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Subsea Gas Pipelines Burst Design Incorporating Hydrate Plugging Risk

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ABSTRACT: Subsea gas transmission pipelines operating in hydrate-prone environments are exposed to a class of integrity threats that are not fully captured by conventional steady-state design philosophies. One of the most critical of these threats is the formation of hydrate plugs followed by rapid transient pressure escalation due to upstream compression, thermal dissociation, or operational intervention. This article presents a framework for incorporating hydrate-induced transient pressure rise explicitly into pipeline burst design. By extending the classical burst pressure equations to include a hydrate plug transient pressure factor, a new methodology is proposed for determining minimum required wall thickness that better reflects realistic subsea operating risks.

KEYWORDS: Subsea gas pipelines, Hydrate plugging, Burst pressure design, Pipeline wall thickness, Flow assurance.

I. INTRODUCTION

A new methodology for determining the wall thickness of hydrates-forming subsea gas pipelines involves modifying the traditional burst limit state equation to account for the transient pressure rise caused by hydrate plugging. Gas hydrate formation is a well-documented flow assurance challenge in subsea gas pipelines. Under high pressure and low temperature conditions, water and light hydrocarbons form crystalline solids that can agglomerate and create partial or full-bore plugs [1], [2]. While hydrate management strategies typically focus on prevention and remediation [3], the structural implications of hydrate plugging events are often addressed only indirectly through conservative design margins.

Traditional pipeline burst design is based on steady or quasi-steady internal pressure, typically defined by maximum allowable operating pressure (MAOP) or design pressure; This approach involves calculating the minimum internal pressure that a pipe can withstand before it ruptures or sustains irreversible damage. For defect-free pipes, analytical formulas and limit state equations are used to predict gas pipeline failure pressure, forming the basis of design ASME B31.8 standard [4]. A common simplified formula for burst pressure in thin-walled pipes is Barlow's formula, given as:

$$S_h = \frac{P_d D}{2t} \quad (1)$$

Hoop stress (S_h) is the circumferential stress in a pipe wall, generated by internal pressure P_d. It acts perpendicular to the pipe's longitudinal axis and depends on the pipe diameter D and wall thickness t. However, these traditional models primarily account for static or slowly changing pressure conditions. They are not inherently designed to handle the effects of transient pressure. A pressure transient is a rapid and significant change in pressure within a pipeline system. Such events can generate high-pressure shock waves that propagate through the pipeline, potentially exceeding the pipe's pressure rating and leading to rupture or long-term fatigue damage [5], [6].

In the context of subsea gas pipelines, the formation of a hydrate plug creates a direct and severe cause for such transient pressure spikes. When a hydrate plug forms, it can abruptly stop or drastically reduce the flow of gas, causing a rapid pressure build-up upstream of the plug (Koh & Creek, 2011; Sloan et al., 2011a, 2011b). This generates a significant pressure transient that traditional design calculations may not cover [8], [9]. Hydrate plug formation introduces the potential for short-duration, high-magnitude transient pressures that may exceed MAOP locally and challenge the burst resistance of the pipe wall. Incorporating these transient effects into burst design represents a more physically realistic approach to subsea pipeline integrity management. Thus, the integrity of the pipeline is thus compromised because it is subjected to forces far greater than its designed maximum operating pressure. The pipeline's wall thickness directly affects how it responds to these transient waves;

conversely, repeated transient events can impact the pipeline's integrity and influence the required wall thickness for safe operation.

Also, when a hydrate plug forms, it effectively creates a closed-end condition in the pipeline. Continued gas inflow, upstream compression, or thermal expansion of trapped gas can result in rapid pressure build-up upstream of the plug [9]. Additional pressure rise may occur during partial dissociation of the hydrate due to heat influx, releasing gas into a confined volume. Therefore, a design methodology that fails to account for hydrate-induced transient pressures overlooks a critical failure mode.

The hydrates-induced transient pressure rise, ΔP_H is governed by gas compressibility, upstream boundary conditions, and the rate of hydrate growth or dissociation. In extreme cases, this pressure can approach or exceed the material burst capacity even if nominal operating pressure is within design limits. Conventional subsea pipeline design codes (e.g., ASME 831.8, 2004; DNVGL-ST-F101, 2017) implicitly assume that internal pressure remains bounded by design pressure envelopes. Accidental limit states typically consider external interference or material defects, but hydrate-induced pressure transients are not explicitly treated as a governing load case for burst.

As a result, pipelines designed solely on MAOP-based burst criteria may be under-designed for rare but credible hydrate plug scenarios. Thus, the proposed approach in this paper ensures that the pipeline's structural integrity is sufficient to withstand the severe, rapid pressure spikes that can occur when a hydrate plug forms and abruptly alters flow conditions, a critical risk not accounted for in conventional static pressure designs.

II. METHODOLOGY

The proposed methodology integrates hydrate flow assurance analysis with structural burst design by explicitly accounting for hydrate-induced transient pressure rise as an internal load case. The approach consists of the following steps:

1. Hydrate Risk Identification: Identify pipeline segments susceptible to hydrate formation based on pressure–temperature envelopes, elevation profile, shutdown frequency, water content, and thermal exposure.
2. Transient Pressure Assessment: Evaluate the maximum credible transient pressure rise associated with hydrate plug formation using transient hydraulic analysis.
3. Definition of Hydrate Transient Pressure Factor: Express the hydrate-induced pressure escalation as a non-dimensional hydrate transient pressure factor, γ_H, relative to normal operating pressure.
4. Modified Burst Design Wall Thickness : Incorporate the hydrate transient pressure into the classical burst pressure formulation to determine the governing wall thickness requirement.

This methodology ensures that rare but high-consequence hydrate plug events are explicitly reflected in pipeline wall thickness design rather than being indirectly absorbed through global safety factors.

III. BURST WALL THICKNESS DESIGN CONSIDERING HYDRATE RISK

To ensure the structural integrity and safety of subsea gas pipelines prone to hydrate formation, a new design methodology is required for determining the burst limit state wall thickness. This approach must move beyond static pressure considerations and explicitly integrate the risk of hydrate plugging and the resulting transient pressure surges. The core principle is to treat the maximum potential transient pressure as a credible design load.

Burst Pressure Formulation

The widely used design pressure formula from ASME B31.8 for gas transmission pipelines is:

$$P_d = \frac{2StFET}{D} \tag{2}$$

Rearranging this to solve for the required nominal wall thickness (t) gives:

$$t = \frac{P_d D}{2SFET} \tag{3}$$

In both equations:

P_d: Design pressure (Pa).

D: Nominal outside diameter of the pipe (m).

S: Specified Minimum Yield Strength (SMYS) of the pipe material (Pa).

t: Nominal wall thickness (m).

F: Design factor, which varies based on the pipeline's location class (-).

E: Longitudinal joint factor (-).

T: Temperature derating factor (-).

For design purposes, this equation is modified by material resistance factors, manufacturing tolerances, and safety factors, resulting in a design burst criterion:

Incorporating Hydrate Plug Transient Pressure

To account for hydrate-induced pressure escalation, a hydrate transient pressure factor γ_H, is introduced. The proposed modification focuses on redefining the design pressure, P. Instead of using only the maximum static operating pressure, the new design pressure must also account for the sharp increase from a transient event.

$$P_H = P_d + \Delta P_H = \gamma_H P_d \tag{4}$$

P_H: effective hydrate transient pressure (Pa)
ΔP_H: transient pressure rise due to hydrate plugging (Pa)
γ_H: hydrate transient pressure factor (-)

The factor γ_H, may be determined from transient hydraulic simulations, coupled thermal–fluid models, or bounding analytical estimates based on gas compressibility and plug length. However, in this study, γ_H is determined from analytical estimation as discussed later. The transient pressure increase equation during hydrates developed in the literature [9], [11] is modified as presented in equation (5), with the assumption that the risk of hydrate plugging in an subsea gas pipeline is heightened by a longer horizontal section. The primary mechanism is the reduction in shear rate with distance from the point of initial hydrate formation, which facilitates plug development [11]:

$$\Delta p_H = 2K_H f \rho_g {v_g}^2 \frac{L}{D} \tag{5}$$

From equation (4), γ_H can be re-arranged as follows:

$$\gamma_H = \left(1 + \frac{\Delta P_H}{P_d}\right) \tag{6}$$

Substituting equation (6)into (5)yields:

$$\gamma_H = \left(1 + \frac{2K_H f \rho_g {v_g}^2 L}{P_d D}\right) \tag{7}$$

Hence, the pipeline wall thickness considering hydrates plugging t_H, should be:

$$t_H = \left(1 + \frac{2K_H f \rho_g {v_g}^2 L}{P_d D}\right) \frac{P_d D}{2SFET} \tag{8}$$

where:
Δp_H: Transient pressure rise (Pa)
K_H: $0.0188v_g + 4.392$; is a dimensionless empirical model fit constant.
f: dimensionless friction factor for gas flowing inside a pipe with hydrate deposition as estimated in the literature [11].
ρ_g: gas density (kg/m^3)
V_g: gas velocity (m/s)
L: hydrates forming pipeline section (m)

Sensitivity Analysis

Equation (7), demonstrates that the new wall thickness calculation incorporates the length of the pipeline's horizontal section, which is the most critical region during hydrate formation. This relationship indicates that a longer horizontal section necessitates a greater wall thickness to prevent burst failure. Furthermore, the equation shows that an increase in the internal friction factor —a key consideration for aging pipelines due to wall roughness—also demands an increase in wall thickness to maintain integrity. Similarly, a higher gas density, which can result from increased water content in the gas stream of an aging reservoir, requires a corresponding increase in wall thickness.

Consequently, for operating gas pipelines prone to hydrate formation, the required wall thickness must account for potential increases in gas density and the friction factor over time. Based on the standard definition of Maximum Operating Pressure (MOP) in the literature[12], the adjusted MOP to prevent hydrate-induced burst—considering both elevated gas density and age-related friction—can be estimated during pipeline operation using equation (9).

$$P_{MOP} < \left(P_d + \frac{2K_H f \rho_g {v_g}^2 L}{D}\right) \tag{9}$$

IV. CONCLUSIONS

Hydrate plugging represents a credible accidental load case capable of inducing transient internal pressures beyond conventional design envelopes. By introducing a hydrate transient pressure factor into traditional burst equations, subsea gas pipelines can be designed with explicit consideration of this risk. The proposed methodology provides a rational, physics-based enhancement to burst design and supports safer, more resilient subsea gas transportation systems. Incorporating hydrate transient pressure into burst design has several design implications hydrates-prone subsea gas pipelines:

- Increased wall thickness may be required in hydrate-prone sections, particularly in deepwater and cold environments.
- Design becomes explicitly linked to flow assurance strategy.
- Localized thickening or higher-grade material may be justified near known hydrate risk zones such as low points or shutdown-prone segments.
- A shorter "tie-back" distance directly reduces the low-shear, horizontal segment where hydrates can form and accumulate.
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NOMENCLATURE

Abbreviation	Description
ASME	American Society of Mechanical Enginee.
DNVGL	Det Norske Veritas and Germanischer Lloyd

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