Fouling in VDU ejector systems

Review of critical ejector-condenser interplay, with an overview of fouling in VDU ejector systems, including a case study where fouling impacted a refiner's bottom line

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Ejector system fouling can cost refiners millions of dollars annually. It leads to lost yield or lower throughput, either of which affects a refiner's bottom line. An ejector system is a combination of ejectors and condensers configured in series, typically ejector-1st intercondenser-ejector-2nd intercondenser-ejector-aftercondenser. Declining thermal efficiency or heat rejection is seen with progressive fouling in heat exchangers and intercondensers. However, the fouling also increases intercondenser pressure.

If intercondenser operating pressure rises beyond the discharge pressure capability of its preceding ejector, overall system performance breaks and vacuum distillation unit (VDU) pressure rises sharply, an undesirable outcome for any refiner. In VDU service, a breakdown to ejector system performance can mean column overhead pressure may be 25-35 mm Hg rather than, for example, at design of 15 mm Hg abs. When overhead pressure rises in such a manner, vacuum tower bottoms (VTB) increases while vacuum gas oil (VGO) cut is reduced.

Condensers within an ejector system serve to a) condense vapours discharging from a preceding ejector at a pressure within the discharge capability of that ejector, b) minimise the mass flow rate of vapours exiting the condenser that must be handled by a downstream ejector to align with the performance capability of that ejector (mass flow rate versus pressure performance curve), and c) in effectively accomplishing a) and b) will keep ejector system energy consumption efficient and vacuum distillation unit pressure within specification.

It is the ejector-condenser interplay that is so critical to a refiner meeting vacuum distillation operating objectives. When fouling surpasses the design basis, the consequence for a refiner can be significant, frustrating, and difficult to troubleshoot.

VDU ejector system

First-stage ejectors maintain vacuum column overhead pressure by evacuating non-condensible gases, hydrocarbon vapours, and steam present in the overhead of the distillation process. The overhead is compressed by the first-stage ejectors and discharged into the first intercondensers, where steam and hydrocarbon vapour are condensed. Non-condensible gases saturated with steam and hydrocarbons flow to the second-stage ejector, where again compression occurs with discharge to the second intercondenser. Condensation of vapours then occurs and saturated non-condensible gases flow to the third-stage ejector, where they are compressed to a pressure above atmospheric pressure and discharged into an aftercondenser.

Due to the large scale of a modern refinery, a VDU ejector system, such as one recent case at a 200,000 bbl/day Asian refinery, may have multiple ejectors and condensers in parallel at each stage. Medium-pressure steam is the energy source for the ejector compression of gases. Water typically is used to effect condensation, such as cooling tower water, river water, or seawater.

Fouling can cause condenser operating pressure to rise above the discharge capability of an ejector that precedes it. When that happens, a performance break occurs where the VDU column rises sharply well above desired operating pressure. An elevated VDU column pressure increases VTB, thereby reducing VGO yield. If one considers a $10/bbl discount for resid versus VGOs, a 1% loss of yield on a 200,000 bbl/day refinery is approximately $7 million per annum.

Heat transfer basics

Most commonly, condensation takes place on the shellside with water flowing tubeside. Several variables influence the shellside heat transfer rate, including:

- Mass flow rate and MW of non-condensibles. The greater the mole fraction of non-condensibles, the lower the shellside heat transfer rate
- Mass flow rate, composition (MW, boiling point, mole fraction) of hydrocarbons. The higher the mole fraction or lighter the hydrocarbon composition, the lower the shellside heat transfer rate
- Proportion of flow that is steam. Higher mole fraction of steam will generally yield a higher shellside heat transfer rate
- Operating pressure correlating to velocity
- Condensate mass flux (pph/ft^2) or condensate film thickness.

The complication that arises in establishing the shellside heat transfer rate is immiscible condensate formation, as water and hydrocarbons are immiscible. The mole fraction of non-condensible gases progressively increases as heat is rejected along the release curve, as does condensate film thickness.

The following condenser heat release curve example discusses the amount of water and hydrocarbon condensates formed. The amount of non-condensible gas is constant.

Fouling at vapor entry section of tube bundle

Fouling formation in coldest section

Fouling generally throughout tube bundle

Waxy (paraffinic) build-up on tubes

Figure 1 Photographs of shellside hydrocarbon fouling build-up on heat transfer tubes

As heat release progresses, the shellside heat transfer rate declines:

Heat release curve along with water plus hydrocarbon condensate formation example (as follows):

The tubeside heat transfer rate is generally a straightforward calculation of forced convection in the turbulent flow:

Overall heat transfer rate clean - $U_{clean} = \dfrac{1}{\dfrac{1}{H_{shellside}} + \dfrac{OD}{ID*H_{tubeside}} + R_{wall}}$

Fouled heat transfer rate - $U_{fouled} = \dfrac{1}{\dfrac{1}{U_{clean}} + OAFF}$

Design or working heat transfer rate - $U_{working} = \dfrac{\text{Heat released}}{\text{Area*LMTD}}$

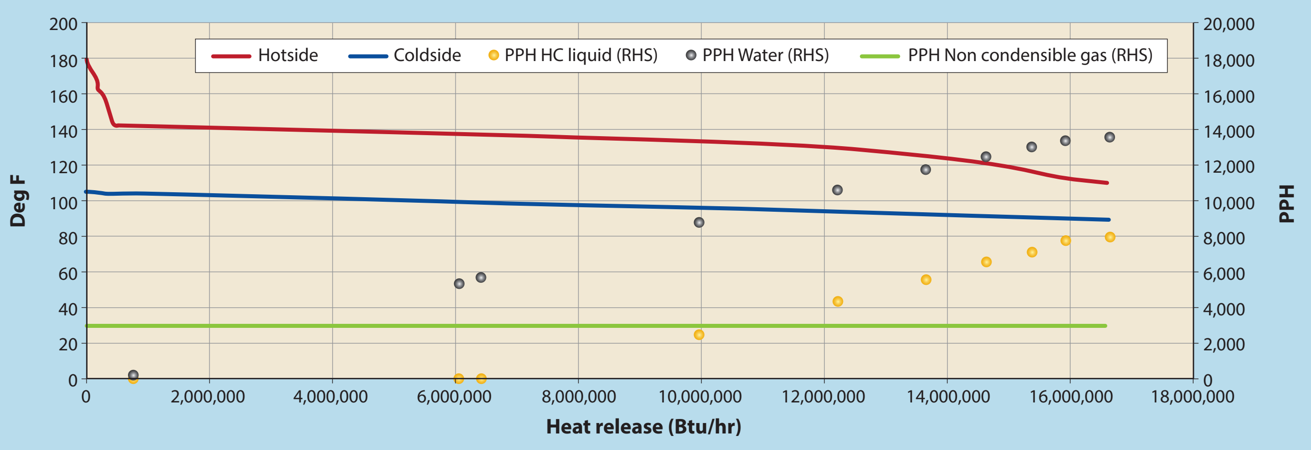

Figure 2 Heat release 30,000 pph mass flow rate (at 200 mm Hg abs for illustration only)

Figure 3 Tubeside fouling photos with plugging of tube holes

Terms:
U_{clean} – Overall clean heat transfer rate, Btu/hr ft² °F
U_{fouled} – Overall fouled heat transfer rate, Btu/hr ft² °F
$U_{working}$ or U_{design} – result of Q/Area * LMTD, Btu/hr ft² °F
OAFF – overall fouling factor incorporating shellside and tubeside fouling factors, hr ft² °F/Btu
Q – thermal duty or heat released, Btu/hr
Area – condenser heat transfer area, ft²
LMTD – log mean temperature difference, °F

Overall fouling factor (OAFF) is an important variable to assess. Crude oils can have different fouling tendencies or foul very little, and the cooling water side can also present fouling issues. A typical vacuum distillation ejector system will have the following condenser overall design heat transfer rates (U_{design}) and consider the cleanliness factor and excess area an OAFF of 0.004 hr ft² °F/Btu provides:

Condenser	Typical U_{design}	OAFF	Cleanliness factor	Excess area
1st Intercondenser	120-150	0.004	40-52%	90-150%
2nd Intercondenser	100-130	0.004	48-60%	67-108%
Aftercondenser	80-110	0.004	56-68%	47-78%

The rates can differ from these bespoke typical ranges based upon the amount of non-condensible gases and hydrocarbon loading, be it vapour and/or liquid. Overall fouling factors for refinery service have generally ranged between 0.0015 and 0.005. The greatest Capex factor for a refinery vacuum distillation ejector system is the size of the first intercondensers. When considering the excess area 0.004 hr ft² °F/Btu overall provides, seemingly twice the area necessary versus a clean design, it can be compelling to consider a lower overall fouling factor. Referring to the previous table, for the first intercondenser, if 0.002 OAFF was applied rather than 0.004, U_{design} might range between 158 to 214 Btu/hr ft² °F and as such the condenser would be about 25% smaller in surface area and the overall system about 15% less expensive.

A careful assessment of OAFF is important. This is evermore true as refiners strive for longer periods between turnarounds. A changing crude slate can introduce risk as lower-cost, poorer-quality crude blends are processed that may have a higher fouling tendency. Rather than a scheduled turnaround every four years, refiners wish to push that to six years or longer. More importantly, an unplanned shutdown to address a performance shortcoming due to fouling is costly, stressing the importance of establishing an appropriate OAFF.

Shellside fouling

The extent to which fouling impedes heat transfer on the shellside varies from refiner to refiner. There are services where shellside fouling is of little worry. In other cases, fouling can become surprisingly high. For some refiners, the uncertainty juxtaposed with the importance of not having an unplanned shutdown led to restrictions for the maximum U_{design} permitted. As an example, a refiner may limit U_{design} for a first intercondenser to less than 100 Btu/hr ft² °F.

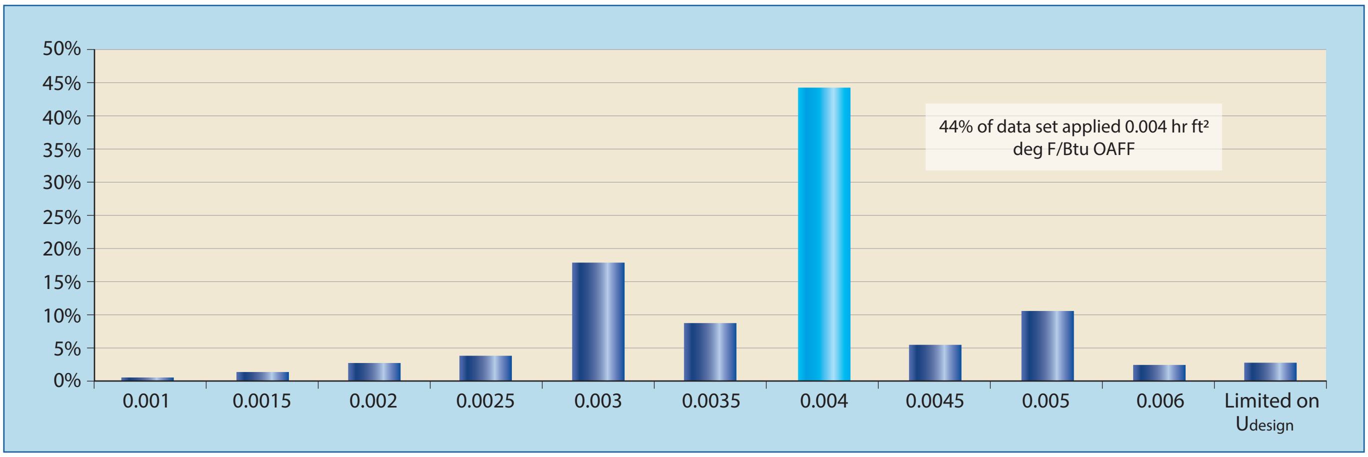

Figure 4 OAFF specified range between 0.001 and 0.008, with six cases where a limitation on maximum U_{design} applied

Fouling can also vary depending on where it occurs. In some services, it is at the entry section of the tube bundle. For others, it occurs in the coldest regions where velocity is lowest and mole fraction of non-condensible the greatest. And then, there are other services where fouling is throughout the shellside.

The bespoke photos in **Figure 1** are from different vacuum distillation ejector system intercondensers and depict the differing type of fouling formation that may occur. The fouling, as indicated, can and will vary, and may be extreme. Applying an appropriate fouling factor to the shellside design is extremely important in order to assure operational reliability throughout the onstream periods between planned turnarounds.

Tubeside fouling

The cooling water source and the filtration systems or backflushing procedures differ from location to location and refiner to refiner. Tubeside fouling is a serious issue and must be considered thoroughly, along with mitigation measures, to reduce its impact.

Understanding the fouling tendency of crude oil processed in a VDU and the extent to which tubeside fouling can develop is important for assuring refinery economics are realised while avoiding an ejector system performance break.

Impact of excessive fouling

When actual fouling is beyond the design basis, it will result in $U_{working} < U_{design}$. Fouling has surpassed the OAFF used in design, and that in itself impedes heat transfer such that the overall actual heat transfer rate is less than the design basis. When this happens, it is important to understand how condenser performance will respond. Problems usually arise in hot summer months when an excessively fouled condenser has the warmest cooling water inlet temperatures and must serve as the heat sink for the discharge of a preceding ejector. It is paramount to understand that an intercondenser will always reject the heat from the ejector that precedes it. However, the essential determinant for satisfactory ejector system performance is at what intercondenser operating pressure will that occur. Is the operating pressure above or below the maximum discharge capability of a preceding ejector?

To understand how an intercondenser responds when $U_{working} < U_{design}$, if water flow rate and temperature are design values, the VDU is operating with design overhead loads. Should $U_{working}$, for example, be 75% of U_{design}, condenser pressure must rise. The condenser pressure must rise until LMTD is approximately 133% of the design LMTD (1/0.75). The duty is essentially unchanged as the VDU is operating at design charge rate. Area is fixed as the condenser is installed. If $U_{working}$ drops 25%, then LMTD must adjust upward by 33%.

To illustrate the point a first intercondenser design basis is 85 mm Hg abs operating pressure and the preceding ejector has a maximum discharge pressure of 90 mm Hg abs. The weighted LMTD of the heat release graph is 16.8°F at design of 85 mm Hg abs. Importantly, the steam initial dew point is 115.5°F. When $U_{working}$ is 75% of U_{design}, the sole response of the intercondenser is to increase operating pressure until weighted LMTD is approximately 22°F or 33% greater.

To reject the heat with $U_{working}$ at 75% of U_{design}, operating pressure rose 18 mm Hg to elevate the steam dew point from 115.5 to 121.9°F, thereby increasing LMTD by approximately 33%.

Under such a circumstance where first intercondenser pressure must rise to 103 mm Hg abs due to excessive fouling, the first-stage ejector will break operation, dissipate its shockwave, and VDU column overhead pressure will rise to 25 to 35 mm Hg abs. A pressure unacceptable to the refiner due to lost yield.

Surprisingly, in winter, when the cooling water inlet temperature is much colder than design, even though $U_{working}$ is 75% of U_{design}, VDU overhead pressure may be perfectly fine. This is because the colder water temperature served to elevate the LMTD, which compensated for $U_{working} < U_{design}$.

An important concept to consider is that excessive overhead hydrocarbon loading will cause the ejector system first intercondensers to exhibit suppressed overall heat transfer rates that might lead one to judge that the condenser is fouled or poorly designed. Large IOC refiners have trended excessive slop level and observed $U_{working}$ decrements to conclude that excessive hydrocarbon loading will suppress condenser heat transfer, causing operating pressure to rise, thus a similar consequence as fouling.

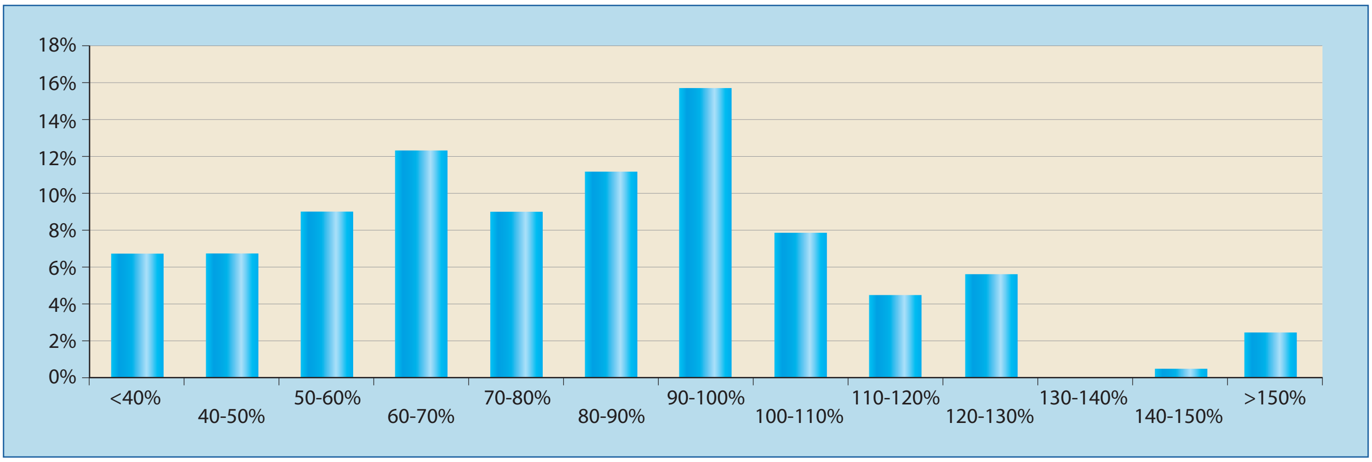

Figure 5 Excess area provided in those cases where 0.004 OAFF was specified for the 200 systems analysed

One refiner shared trend data highlighting that excessive overhead hydrocarbons to the ejector system lowered $U_{working}$ by 15 to 35%, depending on how hydrocarbon loading exceeded the design basis for the ejector system. There are also instances where independent refiners addressed high hydrocarbon loading to the ejector system and adjusted first-stage ejector discharge capability to yield superior performance than when high levels of two-phase hydrocarbon loading were in the VDU overhead stream to an ejector system. Importantly, such cases are not fouling per se, but they exhibit fouling-like behaviour as if that were the root cause of poor ejector system performance.

Industry-specified fouling factor

An analysis of fouling factors specified over the past 30 years for ejector system condensers was undertaken. More than 200 systems were evaluated to assess the fouling factor specified by industry, the U_{design}, and the resultant amount of excess area the fouling factor provided. In this analysis, only the primary condenser was considered. The primary condenser is the condenser within an ejector system that is first to handle the vacuum column overhead hydrocarbon and non-condensible gases.

That may be a precondenser ahead of the first-stage ejector or first intercondenser after the first-stage ejector (see **Figure 4**). The most prevalent OAFF specified by industry is 0.004 hr ft^2 °F/Btu. The OAFF specified ranged between 0.001 and 0.008, with six cases where a limitation on maximum U_{design} applied; for example, U_{design} could not exceed 80 Btu/hr ft^2 °F.

An interesting and deeper analysis is that for nearly 50% of the examples where 0.004 OAFF applied, the amount of safety factor determined by percent excess area varied greatly. **Figure 5** highlights the extent of excess area that 0.004 OAFF provided, and it varied greatly.

The important takeaway for industry is that 0.004 OAFF, for example, is a traditional fouling factor for this type of application; it provides varying degrees of actual safety factor on area. For designs with an increased risk of $U_{working}$ being less than U_{design}, 0.004 OAFF will offer less safety factor.

For cases where load composition to a condenser is low non-condensible and low hydrocarbon vapour, thus the condenser is handling mostly steam, 0.004 OAFF will offer a considerable safety factor, something on the order of 100 to 150% excess area. On the other hand, as hydrocarbon loading increases or the amount of non-condensible gases increases, the degree of safety provided by 0.004 is less.

Component	**Mass flow rate in #/hr**					
Steam	30,000	30,000	30,000	30,000	30,000	8,000
Hydrocarbon	4,000	4,000	4,000	8,000	12,000	30,000
Non-condensible gases	2,000	4,000	6,000	4,000	4,000	4,000
OAFF hr ft^2 °F/Btu	0.004	0.004	0.004	0.004	0.004	0.004
% excess area provided	112	97	85	90	80	50

It is always important to consider an OAFF relative to an anticipated overall heat transfer rate, especially when handling condenser mass flow rate with hydrocarbon as the predominant component, be they vapours or vapours and liquid. When the overall heat transfer rate is comparatively low, such as U_{design} at 50, for example, 0.004 OAFF embedded in U_{design} provides just 25% excess surface area.

This analysis and thorough discussion about the fouling factor must take place in the FEED phase of a project. Once in the EPC phase, it is difficult to modify a procurement specification that drives higher an EPC's procurement costs. There are other techniques for building in conservatism, such as designing for 110 to 125% of the design mass flow rates. Nonetheless, as the preceding pictures suggest, appropriate OAFF is critical to achieving reliable ejector system operation between planned shutdowns or turnarounds.

Case study

A refiner operating a world-scale fuels refinery experienced elevated vacuum distillation column pressure that led to an unacceptable reduction in yield. The increased vacuum column pressure lowered the recovery of more valuable vacuum gas oils, concurrently increasing less valued vacuum tower bottoms. The VDU overhead ejector system was supplied in the mid-1980s and was revamped 20 years later as part of a clean fuels upgrade to produce low-sulphur fuels. As a result of the revamped vacuum column design, overhead pressure was reduced 5 mm Hg to

13 mm Hg abs and the first intercondensers were replaced with larger condensers to address greater heat rejection requirements.

The refiner sought assistance to identify the root cause and develop a solution for achieving 13 Hg abs overhead pressure because 25 to 35 mm Hg abs was the current VDU overhead operating pressure. That was unacceptable as it led to >$18 million per year in lost VGO yield.

The performance improvement engineer requested operating data trends to assess what had been transpiring with the ejector system. From the trend data, it was not possible to deduce what was causing the elevated operating pressure that caused the first-stage ejector to operate in a 'broken' condition. Broken ejector performance occurs when the back pressure the ejector must discharge to exceeds its maximum discharge capability. An engineer was dispatched to the site to conduct a performance survey, speak with operators, and identify the root cause.

A deep dive early in the design phase and prior to ejector system procurement can avoid a costly yield shortfall

The performance survey identified that the first-stage ejectors were subjected to 107-110 mm Hg abs back pressure, while the maximum discharge capability without loss of compression shock wave was 100 mm Hg. Furthermore, the process side (shellside) pressure drop across the first intercondensers varied between 15 to 20 mm Hg. Measured values varied due to the unstable operation of the system. However, it was clear that the pressure drop across the shellside of the condenser well exceeded the expected pressure drop to 5 to 6 mm Hg.

The operating pressures at the suction of the third-stage ejectors confirmed the non-condensible gas load was below design as the measured pressure was about 100 mm Hg below design. With low non-condensible gas mass flow rate load to a second- or third-stage ejector exiting its preceding condenser (non-condensible gases plus vapours of saturation) will be below design, thus enabling that ejector to pull to a lower pressure.

Focus was on the first intercondenser. Potential causes for elevated operating pressure and high pressure drop included:

- Lower cooling water flow rate
- Elevated inlet cooling water temperature
- Excessive hydrocarbon loading from the vacuum column
- Excessive non-condensible gas loading from the vacuum column
- Fouling on the shellside, tubeside, or both.

The engineer ruled out cooling flow rate or temperature issues as both were within acceptable range. Non-condensible gas loading was ruled out, as previously noted, due to lower inlet pressure for the third-stage ejectors. Excess hydrocarbon loading could not be ruled out, nor could fouling.

The refiner had a shutdown planned within a few days, so the performance improvement engineer recommended that the first intercondenser bundles be pulled for inspection to observe the extent of fouling. The system had run for about 10 years since the revamp and installation of new, larger first intercondensers to improve clean fuels production; therefore, some degree of fouling was anticipated.

A long-term trend for the time-based relationship between condenser condensate temperature and cooling water inlet temperature inferred that a fouling issue was likely. The difference between condensate temperature and cooling water inlet temperature progressively increased with operating life. The longer the condenser was in service, the greater the difference became between the two temperatures, inferring fouling was suppressing the overall heat transfer rate.

Bulk condensate, while imperfect, does correlate reasonably to condenser operating pressure. Directionally, warmer condensate temperature correlates to higher operating pressure. The data highlighted that the condenser pressure was increasing with run time. The first intercondenser bundles were pulled, and severe fouling was observed on both the tube and shell sides.

The performance improvement engineer identified the root cause of poor vacuum column overhead pressure with consequent loss in gas oil yield due to fouling on both the shellside and tubeside of the first intercondenser. This caused the working overall heat transfer rate to drop below the design basis, increasing condenser operating pressure beyond the discharge capability of the first-stage ejector.

Conclusion

Fouling is an important design parameter. Applying fouling factors into a design increases ejector system Capex. Failing to apply good fouling factor 'judgment' for ejector system design can result in significant economic loss. A thorough understanding of the fouling tendencies of both the process side and cooling water side is crucial. Mitigating tubeside fouling can be addressed via filtration, chemical treatment, backflushing, and overall good cooling water utility system management.

On the process side, principally with regard to hydrocarbons, knowing the anticipated range of crude feedstock or crude blends to be processed is important. Any prior operational experience with such feedstocks will prove informative with regard to fouling. Striking an appropriate balance between operational reliability to avoid an unplanned shutdown due to fouling and the initial capital cost of the ejector system and its installation must be addressed. A deep dive early in the design phase and prior to ejector system procurement can avoid a costly yield shortfall.

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