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The Potential Impact Radius Formula
Background to Development and Validation

prepared for the

Transportation Research Board

Committee on Criteria for Installing Automatic and Remote-Controlled Shutoff Valves on Existing Gas and Hazardous Liquid Transmission Pipelines

presented by

Mark Stephens, MSc, PEng
Senior Engineering Consultant to C-FER Technologies
m.stephens.contractor@cfertech.com

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The Potential Impact Radius (PIR) Formula

- A formula developed by C-FER (Stephens 2001) for estimating the extent of the significant thermal radiation hazard zone resulting from an ignited rupture of a natural gas pipeline
  - The underlying models idealize a time-varying large-scale fire as a steady-state, ground-level, point-source heat emitter for the purpose of hazard zone estimation
  - A concerted effort was made to develop and describe a modelling approach that would
    - be as simple as possible (to enhance understanding and promote acceptance), but also
    - incorporate factors the reduce conservatism inherent in the adopted modelling approach

Overview of the Model Components

- Effective release rate, Q_{eff} (kg/s)
  - λ = release rate decay factor
  - C_d = discharge coefficient
  - d = pipeline diameter
  - p = internal pressure
  - φ/a_0 = flow factor/sonic velocity
- Emissive power, E (kW)
  - H_c = heat of combustion
  - χ_g = emissivity factor
- Heat intensity, I (kW/m^2)
  - r = horizontal distance
  - η = efficiency factor

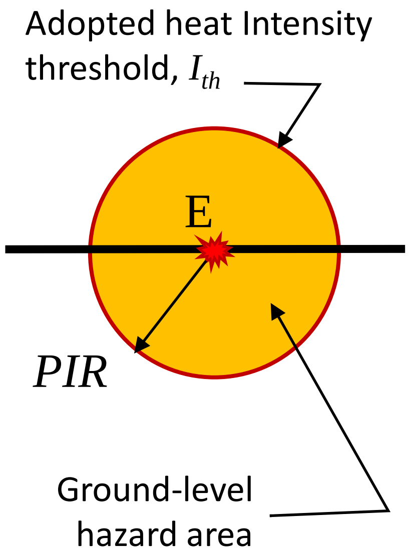
$$Q_{eff} = 2\,\lambda \boxed{C_d \frac{\pi d^2}{4} p \frac{\varphi}{a_0}}$$

Orifice discharge

$$E = Q_{eff}\, H_c\, \chi_g$$

$$I = \frac{E\,\eta}{4\pi r^2} \rightarrow r = \sqrt{\frac{E\,\eta}{4\pi I}} \rightarrow PIR = \sqrt{\frac{E\,\eta}{4\pi I_{th}}}$$

$$PIR = 0.69\sqrt{p d^2}$$



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PIR Model Components Subject to Concern

- Effective release rate, Q_{eff} (kg/s)
  - λ = release rate decay factor
  - C_d = discharge coefficient
  - d = pipeline diameter
  - p = internal pressure
  - φ/a_0 = flow factor/sonic velocity

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$$Q_{eff} = 2\,\lambda\,C_d\,\frac{\pi d^2}{4}\,p\,\frac{\varphi}{a_0}$$

- Emissive power, E (kW)
  - H_c = heat of combustion
  - χ_g = emissivity factor

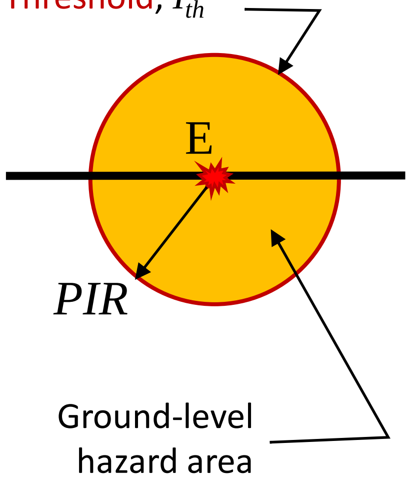
$$E = Q_{eff}\,H_c\,\chi_g$$

- Heat intensity, I (kW/m^2)
  - r = horizontal distance
  - η = efficiency factor

2

$$I = \frac{E\,\eta}{4\pi r^2} \qquad r = \sqrt{\frac{E\,\eta}{4\pi I}}$$

3 Adopted Heat Intensity Threshold, I_{th}

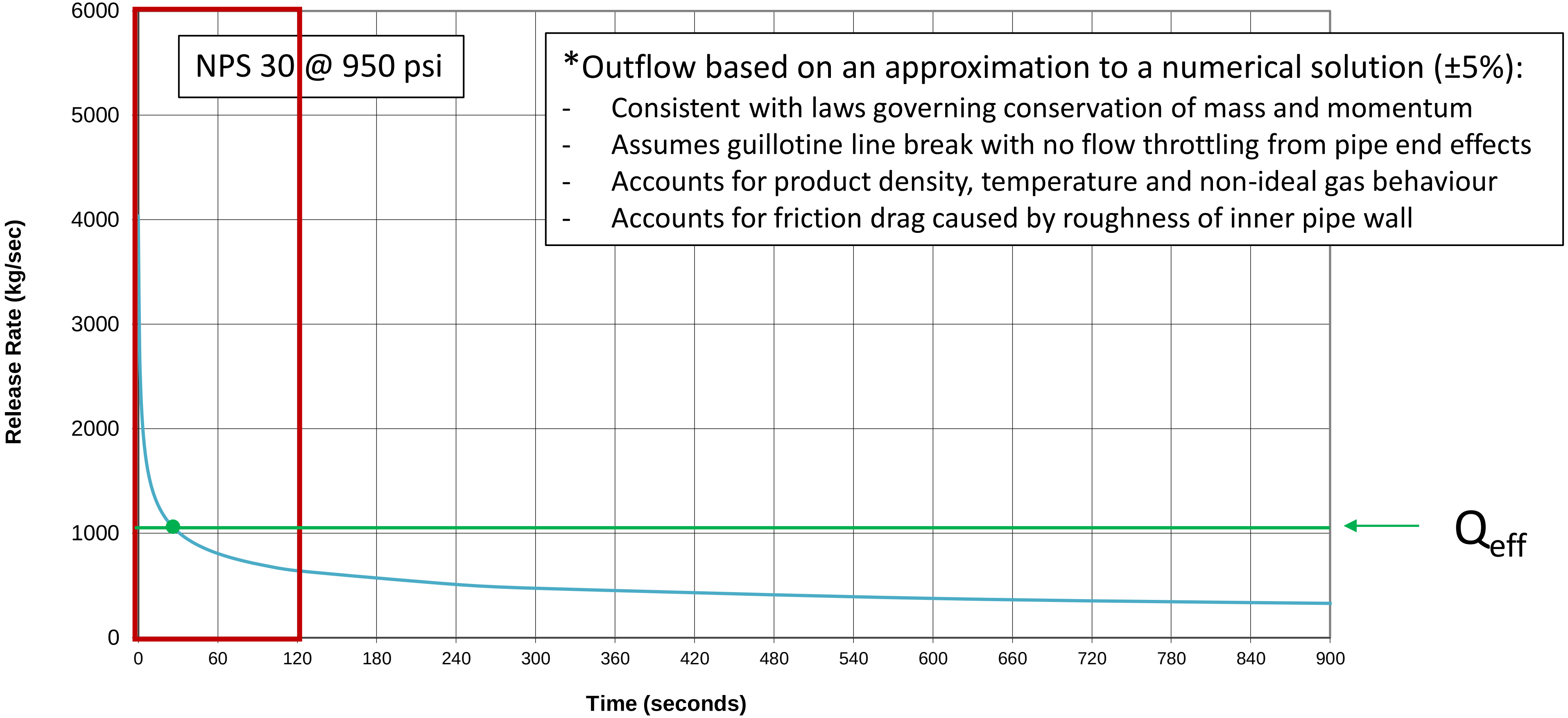


$$PIR = \sqrt{\frac{E\,\eta}{4\,\pi\,I_{th}}}$$

$$PIR = 0.69\sqrt{pd^2}$$

Effective Sustained Release Rate, Q_{eff}

- Comparisons to transient release rates – TNO (1982) rupture blowdown model*



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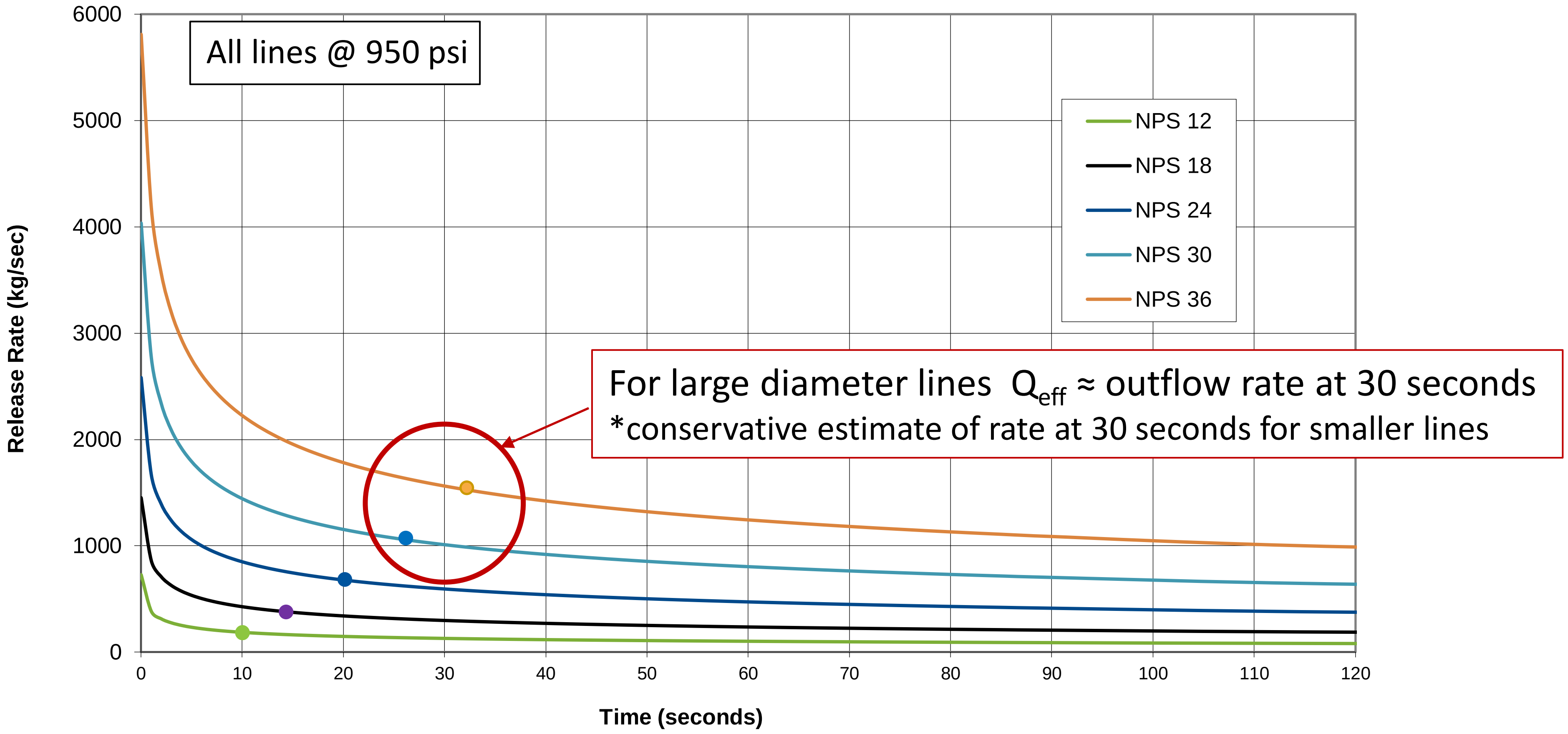
Effective Sustained Release Rate

- Comparisons to transient release rates - TNO (1982) rupture blowdown model



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Efficiency Factor, η

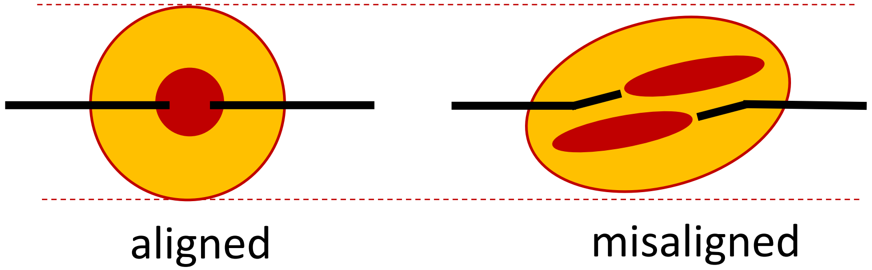
- The efficiency factor incorporated in the Technica (1988) fire model as adopted by C-FER addresses conservatisms inherent in the simplified form of the model used to estimate radiation intensity as a function of horizontal distance from an elevated fire source

- As discussed by Baker/C-FER in a report commissioned by PHMSA (Baker/C-FER 2005), the factor can be shown to effectively account for the following:
  - The effect of high-speed jetting on emmisivity —— a knock-down factor on the order of 0.75 [Chamberlain (1987) and Cook et al. (1987)]
  - The effect of atmospheric absorption on radiant heat reaching receptors —— a transmissivity factor on the order of 0.7 [Bagster and Pitblando (1989)]
  - The effect of fire geometry and flame opacity on the effective view factor —— a view factor adjustment on the order of 0.65 [Cook et al. (1987)]

- Efficiency factor, $\eta = 0.75 \times 0.7 \times 0.65 = 0.34 \approx 0.35$ ← Technica factor

Applicability of Fire Model to Real Rupture Fires

- Models underlying the PIR formula are a defensible basis for estimating radiation intensity from a crater fire associated with near-immediate ignition as a function of horizontal distance
- A crater fire develops when opposing gas jets impinge upon one another and the crater walls redirect flow upwards, effectively creating a vertically oriented flame
    - For such a vertical flame, the hazard zone is circular and centered on break point
- What about a rupture resulting in directed jets?
    - If opposing pipe ends are significantly misaligned, impingement of opposing jets does not occur, jets are still directed upwards by crater walls but two distinct jet flames can develop
        - For directed jets, the hazard zone is more elliptical
        - Total hazard area is comparable to that of crater fire, but generally width is reduced and length is increased



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Heat Intensity Threshold, I_{th}

- Adopted heat intensity threshold is 5,000 Btu/hr/ft^2
  - Impact on people
    - A 1% chance of lethality for individuals subject to approximately 30 seconds of sustained exposure
      - Based on a widely recognized dose-response relationship (i.e. a lethality probit function)
    - Basis for 30 second reference exposure time
      - Individuals assumed to pause for 5 s then travel at 5 mph (2.5 m/s) and find shelter within 200 ft (60 m)
        - » International precedent (BS PD 8010-3:2009) for 2.5 m/s travel speed and sheltered within 50 to 75 m
  - Impact on property
    - Highly unlikely that wooden structures will ignite and burn in the event of extended exposure
      - Adopted heat intensity threshold requires about 20 minutes of exposure to result in piloted ignition (no potential for spontaneous ignition) based on widely recognized dose-response relationship
    - Implications for people indoors — wood-framed dwelling will afford indefinite protection to occupants

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Implications of Adopted Heat Intensity Threshold that Defines Extent of PIR

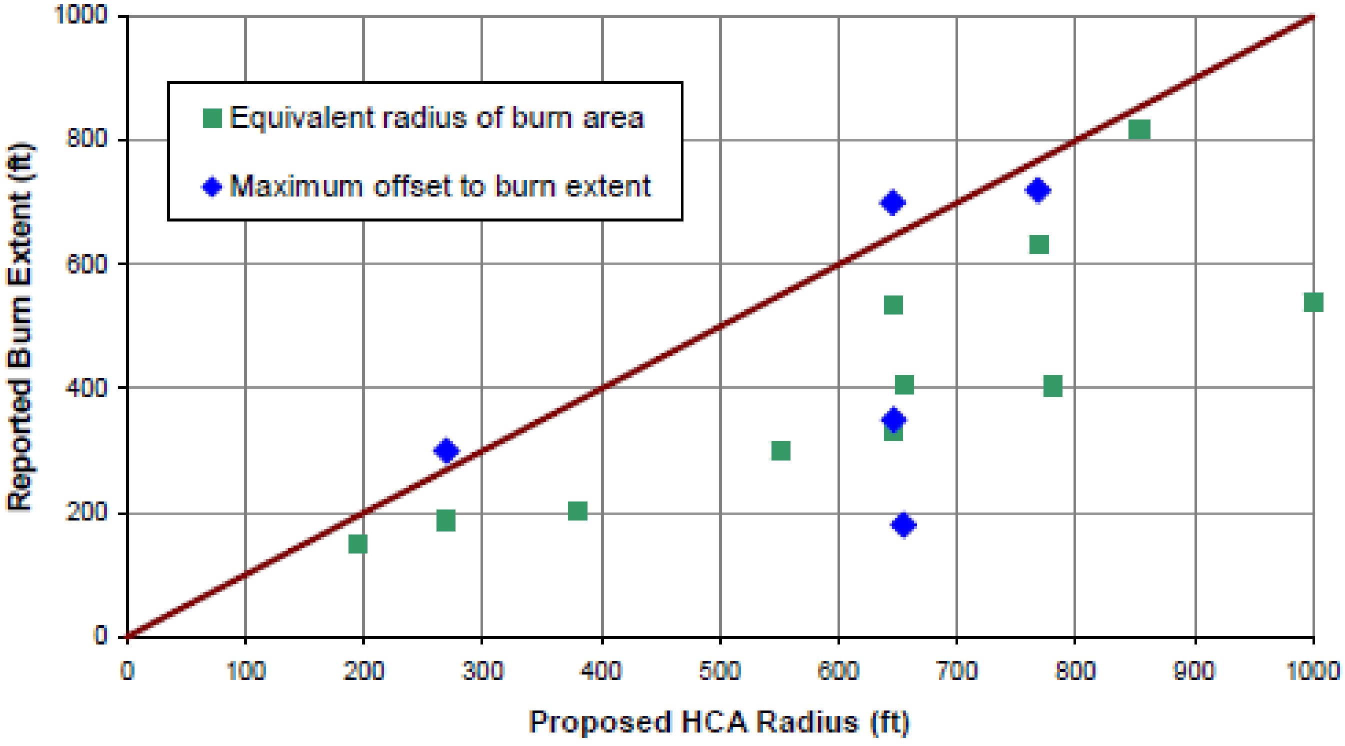
- It does delineate
  - the area within which fatal injury is a significant possibility
  - the area within which wood-framed dwelling destruction is possible

- It does not represent
  - the safe distance beyond which people and property are likely to be minimally affected
  - the perimeter of the emergency response planning zone or the safe approach distance

- Implications for validation by evaluation of historical incidents
  - It does not delineate the extent of the 'burn zone' (due to lower heat intensity required to ignite some vegetation and the potential for fire spread)
  - However, the burn zone is often the only available basis for the evaluation of model accuracy

Original Model Validation – Comparison of Burn Zones

- From GRI Report (Stephens 2001)



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Other Validation Effort – Safety Risk Focused

- A set of safety-related failure consequence analysis results were compared to those obtained from state-of-the-art consequence modelling (Rothwell and Stephens 2006)

- The study compared results obtained from the C-FER models, using an adaptation of the models underpinning the PIR formula, against those obtained using PIPESAFE, a proprietary pipeline risk analysis software tool initial developed under a joint industry project, now maintained by DNV UK
  - PIPESAFE contains a suite of interlinked consequence models specifically developed for gas transmission pipelines that have been validated by tests at scales up to 914 mm OD and 76 km in length
  - PIPESAFE is capable of taking into account many factors reflecting the attributes of the pipeline, its surroundings and contents, the nature of the failure, the meteorological conditions, and the presence and behaviour of potential receptors (see Acton et al. 2002)

Comparison of C-FER Model to PIPESAFE

- Individual risk

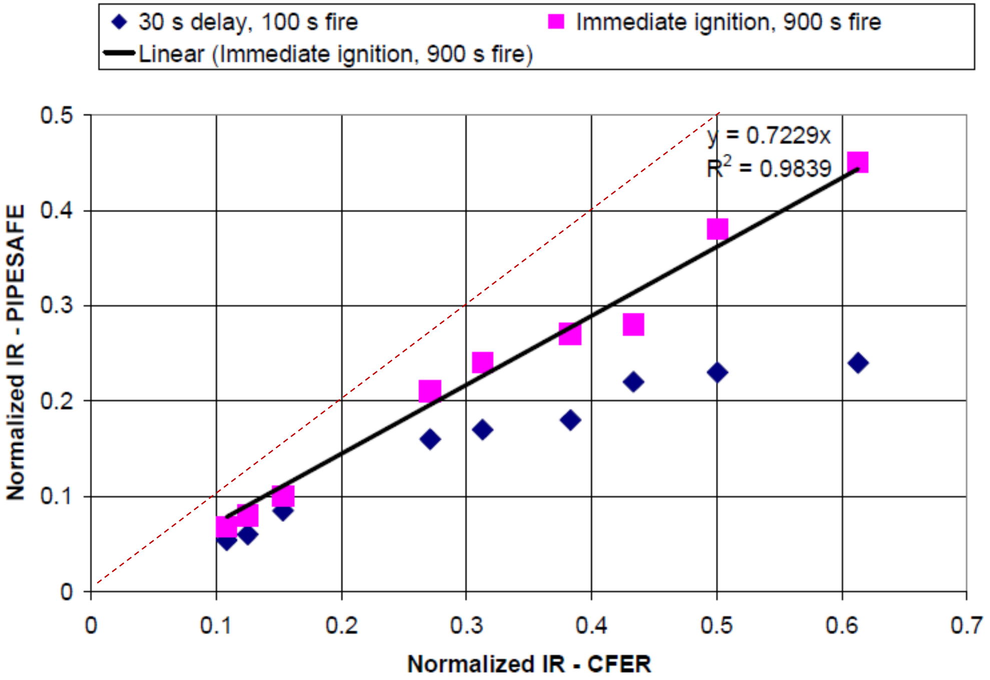

Figure 6 Relationship between normalized individual risk calculated by PIPESAFE and by the C-FER approach

Results from C-FER model plot to the right of the unity line (i.e. dashed red line) indicating conservatism compared to PIPESAFE results

Comparison of C-FER Model to PIPESAFE

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- Societal risk

Pipe diameter		NPS 48	NPS 48	NPS 24	NPS 24	NPS 12	NPS 12
Pressure, psi		1,500	750	1,500	750	1,500	750
Normalized fatalities per rupture	PIPESAFE	14	7	3	2	0.7	0.4
	C-FER	12	6	3	1.5	0.76	0.38

Fatality estimates very similar

Table 2 Normalized societal risk calculated by PIPESAFE and by the C-FER approach

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Summary

- C-FER's position on the current PIR formula:
  - The models used and assumptions that underpin the PIR formula are a reasonable and defensible basis for hazard zone estimation
  - The predictive capability of the PIR formula as currently defined is considered fit for general purpose consequence screening
    - The development focus was to delineate the likely extent of the fatality and property destruction zone for typically populated and developed areas
  - The PIR as currently defined
    - Is not be interpreted to represent the distance beyond which no impact on people or property would be expected

Danville, KY, 2019

NPS 30 @ 926 psi
(MAOP 935 psi)

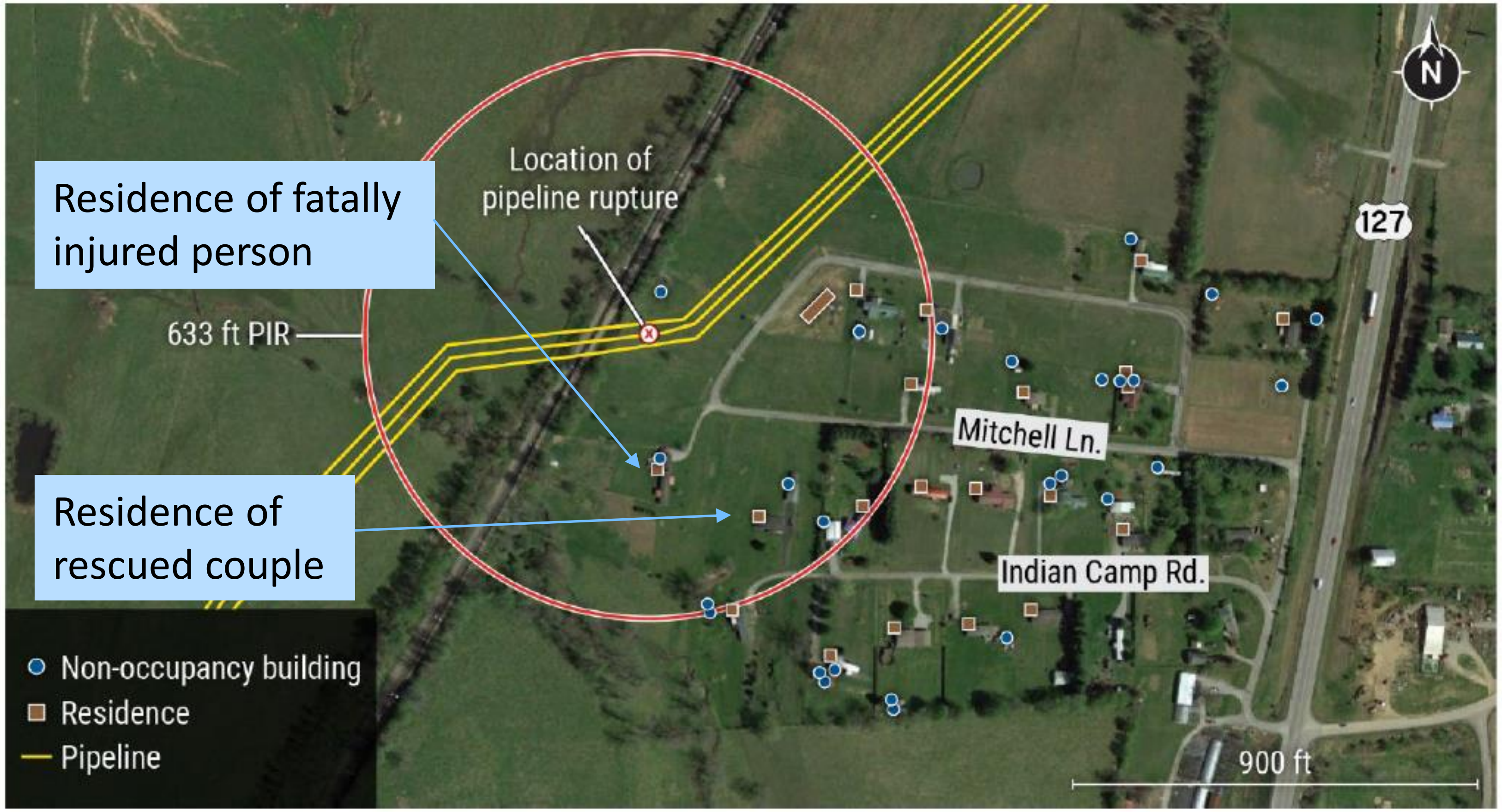

Figure 11. Human-occupancy buildings within the potential impact radius. (Courtesy of Enbridge.)

<u>Comments</u>

- Residence of deceased and all destroyed buildings fall within PIR

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Sissonville, WV, 2012

NPS 20 @ 929 psi
(MAOP 1,000 psi)

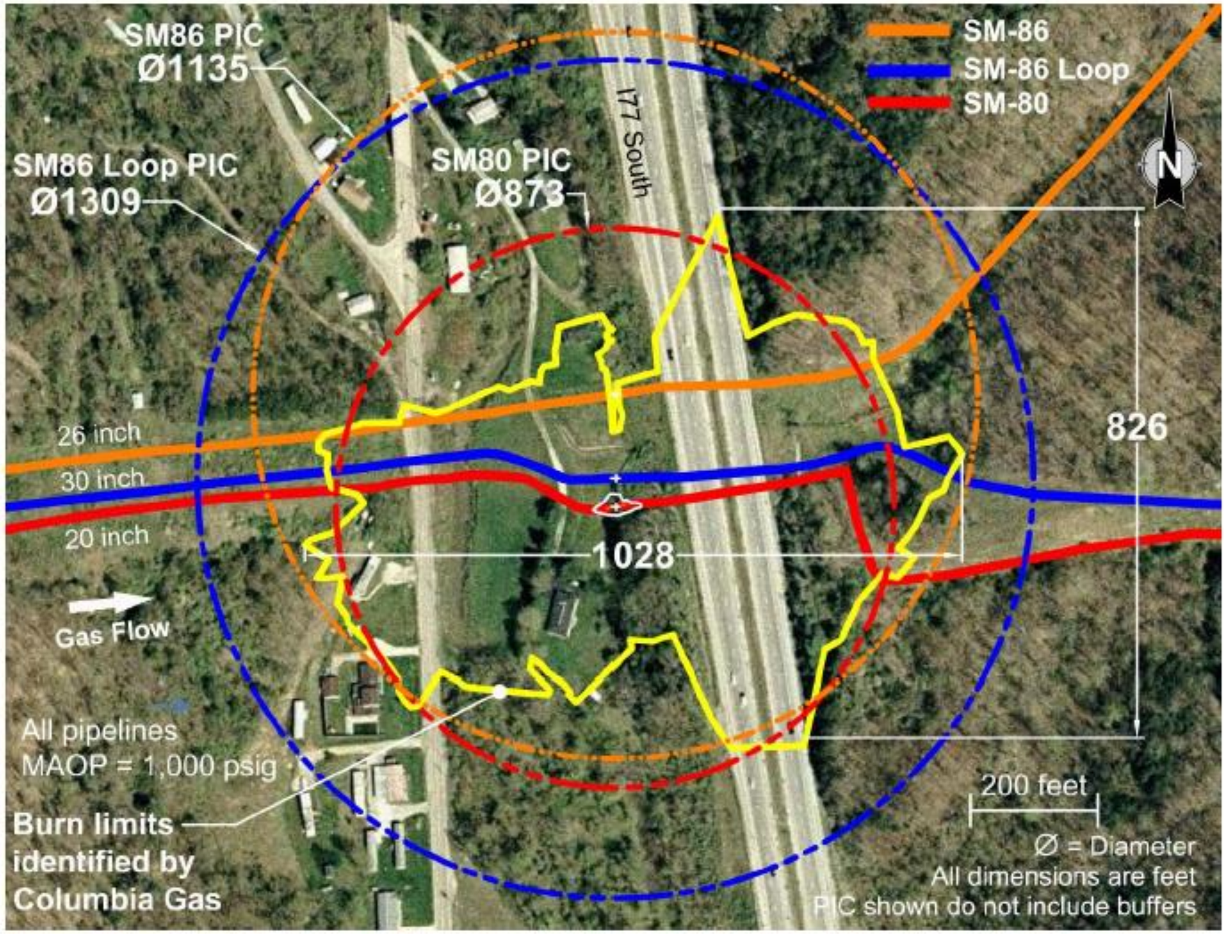

Figure 11. Potential impact radius circles for each pipeline in SM-80 system at rupture location.

<u>Comments</u>
- Area enclosed by PIR (red circle) comparable to area of burnt ground (yellow outline)
- Slight axial burn zone extension attributed to directional jetting

San Bruno, CA, 2010

NPS 30 @ 375 psi
(MAOP 400 psi)

<u>Comments</u>

- extended distance to extent of building destruction and damage likely due to wind driven fire spread
- fire suppression was significantly delayed (water mains damaged; information suggests no water available for firefighting for about 1 hour)

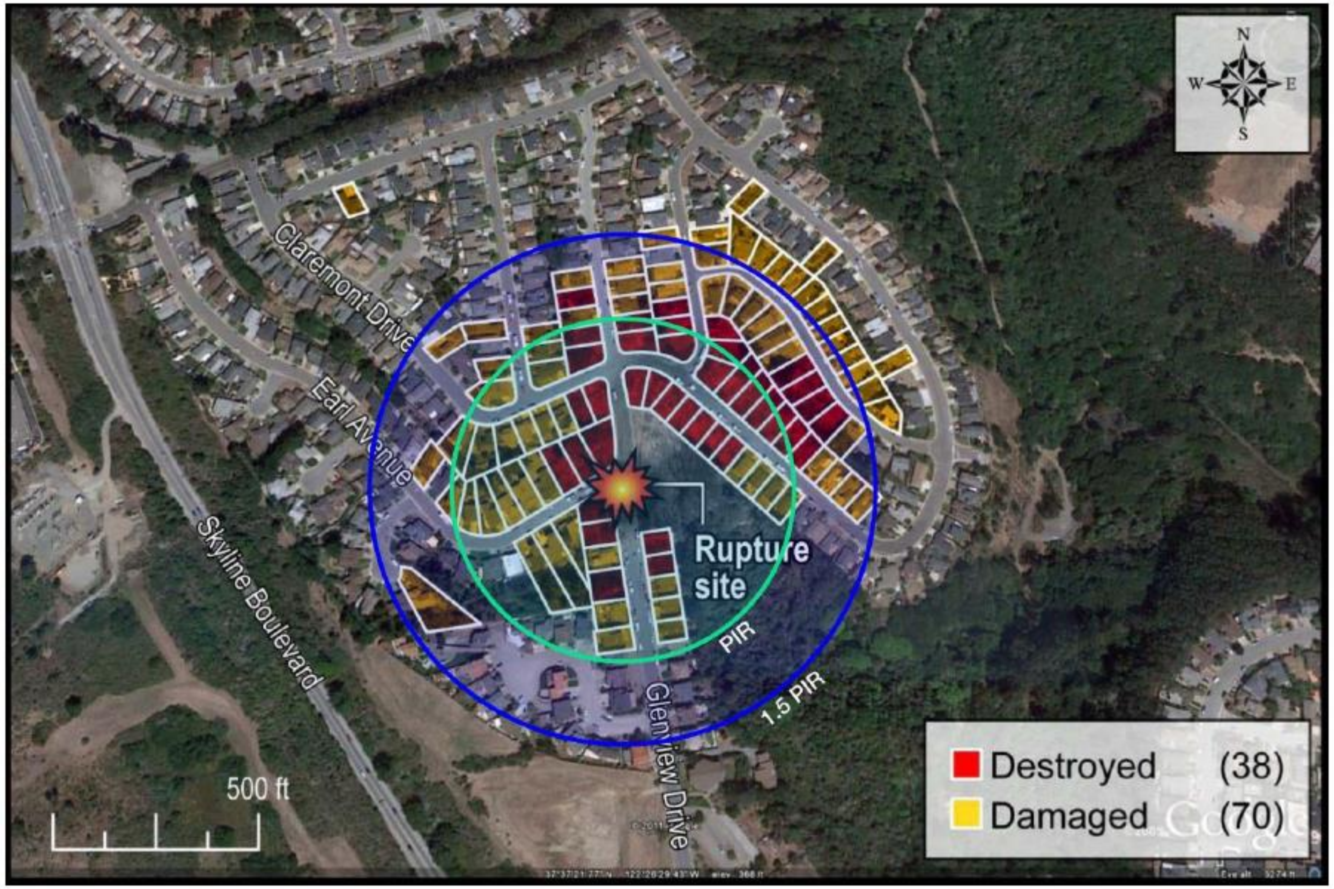

Fig. 3.69. Aerial view of the September 9, 2010 San Bruno natural gas pipeline release showing residential properties damaged and destroyed.

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Carlsbad, NM, 2000

NPS 30 @ 675 psi
(MAOP 837 psi)

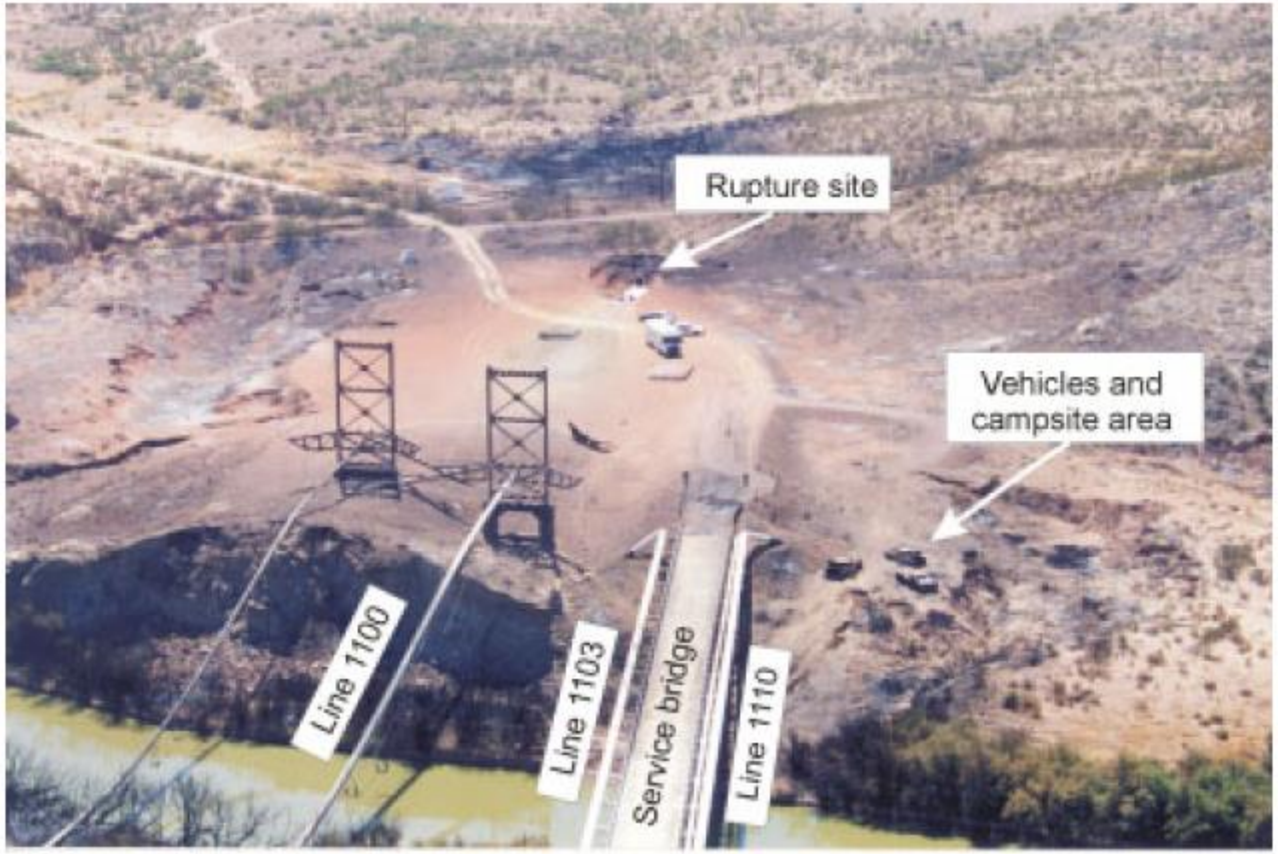

Figure 4. Aerial view of accident site looking east.

<u>Comments</u>

- Circumstances and specifics unclear from report narrative
- Causalities possibly sleeping unsheltered at camp site approximately 675 ft from crater (PIR = 599 ft)
- Fatality beyond PIR potentially attributed to slow reaction time and thereby extended exposure

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