

Pumps and compressors

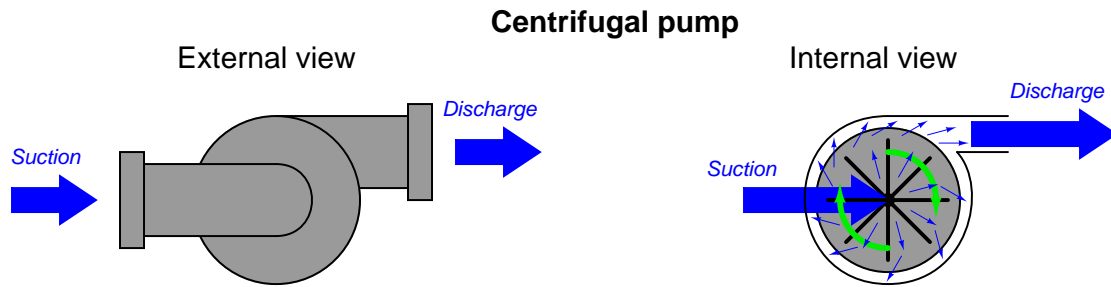
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This worksheet introduces the basic concepts of pumps and compressors used in industry.

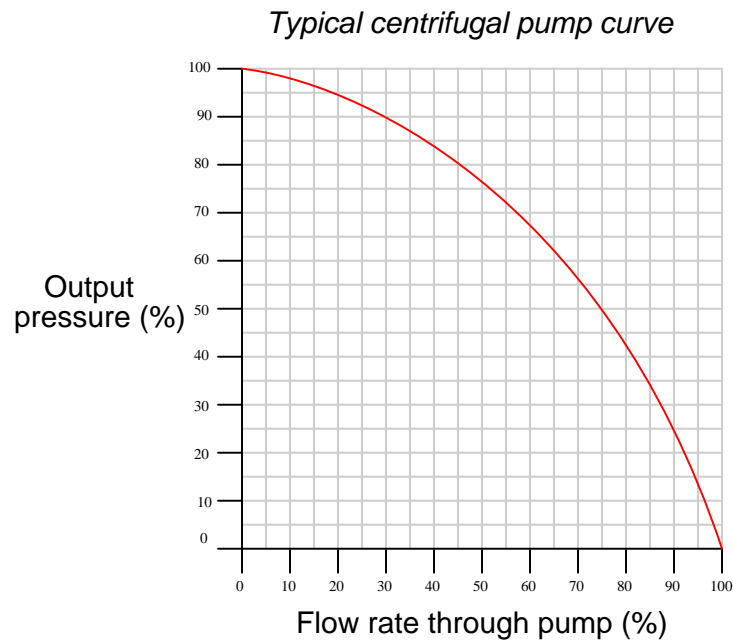
Questions

Question 1

A *centrifugal pump* works by spinning a disk with radial vanes called an “impeller,” which flings fluid outward from the center of the disk to the edge of the disk. This kinetic energy imparted to the fluid translates to potential energy in the form of pressure when the fluid molecules strike the inner wall of the pump casing:



The performance of a centrifugal pump is often expressed in a special graph known as a *pump curve*. A typical centrifugal pump curve appears here, traced for one particular shaft speed:



Examine this pump curve, and explain in your own words what it tells us about the performance behavior of this pump when turned at a constant speed.

Suggestions for Socratic discussion

- One way to describe the operation of a centrifugal pump is to say it generates discharge pressure by converting kinetic energy into potential energy. Elaborate on this statement, explaining exactly where and how kinetic energy gets converted to potential energy. Hint: this might be easier to answer if you consider the “limiting case” of maximum discharge pressure described by the pump curve, where flow is zero and pressure is maximum.

- Appealing to the conversion of energy between kinetic and potential forms, explain *why* discharge pressure for a centrifugal pump falls off as flow rate increases.
- The pump curve shown assumes a constant rotational speed for the pump's impeller. How would the pump curve be modified if the pump were rotated at a slower speed?

[file i01407](#)

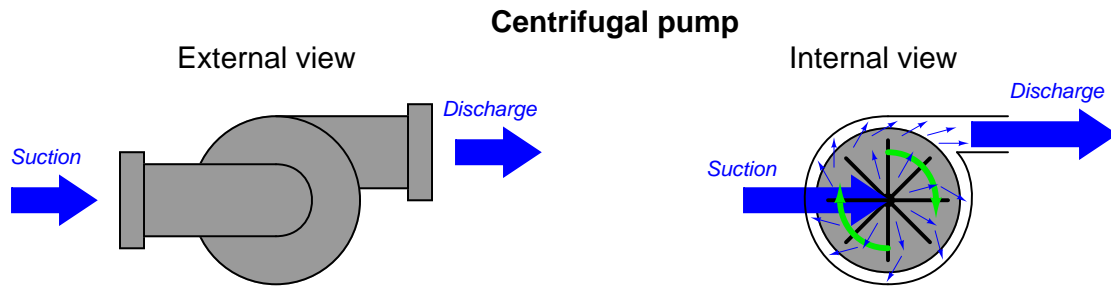
Question 2

Calculate the volumetric flow rate (in units of cubic feet per minute) for water flowing out of the 10-inch diameter discharge pipe of a centrifugal pump at a velocity of 25 feet per second. Then, convert that flow rate into units of gallons per minute.

[file i00732](#)

Question 3

A *centrifugal pump* works by spinning a disk with radial vanes called an “impeller,” which flings fluid outward from the center of the disk to the edge of the disk. This kinetic energy imparted to the fluid translates to potential energy in the form of pressure when the fluid molecules strike the inner wall of the pump casing:



The energy conveyed by the liquid exiting the discharge port of this pump comes in two forms: *pressure head* and *velocity head*. Ignoring differences in elevation (height), we may apply Bernoulli's equation to describe this fluid energy:

$$\text{Fluid Energy at discharge port} = \frac{\rho v^2}{2} + P$$

Where,

Fluid Energy = expressed in units of pounds per square foot, or PSF

P = Gauge pressure (pounds per square foot, or PSF)

ρ = Mass density of fluid (slugs per cubic foot)

v = Velocity of fluid (feet per second)

When the discharge port is completely blocked by an obstruction such as a closed valve or a blind, there is no velocity at the port ($v = 0$) and therefore the total energy is in the potential form of pressure (P). When the discharge port is completely unobstructed, there will be no pressure at the port ($P = 0$) and therefore the total energy is in kinetic form ($\frac{\rho v^2}{2}$). During normal operation when the discharge experiences some degree of resistance, the discharge fluid stream will possess some velocity as well as some pressure.

Assuming that the fluid molecules' maximum velocity is equal to the speed of the impeller's rim, calculate the discharge pressure under these conditions for a pump having an 8 inch diameter impeller spinning at 1760 RPM and a discharge port of 2 inches diameter, with water as the fluid (mass density $\rho = 1.94$ slugs per cubic foot) and assuming atmospheric pressure at the suction port:

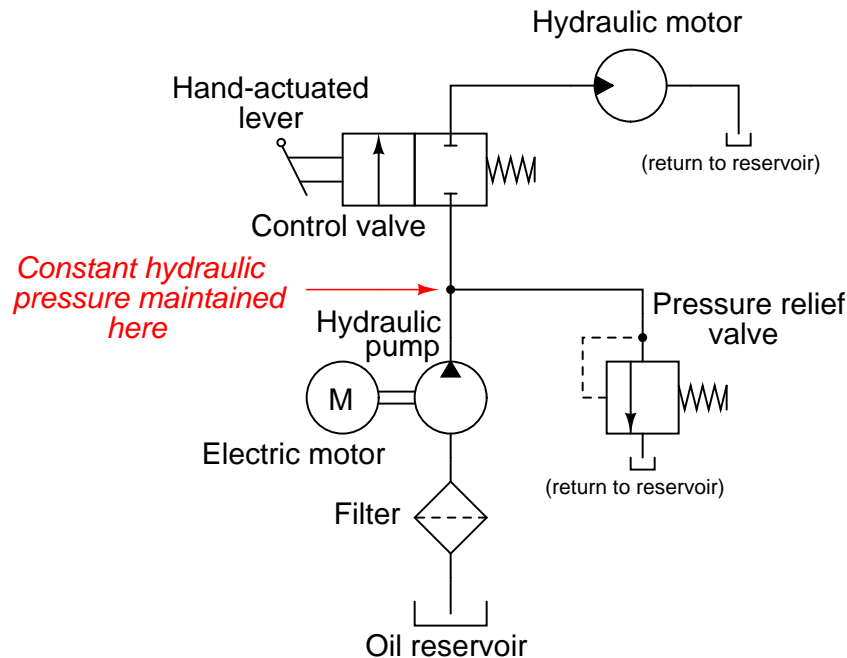
- Discharge flow = 0 GPM ; $P =$ _____ PSI
- Discharge flow = 100 GPM ; $P =$ _____ PSI
- Discharge flow = 200 GPM ; $P =$ _____ PSI
- Discharge flow = 300 GPM ; $P =$ _____ PSI
- Discharge flow = 400 GPM ; $P =$ _____ PSI
- Discharge flow = 500 GPM ; $P =$ _____ PSI

Next, calculate the maximum flow rate out of the pump with a completely open discharge port ($P = 0$).

[file i02588](#)

Question 4

Hydraulic (liquid) power systems require pressure regulation just like pneumatic (air) power systems. However, pressure control must be done differently in a hydraulic system. In a pneumatic system, the electric motor driving the air compressor is simply turned on and off to maintain air system pressure between two setpoints. In a hydraulic system, the electric motor driving the positive-displacement pump continually runs, with a pressure relief valve regulating line pressure:



If not for the pressure-relief valve, the hydraulic pump would “lock up” and refuse to turn whenever the control valve was placed in the “stop” position (as shown in the diagram). With the pressure-relief valve in place, the pump will continue to spin and hydraulic pressure will be maintained.

Explain why a positive-displacement hydraulic pump will “lock up” if its outlet line is blocked, and explain the operating principle of the pressure-relief valve.

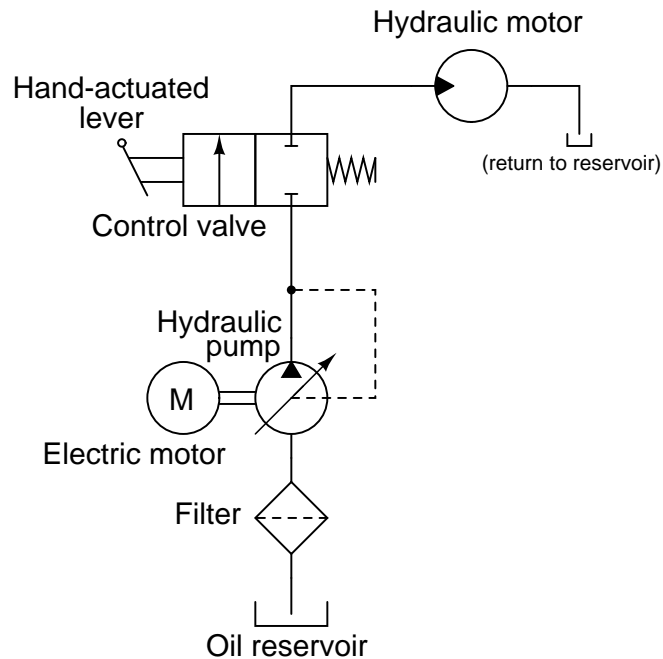
Suggestions for Socratic discussion

- Identify what would have to be altered in this fluid power system to *reverse* the direction of the motor.
- Would this system function adequately if the pressure relief valve were relocated to a location “downstream” of the spool valve?
- If the filter were to entirely plug and prevent flow through it, would the hydraulic pump “lock up” in the same way it would having its discharge port blocked?
- The Law of Energy Conservation states that energy cannot be created or destroyed, but must be accounted for in every system. When the spool valve is left in the “off” position and the motor does not move, where does all the energy go that is input by the pump into the fluid system? For example, if the hydraulic pump is being spun by a 1-horsepower motor, what happens to all that power if it is not directed to the motor to do mechanical work?

[file i00752](#)

Question 5

An alternative to using a pressure-relief valve to control pressure in a hydraulic system is to use a *variable-displacement pump* with hydraulic feedback:

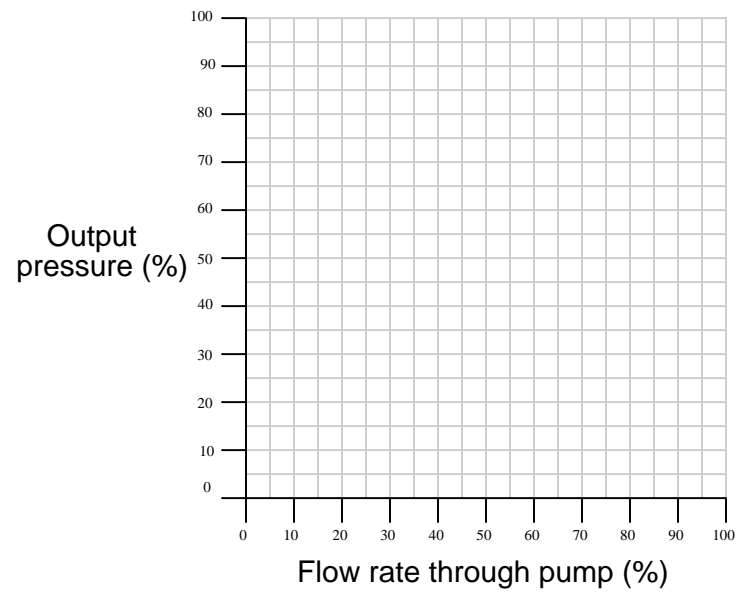


As hydraulic pressure increases, the pump mechanism automatically adjusts to give less volume displacement per rotation. Explain how this works to regulate pressure, and also why it saves energy compared to the more traditional design of a constant-displacement pump combined with a pressure-relief valve.

[file i00763](#)

Question 6

Sketch the *pump curve* for a positive-displacement pump turned at a constant speed by an electric motor:

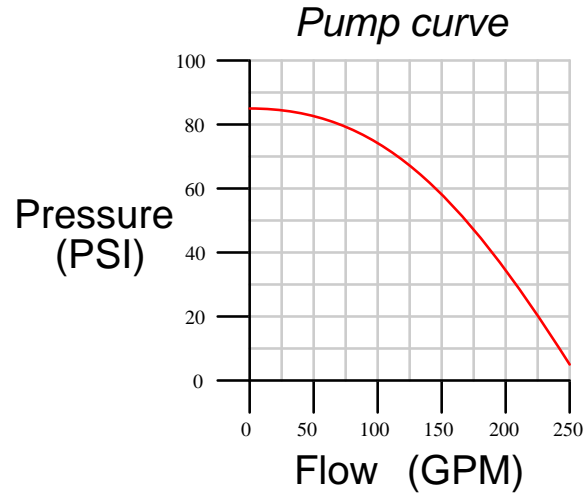


Suggestions for Socratic discussion

- What will change about the pump curve graph if the driving motor's speed changes?
[file i00743](#)

Question 7

Given the following pump curve for a water pump driven at a constant speed by an AC induction motor, determine the maximum flow rate of water it can deliver to different heights above the pump's discharge port:

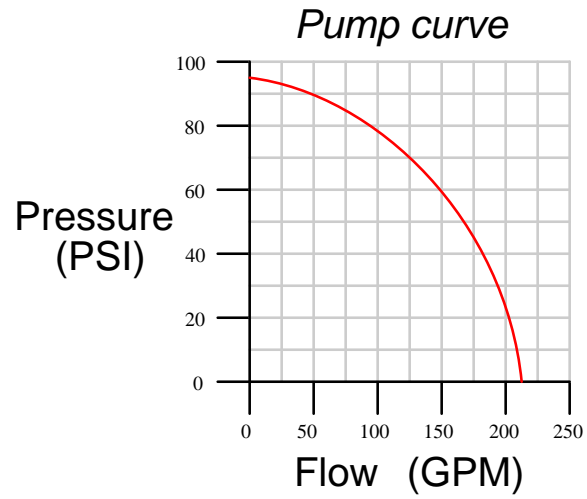


- Maximum flow at 10 feet above pump level = _____ GPM
- Maximum flow at 50 feet above pump level = _____ GPM
- Maximum flow at 100 feet above pump level = _____ GPM
- Maximum flow at 150 feet above pump level = _____ GPM

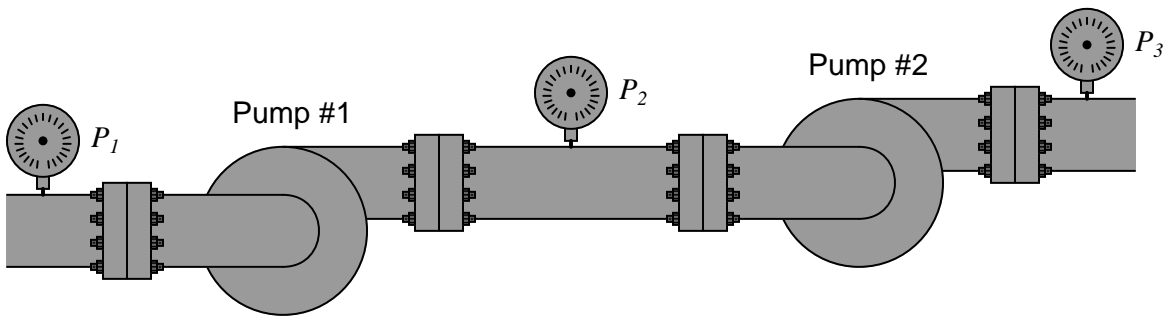
file i02684

Question 8

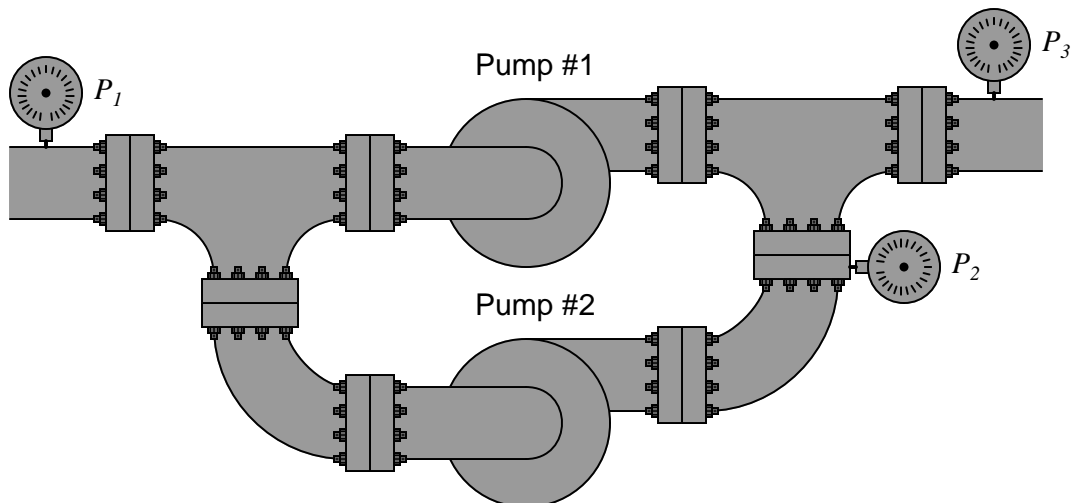
Suppose two identical pumps exhibit the exact same pump curve shown below:



If these two pumps are connected in *series* with a suction pressure of 45 PSI ($P_1 = 45$ PSI), calculate pressures P_2 and P_3 as well as total discharge flow rate when the flow rate through each pump is 150 GPM:



If these two pumps are connected in *parallel* with a suction pressure of 45 PSI ($P_1 = 45$ PSI), calculate pressures P_2 and P_3 as well as total discharge flow rate when the flow rate through each pump is 150 GPM:



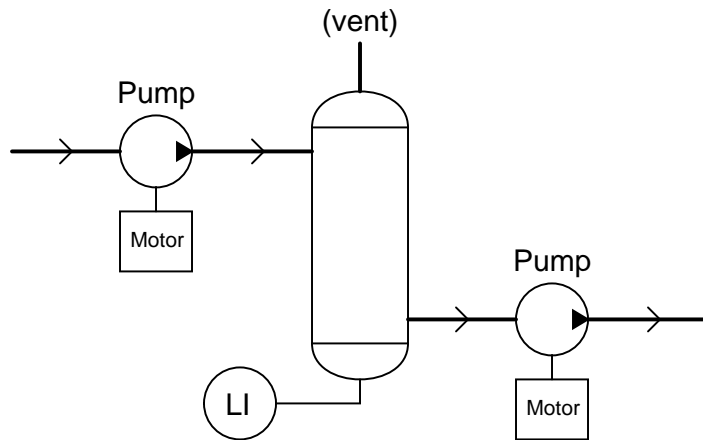
Suggestions for Socratic discussion

- Explain how series and parallel pumps act much the same as series and parallel *electrical* sources.
- Where might an engineer choose to use series pumps versus parallel pumps in a piping system?

[file i03560](#)

Question 9

Examine this P&ID:



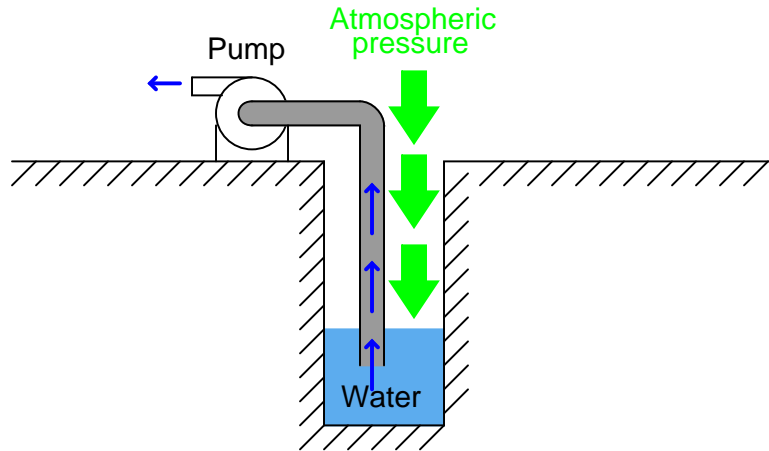
Each pump is of the “reciprocating” type, a form of positive displacement machine. In essence, each rotation of the motor shaft causes the pump to move a measured quantity of liquid from its inlet to its outlet. What will happen to the liquid level inside the vessel over time if one pump is moving more liquid flow?

Would you characterize this process as inherently *self-regulating* or inherently *integrating*?

[file i01658](#)

Question 10

A surface-mounted water pump pulls water out of a well by creating a vacuum, though it might be more technically accurate to say that the pump works by reducing pressure in the inlet pipe to a level less than atmospheric pressure, allowing atmospheric pressure to then push water from the well up the pump's inlet pipe:



Based on this description of pump operation, what is the theoretical maximum height that any pump can lift water out of a well, assuming the well is located at sea level?

Water wells located at altitudes other than sea level will have different theoretical maximum lifting heights (i.e. the farthest distance a surface-mounted pump may suck water out of the well). Research the average barometric pressure in Denver, Colorado (the “mile-high” city) and determine how far up a surface pump may draw water from a well in Denver.

Domestic water wells may be hundreds of feet deep. How can water be pumped out of wells this deep, given the height limitation of vacuum pumping?

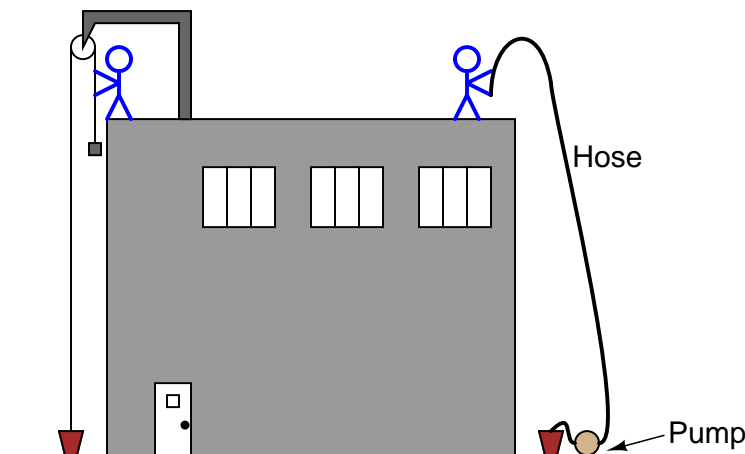
Suggestions for Socratic discussion

- If the liquid in question was something other than water, would the maximum “lift” depth be different? Why or why not?

[file i00147](#)

Question 11

One laborer working on the top of a building uses a manual hoist to lift 10 gallons of water 30 feet up from ground level, while a second laborer uses an electric pump to do the same:

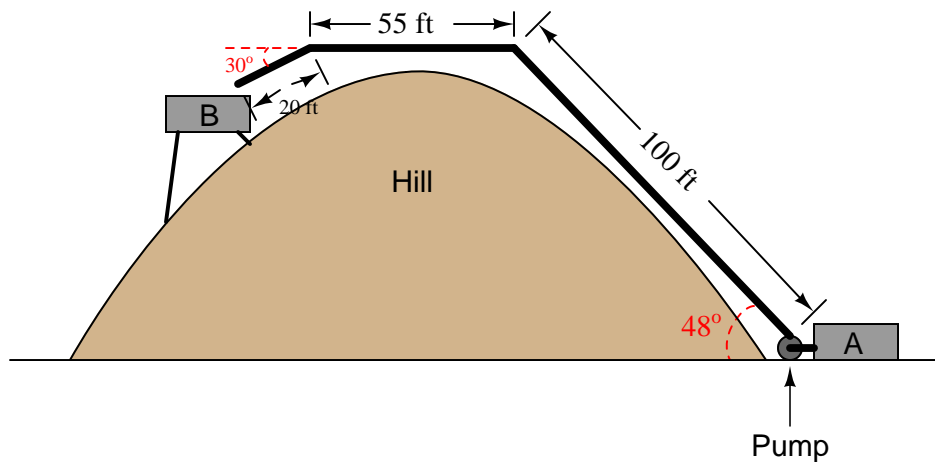


First, calculate the amount of work needed to lift 10 gallons up to the same roof. Then, calculate the time required for the pump to do this job, assuming a rating of 1.5 horsepower.

[file i02612](#)

Question 12

How much work is done pumping 3,000 gallons of water from reservoir "A" to reservoir "B" over the hill?



If the pump's power output is 250 horsepower, how long will it take to pump all 3000 gallons to reservoir "B"?

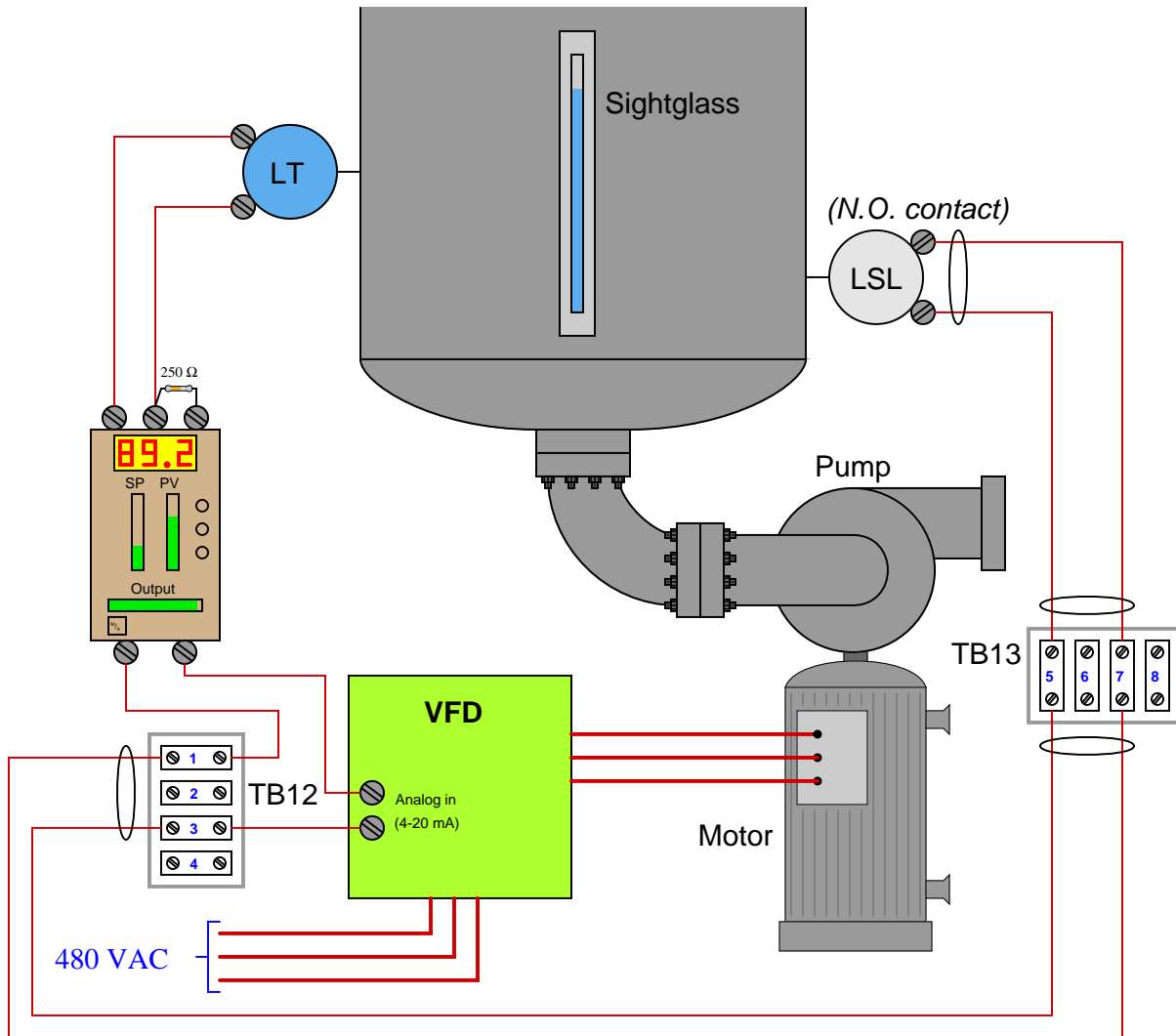
Suggestions for Socratic discussion

- Calculate the amount of pressure at the discharge port of the pump as it lifts water up to reservoir "B"

[file i02613](#)

Question 13

A level control system uses a variable-frequency motor drive (VFD) to control the speed of a pump drawing liquid out of the vessel. The greater the liquid level, the faster the pump spins, drawing liquid out at a faster rate. A low-level cutoff switch is also part of this control system, forcing the pump to a full stop to protect it from running dry if ever a low-level condition is sensed by the switch:



Unfortunately, this system seems to have a problem. The pump refuses to start even though the liquid level is greater than the controller's setpoint (as indicated by both the controller and the sightglass). It was running just fine yesterday, and no technician has touched any of the components since then.

A fellow instrument technician helping you troubleshoot this problem decides to perform a simple test: he uses his multimeter (configured to measure DC current) as a “jumper” wire to momentarily short together terminals 5 and 7 on terminal strip TB13. Still, the motor remains off and does not start up as it should.

Identify the likelihood of each specified fault for this control system. Consider each fault one at a time (i.e. no coincidental faults), determining whether or not each fault could independently account for *all* measurements and symptoms in this system.

Fault	Possible	Impossible
No AC power to VFD		
Controller has dead 4-20 mA output		
Level transmitter out of calibration		
Level switch contacts failed shorted		
Level switch contacts failed open		
250 ohm resistor failed open		
Cable between TB12 and TB13 failed open		
Cable between TB13 and LSL failed open		

Also, explain why the “jumper test” was a very good first step to take.

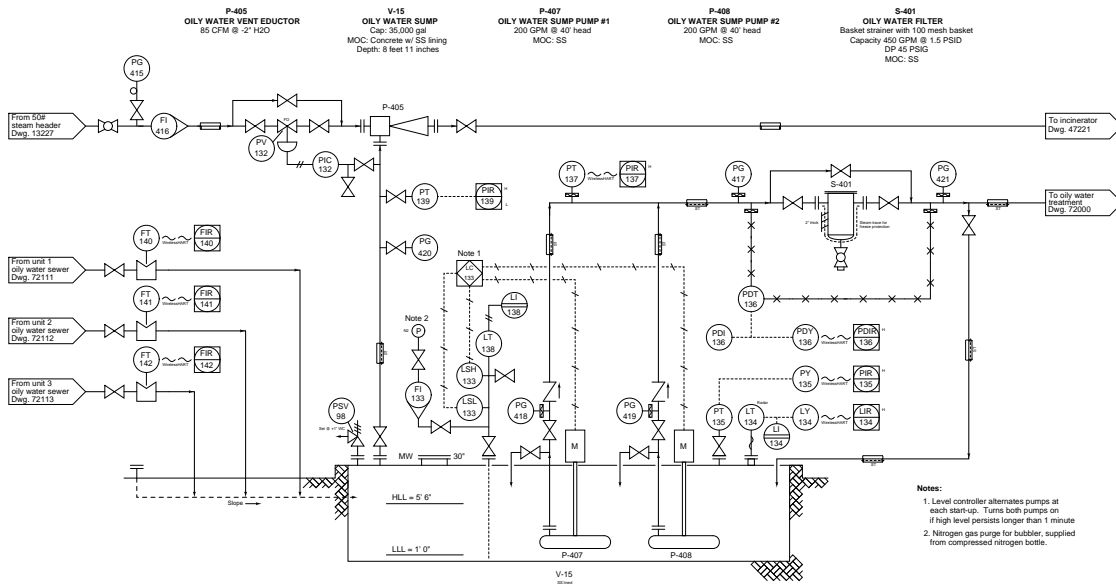
Suggestions for Socratic discussion

- Propose a “next test” to perform on this system to further isolate where the fault is located.
- Is this an example of a *soft-constraint* override system or a *hard-constraint* override system?
- Predict the effects resulting from various wiring faults in this system (e.g. *opens* or *shorts*).
- What does the label *normally open* (NO) mean for a switch such as the one sensing liquid level here?
- For those who have studied PID tuning, how should the level controller be tuned: mostly using proportional action, integral action, or derivative action to control the liquid level?

file i03235

Question 14

In this oily water sump process, two submersible pumps move water out of the sump based on liquid level measurement inside the sump:



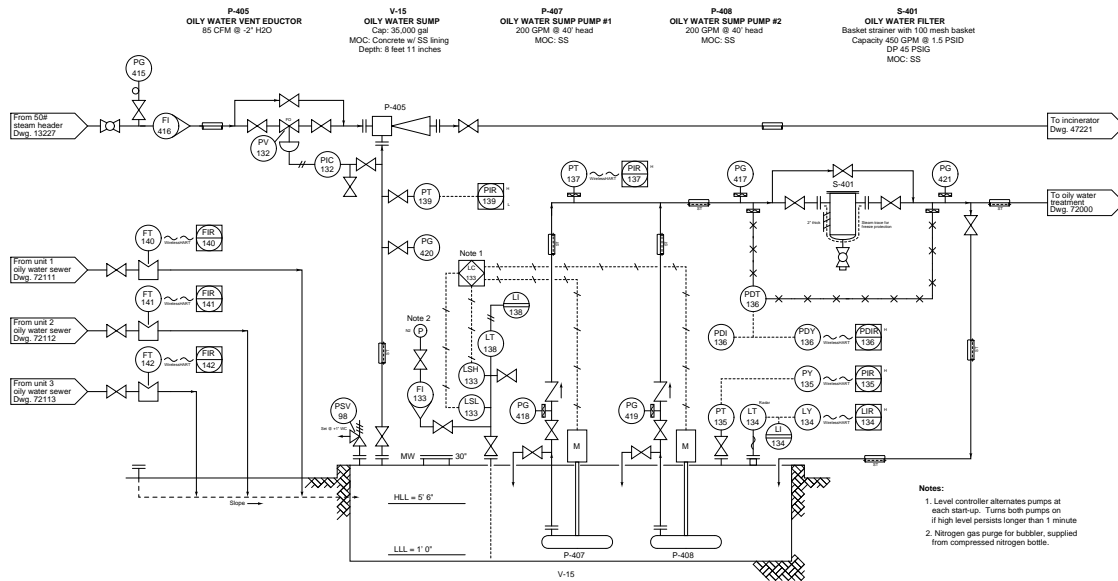
Examine this P&ID and answer the following questions:

- Why are “check” valves installed on the discharge lines of pumps P-407 and P-408?
- Supposing pump P-408 is the only one running, qualitatively determine the effects of pinching off the block valve immediately upstream of pressure gauge PG-419 on the following variables (e.g. *increase*, *decrease*, or *remain the same*):
 - Pressure at the pump’s discharge port
 - Pressure registered by PG-419
 - Electrical current to the driving motor
 - Flow rate of water through filter S-401
 - Pressure registered by PG-419
 - Oily water level inside the sump

[file i04794](#)

Question 15

Suppose operators submitted a “trouble-call” to your instrument shop, claiming sump V-15 had an excessive liquid level inside of it (as indicated by LIR-134), and that the pump was not pumping that level down as it should:



Identify at least three possible faults, each one independently capable of accounting for the high sump level indication. Also, identify any diagnostic tests you could perform on this system to pinpoint the nature and location of the fault.

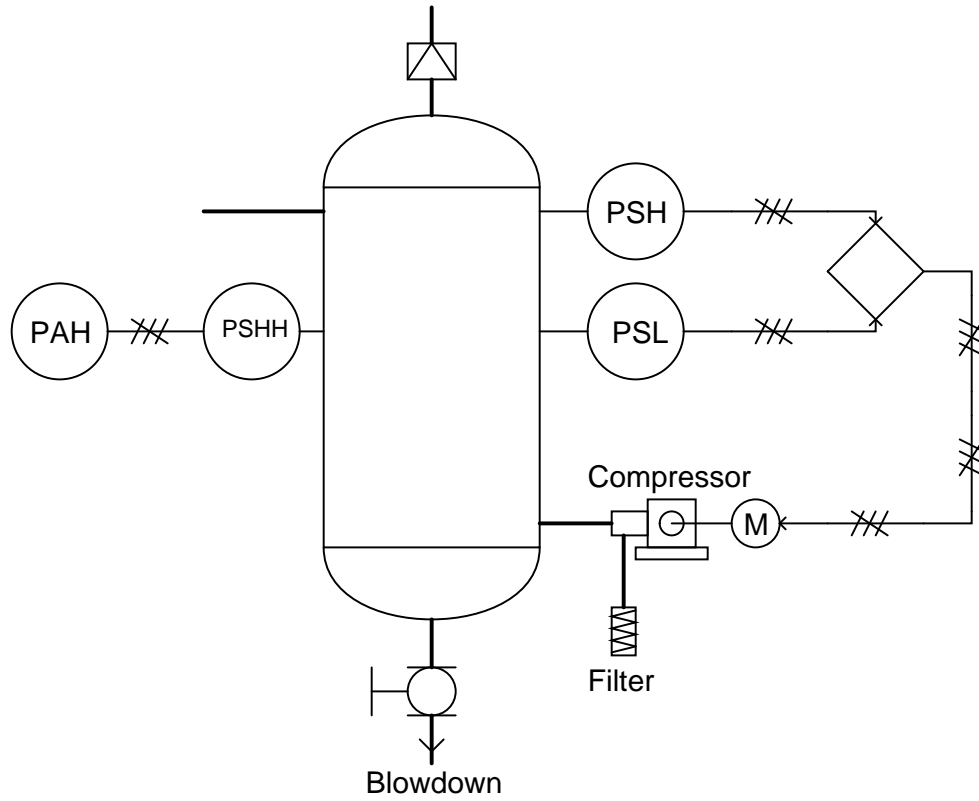
Suggestions for Socratic discussion

- Suppose this trouble-call came to you during a very cold winter day, when the outside temperature was well below freezing. How might this alter the list of potential faults?
- Explain the purpose for having *check valves* on the discharge lines of the two submersible sump pumps.
- Identify some of the different signal line types used in this P&ID, and what each of those line types means.
- Identify some of the different pressure-measurement accessory devices visible in this P&ID.

[file i03513](#)

Question 16

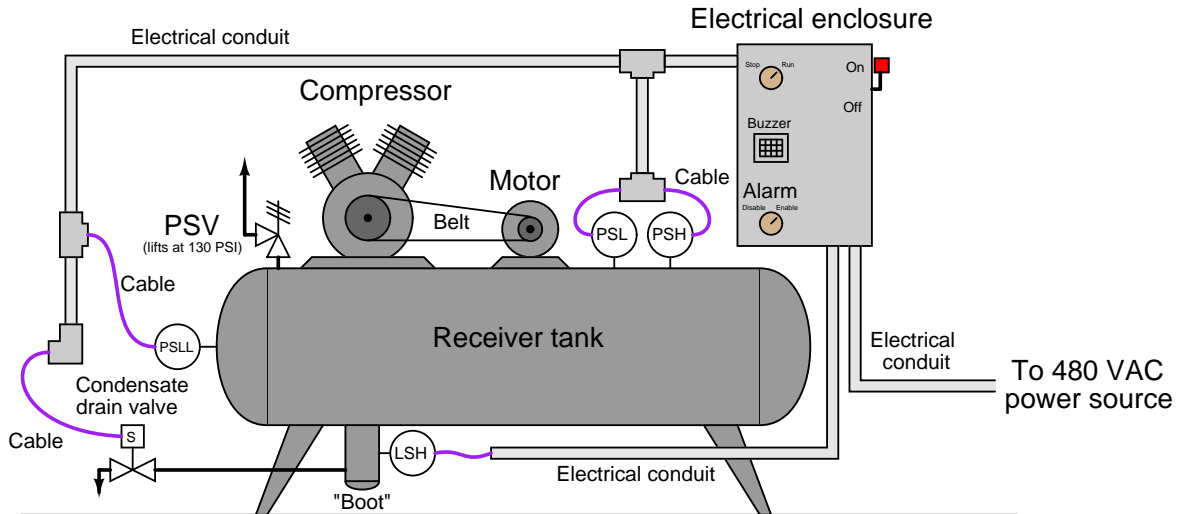
Describe all that is represented by this P&ID:



file i00219

Question 17

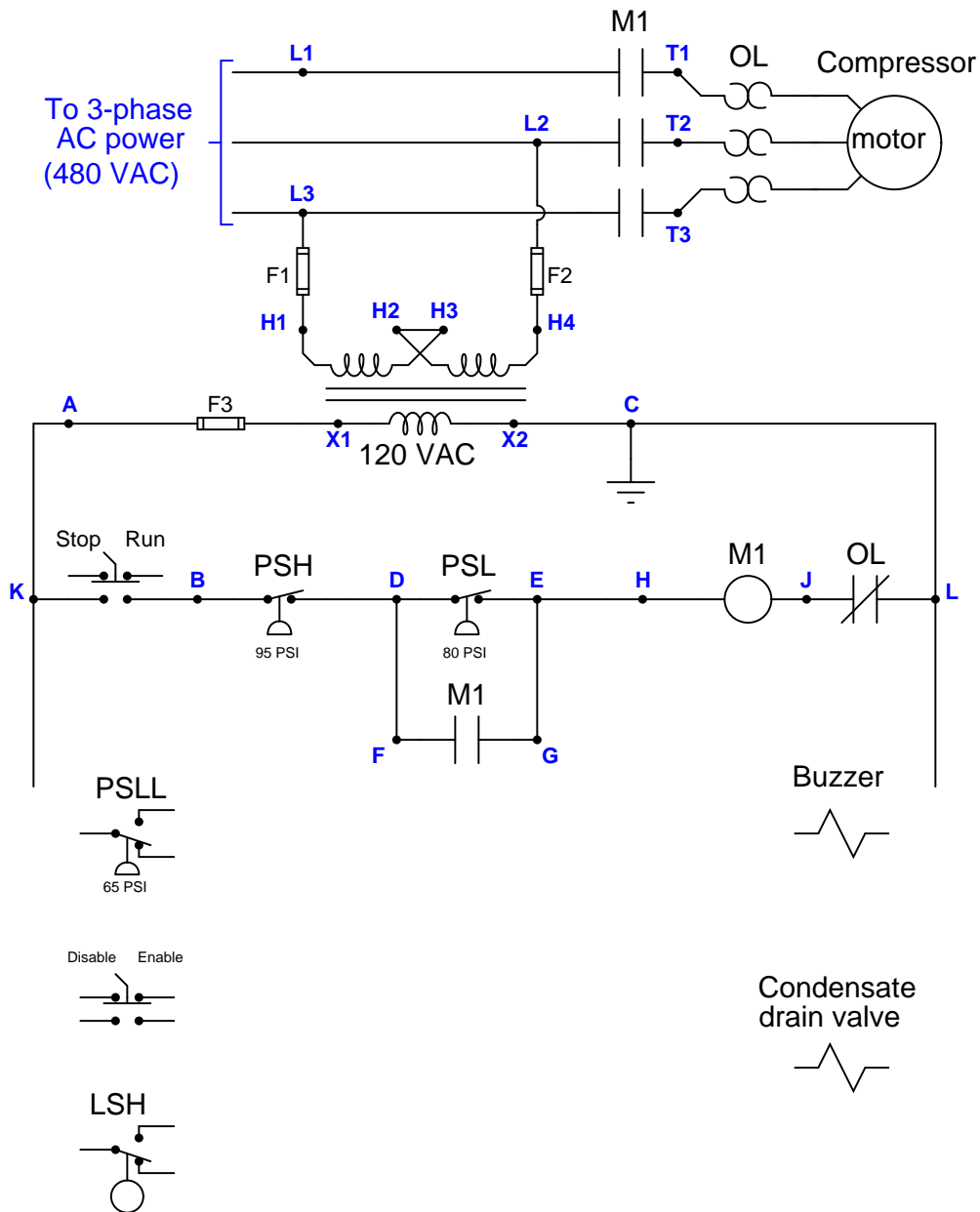
Electrically-powered air compressors are commonly used in many different industries for supplying clean, dry compressed air to machines, instrument systems, and pneumatic tools. A simple compressor system consists of a compressor which works much like a bicycle tire pump (drawing in air, then compressing it using pistons), an electric motor to turn the compressor mechanism via a V-belt, a “receiver tank” to receive the compressed air discharged by the compressor mechanism, and some miscellaneous components installed to control the pressure of the compressed air in the receiver tank and drain any condensed water vapor that enters the receiver:



Electromechanical relay circuitry located inside the electrical enclosure decides when to turn the compressor motor on and off based on the statuses of the high- and low-pressure control switches (PSH = high pressure switch ; PSL = low pressure switch).

Your task is two-fold. First, you must figure out how to wire a new low-low pressure alarm switch (PSLL, shown on the left-hand end of the receiver) so that an alarm buzzer will activate if ever the compressed air pressure falls too low. A newly-installed hand switch located on the front panel of the electrical enclosure must be wired with this PSLL switch in such a way that the buzzer cannot energize if the hand switch is in the “alarm disable” position. Second, you must figure out how to wire a new high-level switch (LSH, shown on the “boot” of the receiver tank) so that the condensate drain valve will energize automatically to open up and drain water out of the receiver boot when the level gets too high, and then automatically shut again when the water in the boot drops down to an acceptable level.

The following schematic diagram shows the basic motor control circuit for this air compressor, with the new switches, buzzer, and drain valve shown unwired:



Complete this control circuit by sketching connecting wires between the new switches, buzzer, and drain valve solenoid. Remember that the way all switches are drawn in schematic diagrams is in their “normal” states as defined by the manufacturer: the *state of minimum stimulus* (when the switch is un-actuated). For pressure switches, this “normal” state occurs during a low pressure condition; for liquid level switches, this “normal” state occurs during a low-level (dry) condition. Note that each of the new process switches has SPDT contacts, allowing you to wire each one as normally-open (NO) or as normally-closed (NC) as you see fit.

[file i02540](#)

Question 18

Suppose a compressor is operating with the following suction and discharge parameters:

Suction:

- Pressure = 45 PSIG
- Volumetric flow = 1300 CFM
- Temperature = 74 deg F

Discharge:

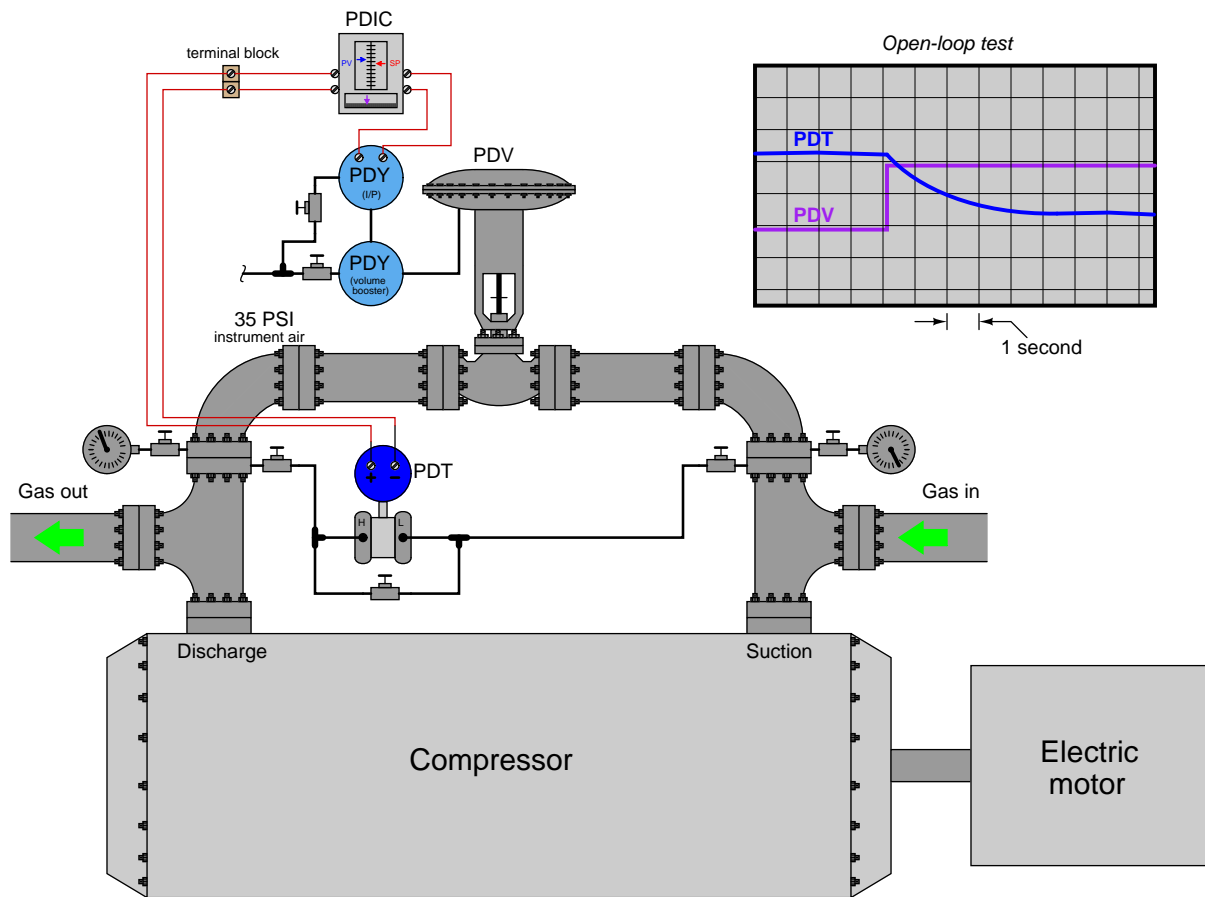
- Pressure = 281 PSIG
- Volumetric flow = 317 CFM
- Temperature = 186 deg F

From these figures, calculate the operating *compression ratio* of this gas compressor.

[file i04795](#)

Question 20

This control system measures and regulates the amount of differential pressure across a gas compressor, by opening a *recirculation* valve to let high-pressure discharge gas go back to the low-pressure “suction” of the compressor. This control system needs to be very fast-acting, and currently it is anything but that, as revealed by the open-loop trend shown in the upper-right of this illustration:



Identify what type of problem you think you are dealing with here, as the compressor’s differential pressure should *not* take several seconds to stabilize following a sudden move by the recirculation valve. Also suggest a next diagnostic test or measurement to take, explaining how the result(s) of that test help further identify the location and/or nature of the fault.

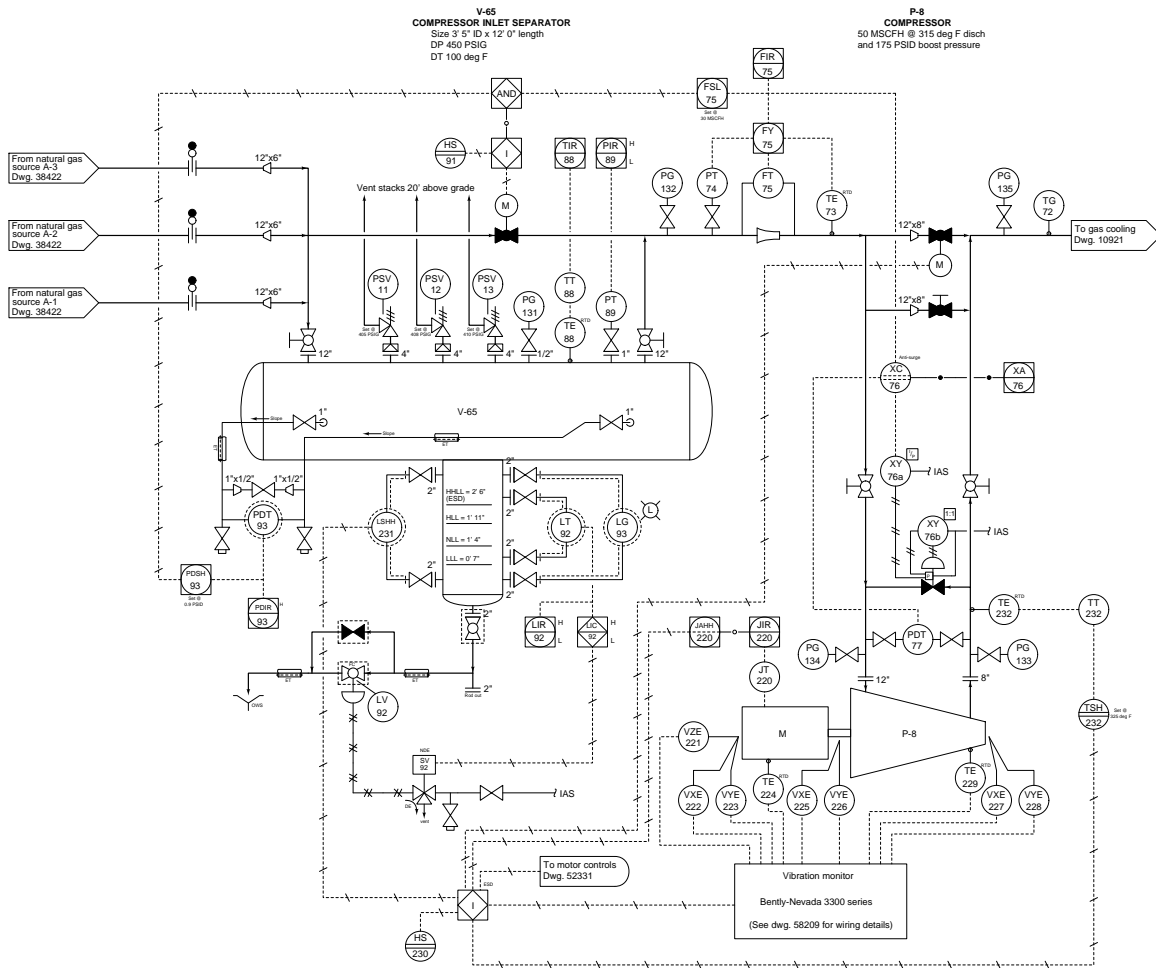
Suggestions for Socratic discussion

- Based on the evidence presented, how do you know this problem is definitely *not* caused by poor PID controller tuning?
- What other methods exist for controlling differential pressure across a large gas compressor, other than using a recirculation valve?

[file i00586](#)

Question 21

Examine this natural gas compressor system with inlet separator vessel:



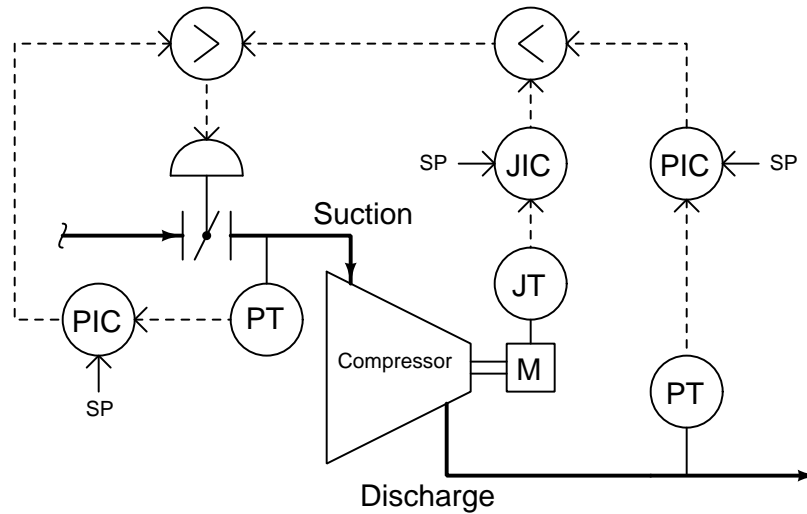
Examine this P&ID and answer the following questions:

- Why is it important that the separator vessel be placed upstream of the compressor? Why not place it on the discharge side of the compressor instead?
- What might cause the compressor to vibrate excessively, thus requiring a vibration monitoring system?
- What effect will opening the recycle valve (XV-76) have on the effective *compression ratio* of this compressor as it is operating?
- What measured variables in this system might indicate that the compressor is being overloaded (i.e. working too hard as it tries to compress more natural gas than it safely can)?

[file i04793](#)

Question 23

This compressor control system uses a pressure transmitter and controller to regulate the discharge pressure to a constant setpoint, allowing either a power controller (JIC) or a suction pressure controller (PIC) to override. The power controller overrides the discharge pressure controller under conditions of high load, throttling back the suction valve to limit power. The suction pressure controller overrides them all under conditions of high inlet vacuum, opening the suction valve in order to ensure the compressor's gland seals are not ruined by excessive vacuum:

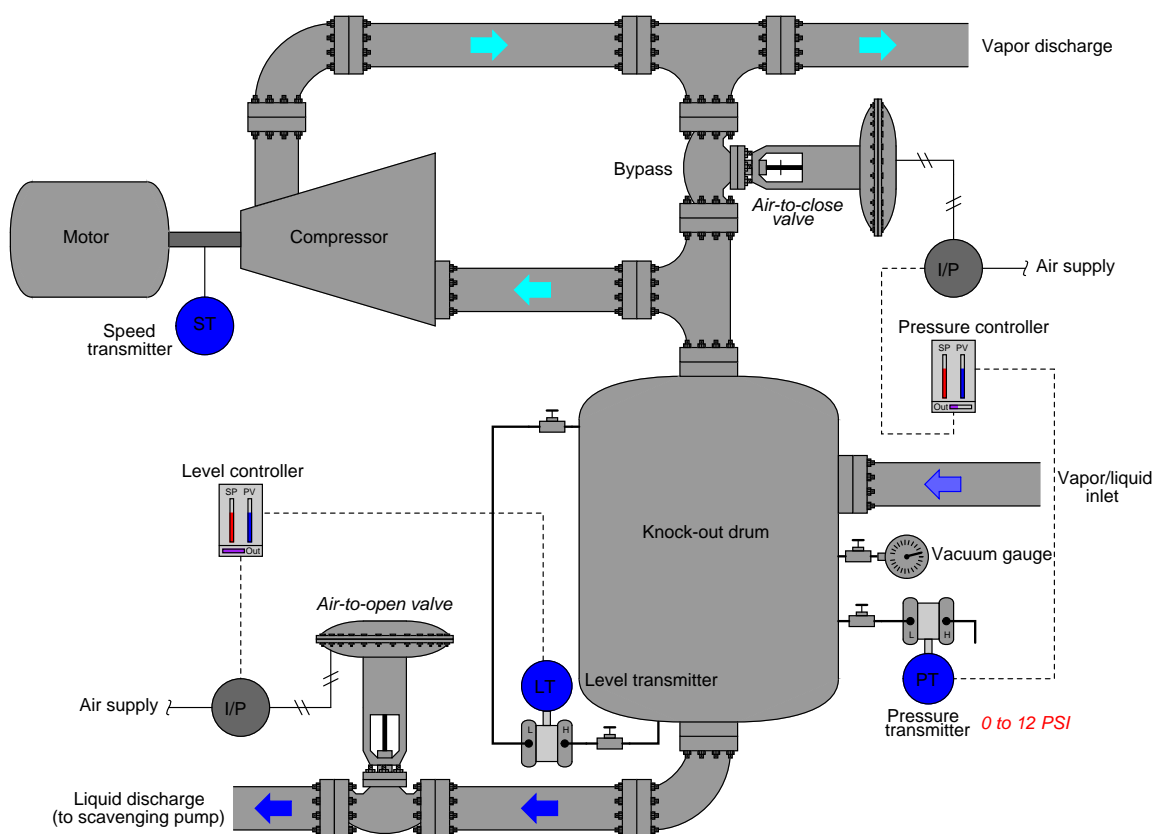


In the event of a high inlet vacuum condition simultaneous with a high load condition, the suction pressure controller will “win” by overriding the power controller. Alter this system so that the override priority is vice-versa: the power controller is able to override the suction pressure controller, yet the suction controller is still able to override the discharge controller.

[file i00179](#)

Question 24

This amount of vacuum (negative pressure) in this knock-out drum is controlled by varying the compressor's bypass valve:



An operator tells you there is a problem with this system, though: the vacuum gauge near the pressure transmitter registers -6.9 PSI, even though the controller faceplate registers -8.0 PSI which is the same as the setpoint. The same operator notes that the control valve position is approximately 30% open, with the controller's output bargraph registering 31.4% open.

Another instrument technician happens to be with you, and recommends the operator place the pressure controller in manual mode to “stroke-test” the control valve. Explain why this test would be a waste of time, and propose a better test for helping to pinpoint the location of the fault.

Suggestions for Socratic discussion

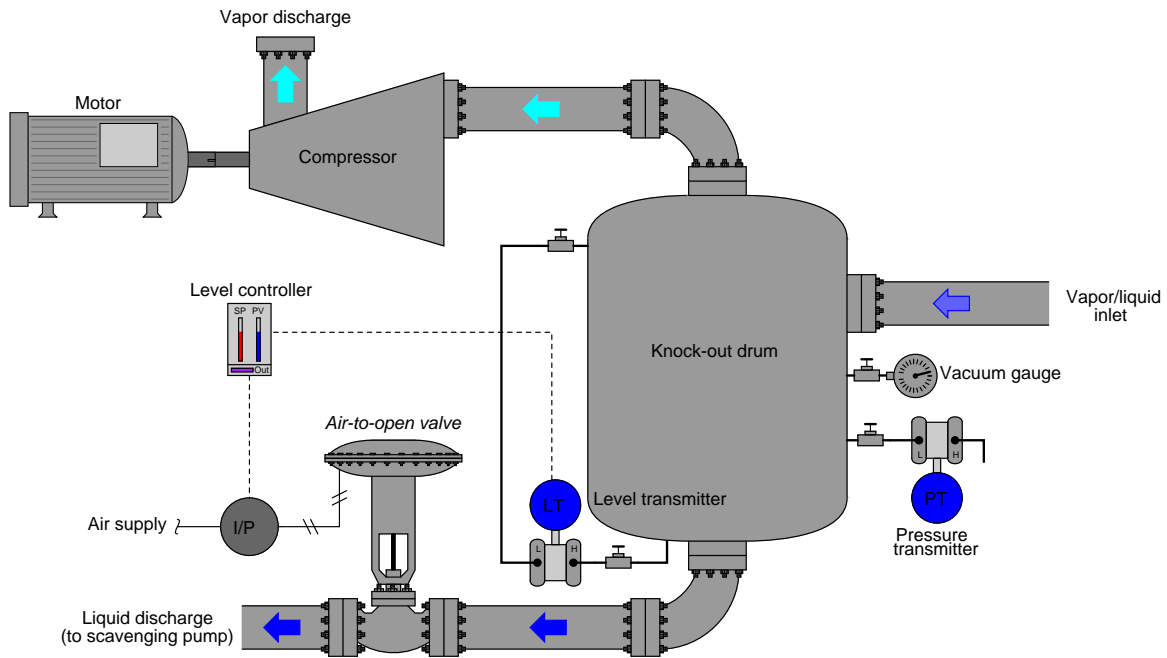
- A valuable principle to apply in a diagnostic scenario such as this is *correspondence*: identifying which field variables correspond with their respective controller faceplate displays, and which do not. Apply this comparative test to the scenario described, and use it to explain why the technician's proposed test was probably not the best first step.
- A problem-solving technique useful for analyzing control systems is to mark the PV and SP inputs of all controllers with “+” and “-” symbols, rather than merely label each controller as “direct” or “reverse” action. Apply this technique to the control strategy shown here, identifying which controller input(s) should be labeled “+” and which controller input(s) should be labeled “-”.
- Predict the effects resulting from one of the transmitters in this system failing with either a *high* or a *low* signal.

- For those who have studied level measurement, explain how the level transmitter (which is nothing more than a DP transmitter) senses liquid level inside the knock-out drum.

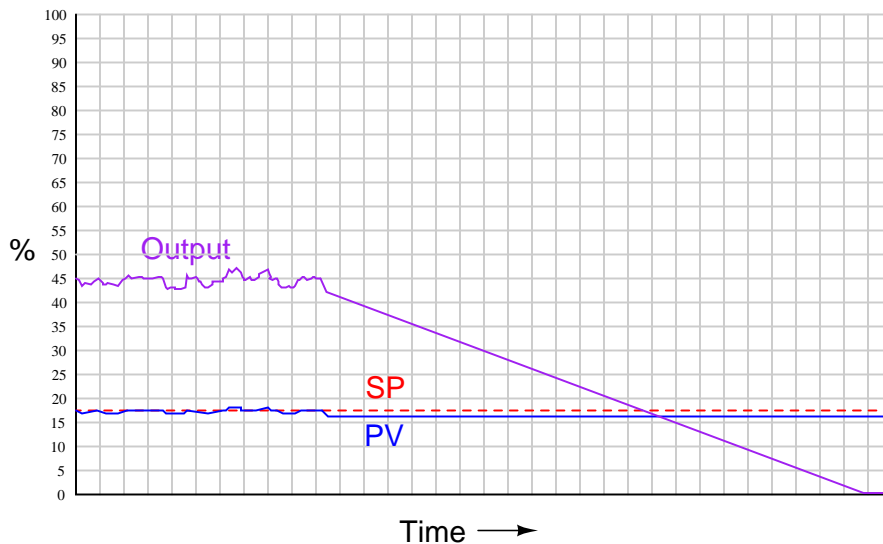
file i02489

Question 25

This level-control system is supposed to maintain a constant liquid level inside the knockout drum, preventing liquid from entering the compressor as well as gas from entering the scavenging pump. Yet, for some reason liquid did manage to enter the compressor, causing the compressor to suffer major damage, and leading to a complete shut-down of the unit:



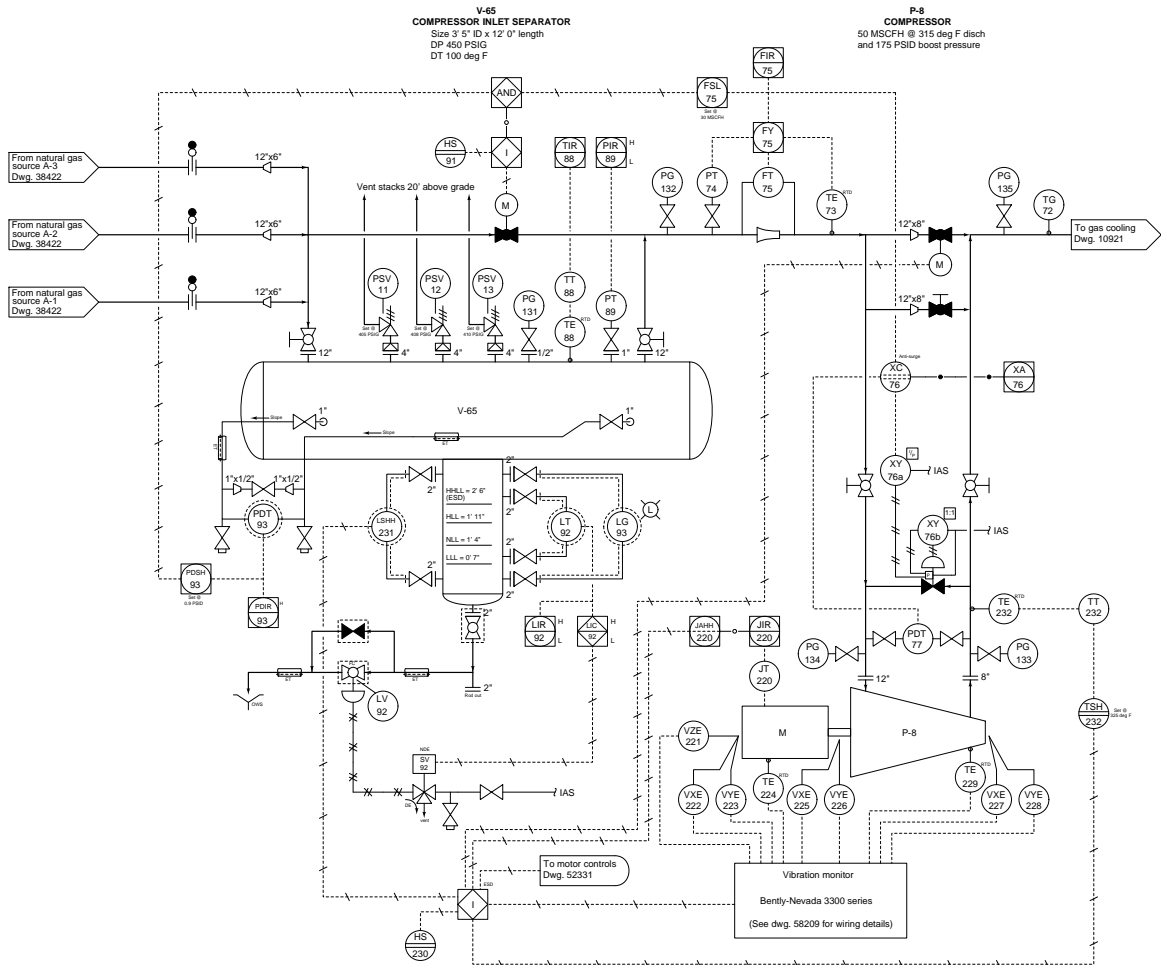
A trend recording of liquid level and control valve position captured before the explosion holds the only clue as to why this happened. Examine it to see if you can determine the source of the trouble:



file i02117

Question 26

The compressor automatically shut down last night, tripped by LSHH-231. The control system alarm log showed a high level alarm LIR-92 about 15 minutes prior to the shutdown:



Identify the likelihood of each specified fault in this process. Consider each fault one at a time (i.e. no coincidental faults), determining whether or not each fault could independently account for *all* measurements and symptoms in this process.

Fault	Possible	Impossible
2-inch line plugged at bottom of separator vessel		
LT-92 failed with high output signal		
Air supply to solenoid valve shut off		
Solenoid vent line plugged		
PSV-11 stuck open		
LSHH-231 failed with high output signal		

Finally, identify the *next* diagnostic test or measurement you would make on this system. Explain how the result(s) of this next test or measurement help further identify the location and/or nature of the fault.

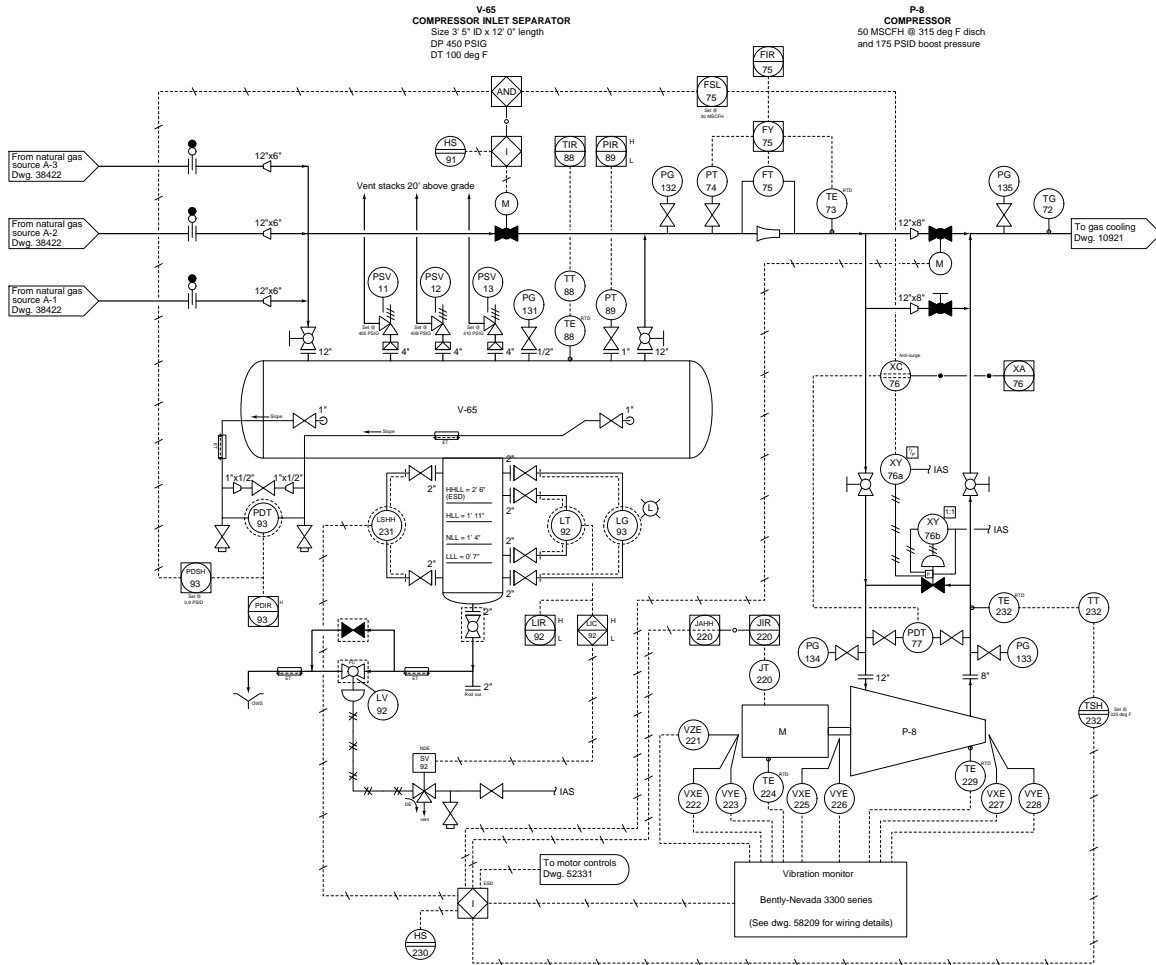
Suggestions for Socratic discussion

- Identify any possible faults not shown on the table.

[file i03475](#)

Question 27

The compressor emergency shutdown system (ESD) has tripped the natural gas compressor off-line three times in the past 24 hours. Each time the operator goes to reset the compressor interlock, she notices the graphic display panel on the interlock system says “Separator boot high level” as the reason for the trip. After this last trip, operations decides to keep the compressor shut down for a few hours until your arrival to diagnose the problem. Your first diagnostic test is to look at the indicated boot level in the sightglass (LG-93). There, you see a liquid level appears to be normal:



First, explain why this first diagnostic test was a good idea. Then, identify what would your *next* diagnostic test be.

Finally, comment on the decision by operations to leave the compressor shut down until your arrival. Do you think this was a good idea or a bad idea, from a diagnostic perspective? Why or why not?

[file i03502](#)

Answers

Answer 1

This graph relates pressure output versus liquid flow rate for a centrifugal-style pump operating at a constant rotational speed.

Answer 2

$$Q = 818.12 \text{ ft}^3/\text{min} = 6120 \text{ GPM}$$

Answer 3

The velocity of the fluid molecules will be equal to the rim speed of the impeller, which is the circumference of the impeller multiplied by its rotational speed:

$$\left(\frac{1760 \text{ rev}}{\text{min}}\right) \left(\frac{8\pi \text{ in}}{\text{rev}}\right) = 44233.6 \text{ in/min} = 61.436 \text{ ft/s}$$

This velocity lets us calculate the velocity head at the impeller's rim. If we assume the water enters the pump with no pressure, this velocity head should be the *only* energy the water possesses at the impeller rim:

$$\text{Fluid Energy at impeller rim} = \frac{\rho v^2}{2} = \frac{(1.94)(61.436)^2}{2} = 3661.1 \text{ PSF} = 25.42 \text{ PSI}$$

This figure of 25.42 PSI will be the blocked-discharge pressure, where 100% of the fluid's kinetic energy is translated into pressure as it finds no place to flow and its velocity stagnates to zero.

Conversely, if we imagine a situation where the discharge port is completely unblocked to achieve zero discharge pressure, the fluid velocity exiting the port will be approximately equal to the impeller rim velocity. Applying this velocity to the Continuity equation to calculate volumetric flow at the 2-inch diameter discharge port:

$$Q = Av$$

$$Q = \pi r^2 v$$

$$Q = (\pi)(1^2)(44233.6) = 138964 \text{ in}^3/\text{min} = 601.6 \text{ GPM}$$

Therefore, the maximum flow rate of this pump at zero discharge pressure will be approximately 600 gallons per minute.

At any flow rate between zero and maximum, the combined sum of velocity and pressure heads at the pump discharge must be equal to the maximum head at the impeller rim (3661.1 PSF equivalent). Therefore:

$$3681.9 = \frac{\rho v^2}{2} + P$$

$$P = 3661.1 - \frac{\rho v^2}{2}$$

Using the Continuity equation to calculate discharge velocity at 100 GPM (23100 in³/min), and then Bernoulli's equation to calculate discharge pressure:

$$v = \frac{Q}{A} = \frac{23100}{\pi} = 7352.96 \text{ in/min} = 10.21 \text{ ft/s}$$

$$P = 3661.1 - \frac{(1.94)(10.21^2)}{2} = 3458.8 \text{ PSF} = 24.02 \text{ PSI}$$

Using the Continuity equation to calculate discharge velocity at 200 GPM (46200 in³/min), and then Bernoulli's equation to calculate discharge pressure:

$$v = \frac{Q}{A} = \frac{46200}{\pi} = 14705.9 \text{ in/min} = 20.42 \text{ ft/s}$$

$$P = 3681.9 - \frac{(1.94)(20.42^2)}{2} = 3256.4 \text{ PSF} = 22.61 \text{ PSI}$$

Using the Continuity equation to calculate discharge velocity at 300 GPM (69300 in³/min), and then Bernoulli's equation to calculate discharge pressure:

$$v = \frac{Q}{A} = \frac{69300}{\pi} = 22058.9 \text{ in/min} = 30.64 \text{ ft/s}$$

$$P = 3681.9 - \frac{(1.94)(30.64^2)}{2} = 2750.6 \text{ PSF} = 19.10 \text{ PSI}$$

Using the Continuity equation to calculate discharge velocity at 400 GPM (92400 in³/min), and then Bernoulli's equation to calculate discharge pressure:

$$v = \frac{Q}{A} = \frac{92400}{\pi} = 29411.8 \text{ in/min} = 40.85 \text{ ft/s}$$

$$P = 3681.9 - \frac{(1.94)(40.85^2)}{2} = 2042.5 \text{ PSF} = 14.18 \text{ PSI}$$

Using the Continuity equation to calculate discharge velocity at 500 GPM (115500 in³/min), and then Bernoulli's equation to calculate discharge pressure:

$$v = \frac{Q}{A} = \frac{115500}{\pi} = 36764.8 \text{ in/min} = 51.06 \text{ ft/s}$$

$$P = 3681.9 - \frac{(1.94)(51.06^2)}{2} = 1132.0 \text{ PSF} = 7.861 \text{ PSI}$$

Summarizing these calculated results:

- Discharge flow = 0 GPM ; $P = \underline{25.42}$ PSI
- Discharge flow = 100 GPM ; $P = \underline{24.02}$ PSI
- Discharge flow = 200 GPM ; $P = \underline{22.61}$ PSI
- Discharge flow = 300 GPM ; $P = \underline{19.10}$ PSI
- Discharge flow = 400 GPM ; $P = \underline{14.18}$ PSI
- Discharge flow = 500 GPM ; $P = \underline{7.861}$ PSI

If we were to plot these flow and pressure data points, we would have a *pump curve* for this centrifugal pump.

Answer 4

A vitally important concept to grasp here is that of *incompressibility*. Air is a compressible fluid, but hydraulic oil is incompressible for all practical purposes. Thus, a positive-displacement pump mechanism will lock up if the incompressible fluid has no place to exit.

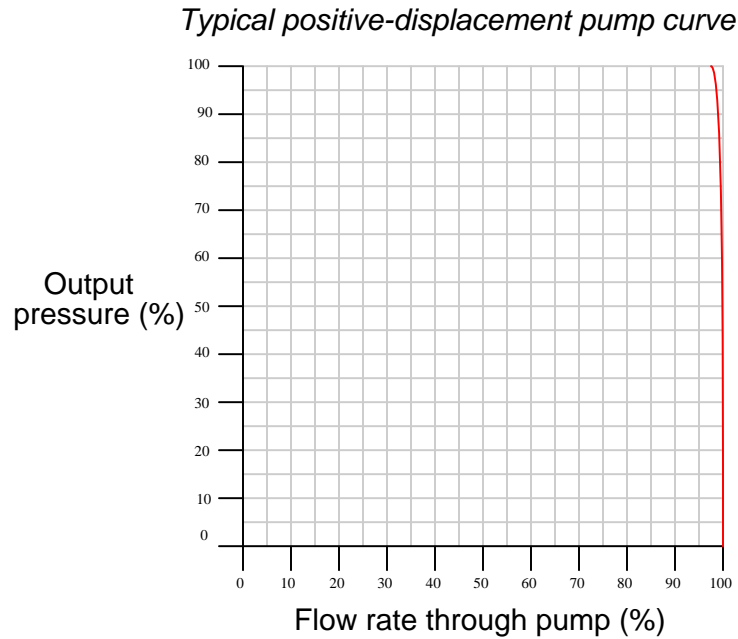
Answer 5

Instead of wasting unused hydraulic energy in a pressure relief valve, this system reduces the amount of hydraulic energy input to the system when it is not needed.

Follow-up question: a common design of variable-displacement hydraulic pump (and motor!) is the *swash plate* style, where the angle of the swash plate changes to alter the pump's per-revolution displacement. Research this pump design and explain how it works.

Answer 6

The ideal pump curve for a positive-displacement pump is a vertical line, but due to internal leakage the real pump curve looks something more like this:



Answer 7

- Maximum flow at 10 feet above pump level \approx 250 GPM
- Maximum flow at 50 feet above pump level \approx 225 GPM
- Maximum flow at 100 feet above pump level \approx 180 GPM
- Maximum flow at 150 feet above pump level \approx 130 GPM

Answer 8

According to the pump curve, the pressure will be 60 PSI at a flow rate of 150 GPM. This means each pump boosts its suction pressure by 60 PSI at the discharge.

In the series configuration, this means $P_2 = P_1 + 60$ and $P_3 = P_2 + 60$. Therefore, $P_2 = 105$ PSI and $P_3 = 165$ PSI. Total flow will be 150 GPM.

In the parallel configuration, this means $P_2 = P_1 + 60$ and $P_3 = P_1 + 60$. Therefore, $P_2 = P_3 = 105$ PSI. Total flow will be 300 GPM.

Answer 9

The liquid level inside the vessel will drift either up or down (depending on which pump moves more liquid) at a rate determined by the differential liquid flow ($Q_{in} - Q_{out}$). This makes it an *integrating* process.

Integrating processes are characterized by the capacity to experience persistent mass and/or energy imbalances, where the out-flow of mass and/or energy does not naturally reach equilibrium the in-flow over time. Self-regulating processes, by contrast, naturally equalize their mass and energy balances as the process variable changes.

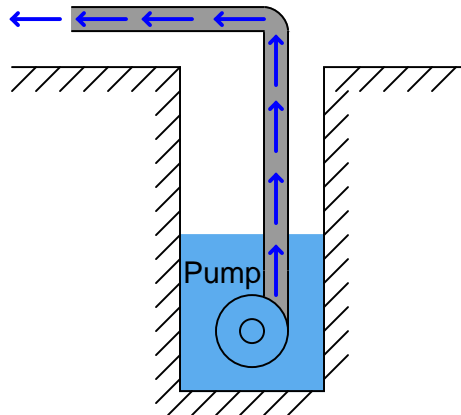
Answer 10

406.9 inches, which is a little bit less than 34 feet. For this amount of “lift height,” the pump would have to create a near-perfect vacuum in the inlet pipe. To calculate this figure, convert 14.7 PSIA into inches of water column absolute (14.7 PSIA)(2.768 ”W.C. / PSI).

Since this kind of water pump works by creating a vacuum (reducing the inlet pressure to something less than 14.7 PSIA), it is inherently limited in lift height. Since atmospheric pressure is always 14.7 PSIA (on Earth, anyway), this kind of pump simply cannot suck water any higher than this amount of pressure expressed in inches or feet of water.

The average barometric pressure in Denver is 24.63 inches of mercury absolute (12.097 PSIA). This equates to a water-lifting height of 334.9 inches, or 27.9 feet.

Submersible pumps overcome this limit by creating a *positive pressure* rather than a *vacuum*. The pumping action is therefore not limited by the relatively low pressure of Earth’s atmosphere, but only by the capacity and design of the pump itself:



Answer 11

Calculating the work in raising 10 gallons of water 30 feet up:

$$\left(\frac{10 \text{ gal}}{1}\right) \left(\frac{231 \text{ in}^3}{1 \text{ gal}}\right) \left(\frac{1 \text{ ft}^3}{1728 \text{ in}^3}\right) \left(\frac{62.4 \text{ lb}}{\text{ft}^3}\right) = 83.42 \text{ lb of water in 10 gallons}$$

Now, knowing both the force (83.42 lb) and the displacement (30 ft), we may calculate the work done:

$$W = Fx \cos \theta$$

$$W = (83.42 \text{ lb})(30 \text{ ft})(\cos 0^\circ) = 2502.5 \text{ ft-lb of work}$$

Now, since we know that 1 horsepower is 550 ft-lbs of work *per second of time*, we may take this total amount of work (2502.5 ft-lb) and divide by the pump's power in foot-pounds per second to arrive at an answer for time in seconds. Since we know the pump's power rating is 1.5 horsepower, it means it is capable of doing 825 ft-lb of work per second:

$$t = \frac{W}{P} = \frac{2502.5 \text{ ft-lb}}{825 \text{ ft-lb/s}}$$

$$t = 3.033 \text{ seconds}$$

First, let's determine the weight of 3,000 gallons of water:

$$\left(\frac{3000 \text{ gal}}{1}\right) \left(\frac{231 \text{ in}^3}{1 \text{ gal}}\right) \left(\frac{1 \text{ ft}^3}{1728 \text{ in}^3}\right) \left(\frac{62.4 \text{ lb}}{\text{ft}^3}\right) = 25025 \text{ lb of water in 3000 gallons}$$

This weight of water will have to be lifted to the peak of the hill through the 100 foot pipe, but we will not use the figure of 100 feet as the displacement, since it is not vertical. Instead, we will use trigonometry to calculate the vertical lift (x):

$$x = (100 \text{ ft})(\sin 48^\circ) = 74.31 \text{ ft vertical lift}$$

So, the work involved with lifting this much water to that height is:

$$W = Fx \cos \theta$$

$$W = (25025 \text{ lb})(74.31 \text{ ft}) \cos 0^\circ$$

$$W = 1,859,719.9 \text{ ft-lb of work}$$

Barring any piping friction, the horizontal section of pipe (55 ft) does not necessitate any work being done. The short, 20 foot section of downward-angled pipe, however, actually *releases* energy (performs negative work) because it lets the water drop in height. This drop is:

$$\text{drop} = (20 \text{ ft})(\sin 30^\circ) = 10 \text{ ft}$$

Since the same amount of water will drop this amount, the negative work done here is:

$$W = Fx \cos \theta$$

$$W = (25025 \text{ lb})(10 \text{ ft}) \cos 180^\circ$$

$$W = -250,250 \text{ ft-lb of work}$$

The total (net) work done, then, is the sum of these two figures:

$$W_{net} = 1,859,719.9 \text{ ft-lb} - 250,250 \text{ ft-lb} = 1,609,469.9 \text{ ft-lb of work}$$

At a pump power output of 250 HP (137,500 ft-lb per second)

$$t = \frac{W}{P}$$

$$t = \frac{1609469.9 \text{ ft-lb}}{137500 \text{ ft-lb/s}} = 11.71 \text{ seconds}$$

Answer 13

Fault	Possible	Impossible
No AC power to VFD	✓	
Controller has dead 4-20 mA output	✓	
Level transmitter out of calibration		✓
Level switch contacts failed shorted		✓
Level switch contacts failed open		✓
250 ohm resistor failed open		✓
Cable between TB12 and TB13 failed open	✓	
Cable between TB13 and LSL failed open		✓

Answer 14

- Why are “check” valves installed on the discharge lines of pumps P-407 and P-408? *To prevent oily water from returning to the sump (from which it came) when only one pump is running.*
- Supposing pump P-408 is the only one running, qualitatively determine the effects of pinching off the block valve immediately upstream of pressure gauge PG-419 on the following variables (e.g. *increase, decrease, or remain the same*):
 - Pressure at the pump’s discharge port (*increase*)
 - Pressure registered by PG-419 (*decrease*)
 - Electrical current to the driving motor (*increase*)
 - Flow rate of water through filter S-401 (*decrease*)
 - Pressure registered by PG-419 (*remain the same*)
 - Oily water level inside the sump (*cannot tell*)

The last effect (oily water sump level) is unknown because we do not know how the reduced flow of pump P-408 compares to the flow rate of water entering the sump. If the flow rate of P-408 still exceeds the input flow to the sump, the level will continue to drop although not as fast as before pinching off the block valve. If the pump’s flow rate exactly equals the influent rate, the sump level will remain constant. If the pump’s flow rate has decreased to a point where it is less than the influent flow rate, the sump level will actually rise!

Answer 15

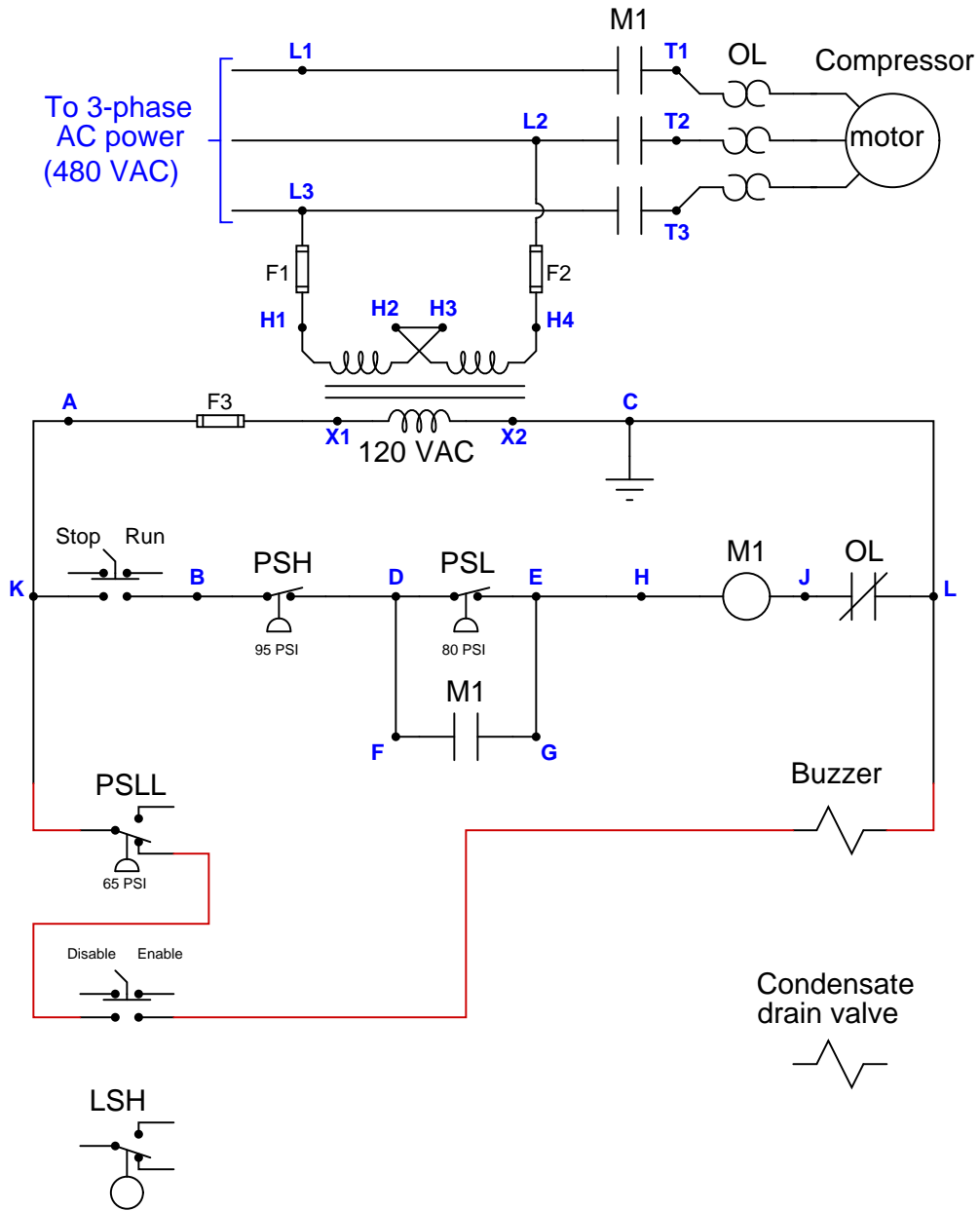
Answer 16

This is a pressure control system for an air compressor. It uses two pressure switches, a high (“PSH”) and a low (“PSL”), sending on-off electrical signals to a logic control circuit (possibly a PLC). The logic then turns the compressor motor on and off.

A rupture disk is provided at the receiver tank for high pressure relief, and a hand-operated ball valve provides blowdown control.

The “PSHH” bubble is a high-high pressure switch, activated only when the receiver tank pressure is above normal operating pressure. It sends an on-off electrical signal to a high pressure alarm (“PAH”) indicator.

Partial answer: (this is just one possible solution to the wiring of the pressure switch):



Answer 18

The compression ratio is simply the reciprocal of the ratio of volumes between outlet and inlet (discharge and suction). Taking the ratio of volumetric flow rates also works, since these are nothing more than volumes per unit measure of time.

$$\text{Compression ratio} = \left(\frac{\text{Suction flow}}{\text{Discharge flow}} \right) = \left(\frac{1300 \text{ CFM}}{317 \text{ CFM}} \right) = 4.101$$

Like all ratios, compression ratio is a unitless quantity because the units of measurement in the numerator and denominator are identical and therefore cancel each other.

Answer 19

The problem is clearly *not* with the controller's action, because according to the faceplate displays it is trying to do the right thing (i.e. shut the control valve to build up differential pressure).

Answer 20

A good step to take next is to figure out whether the problem is on the output side of the control system or on the input side of the control system. Is the slow pressure trend real, and the control valve not responding as quickly as it should? Is the pressure actually changing quickly, but the measurement side of the system not accurately reporting it as it should?

Probably the best first-step here is to actually go to the control valve and observe how fast it responds to step-changes from the controller (manual mode).

Answer 21

- Why is it important that the separator vessel be placed upstream of the compressor? Why not place it on the discharge side of the compressor instead? *Liquids are incompressible, and so the purpose of the upstream separator vessel is to capture any entrained liquid droplets condense before they would have any chance of entering the compressor.*
- What might cause the compressor to vibrate excessively, thus requiring a vibration monitoring system? *Any damage or wear to the compressor's rotating pieces causing it to become imbalanced.*
- What effect will opening the recycle valve (XV-76) have on the effective *compression ratio* of this compressor as it is operating? *Recycling gas through the compressor will reduce the net flow in this natural gas system as well as reduce the amount of differential pressure across the compressor. Both of these effects will reduce the effective compression ratio of the compressor.*
- What measured variables in this system might indicate that the compressor is being overloaded (i.e. working too hard as it tries to compress more natural gas than it safely can)? *Excessive differential pressure (sensed by PDT-77), excessive discharge temperature (sensed by TT-232), excessive electrical power drawn by the compressor's motor (sensed by JT-220).*

Answer 24

The reason that the technician's proposed test would have been a waste of time is because the issue at hand is a significant disagreement between the vacuum gauge and the controller display. No valve problem or controller output problem could cause this to happen.

A far better test would be to place the pressure controller in manual mode, then vent the pressure transmitter to check that the controller reads 0 PSI. If there is a transmitter calibration problem, it will likely appear as a zero error (not reading 0 PSI at 0 PSI).

Alternatively, one could also perform the same test on the vacuum gauge to see if it is in error.

The level controller needs to be direct-acting. The pressure controller needs to be reverse-acting.

Although there is a discrepancy between the controller's output (displayed) and the actual valve position, an error of (approximately) 1.4% is nothing to worry about. In fact, so long as the valve is somewhere within its throttling range, the controller should be able to hold the PV equal to SP.

Answer 25

This is a graded question – no answers or hints given!

Answer 26

Fault	Possible	Impossible
2-inch line plugged at bottom of separator vessel	✓	
LT-92 failed with high output signal		✓
Air supply to solenoid valve shut off	✓	
Solenoid vent line plugged		✓
PSV-11 stuck open		✓
LSHH-231 failed with high output signal		✓

From all the evidence, it seems we really had a high-high level condition in the separator boot, and that the shutdown system acted precisely as it was designed to do: protect the compressor from sucking in any liquid.

A good “next test” to do would be to place controller LIC-92 in manual mode and attempt to cycle control valve LV-92, while monitoring solenoid valve SV-92. If these valves function as they should, the problem may be an obstruction in the drain line. If they do not function as they should, the problem is either in one of those valves or in the wiring/tubing connecting those valves to the rest of the system.

Given the fact that the ESD system keeps indicating a high boot level, you know that it “thinks” the liquid level inside the boot is higher than it should be. The next logical step is to determine whether or not a high liquid level condition does indeed exist. If so, the trip is legitimate and there may be a problem with the liquid level control system. If not, the LSHH-231 or its associated wiring may have a fault that sends a false trip alarm to the ESD system.

However, the decision to leave the compressor idle for a few hours until your arrival was not a good one for diagnosis. If indeed there is a problem with excessive liquid collecting in the boot, this would only be evident during running operation. With the compressor idle and no new gas entering the separator vessel, there will be no new liquid collecting in the boot, which will give the boot level control system ample time to empty that liquid down to a normal level and make it appear as though there is no level problem. In other words, leaving the compressor idle for a few hours “erases” the evidence, making it more difficult to troubleshoot.

Aside from re-starting the compressor and watching it run, you could perform a test on the liquid level control system by simulating a high-level condition inside the boot (e.g. applying pressure to one side of LT-92) and observing how fast or slow the actual liquid drains out (as indicated by LG-93). If there is a problem with the level control valve LV-92 or its associated components, you should be able to tell in the form of a long (slow) drain time. The fact that the blind flange at the bottom of the boot drain line says “Rod out” on the P&ID suggests this line is prone to plugging with debris, which could explain a slow-draining condition and consequently the frequent high-level trips.