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Lawrence Livermore National Laboratory

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CONVERSION FACTORS

Studies involving engineering or environmental aspects of sour-gas operations have not been consistent in their use of English or metric units of measure. To facilitate the interpretation of numerical results, we have used both units of measure in most places in the text. In some instances, though, only one unit of measure was used, either because of convention or to avoid cumbersome wording. For these cases, the following factors can be used to make the necessary conversions of units.

To convert from	To	Multiply by
Length		
inch	centimeter	2.54
feet	mile	1.89×10^{-4}
feet	meter	0.3048
mile	meter	1609
meter	kilometer	1×10^{-3}
Volume		
feet^3	meter^3	0.0283
liter	meter^3	1×10^{-3}
Mass		
pound	gram	453.6
milligram	gram	1×10^{-3}
microgram	gram	1×10^{-6}
gram	kilogram	1×10^{-3}
Area		
inch^2	centimeter^2	6.45
centimeter^2	meter^2	1×10^{-4}
Pressure		
pounds per inch^2	kilopascal	6.89
kilopascal	pascal*	1×10^{3}
millibar	kilopascal	10^{-1}

* Pascal = newton per meter^2.

ABSTRACT

Parts of the Overthrust Belt of western Wyoming and adjoining areas in Utah and Idaho contain geologic formations with significant accumulations of oil and natural gas. Some of these formations, though, yield gas that is contaminated with toxic hydrogen sulfide. As a consequence, the development of these so-called sour-gas reservoirs requires special safety procedures and technologies in order to prevent accidental releases of gas to the atmosphere that could cause adverse occupational and public health effects. To improve the analysis and assessment of wells and collection pipelines completed on lands leased from the Federal Government, the Minerals Management Service, Onshore Operations, now part of the Bureau of Land Management (BLM), asked Lawrence Livermore National Laboratory to conduct a study to test methods and models that could be used to quantify the health risks of sour-gas facilities in the Overthrust Belt. Of particular concern to BLM was the application of such methods to the analysis of the potential risks associated with the development of sour-gas resources located near Evanston, Wyoming.

The process of assessing the health risks of a potential sour-gas release involves estimation of the emission rate of hydrogen sulfide, specification of how the gas is released (e.g., vertically into the atmosphere or horizontally), prediction of downwind concentrations of the gas, analysis of the potential health effects, and finally, review of safety methods required to minimize the potential health risks. The first part of the report includes an analysis of data on the health effects of hydrogen sulfide to determine the nature of its dose-response relationship. Following that review is a study of the different methods of quantifying the emission rate of gas from wells and pipelines. Data on the frequency of accidental releases from those facilities are also analyzed. To assess the health risks of an accidental release from a well under BLM supervision located near Evanston, we collected meteorological data for 1 yr from four stations in that area. Our analysis of a worst-case release scenario (i.e., a gas plume that is near the surface) using those data indicates that the greatest risks of incurring an acute health effect (e.g., unconsciousness, respiratory arrest, pulmonary edema, or death) are located in the northwest sector downwind from the well because of the occurrence of stable atmospheric conditions along with slow winds from the southeast. The risks of an acute health effect in that northwest sector over the 20-yr operation of the well were on the order of 10^{-4} to 10^{-5} -- similar to the risk of accidental death caused by a natural disaster over the same period.

1. INTRODUCTION

Most natural gas wells in the continental United States are completed into geologic formations containing gas that is free of hydrogen sulfide, a toxic gas. Notable exceptions are portions of the Smackover, Edwards, and Tuscaloosa formations found in the Gulf Coast region. Another place where there are gas fields that produce gas contaminated with hydrogen sulfide (i.e., sour gas) is the Overthrust Belt of western Wyoming and adjoining areas in Utah.[1,2] Figure 1-1 shows the locations of the gas fields in this region, including those that produce sour gas. These fields have only been discovered since the late 1970s, and consequently, most of them are not yet under full production. Exploration for new gas deposits continues while the existing fields are developing.

The development of the sour-gas resources of this region poses various kinds of health and environmental risks. Historically, the presence of hydrogen sulfide in oil or gas has constituted an occupational health problem rather than a public health problem. Workers are the ones who are routinely around the facilities (e.g., wells, pipelines, processing equipment, etc.), where accidental gas releases are apt to occur, or where toxic levels of hydrogen sulfide may build up in closed areas; consequently, the workers have been the population at greatest risk. The dose-dependent health effects of inhaling hydrogen sulfide consist of odor annoyance, a chronic-level effect; subacute effects, such as conjunctivitis (i.e., inflammation of the eye) and olfactory paralysis (i.e., no sense of smell); and finally, acute effects including unconsciousness, respiratory arrest, and death.

The hazards of exposing workers to hydrogen sulfide have been recognized for many years. A pioneering study on this problem in the petroleum industry, which focused on occupational exposures to hydrogen sulfide released from crude oils, was actually completed in 1925 by the U.S. Bureau of Mines for the American Petroleum Institute (API).[3] Since that time various kinds of industrial hygiene programs and safety devices have been employed to protect workers from hazardous exposures. The public health risks of operations involving sour gas depend primarily on the characteristics of any atmospheric gas releases that may occur (i.e., the emission rate, duration, and effective height of the release) and characteristics of the resulting population exposures (i.e., ambient concentrations, duration of inhalation, the size of the affected population and individual susceptibilities).

In the long history of handling gases containing hydrogen sulfide there have been only two recorded incidents in which accidental emissions resulted in fatalities among

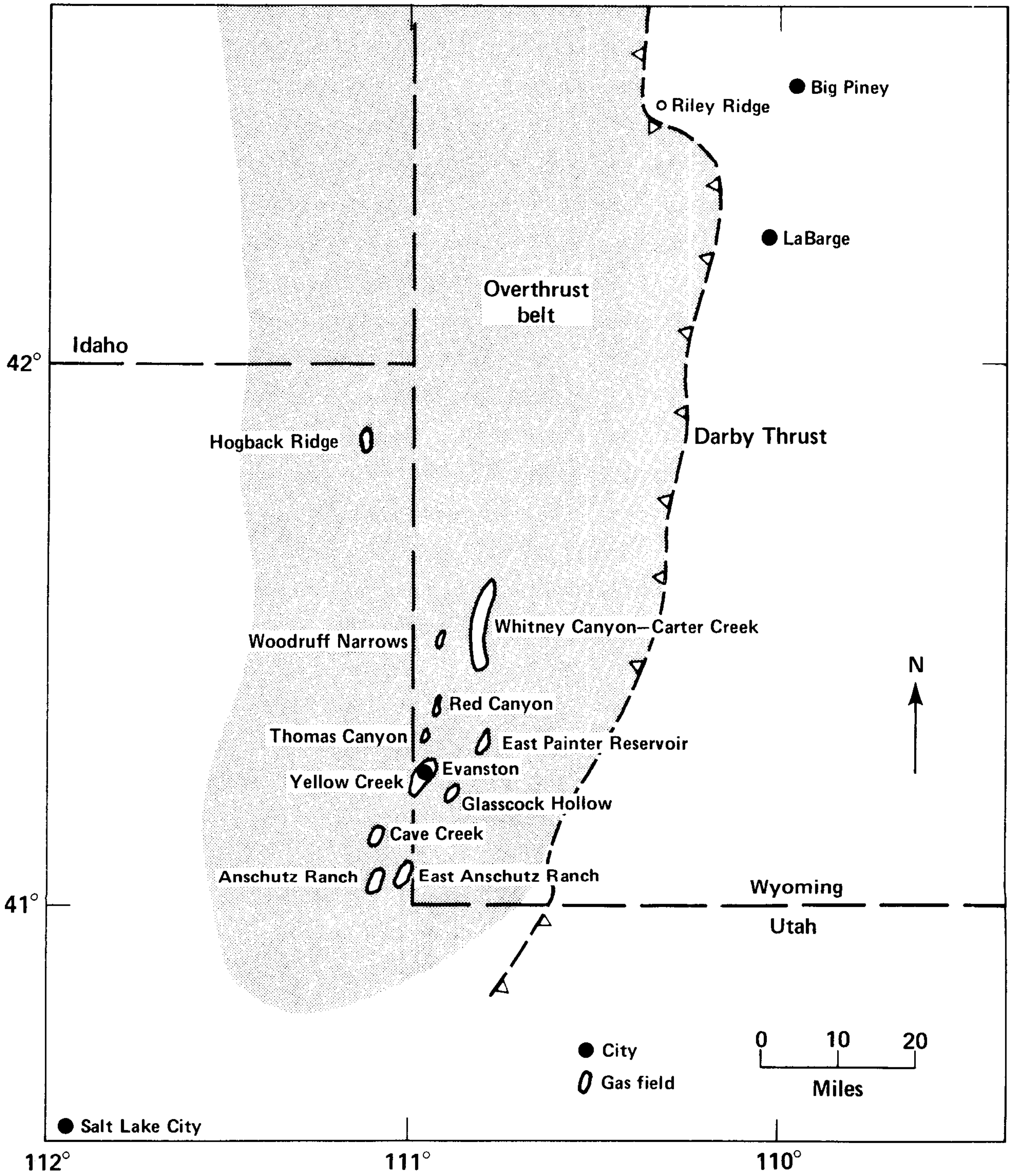

Figure 1-1. Location of natural gas fields in the Overthrust Belt of Western Wyoming and adjoining areas in Utah (after Ver Ploeg and De Bruin[1] and Petroleum Information Corporation[2]).

residents living near sour-gas facilities. The first incident involved a malfunctioning gas purification plant at Poza Rica, Mexico in 1950 that released untreated gas to the atmosphere,[4] and the second event occurred in 1975 near Denver City, Texas, when an atmospheric discharge resulted from the failure of a pipe fitting on the wellhead of a well that was injecting carbon dioxide plus hydrogen sulfide into an oil reservoir.[5] Neither incident, however, directly involved wells and collection pipelines used exclusively for the development of sour-gas fields.

The drilling, completion, and production phases of wellfield development all pose varying degrees of health risk to workers and nearby residents. During drilling, safety devices and procedures (e.g., blowout preventers, alarms, well-control techniques, etc.) are used to prevent sour-gas releases, while contingency plans define the actions needed to respond to an accidental release. The preparation of contingency plans is an integral and necessary part of the process of drilling and completing a sour-gas well. Hamby and Smith, for example, describe how one contingency plan was successfully followed to avoid what could have been a dangerous situation after a sour-gas well blew out near Piney Woods, Mississippi in 1970.[6] More than 600 people were safely evacuated a short time after the blowout took place. No serious incidents were recorded during the four weeks that the gas from the well burned before it was brought under control. API has prepared a report that contains recommended practices and guidelines for drilling sour-gas wells and for preparing contingency plans.[7]

Although much emphasis has been placed on the dangers of drilling wells, the production phase also has potential problems. Producing wells and collection pipelines are possible sources of sour-gas emissions, and therefore, safety systems and contingency plans must be utilized to minimize risks of adverse health effects to workers and local residents. Along with those measures, land-use zoning can be used to limit industrial and residential growth near sour-gas facilities, thereby reducing the population exposures to hydrogen sulfide, if an accidental release were to occur.

Against this background of sour-gas development in the Overthrust Belt, the Bureau of Land Management (BLM) is responsible for regulating oil and gas operations on lands leased from the Federal Government. As part of that responsibility, BLM conducts environmental reviews (e.g., exclusion reviews, environmental assessments, and environmental impact statements) evaluating the effects of those operations in accordance with regulations implementing the National Environmental Policy Act. To carry out the analyses of the potential effects of sour-gas wells and associated collection pipelines that are under the supervision of BLM, data are needed on the concentration of hydrogen sulfide in natural gas and on the expected emission rate of gas in the event of an accidental release. Concentrations of hydrogen sulfide resulting from a release must then be estimated using one or more atmospheric dispersion models together with the appropriate meteorological inputs; and then dose-response data are required to determine the health effects to the population at risk. Unfortunately, there are uncertainties associated with each of the different components of the analysis. For example, the calculation of an accidental emission rate of hydrogen sulfide from a wildcat well is subject to error, because assumptions must be made regarding the composition of the gas as well as the rate at which the gas is discharged to the atmosphere. The error could be large if the well is drilled in an area where background data on subsurface conditions are unavailable. The analysis of new wells added to an existing wellfield is made easier if data are available on earlier wells; however, well tests are still necessary to quantify potential releases during gas production. Estimates of the atmospheric dispersion of gas away from a release point can also be in error due to deficiencies in the dispersion model(s) and inadequate meteorological data. Assessment of the potential health effects caused by the predicted concentrations of hydrogen sulfide is complicated by a lack of data on the variability in acute responses (i.e., death, unconsciousness, etc.) for different exposure levels. Together, the various uncertainties can cause serious under or overpredictions of health risks. There is a need, therefore, to refine the assessment techniques and to quantify the uncertainties of the analyses so that their accuracy is not misrepresented.

The Minerals Management Service, Onshore Operations, now part of the Bureau of Land Management, asked Lawrence Livermore National Laboratory to examine and to test methods and models that can be used to estimate the health and environmental risks of sour-gas releases that could occur during wellfield development and gas production. A second objective is to use the methods and models to assess the risks of accidental emissions from one or more sour-gas wells and related collection pipelines in the vicinity of Evanston, Wyoming that are located on lands leased from the Federal Government. Evanston overlies part of a productive oil field known as the Yellow Creek field, which was first discovered in 1976. Oil produced from that wellfield is derived from relatively shallow formations, and it contains little or no hydrogen sulfide. However, in 1979 an exploration well in the Yellow Creek field area was completed into two deep formations (i.e., the Phosphoria and the Weber), both of which yielded natural gas containing over 10% by volume (or 100,000 ppmv) hydrogen sulfide. Development wells for the Yellow Creek deep field have been completed near the city, and exploratory drilling has taken place to the north of Evanston. Pipelines will gather sour gas from the wells and transport it to a gas purification plant. Application of the assessment methods addressed in this study to sour-gas operations in the Evanston area will provide information that is directly applicable to contingency planning activities directed toward those operations. Furthermore, the exercise of assessing actual wells and pipelines should uncover problems that might be encountered when BLM staff assesses similar sour-gas operations located elsewhere in the Overthrust Belt.

2. HEALTH AND ENVIRONMENTAL EFFECTS OF SOUR-GAS RELEASES

An uncontrolled release of sour gas from a well or pipeline could cause serious occupational and public health effects, depending on its magnitude, duration, and location, as well as the meteorology at the time of the release. The dose-dependent health effects of exposure to ambient concentrations of hydrogen sulfide range from death to temporary odor annoyance. If the sour gas is ignited, hydrogen sulfide will burn to form sulfur dioxide, which is a less toxic gas. Both of those gases can also have toxic effects on plants and animals. Sour gases containing elevated levels of carbon dioxide present an additional safety problem: carbon dioxide at high concentrations can prevent the ignition of the released gas and the subsequent formation of a buoyant plume, which results in ground-level concentrations of sulfur dioxide that are unlikely to cause acute health effects. To evaluate the potential impacts of gaseous exposures resulting from a sour-gas release, data are needed that relate exposures to specific effects in humans, plants, and animals. Accordingly, we devote most of this section to a review and analysis of dose-response relationships for hydrogen sulfide, sulfur dioxide, and carbon dioxide.

TOXIC EFFECTS OF HYDROGEN SULFIDE ON HUMANS

In the literature on the human health effects of hydrogen sulfide, it has become customary to categorize those effects as acute, subacute, or chronic. Acute intoxication refers to systemic effects, involving both the central nervous system and the respiratory system, caused by a single exposure to elevated concentrations of the gas. Subacute intoxication, on the other hand, refers to the irritative effect of hydrogen sulfide on eyes and the respiratory tract. Chronic effects of exposure to low levels of this gas consist primarily of odor annoyances and disorders of a neurasthenic nature.

Acute Toxicity

Hydrogen sulfide is thought to exert its systemic effects by the reversible inactivation of cytochrome oxidase, an enzyme that transfers electrons to oxygen in the chain of enzymatic redox reactions associated with cellular respiration. Inhaled gases like hydrogen sulfide and carbon monoxide bind with cytochrome oxidase with the result that the transport of electrons is blocked and cellular respiration ceases.[8,9] In an aqueous solution hydrogen sulfide dissociates to hydrosulfide (HS^-) and sulfide ($S^=$), depending primarily on the pH of the solution. However, it is the undissociated form of hydrogen sulfide that is the more effective inhibitor of cytochrome oxidase, and at the physiologic pH approximately a third of the total sulfide is not dissociated.[10] Fortunately, hydrogen sulfide absorbed in blood is rapidly oxidized to nontoxic sulfates. Because of this detoxification mechanism and because the inhibition of cytochrome oxidase is reversible, it is regarded as a noncumulative poison. Acute intoxication is believed to result from hydrogen sulfide intake at a rate greater than the body's capacity to oxidize it, leading to perfusion of the central nervous system by undissociated hydrogen sulfide. Nerve centers are first stimulated then paralyzed by the toxic exposure.[11] Respiratory collapse or paralysis can occur due to the action of hydrogen sulfide on the nervous system. Another possible mechanism suggested for toxic effects on the respiratory system is through the stimulative action of the gas on the chemoreceptors of the carotid body, an organ that helps to regulate respiratory reflexes based on body chemistry.[10]

At concentrations over 1000 ppmv, the stimulating effect of hydrogen sulfide can induce rapid breathing (hyperpnea), depleting the blood of carbon dioxide, which results in a period of transient cessation of respiration (apnea). According to Haggard, "If the depletion of the body's supply of carbon dioxide has not progressed too far, this substance may reaccumulate and reestablish respiration before the respiratory mechanism has become damaged by the asphyxia occurring as a result of cessation of respiration".[12] However, if respiration is not reestablished, artifical respiration is then necessary to prevent death by asphyxiation.

Occupational Exposures. Most of the data regarding acute effects are from occupational exposures to elevated levels of hydrogen sulfide. Poda, for example, describes the effects of occupational exposures associated with the operation of facilities producing heavy water by a process relying on the use of hydrogen sulfide as a primary reagent.[13] Of 123 cases of "over exposure" to unspecified levels of the gas at a pilot plant operating for 7 yr, 25 people became unconscious, with 2 requiring artificial resuscitation. During a period of almost 12 yr at another plant, 17 people became unconscious out of 51 overexposures. Four of the unconscious required artifical resuscitation. Unfortunately, there were no data on the concentrations of hydrogen sulfide to which the victims were exposed. Poda further notes that most of the 42 people who became unconscious did not smell the characteristic odor of the gas prior to fainting.[13] Instead, they remembered smelling a sickening sweet odor for a brief moment before losing consciousness. Acute exposures of short duration can produce symptoms of an irritative nature typically associated with less toxic exposures. Table 2-1 summarizes the symptoms that lasted for less than 4 h for the 123 cases of overexposure at the pilot plant. Approximately 10% of the exposures resulted in eye inflammations, which are symptomatic of subacute exposures. Ahlborg reported on similar acute symptoms due to exposures to hydrogen sulfide in Sweden's Shale Oil industry in the middle 1940s.[14] The general symptoms of 59 acute exposures that resulted in unconsciousness are as follows:

Table 2-1. Symptoms associated with 123 separate incidents in which a worker was overexposed to hydrogen sulfide used at a pilot plant producing heavy water (from Poda[13]).

Symptoms	Occurrence*
Weakness	33
Nausea	29
Dizziness	27
Headache	26
Nervousness	20
Eyes burning or watering	13
Shock (clinical)	11
GI upset (not true nausea)	7
Vomiting	6
Elevated blood pressure	5
Dyspneic	4
Sweating	3
Cyanosis	3
Face flushed	3
Abdominal cramps	2
Flatulence	1
Pain in arms and legs	1
Rigidity	1
Irrational and combative	1
Twitching	1
Frothy sputum	1

* Some individuals had multiple symptoms.

> "...a sudden feeling of fatigue, especially in the legs; dizziness, and intense anxiety followed by unconsciousness with or without respiratory failure. The latter symptom usually subsided after a few minutes in fresh air. Only in a few cases was it necessary to apply artificial respiration. Regaining consciousness, the patients complained of pronounced pains in the back of the head, dizziness, and sometimes nausea."[14]

Victims of acute hydrogen sulfide intoxication normally show a complete recovery, without any lingering, long-lasting symptoms or sequelae. On the short term, however, the Ahlborg study identified post-exposure symptoms, such as disturbed equilibrium, headache, and irritability. The average duration of the sequelae was 1.5 mo. In the Poda study most of the overexposed individuals had a basic syndrome of the following sequelae: nervousness, dry nonproductive cough, nausea, headache, and insomnia. With treatment, the symptoms disappeared the next day.

The occupational exposures covered in the Ahlborg and Poda studies did not result in death; however, in other occupational settings many hydrogen sulfide-related deaths have been recorded.[10] In particular, the extraction, transport, and processing of natural gases and oils contaminated with hydrogen sulfide have resulted in many acute exposures that ended in death. For example, during a 4-mo period in West Texas, 17 deaths were attributed to hydrogen sulfide exposure in the oil and gas industry.[15] This experience underscores the lethal nature of hydrogen sulfide.

Doses Causing Acute Effects. The physiologic response to breathing hydrogen sulfide is governed by the ambient concentration of the gas and by the duration of the exposure; that is, the dose. From our analysis of the toxicology of hydrogen sulfide, we know that acute effects will only occur above a threshold value of concentration because of the body's ability to detoxify this gas. We would expect the threshold value to vary from individual to individual because of biochemical differences between individuals. The health effects data also show that as the ambient concentration increases, the duration of inhalation required to induce acute effects decreases. Therefore, to assess the acute effects of an atmospheric release of hydrogen sulfide, we need to relate concentrations of the gas (above a threshold level) to exposures that cause acute responses. Unfortunately, hardly any of the occupational studies dealing with the acute effects of this gas provided data on the doses received by victims. The minimum concentration and associated exposures that resulted in an acute response (i.e., unconsciousness) were approximately 250 ppmv for a 20-min exposure.[14] Data on the exposures that cause acute effects at higher concentrations are derived mainly from studies done with dogs, which according to one early study have toxic responses to hydrogen sulfide that are similar to those of man (see Mitchell and Yant[16]). Yant, for example, estimated that the threshold range for acute responses is 500 to 1000 ppmv,[17] based on animal exposures lasting 0 to 2 min.[16] Haggard found that dogs inhaling air containing 2000 ppmv of hydrogen sulfide would succumb "after a breath or two".[12]

Subacute Toxicity

Subacute intoxication generally refers to the effects of local irritation of the eyes and respiratory tract, as distinct from the systemic effects of acute intoxication, and is usually associated with prolonged or repeated exposures. At concentrations of approximately 50 to over 100 ppmv, exposure to hydrogen sulfide for about 1 hr can produce irritation and inflammation of the eye's mucous membrane (i.e., conjunctivitis).[17] Short exposure to higher concentrations of this gas can also produce eye inflammation. Specific symptoms of ocular damage are photophobia, itching, a sensation of roughness, rainbow phenomena in artificial light, and hazy vision.[18] Moreover, in serious exposures the cornea can become inflamed (i.e., keratitis). Ahlborg noted that eye problems can be minimized by not rubbing the eyes after an exposure and that the average period of healing was 4 d.[14] Olfactory paralysis is another subacute effect, and it is manifested at concentrations of 150 to 250 ppmv.[10] This condition is dangerous because without the sense of smell an individual would not be able to detect potentially lethal concentrations. Pulmonary edema (excessive accumulation of fluid in lungs) is the most serious consequence of subacute intoxication (or as a sequelae of acute intoxication) as it can end in death. This response to hydrogen sulfide may occur after prolonged exposure (more than a half hour) to concentrations of about 400 ppmv and above.[19]

Chronic Toxicity

Chronic intoxication is a lingering condition of mostly subjective disorders, resulting from prolonged exposure to concentrations at or below 100 ppmv. Symptoms include fatigue, behavioral changes, gastrointestinal disturbances, cold sweats, headache, and slow heart rate.[20] The evidence for chronic hydrogen sulfide toxicity as a distinct pathological entity is meager, and there is a lack of consensus as to its existence. Vigil notes that the resolution of this question is hampered by the lack of a firm set of objective symptoms and by the difficulty of isolating the effects of hydrogen sulfide in work environments from the effects of other substances (such as carbon disulfide) and other causative factors (such as humidity or night work).[21] Soviet investigators have reported possible health effects from chronic hydrogen sulfide exposure (see Vigil[21]), but in general, the methodological descriptions are not complete enough to permit any firm conclusions.

From a public health standpoint, odor annoyance is probably the most important chronic effect of atmospheric emissions of hydrogen sulfide. The median threshold for odor perception is approximately 0.005 ppmv, and about 20% of the population can smell this gas at 0.002 ppmv.[22,23]

High Risk Individuals

There are several classes of individuals who may have an increased susceptibility to hydrogen sulfide toxicity. For example, a person who has consumed alcohol 16 to 24 h before exposure is likely to have a stronger reaction to this gas than would be the case without alcohol consumption.[13] Another class of high-risk individuals consists of those with neuropsychiatric problems. There is some evidence that indicates that such individuals will exhibit responses to hydrogen sulfide that are more prolonged and more severe than normal.[13] Other susceptible individuals are those with chronic eye inflammation, anemia, or respiratory problems. Ahlborg recommends that persons with chronic eye inflammation should not work in occupational environments where they may be exposed to hydrogen sulfide.[14] Anemic persons (i.e., persons whose blood is deficient in red blood cells, hemoglobin, or total volume) have been identified as a high-risk group, based on the premise that their blood, being depleted in oxygen, would have a reduced capacity to detoxify hydrogen sulfide absorbed into the blood stream after inhalation.[20] This form of hypersusceptibility has not been directly confirmed in either animal or human studies. The old and very young may also constitute a high risk group.

TOXIC EFFECTS OF SULFUR DIOXIDE ON HUMANS

Sulfur dioxide is an irritating gas, affecting the eyes, throat, and respiratory tract. Its odor can be detected at concentrations as low as 0.5 ppmv, and above 1 ppmv the gas has a strong odor.[24] With concentrations greater than about 5 ppmv, it irritates the nose and throat and can induce coughing.[25,26] Inhalation of air containing approximately

20 ppmv of sulfur dioxide can cause eye inflammation[25] and general discomfort.[27] With an exposure of 50 ppmv for 10 min, lung resistance is apt to show a significant increase.[24] At these concentrations most of the inhaled gas is absorbed by the mucous lining of the nose, and less than a few percent goes deeper than the larynx.[28] Gas absorbed into the blood after inhalation combines with water to form sulfurous acid, which then dissociates into hydrogen, sulfite, and bisulfite ions. The sulfites are subsequently oxidized to sulfate, which is ultimately cleared from the body.[28]

It is difficult to define concentrations and short-term exposures (∿10 min) that produce acute effects, because few studies have carefully addressed this subject. However, the occupational health literature indicates that concentrations of 100 to 500 ppmv are dangerous for exposures lasting for 30 min or more, and above 1000 to 2000 ppmv sulfur dioxide poses an immediate threat to life.[25,26]

TOXIC EFFECTS OF CARBON DIOXIDE ON HUMANS

Carbon dioxide is a respiratory stimulant as well as an asphyxiant. Inhalation of air containing 50,000 ppmv will strongly stimulate respiration.[29] Other observable symptoms of acute exposure include headache, rapid beating of the heart, sweating, shortness of breath, and dizziness.[30] At concentrations of 70,000 to 100,000 ppmv, unconsciousness will occur after a few minutes of exposure.[29] In contrast, the normal concentration of carbon dioxide in the atmosphere is about 320 ppmv. This gas, however, is not a direct threat to public health because downwind concentrations would not reach levels causing acute effects.

EFFECTS OF GASEOUS RELEASES ON PLANTS AND ANIMALS

An accidental well-blowout could pollute air with (1) natural gas contaminated with hydrogen sulfide, (2) a gas composed primarily of carbon dioxide with minor amounts of hydrogen sulfide and methane, or (3) sulfur dioxide and other combustion by-products resulting from the ignition of a gas composed mainly of methane. Each of these gaseous emissions has the potential for injurying plants and animals.

Effects on Animals

The early work on the toxicity of hydrogen sulfide focused on animal exposures. In one such study, described by Mitchell and Yant, canaries, white rats, guinea pigs, dogs, and goats were exposed to varying concentrations of the gas for different periods of

Table 2-2. Summary of the responses of laboratory animals exposed to varying concentrations of hydrogen sulfide. Data from Mitchell and Yant.[16]

Animal	Concentration % by vol	 ppmv	Time to death (min)
Canaries	0.02	200	30-60
	0.03	300	2-30
	≥ 0.04	400	0-2
White rats	0.06	600	30-60
	0.08	800	2-30
Guinea pigs	≥ 0.10	1000	2-30
Dogs	0.08	800	2-30
	0.10	1000	0-2
Goats	≥ 0.10	1000	2-30

time.[16] Table 2-2 summarizes the acute (lethal) effects of the doses administered. Unfortunately, only small numbers of animals (e.g., less than 4) were often used to determine the toxicity at different concentrations. Moreover, the accuracy of the analytical techniques is unknown. Because of these concerns, the dose-response relationships should be considered as indicative of the toxic effects rather than definitive. Haggard also exposed dogs to this gas and found that at 0.15% by volume (1500 ppmv) death would occur after 15 to 30 min[12] -- an exposure value somewhat higher than that recorded for dogs in Table 2-2. Other laboratory studies have shown that mice exposed to about 1200 ppmv live an average of 6 min before dying.[10]

In separate experiments, McCallan and Setterstrom measured the responses of house flies, mice, and rats to continuous concentrations of 1000 ppmv.[31] They found that it took about 15 min before half of the mice and rats were killed and about 8 min before half of the flies died. During exposures to sulfur dioxide, it took over 60 min for 50% of the flies and mice to succumb, while almost 960 min elapsed before the same percentage of rats was killed.

Effects on Vegetation

Thompson and Kats continuously fumigated lettuce, sugar beets, California buckeye, ponderosa pine, Douglas fir, and seedless grapes with hydrogen sulfide at concentrations of 0.03, 0.3, and 3 ppmv.[32] They found that plant stress, as shown by foliar damage or reduced yields, was exhibited at the 0.3 and 3 ppmv concentrations, but not at 0.03 ppmv. In a second fumigation study, Thompson et al.[33] found the phytotoxicity of hydrogen sulfide the same or marginally greater than that of sulfur dioxide under chronic exposures of lettuce and sugar beets. Benedict and Breen[34] exposed several different weeds to daily, 4-h fumigations of hydrogen sulfide at separate treatments of 100 and 500 ppmv for up to 6 wk. Fumigations were conducted from about 10:00 a.m. to 2:00 p.m. to ensure that plant stomata were open. Both exposure levels produced markings on a significant percentage of leaf area; 74% of the leaf area of weeds grown on dry soil after 6 wk of fumigations at 500 ppmv, compared with 18% of leaf area for the 100 ppmv exposures. Fumigations with sulfur dioxide at concentrations of 2 and 5 ppmv resulted in leaf markings over 11 and 8% of the total leaf areas under the same soil conditions as the hydrogen sulfide exposures. In an older study, McCallan and Setterstrom[31] measured the time it took to damage 50% of the leaf area of tomato, tobacco, and buckwheat plants exposed to 1000 ppmv of hydrogen sulfide and sulfur dioxide. It took between 1 to 4 min to achieve 50% leaf area damage on those plants with sulfur dioxide, and with hydrogen sulfide it took over 15 min for the same amount of leaf damage to appear on tomato plants and over 60 min for the tobacco and buckwheat plants.

CASE STUDIES

Additional insights into the potential effects of gas releases containing elevated levels of hydrogen sulfide can be gained by examining actual incidents in which releases produced toxic effects in people and animals. Accordingly, we will examine here four cases involving releases of hydrogen sulfide to the atmosphere. The first case took place in 1950 in the town of Poza Rica, Mexico, where 22 people died from exposure to hydrogen sulfide emitted from a malfunctioning flare at a gas purification plant. The second case concerns a gas injection well near Denver City, Texas in 1975 that released carbon dioxide and hydrogen sulfide to the atmosphere because of a wellhead failure.

Nine people died due to exposure to the gas. Next, we examine a blowout of an exploratory well near Big Piney, Wyoming in 1981, and finally, we review cases where residents were chronically exposed to low levels of hydrogen sulfide in Alton, Illinois and Terre Haute, Indiana.

Incident at Poza Rica, Mexico

The following review of a gas release at Poza Rica is based on a study of the incident prepared by McCabe and Clayton.[4]

In 1950 the town of Poza Rica was the site of a gas desulfurization plant that treated natural gas containing about 3% by volume hydrogen sulfide and 15% carbon dioxide. The plant, which had a design capacity of 60×10^6 standard cubic feet* per day (scf/d) (1.7×10^6 m^3/d), was put into operation a few days before the accidental release occurred. During the startup period 40×10^6 scf/d (1.1×10^6 m^3/d) of gas was sent to the desulfurization units, and since those units were not finished, about 10×10^6 scf/d (2.8×10^5 m^3/d) of partially processed gas was sent to a flare 90 ft (27 m) high.** That gas contained 81% carbon dioxide and 16% hydrogen sulfide. Ignition of the gas was accomplished by burning a purified gas from the desulfurization units. Initially, though, there were some problems with the delivery of this desulfurized gas to the flare and it had to be shut down for servicing. Early in the morning of November 24, 1950, input to the plant was increased to its design capacity. At about 4:50 a.m. the flare evidently began to malfunction, releasing uncombusted gas into the air. Fortunately, the flare was quickly shut down when plant personnel found out what was happening.

Atmospheric conditions during that day were characterized by a low-level temperature inversion and low wind speeds. Gas dispersing away from the flare caused an acute exposure to residents living in a neighborhood situated between 350 to 1100 ft (107 to 335 m) to the north of the flare. The exposure lasted approximately 20 min, and it resulted in the hospitalization of 320 persons and the deaths of 25 people. Of the persons that died, 41% were under 13 yr of age, 45% were between 14 to 35 yr of age, and 14% were between 36 and 50 yr of age. Table 2-3 shows the time-distribution of the deaths after the acute exposure. It is interesting to note that most of the victims (almost 60%)

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* Under standard conditions of 1 atm and 60°F, a lb-mole of gas occupies 379 ft^3 (10.7 m^3).

** This release of gas from an elevated flare is not directly comparable to a sour-gas release from a well, because the well release would be at sonic velocity, which is considerably higher than the subsonic velocity of a flare (<50 m/sec).

Table 2-3. Breakdown of the time-sequence of deaths after the acute exposure to hydrogen sulfide at Poza Rica, Mexico. Data from McCabe and Clayton.[4]

Number of deaths	Percent of total deaths	Time after hospitalization (h)
9	41	Dead on arrival
4	18	2
4	18	6
1	4.5	24 (1 d)
1	4.5	48 (2 d)
1	4.5	120 (5 d)
1	4.5	144 (6 d)
1	4.5	216 (9 d)

died after admission to the hospital. Of the 320 persons hospitalized, 170 (50%) were released after 2 to 3 h, another 90 persons (28%) were released after 6 to 7 h, and the remainder were released after several days. In a sample of 47 patients that were hospitalized, all had lost their sense of smell, half had experienced unconsciousness, 13 individuals had conjunctival irritation, 9 persons had pulmonary edema, 15 persons had nausea, and 11 people had vomiting. Similar symptoms of hydrogen sulfide intoxication are presented in Table 2-1. Hidden within these statistics were some dramatic differences in the responses to hydrogen sulfide exposure. In one case, for example, a woman's two daughters were immediately overcome by the gas just outside the door of their house. They died, but the mother, who was inside the house, experienced only subacute symptoms and lived. Either the concentrations inside and outside the house were significantly different, or the mother was less susceptible to hydrogen sulfide intoxication. In addition to the human health effects, apparently half of the chickens, cattle, pigs, geese, ducks, and dogs in the area were killed. Virtually all of the canaries died from the exposure.

Most of the people seem to have been exposed to concentrations of hydrogen sulfide that were around 300 ppmv for part or all of the 20-min period because (1) a majority of people lost their sense of smell, which means that concentrations were probably over 200 ppmv, and (2) all the canaries died, corresponding to a lethal concentration of approximately 300 ppmv (see Table 2-2). Other people were exposed to much higher concentrations. For example, in some locations people were rapidly overcome by the gas, which indicates that ambient levels were at or above 1000 ppmv. Furthermore, many of the animals in the affected area died, suggesting that concentrations in places were above 600 ppmv (see Table 2-2).

We conclude this review of the incident at Poza Rica with the following observations:

- There was virtually no warning of the early morning, accidental release of hydrogen sulfide from the malfunctioning flare, because the gaseous plume quickly reached the nearby neighborhood and the initial concentrations of the gas were high enough to paralyze the people's sense of smell, negating that warning mechanism.
- The fast shutdown of the gas purification plant prevented more serious or widespread results from happening.
- Ambient concentrations of hydrogen sulfide probably ranged from about 300 ppmv to over 1000 ppmv.
- The toxic effects recorded after the 20-min episode were consistent with effects described in the literature dealing with the toxicology of hydrogen sulfide.
- Although recovery from hydrogen sulfide intoxication was usually rapid, there was still a pronounced need for short-term medical care, as evidenced by the large number of people admitted to a local hospital for treatment.

Incident at Denver City, Texas

The account of this incident is based on memoranda prepared by staff of the Railroad Commission of Texas.[5,35,36] In this particular case of hydrogen sulfide poisoning, nine persons were killed near Denver City, Texas, when they were exposed to gas escaping from a well injecting gas into an oil reservoir as part of an enhanced oil recovery project. The injected gas was composed of 93% by volume carbon dioxide and 5% by volume hydrogen sulfide. At about 5:00 a.m. on February 2, 1975, a pipe connection in the top of the wellhead failed, releasing gas into the atmosphere. A person living 600 ft (183 m) from the well evidently noticed the odor of the gas and then called residents of a house near the leaking well (200 ft (61 m)) to warn them of the possible danger. The people answered the telephone call; however, they were overcome by the gas, and as a result eight people in the house died. Later, an employee responding to the problem was also overcome by the gas and died.

Reviews of the incident suggest that the dispersion of the gas was probably inhibited by low winds and possibly a temperature inversion. Failure of the connector (a wash nipple) at the well may have been due to embrittlement, because it was made of steel that did not have the appropriate hardness for use with hydrogen sulfide. Contributing to the incident was the failure of a pressure-sensor to detect the pressure drop in the injection line.[35]

Well Blowout near Big Piney, Wyoming

The June 21, 1981 blowout of this well, unlike the previous two incidents, did not result in any deaths. The well was situated in a rural area, with the nearest residence about 2 mi (3.3 km) away. According to a report on this incident by Hanson of BLM, gaseous emissions from the well were composed primarily of carbon dioxide (70% by volume) with smaller amounts of methane (∿20% by volume) and hydrogen sulfide (3 to 4% by volume).[37] The high percentage of carbon dioxide combined with the relatively low amount of methane in the emitted gas would have hindered or perhaps prevented attempts to ignite the well in order to produce a buoyant plume of combustion gases. In this particular case, though, there was no immediate threat of hydrogen sulfide intoxication. Nevertheless, had the well been located near homes, it would have posed a serious health hazard to nearby residents. As it was, the only toxic effects attributed to the release, which lasted about 8 d, were the deaths of some jackrabbits and blackbirds in the area around the well, plus 4 antelope and 1 moose that were in a draw or gully 0.3 to 0.5 mi (0.5 to 0.8 km) downwind from the wellsite.[37]

Episodes of Chronic Exposure

The following incidents are different from the previous cases in that there were no acute or subacute effects either to people or animals. Instead, these pollution episodes involved exposure to low levels of hydrogen sulfide, which caused many health-related complaints and complaints of paint damage. In Alton, Illinois the primary sources of the hydrogen sulfide emissions were a clarifier along with a disposal lagoon that were used to process wastes from a box factory. Ambient concentrations measured at monitoring stations in the summer of 1973 near the lagoon ranged from below 0.025 ppmv (lower sensitivity of the monitors) to over 1 ppmv.[38] The majority of the health-related complaints associated with the concentrations involved odor annoyance, but others involved respiratory problems (e.g., labored breathing) and nausea.[10] Oil-based paints on houses were discolored as hydrogen sulfide reacted with metal salts in the paints during the months of June through September to form sulfide stains. In Terre Haute, Indiana the source of the hydrogen sulfide was also a lagoon used for the treatment of an industrial waste. Concentrations of the gas resulting from lagoon emissions ranged from approximately 0.02 to 0.3 ppmv. Health effects included nausea, loss of sleep, shortness of breath, and headache.[38] Paint discoloration was recorded.

SUMMARY

Our review of the dose-response data on hydrogen sulfide, as summarized in Table 2-4, along with the different case studies involving atmospheric emissions indicates

Table 2-4. Summary of the toxic effects of hydrogen sulfide on humans, based on animal studies as well as actual exposures to man.

Concentration[a]		Exposure	
ppmv	mg/m^3	time (sec)	Effect
2000[b]	2880	3-10	Respiratory arrest, unconsciousness, pulmonary edema, or death
500-1000[b]	720-1440	∿3-120	Respiratory arrest, unconsciousness, pulmonary edema, or death
250[c]	360	1220	Unconsciousness
150-250	216-360	--	Olfactory paralysis
50-300+	72-432	<3600	Eye irritation
100	144	--	Neurasthenic disorders
0.005	0.007	--	Median odor threshold

[a] For a pressure of 1 atm and a temperature of 60°F.

[b] Animal data.[12,16]

[c] Based on one incident.[14]

that doses causing subacute as well as acute responses should be considered when assessing the potential risks of sour-gas facilities. Although the risks of acute intoxication are certainly a serious concern in the event of a major sour-gas release, strong odor annoyance and eye irritation among members of an exposed population would result in many complaints, various emotional responses, and requests for emergency assistance. An important contingency action related to a blowout of a sour-gas well is the ignition of the gas to produce a buoyant plume of sulfur dioxide. Table 2-5 reviews the effects associated with different doses of that gas. The short-term exposure of sulfur dioxide to plants shows that it is more phytotoxic than hydrogen sulfide. For chronic exposures, though, the toxicities of hydrogen suifide and sulfur dioxide are comparable. In animal studies, hydrogen sulfide has been shown to be more toxic than sulfur dioxide.

Table 2-5. Health effects of short-term exposures to elevated concentrations of sulfur dioxide.

Concentration[a]		Exposure	
ppmv	mg/m^3	time (sec)	Effect
1000-2000	2710-5420	--[b]	Life threatening
100-500	271-1355	∿1800	Life threatening
50	136	∿600	Increased lung resistance
20	54	--	Eye inflammation
0.5-1	1.4-2.7	--	Odor annoyance

[a] For a pressure of 1 atm and a temperature of 60°F.

[b] Exposure to these concentrations is assumed to be an "immediate" threat to life.

3. ACCIDENTAL RELEASES OF SOUR GAS FROM WELLS AND COLLECTION PIPELINES

To properly assess the potential magnitude of health and environmental risks associated with the development of sour-gas resources, we need information on the frequency of well blowouts and pipeline ruptures that result in the discharge of gas to the atmosphere, and we also need to estimate the emission rates, durations, and compositions of the gaseous releases. In addition, the manner in which the gas is released to the atmosphere must be specified (e.g., a surface-level release or a vertical plume). Estimates of sour-gas emissions after an accident are required as input to models that simulate the dispersion of gas into the atmosphere, and consequently, the accuracy of the ambient concentrations of gas predicted by the dispersion models is directly related to the accuracy of the estimated emission rates and durations. There is a need, therefore, to assess alternative techniques and methods for making estimates of emissions and to determine the magnitude of the uncertainties involved in making those estimates.

Data on the frequencies and characteristics of accidental releases are important for a couple of reasons. First, we can use our knowledge of accident probabilities to weight the health effects of different releases according to their likelihood of occurrence. The resulting estimates of health risk (i.e., the product of the probability of an event and the calculated health effects of the event if it actually happened) can be used in the comparison of low-frequency events that have serious health impacts (i.e., a worst-case event) and events that are more frequent but have less serious consequences. Second, these data can be used in the development of emergency response plans that take into account the relative frequency of different kinds of accidents (e.g., accidental releases from wells being drilled versus producing wells and associated pipelines). Moreover, information on the causes of the releases can be used to devise safety measures and technologies that reduce the likelihood of certain types of accidents.

We begin this section with a review and analysis of the causes, frequencies, and durations of accidental releases of natural gas from wells in Texas and Alberta, Canada. We then examine methods of estimating emission rates of gas from uncontrolled wells and the geochemistry of sour gases. Finally, we study data dealing with pipeline failures and methods of calculating atmospheric discharges of gas after a failure.

BLOWOUTS OF NATURAL GAS WELLS

In rotary well drilling, mud is pumped down through the drill string and out the drill bit and is subsequently returned to the surface via the annulus (i.e., the area between the drill pipe and the wellbore or casing). At the surface the formation cuttings are removed and the processed mud is then recirculated. Primary functions of the drill mud include the removal of formation cuttings, lubrication and cooling of the drill string and drill bit, and the control of subsurface pressures. The downhole hydrostatic pressure exerted by the mud is kept higher than the pressure of the formation fluids at depth to prevent the movement of those fluids into the wellbore. Flow of gas into a well because of a pressure imbalance (i.e., formation pressure is greater than drilling fluid hydrostatic pressure) lowers the density of the drilling fluid and causes a corresponding increase in the volume of drilling fluids in the mud pit or tank.[39] This condition is referred to as kick, and if it is not controlled, a blowout may result.

Kicks are often associated with the improper pulling of drill pipe from the wellbore or running a pipe into a well (i.e., a trip). Removal of drill pipe can create a swabbing effect that produces a pressure differential that is great enough to allow the entrance of formation fluids into the wellbore. In addition, if the hole is not properly filled with drilling fluid to compensate for the volume of the pulled drill pipe, the resulting pressure decline can induce the flow of formation fluids to the wellbore. Kicks can also happen when the circulation of drilling fluids is lost due to the movement of those fluids into a porous or fractured zone. A sharp increase in formation pressure compared to the pressure of the drilling fluid, caused by the penetration of a high pressure gas zone, is another source of well-control problems. An accelerated rate of drilling, known as a drilling break, can also signal the onset of a kick.

We reviewed data[40,41] on the causes of 83 blowouts of natural gas wells in Alberta, Canada during 1960 through 1980 and found that 57% of the blowouts occurred during trips. Most of those releases were attributed to either the swabbing action of the drill pipe, insufficient mud weight, failure to keep the well full of drilling fluid, or a combination of those causes. Other blowouts were due to the penetration of high pressure gas zones (12%), lost circulation (11%), and equipment failures, along with other miscellaneous or unknown causes (10%). These data underscore the significance of the increased likelihood of uncontrolled conditions taking place during the removal or insertion of drill pipe in a well.

Between 1960 and 1980, 24,660 productive gas wells were drilled in Alberta plus 12,602 productive oil wells, 19,001 dry holes, and 3950 miscellaneous wells. Most of the natural gases there are contaminated with hydrogen sulfide. The probability that a new gas well will blow out can be estimated from the historical data by dividing the number of blowouts by the sum of the productive gas wells and dry gas wells. The blowout probability is not simply the ratio of blowouts to productive gas wells, because the resulting probability would only be applicable for estimating the chances of a blowout for a producing well, and we do not know in advance whether a well will be productive or not. Furthermore, we cannot categorically assume that wells that are determined to be "dry" in a commercial sense are incapable of having blowouts. A better estimate of the likelihood of a blowout is obtained by dividing the number of gas blowouts by the total number of productive and unproductive gas wells. The number of dry or unproductive gas wells can be calculated by assuming that the ratio of productive gas wells to the sum of all productive wells is the same as the ratio of dry gas wells to the total number of all types (i.e., oil, gas, and miscellaneous categories) of dry wells, which is the reported statistic. Table 3-1 contains the annual numbers of productive gas wells together with estimates of dry gas wells and blowouts in Alberta for 1960 to 1980.

We defined a blowout as any accidental, uncontrolled release of gas to the atmosphere. This definition was employed because in many instances, estimates of the amount of gas released were unavailable, and consequently, it was not possible to classify releases as large, small, or insignificant. We also excluded wells that were not clearly identified as gas wells in the records. Many of the wells in Alberta produce sour gas, but we did not treat them as a separate class because of a lack of data on hydrogen sulfide concentrations in these wells. A total of 83 releases were defined as blowouts using this classification method.

The total number of productive and unproductive gas wells from 1960 to 1980 was 35,076, and the frequency of blowouts was equal to 83/35,076 or 2.4×10^{-3} blowouts per gas well drilled. For 1970 to 1980 the probability is 1.6×10^{-3}. We reviewed files of the Texas Railroad Commission[42] containing reports of blowouts in Texas in order to obtain data that would allow us to quantify the blowout frequency for gas wells drilled in that state. For 1977 through 1981 there were 99 uncontrolled gas releases for 26,850 gas wells drilled--including 8278 wells that were classified as dry, using the approach described above, and 18,572 that were reported as productive wells. The blowout frequency is therefore 3.7×10^{-3} blowouts per gas well. Even though this frequency is more than a factor of 2 higher than the blowout frequency calculated using data from Alberta, the frequencies are still remarkably similar.

It is not possible to fully explain the reason for the difference between the estimates, however, we note that the geometric mean depth of the wells that had uncontrolled releases in Texas (i.e., 4464 ft (1361 m)) was about 25% greater than the depth of the Alberta wells (i.e., 3582 ft (1092 m)). We would therefore expect a higher frequency of

Table 3-1. Annual summaries of drilling activity and blowouts for gas wells drilled in Alberta, Canada during 1960 through 1980.[40,41]

	Productive wells			Dry holes		
	gas	all types		all types	gas	
Year	A	B	A/B	C	(A/B) x C	Blowouts
1960	242	1190	0.203	434	88	1
1961	287	1097	0.262	437	114	2
1962	252	971	0.260	589	153	5
1963	223	1103	0.202	572	116	2
1964	242	1161	0.208	673	140	2
1965	244	1219	0.200	815	103	3
1966	248	930	0.267	719	192	4
1967	279	956	0.292	676	197	1
1968	358	1004	0.357	884	316	6
1969	393	918	0.428	948	406	7
1970	559	966	0.579	875	507	2
1971	685	1133	0.604	879	531	1
1972	1045	1631	0.641	1005	644	4
1973	1523	2265	0.672	1195	803	4
1974	1623	2393	0.678	1069	725	9
1975	1880	2654	0.708	937	663	6
1976	3180	3831	0.830	1118	928	0
1977	3000	3826	0.784	1202	942	8
1978	3100	4177	0.742	1293	959	3
1979	2905	4151	0.700	1293	905	6
1980	2392	3591	0.666	1388	924	7
Totals	24,660	41,167		19,001	10,416	83

blowouts in Texas, because longer trips would be required to extract drill pipe from wells--increasing the chances of uncontrolled flow conditions. Other factors affecting the blowout frequencies may include drilling regulations (e.g., rules governing the drilling of sour-gas wells), different drilling practices and equipment, the presence of overpressured gas formations, and the experience of drill crews.

We also calculated the frequencies of accidental releases of gas from completed wells, including both shut-in wells and producing wells located in Alberta and Texas. The 1960 to 1980 data for Alberta show that 43 accidental releases took place over 117,320 well-yr of operation, representing a rate of 3.7×10^{-4} releases per well-yr. For 1970 to 1980 the rate was 3.6×10^{-4} releases per well-yr, based on 36 events and 100,126 well-yr. Over the total period of interest, 15 of the 43 accidental releases (35%) were due to problems encountered during the servicing of wells. Of the other 28 releases, 13 were caused by external damage, typically a caterpillar tractor running over a well head. Miscellaneous equipment failures (e.g., valve failures, poor cement jobs, etc.) accounted for most of the remaining releases. It is worth noting that hydrogen sulfide was not identified as a cause of any of those failures. The Texas data for 1977 to 1981 show that 9 accidental releases occurred over 177,323 well-yr of operation, which is equivalent to a rate of 5.1×10^{-5} releases per well-yr, or which is only 14% of the rate calculated for completed wells in Alberta. Using these rates, we calculate that a completed well in Alberta would have a 7.2×10^{-3} probability of accidentally releasing gas to the atmosphere over a 20-yr period compared with a probability of 1×10^{-3} for a completed well in Texas. The geometric mean value of the rates for Alberta and Texas is 1.4×10^{-4} releases/well-yr, and over a 20-yr period the probability of a release becomes 3×10^{-3}.

These calculations indicate that the probability of a gaseous release during the drilling phase of development is comparable to the probability of a release over the entire production or post-completion phase. We should further point out that the blowout probabilities we have calculated are for both sour and sweet gas wells, and consequently, the results may not necessarily provide an accurate prediction of the likelihood of an accidental release from a sour-gas well. At this time we cannot state whether sour-gas wells are more or less likely to have accidental releases. For example, sour gas can cause metallurgical problems (e.g., stress cracking, embrittlement, corrosion, etc.), which would seem to enhance the chances of a well failure; however, special alloys are specified for use in hydrogen sulfide environments to avoid such problems. Corrosion inhibitors provide additional protection against such problems. Moreover, sour-gas wells, like those being completed near Evanston, are usually equipped with special safety valves that reduce the chances of an accidental release. During drilling special precautions are taken before and during the penetration of sour-gas formations. Despite these measures human errors, equipment failures, etc. can still cause accidental releases.

Another important statistic is the duration of the blowouts. This parameter can be useful in the planning for emergency responses that would be needed in the event of a well blowout. Data on blowouts in Alberta and Texas[40,42] show that releases can last from less than an hour to months. More commonly, though, releases last a few days. The geometric mean of durations of the Alberta blowouts is 1.8 d compared to 3.2 d for the blowouts in Texas. When the data for the two areas are combined, the geometric mean is 2.4 d with a geometric standard deviation of 4.5. The lower and upper limits to the 68% confidence interval are 0.5 and 10.8 d.

ESTIMATING GAS DISCHARGE RATES FROM WELLS

One of the most important variables that is required in the calculation of the potential health and environmental risks of a blowout is the emission rate of gas from an uncontrolled well. This variable is not easy to quantify, especially when there are limited data on the properties of the formations and gases that may be encountered during drilling. Until flow test data become available on a well, we must rely on similar data from other nearby wells, or lacking that, we can estimate flow rates based on different assumptions about the properties of the reservoir and the gas it contains. Generally, the only types of information that will be available on nearby wells will be the results of flow tests* used to determine reservoir properties. The results of these tests can be misleading if used to directly estimate flows during a blowout. For example, the flow rate associated with a 24-h well test represents a discharge that is against a backpressure that is often in excess of 1000 psi (6.9 MPa). During a blowout, however, the discharge would be against atmospheric pressure at the surface, which would result in a flow rate of gas that is considerably higher. Similarly, the flow rate of a producing well is not a reliable indicator of the gas discharge under blowout conditions, because such a well delivers gas against the pressure in the pipeline that collects gas from the well.

Estimating Gas Flow from Wells

Blowouts can occur during both the drilling and production phases of well development. Estimates of gaseous emissions from blowouts during the drilling phase usually are based on data from other wells. Improved estimates of potential emissions can be made for completed wells, because measurements are available on reservoir properties and the well design is known.

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* Results of flow tests are reported on well completion reports required by BLM for wells completed on lands leased from the Federal Government.

Emissions from a Completed Well. The uncontrolled flow of gas from a well is governed by properties of the gas reservoir and the flow string (i.e., the pipe or casing through which the gas flows). Figure 3-1 is a simplified diagram of a completed well that shows the pertinent features of a reservoir/well system. Gas flow through the formation and into the wellbore is controlled primarily by the properties of the reservoir, including the permeability of the producing formation and its thickness, the geometry of the reservoir, and the pressure, temperature, and composition of the sour gas within the reservoir. Data on these parameters are acquired from well logs, flow tests, and gas analyses made while the well is being completed. One measure of the potential productivity of a well is termed the calculated absolute open flow (CAOF), or the flow rate of gas into a wellbore when there is atmospheric pressure at the sand face of the

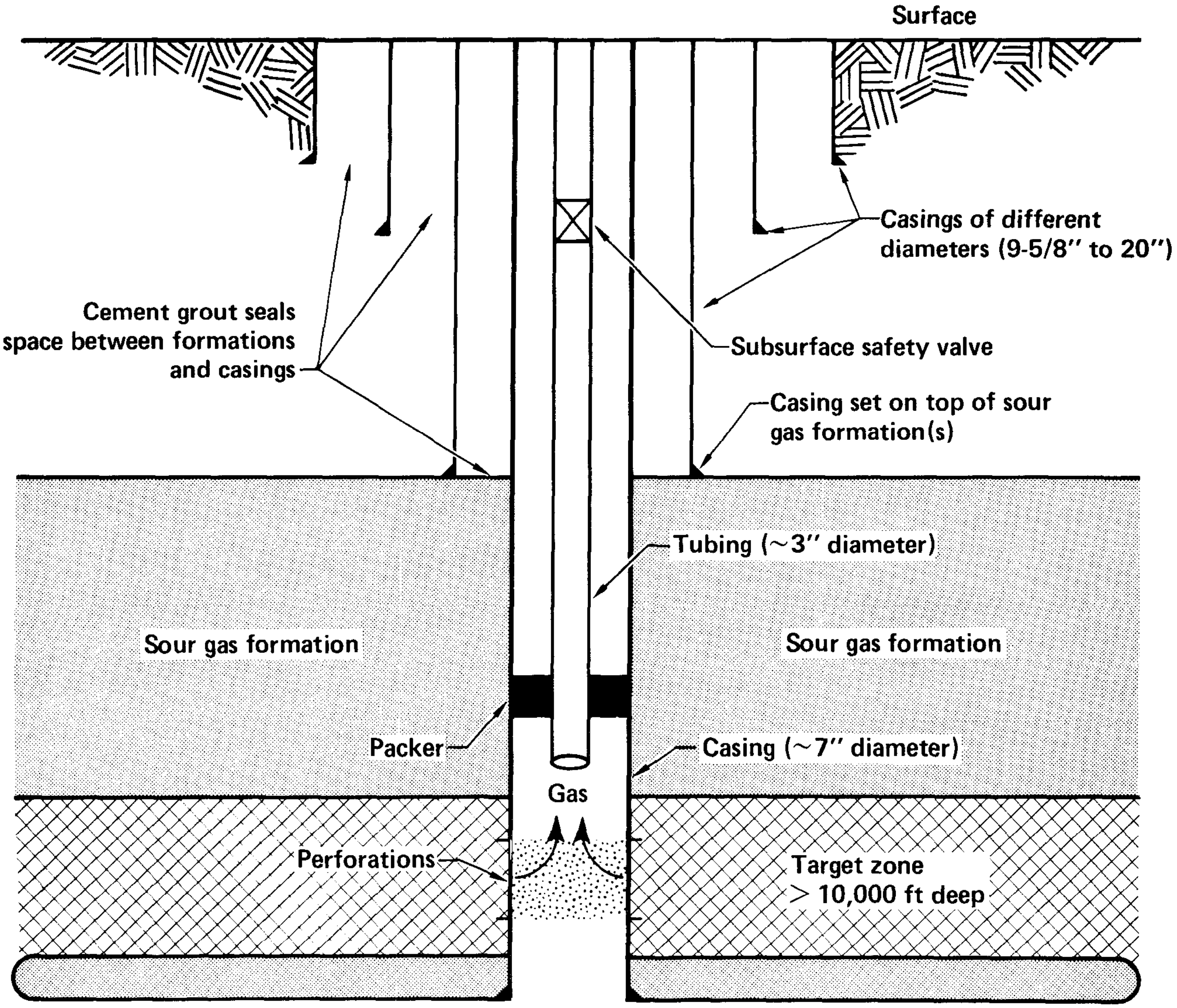

Figure 3-1. Subsurface components of a completed sour-gas well.

producing formation. The CAOF is never attained, though, because the frictional resistance of gas flowing through casing or tubing to the surface creates a downhole pressure that is greater than atmospheric pressure. And because the higher downhole pressure means a lower pressure differential between the reservoir and well, less gas flows into the well. A traditional method of calculating the CAOF of a well is based on the extrapolation of pressure-flow data obtained from a backpressure flow test (see Craft and Hawkins[43]). To illustrate how gas discharge varies with different downhole pressures, we used a reservoir equation (defined in Appendix A) describing the radial, steady-state flow of gas into a well for downhole pressures ranging from 0 to 5160 psi (0 to 35.6 MPa) (see Table 3-2 for properties of the reservoir and gas). The results of those computations are shown as curve A in Fig. 3-2. The CAOF of this well is approximately 64 x 10^6 scf/d (1.8 x 10^6 m^3/d).

Table 3-2. Properties of the reservoir, gas, and flow string used to calculate the flow of gas through a hypothetical well.

Parameter	Value	
Reservoir		
Permeability of reservoir rock	5 mD	
Thickness of the reservoir	100 ft	(30.5 m)
External radius of circular reservoir	3000 ft	(914.6 m)
Average reservoir pressure	5160 psi[a]	(35.6 MPa)
Gas		
Viscosity	0.025 cP	
Temperature	625°R[b]	
Compressibility factor	1	
Gravity	0.75	

[a] Based on a depth of 12,000 ft (3658 m) and a hydrostatic gradient of 0.43 psi/ft (0.01 MPa/m).

[b] Calculated using a temperature gradient of 0.01°F/ft (0.018 °C/m) and a base temperature of 45°F (7°C).

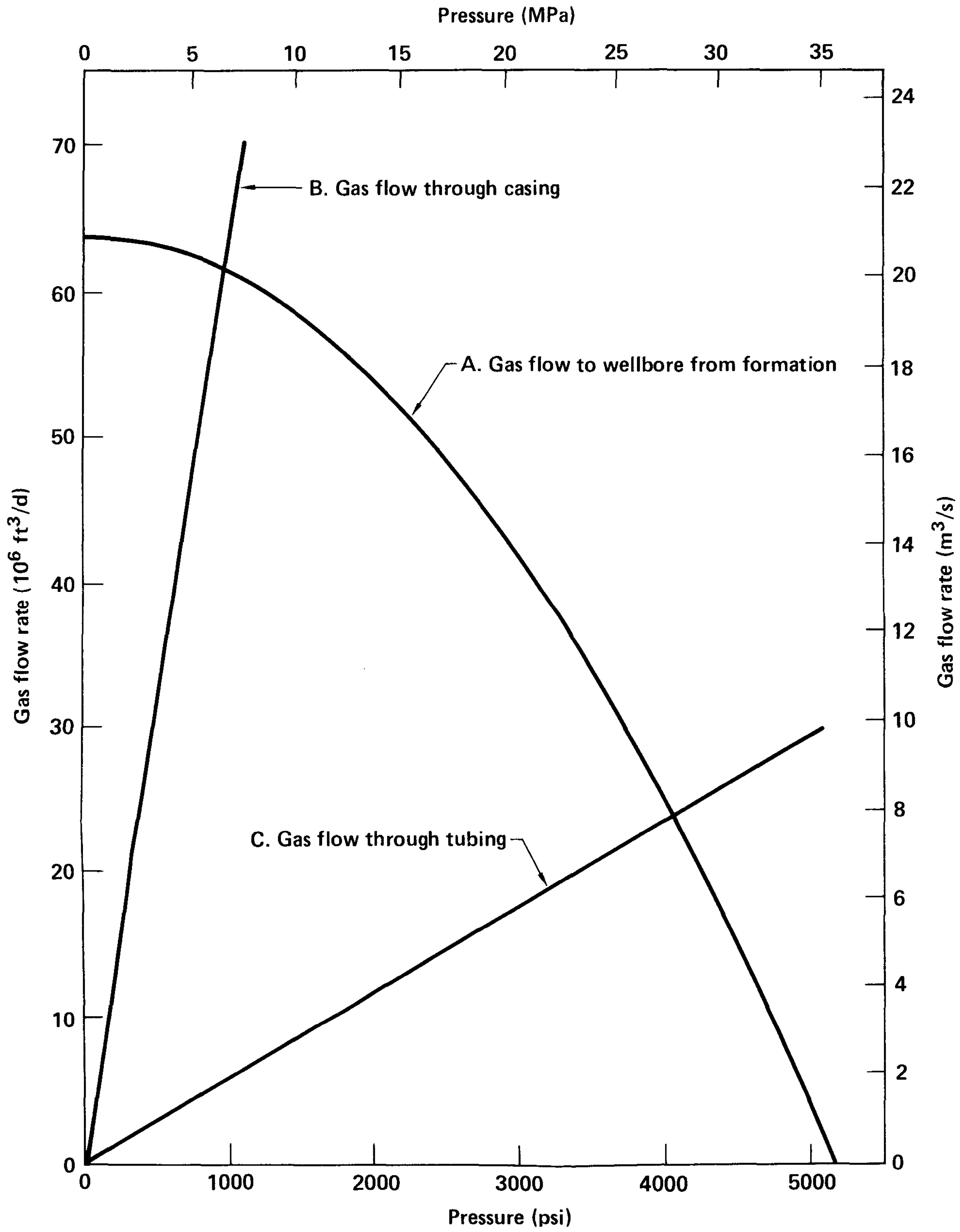

Figure 3-2. Gas flow rates calculated for flow through the producing formation, production tubing, and well casing. The intersections of curves B and C with curve A represent the estimates of gas discharge to the atmosphere.

The atmospheric discharge of gas from a well can be calculated as the intercept of curve A (i.e., the reservoir flow curve) and a second curve that we will call the flow-string curve.[44] The latter curve depicts the relationship between atmospheric discharges of gas and subsurface pressures for a specific flow string. The flowing subsurface pressure is calculated as a function of gas properties; the interior diameter, length, and friction factor of the flow string; and the surface pressure against which gas is discharged (assumed to be atmospheric pressure under blowout conditions). The subsurface pressure is especially sensitive to the interior diameter of the flow string, that is, as the diameter decreases, the frictional resistance to a constant flow rate of gas increases. We used an analytical equation (defined in Appendix A) to calculate flow string curves for two pipes with different interior diameters, both 12,000 ft (3658 m) in length. Curve B represents flow through a liner or casing with an interior diameter of 6 in. (16.2 cm), while curve C, for example, represents gas flow through a production tubing (2.4 in. (6.1 cm) interior diameter). The estimated gaseous discharge rates for the flow strings are 62×10^6 and 24×10^6 scf/d (6.8×10^5 and 1.8×10^6 m^3/d), respectively (see Fig. 3-2).

There are a couple of important points to be made here. First, the flow rate through the larger diameter pipe was close to the CAOF, which means that the uncontrolled flow of gas through a production casing or liner will not produce downhole pressures that greatly inhibit the flow of gas from a formation to a well. Hence, the CAOF represents an upper-bound estimate of the unrestricted, atmospheric discharge of gas from a well without its production tubing in place. With the production tubing in place, though, the flow resistance associated with the smaller diameter pipe causes a downhole pressure that results in an atmospheric discharge that is about 40% of the CAOF. For a completed well, the smaller flow rate represents a practical upper-bound emission rate of gas to the atmosphere for normal production conditions. During well servicing with tubing out of the well, though, the CAOF would also be appropriate.

Emissions from an Incomplete Well. The potential flow rate of gas from a well depends heavily on the geologic properties of reservoir rock, especially the permeability and thickness of productive strata. It is not possible to accurately quantify these properties prior to drilling, unless the target formations are somewhat homogeneous and there are enough wells in the vicinity of the drilling well to suggest trends in permeability, bed thickness, etc. Carbonate rocks with fracture-controlled permeability can have large changes in permeability over relatively short distances, and consequently, well test data on nearby wells are often of little value for predicting gas flows. Wildcat wells drilled in unexplored areas present an even more difficult problem of estimation.

One way of estimating gaseous discharges would be to use the steady-state reservoir equation (see Appendix A) to compute flow rates for various rock permeabilities, thicknesses, gas properties, downhole pressures, etc. It would be difficult to use such a method because of the large variabilities in those parameters. An alternative approach for dealing with the uncertainties inherent in estimating gaseous emissions is to examine the distribution of CAOFs among a sample of wells to determine the CAOF corresponding to the median value of the sample distribution together with the CAOFs at lower and upper confidence limits about the median.

For our sample we chose 15 wells[45] completed at depths of between 9000 and 18,000 ft (2744 and 5488 m) in western Wyoming--the depths where essentially all of the sour-gas formations are located. A probability plot of the CAOFs indicated that the parent population is probably lognormal. The geometric mean of the distribution was 4.7×10^6 scf/d (1.3×10^5 m^3/d) with a geometric standard deviation of 4.7. The 95% confidence interval about the geometric mean (the median value of the distribution) went from 2.1×10^5 to 1.0×10^8 scf/d (5.9×10^3 to 2.8×10^6 m^3/d).

GEOCHEMISTRY OF SOUR GASES

The primary method of estimating the potential composition of gas is by extrapolating compositional data on sour gases found in nearby wells completed through the same target formations. However, in making such extrapolations it is useful to know what the differences in concentrations are between wells completed in the same formation within a gas field. These data are especially pertinent for estimating gas concentrations in a development well. For an exploratory well, though, we also need data on the differences that may exist in several gas fields within a particular formation. In addition to the compositional data, it is also important to know something about the geochemical origins of the gases so that we can interpret the data on gas compositions.

Hydrogen Sulfide

In shallow sediments the primary source of hydrogen sulfide is the reduction of dissolved sulfate by bacteria under anaerobic conditions. The bacteria consume oxygen in the sulfate to oxidize organic material to carbon dioxide, forming hydrogen sulfide as a second reaction product when the pH of the system is below 7.[46] While the sediments age and are gradually buried, most of the biogenic hydrogen sulfide is probably changed to elemental sulfur, metallic sulfides, or organic sulfur compounds.[47] Furthermore, as the temperature of the sediments increases with greater depths of burial, the bacterial reduction of sulfur becomes less effective.

Orr reports that the optimum temperatures for sulfate reduction range from 86 to 113°F (30 to 45°C), while above 140°F (60°C) the process is supposedly slowed considerably.[48] At a geothermal gradient of 0.01°F/ft (0.018°C/m), the 140°F temperature would correspond to a depth of approximately 10,000 ft (3049 m), assuming a base temperature of 45°F (7°C) at the surface. Because of the reactivity of hydrogen sulfide and the effect of temperature on bacterial reduction, it is unlikely that bacterial action on sulfur compounds is a primary source of hydrogen sulfide in deep natural gas reservoirs. Instead, hydrogen sulfide is generated by chemical reactions of sulfur under elevated temperature and pressure conditions after the sediments are buried. This does not mean that hydrogen sulfide from bacterial reduction of sulfur compounds is never encountered in oil and gas operations. Low temperature reservoirs, for example, may be able to sustain the microbial reduction of dissolved sulfates. In addition, biogenic hydrogen sulfide can be a problem during the secondary recovery of oils by water flooding.

A case in point is the Wilmington Oil Field in Southern California. Ocean water along with produced waters were injected into the oil reservoir for the joint purposes of pressure maintenance to control land subsidence and to recover oil.[49] The introduction of sulfate, dissolved in the sea water, to the reservoir served as a major source of sulfur for sulfur-reducing bacteria (genus Desulfovibrio). As a result of bacterial action on the injected waters, the gases and waters produced along with oil became contaminated with sulfides. Efforts were then made to reduce the production of sulfide through the use of biocides. Biogenic hydrogen sulfide can be expected at other water-flooding operations in which sulfur is available in the injection water or oils for bacterial reduction. Another possible source of hydrogen sulfide in shallow formations is through the reduction of sulfate contained in ground waters.

Most, if not all, of the hydrogen sulfide in gas derived from high-temperature natural gas deposits is formed by nonbacterial mechanisms involving the thermally induced decomposition of organic and inorganic sulfur compounds or the thermocatalytic reduction of sulfate dissolved in formation waters mixed with reservoir hydrocarbons. Temperatures for the thermal processes are typically above 212°F (100°C).[47] The thermal reduction of organic matter containing sulfur compounds is probably a major source of hydrogen sulfide in natural gases. Work conducted by LeTran indicates that hydrogen sulfide levels in sediments are directly correlated with the quantity of organic matter, that is, as organic matter increases so does the amount of hydrogen sulfide.[50] The results of that work also indicate that hydrogen sulfide yields increase with the depth of burial. The thermal reduction of inorganic sulfate could also be a source of the hydrogen sulfide. Orr, in a study involving the sulfur content of Paleozoic oils during their thermal maturation in Wyoming's Big Horn Basin, suggests that the formation of hydrogen sulfide in those oils begins with the reduction of sulfate to produce elemental sulfur as well as polysulfides.[48] The sulfur compounds in turn oxidize the hydrocarbons to generate hydrogen sulfide. The oxidation/reduction (redox) reaction of that process, when CH_2 is the hydrocarbon oxidized, is

$$4\,S^\circ + 4/3\,(CH_2) + 8/3\,H_2O \rightarrow 4H_2S + 4/3\,CO_2 \quad . \qquad (3\text{-}1)$$

The net reaction is

$$SO_4^= + 4/3\,(CH_2) + 2/3\,H_2O \rightarrow H_2S + 2\,OH^- + 4/3\,CO_2 \quad . \qquad (3\text{-}2)$$

Another redox reaction in place of Eq. (3-1) involves methane

$$4S^\circ + CH_4 + 2\,H_2O \rightarrow 4\,H_2S + CO_2 \quad . \qquad (3\text{-}3)$$

The primary source of the sulfate initially present in the oil-bearing formations was thought to be a redistributed Permian gypsum. Hydrogen sulfide itself acts as a catalyst in the redox reactions involving sulfur compounds. Toland demonstrated that organic compounds were rapidly oxidized by sulfates at temperatures of 572 to 660°F (300 to 350°C) when hydrogen sulfide was present.[51] The formation of hydrogen sulfide can also be catalyzed by carbonates. Hunt, for example, cites a Russian study that showed that the reaction of gasoline and sulfur at a temperature of 347°F (175°C) was catalyzed by carbonates.[47]

Generally, the greatest concentrations of hydrogen sulfide occur in gas from reservoirs composed of carbonate rocks rather than sands. Hunt lists the following reasons for this phenomenon: (1) carbonate rocks with their sapropelic kerogen generate more hydrogen sulfide than shales with humic kerogen, (2) carbonaceous rocks catalyze the reaction of sulfur with hydrocarbons to produce hydrogen sulfide, and (3) sands and shales contain 3 to 12 times more iron than carbonate rocks, and consequently, less hydrogen sulfide would be present in the sands and shales because the hydrogen sulfide they generate would combine with the iron to form iron sulfide.[47] These generalizations, needless to say, must be applied with caution on a case-by-case basis because of differences in the biological, chemical, and physical processes that occur in sediments after deposition (i.e., diagenesis), chemical alterations of organic matter caused by elevated temperatures (i.e., catagenesis), and the mineralogy of the source rocks.

Carbon Dioxide

Elevated levels of carbon dioxide are sometimes associated with hydrogen sulfide in natural gases. According to Hunt,[47] carbon dioxide can evolve from the thermal decomposition of oxygen bearing compounds in organic material (e.g., carbonyl and methoxyl) contained in reservoir rock as well as from carbonates that have thermocatalytically decomposed. The catalysts of the thermal reactions involving carbonates include limestone impurities such as alumina, magnesium, iron, manganese, and silica. Carbon dioxide derived from carbonates is formed at temperatures as low as 167°F (75°C), but temperatures in the vicinity of 302°F (150°C) are required for optimum production of this gas. The elevated temperatures needed to support the decomposition of carbonates can be from deep burial or by exposure to heat from an igneous intrusion. It is important to note that carbon dioxide is also a by-product of the reduction of sulfur compounds and the oxidation of organic carbon. Moreover, as it was pointed out earlier, such redox reactions are catalyzed by carbonates. The ultimate disposition of the carbon dioxide produced will depend on how it reacts with other substances. Carbon dioxide dissolves in water to form unstable carbonic acid, which in turn reacts with bases to form carbonate and bicarbonate salts.

Sour-Gas Formations in Western Wyoming

The Overthrust Belt of western Wyoming and adjoining parts of Utah, Idaho, and Montana (see Fig. 1-1) is an area that has undergone a complex sequence of deposition and deformation. The geologic complexity of this area has made it difficult to explore for deep oil and gas reservoirs. Nevertheless, improved geophysical exploration techniques (e.g., refined methods of data collection and analysis with seismic techniques) have made it easier to identify and assess candidate formations. The discovery that initiated the current interest in this region was the Pineview oil and gas field in Utah. That reservoir and other subsequent discoveries have similar geologic structures, that is, the producing formations are typically asymmetric, anticlinal folds that are located in the hanging wall of a major thrust.[1] Table 3-3 shows geologic ages of the sour-gas formations located in western Wyoming. The sour-gas formations in this particular region are primarily Permian and older, however Jurassic and Triassic sequences also have the potential for containing sour gas. The following descriptions of productive strata are based on reviews prepared by Ver Ploeg and De Bruin[1] and Everett et al.[52]

Jurassic and Triassic Formations. Included in the productive Jurassic and Triassic sequences are the Nugget, Thaynes, and Dinwoody formations. The Nugget sandstone is a source of both oil and gas in the Overthrust Belt. It was formed predominantly by aeolian deposition, and is composed primarily of quartz (90-95%) with rounded and well-sorted

Table 3-3. Distribution of sour-gas formations among natural gas fields in the Overthrust Belt of western Wyoming and adjacent areas in Utah (after Ver Ploeg and De Bruin[1]).

Formation	Geologic age	Gas field
Dinwoody	Triassic	Whitney Canyon-Carter Creek
Phosphoria	Permian	Yellow Creek
		Whitney Canyon-Carter Creek
		Thomas Canyon[a]
		Cave Creek
		Hogback Ridge
Weber	Pennsylvanian	Red Canyon
		Whitney Canyon-Carter Creek
		Cave Creek
Madison	Mississippian	Whitney Canyon-Carter Creek
		Thomas Canyon
		Cave Creek
		Riley Ridge[b]
Darby	Devonian	Whitney Canyon-Carter Creek
Bighorn	Ordovician	Whitney Canyon-Carter Creek
		Woodruff Narrows

[a] The so-called Thomas Canyon field is still under exploration.

[b] The Riley Ridge field was not included in Ver Ploeg and De Bruin.[1]

sand grains. In some locations, though, the Nugget may have clayey lenses. Everett _et al._ believe that this sandstone* is the youngest stratum that is likely to contain sour gas.[52] They could find no information that would suggest that post-Jurassic strata are potential sources of sour gas. We should point out that even though the Nugget has sour-gas potential, gas derived from that formation in gas reservoirs in the Overthrust Belt to date contain little or no hydrogen sulfide. That is reasonable, given its depositional history (i.e., aeolian deposition with reduced amounts of organic matter) plus the presence of iron oxides that may scavenge any hydrogen sulfide that is produced internally or that migrates into the sandstone. The Thaynes limestone includes beds of fine grained sandstones and silty limestones. This formation in the Whitney Canyon-Carter Creek field produces sweet gas. The Dinwoody Formation is made up of the following strata; silty limestones, calcareous siltstones, and shales. It contains a sweet gas in the Hogback Ridge field in Utah, but one well completed into this formation at the Whitney-Canyon-Carter Creek field did yield sour gas.[2]

Permian-Phosphoria Formation. The Phosphoria is the first formation encountered in the Overthrust Belt gas fields that routinely produces gas containing hydrogen sulfide. Lithologic units of the Phosphoria include phosphatic mudstone and shale, calcareous sandstone, chert, phosphate dolomite, and limestone.

Permian-Pennsylvanian-Weber Formation. The Weber† is a fine-grained marine sandstone containing carbonaceous members. Unlike the Nugget sandstone, which until now has been a sweet gas producer in the Overthrust Belt, the Weber yields sour gas. One explanation for the differences in the gas compositions of the two sandstones involves their depositional environments. The Nugget was formed by aeolian processes, and therefore we would expect it to be depleted in organic sulfur compounds, while the marine origin of the Weber means that organic sulfur is more apt to be dispersed in the deposited sands. The dispersed sulfur would later be converted to hydrogen sulfide during the catagenesis of the sandstone. Moreover, differences in the iron and carbonate contents of the two formations as well as in their historic temperature regimes could affect the production or depletion of hydrogen sulfide.

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* Ver Ploeg and De Bruin indicate that the true age of the Nugget is unknown because of insufficient paleontological data.[1] Until such data become available, it is placed within both the Jurassic and Triassic ages.

† Reports of the U.S. Geological Survey refer to this unit as the Wells formation.[1]

Mississippian-Madison Formation. The two principal members of the Madison are the Mission Canyon and Lodgepole formations. The Mission Canyon member in western Wyoming is composed mainly of dolomite and dolomitic limestone, but it also contains evaporites. The underlying Lodgepole limestone is separated from Devonian sequences by a dark shale.[1] The Madison group delivers sour gas at the Whitney Canyon-Carter Creek gas field. New gas fields in the Big Piney-LaBarge area (e.g., the Riley Ridge field) are composed primarily of carbon dioxide with lesser amounts of methane and hydrogen sulfide. In Montana the Madison formation yields sour gas at the Blackleaf field.

Devonian and Ordovician Formations. The Darby formation (Devonian) and the Bighorn formation (Ordovician) are the oldest sour-gas formations found in the Overthrust Belt. The primary rock in the Darby is a dolomite interbedded with shales and siltstones.[1] The Bighorn formation, in contrast, is almost exclusively dolomite, with some dolomitic limestone. Both of these formations are producers in the Whitney Canyon-Carter Creek field.

Concentrations of Hydrogen Sulfide and Carbon Dioxide

In Table 3-4 we have statistically summarized the data we obtained on the concentrations of hydrogen sulfide in natural gases from wells in the Overthrust Belt. Concentrations range from below 1 mol% (14 g/m^3) in the Bighorn formation to about

Table 3-4. Statistical summary of data on the concentrations of hydrogen sulfide in productive sour-gas formations located in the Overthrust Belt of western Wyoming and adjacent areas in Utah.

Formation	Number of samples	Mean (mol% (g/m^3))	Std dev (mol% (g/m^3))	Geometric mean (mol% (g/m^3))	Geometric std dev
Phosphoria	4	11.9 (171)	3.6 (52)	11.4 (164)	1.4
Weber	5	13.7 (198)	5.6 (80)	12.8 (185)	1.5
Madison	12	13.2 (191)	9.3 (134)	10.2 (147)	2.2
Bighorn	5	1.2 (17)	0.6 (9)	1 (14)	1.8

35 mol% (504 g/m^3) in the Madison formation. Because of the small sample sizes for each of the formations listed in Table 3-4, we were unable to find superior fits for either the normal or lognormal distributions. Accordingly, we have presented the statistics for each distribution. In addition to those data, one measurement was obtained for the Dinwoody formation of 4 mol% (58 g/m^3) and two for the Darby formation of 9 and 9.8 mol% (130 and 141 g/m^3). Figure 3-3 contains normal and log-normal probability plots of the pooled data for all of the formations. Neither plot provides a significantly better fit to the data. The mean of the normal distribution is 10.5 mol% (151 g/m^3) with a standard deviation of 7.9 mol% (114 g/m^3). The geometric mean of the lognormal distribution is 6.9 mol% (100 g/m^3) with a geometric standard deviation of 3. The 68% confidence intervals for the normal and lognormal distributions are therefore 2.6 to 18.4 mol% (37 to 265 g/m^3) and 2.3 to 20.7 mol% (33 to 298 g/m^3).

The compositional data, as summarized in Table 3-4, indicate that the Phosphoria, Weber, and Madison formations generally have similar concentrations of hydrogen sulfide. The Bighorn formation, however, has markedly lower levels of that gas. Even though the data show similarities between some of the formations, care must be exercised in using data on gas from one formation in a multiple-formation gas reservoir to predict the composition of gas extracted from another formation within the same reservoir or the same formation within a separate, unconnected gas reservoir. To illustrate this point, the mean concentration of hydrogen sulfide in gases from 5 wells completed in the Mission Canyon and Lodgepole members of the Madison formation at the Whitney Canyon-Carter Creek field is 13.4 mol% (193 g/m^3), but in the Big Piney-LaBarge area, 70 mi (112 km) to the northeast on the eastern edge of the Overthrust Belt, the concentrations of hydrogen sulfide in gas from the Madison are around 2.8 mol% (40 g/m^3). Furthermore, the concentrations of carbon dioxide are significantly different between the two regions. Most of the natural gases in the Whitney Canyon-Carter Creek field contain under 5 mol% (93 g/m^3) of carbon dioxide, whereas in the Big Piney-LaBarge area carbon dioxide levels exceed 50 mol% (932 g/m^3).

The concentrations of hydrogen sulfide measured in the sour gases from the various formations follow the general trends that would be expected to occur as a result of the thermal decomposition of sulfur compounds in reservoir rocks, that is, natural gases containing hydrogen sulfide should be associated with deep formations, where temperatures have been high enough to sustain the decomposition reactions. The sour-gas formations in the Overthrust Belt are typically below 10,000 ft (3059 m) in depth, where temperatures exceed 140°F (60°C)--beyond the optimum temperatures where biogenic

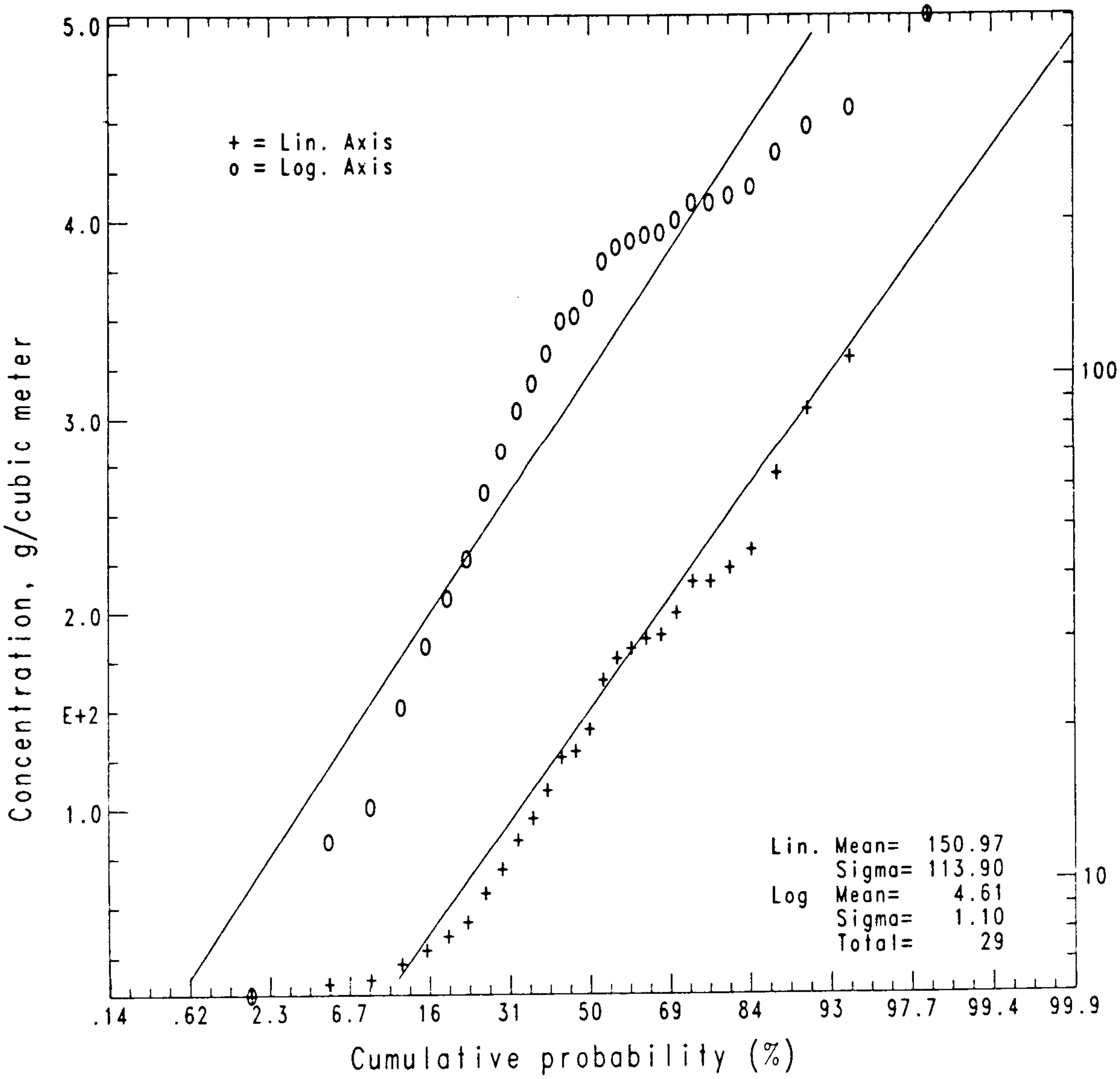

Figure 3-3. Probability plot of the concentrations of hydrogen sulfide in natural gases from several gas fields in the Overthrust Belt of western Wyoming and adjoining areas in Utah.

processes are expected to operate. It should be pointed out, however, that hydrogen sulfide concentrations in sour-gas formations do not necessarily increase with depth (temperature). Rather, once the "threshold" temperatures are reached that are capable of supporting the thermally driven reactions, the geochemistry of the reservoir rock becomes the dominant factor in the production of hydrogen sulfide. In this regard, we note that the sour-gas formations are mainly composed of carbonate rocks or contain carbonate units, types of rocks that can catalytically enhance the thermal decomposition of sulfur compounds. Also, as discussed earlier, carbonate rocks will not scavenge as much hydrogen sulfide as sandstones and shales, because carbonaceous rocks usually contain less iron. The wide variation in carbon dioxide concentrations in sour gases from the Madison limestone at reservoirs in southwestern Wyoming and further to the northeast in the Big Piney-LaBarge area probably reflect differences in subsurface temperatures, depositional environments, rock geochemistry, or a combination of the two factors.

HYDROGEN SULFIDE EMISSIONS FROM UNCONTROLLED WELLS

The mass emission rate of hydrogen sulfide from an uncontrolled sour-gas well is equal to the product of the volumetric flow rate of the gas emitted to the atmosphere and the concentration of hydrogen sulfide in the gas expressed in units of mass per unit volume. In mathematical terms,

$$Q = C \cdot D \quad , \qquad (3\text{-}4)$$

where

Q = emission rate of hydrogen sulfide,
C = concentration of hydrogen sulfide in emitted gas, and
D = gas flow rate.

Calculation of the potential emission rate of hydrogen sulfide from a completed well is a straightforward procedure after flow testing is completed and analyses of hydrogen sulfide gas have been obtained. Estimating emissions from an uncompleted well is more complicated because of the uncertainties associated with the parameters C and D. The effect of those uncertainties on the estimation of Q can be dealt with by propagating the uncertainties (i.e., statistical variances) of C and D to obtain the uncertainty associated with Q. Because Eq. (3-4) is multiplicative, the uncertainty can be quantified analytically if we assume that C and D are lognormally distributed and that they are independent. The variance of Q is then calculated as

$$\ln^2 \sigma_g(Q) = \ln^2 \sigma_g(C) + \ln^2 \sigma_g(D) \quad , \tag{3-5}$$

where $\sigma_g(Q)$, $\sigma_g(C)$, and $\sigma_g(D)$ are the geometric standard deviations of the variables.

Our analyses of the data dealing with hydrogen sulfide indicate that an estimate of the concentration of hydrogen sulfide expected in the natural gas from a new well should be based on concentration data derived from nearby wells completed in the same target formation or formations. If a wildcat well is to be drilled in an area where such data are absent and the subsurface geology is poorly defined, then the best way to estimate the concentration is to use the distribution of the pooled hydrogen sulfide concentrations from sour-gas wells located in different fields and completed into several formations. The geometric mean of these concentration data is 6.9 mol% (100 g/m^3) with σ_g equal to 3.

We can estimate the expected emission rate of gas from an uncompleted well in a similar fashion using the CAOFs from the subset of completed wells in western Wyoming that we discussed earlier. The geometric mean of these flow data was 4.7×10^6 scf/d (1.3×10^5 m^3/d) with σ_g equal to 4.7. The geometric mean of Q is therefore 0.33 lb/s (150 g/sec) with a geometric standard deviation equal to 6.67. The 95% confidence interval about the geometric mean ranges from 0.008 to 14.7 lb/s (3.3 to 6673 g/sec) of hydrogen sulfide.

PIPELINE RELEASES

Once a gas field is completed, pipelines are installed to gather the gas from individual wells for transport to a desulfurization facility via a larger transmission line. An important source of information on the frequency of leaks along gas transmission lines and gathering lines is the U.S. Department of Transportation (DOT), which collects data on such leaks through the use of questionnaires. According to DOT statistics for 1970 to 1980, 15% of leaks on transmission and gathering lines were due to corrosion, 40% were due to damage from an external source, 40% were related to construction or material defects, and 5% were attributed to miscellaneous causes.[53] In addition, nearly 87% of releases occurred along the pipelines, 4% at compressor stations, 3% at stations for dehydration, regulation, and metering, while the remainder were at other parts of the overall gas transmission system.

There were 229 leaks or failures recorded for gathering lines and 5775 failures reported for transmission lines. If we assume that 87% of those incidents actually took place along pipelines, rather than at compressor stations, dehydration plants, etc., then there were 199 and 5024 pipeline-related leaks for the gathering and transmission lines, respectively. For the years of interest, gathering lines operated for a total of about 2.6×10^5 mi-yr (4.2×10^5 km-yr) compared with 2.8×10^6 mi-yr (4.56×10^6 km-yr) for transmission lines. The frequency of leaks for gathering lines is therefore computed as $199/2.6 \times 10^5$ mi-yr, or 7.6×10^{-4} events per mi-yr (4.8×10^{-4}/km-yr). Transmission line leaks occurred at a rate of 1.8×10^{-3}/mi-yr (1.1×10^{-3}/km-yr).

Atwell and Andrews reported that there were 13 major ruptures of gas pipelines in Alberta, Canada during 5.9×10^4/mi-yr of operation, corresponding to a failure frequency of 2.2×10^{-4}/mi-yr (1.4×10^{-4}/km-yr).[54] This frequency value is about a factor of 3 less than the value calculated for gathering lines in the U.S. and a factor of 10 less than the value for U.S. transmission lines. One explanation for the difference is the omission of minor leaks in the calculation of the rupture frequency for gas pipelines in Alberta. In contrast, the U.S. DOT data include all types of leaks, and thus the calculated frequency values for U.S. gas lines are higher. Part of the difficulty with estimating pipeline failure frequencies is that such frequencies are a complex function of pipe age, diameter, type of use, length, depth of cover, corrosion controls, soil conditions, operating pressures, construction techniques, and materials, as well as maintenance and inspection procedures.[55]

4. METHODS FOR ASSESSING THE HEALTH HAZARDS OF SOUR-GAS WELLS AND PIPELINES

The ultimate goal of an assessment of the potential health effects of a sour-gas facility is to provide data that can be used to make decisions regarding safety measures to protect nearby residents. A commonly used analytical technique for analyzing the potential hazard of a sour-gas well involves the calculation of a danger zone around the well, where harmful concentrations of hydrogen sulfide could occur if a major blowout were to happen. Usually, estimates of such a danger zone are based on worst-case assumptions regarding atmospheric conditions and the nature of the atmospheric release to minimize the possibility that the "true" zone will be larger than the predicted one.

For example, a screening equation adopted by the Railroad Commission of Texas predicts the radius to the 500 ppmv isopleth of hydrogen sulfide for a surface-level release occurring simultaneously with very stable atmospheric conditions and a low wind speed, independent of wind direction.[56] A circle is drawn around the sour-gas facility to determine a hazard zone or radius of exposure, as it is sometimes called, which defines the population potentially at risk. A contingency plan is then prepared to protect that population. Although this technique may indeed establish the outer limit of a hazard zone, it does not provide any information on the spatial distribution of health risks, which are primarily a function of a site's dispersion meteorology.

In rural areas where there are isolated residences within a calculated exposure zone, each individual is assumed to be at equal risk, and therefore contingency plans are developed that attempt to provide the same amount of protection for all people in that zone. In residential areas or areas where future development is expected to take place, it becomes desirable to know whether certain sensitive locations (e.g., schools, subdivisions, factories, etc.) are at excess risk. If some populated areas are indeed at excess risk, then decisions can be made regarding the management of that risk.

The risks of incurring an acute health effect due to the inhalation of hydrogen sulfide at a specific site downwind from a sour-gas well are calculated as the sum of the probabilities of incurring acute health effects due to gaseous releases under all possible atmospheric conditions, as defined by discrete sets of atmospheric stability categories and wind speed classes associated with winds passing over the source and then the receptor. Thus, a risk analysis does indeed include worst-case meteorological conditions, but the resulting health effects are weighted according to the frequency of the atmospheric conditions.

In summary, worst-case analysis can be used to define a hazard zone about a sour-gas facility so that contingency plans can be formulated to protect individuals present within the danger zone. This approach is applicable when information on the spatial distribution of risk within the danger zone is unneeded. For situations where knowledge of the spatial distribution of risk is needed to tailor contingency plans or zoning ordinances to minimize potential health effects, then a risk analysis using meteorological data should be considered. The choice between the two techniques depends on site-specific factors, including population distribution and density, expected growth, location of roads, etc. With this background in mind, we now review procedures that can be used to calculate hazard zones and health risks at different downwind locations.

DEMARCATION OF HAZARD ZONES AROUND WELLS

The procedure for determining the extent of a hazard zone around a sour-gas well begins by estimating the release rate of hydrogen sulfide from the well. Rates are calculated as a function of the expected or measured concentrations of hydrogen sulfide plus the gas flow rate under uncontrolled conditions (see Section 3). The estimated emission rate is then used in an atmospheric dispersion equation to calculate a radius of exposure or downwind concentrations.

Calculation of Uncontrolled Emissions of Hydrogen Sulfide

The availability of data for calculating an uncontrolled emission rate of hydrogen sulfide from a well depends largely on whether it is for exploration or development. Data needed for estimating the gas discharge rates for different types of wells are presented in Table 4-1. The greatest amount of uncertainty is associated with exploratory wells because they are drilled in unexplored areas or untested formations to determine the properties of gas-bearing rocks. If an exploratory well confirms the presence of a commercially viable reservoir, the estimation of the uncontrolled discharge rates of hydrogen sulfide during the drilling phase of subsequent development wells can be based on the cumulative data acquired from all completed wells. Potential emissions from accidental releases during the production phase are estimated from actual flow-test data on individual wells.

Exploratory wells. To deal explicitly with the uncertainty of calculating inadvertent emissions of hydrogen sulfide during the drilling of an exploratory well, data on the

Table 4-1. Sources of data for calculating accidental emissions of hydrogen sulfide from three types of wells.

Well type	Variable	
	Gas discharge rate	Hydrogen sulfide content
Exploratory	CAOFs of other wells completed into the target formation(s) at similar depths	Hydrogen sulfide content of gases derived from other wells completed in the target formation(s)
Development	Same as for exploratory wells because of the large variability in gas flow rates	Concentration of hydrogen sulfide in gas from nearest well completed in the target formation within the gas gas field
Production	CAOF and tubing flow as calculated from actual well test data	Hydrogen sulfide content of gas derived from well test

CAOFs and hydrogen sulfide concentrations from other wells need to be analyzed. In Section 3 we reviewed a procedure for analyzing such data and propagating the uncertainties in both parameters. For most exploratory wells drilled in the Overthrust Belt of western Wyoming, we estimated that uncontrolled releases of hydrogen sulfide could range from 0.008 to 14.7 lb/sec (3.3 to 6673 g/sec). The application of this methodology to other sour-gas areas will require the collection and analysis of the same kinds of well completion data. If the CAOFs and the hydrogen sulfide concentrations for other wells are lognormally distributed and independent (an assumption that is consistent with the data we collected on wells in the Overthrust Belt), then the product of the two variables (i.e., the emission rate) is also lognormally distributed. Once the geometric mean (μ_g) and the geometric standard deviation (σ_g) of the emission rate are quantified, then a suitable upper-bound estimate of an emission rate can be calculated. For example, the emission rate corresponding to the 97.5th cumulative percentile (i.e., only 2.5% of the expected emission rates would be higher) is equal to the product of μ_g and σ_g^2.

We will illustrate this method with an example calculation based on hypothetical well completion data.

Example 1 An exploratory well is to be drilled into a subsurface structure that geophysical surveys suggest contains a limestone formation containing sour gas. Five other wells in the area that were drilled into that same formation at similar depths had CAOFs calculated at 4.2×10^5, 10×10^5, 2.9×10^6, 7.1×10^6, and 25×10^6 scf/d. Gas analyses from two wells in that formation in a nearby reservoir were 0.5 and 20 mol%. Calculate an upper-bound emission rate of hydrogen sulfide from the new well.

The geometric mean of the CAOFs can be calculated from

$$\mu_g = \exp[F] \quad , \tag{4-1}$$

where

$$F = \frac{1}{n} \sum_{i=1}^{n} \ln f_i \quad , \tag{4-2}$$

and

n = number of samples,
f_i = the ith CAOF,
F = mean of the transformed data, and
μ_g = geometric mean.

For the CAOFs in this example, the geometric mean is 2.9×10^6 scf/d.

To estimate the geometric standard deviation, the following equation is used.

$$\sigma_g = \exp[\sigma] \quad , \tag{4-3}$$

where

$$\sigma^2 = \frac{1}{n-1} \sum_{i=1}^{n} (\ln f_i - F)^2 \quad , \tag{4-4}$$

and

σ = standard deviation of transformed data, and

σ_g = geometric standard deviation.

The geometric standard deviation is approximately five for the example data set of CAOFs, using Eqs. (4-1) and (4-3) (see Table 4-2 for calculations). The accurate estimation of the statistical properties of the hydrogen sulfide concentrations is more difficult because of the limited number of samples. However, if we assume that the upper and lower concentrations define the 95% confidence interval of a lognormal distribution (i.e., the concentrations are at the 97.5 and 2.5 cumulative percentiles), then the geometric mean can be estimated directly from Eqs. (4-1) and (4-2) as 3.16 mol%. Since the 97.5 cumulative percentile value is equal to $\mu g \cdot \sigma_g^2$, we can compute the geometric standard deviation from $\sigma_g^2 \times 3.16 = 20$, and hence σ_g equals 2.5. If more concentration data are available, we would use Eqs. (4-3) and (4-4) to calculate σ_g.

The mass emission rate of hydrogen sulfide is calculated as the product of the volumetric flow rate of sour gas and the concentration of hydrogen sulfide in the gas. It is therefore necessary to have both parameters in the appropriate units.

The geometric mean of the CAOFs is converted to m^3/sec by

$$2.9 \times 10^6 \ \frac{ft^3}{d} \cdot \frac{d}{24\ h} \cdot \frac{h}{3600\ sec} \cdot \frac{m^3}{35.3\ ft^3} = 0.95\ \frac{m^3}{sec} \quad . \tag{4-5}$$

Similarly, the geometric mean of the concentration data at standard conditions becomes

$$\frac{3.16\ mol\%}{1} \cdot \frac{1}{100} \cdot \frac{1}{mol} \cdot \frac{mol}{0.0236\ m^3} \cdot \frac{34g\ H_2S}{mol} = 45.5\ \frac{g}{m^3} \quad . \tag{4-6}$$

The geometric mean of the hydrogen sulfide emission rate is computed as

$$0.95\ \frac{m^3}{sec} \cdot 45.5\ \frac{g}{m^3} = 43.2\ \frac{g}{sec} \quad . \tag{4-7}$$

Table 4-2. Calculations of μ_g and σ_g for the CAOFs of the sample of wells presented in Example 1.

Observation	Calculated absolute open flow f (scf/d)	ln f	F (calculated below)	$(\ln f - F)^2$
1	4.2×10^5	12.948	14.891	3.775
2	10×10^5	13.816	14.891	1.156
3	2.9×10^6	14.880	14.891	0
4	7.1×10^6	15.776	14.891	0.783
5	25×10^6	17.034	14.891	4.592
		Σ 74.454		Σ 10.306
		$F = 74.454/5 = 14.891$		$\sigma = (10.306/4)^{1/2}$ $= 1.61$
		$\mu_g = \exp[14.891] = 2.9 \times 10^6$ scf/d		$\sigma_g = \exp[1.61] = 5$

Eq. 3-5 is used to propagate the uncertainty of the two parameters. For this example, the geometric standard deviation is computed as

$$\sigma_g = \exp\,[\ln^2 5 + \ln^2 2.5]^{1/2} = 6.4 \quad . \tag{4-8}$$

The upper-bound estimate for the emission rate is then

$$43.2 \ \frac{g}{sec} \times 6.4^2 = 1769 \ \frac{g}{sec} \quad . \tag{4-9}$$

Development wells. The calculation of an upper-bound estimate of the emission rate of hydrogen sulfide from a planned development well is made somewhat easier because of the availability of data on hydrogen sulfide concentrations from previously completed wells. The statistical properties of gas concentrations derived from existing wells are used in the calculational procedure outlined in the previous example. The uncertainty in the CAOF is more difficult to quantify due to the wide variation in reservoir properties (e.g., fracture-controlled permeabilities) that is often characteristic of limestone formations. If only a couple of CAOFs are available on wells in the reservoir that is being developed, then additional data from wells completed into similar rock types and at approximately the same target depths in nearby reservoirs should be collected. Once these data have been collected, then estimates of the expected emission rate can be made.

Production wells. Estimates of hydrogen sulfide emissions from a completed well should be based directly on flow test data (i.e., upon which the CAOF is based) and measured gas composition. In this case, the mass emission rate of hydrogen sulfide is simply the product of the CAOF (expressed in volume per unit time) and the gas concentration (expressed in mass per unit volume). It is unnecessary to propagate measurement errors in the calculation of the emission rate, since such errors are small compared to the uncertainty in the interwell variations in reservoir parameters and gas composition.

Hazard Zone Calculations Using Screening Equations

Field personnel estimating the extent of hazard zones around sour gas facilities have typically used screening equations that are solutions to the Gaussian diffusion equation. Such screening equations are relatively easy to apply; however, there are issues involving the accuracy of the predictions and the applicability of the underlying diffusion equation for different meteorological and topographical conditions. A number of authors have studied the accuracy and performance of Gaussian diffusion models. We reviewed several such studies in Appendix B with the intent of determining the adequacy of the model for screening calculations involving sour-gas facilities. Our review indicates that despite some of the limitations of this steady-state model, it still represents a valuable tool for screening applications--especially in situations where the uncertainties associated with the estimate of the gas emission rate as well as the nature of the release (i.e., vertical or horizontal) are often of the same magnitude as the uncertainties associated with the Gaussian model.

For example, over all atmospheric conditions, Gaussian models can be expected to predict nearly all short-term (10-min) concentrations within a factor of 10, with most values falling within a factor of 2 to 5. In contrast, the geometric standard deviation of the CAOFs for wells in the Overthrust Belt is approximately 5, which means that 68% of the gas discharge rates are within a factor of 5 of the geometric mean. Moreover, according to the sensitivity analysis presented in Appendix B on the effect of plume height on predicted concentrations, an error in the specification/prediction of plume height can produce a factor of 10 difference in computed concentrations.

The Gaussian equation may not be applicable to rough terrain situations or when vertical dispersion is reduced by an inversion. One situation that is not amenable to such screening equations is the case where a source is located in a canyon where both horizontal and vertical dispersion could be restricted. In such situations it is best to consult with a meteorologist familiar with air pollution dispersion. A key uncertainty associated with the estimation of downwind concentrations of hydrogen sulfide following an accidental release is the effective height of the plume of dispersing gas. To handle this uncertainty, we divide releases into two categories: elevated emissions, in which gas is discharged vertically in the atmosphere (a momentum-dominated plume rise) and near-surface releases, where gas is discharged horizontally. These two conditions bound the cases that can occur.

Vertical Releases. The upper-bound estimate of a CAOF should only be used in a screening equation that includes plume rise. The CAOF is based on discharge through the completely open casing, which means that the discharge at the surface is unrestricted. Under those conditions, the gas is emitted at sonic velocity from the well, and a momentum-dominated rise of gas into the atmosphere is produced. The Gaussian dispersion equation can be used to calculate the ground-level concentrations of gas along the centerline of a plume of dispersing gas:

$$\chi = \frac{Q}{\pi u \sigma_y \sigma_z} \exp \left[\frac{-0.5\ h^2}{\sigma_z^2}\right] \quad , \qquad (4\text{-}10)$$

where

χ = ambient concentration of gas, g/m^3,

Q = gas emission rate, g/sec,

σ_y = standard deviation of gas concentration in cross-wind (y) plane at a given downwind distance, m,

σ_z = standard deviation of gas concentration in vertical (z) plane, m,

u = mean wind speed at the height of the plume, m/sec, and

h = effective height of the plume, m.

Figure 4-1 depicts the calculational procedure for determining the distance to the maximum downwind concentrations under different atmospheric conditions. After an estimate of the upper-bound emission rate of hydrogen sulfide is made, then the plume rise Δh is calculated from the following equation

$$\Delta h = 205\, u^{-0.96} \quad , \qquad (4\text{-}11)$$

where Δh is in meters and u is in m/sec, measured at 2 m. This function was empirically derived from a series of pipeburst studies carried out under the auspices of the Alberta Petroleum Industry, Government Environmental Committee on Hydrogen Sulfide Isopleth Prediction.[57] According to this relationship, the rise of a momentum-dominated plume decreases as wind speed increases and causes the plume to be bent over. The effective plume height h is then the actual release height plus plume rise Δh. If the discharge of gas is at some angle less than vertical (i.e., <90°), then Δh can be multiplied by $\sin \phi$ to adjust for a nonvertical discharge.

The distance to the maximum concentration from a plume with an effective release height of h is expressed as[58]:

$$x_{max} = [dh^2/(c^2(d+b))]^{\frac{1}{2d}} \quad , \qquad (4\text{-}12)$$

where the variables b, c, and d are stability-dependent coefficients used to predict the values of σ_y and σ_z at different downwind distances. The appropriate formulae for the standard deviations are

$$\sigma_y = ax^b \quad , \qquad (4\text{-}13)$$

and

$$\sigma_z = cx^d \quad , \qquad (4\text{-}14)$$

where x is downwind distance in meters, and the values of a and b are shown in Table 4-3, while the values of c and d are presented in Table 4-4. Once the distance to the maximum concentration is computed, then Eq. (4-10) is used to calculate the actual concentration at the downwind distance predicted by Eq. (4-12). The calculational procedure employing the above equations is illustrated by the following example.

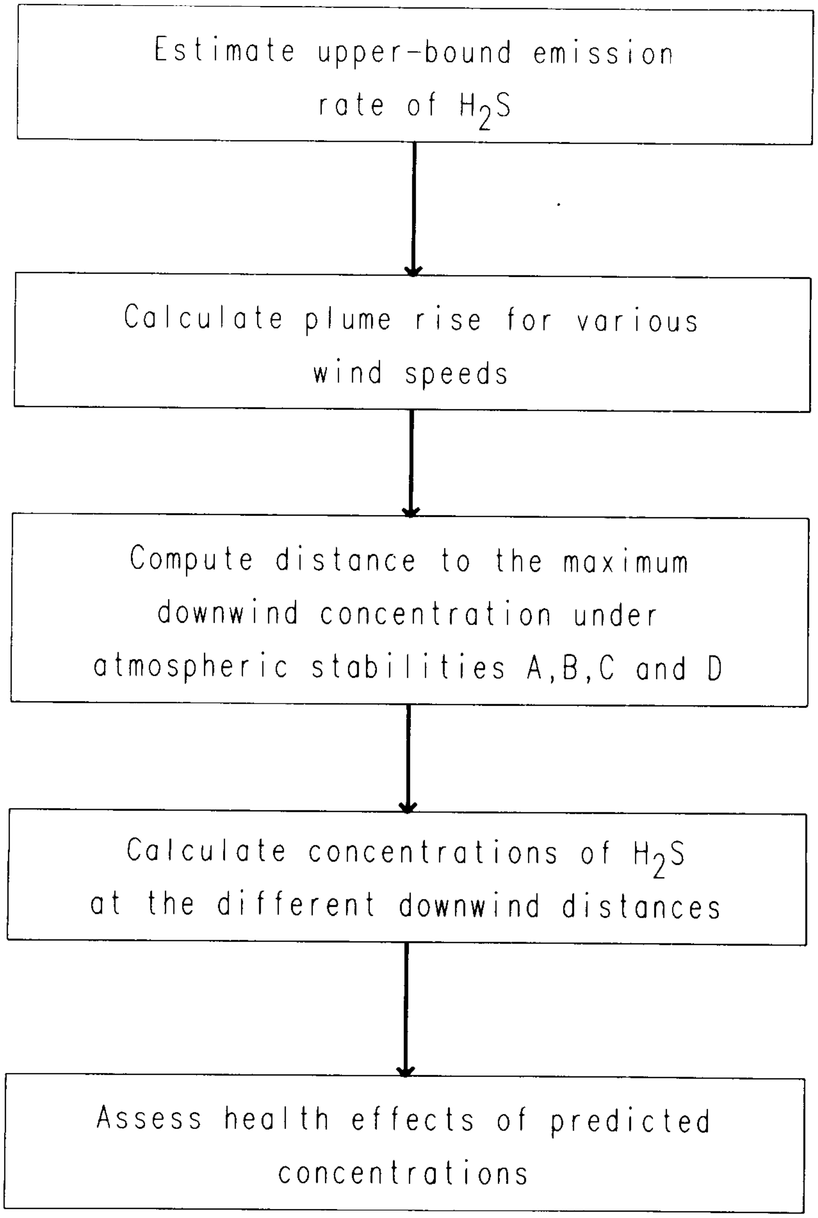

Figure 4-1. Diagram of the procedure for analyzing and assessing the health hazard of momentum-dominated releases of hydrogen sulfide from a sour-gas well.

Table 4-3. Coefficients for the power-law equation of σ_y for distances from 100 m up to 10,000 m (from Ref. 58).

Atmospheric stability class	Power-law coefficient a	Power-law coefficient b
A very unstable	0.495	0.873
B moderately unstable	0.310	0.897
C slightly unstable	0.197	0.908
DD neutral (day)	0.122	0.916
DN neutral (night)	0.122	0.916
E slightly stable	0.0934	0.912
F moderately stable	0.0625	0.911

Table 4-4. Coefficients for the power-law equation of σ_z (from Ref. 58).

	Downwind distance (m)					
	$100 < x \leq 500$		$500 < x \leq 5000$		$5000 < x \leq 50{,}000$	
Atmospheric stability class	Power-law coefficients c	d	c	d	c	d
A very unstable	0.0383	1.281	0.0002539	2.089	0.0002539	2.089
B moderately unstable	0.1393	0.9467	0.04936	1.114	0.04936	1.114
C slightly unstable	0.1120	0.9100	0.1014	0.926	0.1154	0.9109
DD neutral (day)	0.0856	0.8650	0.2591	0.6869	0.7368	0.5642
DN neutral (night)	0.0818	0.8155	0.2527	0.6341	1.297	0.4421
E slightly stable	0.1094	0.7657	0.2452	0.6358	0.9204	0.4805
F moderately stable	0.05645	0.8050	0.1930	0.6072	1.505	0.3662

Example 2 An upper-bound estimate of the emission rate of hydrogen sulfide from a sour-gas well located at an elevation of 6000 ft above mean sea level (MSL) is 1769 g/sec. Calculate the distances to the maximum ground-level concentrations under different atmospheric conditions and assess the potential health significance of the concentrations at those distances. Assume that the gas is discharged vertically into the atmosphere.

The plume centerline maximum ground-level concentrations from elevated plumes generally occur under unstable or neutral atmospheric conditions.[59] Since we do not know which combinations of wind speed and stability class will produce the highest concentrations, we have selected a series of combinations, as shown in Table 4-5, to compute ranges of concentrations. The values of h were calculated for a range of plausible wind speeds associated with different stability classes. The appropriate values of b, c, and d were obtained from Tables 4-3 and 4-4. The maximum concentrations were calculated from Eq. (4-10), based on the specific atmospheric stability, wind speed, downwind distance (x_{max}), and plume height. Eq. (4-10) predicts χ in units of g/m^3. To convert to units of ppmv for hydrogen sulfide, we use the following equation:

$$\chi_{ppmv} = \chi_{g/m^3} \left[\frac{T_a \; 8.31 \times 10^4}{P_a \; 34} \right] , \qquad (4\text{-}15)$$

where

T_a = ambient temperature, °K (°C + 273.2), and
P_a = atmospheric pressure, mb.

The barometric pressure at a given elevation can be approximated by this formula:

$$P_a = P_s \left[\frac{288 - 0.006Z}{288} \right]^{5.256} , \qquad (4\text{-}16)$$

where

Z = elevation above mean sea level, m,
P_a = barometric pressure, mb, and
P_s = sea level barometric pressure (1013 mb).

For an elevation of 6000 ft (1829 m), the value of P_a from Eq. (4-16) is 812 mb and from Eq. (4-15), the conversion factor is calculated as 869 ppmv•m^3/g, based on an ambient

Table 4-5. Calculations for analyzing the downwind, plume centerline, ground-level concentrations of hydrogen sulfide resulting from a momentum-dominated release from a sour-gas well (see Example 2 in text).

Wind speed	Stability	Effective height h				Distance to χ_{max}	χ_{max}	
(m/s)	class	(m)	b	c	d	(m)	(g/m^3)	(ppmv*)
1	A	205	0.873	0.0002	2.089	693	0.0098	8
5	A	44	0.873	0.0383	1.281	200	0.0284	25
1	B	205	0.897	0.0494	1.114	1581	0.0072	6
5	B	44	0.897	0.1393	0.947	307	0.0256	22
1	C	205	0.908	0.1014	0.926	2590	0.0058	5
5	C	44	0.908	0.1120	0.910	485	0.0246	21
10	C	22	0.908	0.1120	0.910	226	0.0494	43
1	D	205	0.916	0.7368	0.564	9152	0.0023	2
5	D	44	0.916	0.2591	0.687	972	0.0187	16
10	D	22	0.916	0.0856	0.865	402	0.0440	38
15	D	15	0.916	0.0856	0.865	258	0.0647	56

* Obtained by multiplying the value of χ_{max} in g/m^3 by 869 ppmv•m^3/g.

temperature of 60°F (15.6°C or 288.8°K). For an ambient temperature of 32°F (0°C or 273.2°K), the conversion factor is 832 ppmv•m^3/g-- a difference of only about 4%. Peak concentrations (on the plume centerline) of 56 ppmv were located within a radius of about 260 m (853 ft) from the well. These concentrations are not high enough to cause acute health effects; however, the odor of hydrogen sulfide would be very strong. In fact, because the median odor detection threshold is approximately 0.005 ppmv, people will be able to smell the sour gas for several miles downwind. In addition, the predicted concentration is above the lower limit of eye irritation (see Table 2-4).

Horizontal Releases. A horizontal discharge of sour gas under stable atmospheric conditions and a low wind speed represents a worst-case release scenario, because high concentrations of hydrogen sulfide would occur as the plume slowly disperses near the ground. The principal safety concern from this type of release is the potential for acute health effects, including respiratory arrest, unconsciousness, and possibly death. Based on our review of the inhalation toxicology of hydrogen sulfide (see Section 2), a reasonable threshold concentration for acute effects is about 300 ppmv over a time period of approximately 10 min (σ_y and σ_z are valid for about 10 min).

An important source of uncertainty for horizontal releases is the effective rise of the plume. A horizontal release of sour gas at sonic velocity would produce an expanding jet of gas that contains considerable turbulence and interacts with the ground surface. Consequently, the center of mass of the resulting plume is at some elevation above the release point. It is not possible to accurately predict the actual height to which this type of plume rises, because no experiments have directly addressed this situation. In Appendix B we have prepared a sensitivity analysis in which we compute the distance to the 300 ppmv isopleth for various emission rates of hydrogen sulfide and plume heights of 0, 2, 5, and 10 m. We believe that these plume heights effectively bound the heights expected under turbulent release conditions. For the purposes of preparing screening calculations that are conservative, yet realistic, we have chosen a height of 5 m to represent the plume rise for horizontal releases. This particular value gives estimates of the downwind distance to the 300 ppmv isopleth that are about 10 to 50% higher than the distances predicted using an assumed release plume height of 10 m (at emission rates of 2700 to 500 g/sec, see Appendix B for details).

To demarcate the hazard zone for a horizontal release of gas, we have solved Eq. (4-10) for the downwind distances to the 300 ppmv isopleth of hydrogen sulfide for different emission rates and surface elevations (under class F stability with h equal to 5 m, and u equal to 1.5 m/sec).* Figure 4-2 presents the curves relating emission rate and surface elevation to the distance to the 300 ppmv isopleth. When using these curves, one must use care in the selection of the appropriate emission rate of gas. A surface-level release could result from the failure or rupture of pipe used to transport gas away from a well; failure of piping that is part of a wellhead safety system is also possible. In any case, the uncontrolled flow of gas through one of those pipes would be smaller than the CAOF of gas through the production casing.

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* According to Hanna et al.,[60] the smallest value of u that should be used with a Gaussian model is 0.5 m/sec (1.12 mph). We note, however, that the Gaussian model tends to overestimate concentrations during stable atmospheric conditions (see Appendix B), and therefore we question the use of such a low wind speed. We have selected, as an alternative, a wind speed of 1.5 m/sec.

Our previous analysis of the uncontrolled flow of gas from both large (6 in. or 15 cm) and small (2.4 in. or 6 cm) pipes suggests that a plausible upper-bound estimate of discharge is 40% of the CAOF (see Section 3). This type of discharge could only occur if there were a horizontal release at the wellhead that was unrestricted by chokes or valves (i.e., a completely severed line). One other consideration in using the curves in Fig. 4-2 is that surface releases will not necessarily be continuous, because safety valves will shut off gas flow in the event of a leak or a rupture. For example, sour-gas wells that are in production can have surface safety valves plus a subsurface valve to prevent major atmospheric releases. When a safety valve is actuated due to a pipe failure or rupture, a puff of gas will be emitted to the atmosphere during the time it takes for the valve to close. The puff dispersion model discussed later is more appropriate for the transient release case (i.e., for modeling purposes, releases that last less than 10 min).

Example 3 The flow rate of hydrogen sulfide from a well is estimated to be 1769 g/sec (from Example 2). Use Fig. 4-2 to calculate the distance to the 300 ppmv isopleth of hydrogen sulfide for a continuous, horizontal release. The well is at an elevation of 3000 ft MSL.

The adjusted flow rate of gas for a horizontal release becomes 0.4 x 1769 g/sec = 708 g/sec, which when used with Fig. 4-2 gives a distance of about 950 m (0.6 mi). For this particular example, the risk zone for acute effects extends nearly a kilometer from the well,* and consequently, the population potentially at risk would not necessarily be restricted to workers, unless of course the well was located in an uninhabited area. It should be pointed out that ground-level concentrations in the plume at greater downwind distances could be high enough to cause odor-related complaints and eye irritation at even greater distances.

QUANTIFICATION OF THE HEALTH RISKS FROM AN ACCIDENTAL, CONTINUOUS RELEASE OF SOUR GAS

The probability that an individual living near a sour-gas well will incur an adverse health effect (i.e., health risk) after an accidental gas release can be calculated as the product of the probability that the well will accidentally release

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* The pattern of concentration isopleths for the plume is long downwind and narrow crosswind, such that as one moves off the centerline, the concentrations drop off rapidly.

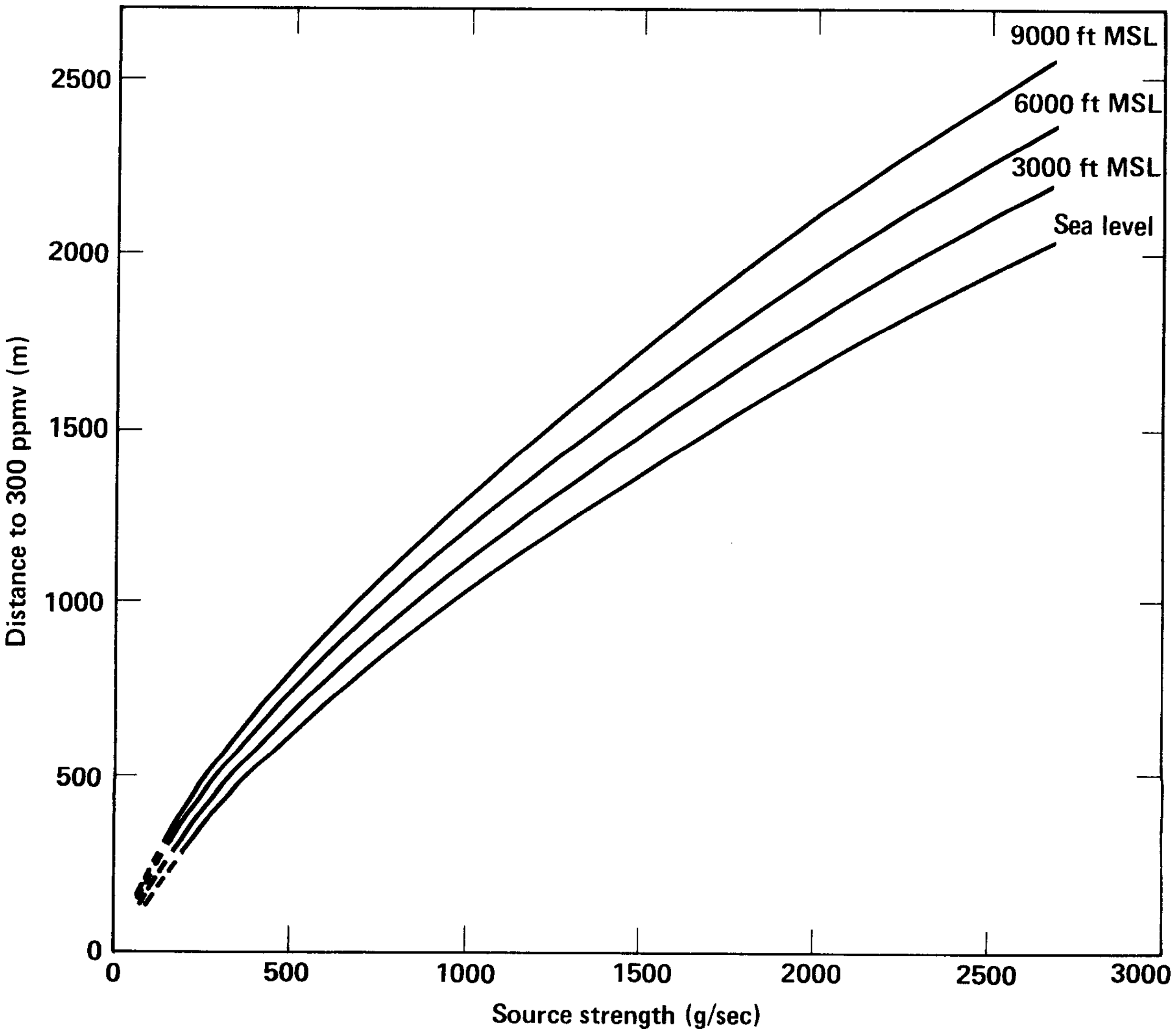

Figure 4-2. Maximum downwind distance (m) to the 300 ppmv ground-level concentration for varying source strengths (g/sec) and surface elevations (ft MSL); calculations made for release at h = 5 m under stable (class F) conditions, 1.5 m/sec wind speed, and 60°F air temperature.

gas to the atmosphere during a certain time period and the sum of the effect probabilities associated with such a release occurring randomly among different meteorological conditions defined by six wind speed classes, seven atmospheric stability categories, and 16 wind directions (i.e., each wind sector is 22.5°). The basic equation for calculating the health risk at a fixed location (i.e., receptor) near a sour-gas well is

$$R_k = P_r \sum_{j=1}^{7} \sum_{i=1}^{6} T_{ij} O_{ijk} \quad , \tag{4-17}$$

where

R_k = risk of a health effect at a fixed distance in downwind sector k,
P_r = probability that an accidental release occurs,
i = subscript representing wind speed class,
j = subscript representing the atmospheric stability category,
T_{ij} = probability of a toxic response to inhaling air containing a concentration of hydrogen sulfide predicted with stability category j and wind speed class i at a fixed distance downwind in the wind sector k where the receptor is located, and
O_{ijk} = joint probability of stability class j and wind speed class i occurring simultaneously in wind sector k where the receptor is located.

Variations of this method of calculating the risks from a sour-gas release have been described by Ledbetter[61] and Atwell and Andrews.[54] Ambient concentrations are computed for each of the 42 combinations of wind speed and atmospheric stability for the downwind sector where the receptor is located, and then the predicted concentrations are related to an individual's probability of experiencing a health effect by a dose-response function. That estimate is multiplied by the joint frequency of wind speed, atmospheric stability, and wind direction used to calculate the ambient concentration of hydrogen sulfide at the receptor. We conservatively assume that if the wind direction is within a 22.5 degree sector, the plume centerline will directly impact a receptor in that sector. To support those calculations, data are needed on the joint frequencies of wind speed and atmospheric stability for different wind directions. These data can be obtained from onsite meteorological measurements, or if that is not possible, then atmospheric stability and wind data can be obtained from the National Climatic Center (NCC) in Asheville, North Carolina. However, the data from the NCC are normally from weather stations at major airports, and consequently their use at a site far removed from the airport could result in distinct biases due to topographic effects, wind flow patterns, etc.

The procedure for calculating the health risks at a fixed location downwind from a sour-gas facility that is accidentally releasing sour gas can be described through the use of the following example.

Example 4 An exploratory well is going to be drilled into a subsurface structure that could contain two or more sour-gas formations. No direct measurements of gas flow or hydrogen sulfide concentrations are available for nearby wells. The well will be drilled at an elevation of 6000 ft MSL in an area of the Overthrust Belt where there are isolated residences and a major state highway. The highway is 4920 ft (1.5 km) to the northwest of the proposed well, and the nearest residence is 6560 ft (2 km) to the south of the well. Using the atmospheric stability data in Table 4-6, calculate the risk of an acute health effect at those two locations if a release occurs during drilling.

The first step is to determine whether to analyze a gas release that is vertical or horizontal. In this case, we would choose to analyze the horizontal release because it produces the highest downwind concentrations, and hence would pose a greater risk for causing acute health effects. Our analysis in Section 3 regarding potential emissions of hydrogen sulfide from sour-gas wells in the Overthrust Belt showed that a reasonable upper-bound emission rate of hydrogen sulfide from a well is 6673 g/sec, based on CAOF data and concentrations of hydrogen sulfide in sour gases. That emission rate, however, would be for the direct, vertical discharge of gas to the atmosphere through the production casing. A horizontal release, in contrast, is likely to result from the failure of surface piping or the wellhead assembly, and therefore the upper-bound estimate of the hydrogen sulfide emission rate must be adjusted downward to account for the increased resistance to flow caused by the smaller pipe. A first-order estimate is 40% of the CAOF. The adjusted discharge rate of hydrogen sulfide then becomes 2669 g/sec.

The second step is to calculate the ambient, ground-level concentrations of hydrogen sulfide to predict the health response to the predicted concentrations. In this regard, the concentrations likely to cause acute effects would probably occur under Pasquill-Gifford stability classes E and F. To calculate the concentrations for different wind speeds, we solve Eq. (4-10) for h = 5 m and multiply both sides of the equation by u/Q to obtain

$$\chi u/Q = \frac{1}{\pi \sigma_y \sigma_z} \exp\left[\frac{-12.5}{\sigma_z^2}\right] \quad . \tag{4-18}$$

Table 4-6. Joint frequency of occurrence for Pasquill-Gifford stability categorgies E and F and six wind speed classes for two wind sectors downwind from the source specified in Example 4.

Stability category	Sector at risk[a]	Wind speed class	Frequency of occurrence[b]
E	NW	1	0.0181
E	NW	2	0.0058
E	NW	3	0.0012
E	NW	4	0
E	NW	5	0
E	NW	6	0
F	NW	1	0.0961
F	NW	2	0.0043
F	NW	3	0
F	NW	4	0
F	NW	5	0
F	NW	6	0
E	S	1	0.0007
E	S	2	0.0032
E	S	3	0.0004
E	S	4	0
E	S	5	0
E	S	6	0
F	S	1	0.0032
F	S	2	0.0007
F	S	3	0
F	S	4	0
F	S	5	0
F	S	6	0

[a] For a receptor in the NW sector, winds would come from the SE sector, or 180° in the opposite direction. Similarly, receptors in the S sector receive winds out of the N sector.

[b] The frequency with which stability class E and wind speed class 1 occur simultaneously with winds blowing from the SE for the receptor located in the NW downwind sector and from the N for the receptor located in the S sector.

Equations (4-13) and (4-14) along with Tables 4-4 and 4-5 are then used to calculate σ_y and σ_z as a function of downwind distance to a receptor and atmospheric stability. The value of χ in g/m^3 for various wind speeds is then computed by multiplying $\chi u/Q$ by Q/u. The wind speeds used to represent the six different wind speed classes are 1.5, 2.46, 4.47, 6.93, 9.61, and 12.52 m/sec (for further information on the wind speed classes see Appendix C). Table 4-7 shows the values of $\chi u/Q$* for stabilities E and F for the hypothetical highway 1.5 km downwind of the sour-gas well described in the example. The corresponding values of χ for different wind speeds are also shown.

The third step is to calculate the probability of an acute effect for each of the predicted 10-min average concentrations. Unfortunately, it is not possible to quantify the actual effect probability for a given concentration; that is, at a concentration of 400 ppmv for 10-min, for example, we cannot say that an individual's mean risk of incurring an acute effect is 0.5. Nevertheless, previous studies do allow us to make some general statements about the nature of the dose-response function.

At concentrations of around 1000 ppmv, the gas exerts its toxic effect by paralyzing the respiratory system, and consequently, individuals exposed to that level would suffer respiratory arrest after a few breaths. With decreasing concentrations, though, the gas exerts its effect systemically, and variations in the responses of individuals are mediated more by the biochemical differences between individuals--especially in their ability to detoxify the gas. The lowest concentration reported in the literature causing an acute response (in this case, unconsciousness) was 250 ppmv for approximately 20 min. We have set the threshold level for acute effects at 300 ppmv, because the concentrations predicted by a Gaussian diffusion model using Pasquill-Gifford dispersion parameters are for an averaging time of about 10 min.[60] Because of the differences between individuals and the lack of human effects studies at the concentrations of concern, we assume that the probability of an acute effect is equal to one whenever the predicted concentration of hydrogen sulfide is greater than or equal to 300 ppmv. The effect probability is set to zero when the concentrations are below 300 ppmv. We define an acute response as either unconsciousness, respiratory arrest, pulmonary edema, or death.

Table 4-7 reveals that none of the predicted concentrations were above 300 ppmv (i.e., 0.34 g/m^3) at stability E. Accordingly, all of the effect probabilities are zero. It should be pointed out, though, that if the receptor had been closer to the source, the

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* These values were based on the assumption that if the wind direction is within 22.5 degrees of a downwind receptor, the plume centerline impacts that receptor.

Table 4-7. Calculations of the risk of an acute effect at a receptor located 1.5 km downwind from the sour-gas well described in Example 4.

Stability category	$\chi u/Q$	u (m/sec)	Q (g/sec)	χ (g/m^3)	Effect probability E	Frequency of occurrence O	Health risk
E	1.65×10^{-4}	1.5	2669	0.29	0	0.0181	0
E	1.65×10^{-4}	2.46	2669	0.18	0	0.0058	0
E	1.65×10^{-4}	4.47	2669	0.10	0	0.0012	0
E	1.65×10^{-4}	6.93	2669	0.06	0	0	0
E	1.65×10^{-4}	9.61	2669	0.05	0	0	0
E	1.65×10^{-4}	12.52	2669	0.04	0	0	0
F	3.80×10^{-4}	1.5	2669	0.68	1	0.0961	0.0961
F	3.80×10^{-4}	2.46	2669	0.41	1	0.0043	0.0043
F	3.80×10^{-4}	4.47	2669	0.23	0	0	0
F	3.80×10^{-4}	6.93	2669	0.15	0	0	0
F	3.80×10^{-4}	9.61	2669	0.11	0	0	0
F	3.80×10^{-4}	12.52	2669	0.08	0	0	0
							Σ 0.1004

concentrations could have exceeded the 300 ppmv level under category E stability. For category F stability (i.e., the most stable atmospheric condition), concentrations of hydrogen sulfide were above the threshold level for wind speeds of 1.5 and 2.46 m/sec. Table 4-7 shows that a wind speed of 1.5 m/sec (representative of the first wind speed class) occurs simultaneously in the northwest downwind sector (i.e., winds from the southeast) with category F stability 9.6% of the time. The health risk is therefore calculated as the product of 1 x 0.096. We are assuming that an accidental release occurs randomly over the time frame of interest. Thus, the total risk is actually the sum of the effect probabilities (T in Eq. (4-17)) and the joint frequencies of the corresponding atmospheric stabilities and wind speeds (0 in Eq. (4-17)). The risk of an acute effect is calculated as 1 x 10^{-1}, assuming that an accidental release has occurred (i.e., $P_r = 1$), the hydrogen sulfide gas has been emitted to the atmosphere at the rate of 2669 g/sec, and the gas was discharged horizontally, and the receptor is on the plume centerline. These conditions essentially define a worst-case scenario of risk.

Now, if we set $P_r = 2.4 \times 10^{-3}$, which is the geometric mean of the blowout frequencies for samples of exploratory wells in Alberta, Canada and Texas (see Section 3), the risk of an acute effect at the receptor 1.5 km downwind during the drilling of the well becomes 2.4 x 10^{-4}. Table 4-8 presents the calculations of the health risk at the residence 2 km to the south of the well. A quick calculation using category E stability and a wind speed of 1.5 m/sec produced a concentration below 300 ppmv, and so category F stability alone was addressed. The cumulative health risk was 2.7 x 10^{-3}, assuming that P_r equals 1. With $P_r = 2.4 \times 10^{-3}$, the risk is 6.5 x 10^{-6}.

Both risk estimates assumed that a horizontal release occurred; in reality, the probability of this type of release is less than one (vertical, momentum-dominated releases could also occur). It is not possible to quantify accurately the likelihood of a horizontal release because of insufficient data on the nature of uncontrolled releases from gas wells. If vertical, momentum-dominated releases take place, our calculations show that acute health effects will not occur, and therefore the risk is zero. So, the risk of an acute health effect for the receptor 1.5 km away from the well ranges from 0 to 2.4 x 10^{-4}, and 0 to 6.5 x 10^{-6} for the other receptor (2 km downwind).

What is the significance of these risk levels? One way of answering that question is to compare them with other risks. According to data in Coppola and Hall, there are approximately 100,000 accidental deaths (e.g., caused by motor vehicle accidents, poisonings, falls, fires, etc.) in the U.S. each year.[62] This translates to an individual risk

Table 4-8. Calculations of the risk of an acute effect at a receptor located 2 km downwind from the sour-gas well described in Example 4.

Stability category	$\chi u/Q$	u (m/sec)	Q (g/sec)	χ (g/m^3)	Effect probability E	Frequency of occurrence O	Health risk
F	2.49×10^{-4}	1.5	2669	0.44	1	0.0032	0.0027
F	2.49×10^{-4}	2.46	2669	0.27	0	0.0007	0
F	2.49×10^{-4}	4.47	2669	0.15	0	0	0
F	2.49×10^{-4}	6.93	2669	0.10	0	0	0
F	2.49×10^{-4}	9.61	2669	0.07	0	0	0
F	2.49×10^{-4}	12.52	2669	0.05	0	0	0
						Σ	0.0027

of 5×10^{-4}/yr (i.e., 1×10^5 accidents divided by a population of 2×10^8). In contrast, accidental deaths caused by natural disasters are on the order of 7×10^{-6}/yr. So, if we accept the risk of death from a natural hazard as an acceptable baseline,* and if the modeling assumptions are correct, then the first receptor (1.5 km NW of well) is at excess risk, while the predicted risk at the other receptor is similar to the natural-hazard baseline.

ASSESSING THE HEALTH RISKS OF TRANSIENT RELEASES FROM SOUR-GAS WELLS AND PIPELINES

The release of gas after an inadvertent rupture of a sour-gas pipeline is controlled by block valves that are spaced along the pipeline. When a rupture occurs, the pressure-activated block valves on both sides of the ruptured portion of pipe close, causing an atmospheric discharge that decreases with time until the pressure within the pipe equals atmospheric pressure. Similarly, an accidental release of gas from a producing well will result in a transient discharge as safety valves close off the gas flow from the well. Gas released from such failures disperses in the form of an elongated puff or cloud. Previous assessments of the potential effects of pipeline ruptures have used different kinds of analytical and numerical models to simulate both the time-varying emission rate of gas and the subsequent dispersion.[63,64] Unfortunately, those models suffer from a lack of validation because few tracer studies have been completed (at least compared with similar studies for continuous gas releases).

Recently, Blewitt[65] and Berman _et_ _al._[66] have used models developed by Wilson[64,67,68] to analyze the potential effects of transient releases of sour gas from pipelines in western Wyoming. We will not duplicate their work here but rather will focus on a simplified screening procedure, based on an instantaneous puff model, that can be used by field personnel of BLM to assess the extent of a hazard zone around a pipeline used to gather gas from a well. The total mass in the puff is only a fraction of the total mass in the pipeline. This puff represents the most hazardous part of the release when, during the first 5 to 20 sec, the greatest emission rate leads to the highest downwind concentrations. The method of determining the mass for this "leading puff" is explained in some detail in Appendix B.

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* Although it is difficult to find risks that are truly comparable, the risk of death by a natural disaster is a useful baseline in this case, because it represents an involuntary risk with which most people are familiar.

The instantaneous puff model for calculating ground-level centerline concentrations for a release is[69]

$$\chi = \frac{2\ M}{(2\pi)^{1.5}\sigma_x\sigma_y\sigma_z}\left[\exp\frac{-0.5\ h^2}{\sigma_z^2}\right] , \tag{4-19}$$

where

χ = ambient concentration of gas, g/m^3,

M = total mass of the pollutant released in leading puff, g,

σ_x = standard deviation of concentration in the along-wind (x) plane, m,

σ_y = standard deviation of concentration in the cross-wind (y) plane, m, and

σ_z = standard deviation of concentration in the vertical (z) plane, m.

The values of σ_y and σ_z for different downwind distances and atmospheric stabilities are estimated by Eqs. (4-13) and (4-14). The value of σ_x (for a near-surface release) is calculated from Wilson[68] as

$$\sigma_x = \left[0.09\left(\frac{nx}{z_r}\left(\frac{z_r}{z_c}\right)^n\right)^2 + \frac{\sigma_{xt}^2}{\sigma_z^2}\right]^{0.5} \sigma_z \quad , \tag{4-20}$$

with z_r, z_c, and σ_{xt} defined as

$$z_r = h + 0.484\,\sigma_z , \tag{4-21}$$

$$z_c = h + 0.165\,\sigma_z , \tag{4-22}$$

$$\sigma_{xt}^2 = 6\,\sigma_z^2 \text{ (for unstable and neutral atmospheric conditions), and} \tag{4-23}$$

$$\sigma_{xt}^2 = 10\,\sigma_z^2 \text{ (for stable atmospheric conditions),} \tag{4-24}$$

where

n = exponent of the power law for the wind velocity profile, real number,

h = effective height of the source, m,

x = downwind distance from the source, m,

z_r = reference height for effective wind shear, m,
z_c = convection height, m, and
σ_{xt} = component of σ_x caused by turbulence, m.

The values of n for different stability classes are found in Table 4-9. The calculated value of χ represents an average concentration over a period of approximately 10 min. To compute the concentration for a shorter period of time (e.g., 3 min) to assess the potential health effect of exposure to a puff release, we multiplied the value of σ_y by 0.8, according to a procedure suggested by Gifford[70] and reported by Hanna et al.[60] Because the exposure period for an instantaneous puff release would be much shorter (a few minutes) than the exposure to a continuous source, we have set the threshold of effects concentration at 500 ppmv. This value is the same as that used by Whittaker et al.[71] in an analysis of the health risks of sour-gas pipelines.

The total quantity of hydrogen sulfide released in the leading puff after a pipeline rupture, M, can be calculated from this formula (described in more detail in Appendix B):

$$M = \frac{F\beta K\dot{m}_o}{1+\alpha}\left(\alpha^2[1 - \exp(-t_1/\alpha^2\beta)] + \alpha[1 - \exp(-t_1/\beta)]\right) \quad . \tag{4-25}$$

where

$\dot{m}_o$ = initial isentropic release rate, kg/sec,
K = overburden resistance factor, (0.9), dimensionless,
α = mass conservation factor, dimensionless,
β = isothermal flow time constant, sec,
t_1 = time after rupture defining end of puff, (10 sec), and
F = weight fraction of H_2S in pipeline gas.

To illustrate the use of this procedure, we present the following example.

Table 4-9. Values of n for different stability classes.[60]

	Stability class					
	A	B	C	D	E	F
Urban	0.15	0.15	0.20	0.25	0.40	0.60
Rural	0.07	0.07	0.10	0.15	0.35	0.55

Example 5 A pipeline that is one mile long with an interior diameter of 4 in. collects sour gas, containing 15% by volume hydrogen sulfide, from a well. The pipeline operates under a line pressure of 1200 psi and carries sour gas with a molecular weight of 25, a temperature of 104°F, and a compressiblity factor of 0.8. Calculate the concentrations of hydrogen sulfide at distances of 500, 1000, 1500, and 2000 m from a completely severed pipe for a surface-level release with no initial dispersion. Analyze the extent of the hazard zone, under Pasquill-Gifford stability category F. In addition, calculate the downwind concentrations at the same distances for an elevated source of 10 m, with initial values of σ_x, σ_y, and σ_z equal to 10 m.

First, the mass of the hydrogen sulfide in grams must be calculated using Eq. (4-25). The value of F is computed from the hydrogen sulfide concentration and the molecular weight of gas.

$$F = \frac{0.15 \text{ mol } H_2S}{\text{mol gas}} \cdot \frac{34\text{g } H_2S}{\text{mol } H_2S} \cdot \frac{\text{mol gas}}{25\text{g gas}} = 0.20 \quad . \tag{4-26}$$

The pressure in N/m^2 is

$$P = \frac{1200 \text{ psi}}{1} \cdot \frac{6.89 \times 10^3 \text{N}}{\text{m}^2 - \text{psi}} = 8.27 \times 10^6 \frac{\text{N}}{\text{m}^2} \quad . \tag{4-27}$$

The cross-sectional area is equal to πr^2, where $r = 0.051$m (i.e., 4 in./2 • 2.54 cm/in. • m/100 cm) and so A equals 0.008 m^2. The length of the pipeline is 5280 ft • m/3.28 ft or 1610 m. The gas temperature is 104°F, which is 40°C or 313°K.

The gas constant R is calculated from the universal gas constant and the molecular weight of the gas as follows:

$$R = 8.31 \frac{\text{N - m}}{\text{mol °K}} \cdot \frac{\text{mol gas}}{25 \text{ g gas}} = 0.332 \frac{\text{N - m}}{\text{g-°K}} \quad . \tag{4-28}$$

Referring to Eqs. (B-5) to (B-9) in Appendix B, the following values are obtained. The initial isentropic release rate is

$$\dot{m}_o = 8.27 \times 10^6 \frac{\text{N}}{\text{m}^2} \cdot \frac{10^3\text{g-m}}{\text{N-sec}^2} \cdot \frac{0.008 \text{ m}^2}{0.8}$$

$$\cdot \left(\frac{\text{g-°K}}{0.332 \text{ N - m}} \cdot \frac{\text{N-sec}^2}{10^3\text{g-m}} \cdot \frac{1}{313\text{°K}} \right)^{0.5} \cdot 0.671$$

$$= 1.72 \times 10^5 \text{g/sec} \quad . \tag{4-29}$$

The initial mass in the pipeline is calculated as

$$W = \frac{(8.27 \times 10^6)(0.008)(1610)}{(0.332)(313)(0.8)} = 1.28 \times 10^6 g \quad . \qquad (4\text{-}30)$$

The speed of sound in the pipeline is

$$C = \left[(1.32)(0.332)\ \frac{N\text{-}m}{g\text{-}°K} \cdot \frac{10^3 g\text{-}m}{N\text{-}sec^2} \cdot 313°K\right]^{1/2} = 370\ m/sec \quad . \qquad (4\text{-}31)$$

The isothermal flow time constant is

$$\beta = \frac{1610}{370}\ \frac{2}{3}\left(\frac{1.32 \cdot 0.013 \cdot 1610}{0.102}\right)^{0.5} = 47.7\ sec \quad . \qquad (4\text{-}32)$$

The mass conservation factor is then

$$\alpha = \frac{1.28 \times 10^6}{47.7 \cdot 0.9 \cdot 1.72 \times 10^5} = 0.173 \quad . \qquad (4\text{-}33)$$

Thus, the total mass in the leading puff (for t_1 = 10 sec) is

$$M = \frac{0.20 \cdot 47.7 \cdot 0.9 \cdot 1.72 \times 10^5}{1.17}\ [(0.031 \cdot 0.999) + (0.177 \cdot 0.189)] \qquad (4\text{-}34)$$

$$= 8.04 \times 10^4 \text{ g of hydrogen sulfide} \quad .$$

Table 4-10 contains the results of the calculations for the four downwind concentrations produced by the surface-level release described in Example 5. The maximum downwind concentration at 300 m for an effective puff height of zero and no initial cloud dispersion is 885 ppmv. With an initial rise of 10 m and $\sigma_x = \sigma_y = \sigma_z$ = 10 m (see Table 4-11), the concentration at that distance is 609 ppmv or 31% lower than the concentration resulting from the surface-level release. However, at 600 m the concentration for the elevated release with initial dispersion is about the same as that for the surface release. Since these two release scenarios bracket the conditions for worst-case releases, the danger zone for 500 ppmv extends to about 350 m downwind of the release point. Clearly the worst-case scenario is for a horizontal release so that the effective plume height is minimized. If the rupture occurred in the top of the pipe, the vertical discharge and subsequent plume rise would result in substantially lower downwind concentrations.

Table 4-10. Calculations of χ, σ_x, σ_y, and σ_z for four downwind distances after an instantaneous puff release of 8.04 x 10^4 g of hydrogen sulfide at the ground surface under category F stability (Example 5 in text).

Distance (m)	σ_x (m)	σ_y (m)	σ_z (m)	χ ppmv	χ g/m^3
300	186	9	6	885	0.988
400	248	12	7	429	0.479
500	309	14	8	245	0.273
600	371	17	9	155	0.173

Table 4-11. Calculations of χ, σ_x, σ_y, and σ_z for four downwind distances after an instantaneous puff release of 8.04 x 10^4 g of hydrogen sulfide under category F stability with an effective height of 10 m and initial values of σ_x, σ_y, σ_z equal to 10 m (Example 5 in text).*

Distance (m)	σ_x (m)	σ_y (m)	σ_z (m)	χ ppmv	χ g/m^3
300	66	13	12	609	0.680
400	98	15	12	354	0.395
500	132	18	13	226	0.252
600	168	20	14	154	0.172

* If initial dispersion is considered, the downwind standard deviations for concentration are calculated as the square root of the sum of the variances for initial dispersion and those calculated from Eqs. (4-13), (4-14), and (4-20) (e.g., $\sigma_z = [\sigma_z^2 \text{ (Eq. (4-14))} + \sigma_z^2 \text{ initial value}]^{1/2}$).

5. ASSESSING THE HEALTH RISKS OF SOUR-GAS FACILITIES: APPLICATIONS TO DEVELOPMENT NEAR EVANSTON, WYOMING

In earlier sections we examined a number of different topics related to the assessment of the potential health risks of sour-gas facilities, including the evaluation of health effects, calculation of gaseous emissions, estimation of atmospheric dispersion, and finally, quantification of health risks. In this section we will apply the assessment techniques discussed previously to sour-gas development near Evanston, Wyoming. At the present time there are six sour-gas wells situated on the outskirts of Evanston (see Fig. 5-1). A pipeline gathering system is planned to transport gas from the wells to a gas purification plant located about 15 mi to the northeast of the town.[72]

The primary focus here will be on the assessment of the potential health risks associated with the one well that is under BLM jurisdiction. We will also demonstrate a methodology for assessing the health risks of future wells in the area that may need federally mandated environmental analyses. A primary input to our assessment of the health risks of the sour-gas facilities is data we collected from meteorological stations we installed near Evanston. Accordingly, this section begins with a discussion of the meteorological network and the data that were collected.

METEOROLOGICAL DATA FOR EVANSTON, WYOMING

We established four meteorological stations in and around Evanston during December 1981, with the objective of collecting a year's worth of measurements on wind speed, wind direction, and air temperature to characterize the dispersion meteorology of the area. The meteorological stations, shown in Fig. 5-1, were designated as Carpenter (6790 ft (2070 m) above mean sea level (MSL)), Disposal (6690 ft (2040 m) above MSL), Airport (6595 ft (2011 m) above MSL), and Hill (7160 ft (2183 m) above MSL). Measurements were made of wind speed, wind direction, and temperature at 13.1 ft (4 m) and the air temperature difference between 13.1 and 1.6 ft (4 and 0.5 m). At the Disposal station we made additional measurements of wind speed and direction at 32.8 (10 m), standard deviation of wind direction at 32.8 ft and 13.1 ft (10 and 4 m), plus redundant measurements of the air temperature difference between 1.6 and 13.1 ft (0.5 and 4 m). Data were recorded at eight-minute intervals onto cassettes, which were sent to Lawrence Livermore National Laboratory every two weeks for data editing and storage in a computerized data base.

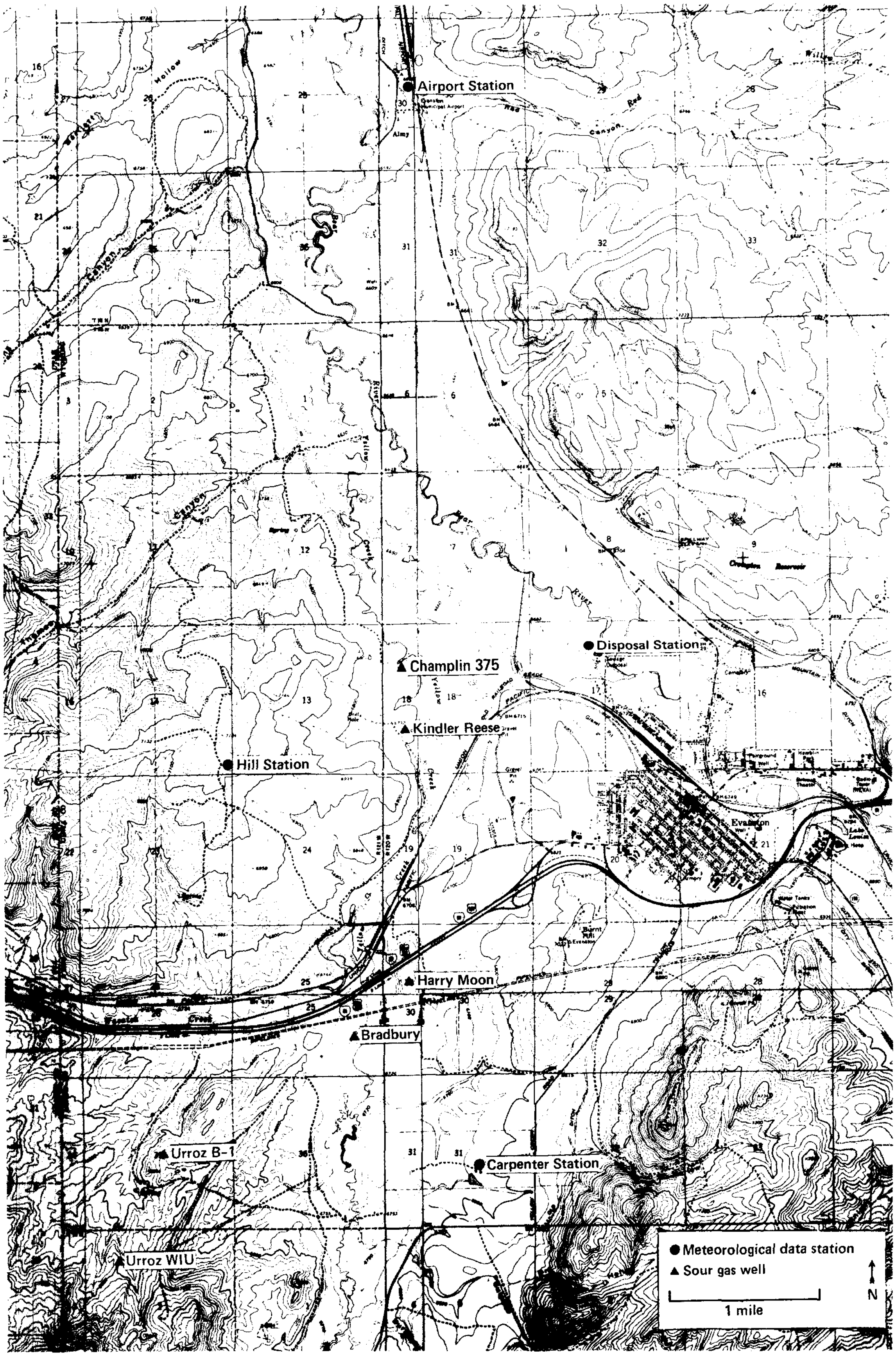

Figure 5-1. Locations of sour-gas wells and meteorological stations near Evanston, Wyoming.

There is a number of schemes for estimating the dispersion coefficients σ_y and σ_z. Since we were making actual meteorological measurements where the risk assessment methodology was to be applied (i.e., Evanston, Wyoming), we employed an approach that was suited to the kinds of measurements we were making. In our approach we calculated a Richardson number (RI)* from the meteorological data we collected and then related that variable to one of seven Pasquill-Gifford stability categories according to a procedure proposed by Golder.[73] Weber et al. compared Gaussian model predictions with field data for near-surface, ground-level releases over flat terrain and found that the determination of Pasquill-Gifford categories by use of RI gave better agreement than other meteorological parameters.[74] Appendix C contains details on the relationship between RI values and stability categories used in this analysis.

For purposes of the risk assessment, we prepared a composite set of meteorological data that is representative of the meteorology along the valley floor. Hourly data for the composite station were normally computed as the average of the Airport and Disposal stations; however, if hourly data were missing from one or the other of those stations, we used the data directly from the operating station. In instances when neither of those stations was operating, we used data from the Carpenter station, which were adjusted for known differences from average conditions at Airport and Disposal. When none of those stations was operating (less than 1% of the time), we left the data blank. The resulting hourly data file representing 8290 h was processed to produce a joint probability matrix of wind speed, wind direction, and atmospheric stability. Joint frequency distributions were calculated for 16 wind directions, 6 wind speed classes, and 7 Pasquill-Gifford stability classes. Appendix C contains a tabulation of the joint frequencies for the composite station (see Shinn and Cederwall for details regarding the meteorological measurements and calculations[75]). Also included in Appendix C are wind roses for each stability class. These wind roses graphically demonstrate the predominance of low speed flow from the southeast under stable conditions and high speed flows from the west and southwest under neutral and slightly unstable conditions.

HEALTH RISKS FOR THE URROZ WIU #1 WELL

The Urroz WIU #1 (see Figure 5-1) is presently shut in awaiting the completion of the necessary gas pipelines that will transport its gas, along with the gas from other wells, to the Whitney Canyon gas purification facility.[72] The primary source of health risk from

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* A stability parameter that incorporates terms describing both mechanical and buoyant components of atmospheric turbulence.

this well is an inadvertent release of sour gas over its productive life. The nature and magnitude of the health risks depend on the characteristics of a release (e.g., emission rate and rise of gas plume) together with probabilistic data regarding meteorological conditions and the likelihood of a specific type of release (e.g., a continuous, horizontal release) during the years of production. To establish an upper-bound estimate of the potential health risks associated with the production phase of the well, we analyzed the risks of acute effects for a horizontal release of sour gas with gas concentrations calculated along the plume centerline. We further assumed that there is an equal probability that the plume centerline will impact any receptor along a 22.5° arc within a downwind sector. This approach is conservative as the stability F plume is narrower than the width of the 22.5° sectors, and consequently receptors off of the centerline will have lower concentrations.

We employed the computerized methodology depicted in Fig. 5-2 to estimate the potential risks. This methodology requires, as input, data on the joint frequency of occurrence of wind speeds and atmospheric stabilities for the downwind locations for which risk is being estimated. These data are presented in Appendix C. In addition, estimates are required of the emission rate, release height, and the probability of an effect for a predicted ground-level concentration. Our analyses were based on a worst-case release scenario in which sour gas is continuously discharged from the wellhead to the atmosphere in a horizontal direction. In addition, we assume that the discharged gas does not ignite. We believe that this is a worst-case scenario because the typical operation of the surface safety valves along with the subsurface valve at the well would normally result in a transient release of gas as the valves close in response to the loss of line pressure. The discharge rate of sour gas at the surface was set equal to the calculated flow through the production tubing against atmospheric pressure at the surface. According to estimates provided by staff of Amoco, the flow rate of sour gas in this case would be 32.5×10^6 scf/d (9.2×10^5 m^3/d).[76] The mass discharge rate of hydrogen sulfide was estimated at 4.7 lb/sec (2150 g/sec), based on a concentration of 14% by volume in the sour gas. We calculated the values of χ/Q (see Fig. 5-2) for an effective release height of 5 m.

To facilitate our analysis of this particular case, we have estimated the health risks at downwind locations around the Urroz WIU #1 well for a release that occurs randomly over the life of the well with the assumed characteristics of release rate and plume height.

Figure 5-3 depicts the spatial distribution of risk around the Urroz WIU #1 well for the assumed set of conditions. Each isopleth represents the probability of incurring an

	Computational steps	Input
A.	Compute values of χ/Q for 42 combinations of wind speed and atmospheric stability.	Meteorological and source parameters
B.	Multiply each χ/Q value by the Q for the well being assessed.	
C.	Calculate the probability of incurring an acute or subacute health effect for each of the 42 values of χ.	Dose-response function
D.	Multiply each of the health effect probabilities by the appropriate joint probability of wind speed and atmospheric stability in the wind sector of interest.	Joint probability matrix of wind speed, atmospheric stability, and wind direction
E.	Compute the health risk as the product of the probability of a release and the sum of the 42 health effect probabilities calculated in D.	Data on the frequency of well releases

Figure 5-2. Procedure for calculating the health risk at a single receptor downwind from an accidental release of hydrogen sulfide. Here, χ/Q is the concentration normalized by the unit emission rate.

acute health effect if an accidental, horizontal release were actually to occur during the production period (i.e., P_r equals one in Eq. (4-16)). According to our analyses in Section 3, we estimate that P_r for a producing well is approximately 3×10^{-3} over a 20-yr period (calculated from the geometric mean of the release rates for producing wells in Alberta, Canada and Texas). If each of the isopleths in Fig. 5-3 is multiplied by this value, then the isopleths of risk range from about 3×10^{-4} to 3×10^{-5}. The frequency of accidental releases from wells in Alberta was calculated as 3.6×10^{-4}/well-yr, or

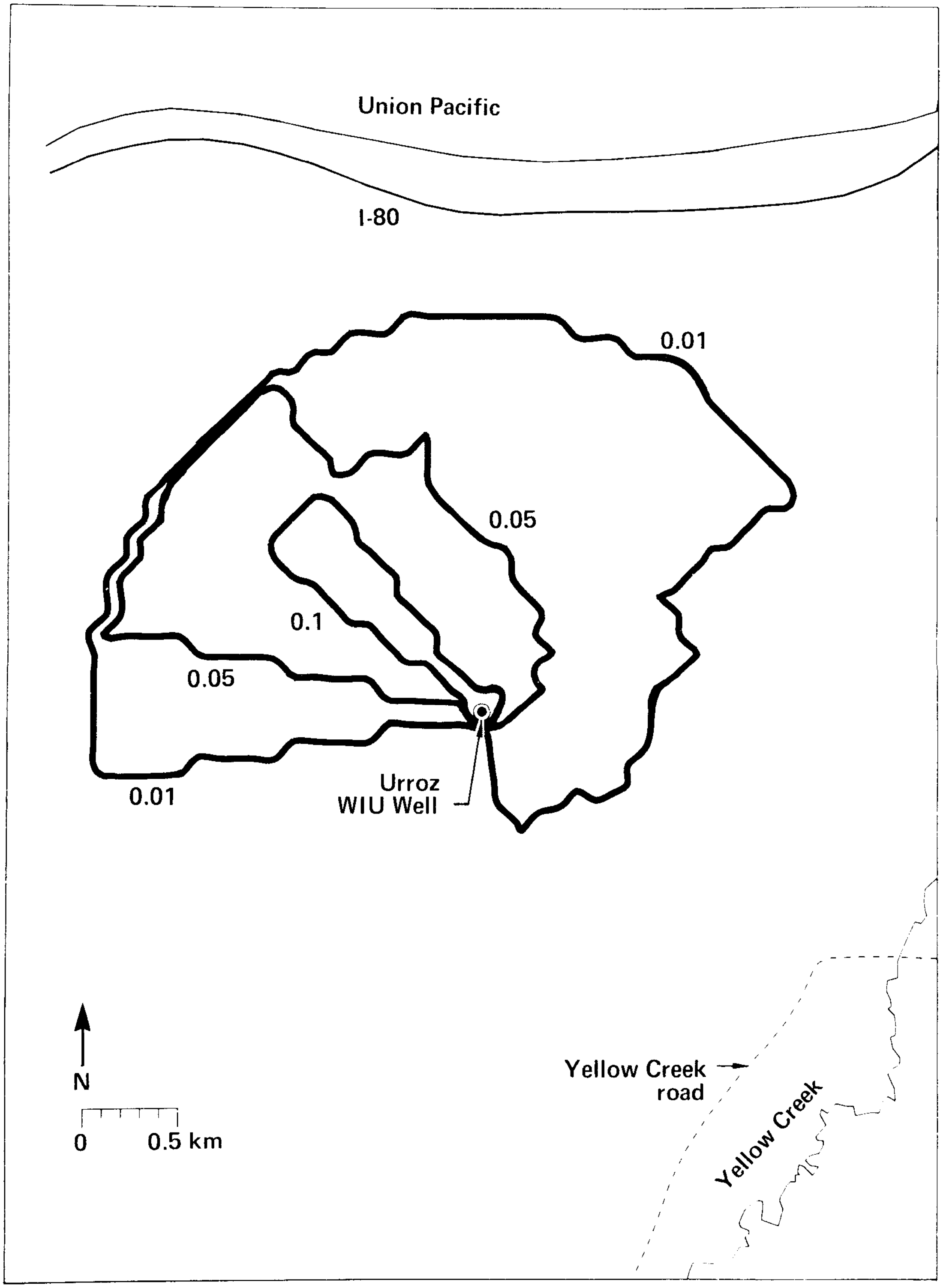

Figure 5-3. Upper-bound estimates of the risk of incurring acute health effects (i.e., unconsciousness, respiratory arrest, pulmonary edema, or death) if an accidental, uncontrolled release of sour gas from the Urroz WIU No. 1 well occurred over the period of a year. A horizontal release is assumed. To estimate the actual risks, each of the isopleths must be multiplied by the probability of an accidental release (e.g., 0.001).

7.2×10^{-3} for 20 yr. With that estimate of P_r, the risk isopleths range from 7.2×10^{-4} to 7.2×10^{-5}. The lower-bound estimate of risk for each of these cases is zero, because a vertical release of gas into the atmosphere would not cause acute health effects.

Because the Urroz WIU #1 is on the outskirts of Evanston where future population growth could occur, an important question is how can the potential risks of well operation be managed? There are basically two methods of managing risks, and they can be employed jointly or separately. The first method is to minimize the likelihood of an accidental release. Our analysis in Section 3 showed that 35% of the accidental releases from a sample of wells in Alberta, Canada were due to problems encountered during well servicing, 30% were caused by external damage, while miscellaneous equipment failures accounted for the rest. Therefore, to minimize the likelihood of a hazardous or harmful release from the Urroz well, well servicing (including reentry for downhole work) should be done under strict safety standards and protocols. If it is ever necessary to reenter the well, then work should proceed under an updated contingency plan. To reduce the possibility of external damage caused by tractors, trucks, etc., access to the wellsite should be restricted by fences, gates, etc. The second method of managing risk is to limit the potential population exposure from an inadvertent release. In this case, residential development would be restricted from the northwest sector downwind from the well since this is the area that is at excess risk for the conservative release case that we have previously described. Land-use zoning is one method of limiting such development.[77]

If we use the risk of death from natural hazards ($\sim 1 \times 10^{-4}$ over 20 yr) as a reasonable baseline of comparison (or acceptability), then only the northwest sector around the well would be at excess risk. This sector is at risk (under our conservative release scenario) due to the relatively high frequency of elevated concentrations of hydrogen sulfide (i.e., >300 ppmv) associated with stable atmospheric conditions that take place simultaneously with low winds out of the southeast. The hazard zone in the northwest sector extends to a maximum distance of about 2 km, which is consistent with the radius of exposure predicted in Fig. 4-2.

ASSESSING THE HEALTH RISKS OF FUTURE WELLS

In the future other exploratory sour-gas wells could be drilled in the Evanston area on lands under the jurisdiction of BLM. To assist in the preliminary safety analyses of the potential health risks of future wells, we have prepared upper-bound estimates of the risks of acute health effects resulting from the assumed release of 2669 g/sec of hydrogen sulfide at sour-gas wells located at an elevation of 6000 ft MSL. This emission rate represents a value that is unlikely to be exceeded, based on our previous analyses of gas flow rates and hydrogen sulfide concentrations associated with natural gas wells located in the Overthrust Belt (see Section 3). Figures 5-4 and 5-5 are plots of the risks of acute health effects versus downwind distances in four wind sectors (i.e., Fig. 5-4 includes the N, NE, E, and SE downwind sectors, while Fig. 5-5 includes the NW, W, S, and SW sectors). These risks are based on the assumption that a release has actually occurred (i.e., $P_r = 1$). Therefore, each curve must be multiplied by the probability of a release during the particular phase of drilling that is being assessed (for the purposes of the risk analyses we assume that the annual joint probabilities of wind speed, atmospheric stability, and direction are indicative of the average conditions associated with either drilling or production). For example, according to our analyses in Section 3, the probability of a blowout during drilling is approximately 1×10^{-3}. If the curves in Fig. 5-4 are multiplied by this value, only locations in the immediate vicinity of the well would have risks exceeding 10^{-4}. In Fig. 5-5, however, the NW downwind sector is at excess risk because of the joint occurrence of stable atmospheric conditions and low wind speeds from the southeast. The curves are truncated at a distance of about 2.3 km because this is the maximum distance to the threshold concentration (i.e., 300 ppmv) for acute effects, as predicted by the Gaussian dispersion equation for the assumed emission rate and effective release height of gas. This distance is also predicted in Fig. 4-2, which presents curves defining the maximum distance to the 300 ppmv concentration of hydrogen sulfide.

To interpret the risk curves in Figs. 5-4 and 5-5 correctly, it should be recognized that they represent upper-bound estimates for the following reasons: (1) an accidental blowout could result in a vertical release of gas, resulting in ground-level concentrations of hydrogen sulfide that are not above 300 ppmv in situations where provisions have been made to ignite the escaping gas (e.g., as specified in contingency plans for drilling), (2) the combusted gas will not cause acute effects, and (3) the operation of safety valves on the well will produce a transient release of gas rather than a continuous one. We should also point out that Figs. 5-4 and 5-5 should only be used for well locations near the Bear River and Yellow Creek Valleys. The further a well is from these areas, the lower the reliability of the risk estimates due primarily to changing wind fields.

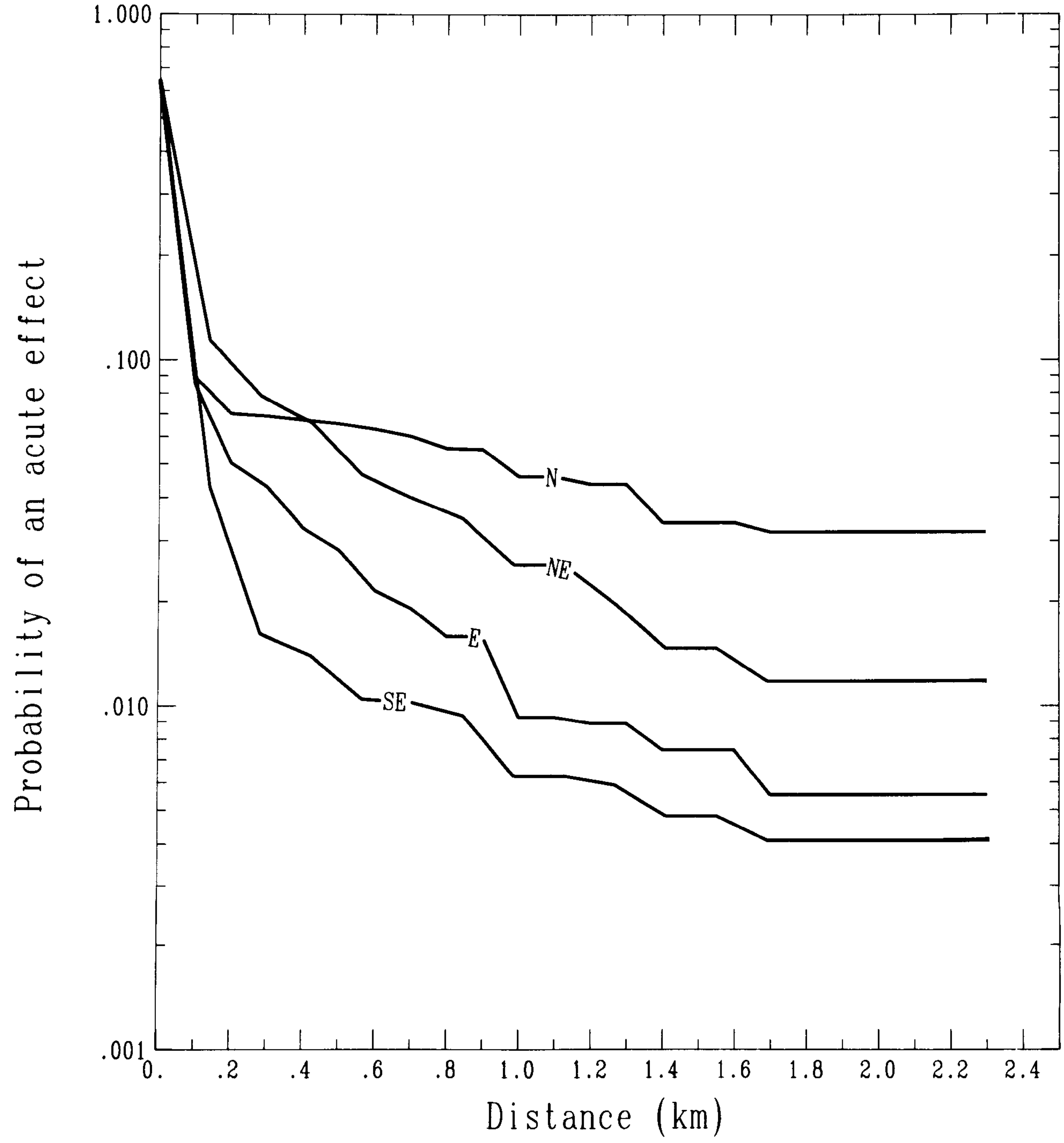

Figure 5-4. Upper-bound estimates of the risk of incurring acute health effects if an accidental, uncontrolled release of sour gas occurred during the drilling of an exploratory well in the vicinity of Evanston, Wyoming. To estimate the actual risks in the four downwind sectors, (i.e., the N, NE, E, and SE sectors) each curve must be multiplied by the probability of an accidental release.

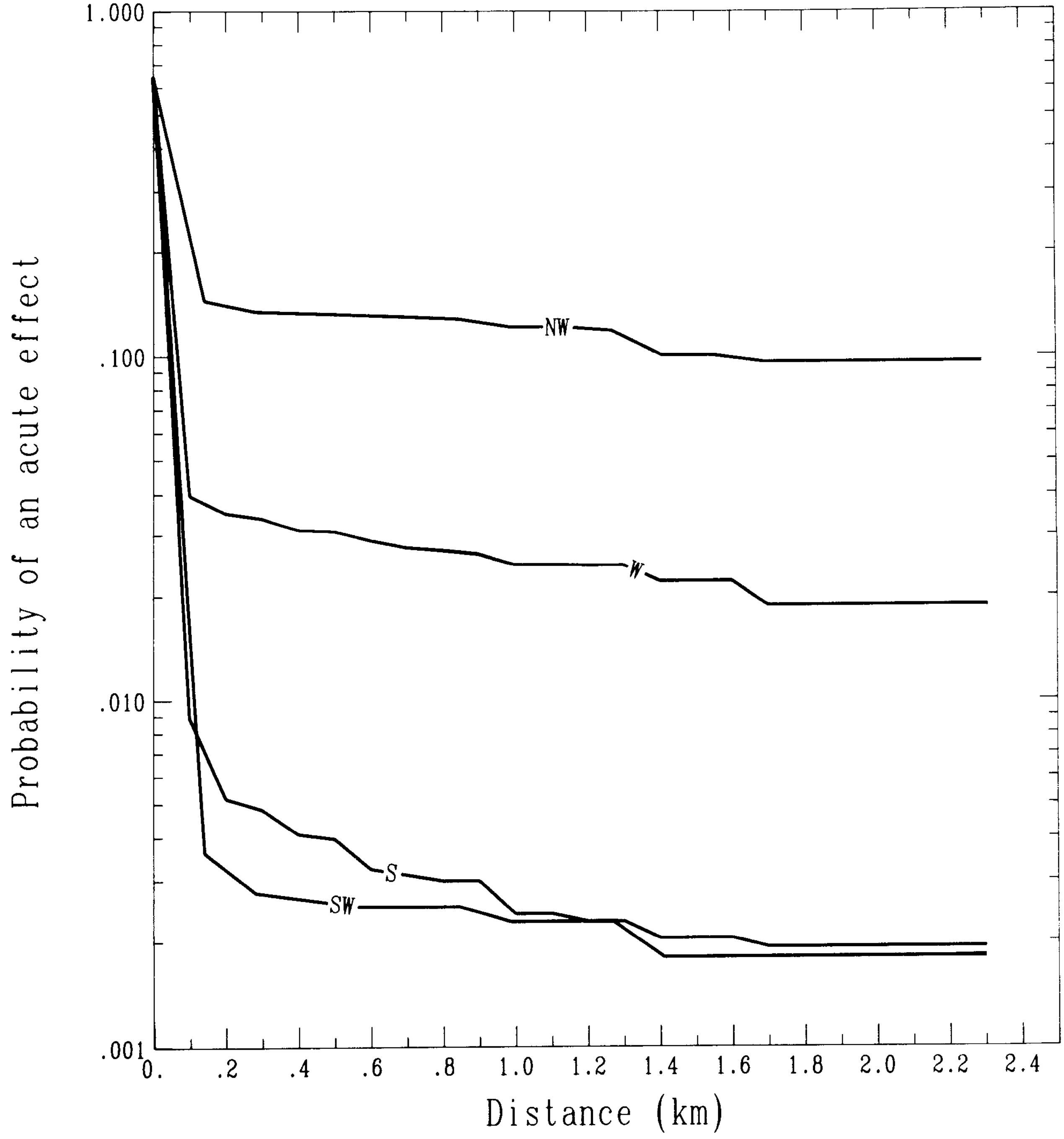

Figure 5-5. Upper-bound estimates of the risks of incurring acute health effects if an accidental, uncontrolled release of sour gas occurred during the drilling of an exploratory well in the vicinity of Evanston, Wyoming. To estimate the actual risks in the four downwind sectors (i.e., the NW, W, S, and SW sectors), each curve must be multiplied by the probability of an accidental release.

6. OVERVIEW OF SAFETY TECHNOLOGIES AND CONTINGENCY ACTIONS RELATED TO SOUR-GAS OPERATIONS

The safe drilling and completion of a well into formations that contain sour gases begins with the preparation of a well design or plan that incorporates the necessary safety features for both subsurface and surface equipment. Complementing that plan are procedures for checking the quality of equipment and materials. When drilling has commenced, safety systems and sound drilling practices represent the "first line" of protection against the uncontrolled flow of reservoir gases into a well and any subsequent release of those gases to the atmosphere. Predefined contingency plans that are carried out in the event of a blowout are meant to minimize dangers to workers and local residents. In the production phase of wellfield development public health protection again lies with careful facility planning and the implementation of the appropriate safety systems as well as maintenance and monitoring programs. Zoning of land near sour-gas facilities should be considered a safety measure insofar as it would limit potential population exposures to any accidental releases of sour gas that might occur over the life of such facilities. The following discussions provide an overview of safety-related technologies and procedures available during drilling and production phases of wellfield development, with an emphasis on those measures that relate to the protection of public health.

DRILLING PRACTICES AND TECHNOLOGIES

Although drilling is usually perceived as the "riskiest" phase of well development, our analyses of the frequencies of uncontrolled releases of gas from wells indicate that the likelihood of an inadvertent release from a producing well over a 20-yr period is similar to the probability of a release during the time it was being drilled. The drilling phase seems riskier because the probability of an inadvertent release is greater per unit of time. The likelihood that an accidental release will occur during either drilling or production can be reduced by utilizing safety measures, technologies, and designs that address the potential causes of such releases. During drilling the most important safety measures and technologies involve the control of reservoir fluids, the prevention of corrosion problems, and the removal of hydrogen sulfide from drilling fluids in the event of a gas kick.

Prevention, Detection, and Control of Kicks

To ensure that formation gases do not enter the well, the proper amount and density of drilling mud must be maintained in the well during drilling and during trips. When pipe is being removed from the well, mud is added to compensate for the volume of the extracted pipe. If gas should enter the wellbore during the trip and displace mud, it will not be possible to add the full volume of mud required, indicating a kick. Conversely, when inserting drill pipe, mud will be displaced to the surface mud tanks, and if more mud is discharged than can be accounted for by the drill string, formation gases are probably entering the well. The detection of kicks requires the careful and constant monitoring of mud in the circulating system, comparing, for example, the volume of mud added to a well hole during the removal of a drill string with the calculated displacement volume to see if there are any significant discrepancies that could indicate a kick. The detection of kicks is aided by using trip tanks, flow indicators, and pit volume monitors.[78] Aside from the measurement of volumetric changes in mud, the content of hydrogen sulfide (liberated from the reaction of acid with metal sulfides) in mud can be monitored as well to provide additional data on a kick.[79] Kick prevention basically involves keeping the appropriate amount and density of mud in the well to balance formation pressures during drilling, tripping, and when the drill string is completely out of the hole.

Once a kick is detected, the drill crew must immediately initiate remedial actions, which will vary according to the status of the well operations (e.g., drilling or tripping). In most situations the well is quickly closed in by sealing the well with one or more blowout preventers (BOPs). The preventers consist of individual mechanical rams plus an annular preventer, all of which are part of an assembly of chokes and valves attached to the wellhead. The rams either close around a pipe (i.e., a pipe ram), thereby sealing the annulus, shut off the drill hole without pipe present (i.e., a blind ram), or sever the pipe in the hole (i.e., shear ram). The annular preventer hydraulically expands a flexible gasket to close around the pipe or to completely seal an open hole (for more detail see Adams[80]). Once the well is shut in, fluid flow from the well is routed through a choke line, which controls the flow of well fluids, to a degassifier, which separates the formation gas from the mud. Separated gas is then burned by a flare. Drilling mud is injected into the well via kill lines or through the drill pipe to replace discharged fluids. More comprehensive discussions of various well-killing procedures and well-control equipment are found in Goins[39] and Adams *et al.*[81]

A kick can turn into a blowout because of mechanical failures, human error, or a combination of the two. Blowout preventers may fail to operate properly, with the result that mud and gas are discharged from the well along with the drill string if it is in the hole. And even when the preventers are correctly engaged, there is always the possibility that excessive pressures may cause the failure of some other component of the blowout preventer stack or well casing. Human error, in the form of slow responses to the situation, incorrect decisions, or panic, can also be part of the events leading to a blowout. These potential problems are minimized, though, through well planning, quality control of installed equipment, testing of blowout preventers, and emergency response drills. During the planning of a sour-gas well, equipment and piping are specified that can withstand the effects of the pressures and gases that could be encountered under various drilling conditions. Quality control of equipment together with pressure testing of BOPs and other valves and lines are recognized as an integral part of sour-gas drilling.[7,82] Regularly scheduled drills on the use of BOPs are necessary to ensure that drilling crews are ready to respond to various well-control difficulties.[39]

Sour Gas and Corrosion

Natural gas containing hydrogen sulfide can have a corrosive effect on some steel alloys. This type of corrosion is generally referred to as stress corrosion cracking (SCC), which is a form of hydrogen embrittlement.[83] Hydrogen embrittlement takes place when hydrogen is absorbed into a metal, causing a blistering in the metal that gradually intensifies as hydrogen diffuses into the stressed zone. If allowed to continue, the embrittlement will cause the metal to fail. The way in which the hydrogen sulfide induces corrosion cracking is not fully known, but according to one idea, the presence of sulfide ions is believed to enhance the movement of hydrogen into metal.[84] Corrosion cracking can be controlled by chemically altering the composition of the fluids that come in contact with susceptible metals or by using metals that resist this type of corrosion.[82] Generally, the harder the metal alloy the more susceptible it is to SCC. Accordingly, softer metals are prescribed for use with sour gas and, in general, steels with a Rockwell hardness of 22 have been acceptable in drilling operations. The National Association of Corrosion Engineers (NACE) has prepared guidelines for selecting materials suitable for sour-gas service.[83]

Removal of Hydrogen Sulfide in Drilling Muds

Two problems associated with the presence of sour gas in drilling mud are the effect of hydrogen sulfide on equipment, as previously discussed, and the possible emission of the gas to the atmosphere. Both of these problems can be dealt with by chemically conditioning the mud. The basic method of controlling hydrogen sulfide has been to maintain the pH of the circulating mud above 9, causing the dissociation of the hydrogen sulfide to less corrosive sulfide and bisulfide ions.[85] A further step of conditioning involves the introduction of chemicals that react with the sulfide ions to produce precipitates. Copper, zinc, and iron compounds have been used as additives to form metal sulfides.[85] The effectiveness of such additives in scavenging hydrogen sulfide was demonstrated during a gas kick in a well that was being drilled into the Phosphoria formation.[86] A drilling break had induced a substantial inflow of sour gas to the well hole, however, the introduction of an iron oxide scavenger allowed conversion of the hydrogen sulfide to iron sulfide with the result that no measurable amounts of that toxic gas were released into the atmosphere via the mud circulation system. In addition, the drilling equipment was not exposed to harmful quantities of the gas.

SAFETY PLANS AND EMERGENCY RESPONSES FOR DRILLING

Safety plans prepared prior to the drilling of a sour-gas well should address items such as the layout of the drilling and ancillary equipment, onsite procedures and equipment needed to respond to different kinds of emergency situations, training of drill crews, testing of equipment, and importantly, actions needed to protect local residents in the event of an accidental release. Table 6-1 summarizes the topics normally included in safety plans, and described in greater detail by Goins,[39] Hamby and Smith,[6] and API.[7] Those topics are also the subject of short courses offered by different companies. From a public health standpoint, the critical actions that need to be followed in the event of an uncontrolled release include the notification and evacuation of residents, ignition of the well, plus post-release monitoring and site security.

Notification and Evacuation of Local Residents

A contingency plan should contain specific guidelines and protocols for deciding when to alert local residents and emergency services personnel of a hazardous or potentially hazardous situation, what action those individuals need to take, and how to communicate that information effectively. The decision on when to notify residents

Table 6-1. Summary of the items normally addressed in safety plans for sour gas wells.

Onsite safety measures	Safety equipment and quality control	Drill crew training	Equipment testing	Public safety
- Layout of drill rig and ancillary equipment - Identification of escape routes for different wind directions - Location of safety facilities - Procedures for dealing with well control problems - Chemical scavengers to remove hydrogen sulfide in drilling mud - Special precautions for drill stem tests and coring	- Hydrogen sulfide detectors and alarms - Windsocks for determining wind direction - Warning flags and signs - Communications - Blowout preventers; specifications and quality control - Resuscitators/breathing devices - First aid kits - Mud degasser and flare system	- Use of blowout preventers - Kick control procedures - First aid - Rescue techniques - Escape routes	- Testing of blowout preventers - Testing hydrogen sulfide sensors and alarms - Maintenance of rescue equipment - Materials specification, e.g., hardness	- Notification and evacuation of residents - Well ignition - Post-release monitoring - Site security

regarding a necessary response on their part is dictated by the status of the well (e.g., uncontrolled flow of gas to the atmosphere, gas flaring, critical control problems, etc.), the proximity and size of the population at risk, and the estimated emissions of hydrogen sulfide.

The benefit of including protocols regarding the notification and evacuation of nearby residents was demonstrated during the completion of a sour-gas well in Mississippi several years ago. According to the account given by Bruist,[87] pipe was being removed from the Cox No. 1 well when a kick developed and the annular preventer was closed. Attempts to restore circulation of the drilling fluids failed, and the pipe rams were engaged. Orders were then issued to begin evacuating people near the wellsite, as specified by procedures contained in the contingency plan. Shortly after that, the blowout-preventer stack failed, "releasing a jet stream of gas and mud".[87] The time between the closure of the annular preventer and the failure of the entire blowout-preventer stack, with the subsequent ignition of the escaping gases, was nearly 7 h.

In a situation like this, where well-control problems develop over several hours, decisions need to be made on the responses that local residents need to take to ensure their own safety. If some level of response is considered appropriate (e.g., standby alert, immediate evacuation, etc.), then the public is notified. The monitored situations requiring alerting of emergency response personnel and citizens should be thoroughly analyzed by the authors of a contingency plan. Results of those analyses can be summarized in the form of flow charts that graphically lead an individual through the sequence of actions needed to make a decision on the timing and content of alerts. Such protocols will of course vary from well to well, depending on the nature of potential public safety hazards.

For example, if serious well-control problems occur at a well that is upwind of a heavily traveled roadway, it would be prudent to notify police of a possible need to set up road blocks as a precautionary measure. Implicit in such protocols is the definition of the "serious" or "dangerous" well-control problems that would trigger the required alerts. Those protocols should address not only the conditions of the well and potential sour-gas emissions, but also external factors like wind speed and direction. Wind speed is important for determining how quickly it would take a plume of toxic gas to reach nearby residences, while wind direction needs to be constantly monitored to determine the downwind areas at greatest risk in the event of a major release.

Hamby and Smith presented three sets of hazardous operating conditions ranging from minor leaks of sour gas from the mud circulation system to the uncontrolled discharge of gas to the atmosphere.[6] They defined those conditions according to the source and severity of gaseous emissions. Each condition required some sort of remedial action or emergency response. Warning signs were recommended as a means of alerting onsite personnel and others in the vicinity of the well of its status.

Well blowouts also occur with little, if any, warning. Under these circumstances, the notification of local residents to evacuate must be done in an orderly and expeditious manner. To facilitate that effort, the addresses and telephone numbers of local residents should be listed in a contingency plan by wind sector and distance from the wellsite to ensure that those nearest are indeed contacted first. In this regard, wind socks must be clearly visible at all times so that wind direction is easily determined. Maps of the local area showing topography, roads, and residences must be available as well.

The types of messages to be given to residents under different conditions should be specified in the contingency plan. Special attention needs to be placed on the content of the messages and their credibility--especially when many homes need to be contacted and more than one method of communication is used (e.g., telephone, loud speakers, person-to-person contact, sirens, etc.). Sorensen, in an evaluation of an emergency warning system for a nuclear power plant, noted that the following factors directly affect the communication and credibility of warnings[88]:

- Repetition - Believability of warnings increases with repetition
- Source of warning - Official sources enhance credibility
- Communication method - Personal contact is more believable than indirect or impersonal contacts
- Message - Should be accurate, clear, and noncontradictory for greatest effect
- Timing - Believability tends to increase as time to impact decreases
- Location - Generally, the further people are from an impact location, the less responsive they will be to a warning
- Certainty - As the likelihood of an event increases, a warning becomes more believable
- Risk - The greater the forecasted consequences become, the more believable the warning
- Rumor - Conflicting rumors damage the credibility of warnings

One way of enhancing the credibility of warnings is to contact local residents personally prior to the commencement of drilling operations in which sour-gas formations may be encountered. The purpose of such contacts would be to inform the residents of the potential hazards of the drilling, the safety technologies and procedures employed to protect against those hazards, and the types of responses required in the event of a well blowout. Information conveyed in this manner would serve to reduce uncertainties or confusion that might arise during an actual emergency.

Communication and Involvement of Emergency Services Personnel

An important part of contingency planning involves the coordination of company personnel at a wellsite and local emergency service personnel. To establish this coordination, meetings should be held between safety officials of the company drilling a sour-gas well and representatives of organizations that would provide services during an emergency situation (e.g., police, fire, rescue, emergency response coordinators, applicable Federal agencies, etc.). The results of such coordination should include a clear definition of the emergency services required during a well blowout (e.g., communications, rescue, traffic control, evacuation, etc.) and organizations responsible for providing each service. Contingency plans should include brief descriptions of the involvement of each organization together with the points of contact with those organizations.

Ignition of Well

Once a blowout has occurred, a primary response is the ignition of the sour gas to produce a buoyant plume of combusted gases including sulfur dioxide, which is formed from the combustion of hydrogen sulfide:

$$H_2S + 3/2\ O_2 \rightarrow H_2O + SO_2 \ . \qquad (6\text{-}1)$$

Thus, 1 mol of sulfur dioxide is generated for every mole of hydrogen sulfide that is burned. This means that the emission rate of sulfur dioxide is 1.88 times higher than the emission rate for hydrogen sulfide due to the difference in the molecular weights of the two gases. Despite the larger emission rate, sulfur dioxide does not constitute a significant public health problem because the heat of the combusting gas produces an elevated, buoyant plume of gas. To determine whether such a plume would indeed pose any serious public health risks, we employed the technique proposed by Baasel[59] that predicts the maximum ground-level concentration associated with an elevated gas release. We calculated the plume rise using Briggs' equation (see Hanna et al.[60]) for a buoyancy-dominated rise under neutral conditions (class D stability). A rise of 60 m was computed at a distance of 100 m from a buoyancy flux* of 6,655 m^4/sec^3 and a wind speed of 12.5 m/sec. With an emission rate of 12,545 g/sec of sulfur dioxide (i.e., from the combustion of 6673 g/sec of hydrogen sulfide), the maximum downwind concentration was 35 ppmv (40 mg/m^3), which is enough to cause eye inflammation and odor annoyance, but not acute effects. This is a conservative case because at 100 m downwind the plume is still rising, thereby reducing the ground-level concentrations. For the unstable case (Class A stability), a wind speed of at least 7.6 m/sec (very infrequent in A stability) would be required to produce a maximum ground-level concentration of 35 ppmv. Thus the effect of wind speed in reducing plume rise is more important than the subsequent mixing due to atmospheric instability.

When the sour gas contains high levels of carbon dioxide, it may not be possible to ignite the well if a blowout occurs. This possibility should be clearly explained in the contingency plan in order to prevent personnel from attempting to ignite the inflammable gas, thereby endangering themselves unnecessarily. High carbon dioxide wells present a more serious public health hazard than high methane sour gases, which are ignitable, and consequently, extra attention should be given to the definition of protocols relating to the notification of nearby residents.

Post-Release Monitoring and Modeling

Contingency plans also need to address the actions that might be necessary several hours and even days after a blowout has taken place. Our review in Section 3 of the data on the durations of blowouts revealed that most uncontrolled releases last anywhere from a half day to over a week; some can last months, if efforts to kill the well are hampered by various kinds of problems. During this period attention must be given to the collection of monitoring data on ambient concentrations of escaping gases, modeling of ambient concentrations, and the security of the wellsite.

The process of assessing the consequences of an accidental release of gas containing hydrogen sulfide begins with pre-release analyses. In this phase of the procedure preliminary analyses are carried out to define the population potentially at risk (see

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* The buoyancy flux was calculated as the product of the net heat flux (adjusted for heat loss due to radiation) of the burning gas and 3.7×10^{-5} (see Texas Air Control Board[58]). The gross heat flux was obtained for an upper-bound flow rate of 10^8 cf/d (see Section 3) of gas with a heat content of 1000 BTU/cf. The net flux was then about 60% of this value.

Section 4) and to define sources of meteorological data that could be used in the event of an actual emergency. After a release has occurred, an evaluative process as portrayed in Fig. 6-1 can be adopted to provide guidance for emergency services personnel. Most of the assessment procedure is adapted from a paper by Greenly and Dickerson,[89] which involves their experience with an advanced emergency response system for providing advisory information or the transport of hazardous air pollutants after accidental releases.

The proposed method for analyzing atmospheric concentrations of a toxic gas has two basic modes. If the general public is not at risk of a release, then only meteorological data and air quality data are collected. For example, the ignition of a well will produce a hot, bouyant plume of sulfur dioxide that virtually eliminates the risk of acute intoxication from the inhalation of the emitted gases. In this case, the emphasis should be on the monitoring of ambient concentrations of sulfur dioxide. However, when the well is extinguished and there are nearby residents at risk, then there should be a capability to model the released gases to advise emergency response personnel. If the public is at risk (as revealed by preliminary analyses), then provisions should be made to have a team of experts acquire and analyze data on the gases released. They should be supported by instruments for monitoring toxic gases and for acquiring meteorological data.

Concentrations of hydrogen sulfide and sulfur dioxide should be monitored at both fixed and mobile stations around the wellsite to define the hazard zone around the well accurately. This is necessary for the protection of local residents and workers responsible for killing the well. Instruments should be able to detect concentrations of hydrogen sulfide from below 10 ppmv to as much as 300 ppmv (lower limit of acute toxicity threshold). Concentrations of sulfur dioxide should be measurable to 100 ppmv. In addition to those measurements, real-time data should be collected on wind speed and direction. Such data would be needed in support of crews involved in well-control operations and other emergency response activities (e.g., evacuation, rescue, etc.).

Access to local weather forecasts may also prove useful, especially when decisions are being made on the timing of well-control efforts. More sophisticated measurements would be necessary if there were a need to predict downwind concentrations of either gas (e.g., close proximity of well to residential areas, roadways, railroad track, etc.). For example, it would be particularly important to determine the height of the plume of emitted gas. In this regard, infrared imagery could prove useful in delineating the morphology of cold plumes (i.e., uncombusted sour gas) or hot plumes (i.e., sulfur dioxide). In terms of modeling, Greenly and Dickerson[89] recommend that initial calculations of atmospheric transport be carried out using a Gaussian model to bound the

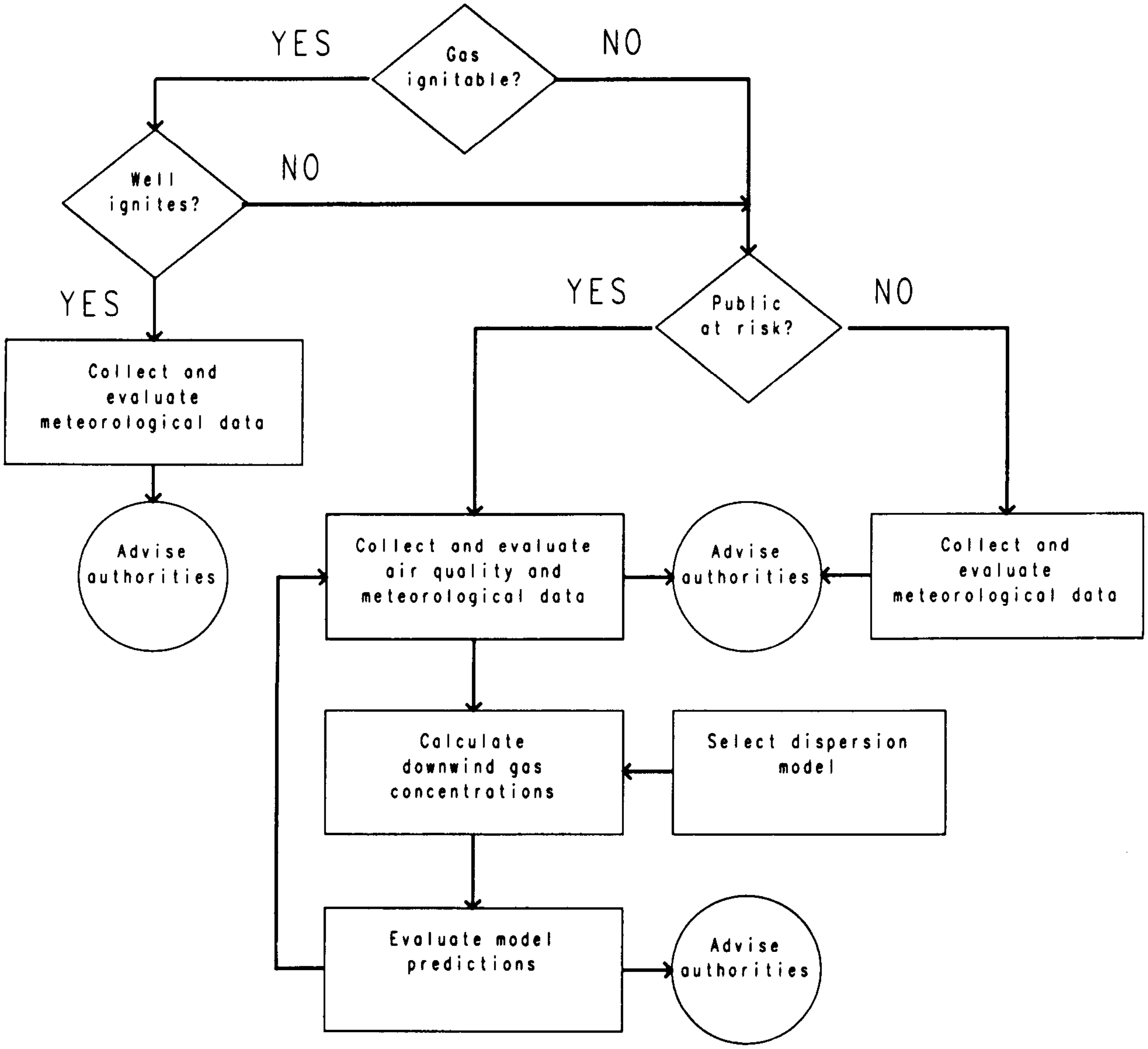

Figure 6-1. Proposed methodology for analyzing the ambient concentration of a toxic gas release from a natural gas well.

problem. More advanced models should then be available to calculate downwind concentrations as meteorological data are collected. For example, with information on wind fields, trajectory puff and three-dimensional numerical models can be used to analyze the movement of released gases.

Atmospheric models used in conjunction with measurements of meteorological and pollutant concentrations can also be used to estimate gaseous emissions from a source. With this approach, values of χ/Q (where Q is a unit emission rate) are predicted for receptors at specific locations within a plume, and then estimates of emission rates are computed by dividing measurements of pollutant concentrations at the receptors by the corresponding values of χ/Q. This approach requires the use of aircraft to obtain data on the concentration profile of the pollutant within a plume. Dickerson reported how such a methodology was utilized to provide early estimates of the emission rate of radioactive gas from the damaged Three Mile Island nuclear reactor.[90] When applied to sour-gas releases, though, it may not be advisable to use an aircraft over a well because of the potential toxicity of the plume. As a consequence, aircraft might have to fly at downwind distances where accurate measurements would be more difficult to make. An alternative would be to use small, radio-controlled drones equipped with pollutant monitors to collect data in a plume near a well. According to Dickerson, atmospheric models could also be used as tools during emergency situations to provide guidance to measurement activities, estimates of potential concentrations, checks to the consistency of measurements, interpolations and extrapolations of measurements, and assistance to the development of safety guidelines.[90]

It should be emphasized here that this methodology is based on the assumption that there is a public or private emergency response organization that is available to carry out the necessary analyses. One way of insuring that such a capability exists is for either BLM, a gas producer, or perhaps state or local governments (or even a consortium of all interested organizations) to establish a contract with a company specializing in such emergency response situations. Ideally, such a company should possess the following equipment, resources, and staff:

- Meteorologists trained in the acquisition and analysis of meteorological data as well as the use of atmospheric transport models
- A selection of computerized dispersion models for estimating ambient concentrations of emitted gases
- An automated system for collecting real-time meteorological data to support the operation of the dispersion models

- Field deployable sensors for measuring sulfur dioxide and hydrogen sulfide over a wide range of ambient concentrations
- A well-rehearsed methodology for analyzing the various data produced

Once a suitable contractor has been selected, periodic exercises should be held to evaluate the performance of its staff and equipment.

PUBLIC SAFETY DURING PRODUCTION

The safe operation of sour-gas facilities depends on the prevention of corrosion and other materials-related problems in a well and its associated collection pipeline, the rapid detection of accidental gas releases by different sensors, and the isolation of a leak through the automatic or remotely controlled closure of one or more safety valves at the well or along the pipeline. The production tubing and casing in a sour-gas well are protected against the corrosive effect of hydrogen sulfide by the injection of a corrosion inhibitor into the annulus below the packer to produce a protective film on the inside of the tubing. Hamby indicates that such inhibitors have worked effectively in deep sour-gas wells* completed in the Smackover formation in Mississippi, provided that the inhibitor does not vaporize under downhole conditions.[82] If vaporization occurs, then the protective film is not formed and corrosion will occur. This problem is avoided by selecting the proper inhibitor. Corrosion is also inhibited through the use of steels with a Rockwell hardness less than 22. As noted earlier, quality control of all materials received for sour-gas service is essential to ensure that they meet existing guidelines (e.g., NACE standard MR-01-75).[82,83]

Corrosion in the collection pipeline can be monitored with hydrogen probes, corrosion coupons inserted into the pipe, and ultrasonic measuring devices that can be used to detect changes in the thickness of the pipe. Adams and Rowe reported that hydrogen probes were particularly valuable tools in the monitoring of a pipeline in Texas conveying a high carbon dioxide gas containing about 30% by volume hydrogen sulfide.[91] The probes measure a pressure buildup of hydrogen gas with a hollow probe inserted into a pipeline. The pressure of the hydrogen provides a qualitative measure of the corrosion taking place within the pipeline. Periodic monitoring of sour-gas pipelines using the equipment noted above should provide early warning of any potential corrosion problems. Remedial actions to improve unacceptable corrosion rates might include a higher rate of inhibitor injection or possibly a change in the type of inhibitor employed.

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* Greater than 19,000 ft deep, bottom hole pressures greater than 17,000 psi, and gas containing between 30 and 50% by volume hydrogen sulfide.[82]

To detect minor leaks or major releases of sour gas, various kinds of sensors are deployed at the wellsite and along the collection pipeline.[82] Separate sensors measure line pressures, ambient concentrations of hydrogen sulfide, and even the presence of elevated temperatures at the wellhead. The status of the sensors and valves is monitored at a manned facility, such as a gas purification plant. Pressure sensors are designed to detect pressures that are above or below a prescribed pressure range. Unacceptable pressures will result in the closure of one or more safety valves at the wellhead. Closure of the valve(s) is usually accomplished by bleeding off the hydraulic line to the valve actuator, which is kept pressurized to keep the valve open. So, if for any reason pressure is lost in the hydraulic system, valves will automatically close. The same is true of the subsurface safety valve. It is kept pressurized by a hydraulic line from the surface. Subsurface safety valves were first used in offshore oil and gas operations,[92] and their application to onshore sour-gas operations is relatively recent. Normally, these downhole valves are only actuated if surface safety systems fail. The long-term (∿ 20-30 yr) reliability of such valves in sour-gas environments is unknown, but it would appear that the extra measure of safety they provide justifies their implementation and continued improvement.

Hydrogen sulfide sensors are also utilized in the activation of safety valves. In one mode of detection, a sensor will set off an alarm or beacon at the wellsite and at the manned facility when a low level of gas is detected (e.g., ∿20 ppmv). At a higher predetermined level, say 50 ppmv, the sensor will shut in the well. Temperature sensors, in the form of fusible plugs, are designed to respond to elevated temperatures at the wellhead caused by fire or an explosion. Another mode of well control involves the routing of gas from the well to a flare, if excessive pressures are detected at the wellhead. This situation will result in the activation of pressurized safety valves. The collection pipeline incorporates safety valves known as block valves. These pressure-activated valves will close when line pressures drop below a specified level (or exceed a pressure differential), as would happen if a rupture were to occur. However, if a small leak develops, and the line-pressure drop is smaller than the "trigger" level, the valves will not close. In that event, hydrogen sulfide sensors can be used as backup detection devices at sensitive locations, for example, at road crossings (see Adams and Rowe[91]).

Our previous review of the causes of gas releases at producing wells located in Alberta, Canada showed that problems associated with well servicing and external damage accounted for nearly all of the releases. This suggests that extra precautions are needed when workover operations are taking place. Contingency plans specific to drilling operations should be implemented during such operations to protect local residents, if an accidental release occurs. The possibility of external damage by trucks, tractors, earth moving equipment, etc. should be minimized by limiting access to the wellsite and by installing protective fencing. External damage was identified as an important source of leaks in transmission and gathering lines. Accordingly, measures are needed to prevent that type of damage. One obvious approach is to bury those lines deeper than normal utility lines to reduce the likelihood that a line would be ruptured during excavation work. Signs along the right-of-way warning construction crews of the sour-gas line would provide additional protection against damage caused by unauthorized excavation.

The careful siting and design of sour-gas facilities is another means of reducing the potential health risks of those facilities. For example, the spacing of block valves (i.e., automatic safety valves) can be adjusted to minimize the release of sour gas along a stretch of pipe where there are sensitive receptors (e.g., residences, roads, schools, etc.). The effects of changing the position of block valves and pipeline alignments can be analyzed by modelling the atmospheric dispersion of gas after an accidental release. If unacceptably high concentrations are predicted to occur near a sensitive receptor, further modifications in the pipeline could be made.

Wells can be directionally drilled to yield an offset on the surface that increases the safety of drilling. In some places the siting and operation of sour-gas facilities are controlled by specific regulations. The Railroad Commission of Texas has adopted a regulation known as Rule 36 that prescribes safety measures for sour-gas facilities that could emit enough hydrogen sulfide to endanger nearby residents.[93] Facilities are screened through the use of equations that estimate the distances to the 100- and 500-ppmv concentrations, based on an estimated emission rate (see Section 4 for a discussion of screening equations). The safety measures (e.g., control equipment, contingency plan, etc.) stipulated depend on the exposure radii calculated for the well.[56] Sour-gas facilities completed in Alberta, Canada are required to have specific separation distances from houses and public facilities; the distances are defined by the potential amounts of hydrogen sulfide released.[77] Those regulations define the gas discharge rate from a well as the "maximum wellhead deliverability that can be attained at any time through the tubing against zero wellhead pressure..."[77] For pipelines, the separation distance is based on the total volume that could be released from a line segment under the highest operational pressure, assuming the instantaneous closure of block valves when a rupture occurs.

A potential concern associated with the long-term operation of sour-gas facilities is the gradual encroachment of development near the facilities. In rural areas this may never become a problem, but in other places, this could mean that the population potentially at risk increases over time. Land-use zoning is one option available to limit the construction of buildings near sour-gas facilities over a long period of time. The best example of the kind of zoning that could be used to regulate development is flood plain zoning, which seeks to restrict development from the high-risk area of a flood plain (e.g., the land over the 100-yr flood plain) to minimize flood-related property damage. This type of zoning, though, does require data on the frequency of flood events as well as a decision on the level of acceptable risk. To be effective, local land-use guidelines, ordinances, or restrictions should be adopted before wells are drilled that could encounter sour-gas formations. Putting in land-use ordinances after wells are drilled could result in undesirable restrictions on future growth. It is not clear how BLM could effectively incorporate land-zoning guidelines for sour-gas wells under its jurisdiction, because land-use controls are inherently site-specific matters that do not lend themselves to general regulations. However, BLM could adopt review and consultation protocols for proposed wells that could pose public health risks as identified by preliminary analyses. With this approach such wells would only be drilled under conditions specified by BLM and local governments. The primary issue addressed under these circumstances is whether the well would pose an unacceptable risk to existing or future residents, if it was successfully completed and operated.

7. CONCLUSIONS AND RECOMMENDATIONS

The analysis and assessment of the health and environmental risks of a potential sour-gas release from a well or collection pipeline can be viewed as a sequential process consisting of these primary elements:

- Estimation of the emission rate of hydrogen sulfide
- Prediction of the downwind concentrations of hydrogen sulfide after an accidental release
- Analysis of the potential health effects resulting from the predicted concentrations
- Review of the safety measures and technologies required to minimize the risks of a sour-gas release

The quantification of the potential emission rate is most difficult for exploratory wells because of uncertainties regarding the productivity of the geologic formations that might be encountered and the composition of the natural gas in those formations. To deal with those uncertainties in a quantitative manner, we recommend a statistical approach, discussed in Section 3, in which an upper-bound emission rate is calculated from a lognormal distribution that is a product of two other lognormal distributions; one representing concentrations of hydrogen sulfide measured in natural gases in the region where exploration is taking place and the other representing the CAOFs of wells completed into similar formations. We used the 98th cumulative percentile to define the upper-bound emission rate for assessing the hazards of an accidental gas release. For development wells, actual flow test data and measurements of gas composition are used to determine the emission rate.

Gas discharge to the atmosphere through production tubing also needs to be considered, because this type of a release is more likely to result in a near-surface release of gas. For exploratory wells, an estimate of this rate can be made by taking 40% of the CAOF, while for development wells this rate is determined from flow test data. To support the use of the probabilistic approach for quantifying emissions of hydrogen sulfide from exploratory wells, we recommend that BLM compile additional data on the concentrations of hydrogen sulfide in natural gases from wells completed in the Overthrust Belt. Those data, together with data on potential flow rates of gas from wells, can then be used to make better estimates of accidental gas discharges.

The frequency of accidental well releases during drilling is higher per unit time than during gas production. However, over the 20-yr life of a well, we calculated that the probability of release was on the same order as drilling, that is, 10^{-3}. Releases from pipelines are somewhat easier to calculate since the values of the parameters affecting the release rate are known. The frequency of accidental releases from collection pipelines was estimated to be 7.6×10^{-4}/mi-yr (4.8×10^{-4}/km-yr). The likelihood of accidental releases from both types of facilities can be reduced by implementing safety measures directed at the causes of the releases. For example, accidental ruptures of sour-gas pipelines can be minimized by increasing the depth of burial to avoid inadvertant ruptures caused by excavation. Similarly, external damage to well head assemblies can be reduced by securing the wellsite by fencing.

The methods used to assess the health risks of gas releases depend a great deal on the location of sour-gas facilities. Normally, screening-type equations have been employed to determine the distance to a toxic concentration of gas (e.g., 100 to 500 ppmv) under very stable atmospheric conditions. In other situations, though, more detailed analyses of the spatial distribution of risks around a well are advantageous--especially in an area where sensitive receptors (e.g., schools, hospitals, future developments, etc.) are located or where future development is expected. Knowledge of such risks can be used to adjust contingency plans to protect areas that are at greater risk than others or to develop land-use zoning guidelines to minimize the size of the population at risk.

We applied a risk assessment methodology to a sour-gas well located on land under the jurisdiction of BLM outside of Evanston, Wyoming. A year's worth of meteorological data were collected to describe the meteorology of the area as input to the atmospheric modelling component of the assessment. Under worst-case conditions of a continuous surface-level release through production tubing, we found that the northwest sector around the well was at greatest risk because stable atmospheric conditions and low wind speeds were frequently associated with southeasterly winds. The risks of incurring an acute health effect (i.e., unconsciousness, respiratory arrest, pulmonary edema, or death) were predominantly in the range of 10^{-4} to 10^{-5} and below over 20-yr--risks that are comparable to dying from a natural disaster. A vertical, momentum-dominated release of gas into the atmosphere at a rate near the CAOF of the well would not produce concentrations high enough to cause acute effects.

Safety technologies and procedures for sour-gas facilities have been developed and improved over many years, with a primary focus on occupational safety. Our review of safety measures emphasized techniques related to public safety. Implementation of contingency actions specified in a contingency plan has historically been the principal method of protecting residents against adverse effects in the event of a major sour-gas release. In this regard, we note that such plans need to deal explicitly with protocols for notifying residents of possible emergency responses so that decisive actions can be taken under emergency conditions. Residents should be listed in a contingency plan by wind sector and downwind distance to facilitate the notification of those residents at greatest risk. Protocols related to the ignition of the well should also be included in contingency plans. The production of a thermal plume of sulfur dioxide minimizes the health risks of a major uncontrolled release, and therefore the timing of ignition is a high priority response. To obtain timely information on the potential hazard of atmospheric concentrations of hydrogen sulfide during an actual release near an inhibited area, we recommend that BLM together with other public and private organizations retain the services of one or more firms that could respond to such an emergency with the necessary meteorological equipment and trained personnel.

To improve the analysis and assessment of the risks from sour-gas releases, more work needs to be conducted on the behavior of the gas plume after a release, particularly the rise of the plume under different source conditions. In addition, we believe a case can be made for further research into the dispersion of momentum-dominated releases of sour gas containing an elevated concentration of carbon dioxide. There is some evidence that suggests existing models would underpredict the concentrations of hydrogen sulfide resulting from that type of release. Field studies of actual releases of carbon dioxide might be one way of addressing this problem.

APPENDIX A

ANALYTICAL EQUATIONS DESCRIBING THE FLOW OF GAS TO A WELL AND THE FLOW THROUGH CASING OR PRODUCTION TUBING

The steady-state equation for the radial flow of gas into a wellbore at depth is given by

$$Q = \frac{0.703\ kh\ (P_e^{\ 2} - P_w^{\ 2})^n}{uTz\ \ln(r_e/r_w)} \quad , \qquad \text{(A-1)}$$

where

Q = is the volumetric discharge rate, in 10^6 scf/d,
k = permeability of the reservoir, mD,
h = reservoir thickness, ft,
r_e = external radius of the circular reservoir, ft,
r_w = the internal radius of the drill pipe or casing, ft,
P_e = pressure at the boundary of the reservoir (at r_e), psi,
P_w = downhole pressure within the wellbore, psi,
u = average gas viscosity, centipoise,
T = reservoir temperature, °R,
z = average gas deviation factor, dimensionless, and
n = exponent between 0.5 and 1.

The exponent n in Eq. (A-1) is used to adjust the flow-rate predictions to account for turbulence that can develop as gas flows through the formation to the well. The effect of the exponent, which varies between 0.5 and 1, is to reduce the flow rate as turbulence increases (with laminar flow, $n = 1$). Because of the potentially large variations in turbulence between wells and changes in the thicknesses and permeabilities of producing formations, it is difficult to use this equation to estimate the CAOF of wells--especially for exploratory wells. However it could be applied judiciously in situations where there are adequate data on the various parameters.

The frictional resistance of gas flowing through a well to the surface creates a downhole pressure that slows the movement of gas from the formation into the wellbore.

The flowing subsurface pressure for a well can be calculated from the following equation[94]:

$$P_s^2 = P_w^2 e^S + \frac{25\, G \bar{T} \bar{z} f\, L\, (e^S - 1)\, Q^2}{S D^5} \qquad \text{(A-2)}$$

where

P_s = flowing bottom hole pressure, psi,
P_w = flowing wellhead pressure, psi,
S = $2\,GL/53.34\,\bar{T}\,\bar{z}$,
G = gas gravity,
$\bar{T}$ = average bottom hole and well head temperatures, °R,
$\bar{z}$ = average gas compressibility factor,
f = moody friction factor,
L = length of flow string, ft,
Q = gas flow rate, 10^6 scf/d, and
D = flow string diameter, in.

The potential emission rate of gas to the atmosphere for a well (properties of the reservoir and well are known) is defined by the intercept of a curve that describes the flow of gas to the wellbore for various downhole pressures (predicted from Eq. (A-1)) and a second curve that describes the relationship between downhole pressures and gas flow rates at the surface (predicted from Eq. (A-2)). Intercepts for both types of curves are shown in Fig. 3-2.

APPENDIX B

REVIEW OF THE GAUSSIAN DISPERSION MODEL FOR SCREENING APPLICATIONS AND RISK ANALYSES

The Gaussian dispersion model is used to simulate the atmospheric dispersion of a gas that is released continuously (plume) or instantaneously (puff) from a point source into an atmosphere with steady-state properties. The uncertainty associated with the concentrations predicted by the model depends on the degree to which the mathematical model accurately describes the dispersion of gas under the conditions being assessed, as well as the accuracy of the input parameters (e.g., emission rate of gas, wind speed, etc.). Our review of the accuracy of the model for screening applications and risk analyses focuses on the performance of the model as measured by different tracer studies and field validations, and the sensitivity of the model to input parameters.

MODEL PERFORMANCE

The performance of the Gaussian model has been studied through various tracer experiments. Generally, the design of those experiments is simple; a tracer (e.g., fluorescein particles, sulfur hexafluoride, etc.) is released at the surface or from a tower, and downwind concentrations of the tracer are measured over a network of fixed stations. Measurements of meteorological parameters are made as well to characterize the dispersive properties of the atmosphere. Using the tracer release rate and the meteorological data as input, the Gaussian model is used to predict tracer concentrations at the monitoring stations. The predicted concentrations are then compared with the measured tracer concentrations to assess the model's predictive ability. Because the accuracy of the model depends on both the model formulation <u>and</u> on the accuracy of its inputs, it is often difficult to determine whether differences between the predicted and observed concentrations are due purely to model error/inadequacy or uncertainties in the data--especially the categorization of atmospheric stability.

With this qualification in mind, independent evaluations of the performance of Gaussian models against tracer data have shown mixed findings. Londergan <u>et</u> <u>al.</u>,[95] for example, found that a variety of Gaussian models tended to overpredict short-term concentrations (10 min to an hour) by over a factor of 5 for near-surface releases over rural, flat terrain and under stable atmospheric conditions. However, the same models slightly underpredicted downwind tracer concentrations under unstable conditions.[95] Gifford indicates that the variability in predictions based on averaged data are within factors of 2 to 4.[96] Draxler showed that the accuracy of two Gaussian models improved as the averaging time increased.[97] Irwin, in an analysis of several schemes for classifying σ_y and σ_z from tracer studies, discovered that predictions based on Pasquill-Gifford (P-G) coefficients "tended to overestimate the surface concentrations for the near-surface releases and to underestimate the surface concentrations for the elevated releases during unstable stratification."[98] In general, the various stability schemes examined typically overpredicted concentrations in neutral and stable conditions. He also found that over all stability conditions and downwind distances, the Gaussian model with the P-G coefficients predicted approximately 50% of the values within a factor of 2. In a separate study, Fields et al. showed that for 22.5°-sector averaged ground-level concentrations, a variety of sigma schemes used in a Gaussian model tended to underpredict measured values in close to the source and to overpredict beyond a few kilometers.[99] Guzewich and Pringle compared the concentrations of a tracer gas measured at points downwind from an elevated release point with the concentrations predicted from a short-term Gaussian dispersion model.[100] They found that 89% of all the predicted concentrations were within a factor of 3 of those actually measured. It is difficult to draw any solid conclusions about the general behavior of Gaussian model predictions versus data, except that the uncertainty for short-term concentrations, predicted over different atmospheric conditions, is probably no less than a factor of 2, with the direction of error inconsistent.

INPUT PARAMETERS

When using the Gaussian model to assess the dispersion of gas away from a source at a particular site, estimates of the atmospheric stability (as represented by σ_y and σ_z), wind speed, and the effective height of the gaseous plume are required. The quantification of each of these parameters is subject to different sorts of errors. To illustrate, the measurement of wind speeds used in the model should coincide with the height of the released plume; therefore, winds measured at one height often must be extrapolated to another height using a power-law approximation.[60] As the difference between the measurement height and the effective plume height (i.e., the actual release height plus plume rise) increases, the possible error in extrapolation becomes greater. Measurements of low wind speeds are slightly biased because anemometers have a threshold velocity below which they do not operate. As a consequence, more calms are recorded and the cumulative effect is that the slowest wind speed class will have an average speed that is too low.[101] The Gaussian model also requires a uniform wind speed, both in time and space. Nonuniform, random variations will therefore cause errors in prediction. One other noteworthy characteristic of this model is that predicted concentrations can become very large when wind speed decreases toward zero. The model should be used with caution in applications where very low wind speeds are encountered.[102]

Specification of wind direction is another potential source of error. Meteorological data are normally summarized by wind sectors, for example, one common approach is to have 16 separate sectors that are 22.5° in width around the compass. When these sectors are used to simulate the downwind concentrations around a release point, there will be discontinuities in the isopleths that reflect the categorization of the directional data. Normally, such effects are not significant. One other fact related to wind direction is that it is assumed to be constant over the time interval for which an estimate of concentration is made. Clearly, this may not be the case as wind directions can change with height and distance downwind from a release. Only numerical models with time-varying wind fields can handle this situation. This deficiency in the Gaussian model has its greatest effect, when specific meteorological conditions lasting several hours or more are being modeled. When average conditions are being simulated, such time-varying conditions would usually have a small effect on the results (except perhaps in locations where rough terrain features could be expected to significantly alter wind flow patterns).

For optimum performance of the Gaussian model in a site-specific application, the lateral and vertical dispersion coefficients, σ_y and σ_z, must be estimated as precisely as possible. Needless to say, the estimation of those parameters has been one of the more intensely studied topics in diffusion meteorology. The most frequently used method for quantifying the sigmas consists of a two-step procedure in which the stability of the atmosphere is classified into one of six or seven stability classes according to various meteorological criteria, and then the corresponding sigma values are calculated as a function of downwind distance using power-law equations. In applying such methods, for example the Pasquill-Gifford scheme, misclassifications of stability must be minimized because predicted concentrations are inversely proportional to the product of σ_y and σ_z, and hence errors are propagated multiplicatively.

To demonstrate the effect of stability misclassification, we calculated σ_y and σ_z for classes E (i.e., slightly stable) and F (i.e., moderately stable) at a distance of 3280 ft (1000 m), using power-law equations and coefficients presented in the user's guide for the Texas Episodic Model (TEM), a Gaussian diffusion code.[58] For class E the product of σ_y and σ_z was 10,823 ft^2 (1006 m^2), compared with 4658 ft^2 (433 m^2) for the more stable class F--smaller by a factor of 2.3. Therefore, if the actual stability was E, but was incorrectly classified as F, the predicted ground-level concentrations (along the plume centerline after a surface release) would be 2.3 times too high. Another misclassification can occur in low wind speeds under stable conditions (i.e., class F). The large variation of wind direction under these conditions can significantly enhance horizontal diffusion; σ_y has been observed to more appropriately reflect the class A value.[103] Here, the specification of both σ_y and σ_z according to a single stability class (e.g., class F) can result in an overprediction of centerline concentrations and underprediction of plume width.

The selection of power law equations for obtaining σ_y and σ_z, as a function of downwind distance and stability, leads to some variability. For example, a commonly used set of equations, given in Hanna *et al.*,[60] gives values of σ_y under E stability, which are about 10% larger at a downwind distance of 1500 m than those obtained from the scheme we used. Hence, in this case, the approach we have chosen is the more conservative.

The effective release height is the sum of the actual release height and the rise of the plume due to buoyancy and momentum. We examined the sensitivity of χ, as predicted by three different Gaussian plume codes that are part of the Environmental Protection Agency's User's Network for Applied Modeling of Air Pollution (UNAMAP), to three different release heights and two atmospheric stabilities. Tables B-1 and B-2 depict the results of the sensitivity analyses for stability classes A and E, respectively. In both cases the concentrations predicted by the models were in good agreement. Differences between the model predictions were caused primarily by the use of different constants and/or exponents in the power-law formulas for estimating wind speed with height and dispersion coefficients. A comparison of the two tables shows that the effective release height has the greatest effect on the concentrations predicted for stable conditions (Table B-2). Diffusion of the plume under such conditions is slow (reflected by small sigma values), which means that the plume does not intersect the ground until after it has been transported some distance downwind. At the 164-ft (50-m) release height, the plume reaches the ground at 1968 ft (600 m), and with a height of 328 ft (100 m), the plume does not touch down before 3280 ft (1600 m). However, for the unstable case (Table B-1), the greater plume diffusivity produces ground-level concentrations near the source. As a *general* rule, maximum downwind concentrations for an elevated plume will occur under unstable conditions, while with surface-level releases, the maximum concentrations occur under stable conditions.

Table B-1. Concentrations versus downwind distance and release height as predicted by three UNAMAP Gaussian dispersion models for P-G stability class A. The emission rate is 1 g/sec, the wind speed is 0.45 mph (1 m/sec), and the mixing height is 656 ft (200 m). Concentrations are in µg/m^3.

Downwind	Effective release height (ft (m))								
distance	MPTER[a]			PAL[b]			TEM8[c]		
(km)	3.3(1)	164(50)	328(100)	3.3(1)	164(50)	328(100)	3.3(1)	164(50)	328(100)
0.1	848	1	0	778	2	0	824	1	0
0.2	217	45	1	208	42	1	185	53	2
0.3	93	48	9	90	42	8	77	45	13
0.4	48	34	15	47	29	13	42	30	16
0.5	27	22	15	26	18	12	29	21	14
0.6	17	14	13	16	12	10	22	17	12
0.7	13	12	11	13	10	9	17	13	10
0.8	12	10	10	12	9	8	13	11	9
0.9	10	9	9	10	8	7	11	9	8
1.0	10	8	8	10	7	7	10	8	8

[a] A multiple point-source model with terrain adjustments.

[b] A model for estimating dispersion from point, area, and line sources.

[c] An episodic model for simulating short-term releases.

Table B-2. Concentrations versus downwind distance and release height as predicted by three UNAMAP Gaussian dispersion models for P-G stability class E. The emission rate is 1 g/sec, the wind speed is 0.45 mph (1 m/sec), and the mixing height is 656 ft (200 m). Concentrations are in $\mu g/m^3$.

Downwind	Effective release height (ft (m))								
distance	MPTER[a]			PAL[b]			TEM8[c]		
(km)	3.3(1)	164(50)	328(100)	3.3(1)	164(50)	328(100)	3.3(1)	164(50)	328(100)
0.1	14131	0	0	10720	0	0	--	0	0
0.2	4333	0	0	3738	0	0	4240	0	0
0.3	2152	0	0	1955	0	0	2160	0	0
0.4	1332	0	0	1238	0	0	1336	0	0
0.5	918	0	0	866	0	0	920	0	0
0.6	677	1	0	645	1	0	695	1	0
0.7	523	3	0	502	3	0	547	2	0
0.8	419	6	0	404	6	0	445	4	0
0.9	344	8	0	333	8	0	371	6	0
1.0	289	11	0	281	11	0	315	8	0

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[a] A multiple point-source model with terrain adjustments.

[b] A model for estimating dispersion from point, area, and line sources.

[c] An episodic model for simulating short-term releases.

HAZARD ZONE SCREENING EQUATION AND HEIGHT SENSITIVITY

Using the Gaussian equation (Eq. (4-10)) and power law equations for σ_y and σ_z, one may develop an expression for the downwind distance to a specified concentration, as follows. Beginning with

$$\chi = \frac{Q}{\pi u \sigma_y \sigma_z} \exp\left[-\frac{h^2}{2\sigma_z^2}\right] , \qquad \text{(B-1)}$$

and using $\sigma_y = ax^b$ and $\sigma_z = cx^d$, one may write

$$\chi = \frac{Q}{\pi u a c x^{b+d}} \exp\left[-\frac{h^2}{2c} x^{-2d}\right] . \qquad \text{(B-2)}$$

From Eq. (B-2), an expression may be formed:

$$x = A \exp\left(-Bx^{-2d}\right) , \qquad \text{(B-3)}$$

where

$$A = \left(\frac{Q}{\chi \pi u a c}\right)^{\frac{1}{b+d}} \quad \text{and } B = \frac{h^2}{[2c^2(b+d)]} .$$

Equation (B-3) must be solved iteratively for x, once other terms are specified for given source and meteorological conditions and critical concentration level. Writing Eq. (B-3) as $f(x) = x - A \exp(-Bx^{-2d})$, one may use a technique such as Newton's method to find x_m such that $f(x_m) = 0$.

For horizontal, near-surface releases at high exit velocities, the effective plume height (centerline) is likely to be several meters above the release point as the rapidly expanding jet interacts with the ground. To evaluate the sensitivity of the screening equation to effective plume height (h), four runs were made with h = 0, 2, 5, and 10 m. Source strength was varied over the range of expected accident scenarios (150 - 2669 g/sec), under constant meteorological conditions (wind speed 1.5 m/sec, F stability, 60°F at 6000 ft MSL). The resulting family of curves of distance (m) to 300 ppmv concentration are shown in Fig. B-1. The curves are all quite similar in shape. At h = 10 m, source strengths less than about 450 g/sec fail to produce a ground level concentration of 300 ppmv. The curve for h = 5 m reflects a conservative central value between h = 0 and 10 m.

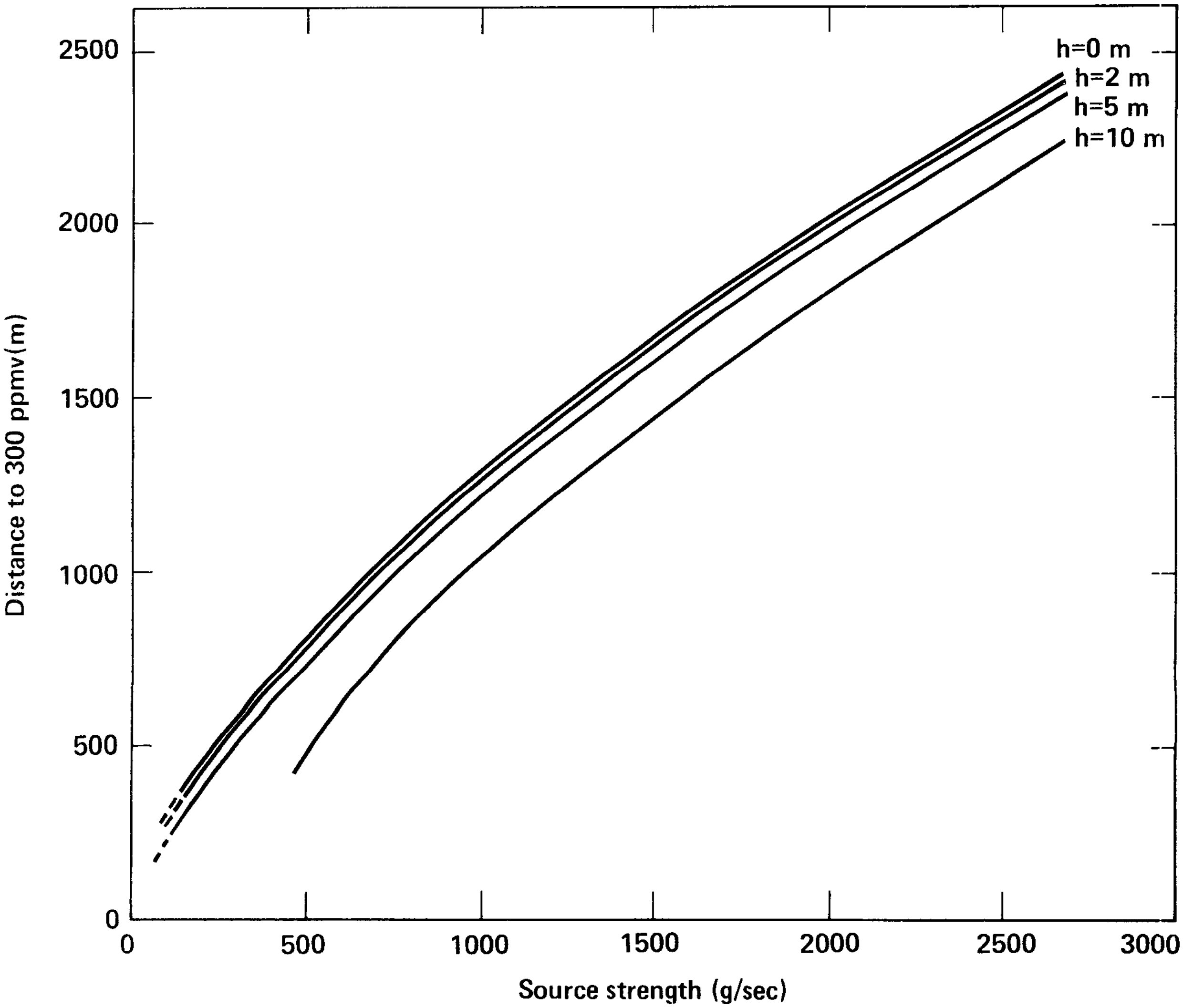

Figure B-1. Maximum downwind distance (m) to the 300 ppmv ground-level concentration for varying source strengths (g/sec) and release heights (m); calculations made for surface elevation of 6000 ft MSL, 60°F air temperature, stable (class F) conditions, and 1.5 m/sec wind speed.

CALCULATING THE SOURCE TERM FOR PUFF MODEL OF PIPELINE RUPTURE

Maximum downwind concentrations from a pipeline rupture will be associated with the dispersion of the leading portion of the plume since the source term decreases rapidly with time. If the continuous plume is approximated by a sequence of discrete puffs, then the highest concentrations are associated with the "leading puff." We propose the following way to approximate the source strength of the leading puff.

From Wilson,[64] the source rate for a pipeline rupture is

$$\dot{m} = \frac{K\dot{m}_o}{1 + \alpha} \quad [\exp(-t/\alpha^2\beta) + \alpha \exp(-t/\beta)] \ , \qquad \text{(B-4)}$$

where

$$\alpha = \frac{W}{\beta K \dot{m}_o} \ , \qquad \text{(B-5)}$$

$$W = \frac{PAL}{RT_g Z} \ , \qquad \text{(B-6)}$$

$$\dot{m}_o = \frac{PA}{Z\sqrt{RT_g}} \left[k \left(\frac{2}{k + 1} \right)^{\frac{k+1}{k-1}} \right]^{0.5} \ , \qquad \text{(B-7)}$$

$$\beta = \frac{L}{C} \ \frac{2}{3} \left(\frac{kfL}{D} \right)^{0.5} \ , \text{ and} \qquad \text{(B-8)}$$

$$C = \sqrt{kRT_g} \ , \qquad \text{(B-9)}$$

with

m = gas emission rate, g/sec,
m_o = initial isentrophic release rate, g/sec,
α = a mass conservation factor, dimensionless,
β = time constant for isothermal flow, sec,
t = time since rupture, sec,
K = resistance factor for overburden, dimensionless, (0.9),
W = initial mass of pipeline gas, kg,
P = initial line pressure, N/m^2,
A = cross-sectional area of pipe, m^2,
L = length of pipeline segment, m,

D = inside diameter of pipe, m,
T_g = temperature of pipeline gas, °K,
C = speed of sound at pipeline temperature T_g, m/sec,
Z = gas compressibility factor, dimensionless, (0.8),
f = pipe friction factor, dimensionless, (0.013),
R = gas constant, N-m/g-°K, and
k = specific heat ratio of gas, dimensionless, (1.32).

The "leading puff" is defined as a discrete representation of the initial period ($t = 0$ to t_1) of plume evolution. Thus the total mass M of hydrogen sulfide in this puff is obtained by integrating Eq. (B-4) over the initial period:

$$M = F \int_0^{t_1} \dot{m}\, dt, \tag{B-10}$$

where F is the weight fraction of hydrogen sulfide in the pipeline gas. Since all the terms used in Eq. (B-4) are invariant with time (except time itself), Eq. (B-4) is easily integrated to give

$$M = \frac{F\beta K\dot{m}_o}{1+\alpha} \left(\alpha^2[1 - \exp(-t_1/\alpha^2\beta)] + \alpha[1 - \exp(-t_1/\beta)]\right) . \tag{B-11}$$

To determine the appropriate value of t_1, we look at work by Blewitt.[65] He compared the impact predicted by a single puff (using t_1 = 10 sec) to the predicted impacts using all the decreasing emissions given by Eq. B-4. He found that 92% of the maximum impact were contributed by the "leading puff". Hence we will use a value of 10 sec for t_1. A second value to be determined is K. Comparisons by Wilson[64] between modeled and measured emission rates show that K lies somewhere between 0.5 and 1.0. Considering that we are interested most in the initial period, a value of K = 0.9 gives the best fit to the data cited by Wilson.[64]

APPENDIX C

SUMMARY OF METEOROLOGICAL DATA FOR CHARACTERIZING DISPERSION NEAR EVANSTON, WYOMING

Detailed analyses of the year's worth of meteorological data collected near Evanston are contained in a separate report.[75] Summaries are given here that help in determining parameter values to characterize the dispersion of airborne material.

The critical parameters are wind speed and atmospheric stability. The ranges of wind speed associated with each speed class are given in Table C-1. The value used to characterize the first wind speed class is larger than the class mid-point to account for erroneously low recorded values due to instrument starting threshold.[101]

Atmospheric stabilities classes were determined by calculating the Richardson number (RI) from measured wind speed and temperature data. The ranges of RI associated with each P-G stability class are given in Table C-2.

Wind direction classes were determined by dividing the 360-degree direction range into 22.5-degree sectors, each centered on one of the 16 points of the compass. Thus, the first class, labeled N, represents wind directions from 348.75 to 11.24 degrees and so on.

Given the above classifications, one year (8290 h) of hourly data from December 1981 to December 1982 were analyzed to evaluate joint frequency distributions of wind speed, direction, and atmospheric stability for the Evanston, Wyoming area. These joint

Table C-1. Richardson numbers used to predict Pasquill-Gifford stability categories.

Atmospheric stability class	Description	Range of Richardson numbers RI
A	Very unstable	RI < - 0.452
B	Moderately unstable	-0.452 < RI < - 0.236
C	Slightly unstable	-0.236 < RI < - 0.066
DD	Neutral (day)	-0.066 < RI < 0.066
DN	Neutral (night)	-0.066 < RI < 0.066
E	Slightly stable	0.066 < RI < 0.0236
F	Moderately stable	0.236 < RI

Table C-2. Wind speed classes used to define the dispersion meteorology of Evanston, Wyoming.

Wind speed class	Range of wind velocities (mph (m/sec))		Velocity used for dispersion calculations (mph (m/sec))	
1	0 - 3.6	(0- 1.6)	3.4	(1.5)
2	3.8 - 7.6	(1.7- 3.4)	5.5	(2.46)
3	7.8 - 12.1	(3.5- 5.4)	10	(4.47)
4	12.3 - 17.4	(5.5- 7.8)	15.5	(6.93)
5	17.7 - 23.9	(7.9-10.7)	21.5	(9.61)
6	>23.9	(>10.7)	28	(12.52)

frequency distributions, shown in Table C-3, are most representative of the valley area from the airport station to the disposal station (see Figure 5-1); extrapolation can be made to the town of Evanston. However, large extrapolation to the southwest or southeast of Evanston or far north of the airport must be done with caution; furthermore, large extrapolations into the hills north, south, or west of Evanston is inappropriate, especially during low wind speed, stable conditions.

A graphical display of the information in Table C-3 is shown below in Figures C-1 to C-7, in the form of wind roses for each stability class. Here, the spokes represent joint frequencies for given directions from which the wind blows. The length of the spoke is proportional to frequency, which has been normalized so that all spokes in each wind rose sum to give a total frequency of one. Spokes are subdivided into segments representing frequencies associated with different wind speed classes; here, frequencies for the first two speed classes are represented separately, while frequencies for the last four classes are combined in the third segment.

Several features of the joint frequency distribution are much more evident from the wind roses than from Table C-3. First, the winds associated with stability class F are predominately of low speed and from the southeast. Second, low speeds are also associated with stability classes A and E. Class B, C, and D (day) are predominately of moderate to high speed from the west and southwest. Finally, frequencies are spread across more directions in classes A, D (night) and E. These are just some of the conclusions that can be drawn from the figures below.

Table C-3. Joint frequency distributions of wind speed, direction, and atmospheric stability for the Evanston, Wyoming area based on 8290 h of data collected from December 1981 to December 1982.

Stability class	Wind direction	Wind speed class					
		1	2	3	4	5	6
A	N	0.000844	0.001930	0.000362	0.000241	0.000000	0.000000
	NNE	0.000603	0.001327	0.000603	0.000000	0.000000	0.000000
	NE	0.000724	0.000121	0.000000	0.000000	0.000000	0.000000
	ENE	0.000241	0.000362	0.000241	0.000000	0.000000	0.000000
	E	0.000241	0.000965	0.001448	0.000121	0.000000	0.000000
	ESE	0.001689	0.002654	0.000603	0.000000	0.000000	0.000000
	SE	0.006996	0.002292	0.000121	0.000000	0.000000	0.000000
	SSE	0.011460	0.005428	0.000121	0.000000	0.000000	0.000000
	S	0.012304	0.006634	0.000121	0.000000	0.000000	0.000000
	SSW	0.008323	0.008203	0.000362	0.000000	0.000000	0.000000
	SW	0.006876	0.009650	0.004946	0.000000	0.000000	0.000000
	WSW	0.007841	0.008806	0.009168	0.000241	0.000000	0.000000
	W	0.008565	0.008082	0.006393	0.000121	0.000000	0.000000
	WNW	0.005428	0.007841	0.002292	0.000000	0.000000	0.000000
	NW	0.005669	0.010133	0.004222	0.000483	0.000000	0.000000
	NNW	0.002533	0.007720	0.004463	0.000000	0.000000	0.000000
B	N	0.000121	0.000121	0.000241	0.000362	0.000000	0.000000
	NNE	0.000000	0.000121	0.000000	0.000000	0.000000	0.000000
	NE	0.000121	0.000000	0.000000	0.000000	0.000000	0.000000
	ENE	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
	E	0.000121	0.000241	0.000603	0.000483	0.000000	0.000000
	ESE	0.000000	0.000362	0.000362	0.000000	0.000000	0.000000
	SE	0.000121	0.000241	0.000121	0.000000	0.000000	0.000000
	SSE	0.000603	0.001327	0.000241	0.000000	0.000000	0.000000
	S	0.000362	0.000603	0.000000	0.000000	0.000000	0.000000
	SSW	0.000000	0.001206	0.000965	0.000000	0.000000	0.000000
	SW	0.000000	0.000965	0.003136	0.000483	0.000000	0.000000
	WSW	0.000000	0.000724	0.006996	0.000603	0.000000	0.000000
	W	0.000000	0.000844	0.003981	0.001206	0.000000	0.000000
	WNW	0.000000	0.000483	0.001689	0.000844	0.000000	0.000000
	NW	0.000000	0.000362	0.001206	0.000844	0.000000	0.000000
	NNW	0.000121	0.001086	0.001327	0.000362	0.000000	0.000000
C	N	0.000000	0.000000	0.000121	0.000000	0.000000	0.000000
	NNE	0.000000	0.000121	0.000121	0.000000	0.000000	0.000000
	NE	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
	ENE	0.000000	0.000121	0.000000	0.000121	0.000000	0.000000
	E	0.000000	0.000241	0.000844	0.000724	0.000000	0.000000
	ESE	0.000000	0.000241	0.000121	0.000000	0.000000	0.000000
	SE	0.000241	0.000965	0.000121	0.000000	0.000000	0.000000
	SSE	0.000121	0.000603	0.000724	0.000121	0.000000	0.000000
	S	0.000362	0.000724	0.000483	0.000000	0.000000	0.000000
	SSW	0.000483	0.001206	0.000603	0.000362	0.000241	0.000000
	SW	0.000121	0.002774	0.004825	0.002654	0.000241	0.000000
	WSW	0.000121	0.001448	0.004946	0.004343	0.000121	0.000000
	W	0.000121	0.001568	0.005187	0.006755	0.000000	0.000000
	WNW	0.000121	0.000724	0.003860	0.004825	0.000241	0.000000
	NW	0.000121	0.000483	0.001809	0.001448	0.000724	0.000000
	NNW	0.000121	0.000965	0.000724	0.000362	0.000000	0.000000

Table C-3 (continued).

Stability class	Wind direction	Wind speed class					
		1	2	3	4	5	6
DD	N	0.000000	0.000121	0.000121	0.000121	0.000121	0.000000
	NNE	0.000000	0.000121	0.000000	0.000000	0.000000	0.000000
	NE	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
	ENE	0.000000	0.000000	0.000000	0.000241	0.000000	0.000000
	E	0.000000	0.000241	0.000241	0.000362	0.000121	0.000000
	ESE	0.000000	0.000362	0.001327	0.000362	0.000121	0.000121
	SE	0.000965	0.000483	0.000483	0.000121	0.000000	0.000000
	SSE	0.000844	0.000603	0.000241	0.000121	0.000000	0.000000
	S	0.000362	0.001448	0.001327	0.000483	0.000000	0.000000
	SSW	0.000241	0.003016	0.001930	0.001086	0.000362	0.000000
	SW	0.000121	0.003619	0.008444	0.005669	0.001327	0.000121
	WSW	0.000000	0.001689	0.007600	0.004463	0.000483	0.000000
	W	0.000000	0.000724	0.004343	0.005790	0.001206	0.000000
	WNW	0.000000	0.000483	0.000965	0.002413	0.001086	0.000483
	NW	0.000000	0.000241	0.000483	0.000483	0.000362	0.000241
	NNW	0.000362	0.000121	0.000362	0.000121	0.000000	0.000000
DN	N	0.000121	0.000121	0.000724	0.000483	0.000000	0.000000
	NNE	0.000241	0.000241	0.000121	0.000121	0.000000	0.000000
	NE	0.000000	0.000000	0.000121	0.000000	0.000000	0.000000
	ENE	0.000000	0.000121	0.000121	0.000483	0.000000	0.000000
	E	0.000000	0.000483	0.001930	0.001809	0.000241	0.000000
	ESE	0.000965	0.000965	0.001930	0.000483	0.000121	0.000000
	SE	0.003016	0.001809	0.000844	0.000241	0.000000	0.000000
	SSE	0.002171	0.002895	0.000724	0.000241	0.000000	0.000000
	S	0.002171	0.004704	0.002413	0.000241	0.000000	0.000000
	SSW	0.001327	0.006996	0.002413	0.000121	0.000000	0.000000
	SW	0.000965	0.005066	0.008926	0.003860	0.000121	0.000000
	WSW	0.000603	0.005549	0.006996	0.002171	0.000241	0.000000
	W	0.000362	0.003257	0.006634	0.003016	0.000000	0.000000
	WNW	0.000362	0.001930	0.005308	0.002171	0.000241	0.000000
	NW	0.000362	0.000844	0.002774	0.000724	0.000483	0.000000
	NNW	0.000483	0.002051	0.001327	0.000603	0.000000	0.000000
E	N	0.000241	0.000603	0.000000	0.000000	0.000000	0.000000
	NNE	0.000362	0.000241	0.000000	0.000000	0.000000	0.000000
	NE	0.000483	0.000241	0.000000	0.000000	0.000000	0.000000
	ENE	0.001086	0.000844	0.000000	0.000000	0.000000	0.000000
	E	0.002533	0.001809	0.001086	0.000121	0.000000	0.000000
	ESE	0.004463	0.005308	0.001689	0.000121	0.000000	0.000000
	SE	0.018094	0.005790	0.001206	0.000000	0.000000	0.000000
	SSE	0.013631	0.004825	0.000121	0.000000	0.000000	0.000000
	S	0.009891	0.009168	0.001448	0.000000	0.000000	0.000000
	SSW	0.007961	0.010374	0.002292	0.000121	0.000000	0.000000
	SW	0.005066	0.007961	0.002292	0.002051	0.000362	0.000000
	WSW	0.002292	0.009409	0.002654	0.001206	0.000241	0.000000
	W	0.001448	0.006634	0.001689	0.000121	0.000000	0.000000
	WNW	0.001448	0.003498	0.000724	0.000000	0.000000	0.000000
	NW	0.001086	0.003136	0.000000	0.000121	0.000000	0.000000
	NNW	0.000724	0.003257	0.000362	0.000000	0.000000	0.000000

Table C-3 (continued).

Stability class	Wind direction	Wind speed class					
		1	2	3	4	5	6
F	N	0.001930	0.000121	0.000000	0.000000	0.000000	0.000000
	NNE	0.002292	0.000000	0.000000	0.000000	0.000000	0.000000
	NE	0.001809	0.000000	0.000000	0.000000	0.000000	0.000000
	ENE	0.001930	0.000603	0.000000	0.000121	0.000000	0.000000
	E	0.018818	0.003257	0.000121	0.000603	0.000000	0.000000
	ESE	0.052955	0.003981	0.000121	0.000000	0.000000	0.000000
	SE	0.096140	0.004343	0.000000	0.000000	0.000000	0.000000
	SSE	0.048251	0.003136	0.000000	0.000000	0.000000	0.000000
	S	0.031966	0.002051	0.000000	0.000000	0.000000	0.000000
	SSW	0.021834	0.002533	0.000965	0.000121	0.000000	0.000000
	SW	0.011821	0.002895	0.004825	0.001206	0.000844	0.000000
	WSW	0.007479	0.001086	0.000362	0.000844	0.000362	0.000000
	W	0.005549	0.001930	0.000000	0.000000	0.000000	0.000000
	WNW	0.006393	0.000603	0.000000	0.000000	0.000000	0.000000
	NW	0.004101	0.000724	0.000000	0.000000	0.000000	0.000000
	NNW	0.003257	0.000724	0.000000	0.000000	0.000000	0.000000

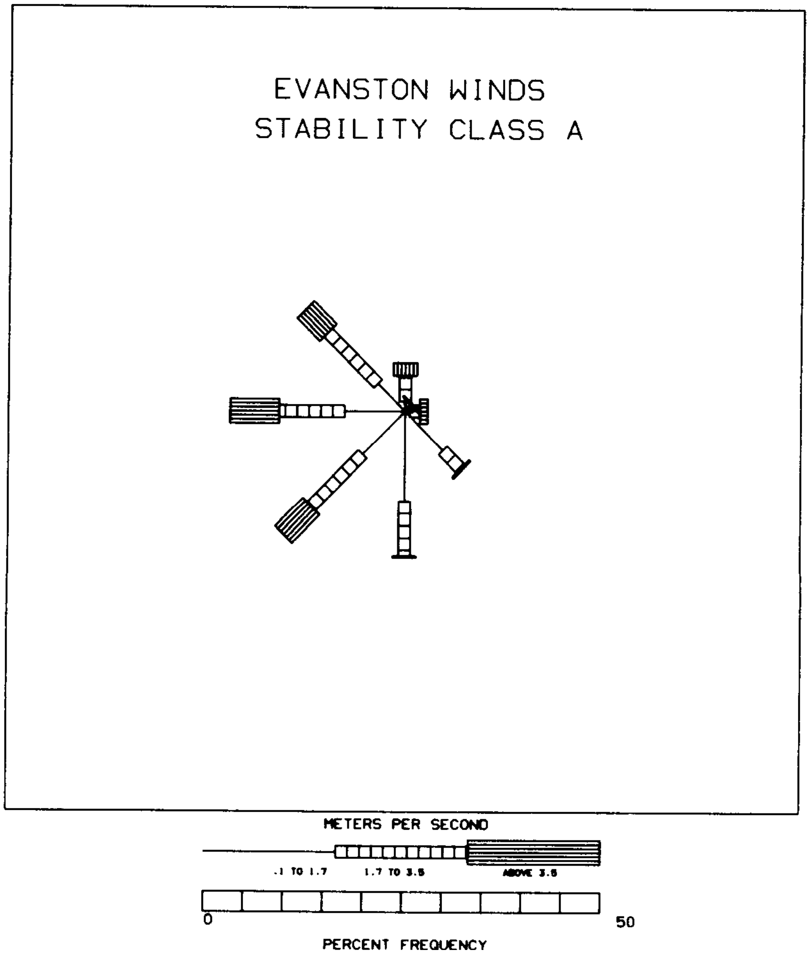

Figure C-1. Wind rose for winds associated with Pasquill-Gifford stability class A. Based on hourly data (December 1981 to December 1982) collected at Evanston, Wyoming.

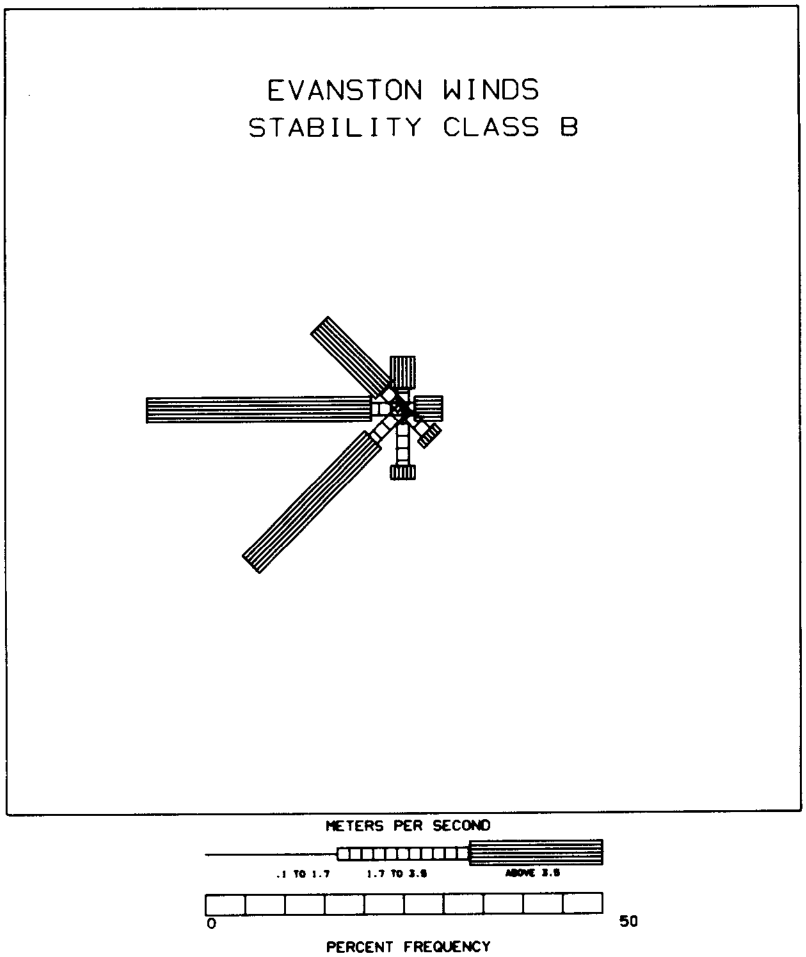

Figure C-2. Wind rose for winds associated with Pasquill-Gifford stability class B. Based on hourly data (December 1981 to December 1982) collected at Evanston, Wyoming.

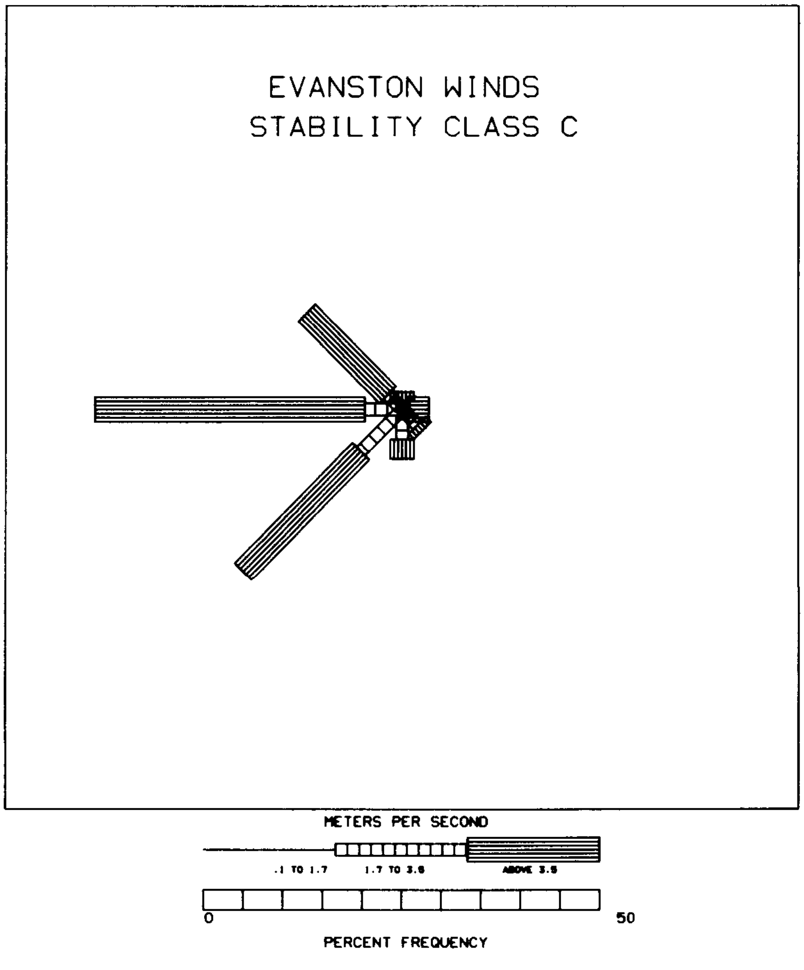

Figure C-3. Wind rose for winds associated with Pasquill-Gifford stability class C. Based on hourly data (December 1981 to December 1982) collected at Evanston, Wyoming.

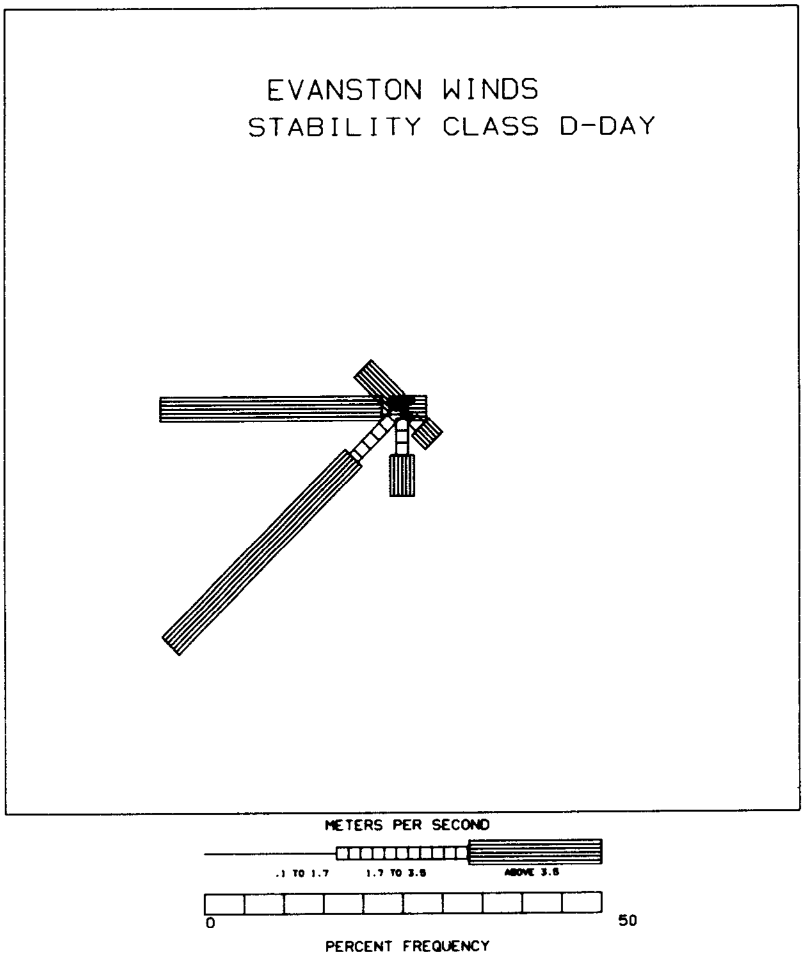

Figure C-4. Wind rose for winds associated with Pasquill-Gifford stability class D-day. Based on hourly data (December 1981 to December 1982) collected at Evanston, Wyoming.

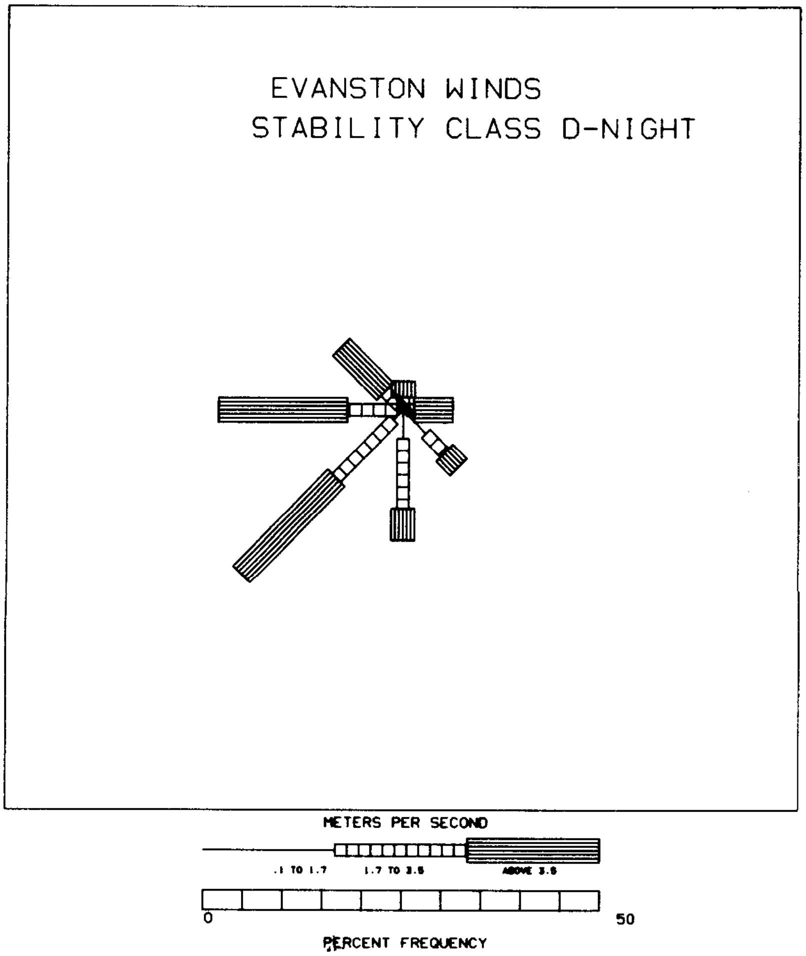

Figure C-5. Wind rose for winds associated with Pasquill-Gifford stability class D-night. Based on hourly data (December 1981 to December 1982) collected at Evanston, Wyoming.

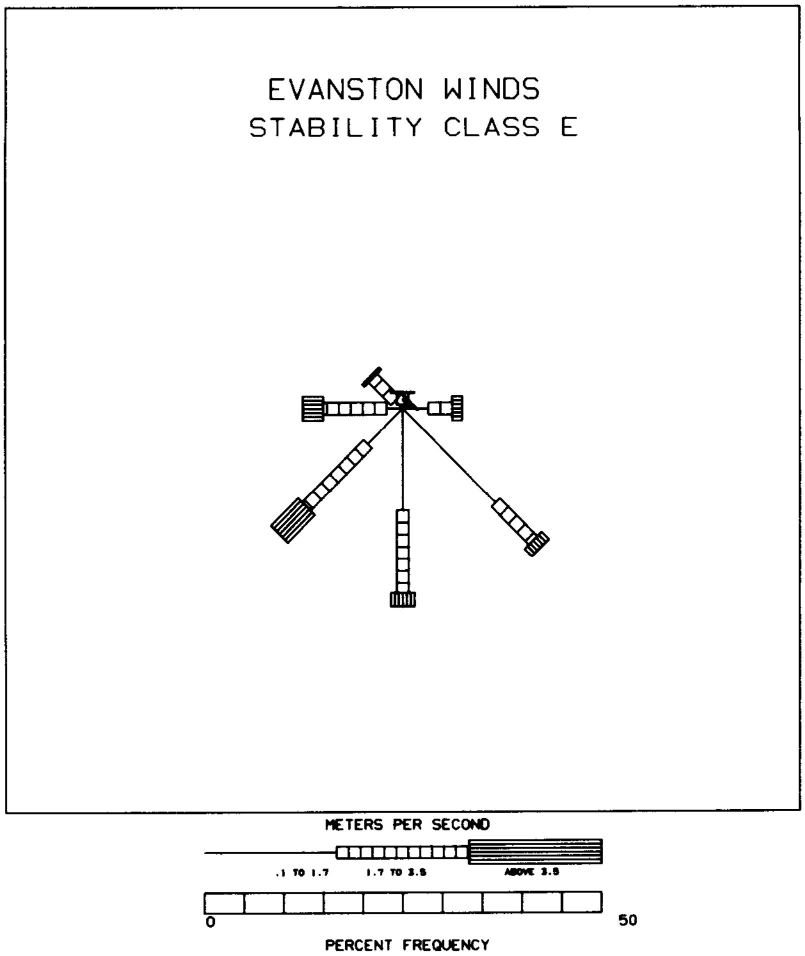

Figure C-6. Wind rose for winds associated with Pasquill-Gifford stability class E. Based on hourly data (December 1981 to December 1982) collected at Evanston, Wyoming.

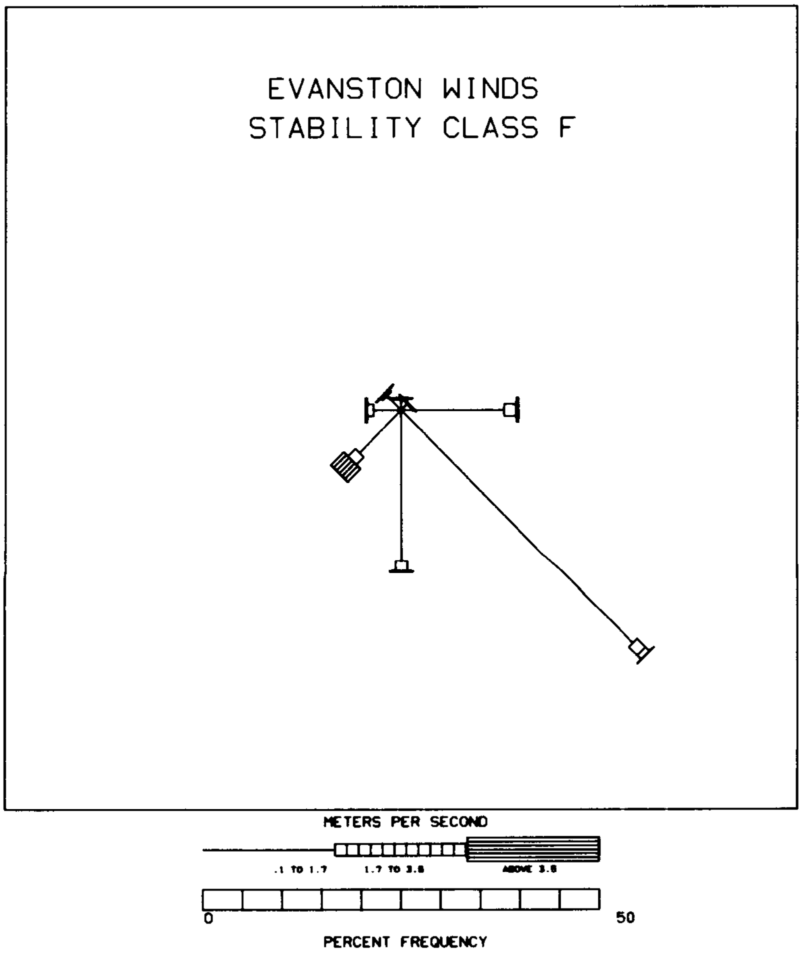

Figure C-7. Wind rose for winds associated with Pasquill-Gifford stability class F. Based on hourly data (December 1981 to December 1982) collected at Evanston, Wyoming.

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