Vacuum ejector performance break

Understanding vacuum ejector performance is the key to maintaining reliability and distillate yields. A low VGO yield may result from a breaking ejector system, but bypassing a fouled inter-condenser can restore lost yield

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Poor ejector system performance continues to reduce vacuum gas oil (VGO) product yield due to design and reliability problems (Figure 1). Since poor performance increases column operating pressure, profit is significantly reduced too, especially during high margin periods. Although there are many potential trouble spots in multi-stage or parallel multi-stage ejector systems, this article focuses on the event called "breaking". Experience shows that breaking can easily reduce VGO yield by 2–4% on crude charge.

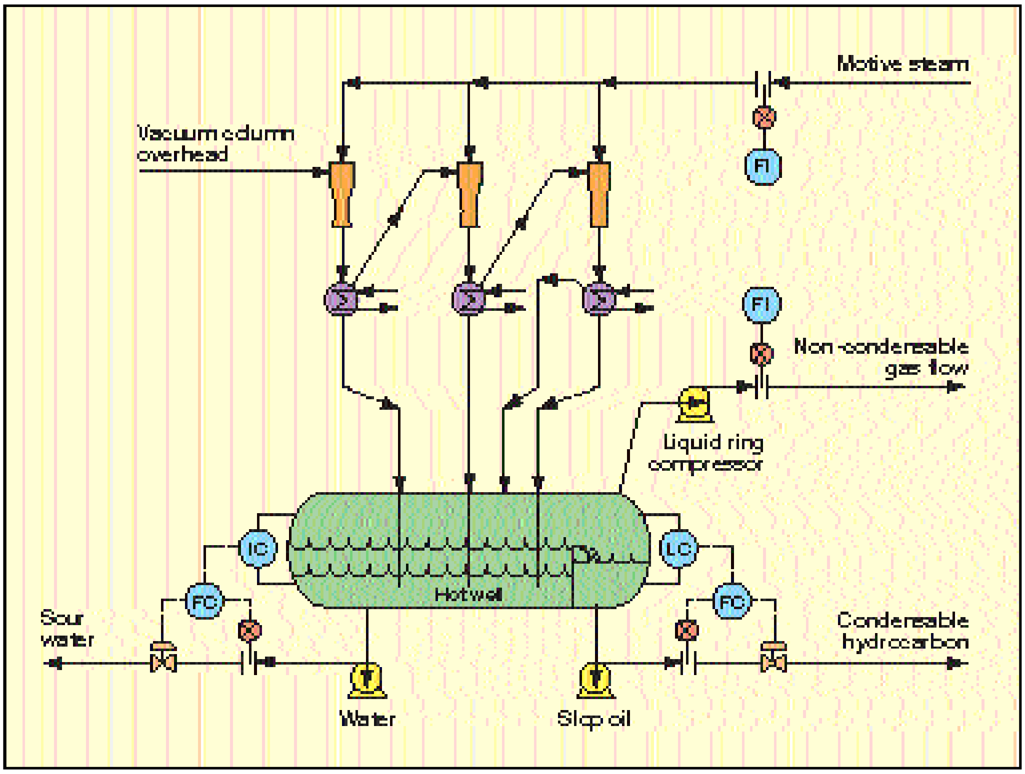

Figure 1 Vacuum ejector system

Normally, changes in the first-stage ejector system's suction pressure are predictable, with gas loads based on the manufacturer's certified performance curve. However, when the first-stage ejector's operation breaks, it no longer operates on this curve and its suction pressure increases abruptly. Consequently, pressure in the vacuum column flash zone goes up rapidly, the VGO product yield drops and the vacuum tower bottom (VTB) rate increases. The amount of VGO yield loss depends on the pressure in the vacuum column, which in recent cases has shown increases of 15–50 mmHg in the flash zone pressure when an ejector's performance breaks.

Although there are numerous ejector system problem areas, breaking is caused by a high first-stage ejector discharge pressure. Since the symptoms of breaking are distinct, field pressure measurements can pinpoint the problem so that speculation and theories which have little to do with the root cause can be avoided. While the trend today is to undertake sophisticated tests such as neutron back-scatter or isotope injection, as well as "wasting" time in meetings or performing computer simulations, in reality it is field measurements and the application of fundamental vacuum ejector system principles that can improve operations and increase profitability.

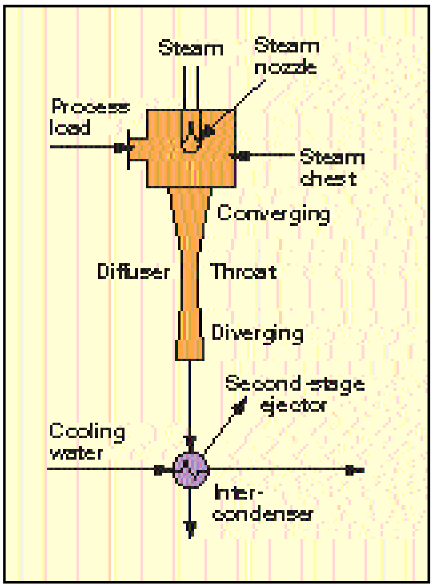

Figure 2 Vacuum ejector major system components

How ejectors work

The major system components are the ejector and the condenser (Figure 2). These must operate together to minimise column operating pressure. The ejector consists of a steam nozzle, steam chest and diffuser. The choice of steam nozzle is based on the gas load it was designed for (rate and composition), steam pressure and temperature, as well as maximum discharge pressure (MDP). Since the steam nozzle is a critical flow orifice, steam pressure sets the flow rate, with higher or lower steam pressure controlling the nozzle's steam flow rate. As the steam flow provides the power for compression, the flow rate it was designed for must be maintained, otherwise the vacuum column operating pressure will increase.

The steam ejector educts process gases into the steam chest and then through a specially designed converging-diverging device that is part of the diffuser. The diffuser dimensions and throat area are specified to meet the motive steam rate it was designed for, process gas load and MDP. Each component needs to work properly to compress the process gas and minimise the column operating pressure.

Steam ejectors work by converting the pressure energy of the motive steam into velocity. For a critical flow ejector, the motive steam enters the steam chest through the steam nozzle at velocities typically in the range of Mach 3.0–4.0. Localised pressure inside the steam chest drops slightly below suction pressure so that the process gas flows into the steam chest from the suction piping. The mixture (motive steam and process gas) then enters the diffuser. This consists of the converging (narrowing nozzle) section, the throat (straight piece of pipe), and the diverging (widening) section. The shape of the diffuser allows the mixture velocity to exceed Mach 1.0, whereas in a straight pipe it cannot.

In the converging section of the diffuser, process gas is accelerated above Mach 1.0 and the motive steam velocity drops. Motive energy is transferred to the process gas, and the fluids begin to mix. Pressure rises across the converging section. The motive steam and process gas finally reach the same velocity toward the end of the converging section. If the ejector's discharge pressure is below its MDP, the mixture enters the throat above Mach 1.0. Since compressible fluid flow in a straight pipe cannot exceed sonic velocity, there is a sonic shock wave inside the throat where velocity drops below Mach 1.0. Across the sonic shock wave (sonic boost), the mixture pressure rises rapidly. In the diverging section, velocity decreases as the nozzle opening gets wider, and thus kinetic energy is converted to pressure. A large portion of the first-stage ejector's compression ratio occurs from the sonic shock wave.

A single ejector's operation can be thought of as a multi-stage compressor with no moving parts. In the converging section, pressure rises as energy is transferred from the motive steam to the process gas. In the throat, there is a pressure rise across the sonic shock wave, or sonic boost. In the diverging section, kinetic energy is converted to pressure energy.

The pressure rise in the throat from the sonic boost is large. If the mixture velocity in the converging section and entrance to the throat exceeds the sonic velocity, the entire sonic boost is maintained. But if the ejector's discharge pressure exceeds a value (MDP) sufficient to cause the mixture velocity in the diffuser throat to fall below Mach 1.0, or critical flow, the pressure rise from the sonic boost is lost. The ejector is then said to break. While the ejector will run quieter, it will also have a much lower overall compression ratio, because the pressure boost across the shock wave suddenly disappears.

Process gas load – dry vacuum unit

On a dry vacuum unit, the process gas load to the first-stage ejector comes from cracked gas, condensable hydrocarbons, air leakage and saturated water in the feed. Air leakage is generally small. Hotwell off-gas should normally have less than 10 mole % nitrogen. If the sample contains 30–40% nitrogen, this indicates that there is a large air leak that is unnecessarily raising the gas load and column operating pressure.

Typically, cracked gas generated in the heater is the largest source of first-stage process gas load. Since most refiners meter hotwell gas, production changes can be monitored. Condensable hydrocarbon load is primarily a function of the upstream crude column residue stripping section and the vacuum column top temperature. Poor stripping increases 300–700°F boiling-range hydrocarbons in the vacuum unit feed, which raises the ejector's condensable hydrocarbon load. Inadequate stripping is caused by a low steam rate, poor tray efficiency or tray damage. The condensable load is also influenced by the vacuum column's overhead temperature, but its effect is small. Since slop oil is metered from most ejector hotwells, increased slop oil production indicates a rise in condensables.

Ejector system fundamentals

The vacuum column's overhead stream flow rate and composition set the operating pressure in the first-stage ejector (Figure 3). Since most refinery first-stage ejectors are designed for critical pressure ratios, their suction pressure depends only on the gas load as long as their discharge pressure is below their MDP. Thus, the performance of the second- and third-stage ejectors or the hotwell off-gas liquid ring pump have no influence on the first-stage ejector's suction pressure as long as the first-stage discharge pressure is below its MDP.

Understanding this is essential, otherwise during revamps money may be wasted by adding more capacity to the second- and third-stage ejectors or liquid ring pumps. Also, during troubleshooting, time may be wasted chasing irrelevant factors. In one instance, the authors lowered the third-stage ejector's discharge pressure from 1100 mmHg absolute to 800 mmHg by online cleaning the after-condenser. In another case, hotwell pressure was reduced from 1200 mmHg absolute to 760 mmHg by lowering the suction pressure controller's set point on the liquid ring pump. In each instance, the first-stage ejector's suction pressure did not change.

During the design of the ejector system, the MDP for the first and second stages is determined by optimising overall motive steam, cooling water consumption and capital costs. Third-stage discharge is fixed by the hotwell operating pressure. This is generally between 890 and 1200 mmHg, depending on where it is routed. But once installed, each ejector stage has a certified performance curve and its MDP cannot be exceeded or its operation will break from its performance curve. Breaking the second- and third-stage ejectors only affects the first-stage suction pressure when the first-stage discharge pressure exceeds its MDP.

Since an ejector is a thermal compressor, power comes from steam

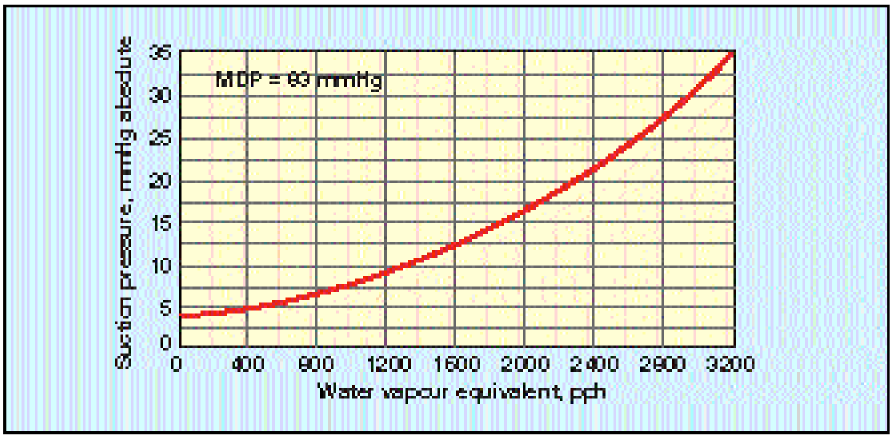

Figure 3 *First-stage ejector curve*

flow rate and pressure. Typically, steam temperature is slightly above saturation. Since the steam nozzle is a critical flow orifice, flow is set by supply pressure. Thus, steam pressure must be controlled at design conditions to ensure that energy input is maintained (a higher steam flow rate raises the MDP, but it also raises the condensing load). Each ejector has a MDP above which it cannot operate, because the motive steam energy is not sufficient to compress the process gas from the suction pressure to above its MDP.

Since most first-stage ejectors are designed for compression ratios between 5 and 15 (discharge pressure/suction pressure), their MDP does not change with the gas load over normal day-to-day variability. Thus, for practical purposes, the MDP is constant and does not vary with the gas load. But when the first-stage ejector's discharge pressure is higher than its MDP, its performance breaks and the suction pressure increases dramatically.

The first-stage ejector's performance curve determines its suction pressure as long as its discharge pressure is below its MDP. But the discharge pressure depends on the inter-condenser and the second-stage ejector's performance curve. The second-stage ejector's suction pressure is set by its process gas load, which is primarily cracked gas, air and a small amount of steam that is not condensed in the first-stage inter-condenser. Thus, for a fixed amount of cracked gas and air, the temperature leaving the inter-condenser determines the second-stage gas load. Typically, the second-stage ejector's suction pressures operate at 75–110 mmHg absolute, with its first-stage discharge pressure about 5-10 mmHg higher, depending on the actual inter-condenser pressure drop. Fouled exchangers or plugged condensate drains can raise the pressure drop by 10–60 mmHg.

When the inter-condenser (not plugged or fouled) and the second-stage ejector operate properly, cooling water flow and temperature determine the first-stage discharge pressure. As the temperature of gas leaving the first-stage inter-condenser increases, the amount of water that does not condense rises. Hence, the process gas load to the second-stage ejector goes up and the suction pressure increases. This raises the first-stage discharge pressure.

Since the first-stage ejector's discharge is primarily steam, the inter-condenser duty varies as the cooling water flow rate and temperature change. In the summer, the cooling water temperature increases. Thus, the second-stage ejector's gas load rises, upping the first-stage ejector's discharge pressure. Table 1 shows the saturation temperature for condensing steam. This helps explain why ejectors have more problems with breaking in the summer. As the cooling water temperature increases from winter temperatures of 65–80ºF to 80–95ºF in the summer, the condensing pressure must also rise. A higher condensing pressure increases the first-stage ejector's discharge pressure. Hence, during the summer, the first-stage ejector's discharge pressure often exceeds its MDP. For ejectors designed for non-critical pressure ratios, the first-stage ejector's suction pressure is dependent on the discharge pressure. In the few instances where these types of ejectors are installed, the suction pressure varies with the gas load and discharge pressure.

Steam tables

Pressure (mmHg)	Temperature (°F)
65	110
75	115
95	123
105	127
115	130

Table 1

Most first-stage inter-condensers are marginally or grossly undersized, because typical bid specifications state "steam consumption and cooling water rate should be optimised so that capital cost is minimised". Hence, the only way the vendor can sell the system is to marginally size the inter-condensers, as they represent a large percentage of the total ejector system cost. Since the motive steam rate largely sets the condensing duty, it determines the size of the inter-condenser.

Another factor is the cooling water flow rate. Since many ejector systems are installed during revamps, actual cooling water flow rates are subject to the overall unit or refinery cooling water system performance. Consequently, after startup, the actual cooling water flow rate may be lower than expected. Low cooling water flow, in conjunction with a marginally sized inter-condenser, often raises the first-stage ejector's discharge pressure above its MDP. Thus, breaking is a consequence of buying the low bidder's solutions and a lack of understanding of the consequences of undersizing inter-condensers.

Inter-condenser performance

First-stage inter-condensers must condense process steam (from heater coil injection and column stripping steam if used), motive steam and most of the condensable hydrocarbons. Therefore, most of their duty is for steam condensing. Steam that is not condensed increases the gas load to the second-stage ejector, causing a higher discharge pressure in the first-stage ejector. Since the inter-condenser's duty determines both the gas outlet temperature and the second-stage ejector's gas load, it sets the first-stage ejector's discharge pressure. Thus, inter-condenser design deficiencies or undersizing can cause a higher column operating pressure due to breaking. Consequently, undersized first-stage inter-condensers will cause a large VGO product yield loss and reduced profits during the summer gasoline season when margins are generally highest.

Fouling affects exchanger duty. It occurs on both the tube and shell side of the exchanger. Tube-side fouling is caused by poor cooling water quality and low velocity. Corrosion and amine salts raise the shell-side fouling factor and increase pressure drop. Since increased fouling reduces the overall heat-transfer coefficient, it requires higher exchanger LMTD to meet the condensing duty (Equation 1).

$$Q = U * A * LMTD \qquad \text{(Equation 1)}$$

Q = Btu/hr	Exchanger duty
U = Btu/h-ft^2-°F	Heat-transfer coefficient
A = ft^2	Exchanger surface area
LMTD =°F	Log mean temperature difference

Increasing LMTD at a constant cooling water rate and temperature requires a higher condensing temperature. Table 1 shows the relationship between condensing temperature and the pressure of steam. Therefore, fouling increases the first-stage ejector's discharge pressure.

Another common problem is condensate drain plugging. When this occurs, condensate floods the inter-condenser tubes, reducing the surface area. By reducing the area in Equation 1, duty decreases and gas outlet temperature increases, raising the first-stage ejector's discharge pressure.

Determining ejector MDP

Sometimes manufacturer-certified ejector curves are not available and in a few instances the manufacturer's stated MDP is proved to be wrong. Since most ejector systems have block valves on their inter-condensers, a simple throttling test can determine the MDP. Two accurate electronic gauges are placed on the ejector's suction and discharge. If the pressure tap is located downstream of the inter-condenser's block valve, the isolation valve on the inter-condenser outlet can be used for throttling. Slowly close the block valve to increase the discharge pressure and monitor the suction pressure. The suction pressure on an ejector designed for a compression ratio greater than 5.0 (discharge pressure/suction pressure) will not materially change with an increased discharge pressure. The discharge pressure should be raised until the ejector's suction pressure makes an abrupt step change. This pressure marks the MDP. Prior to this step change, the ejector may surge, with suction pressure oscillating rapidly (Figure 4). However, once the performance breaks, the suction pressure increases to a new stable operating condition. Opening the throttle valve will reduce the ejector's discharge pressure, returning the ejector to normal operation.

Surging ejectors

When an ejector jumps in and out of the sonic boost mode, it causes the surging noise commonly heard. This happens when the ejector's discharge pressure approaches its MDP. Once the ejector's operations break, the discharge pressure must be reduced to the pick-up pressure where the ejector can again operate stably. The pick-up pressure will vary, depending on the ejector's design. However, it is generally a few to several mmHg lower than its MDP. For example, when condenser performance deteriorates as cooling water warms in the morning, the ejector gets quiet and stops surging, the sonic boost stage is lost. The compression ratio remaining is much lower, so it breaks. The suction pressure dramatically increases. The cooling water temperature must decrease sufficiently for the ejector's discharge pressure to reach its pick-up pressure. Between the pick-up pressure and as it approaches its MDP, the ejector can go in and out of the sonic boost. Thus, suction pressure will be erratic.

Case study

Fouled inter-condensers

Over several weeks, the VTB product flow rate increased and the yield of VGO decreased. During this time, the column flash zone pressure rose from 30 mmHg absolute to 40 mmHg, corresponding to a rise in the first-stage ejector's suction pressure from 15–28 mmHg. Then, suddenly, the suction pressure went up to 60 mmHg. At this point, a brainstorming meeting was held, but there was no field data to support any of the theories and speculation. Since the importance of inter-condenser performance is often overlooked, it did not even make the list of possible causes. Furthermore, a review of operations showed that ammonia was being injected in the top of the vacuum column to maintain the first-stage ejector's condensate pH and thus control corrosion. This is a common source of first-stage inter-condenser fouling.

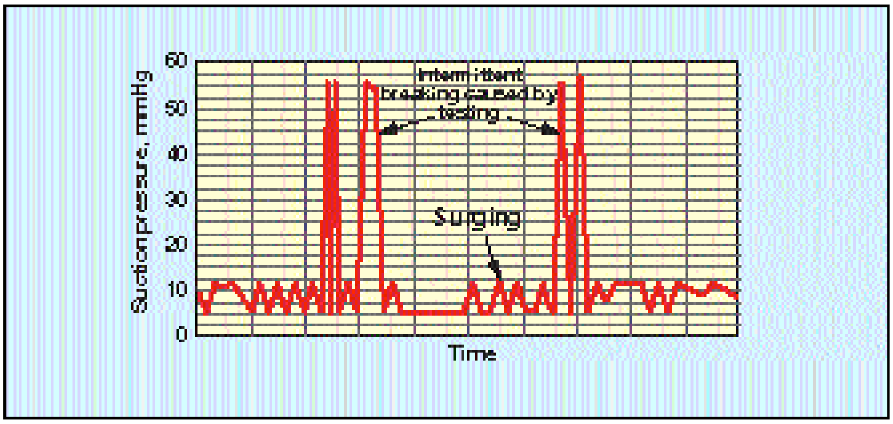

Figure 4 *Process data showing ejector breaking*

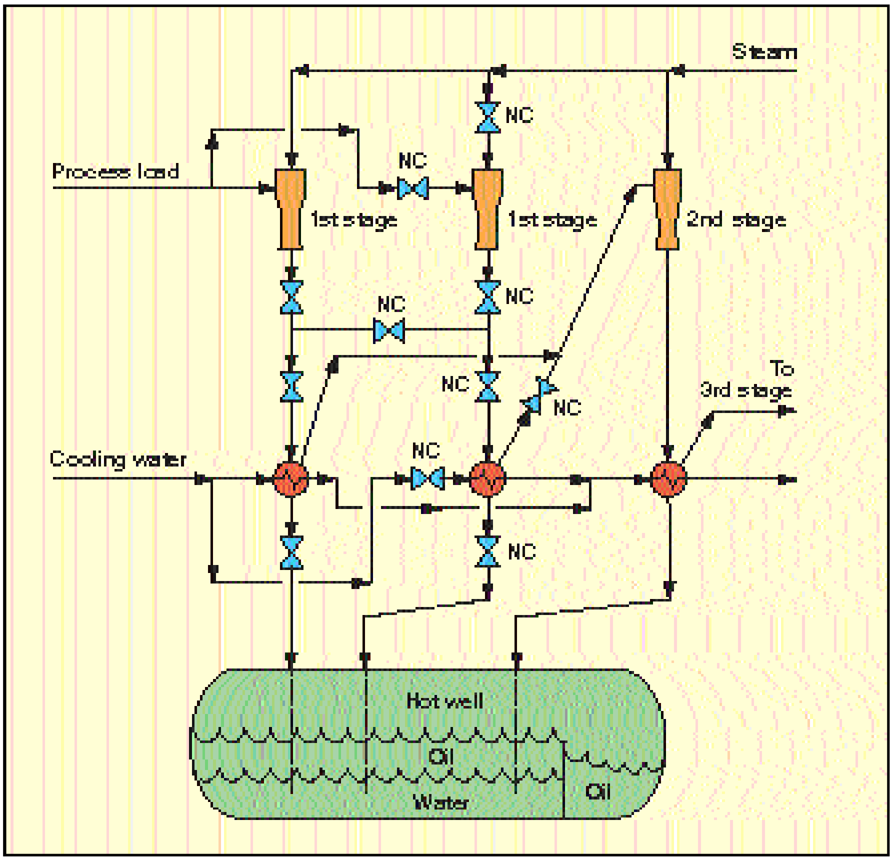

Figure 5 *Ejector design*

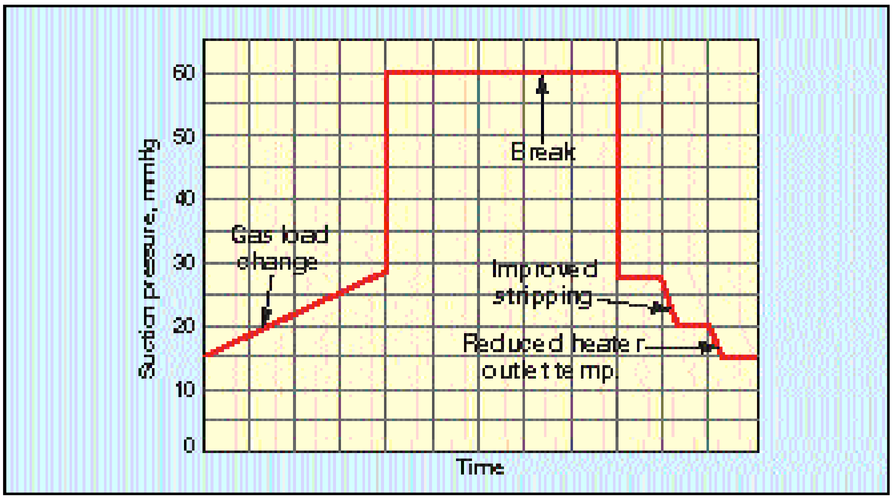

Figure 6 *Field testing results*

The first-stage ejector's suction pressure is set by its gas load, so an increase in suction pressure from 15–28 mmHg indicated that the gas load had increased over time. As this was a dry vacuum unit, the first-stage gas load is primarily cracked gas with some condensable hydrocarbons and only a small amount of air from leakage. Since the ejector system had flow meters on the gas and slop oil leaving the hotwell, both showed increases during the period when the suction pressure had gone up from 15–27 mmHg. Yet there was no change in the flow rate of these streams when the pressure made the step change.

However, when the discharge pressure was finally measured, it was significantly above the MDP it was designed for. The measured pressure drop across the first-stage inter-condenser was more than 30 mmHg. Since the system was designed with two parallel first-stage ejectors and inter-condensers with inter-connecting piping (Figure 5), bypassing the plugged exchanger required some simple piping line-up changes.

The spare inter-condenser was put in service and the suction pressure immediately dropped to 27 mmHg (Figure 6). It was the first-stage ejector's performance that was breaking, which caused large VGO yield loss.

Further optimisation of the atmospheric column stripping steam lowered the condensable load. The heater outlet temperature was also reduced by 10°F, lowering cracked gas production. These steps reduced the gas load, and the suction pressure decreased to 15 mmHg. Breaking significantly reduced the VGO yield, but finally identifying the root cause of the trouble and correcting the problems required no capital. (This case study highlights the influence of the first-stage inter-condenser's performance on VGO yield.) The lesson to be learned is that an abrupt change in the first-stage ejector's suction pressure almost always can be attributed to the first-stage ejector's discharge pressure being higher than its MDP. Causes of breaking include mechanical damage, changes in process conditions, damaged sealing strips on the inter-condenser, low cooling water flow, an increased second-stage gas load, damage to downstream ejectors and high seal drum pressure.

Other factors that can cause the loss of the sonic boost are low steam pressure, wet steam, steam nozzle erosion, steam nozzle plugging, an excessive cracked gas load, air leakage, and overloading of the first-stage ejector with condensables. Finally, one common problem resulting in the loss of sonic boost is running a weak ejector in parallel with a properly operating (strong) ejector. The strong ejector sucks steam from the weak one, thereby loading the strong ejector and its inter-condenser. This steam must be condensed in the inter-condenser, thus raising discharge pressure. When it exceeds its MDP, the sonic boost is lost.

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