Troubleshooting Rotating Machinery: Including Centrifugal Pumps and Compressors, Reciprocating Pumps and Compressors, Fans, Steam Turbines, Electric Motors, and More.
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Appendix B

Troubleshooting Matrices and Tables

This appendix includes troubleshooting matrices and tables designed to assist field troubleshooters in the identification and resolution of the following categories of process machinery problems:

1. Centrifugal pump problems
2. Centrifugal compressor problems
3. Reciprocating compressor problems
4. Reciprocating pump problems
5. Fans problems
6. Steam turbine problems
7. Electric motor problems
8. Hot bearing problems

Keep in mind that the following troubleshooting matrices and tables contain only the more common symptoms and causes found in the field. Theses matrices should be considered a starting point for your analysis. You may need contact the manufacture for assistance in solving rarely encountered or subtle problems.

Centrifugal Pump Troubleshooting Matrix

Here's an example illustrating how the centrifugal pump matrix can be used. Let's assume you are experiencing a high power load on an electric motor driver. You first select the column titled "Power too high" and then write down all the "Common Root Causes" for further review (see Table B.1). The matrix indicates that 1) an incorrect impeller diameter, 2) the incorrect impeller speed, 3) back pressure too low, 4) spillback or bypass valve is leaking or open, and 5) pump worn out are all potential causes. Next, you systematically pare down the list by determining which potential causes are unlikely based on the available information and data collected. This will leave you with the most likely cause, or root cause, of your problem.

Table B.1 How to use the centrifugal pump troubleshooting matrix.

Instructions: First find the "Common Symptom" column that best describes your field condition and then follow the column down to find all the possible causes (denoted by the symbol "X"). The "Common Root Causes" identified with an "X" are all the possible causes that should be investigated to determine the actual root cause of the problem.

Note: Refer to Chapter 8 in *Is My Machine OK?* for more information on centrifugal pump performance.

	Common symptoms								
	Flow too low	Flow too high	Unstable or erratic flow	Discharge pressure too high	Discharge pressure too low	High pressure pulsations	Power too high (2)	Power too low (2)	High vibrations or noisy (3)
a. Incorrect impeller diameter(s)	X	X	X	X	X	X	X	X	
b. Incorrect impeller speed	X	X	X	X	X	X	X	X	
c. Impeller installed backwards or rotor is turning backwards	X				X			X	
d. Back pressure too high (1)	X		X	X		X		X	X
e. Back pressure too low		X	X		X	X	X		X
f. Plugged suction strainer, valve, or piping	X		X	X	X	X		X	X
g. Suction level too low	X		X		X	X			X

Common root causes	h. Cavitation	X		X		X	X		X	X
	i. Air or vapor entrainment	X		X			X		X	X
	j. Flow much less than design (1)			X	X		X		X	X
	k. Flow much higher than design			X		X	X	X		X
	l. Spillback or bypass valve is leaking or open	X				X		X		
	m. Rotor imbalance									X
	n. Pump to driver misalignment									X
	o. Pump internal seals and/or bushing clearances worn excessively	X				X	X	X		X
	p. Driver issue or malfunction. Go to "Electric Motor" or "Steam Turbine" troubleshooting tables for more guidance	X	X	X	X	X				

(1) There is a potential for a no-flow condition If the pump has a check valve and the pump cannot generate sufficient pressure to open the check valve. Shut the pump down immediately if there appears to be no pump flow and thoroughly investigate the situation before attempting to restart.
(2) The potential root causes for these two columns only apply if horsepower increases with flow. These column headings must be reserved if horsepower decreases with flow. Refer to the "How Horsepower Varies with Flow" at the end of this section for more information on this topic.
(3) For more information on potential causes of vibration, refer to Chapters 14 and 15 in *Is My Machine OK?*

Table B.2a Centrifugal pump troubleshooting matrix.

	Common symptoms								
Instructions: First find the "Common Symptom" column that best describes your field condition and then follow the column down to find all the possible causes (denoted by the symbol "X"). The "Common Root Causes" identified with an "X" are all the possible causes that should be investigated to determine the actual root cause of the problem. Additional troubleshooting advice can be found in Table B.2b. Note: Refer to Chapter 8 in *Is My Machine OK?* for more information on centrifugal pump performance.	Flow too low	Flow too high	Unstable or erratic flow	Discharge pressure too high	Discharge pressure too low	High pressure pulsations	Power too high (2)	Power too low (2)	High vibrations or noisy (3)
a. Incorrect impeller diameter(s)	X	X	X	X	X	X	X	X	
b. Incorrect impeller speed	X	X	X	X	X	X	X	X	
c. Impeller installed backwards or rotor is turning backwards	X				X			X	
d. Back pressure too high (1)	X		X	X		X		X	X
e. Back pressure too low		X	X		X	X	X		X
f. Plugged suction strainer, valve, or piping	X		X	X	X	X		X	X

Common root causes	g. Suction level too low	X		X		X	X			X
	h. Cavitation	X		X		X	X		X	X
	i. Air or vapor entrainment	X		X			X		X	X
	j. Flow much less than design (1)			X	X		X		X	X
	k. Flow much higher than design			X		X	X	X		X
	l. Spillback or bypass valve is leaking or open	X				X		X		
	m. Rotor imbalance									X
	n. Pump to driver misalignment									X
	o. Pump internal seals and/or bushing clearances worn excessively	X				X	X	X		X
	p. Driver issue or malfunction. Go to "Electric Motor" or "Steam Turbine" troubleshooting tables for more guidance	X	X	X	X	X				

(1) There is a potential for a no-flow condition If the pump has a check valve and the pump cannot generate sufficient pressure to open the check valve. Shut the pump down immediately if there appears to be no pump flow and thoroughly investigate the situation before attempting to restart.

(2) The potential root causes for these two columns only apply if horsepower increases with flow. These column headings must be reserved if horsepower decreases with flow. Refer to the "How Horsepower Varies with Flow" at the end of this section for more information on this topic.

(3) For more information on potential causes of vibration, refer to Chapters 14 and 15 in *Is My Machine OK?*

Table B.2b Centrifugal pump troubleshooting tips

Instructions: This table is intended to complement Table B.2a by providing additional troubleshooting advice. Additional field inspections or tests may be required to identify the hidden cause of a given machinery problem. For example: If you suspect that "back pressure is too high" is a likely root cause, go to the "Field Troubleshooting Tips" column and read the advice provided. For this potential root cause, it is recommended that you check for a flow obstruction or a change in the downstream pressure.	Centrifugal Pump Field Troubleshooting Tips 

Common root causes	a. Incorrect impeller diameter(s)	1. Check repair records to see if there is any written record of the installed impeller diameter(s) and then compare it to the design diameter(s). 2. Check the speed to make sure you are at the rated speed before pulling the rotor to check impeller diameter(s).
	b. Incorrect impeller speed	Check the speed with tachometer and compare with design speed. A speed issue can be the result of an erroneous input speed signal to a VFD.
	c. Impeller installed backwards or rotor is turning backwards	1. First check that you have the correct driver rotation. 2. If the driver rotation is correct, the speed is correct, and the pump differential is only a fraction of the rated differential, then you should consider pulling the rotor to see if the impeller(s) are installed backwards.

(*Continued*)

Table B.2b Cont.

	d. Back pressure too high	1. Check for a flow obstruction, such as a partially closed valve or a plugged strainer, in the discharge line. If there is a strainer in the discharge line, pull the strainer to see if it's clean. Check with operator to see if there has been a history of line pluggage. 2. Check the downstream system pressure to see if it is higher than normal due to a change in the process or an upset condition.
	e. Back pressure too low	1. Check the downstream system pressure to see if it is lower than normal due to a change in the process or an upset condition. 2. Check for malfunctioning back-pressure control valve on the discharge of the pump.
	f. Plugged suction strainer, valve, or piping	1. Check for flow obstruction in the piping. 2. Check any strainers in the suction and discharge line to see if they are plugged. 3. Ask the operator if the pump piping has a history of pluggage.

	g. Suction level too low	Check to see if the product suction level is normal. If not, restore the level to normal and see if flow symptoms disappear.
	h. Cavitation	1. Check to see if the product suction level is normal. If not, restore the level to normal and see if cavitation symptoms disappear. 2. Check to see of the product temperature is normal. If not, attempt to restore back to normal and see if cavitation symptoms disappear. 3. Check for a flow obstruction such as a plugged strainer, in the suction line. Pull the strainer to see if it's clean. Check with operator to see if there has been a history of line pluggage. 4. Check to see if the pump flow is in a normal range, i.e. ± 20% of the best efficiency point. Low or high flow operation can result in cavitation-like symptoms. If possible, operate the pump at normal flows and see if cavitation-like symptoms disappear.

(*Continued*)

Table B.2b Cont.

	i. Air or vapor entrainment	1. Check to see if the product tank or sump suction level is normal. If not, restore the level to normal and see if flow symptoms disappear. 2. If this is a new installation, check to see if the suction entrance is at an adequate submergence depth.
	j. Flow much less than design	1. Check the flow and determine if you are significantly below (<50%) of the design flow. 2. Perform a test by temporarily increasing the flow through the pump. If symptoms disappear, you may need to resize the pump or install a minimum flow spill back line.
	k. Flow much higher than design	1. Check the flow and determine if you are significantly above (>120%) of the design flow. 2. Perform a test by temporarily decreasing the flow through the pump. If symptoms disappear, you may need to resize the pump to handle the higher flow.

	l. Spillback or bypass valve is leaking or open	1. Check all potential bypass valves to ensure they are closed or are not leaking. 2. Check relief valves with a ultrasonic gun for any indications of leakage.
	m. Rotor imbalance	1. The predominate vibrational component will be 1x running speed if imbalance is truly the problem. 2. The horizontal 1x component should be approximately equal to the vertical 1x component.
	n. Pump to driver misalignment	1. Usually this type of misalignment will show up as 1x or 2x vibrational components in the spectrum. High axial vibration is another indication of pump to driven misalignment. 2. Start by checking the driver to pump alignment if vibration analysis suggests misalignment is present. 3. Misalignment can be the result of piping strain. If driver to machine alignment looks okay, then check piping fit-up for possible pipe strain issues.

(*Continued*)

Table B.2b Cont.

	o. Pump internal seals and/or bushing clearances worn excessively	1. Begin by checking pump performance in the field to determine if degradation has occurred. Find out if the pump is on its performance curve. Refer to assessment methods described in Chapter 8 of *Is my Machine OK?* 2. Loss of seal and bushing clearances may lead to an increase in 1x amplitudes. 3. As clearances increase significantly, you may begin to see 1x, 2x, and 3x, and nx components in the vibration spectrums.
	p. Driver issue or malfunction. Go to “Electric Motor” or “Steam Turbine” troubleshooting tables for more guidance	1. Failing to reach rated speed is an indication of a driver issue. 2. Erratic speed is another indication of driver control issue. 3. It is a good idea to have the OEM on site whenever steam turbines or electric motors with VFDs are first commissioned.

Centrifugal Compressor Troubleshooting Matrix

The centrifugal compressor troubleshooting matrix below can be used to determine the most likely cause of a particular symptom. The troubleshooting procedure is similar to the centrifugal pump matrix example shown in Table B.3:

1. First, find the column with the symptom that best describes what is seen in the field.
2. Then, locate all the "Common Root Causes" with an "X" in the "Common Symptoms" column for further review.
3. Next, systematically pare down the list of potential root causes by eliminating those that are unlikely, based on the information and data collected.
4. The remaining potential cause of all the "Common Root Causes" represents the most likely cause, or root cause, of your problem.

Table B.3a Centrifugal compressor troubleshooting matrix.

	Common symptoms									
Instructions: First find the "Common Symptom" column that best describes your field condition and then follow the column down to find all the possible causes (denoted by the symbol "X"). The "Common Root Causes" identified with an "X" are all the possible causes that should be investigated to determine the actual root cause of the problem. Additional troubleshooting advice can be found in Table B.3b.	Flow too low	Flow too high	Unstable or erratic flow	High discharge temperature	Discharge pressure too high	Discharge pressure too low	High pressure pulsations	Power too high (1)	Power too low (1)	High vibrations or noisy (2)
a. Incorrect impeller diameter(s)	X	X		X	X	X	X	X	X	
b. Incorrect rotor speed	X	X		X	X	X	X	X	X	X
c. Impeller(s) installed backwards or rotor turning backwards	X					X			X	
d. Back pressure too high	X		X	X	X		X	X	X	X
e. Suction pressure too low	X			X		X		X	X	X
f. Plugged suction strainer or piping	X		X	X		X		X	X	

Common Root Causes	g. Gas density lighter than design	X					X	X		X	
	h. Gas density higher than design		X		X	X		X	X		
	i. Flow much less than design			X	X	X		X	X	X	X
	j. Flow much higher than design			X			X	X	X	X	X
	k. Open or leaking spillback valve	X					X		X	X	
	l. Rotor imbalance										X
	m. Compressor to driver misalignment										X
	n. Suction temperature higher than design	X			X		X			X	
	p. Excessive internal compressor wear	X			X		X		X	X	X
	q. Driver issue or malfunction. Go to "Electric Motor" or "Steam Turbine" troubleshooting tables for more guidance	X	X	X	X	X	X				
	r. Surge control system malfunction	X	X	X	X	X	X	X	X	X	X

(1) The potential root causes for these two columns only apply if horsepower increases with flow. These column headings must be reserved if horsepower decreases with flow. Refer to the "How Horsepower Varies with Flow" at the end of this section for more information on this topic.
(2) For more information on potential causes of vibration, refer to Chapters 14 and 15 in *Is My Machine OK?*

Table B.3b Centrifugal compressor troubleshooting tips.

Instructions	Centrifugal Compressor Field Troubleshooting Tips
Instructions: This table is intended to complement Table B.3a by providing additional troubleshooting advice. Additional field inspections or tests may be required to identify the hidden cause of a given machinery problem. For example: If you suspect that "back pressure is too high" is a likely root cause, go to the "Field Troubleshooting Tips" column and read the advice provided. For this potential root cause, it is recommended that you check for a flow obstruction or a change in the downstream pressure.	Centrifugal Compressor Field Troubleshooting Tips 

Common root causes	a. Incorrect impeller diameter(s)	1. Check repair records to see if there is any written record of the installed impeller diameter (s) and then compare it to the design diameter (s). 2. Check the speed to make sure you are at the rated speed before pulling the rotor to check impeller diameter (s).
	b. Incorrect rotor speed	Check the rotor speed indication if installed or by using a tachometer and compare with design speed. A speed issue can be the result of an erroneous input speed signal to a VFD.
	c. Impeller(s) installed backwards or rotor turning backwards	1. First check that you have the correct driver rotation. 2. If the driver rotation is correct, the speed is correct, and the pump differential is only a fraction of the rated differential, then you should consider pulling the rotor to see if the impeller(s) are installed backwards.

(*Continued*)

Table B.3b Cont.

	d. Back pressure too high	1. Check for a flow obstruction, such as a partially closed valve or a plugged strainer, in the discharge line. If there is a strainer in the discharge line, pull the strainer to see if it's clean. Check with operator to see if there has been a history of line pluggage. 2. Check the downstream system pressure to see if it is higher than normal due to a change in the process or an upset condition.
	e. Suction pressure too low	1. Check the upstream system pressure to see if it is lower than normal due to a change in the process or an upset condition. 2. Check for flow obstruction in suction piping.
	f. Plugged suction strainer or piping	1. Check for flow obstruction in the piping. 2. Check any strainers in the suction and discharge line to see if they are plugged. 3. Ask the operator if the compressor piping has a history of pluggage.

	g. Gas density lighter than design	Pull a representative process gas sample in order to determine its molecular weight. The compressor differential pressure and amp draw are directly proportional to the molecular weight of the gas. Watch out for significant deviations from the normal molecular weight of the gas during start-ups.
	h. Gas density higher than design	Pull a representative process gas sample in order to determine it's the molecular weight. The compressor differential pressure and amp draw are directly proportional to the molecular weight of the gas. Watch out for significant deviations from the normal molecular weight of the gas during start-ups.

(*Continued*)

Table B.3b Cont.

	i. Flow much less than design	1. Check the flow and determine if you are significantly below (<80%) of the design flow. 2. If the compressor has a surge control system, check to see it is functioning properly. 3. If the compressor doesn't have a surge control system, perform a test by temporarily increasing the flow through the compressor. If symptoms disappear, you may need to review the compressor sizing and piping system to understand the source of the problem.
	j. Flow much higher than design	1. Check the flow and determine if you are significantly above (>120%) of the design flow. 2. Perform a test by temporarily decreasing the flow through the compressor. If symptoms disappear, you may need to review the compressor sizing and piping system to understand the source of the problem.

	k. Open or leaking spillback valve	1. Check all potential bypass valves to ensure they are closed or are not leaking. 2. If the compressor has a surge control system, make sure it is working properly. 3. Check relief valves with a ultrasonic gun for any indications of leakage.
	l. Rotor imbalance	1. The predominate vibrational component will be 1x running speed if imbalance is truly the problem. 2. The horizontal 1x component should be approximately equal to the vertical 1x component.

(*Continued*)

Table B.3b Cont.

	m. Compressor to driver misalignment	1. Usually this type of misalignment will show up as 1x or 2x vibrational components in the spectrum. High axial vibration is another indication of compressor to driven misalignment. 2. Start by checking the driver to compressor alignment if vibration analysis suggests misalignment is present. 3. Misalignment can be the result of piping strain. If driver to machine alignment looks okay, then check piping fit-up for possible pipe strain issues.
	n. Suction temperature higher than design	Check to see of the compressor suction temperature is deviating from the design value by more than 5%. A deviation greater than 5% will affect horsepower and performance.

	p. Excessive internal compressor wear	1. Begin by checking compressor's performance in the field to determine if degradation has occurred. Plot a few performance points of the performance map to see if the compressor is on its curve. 2. Compare the actual discharge temperature to the design discharge temperature. The discharge temperature will begin to rise above the design discharge temperature as internal compressor wear occur.
	q. Driver issue or malfunction. Go to "Electric Motor" or "Steam Turbine" troubleshooting tables for more guidance	1. Failing to reach rated speed is an indication of a driver issue. 2. Erratic speed is another indication of driver control issue. 3. It is a good idea to have the OEM on site whenever steam turbines or electric motors with VFDs are first commissioned.

(*Continued*)

Table B.3b Cont.

	r. Surge control system malfunction	The combination of low flow, low pressure differential, and high horsepower indications usually point to an open spillback valve. If a surge control system is installed, it is possible that the surge valve is leaking or open. First check if the valve if open. If it is, determine if it's due to a malfunctioning surge control system or due malfunctioning valve. If in doubt, have the surge control system designer double check the surge algorithms to ensure they are correct.

How Horsepower Varies with Flow

Centrifugal Pumps

Common sense tells us that, for a given speed, the horsepower required by a centrifugal pump increase as flow increases—which is not always a correct statement. Let's review performance curves for three types of centrifugal pumps:

Figure A.1 shows that the head curve for a radial flow pump is relatively flat and that the head decreases gradually as the flow increases. You will also notice that the brake horsepower increases gradually over the flow range with the maximum normally at the point of maximum flow.

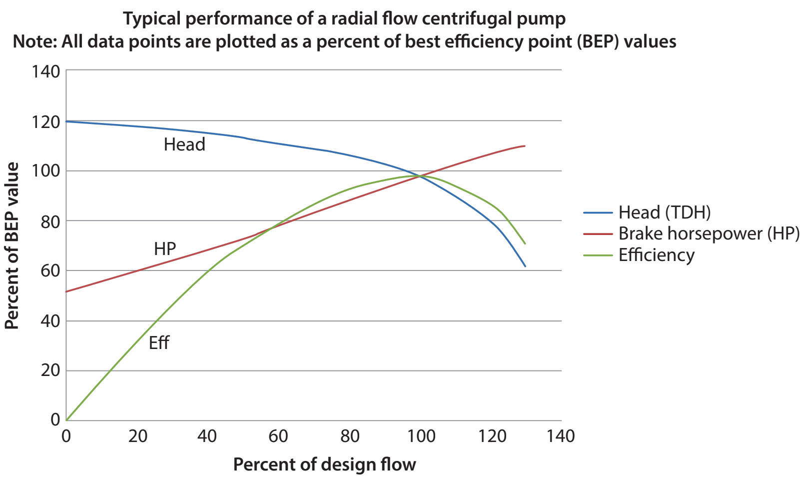


Figure A.1 Radial flow pump.

In contrast, mixed flow centrifugal pumps and axial flow or propeller pumps have considerably different characteristics as shown in Figures A.2 and A.3 below. The head curve for a mixed flow pump is steeper than for a radial flow pump. The shut-off head is usually 150% to 200% of the design head and the brake horsepower remains fairly constant over the flow range. For a typical axial flow centrifugal pumps, the head and brake horsepower both increase drastically near shutoff as shown in Figure A.3.

There are many pumps with characteristics falling somewhere between the three pump design examples shown here. These examples illustrate points on a continuum of pump performance designs. For instance, the Francis vane impeller would have a characteristic between the radial

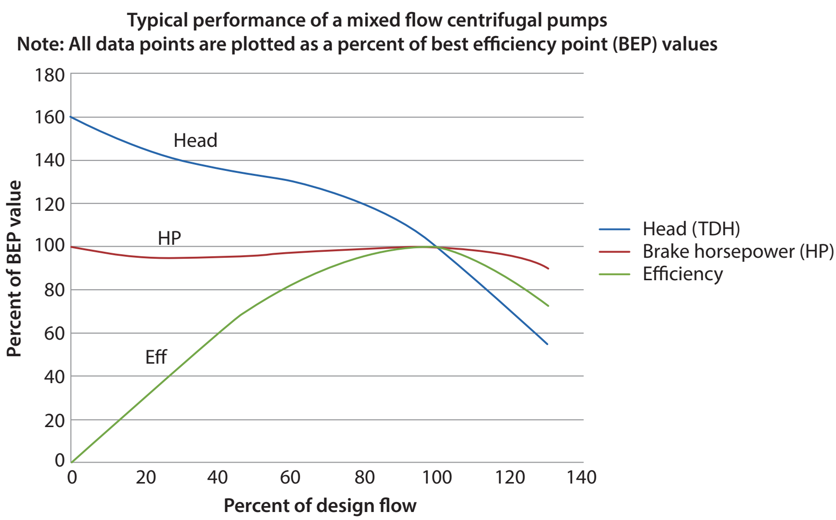


Figure A.2 Mixed flow pump.

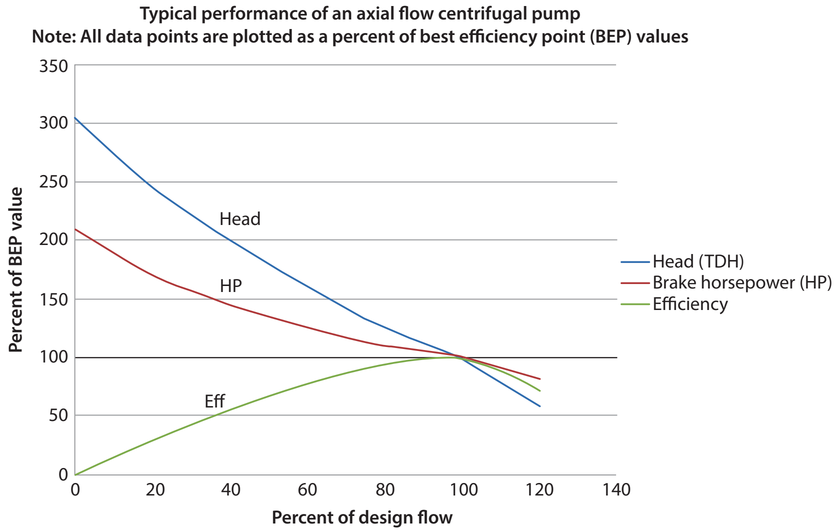


Figure A.3 Axial flow pump.

and mixed flow classes. The purpose of this discussion to illustrate how pump performance can vary based on their design.

Centrifugal Compressors

Just as the shape of a centrifugal pump head versus flow curve affects its horsepower versus flow curve, the shape of a centrifugal compressor head versus flow curve determines the shape of its horsepower versus flow curve. For a given gas density, speed, and inlet guide vane position (if applicable), we typically see:

1. Centrifugal compressors with relatively flat head versus flow curves, similar

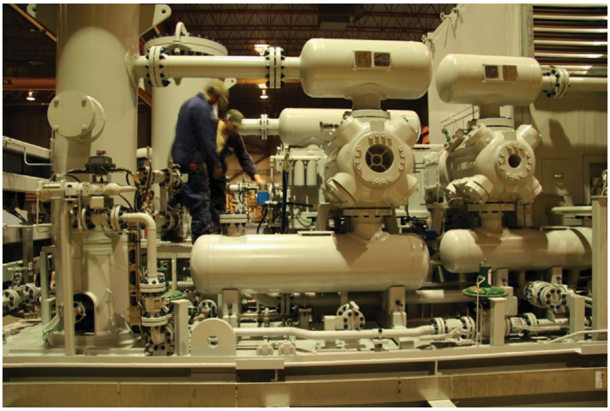
to Figure 1, tend to have horsepower curves that rise continuously as flow increases.

2. Centrifugal compressors with steep head versus flow curves, similar to Figure 3, tend to have horsepower versus flow curves that drop continuously as flow increases.

Conclusion

When dealing with centrifugal machinery, never assume that horsepower rises with flow. Always review the pump or compressor's performance curve for the specific machine you are dealing with to better understand the actual shape of the head versus flow curve and the horsepower versus flow curve.

Reciprocating Compressor Troubleshooting Matrix



The reciprocating compressor troubleshooting matrix below can be used to determine the most likely cause of a particular symptom. The troubleshooting procedure is similar to the centrifugal pump matrix example shown in Table B.4:

1. First, find the column with the symptom that best describes what is seen in the field.
2. Then, locate all the "Common Root Causes" with an "X" in the "Common Symptoms" column for further review.
3. Next, systematically pare down the list of potential root causes by eliminating those that are unlikely, based on the information and data collected
4. The remaining potential cause of all the "Common Root Causes" represents the most likely cause, or root cause, of your problem.

Table B.4a Reciprocating compressor troubleshooting matrix.

	Common symptoms								
Instructions: First find the "Common Symptom" column that best describes your field condition and then follow the column down to find all the possible causes (denoted by the symbol "X"). The "Common Root Causes" identified with an "X" are all the possible causes that should be investigated to determine the actual root cause of the problem. Additional troubleshooting advice can be found in Table B.4b.	Flow too low	Flow too high	High Discharge Temperature	Discharge pressure too high	Discharge pressure too low	High pressure pulsations	Power too high	Power too low	High vibrations or noisy
a. Incorrect cylinder clearance volume	X	X		X	X	X	X	X	
b. Wrong compressor speed	X	X		X	X	X	X	X	X
c. Intercooler ineffective (multistage units)	X		X					X	
d. Pulsation dampner damaged or plugged				X	X	X		X	X
e. Pulsation dampner ineffective						X			X

Common root causes	f. Suction pressure too low	X		X		X			X	
	g. Plugged suction strainer, valve, or piping restriction	X		X		X	X	X	X	
	h. Open or leaking spillback valve	X						X		
	i. Mechanical or acoustic resonance						X			X
	j. Inadequate compressor support									X
	k. Leaking cylinder valve	X		X		X			X	
	l. Unbalanced reciprocating weights									X
	m. Broken hold down bolt or support member									X
	n. Suction temperature higher than design	X		X				X		
	o. Gas is lighter than design	X				X	X		X	
	p. Gas is heavier than design		X	X	X		X	X		
	q. Leaking piston rings	X		X		X		X	X	
	r. Excessive cylinder valve losses			X		X		X		
	s. Driver issue or malfunction	X	X	X	X	X	X			

Table B.4b Reciprocating compressor troubleshooting tips.

Instructions: This table is intended to complement Table B.4a by providing additional troubleshooting advice. Additional field inspections or tests may be required to identify the hidden cause of a given machinery problem. For example: If you suspect that "wrong compressor speed" is a likely root cause, go to the "Field Troubleshooting Tips" column and read the advice provided. For this potential root cause, it is recommended that you check the compressor speed indication if installed or by using a tachometer and compare the indicated speed with the design speed.	Reciprocating Compressor Field Troubleshooting Tips 

Common root causes	a. Incorrect cylinder clearance volume	1. If volume unloaders are installed, first check to make sure they are all in the correct positions. Leaking volume unloaders can significantly affect compressor flow. 2. Check the repair records to determine if the clearance volumes were measured and recorded. 3. Conduct a compressor performance (PV) analysis and see if cylinder performance appears to be normal.
	b. Wrong compressor speed	Check the compressor speed indication if installed or by using a tachometer and compare with design speed.
	c. Intercooler ineffective (multi-stage units)	Check the inlet and outlet temperatures on your coolers and compare them to the design values. A high inlet temperature is an indication of a compressor issues. A normal inlet temperature with a high outlet temperature is an indication of a cooler issue.

(*Continued*)

Table B.4b Cont.

	d. Pulsation dampner damaged or plugged	If the problem has suddenly appeared, you may have a problem internal to the pulsation dampner. When possible, use a boroscope to inspect the pulsation dampner internals. Look for plugage, or broken internal components.
	e. Pulsation dampner ineffective	If the problem is present immediately after commissioning, it may be a pulsation dampner design problem. Have someone verify the design.
	f. Suction pressure too low	1. Check the upstream system pressure to see if it is lower than normal due to a change in the process or an upset condition. 2. Check for flow obstruction in suction piping.
	g. Plugged suction strainer, valve, or piping restriction	1. Check for flow obstruction in the piping. 2. Check any strainers in the suction and discharge line to see if they are plugged. 3. Ask the operator if the compressor piping has a history of pluggage.

	h. Open or leaking spillback valve	1. Check all potential bypass valves to ensure they are closed or are not leaking. 2. Check relief valves for any indications of leakage.
	i. Mechanical or acoustic resonance	Check vibration and pulsations as a function of speed. Resonances will appear as defined spikes in the data. Refer to Chapter 18 in *Is My Machine OK?* for ways to identify resonances.
	j. Inadequate compressor support	Start you investigation by checking compressor vibration levels close to the skid or sub-base. If vibration levels are high near hold down bolts, then you skid or sub-base is not providing adequate support.
	k. Leaking cylinder valve	Use an infrared temperature gun or contact thermometer to check for hot valve caps. An isolated hot valve cap is an indication of a leaking cylinder valve. Then, replace all valves with hot valve caps and see if the symptoms disappear.

(*Continued*)

Table B.4b Cont.

	l. Unbalanced reciprocating weights	Imbalanced reciprocating weights should show up as high 1x vibrational components in the spectra.
	m. Broken hold down bolt or support member	If the vertical vibration levels are more than 2 times higher than the horizontal vibrating level, you should suspect that you have a broken or loose hold down bolt or support member.
	n. Suction temperature higher than design	Check to see of the compressor suction temperature is deviating from the design value by more than 5%. A deviation greater than 5% will affect horsepower and performance.
	o. Gas is lighter that design	Pull a representative process gas sample in order to determine its molecular weight. The compressor amp draw is directly proportional to the molecular weight of the gas. Watch out for significant deviations from the normal molecular weight of the gas during start-ups.

	p. Gas is heavier that design	Pull a representative process gas sample in order to determine its molecular weight. The compressor amp draw is directly proportional to the molecular weight of the gas. Watch out for significant deviations from the normal molecular weight of the gas during start-ups.
	q. Leaking piston rings	Conduct a compressor performance (PV) analysis to determine if excessive leakage is present.
	r. Excessive cylinder valve losses	Perform a compressor performance analysis (PV) to evaluate the magnitude of the cylinder valve losses. Compare the valve losses with the manufacturer's estimate.
	s. Driver issue or malfunction.	1. Failing to reach rated speed is an indication of a driver issue. 2. Erratic speed is another indication of driver control issue.

Reciprocating Pump Troubleshooting Table

The reciprocating pump troubleshooting table below can be used to determine the most likely cause of a particular symptom. The troubleshooting procedure is similar to the centrifugal pump matrix example shown in Table B.5:

1. First, select the symptom that best describes what is seen in the field.
2. Then, locate all the "Possible Causes" for further review.
3. Next, systematically pare down the list of possible causes by eliminating those that are unlikely, based on the information and data collected
4. The remaining possible cause represents the most likely cause, or root cause, of your problem.

Table B.5 Reciprocating pump troubleshooting table.

Symptom	**Possible cause**	**Field troubleshooting tips**
Low discharge pressure		
	1. Restriction in suction system	Check for potential flow obstruction in the piping.
	2. Leaking spillback valve or relief valve	1. Check all potential bypass valves to ensure they are closed or are not leaking. 2. Check relief valves with a ultrasonic gun for any indications of leakage.
	3. Pump not fully primed	Check to make sure the suction line is liquid full and vapor free. You may have to shut down the pump and vent the suction line to ensure it is liquid full. If you are unable to fill the suction line with liquid ensure there is an ample supply of liquid available to the pump.

(*Continued*)

Table B.5 Cont.

Symptom	Possible cause	Field troubleshooting tips
	4. Pump speed too low	Check the pump speed indication if installed or by using a tachometer and compare with design speed.
	5. Leaking pump valves	Pull valves and inspect for damage or installation issues.
	6. No back pressure on pump	Check to make sure the discharge pressure is normal.
	7. Gas entering fluid cylinder	1. Check to make sure the suction line is vapor free. You may have to shut down the pump and vent the suction line to ensure it is liquid full. 2. Check that you are not sucking in air or vapor in the suction tank due to vortexing.

	8. Low suction pressure causing cavitation due to inadequate NPSHa	1. First check to see if the suction pressure is normal. 2. Check for flow obstruction in the piping. 3. If possible, reduce the inlet fluid temperature. 4. Reduce suction lift or raise supply tank level.
	9. Excessive packing leakage	Visually inspect the packing boxes for external leakage. If leakage is excessive, have a qualified mechanical attempt to reduce leakage by adjusting packing glands.
	10. Driver issue or malfunction	1. Failing to reach rated speed is an indication of a driver issue. 2. Erratic speed is another indication of driver control issue.

(*Continued*)

Table B.5 Cont.

Symptom	Possible cause	Field troubleshooting tips
Low total flow into the process		
	1. Restriction in suction system	Check for flow obstruction in the piping.
	2. Leaking spillback valve or relief valve	1. Check all potential bypass valves to ensure they are closed or are not leaking. 2. Check relief valves with a ultrasonic gun for any indications of leakage.
	3. Pump speed too low	Check the pump speed indication if installed or by using a tachometer and compare with design speed.
	4. Leaking pump valves	Pull valves and inspect for damage or installation issues.
	5. Gas entering fluid cylinder	Check to make sure the suction line is vapor free. You may have to shut down the pump and vent the suction line to ensure it is liquid full.

	6. Insufficient suction pressure	1. Check the upstream system pressure to see if it is lower than normal due to a change in the process or an upset condition. 2. Check for flow obstruction in suction piping.
	7. Pump not fully primed	Check to make sure the suction line is liquid full and vapor free. You may have to shut down the pump and vent the suction line to ensure it is liquid full. If you are unable to fill the suction line with liquid ensure there is an ample supply of liquid available to the pump.
	8. Leaking packing	Visually inspect the packing boxes for external leakage. If leakage is excessive, have a qualified mechanical attempt to reduce leakage by adjusting packing glands.

(Continued)

Table B.5 Cont.

Symptom	**Possible cause**	**Field troubleshooting tips**
	9. Driver issue or malfunction	1. Failing to reach rated speed is an indication of a driver issue. 2. Erratic speed is another indication of driver control issue.
Excessive vibration		
	1. Insufficient NPSHA causing cavitation	1. Check the upstream system pressure to see if it is lower than normal due to a change in the process or an upset condition. 2. Check for flow obstruction in suction piping. 3. If possible, reduce inlet fluid temperature. 4. Reduce suction lift or raise supply tank level. 5. A malfunctioning or improperly sized pulsation dampner can result in cavitation due to excessive pressure swings in the suction line.

	2. Gas entering fluid cylinder	1. Check to make sure the suction line is vapor free. You may have to shut down the pump and vent the suction line to ensure it is liquid full. 2. Check that you are not sucking in air or vapor in the suction tank due to vortexing.
	3. Broken valve spring or foreign material under pump valve	Pull valves and inspect for pluggage, damage, or installation issues.
	4. Excessive valve lift	Have the pump OEM evaluate the valve lift for your application.
	5. Relief valve or other accessory causing noise	Check relief valve for internal issues using an ultrasonic gun.
	6. Pulsation dampners not properly primed	De-pressure pulsation dampner and ensure the bladder is properly charged.

(*Continued*)

Table B.5 Cont.

Symptom	Possible cause	Field troubleshooting tips
	7. Pulsation dampner bladder damaged or ineffective	De-pressure pulsation dampner and see if the bladder is holding the proper charge. If the bladder is holding the proper charge, the pulsation dampner may be undersized.
	8. Acoustic resonance in suction or discharge piping	Check pressure pulsations as a function of speed. Resonances will appear as defined spikes in the data. Refer to Chapter 18 in *Is My Machine OK?* for ways to identify resonances.
	9. Piping resonance	Check vibration as a function of speed. Resonances will appear as defined spikes in the data. Refer to Chapter 18 in *Is My Machine OK?* for ways to identify resonances.

	10. Broken hold down bolt or support member	If the vertical vibration levels are more than 2 times higher than the horizontal vibrating level, you should suspect that you have a broken or loose hold down bolt or support member.
	11. Inadequate baseplate stiffness	Start you investigation by checking pump vibration levels close to the skid or sub-base. If vibration levels are high near hold down bolts, then you skid or sub-base is not providing adequate stiffness.
	12. Inadequate mass of foundation	The mass of the foundation should be 5 to 10 times that of the pump.

(*Continued*)

Table B.5 Cont.

Symptom	Possible cause	Field troubleshooting tips
High temperature in the drive end		
	1. Pump overloaded due to an excessively high discharge pressure	1. Check for a flow obstruction, such as a partially closed valve or a plugged strainer, in the discharge line. If there is a strainer in the discharge line, pull the strainer to see if it's clean. Check with operator to see if there has been a history of line pluggage. 2. Check the downstream system pressure to see if it is higher than normal due to a change in the process or an upset condition.

	2. Discharge valve partially or completely closed	Check all discharge valves to ensure they are fully open.
	3. Internal pump valves have inadequate clearances	Pull and inspect the pump valves. Have a spare set of valves to compare them to. If this is a new installation, have the OEM check the valve design.
	4. Spillback control not operating correctly	If the pump has a spillback control, system, have the design and logic check out by an instrument engineer or technician. The control system must never force the pump to see a higher than normal discharge pressure.

Fan Troubleshooting Matrix

Instructions: First drop down to the "Symptoms" column and find all the combination of symptoms that best describe your field observations. The "Possible Causes" found in the far right column, corresponding to the identified symptoms, are all the possible causes that should be investigated to determine the actual root cause of the problem.

Table B.6 Fan troubleshooting.

Symptoms					Possible causes
Flow	**Pressure**	**Power**	**Vibration**	**Pulsations**	
Low	Low	Low			Speed lower than design
Low	Low	Low			V-belts slipping (If V-belts are slipping, tighten or replace.)
Low	Low	Low			Wrong drive sheaves (Make sure drive sheaves diameters are correct.)
Low	Low	Low			Suction pressure too low
Low	Low	Low			Air or gas density lower than design
Low	Low	Low			Excessive ducting losses (Compare fan inlet pressure to the upstream pressure to see if losses are excessive.)

(*Continued*)

Table B.6 Cont.

Symptoms					Possible causes
Flow	**Pressure**	**Power**	**Vibration**	**Pulsations**	
Low	Low	Low			Axial fan blade settings lower than design (Shut down the fan and check blade attack angles with protractor.)
Low	Low	Low			System losses higher than design (Compare fan exhaust pressure to the downstream pressure to see if losses are excessive.)
Low	Low				Driver issue or malfunction (Check driver or driver controls if speed is running well below rated speed.)

Low	High	Low			Blockage in system
Low	High	Low			Damper closed
Low	High	Low			Fan operating in stall below the peak pressure flow (Attempt to increase the flow and see of the symptoms disappear.)
High	Low	High			System pressure losses lower than design
High	Low	High			Missing system components
High	High	High			Speed is higher than design
High	High	High			Air or gas temperature lower than design
High	High	High			Air or gas density higher than design

(*Continued*)

Table B.6 Cont.

Symptoms					Possible causes
Flow	**Pressure**	**Power**	**Vibration**	**Pulsations**	
High	High	High			Wrong wheel rotation (Shut down; uncouple the fan from the driver in order to check the rotational direction of the driver.)
High	High	High			Fan running backwards (First check the driver rotation before considering inspecting or pulling the rotor.)
High	High	High			Axial fan blades set higher than design (Shut down the fan and check blade attack angles with protractor.)

High	High				Driver issue or malfunction (1. Failing to reach rated speed is an indication of a driver issue. 2. Erratic speed is another indication of driver control issue.)
Normal	Normal	High			Undersized motor or driver (Check with OEM on fan horsepower requirements.)
Normal	Normal	High			Excessive driveline losses (Wheel or seal rubbing, tight bearings, misaligned v-belts, etc.)
Normal	Normal	High			Motor has wrong voltage or is wired wrong (Recheck motor nameplate for proper wiring sequence.)

(*Continued*)

Table B.6 Cont.

Symptoms					Possible causes
Flow	**Pressure**	**Power**	**Vibration**	**Pulsations**	
Unsteady	Unsteady	Unsteady	High	High	Fan is blocked off (Check for blockages in the fan outlet ducting.)
Unsteady	Unsteady	Unsteady	High	High	Fan is operating in stall or on an unstable part of the curve (Consult the OEM concerning this potential issue.)
Unsteady	Unsteady	Unsteady	High	High	Fan operating in parallel and not properly rated (Shut one of the fans down and see of the symptoms disappear.)
			High	High	Blade-pass frequency due to tight wheel clearance (Consult the OEM concerning this potential issue.)

			High	High	Rotating stall due to low flow or wrong fan selection (Consult the OEM concerning this potential issue.)
			High	High	Surging due to low flow (Check to see if you are well below rated flow. IF you are, raise flow to see if symptoms disappear.)
			High	High	Vortex shedding (Consult the OEM concerning this potential issue.)
			High	High	Flow turbulence due to poor installation or obstruction (Look for flow turbulence vibrational components in the vibration spectra.)

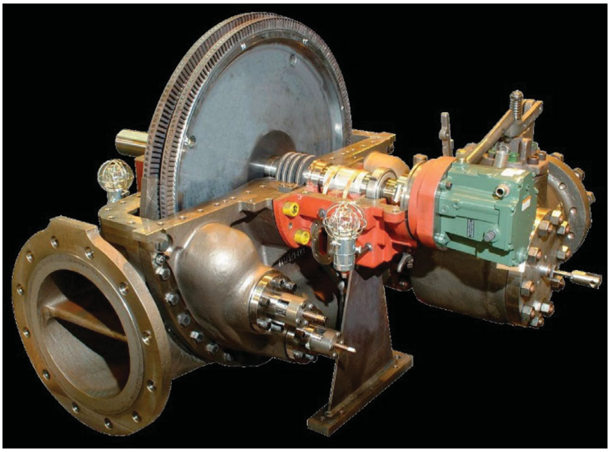
(*Continued*)

Table B.6 Cont.

Symptoms					Possible causes
Flow	**Pressure**	**Power**	**Vibration**	**Pulsations**	
			High		Imbalance (1. The predominate vibrational component will be 1x running speed if imbalance is truly the problem. 2. The horizontal 1x component should be approximately equal to the vertical 1x component.)
			High		Resonance (Check vibration as a function of speed. Resonances will appear as defined spikes in the data. Refer to Chapter 18 in *Is My Machine OK?* for ways to identify resonances.)

			High		Looseness (In the vibration spectra, indications of looseness usually appear as a predominant 1x vibrational component with higher order multiples, i.e. 1x, 2x, 3x, 4x, etc.)
			High		Internal rubbing (1. More likely on a new installation or after a rebuild. 2. Check for duct to fan fit-up issues.)

Steam Turbine Troubleshooting Table



Note: This troubleshooting table only applies to general purpose steam turbines rated at 1000 horsepower or less. It should not be applied to condensing turbine installations.

Instructions: Find the symptom that best describes your observation. Next record all the possible causes listed in the "Possible Cause" column. These are all the possible causes that should be investigated to determine the root cause of the problem.

Table B.7 Steam turbine troubleshooting.

Symptom	Possible cause (Advice)
Steam turbine does not achieve rated power.	
	1. Too many hand valves closed
	2. Speed governor set too low
	3. Inlet steam pressure too low
	4. Exhaust pressure too high
	5. Malfunctioning governor
	6. Horsepower required by driven machine too high
	7. Throttle valve not opening completely
	8. Nozzles plugged
	9. Inlet steam strainer plugged
	10. Turbine steam pathway fouled due to poor steam quality

(*Continued*)

Table B.7 Cont.

Symptom	Possible cause (Advice)
Speed increases excessively when load is decreased	
	1. Throttle valve not closing completely
	2. Throttle valve and valve seats cut or worn
	3. Malfunctioning governor
	4. Salt build-up on trip and throttle valve stem
Excessive speed variation	
	1. Governor droop adjustment required
	2. Malfunctioning governor controls
	3. Throttle assembly friction (Replace components that are sticking or binding)
	4. Throttle valve looseness
	5. Horsepower load too light with full inlet pressure

Table B.7 Cont.

Symptom	Possible cause (Advice)
	6. Rapidly changing load from the driven machine due to process conditions
	7. Backpressure too low
Slow turbine speed acceleration	
	1. See all possible causes for "Insufficient power" above
	2. High starting torque of driven machine
	3. High rotational inertia of entire machine train
Governor not operating properly	
	1. Restricted throttle valve travel
	2. Governor not installed properly
	3. Verify governor is designed for the proposed speed range
	4. Trip and throttle valve sticking due to salt build-up on stem

(*Continued*)

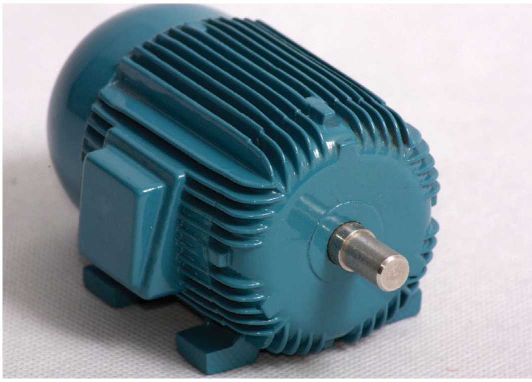
Table B.7 Cont.

Symptom	Possible cause (Advice)
Overspeed trip activates at normal operating speed	
	1. Excessive vibration
	2. Trip speed setting too low
	3. Malfunctioning governor
	4. Incorrect tachometer signal
Overspeed does not trip at set speed	
	1. Trip speed setting set too high
	2. Bolt trip mechanism problem (Examine trip mechanism)
	3. Over speed trip valve unable to close (Inspect trip valve)
	4. Sticking trip and throttle valve due to salt build-up
Excessive vibration or noise	
	1. Misalignment
	2. Worn bearing

Table B.7 Cont.

Symptom	Possible cause (Advice)
	3. Worn coupling (Likely with gear type couplings)
	4. Unbalanced coupling
	5. Unbalanced rotor
	6. Piping strain (Check cold piping fit up and ensure allowances have been made for thermal expansion)
	7. Excessive end play
	8. Bent shaft
	9. Excessive rubbing at shaft seal
	10. Worn steam seals. Look for a) water in the oil and/or b) a temperature increase on bearing housing.

Electric Motor Troubleshooting Table



Note: This troubleshooting table is not intended to cover variable frequency drive and motor systems.

Instructions: Find the symptom that best describes your observation. Next record all the possible causes listed in the "Possible Cause" column. These are all the possible causes that should be investigated to determine the root cause of the problem.

Table B.8 Electric motor troubleshooting table.

Symptom	Possible cause (Advice)
Motor starts up and runs but then trips off line	
	1. Voltage drop
	2. Load increases beyond rated horsepower
	3. Incorrect wiring (Recheck motor nameplate for proper wiring sequence)
Motor takes too long to accelerate	
	1. Voltage too low
	2. Rotational inertia of entire train too high
	3. Bad bearings
	4. Internal rub
	5. Load of driven machine too high
Motor frequently trips	
	1. Load of driven machine too high
	2. Ambient temperature too high

(*Continued*)

Table B.8 Cont.

Symptom	Possible cause (Advice)
	3. Fuse(s) or circuit breaker(s) may be incorrectly sized or is defective (Check and replace if required)
	4. Winding shorted or grounded
	5. High winding temperature
Motor vibrates	
	1. Motor misaligned to driven machine
	2. Bad bearings
	3. Rotor out of balance
	4. Rotor short or cracked rotor bars
	5. Loose stator
	6. Soft foot (Check for soft foot issues)
	7. Weak baseplate or foundation
	8. Broken grout
	9. Rubbing or imbalance due to excessive bearing grease getting into the motor windings

Hot Bearing Problems

High radial or thrust bearing temperatures are commonly encountered machinery field problems that have the potential of leading to catastrophic bearing failures and costly repairs. High bearing temperatures are either determined by embedded thermocouples or measured manually with temperature measuring devices, such as infrared or contact thermometers or infrared thermography camera. The first question to ask is: Is the bearing failing or is the high temperature caused by a support system issue or a design or lubrication problem? Before drawing any conclusions, it is important to conduct a field survey yourself using an infrared temperature gun, contact thermometer or infrared thermography camera. Between an infrared temperature gun and a contact thermometer, the contact thermometer is preferred due to its accuracy. You can use the IR thermometers for quick field surveys to pinpoint problem areas and then use the contact thermometers for accurate surface temperature values.

> Should I use an infrared gun or contact thermometer?
>
> If a quantitative temperature analysis is required, a contact thermometer should be considered over an infrared thermometer. Contact thermometers are inexpensive and accurate temperature measuring devices that deliver repeatable results, regardless of the color or finish of the surface being analyzed. In contrast, infrared thermometers are more accurate when used on flat, dark-colored surfaces and tend to yield low readings on shiny surfaces.

Here are locations where temperatures should be taken:

Closed looped oil circulation systems

1. Bearing cap or bearing housing temperatures
2. Inlet and outlet oil cooler temperatures — A small differential on the cooler means the cooler is not removing heat from the return oil.

3. Bearing supply oil and drain oil temperatures
   a. A high inlet temperature indicates an oil cooling issue
   b. A normal inlet temperature and high drain temperature indicated a problem at the bearing or with the lubricant properties.

Sump lubrication systems

1. Bearing cap temperature
2. Oil sump temperature
3. Cooling water supply and outlet temperatures (if cooling coils are used)

Greased bearing

1. Bearing cap temperature

How Serious Is the Problem?

Two factors determine the extent of the problem. The first is the actual bearing temperatures. Chapter 19 in *Is My Machine OK?* contains bearing temperature guidelines for the various bearing types. The second factor is how temperatures are trending with respect to historical temperature data. If the temperature is in the alarm range and climbing rapidly, it is time to shut down; however if the bearing is in the alarm range or close to it but stable, then there is time to investigate the problem further.

The bearing temperature troubleshooting table below can be used to hone in on potential causes of the high temperature issue. Use this information along with the 5Qs method to decide how to proceed. Keep in mind that once the bearing temperature reaches the danger range, it is time to shut down before secondary damage occurs.

Table B.9 Troubleshooting tips for hot bearings.

Lubrication method	**Problem category**	**Potential Issue**	**Comment(s)**
C,S,G	Design	Bearing design errors	Have manufacturer or OEM review design.
C,S,G	Design	Bearing undersized (load miscalculated)	Have manufacturer or OEM review design.
C,S	Installation	Wrong bearing clearance	Check clearance.
C,S	Installation	Wrong bearing crush	Check crush.
C,S,G	Installation	Wrong bearing	Check bearing part number.
C,S,G	Installation	Wrong installation procedure	Confirm the proper installation procedure was used.
C,S,G	Installation	Bearing damage during installation	Confirm that the proper installation procedure was used.
C	Cooling	Oil cooler bypassed (pressurized lube systems)	Check operation of thermostatic bypass valve. Use temperature gun to check operation of bypass valve.

(*Continued*)

Table B.9 Cont.

Lubrication method	Problem category	Potential issue	Comment(s)
C	Cooling	Oil cooler undersized (pressurized lube systems)	Check inlet and outlet oil temperatures on cooler. Low delta T indicates the cooler is ineffective. Possible design issue.
C	Cooling	Oil cooler plugged (pressurized lube systems)	Check inlet and outlet oil temperatures on cooler. Low delta T indicates the cooler is ineffective. Maintenance issue.
C,S	Cooling	Oil cooler fins plugged or damaged	Check inlet and outlet oil temperatures on cooler. Low delta T indicates the cooler is ineffective. Maintenance issue.
C	Cooling	Oil cooler louvers closed (pressurized lube systems)	Check inlet and outlet oil temperatures on cooler. Low delta T indicates the cooler is ineffective.
S	Cooling	Cooling coils fouled or plugged (small oil sumps)	Check inlet and outlet cooling water temperatures. Low delta T indicates the cooling coil is ineffective. Maintenance issue.

C	Flow	Wrong oil flow orifice (pressurized lube systems)	A single hot bearing might indicate that a wrong orifice was supplied. Installation or assembly issue.
C	Flow	Flow orifice plugged (pressurized lube systems)	A sudden increase in temperature of single bearing might indicate that an oil flow orifice is plugged. Maintenance issue.
S	Flow	Oil ring, slinger or flinger ineffective.	Open bearing housing view port and inspect operation of oil ring, flinger or slinger. This could be a design or maintenance issue.
C	Flow	Oil supply pressure too low (pressurized lube systems)	Look for 1) leaking spill back valve or 2) relief valve or worn pump(s).
S	Flow	Oil level too low (small oil sumps)	Check sump level. 1) A clogged oil level gauge line can give a false reading of lubrication level. 2) For closed systems use an expansion chamber or a balance line to prevent pressure buildup in bearing housing. 3) For open systems watch for clogged vent.

(*Continued*)

Table B.9 Cont.

Lubrication method	Problem category	Potential issue	Comment(s)
C,S,G	Operational Issue	Speed too high	Check machine speed and compare with design speed.
C,S,G	Operational Issue	Excessive load	Check to see if operating conditions are normal (pressures, flows, density, etc.).
C,S,G	Lubrication	Wrong lubricant	Review lubricant data or test lubricant properties.
C,S	Lubrication	Oil sump contamination (pressurized oil systems and oil sumps)	Analyze lube oil.

G	Lubrication	Lack of grease or old grease (greased bearings)	Remove grease drain plug. If nothing comes out of drain, add fresh grease and recheck bearing temperature.
G	Lubrication	Too much grease (greased bearings)	Remove grease drain plug. If grease or oil comes out, wait until bearing reaches operating temperature. Then replace drain plug and recheck bearing temperature.

Lubrication Methods: C-closed loop oil circulation system, S-sump oil system, G-grease lubrication

Review Questions & Exercises

1. Select the best statement that completes the definition of **Failure analysis**:

Failure analysis is the process of ____________

   a. Determining why a machine is not performing as expected
   b. Collecting and analyzing data to determine the cause of a machine failure
   c. Collecting and analyzing data to better understand a machine's environment

2. Complete the definition for Field troubleshooting

Field troubleshooting is a process of determining the cause of an apparent machine problem ________________.

   a. After it has failed and has been dissembled in a repair shop

b. After its installation, but before it's started up
c. While it is still operating under process conditions and before it has failed.

3. There are two types of machine loads:

a. Static and modal loads
b. Modal and pressure loads
c. Static and dynamic loads

4. The Pareto Principle, also known as the 80–20 rule, states that, for many events, roughly __________ of the observed effects come from ___________of the causes.

5. One of the most challenging aspects of machinery professional or operator's job is deciding whether an operating machine should be __________ due to a perceived problem or be allowed to _________.

6. Machines are mechanical systems composed of internal elements that basically fall under various categories of functions.

a. Give three examples of internal elements that make up a centrifugal pump.
b. Give two examples of internal elements that make up centrifugal compressors.

7. How a machine component responds to a load depends on:

   a. The component's geometry and material properties
   b. The component's length and finish
   c. The type of coating applied to the component

8. Give an example of how a process system problem can affect pump performance.
9. Give an example of how a process system problem can affect compressor performance.
10. List some potential risks associated with a catastrophic centrifugal compressor failure.
11. List some potential risks associated with a catastrophic pump failure.
12. List some potential risks associated with an electric motor.
13. Rank the following list of risks in order of highest to lowest:

    a. Likely possibility of $500,000 in production losses
    b. Likely possibility of an injury
    c. Very likely possibility of $10,000 repair costs
    d. Very likely possibility of a major environmental release of a regulated liquid

14. Who would you talk to if you needed to get information on each of the following situations?

    a. Details about a new compressor installation
    b. Details on a pump bad actor

15. If a vibration problem is detected immediately following a centrifugal compressor repair, what possible causes could be postulated?

16. If pump performance has dropped off after seven years of operations, what possible causes could be postulated?

17. If centrifugal compressor vibration levels are extremely speed sensitive, what possible causes could be postulated?

18. What data plot could you generate to prove that a high discharge temperature on a compressor coincides with a changing high discharge pressure?

19. Let's assume you measure high vibrations in the vertical direction of a motor foot. If you find that the baseplate is not vibrating but the foot is, what can you conclude?

20. What can you infer if one radial bearing of a compressor train with a force feed lubrication is running hot and the other bearings are operating at normal temperatures?

21. Describe a possible test to determine if a pump bearing housing resonance is aggravating a vibration problem.

22. Describe a possible test to prove low pump flow is causing high pump vibration.

23. Describe a possible test to prove that low reciprocating compressor flow is caused by a leaking spillback valve.

24. Name the 5Qs that apply to news reporting and troubleshooting.

25. Draw a cause map that can explain the reasons a light bulb in your house won't turn on.

26. Pump troubleshooting exercise:

Using the troubleshooting matrix below, draw a cause map with all the possible causes that can cause a high pump pressure.

Centrifugal Pump Troubleshooting Matrix

	Common symptoms								
Instructions: Find the "Common Symptom" that best describes your field condition and then go down and find all the possible "Common Root Causes," which are denoted by the symbol "X." These are all the possible causes that should be investigated to determine the actual root cause.	Flow too low	Flow too high	Unstable flow	Pressure too high	Pressure too low	High pressure pulsations	Power too high (1)	Power too low (1)	High vibrations or noisy (2)
a. Wrong impeller diameter(s)	X	X	X	X	X	X	X	X	
b. Wrong impeller speed	X	X	X	X	X	X	X	X	
c. Impeller installed backwards	X				X			X	
d. Pump turning backwards	X				X			X	

(*Continued*)

		Common symptoms								
Common root causes	e. Back pressure too high	X		X	X		X		X	
	f. Back pressure too low		X	X		X	X	X		
	g. Plugged suction strainer or piping	X		X		X	X		X	X
	h. Suction level too low	X		X		X	X			X
	i. Cavitation	X		X		X	X		X	X
	j. Air or vapor entrainment	X		X			X		X	X
	k. Too far away from BEP, i.e., flow too high or too low relative to design			X	X		X			X
	l. Rotor imbalance									X
	m. Pump to driver misalignment									X
	n. Pump worn out	X				X		X		X

(1) The potential root causes for these two columns only apply if horsepower increases with flow. These column headings must be reserved if horsepower decreases with flow. Refer to the "How Horsepower Varies with Flow" at the end of this section for more information on this topic.

(2) For more information on potential causes of vibration, refer to Chapters 14 and 15 in *Is My Machine OK?*

27. Using the centrifugal pump troubleshooting matrix list all the "Common Root Causes" of high flow.

28. Using the reciprocating troubleshooting matrix in the back of the book list all the "Common Root Causes" of high horsepower load.

29. List the team members you would select for a complex problem involving steam turbine driving a centrifugal pump. The steam turbine can't reach rated speed during start-ups.

30. Assume you have concluded that a centrifugal compressor is failing and needs to be shut down for repair. Who would you invite to a meeting to finalize your plan of action?

31. Assume you have concluded that a fully spared reciprocating compressor has some failing cylinder valves. What are your options going forward?

32. ______________ is the methodology that uses information gathered with internally or internally mounted motion sensors to assess a machine's mechanical condition.

33. The methodology in question 32 can be used to:

    a. Determine when a catastrophic failure is going to occur

b. Determine the general nature of the machine defect by identifying the magnitude of the dynamic motion
c. Determine the general nature of the machine defect by identifying the predominate frequency of the dynamic motion

34. A rotordynamics analysis uses rotor geometry and bearing support information to determine:

a. Critical speeds
b. How the rotor will respond to imbalance
c. How rotor or bearing design changes will effect vibration
d. All of the above

35. A ________________________ (choose from the options below) should be performed before any major modifications to the rotor or bearings:

a. Rotordynamic analysis
b. Oil Analysis
c. Hazard analysis

36. List a few ways you can improve troubleshooting capabilities at your site.

Answers to the Review Questions & Exercises

1. Select the best statement that completes the definition of **Failure analysis**:

Failure analysis is the process of collecting and analyzing data to determine the cause of a machine failure.

2. Complete the definition for Field trouble-shooting

Field troubleshooting is a process of determining the cause of an apparent machine problem while it is still operating under process conditions and before it has failed.

3. There are two types of machine loads:

   a. Static and dynamic loads

4. The Pareto Principle, also known as the 80–20 rule, states that, for many events, roughly **80%** of the observed effects come from **20%** of the causes.

5. One of the most challenging aspects of a machinery professional or operator's job is deciding whether an operating machine should be shut down due to a perceived problem or be allowed to keep operating.

6. Machines are mechanical systems composed of internal elements that basically fall under various categories of functions.

    a. Give three examples of internal elements that make up a centrifugal pump.
        i. Shaft, seal, bearing, impeller, coupling hub, pump casing, etc.
    b. Give two examples of internal elements that make up centrifugal compressors
        i. Shaft, seal, bearing, impeller, coupling hub, compressor casing, diaphragms, etc.

7. How a machine component responds to a load depends on: c. The component's geometry and material properties.

8. Give an example of how a process system problem can affect pump performance.

   a. A blockage in the discharge of a pump can lead to low pump flow.
   b. Entrained vapors in the suction of a pump can lead to a low pump discharge pressure.

9. Give an example of how a process system problem can affect compressor performance

   a. Light gas will reduce the head capability of the compressor
   b. Light gas could cause a compressor to surge
   c. Heavy gas can lead to high horsepower requirements

10. List some potential risks associated with catastrophic centrifugal compressor failure

    a. Loss of containment
    b. Major equipment damage
    c. Potential fire if gas is flammable
    d. Loss of production

11. List some potential risks associated with catastrophic pump failure

    a. Loss of containment
    b. Major equipment damage

c. Potential fire if pumped liquid is flammable
d. Loss of production if pump is not spared

12. List some potential risks associated with an electric motor

a. Major equipment damage
b. Loss of production if unspared

13. Rank the following list of risks in order of highest to lowest:

Here is how the authors rank these risks:

a. Likely possibility of an injury
b. Very likely possibility of a major environmental release of a regulated liquid
c. Likely possibility of $500,000 in production losses
d. Very likely possibility of $10,000 repair costs

Answer: The actual ranking depends on your personal risk profile. Here is one risk ranking that seems reasonable: b, d, a, c.

14. Who would you talk to if you needed to get information on each of the following situations?

a. Details about a new compressor installation: 1) The project manager for the design details, 2) the construction foremen for insight into the compressor's installation, and 3) the mechanics for insight into compressors start-up issues.
b. Details on a pump bad actor: The operators of the pumps and the mechanics that work on them.

15. If a vibration problem is detected immediately following a centrifugal compressor repair, what possible causes could be postulated? 1. A bad repair, 2. Poor alignment, 3. Poor rotor balance.

16. If pump performance has dropped off after seven years of operations, what possible causes could be postulated? 1. Pump wear clearances have opened up. 2. Impeller has experienced severe erosion.

17. If centrifugal compressor vibration levels are extremely speed sensitive, what possible causes could be postulated? Speed sensitivity either means a critical speed is present or there is a rotor instability present.

18. What data plot could you generate to prove that a high discharge temperature on a compressor coincides with a changing high

discharge pressure? A correlation plot of the compressor's discharge temperature versus the compressor discharge pressure should reveal is there is a strong correlation between these two variables.

19. Let's assume you measure high vibrations in the vertical direction of a motor foot. If you find that the baseplate is not vibrating but the foot is, what can you conclude? The hold down bolt is probably loose or broken.

20. What can you infer if one radial bearing of a compressor train with a force feed lubrication is running hot and the other bearings are operating at normal temperatures? Either the oil feed to the hot bearing is plugged or the hot bearing is failing.

21. Describe a possible test to determine if a pump bearing housing resonance is aggravating a vibration problem. An impact test, also known as a bump test, can be used to determine if there is a bearing housing resonance present. The bearing housing will "ring down" when impacted sharply. The frequency of the ringing is the bearing housing resonance frequency.

22. Describe a possible test to prove low pump flow is causing high pump vibration. Increase

the pump flow by opening a bypass line and see if vibration levels change.

23. Describe a possible test to prove that low reciprocating compressor flow is caused by a leaking spillback valve. Perform a field audit and ensure all potential spillback lines are closed. Also, check for possible leaking valves.

24. Name the 5Qs that apply to news reporting and troubleshooting. What, Who, When, Where, and Why.

25. Draw a cause map that can explain the reasons a light bulb in your house won't turn on.

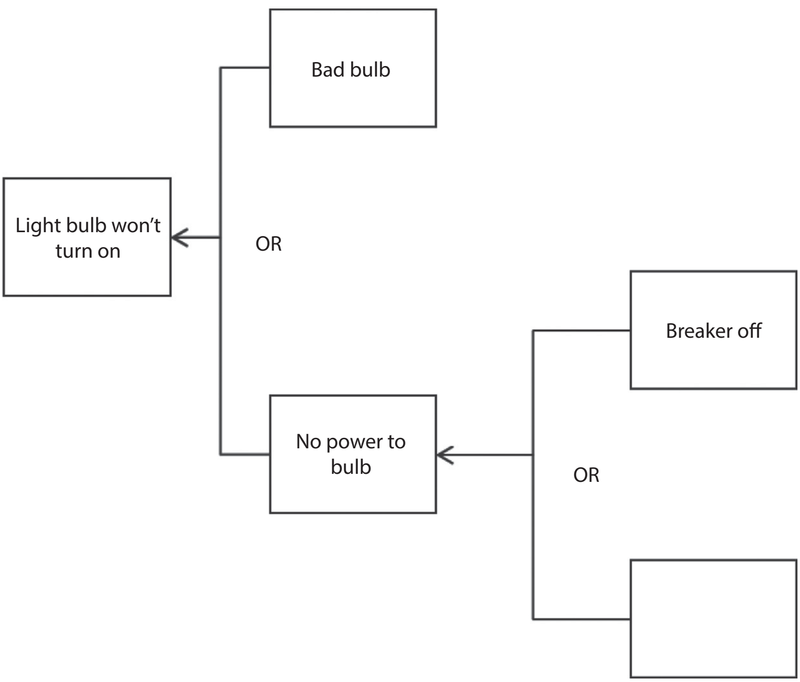


Figure A Light bulb cause map.

26. Pump troubleshooting exercise:

Using the troubleshooting matrix below, draw a cause map with all the possible causes that can cause a high pump pressure.

Centrifugal Pump Troubleshooting Matrix

By inspection, we see that there are four possible causes of a high pump pressure:

1) Wrong diameter impeller, 2) wrong impeller speed, 3) back pressure too high, and 4) too far away from BEP

Instructions: Find the "Common Symptom" that best describes your field condition and then go down and find all the possible "Common Root Causes," which are denoted by the symbol "X." These are all the possible causes that should be investigated to determine the actual root cause.	Common symptoms: Flow too low	Flow too high	Unstable flow	Pressure too high	Pressure too low	High pressure pulsations	Power too high (1)	Power too low (1)	High vibrations or noisy (2)
a. Wrong impeller diameter(s)	X	X	X	X	X	X	X	X	
b. Wrong impeller speed	X	X	X	X	X	X	X	X	
c. Impeller installed backwards	X				X			X	
d. Pump turning backwards	X				X			X	
e. Back pressure too high	X		X	X		X		X	

Common root causes	Common symptoms								
f. Back pressure too low		X	X		X	X	X		
g. Plugged suction strainer or piping	X		X		X	X		X	X
h. Suction level too low	X		X		X	X			X
i. Cavitation	X		X		X	X		X	X
j. Air or vapor entrainment	X		X			X		X	X
k. Too far away from BEP, i.e. flow too high or too low relative to design			X	X		X			X
l. Rotor imbalance									X
m. Pump to driver misalignment									X
n. Pump worn out	X				X		X		X

(1) The potential root causes for these two columns only apply if horsepower increases with flow. These column headings must be reserved if horsepower decreases with flow. Refer to the "How Horsepower Varies with Flow" at the end of this section for more information on this topic.

(2) For more information on potential causes of vibration, refer to Chapters 14 and 15 in *Is My Machine OK?*

Using the four possible causes found in the troubleshooting table we can draw the following cause map:

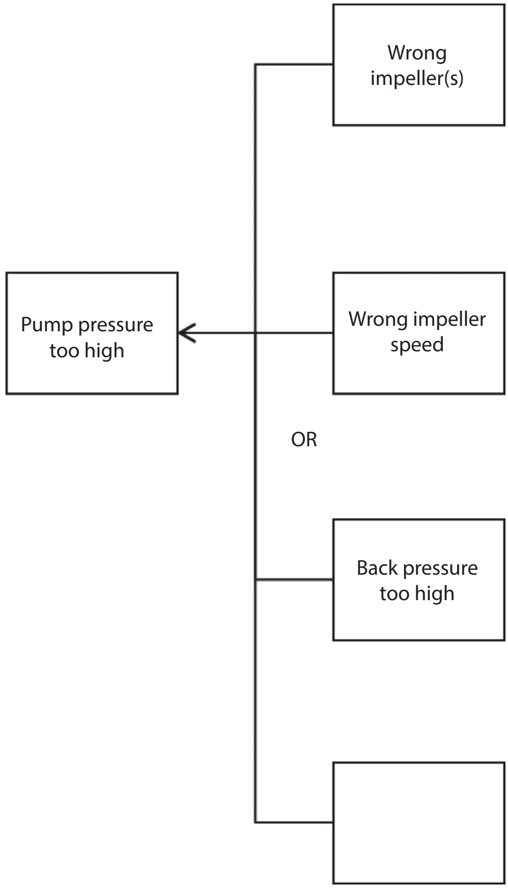


Figure B Centrifugal pump cause map

27. Using the centrifugal pump troubleshooting matrix list all the "Common Root Causes" of high flow.

    a. Wrong impeller diameter
    b. Wrong impeller speed
    c. Back pressure too high

28. Using the reciprocating troubleshooting matrix in the back of the book list all the "Common Root Causes" of high horsepower load.

    a. Wrong clearance volume
    b. Wrong compressor speed
    c. Discharge pressure too high
    d. Plugged strainer or piping restriction
    e. Gas denser than design
    f. Leaking piston ring
    g. High valve losses

29. List the team members you would select for a complex problem involving steam turbine driving a centrifugal pump. The steam turbine can't reach rated speed during start-ups. Answer: Operations, maintenance mechanics, instrument specialist, and a machinery specialist. The steam turbine and centrifugal pump manufacturers may also need to be included in the team if the initial team can't determine the cause of the problem.

30. Assume you have concluded that a centrifugal compressor is failing and needs to be shut down for repair. Who would you invite to a meeting to finalize your plan of action? Answer: Operations, maintenance planning, compressor specialist, and the contractor performing the compressor repair.

31. Assume you have concluded that a fully spared reciprocating compressor has some failing cylinder valves. What are you options going forward?

    a. Run to failure
    b. Monitor compressor performance and hope to get a few more weeks of life out of the valves.
    c. Preemptively replace valves.

32. ______________ is the methodology that uses information gathered with internal or internal mounted motion sensors to assess a machine's mechanical condition? Answer: Vibration Analysis.

33. The methodology in question 32 can be used to: Answer: c. Determine the general nature of the machine defect by identifying the predominant frequency of the dynamic motion.

34. A rotordynamics analysis uses rotor geometry and bearing support information to determine: Answer: d. all the above

35. A rotordynamic analysis should be performed before any major modifications to the rotor or bearings:

36. List a few ways you can improve troubleshooting capabilities at your site.

    a. Practice the 5Qs method whenever possible
    b. Provide training on fault trees and cause mapping to all those in a position to use these methods
    c. Employ team approach for complex problems
    d. Get management's support