

APPLICATION OF QUALITATIVE AND QUANTITATIVE RISK ANALYSIS TECHNIQUES TO BUILDING SITING STUDIES

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**Presented At
1998 Process Plant Safety Symposium
Houston, Texas
October 26-27, 1998**

**Presented By
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ABSTRACT

API Recommended Practice 752, *Management of Hazards Associated with Location of Process Plant Buildings*, describes a methodology that can be used to meet the facility siting requirement in OSHA's PSM rule (29 CFR 1910.119, Section (e)). The methodology is presented in very general terms in API RP 752. This allows it to be applied to a wide range of facilities and buildings, but also requires each company to decide how it should be applied to specific installations.

In keeping with the API RP 752 methodology, a protocol was developed where each process plant building is analyzed individually. The analysis proceeds until the results indicate the risk to occupants is within the acceptable range. The acceptable risk is defined differently in each of the protocol steps. In the first step, the risk is determined by building use, occupancy, etc. In the second step, the acceptable risk is based upon a qualitative estimate of vulnerability. In the last step, quantitative risk analysis techniques are applied to all buildings that were not excluded from further analysis by either of the first two steps.

This paper reviews the procedures, analysis, and results of a building siting study for a process facility which required a quantitative risk analysis. The protocol is outlined, intermediate qualitative risk results are presented, and application of quantitative risk analysis techniques is discussed.

INTRODUCTION

Chevron, while in the process of designing a chemical process plant, was faced with conducting a building siting assessment. Although not a regulatory requirement at the facility's location, Chevron management systems specify this type of analysis. Chevron teamed with Quest Consultants Inc. to conduct the analysis. This type of assessment is intended to provide a better understanding of the potential exposure of plant

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buildings and building occupants to hazardous incidents that might occur within the facility. Hazardous incidents of interest include releases of toxic or flammable materials that could result in toxic vapor clouds, fires, or explosions.

This paper discusses the methodology used to conduct the assessment, and the results of the assessment.

OVERVIEW OF METHODOLOGY

API RP 752, *Management of Hazards Associated with the Location of Process Plant Buildings*, describes a methodology for conducting building siting assessments. Using that publication as a basis, Chevron developed company criteria and guidelines for implementing API RP 752 in a consistent manner. The methodology used for the facility conforms to API RP 752, as implemented by Chevron.

A brief summary of Chevron’s methodology is presented. The methodology divides a building siting assessment into three stages that are to be undertaken sequentially. At the end of each stage, some of the buildings may be removed from further analysis. Thus, it is not always necessary to complete all three stages for each building.

Stage 1 - Building and Hazard Identification

In this stage, occupancy levels and criticality of all process plant buildings are identified. Figure 1¹ outlines the basic logic used in Stage 1. Buildings that are not routinely occupied or are clearly not subject to toxic, fire, or explosion hazards are removed from further study at this point.

This stage also includes a preliminary hazard assessment, which simply determines if the facility has the potential to impact one or more buildings with a vapor cloud explosion, physical explosion, fire, or toxic vapor cloud. If the facility has the potential to produce one or more of these hazards, the occupancy level and criticality of each building are then compared to the following screening criteria.

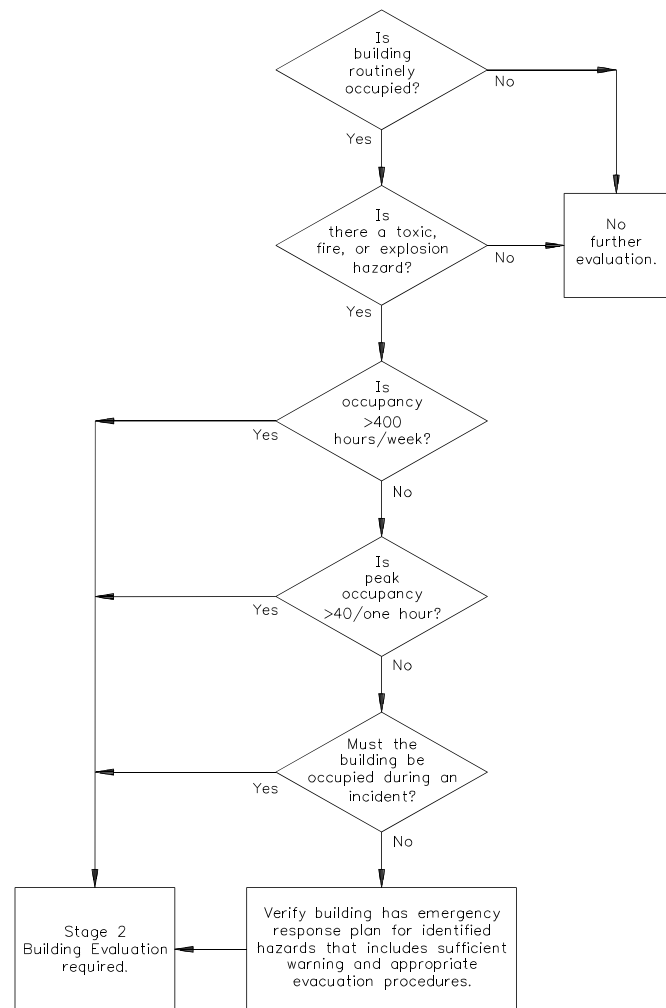


Figure 1
Chevron’s Hazard/Occupancy Screening Flowchart for Stage 1

¹*Building Siting Assessments: Supplemental Guidelines for API RP 752 - Management of Hazards Associated with Process Plant Buildings.* Chevron Research and Technology Company, January 1997.

- Occupied >400 hours per week
- Peak occupancy >40 persons for one hour
- Must be occupied during incidents for safe shutdown of the facility
- Designated as an emergency response shelter

Any building that meets one or more of these criteria is subject to further analysis in Stage 2. For each building that does not meet any of these criteria, it is only necessary to verify that the facility emergency response plans include sufficient warning and evacuation plans appropriate for the identified hazards (see Figure 1).

Stage 2 - Building Evaluation

Stage 2 includes consequence modeling of:

- toxic vapor clouds that could result from releases of toxic materials
- vapor cloud explosions that could result from releases of flammable materials
- physical explosions that could result from ruptures of pressure vessels

With respect to toxic vapor clouds and vapor cloud explosions, the largest release scenarios to be modeled are:

- releases from a 2-inch diameter hole in process equipment
- releases from a 2-inch diameter hole in piping systems, or from a hole equal to the maximum diameter of the pipe if the piping is less than 2 inches in diameter

Consequences of each potential accident are quantified for each of the buildings included in the Stage 2 analysis. If the consequences exceed certain criteria, mitigating measures may be recommended, or it may be necessary to proceed to Stage 3. Chevron's criterion of interest for toxic vapor clouds is the ERPG-2 level. For explosions, the criterion of interest is the maximum side-on overpressure.

Based on fire protection guidelines, buildings should be at least 50 feet from a process area that contains a flammable gas, a flammable liquid, or a combustible liquid at a temperature above its flash point. All buildings within 50 feet are compared to a checklist to see if they meet fire hazard requirements. If a building does not meet one or more of the requirements, a recommendation is made to upgrade the building.

Stage 3 - Risk Assessment

According to Chevron's building siting assessment guidelines, many assessments will be complete following Stage 2 (i.e., either the hazard levels for buildings and building occupants are acceptable, or mitigation measures will be undertaken to make them acceptable). It may be necessary to proceed to Stage 3 and conduct a risk assessment in cases where mitigation measures are impractical or are not cost effective.

The first type of risk assessment to be conducted in Stage 3 is a qualitative evaluation. It combines HAZOP techniques, consequence analysis, estimates of accident frequencies, and a risk ranking matrix to arrive at a qualitative measure of the risk posed to the building and its occupants. If the risk is low enough to be deemed acceptable, no additional analysis or mitigation is required. If the risk appears to be unacceptable, a quantitative risk analysis (QRA) can be performed.

A QRA combines a broad range of accident scenarios (including those from Stage 2) with their associated failure frequencies. The results from a QRA are individual risk contours that describe the annual probability

of a specified hazard at any location around the process unit(s). The predicted risk level at any building can then be compared to international or industry standards to determine if the risk is acceptable.

IMPLEMENTATION OF METHODOLOGY

This section describes how each of the stages in Chevron's methodology was implemented for the facility.

Stage 1 - Building and Hazard Identification

Building Identification

A list of buildings was provided at the outset of the analysis. This list contained twenty-four structures, plus an undefined number of analyzer houses. Each building on the project site is listed in Table 1, along with its occupancy and construction characteristics. This information is the basis for all Stage 1 decisions.

Five smoking shelters on the list were described as "open structures;" thus, they do not meet Chevron's definition of a building—a structure "having a roof and 75% of the perimeter enclosed."² However, since they were listed as routinely occupied, they were not excluded from the study at this point.

Ten of the twenty-four buildings, and the analyzer houses, were listed as not being routinely occupied. On this basis, these buildings were excluded from further analysis.

Hazard Screening

Several process streams in the facility contain light hydrocarbons and/or heavier hydrocarbons at temperatures above their flash points. Therefore, buildings in the area are subject to vapor cloud explosion (VCE) hazards.

None of the processes involves exothermic chemical reactions that could result in vessel rupture under runaway conditions. Therefore, buildings in the area are not subject to physical explosion hazards.

Each building listed in Table 1 was evaluated for its proximity to a process unit. Any building within 50 feet of a process area that contains flammable gases, flammable liquids, or combustible liquids at temperatures above their flash points, is subject to a potential fire hazard. Buildings that fall within the 50-foot guideline were evaluated for their fire resistance and mitigation systems, and possible relocation in the plant design.

Most of the process streams within the facility do not contain any of the highly hazardous chemicals listed in OSHA's PSM rule, 29 CFR 1910.119. However, some of the process streams in the naphtha hydrotreater (NHT) unit contain hydrogen sulfide (H₂S) in concentrations greater than its ERPG-2 value. Therefore, building occupants are potentially subject to toxic hazards.

Occupancy/Function Screening

The four criteria for continued inclusion in the analysis were applied to the nine buildings and five smoking shelters that reached this point in the analysis. The five smoking shelters and four operator shelters were dropped from further analysis since they do not satisfy any of the four occupancy/function criteria.

²See Note 1.

**Table 1
Process Plant Buildings**

Description	Routinely Occupied?	Peak Occupancy	Average Hours/Week	Required to be Occupied During Incident?	Size (m ²)	Construction Details	Stage 2 Building Evaluation Required?
Administration Building	Yes	150	3,600	Yes	1,295		Yes
Entrance Building	Yes	50	1,450	Yes	810		Yes
Central Control Building (w/lab)	Yes	50	3,708	Yes	1,900	Concrete block	Yes
North Guard House	Yes	2	168	Yes	9		Yes
South Guard House	Yes	2	168	Yes	9		Yes
Analyzer Houses (various)	No	4	12	No			No
Substations							
Main/Utility/PX Recovery	No	25	40	No	2,250		No
Reforming and Tank Farm	No	15	25	No	580		No
Benzene Recovery	No	10	20	No	250		No
Offsites	No	5	10	No	150		No
Process Interface Buildings (PIBs)							
Reforming (Platformer)	No	5	16	No			No
Reforming (Aromax)	No	5	16	No			No
Benzene Recovery	No	5	16	No			No
PX Recovery	No	5	16	No			No
Tank Farm #1	No	3	8	No			No
Tank Farm #2	No	3	8	No			No
Smoking Shelters							
Administration	Yes	12	100	No	11	Open structure	No
Central Control Building	Yes	8	210	No	11	Open structure	No
Process #1	Yes	8	40	No	11	Open structure	No
Process #2	Yes	8	40	No	11	Open structure	No
Offsites/Tank Farm	Yes	8	40	No	11	Open structure	No
Operator Shelters (w/field lab)							
Reforming	Yes	10	252	No	20	Concrete block	No
Benzene Recovery	Yes	10	252	No	20	Concrete block	No
PX Recovery	Yes	10	252	No	20	Concrete block	No
Offsites/Tank Farm	Yes	10	252	No	20	Concrete block	No

Five buildings were selected for Stage 2 analysis, as shown in Table 1. Three of these buildings—the administration building, entrance building, and central control building (with lab)—meet the criteria for peak occupancy (greater than 40 persons for one hour), average occupancy (greater than 400 hours per week), and occupancy during emergencies.

The two guard houses do not meet the occupancy criteria but were selected for further analysis because they are to be occupied during emergencies.

Stage 2 - Building Evaluation

Toxic Hazards

According to Chevron guidelines, occupants of the five buildings included in the Stage 2 analysis may be subject to toxic hazards due to the presence of hydrogen sulfide in the naphtha hydrotreater (NHT). Therefore, the consequence analysis in Stage 2 included modeling of toxic vapor clouds from releases in the NHT unit.

Based on a review of the process flow diagrams (PFDs) and other process information, a list was compiled of four potential releases that could result in toxic (H₂S) vapor clouds. (These are not the only releases that could result in toxic vapor clouds, but they are representative of the full range of potential releases.) The consequence analysis software package, CANARY by Quest®, was used to model the toxic vapor clouds that could result from the four potential releases in the NHT unit. All of these releases are capable of producing vapor clouds with H₂S concentrations greater than the ERPG-2 level at one or more of the five buildings selected for Stage 2 analysis.

Table 2 presents the toxic vapor cloud predictions for the worst-case release that involves hydrogen sulfide (Case NHT-13). It includes the maximum airborne concentration of H₂S at each of the five buildings.

**Table 2
Toxic Vapor Cloud Results
(Release from the Desulfurizer Overhead Line)**

Building	Distance from Release Point (m)	Maximum H₂S Concentration (ppm)
Control Room	140	75
Entrance	275	28
Administration	250	33
North Gate House	315	21
South Gate House	155	68

All vapor dispersion modeling was based on a wind speed of 5 mph and Pasquill F atmospheric stability. These are generally considered worst-case atmospheric conditions.

Fire Hazards

None of the five buildings that are included in the Stage 2 analysis were located within 50 feet of a process unit, and did not require any special upgrades for fire protection.

Explosion Hazards

The five buildings included in the Stage 2 analysis are subject to potential explosion hazards, but only from VCEs, not from physical explosions. Therefore, the consequence analysis in Stage 2 included vapor cloud explosions.

Initial VCE Screening

Quest reviewed process flow diagrams (PFDs) and other process information supplied by Chevron. Based on that review, a list was compiled of 134 potential releases that could result in VCEs. (These are not the only releases that could result in VCEs, but they are representative of the full range of potential releases.) The consequence analysis software package, CANARY by Quest, was used to model the release, dispersion, and vapor cloud explosion associated with each of these 134 potential releases. All vapor dispersion modeling was based on a wind speed of 5 mph and Pasquill F atmospheric stability.

Several potential releases were removed from further consideration at this point because they did not produce an explosion overpressure of at least 1 psig at any of the five buildings selected for Stage 2 analysis. Releases that were not excluded by this screening procedure became the subjects of further analysis using the Baker-Strehlow VCE modeling method specified in Chevron's guidelines.

The vapor cloud explosion model in CANARY is a distributed-source form of the TNT equivalence model. With this type of model, the strength of the blast wave produced by a vapor cloud explosion is related to the mass of fuel in that portion of the flammable vapor cloud in which the concentration of flammable gas is between the lower flammable limit (LFL) and the upper flammable limit (UFL). To ensure the predictions are conservative, CANARY assumes the VCE occurs when the flammable vapor cloud has reached its maximum size, thus maximizing the mass of fuel involved in the VCE. In addition, the release scenarios have been set up such that every release is oriented horizontally with the wind, near grade. The presence of obstructions or degree of confinement of the vapor cloud is not considered in the analysis. As a result, the distance from the point of release to the point at which the blast wave overpressure has decayed to a given value is dependent on the size and shape of the flammable vapor cloud and the mass of vapor in the flammable range. Since the highest overpressures occur within the flammable cloud, the model will generally predict that a building that is within a flammable vapor cloud at the time the vapor cloud explodes could be exposed to a high overpressure, even if the cloud is not obstructed or confined.

Baker-Strehlow VCE Analysis

In contrast to the CANARY vapor cloud explosion model, the strength of the blast wave predicted by the Baker-Strehlow VCE model is related to the obstructed or partially confined volume that is assumed to be filled with a flammable mixture of gas and air. Within that volume, the mixture is assumed to be homogeneous, with the flammable gas concentration being equal to its stoichiometric value. The amount of energy released in a VCE of a stoichiometric mixture, per unit volume of reactants, is very similar for the majority of hydrocarbons. As a result, if two potential releases both release amounts of flammable fluid sufficient to create stoichiometric mixtures within the same obstructed or partially confined volume, the Baker-Strehlow method will predict identical blast waves for both VCEs. This result can occur even if the two release scenarios have significantly

different release rates and require significantly different release durations in order to produce stoichiometric mixtures of equal volume.

In this analysis, the volume occupied by the stoichiometric mixture was limited to the lesser of:

- the obstructed or partially confined volume of the process area in which the release occurs, or
- the volume of stoichiometric mixture that contains a mass of flammable gas equal to the mass of fuel in that portion of the flammable vapor cloud in which the concentration of flammable gas is between the LFL and the UFL (as predicted by CANARY).

The strength of the blast wave predicted by the Baker-Strehlow method depends not only on the obstructed or partially confined volume that is occupied by a stoichiometric mixture of gas and air, but also on the reactivity of the gas, the degree of obstruction or confinement, and whether the expansion of combustion products is assumed to be two-dimensional (2D) or three-dimensional (3D). The flammable process fluids in the facility all have “medium” reactivities, the process areas were judged to provide “medium” confinement, and the expansion of gas was assumed to be two-dimensional (2D).

The obstructed or partially confined volumes in the various process areas correspond to the walkways that are bounded by horizontal and vertical vessels on both sides and by elevated pipeways, cable trays, and aerial fin-fan heat exchangers on top. The stoichiometric cloud was assumed to fill the area bounded by the pipe rack structure (20 m x 6 m), with the length of the confined area determined by location of the release, size of the release, and size of the available area.

Results of the Baker-Strehlow analysis for one potential release are presented in Table 3. These results show that a large release scenario produces less than 2.0 psig overpressure at three of the five buildings of interest.

Table 3
Baker-Strehlow VCE Results
(Release of Product within the West Reformer)

Building	Distance from Release Point (m)	Maximum Side-On Overpressure (psi)	Positive Phase Duration (msec)	Positive Impulse (psi•msec)
Control Room	110	3.26	55	90
Entrance	250	1.49	56	42
Administration	220	1.67	56	47
North Gate House	270	1.37	57	39
South Gate House	150	2.42	56	67

Volume of stoichiometric cloud = 6,492 m³
 Mass of fuel in stoichiometric cloud = 996 kg
 Minimum time to release this mass of fuel = 762 sec

The Table 3 results represent a release that requires specific conditions to exist. The relatively large release (2-inch hole) must continue for several minutes, the wind must be light, the atmosphere must be stable, the vapors must be semi-confined within the process equipment, and ignition can occur only after a large volume of vapor is accumulated.

In the original siting analysis, work was stopped at the end of Stage 2. The project was placed on hold while further design modifications were being completed. The Stage 1 and Stage 2 results were communicated to the design team and used for an initial building location review. For the purposes of this paper, the analysis was continued into the risk assessment stage.

Stage 3 - Risk Assessment

Based on the results of the consequence modeling in Stage 2, it was determined that vapor cloud explosions posed the primary hazard to buildings around the process units. All toxic hazards were determined to have a small impact compared to vapor cloud explosions. Further analysis was thus constrained to the impact of VCEs only.

At this stage of the analysis, the goal was to provide a qualitative and/or quantitative measure of the risk that vapor cloud explosions pose to occupants of one of the five buildings remaining in the study. The building evaluation stage had already provided a great deal of information about the severity of potential accidents in the facility. At this point, no HAZOPs or risk ranking reviews had been done on the process units. If a qualitative measure of risk were to be generated, the process team would need to determine the probability of individual accident scenarios. Because many of the selected releases could adversely affect one or more of the five buildings, and because the overall size of this analysis (12 process units and 134 release scenarios) was large, a quantitative risk analysis was chosen for Stage 3. The 134 accident scenarios defined by the team in Stage 2 were used as the basis of the QRA. Each of these release scenarios was split into three hole sizes: a rupture, a puncture, and a leak. A vapor dispersion analysis was run for each of the resulting 402 scenarios, for a variety of wind speed/atmospheric stability combinations. For each of the resulting scenarios, two vapor cloud explosion calculations were performed: one for a release that travels outside the unit, develops to its full extent, and is ignited; and one that is semi-confined in the process equipment near the release point and accumulates a substantial flammable mixture before igniting. Both vapor cloud explosion calculations use the mass of vapor between the lower and upper flammable limits as the mass involved in the explosion. The final step in the analysis considers all wind directions, thereby distributing the hazard in all directions around the release point.

Each of the resulting hazard footprints, as defined by the above consequence analysis, has an annual probability of occurrence associated with it. This probability is defined by the annual failure rate of the equipment associated with the release, the probability of the development of a vapor cloud explosion, and the probability of the wind speed/stability/wind direction combination. By combining the hazard and probability, and mapping them onto the area surrounding the process units and buildings, individual risk contours are developed. These contours represent the annual risk of a vapor cloud explosion following a release from any one of the facility's process units.

Because of the complexity of the consequence analysis and specific nature of the probability development, Baker-Strehlow calculations were not used within the framework of the QRA. Thus, the explosion overpressure predictions from CANARY were used. Instead of providing the impulse-duration information that Baker-Strehlow does, this model provided overpressures that correspond to a specific damage level. With this consideration, an overpressure versus fatality relationship published by CCPS³ was chosen by Quest for the endpoints for this analysis. This relationship applies to persons within buildings of normal construction (i.e., those that are not reinforced to withstand blast overpressure). The threshold for fatality, 1%, was set at 0.5 psig; 2.6 psig is expected to cause 50% fatalities; and 5.0 psig will cause nearly 100% fatalities, as well as total building destruction.

³*Guidelines for Evaluating Process Plant Buildings for External Explosions and Fires.* Center for Chemical Process Safety, New York, 1996.

Individual risk contours generated by this process are shown in Figure 2. No buildings lie within the 1.0×10^{-3} contour, and all buildings lie within the 1.0×10^{-5} contour, which envelops the entire site, and is not shown in Figure 2. Of the five buildings of concern, two lie between the 1.0×10^{-4} and 1.0×10^{-3} contours. Thus, the annual risk of fatality to an occupant of the south guard house or control room/lab, due to a vapor cloud explosion following a release from any of the process units is *approximately* 5.0×10^{-4} , or one chance in 2,000 per year. This assumes that each of these buildings is of normal construction, and that the buildings are occupied at all times.

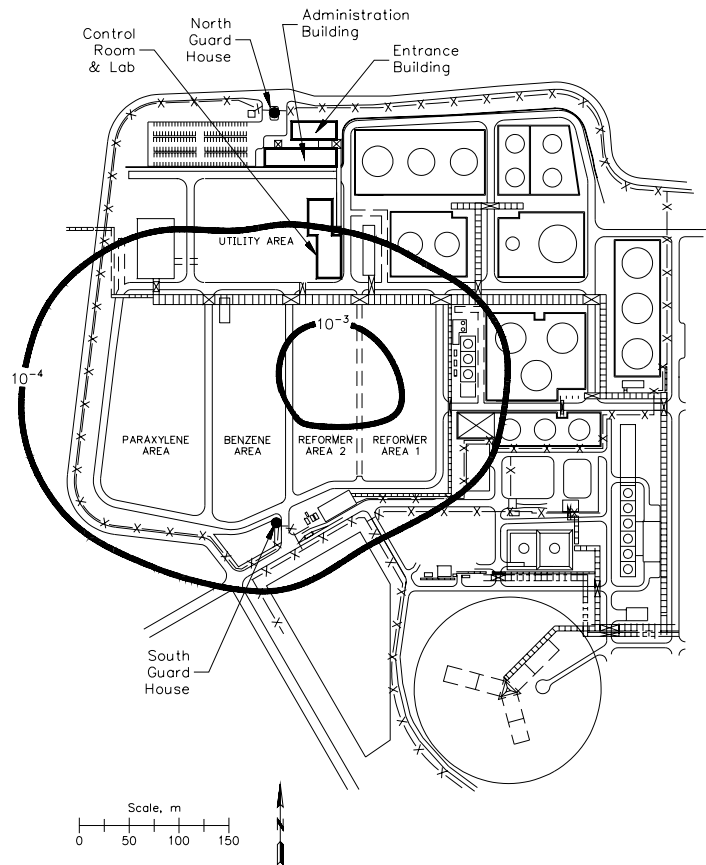


Figure 2
Individual Risk Contours for Persons Inside Plant Buildings

SUMMARY

All process plant buildings associated with the chemical plant project were compared to Chevron's occupancy and usage criteria in Stage 1. Based on that review, all but five of the buildings were excluded from further consideration.

In Stage 2, it was determined that the five remaining buildings are potentially subject to toxic vapor cloud and vapor cloud explosion hazards. Based on a review of process flow diagrams, four toxic (H_2S) vapor cloud scenarios and 134 vapor cloud explosion scenarios were selected, and CANARY by Quest was used to model the consequences of those release scenarios.

The maximum toxic vapor cloud impacts were found to be small compared to vapor cloud explosion hazards. The initial VCE modeling results from CANARY were reviewed and several release scenarios were selected for further analysis using the Baker-Strehlow VCE model. These scenarios were selected on the basis of their severity and their location within the process area. In the original project, the study was stopped at Stage 2 while design changes were being made.

For the purposes of this paper, the analysis was continued in Stage 3 with a quantitative risk analysis. Although not part of the original study, the individual risk contours generated in this stage provide valuable information concerning the placement of buildings. The contours give a measure of the overall risk from vapor cloud explosions to persons in a building of normal construction. This information can be used to determine building placement and design in the final plant design.