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Development of a Model, Guidelines, and Cost Analysis for Balancing Pipeline Safety and Efficiency with Hydrogen Blending

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Blending hydrogen into existing natural gas pipelines introduces a unique trade-off between energy delivery efficiency and material integrity. On one hand, hydrogen embrittlement of steels increases the risk of fracture and fatigue failures in high-pressure pipelines. On the other hand, the lower energy density of hydrogen results in a higher pressure required to maintain a sufficient energy throughput. This work aims to identify design and operating condition ranges that can be used to minimize both risk and energy loss, as well as the expected maintenance/repair costs and revenues associated with those ranges. To achieve this, a pipeline fatigue failure model was developed using a combination of fracture mechanics approaches with laboratory data, and this model was combined with an energy flow prediction based on fluid properties determined using the REFPROP software. Both models were then evaluated under a wide range of input combinations to determine the optimal ranges for operating conditions and expected costs and revenues for those ranges.

Keywords: Hydrogen, energy flow, fracture, fatigue, risk modeling, cost analysis.

1. Introduction

In recent decades, significant research efforts have been directed toward identifying sustainable alternatives for energy production, with hydrogen identified as a potential clean energy carrier. Its high gravimetric energy density and clean combustion profile make it an attractive energy carrier. However, the successful deployment of hydrogen through pipelines requires addressing several challenges related to infrastructure compatibility, safety, and efficiency. A key consideration in this transition is the feasibility of transporting hydrogen, either as a pure gas or in blends with methane, through existing natural gas pipeline networks.

The differences between the properties of hydrogen and natural gas result in several key effects on pipeline risk and performance (Chuayboon et al. 2014):

- EFFECT ONE: Hydrogen produces no carbon emissions
- EFFECT TWO: Hydrogen molecules have $1/8^{th}$ the molecular weight of natural gas. The smaller molecules can cause hydrogen embrittlement
- EFFECT THREE: Hydrogen has a wider flammability range, increasing the risk of an explosion if a leak occurs
- EFFECT FOUR: Hydrogen has a faster flame speed, which additionally increases the severity of leaks or accidents.

- EFFECT FIVE: Hydrogen has about three times lower energy density than natural gas, requiring more volume for the same energy delivery

The goal of this project is to reduce emissions via effect one while minimizing risk and productivity losses caused by effects two and five, respectively. Effects three and four are not explicitly modelled in this project, but are considered as increased consequences of a pipeline failure.

2. Methodology

The model incorporates a flow model (volumetric and energy flow) and a probabilistic failure prediction algorithm based on fracture mechanics principles. Key operational parameters such as hydrogen volume percentage, operating pressure, and pipeline dimensions are varied to analyze their influence on flow performance and failure risk.

2.1. *Flow model*

To calculate the volumetric flow rate (Q) of gas through pipelines, the standard equation by the California Natural Gas Association (CNGA) is employed as given in Equation 1.

$$Q = 77.4\left(\frac{T_b}{P_b}\right)\left[\frac{(P_1^2 - e^s P_2^2)}{G T_f L Z f}\right]^{0.5} D^{2.5} \qquad (1)$$

Where Q is the standard gas flow rate in ft^3/day, L is the pipe length in miles, D is the inner diameter in inches, P_1 and P_2 are the upstream and downstream pressures in psia, and T_f is the flow temperature in °R. The base temperature (T_b) and pressure (P_b) are assumed as constants with values of 540 °R and 14.7 psia, respectively.

The gas compressibility factor (Z), elevation adjustment factor (s), friction factor (f), gas specific gravity (G) and viscosity (μ, which is needed to calculate the friction factor) must be calculated dynamically for each pressure, temperature and gas composition. For non-ideal gases, the specific gravity and viscosity is calculated using a neural network trained on data from REFPROP, a software developed by NIST.

The energy flow is then calculated as the product of the energy density for the specified gas composition with the volumetric flow calculated according to the CNGA model.

2.2. *Risk model*

The pipeline risk model is composed of three major components: prediction of the reduction in the steel fracture toughness, a hydrogen-specific model for crack growth rate, and a failure model which combines the first two predictions to determine if failure will occur.

The steel fracture toughness is predicted using a power law regression model which reduces toughness as a function of the fugacity of hydrogen. The regression model is built on a database of laboratory data collected by Sandia and DNV on the fracture toughness of pipeline steel grades from X42 to X120 in a variety of hydrogen pressures (Ayello et al. 2026). The power model and data are shown on a plot in Fig. 1, where all predictions and data points are normalized to the fracture toughness in air for that steel grade.

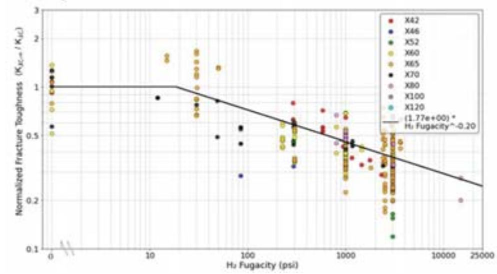

Fig. 1. Fracture toughness data and regression model

The fatigue crack growth in hydrogen blended conditions is calculated using a model developed by Sandia National Laboratories to serve as bounding curves for the fatigue behavior of steels in hydrogen (San Marchi and Ronevich 2022). The bounding equations are shown in Equation 2, where R is the ratio of the minimum stress intensity (K_{min}) to maximum stress intensity (K_{max}), ΔK is equal to the difference between K_{min} and K_{max}, and f_{H_2} is the fugacity of hydrogen. The first equation will be used at low ΔK values, and the second equation is used for high ΔK values.

$$\begin{aligned} &Low\ \Delta K: \\ &\frac{da}{dN} = 7.6 \cdot 10^{-16}\left(\frac{1+0.429R}{1-R}\right)\Delta K^{6.5}\sqrt{f_{H_2}} \\ &High\ \Delta K: \\ &\frac{da}{dN} = 1.5 \cdot 10^{-11}\left(\frac{1+2R}{1-R}\right)\Delta K^{3.66} \end{aligned} \qquad (2)$$

Pipe failure due to fracture or fatigue is determined using a failure assessment diagram as defined by API 579 (API 2021). The reference stress (σ_{ref}) and stress intensity factor (K_{max}) are determined from the flaw dimensions and stress analysis as defined in the assessment methodology. The ratio of K_{max} to the fracture toughness and ratio of the σ_{ref} to the yield strength are compared against a failure envelope. The flow chart of the failure model is shown in Fig. 2.

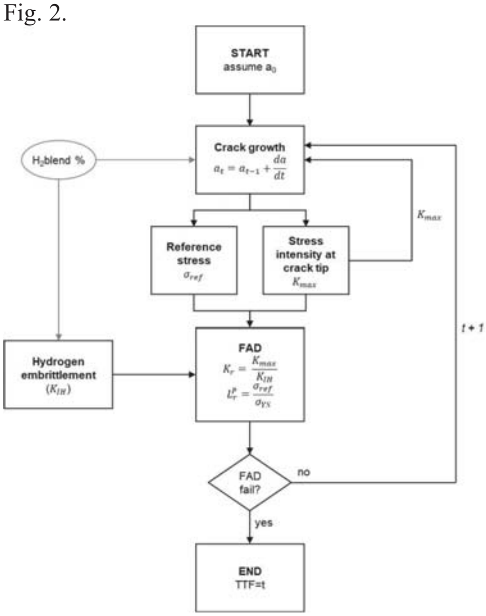

Fig. 2. Flow chart for simulation of crack growth and fracture

2.3. *Tree search*

A Monte Carlo Tree Search (MCTS) was performed to evaluate ideal conditions for minimizing risk and energy loss in pipelines under a full range of hydrogen blending conditions. Due to the long simulation time of the model, the standard MCTS method was altered by pre-generating the Monte Carlo samples. Five million random samples were generated using the input ranges shown in Table 1. For each sample, it was assumed the sampled conditions will remain constant over time.

Table 1. Input Ranges for Monte Carlo Tree Search

Input	Min	Max
Outer Diameter, *OD* (in)	8	36
Wall Thickness, *WT* (in) [1]	0.109	2
Hydrogen Blend, Y_{H2} (Mass %)	0%	100%
Temperature, *T* (°C)	20	80
Maximum Operating Pressure, *MOP* (psi)	200	1400
Pressure Drop Ratio, P_d [2]	0	0.5
Pipe Length, *L* (ft)	3281	164042
Loading Cycle Frequency, *f* (Hz)	0.0001	0.05
Loading Cycle Ratio, *R* [3]	0.7	0.99
Initial Flaw Depth, a_0 (in)	0.01	0.15
Flaw Length / Depth Ratio, *c ratio*	1.5	100
Pipe Yield Strength, *SMYS* (psi) [4]	60200	110200
Fracture Toughness, K_{IC} (MPa m$^{1/2}$) [4]	120.6	155

[1] Wall thickness is bounded in bins depending on the outer diameter as defined by ANSI / ASME B36.10M and API 5L

[2] $P_d = \frac{P_{inlet} - P_{outlet}}{P_{inlet}}$, where $P_{inlet} = MOP$

[3] Sampled logarithmically (more sample points at high R-ratios)

[4] Corresponds to properties of X60 Steel

The simulation results predict the time-to-failure (TTF) and energy flow with and without hydrogen for each sample. To evaluate the acceptability of these results for the tree search, a minimum acceptable TTF of 50 years and a maximum energy loss of 10% were applied as thresholds. The results of the Monte Carlo simulations are summarized in Fig. 3.

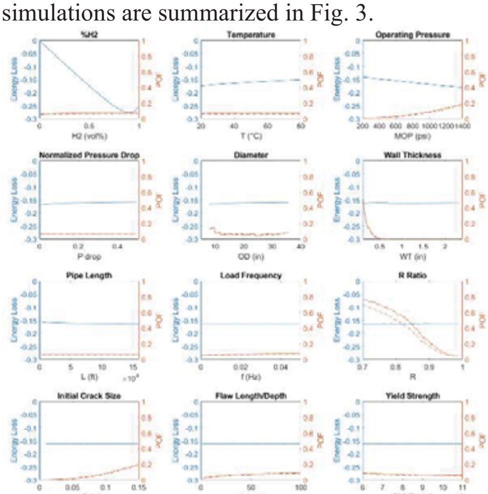

Fig. 3. Monte Carlo results for probability of failure (orange, solid line for 50 years, dashed line for 20 years) and percentage energy loss (blue) as a function of each input

A MCTS model is built by segregating the sample set recursively to maximize the prediction accuracy. The most effective split points serve as "rules" which identify inputs that significantly affect either the probability of failure within 50 years or the probability of energy loss greater than 10%.

3. Model Results

To achieve minimal risk of failure and energy loss, four rules have been identified and are listed below. Rule 1 limits the concentration of hydrogen, greatly reducing the energy loss. Rules 2 – 4 are then focused on reducing the probability of failure through reduced pressure, higher wall thickness, and maintaining a high load ratio (R).

- Rule 1: Y_{H2} less than 29%
- Rule 2: *MOP* less than 895 psi
- Rule 3: *WT* greater than 0.2 inch
- Rule 4: *R* greater than 0.899

The impacts of each input on failure risk and energy loss are re-evaluated after each rule is applied, allowing for the observation of rule effectiveness and evolution of trends as a function of input. This can be seen in Fig. 4 for wall thickness and outer diameter. The energy loss remains relatively unchanged as a function of each input, but due to the application of the first rule (low hydrogen concentration), the average energy loss has decreased from ~15% to ~5%. After the application of the first two rules, the wall thickness is seen to have an even greater influence on the probability of failure with a subtle "elbow" in the curve that serves as a cut-off point for rule 3. The probability of failure as a function of diameter does not show any clear trend in either direction until rule 3 is applied, at which point the effects of thin-walled pipes are insignificant and a trend of increasing risk as a function of diameter can be seen.

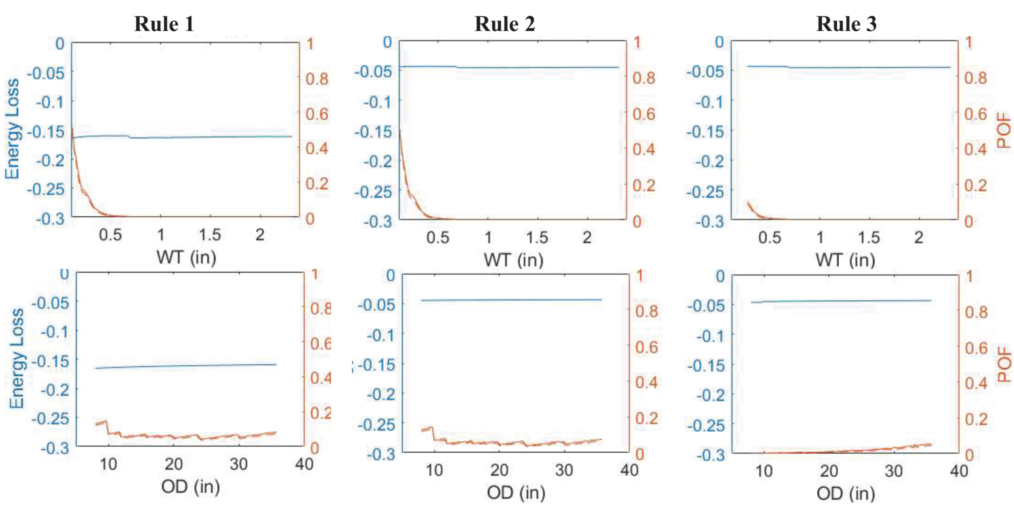

Fig. 4. Evolution of energy flow and probability of failure as a function of wall thickness and outer diameter as rules are applied

Focusing only on risk, a set of rules were developed manually by identifying cutoffs at each step to achieve a 50-year probability of failure less than five percent with one rule, less than one percent with two rules, and less than 0.1% with three rules. Multiple pathways to achieve this are shown in Table 2. To use the rules in this table, a secondary rule must be used with a primary rule, and a tertiary rule must be used with both a primary and secondary rule.

Table 2. Multiple Rule Sets for Minimizing Pipeline Risk in Hydrogen using Probability of Failure Thresholds

Input	Primary Rule POF<5%	Secondary Rule POF<1%	Tertiary Rule POF<0.1%

MOP	< 470 psi	< 640 psi	< 730 psi
OD	NA	NA	≤ 13 in
WT	≥ 0.531 in	≥ 0.312 in	NA
f	NA	NA	NA
R	≥ 0.98	≥ 0.93	≥ 0.91
a₀	< 0.04	NA	NA
c-ratio	NA	NA	NA
SMYS	NA	NA	NA

4. Application to Techno-economic Analysis

To translate the operational guidelines into lifecycle economic implications, we map the rule sets to a 50-year Probability of Failure (*PoF*50) and a physics-aware energy delivery model for a hypothetical 50 year life span of the pipelines. The four rules—hydrogen blend (*YH*2<29%), maximum operating pressure (*MOP*<895 psi), wall thickness (*WT*>0.2 in), and load ratio (*R*>0.899)—define 16 distinct binary scenarios as determined by equation 3. These scenarios dictate the initial risk profile and the revenue-generating capacity of the pipeline asset.

$$z = [z_{H2}, z_{MOP}, z_{WT}, z_R] \in \{0,1\}^4 \quad (3)$$

yielding $2^4 = 16$ discrete scenarios.

Figure 5 shows the Probability of Failure of the highest (a) and lowest (b) risk classes.

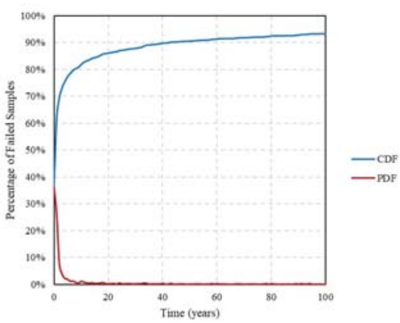

Fig 5.a. PoF_t value increase over time for class 0000

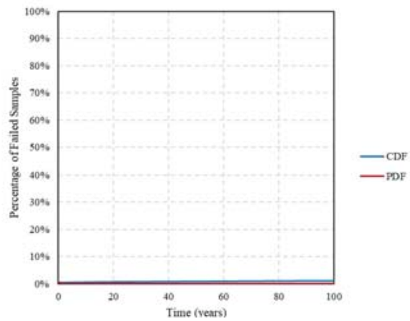

Fig 5.a. PoF_t value increase over time for class 1111

4.1. Physics-Aware Energy Flow and Revenue Model

Revenue is modeled as a direct function of the annual energy transported ($\dot{E}$), which is constrained by mixture hydraulics and system availability.

• **Energy Flow Rate:** Volumetric flow (*Q*) is calculated using the California Natural Gas Association (CNGA) equation, with gas properties (density, viscosity) predicted by neural networks. The energy flow is then derived according to equation 4.

$$\dot{E} = [(X_{H2} \cdot \rho_{H2} \cdot e_{H2}) + (1 - X_{H2}) \cdot \rho_{CH4} \cdot e_{CH4}] \cdot Q \quad (4)$$

where e_{H2}=120 MJ/kg and e_{CH4}=50 MJ/kg. Blending at constant pressure results in a volumetric energy density reduction of up to 31% at high concentrations, directly impacting revenue potential.

• **Annual Revenue (*Ry*):**

$$Ry = \dot{E} \cdot 365 \cdot Avy \cdot Unit\ Energy\ Price \quad (5)$$

Availability (*Avy*) is decreased by downtime (1–2 weeks) during repair events triggered by the integrity model.

4.2. Risk Banding and Proportional Integrity Policy

Following the logic in Table 3, scenarios are categorized into risk bands based on the number of rules satisfied and the resulting PoF_{50}. Inspection intervals (*I*) are sized proportionally to the simulated Time-to-Failure (TTF) and capped by the 7-year regulatory maximum, which is the baseline standard defined by PHMSA standard.

Table 4. Effect of Risk Band on the reduced inspection intervals

Risk Band	Logic (Rules Satisfied)	*PoF*50 Threshold	Inspection Interval (*I*)
Band D (Very Low)	4 Rules Satisfied	<0.1%	7 Years
Band C (Low)	3 Rules Satisfied	0.1%≤*PoF*<1%	5 Years
Band B (Medium)	1–2 Rules Satisfied	1%≤*PoF*<5%	3 Years
Band A (High)	0 Rules Satisfied	≥5%	1 Year

The 50-year PoF is converted into an annual trajectory using an exponential hazard model in equation 6.

$$\lambda = -\ln(1 - PoF_{50})/50 \tag{6}$$

Maintenance actions reset the effective "hazard age" to zero, lowering the PoF for subsequent periods

4.3. Cost Model and Net Present Value (NPV)

The model evaluates annual cashflows (C_y) over a 50-year horizon, discounting at r=5%. Total annual cost per mile includes:

• Inspection OPEX (C_{insp}): A blended cost of $130,000 per mile applied in scheduled inspection years.

• Maintenance OPEX (C_{rep}): Calculated as $n \cdot C_m$, where n is the expected actionable conditions per mile (n_A=0.173,n_B=0.144,n_C=0.072,n_D=0.036); this value is considered $ 65,000 per intervention.

$$\lambda NPV = \sum_{y=1}^{50} \frac{R_y - (C_{insp,y} + C_{rep,y})}{(1+r)^y} \tag{7}$$

For each scenario z, we simulate annual cashflows over a 50-year horizon. Each year y∈ {1,…,50} includes:

- Inspection cost C_{insp} only in scheduled inspection years; otherwise zero.
- Maintenance cost only if the PoF threshold is exceeded at an inspection year.
- Revenue generation due to Energy transportation.

A variable distribution of the 4 rules over their defined ranges has been considered for the PoF and energy flow simulations in each year, based on which the cashflow models of each class is made, as presented in Table 5, for instance, for class 0000 and class 1111, the most risky class and the least risky class respectively.

4.3. Results across 16 scenarios

The 16-scenario techno-economic simulation shows that rule combinations yielding lower PoF lead to fewer interventions and lower discounted costs. Across scenarios, inspection counts ranged from 7 to 10 assessments over 50 years (driven by the I_{max} cap and risk-triggered shortening). Maintenance events ranged from 0 to 10, with high-risk scenarios triggering maintenance at most inspection years.

Threshold timing provides additional insight into intervention urgency: among scenarios where the threshold is exceeded, PoF≥0.1% occurs within the first 1–2 years (15/16 scenarios), PoF≥1% occurs within 1–14 years (15/16 scenarios), while only half of the scenarios (8/16) ever reach the PoF≥5% immediate-action threshold within the horizon (and when they do, it occurs within 1–3 years after a reset).

Lifecycle costs are strongly influenced by the maintenance alternative once repairs are required. Under the adopted unit costs and repair-rate assumptions, composite wrap yields the minimum NPV in 15 of 16 scenarios; in the single very-low-risk scenario where maintenance never triggers, all alternatives are cost-equivalent and the “best option” is not uniquely defined (NPVs equal because only inspection costs occur).

The overall best-performing scenario in this dataset is z=1110 (three rules satisfied), which exhibits near-zero PoF_{50}, does not trigger maintenance, and achieves the minimum discounted cost. The worst-performing scenario is z=0000, which produces near-certain failure within the 50-year horizon and triggers frequent annualized integrity activity once thresholds are exceeded, resulting in the maximum NPV among the 16 cases. These results illustrate how rule-based screening can be used as a tractable bridge between physics-based reliability simulation and techno-economic planning, enabling rapid comparison of integrity OPEX profiles under hydrogen blending and pressure variations. Table 6 presents a summary table for each of the classes.

Table 5.a. Annual cash flow of the most risky class (0000)

Year	*PoFt*	TTF (Avg)	Rem. Life	Action Triggered	Insp. Cost ($)	Maint. Cost ($)	Capex ($M)	Availability	Energy Flow (MJ/day)	Energy revenue ($M)
0	0.0581	3.0	0.0	Retrofit Trigger	130,000	0	$1.00	96.16%	2.46×10^7	$0.44
1	0.0032	49.0	47.0	Annual Insp.	130,000	0	$0.00	96.16%	2.46×10^7	$0.44
2	0.0085	48.0	46.0	Annual Insp.	130,000	0	$0.00	96.16%	2.46×10^7	$0.44
3	0.0125	47.0	45.0	Scheduled Maint.	130,000	65,000	$0.00	96.16%	2.46×10^7	$0.44
4	0.0000*	50.0	50.0	Age Reset	130,000	0	$0.00	100%	2.46×10^7	$0.46
5	0.0032	49.0	47.0	Annual Insp.	130,000	0	$0.00	96.16%	2.46×10^7	$0.44
6	0.0085	48.0	46.0	Annual Insp.	130,000	0	$0.00	96.16%	2.46×10^7	$0.44
7	0.0125	47.0	45.0	Scheduled Maint.	130,000	65,000	$0.00	96.16%	2.46×10^7	$0.44
8	0.0000*	50.0	50.0	Age Reset	130,000	0	$0.00	100%	2.46×10^7	$0.46
...	...	...	...	...	...	...	...	...	...	...
49	0.0509	3.0	1.0	Immediate Maint.	130,000	65,000	$0.00	96.16%	2.46×10^7	$0.44
50	0.0000*	50.0	0.0	Horizon End	130,000	0	$0.00	100%	2.46×10^7	$0.46

Table 5.b. Annual cash flow of the least risky class (1111)

Year	*PoFt*	TTF (yrs)	Rem. Life	Action Triggered	Insp. Cost ($)	Maint. Cost ($)	Capex ($)	Availability	Energy Flow (MJ/day)	Energy Cost ($M)
0	< 0.001	> 50	50.0	Baseline	0	0	0	100%	6.41×10^7	$1.200
1-6	< 0.001	> 50	44.0	Normal Ops	0	0	0	100%	6.41×10^7	$1.200
7	0.0015	> 50	43.5	Routine Insp.	130,000	0	0	96.16%	6.41×10^7	$1.154
8-13	0.0018	> 50	38.0	Normal Ops	0	0	0	100%	6.41×10^7	$1.200
14	0.0025	> 50	36.0	Routine Insp.	130,000	0	0	96.16%	6.41×10^7	$1.154
15-20	0.0030	> 50	30.0	Normal Ops	0	0	0	100%	6.41×10^7	$1.200
21	0.0041	> 50	29.0	Routine Insp.	130,000	0	0	96.16%	6.41×10^7	$1.154
...	...	...	...	...	...	...	...	...	...	...
49	0.0098	> 50	1.0	Routine Insp.	130,000	0	0	96.16%	6.41×10^7	$1.154
50	0.0105	> 50	0.0	Scheduled Maint.	0	65,000	0	96.16%	6.41×10^7	$1.154

Table 6. Comparison of NPVs of different classes

Class ID	Rules Met	Start Band	Highest PoF reached	Lowest TTF (yrs)	Highest Energy Flow (MJ/day)	Total Insp.	Total Maint.	Capex ($M)	NPV Insp. ($M)	NPV Maint. ($M)	NPV Energy Rev ($M)	Total Net NPV ($M)
1111	4	D	< 0.1%	> 50	6.41×10^7	7	0.29	$0.00	$0.70	$0.01	$21.94	$21.23
1110	3	C	0.1–1%	> 50	6.41×10^7	10	0.79	$0.00	$0.88	$0.04	$21.84	$20.92
1101	3	C	0.1–1%	> 50	6.41×10^7	10	0.79	$0.00	$0.88	$0.04	$21.84	$20.92
1011	3	C	0.1–1%	> 50	1.14×10^8	10	0.79	$0.00	$0.88	$0.04	$21.84	$20.92
0111	3	C	0.1–1%	> 50	4.42×10^7	10	1.15	$0.00	$0.88	$0.06	$15.26	$14.32
1100	2	B	1–5%	> 50	6.41×10^7	17	2.59	$0.00	$1.27	$0.11	$21.68	$20.30
1010	2	B	1–5%	> 50	1.14×10^8	17	2.59	$0.00	$1.27	$0.11	$21.68	$20.30
1001	2	B	1–5%	> 50	1.14×10^8	17	2.59	$0.00	$1.27	$0.11	$21.68	$20.30
0110	2	B	1–5%	> 50	4.42×10^7	17	3.82	$0.00	$1.27	$0.16	$15.14	$13.71
0101	2	B	1–5%	> 50	4.42×10^7	17	3.82	$0.00	$1.27	$0.16	$15.14	$13.71
0011	2	B	1–5%	> 50	4.42×10^7	17	3.82	$0.00	$1.27	$0.16	$15.14	$13.71
1000	1	B	1–5%	> 50	1.14×10^8	17	2.59	$0.00	$1.27	$0.11	$21.68	$20.30
0100	1	B	1–5%	> 50	4.42×10^7	17	3.82	$0.00	$1.27	$0.16	$15.14	$13.71
0010	1	B	1–5%	> 50	4.42×10^7	17	3.82	$0.00	$1.27	$0.16	$15.14	$13.71
0001	1	B	1–5%	> 50	4.42×10^7	17	3.82	$0.00	$1.27	$0.16	$15.14	$13.71
0000	0	A	≥ 5.0%	~3	2.46×10^7	50	8.65	$1.00	$2.38	$0.42	$14.96	$11.16

4.4. **Qualitative Rule Effects:**

Rule 1 (*H*2 Blend < 29%): Dominates the energy flow rate. Violating this rule (seen in all "0XXX" classes) reduces energy revenue by up to 62% due to lower volumetric energy density. Rule 2 (MOP < 894.5 psi): Acts as the primary safety pivot. Compliance with Rule 2 significantly extends the TTF by reducing the stress intensity at crack tips, preventing the asset from reaching the 1% or 5% PoF thresholds prematurely. Rules 3 (WT) and 4 (R): Govern mechanical durability. Adherence to these rules provides a structural buffer and minimizes cyclic fatigue damage. Violating them (moving from Band D to B) nearly doubles the NPV of inspection costs as the interval drops from 7 years to 3 years.

Regarding economic Performance, the 1111 Class remains the most economically viable lifecycle option, maintaining the highest NPV ($21.23M) through high availability and minimal integrity overhead. The 0000 Class NPV is significantly further eroded by the $1,000,000 retrofit penalty, highlighting the extreme financial risk of operating vintage, thin-walled pipelines at high hydrogen blend ratios without pre-injection system hardening.

5. Conclusion

This paper presents part of a California Energy Commission project to assess the viability of hydrogen blending in existing natural gas infrastructure. Specifically, two models were developed to predict the increase in fracture and fatigue risk and predicted energy loss that results from hydrogen blending in transmission pipelines of varying sizes and operating pressures.

Predictions from the model show significant trade-offs between both types of losses, as increases in pressure to minimize energy loss increase fracture risk, and decreasing pressure to minimize risk results in increased energy loss. Measures can be taken to mitigate these trade-offs, but making predictions requires running a complex simulation model that is not user friendly.

- Simulation model results were approximated into a set of rules that give best and worst case scenarios
- The Monte Carlo simulation results were distilled into a compact rule set that separates operating/design conditions into higher- and lower-risk regions while retaining interpretability for decision makers. Extending these rules to a 50-year techno-economic simulation shows that hydrogen blending and pressure-driven risk amplification propagates directly into shorter reassessment intervals, higher expected repair frequency, and higher discounted integrity OPEX. Across the 16 rule-combination scenarios, the proposed workflow produces scenario-specific inspection and maintenance schedules and enables direct comparison of NPVs under alternative repair strategies, supporting rapid screening of safety–efficiency trade-offs when repurposing pipelines for hydrogen blends.

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(Optional supporting standard context) ASME B31.8S / hydrogen blends code-and-standards assessments (risk-based integrity framing).