



Selective Caustic Scrubbing Design Study for H₂S Removal at TA-58

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1 Executive Summary

This report presents a comparative engineering study of caustic scrubbing technologies for sour gas sweetening at the TA-58 production facility. The objective is to enable displacement of diesel fuel consumption (estimated at 500 000\$/yr) by treating associated gas to meet the 45 ppmv H₂S specification for the installed Caterpillar G3408 gas engines.

1.1 Design Basis

The study evaluates treatment of **660,000 SCFD** associated gas containing 1 800 ppmv H₂S and 2.86 % CO₂. The required removal efficiency is 97.5% to achieve the engine fuel specification. At this scale:

- H₂S load: 0.056 kmol/h (1.9 kg/h)
- CO₂ load: 0.90 kmol/h (39 kg/h)
- Molar ratio CO₂/H₂S: approximately 16:1

The 16-fold excess of CO₂ creates the central design challenge: non-selective absorption would consume caustic at rates that render the project economically non-viable.

1.2 Technology Comparison

Two caustic scrubbing configurations are evaluated:

Table 1.1: Technology comparison summary at 660,000 SCFD

Parameter	Packed Column	SCT Static Mixer
Equipment size	0.75 m dia. × 5.5 m height	0.3 m × 1.5 m inline
H ₂ S removal	97.5%	>98%
CO ₂ co-absorption	50–80% (equilibrium)	2–10% (kinetic control)
NaOH consumption	300–500 ton/yr	46–90 ton/yr
NaOH cost	\$150,000–250,000/yr	\$23,000–45,000/yr
Technology maturity	Well-established	Emerging (growing field data)

The SCT technology exploits the 10⁶ difference in reaction rate constants between H₂S and CO₂, achieving selective removal through controlled short contact time (50–200 ms) rather than relying on pH control.

1.3 Economic Assessment

The economic analysis reveals a critical finding: **at the 660,000 SCFD scale, selectivity determines project viability.**

Table 1.2: Economic comparison (base case)

Indicator	Packed Column	SCT System	Assessment
Capital cost (TIC)	\$2.53M	\$1.78M	SCT 30% lower
Net annual benefit	\$211,000/yr	\$417,000/yr	SCT 2× higher
Simple payback	12.0 years	4.3 years	SCT 2.8× faster
IRR (15-year)	5.3%	22.8%	SCT exceeds hurdle
NPV at 12%	-\$87,000	+\$1,060,000	SCT creates value

Key conclusions:

- The **packed column fails to meet the 15% IRR hurdle rate** at base case assumptions due to high caustic consumption from CO₂ co-absorption.
- The **SCT system exceeds the hurdle rate** (22.8% IRR) and delivers positive NPV of \$1.06M over the 15-year project life.
- The economic cost of non-selective CO₂ absorption is approximately \$1.15M in lifetime value destruction.

1.4 Technology Recommendation

Based on the quantitative analysis, **SCT static mixer technology is recommended** for the TA-58 application. The recommendation is supported by:

- Superior economics: 5–10× lower caustic consumption provides \$200,000/yr operating cost advantage
- Inherent selectivity: Design-based selectivity reduces operational risk versus pH-controlled selectivity
- Compact footprint: Inline installation minimises plot space requirements
- Growing field experience: SCT caustic scrubbers have demonstrated performance in refinery applications

The packed column remains a viable fallback if vendor engagement identifies concerns with SCT technology availability, but the economic penalty should be explicitly considered.

1.5 Critical Uncertainties

Resolution of the following is required before project sanction:

- Vendor quotations:** Budgetary quotes from 2–3 SCT suppliers to validate capital estimate
- Diesel displacement:** Historical fuel records to confirm \$500,000/yr benefit
- Selectivity guarantee:** Vendor performance guarantees for CO₂ co-absorption limits
- Spent caustic treatment:** MBBR vendor confirmation for 43 kg S/day capacity

1.6 Recommended Next Steps

1. Issue RFQ to SCT caustic scrubber vendors (e.g., Merichem, Trimeric, Koch-Glitsch)
2. Validate diesel displacement through operational data analysis
3. Conduct HAZID workshop for hazard identification
4. If required, plan pilot testing to validate selectivity under field conditions
5. Following vendor responses, proceed to detailed feasibility and FEED

This study demonstrates that selective H₂S removal using SCT technology provides a technically feasible and economically attractive solution for the TA-58 sour gas treatment. The project creates an estimated \$1.06M NPV over 15 years while enabling diesel displacement and emissions reduction.

2 Introduction and Design Basis

2.1 Problem Definition

TA-58 produces a methane-rich associated gas stream containing 1 800 ppmv H₂S, exceeding the 45 ppmv fuel specification for the installed Caterpillar G3408 (HPG) dual-gas engines [1]. Under current practice, most associated gas is routed to flare while the pump station relies on diesel at an estimated 500 000 \$/yr. Implementation of an H₂S removal system enables: (i) on-spec fuel gas for engine operation; (ii) reduced routine flaring and SO₂ emissions; and (iii) diesel displacement with corresponding CO₂ and cost reductions.

The gas stream also contains 2.86 % CO₂ (28 550 ppmv), which creates a selectivity challenge: non-selective absorption would consume caustic at rates that render the project economically unviable. As Pudi et al. [2] note in their comprehensive review of H₂S capture technologies, the presence of CO₂ fundamentally influences technology selection and operating strategy for sour gas treatment.

2.2 Study Scope

This study evaluates the technical and economic feasibility of treating the TA-58 sour associated gas to engine fuel-gas specification. The scope comprises:

- (i) feed characterisation and design basis establishment;
- (ii) comparative evaluation of applicable H₂S removal technologies;
- (iii) conceptual equipment sizing with material balances;
- (iv) techno-economic assessment against the diesel displacement baseline;
- (v) integration requirements with existing systems.

Exclusions: detailed engineering, vendor guarantees, formal process safety studies (HAZID/HAZOP/LOPA), procurement, permitting, and commissioning support.

2.3 Design Basis

The key design inputs are summarised in Table 2.1, based on operational data from the TA-58 facility [1].

Table 2.1: Design basis parameters

Parameter	Value	Units
Gas source	VRU discharge	—
Flow rate (standard)	660,000	SCFD
Flow rate (SI equivalent)	779	Nm ³ /h
Total molar flow	31.3	kmol/h
Inlet H ₂ S	1,800	ppmv
Inlet CO ₂	28,550	ppmv (2.86%)
Required outlet H ₂ S	< 45	ppmv
Removal efficiency	> 97.5	%
Operating temperature	25–40	°C
Operating pressure	Atmospheric	—

At the design flow rate, the component molar flows are:

- **H₂S load:** $31.3 \times 0.0018 = 0.056 \text{ kmol/h}$ (1.9 kg/h or 46 kg/day)
- **CO₂ load:** $31.3 \times 0.0286 = 0.90 \text{ kmol/h}$ (39 kg/h)
- **Molar ratio CO₂/H₂S:** $\approx 16 : 1$

The 16-fold excess of CO₂ relative to H₂S creates the central design challenge: if CO₂ is absorbed non-selectively alongside H₂S, caustic consumption becomes economically prohibitive (see Section 3).

2.4 Technology Screening Summary

The screening evaluation considered technologies capable of reducing H₂S from 1 800 ppmv to < 45 ppmv (approximately 97.5% removal). Caustic scrubbing was selected for detailed evaluation based on operability at low pressure, tolerance to liquid carryover, and potential for sulfide stabilisation via biological treatment [2]. Alternative technologies (membrane + ZnO, liquid redox, chemical scavengers) were not advanced due to technical or economic limitations at the site scale.

A key design consideration is the presence of CO₂: the rate constant for CO₂ absorption in caustic is approximately 10⁶ times slower than for H₂S, which can be exploited through contactor design to achieve selective removal and limit caustic consumption [3, 4, 5].

Figure 2.1 illustrates the design logic flow from feed characterisation through to operability limits, highlighting the critical linkages between feed conditions, solvent selection, and equipment sizing.

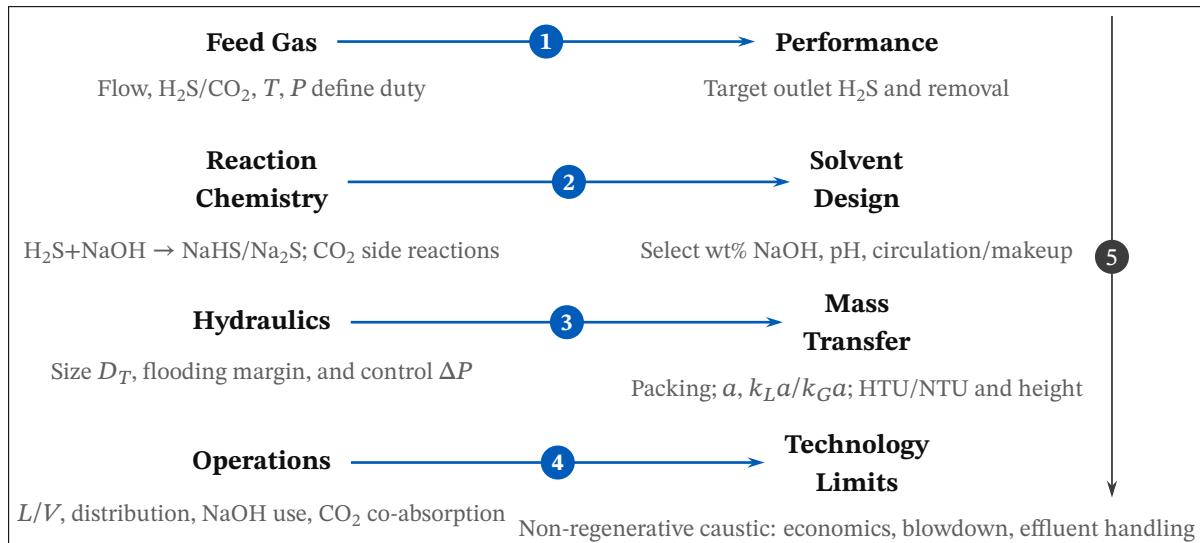


Figure 2.1: Design logic map for caustic H₂S scrubbing. The diagram links feed conditions and performance targets to solvent selection, hydraulic sizing, mass-transfer design, and operability limits.

2.5 Decision Criteria

Project progression is recommended when:

- (i) treated gas meets 45 ppmv H₂S specification;
- (ii) a practical sulfur-handling route is defined;
- (iii) screening-level risk assessment indicates manageable hazards;
- (iv) positive economics relative to diesel displacement at AACE Class 3 maturity;
- (v) tie-ins are feasible within site constraints.

3 Technology Options Analysis

Two caustic scrubbing configurations are evaluated for the TA-58 application: a conventional packed column absorber and a Short Contact Time (SCT) static mixer system. Both technologies exploit the fast irreversible reaction between H₂S and NaOH but differ fundamentally in their approach to CO₂ selectivity—a factor that, at the 660,000 SCFD scale, determines project economic viability.

3.1 Mass Transfer Fundamentals

Before comparing technologies, it is essential to establish the theoretical basis for selective H₂S absorption. The classical two-film model, as developed by Danckwerts [4], describes gas absorption with chemical reaction through the flux equation:

$$N_A = k_L \cdot a \cdot E \cdot (C_i - C_b) \quad (3.1)$$

where $k_L a$ is the liquid-side mass transfer coefficient, E is the enhancement factor due to chemical reaction, C_i is the interfacial concentration, and C_b is the bulk liquid concentration.

For gas-phase controlled absorption (as with H₂S in strong caustic), the overall transfer rate simplifies to:

$$N_A = K_G \cdot a \cdot \Delta p_A \quad (3.2)$$

The enhancement factor depends on the Hatta number (Ha), which quantifies the ratio of reaction rate to diffusion rate [4, 5]:

$$Ha = \frac{\sqrt{k_2 \cdot D_A \cdot C_{OH}}}{k_L} \quad (3.3)$$

where k_2 is the second-order rate constant, D_A is the diffusivity of species A, and C_{OH} is the hydroxide concentration.

For fast reactions (Ha > 3), the enhancement factor approaches Ha:

$$E \approx Ha \quad \text{when } Ha > 3 \quad (3.4)$$

3.1.1 Kinetic Rate Constants

The critical selectivity opportunity arises from the dramatically different reaction kinetics of H₂S and CO₂ with hydroxide [4, 5]:

Table 3.1: Reaction kinetics for H₂S and CO₂ with NaOH at 25–40°C

Reaction	Rate Constant	Regime
H ₂ S + OH ⁻ → HS ⁻ + H ₂ O	$k_{H_2S} \approx 10^{10} \text{ L}/(\text{mol s})$	Instantaneous
CO ₂ + OH ⁻ → HCO ₃ ⁻	$k_{CO_2} \approx 10^3\text{--}10^4 \text{ L}/(\text{mol s})$	Finite rate

The rate constant ratio of approximately 10⁶ provides the thermodynamic basis for selective H₂S removal. The practical question is whether the contactor design can exploit this kinetic difference.

3.1.2 The Damköhler Framework for Selectivity

The Damköhler number (Da) relates reaction rate to residence time [5]:

$$Da = k_2 \cdot C_{OH} \cdot \tau \quad (3.5)$$

where τ is the gas-liquid contact time.

For selective absorption, the operating window must satisfy:

$$Da_{H_2S} \gg 1 \quad (\text{complete H}_2\text{S reaction}) \quad Da_{CO_2} \ll 1 \quad (\text{negligible CO}_2 \text{ reaction}) \quad (3.6)$$

At 5 wt% NaOH ($C_{OH} \approx 1.25 \text{ mol/L}$), the critical contact times are:

$$\tau_{H_2S} = \frac{1}{k_{H_2S} \cdot C_{OH}} \approx \frac{1}{10^{10} \times 1.25} \approx 0.08 \text{ ns} \quad (\text{instantaneous}) \quad (3.7)$$

$$\tau_{CO_2} = \frac{1}{k_{CO_2} \cdot C_{OH}} \approx \frac{1}{10^4 \times 1.25} \approx 80 \mu\text{s} \quad (3.8)$$

This analysis reveals the selectivity window: contact times of 10–100 ms allow complete H₂S absorption while limiting CO₂ uptake to single-digit percentages.

3.2 Packed Column Scrubber

3.2.1 Operating Principle

The packed column absorber operates in counter-current flow, with sour gas entering the bottom and aqueous NaOH distributed over structured or random packing from the top. Mass transfer occurs as gas contacts the liquid film on packing surfaces. The required packed height is determined by the number of transfer units [6]:

$$N_{TU} = \ln\left(\frac{y_{in}}{y_{out}}\right) = \ln\left(\frac{1800}{45}\right) = 3.69, \quad Z = HTU \times N_{TU} \quad (3.9)$$

3.2.2 Column Sizing for 660,000 SCFD

The column diameter is sized for flooding avoidance. Following the correlation approach of Strigle [7] and validated against the Onda correlation [8], the design proceeds as:

Gas flow properties:

- Volumetric flow: $660,000 \times 0.0283/86,400 = 0.216 \text{ m}^3/\text{s}$ (actual)
- Gas density: $\rho_G \approx 0.95 \text{ kg/m}^3$ (methane-rich at 30°C, 1 atm)
- Design velocity: 70% of flooding, $u_G \approx 0.8 \text{ m/s}$

Column diameter:

$$D = \sqrt{\frac{4 \cdot Q_G}{\pi \cdot u_G}} = \sqrt{\frac{4 \times 0.216}{\pi \times 0.8}} = 0.59 \text{ m} \quad (3.10)$$

Applying a safety factor for maldistribution and allowing for structured packing installation, the recommended column diameter is **0.75 m (30 in)**.

Packed height:

Using the HETP correlation from Wankat [6] for 50 mm structured packing (Sulzer Mellapak 250Y):

$$\text{HETP} \approx 0.4\text{--}0.6 \text{ m}, \quad Z = N_{TU} \times \text{HETP} \approx 3.69 \times 0.5 = 1.85 \text{ m} \quad (3.11)$$

With 50% design margin for mass transfer uncertainty [9], the recommended packed height is **2.8 m**.

3.2.3 Caustic Consumption Analysis

The critical economic parameter is caustic consumption. At the packed column's typical residence time (5–15 s), equilibrium is approached for both H₂S and CO₂:

H₂S consumption (stoichiometric):

$$\dot{m}_{\text{NaOH,H}_2\text{S}} = 0.056 \text{ kmol/h} \times 40 \text{ kg/kmol} = 2.2 \text{ kg/h} \quad (3.12)$$

CO₂ consumption (70% absorbed at pH 12–13):



$$\dot{m}_{\text{NaOH,CO}_2} = 0.90 \text{ kmol/h} \times 0.70 \times 2 \times 40 \text{ kg/kmol} = 50 \text{ kg/h} \quad (3.14)$$

Total annual consumption:

$$\text{Total} = (2.2 + 50) \times 8,000 \text{ h/yr} = 418 \text{ ton/yr} \quad (3.15)$$

At a delivered NaOH cost of \$500/ton [10], the annual caustic cost is approximately **\$209,000/yr**.

Table 3.2: Packed column design summary for 660,000 SCFD

Parameter	Value	Units
Column diameter	0.75	m (30 in)
Packed height	2.8	m (9.2 ft)
Total column height	5.5	m (including sump, distributor, demister)
Packing type	Mellapak 250Y	Structured
N_{TU} (H_2S)	3.69	—
HETP	0.50	m
Operating velocity	0.8	m/s (70% flood)
H_2S removal	97.5	%
CO_2 removal	50–80	% (pH dependent)
NaOH consumption	418	ton/yr
NaOH cost	209,000	\$/yr

3.2.4 Economic Reality Check

With diesel displacement benefit of \$500,000/yr and caustic cost of \$209,000/yr (assuming 70% CO_2 absorption), the operating margin before other OpEx is:

$$\text{Margin} = 500,000 - 209,000 = \$291,000/\text{yr} \quad (3.16)$$

However, if CO_2 absorption increases to 90% (possible at higher pH operation), caustic cost rises to \$296,000/yr, leaving only \$204,000/yr margin. At 95% CO_2 absorption:

$$\text{Caustic cost} = (2.2 + 68) \times 8,000 \times 0.5 = \$281,000/\text{yr} \quad (3.17)$$

This sensitivity demonstrates that **packed column viability depends critically on maintaining low CO_2 absorption**, which requires careful pH control—a non-trivial operating challenge.

3.3 Short Contact Time (SCT) Static Mixer Scrubber

3.3.1 Operating Principle

The SCT concept deliberately limits gas-liquid contact time to exploit the 10^6 kinetic rate difference between H_2S and CO_2 absorption [3]. By maintaining contact time in the 10–100 ms range, the instantaneous H_2S reaction completes while the slower CO_2 reaction achieves negligible conversion. Fig 3.1, showcases the general layout for an single-stage SCT caustic scrubber.

Field data from refinery applications [3] demonstrate selectivities (defined as % H_2S removal / % CO_2 removal) of 20–50, with CO_2 co-absorption limited to 2–10% while achieving >98% H_2S removal.

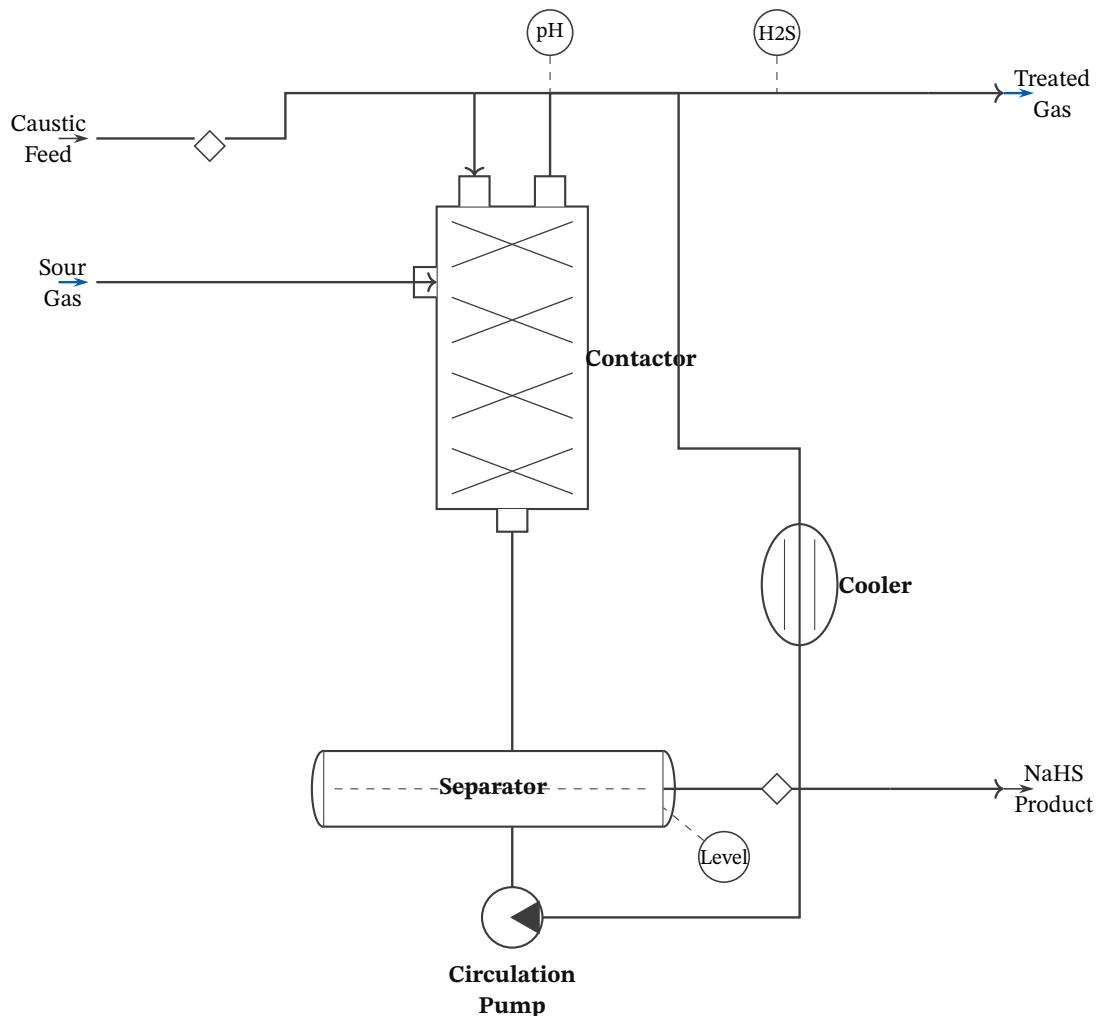


Figure 3.1: Process flow schematic of the caustic-based sour gas sweetening system, showing sour gas contacting a circulating NaOH solution for H₂S removal. The diagram illustrates the main equipment—contactor, separator, cooler, and pump—and the flow of treated gas and NaHS product.

3.3.2 Static Mixer Configuration

The contactor uses structured packing static mixers (Sulzer SMV-type or Kenics-type) with element L/D ratio of 1.0–1.5. The compact geometry provides high interfacial area with controlled, short residence time.

Sizing for 660,000 SCFD:

For a design superficial velocity of 3 m/s (typical for SMV mixers):

$$A = \frac{Q_G}{u_G} = \frac{0.216}{3.0} = 0.072 \text{ m}^2, \quad D = \sqrt{\frac{4A}{\pi}} = 0.30 \text{ m} \quad (3.18)$$

Multiple parallel trains or a single larger mixer (300 mm diameter) are viable configurations.

Contact time verification:

For 4 mixer elements at L/D = 1.5:

$$L_{\text{total}} = 4 \times 1.5 \times 0.30 = 1.8 \text{ m}, \quad \tau = \frac{L}{u_G} = \frac{1.8}{3.0} = 0.6 \text{ s} \quad (3.19)$$

This is longer than the ideal 10–100 ms window, suggesting shorter element trains or higher velocities. With optimised design (2 elements, $u_G = 5 \text{ m/s}$):

$$\tau = \frac{0.9}{5.0} = 180 \text{ ms} \quad (3.20)$$

At 180 ms contact time, Damköhler analysis predicts:

- $\text{Da}_{\text{H}_2\text{S}} \gg 1$: complete H_2S absorption
- $\text{Da}_{\text{CO}_2} \approx 0.02$: approximately 2% CO_2 absorption

3.3.3 Caustic Consumption Analysis

At 5% CO_2 co-absorption:

$$\dot{m}_{\text{NaOH},\text{H}_2\text{S}} = 2.2 \text{ kg/h} \quad (3.21)$$

$$\dot{m}_{\text{NaOH},\text{CO}_2} = 0.90 \times 0.05 \times 2 \times 40 = 3.6 \text{ kg/h} \quad (3.22)$$

$$\text{Total} = (2.2 + 3.6) \times 8,000 = 46 \text{ ton/yr} \quad (3.23)$$

Annual caustic cost: $46 \times 500 = \$23,000/\text{yr}$

Table 3.3: SCT static mixer design summary for 660,000 SCFD

Parameter	Value	Units
Mixer diameter	300	mm (12 in)
Number of elements	2–4	—
Total length	0.6–1.8	m
Contact time	50–200	ms
Superficial velocity	3–5	m/s
H_2S removal	> 98	%
CO_2 co-absorption	2–10	%
Selectivity ($\text{H}_2\text{S}/\text{CO}_2$)	10–50	—
NaOH consumption	46–90	ton/yr
NaOH cost	23,000–45,000	\$/yr

3.4 Comparative Evaluation: The Selectivity Imperative

At the 660,000 SCFD scale with a fixed \$500,000/yr diesel displacement benefit, the economics are dominated by caustic consumption. Table 3.4 quantifies this critical difference.

Table 3.4: Technology comparison at 660,000 SCFD scale

Parameter	Packed Column	SCT Static Mixer
H ₂ S removal	97.5%	>98%
CO ₂ co-absorption	50–80% (equilibrium-driven)	2–10% (kinetically limited)
Selectivity mechanism	pH control (operationally challenging)	Contact time (inherent to design)
NaOH consumption	300–500 ton/yr	46–90 ton/yr
NaOH cost	\$150,000–250,000/yr	\$23,000–45,000/yr
Operating margin	\$250,000–350,000/yr	\$455,000–477,000/yr
Equipment footprint	0.75 m × 5.5 m column	0.3 m × 1.5 m inline
Control complexity	Standard (pH, level, flow)	pH-critical (± 0.3 units)
Technology maturity	Well-established	Emerging (growing field experience)

3.4.1 Economic Comparison

The following analysis assumes 8,000 operating hours/year and \$500/ton delivered NaOH:

Table 3.5: Annual operating cost comparison

Scenario	NaOH (ton/yr)	NaOH Cost (\$/yr)	Net Margin (\$/yr)
<i>Packed Column</i>			
50% CO ₂ absorption	298	149,000	351,000
70% CO ₂ absorption	418	209,000	291,000
90% CO ₂ absorption	538	269,000	231,000
<i>SCT Static Mixer</i>			
2% CO ₂ absorption	32	16,000	484,000
5% CO ₂ absorption	46	23,000	477,000
10% CO ₂ absorption	75	38,000	462,000

Key finding: The SCT technology provides **1.4–2.1× higher operating margin** than packed column across the range of plausible CO₂ absorption scenarios. This margin difference of \$130,000–250,000/yr dominates the capital cost differential (see Section 5).

3.4.2 Selectivity Visualisation

The kinetic basis for selectivity is illustrated in Figure 3.2, which shows conversion versus contact time for both species.

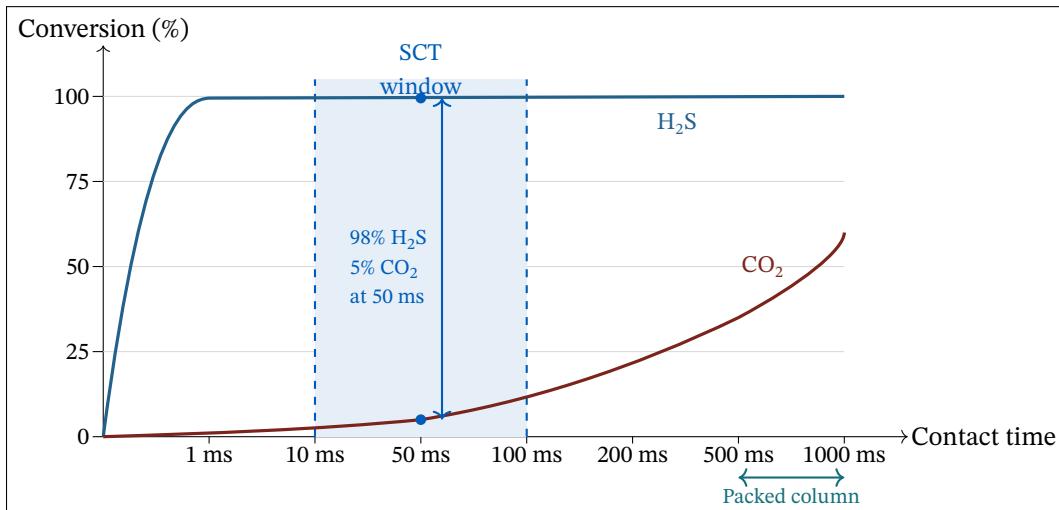


Figure 3.2: Conversion versus contact time for H₂S and CO₂ absorption in caustic. The shaded region indicates the SCT selectivity window (10–100 ms) where H₂S absorption is complete while CO₂ absorption remains negligible. Packed columns operate at longer contact times (0.5–5 s), approaching equilibrium for both species.

3.4.3 Selection Recommendation

Based on the quantitative analysis, **SCT static mixer technology is recommended** for the TA-58 application:

- (i) **Economic superiority:** The 5–10× reduction in caustic consumption provides \$130,000–250,000/yr operating cost advantage, which compounds over the 15-year project life.
- (ii) **Inherent selectivity:** SCT selectivity derives from the fundamental design (short contact time) rather than requiring precise pH control, reducing operational risk.
- (iii) **Compact footprint:** The inline mixer configuration (<2 m) requires minimal plot space compared to the 5.5 m packed column.
- (iv) **Growing field experience:** While less established than packed columns, SCT caustic scrubbers have demonstrated performance in refinery fuel gas applications [3].

The packed column remains a viable fallback if vendor engagement identifies concerns with SCT technology availability or if site personnel strongly prefer conventional equipment. However, the economic penalty of non-selective CO₂ absorption should be explicitly considered in the final technology selection.

4 Spent Caustic Treatment

4.1 Process Requirement

The caustic scrubbing process generates a spent caustic stream containing dissolved sodium hydro-sulfide (NaHS) and sodium sulfide (Na₂S), which require treatment before disposal. Direct discharge is not acceptable due to toxicity, oxygen demand, and odour [11]. Biological oxidation using sulfur-oxidising bacteria (SOB) was selected as the preferred treatment approach, offering conversion of sulfide to stable elemental sulfur and/or sulfate with potential for partial caustic alkalinity recovery [12, 13].

4.2 Design Basis at 660,000 SCFD Scale

The spent caustic treatment capacity depends on the upstream scrubber configuration. At the 660,000 SCFD scale, the sulfide load is substantially higher than for small-scale installations. Key design parameters are summarised in Table 4.1.

Table 4.1: Spent caustic treatment design basis

Parameter	Packed Column	SCT Option	Units
H ₂ S absorbed	0.056	0.056	kmol/h
Sulfide load	1.8	1.8	kg S/h
Sulfide load (daily)	43	43	kg S/day
CO ₂ co-absorbed	0.63 (70%)	0.045 (5%)	kmol/h
Carbonate formed	High	Low	—
Blowdown pH	10–12	11–13	—
Blowdown rate (est.)	200–400	50–100	L/h

The sulfide load of approximately **43 kg S/day** is independent of scrubber technology (both remove the same H₂S). However, the blowdown composition differs significantly:

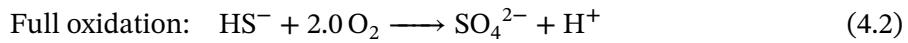
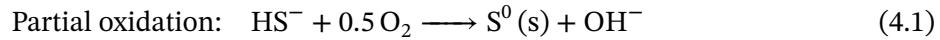
- **Packed column:** High carbonate content from CO₂ co-absorption; larger blowdown volume to manage carbonate buildup.
- **SCT option:** Lower carbonate content; smaller blowdown volume; higher sulfide concentration per unit volume.

4.3 MBBR Configuration

A Moving Bed Biofilm Reactor (MBBR) is proposed for biological oxidation. This technology was selected over conventional activated sludge due to compactness, biofilm stability against hydraulic surges, and proven performance for sulfide oxidation [14, 15].

4.3.1 Process Microbiology

Autotrophic sulfur-oxidising bacteria (SOB), primarily *Thiobacillus* and *Paracoccus* species, oxidise sulfide using dissolved oxygen [15, 13]. The oxidation endpoint is controlled by oxygen availability:



Operation under oxygen-limiting conditions (DO < 1.0 mg/L) favours partial oxidation to elemental sulfur, which can be separated by settling, rather than generating high-salinity sulfate waste. Borges et al. [13] demonstrated 90–95% sulfide removal in biotrickling filters treating high-strength sulfide streams at loading rates up to 100 g S/(m³ · h).

4.3.2 Preliminary Sizing

Based on the material balance from Section 3 and conservative design loading rates from literature [14, 15]:

Table 4.2: MBBR preliminary sizing for 43 kg S/day

Parameter	Value	Basis
Design sulfide load	43	kg S/day
Volumetric loading rate	0.5–1.0	kg S/(m ³ ·day)
Required reactor volume	43–86	m ³
Design reactor volume	50	m ³ (conservative)
Media fill fraction	40	%
Media type	K3 (500 m ² /m ³)	Polyethylene carriers
Hydraulic retention time	8–16	hours
Aeration	Fine bubble diffuser	Blower-supplied

The MBBR effluent flows to a lamella clarifier for biomass and elemental sulfur separation. Settled sulfur can be periodically removed for disposal or, if quantities justify, potential sale.

4.3.3 Alkalinity Recovery

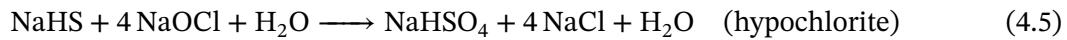
A significant benefit of the partial oxidation route is hydroxide regeneration:



This reaction theoretically regenerates 1 mol OH⁻ per mol sulfide oxidised. In practice, Borges et al. [13] report 40–60% alkalinity recovery, which can reduce fresh caustic makeup requirements.

4.4 Alternative: Chemical Oxidation

If biological treatment proves impractical at this scale (due to space constraints or operator preference), chemical oxidation with hydrogen peroxide or sodium hypochlorite provides a fallback:



Chemical oxidation is operationally simpler but has higher operating cost (\$50–100/kg S vs \$5–15/kg S for biological treatment) and produces high-salinity sulfate waste requiring disposal.

4.5 Further Study Required

Resolution of the following items is required during detailed engineering:

- (i) Final scrubber technology selection to determine blowdown composition and rate
- (ii) Vendor engagement for packaged MBBR systems at 50 m³ scale
- (iii) Laboratory treatability study to confirm loading rates and alkalinity recovery

- (iv) Evaluation of elemental sulfur handling and disposal options
- (v) Fallback assessment: chemical oxidation cost comparison if MBBR is not viable

The spent caustic treatment system represents a critical path item for project economics. Selection of SCT technology would reduce blowdown volume and simplify treatment by minimising carbonate content, though the sulfide load remains unchanged.

5 Economic Evaluation

The economic viability of the TA-58 sour gas project depends critically on the balance between capital investment, operating costs (dominated by caustic consumption), and the diesel displacement benefit. At the 660,000 SCFD scale, selectivity—the ability to remove H₂S while minimising CO₂ co-absorption—determines whether the project creates or destroys value.

5.1 Economic Framework

5.1.1 Fixed Benefit

The diesel displacement benefit is approximately **\$500,000/yr**, based on the fuel consumption of two Caterpillar G3408 dual-fuel engines. This benefit is independent of gas flow rate (the engines consume a fixed amount of fuel) and represents the maximum possible annual saving.

5.1.2 Variable Costs

Operating costs are dominated by:

- **Caustic consumption:** \$500/ton delivered (50% NaOH solution) [10]
- **Biological treatment:** \$10–20/kg S for MBBR operation
- **Utilities:** Electricity for pumps, blowers (estimated \$15,000–25,000/yr)
- **Maintenance:** 3% of TIC annually

5.2 Operating Cost Comparison

Table 5.1 presents the complete operating cost comparison for both technologies across the range of plausible CO₂ absorption scenarios.

Table 5.1: Annual operating cost comparison at 660,000 SCFD

Technology / Scenario	NaOH (ton/yr)	NaOH Cost (\$/yr)	Other OpEx (\$/yr)	Total OpEx (\$/yr)
<i>Packed Column</i>				
Conservative (50% CO ₂)	298	149,000	75,000	224,000
Base case (70% CO ₂)	418	209,000	80,000	289,000
High CO ₂ (90%)	538	269,000	85,000	354,000
<i>SCT Static Mixer</i>				
Optimistic (2% CO ₂)	32	16,000	55,000	71,000
Base case (5% CO ₂)	46	23,000	60,000	83,000
Conservative (10% CO ₂)	75	38,000	65,000	103,000

5.2.1 Net Annual Benefit

The net annual benefit is calculated as diesel displacement minus total operating cost:

Table 5.2: Net annual benefit comparison

Scenario	Total OpEx (\$/yr)	Net Benefit (\$/yr)
<i>Packed Column</i>		
Best case (50% CO ₂)	224,000	276,000
Base case (70% CO ₂)	289,000	211,000
High CO ₂ (90%)	354,000	146,000
<i>SCT Static Mixer</i>		
Optimistic (2% CO ₂)	71,000	429,000
Base case (5% CO ₂)	83,000	417,000
Conservative (10% CO ₂)	103,000	397,000

Key finding: The SCT option delivers **1.5–3× higher net annual benefit** than the packed column across all scenarios. This \$140,000–280,000/yr difference compounds over the project life.

5.3 Capital Cost Estimates

Capital costs are estimated using the factored approach per AACE Class 4/5 methodology [16], scaled from industry benchmarks [17, 18].

Table 5.3: Capital cost estimates (AACE Class 4)

Cost Element	Packed Column	SCT System
Scrubber/contactor	\$450,000	\$180,000
Caustic storage & dosing	\$150,000	\$120,000
Spent caustic treatment (MBBR)	\$350,000	\$300,000
Instrumentation & controls	\$180,000	\$200,000
Piping & bulks	\$220,000	\$150,000
Direct costs	1,350,000	950,000
Engineering & procurement (15%)	203,000	143,000
Installation (35%)	473,000	333,000
Contingency (25%)	507,000	357,000
Total Installed Cost (TIC)	\$2,530,000	\$1,780,000

The SCT system has **30% lower capital cost** due to the compact contactor and simpler auxiliary systems.

5.4 Economic Performance Indicators

Using the base case assumptions (packed column at 70% CO₂, SCT at 5% CO₂), the economic indicators are:

Table 5.4: Economic performance summary (15-year life, 12% discount rate)

Indicator	Packed Column	SCT System	Advantage
Net annual benefit	\$211,000/yr	\$417,000/yr	SCT +\$206k/yr
Simple payback	12.0 years	4.3 years	SCT 2.8× faster
IRR (15-year)	5.3%	22.8%	SCT +17.5 pp
NPV at 12%	-\$87,000	+\$1,060,000	SCT +\$1.15M

Critical observations:

- (i) The **packed column fails to meet the 15% IRR hurdle rate** at base case assumptions (70% CO₂ absorption). Only at the optimistic 50% CO₂ scenario does IRR approach 10%.
- (ii) The **SCT system exceeds the hurdle rate by a comfortable margin** (22.8% IRR vs 15% hurdle) and delivers positive NPV of \$1.06M.
- (iii) The difference in lifetime value creation is approximately **\$1.15M**—the economic cost of non-selective CO₂ absorption.

5.5 Sensitivity Analysis

5.5.1 Parametric Sensitivity

Table 5.5 shows IRR sensitivity to key parameters for both technologies.

Table 5.5: IRR sensitivity analysis (15-year life)

Parameter	Range	Packed Column		SCT System	
		Low	High	Low	High
CO ₂ absorption	50–90% / 2–10%	10.2%	1.8%	24.3%	21.0%
Capital cost	±30%	9.5%	2.3%	30.1%	17.4%
Diesel benefit	\$400k–\$600k/yr	1.2%	9.3%	17.6%	27.7%
NaOH price	\$400–\$600/ton	6.8%	3.7%	23.5%	22.0%

5.5.2 Selectivity Threshold Analysis

A critical question is: *What level of CO₂ selectivity is required for the packed column to be viable?*

Setting the NPV = 0 threshold (breakeven) and solving for the required CO₂ absorption percentage:

$$\text{Maximum CO}_2 \text{ absorption for NPV} = 0 : \text{ approximately } 55\% \quad (5.1)$$

This represents a stringent operating requirement that may be difficult to achieve consistently in practice. Field experience [3] suggests packed columns typically operate at 60–80% CO₂ absorption at the high pH required for reliable H₂S removal.

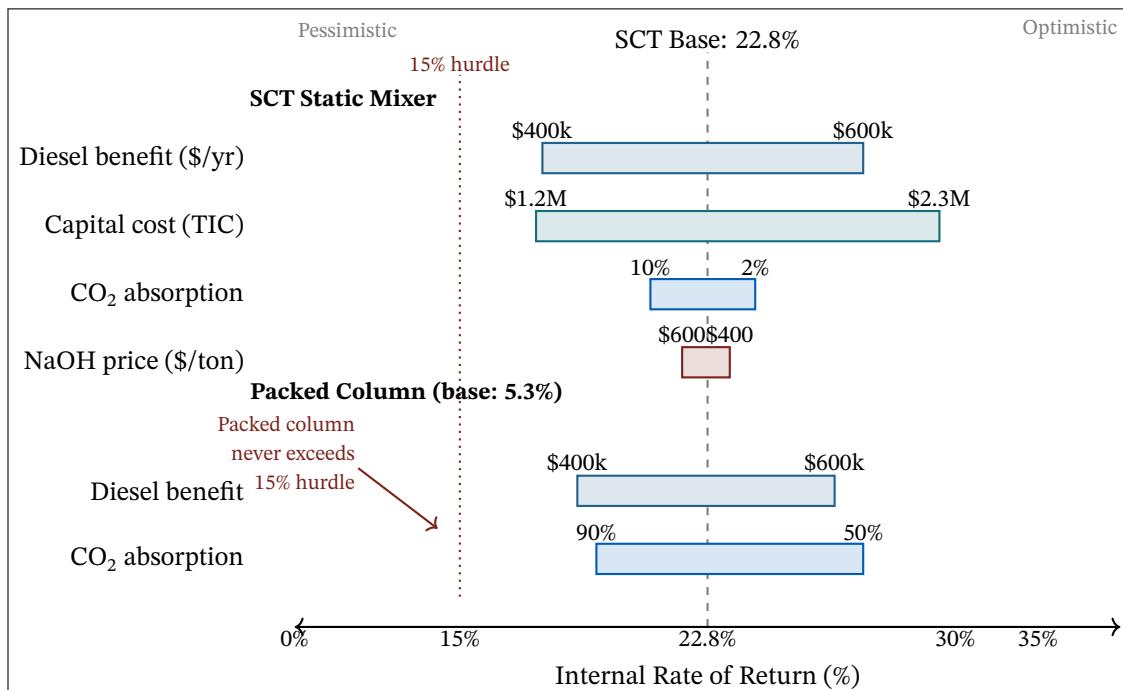


Figure 5.1: Tornado diagram comparing IRR sensitivity for SCT (top) and packed column (bottom) technologies. The SCT system maintains IRR above the 15% hurdle across all scenarios, while the packed column fails to reach the hurdle even in optimistic cases.

5.6 Risk-Adjusted Recommendation

The economic analysis leads to a clear recommendation:

Table 5.6: Technology recommendation summary

Factor	Packed Column	SCT System
Base case IRR	5.3% (below hurdle)	22.8% (exceeds hurdle)
NPV (15-year, 12%)	-\$87,000 (value destruction)	+\$1,060,000 (value creation)
Downside risk	High (sensitive to CO ₂ absorption)	Low (robust economics)
Upside potential	Limited	Moderate
Recommendation	Not recommended	Recommended

5.7 Validation Requirements

Before project sanction, the following economic uncertainties require resolution:

1. **Vendor quotations:** Obtain budgetary quotes from 2–3 SCT technology providers to validate the \$1.78M TIC estimate.
2. **Diesel displacement:** Analyse historical fuel consumption records to confirm the \$500,000/yr benefit assumption.
3. **Selectivity performance:** Review vendor performance guarantees for CO₂ co-absorption limits. Consider pilot testing if guarantees are not available.
4. **NaOH logistics:** Confirm delivered caustic pricing including freight to the TA-58 site.

The project demonstrates strong economic potential with SCT technology, provided the selectivity performance can be achieved. The packed column option should only be reconsidered if SCT vendors cannot provide acceptable performance guarantees.

6 Risk Assessment

6.1 Key Technical Risks

Three primary risks require management during project advancement:

Table 6.1: Primary risk register

Risk	L	C	Mitigation
H ₂ S breakthrough	2	3	Conservative design margin; continuous outlet H ₂ S monitoring with fuel-divert interlock
CO ₂ co-absorption variability	3	2	Evaluate selective operation via simulation; SCT option inherently provides kinetic selectivity
Biological treatment scale	2	2	Vendor feasibility confirmation for 43 kg S/day capacity; fallback to chemical oxidation if MBBR not viable

Likelihood (L): 1=Rare, 2=Possible, 3=Likely. Consequence (C): 1=Minor, 2=Moderate, 3=Major.

6.2 HSE Considerations

H₂S toxicity and NaOH chemical burns represent the primary HSE hazards. Minimum safeguards include:

- Fixed H₂S gas detection integrated with site DCS
- Secondary containment for caustic storage areas
- Safety showers within 10 m of process areas
- Respiratory protection program and PPE training

Formal HAZID/HAZOP studies are required in the detailed engineering phase to identify additional site-specific hazards.

6.3 Risk Closure Requirements

Prior to detailed engineering, the following activities are required:

- (i) Process simulation with electrolyte thermodynamics to refine CO₂ absorption kinetics
- (ii) Vendor engagement to validate mass transfer performance data
- (iii) Confirmation of biological treatment feasibility at design sulfide loading
- (iv) Diesel benefit validation through operational data analysis

Residual risks (packing performance uncertainty ±20%, CO₂ co-absorption variability ±30%) are acceptable provided project IRR remains above 15% hurdle under sensitivity analysis.

7 Control Philosophy and Safety

7.1 Control Philosophy Overview

The control system for the caustic scrubber must achieve two objectives: (i) maintain treated gas quality at <45 ppmv H₂S, and (ii) manage caustic consumption by controlling CO₂ co-absorption. For the SCT technology, the second objective is achieved through inherent design (short contact time), while pH control ensures the first objective is reliably met.

Figure 7.1 illustrates the control architecture, comprising two primary control loops and two critical safety interlocks.

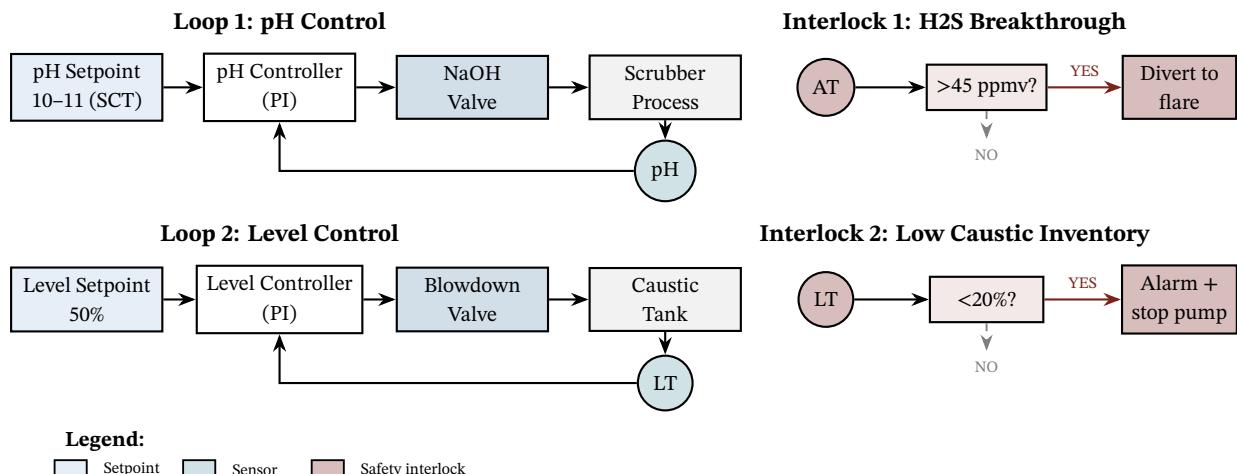


Figure 7.1: Control philosophy block diagram showing primary control loops (pH and level) and safety interlocks (H_2S breakthrough and low caustic inventory). The pH control loop is critical for SCT operation, requiring ± 0.3 pH unit tolerance.

7.2 Primary Control Loops

Table 7.1 summarises the essential control loops for stable scrubber operation.

Table 7.1: Primary control loop specifications

Loop	Controller	Purpose	Setpoint
pH control	PI (tuned for fast response)	Maintain solvent alkalinity for complete H_2S removal; for SCT, tighter control prevents over-absorption of CO_2	10–11 (SCT)
Level control	PI (slow integral)	Manage sulfide/carbonate inventory in recirculation tank; prevent accumulation	50%
Recirculation flow	Manual or ratio	Maintain design L/G ratio and ensure adequate wetting of contactor	2–5× stoichiometric

7.2.1 pH Control for SCT Operation

For the SCT option, pH control is the critical variable for maintaining selectivity. The operating philosophy differs from conventional packed column operation:

- Setpoint:** pH 10–11 (lower than packed column's pH 12–13)
- Tolerance:** ± 0.3 pH units (tighter than packed column's ± 1.0)
- Response time:** Fast PI tuning required; pH must respond within 30 s to feed changes
- Measurement:** Industrial pH electrode with automatic temperature compensation; redundant sensors recommended

The lower pH setpoint reduces hydroxide availability, which further limits CO_2 reaction kinetics while maintaining sufficient driving force for the instantaneous H_2S reaction.

7.2.2 Level Control and Blowdown Strategy

The blowdown rate determines the steady-state sulfide and carbonate concentrations in the recirculating caustic:

$$C_{\text{sulfide,ss}} = \frac{\dot{n}_{\text{H}_2\text{S}}}{F_{\text{blowdown}}} \quad (7.1)$$

For the SCT system at 5% CO₂ absorption:

- Target blowdown rate: 50–100 L/h
- Sulfide concentration: 2–4 wt% (as NaHS)
- Carbonate concentration: <1 wt%

The low carbonate content simplifies downstream biological treatment compared to the packed column option.

7.3 Critical Safety Interlocks

Two safety interlocks are required for engine fuel protection and personnel safety:

7.3.1 Interlock 1: H₂S Breakthrough

Table 7.2: H₂S breakthrough interlock specification

Parameter	Specification
Measurement	Continuous H ₂ S analyser (electrochemical or IR)
Location	Treated gas outlet, downstream of demister
High alarm	30 ppmv (operator warning)
High-high alarm & action	45 ppmv (automatic diversion)
Action	Close fuel gas valve; open flare diversion valve
Reset	Manual (requires operator confirmation after investigation)

The interlock ensures that off-spec gas cannot reach the engine fuel header. Upon H₂S breakthrough:

1. Treated gas is diverted to the flare header
2. Alarm annunciates in control room
3. Operator investigates root cause (low caustic, pH deviation, flow upset)
4. System remains diverted until manual reset after investigation

7.3.2 Interlock 2: Low Caustic Inventory

Table 7.3: Low caustic inventory interlock specification

Parameter	Specification
Measurement	Level transmitter on caustic storage tank
Low alarm	30% (operator warning)
Low-low alarm & action	20% (inhibit dosing pump)
Action	Inhibit NaOH dosing pump start; alarm
Purpose	Prevent dry running; ensure caustic availability

7.4 Instrumentation Requirements

Table 7.4 lists the minimum instrumentation for safe operation.

Table 7.4: Minimum instrumentation list

Tag	Description	Type	Purpose
AIT-001	Outlet H ₂ S analyser	Electrochemical/IR	Product quality; interlock
pHIT-001	Recirculation pH	Industrial electrode	Control; selectivity
LIT-001	Recirculation tank level	Differential pressure	Level control
LIT-002	Caustic storage level	Radar/ultrasonic	Inventory; interlock
FIT-001	Sour gas inlet flow	Orifice plate	Mass balance
FIT-002	NaOH dosing flow	Magnetic flowmeter	Consumption tracking
PdIT-001	Contactor differential pressure	DP cell	Fouling/flooding detection

7.5 Safety Considerations

H₂S is immediately dangerous to life at concentrations above 100 ppmv [11, 19]. The scrubber system handles gas streams at 1 800 ppmv inlet concentration. Minimum safety provisions:

- Fixed H₂S detectors at scrubber inlet/outlet and pump areas (alarm at 10 ppmv, evacuate at 20 ppmv)
- Integration with site emergency shutdown system
- Respiratory protection (SCBA) available within egress distance
- Wind sock/indicator at scrubber location
- Caustic handling per site chemical management procedures (PPE: face shield, chemical-resistant gloves, apron)

7.6 HAZOP Scope

Formal HAZOP study during detailed engineering will address:

- (i) Deviation analysis for all process nodes (feed, scrubber, caustic system, treated gas)
- (ii) Safeguard verification for identified hazards

- (iii) Safety integrity level (SIL) determination for H₂S breakthrough interlock
- (iv) Operability issues including startup, shutdown, and upset conditions
- (v) Human factors for operator interface design

The conceptual design provides sufficient definition for meaningful HAZOP review. The control philosophy outlined in this section establishes the framework for safe operation pending detailed engineering validation.

8 Conclusions and Recommendations

8.1 Summary of Findings

This study demonstrates the technical feasibility of caustic scrubbing for H₂S removal from the TA-58 sour gas stream. However, the economic analysis reveals a critical insight: **at the 660,000 SCFD scale, selective H₂S removal is not optional—it is the determining factor for project viability.**

Two technology options were evaluated:

- **Packed column scrubber:** Well-established technology with straightforward operation. Equipment sized at 0.75 m diameter × 5.5 m height. Caustic consumption of 300–500 ton/yr due to 50–80% CO₂ co-absorption results in \$150,000–250,000/yr operating cost. At base case assumptions, **IRR of 5.3% fails to meet the 15% corporate hurdle rate.**
- **SCT static mixer:** Compact inline design (0.3 m × 1.5 m) exploiting the 10⁶ kinetic rate difference between H₂S and CO₂. Caustic consumption of 46–90 ton/yr (2–10% CO₂ co-absorption) yields \$23,000–45,000/yr operating cost. At base case assumptions, **IRR of 22.8% exceeds the hurdle rate**, delivering NPV of +\$1.06M.

8.2 Technology Recommendation

Based on the quantitative analysis, **SCT static mixer technology is recommended** for the TA-58 application. The recommendation is supported by:

Table 8.1: Technology selection rationale

Factor	Packed Column	SCT Mixer (Recommended)
Economic viability	IRR 5.3% (below hurdle)	IRR 22.8% (exceeds hurdle)
NPV (15-year, 12%)	-\$87,000 (value destruction)	+\$1,060,000 (value creation)
Selectivity mechanism	pH control (operationally challenging)	Contact time (inherent to design)
Caustic cost sensitivity	High (±\$100k/yr swing)	Low (±\$15k/yr swing)
Capital cost	\$2.53M TIC	\$1.78M TIC (30% lower)
Footprint	0.75 m × 5.5 m column	0.3 m × 1.5 m inline

The packed column should only be reconsidered if:

- (i) SCT vendors cannot provide acceptable performance guarantees for CO₂ co-absorption limits
- (ii) Site personnel have strong preference for conventional equipment despite the economic penalty
- (iii) Pilot testing reveals selectivity performance below vendor claims

8.3 Key Trade-offs

The technology selection involves the following considerations:

Table 8.2: Trade-off summary

Factor	Packed Column Favoured	SCT Mixer Favoured
Technology maturity	Decades of field experience	—
Operating cost	—	5–10× lower caustic consumption
Capital cost	—	30% lower TIC
Footprint	—	Compact inline installation
Control simplicity	More forgiving pH tolerance	—
Economic return	—	Meets hurdle rate; positive NPV

The economic analysis demonstrates that the packed column's advantages in maturity and control simplicity do not compensate for its fundamental economic disadvantage at this scale.

8.4 Data Gaps Requiring Resolution

Before project sanction, the following uncertainties require closure:

1. **Vendor quotations:** Budgetary quotes from 2–3 SCT technology providers to validate the \$1.78M TIC estimate. Target vendors include Merichem, Trimeric, and Koch-Glitsch.
2. **Selectivity guarantee:** Written vendor guarantee for maximum CO₂ co-absorption (target: <10%). If guarantee cannot be obtained, pilot testing should be considered.
3. **Diesel displacement:** Analysis of historical fuel consumption and engine runtime records to confirm the \$500,000/yr benefit assumption.
4. **Spent caustic treatment:** MBBR vendor engagement for packaged systems at 43 kg S/day capacity, or confirmation of chemical oxidation as fallback.
5. **NaOH logistics:** Delivered caustic pricing including freight to the TA-58 site; storage requirements and delivery frequency.

8.5 Recommended Next Steps

1. **Vendor engagement (immediate):** Issue RFQ to 2–3 SCT caustic scrubber vendors with process data package including:
 - Gas flow rate, composition, and operating conditions
 - Required H₂S removal efficiency and outlet specification
 - Maximum acceptable CO₂ co-absorption (target 5–10%)
 - Request for performance guarantee and reference list
2. **Diesel benefit validation:** Review 12–24 months of operational data to confirm engine runtime and fuel consumption patterns.

3. **HAZID workshop:** Conduct technology-neutral hazard identification with site operations, maintenance, and HSE stakeholders.
4. **Pilot testing (if required):** If vendor guarantees are insufficient, plan field pilot at TA-58 using slip-stream from VRU discharge.
5. **FEED phase:** Following vendor selection, proceed to front-end engineering with selected technology provider.

8.6 Concluding Statement

This study provides sufficient technical and economic basis for management decision on project advancement. The analysis demonstrates that:

- (i) Selective H₂S removal using SCT technology is technically feasible and economically attractive
- (ii) Non-selective packed column technology fails to meet economic hurdles at this scale
- (iii) The project creates an estimated \$1.06M NPV over 15 years while enabling diesel displacement
- (iv) The selectivity imperative—achieving high H₂S removal while minimising CO₂ co-absorption—is the critical success factor

The project is recommended for advancement to vendor engagement and detailed feasibility, with SCT static mixer technology as the preferred configuration.

List of Symbols		VRU	Vapor Recovery Unit
Abbreviations		Parameters	
HETP	Height Equivalent to a Theoretical Plate	<i>E</i>	Enhancement factor (dimensionless)
IRR	Internal Rate of Return	<i>HTU</i>	Height of a Transfer Unit (m)
MBBR	Moving Bed Biofilm Reactor	<i>N_{TU}</i>	Number of Transfer Units (dimensionless)
NPV	Net Present Value	<i>S</i>	Selectivity (dimensionless)
SCFD	Standard Cubic Feet per Day	<i>Da</i>	Damköhler number (dimensionless)
SCT	Short Contact Time	<i>Ha</i>	Hatta number (dimensionless)
TIC	Total Installed Cost		

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