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Reliability improvement for reciprocating compressor in CCR reformer process

SK Energy: Founded as the first oil company in South Korea in 1962, SK energy has been producing various petroleum products at the Ulsan Complex, which has a refining capacity of **840,000** barrels of crude oil per day, selling them in both domestic and overseas markets.

In response to the demand for increased production, the three reciprocating booster gas compressors in the Continuous Catalyst Regeneration (CCR) reformer process had been operating unspared, without backup, since a revamping project in 2009. Subsequently, the number of unplanned downtime incidents and related costs began to increase due to the number of unexpected failures and ensuing maintenance actions. In fact, the three CCR compressors consumed up to 90% of the maintenance costs out of 100 reciprocating compressors in the plant.

This article describes how SK Energy overcame the challenges in process control, mechanical design, and condition monitoring for the reciprocating compressors to improve the reliability of those assets and reduce the maintenance cost.

Machine Description

The three reciprocating compressors in the CCR reformer process were installed in 2005. The booster compressors in CCR reformer process transfers rich hydrogen(H_2) gas from reactor to H_2 plant.

Compressor Specification			
No. of compressors	3 ea (A/B/C)		
No. of stage/cylinder	3 stage / 4 cylinder		
Speed	400 rpm		
Suction Pressure (kg/cm2g)/(psig)	1st	2.1 kg/cm²	29.8 psig
	2nd	5.7 kg/cm²	81.1 psig
	3rd	14.0 kg/cm²	199.1 psig
Discharge Pressure (kg/cm2g)/(psig)	1st	6.1 kg/cm²	86.8 psig
	2nd	14.5 kg/cm²	206.2 psig
	3rd	33.6 kg/cm²	447.9 psig
Flow	41,933 Nm³/h		
Motor Power	5 MW (6,702 HP)		

Table 1. Compressor specification for CCR reformer process

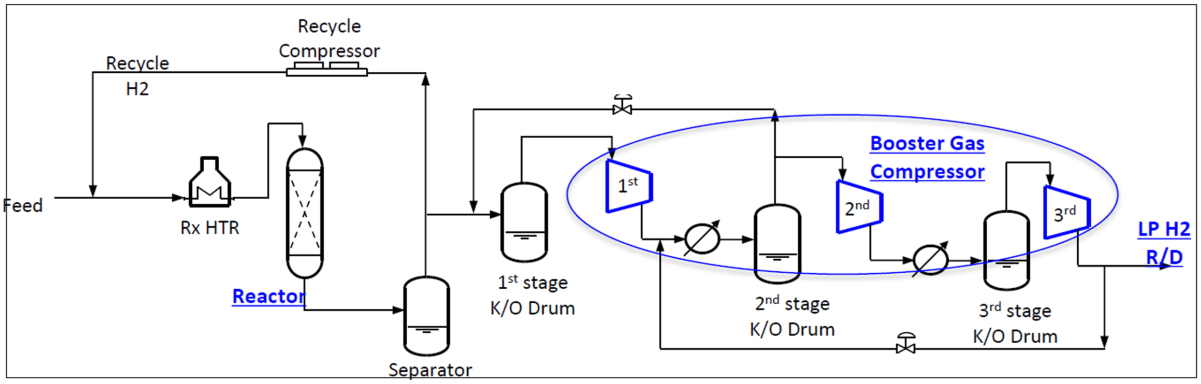


Figure 1. CCR reformer process diagram

Problem Statement

Since the machines were revamped in 2009 to increase the production capability, these three compressors have been operated unspared. However, the number of machine problems increased drastically. Most problems were identified as damaged valves and cracked pistons.

Following the revamping project, the pressure ratios did not change significantly, but, discharge temperatures were all observed to have increased slightly higher than the original levels. After the revamping project, the discharge temperature setpoint was set at 145 °C.

Process revamp in 2009		Before	After
Compressor at operating		2 run out of 3	3 run out of 3
Total load		80,983 Nm^3/h	102,648 Nm^3/h
Pressure Ratio	1st stage	2.20	2.24
	2nd stage	2.39	2.41
	3rd stage	2.31	2.32
Discharge Temperature	1st stage	105 °C	112 °C
	2nd stage	101 °C	106 °C
	3rd stage	106 °C	113 °C

Table 2. Machine revamp 2009

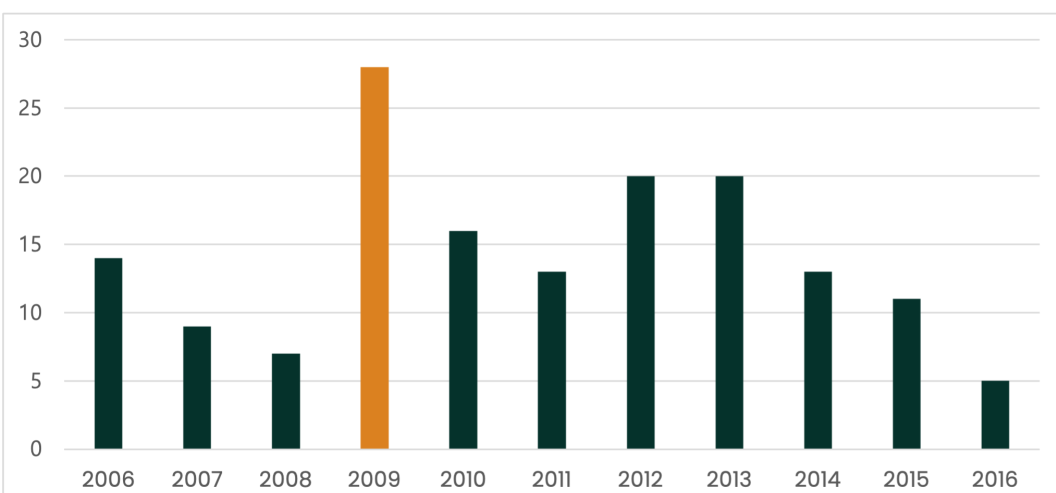


Figure 2. Maintenance events on the booster compressor 2009-2016

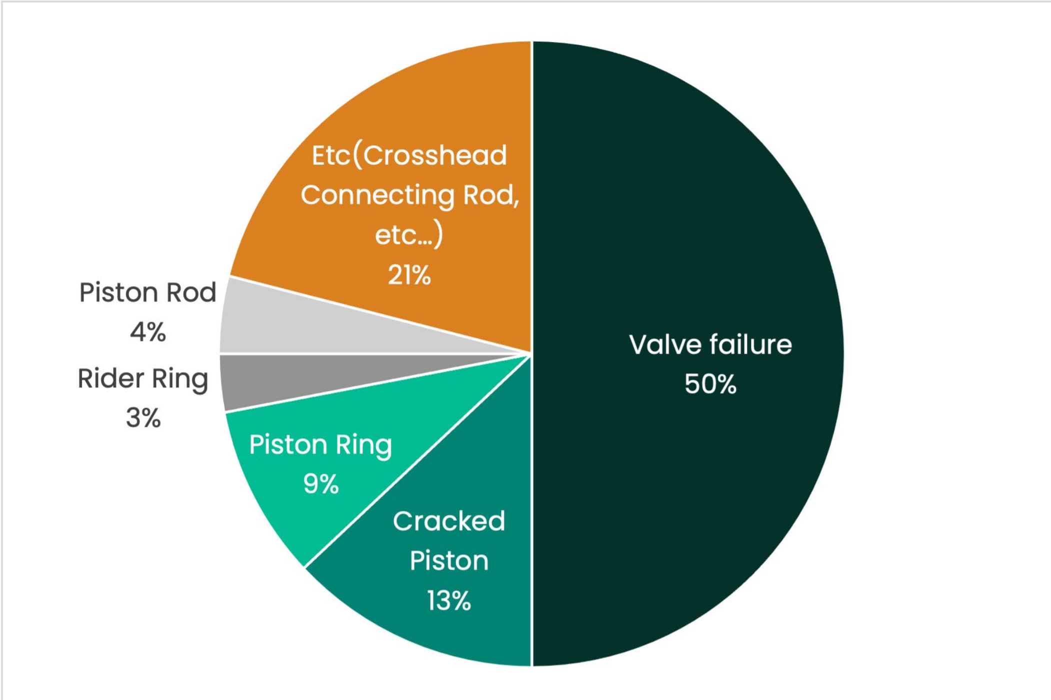


Figure 3. Failure modes distribution 2009-2016

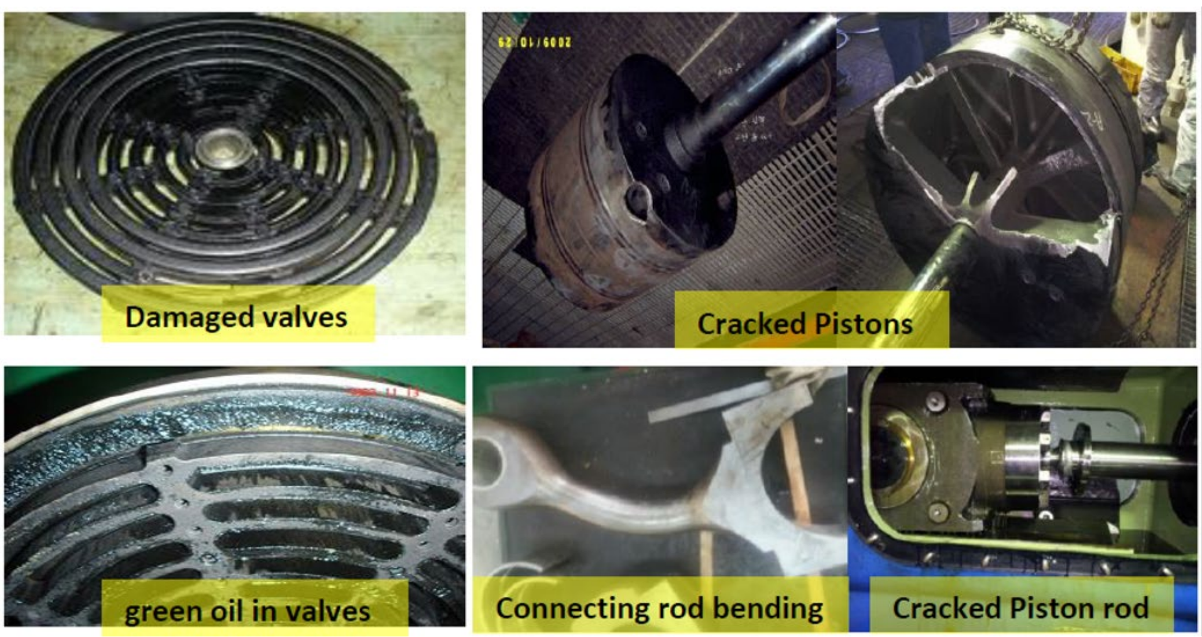


Figure 4. Damaged parts on 3 booter gas compressor

Cause and effect Analysis

SK Energy carried out a cause-and-effect analysis to identify the root cause of the recuring valve and cracked piston rod problems, covering every aspect of the process and the mechanical design & integrity of the compressor.

Process

Through the process review, it was found that an increase in Iron(III), oxide(Fe_2O_3) and Chloride(Cl_2) dust contributed to polymerization of a green oil residue, due to changed process conditions. Also found that the Hydrogen/Hydro Carbon(H_2/HC) ratio is one factor which could increase light olefins, another factor in formation of green oil.

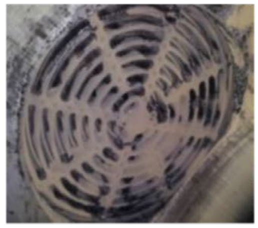
Process revamp	Before	After
Hydrogen(H2)/ Hydrocarbon(HC) ratio	High	Low
Green Oil Presence		

Figure 5. H_2/HC ratio in process gas composition

Fe_2O_3 was generated in the pipe by exposure to the atmosphere during turnaround, and the Cl_2 dust was created during initial period of start-up, and by using new catalyst type. The Fe_2O_3 and Cl_2 dust are catalysts which lead to formation of viscous green oil which collects as condensate in the compressor cylinder.

Machine Design & integrity

Before the revamping project, a concentric ring type discharge valve was used, however the valve was found to be not strong enough to endure foreign substances.

- Sticking occurs due to foreign substance between valve sheet (seat) and ring.
- Late opening and differential pressure increase between A and B area (refer Figure 7).
- Increase impact and tumbling between the ring and guard. (Because outer ring's stiffness is lowest, outer ring breaks easily.)

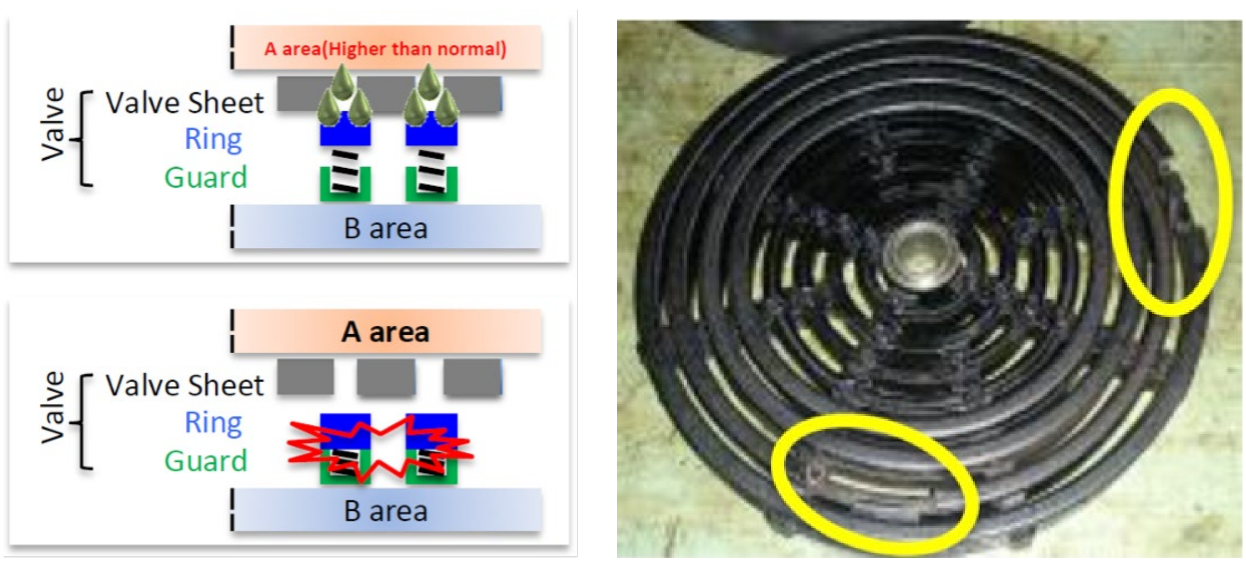


Figure 6. Valve failure on discharge valve

One of the unique features of these compressors' design is the use of a Free-Floating Piston (FFP). Because of the unique operation, the piston is made of lightweight material. It was determined that the material strength was not enough to withstand the large stress exerted by the green oil.

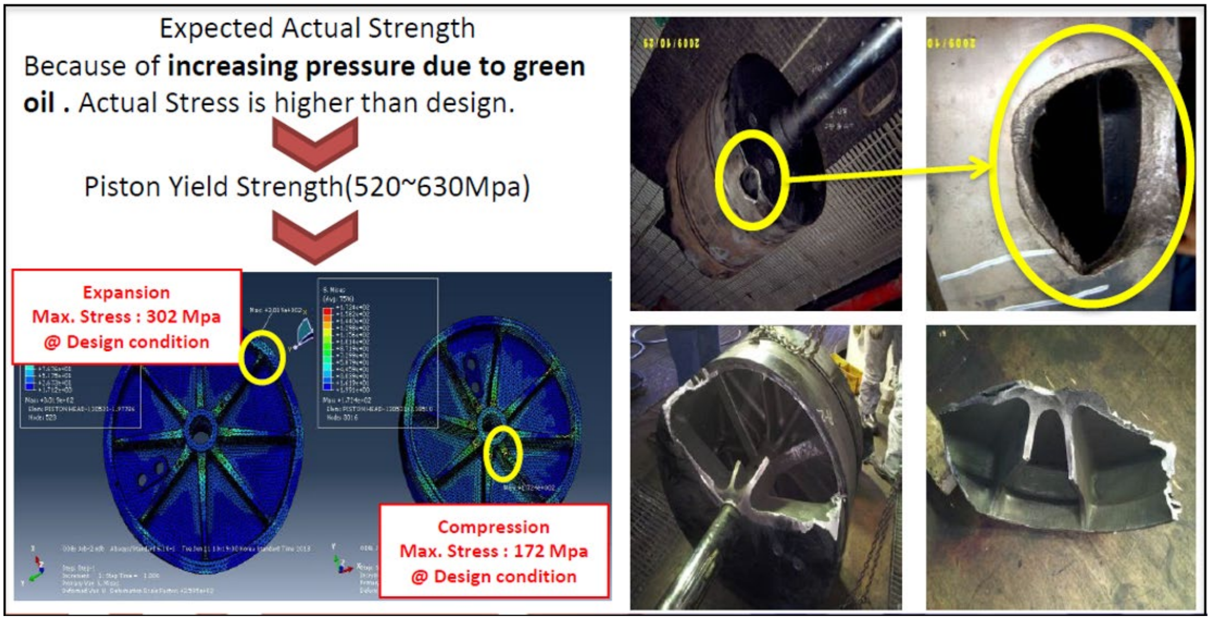


Figure 7. Piston failure due to green oil

Improvement

Based on what was found during the investigation phase, the following actions were taken for both the process side and mechanical integrity side. In addition to these, the Condition Monitoring system was upgraded to precisely monitor the condition of the machines.

Process

To avoid further generation of green oil, catalysts like Fe_2O_3 and Cl_2 were completely purged from the piping system and the knockout drum to the discharge line during turnaround maintenance.

Figure 8. Water washing and purging on the pipe

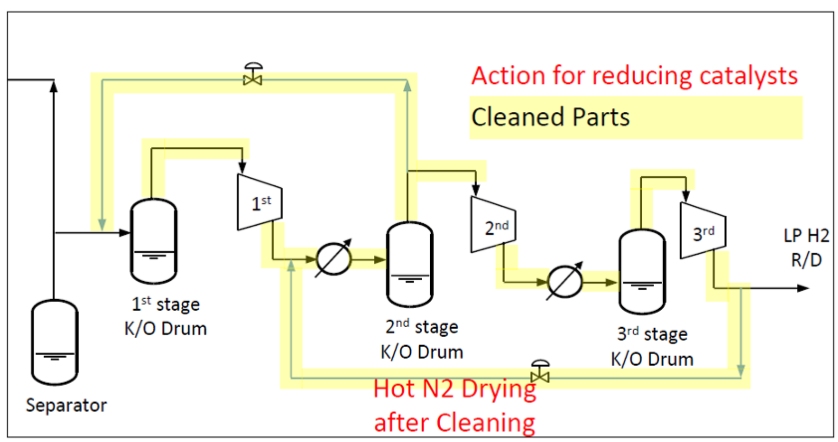


Figure 9. Improve pipe line cleaning

To minimize the formation of green oil, the reformer process reduced the amount of light olefin and adjusted the operating conditions at startup to reduce chloride (Cl).

Machine Design & integrity

Replaced the original concentric ring valves with a poppet type valves which have high reliability under liquid carry-over and sticking scenarios.

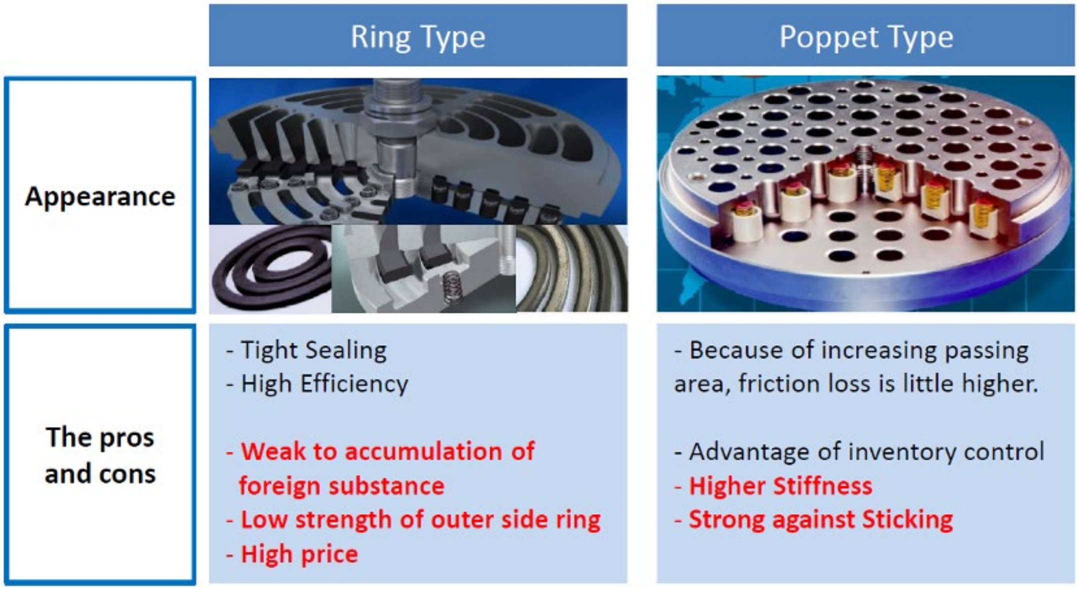


Figure 10. Improve valve type

Improved the geometry of the piston to increase its mechanical strength. As the material and method of production changed, the strength increased ~48% above original and without weight change.

Figure 11. Improve the geometry

In addition, to further improve the strength, the piston manufacturing process was changed to a drop forging method, resulting in a 26% strength improvement over the original cast design.

EN Standard	Yield Strength (MPa)	Tensile Strength (MPa)	Elongation (%)	Hardness (HRC)	Charpy Impact Valve (J) (min)
Original Material (X3CrNiMo13-4)	520 ～ 630	650 ～ 810	18 ～ 24	16 ～ 24	80 (50)
Improvement Material (X4CrNiMo16-5-1)	550 ～ 810	760 ～ 960	16 ～ 22	24 ～ 32	190 (70)

Table 3. Improve the material of piston

Condition monitoring system for reciprocating compressor

The original condition monitoring system could monitor only frame & crosshead vibration and simple process conditions (Suction & differential pressure, discharge temperature). Root-cause diagnosis could not be done due to the limited system.

Type of Measurement	Original	Recommended
Frame Vibration	O	O
Crosshead Vibration	O	O
Rod Position V	O	O
Rod Position H	X	O
Cylinder Pressure	X	O
Multi-Event KPH	X	O

Legend: O = present. X = not present

Table 4. Instrumentation List for improvement

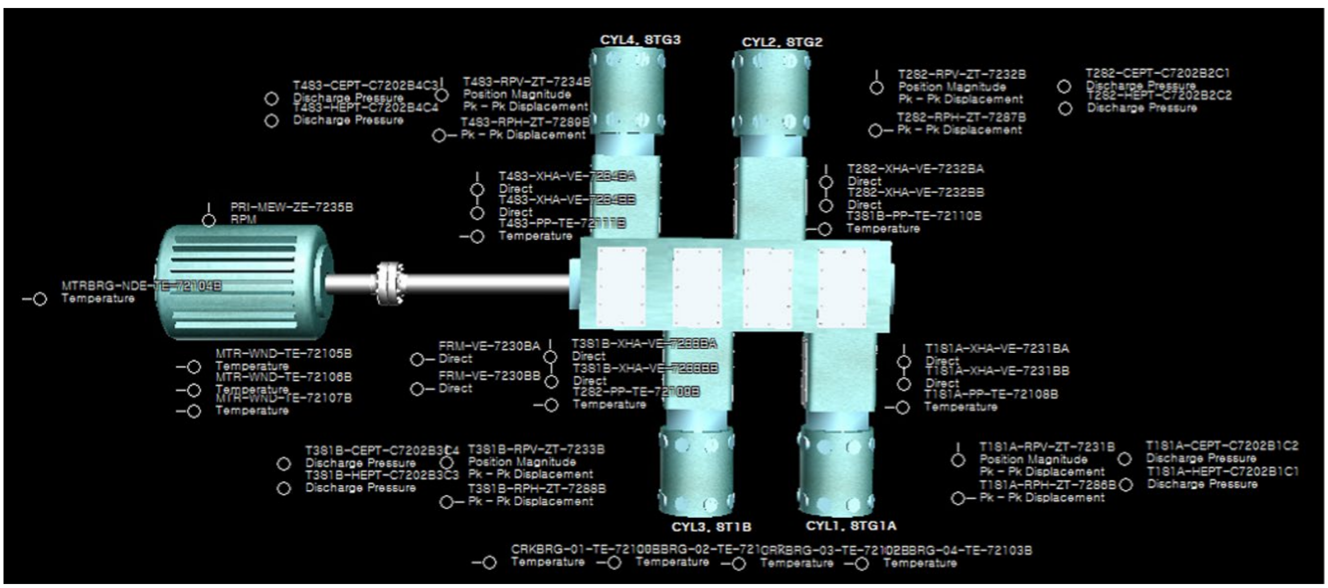


Figure 12. Machine Diagram in Bently Nevada System 1

A permanent reciprocating compressor monitoring and diagnosis system was recommended. It included measuring and logic for installed cylinder pressure indicators, dual plane rod position and multi-event-wheel (MEW) key phasor. The corresponding diagnostic software, Bently Nevada System 1, allows precision diagnosis to be performed through P-V diagram analysis, and monitoring compressor events and vibration per each degree of crank angle.

Below are the advanced diagnostic variables enabled in System 1 software on a fully instrumented reciprocating compressor with cylinder pressure transducers and MEW Keyphasor:

- Discharge Volumetric Efficiency
- Suction Volumetric Efficiency
- Indicated Horsepower
- Adiabatic Discharge Temperature
- Discharge Capacity
- Suction Capacity
- Median Capacity
- Adiabatic Median Capacity
- Flow Balance
- Adiabatic Flow Balance
- Power to Median Capacity
- Indicated Clearance Volume
- Discharge Power Loss
- Suction Power Loss

Based on the review, it was determined that the maximum pressure inside the chamber tended to increase over normal values whenever a foreign substance entered the chamber, and subsequently deposited or built up around the discharge valve, preventing the valve from operating properly. Therefore, it was postulated the effective compression ratio was higher than typical ratio of discharge pressure to suction pressure due to the stiction effect (sticky valves), which in turn resulted in more heat of compression until the sticking discharge valves opened.

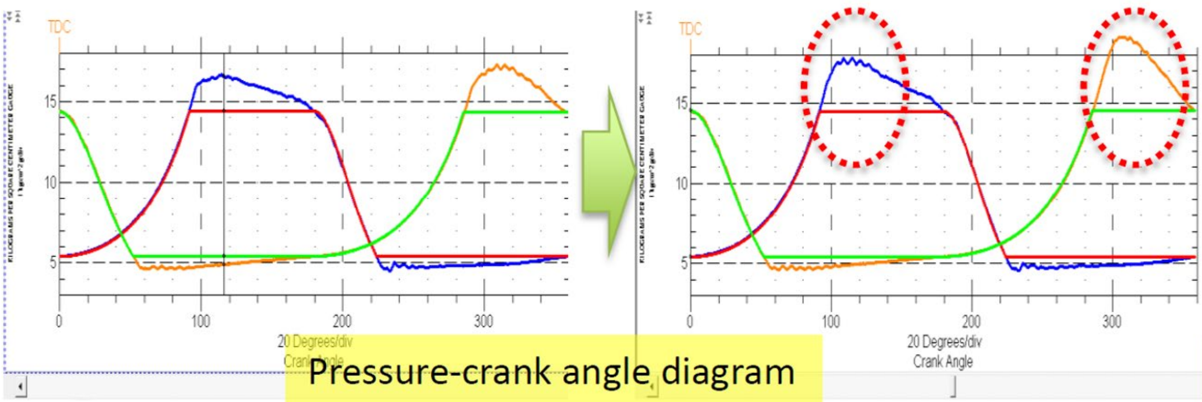


Figure 13. Determine valve maintenance timing

Based on Bently Nevada's recommendations and its technical review, rod position proximity probe transducer pairs and a cylinder pressure transducer at each chamber were newly installed to verify piston rod behavior and valve condition. Before this improvement, the available quantitative data was not enough to make an accurate assessment. With the enhancement to online condition monitoring parameters, it was demonstrated that chamber pressure measurements could give rich information in terms of compression performance as well as valve condition.

Outcome

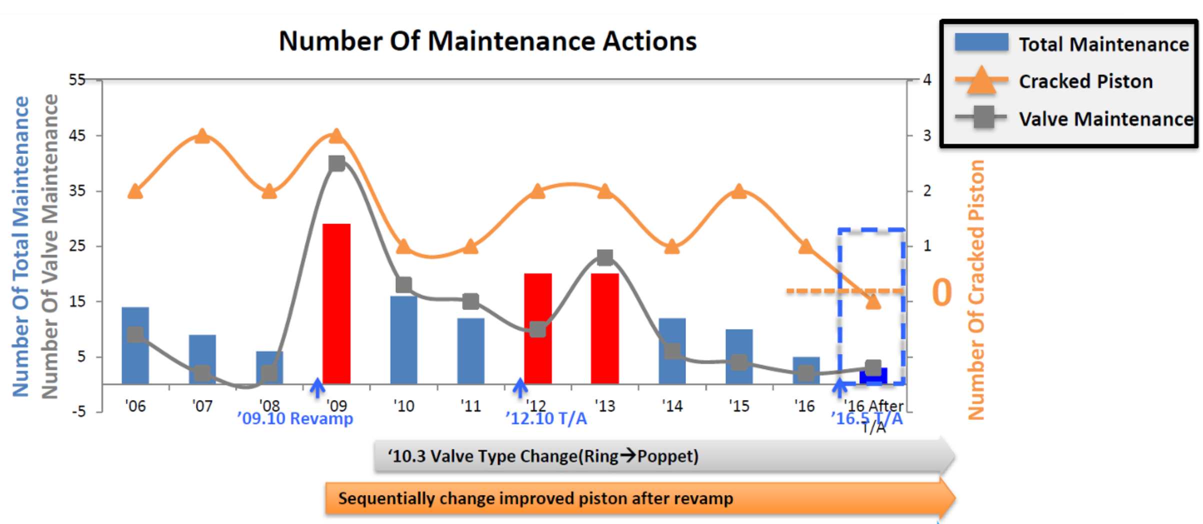


Figure 14. Outcome of the improvement

Soon after unit revamping in 2009, maintenance costs on these three compressors increased over 30 times due to the abovementioned process and mechanical problems. Through the condition monitoring improvement in 2016, the unit saw a reduction to just four maintenance incidents per year and zero cracked pistons. Those are the lowest numbers for the last 10 years, an outstanding outcome which can be attributed to the successful and collaborative cross-discipline efforts.

For this reciprocating compressor in CCR reformer process, the following considerations were key to the successful reliability improvement outcome:

Process

- Optimize operating condition to minimized liquid carry-over.
- Purge the piping system to reduce catalyst of green oil after turn-around.

Mechanical design

- Based on the improvement, a piston with higher strength of material was needed in case foreign substance come in.
- The ring-type valve was not strong enough when external foreign substances came in.

Condition monitoring

- Ability increased to discuss with quantitative data which came from System 1 and process data. The calculated variables due to the pressure measurement give plenty of information for each throw on the machine which was able to determine a corrective action to take.
- Also, pressure monitoring in System 1 gave an exact timing to do maintenance for the valves using the P-V diagram.

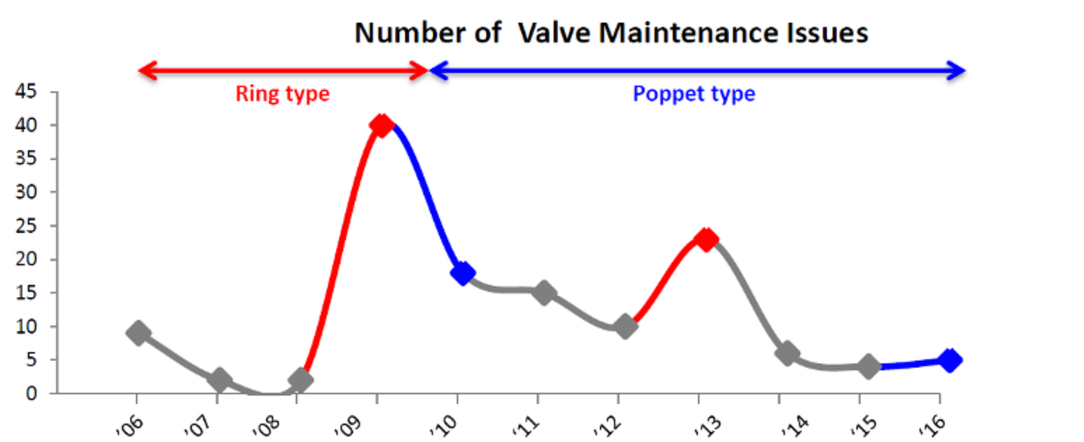


Figure 15. Outcome of valve replacement

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