"DO AS I SAY"
(THE EFFECT OF THE PROCESS ON TURBOMACHINERY RELIABILITY)

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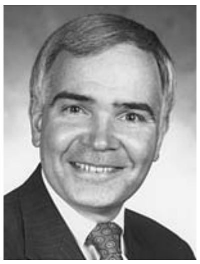

William E. (Bill) Forsthoffer spent six years at the Delaval Turbine Company, as Manager of Compressor Project Engineering, where he designed and tested centrifugal pumps and compressors, gears, steam turbines, and rotary (screw) pumps.

Mr. Forsthoffer then joined the Mobil Research and Development Corporation. For five years, he directed the application, selection, design, testing, site precommissioning, and startup of the Yanbu Petrochemical complex in Yanbu, Saudi Arabia. Following that, he returned to MRDC and established a technical service program for Mobil affiliates to provide application, troubleshooting, and training services for rotating equipment. He left Mobil in 1990 to found his own company, Forsthoffer Associates, Inc., to provide training, critical equipment selection, and troubleshooting services to the refining, petrochemical, utility, and gas transmission industries.

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ABSTRACT

This tutorial examines the primary cause of lower than expected reliability in turbomachines, the effect of the process on machinery component life. Over 95 percent of the rotating equipment installed in any refinery, petrochemical, or gas plant is the dynamic or "turbo" type. Their characteristics are limited energy output and variable flow rate determined by process energy requirements.

INTRODUCTION

The objective of this tutorial is to emphasize the importance of understanding the effect of the process on turbomachinery reliability. This tutorial is intended for all disciplines—operators, machinists, process and reliability engineers. Process condition changes and upsets can and will cause damage and/or failure of all machinery components.

Figure 1 shows a typical centrifugal pump. Figure 2 presents the causes and damage that can occur to any type centrifugal pump depending on its flow rate. A turbocompressor, shown in Figure 3, can experience the same type of damage as a centrifugal pump depending upon the flow rate at which it operates.

The title of this tutorial says it all—"do as I say." This is the message that any process system gives to rotating equipment. The response from the equipment to this command depends upon the type and characteristics of the equipment installed in the process system.

There are two classifications of any type of rotating equipment.

- Positive displacement
- Dynamic turbomachine

The characteristics are shown in Table 1.

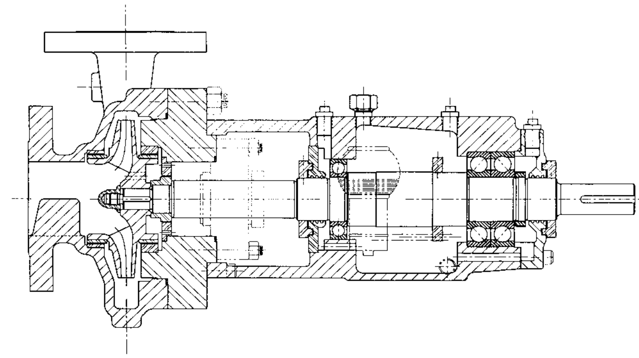


Figure 1. Diagram of Centrifugal Pump.

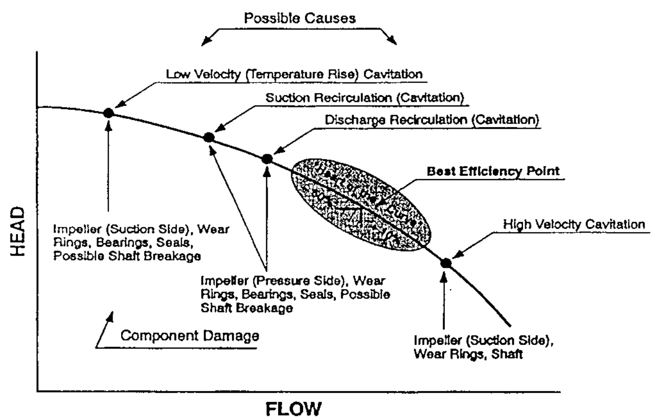


Figure 2. Centrifugal Pump Component Damage and Causes.

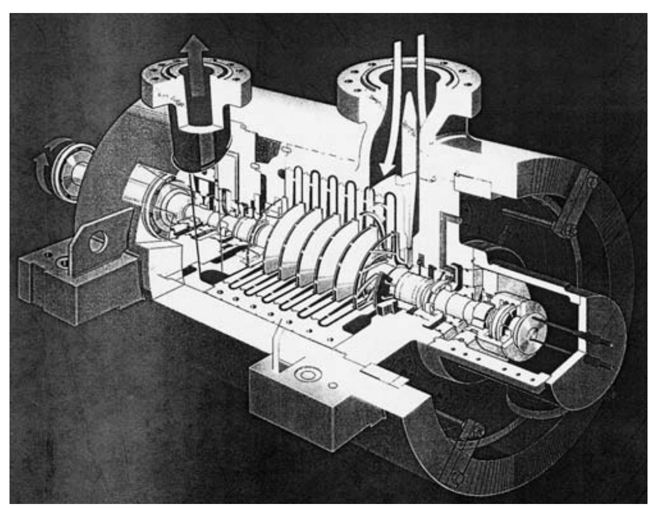
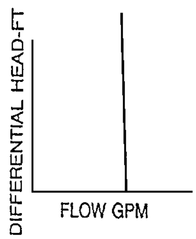
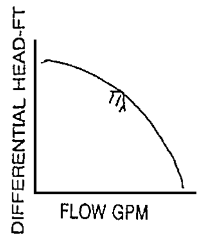


Figure 3. Barrel Compressor Assembly Drawing. (Courtesy Siemans/Demag Delaval)

Table 1. Positive Displacement Versus Dynamic Machinery Characteristics.

	POSITIVE DISPLACEMENT	DYNAMIC
Definition	Increases pressure by operating on a fixed volume in a confined space	Increases pressure by using rotary blades to increase fluid velocity
Types	Screw, gear, reciprocating	Centrifugal, axial
Characteristics	• Constant volume • Variable differential head • Relatively insensitive to liquid properties • Relatively insensitive to system changes • Not self-limiting	• Variable volume • Constant differential head • Sensitive to liquid properties • Sensitive to system changes • Self-limiting
Characteristic flow vs. differential head curves		

In answer to the command of the process system, positive displacement equipment's response is: "Yes sir or yes ma'am!"

Refer to Table 1 and observe that this answer is possible since positive displacement equipment can produce infinite energy (provided sufficient driver power is available) and is not affected by the density of the fluid in the process. Regardless of process differential pressure, density, and viscosity (within limits) any positive displacement machine will do what the process demands. The action of meeting process system pressure requirements taking fluid density into account is known as the head required by the process.

Figure 4 depicts the process energy or head requirements for a pump or a compressor. In each case, the process requirements are the same, to increase the fluid pressure by 100 psi. However, the density of the fluids is significantly different. As a result, the head required by the process is approximately 370 times greater. By observing this graphic, it is easy to see how a pump can "lose suction" or "vapor lock" if the pumped liquid decides to vaporize.

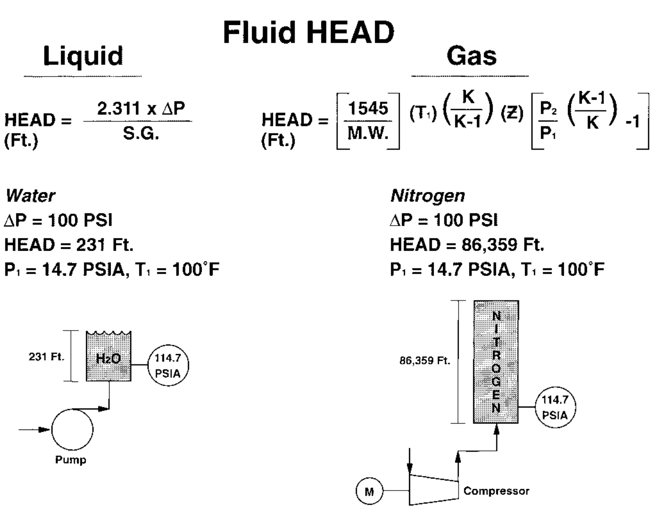


Figure 4. Head Required by the Process for a Pump and a Compressor.

Figure 5 presents an assembly of a positive displacement reciprocating cylinder. Any positive displacement machine (pump or compressor) will continue to deliver essentially the same volume flow regardless of the process system's requirements. Therefore, if a positive displacement machine is installed in the process system, the answer is definitely yes.

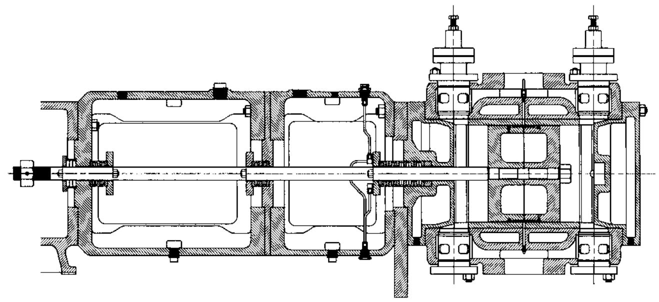


Figure 5. Diagram of a Positive Displacement Compressor Cylinder. (Courtesy Cooper Industries)

Approximately 95 percent of the rotating equipment installed in a typical plant is the dynamic or "turbo" type. The turbo type is favored because it can handle higher flow rates and requires significantly less maintenance than positive displacement equipment if it can meet the requirements of the process. Therefore, the answer that turbomachines give to the process system's demand "do as I say" is: "Maybe."

It will depend on how much maximum energy the turbomachine can produce. Turbomachines produce energy by increasing the velocity of the fluid in the impeller or blades and reducing the fluid velocity in the diffuser or stator vanes. This classification of machinery has a limited energy production and is affected by fluid density (refer again to Table 1).

Figure 6 shows how a turbocompressor impeller generates energy. Therefore, the only way a turbomachine can produce more energy, once it is designed, is a lower flow rate (unless shaft speed or inlet fluid angles are changed).

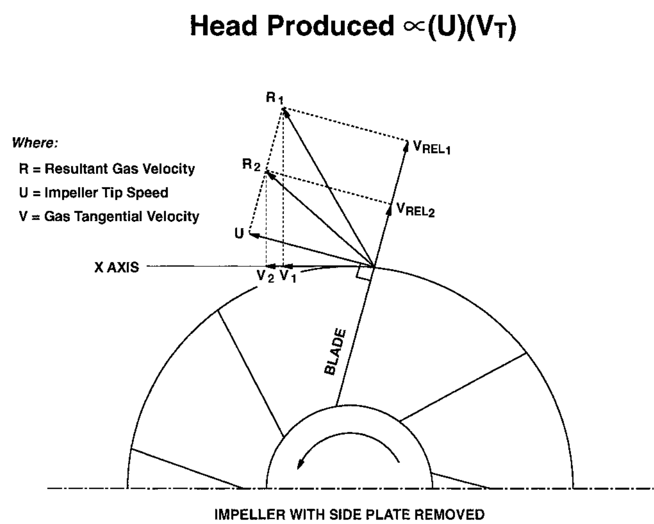


Figure 6. Simplified Turbocompressor Discharge Triangle for Two Flow Cases.

Figure 7 presents a typical head versus flow curve. Also shown in Figure 7 are three different process system head requirements (shown as horizontal lines) that can result from any one or all of the following changes:

- Molecular weight.

- Inlet gas temperature.
- Inlet pressure.
- Discharge pressure.

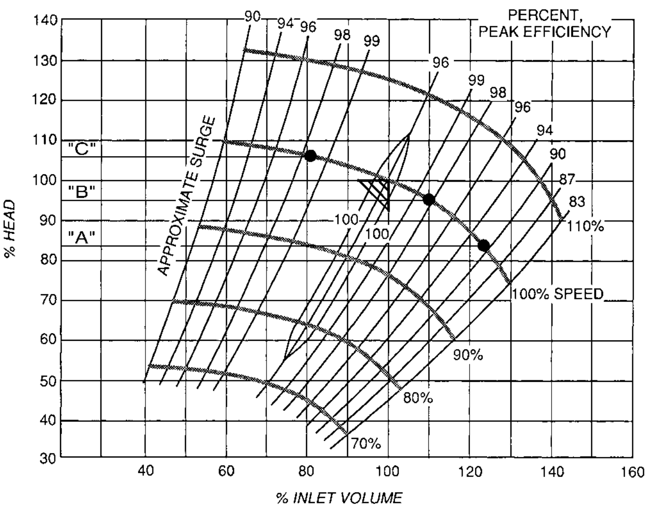


Figure 7. Typical Centrifugal Compressor Head Versus Flow Curve. (Courtesy IMO Industries, Inc.)

It is good to remember that any turbomachine responds to process head (energy) requirements and allows the flow rate to enter the machine that may or may not do what the process system requires.

Any dynamic machine (centrifugal or axial pump or compressor) delivers flow inversely proportional to the process head required. Process flow is very simply, money. Therefore, dynamic machine control philosophies must be developed to maintain a constant flow rate for changing process conditions (head requirements). There are two alternatives:

- Vary the process system head required—most common approach
- Vary the head produced —most efficient approach

Figure 8 shows a typical turbocompressor system where the head required by the process can be regulated by throttling either a suction or discharge valve. Suction throttling is approximately 3 to 5 percent more efficient than discharge throttling depending upon the compressor curve shape. Of course, pumps cannot be suction throttled, since any excessive suction drop can cause vaporization and cavitation. However, many installations use compressor discharge throttling since the initial cost of a smaller throttle valve is less than the larger suction valve. Regardless of the type of throttling, it wastes energy since at the "rated" flow condition, the throttle valve is approximately 70 percent open. Therefore, a constant amount of energy is dissipated across the valve internals.

The most efficient control approach is to vary the head produced by the turbomachine. As was shown in Figure 6, there are two velocities that determine the energy (head) generated by any turbomachine:

- Blade velocity—"Tip velocity or tip speed"
- Fluid velocity—"Relative velocity"

The most common approach is to vary the tip speed by changing the speed of the driver. For turbocompressors and large pumps, a steam or gas turbine is used to provide variable speed capability. In the last 10 years, VFDs—variable frequency electric motors—have gained popularity and should be considered for pump and compressor applications. Figure 9 shows a typical process loop with the variable speed control method.

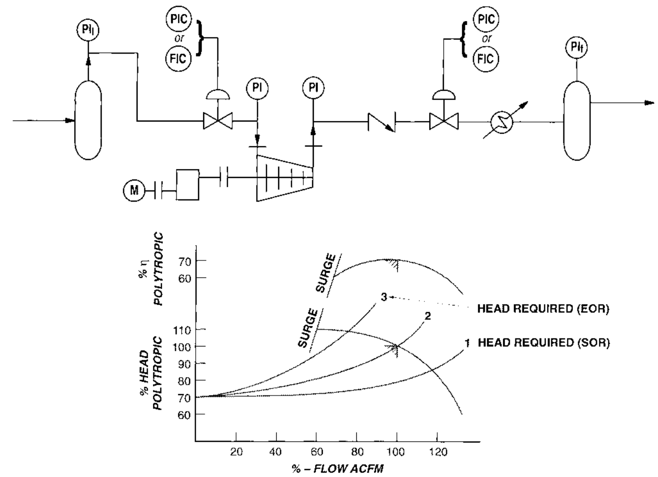


Figure 8. Process Control—Adjusting Head Required.

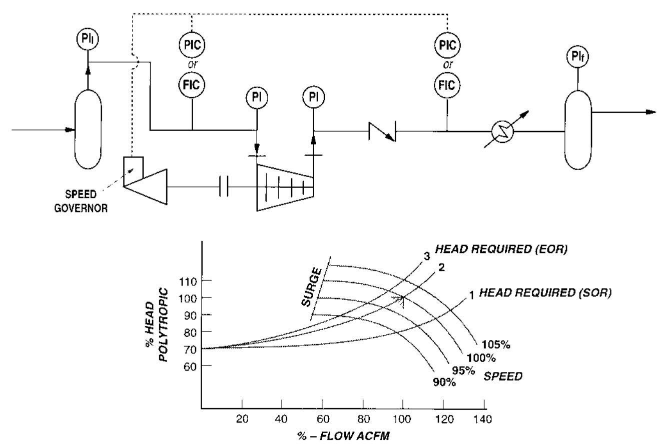


Figure 9. Process Control—Adjusting Head Produced.

Whether the chosen control method is to vary the head required by the process or the head produced by the turbomachine, the set point is determined by a selected process variable:

- Suction drum level (pumps)
- Pressure
- Flow

The selected process transmitter sends a signal to the valve (the variable head required approach) or the driver control (the variable head produced approach).

Having presented the background concerning rotating machinery performance characteristics, the remainder of this tutorial is devoted to understanding the various requirements of an operating process. To meet this objective, a hydrogen compressor recycle loop is examined in the following manner:

- Process unit design review for a "recycle application"
- Process requirements
  - Startup
  - Normal operation
  - Emergency shutdown
  - Manual shutdown
  - Regeneration
- Turbocompressor unit condition monitoring requirements
  - Component condition monitoring

PROCESS OVERVIEW

The function of a recycle compressor is to continuously provide sufficient recycle flow to the reactor to achieve the desired effect of adding recycle gas to the product stream. The ratio of recycled gas to product is known as the recycle ratio. Figure 10 shows a block diagram of the unicracker process.

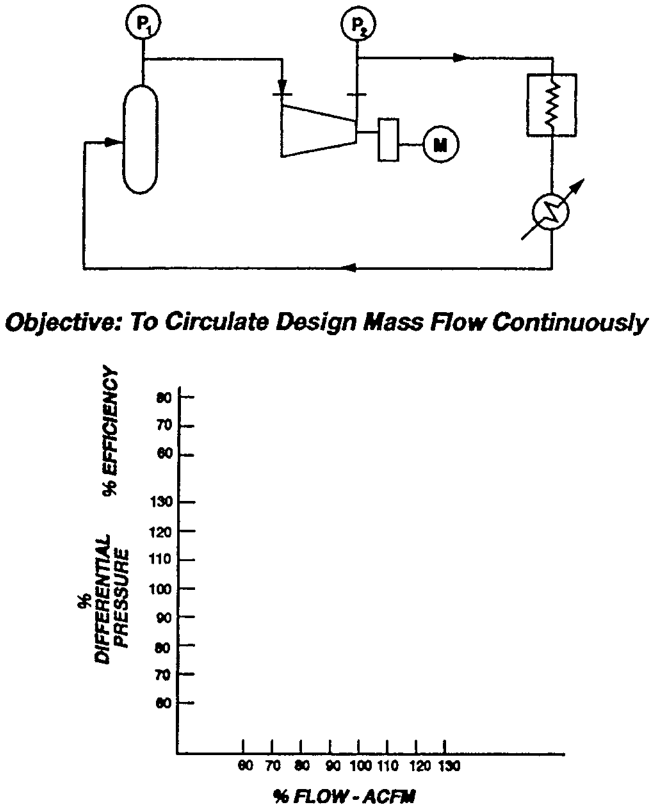


Figure 10. Typical Recycle Process Loop.

Depending on the type of unit incorporating a recycle compressor, the following process effects will be experienced by the recycle compressors.

- Variance of gas molecular weight caused by reactor catalyst bed changes
- Variance of compressor ratio
- Fouling
- Significant molecular weight changes (400 to 500 percent increase) during regeneration of catalyst.

UNICRACKER RECYCLE LOOP OPERATION REQUIREMENTS

This section of the tutorial covers the following operational modes of the recycle loop compressor.

- Startup
- Normal operation from new reactor catalyst fill until the end of run (start of run to end of run)
- Normal shutdown
- Emergency shutdown (ESD)
- Regeneration procedure

For each operational mode, the effects on the recycle compressor unit components will be defined. Table 2 lists the operating mode, process changes, and the effect on components.

Table 2. Operating Modes and Component Effects.

Operating Mode	Process Changes	Component Effects
Start-up	Use of Nitrogen. M.W. = 28 vs. 6-10 H2 Low Suction Pressure Possible Liquids	Balance Drum Seal High Temp. Driver Overload Low Oil Seal Cooling Flow Seal System Control Valves out of range Coupling Damage
Normal Operation	Variance of M.W. (3 - 10 M.W.)	Possible Surge Damage to: Interstage Labyrinths Balance Drum Seal Impeller, Thrust Bearing Journal Bearings & Seals
Normal Shutdown	Necessity of Seal System continued operation if loop is pressurized	Seal and Seal system damage Possible Gas release
Emergency Shutdown	Necessity of continued operation of Lube and Seal system	Seal damage,Bearing damage, Internal Labyrinth damage, Rotor damage, Gas release
Regeneration of Catalyst	Significant change of M.W. (Nitrogen) Introduction of Chlorides in to System Ammonium Chloride Fouling	Fouling damage to Rotor, Labyrinths, Diffusers, Thrust Bearing and Journal Bearings (Vibration damage to Journal Bearings

Startup Mode

Typically, the recycle compressor is started using nitrogen at the lowest possible pressure to overcome the loop pressure drop. This approach minimizes the amount of costly nitrogen to be used and keeps the driver horsepower below the limit. In addition, it is very important to drain liquids from the casing. Since all compressors used are radial split (barrel) types, individual stage casing drains should be installed.

Using nitrogen on startup can affect the condition of internal seals (balance drum seal and interstage labyrinth seals). Potential high temperature generated by the 28 MW nitrogen can damage seals. Operation is usually limited to a maximum of 350°F.

Failure to properly drain the compressor casing of liquids prior to startup can produce high torques that can result in coupling slippage.

Normal Operating Mode

During normal operation, gas molecular weight can vary sufficiently to change the operating point and possibly surge the compressor. It is very helpful to have a "real time" performance monitoring system installed to trend normalized head (corrected for speed) and efficiency.

Normal Shutdown Mode

A normal shutdown should not affect the reliability of the recycle compressor unit. However, if the compressor is driven by a steam turbine without an installed auto sequence system (similar to a gas turbine), possible excitation of a lateral or torsional critical speed could occur if the unit speed remains in the critical speed range during shutdown.

Once the unit is shutdown, it is essential that liquid seal systems be kept in operation until the compressor is blocked out, vented, and purged. Mechanical contact type liquid mechanical seals can theoretically seal up to approximately 200 psi, if they are in clean condition. However, experience has shown this to be a potential safety issue. Bushing type liquid seals function by having seal liquid continuously supplied at a pressure higher than the reference gas pressure in the compressor case. If the seal system is not in operation and gas is in the compressor, gas will be released to the atmosphere and the seal supply system will be contaminated with solid debris from the process.

Emergency Shutdown Mode

The "ESD" mode is activated for any abnormal process variable in the compressor unit or process system (e.g., high suction drain level). During this time, continuous supply of all auxiliaries (lube oil, seal fluid, cooling medium, etc.) is necessary to prevent component damage. The author experienced a case where the auxiliary pump did not start and the unit was shutdown on low lube oil pressure. The inertia of the compressor train was large enough to roll the rotors for five minutes. The unit was immediately restarted without a check of the bearings. The result was sudden seizure of the 8 inch diameter motor journal to the bearing housing, which fractured the shaft at the keyway. It took three months to fabricate and install a new motor rotor. The revenue loss for this incident was in excess of $20,000,000.

Regeneration Mode

Many recycle compressor operation modes are "noncontinuous," meaning that the catalyst cannot be generated online. Furthermore, for cost reduction purposes, the recycle compressor also operates as the regeneration compressor. In this mode it processes nitrogen contaminated with catalyst debris and chlorides during the regeneration period. This period can last for one to three days.

The common material formed during this process is ammonium chloride, which adheres to the rotor, interstage seals, and diffuser passages. Initially, the internals are evenly coated with this compound that "sublines" from a gas to a solid.

Figures 11 and 12 show a recycle compressor rotor coated with ammonium chloride. The rotor was installed "new" and became fouled in the first 24 hours of operation. The "foulant" completely coated the interstage labyrinths resulting in vibration instability (subsynchronous whirl) since the interstage labyrinths acted as five additional bearings. Vibration in excess of 3.5 mils required a shutdown of the 9000 rpm rated speed compressor.

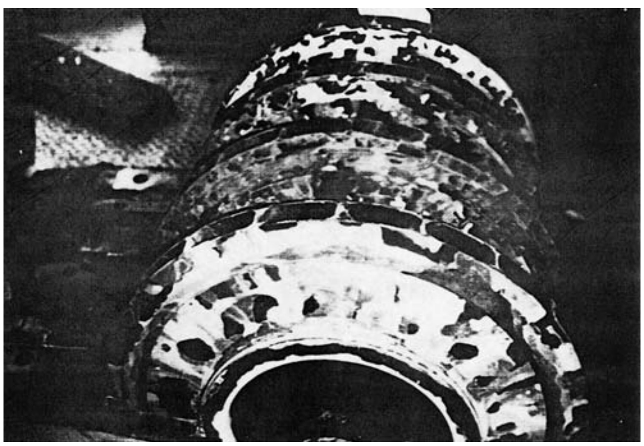


Figure 11. Reformer Recycle Compressor Rotor Fouling.

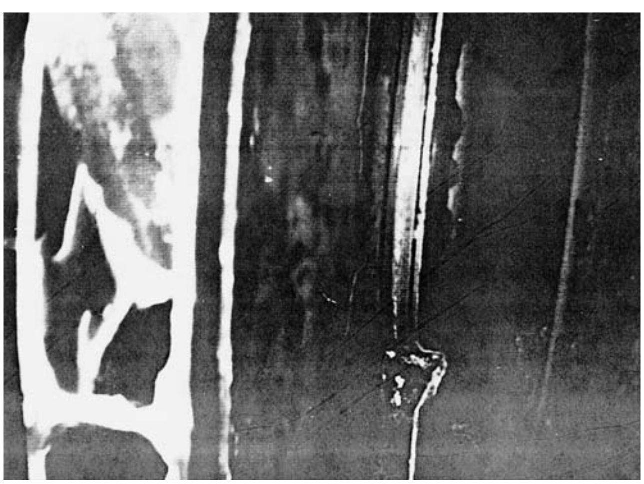


Figure 12. Reformer Recycle Compressor Closeup of Impeller Fouling.

CONDITION MONITORING OF THE RECYCLE COMPRESSOR UNIT FOR THE EFFECTS OF PROCESS SYSTEM CHANGES

The Principal of Component Conditioning Monitoring

One method of organizing the data obtained from any operating machinery unit is to use component condition monitoring. This method requires that all the parameters that define the condition of the major machinery components are monitored. Figure 13 presents the five major components and their related systems present in any type of rotating equipment.

- ROTOR
- RADIAL BEARING
- THRUST BEARING
- SEAL
- AUXILIARY SYSTEMS

Figure 13. The Five Major Components and Their Related Systems.

By trending the parameters, which define each major component, the condition of each component and its effect on the machinery unit can be determined. Of particular importance is the condition monitoring of the "rotor" or internal machinery condition. The condition monitoring of the internal condition of rotating machinery is often neglected. Experience has shown that internal machinery condition is the leading area of failure root causes, with auxiliary systems being second. In addition, internal condition monitoring greatly aids predictive maintenance techniques to eliminate costly, time-consuming machinery disassembly for preventive maintenance.

Included in the APPENDIX of this tutorial are guidelines for component condition monitoring along with limits.

CONCLUSION

It is truly hoped that the principals presented along with the recycle compressor example used will make one more aware of the effects of the process on turbomachine reliability. The knowledge gained in this tutorial can be used during the following phases of rotating equipment life to maximize reliability and MTBF.

- Initial specification and data sheet preparation
- Coordination meetings
- Shop test agenda requirements and shop test review
- Preparation of field operating procedures for:
  - Startup
  - Normal operation
  - Shutdown
  - Emergency shutdown
  - Abnormal conditions
- Predictive maintenance procedures (PDM)
- Preventive maintenance procedures (PM)

Remember, all rotating equipment "does what the process says." Failure to include experienced operators and process engineers in all phases of "rotating equipment life" will result in unnecessary life-cycle costs and reduced machine reliability.

APPENDIX A— GUIDELINES FOR COMPONENT CONDITION MONITORING

1. CALIBRATED: PRESSURE AND TEMPERATURE GAUGES AND FLOW METER
2. KNOW GAS ANALYSIS AND CALCULATE K, Z, M.W.
3. PERFORM AS CLOSE TO RATED SPEED AND FLOW AS POSSIBLE
4. RELATIONSHIPS:

A. $$\frac{N-1}{N} = \frac{LN\frac{(T_2)}{(T_1)}}{LN\frac{(P_2)}{(P_1)}}$$

B. $$EFFICIENCY_{poly} = \frac{\frac{K-1}{K}}{\frac{N-1}{N}}$$

C. $$HEAD_{poly} = \left(\frac{Ft-Lb_f}{Lb_m}\right) = \frac{1545}{M\,W} \times T_1 \times \frac{N}{N-1} \times Z_{avg} \times \left[\left(\frac{P_2}{P_1}\right)^{\left(\frac{N-1}{N}\right)} - 1\right]$$

5. COMPARE TO PREVIOUS VALUE. IF DECREASING TREND EXISTS GREATER THAN 10%, INSPECT AT FIRST OPPORTUNITY.

Figure A-1. Centrifugal Compressor-Rotor (Performance) Condition Monitoring Guidelines.

Table A-1. Radial Hydrodynamic Bearing Condition Monitoring Guidelines.

CONDITION MONITORING PARAMETERS AND THEIR ALARM LIMITS (ACCORDING TO COMPONENT)

I. JOURNAL BEARING (HYDRODYNAMIC)

	PARAMETER	LIMITS
1.	RADIAL VIBRATION (PEAK TO PEAK)	2.5 MILS (60 MICRONS)
2.	BEARING PAD TEMPERATURE	220°F (108°C)
3.	RADIAL SHAFT POSITION*	> 30° CHANGE AND/OR 30% POSITION CHANGE
4.	LUBE OIL SUPPLY TEMPERATURE	140°F (60°C)
5.	LUBE OIL DRAIN TEMPERATURE	190°F (90°C)
6.	LUBE OIL VISCOSITY	OFF SPEC 50%
7.	LUBE OIL FLASH POINT	BELOW 200°F (100°C)
8.	LUBE OIL PARTICLE SIZE	GREATER THAN 25 MICRONS

*EXCEPT FOR GEARBOXES WHERE GREATER VALUES ARE NORMAL FROM UNLOADED TO LOADED OPERATION

Table A-2. Hydrodynamic Thrust Bearing Condition Monitoring Guidelines.

CONDITION MONITORING PARAMETERS AND THEIR ALARM LIMITS (CONTINUED)

III. THRUST BEARING (HYDRODYNAMIC)

	PARAMETER	LIMITS
1.	AXIAL DISPLACEMENT*	>15-20 MILS (0.4-0.5 MM)
2.	THRUST PAD TEMPERATURE	220°F (105°C)
3.	LUBE OIL SUPPLY TEMPERATURE	140°F (60°C)
4.	LUBE OIL DRAIN TEMPERATURE	190°F (90°C)
5.	LUBE OIL VISCOSITY	OFF SPEC 50%
6.	LUBE OIL FLASH POINT	BELOW 200F (100°C)
7.	LUBE OIL PARTICLE SIZE	> 25 MICRONS
8.	PRODUCED HEAD	MAXIMUM VALUE FOR MACHINE

*AND THRUST PAD TEMPERATURES > 220°F (105°C)

Table A-3. Shaft End Liquid Seal Condition Monitoring Guidelines.

CONDITION MONITORING PARAMETERS AND THEIR ALARM LIMITS (CONTINUED)

VI. COMPRESSOR LIQUID SEAL

	PARAMETER	LIMITS
1.	GAS SIDE SEAL OIL/GAS ΔP	
	• BUSHING	< 12 FT. (3.5M)
	• MECHANICAL CONTACT	< 20 PSI (140 KPA)
2.	ATMOSPHERIC BUSHING OIL DRAIN TEMPERATURE	200°F (95°C)
3.	SEAL OIL VALVE* POSITION	> 25% POSITION CHANGE
4.	GAS SIDE SEAL OIL LEAKAGE	> 20 GPD PER SEAL

*SUPPLY VALVE = + 25%
RETURN VALVE = - 25%

NOTE THIS ASSUMES COMPRESSOR REFERENCE GAS PRESSURE STAYS CONSTANT

Table A-4. Seal Oil System Condition Monitoring Guidelines.

CONDITION MONITORING PARAMETERS AND THEIR ALARM LIMITS (CONTINUED)

X. SEAL OIL SYSTEMS

	PARAMETERS	LIMITS
1.	OIL VISCOSITY	OFF SPEC 50%
2.	OIL FLASH POINT	BELOW 200°F (100°C)
3.	AUXILIARY OIL PUMP OPERATING YES/NO	OPERATING
4.	BYPASS VALVE POSITION (P.D. PUMPS)	CHANGE > 20%
5.	TEMPERATURE CONTROL VALVE POSITION	CLOSED, SUPPLY TEMPERATURE > 130°F (55°C)
6.	FILTER ΔP	> 25 PSID (170 KPAG)
7.	SEAL OIL VALVE POSITION	CHANGE > 20% OPEN (SUPPLY) > 20% CLOSED (RETURN)
8.	SEAL OIL DRAINER CONDITION	(PROPER OPERATION)
	• CONSTANT LEVEL (YES/NO)	LEVEL SHOULD BE OBSERVED
	• OBSERVED LEVEL (YES/NO)	LEVEL SHOULD NOT BE CONSTANT
	• TIME BETWEEN DRAINS	APPROXIMATELY 1 HOUR (DEPENDS ON DRAINER VOLUME)

Table A-5. Lube Oil System Condition Monitoring Guidelines.

CONDITION MONITORING PARAMETERS AND THEIR ALARM LIMITS (CONTINUED)

IX. LUBE OIL SYSTEMS

	PARAMETERS	LIMITS
1.	OIL VISCOSITY	OFF SPEC 50%
2.	OIL FLASHPOINT	BELOW 200°F (100°C)
3.	AUXILIARY OIL PUMP OPERATING YES/NO	OPERATING
4.	BYPASS VALVE POSITION (P.D. PUMPS)	CHANGE > 20%
5.	TEMPERATURE CONTROL VALVE POSITION	CLOSED, SUPPLY TEMPERATURE > 130 (55°C)
6.	FILTER ΔP	> 25 PSID (170 KPAG)
7.	LUBE OIL SUPPLY VALVE POSITION	CHANGE > +/- 20%