PDHonline Course G465 (3 PDH)

Coping With Murphy's Law

Instructor: Michael J. Hamill, PE

2020

PDH Online | PDH Center

5272 Meadow Estates Drive
Fairfax, VA 22030-6658
Phone: 703-988-0088
www.PDHonline.com

An Approved Continuing Education Provider

Table of Contents

General Overview

Murphy’s Law simply states, “*Anything that can go wrong — will go wrong.*” A related version more familiar to the author is: “*If something can go wrong, it will.”*

Engineers are usually practical people. In their work, they are more likely to encounter Murphy’s Law in action than those in other occupations. Their work requires them to focus on concerns such as the reliability and durability of products, equipment and systems; and the competence and reputations of others.

Realistically, mentions of Murphy’s Law are often laments about inevitable appearances of the laws of natures, and the imperfect nature of people.

Failures, difficulties, and problems in day-to-day life can’t be avoided. But people can minimize their occurrences by understanding the applicable laws of nature, and following practices which allow them to minimize occurrences.

This course has three main subdivisions. **First**, it discusses common organizational and technical reasons for failures. Instances of some corporate disasters are presented, followed by some specific instances of common failure mechanisms. (Most of the quiz questions are based on technical reasons for failure.) **Second**, some commonly used industrial components and their most common failure mechanisms are presented. **Third**, it discusses some common practices successful organizations use. These practices subdivide between the technical and organizational aspects of projects. Good practices that work to the benefit of service providers and clients, and sellers and customers are presented. Some examples of accidents due to management oversights and other disasters are presented.

The body of the course concludes with a summary of the most common types of failures which occur in the real world.

Some examples of management and organizational issues which have caused problems

Chief Executive Officers (CEOs) of businesses and government agencies must decide what the most important priorities are. Resources and budgets are always limited. CEOs of businesses are, by necessity, focused mainly on maintaining profitability. The backgrounds of CEOs and managers vary. Yet it's fairly common for CEOs to have degrees in business administration, accounting, or marketing. Most CEOs as well as managers at lower levels often do well at understanding "the overall picture". But these decision makers often lack a technical background. They don't always have a good feel for the technical aspects of what goes on at lower levels. So, it's sometimes hard for engineers to persuade upper management of the importance of devoting resources to maintaining safety and reliability. Unfortunately, disasters have occurred from time-to-time, and the writer believes some of them happened because top management failed to appreciate what could go wrong, and how expensive it could be to address disasters and accidents. Listed below are some disasters and accidents which either did occur, or probably occurred, because of management's failure to devote resources to reliability and safety concerns:

- 29 miners died in an explosion at a coal mine in West Virginia on April 5, 2010. Subsequent investigations found that some methane detectors in the mines were not working prior to the incident. A total of $210 million was ultimately paid out in fines and settlement fees by the owner.
- The Deepwater Horizon drilling disaster in the Gulf of Mexico in 2010. 11 workers were killed in the initial explosion, and the oil leak into the gulf lasted almost 3 months.
- A refinery explosion at a British Petroleum plant in Texas in 2005 led to the deaths of 15 workers. B.P. was later found culpable for the explosion, and paid heavy fines.
- At a nuclear power plant east of Toledo, Ohio, a hole was nearly eaten through the liner of a reactor's cap in early 2002 due to leak of corrosive boric acid coolant solution escaping from a cracked control rod drive mechanism. The owner had requested, and the Nuclear Regulatory Commission (NRC) accepted, the owner's request to keep the generating unit and reactor on line past the NRC-preferred maintenance shutdown date of Dec. 31, 2001. The generator and reactor were not removed from service for maintenance until February 2002. The owner incurred a substantial expense to fix the problem and ultimately paid a fine of over $5 million to the NRC.

Here are some examples of a few more ordinary management shortcomings that have occurred in the past:

- Product assembly was done too quickly, resulting in poor quality.
- Production line workers with unvaried routines suffered repetitive motion injuries that damaged joints in their bodies.
- Installation problems were missed due to inadequate numbers of qualified inspectors.

Examples of some common problems conditions

This discussion now moves on to technical factors.

In the real world, problem conditions usually occur for simple rather than complicated reasons. For example, power is more likely to be lost due to lightning, or a blown fuse than from the effects of solar flares. Listed below are some frequently occurring problem conditions that engineers (and mechanics & technicians) often encounter:

- Corrosion started by contact between dissimilar metals.
- Condensation of water vapor.
- Water intrusion.
- Undersized or oversized electrical wires, equipment, or structures.
- Overuse of equipment.
- Poor documentation of existing equipment which hampers maintenance.

Some phenomena which often cause failures and disturbances:

A. The Effects of Water

Water is vital to life on earth. But it also poses design challenges to engineers and architects.

Water is a highly “polar” molecule that reacts with many elements and compounds, and in doing so, creates ions and minerals within water. Such ions and minerals in water often aggravate corrosion.

Water also has the unique property that it expands as it freezes due to a decrease in its density. Because of this, in freezing weather pipes with trapped water often burst. In cold weather, potholes in road surfaces develop due to two effects of water. First, water typically weakens some bed material beneath a road after it passes through pores in a road surface. Then, when water freezes within the pavement and the underlying bed material, it expands in all directions, putting stress on the pavement. Later, when it melts, it contracts, and the weight of vehicles on a road creates potholes over voided areas.

Water in soil often causes related problems. One is “frost heaving”. Frost heaving occurs when water below the ground freezes and expands. Usually, it results in upward and outward movements of soil. It affects equipment mounted outdoors such as large transformers. Expansions and contractions of freezing and thawing wetted soil can affect the supporting structures for such equipment units, and the equipment itself.

Gravity also pulls liquid water into soil. The weight of watery soil presses on buried supporting structures of buildings such as foundation walls. Such structures often need to be steel-reinforced, and externally coated with a water sealant.

Above ground, rain and snow must be kept from penetrating the roofs, walls, windows, doors, and openings of buildings. If water vapor can’t escape from an attic, it will condense, and cause surfaces such as ceilings, or insulation, to get wet. Mold may also form. Within homes and buildings, water vapor moving from inside to outside can condense when it reaches the colder walls, and make insulation wet and less effective in keeping the occupancy warm. Vapor barriers between inside walls and insulation are used to prevent this.

Water vapor in outdoor pipes and conduits will condense when the temperature falls to the dew point, and in freezing weather, ice particles may form.

B. Corrosion

Corrosion causes or precedes many failures. It’s a complex topic. This course will only discuss some notable facts about corrosion, and it will focus on how corrosion damages finished products. Common measures used to guard against or avoid corrosion through material selection are also discussed.

In general, atoms and molecules (a) readily give up one or more electrons in a chemical reaction, or, (b) readily accept one or more electrons in a reaction; or, (c) are mostly or very stable so they don’t normally react with other atoms or molecules. Atoms like hydrogen and sodium easily combine with another atom or molecule by donating an electron in an *ionic* bond. And atoms and molecules like chlorine easily combine with another atom or molecule by accepting an electron. Some atoms, notably hydrogen, nitrogen, and oxygen, share electrons with like atoms, resulting in *covalent* bonds. The strength of covalent bonds varies; the bonds of "diatomic" hydrogen molecules, or H_2, and diatomic oxygen, or O_2 molecules, are weaker than those of diatomic nitrogen, or N_2, which is very resistant to combining with other molecules. And single-atom "noble" gases like neon and xenon with filled outer "shells" of electrons are extremely stable.

All the elements are aptly summarized in the Periodic Table, first constructed by the Russian chemist Mendeleev in the 19th century. H_2 molecules easily combine with oxygen and sulfur to form, respectively, water (H_2O) and hydrogen sulfide (H_2S). And O_2 molecules also easily combine with many substances. Water is very prevalent on our planet, and 21% of earth's atmosphere consists of O_2 molecules.

In short, a material's susceptibility to corrosion – or *oxidation* – is generally related to the ease with which it shares electrons with, or donates electrons to other materials, and forms a new molecule in the process. Oxidation frequently occurs in the presence of water, which in nature always has charge carriers (ions) present to some degree. The water can be in liquid or vapor form.

The most commonly used metals are **steel**, which in its simplest form consists of iron atoms combined with a relatively small percentage by weight of carbon atoms; and **aluminum**. Steel is very useful because it is strong and relatively cheap, but it is also very susceptible to corrosion. Steel also can be and is used with concrete, usually in the form of reinforcing rods to make concrete stronger. Aluminum is far less prone to corrosion than steel, but it is also much lighter and more ductile, so it can easily be formed into varying shapes. But aluminum has limits as a structural material. (Aluminum exposed to oxygen in the air will form an oxide layer on its surface which prevents further corrosion in most circumstances.)

Steel readily combines readily with oxygen in air. Rusting, or oxidation, of steel is hurried up by the presence of ions in water. Over a long enough period of time, exposed steel will first be lessened in strength, then rust away entirely; or a part made of steel may fail before it is totally rusted.

Rusting of steel can be countered or greatly slowed by several means. Three are cited here. First, it can be painted. But when a paint cover is breached, steel becomes exposed to air and water, and susceptible to rusting. Second, an enamel or epoxy can also be applied to its surface to protect it from air, water, etc. Last, it can be galvanized. In the most common type of galvanization (also known as electroplating), steel is coated with a thin layer of zinc which protects it from corrosion. In this way, if the zinc layer is breached and steel is exposed, the zinc acts as a “sacrificial anode” in which the layer combines with the free electrons of any substances to which it may be exposed – usually O_2 in air – until it is consumed. (When a galvanic coating is completely used up, the steel part will corrode where it is exposed.) Usage of galvanized steel is very common. Parts as diverse as small metal fasteners like bolts, nuts and sheet metal screws to corrugated pipe are usually galvanized.

Corrosion often makes disassembly of something quite difficult. Contacting parts of made of steel (or of steel and another metal) are often hard to pull apart due to rust buildup. Sometimes corrosion also makes it impossible to loosen nuts from bolts.

Stainless steels were developed in the early 1900s to provide enhanced protection from corrosion. In stainless steels, chromium is mixed with steel and iron. Nickel and manganese are also included with most stainless steels.

Three widely used types of stainless steels used in the U.S. are AISI 304, 316 and 316L. 304 SS costs less than 316 SS and 316L SS, and 304 SS is easier to shape than 316 SS. 316 SS and 316L SS have better corrosion resistance than 304 SS. 316L SS offers more resistance to corrosion for applications involving welding. Stainless steels are significantly more expensive than normal carbon steels, but their corrosion-resistance and strength make them the best choice for many applications.

Ions and minerals in water can cause corrosion and/or mineral deposits in pipes, tanks, and structures. Also, water condensed from atmospheric water vapor has ions that also affect hydraulic fluids. Given enough time and volume, water within brake fluid in motor vehicles will corrode master cylinders and wheel cylinders. Industrial hydraulic system parts are often made of stainless steel because of superior corrosion resistance.

When enclosures are mounted outdoors, one corrosion deterrent that’s widely used is to use a heater and thermostat to keep the air temperature within the enclosure above freezing, so water vapor will not condense and start internal corrosion.

Many parts are made from the alloys brass and bronze. In general, these materials are durable and offer lasting corrosion resistance to air and many liquids. Each of these alloys comes in different varieties, with different degrees of resistance to corrosion and chemical attack by various solutions.

PDHOnline.org has several courses on Corrosion. The reader may wish to take one or more of these courses to learn more about the subject.

C. Metal Fatigue

Materials have limits on how much stress they can take before breaking. Metal fatigue is a common reason for the failure of parts and devices.

Fatigue typically occurs when the levels of stress imposed on parts repeatedly fluctuates. Parts and materials subject to fluctuating stresses include shafts and blades of rotating machinery like compressors; valve springs within engines; and steel used to reinforce concrete roadbeds, “rebar”.

Fatigue failures usually happen suddenly, although the reduction to a material’s strength before failure takes place gradually. Turbine blades have been thrown at high velocity, and engine drive shafts have suddenly fractured due to fatigue failures.

Manufacturers have recognized metal fatigue as a risk for generations, and have worked hard to reduce the chances that it will happen. Critical parts which might fail due to fatigue are carefully manufactured, are sometimes made of expensive alloys, and are typically subjected to treatments like annealing to minimize risks of failures. Also, parts at risk of failure by fatigue are overdesigned by means of a safety factor so they will be able to bear more stress than they will usually encounter.

When a part does fail due to metal fatigue, it often does so because it was degraded by corrosion before the failure. Thermal shocks sometimes also precede fatigue failures.

For rotation machinery, vibration monitors can detect abnormalities that sometimes precede a fatigue failure – or other destructive consequences.

D. Chemical incompatibilities

In general, plastics and polymers are much more resistant to degradation than metals and alloys. But plastics and related compounds are not safe from all chemical attacks. For example, Type 1 PVC, which is widely used for pipes, will not be attacked by 100% Hydrochloric Acid or 50% Nitric Acid, but is not recommended for Benzene[1]. Alert engineers will check to see that each material they might use for an application – whether it's steel, an alloy, a plastic or a polymer - will not be degraded by any gases, solutions or chemicals it's likely be exposed to. Also, anything to be used outdoors should resist degradation by ultraviolet radiation from the sun.

E. Air bubbles

Air bubbles in equipment and systems rarely cause sudden failures, but they do tend to lower efficiency and operational effectiveness. Water with entrained air can cause corrosion in boiler tubes or heat exchangers. It will also lower efficiency by reducing heat transfer. To release entrained air, some elevated pipes have purely mechanical air release valves located at a high point which operate automatically. Air can also make its way to a pump if the pressure of its suction line falls below atmospheric pressure and an air leakage point exists. Many pumps are "self-priming", that is, they automatically purge air on startup. But pump specialists know that there are a number of ways a pump can lose its prime and stop working effectively. For hydraulic systems, air within hydraulic fluid is minimized by locating the opening of each pump's intake line near the bottom of a hydraulic fluid tank, and installing deflector plates between fluid return lines and pump intake lines in the tank. Such tanks usually have a vent line fitted with a breather cap so any air bubbles in the fluid can escape the tank. A desiccant cartridge in a tank's vent cap can help prevent water vapor in air from contaminating fluid in the tank and causing corrosion.

Failure modes of some commonly used devices

Self-operated pressure regulating valves

This type of valve is widely used when automatic control of a pressure downstream of a pressure source is sought. (See Figure 7.) They are useful for applications like regulation of a compressed air pressure, and controlling seal water pressure to a pump's shaft. These valves don't need an externally powered actuator such as a motor. Fluid pressure on the downstream side of the actuator is used to reposition the actuator even as supply pressure and/or downstream conditions change. The adjustment spring is used to change downstream set point pressure. If the supplied pressure drops to zero, this type of valve will close.

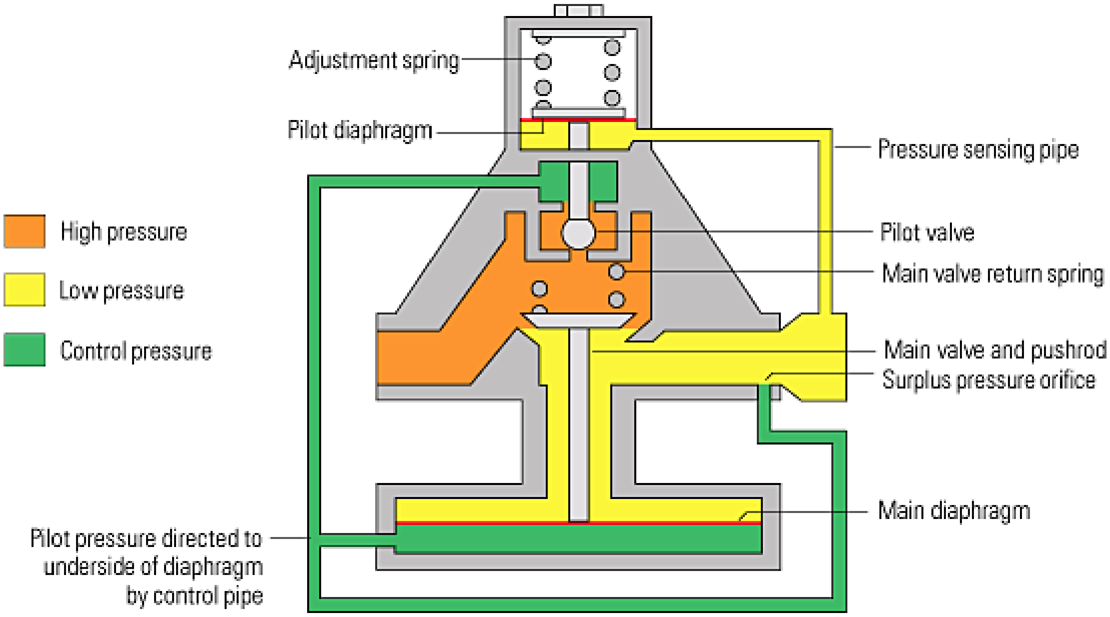


FIGURE 7 – Self-Operated Pressure Regulating Valve

These valves are simple and not many things can wrong with them. Yet there are a few. Minerals or ions in the fluid, or in water droplets in compressed air – can deposit on the internal main valve or its seat, and hinder valve operation. But the most common reason for failure or reduced performance of this type of valve is that particles find their way into internal openings and hinder smooth operation. Where self-operating pressure regulating valves are used, a strainer located upstream of the high-pressure connection may be a useful accessory.

3-phase motors

3-phase motors are very widely used. The most widely-used type of 3-phase motor used is the squirrel cage induction motor powered by a 3-phase 480 volts AC (VAC) power source. Figure 9 shows the power feed to a motor's stator (stationary) windings connected in a 3-phase, 3-wire "delta" configuration. There are no external power connections to the rotor in this type of motor. A typical rotor is constructed so it is functionally equivalent to 3 (or a multiple of 3) magnets. When voltage is applied to the stator windings, magnetic forces cause the rotor and its shaft & load to rotate. The metallic frame of the motor is grounded. Sometimes the speed of the motor is controlled by an external device like a Variable Speed Drive (VSD). In normal use each motor will use no more current than its maximum rated current. The power feed to the motor is protected from short circuit current conditions by a 3-pole circuit breaker, and from lower overcurrents of longer duration by a 3-pole thermal overload.

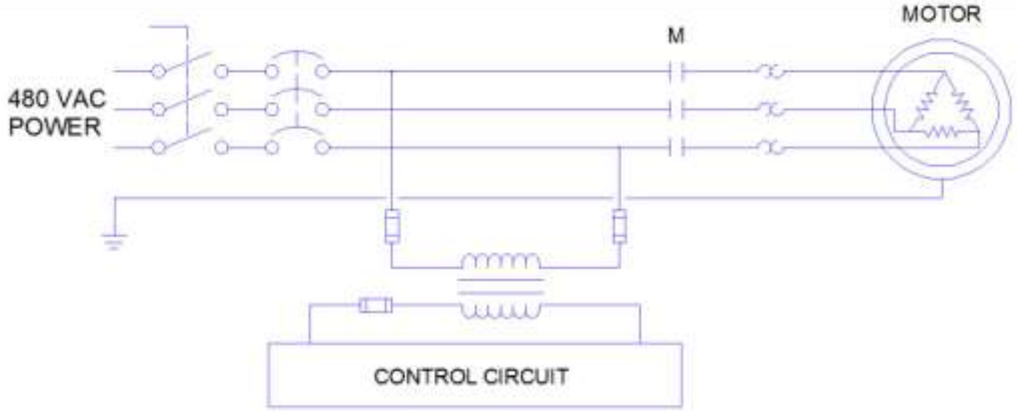


FIGURE 9

FIGURE 9 SHOWS A TYPICAL 3-PHASE MOTOR CONNECTED TO 480 VAC. POWER FLOWS THROUGH A DISCONNECT SWITCH, CIRCUIT BREAKER, MOTOR STARTER CONTACTS, AND OVERLOAD. THE MOTOR'S FRAME IS GROUNDED.

Such motors can experience operational problems if bearings that support the motor or its load start to fail, resulting in higher motor load. Many motors also have built-in fans which provide some cooling to the motor. If such a fan fails, the motor will run hotter and draw more current.

One Institute of Electrical and Electronics Engineers (IEEE) survey found that the most common reason for failures of 3-phase motors was a bearing failure[2]. The next most common reason was failure of a stator winding. Regarding the latter, most motors experience a current inrush called a Locked Rotor Current at the instant of motor start that is about 6 times higher than maximum rated current. This current is brief, and as a motor speeds up, the current drops to the rated current quickly. However, these high currents put mechanical and thermal stresses on the insulation of a motor's stator windings. Also, if a motor is running at only slightly above rated current for sufficiently long periods, the insulation on the stator's wires will also be heated and stressed. Eventually, insulation will break loose from wires. When that happens, a short-circuit will either develop due to a phase-to-ground fault, where fault current passes through the motor's casing, or as a phase-to-phase fault. In such cases, the circuit breaker will limit the duration of the short circuit, but the motor will be useless.

Note: A phase-to-phase fault (between wires with deteriorated insulation) or phase-to-ground fault (between a cable with degraded insulation and metal conduit) can also happen inside a conduit carrying conductors to a motor without damaging the motor.

Centrifugal Pumps

Though many different pump types are used, Centrifugal Pumps are the most commonly used sort. A Centrifugal Pump typically includes these components:

- A **Casing**, or housing that contains its internal components, and flanged or threaded inlet and discharge pipes.
- An **Impeller** that is connected to a rotating shaft. The impeller usually consists of two parallel discs with arced blades between them. One plate has an opening in its center so fluid can flow in from the inlet pipe. Fluid discharge is into the **Volute**, the space between the inner casing and impeller. Impeller shafts are usually but not always powered by an electric motor. The impeller's shaft for the connecting motor will penetrate the casing.
- **Bearings**. The type of bearing(s) used are not uniform, they depend on application-specific factors and the manufacturer. Bearings may have stationary lubricating grease, but for some heavy-duty pumps, lube oil under pressure may be used. Centrifugal pumps bearings are typically subject to axial loads parallel to the shaft.
- A **Stuffing Box** that contains **Packing Glands** with **Packing Material**. The latter two limit escape of fluid under pressure through the body of the casing. In some pumps, **mechanical seals** (for *preventing* fluid leakage) are used in place of the former.
- Some centrifugal pumps also have a **seal water** connection. Seal water under

pressure is applied at the pump region along the impeller shaft where it penetrates the casing. Seal water prevents abrasives particles in the fluid from getting into and bearings and causing their premature failure.

A **Startup Bypass Valve** and/or **Discharge Check Valve** may also be provided after a centrifugal pump's discharge. Furthermore, a pump may be also self-priming (removing air while starting). But air must be removed from a centrifugal pump to operate it.

An image on the next page shows a sectional view through a centrifugal pump.

Many factors affect an engineer's selection of a centrifugal pump for an application. An electrical engineer's help may also need to specify the appropriate pump motor. But usually, the pump supplier will tell the user what motor type should be used.

Centrifugal pumps usually endure the most stress during startup.

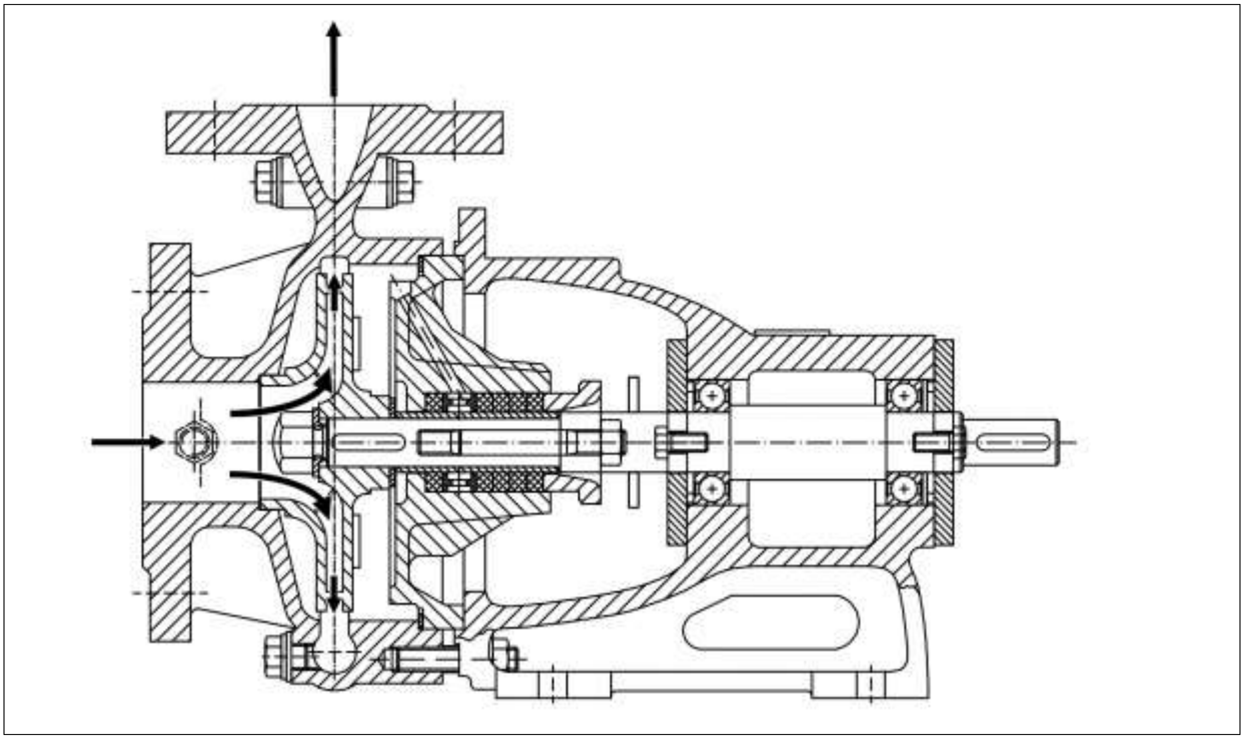
Frequently, one or more of the following pump parameters are monitored: Speed, Discharge Pressure, Vibration, and Lube Oil Temperature. High Vibration and/or Lube Oil Temperature conditions will sometimes trigger remote alarms.

Except where a pump's use is only occasional (as with many sump pumps), where reliable operation is needed, 2 or more pumps will be used in parallel in an application, so maintenance can be done on an out-of-service pump. Two very common pump maintenance tasks are replacing worn packing material, and changing lubricating oil.

Significant enough wear of any key component – for example, its bearings – will shorten the pump's life, and can lead to premature failure, especially if regular maintenance is not done on the pump.

Two factors that frequently shorten a pump's life, or create operational difficulties, are **cavitation** and **instrument problems**.

Cavitation is the primary risk to centrifugal pumps, and every pump should be installed and operated to prevent its possible occurrence. Cavitation in a pump occurs when fluid pressure at the impeller falls below atmospheric pressure and tiny bubbles form in the fluid. When that happens, bubbles collapse as fluid tries to fill the void, and set off small explosions. Typically pump impellers, and sometimes casing surfaces become damaged, and their useful lifetime is reduced. It usually causes visible surface pitting.



Cross Sectional View through a Centrifugal Pump

The following formula[3] may be used to calculate the key parameter, *Available NPSH* (Net Positive Suction Head), which must exceed the pump manufacturer's *Required NPSH* to avoid cavitation.

$$\text{NPSH}_{\text{(available)}} = H_{\text{abso}} + H_s - H_f - H_{vp}$$

Wherein: $\text{NPSH}_{\text{(available)}}$ = Net Positive Suction Head (in feet)
H_{abso} = absolute air pressure on the suction well's liquid surface (in feet). It will drop as atmospheric pressure falls; and with increasing elevation[1].
H_s = static elevation of the liquid above the centerline of the pump. H_s is negative if the liquid level is below the pump centerline.
H_f = friction head and entrance losses in the suction piping in feet.
H_{vp} = absolute vapor pressure of the fluid at the pumping temperature in feet. H_{vp} will rise as fluid temperature rises.

Cavitation can occur even in a properly designed installation if enough debris and/or fine particles make their way into the pump's well. In such cases, H_f can rise enough that cavitation happens. Debris and particles can also clog the pump's inlet or impeller.

---

[1] Normal sea level atmospheric pressure of 14.7 PSIA equates to 2.31 feet (27.72 inches) of water at 20° C (68°F).

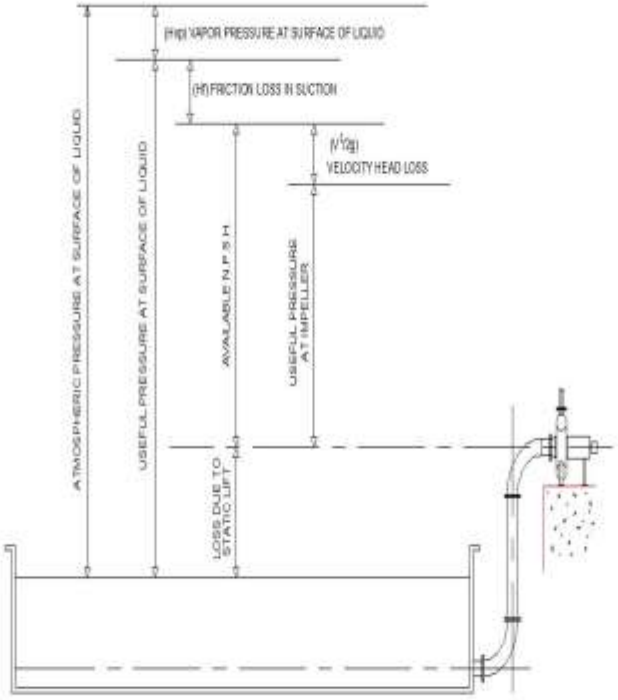


FIGURE 3 - NPSH FOR CENTRIFUGAL PUMP WITH LIFT

Figure 3

Instrument problems: Many pumps turn on and off in response level signals from instruments, or as floats move up and down. But float switches can become weighted with scale or scum; or floats may become entangled if suspended from above by cables. Either can lead to improper operation. A variety of instrument types, such as immersed capacitative sensors, and non-contact technologies like radar and ultrasonic devices are also used. Each has its advantages and disadvantages.

Murphy in Action: In one instance of the author's experience, pumps could not be started because pressure switches used to detect seal water pressure became inoperable as (simultaneously) seal water lines became too plugged with particles.

Some common examples of good practices

Over time, people have devised many ways of improving safety and reliability, or addressing problems conditions. Here are some mostly simple (if not banal) practices that have been widely adapted in the last 25 or more years. Many of these practices relate to electricity.

- Ground Fault Interrupter (GFI) circuit breakers are routinely used now. GFI breakers help prevent electrocutions.
- Intrinsic Safety (I.S.) Barriers in electrical circuits wired to devices located in hazardous environments help prevent explosions by limiting current flow.
- Surge suppressors built into power strips prevent most voltage spikes in the electric power supply from affecting devices connected to them.
- Uninterruptible Power Supplies allow continued operation of critical equipment in event of power failures.
- Power disconnect switches which can be locked in place improve safety for electrical workers.
- Use of line reactors with motors with Variable Speed Drives (VSDs) allow the motors to last longer in the presence of high harmonic currents generated by the VSDs.
- Redundant sensors are used for critical measurements, so ability to monitor a process won’t be interrupted if one sensor fails.
- Material Safety Data Sheets in workplaces warn people of potentially dangerous substances, and provide information on remedies in cases of exposure to them.
- Motor vehicle brakes are now engineered so loss of brake fluid will affect only two instead of all four wheels. (Before the 1960s this wasn’t universal practice.)
- Loop seals below toilets prevent hazardous gases from sewers from getting into buildings.
- Soffet vents built into the eaves of homes prevent condensation of water vapor in attics.
- Ducts connected to the outdoors are located in furnace rooms and provide both adequate air for combustion and makeup air for buildings.

Some guidelines for avoiding and coping with human errors and oversights:

This list of guidelines is long and somewhat tedious, but useful.

1. For projects, expect there will be some installation issues which can't reasonably be foreseen. Expect that time and money will be needed to address some unforeseen problems.
2. Appropriate Quality Assurance/ Quality Control (QA/QC) measures are needed by each organization. The appropriate QA/ QC measures will vary widely depending upon the nature of the business and its projects.
3. Budget time for error checking, because there's a multiplier effect with design errors: investing time & money in checking for design errors and engaging in peer review before something faulty is shipped – or documents are released - is usually less costly than fixing a problem in the field.
4. A specification for something should be placed only in one document, and if warranted, citations to this specification should be located in other specification documents. Try to avoid differences between specifications for the same thing.
5. Make sure devices used in an application will be able to withstand any gases or chemicals to which they're likely to be exposed.
6. Be aware of the temperature limitations of devices.
7. Engineers should size equipment so it will work as efficiently as possible for the application. But when the engineer's selection is limited by what suppliers offer, it should be the best fit for the application.
8. Equipment units that will work with each other should have capacities that are comparable. Otherwise, one unit may be undersized or oversized. The drawbacks of undersized equipment are obvious. Oversized equipment may turn on and off too frequently, wear out too quickly, work inefficiently, or deliver too much of something to one or more equipment units.
9. Before designing or installing something for a client, try to get an idea of the level of expertise of the end user's, or client's maintenance staff.
10. Clear communications about applicable control requirements are needed between installation and startup personnel, and owners/operators of equipment.
11. Electrical and Controls Engineers are typically part of a supporting cast during project work. They need to clearly understand the requirements of the major equipment engineers.
12. If there need to be any electrical interlocks between equipment located in different places, these need to be established. For example, a conveyor dropping material on a second conveyor should not run unless the second conveyor is running.
13. The failure mode of each actuator upon loss of electrical, compressed air, or hydraulic power must be known, and defined. (Note: some actuators fail in place – with valve, damper, etc. partly open.)
14. Evaluate how transport delays will affect a process.
15. Engineers should ask themselves what kinds of process upsets and stress conditions could occur, and prepare for such possibilities. For example, sometimes

"soft-start" motors can be used to reduce current inrush when starting a motor. Use of slowly-opening check valves can reduce shocks to piping when starting pumps. Shock-absorber like devices to resist water hammer will sometimes be necessary.

16. Consider allowing some motors to be jogged. Spring return switches or momentary push buttons can be used for such purposes.
17. Strive for designs in which maintenance can be done without too much difficulty, and operations can be continued if one or more problem conditions arise.
18. Establish what the failure mode is for each device in an assembly or system. Then ask yourself what the consequence would be on the assembly of parts, or system as a whole, if a part or device fails.

    EXAMPLE 1: Ask yourself, what underlying assumptions are you making when you design something? And is there anything wrong with your assumptions?

    EXAMPLE 2: Might fluids become hard to pump, or materials difficult to transport for some reason? And what measures can be taken to prevent a plug or hang-up from happening, when pumping something, or moving bulk materials?
19. These days, organizations tend to be run with minimal numbers of operators and maintenance staff. So, there is virtue in designing something that will hold up over time and is fairly easy to maintain. It's suggested these practices be followed:
    - Use the most appropriate technology for each application. Don't use something that's more complicated than it has to be.
    - Access ways, safety devices and control panels need to have good and readily visible labels that will hold up over time. For example, labels on panels located outside tend to be degraded by sunlight over time.
20. Engineers often have to use devices which are rather crude, such as control valves or circuit breakers with bimetals. Be aware of their limitations.

    EXAMPLE 1: Control valves are often used to control the flow rate of gases and steam in plants. But even if upstream and downstream conditions are stable, the change in flow rate between 60% and 80% open may be much larger than the change in flow rate between 40% and 60% open. This makes good control of many processes difficult.

    EXAMPLE 2: Bimetals are used in thermal magnetic circuit breakers, thermal overloads for motors, and thermostats of car radiators. The time for a thermal overload to cut off a motor at 130% rated current might be 65 seconds one day and 90 seconds another day. Bimetallic devices have poor "repeatability."

21. Whenever trying out something that's new, use it for only one application to start, and accumulate experience from the trial application before using it in place of an existing method. This guideline is also helpful in assembly and manufacturing situations – evaluate how workers react to changes from an existing routine.
22. Most important of all, in the writer's judgment: Engineers are often in situations involving **tradeoffs** – where achieving one desirable aspect of performance comes at the expense of one or more other performance aspects. Designers need to be clear about what the tradeoffs are, decide what the most important performance aspects are, and proceed accordingly.
23. When involved in a project where end users will be operators, strive to develop systems which are easy for operators to use.
24. Make sure all software programs that have to work together are interoperable.
25. If possible, it's best to pre-test something before shipping or installing it. If possible, pretests should test response to the most disruptive conditions that might occur.
26. Sooner or later someone besides the original coder will have to work on code developed by someone else. So, PLC/DCS programmers, and coders in general, should always add comments to their code, so it won't be too hard for 3rd parties to understand.

CSI MasterFormat specifications

For decades, A/E (Architectural / Engineering) firms, Design Firms, Construction Contractors, as well as commercial and governmental organizations which operate plants and buildings have used CSI specifications. **CSI** is a contraction for the **Construction Specifications Institute**. The CSI has developed a "MasterFormat" for specifications with both major and minor divisions which cover the many aspects of projects. The 2012 version of the CSI "Master Format" has 49 major divisions for specifications, from Division 0 through Division 48. (A few major divisions are currently unused - including Division 47 - and are available for future additions.) The first 4 and last 3 of the major divisions are listed below:

Division 0:	Procurement and Contracting Requirements
Division 1:	Solicitation
Division 2:	Instructions for Procurement
Division 3:	Concrete
Division 45:	Industry-Specific Manufacturing Equipment
Division 46:	Water and Wastewater Equipment
Division 48:	Electric Power Generation

Each major division of CSI MasterFormat specification is subdivided. The reader can get an idea of the complexity of the CSI MasterFormat by referring to Appendix A, where the subdivisions for Division 45 are listed.

CSI does not tell its users what should be in a specification. Rather, CSI provides some guidance on how individual specifications should be structured, but it's up to individual organizations to develop the details for individual specifications. In that way, organizations can – and do - develop specifications for their specific needs. So, for example, a power company which uses only gas and coal-fired boilers to generate power would have many differences in its specifications than a power company that generates all its electricity at hydroelectric dams.

Divisions 3 through 48 specifications relate to technical aspects of construction projects.

The Divisions 0 through Division 2 MasterFormat specifications relate to non-technical aspects of construction contracts. In contracts, the Divisions 0 through 2 specifications are generally patterned from either of two guidelines: Engineers Joint Contract Documents Committee (EJCDC) standard **C-700**, **Standard General Conditions of the Construction Contract**; or the American Institute of Architects (AIA) standard **A-201**, **General Conditions of the Contract for Construction**.

What do CSI MasterFormat specifications, and standards EJCDC C-700 and AIA A-201 have to do with a course on coping with Murphy's Law? Organizations which use the CSI MasterFormat specs, and EJCDC C-700 or AIA A-201, will work towards three valuable goals:

1. An outline is provided by the CSI MasterFormat for the dozens, if not hundreds of technical aspects of a project.
2. EJCDC C-700 and AIA A-201 and provide a framework for addressing the contractual, logistical and practical aspects of construction projects.
3. Use of CSI MasterFormat specifications, and EJCDC C-700 or AIA A-201 helps those involved in project work to *build Quality Control into their projects*.

In practice, A/E or Design firms will also develop drawings to provide more detail on the project requirements. Both specifications and drawings are usually needed for projects.

ISO 9000

A Quality Management System widely used in manufacturing industries is ISO 9000. ISO is a contraction for the International Organization of Standards. ISO 9000 has a group of standards for quality management. With regards to manufacturers, perhaps the key one is ISO 9001:2015. (This standard was previously updated but remains current in 2021.) It sets out the criteria for a quality management system. ISO gives individual firms a lot of latitude on how to achieve compliance with one or more ISO 9000 standards. An independent auditor examines and verifies a firm's measures for

for compliance. ISO 9000 certification allows customers of a firm to have a high degree of confidence in the quality of their products and services. But compliance with ISO 9000 standards is hardly free. It requires a real dedication to quality control, and often, more manpower. Many businesses have had to change their operations to achieve ISO 9000 compliance. And some manufacturers which rely on suppliers to furnish parts of demonstrable quality require their suppliers to be compliant with one or more ISO 9000 standards. But in many cases, the extra costs of ISO 9000 compliance are more than offset by improvement in product quality.

Guidelines for successful projects

Successful businesses and organizations typically use practices tailored to specific needs to conduct business. Among businesses and government agencies, the sorts of organizations vary a lot. Listed below are some commonly used practices:

- The Project Manager must make decisions when representatives of different groups disagree about what should be done about a disputed matter.
- Personnel at all levels of an organization should have a clear understanding of the roles and responsibilities of each department.
- At the start of a project, develop a written plan of action. It doesn't have to include all steps, but it should include all important steps.
- For Project Work, Design Firms, Clients, and Contractors should have a clearly defined scope of work. The respective roles and responsibilities of each party should be defined as clearly as possible.
- Any applicable building codes and environmental regulations must be observed.
- For projects that involve an addition or upgrade of a client’s facility, Design Firms or Contractors need to be aware of all relevant site conditions. A site inspection is often warranted.
- If a project is large enough, it's generally a good idea for A/E or Design firm and the Client to have a kickoff meeting.
- For projects of several months or longer, at least one progress meeting is recommended to discuss issues, ensure that the parties are communicating clearly with each other, review any applicable documents, answer the Client’s questions, and, at times, get the Client’s approval for something.
- Design firms that are relying on 3rd parties (e.g., Contractors, packaged equipment suppliers, panel fabricators, etc.) should require that each 3rd party submit shop drawings for review and approval.
- Particularly large or important equipment often needs to be pretested by the

Manufacturer to verify that the performance specifications are met. In many cases, an Engineer from the A/E or Design firm should witness such tests.

- A/E and Design firms should be aware of the Client's manufacturer/ brand requirements or preferences.
- Schedules which provide key characteristics of related groups of equipment are usually developed. Schedules are often created for HVAC equipment, instruments, piping, pumps and valves. If a PLC will be used, a PLC Input-Output Schedule is also usually helpful.
- System Functional Descriptions are usually helpful and often essential. Functional Descriptions should detail how different equipment units will work with each other; and how equipment and systems should be started up, controlled, and shut down. They should include pertinent information about equipment interlocks, and operation of safety devices. Functional Descriptions are often used by outside parties such as System Integrators to implement system control measures through a PLC, and to develop operators' computer screens.
- In project work, Operating Instructions will also usually be necessary. They should provide directions for starting up and shutting down equipment and systems. They should also provide instructions for operating equipment in both manual and automatic control modes. Additionally, directions for responding to alarms and emergency situations should be provided.
- Time and money should always be budgeted for startup/ initial run periods. During this time, it will usually be necessary to make some adjustments based on experience gained and/or the end user's preferences.
- Always develop and use clear metrics such as check-off lists, etc., for assessing the state of completion of a project.
- Clients should insist that Contractors provide up-to-date drawings for an installation upon completion of a project. It's recommended that a management representative enforce this.
- Spare parts should be provided for all crucial items. Sometimes parts become obsolete quickly, and then it's hard to find an in-kind replacement for the original. They are also usually cheaper when bought with original equipment.
- At least one year's stock of consumable items (e.g., lubricants, disposable filters, solutions used for calibration of some instruments) should be supplied.
- Plant and building owners & operators should have a management system to document changes made by their own personnel after a contractor has completed a project.

- Organizations should have at least 2 persons with sufficient technical expertise to fix any problem which might arise.
- Organizations should be willing to rely on outside firms to provide specialized services. Some examples: tuning of control loops, and use of non-destructive testing technologies like vibration testing of rotating machinery.
- Redundant equipment like pumps, valves, gates and dampers should NOT be left unused for a protracted period. It's best to rotate use of equipment. Otherwise, something might lock up.
- Devote as much manpower and money as possible to maintenance to prevent equipment degradation. (Some managers resist this, because it requires justification of a higher payroll for maintenance staff.).
- It's suggested that all crucial equipment and protective devices (e.g., relief valves) be inspected at least once per year.
- Passwords for access to restricted systems should be known by at least 2 persons.

Some common electrical reasons for failures or degraded performance:

Problem condition	Possible preventive/ remedial actions
Loose, poorly joined, frayed or open electrical connections. (This is the most common reason for problems with electrical circuits.)	Resistance tests can be used in de-energized circuits. Infrared cameras can be used to find many poor connections in energized circuits if there is adequate loading.
Effects of high or low supply voltage such as overheating of power handling components and/or overloading of electrical circuits.	Appropriate sensors can trigger alarms on high or low voltages.
High harmonic currents.	Line reactors and/or harmonic filters used in three-phase power supplies do a lot to protect motors from the effects of harmonics.
Undersized or oversized power handling components, e.g., fuses.	A competent Electrical Engineer will size components correctly. However, an installer or maintenance person could make an error. For new projects, an electrical inspector is needed.

Electromagnetic Interference and Radio Frequency Interference (EMI/RFI)	Appropriately designed metal enclosures help guard against EMI & RFI. Consult with manufacturers about this problem.
Aging of electrical and electronic components.	Usually, high-quality devices from reputable manufacturers will outlast and provide more customer value than the most competitively priced devices.
Problems resulting from lack of working alarm devices.	It's best to use alarm sensors and systems that include a test mode.
Aging of electrical and electronic components.	Usually, high-quality devices from reputable manufacturers will outlast and provide more customer value than the most competitively priced devices.
Effects of buildup of dirt, dust, crud, spider webs, or biological growth.	Sometimes purge air is used in particularly aggressive environments. Otherwise, it's up to Maintenance staff to address these.

Some other common reasons for failures or degraded performance:

Problem Condition	**Comments**
Mechanical wear of parts.	Simultaneous excessive noise, heat, or vibration is (are) likely.
Loss of or impaired lubrication.	Ditto.
Use of improper lubricants.	Ditto.
Loose, worn, or overtightened belts.	Periodic inspection of belts is suggested.
Problems brought on by lack of maintenance and/or equipment use.	Rotation of equipment units is recommended where possible.
Mechanical binding or jamming due to obstructing material.	For motorized equipment, overloads and torque switches help protect equipment.
Pluggages.	Design engineers need to build in appropriate means of dealing with possible pluggages.
Failures due to metal fatigue.	Very common. Speeded up by corrosion.
Failures due to corrosion.	Very common.
Gradual fusion of parts made of different materials in contact with each other.	Where there is a risk that critical parts in contact could fuse together, periodic disassembly can deter this effect.
Failures or degradation due to unanticipated chemical reactions	

Over-torqued or under-torqued bolts.	Quite common. Anti-seize compounds can be applied to bolts to make future disassembly easier.
Failures of seals or sealing systems.	These are “weak links” for a lot of equipment and deserve careful attention by Design Engineers.
Contamination.	It happens all too frequently.
Loosening of bolts due to vibrations.	Serious accidents sometimes occur when this happens.
Improper installation (or reinstallation).	Human error lives on.
Replacement of failed parts with improper parts.	Ditto.
Seizing (galling) of metallic parts made of the same material.	Design engineers need to be aware of which materials are most likely to gall. Nowadays this is not as much of a problem as in generations past.
Failures due to thermal shock.	Design engineers can do a lot to prevent these in plant environments. They happen most often outdoors in cold weather.
Selection of inappropriate equipment for an application.	Design Engineers sometimes err by specifying equipment which is not as strong and durable as it should be. Some applications are very demanding, and the end user will have to pay a high price for reliable operation and a durable product.
The effects of condensation, freezing, or freezing followed by melting.	Design engineers need to be very aware of what water can do and act appropriately.
Effects of soil erosion caused by water and/or wind.	Competent Civil and Geotechnical Engineers respect these phenomena.

Dedication

This text is dedicated to all those mechanics, technicians, and electricians who helped the author fill many gaps in his knowledge.

APPENDIX A

CSI MasterFormat Division 45 Specification Subdivisions

45 00 00	Industry-Specific Manufacturing Equipment
45 08 00	Commissioning of Industry-Specific Manufacturing Equipment
45 11 00	Oil and Gas Extraction Equipment
45 13 00	Mining Machinery and Equipment
45 15 00	Food Manufacturing Equipment
45 17 00	Beverage and Tobacco Manufacturing Equipment
45 19 00	Textiles and Apparel Manufacturing Equipment
45 21 00	Leather and Allied Product Manufacturing Equipment
45 23 00	Wood Product Manufacturing Equipment
45 25 00	Paper Manufacturing Equipment
45 27 00	Printing and Related Manufacturing Equipment
45 29 00	Petroleum and Coal Products Manufacturing Equipment
45 31 00	Chemical Manufacturing Equipment
45 33 00	Plastics and Rubber Manufacturing Equipment
45 35 00	Nonmetallic Mineral Product Manufacturing Equipment
45 37 00	Primary Metal Manufacturing Equipment
45 39 00	Fabricated Metal Product Manufacturing Equipment
45 41 00	Machinery Manufacturing Equipment
45 43 00	Computer and Electronic Product Manufacturing Equipment
45 45 00	Electrical Equipment, Appliance, and Component Manufacturing Equipment
45 47 00	Transportation Manufacturing Equipment
45 49 00	Furniture and Related Product Manufacturing Equipment
45 51 00	Other Manufacturing Equipment

Endnotes:

---

[1] METTLER-TOLEDO Weigh Module System Handbook, Chemical Resistance Chart (www.mt.com)

[2] IEEE Petro-Chemical Paper PCIC-94-01.

[3] Pump Selection – A Consulting Engineer's Manual (Ann Arbor Science Publishing, 1972; Author: Rodger Walker, P. Eng.)