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The Potential Impact Radius Formula
Background to Development and Validation

presented by
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The Potential Impact Radius (PIR) Formula

- A formula developed by C-FER (Stephens 2001) for estimating extent of thermal radiation hazard zone resulting from 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

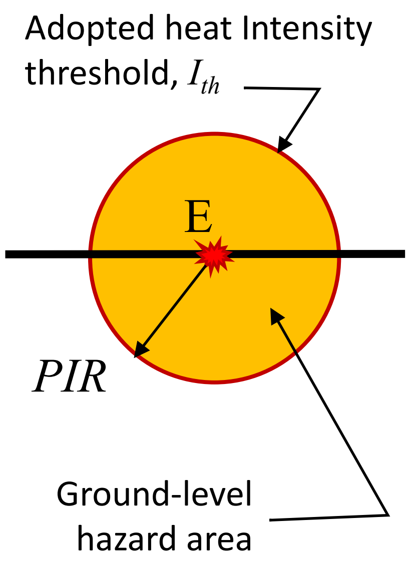
- Effective release rate, Q_{eff} (kg/s)
  - λ = release rate decay factor
  - C_d = discharge coefficient
  - d = pipeline diameter
  - p = internal pressure
  - φ/a_0 = flow factor/sonic velocity
- Emissive power, E (kW)
  - H_c = heat of combustion
  - χ_g = emissivity factor
- Heat intensity, I (kW/m^2)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

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

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



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

PIR Model Components Subject to Concern

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- Effective release rate, Q_{eff} (kg/s)
  - λ = release rate decay factor
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  - d = pipeline diameter
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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

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

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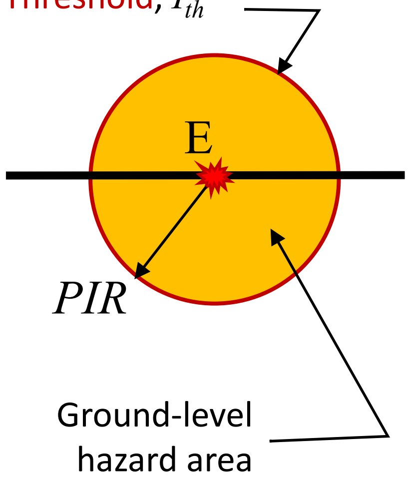
Adopted Heat Intensity Threshold, I_{th}



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

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

Effective Sustained Release Rate, Q_{eff}

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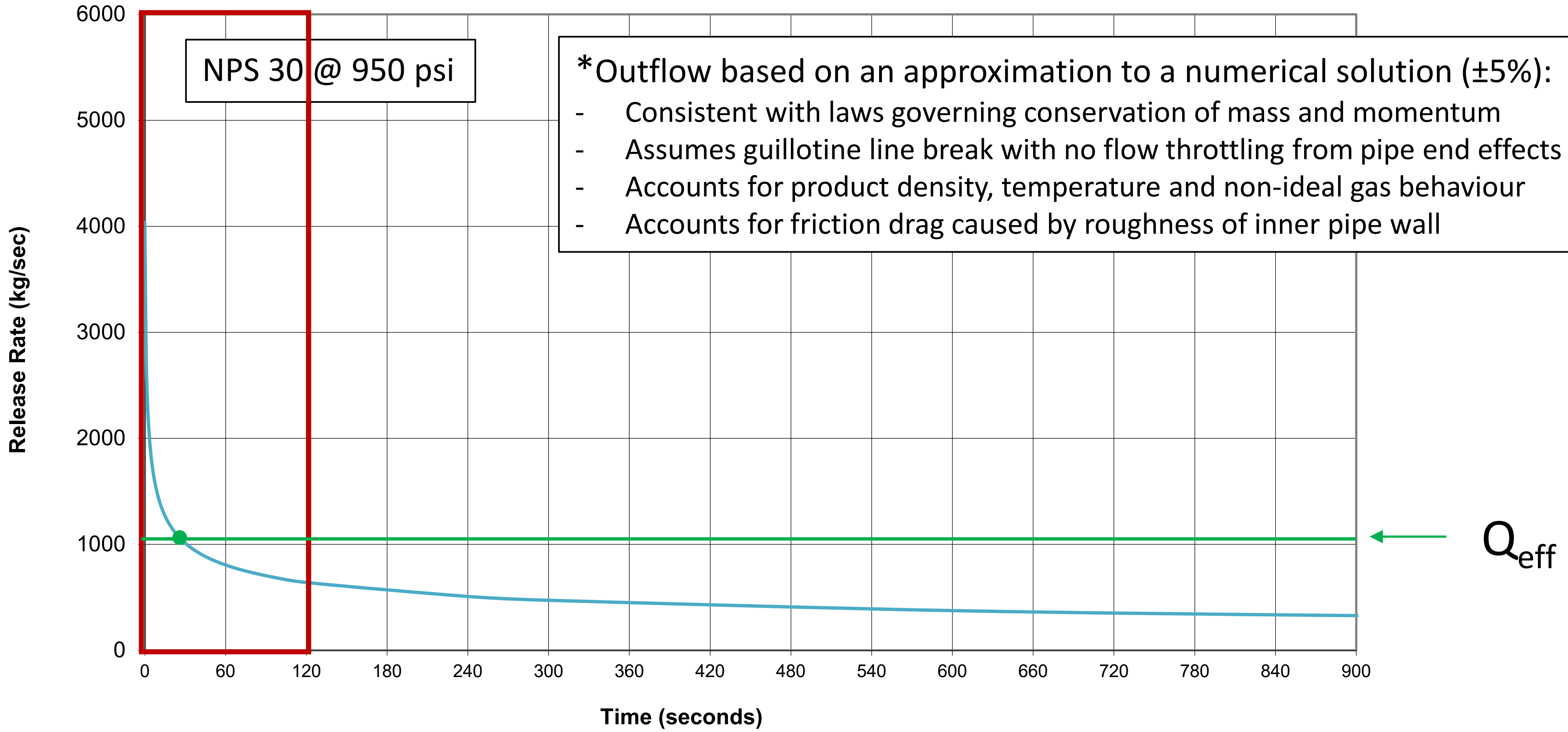
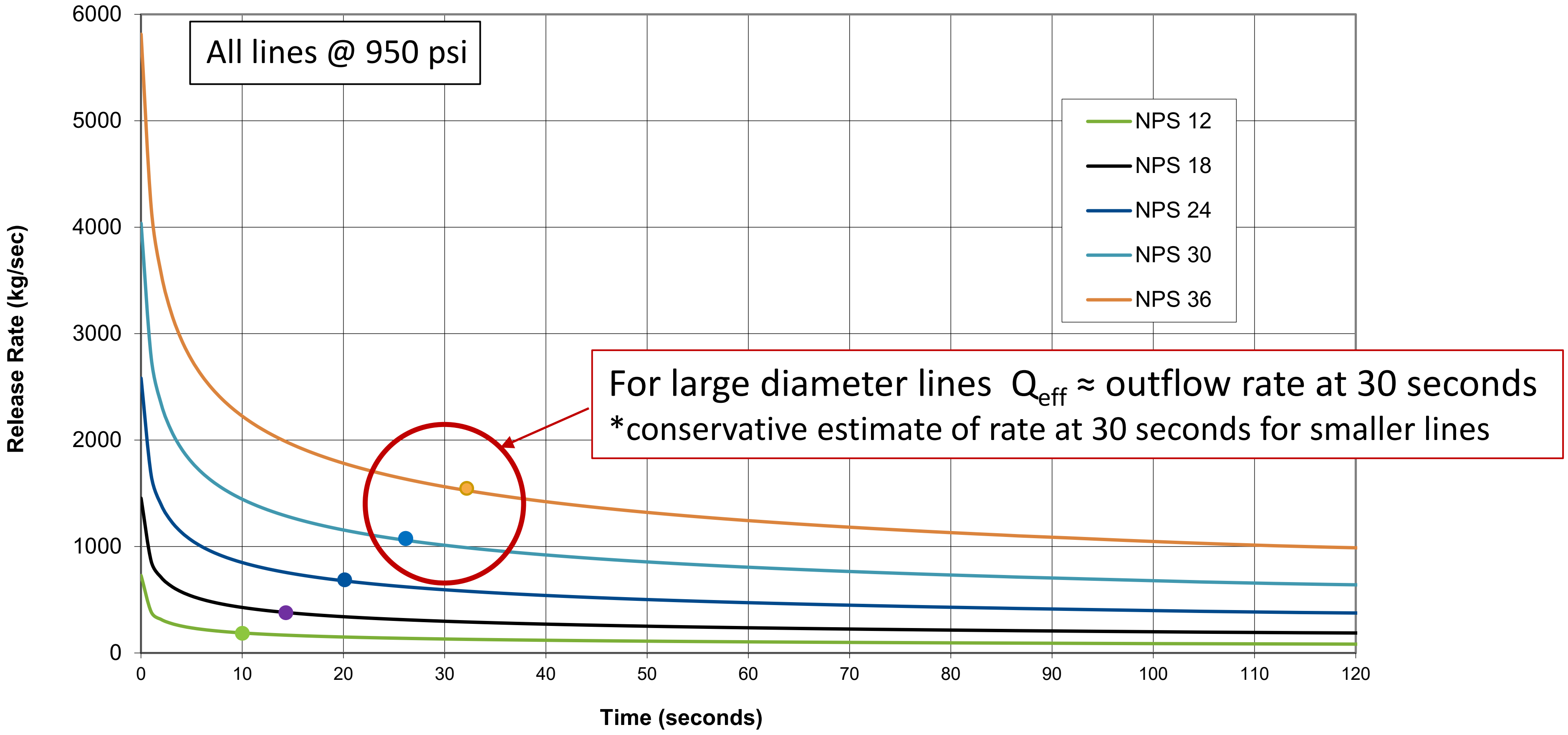
- Comparisons to transient release rates – TNO (1982) rupture blowdown model*



*Outflow based on an approximation to a numerical solution (±5%):
- Consistent with laws governing conservation of mass and momentum
- Assumes guillotine line break with no flow throttling from pipe end effects
- Accounts for product density, temperature and non-ideal gas behaviour
- Accounts for friction drag caused by roughness of inner pipe wall

Effective Sustained Release Rate

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



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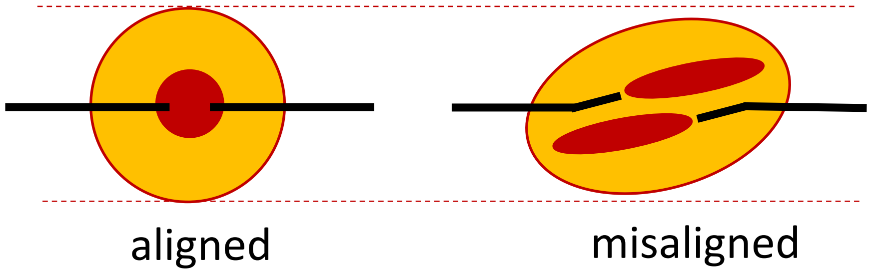
2 Efficiency Factor, η

- 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 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

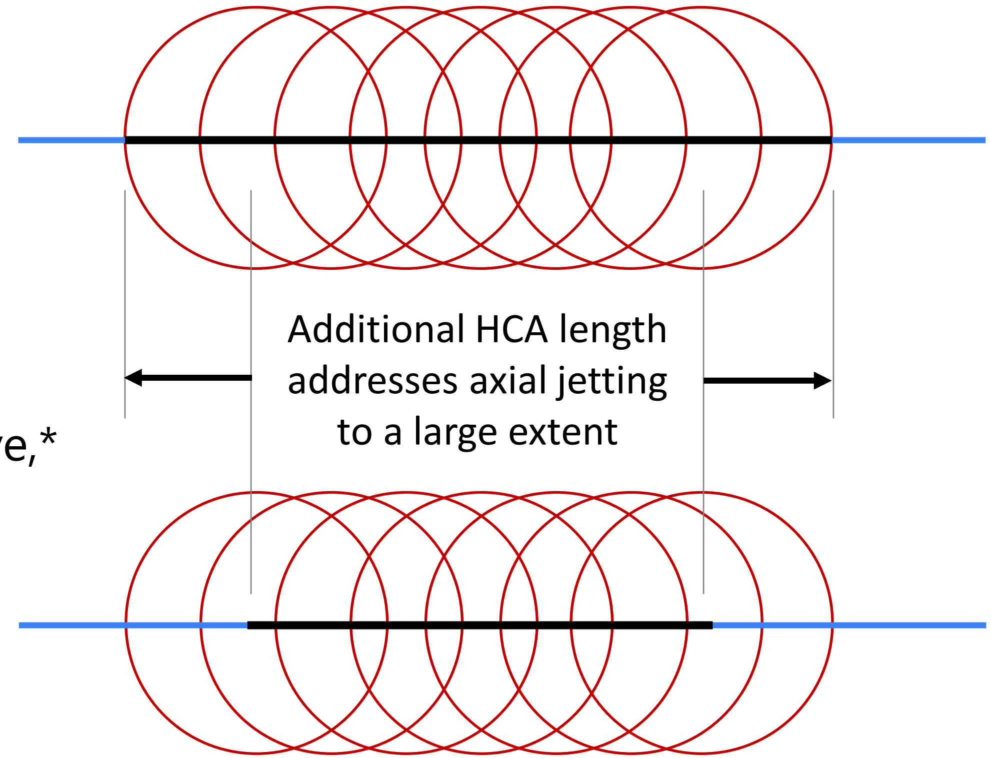
- Models underlying the PIR formula are a defensible basis for estimating radiation intensity from a crater fire associated with near-immediate ignition as a function of horizontal distance
- A crater fire develops when opposing gas jets impinge upon one another and the crater walls redirect flow upwards, 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



Hazard Zone Elongation Due to Directional Jetting – Consideration in Defining an HCA

- As per ASME B31.8S and 49 CFR 192, the length of pipeline affecting an HCA extends from the start of the first to the end of the last circle

- However, from a technical perspective,* the length of pipeline affecting an HCA should only extend from the center of the first to the center of last circle



** assuming circular hazard zone areas*

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3 Heat Intensity Threshold, I_{th}

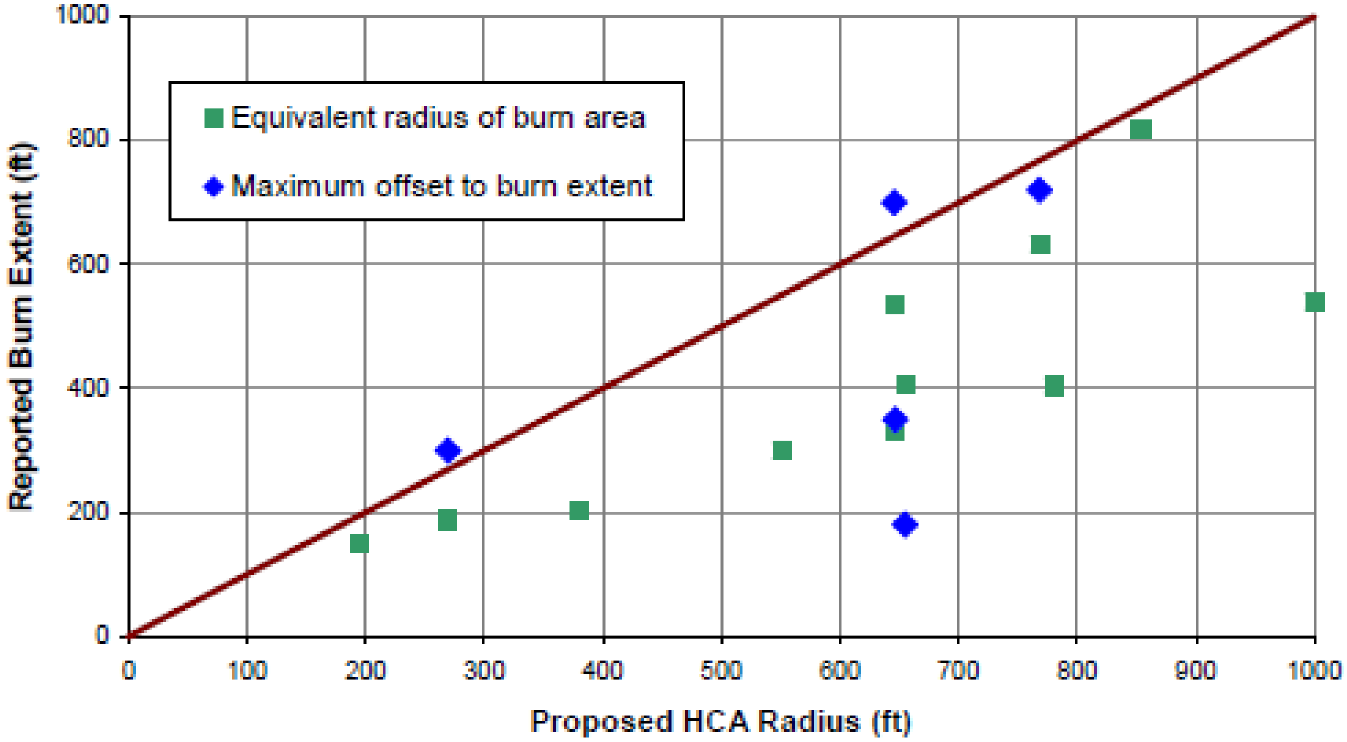
- Adopted heat intensity threshold is 5,000 Btu/hr/ft^2
  - Impact on people
    - 1% chance of lethality for individuals subject to approximately 30 seconds of sustained exposure
      - Based on a widely recognized probabilistic dose-response relationship (i.e. a lethality probit function)
    - Basis for the 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 (e.g. BS PD 8010-3:2009) for 2.5 m/s travel speed and shelter within 50 to 75 m
  - Impact on property
    - Highly unlikely that wooden structures will ignite and burn as a result of extended exposure
      - Adopted heat intensity threshold requires about 20 minutes of exposure to result in piloted ignition based on a widely recognized dose-response relationship (also, there is no potential for spontaneous ignition)
    - Implications for people indoors → wood-framed dwelling will afford indefinite protection to occupants

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
- Considerations 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 materials and the potential for fire spread)
  - However, the burn zone is often the only available basis for model accuracy evaluation

Original Model Validation – Comparison of Burn Zones

- From GRI Report (Stephens 2001)



- Model shown to consistently overpredicted total burn area
- Model occasionally underpredicted maximum burn extent*

**recall issue of fire spread*

See PHMSA presentation for update based on more recent incident data

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Other Validation Effort – Safety Risk Focused

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

- 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 large scale on lines up to 36 inches in diameter and 50 miles 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

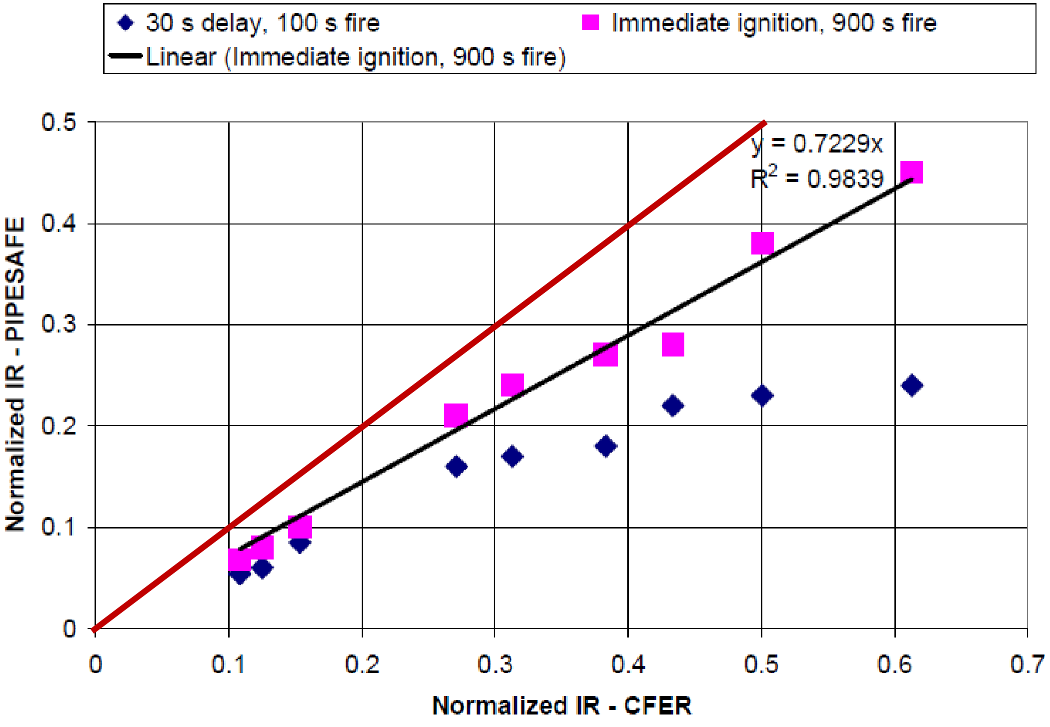

Figure 6 Relationship between normalized individual risk calculated by PIPESAFE and by the C-FER approach

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

Comparison of C-FER Model to PIPESAFE

- 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 generic 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

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Comments on Incidents Referenced in NTSB Report on Danville Pipeline Incident

- Danville KY - 2019
- Sissonville WV - 2012
- San Bruno CA - 2010
- Carlsbad NM - 2000

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Danville KY 2019

NPS 30 @ 926 psi
(PIR = 633 ft)

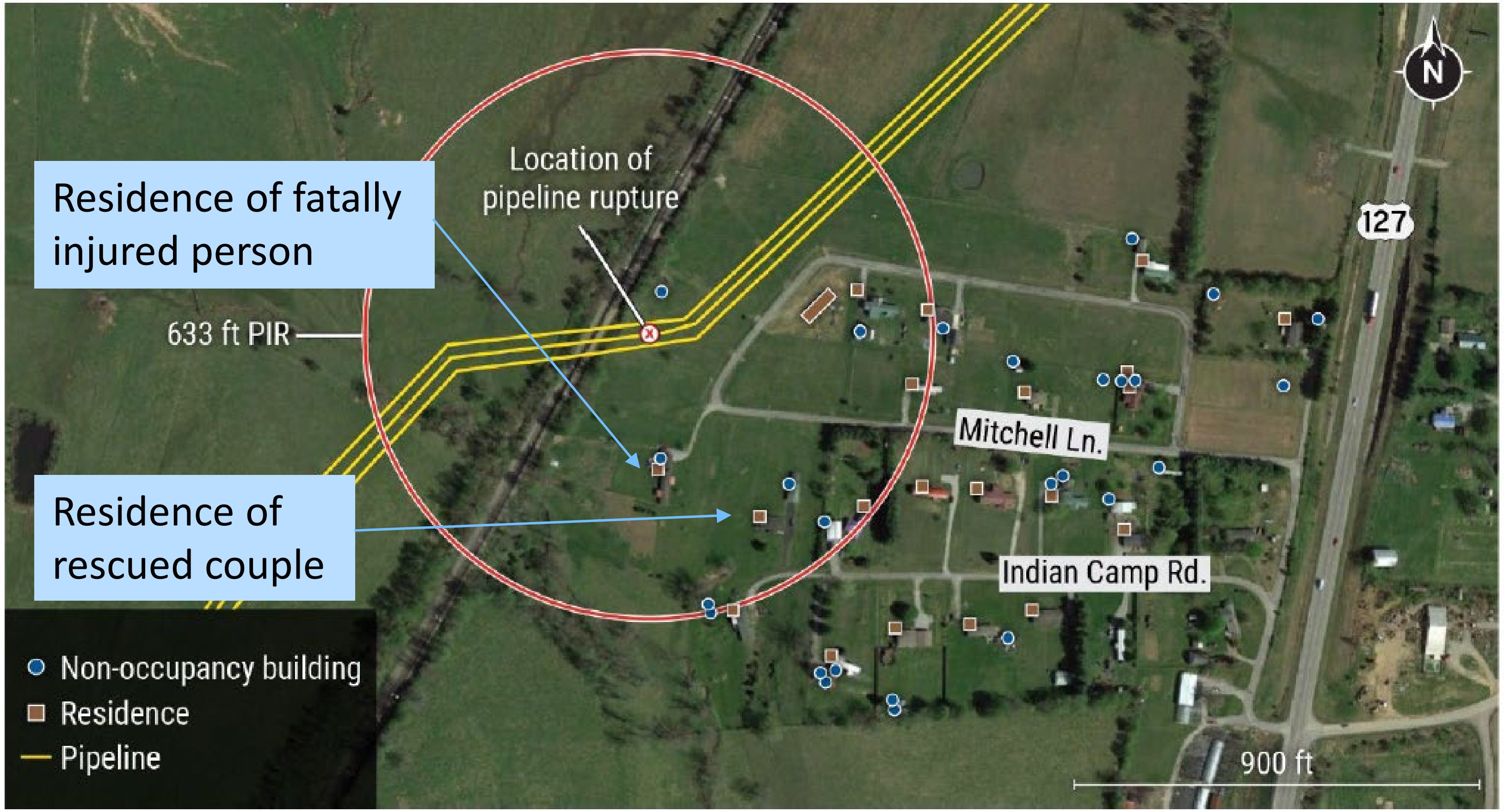

Figure 11. Human-occupancy buildings within the potential impact radius. (Courtesy of Enbridge.)

Comments

- Residence of deceased and all destroyed buildings fall within PIR

Sissonville, WV, 2012

NPS 20 @ 929 psi
(PIR = 436 ft)

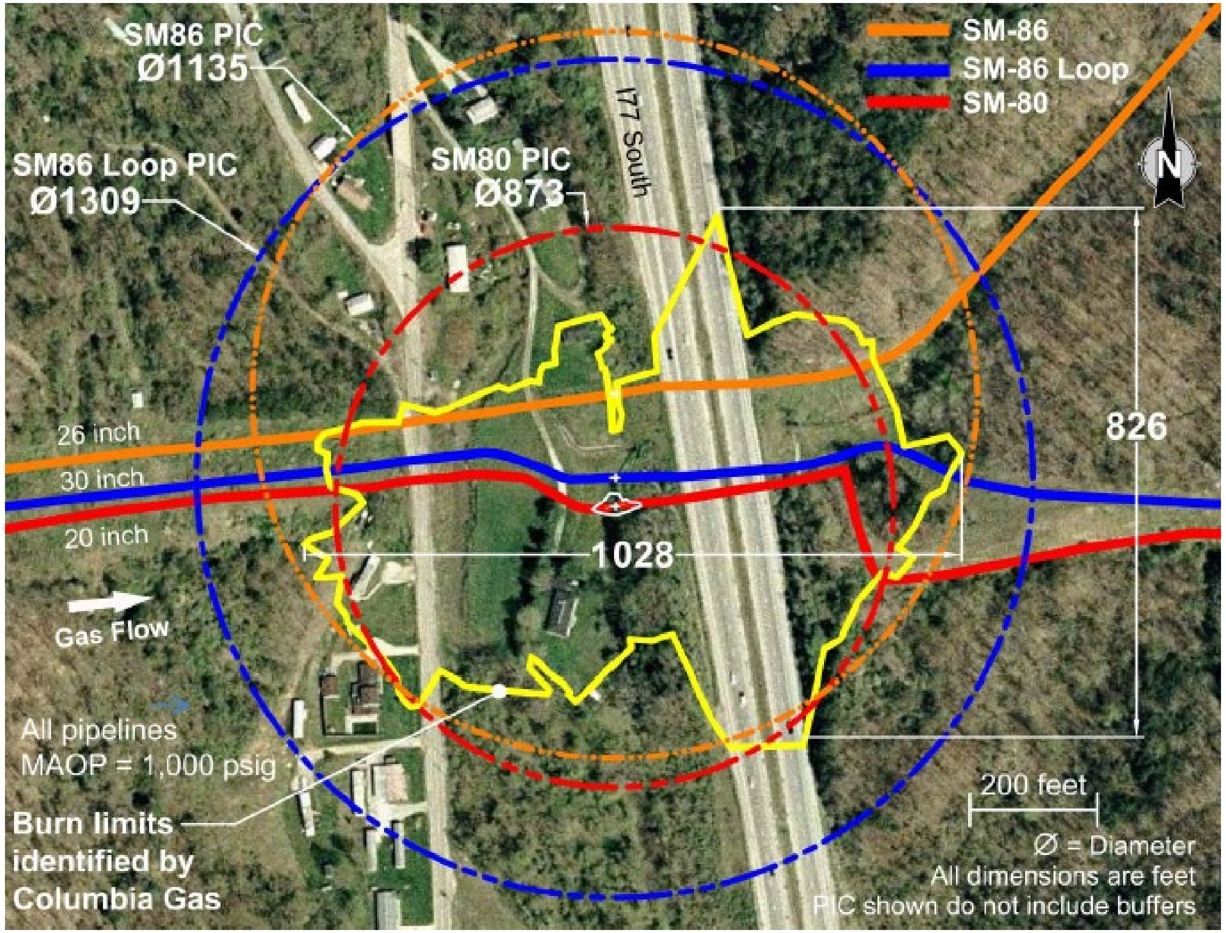

Figure 11. Potential impact radius circles for each pipeline in SM-80 system at rupture location.

<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
(PIR = 414 ft)

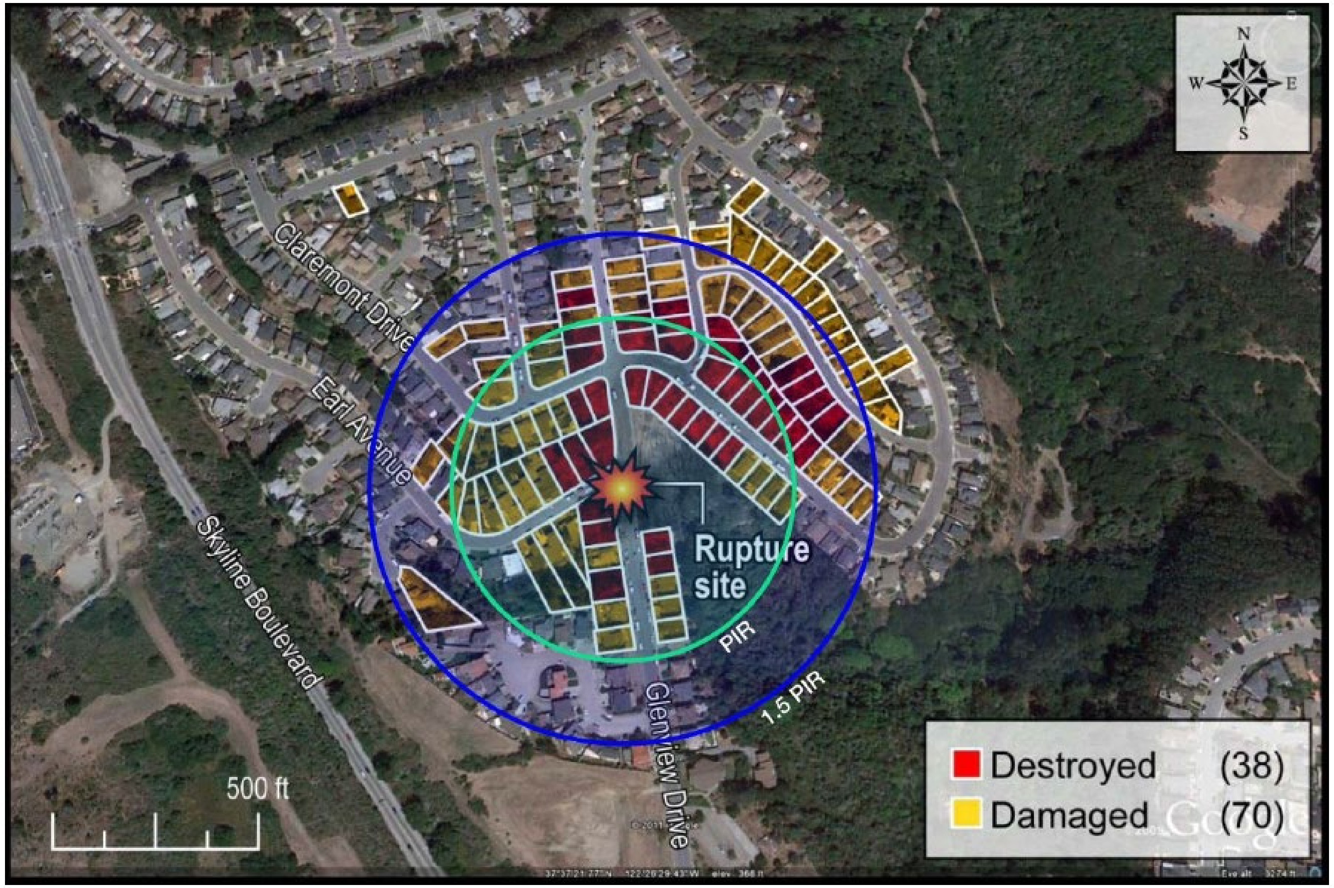

Fig. 3.69. Aerial view of the September 9, 2010 San Bruno natural gas pipeline release showing residential properties damaged and destroyed.

<u>Comments</u>

- radial distance to maximum extent of the building destruction zone likely influenced by wind driven fire spread*

** fire suppression was significantly delayed (water mains damaged; information suggests no water available for firefighting for about 1 hour)*

Carlsbad, NM, 2000

NPS 30 @ 675 psi
(PIR = 599 ft)

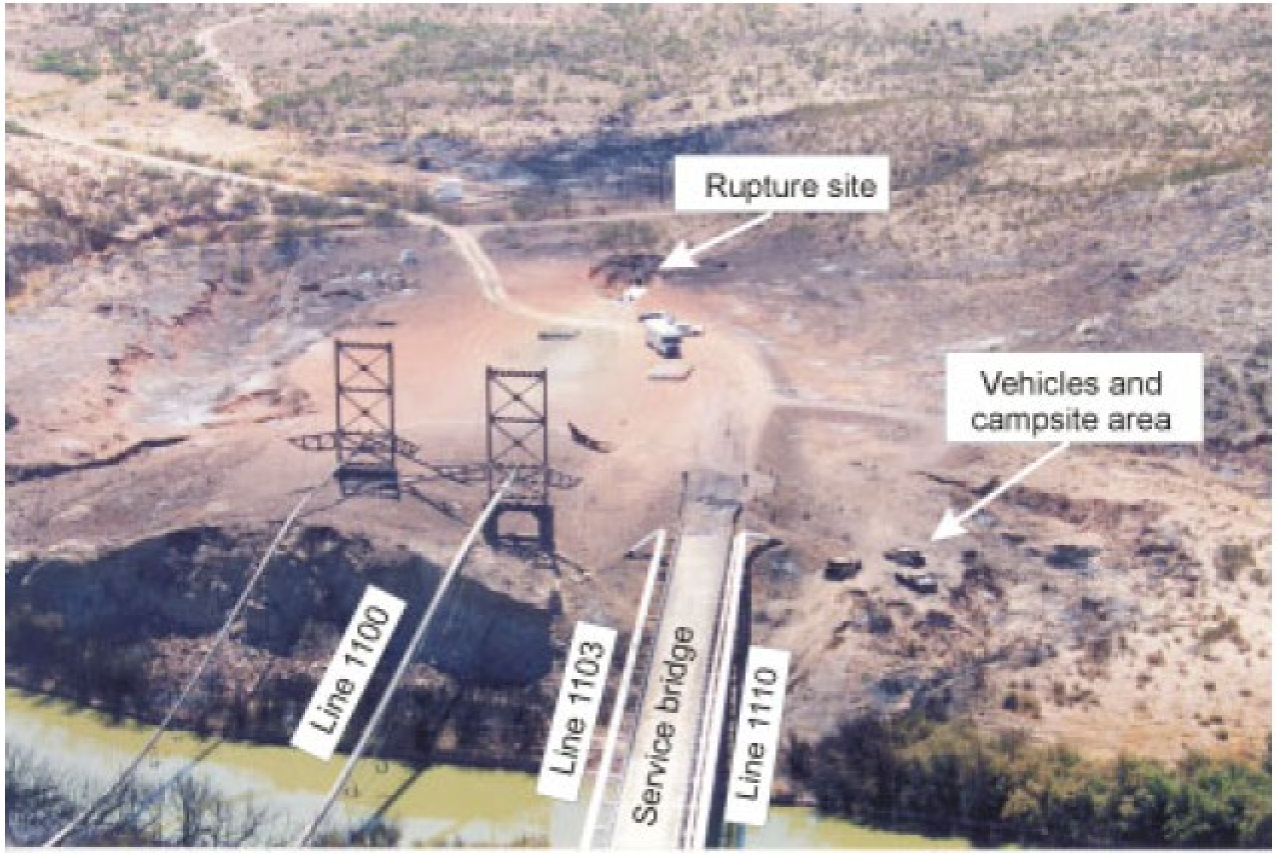

Figure 4. Aerial view of accident site looking east.

<u>Comments</u>

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

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