy on our Building 332 Plutonium Handling Facility. This SAR includes an analysis of potential accident scenarios which could lead to offsite consequences to the public having not only radiological exposures, but also exposures to toxic gases such as chlorine. This paper presents a risk analysis of pressurized chlorine gas system proposed for use at Building 332.

The focus of the analysis is to calculate the predicted frequency of an unmitigated leak of chlorine from the system which could result in the dispersal of the entire contents of the gas cylinder to the environment. Modeled are postulated valve leaks or pipe ruptures occurring anywhere in the distribution system, as well as the potential failure of leak mitigation.

The fundamental credibility of this type of accident is established. The importance of a reliable leak mitigation system is demonstrated, and the dependence of the results on less than optimal data is discussed in the context of uncertainty and sensitivity analyses.

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II EXECUTIVE SUMMARY

Compressed toxic gas systems are widely used throughout industrial and research facilities, in both the private and government sectors. Though the use of gasses such as chlorine is well accepted by the public, the risks of their use are not well understood and often ignored until a major leak or accident occurs. At the Lawrence Livermore National Laboratory, we have prepared a Safety Analysis Report (SAR) for the Department of Energy on our Building 332 Plutonium Handling Facility. This SAR includes an analysis of potential accident scenarios which could lead to offsite consequences to the public having not only radiological exposures, but also exposures to toxic gases such as chlorine.

This paper presents a risk analysis of compressed chlorine gas system proposed for use at Building 332. The focus of the analysis is to calculate the predicted frequency of an unmitigated leak of chlorine from the system which could result in the dispersal of the entire contents of the gas cylinder to the environment. Modeled are postulated valve leaks or pipe ruptures anywhere in the system from the gas cylinder stored outside the building, through various valve and piping sections, ending at the laboratory inside the building. Also modeled is potential failure of leak mitigation, composed of a gas sensor inside the gas cabinet, remote alarm in the control room, and human intervention to control the leak. The leaks are assumed to be initiated by the random failure of the components. The analysis does not include potential leaks occurring during bottle changeover procedures due to human errors such as cylinder mishandling, or natural phenomena initiators such as earthquakes.

The predicted leak frequency is calculated via a computerized fault tree analysis, and evaluated with published industrial component and human error failure rate data. Since the system is only operational during normal working hours, the total leak frequency is found by summing separate calculations for normal and off-normal hours.

During off-normal hours, the system is in a standby mode, dependent upon daily human action to effect that lower-risk state.

Several cases are calculated to illustrate the sensitivity of the model to changes in data and to demonstrate reduced risk through potential changes in operational procedures. For each case, the fault tree is solved for the minimal cut sets and the mincut upper bound. Then an importance analysis and an uncertainty analysis is presented.

Several conclusions are evident. The fundamental credibility of this type of accident is established, with implications for toxic gas systems throughout the Laboratory and DOE complex. The importance of a reliable leak mitigation system is demonstrated, and the dependence of the results on less than optimal data is discussed in the context of the uncertainty and sensitivity analyses.

This paper presents the first part of series of two papers on this topic. In order to complete the risk analysis, the second paper discusses the consequence calculations done for chlorine releases at the site. Then the appropriate regulations and dose guidelines are presented, as well as comparison with potential hazards and the standards set for a nearby water treatment plant also using chlorine.

III SYSTEM DESCRIPTION

The proposed compressed chlorine gas system is shown in Fig. 1. It is composed of a gas cabinet located outside the building, with piping and monitoring signals extending inside the building. A single gas cylinder with manual shutoff valve is placed inside the gas cabinet. This is connected by a 1-inch pipe to a solenoid-operated excess flow valve. Downstream of the flow valve, a 40-inch pipe connects to the emergency shutoff valve. The chlorine is then distributed through an 8-foot pipe which exits the cabinet, and continues with 110-foot pipe terminating inside the building. The excess flow valve is self-actuated to shut off when it detects flow above the set point.

The emergency valve shuts off automatically upon either detection of excess flow by the flow sensor or detection of a gas release inside the cabinet by the gas sensor located there. The gas sensor also sends a signal to the control room triggering an alarm. The system is operational during working hours only. At the end of each day, an operator manually closes the main cylinder valve.

IV MODEL ASSUMPTIONS

The purpose of the analysis is to estimate the frequency of unmitigated leaks of chlorine during normal operation, including standby conditions. This model does not include leaks incurred during bottle changeover operations, which would require a separate human factors analysis. An unmitigated leak is defined as a leak which has the potential to release a significant quantity of chlorine, up to the entire inventory at the maximum theoretical rate. They are assumed to originate from either external valve or cylinder leaks, or rupture of piping sections. It is assumed that leaks have a small enough flow that they can be mitigated through emergency operator response. Therefore failure of leak mitigation is also modeled. This includes the gas sensor, control room alarm, and human action. If leak detection fails, the leak is assumed to develop into a major failure (i.e. "leak-before-break" is assumed). It is also assumed that pipe ruptures can only be mitigated by automatic actuation of those valves located upstream of the rupture. Therefore, failure of the appropriate valves to close on demand is also modeled. Failure of the operator to shut off the system at the end of each day is included as a basic event. The working hours are taken to be 5 days/week at 10 hours/day (to be conservative), less 10 holidays/year, which comes to 2500 hours/year. Off hours are then 6260 hours/year.

V FAULT TREE CONSTRUCTION

A fault tree was developed using the IRRAS computer code (Russell, et al.,1992). The high-level fault tree [Fig. 2] has three branches from the OR Gate leading to the top event. The branches represent: 1) leaks in the cylinder/manual valve unit which is always at risk; 2) leaks in the distribution system during working hours (downstream of the manual valve); and 3) leaks in the distribution system during off hours, which include the human error of failing to close the manual valve [Fig. 3]. In Figure 3, the developed paths include a rupture of the piping upstream of the flow valve, a leak at the flow valve, a rupture of the piping connecting the flow and emergency valves, a leak at the emergency valve, a rupture of the piping downstream of the emergency valve and inside the cabinet, and a rupture of the piping outside the cabinet. Failure of leak mitigation [also Fig. 2] is developed as a subtree and appears as an input to an AND Gate along with each valve or cylinder leak event. The fault tree for distribution system leaks during working hours is not shown, however it has a similar structure to Figure 3. The only difference is that the upper OR gate now becomes the top event, since the human error failing to close the manual valve is not applicable, and the top AND gate is therefore deleted.

VI QUANTIFICATION

The fault tree was quantified with data from the Savannah River Data Base (Blanton and Eide,1993, and Benhardt, et al., 1994). Table 1 lists the basic events as they appear on the fault tree, along with the baseline values used and the source. Values for pipe ruptures and valve leaks are given in units of events/year, and must be mulitiplied by the appropriate ratio to represent either working or off hours to get the values used in each fault tree.

The fault tree was solved for the minimal cut sets and mincut upper bound. The top four of the 27 total cut sets contribute approximately 98% of the mincut upper bound. These cut sets are: 1) cylinder leak AND alarm failure (57%); 2) cylinder leak

AND gas sensor failure (19%); 3) flow valve leak during working hours AND alarm failure (16%); 4) flow valve leak during working hours AND gas sensor failure (5%). The mincut upper bound is 2.0×10^{-4} /year. An importance calculation ranked the top 4 basic events according to both the Fussell-Vesely equation and the Risk Reduction Ratio as: 1) cylinder leak; 2) alarm failure; 3) gas sensor failure; 4) flow valve leak during working hours.

Undetected leaks from the cylinder/manual valve clearly dominate the system failure frequency for the base case. These leaks contribute 77.6% of the mincut upper bound. Leaks or ruptures in the distribution system during working hours contribute 22.3% to the mincut upper bound, while off-hours leaks or ruptures contribute only .03%. However, since the cylinder leak risk is spread over the entire time, the predicted frequency of off-hours leaks from all sources is actually higher than the working-hours rate, contributing 55.5% and 44.5% respectively to the mincut upper bound.

VII SENSITIVITY AND UNCERTAINTY

Three additional cases were run in order to conduct a sensitivity study on some parameters of interest. For the base case, it was assumed that the chlorine monitoring system was tested annually, therefore a mean time to failure of 6 months was applied to the failure rates from the data base. Since these components, the gas sensor and alarm, are highly ranked in the importance calculation, it is interesting to study the effects of a more frequent inspection schedule. A calculation was done using a monthly inspection period, which implies a mean time to failure of 0.5 months for the gas sensor and alarm, a factor of 12 smaller than the base case. This results in a mincut upper bound estimate of 2.0×10^{-5} /year, or a factor of 10 decrease in the system failure rate. However, the alarm and gas sensor still remain ranked in the top 4 most important basic events.

The next case studies the effects introduced by assumptions made in development of the data base. In Blanton and Eide (1993), it is noted that the values listed for compressed gas systems are "based on comparisons of (limited) compressed gas system data for component groups with the much more extensive water system data." The failure rates used for pipe ruptures and cylinder leaks were taken from water system results and multiplied by 10. Similarly, the failure rates for valve leaks were taken from water system results and multiplied by 3. Since no justification is presented in Blanton and Eide (1993) for these factors, we ran a calculation removing these multipliers from the water system data. With the leak and rupture failure rates reduced as described, the mincut upper bound result is 3.1×10^{-5} /year.

The final case combined the changes from the two previous cases, giving the most optimistic view of system failure by using the lower failure rates for water system data and the monthly inspection for the monitoring system. This results in a mincut upper bound of 3.0×10^{-6} /year.

A Latin Hypercube uncertainty calculation was performed for all four cases. A lognormal probability distribution was assumed for all basic events, with error factors taken from the data bases. Pipe ruptures have an error factor of 30., sensors have an error factor of 3.0, and the remainder of the basic events all use 10. Table 2 summarizes the results of the uncertainty calculations based on 10,000 runs for each case, and Figure 4 plots the frequency distributions.

Table 1. Baseline Data Used in Quantification

Basic Event Name / Description	Value	Data Source / Justification
ALARM-FAILS / Toxic gas alarm fails to annunciate in control room.	1.3×10^{-1}	Ref. 2 page 41, 3.0×10^{-5}/hr * 8760 / 2, assuming yearly inspection, take mean time to leak as .5 year.
CONNECT-PIPE-BRK / Rupture in piping between valves.	2.9×10^{-5} per year	Ref. 2 page 31 1.0×10^{-9}/hr-ft * 8760hr/year * 40 in. length
EMERG-VALVE-FAIL / Emergency solenoid-operated shutoff valve fails to close upon demand.	3.0×10^{-3} per demand	Ref. 2 page 30
EMERG-VALVE-LEAK / Emergency solenoid-operated shutoff valve leakage (external).	8.8×10^{-4} per year	Ref. 2 page 30, 1.0×10^{-7}/hr * 8760 hr/year
FLOW-SENSOR-FAIL / Flow sensor fails to detect leak.	1.3×10^{-2}	Ref. 2 page 41 3.0×10^{-6}/hr * 8760 / 2, assuming yearly inspection.
FLOW-VALVE-FAILS / Solenoid-operated flow valve fails to close upon demand.	3.0×10^{-3} per demand	Ref. 2 page 30
FLOW-VALVE-LEAK / Solenoid-operated flow valve leakage (external)	8.8×10^{-4} per year	Ref. 2 page 30, 1.0×10^{-7}/hr * 8760 hr/year
GAS-SENSOR-FAILS / Chlorine gas sensor fails to detect leak or rupture inside cabinet.	4.4×10^{-2}	Ref. 2 page 41 1.0×10^{-5}/hr * 8760 / 2, assuming yearly inspection, take mean time to leak as .5 year.
HUMAN-RESPONSE / Control room operator fails to respond to toxic gas alarm.	3.0×10^{-3}	Ref.3 p.13, failure to respond to compelling signal assuming few competing signals.
INSIDE-PIPE-BRK / Piping rupture downstream of valves and inside cabinet.	7.0×10^{-5} per year	Ref. 2 page 31 1.0×10^{-9}/hr-ft * 8760 hr/year * 8 ft length
MAN-VALVE-OPEN / Operator fails to close manual valve at end of day	5.0×10^{-4}	Ref. 3 page 31, failure to lockout, typical lockout plan
OUTSIDE-PIPE-BRK / Piping rupture downstream of valves and outside cabinet	9.6×10^{-4} per year	Ref. 2 page 31 1.0×10^{-9}/hr-ft * 8760hr/yr * 110 ft length
TANK-LEAK / Pressurized chlorine cylinder leakage (external)	8.8×10^{-4} per year	Ref. 2 page 32 1.0×10^{-7}/hr * 8760 hr/year
UPSTREAM-PIPE / Piping rupture upstream of both valves.	7.3×10^{-7} per year	Ref. 2 p.31 1.0×10^{-9}/hr-ft * 8760 hr/year * 1 inch length.

Table 2. Uncertainty Study Results

CASE	95%	MEAN	MEDIAN	5%
Base	$6.88x10^{-4}$	$1.85x10^{-4}$	$6.04x10^{-5}$	$6.88x10^{-6}$
Monthly Inspections	$7.05x10^{-5}$	$2.01x10^{-5}$	$6.71x10^{-6}$	$8.38x10^{-7}$
Water system data	$9.95x10^{-5}$	$2.74x10^{-5}$	$9.93x10^{-6}$	$1.22x10^{-6}$
Combined study	$1.09x10^{-5}$	$3.09x10^{-6}$	$1.06x10^{-6}$	$1.43x10^{-7}$

VIII CONCLUSIONS

We estimated the frequency of a significant release of chlorine from postulated hardware failures and human errors involved in the normal operation of the system during both working hours and in standby condition during off-hours. The basic credibility of this type of accident was established to be on the order of 10^{-4} per year. Reliability improvements in the monitoring system are easily achievable which would bring this frequency down by an order of magnitude. These estimates are conservative, in that they are based on data which has been conservatively extrapolated from water systems. However, the total risk of a chlorine release at the facility must also account for human errors in bottle changeover procedures, which has not been addressed in this study.

IX REFERENCES

1. Integrated Reliability and Risk Analysis System (IRRAS) Version 4.0, K. D. Russell, et al., NUREG/CR-5813 EGG-2664, January 1992.

2. Savannah River Site Generic Data Base Development, C. H. Blanton and S. A. Eide, WSRC-TR-93-262, June 1993.

3. Savannah River Site Human Error Data Base Development for Nonreactor Nuclear Facilities, H. C. Benhardt, et al., WSRC-TR-93-581, February 1994.

Figure 1. Toxic Gas System Schematic Used for Fault Tree Analysis

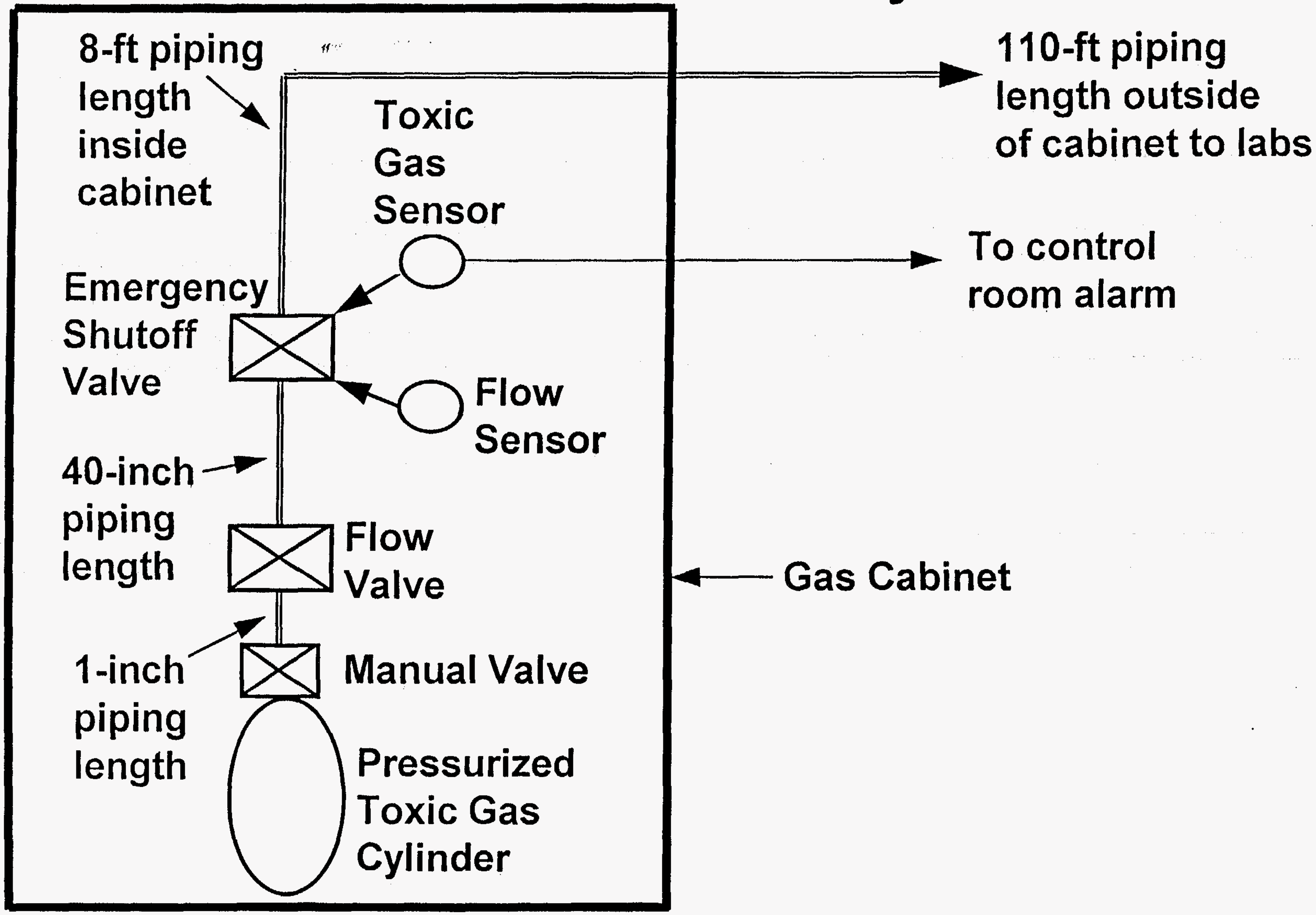
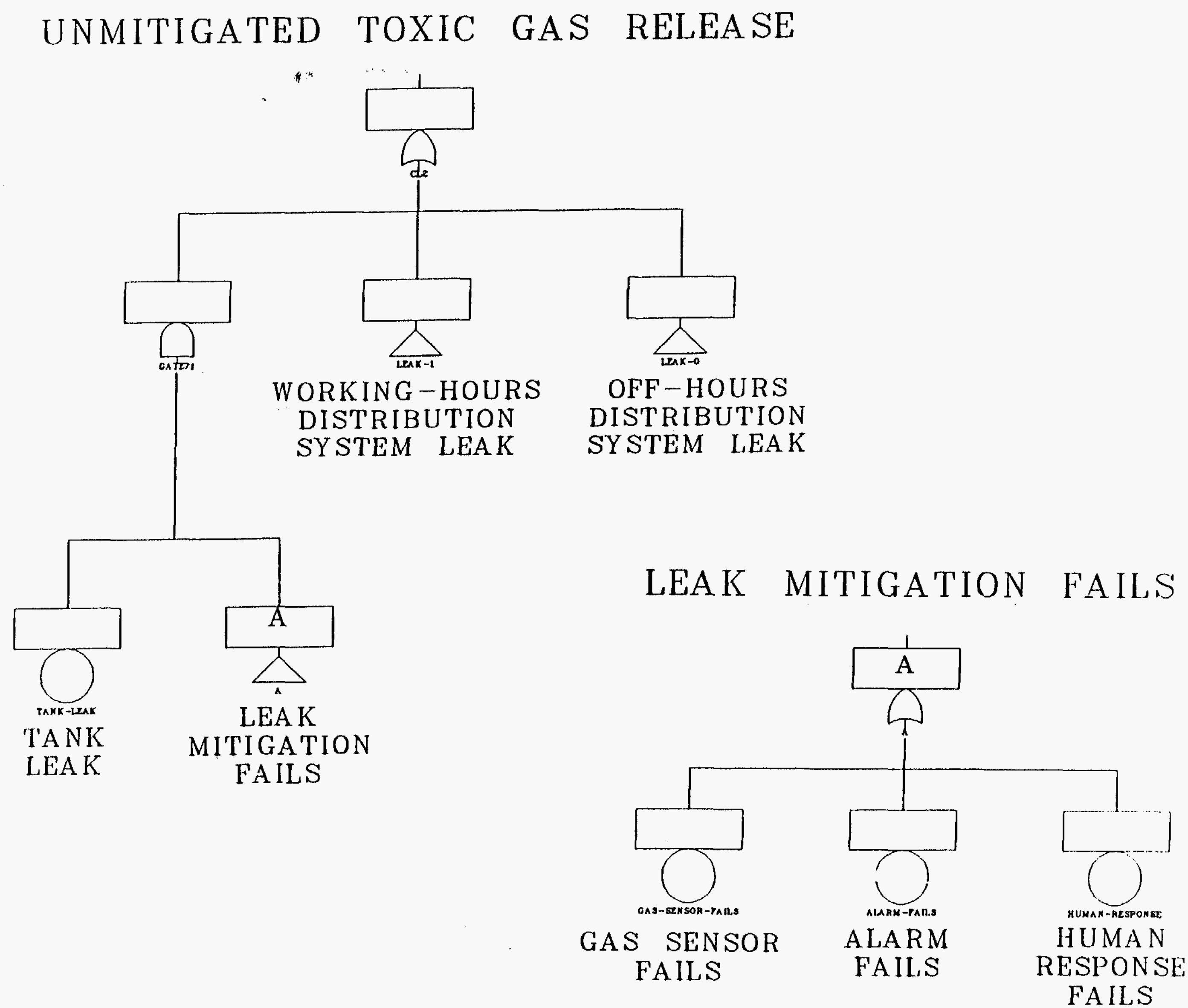


Figure 2.



UNMITIGATED TOXIC GAS RELEASE
GATE1
LEAK-1
LEAK-0
WORKING-HOURS DISTRIBUTION SYSTEM LEAK
OFF-HOURS DISTRIBUTION SYSTEM LEAK
A
TANK-LEAK
TANK LEAK
LEAK MITIGATION FAILS
LEAK MITIGATION FAILS
A
GAS-SENSOR-FAILS
ALARM-FAILS
HUMAN-RESPONSE
GAS SENSOR FAILS
ALARM FAILS
HUMAN RESPONSE FAILS

Figure 3. DISTRIBUTION SYSTEM LEAK DURING OFF HOURS

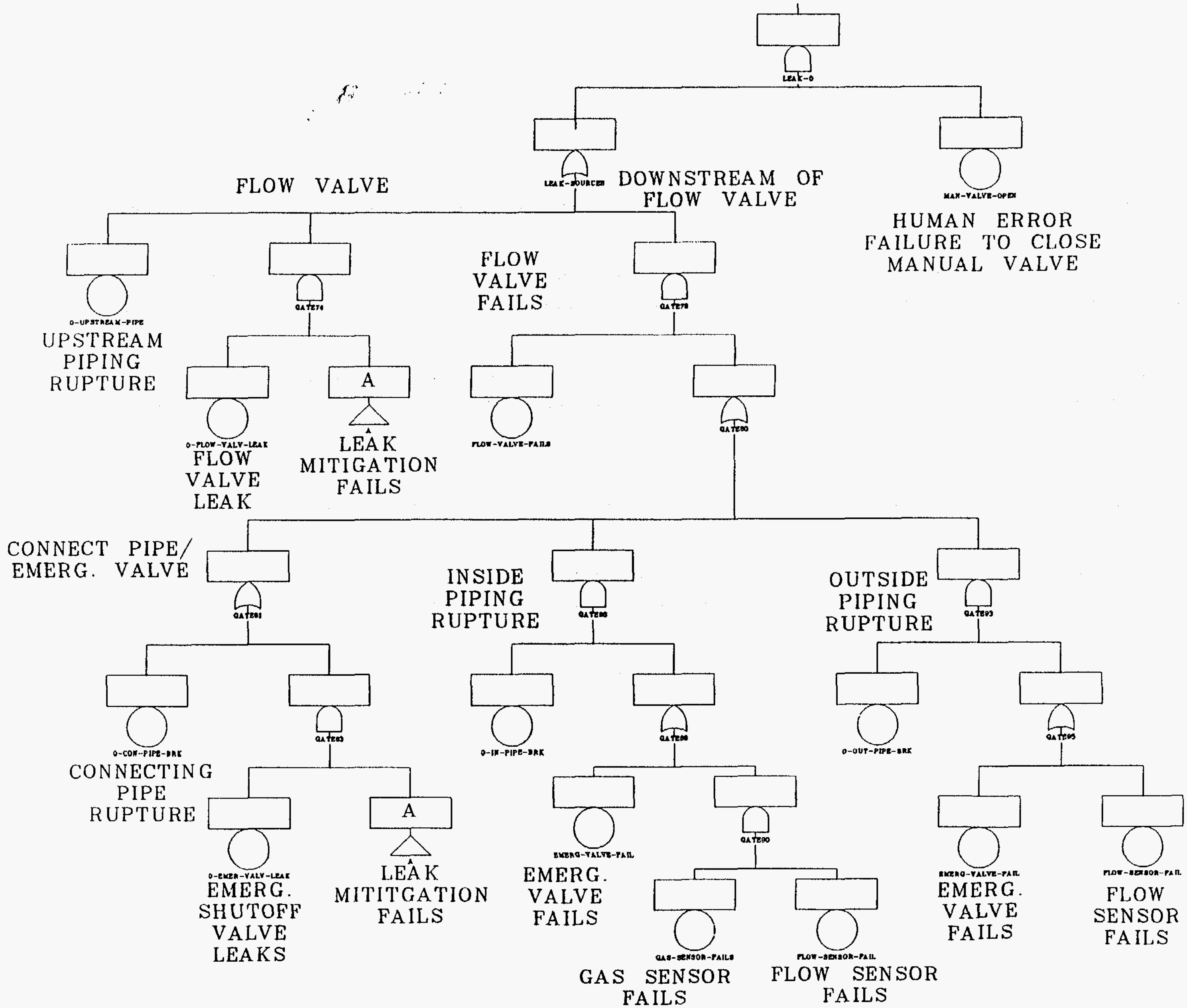


Figure 4. Chlorine Release Frequency Distributions