

# Development of Wellhead Safety Zone Criteria for Underground Gas Storage Facilities



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## ABSTRACT

Underground natural gas storage facilities are a vital part of the U. S. national infrastructure. However, the concept of hazard zones from fires and explosions at these facilities is not nearly as well defined as it is for natural gas transmission pipelines. This report will take a well-established criterion for pipeline hazard zones (the Pipeline Impact Radius or PIR) and adapt it to underground gas storage facilities. The new safety area predicted for an underground gas storage facility will be called the Wellhead Safety Zone or WSZ. Comparisons will be made between the resulting WSZ formula and the observed damage zone from known accidents at gas storage facilities.

## 1. INTRODUCTION

A widely accepted criterion for the potential hazard zone due to fire following a natural gas pipeline break was developed by Mark J. Stephens of the Gas Research Institute [1]. Stephens expressed his hazard zone in terms of the area that would be subjected to an average radiant heat flux greater than 5000 Btu/hr-ft<sup>2</sup> over the first 30 seconds of the fire. Gas ignition was assumed to take place simultaneously with the pipeline rupture. This set of criteria gives rise to a Pipeline Impact Radius (PIR) defined by the formula:

$$\text{PIR} = 0.685*(Pd^2)^{1/2}, \quad (1)$$

where P is the absolute pipeline pressure in psia, d is the line diameter in inches, and the PIR is expressed in feet [1]. Stephens assumed a double-ended break of the pipeline, with gas discharging from both ends. He also assumed a combustion efficiency of 0.35 for the gas and that average gas flow over the first 30 seconds of the blowdown would be only 33% of the initial instantaneous flow rate [1].

As part of the effort at Oak Ridge National Laboratory (ORNL) to establish a wellhead safety zone for natural gas storage facilities, adjustments will be made to Stephens' assumptions to adapt his PIR formula to this new set of facility conditions.

## 2. METHODOLOGY

A key aspect of analyzing natural gas storage facility releases is developing a model for the gas discharge rate as a function of time. The solution is a blowdown calculation using a specified reservoir volume and adiabatic expansion of the gas through the orifice with the flow rate given by the expression for choked flow. The result gives closed-form expressions for pressure and temperature as functions of time and mass loss rate through the orifice as a function of time.

### 2.1 GAS DYNAMICS OF RESERVOIR DISCHARGE

According to the work of Stephens [1], the choked discharge of gas from a reservoir has a mass flow rate  $\dot{m}$  given by:

$$\dot{m} = C_D P A_c [(\gamma/RT) (2/(\gamma+1))^{(\gamma+1)/(\gamma-1)}]^{1/2}, \quad (2)$$

where P is the absolute reservoir pressure, T is the absolute temperature,  $\gamma$  is the ratio of specific heats for the gas, and R is the ideal gas constant for the gas involved. In Eq. (2)  $A_c$  is the cross-sectional area of the opening and  $C_D$  is an empirical factor called the discharge coefficient ( $\approx 0.62$ ), which accounts for the fact that the outflow stream tends to narrow and not make full use of the entire cross-sectional area of the opening. The minimum flow area is called the "vena contracta."

## 2.2 THERMODYNAMIC CONSIDERATIONS

Equation (2) shows that the discharge mass flow rate depends on both the reservoir pressure and reservoir temperature, which are themselves changing throughout the transient blowdown. The blowdown process is relatively rapid and there is not much time for heat transfer between the reservoir walls and the gas. Thus, it is reasonable to assume an adiabatic condition for the gas, and a relationship between the reservoir gas temperature and pressure can be obtained by applying the energy equation. Under adiabatic conditions, the energy equation requires that the time rate of change for the internal energy of the gas in the reservoir plus the rate of enthalpy transport by the escaping gas equals 0:

$$d/dt (mu) + \dot{m} h = 0 , \quad (3)$$

where  $m$  is the mass of gas in the reservoir,  $u$  is the internal energy of the gas, and  $h = u + Pv$  is the enthalpy [2].

If one expands the first term in Eq. (3) and notes that  $\dot{m} = -dm/dt$  from the conservation of mass, then

$$m (du/dt) + u (dm/dt) - h (dm/dt) = 0 . \quad (4)$$

Since  $h = u + Pv$  and  $Pv = RT$  from the ideal gas law, it follows that

$$m(du/dt) = RT (dm/dt) . \quad (5)$$

Now the internal energy of an ideal gas can be expressed in terms of the gas temperature as  $u = c_v T$  where  $c_v$  is the specific heat of the gas at constant volume

$$m c_v (dT/dt) = RT (dm/dt) . \quad (6)$$

One can simplify Eq. (6) using the chain rule by noting that  $dT/dt = (dT/dm)(dm/dt)$  so that

$$m c_v (dT/dm) = RT . \quad (7)$$

Furthermore  $R/c_v = \gamma - 1$ , so Eq. (7) can be separated and expressed as:

$$dT/T = (dm/m) (\gamma - 1) . \quad (8)$$

Integrating Eq. (8) from the initial reservoir temperature and gas mass ( $T_i$  and  $m_i$ ) to some later condition yields:

$$T/T_i = (m/m_i)^{\gamma-1} . \quad (9)$$

It is possible to convert Eq. (9) into a relationship between pressure and temperature by recognizing that the gas specific volumes must be in the inverse ratio of the reservoir gas masses so that

$$T/T_i = (v_i/v)^{\gamma-1} , \quad (10)$$

and noting that  $Pv = RT$  from the ideal gas law. Carrying out the calculation yields:

$$T/T_i = (P/P_i)^{(\gamma-1)/\gamma} , \quad (11)$$

which matches a standard relationship for the temperature and pressure of an ideal gas undergoing an isentropic process [2].

### 2.3 SOLUTION FOR GAS DISCHARGE

Returning to Eq. (2), one can replace  $m_{\text{dot}}$  by  $-dm/dt$ . If the reservoir consists of a volume  $V$  and the rupture is a guillotine break with the same cross-sectional area as the wellhead pipe

$$m = PV/(RT) , \quad (12)$$

and

$$(d/dt) [P V/(RT)] = -C_D P A_c [(\gamma/RT) (2/(\gamma+1))^{(\gamma+1)/(\gamma-1)}]^{1/2} . \quad (13)$$

Equation (11) can be used to eliminate  $T$  in terms of  $P$  in Eq. (13) to obtain a single differential equation for the reservoir pressure as a function of time,

$$P_i^{(\gamma-1)/(2\gamma)} (L V/T_i^{1/2})(1/\gamma) P^{(1/\gamma)-1} (dP/dt) = -C_D A_c [\gamma R (2/(\gamma+1))^{(\gamma+1)/(\gamma-1)}]^{1/2} P^{(\gamma+1)/(2\gamma)} . \quad (14)$$

Defining the constant  $\zeta$  as

$$\zeta = -C_D A_c [\gamma R (2/(\gamma+1))^{(\gamma+1)/(\gamma-1)}]^{1/2} P_i^{-(\gamma-1)/(2\gamma)} T_i^{1/2}/V , \quad (15)$$

and separating variables in Eq. (15) gives

$$(1/\gamma) P^{(1-3\gamma)/(2\gamma)} dP = \zeta dt , \quad (16)$$

which can be integrated between pressure  $P_i$  at time  $t = 0$  and pressure  $P$  at some later time.

The resulting equation is:

$$P(t) = [((1-\gamma)/2) \zeta t + P^{(1-\gamma)/(2\gamma)}]^{2\gamma/(1-\gamma)} . \quad (17)$$

Once the pressure at time  $t$  has been determined from Eq. (17), the temperature for that time is obtained from Eq. (11) and the corresponding discharge mass flow rate is then obtained from Eq. (2). The calculated flow rate will remain valid as long as the reservoir pressure is high enough to cause choked flow at the exit plane, which requires [3]

$$P > P_{\text{atm}} [(\gamma+1)/2]^{\gamma/(\gamma-1)} . \quad (18)$$

Using  $\gamma = 1.32$  for natural gas and  $P_{\text{atm}} = 14.7$  psi for the absolute atmospheric pressure, Eq. (18) indicates that choked flow will occur for reservoir pressures of  $P > 27.1$  psi.

The preceding model has been coded as an Excel spreadsheet for determining the mass flow rates of escaping gas from a broken gas storage wellhead as a function of time following the break.

The instantaneous hazard radius,  $r$ , for a particular heat flux level from the natural gas fire can be found from the instantaneous gas discharge rate  $m_{\text{dot}}$  using the formula:

$$r = [0.2 \eta H_c m_{\text{dot}} / (4\pi I)]^{1/2} , \quad (19)$$

where  $\eta$  is the gas combustion efficiency factor,  $H_c$  is the heat of combustion for the gas (about 50,000 kJ/kg for methane), and  $I$  is the heat flux level of interest.

### 3. RESULTS

Equation (19) has been used to track the radius associated with a particular heat flux level in the Excel spreadsheet at each stage of the gas storage wellhead blowdown.

#### 3.1 BOUNDING CASES FOR GAS STORAGE FACILITIES

Some results are collected below for the 5000 Btu/hr-ft<sup>2</sup> radius as a function of time for a reasonable bounding range of blowdown cases: a very large, high-pressure design of gas storage facility [22.2 billion cubic feet (BCF) of gas at 3600 psi pressure and a 19.25 inch wellhead diameter] and a much smaller facility (0.83 BCF at 2200 psi with a 7 inch wellhead).

##### Large Gas Storage Facility Case

Initial pressure = 3600 psi

Reservoir V = 22.2 BCF

Well D = 19.25 inches

$$\text{PIR} = 0.685 \cdot (\text{Pd}^2)^{1/2} = 791 \text{ ft}$$

Time (hrs)	5000 Btu/hr-ft <sup>2</sup> radius from fire		
	burn $\eta = 0.35$	burn $\eta = 1.0$	burn $\eta = 0.5$
0	974.7 ft	1647.6 ft	1165.0 ft
0.5	963.0 ft	1627.7 ft	1151.0 ft
1	951.4 ft	1608.1 ft	1137.1 ft
12	736.0 ft	1244.1 ft	879.7 ft
24	566.7 ft	957.9 ft	677.3 ft
48	352.8 ft	596.3 ft	421.6 ft

##### Small Gas Storage Facility Case

Initial pressure = 2200 psi

Reservoir V = 0.83 BCF

Well D = 7 inches

$$\text{PIR} = 0.685 \cdot (\text{Pd}^2)^{1/2} = 224.9 \text{ ft}$$

Time (hrs)	5000 Btu/hr-ft <sup>2</sup> radius from fire		
	burn $\eta = 0.35$	burn $\eta = 1.0$	burn $\eta = 0.5$
0	277.1 ft	468.3 ft	331.2 ft
0.25	273.5 ft	462.2 ft	326.9 ft
0.5	269.9 ft	456.2 ft	322.6 ft
1	263.0 ft	444.5 ft	314.3 ft
12	154.7 ft	261.5 ft	184.9 ft
24	93.4 ft	157.9 ft	111.6 ft



In both these cases, blowdown of the gas storage reservoir requires from one to several days to complete. It is important to note that the blowdown for even a small gas storage well is much slower than Stephens found for pipeline break transients [1], and there is little decrease in the initial hazard radius over the first few hours (much less the first 30 seconds as observed by Stephens for pipelines) of the blowdown. Also, the 5000 Btu/hr-ft<sup>2</sup> radius at time t = 0 is greater than the Stephens PIR, even when the same burn efficiency of 0.35 is assumed.

There are definitely two things that need to be done to adapt the PIR methodology from a pipeline case to an underground gas storage reservoir. The PIR derivation assumes a double-ended break of the pipeline, with both ends discharging gas. A gas storage well only has a one-sided situation with gas emerging from the reservoir, so this factor of two is not needed. The PIR also applies an averaging factor of 0.33 to the initial flow rate to account for reduction in flow over the first 30 seconds of the blowdown (which is appreciable in a pipeline where the ratio of gas volume to hole size is much less). For an underground reservoir the gas flow decays much slower and, one certainly should not use this factor of 0.33. Therefore, the true radius from a well rupture where one would have a heat flux of 5000 Btu/hr-ft<sup>2</sup> is given by  $PIR * [(1/2) * (1/0.33)]^{1/2} = PIR * 1.2309$  if one continues to assume a burn efficiency of  $\eta = 0.35$ .

Applying this factor of 1.2309 to the Stephens PIR values yields  $1.2309 * (791 \text{ feet}) = 974 \text{ feet}$  for the large high-pressure gas storage case and  $1.2309 * (224.9 \text{ feet}) = 277 \text{ feet}$  for the smaller low-pressure case. In both of these instances, the adjusted PIR now matches the calculated 5000 Btu/hr-ft<sup>2</sup> radius at time t = 0 for an assumed burn efficiency of 0.35.

### 3.2 COMPARISON WITH MOSS BLUFF INCIDENT

The Moss Bluff, TX accident of August 2004 provides an opportunity to refine the formula further and select an appropriate value for the burn efficiency. Moss Bluff involved blowdown of 5.4 BCF of gas with an initial pressure of 1898 psi and a wellhead diameter of 20 inches. The results of simulating these blowdown conditions with the Excel spreadsheet are shown below:

#### Moss Bluff parameters

Initial pressure = 1898 psi

Reservoir V = 5.4 BCF

Well D = 20 inches

$$PIR = 0.685 * (Pd^2)^{1/2} = 596.9 \text{ ft}$$

Time (hrs)	5000 Btu/hr-ft <sup>2</sup> radius from fire		
	burn $\eta = 0.35$	burn $\eta = 1.0$	burn $\eta = 0.5$
0	735.3 ft	1242.9 ft	878.9 ft
0.25	725.0 ft	1225.4 ft	866.5 ft
0.5	714.8 ft	1208.2 ft	854.3 ft
1	695.0 ft	1174.7 ft	830.6 ft
12	392.7 ft	663.8 ft	469.4 ft
24	229.4 ft	387.8 ft	274.2 ft
48	94.4 ft	159.5 ft	112.8 ft

Moss Bluff took several days to blow down the 5.4 BCF of gas, so the spreadsheet calculation is reasonably consistent with this timeline. According to the best available information, the burn radius at Moss Bluff

was 840 feet. This is somewhat greater than the calculated Moss Bluff PIR of 596.9 feet, indicating some adjustments to the pipeline PIR formula are necessary.

#### 4. CONCLUSIONS

Correcting for the double ended issue and the slower nature of a reservoir blowdown compared to a pipe break would give a new PIR of  $1.2309 \times 596.9$  feet = 735 feet at Moss Bluff, as can be seen in the tabulated blowdown model results with  $\eta = 0.35$ , which is still too small compared to the observed burn radius of 840 feet.

The other possible change to the PIR concerns increasing the assumed burn efficiency of  $\eta = 0.35$ . As shown from the Moss Bluff tables above, assuming  $\eta = 1.0$  would indicate a radius of 1242.9 ft under Moss Bluff conditions, which is too big. The exact  $\eta$  needed to match the observed 840 ft radius is actually  $\eta = 0.46$ . Given the uncertainties involved, it seems reasonable to use  $\eta = 0.50$  for simplicity and to include a small amount of conservatism in the formula. The new adjusted PIR for a gas storage facility will be referred to as a Wellhead Safety Zone (or WSZ).

This means the new WSZ formula would be given by:

$$\text{WSZ} = [0.685 \times 1.2309 \times (0.50/0.35)^{1/2}] \times (P \times d^2)^{1/2}$$

$$\text{WSZ} = 1.008 \times (P \times d^2)^{1/2} .$$

Thus, the new coefficient in the WSZ formula is 1.008 instead of the 0.685 PIR value found in Stephens' Gas Research Institute report for pipeline breaks (an increase of 47%), and the WSZ for Moss Bluff would be 878 feet, which is a very good correspondence with the 840 feet burn radius observed at Moss Bluff.

The new WSZ formula will also need to be tested against any other fires at gas storage facilities (such as the accident at Dominion, PA) for which data on the damage radius can be obtained.

#### REFERENCES

1. M. J. Stephens, *A Model for Sizing High Consequence Areas Associated with Natural Gas Pipelines*, Topical Report prepared for the Gas Research Institute by C-FER Technologies, GRI-00/0189, October 2000.
2. G. J. Van Wylen and R. E. Sonntag, *Fundamentals of Classical Thermodynamics*, 3<sup>rd</sup> Ed., John Wiley & Sons, Inc., New York, NY, 1985.
3. J. E. A. John, *Gas Dynamics*, 2<sup>nd</sup> Ed., Allyn and Bacon, Boston, 1984.

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