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Full Length Article

# Updating temperature monitoring on reciprocating compressor connecting rods to improve reliability

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ABSTRACT

In recent years, formerly depleted domestic oil fields have become producers once again through tertiary oil recovery. In tertiary oil recovery, water and Carbon Dioxide ($CO_2$) are alternatively injected into reservoirs through injection wells. This raises the field pressure and forces oil to producing wells where it is then pumped to a storage tank referred to as a battery. This paper is focused on an operating division in the Permian Basin (USA). The $CO_2$ is acquired from underground domes in Colorado and then transferred through pipelines to oil fields in West Texas and New Mexico.

The compressors are used to move $CO_2$ and boost the gas to the required field pressure, usually around 2,200 psig. Reciprocating compressors are flexible and able to handle wide capacity and condition swings, offer an efficient method of compressing almost any gas composition in a wide range of pressures and have numerous applications and wide power ratings. This makes them a vital component in various industrial facilities. Condition monitoring of critical rotating machinery is widely accepted by operators of centrifugal compressors. However, condition monitoring of reciprocating machinery such as compressors and internal combustion engines has not received the same degree of acceptance. This paper examines the reliability impact as a result of upgrading the temperature monitoring devices on the connecting rods of electric driven reciprocating compressors. A cost analysis is also presented to demonstrate that the upgrade in hardware and software will eventually yield a saving in the operating cost.

## 1. Introduction

In recent years, formerly depleted domestic oil fields have become producers once again through tertiary oil recovery. In tertiary oil recovery, water and Carbon Dioxide ($CO_2$) are alternatively injected into reservoirs through injection wells. This raises the field pressure and forces oil to producing wells where it is then pumped to a storage tank referred to as a battery. The $CO_2$ tertiary recovery business was built using reserves found and depleted decades ago during the oil boom that ended in the early 1980s [1]. Companies have injected 10.8 trillion cubic feet of $CO_2$ since the 1970s to raise the yield from oil fields by some 650,000 extra barrels per day, more than 10 percent of daily US total production [2]. This paper is focused on an operating division in the Permian Basin (USA). Currently, 67 of the nation's 127 $CO_2$ tertiary oil recovery projects are located in the Permian Basin [3]. The $CO_2$ is acquired from underground domes in Colorado and then transferred through pipelines to oil fields in West Texas and New Mexico (see Fig. 1). The new and specialized use for $CO_2$ in the upstream oil and gas industry has created a need for compressor stations in the field to handle the gas [4].

Reciprocating compressors are the dominant style of compressor utilized due to their capacity control which allows them to adapt to changes in flow and pressure easily. The compressors are used to move $CO_2$ and boost the gas to the required field pressure, usually around 2200 psig. Reciprocating compressors are flexible and able to handle wide capacity and condition swings, offer an efficient method of compressing almost any gas composition in a wide range of pressures and have numerous applications and wide power ratings. This makes them a vital component in various industrial facilities. Condition monitoring of critical rotating machinery is widely accepted by operators of centrifugal compressors. However, condition monitoring of reciprocating machinery; such as compressors and internal combustion engines, has not received the same degree of acceptance. This paper examines the reliability impact as a result of upgrading the temperature monitoring devices on the connecting rods of electric driven reciprocating compressors.

In reciprocating compressors, pistons are moved in a reciprocating action to compress gas. They can be arranged in a single or double acting design. In the double acting configuration,

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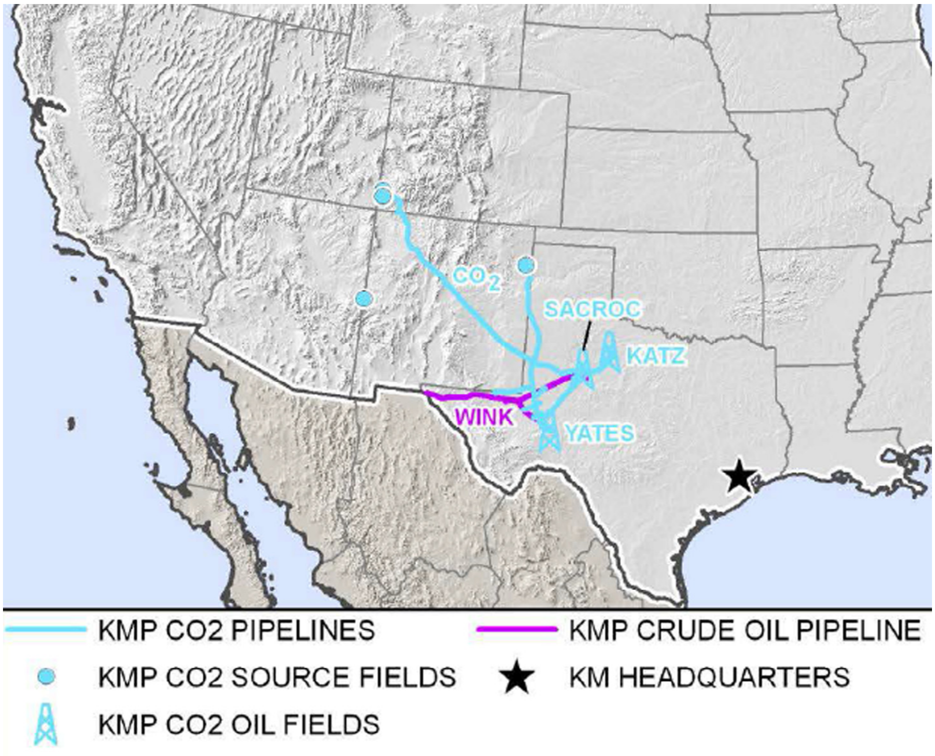


**Fig. 1.** KM HQ and KMP locations.

compression occurs on both sides of the piston during both the advancing and retracting stroke [5]. In a reciprocating compressor, the oil flows from the main bearing through a passage in the crankshaft to the crank pin bearing. It then flows from the crank pin bearing through a rifle-drilled hole in the connecting rod to the crosshead bearing. The crosshead bearing is the last point of lubrication. The load on the crosshead bearing depends on the gas pressure in the cylinder and the inertia force of the reciprocating parts [6].

The dynamic piston load in double acting cylinders changes direction from compression and tension. The change in direction creates clearance between the crosshead bearing and crosshead pin which is the point of lubrication. A lack of direction change starves the crosshead bearing for oil and heat is generated between the crosshead bearing and the crosshead pin. The heat has the potential to seize the pin and the bearing, causing a catastrophic failure. The lack of change is referred to as a lack of reversal [6]. The crosshead pin transfers the load from the connecting rod to the piston. The deformation that it undergoes during operation must be considered so it does not have surface contact with both simultaneously [7].

A guideline is that reversal must occur for at least fifteen degrees of rotation and have a magnitude greater than three percent of the loading in the opposite direction [8]. The rod load by API definition is not actually a rod load, but a pin load. It should also be noted that different OEMs evaluate rod loads differently [9]. All operating cases, such as low suction pressures and part-load steps, should be carefully studied to ensure rod reversal is sufficient for long term reliability [10]. A non-reversing load can occur when an application contains slow speed operation, single acting head end operation and low volumetric efficiencies [11]. In most reciprocating compressors, the maintenance costs for valves, packing and rings amount to approximately 65 percent of the overall maintenance budget [12]. However, what is often overlooked is the effect leaking valves and rings have on the dynamic forces of the compressor which can reduce the rod reversal and cause catastrophic failure of the crosshead bearing and pin [13].

Most common reasons for unscheduled shutdowns are: broken sealing elements of valves (about 36%), faulty pressure packing (about 18%) and piston rings (about 7%) [14,15]. Monitoring systems enable condition-based maintenance for detecting abnormal behaviors pointing to faults or to system failures. Several papers have been published about valve fault (i.e., leaking valve) detection in reciprocating compressors [14,15]. Condition monitoring can be based on measurements of various physical states: vibration, flow rate, power, position, temperature, and pressure. The data required for diagnostic evaluation depend mainly on the types of faults expected and observed. Pichler et al. [15] have presented vibration analysis and pV diagram analysis and Pichler et al. [14] have described pV diagram analysis for early detection of cracked or broken valves.

One of the methods to detect non-reversal is temperature monitoring of the connecting rod bearings and this article deals with the temperature monitoring. However, the movement between the connecting rod and compressor frame makes it challenging to make a temperature measurement on the crosshead pin bearing [16]. Eutectic probes are characterized as an offline solution that is unable to provide any quantitative information about the bearing temperature. They provide only an alarm or shutdown indication with no temperature data to support corrective action or indicate false alarm. Radar-wireless measurement of bearing temperatures uses a sensor in direct contact with the bearing shell to provide fast, accurate, real-time continuous temperature monitoring. It provides a constant indication of a potential issue and justification for an emergency shutdown [17].

The compressors currently utilize eutectic temperature sensors in the connecting rods. Often compressors have been saved by shutdowns due to eutectic or “turkey popper” temperature devices in connecting rod bearings [18]. The sensors use a fusible eutectic material that is designed to fail at a designated temperature, in this case 200 °F. The fuse rod threads into a thermowell in the connecting rod parallel to the bore of the sleeve bearing in the connecting rod. When the fuse rod fails under spring tension it trips a

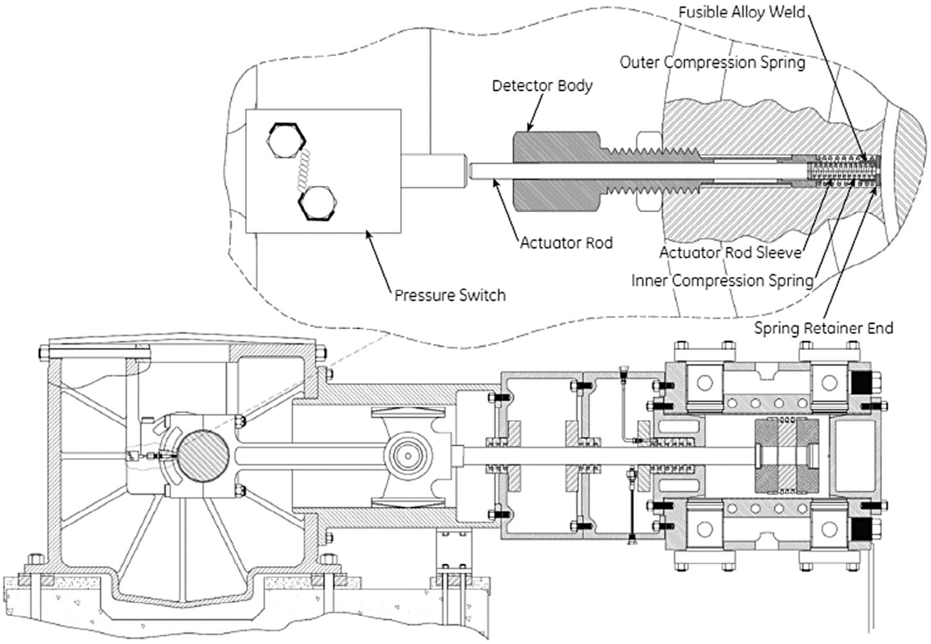
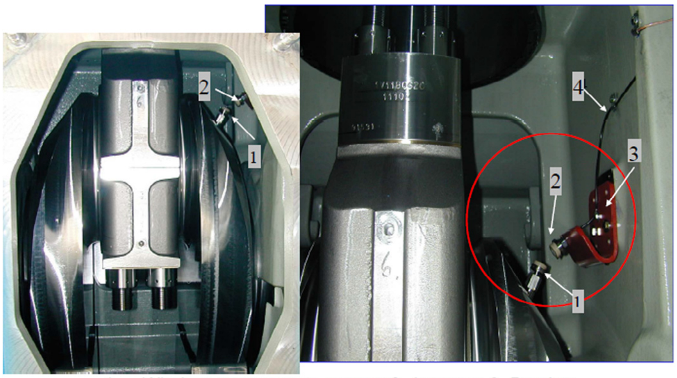


**Fig. 2.** Cross section diagram.

pneumatic switch and the compressor is shutdown (see Fig. 2). Due to the design, the devices cannot be recalibrated and even testing requires replacing the fuse rod. For this reason, the fuse rods are replaced annually [19]. The operators have no advance warning of an issue; detection occurs only at the point the unit shuts down from a fuse rod failure/trip.

The upgraded temperature sensors utilized in this project consist of a wireless measurement system based on wireless radar technology without the need of an external power source. A wireless sensor replaces the eutectic device in the connecting rod's thermowell. An antenna replaces the pneumatic switch and receives a signal from the wireless sensor every time it passes, once per revolution (see Fig. 3). The processing unit software calculates the temperature and transmits it to the supervisory control and data acquisition (SCADA) system [20]. The SCADA system can trend the temperatures in real time with low level, high level and differential alarms created to provide operations an early warning. This affords operations critical information needed to make the decision to shut down or remain running until maintenance personnel are on-site.



1. Wireless temperature sensor; 2. Antenna; 3. Bracket
4. Antenna coaxial cable

**Fig. 3.** Wireless configuration.

After the initial installation of the wireless temperature monitoring system, the eutectic device shutdown point of 200 °F will be used as the high level alarm. The low level alarm will be determined after baseline temperature data are collected and trended over time. Temperature differential alarms will be determined once baseline deviations can be established and analyzed. After the accumulation of connecting rod temperature data, additional SCADA values already being collected can potentially be utilized to normalize the connecting rod temperature data. Existing data collected includes capacity load steps, crankshaft bearing temperatures, cylinder and frame vibration, and the motor's temperature, amperage and vibration. A series of equations can be created for connecting rod temperature alarms to consider the existing SCADA values collected.

A design, cost estimate and reliability analysis were completed to determine the impact of updating the temperature monitoring on the connecting rods of the reciprocating compressors. The fourteen compressors included in the project are located throughout six compressor stations in Southwestern Colorado. The upgrade includes temperature modules capable of taking readings from installed transmitters mounted on each connecting rod. In this project the total quantity of temperature measurements upgraded will be 56. Each of the existing eutectic temperature sensors on each connecting rod will be replaced on all compressors. The temperature module will provide a wide variety of critical process data for monitoring, trending, and alarming. At completion, the system will increase the operability and reliability of the units. The cost for the upgrade of all compressors including installation, commissioning and training is approximately $276,200. The expected improvement in reliability is estimated to add thirteen production hours per year.

The project includes all elements of the system. The field machining necessary to route the temperature transmitter cables out of the crank case, as well as the installation and loop checks of all instrumentation have also been included in the estimate. In addition, modifications to the existing human machine interface (HMI) and SCADA system to incorporate the additional monitored parameters will be completed (see Fig. 4). A set of updated drawings and all necessary training for operators and technicians to use and

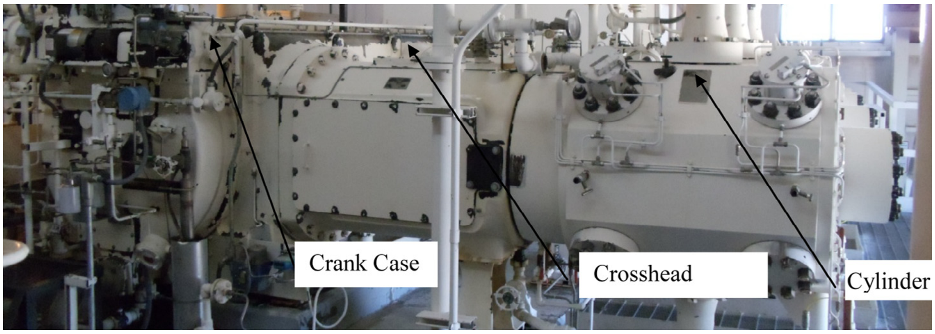


**Fig. 4.** Equipment photographs.

maintain the system will be completed (see Fig. 5 for a schematic diagram).

## 2. Discussion of the project

This project will be installed on reciprocating compressors transferring $CO_2$ for tertiary oil recovery. There are six compressor stations with fourteen total compressors located in mountainous terrain in Southwestern Colorado that source the $CO_2$. The stations are manned only during the day shift and most stations require a thirty minute or longer drive after turning off the last paved road in the area. The stations are relatively climate controlled, and the compressors currently have minimal condition monitoring implemented, which provides only the basic alarms and shutdowns to protect the equipment from catastrophic failures. The project will update the temperature monitoring on the connecting rods of the compressors. In addition, the system will provide the control room with real time temperature data on each connecting rod. The compressor stations have no excess capacity, so the compressors are expected to operate continuously except for planned preventive maintenance (PM) outages. Table 1 provides the unit details.

## 3. Integration details

After normal working hours, the existing system is monitored by a SCADA control room located in the closest town to the compressor stations. When a compressor shuts down, the SCADA operator must contact the on-call operator to troubleshoot, repair and place the unit back into service. This usually takes several hours to complete depending on the specific conditions that caused the issue.

## 4. Reliability

The RBD (Reliability Block Diagram) used for reliability analysis of this complex system is shown in Fig. 6 below. Although each unit has been given its own reference designator, all eutectic devices are identical and have the same reliability. Compressors and Compressor Stations also have unique reference designators. Compressor Stations at the six locations are denoted CS, Compressors as C, and eutectic devices as E. The eutectic devices are in series within each compressor and multiple compressors are in parallel at any given station that has more than one compressor. The dashed lines between compressor stations attempt to indicate that each location operates independently. A failure in any given eutectic device results in a failure in the compressor; however, redundancy is designed in each compressor station location having more than one compressor, because the compressors are in parallel.

The eutectic devices are at the component level, and must perform continuously for 1 year, according to the planned rod replacement. The devices are non-repairable, and the system is a time dependent based system. A best estimate of the eutectic device failure rate was obtained from the observation data in Table 2 consisting of all failures over a designated time period.

From Table 2, the time for all eutectic devices to fail was 4597 days. There were a total of 26 failures and an average of 1.48 downtime hours per failure. It should be noted that eutectic devices

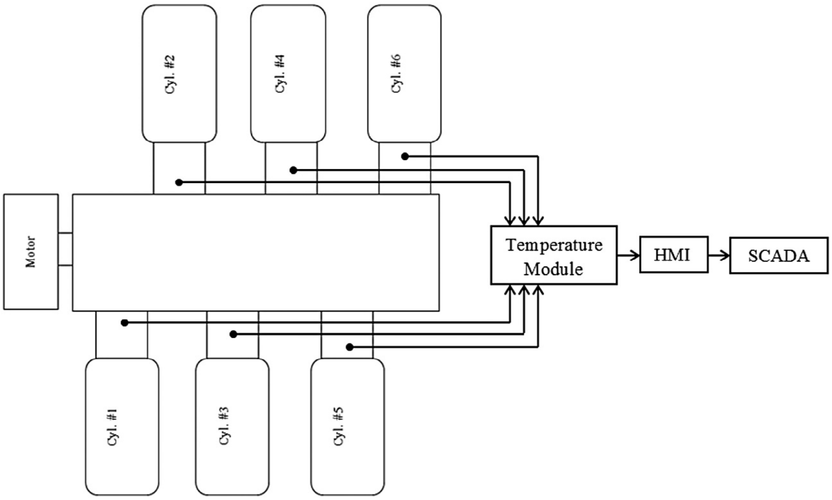


**Fig. 5.** Schematic diagram.

**Table 1**
Unit details at six locations.

| Station | Unit | Cylinders | Comments |
|---|---|---|---|
| Doe Canyon | K320A | 3 | 2 Compressors, 3 devices each |
| | K330B | 3 | |
| Goodman Point | K320A | 3 | 2 Compressors, 3 devices each |
| | K320B | 3 | |
| Hovenweep | K101A | 4 | 4 Compressors total |
| | K101B | 4 | 3 Compressors have 4 devices each |
| | K101C | 4 | 1 Compressor, 6 devices |
| | K101D | 6 | |
| Moqui | K320 | 4 | 1 Compressor, 4 devices |
| Sand Canyon | K101 | 4 | 1 Compressor, 4 devices |
| Yellow Jacket | K101A | 4 | 4 Compressors total |
| | K101B | 4 | 3 Compressors have 4 devices each |
| | K101C | 4 | 1 Compressor, 6 devices |
| | K101D | 6 | |
| | | *56* | *Total eutectic devices* |

operate continuously for one year and are replaced annually. If a eutectic device fails prior to completing one year, it is replaced. In Table 2, for instance, a device failed in 581 days (i.e., in the second year), this means there was no failure (hence no downtime) in the first year. The device was replaced with a new one on completing the first year. The new device failed in the second year making the failure causing downtime in 581 days. The best estimate of MTTF (Mean Time To Failure) given that the eutectic devices are non-repairable items was calculated as explained in Reference 21. Failure here refers to the failure which causes downtime. Annual replacement of the devices due to preventive maintenance was not considered causing downtime.

T = total operating time = 4597 days = 110,328 hours
c = number of failures during time T = 26
r = c if the operating time is failure terminated (this is the present case) or c + 1 otherwise

$$MTTF_{Best} = \frac{T}{c} \cong 4243.38\,\text{hours} \tag{1}$$

Likewise, the best estimate of the eutectic device failure rate is:

$$\lambda_{Best} = \frac{1}{MTTF_{Best}} \cong 0.000235661\,\text{per hour} \tag{2}$$

The 90% upper and lower confidence estimates are as follows, respectively:

$$\lambda_{0.90} = \frac{\chi^2_{0.90,2r}}{2T} \cong 0.00028641867885\,\text{per hour} \tag{3}$$

$$\lambda_{\_0.90} = \frac{\chi^2_{0.10,2c}}{2T} \cong 0.0001708541803\,\text{per hour} \tag{4}$$

Hence, there is 80% confidence that the failure rate of the eutectic device failure rate is between 0.0001708541803 and 0.00028641867885. The reliability of the eutectic devices, having a constant failure rate, using the upper 90% confidence estimate, is found to be approximately 0.081347 for a 1 year mission as:

$$R(t) = e^{-\lambda t} \cong 0.081347300737168 \tag{5}$$

Using the best estimate, the reliability is found to be approximately 0.126896:

$$R(t)_{Best} = e^{-\lambda t} \cong 0.126895627642149 \tag{6}$$

Either reliability prediction estimate for the eutectic device is staggering as compared to that of the expected reliability of

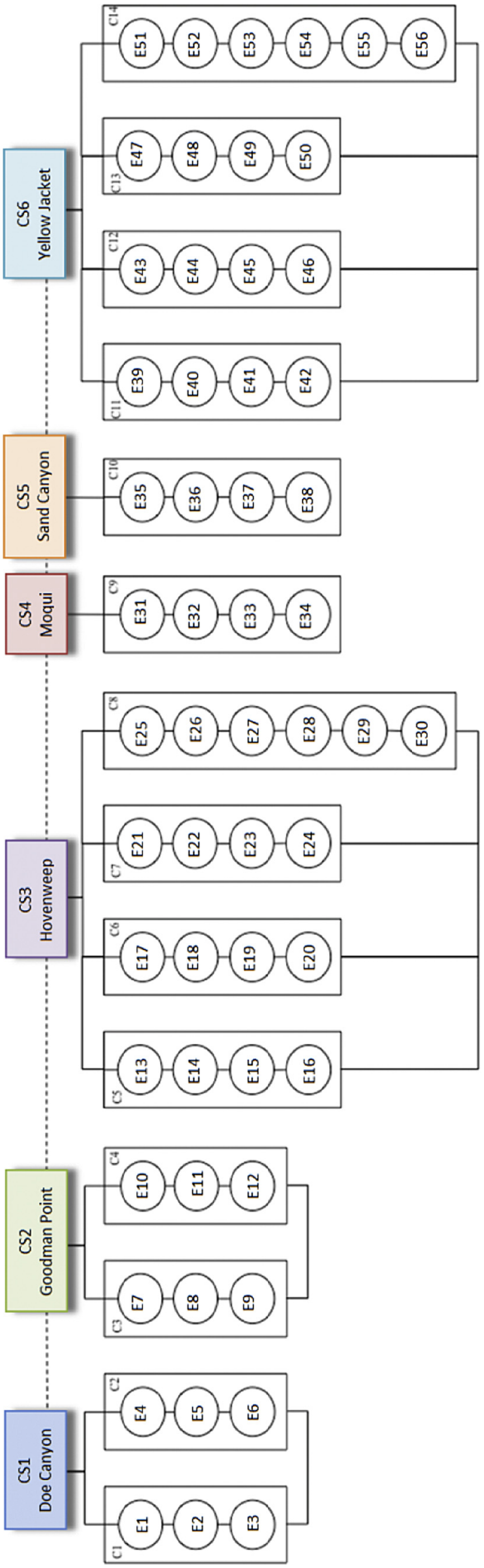


**Fig. 6.** Reliability block diagram.

**Table 2**
Failure observation data for best estimate.

| Location | Time (days) | Failure | Downtime (hours) |
|---|---|---|---|
| Yellow Jacket | 0 | 1 | 1.5 |
| Yellow Jacket | 0 | 1 | 1.25 |
| Hovenweep | 65 | 1 | 1.5 |
| Hovenweep | 66 | 1 | 1.35 |
| Hovenweep | 124 | 1 | 1 |
| Hovenweep | 307 | 1 | 1.25 |
| Moqui | 581 | 1 | 1.24 |
| Hovenweep | 653 | 1 | 1.63 |
| Moqui | 669 | 1 | 1.96 |
| Sand Canyon | 690 | 1 | 0.9 |
| Sand Canyon | 693 | 1 | 1.25 |
| Sand Canyon | 746 | 1 | 2.16 |
| Sand Canyon | 782 | 1 | 1.17 |
| Yellow Jacket | 858 | 1 | 1.71 |
| Yellow Jacket | 972 | 1 | 0.91 |
| Yellow Jacket | 1036 | 1 | 1.19 |
| Hovenweep | 1070 | 1 | 1.75 |
| Yellow Jacket | 1248 | 1 | 1.26 |
| Hovenweep | 4358 | 1 | 1 |
| Hovenweep | 4358 | 1 | 3.25 |
| Yellow Jacket | 4390 | 1 | 1.28 |
| Yellow Jacket | 4401 | 1 | 1.67 |
| Hovenweep | 4446 | 1 | 2 |
| Hovenweep | 4471 | 1 | 1 |
| Hovenweep | 4538 | 1 | 1.19 |
| Hovenweep | 4597 | 1 | 2 |
|  | 4597 | 26 | 1.48 |

wireless devices, anticipated to be near 1; a reliability of 0.999999 was used for wireless device reliability analysis herein. Please note that being a future upgrade, there is no field observation data pertaining to the failure rate of the wireless devices; manufacturer specifications of the device reliability must be utilized for analysis and comparison purposes. The wireless device will provide quantitative data and not be capable of shutting down a compressor. Given the expected wireless device reliability estimate, we ascertain the failure rate to be:

$$\ln(0.999999) = -\lambda t \tag{7}$$

$$\lambda = \frac{-\ln(0.999999)}{t} \cong 0.00000000011416 \ \mathit{failures/hour}$$

The devices are in series for each compressor. Therefore, the subsystem reliabilities (at the compressor level) will be $R^3$, $R^4$, and $R^6$ for compressors with 3, 4, or 6 devices, respectively, since all eutectic devices are identical and have the same reliability (best estimate is used) and all wireless devices will be the same identical unit, having equal reliabilities. For example, the compressor reliability containing 3 devices is estimated as follows for the eutectic and wireless devices:

$$R_{sys} = R_1 R_2 R_3 = R^3 \tag{8}$$

To simplify calculations, the remaining of the compressor reliability estimates has been computed with the aid of MS Excel; the comparison results of reliabilities of the compressors using wireless versus eutectic devices are provided in Table 3:

**Table 3**
Compressor estimated mission reliabilities: eutectic versus wireless devices.

| Device type | Compressor type |  |  |
|---|---|---|---|
|  | 3 Devices | 4 Devices | 6 Devices |
| Eutectic | 0.002043337 | 0.000259291 | 0.000004175225622 |
| Wireless | 0.999997 | 0.999996 | 0.999994 |

Clearly, the wireless devices are estimated to have a much better reliability at the compressor/subsystem level than the eutectic devices.

At the compressor station subsystem level, CS4 (Moqui) and CS5 (Sand Canyon) have only one compressor each; their reliability will be equal to their compressor. The remaining compressor stations have their compressors in parallel. CS1 (Doe Canyon) and CS2 (Goodman Point) have the same setup, as do CS3 (Hovenweep) and CS6 (Yellow Jacket). CS1 and CS2 are both composed of two compressors containing three devices each; their compressor station subsystem level reliability estimates are:

$$R_{CS1,CS2} = 1 - \left(1 - R(t)_{3device}\right)^2 \tag{9}$$

The reliability estimate for CS3 and CS6 is as follows:

$$R_{CS3,CS6} = 1 - \left(1 - R(t)_{4device}\right)^3 \left(1 - R(t)_{6device}\right) \tag{10}$$

MS Excel was again used to simplify the calculations and tabulate the data; the results are provided in Table 4.

The compressor station level subsystem reliability estimates continue to look much better for the wireless devices than for the eutectic ones. The reliability estimate for CS3 and CS6, with the use of the wireless devices, is nearing optimal.

Finally, since the compressor stations operate independently, the overall system reliability estimate was calculated as follows:

$$R_{sys} = R_{CS1} R_{CS2} R_{CS3} R_{CS4} R_{CS5} R_{CS6} = R_{CS1}^2 R_{CS3}^2 R_{CS4}^2 \tag{11}$$

Once again, MS Excel was utilized for calculations and to tabulate the data; the results of the reliability estimates at the system level, with eutectic versus wireless devices, are provided in Table 5.

The wireless devices are estimated to have much better reliability than the eutectic devices at the system level; the decision for performance purposes is clear.

## 5. Hardware and software specification and justifications

All hardware and sensors are being sourced from Kongsberg Maritime. The delivery time for the materials is three to six weeks [20].

- Wireless temperature sensors for connecting rods – There are a total of 56 sensors required; one per connecting rod. They will send a temperature measurement once per revolution to the temperature module. Includes cables, grommets, connectors, etc. Cost = *$154,000*
- Temperature module – Monitors connecting rod temperatures, contains the alarm set points, and provides data to the HMI. Cost = *$96,600*

**Table 4**
Compressor station subsystem estimated reliabilities (eutectic versus wireless devices).

| Device type | CS1, CS2 | CS3, CS6 | CS4, CS5 |
|---|---|---|---|
| Eutectic | 0.004082499 | 0.000781842 | 0.000259291 |
| Wireless | 0.999999999991000 | 1.000000000000000 | 0.999996 |

**Table 5**
System level reliability estimate: eutectic versus wireless devices.

| Device type | System reliability |
|---|---|
| Eutectic | 6.84957E–19 |
| Wireless | 0.999992 |

**Table 6**
Estimate details.

| Description | Cost |
|---|---|
| Drawing updates | \$800 |
| Hardware and software | \$256,200 |
| Field machining | \$5,600 |
| SCADA modifications | \$5,600 |
| Installation and commissioning | \$5,600 |
| Training | \$2,400 |

- Existing HMI – Programming changes will be required to utilize the information available from the temperature module software. The HMI was installed in 1996.
  Cost = *\$11,200*

## 6. Cost factor estimates

The project costs will consist of drawing updates, hardware, software, field machining, installation, SCADA modifications and training. The installation will be completed in conjunction with an annual PM so lost production will not be a consideration. The total project is estimated to be \$276,200. Table 6 shows details of the estimate.

The supply of $CO_2$ to the producing field can be directly related to oil production. Based on current reservoir pressures the following economic estimates can be made.

- 1 MMSCFD $CO_2$ = 50 bbl oil per day
- 1 bbl oil = \$75
- Compressor capacity = 132 MMSCFD $CO_2$
- Compressor downtime cost per day = *\$495,000*
- Compressor downtime cost per hour = *\$20,625*

The Infor EAM system was utilized to query the maintenance history from May 2010 thru October 2013 for unplanned downtime by failure codes that indicate eutectic device failures. The annual average downtime that is expected to be eliminated is thirteen hours and is considered a conservative estimate as improper failure coding cannot be captured. Based on the current economic estimates, the annual operating cost savings as a result of increased run time are \$268,125. Table 7 shows the breakdown of failure codes. The return on investment (ROI) or payback period [22] is estimated as follows:

ROI = Project cost ÷ Annual operating cost saving
ROI = 12.36 months.

## 7. Potential problem areas

Integrating the new technology into an organization is a challenge that must be addressed. As with any new technology, there will be a process of learning both the hardware and software. Training employees to use and maintain the new system, as well as its benefits, will be important to ensure success. Additional calibration of instrumentation will need to be included during PM shutdowns. It will be difficult to further extend outages as production is at maximum capacity, and there are no spare units. The additional sensors and cables mounted on the equipment will require plant millwrights to be cognizant while working on the units so as not to cause damage.

## 8. Recommendations and conclusions

After the system has been in service for one full year, a follow-up reliability study and economic analysis must be performed. The study will examine the same fault codes to determine the actual reliability improvements versus the projected improvements as well as the actual operating costs saved versus the projected savings. In addition, the operators must be consulted to assess the benefits of remote access to real-time compressor data and calculated parameters.

Maintenance costs of reciprocating compressors are approximately three and a half times greater than centrifugal compressors. The worldwide operating horsepower of reciprocating compressors is three times the horsepower of centrifugal compressors [23]. Reciprocating compressor operators must achieve the level of

**Table 7**
System failure data.

| Location | Date | Name | Remarks | Failure | Dwn Hrs |
|---|---|---|---|---|---|
| Hovenweep | 8/19/2013 | K101D | Eutectic failure, cylinder 1 rod bearing – 2.00 hours downtime, minimal impact to deliveries. | 1 | 2 |
| Hovenweep | 7/8/2009 | K101A | Fuse rod replacement on cylinder 3 | 1 | 1 |
| Hovenweep | 5/11/2009 | K101B | Replaced right hand fuse rod on cylinder 3 TG RG JW | 1 | 1.35 |
| Hovenweep | 5/10/2009 | K101C | Replaced right hand side fuse rod on cylinder 4. (TG) | 1 | 1.5 |
| Hovenweep | 6/21/2013 | K101A | Failed eutectic device | 1 | 1.19 |
| Hovenweep | 1/7/2010 | K101B | Replaced AMOT thermostats L.H. R.B. | 1 | 1.25 |
| Hovenweep | 12/19/2010 | K101B | Failed temperature detector | 1 | 1.63 |
| Hovenweep | 2/9/2012 | K101B | High rod bearing temp.; replaced fuse rod | 1 | 1.75 |
| Hovenweep | 12/23/2012 | K101D | Replaced fuse rod | 1 | 1 |
| Hovenweep | 12/23/2012 | K101D | Rod bearing temp, eutectic device failure | 1 | 3.25 |
| Hovenweep | 3/21/2013 | K101D | Failed eutectic device on cylinder 5 | 1 | 2 |
| Hovenweep | 4/15/2013 | K101D | Failed eutectic | 1 | 1 |
| Moqui | 10/8/2010 | K320 | High rod bearing temp; replaced temp detector | 1 | 1.24 |
| Moqui | 1/4/2011 | K320 | Rod temp detector failure | 1 | 1.96 |
| Sand Canyon | 1/25/2011 | K320 | Rod bearing temperature detector failure | 1 | 0.9 |
| Sand Canyon | 1/28/2011 | K320 | Rod bearing temp detector failure | 1 | 1.25 |
| Sand Canyon | 4/27/2011 | K320 | replaced high rod bearing temperature detector | 1 | 1.17 |
| Sand Canyon | 3/22/2011 | K320 | Replaced high rod bearing temp indicators | 1 | 2.16 |
| Yellow Jacket | 3/6/2009 | K101D | Turkey popper cyl#1 motor side | 1 | 1.5 |
| Yellow Jacket | 3/6/2009 | K101A | Replaced turkey popper on motor end S.A. C.O. | 1 | 1.25 |
| Yellow Jacket | 11/3/2011 | K101A | Failed rod bearing temperature detector | 1 | 0.91 |
| Yellow Jacket | 8/5/2012 | K101C | Failed eutectic device | 1 | 1.26 |
| Yellow Jacket | 7/12/2011 | K101D | Rod bearing temp detector failure | 1 | 1.71 |
| Yellow Jacket | 1/6/2012 | K101D | High rod bearing temp detector failure | 1 | 1.19 |
| Yellow Jacket | 1/24/2013 | K101D | Failed eutectic device and multilin lockout | 1 | 1.28 |
| Yellow Jacket | 2/4/2013 | K101D | Failed eutectic device and multilin lockout | 1 | 1.67 |
|  |  |  |  | 26 | 38.37 |

condition monitoring that centrifugal users have implemented for decades. Only after economic analysis proves the benefit of reciprocating compressor and engine online condition monitoring will operators begin to take advantage of the technology that is becoming available. After the demand for the technology increases, the reciprocating compressor and engine users will learn to benefit from the data the same way centrifugal users have for years.

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