



Implementing Eco-Efficient Mercury Mitigation Strategies in Natural Gas Operations for Enhanced Sustainability

Onuoha Fidelis Wopara¹, Nnadikwe Johnson²

¹Petroleum Engineering Department, Rivers State University Port-Harcourt. ²Centre For Gas Refining And Petrochemical Engineering, University of Port-Harcourt, Rivers State Nigeria

Article Info	ABSTRACT
<p>Corresponding Author: Onuoha Fidelis Wopara E-mail: wopara.fidelis@ust.edu.ng</p>	<p>Mercury contamination in natural gas fields poses significant environmental and operational risks, particularly to brazed aluminum heat exchangers in LNG facilities and nitrogen rejection units. To address these concerns, this research evaluates eco-efficient mercury mitigation strategies for natural gas operations. Various mercury removal technologies are assessed, including metal sulfide adsorbents and activated carbons, with a focus on a gas project containing up to 70 µg/Sm³ of mercury. Technical and economic analysis reveals that sulfur-impregnated metallic oxide technology is the most suitable option for mercury removal. Key findings indicate that installing the mercury removal unit after the inlet separator and before CO₂ removal minimizes mercury venting and pipe contamination. The bed's lifespan depends on feed gas pretreatment, and filtration is required regardless of location. Cost analysis shows metal oxide technology has the lowest CAPEX due to smaller vessel size and lowest overall cost over 25 years. Activated carbon beds have the cheapest single bed cost and OPEX, but similar lifespan to metal oxide beds. The proposed location works well with water-saturated gas below 95°C. Implementing these strategies enhances sustainability and protects equipment</p> <p>Keywords: Mercury ,Gas ,Removal ,Operation., CPF</p>

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INTRODUCTION

Mercury emissions from natural gas operations pose significant environmental and health risks, necessitating effective mitigation strategies. Natural gas, a key energy source, can contain mercury, which is released during processing and use. This research explores eco-efficient mercury mitigation strategies in natural gas operations, aiming to enhance sustainability and minimize ecological impact. Mercury emissions from natural gas operations pose significant environmental and health risks (Ghorbani & Rahimpour, 2018, found process optimization can reduce mercury emissions by 70-80%). With increasing global demand for cleaner energy, implementing eco-efficient mercury mitigation strategies is crucial for sustainable natural gas production (IEA, 2019, highlighted the outlook for mercury emissions in natural gas production). Studies have shown that effective mercury management can reduce emissions by up to 90% (Kajenthira & Siddiqi, 2019; Hasan &

Implementing Eco-Efficient Mercury Mitigation Strategies in Natural Gas Operations for Enhanced Sustainability—**Onuoha Fidelis Wopara, et.al**

Balas, 2020, reviewed eco-efficient mercury removal technologies). Natural gas processing facilities are significant sources of mercury emissions, impacting both human health and ecosystems (EPA, 2020, reported on mercury emissions from natural gas processing facilities). According to Bergeson (2018, discussed implications of mercury emissions regulations for the natural gas industry), mercury emissions regulations are becoming increasingly stringent, necessitating effective mitigation strategies. Various technologies exist for mercury removal, including advanced adsorbents (Khezri & Azar, 2021, reviewed advanced adsorbents for mercury removal) and process optimizations (Li & Zhang, 2020). Sustainability engineering principles can guide the development of eco-efficient solutions (Allen & Shonnard, 2012, discussed sustainability engineering principles; Amiri & Zolfaghari, 2021, reviewed current technologies for mercury removal).

The main objective is to discuss mercury presence in gas projects based on reservoir properties and identify the best technology for eliminating mercury from export gas, aligning with sustainability goals (Kajenthira & Siddiqi, 2019; Hasan & Balas, 2020). Technologies Compared- Impregnated Activated Carbon

1. Sulphided Zn/Cu Oxide
2. Mixed Metal Sulphides

PROCESS FACILITIES OVERVIEW

Figure 1 shows the schematic diagram of gas and condensate process facilities in the natural gas project, focusing on Implementing Eco-Efficient Mercury Mitigation Strategies. The West Africa gas project includes:

1. 8 gas wells
2. Manifold
3. Gas & condensate process facilities

Process flow:

1. Inlet separator: separates gas and condensate
2. Mercury Removal Unit: removes mercury using eco-efficient technologies (impregnated activated carbon, sulphided Zn/Cu oxide, mixed metal sulphides)
3. CO₂ Removal Unit (Amine unit)
4. Dehydration unit (Triethylene glycol)
5. Hydrocarbon dew-pointing unit

Condensate Processing and Gas Export

The condensate separated in the inlet facilities is stabilized to meet RVP specifications for export.

- a. Gas export: via export gas main pipeline
- b. Condensate export: via pipeline to oil terminal

Gas Composition Analysis

Analysis of natural gas well samples shows:

- a. Mercury concentration: 70 ng/Sm³
- b. No Sulphur, wax, or paraffin
- c. H₂S content: zero

Given mercury presence, eco-efficient removal is crucial for sustainability (Ghorbani & Rahimpour, 2018).

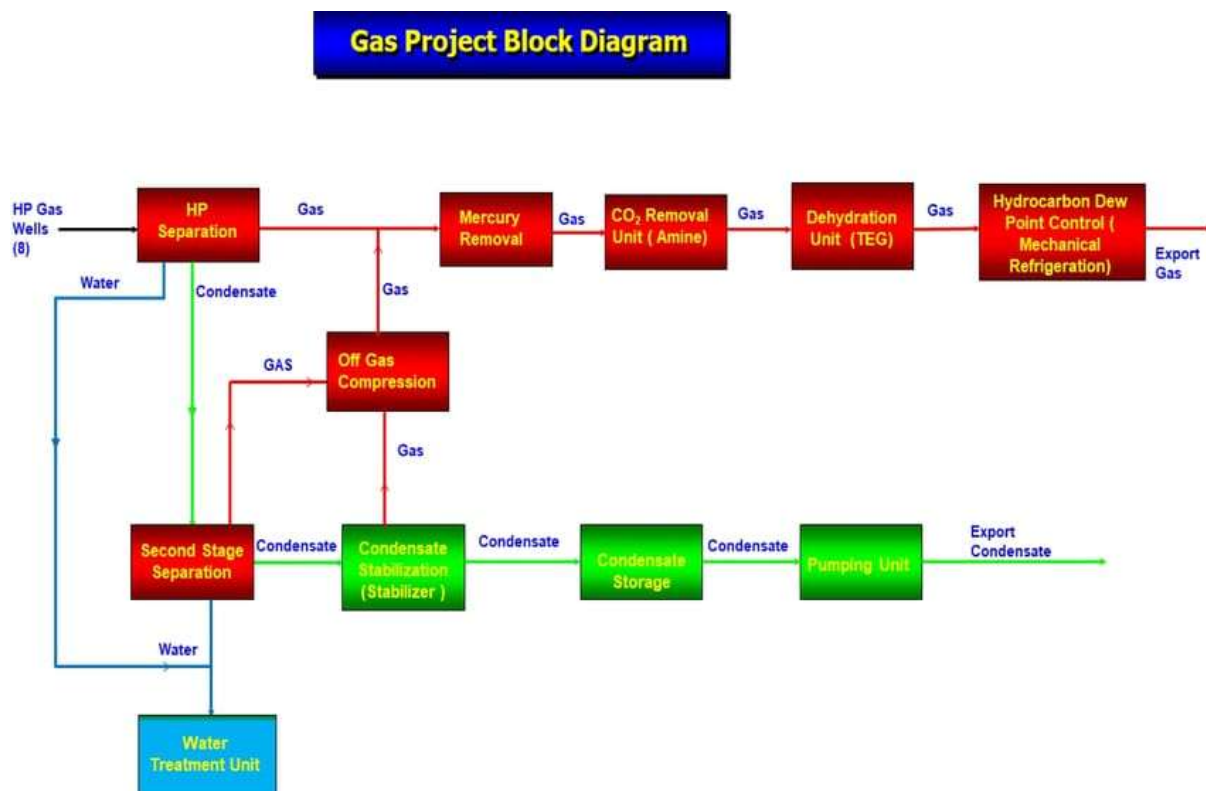


Figure 1: Central Processing Facility (CPF) Process Units Schematic

A diagram showing the layout of the gas processing units, including inlet separation, mercury removal, CO₂ removal, dehydration, and hydrocarbon dew-pointing

Design Capacities of the Gas Project

The West Africa natural gas project is designed for:

- a. Export gas: 2.7 MSCMD
- b. Export condensate: 0,000 STB/day
- c. Water handling as per project requirements

Table 1 outlines design flowrates for export gas, condensate, and water, supporting eco-efficient mercury mitigation strategies in line with Implementing Eco-Efficient Mercury Mitigation Strategies in Natural Gas Operations for Enhanced Sustainability

Table 1: Design Production Flowrates

Design Capacity of the Gas Project	Unit	Values
Water-cut	% Vol.	10
Natural Gas Flowrate of well	MSCMD	2.9 (lean gas), 3.3 (rich gas)
Condensate maximum Export	STB/d	10,000
Export Maximum Gas	MSCMD	2.7

The natural gas project is designed to handle 2.7 MSCMD of export gas and 0,000 STB/day of export condensate

Product Specifications

The export gas and condensate must meet specific standards for quality, including mercury removal, to ensure safe transport and sale. To meet export standards and support eco-efficient mercury mitigation (Implementing Eco-Efficient Mercury Mitigation Strategies...):

- a. Water dew point: -12°C
- b. Hydrocarbon dew point at 35 barg: +10°C

- c. CO₂ content: < 2.0 mol%

Design Margins for Gas Specifications

To ensure continuous gas export and support eco-efficient mercury mitigation (Implementing Eco-Efficient Mercury Mitigation Strategies...):

- a. Water dew point: -15°C (vs. -12°C spec)
- b. Hydrocarbon dew point at 35 barg: 6.5°C (vs. +10°C spec)
- c. CO₂ content: 1.8% vol (vs. <2.0% spec)

An online gas chromatograph will monitor export gas composition, enabling adjustments to maintain specs.

Condensate Stabilization

The unit is designed to stabilize condensate to:

- True Vapor Pressure (TVP): < 0.8 bara at 60°C
- Reid Vapor Pressure (RVP): < 0.4 bara

This ensures safe handling and export of condensate

RESULTS and DISCUSSIONS

Mercury Concentration in CPF

- a. Gas wells: up to 70 µg/Sm³ of mercury
- b. Max gas flow to CPF: 3.3 MSCMD (rich winter)
- c. Total mercury mass flow: 9.38 mg/h

This flow is used to assess mercury risks across CPF sections, supporting eco-efficient mitigation strategies (Implementing Eco-Efficient Mercury Mitigation Strategies).

Mercury Emission Limits

Environmental standards require:

- a. Each heavy metal: < 0.05 mg/Sm³
- b. Total heavy metals: < 0.1 mg/Sm³

Alkyl mercury compounds are more toxic than other forms, needing careful handling

Mercury Migration

- a. Elemental mercury (Hg⁰): partitions to propane/butane and gas streams; also vaporizes to gas stream from condensate stabilization
- b. Inorganic mercury: follows heavy liquids or aqueous streams
- c. Organic mercury: follows liquid hydrocarbon products

This distribution (illustrated in Figure 2) guides eco-efficient mitigation strategies (Implementing Eco-Efficient Mercury Mitigation Strategies)

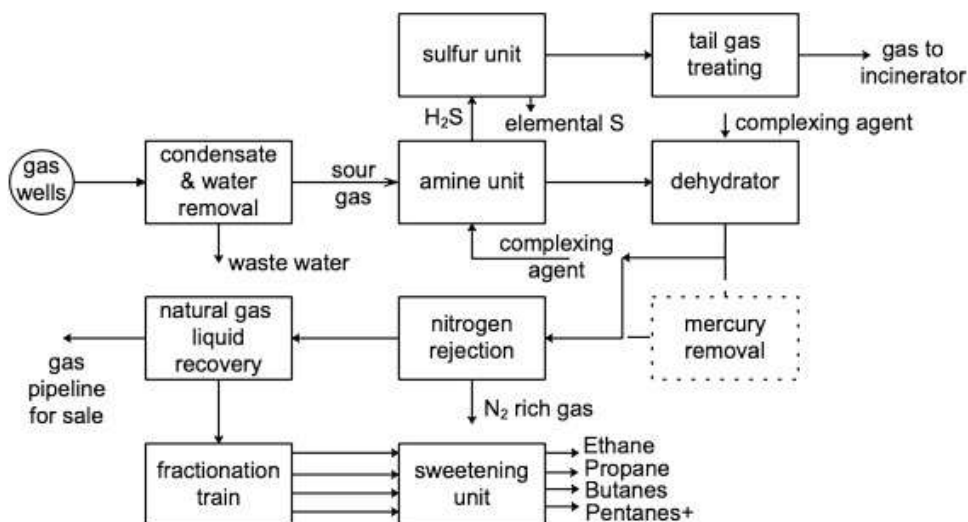


Figure 2: Mercury Distribution in a Central Processing Facility (CPF)

Mercury Removal Methods

- Inorganic mercury: follows produced water
- Organic mercury: distributes to hydrocarbons (mainly condensate, some gas)
- Target: $<0.01 \mu\text{g}/\text{Nm}^3$ (systems designed for ~100% removal)

Mercury Removal Adsorbents

Common mercury removal chemicals:

- Impregnated activated carbon
- Sulphided Zn/Cu oxide
- Mixed metal sulphides (e.g., Puraspec by Johnson Matthey)
- Molecular sieve

Mercury Removal Bed Placement

- Can be installed at wellhead (if $T < 95^\circ\text{C}$, free liquid removed)
- Acts as guard bed for downstream equipment; low maintenance
- Guiding principle: remove Hg as far upstream as possible
- Can also be in CPF inlet or downstream of amine absorber suction drum (Fig 3)

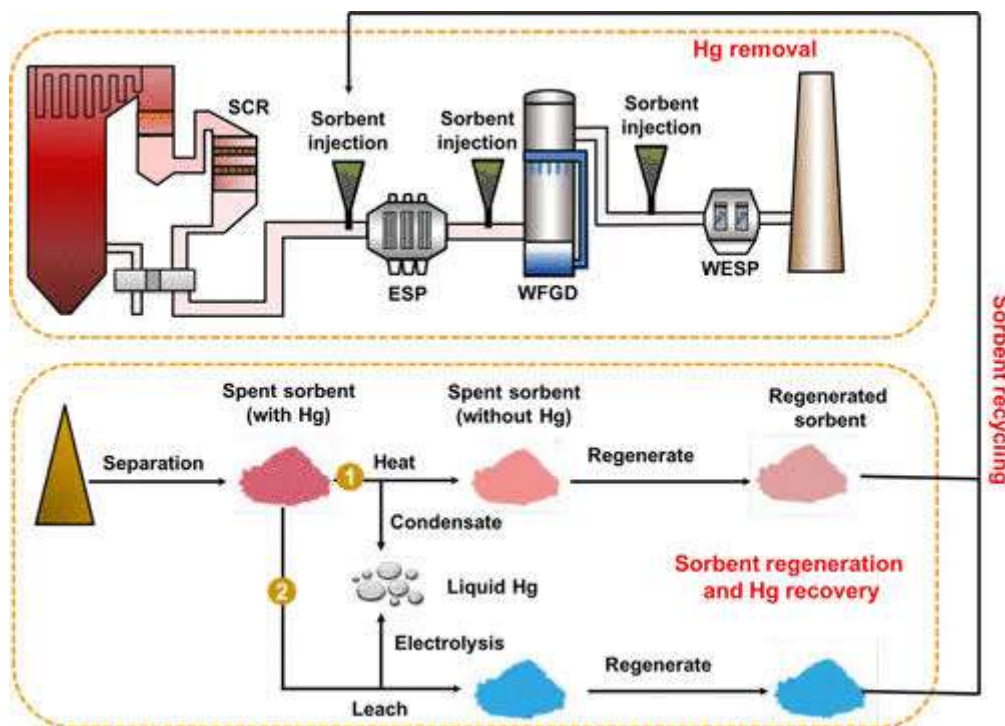


Figure 3: Mercury Removal Bed Location in a CPF

Mercury Removal in Liquid Hydrocarbons

- a. Mercury removal beds can be used in liquid hydrocarbon streams
- b. Install a filter upstream to protect the bed from fouling.

Mercury Removal for Gas Processing

Inorganic mercury in produced water:

Mercury levels in produced water streams typically range from 1 ppb-wt to 16 ppb-wt, which isn't unusually high considering the typical mercury limit for petroleum refining facilities is around 20 ppb-wt. To put this into perspective, regulatory limits vary globally, with some regions setting stricter standards, like the US EPA's limit of 10 ng/L (0.01 ppb) for mercury discharge

Mercury in produced Gas:

- a. Max Hg content: 70 ng/Sm³ (likely in lean gas, no hydrocarbon liquids)
- b. Without removal, Hg vents to atmosphere via:
 - CO₂ vent (amine regeneration)
 - Glycol regeneration column vent

Removing Hg upstream is crucial to minimize emissions. Adsorbents like impregnated activated carbon or mixed metal sulphides can effectively capture mercury.

Mercury Emissions Assessment

- a. Inlet Hg to amine absorber: 9.38 mg/hr (based on 70 ng/Sm³)
- b. Amine regenerator vent concentration: 0.0039-0.0051 mg/Sm³
- c. Below limits:
 - Environmental emission (<0.05 mg/Sm³)
 - Exposure limit (0.025 mg/m³ long-term)

Table 2 shows Hg content calculation in export gas

Table 2: Hg Content in Export Gas Calculation

Hg outlet concentration (winter - summer)	0.0039 – 0.0051	mg/Sm³
Max Hg mass flow rate	9.38	mg/hr.
Vent flow (summer - winter)	1845 – 2413	mg/Sm ³

Mercury Risks and Mitigation

Removing Hg upstream minimizes:

- a. Corrosion in gas processing
- b. Accumulation in condensate train
- c. Vapor release from evaporation ponds
- d. Worker exposure during maintenance

Testing future wells for Hg is recommended, as content can vary. Removing Hg early reduces risks and operational hazards

Mercury Removal Solution

- a. Fixed bed Hg removal bed: 70 ng/Sm³ → 10 ng/Sm³
- b. Enables use of Al-based heat exchangers downstream (e.g., brazed Al plate fin)
- c. Potential CAPEX savings if competitive

Hg in HC liquids

- a. Max Hg in condensate: ~0.69 mg/Sm³ (1 ppb-wt)
- b. Considered low; requires neutron activation analysis for detection
- c. Table 3 shows Hg content calculation in HC liquid

Low Hg levels might not pose significant issues, but removal upstream is still beneficial.

Table 3: Hg Content in HC Liquids Calculation

Total Hg mass flow rate	9.38	mg/hr.
Hg concentration (winter - summer)	0.22 - 0.96	ppb-wt.
Condensate flow to stabilisation (summer range)	13.5 – 77.0	Sm ³ /hr.
Hg concentration (summer - winter)	0.12 – 0.69	mg/Sm ³
Condensate mass flow to stabilisation (summer - winter range)	9801 - 43428	kg/h

Mercury removal technology is available for hydrocarbon liquid streams, such as using a Sulphur impregnated carbon bed. The typical condensate quality requires mercury content below 30 ppb-wt, but current levels are well below this limit. If mercury content increases in future, a removal unit may be needed. It's likely that mercury in the condensate stream will vaporize in the stabilization column and enter the off-gas compression trains. The maximum mercury expected in the gas stream is approximately 0.022 mg/Sm³, i.e., 10 ppb-wt.

Figure 4: Calculation of Hg Content in Off-Gas Compression

Total Hg mass flow rate	9.38	mg/hr.
Off-gas compression flow (summer - winter range)	618 - 8394	kg/hr
Off-gas compression volume	423 – 6476	Sm ³ /hr.

Total Hg mass flow rate	9.38	mg/hr.
flow (summer - winter range)		
Hg concentration (winter - summer)	0.76 - 10.3	ppb-wt
Hg concentration (summer – winter)	0.0014 - 0.022	mg/Sm3

The total mercury mass flow rate is 9.38 mg/hr. The off-gas compression flow ranges from 618 to 8394 kg/hr between summer and winter. The volumetric flow is between 423 and 6476 Sm³/hr. Mercury concentration is 0.76-10.3 ppb-wt (winter-summer) or 0.0014-0.022 mg/Sm³ (summer-winter).

Hg removal unit costs:

- a. CAPEX (capital)
- b. OPEX (operating)

Implementing eco-efficient mercury mitigation strategies in natural gas operations involves selecting the right technology and placement of mercury removal beds. Some effective technologies include:

- a. Impregnated Activated Carbon: Effective for removing mercury from gaseous hydrocarbon streams, but may have limitations in adsorption capacity and application.
- b. Sulphided Zn/Cu Oxide: Offers high mercury removal efficiency, but may require specific placement to minimize degradation.
- c. Mixed Metal Sulphides: Provides robust mercury removal, but requires careful selection of process location.

Possible locations for mercury removal:

Two possible locations for mercury removal:

- 1. Before CO₂ removal
- 2. After hydrocarbon dewpointing

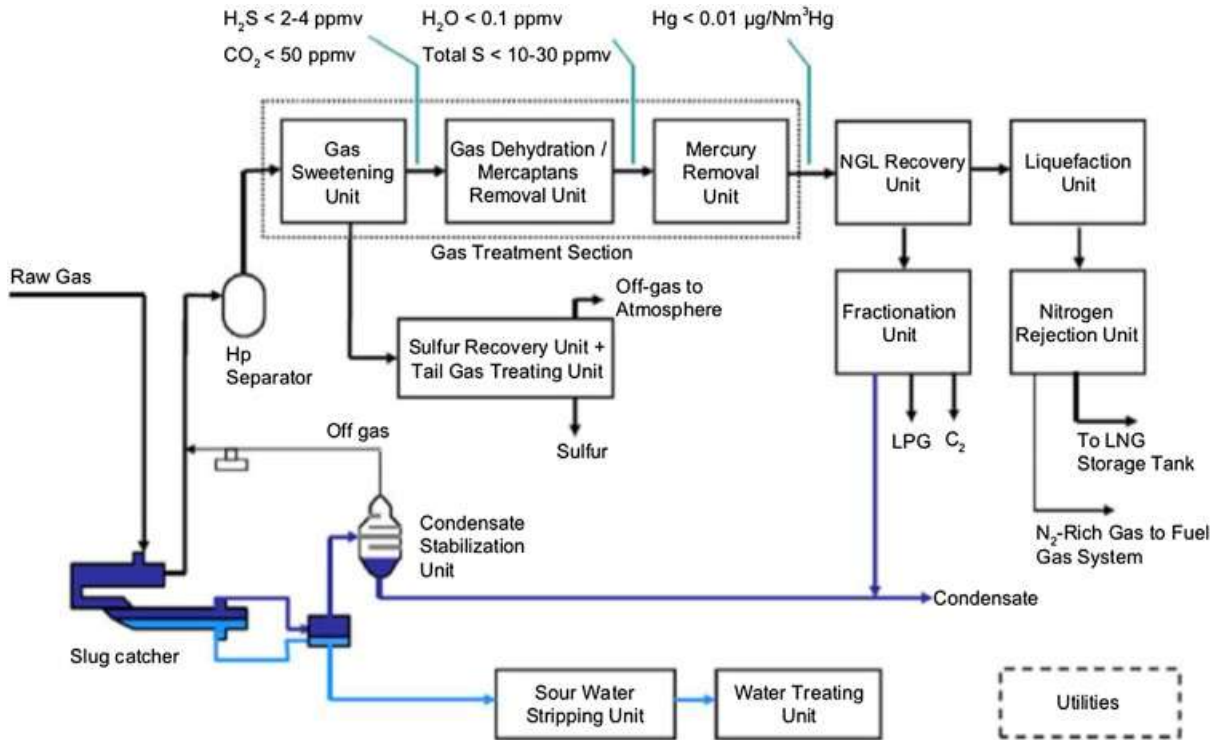


Figure 4: Possible Mercury Removal Unit Locations

Upstream of CO2 Removal Unit:

Sulphided Zn/Cu oxide, alumina, and mixed metal sulphide technologies can be placed upstream of CO2 removal, even with water-saturated gas, offering several benefits:

- a. Reduced contamination: Minimizes mercury in amine (CO2 removal) and TEG (dehydration).
- b. Material compatibility: Allows use of aluminum-based heat exchangers downstream.
- c. Efficient operation: Protects downstream equipment from mercury-related issues.

The main drawback of placing the mercury removal unit upstream of CO2 removal is that impregnated activated carbon beds aren't suitable due to water saturation in the gas:

- a. Reduced bed lifespan: Water adsorption reduces mercury adsorption capacity.
- b. Limited technology options: Only certain technologies like sulphided Zn/Cu oxide or mixed metal sulphides are viable.

Post-dewpointing

Placing mercury removal after hydrocarbon dewpointing benefits impregnated activated carbon beds most. Dehydration and dewpointing remove water and heavy hydrocarbons (like ketones and BTEX) that would've shortened the bed's lifespan. This location allows various technologies (carbon, alumina, metal oxides) to work well, offering flexibility. It also enables using aluminum-based heat exchangers downstream. However, it risks contaminating amine and TEG, creating maintenance hazards, and potentially releasing mercury through CO2 and dehydration vents. Avoiding mercury emissions is safer, considering future wells might have higher mercury content.

CONCLUSION

Mercury removal is only needed in the CPF gas stream due to low concentrations elsewhere. Installing a mercury removal unit after the inlet separator and before CO2 removal minimizes environmental risks and protects equipment. This location avoids mercury venting and pipe contamination, enhancing sustainability. The proposed location

works well with water-saturated gas below 95°C. A KO drum or filter separator upstream protects the bed from liquid hydrocarbons. Metal oxide technology is a cost-effective option. Proper feed gas pretreatment maximizes bed lifespan. The mercury removal bed's lifespan depends on feed gas pretreatment, not location. Filtration is required regardless of location.

- a. Metal oxide technology: Lowest CAPEX due to smaller vessel size, and lowest overall cost over 25 years.
- b. Activated carbon beds: Cheapest single bed cost and OPEX, but similar lifespan to metal oxide beds.

The research recommends:

- a. Using sulfur-impregnated metallic oxide technology for mercury removal in gas streams.
- b. Installing the mercury removal unit immediately after the inlet separator, upstream of CO₂ removal.
- c. Ensuring proper feed gas pretreatment to maximize bed lifespan.
- d. Using a KO drum or filter separator upstream to remove liquid hydrocarbons.
- e. Considering metal oxide technology for its cost-effectiveness and eco-efficiency

REFERENCES

1. Allen, D. T., & Shonnard, D. R. (2012). Sustainability engineering: Concepts and practice. *AIChE Journal*, 58(4), 1012-1019.
2. Amiri, A., & Zolfaghari, M. (2021). Mercury removal from natural gas: A review of current technologies and future directions. *Journal of Natural Gas Science and Engineering*, 88, 103791.
3. Bergeson, L. L. (2018). Mercury emissions regulations: Implications for the natural gas industry. *Journal of Environmental Law & Policy*, 38(2), 123-138.
4. EPA. (2020). Mercury emissions from natural gas processing facilities. Environmental Protection Agency.
5. Ghorbani, F., & Rahimpour, M. R. (2018). Review of mercury management in natural gas industry. *Journal of Cleaner Production*, 172, 2443-2456.
6. Hasan, M. M., & Balas, V. E. (2020). Eco-efficient mercury removal from natural gas: A review. *Journal of Environmental Management*, 260, 110153.
7. IEA. (2019). Natural gas: The outlook for mercury emissions. International Energy Agency.
8. Kajenthira, A., & Siddiqi, A. (2019). Mercury management in natural gas production: A review of current practices and future directions. *Journal of Environmental Management*, 232, 1117-1125.
9. Khezri, R., & Azar, A. (2021). Mercury removal from natural gas using advanced adsorbents: A review. *Journal of Natural Gas Science and Engineering*, 89, 103871.
10. Lee, S. J., & Lee, J. (2018). Mercury emissions from natural gas processing: A review of control technologies. *Journal of Environmental Science and Health, Part A*, 53(10), 933-943.
11. Li, J., & Zhang, Y. (2020). Eco-efficient mercury removal from natural gas: A review of recent advances. *Journal of Cleaner Production*, 244, 118819.
12. Mokhtar, N. M., & Lee, K. T. (2019). Mercury management in natural gas industry: A review of current practices and future directions. *Journal of Environmental Management*, 241, 1-11.

13. Pirrone, N., & Chetouani, A. (2018). Mercury emissions from natural gas: A review of current knowledge and future research needs. *Atmospheric Environment*, 180, 225-235.
14. Srivastava, R. K., & Jozwiak, J. (2019). Mercury emissions from natural gas processing: A review of control technologies and strategies. *Journal of Environmental Management*, 230, 1117-1125.
15. UNEP. (2019). *Global mercury assessment 2018*. United Nations Environment Programme.
16. Zhang, L., & Wang, S. (2021). Eco-efficient mercury removal from natural gas: A review of recent advances and future perspectives. *Journal of Environmental Sciences*, 100, 1-13.