A SunCam online continuing education course

Reliability in Mission Critical Applications Part II – Mechanical Systems

by

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A. Introduction

This course is developed to provide a follow up to a previous course on electrical reliability associated with mission critical applications. This course is also "introductory" in nature in that it will cover basics of reliability, albeit from the perspective of mechanical systems. This course may be considered a good refresher course for those who work in the mechanical engineering field and already have a familiarity with mission critical systems. Mission critical reliability is also a useful topic for any Engineer to be familiar with associated with their interest in the design of mission critical systems. Any discussion on reliability should generally include both electrical and mechanical systems reliability, however for the purposes of this course, and simplicity's sake, electrical systems reliability will NOT be addressed but may be reviewed in a SunCam's course entitled "Reliability in Mission Critical Applications Part I – Electrical Systems".

This course will review some Heating, Ventilation, and Air Conditioning (HVAC) system basics (including the Refrigeration Cycle), it will provide an explanation of several HVAC components important to understanding in providing redundancy, and it will review previously established definitions (from a mechanical perspective) so as to help to reader understand how different levels of reliability can be and are frequently quantified from a mechanical perspective.

This course is intended to be useful to individuals at all levels of experience as well as a topic of interest to the full variety of those of an engineering (civil, mechanical, electrical, etc.), architectural, and/or facilities management background. As a result, some basics will be touched upon that may seem rudimentary to some, but for others will be useful to hear for the first time or as a refresher. Regardless, it should be valuable to establish this information and have it in one place for the reader's reference.

The reader of this course should be able to use the tools gained to have an even greater understand of reliability in mission critical applications.

B. Basics

Background

Mission critical systems are systems that are needed in order to keep the business purpose of an organization functional. If a mission critical system does not fulfil its mandate then the operation of the company will likely be impacted in a significant way, including financially. Often times they serve the purpose of keeping data processing, or keeping a life safety functions on line. As a result, mission critical system design must be performed with an understanding of the risks and be carried out in a way that meets the needs of the end user organization.

All component will fail eventually. This is an extremely important fact to recognize in approaching the incorporation of reliability into a system so that it fulfills its mission critical system mandate. Keep this in mind as the information unfolds. It is worth noting that "equipment reliability" is a different topic and for information on analysis of mean time to failure and topics related to "non-mission critical" equipment reliability refer to other courses available from SunCam associated with reliability in building systems.

Given the fact that all components will eventually fail, "reliability" as discussed in this course is related the reliability of the overall system and its ability to achieve the mission of the business.

It should be recognized that reliability is validated as a function of the availability of the critical system.

It is worth noting that in the industry there are differences of opinion associated with the percentages of "uptime" without "downtime" that various availability configurations of the equipment can provide for a system. *Uptime* is a term that expresses the condition of mission critical systems when they are functioning as required / desired and the services are and continue to be available. *Downtime* is the term assigned to the period of time after a failure occurs; while services are not available, and until the critical support systems are restored.

Reliability in general is ensured by providing "redundancy" and fault tolerance (i.e. avoiding single points of failure).

There are several organizations that established definitions and levels or tier ratings associated with mission critical systems. This course will not discuss or comment on those types of rating systems only to say that they do have value in establishing a baseline for those in the industry to work from within their understanding. There are some ways of expressing reliability that have different interpretations, as a result there is some subjectivity associated with a discussion on the topic of reliability and uptime.

As noted above, this course will in general focus on and mainly discuss the reliability of mechanical cooling systems for mission critical systems. The engineer should keep in mind that electrical power supply is also typically a critical aspect of any mission critical system. If the electrical systems fail, some aspect of the critical equipment (for example critical computing equipment) may be lost. To expand your understanding of this and for information on reliability in electrical systems, refer to a course that specializes in that topic.

Some Mechanical Engineering Background and Basics

As a refresher to anyone who has taken the appropriate science courses, many years ago the thermal sciences came to understand that there is technically no quantifiable parameter known as cold, only a relative scale of how much heat/energy exists in a system. In the Centigrade/Celsius (C) scale of temperature reckoning, -273.15° C or “absolute zero” (i.e. 0° K (Kelvin) is the theoretical temperature where “molecular activity” ceases. Every temperature above that represents an increase of heat in the system from absolute zero. Based on equation E-1, absolute zero can be calculated as -459.67° F (Fahrenheit).

The mathematical conversion between C° and F° is expressed in Equation E-1:

$$\mathrm{F}^\circ = \left(\frac{9}{5}\ \mathrm{x}\ \mathrm{C}^\circ\right) + 32^\circ$$

EQUATION E-1

When hot/cold is understood in this manner (as a representation of the amount of heat in the system), then one can easily understand that conceptually cooling is really just the transfer of heat from one place to another.

There are different established units of measuring heat and the transfer of heat. A common unit traditionally used in the United States (in the English system of units) is the British Thermal Unit (BTU). A BTU is defined as the amount/quantity of heat energy required to raise one (1) pound (lb.) of water by one 1° F. The metric system and SI metric systems utilize different expressions of heat energy which will not be discussed here.

A refrigerant ton (RT) or "ton" of cooling capacity of an air conditioning system (again, in the English system) is the amount of BTU required to melt one (1) ton of ice (2,000 lbs.) in a 24-hr period. This is a more convenient measure of the rate of heat flow. When 1 lb. of ice melts, it absorbs 144 BTU. As a result, 1-ton of cooling is 288,000 BTU (i.e. 144 x 2000 = 288,000; therefore it takes 288,000 BTU to melt a ton of ice in 24 hours.)

A simple calculation of 288,000 BTU / 24 hr = 12,000 BTU/hr. As a result, a 1-ton air conditioner is rated at 12,000 BTU/hr while a 2-ton unit is rated at 24,000 BTU/hr. This is reflected in Equation E-2.

$$1 \text{ ton} = 12{,}000 \text{ BTU/hr}$$

<u>EQUATION E-2</u>

Since mission critical cooling is often tied to the amount of heat generated by electrical equipment, the amount of cooling a unit can cool is sometimes defined by the electrical heat in kilowatts (kW) since this is the amount of electrical power/heat that must be transferred from the system. The equation to convert tons to kW are shown in Equations E-3 and E-4.

$$1 \text{ kW} = 0.284345 \text{ tons}$$

<u>EQUATION E-3</u>

$$1\ \text{ton} = 3.51685\ \text{kW}$$

EQUATION E-4

It needs to be stressed that in sizing the capacity of mechanical equipment, engineers often refer to the equipment in terms of its “nominal capacity”. For example one might say, “We need to specify a 20-ton roof top unit”. However to be clear, the actual amount of cooling that the equipment will actually provide depends on a number of factors such as the local high/low temperatures, dew point, the change in air temperature the equipment will be set/required to provide (often referred to as “delta t” or ΔT), and the humidity level of the environment, which may or may not be provided by the equipment.

As a caveat, since this is a high level course on reliability, the narrative will generally use approximations and rounded figures, including labels in terms of “nominal” capacities. This course will also use rounded and approximate figures and take for granted the other parameters that an design engineer needs to take into account in “right sizing” the equipment for the location, application, and load.

The Refrigeration Cycle

Based on the information above, and without getting into detail on methods of heat transfer, etc., a fundamental aspect of mechanical cooling design that must be considered and discussed is the ***Refrigeration Cycle***. The refrigeration cycle is the process by which a closed mechanical system can be developed through the cyclical evaporation, compression, condensation and expansion of a refrigerant. A ***refrigerant*** is a substance with the property that transitions between its liquid and gas state within a pressure range that mechanical equipment (i.e. a compressor) can easily develop.

Various “pure” substances (herein after referred to as substances) change state at different pressures and temperatures. For example, at *atmospheric* pressure, water will freeze at approximately 32° F and will turn to steam at approximately 212° F. At a different pressure, the temperatures at which the substance (in this case water) transitions are different.

Figure F-1 shows a sample "phase diagram" that reflects this phenomenon. It is worth noting that this diagram is exaggerated; to help the viewer see the implications.

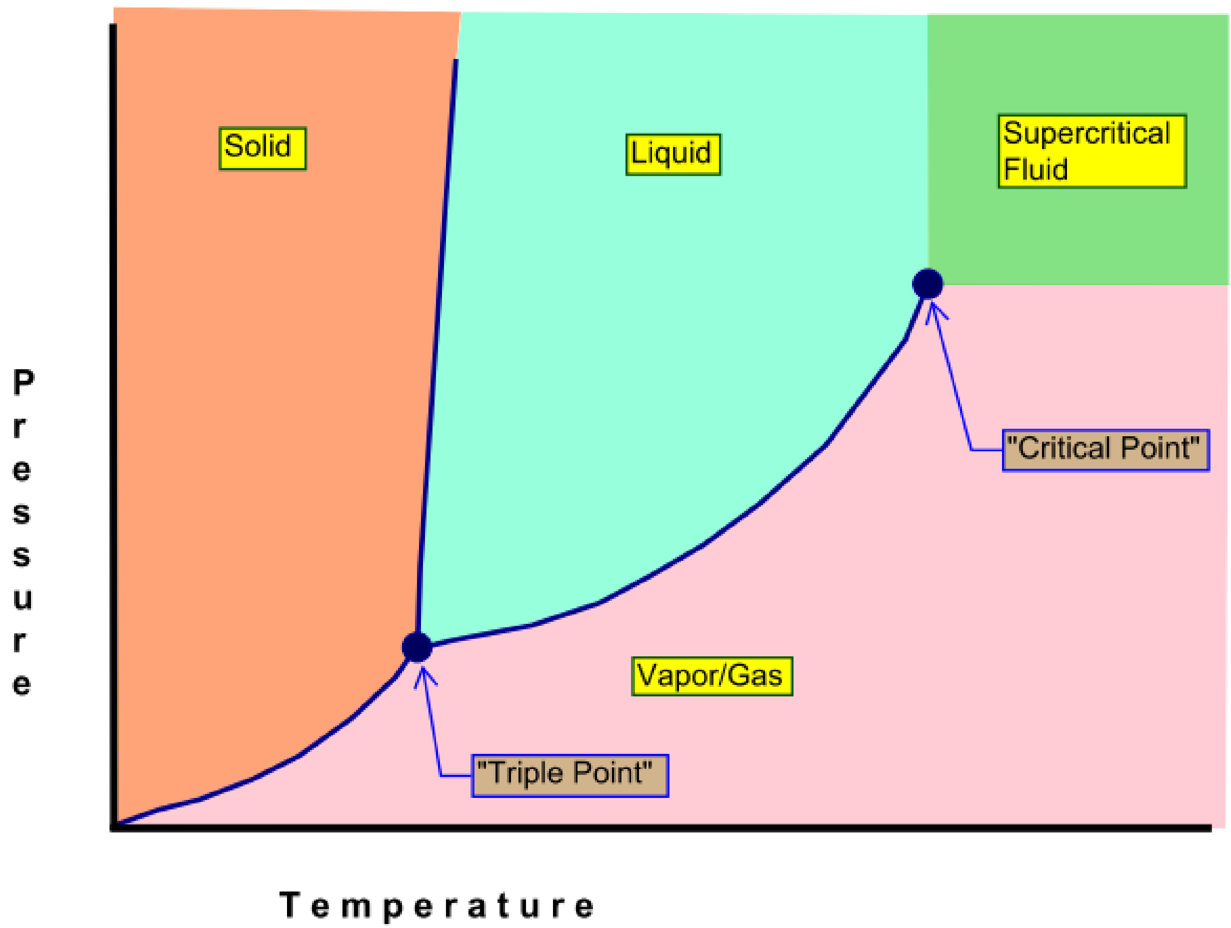


Figure F-1
(A Sample Temperature/Pressure Phase Diagram)

In the case of an increase in heat applied to a substance (at a constant pressure), the substance will increase in heat until it reaches the transition temperature. When the substance transitions from one state to another (for example water to steam), the temperature of the substance remains constant until the substance completely changes state. Figure F-2A reflects this phenomenon.

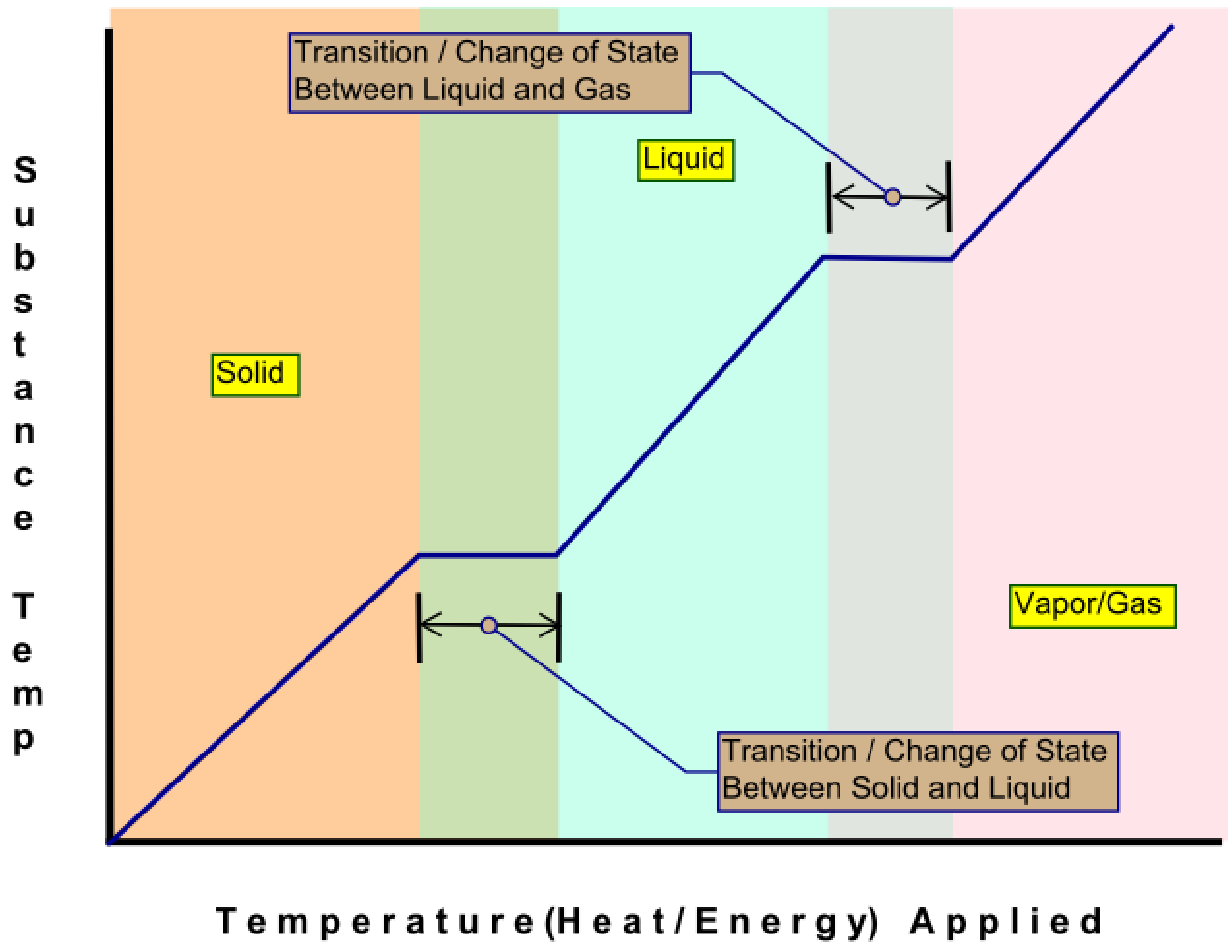


Figure F-2A
(A Transition Temperature Diagram)

From this visual it is easy to recognize that heat is absorbed by the substance when the substance transitions from liquid to gas. This transitory phase is also referred to as vaporization. Heat is released when a substance transitions from gas to liquid. This phase is referred to as condensation.

What is not as clear from this diagram, yet of interest, is the amount of relative energy required to transition a substance between states. Figure F-2B outlines a commonly considered summary to help explain this, and to clarify understanding the effect of transferring heat. As can be seen, there is a substantial amount of heat energy required in the phase transition between liquid and gas.

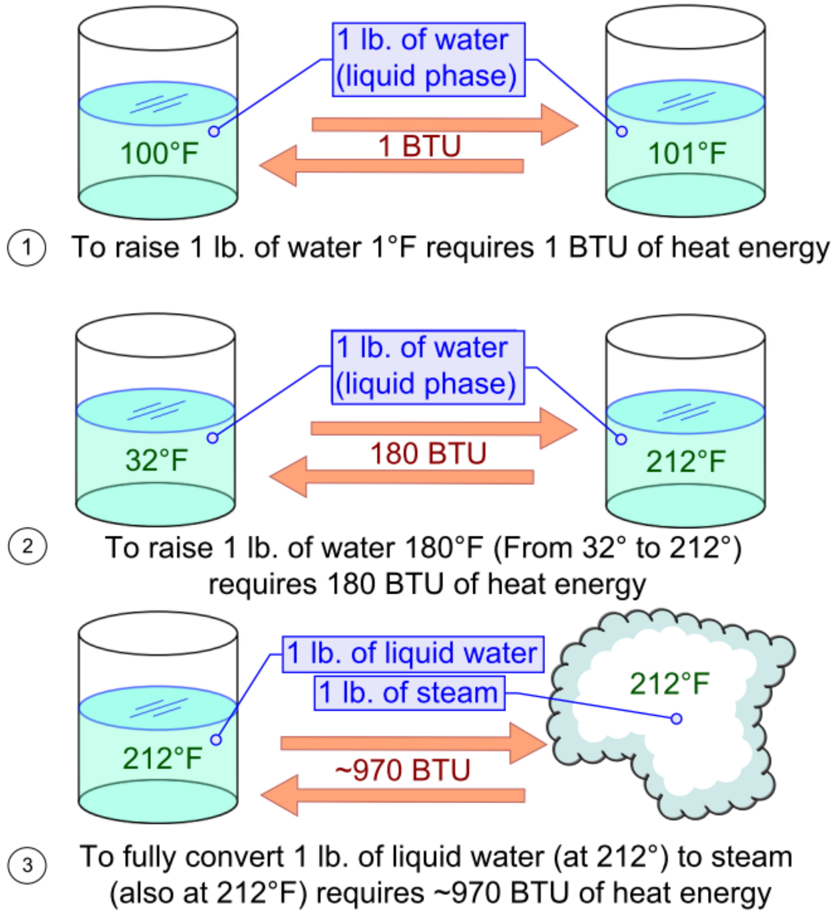


Figure F-2B
(The Effect of Transferring Heat)

Latent heat is term associated with the energy required to change the state of the substance. As this heat is applied, the substance changes state but stays the same temperature. ***Sensible heat*** is the term used associated with the heat energy that, when added to or removed from a substance, results in a measurable change in substance temperature. Another term often discussed associated with substance properties is the "specific heat", which is defined as the quantity of heat in BTUs required to raise 1 lb. of that substance 1°F, in the case of water, its specific heat is 1.

Refrigerants are substances that transition between liquid and gas easily at working pressures, which allows them to be easily transitioned by the various components of the mechanical cooling equipment. Figure F-3 is a simple diagram of the refrigeration cycle as it exists in cooling equipment.

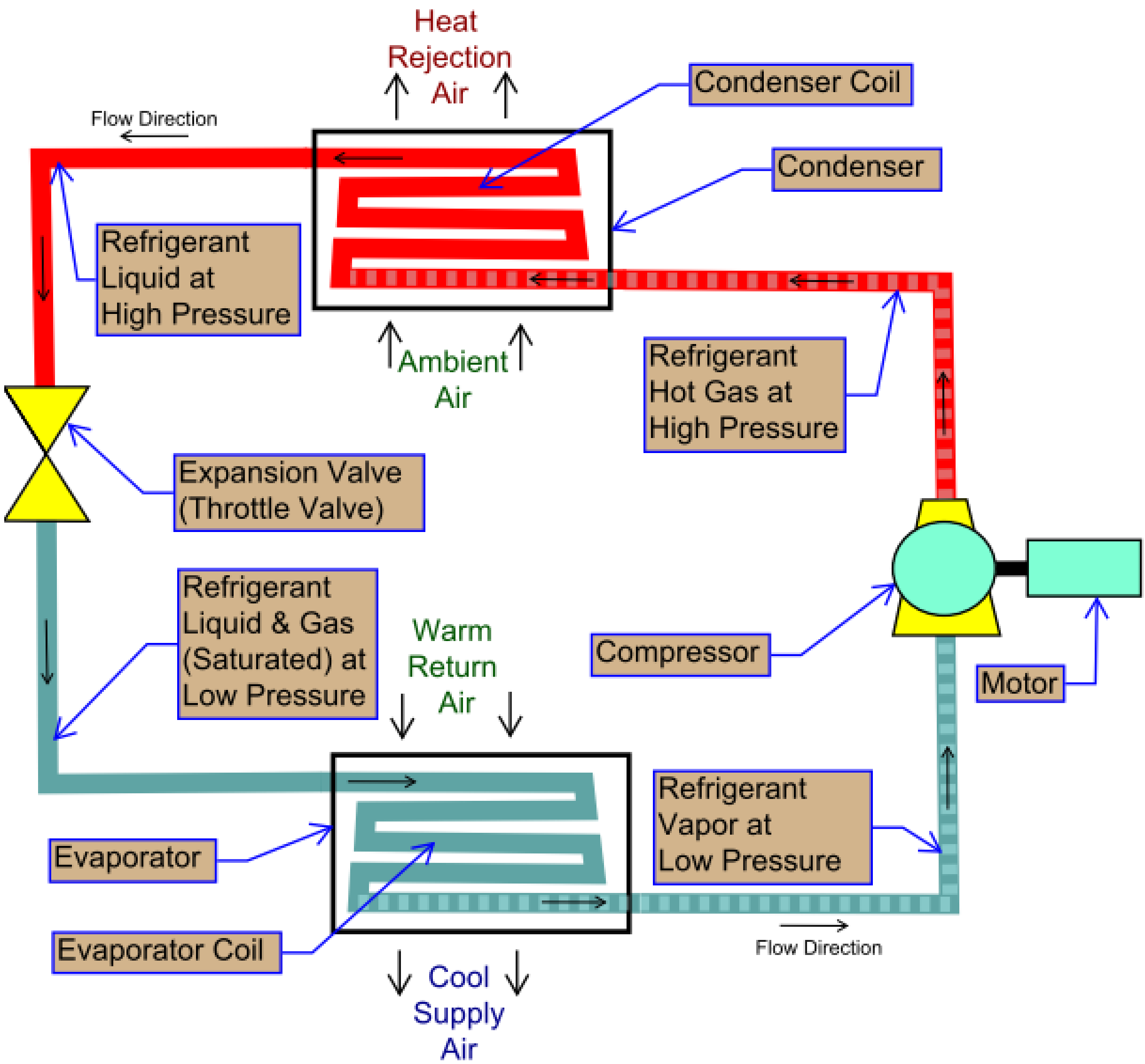


Figure F-3
(The Refrigeration Cycle)

The refrigeration cycle works by utilizing a closed loop of refrigerant that is pressurized by a compressor while in the gas state. The gas then condenses, releasing heat. This heat is rejected to the environment via a condenser coil. The term coil refers to the pipe being "coiled" or run back and forth, typically with "fins" to maximize the heat transfer by the coil. The refrigerant in liquid state (in the pipe) is allowed to release pressure via an expansion valve. The liquid then vaporizes, absorbing heat from the adjacent environment. As the heat is absorbed, a supply of cooler air is introduced into the environment through an evaporator coil, sometimes referred to as the cooling coil. The low pressure gaseous refrigerant returns back to the compressor where the cycle repeats. Unless fans are used to pass air across the coils, the energy inserted into the system only occurs at the compressor, which is typically electrically powered by a motor.

While this diagram shows mechanical cooling via a compressor, it is worth noting that there are actually ways to configure components so that under certain conditions, the cycle will occur without any energy being applied to the system (i.e. compressor-less). Discussion on this sort of system is beyond the scope of this course.

Another topic beyond this course, but worth mentioning is the concept of a heat pump. An air conditioning unit is technically a heat pump that only supplies cool air. A heat pump uses the refrigeration cycle in both directions so that it can heat a space as well as cool it depending on the seasonal outdoor temperature.

There are many types and nuances associated with the various types of equipment available that utilize the refrigeration cycle, many of which will not be discussed here. The following section will merely highlight a few of the more common types required for mission critical cooling.

This course will not go into detail about other useful cooling equipment and strategies such as “heat wheel” technology, but it is worth mentioning so the reader is aware of its existence.

C. Simple Direct Exchange Systems

In order to understand reliability in mechanical configurations, there needs to be a discussion on the various systems of providing cooling and the related components. Since reliability may be approached in different ways depending on the mechanical cooling system, this course will generally discuss two (2) types of systems, Direct Exchange (Dx) systems and Chilled Water Systems. Both require the refrigerant cycle. Components of each type of system will need to be understood and will be reiterated later.

In order to understand the more complex chilled water systems, the functionality of Dx systems will be outlined first. It is worth noting that the equipment manufacturers have data sheets that provide all of the information about the functionality and limitations of the various pieces of equipment and that is beyond the scope of this course. A qualified mechanical engineer with mission critical systems experience should always be consulted related to any specific design. The following are some Dx systems:

Window Air Conditioner

Window Air Conditioners are not typically used in the mission critical field as a best practice. These are discussed here just to illustrate the refrigeration cycle at work and how it is implemented. Since the system is all in one unit and the unit is "air cooled", it is virtually identical to putting a box around the refrigeration cycle diagram shown in Figure F-3. Figure F-4 shows a section of how this works.

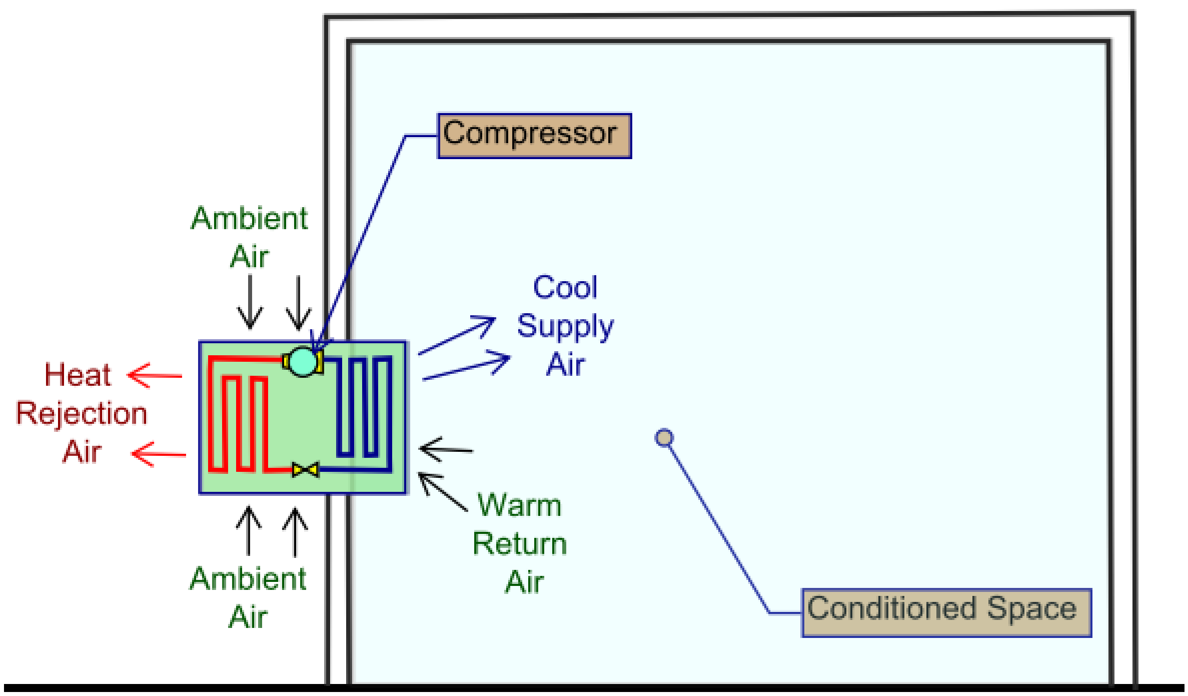


Figure F-4
(The Refrigeration Cycle Components in a Window Unit)

It is worth noting, Refrigeration units work on much the same principal, cooling to lower, even freezing temperatures. The conditioned space is the walk-in unit or refrigerator, and heat rejection goes into the adjacent spaces.

Packaged Air Conditioning Unit

A packaged air conditioning unit is a unit that has both air conditioning (the refrigeration cycle) and an air handler combined. Many times these are on the roof and are referred to as rooftop units or RTUs. These can be considered similar to a window unit, but will often serve several rooms with a distribution of ductwork from the unit to each room.

Other Direct Expansion Systems - Split Systems and “Dx CRAC systems”

A “split system” is a Dx cooling system that places the heat rejection equipment remotely away from the cooling coil. When most engineers think of a split system, they are envisioning the compressor and expansion valve portions of the cooling cycle occurring within the outdoor or remote heat rejection equipment. In this scenario, the heat rejection equipment is typically referred to as a ***condensing unit*** and the interior section is called the cooling coil or evaporator section. In the past the expansion valve may have been located “inside” with the cooling coil, but generally most expansion valves are located in the modern condensing unit.

One major benefit to installing a split system is the quietness of the system near the location being cooled since most of the noise of refrigeration is due to the compressor. Any noise on the evaporator section of the unit comes from the fan.

Figure F-6 provides a diagram of how a split system works.

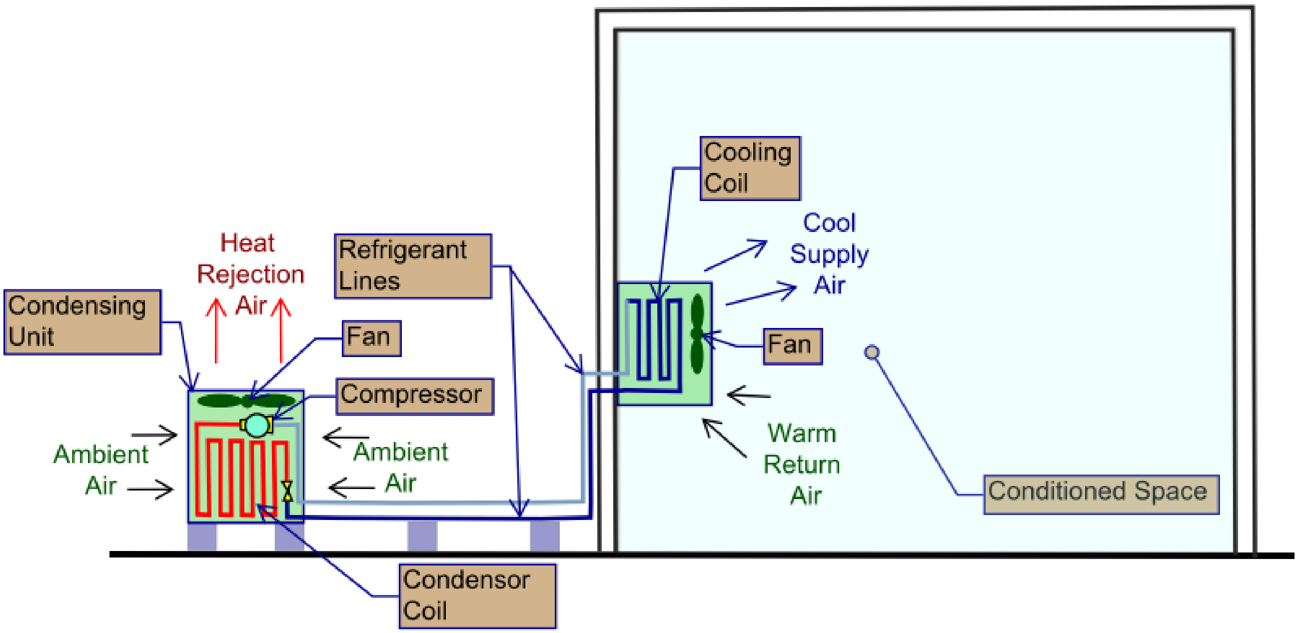


Figure F-6
(The Refrigeration Cycle Components in a Split System)

There are split system on the market with ports to accommodate several evaporator sections connected to a single condensing unit.

Another Dx configuration places the compressor inside the section with the evaporator section, and only the condenser coil and fan are located outside. This is the configuration, for example, of most precision cooling computer room air conditioners (CRACs) where noise is not a concern. It is worth noting that in this scenario the outside unit is referred to as the ***condenser***, distinct from the term condensing unit used in the prior split system example.

Figure F-7 provides an example configuration for a Dx CRAC Unit positioned on a raised floor in a computer room / data center.

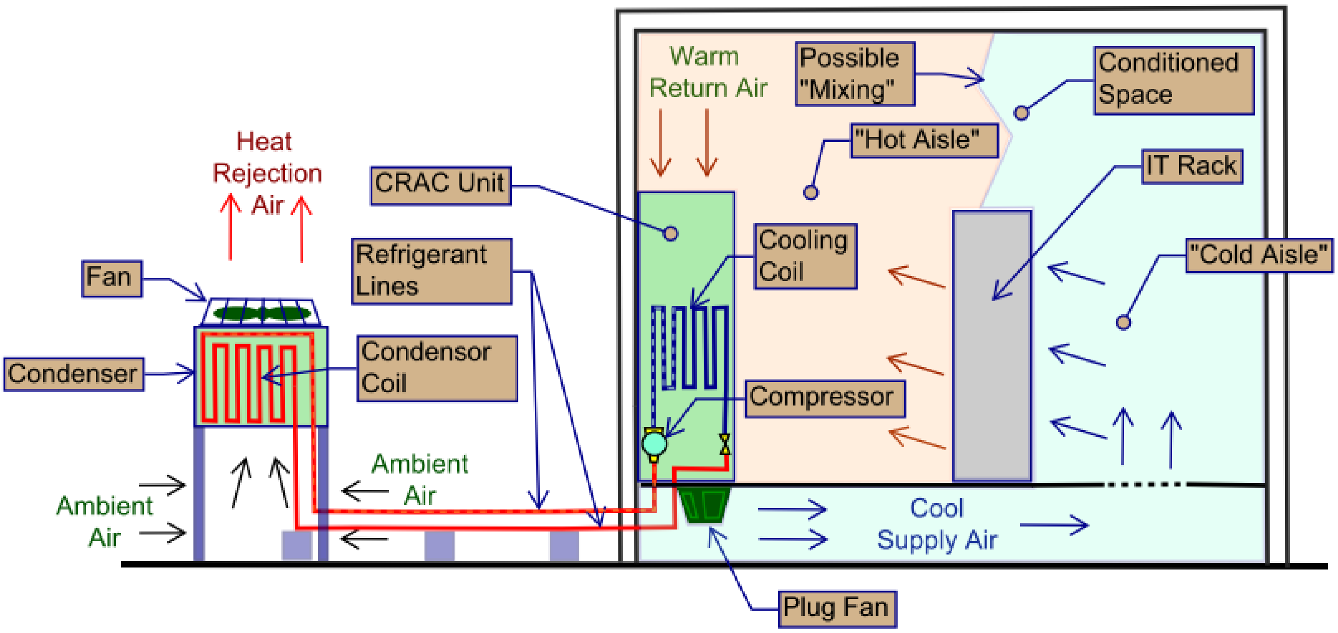


Figure F-7
(The Refrigeration Cycle Components in Dx CRAC System)

D. Chilled Water Systems

While there are a few exceptions, for the purposes of this course it is stated that in all "mechanical" cooling systems, the refrigeration cycle occurs. In order to provide higher capacity systems and in order to connect multiple air handling units to a single source of the refrigeration cycle, chilled water systems were developed. Chilled water systems can seem complicated, but in each case it is merely introducing another medium in order to reject the heat. The following sections will touch on a few of these systems and components.

Air Cooled Chiller Systems

A chilled water system that uses air to reject the heat of compression are referred to as an Air Cooled Chiller system. An air cooled chiller chills water (referred to as Chilled Water); that is pumped through the chiller unit. The chilled water is conveyed via pump(s) and a pipe network to air handling units that use the chilled water to remove heat from (i.e. cool) local air. The water is heated up by the air handlers and warmer return water comes back to the air cooled chiller (via the chilled water pump) to be cooled down again.

Figure F-8A provides a diagram to understand the refrigeration cycle and chilled water process with an air cooled chiller system. It is worth noting that these figures are high level in nature, and not intended to properly capture all of the inner workings of the equipment.

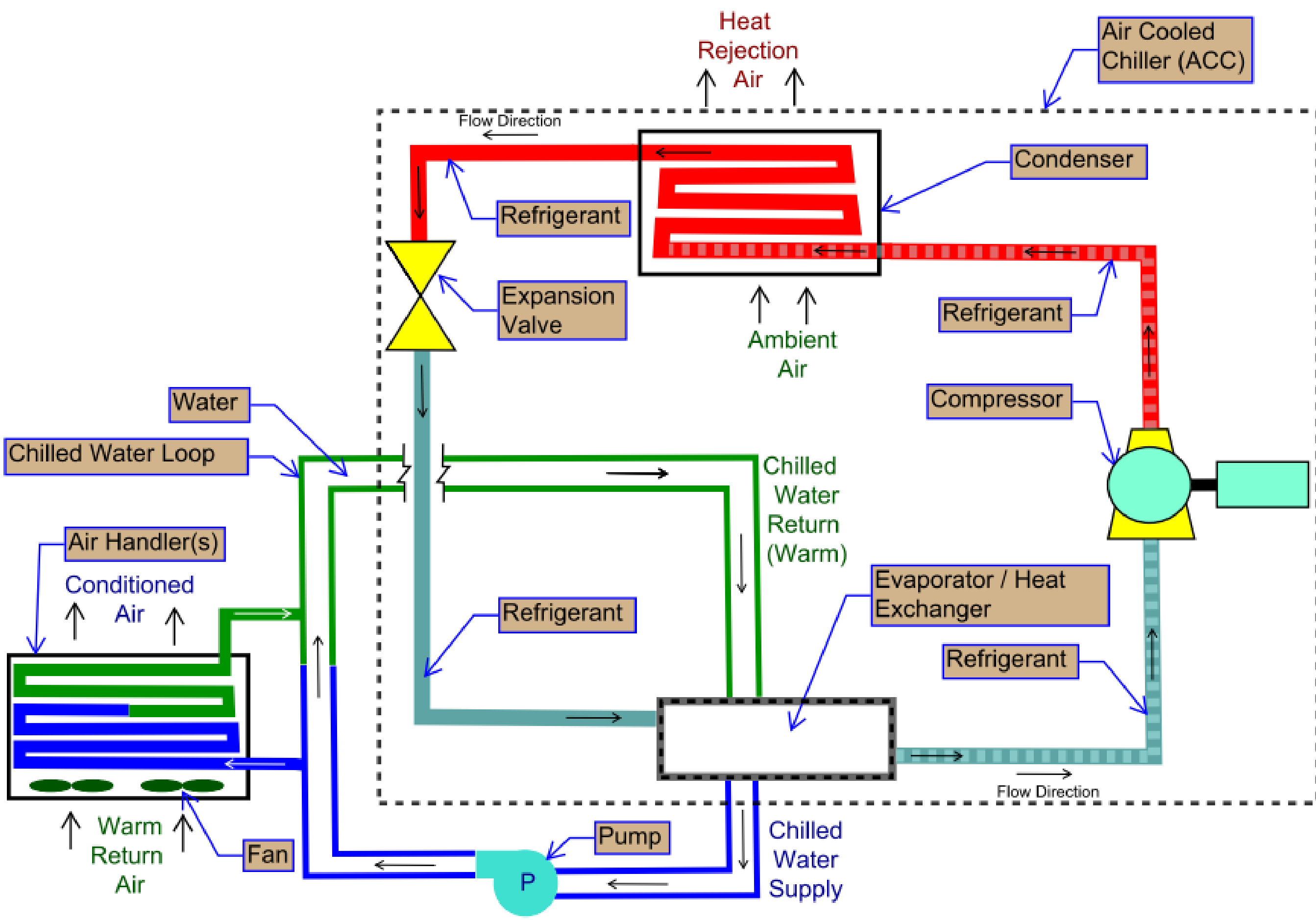


Figure F-8A
(Refrigeration Cycle in an Air Cooled Chilled Water System)

Figure F-8B provides an example configuration of an air cooled chiller system.

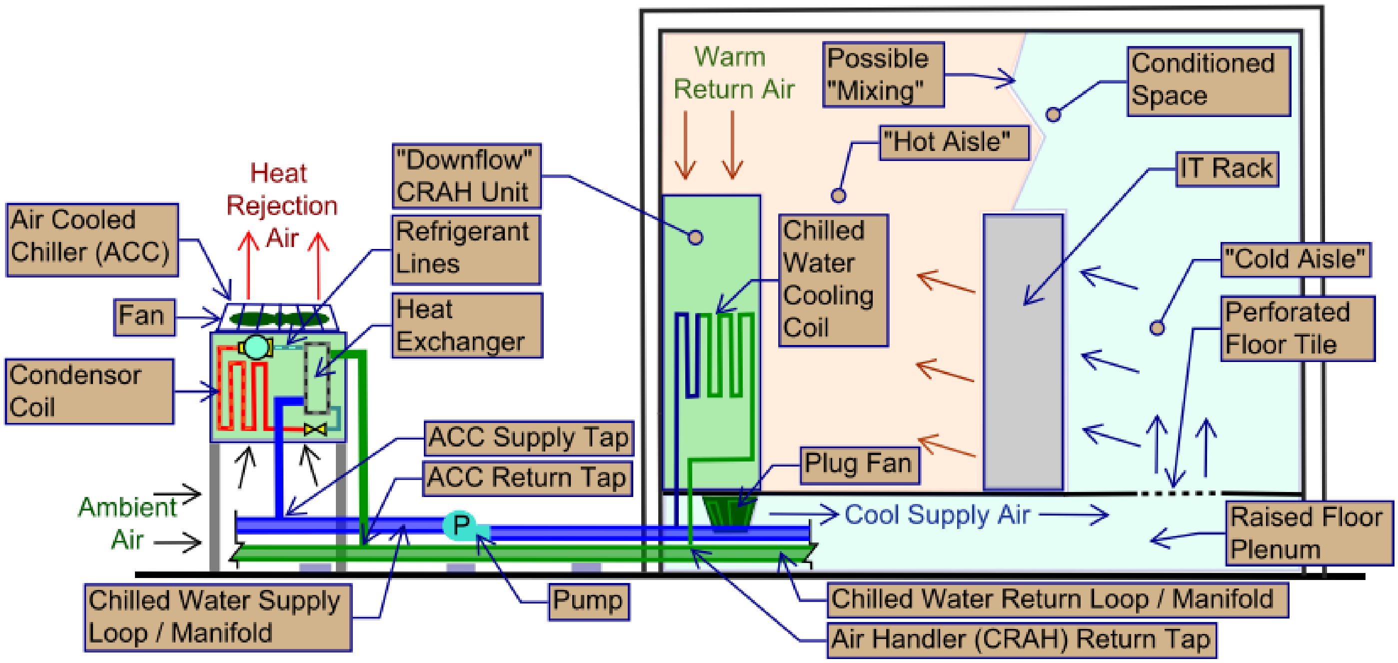


Figure F-8B
(An Air Cooled Chiller Configuration)

Air cooled chiller systems may often have an "antifreeze" solution (such as Glycol) added to the chilled water depending on the climate of the installation. While this allows the system to function in the cooler climate, it is worth noting that the transfer of heat in a system with glycol added does not have the rated cooling capacity of the same system utilizing just water. The engineer will typically work with the manufacturer to understand the de-rated capacity of the equipment depending on the percentage of glycol added to the mix.

Water Cooled Chiller Systems

The primary piece of equipment in a chilled water system (that uses water to reject the heat (from the refrigeration cycle)) is referred to as a Water Cooled Chiller. A water cooled chiller chills water that is pumped through the unit and the heat generated by chilling the water is rejected via water elsewhere (typically a cooling tower). As with an air cooled chiller system, the chilled water is conveyed via pump(s) and a pipe network to air handling units that use the chilled water to remove heat from the local air. The now warmer water (having been heated by the air handlers) returns to the chiller to have its heat rejected elsewhere to send cooler water back to the air handlers again.

The condenser section of the chiller is cooled by another "circuit" of water referred to as Condenser Water (and sometimes but rarely "cooling tower water"). The condenser water is pumped to equipment that can cool the condenser water, typically, a cooling tower. It is worth reiterating that the chilled water and condenser water are separate "circuits" and the water does not mix within the chiller.

A cooling tower uses evaporation to bring the temperature of the condenser water down and return it again to cool the refrigerant in the chiller's condenser section. It is worth noting that in systems with evaporative cooling towers, the system requires make up water. Since this is a course on redundancy, the engineer should keep in mind that redundancy in the make-up water system is always a good consideration.

Figure F-9A provides a diagram to understand the refrigeration cycle and chilled water process with a water cooled chiller system.

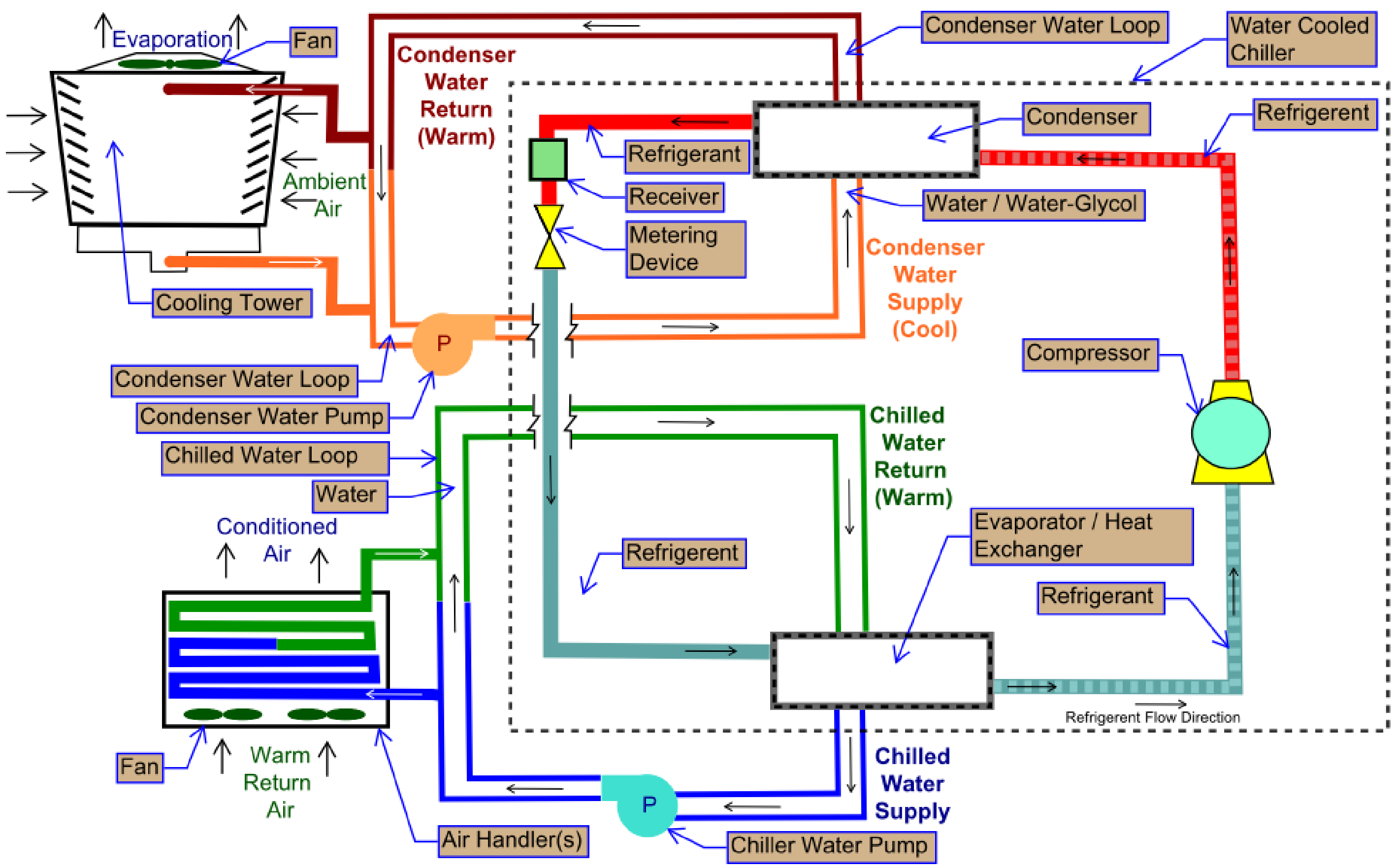


Figure F-9A
(Refrigeration Cycle in a Water Cooled Chilled Water System)

Figure F-9B provides an example configuration of a water cooled chiller system.

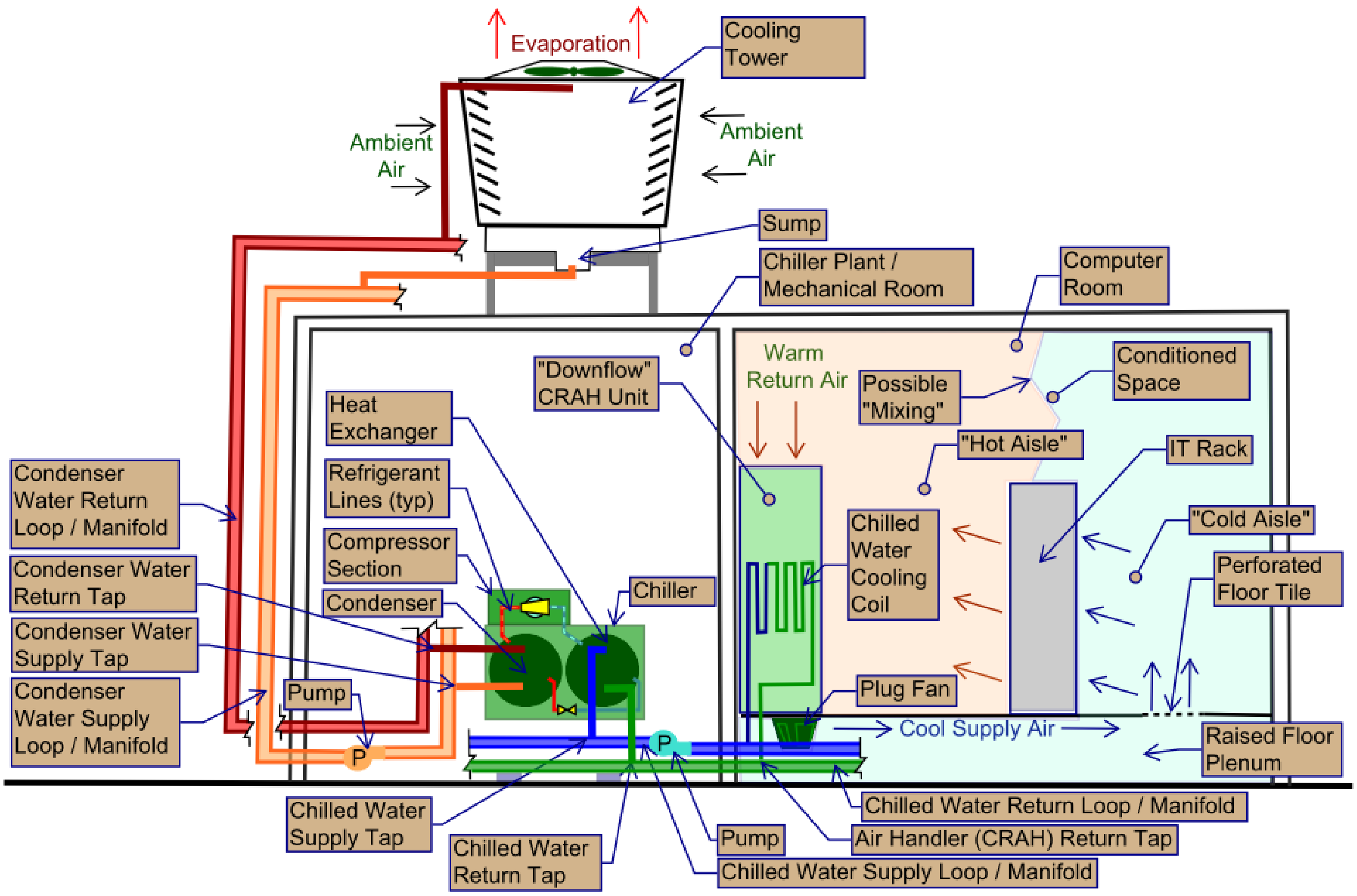


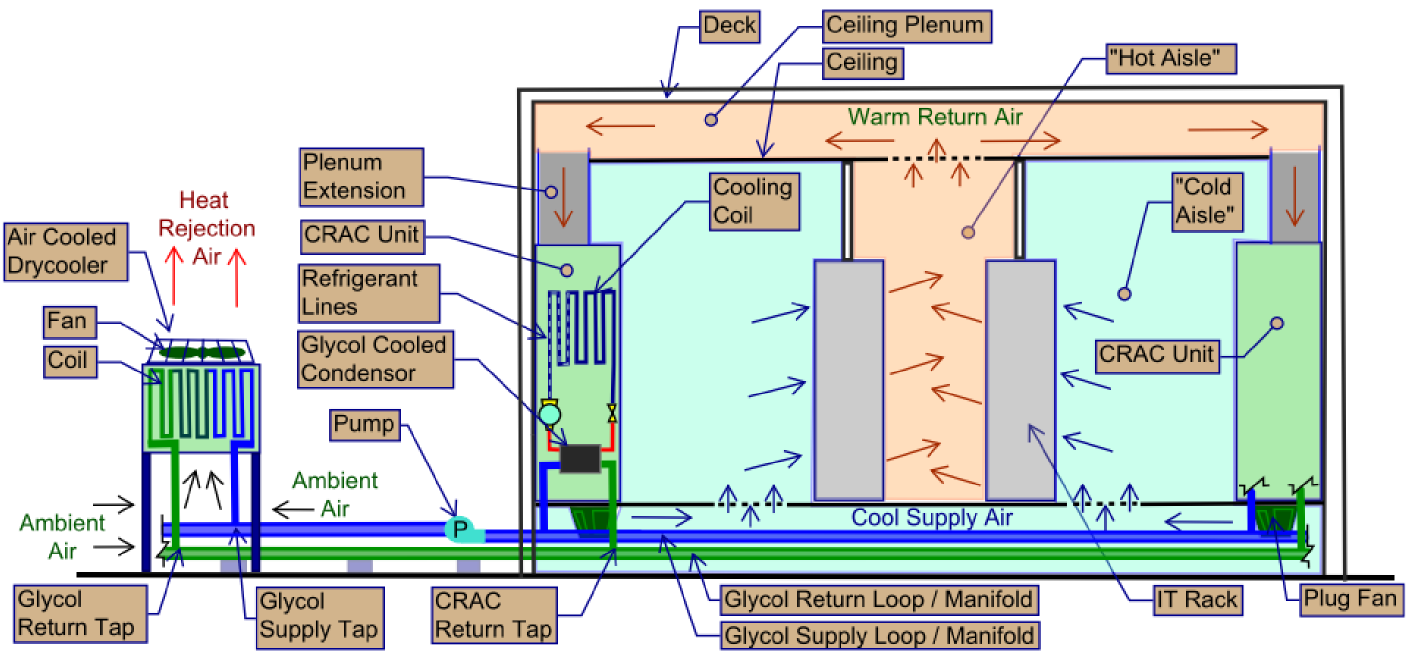
Figure F-9B
(A Water Cooled Chiller Configuration)

Glycol Systems (Dry Coolers)

As was explained above, there are “antifreeze” additives that can be incorporated into a chilled water system depending on the climate. Distinct from chilled water systems, are systems frequently referred to as closed loop ***glycol systems***. These systems utilize a component referred to as a dry cooler to “air cool” / reject the heat of a chilled water/glycol system that has the refrigeration cycle occurring within the inside air conditioner(s). This type of system may appear similar to a split system or a Dx system, but they are not the same.

In this scenario, within for example a computer room, the Computer Room Air Conditioner (CRAC) is properly termed. Often people will refer to a chilled water system air handler as an air conditioner, but as you may have noticed above, the proper terminology of the unit in the room (of a chilled water system) is a Computer Room Air Handler (CRAH) since the refrigeration cycle is not taking place within the unit. This is a minor nuance, and perhaps even a pet peeve of some designers, but for the purpose of this course, it is hoped that the student follows the distinction.

Figure F-10 provides an example configuration of a glycol / dry cooler system.



<u>Figure F-10</u>
<u>(A Glycol / Dry Cooler Configuration)</u>

<u>E. Components Summary</u>

The prior section gave a good basis of understand some very common configurations through which the heat of compression (occurring during a "mechanical implementation" of the refrigeration cycle) is rejected in many mission critical systems. To build upon the previous section we will take a tangential approach, and reiterate from a component perspective, some components commonly seen in the industry, most of which are noted above.

CRAC (Computer Room Air Conditioning) Units

A CRAC unit is an air conditioner placed in a computer room. These units can be "up-flow" or "down-flow". In the past it was common for a down-flow CRAC unit to be set on a raised floor plenum and the system pressurizes the plenum to "push" supply air through perforated tiles up into the computer room space. Configurations with separately partitioned "galleries" have been utilized to create a physical access separation from those maintaining CRAC units and the critical computer room. With higher heat load densities in computer rooms it has become more common to avoid raised floors and for there to be unit duct extensions and/or hot or cold containment of the IT heat via overhead plenum.

The refrigeration cycle occurs within a CRAC unit and they therefore have a compressor within the unit which creates additional sound volume in the environment. The heat is either rejected via a separate "one to one" condenser, or a water (glycol) cooled condenser located on the unit (which must have its heat rejected to a dry cooler). Refer to Figure F-11 for a picture of a CRAC (or CRAH) unit.

CRAH (Computer Room Air Handling) Units

A CRAH unit is an air handler placed in a computer room. As with CRAC units, these units can also be "up-flow" or "down-flow" which may or may not be set on raised floor.

The refrigeration cycle associated with a CRAH unit occurs at the chiller (air cooled or water cooled (or in theory at the cooling tower)). The chilled water supply/return to/from the CRAH unit is used to reject heat and maintain the units' ability to achieve the supply air set point.

Since a CRAC and CRAH unit look very similar and are used within the computer room in a similar way, many in the industry do not recognize the distinction and CRAH units are referred generically as CRAC Units. As mentioned above, it is a minor distinction, but worth recognizing.

Refer to Figure F-11 for a picture of a CRAC/CRAH unit.

Dual Source Computer Room Air Conditioning Units

A dual source CRAH/CRAC unit is a single unit that has its heat rejection handled by multiple sources. One typical example of this is a unit that has a chilled water cooling coil and a Dx cooling coil. These are separate circuits and typically only one circuit functions at a time.

A dual source CRAC/CRAH unit provides an alternate way to achieve cooling redundancy in a system. It is also a good way to take advantage of a campus chilled water system, which may be considered less reliable, but may provide less expensive cooling for the end user. In such a scenario, the Dx circuit can be used for the occasion of a failure or maintenance of the chilled water system. It is worth noting that best practices would suggest the end user needs to make sure to exercise both the primary (in this case chilled water) and the secondary (Dx) functionality of the unit on a regular basis. Obviously dual source units cost more that single source units, so the engineer must balance the needs of the system, return on investment, and total cost of ownership when determining the reliability approach.

Dual Circuit Computer Room Air Handling Units

A dual circuit CRAH unit is a single unit that is provided chilled water from two separate loops. This sort of unit is useful in a scenario where there are multiple chiller plants providing chilled water on separate loops. Similar to the dual source unit, perhaps one loop is a shared “non-critical” campus loop and the alternate circuit is fed from a dedicated mission critical loop established so that a second source of chilled water is available to carry the critical cooling load in an “emergency”.

A CRAC/CRAH dual source and/or dual circuit unit may all look identical and appear to function the same to the targeted cooling space to a casual observer. As noted above, Figure 11 has a picture of a CRAH/CRAC unit.

<u>Figure F-11</u>
<u>(A Picture of a CRAC/CRAH Dual Source CRAC Unit)</u>

<u>Condensing Units</u>

A condensing unit is a Dx heat rejection unit (typically the exterior based portion of a split system) where the compressor is located in the exterior unit. The cooling coil of the air handler is located inside. Split systems using a condensing unit are not typically used in mission critical applications as a best practice, however systems in configurations such as this exist. Condensing units are very common in a residential central air conditioning systems. Figure F-12 is a Condensing Unit.

<u>Figure F-12</u>
<u>(A Picture of a Condensing Unit)</u>

Condensers

A condenser is the Dx heat rejection unit located outside where the precision cooling unit containing the compressor is located within the targeting cooling space.

Figure F-13 is of condensers.

Figure F-13
(Pictures of a Condenser)

Dry Coolers

A dry cooler is an exterior based air cooled unit that cools the fluid of a system that has multiple air conditioning units (for example CRAC units). The coil cools the fluid by air flow across the coil with a fan. The loop will often circulate a fluid that is glycol based. The compressors associated with the refrigeration cycle are located within the air conditioners inside the targeted cooling location.

Air Cooled Chillers

An air cooled chiller is an air cooled unit provides chilled water to air handlers. The compressor section is located within the unit.

Figure F-14 is an air cooled chiller.

Figure F-14
(A Picture of an Air Cooled Chiller)

Water Cooled Chillers

A water cooled chiller is a unit that provides chilled water to air handlers. The compressor section is located within the unit and the heat is rejected via condenser water typically to a cooling tower system. Figure F-15 is a water cooled chiller.

Figure F-15
(Pictures of a Water Cooled Chiller)

Cooling Towers

Cooling towers are generally used to cool condenser water from a water cooled chiller. However, there are applications where cooling towers are used (via heat exchangers) to reject heat "directly" from air handlers (i.e. without the use of a chiller or "the refrigeration cycle"). It is beyond the purpose of this course to explore in much detail, but a system such as this may very well be appropriate for the mechanical engineer to consider depending on the location/climate of the project in consideration.

Figure F-16
(Pictures of Cooling Towers)

Refrigeration Units

In some medical and healthcare/pharmaceutical industries, refrigeration units are mission critical and require redundant components to make sure the materials being stored in the units are kept at the specified temperatures. Refrigeration units are mentioned but not discussed in detail here.

Pumps

In chilled water systems (and condenser water / cooling tower water systems) the water must flow through the system via pumps. The pumps are a critical part of the system and are a component that must be considered for failure in terms of redundancy planning.

Other Ancillary Systems (Fuel Systems)

Often associated with the mechanical system design the fuel systems to the generator should be considered for redundancy and reliability. This course will generally only discuss the cooling systems, but the principles gleaned in terms of tanks and pumps will apply to redundancy planning.

F. Redundancy Quantified

In the industry there is some confusion and a lack of a common acceptance among all users and stake-holders associated with the proper nomenclature for redundancy. That said, this course will define and depict redundancy in terms of system redundancy and component redundancy. It is valuable to recognize that although this course will present redundancy in the way described, there are other interpretations and paradigms through which industry experts present these terms.

Single Line Flow Diagrams

In order to simplify the intent of a mechanical system, often times a simple flow diagram is provided. This is different than the diagrams covered above that were provided to help the reader understand where the refrigeration cycle occurs in the various mechanical systems. In single line flow diagrams, the major components are shown with the supply and return lines relate to systems functionality. As will be seen below, single line flow diagrams grow with the complexity of the redundancy needed.

Need vs. Capacity

In order to fully appreciate redundancy and the terminology used, a discussion on *Need* versus *Capacity* must be considered. *Need* is the term for the "demand load" of the systems (i.e. how much cooling does the system NEED to provide).

The *capacity* is the amount of cooling / flow the system or component CAN provide. If the capacity of a system is designed to provide the demand without any additional components, then it is considered to be an "N" system. If the system has components that can be lost and the need still met, the phrase "redundant capacity" may be used. This will be explained in further detail below. Most regular building mechanical cooling distribution systems would be considered need based, and may or may not have any sort of reliability built in.

As noted above, this course does not get into how to size the components of the system, which requires the services of a qualified mechanical engineer to consider the parameters of the equipment, the location/region of the application, and any site constraints which might impact full capacity of the equipment. For the purposes of this course, it will just be assumed that the components have been sized to provide the capacity defined, for the heat load given.

Fault Tolerance

As a refresher, "fault tolerance" is defined and is a term used to identify the degree to which a system does not contain any "single points of failure" (SPOFs) that will cause a loss of the load if the failure occurs. For example, if a system has redundancy on the components that provide the cooling, but only a manifold then the system still contains SPOFs leaving the facility exposed, and often difficult to maintain without downtime. So while redundant components to provide the cooling IS beneficial, if SPOFs remain, then the facility is not fault tolerant.

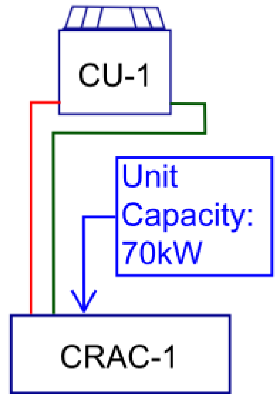
In order to analyze fault tolerance and reliability, redundancy definitions (N, N+1, 2N, etc.) must be considered. Since Dx systems are adequate for low load systems and they are simple systems, they will be discussed first in terms of redundancy definitions

N (Dx Systems)

As noted above, *N* is the term used to describe a single system or a single component within that system providing the demand need.

Figure F-17A depicts an example of an N Dx system with N components.

System Capacity: 70 kW
(Redundant Capacity: 0 kW)

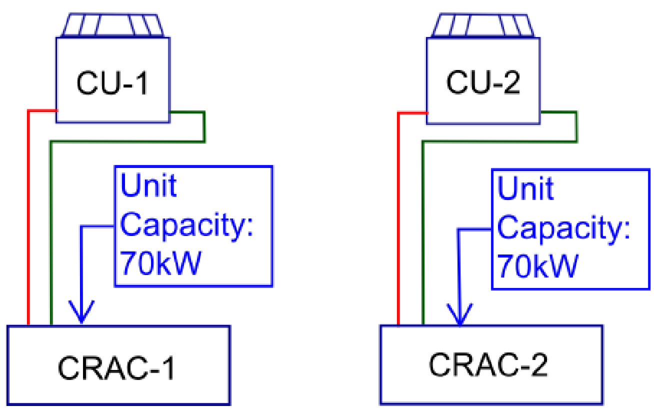


Heat Load: 70 kW

Figure F-17A
(A single line of an "N" Dx system with "N" components)

Figure F-17B depicts an alternate example of an N Dx system with N components.

System Capacity: 140 kW
(Redundant Capacity: 70 kW)



Heat Load: 140 kW

Figure F-17B
(A single line of an alternate "N" Dx system with "N" components)

N+1 Components (Dx Systems)

N+1 is the term used for the addition of components to the system for redundancy and to accomplish the mission of additional reliability and/or maintainability of the components. The business drivers behind why one would choose this strategy are many and are not be discussed in this course.

Figure F-18 shows an example of an N+1 configuration since the demand load is equal to the capacity / size of two (2) of the Dx systems, and an additional system is provided in the design. In this example, the demand load is 140 kW and the system is capable of providing 210 kW.

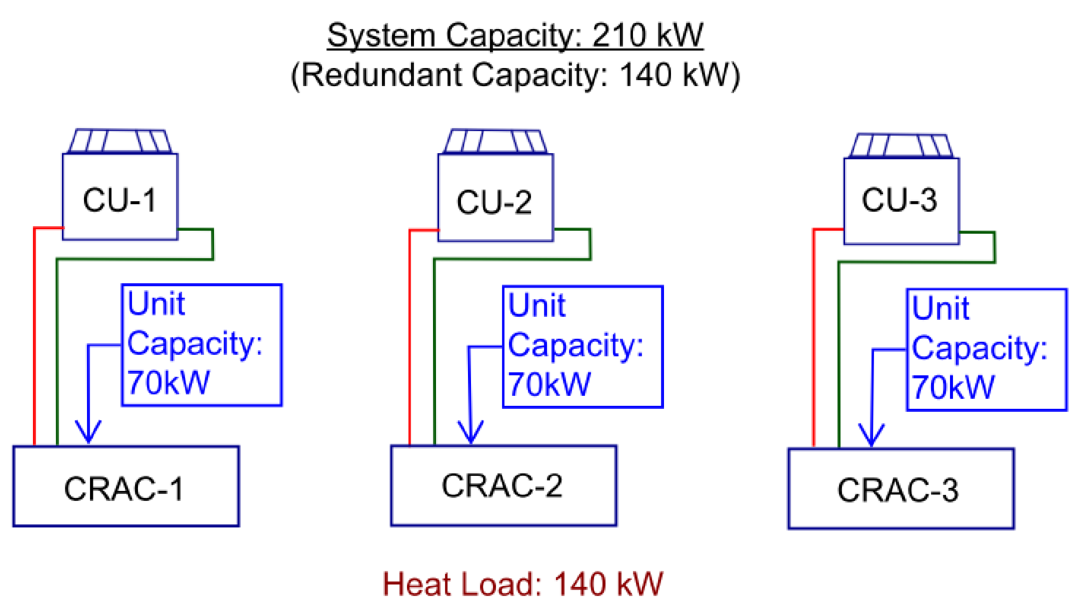


Figure F-18
(A single line of an "N+1" Dx system)

As noted in *Reliability in Mission Critical Applications – Part 1 (Electrical Systems),* the main benefits of an N+1 system are two-fold:

1. If the major components need to be serviced / maintained, they can be temporarily taken out of service one at a time in a planned fashion and the load will theoretically still be handled by the other components if the need arises.

2. Since all components can and will fail at some point in time, if there is a major equipment component failure, the system will statistically be anticipated to continue to ride through the event on the remaining components without dropping the load.

2N Configuration (Dx Systems)

2N systems are useful when looking to establish a Fault Tolerant (no single points of failure) systems.

In Figure F-19, the capacity of the system is 140 kW, and the "redundant capacity" of the system is 70 kW.

This is technically both a 2N configuration, and an N+1 configuration. Since this Dx system is generally a low load system it is acceptable to refer to the system as a 2N cooling system. As will be seen later, a 2N chilled water system is more complex.

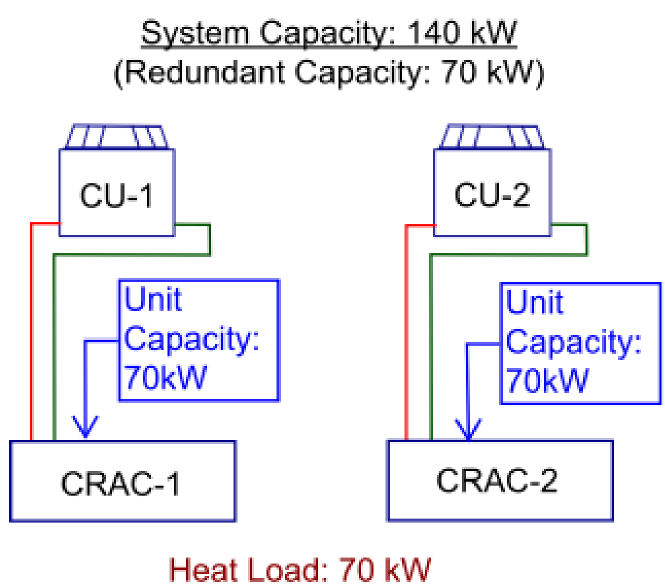


Figure F-19
(A 2N Dx system)

N (Chilled Water Systems)

As identified in the sections above, an *N* system has equipment that meets the needs of the demand. There is no redundancy in equipment. Figure F-20 depicts a simple single line flow diagram of a chilled water system that delivers the cooling capacity to meet the heat load. In this example there is a 100-ton air cooled chiller provided to meet the 100-ton heat load. There are five (5) 20-ton CRAH Units to distribute the cooling around the targeted cooling area.

Please note that the pump symbol used in the diagrams contained herein are used to identify the location of pumps, not the connection or configuration of the pumps. Engineering drawings would typically use a different pump symbol than that used in the following section.

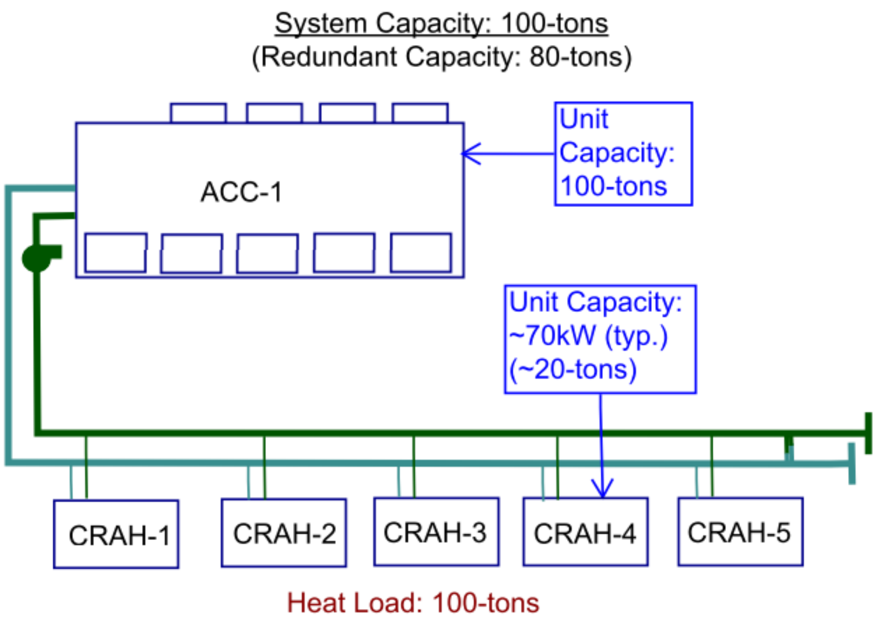


Figure F-20
(A flow diagram of an N chilled water system)

N+1 Components (Chilled Water Systems)

An N+1 system needs to have an additional component for each aspect of the load. The system needs to be able to lose any one (1) component (i.e. chiller, cooling tower (if applicable), pump, air handlers, etc.) and still carry the load. As a result, there is redundancy in the equipment.

Figure F-21A depicts a simple single line flow diagram of a chilled water system that delivers "redundant cooling capacity" to meet the heat load. In this example there are three (3) 50-ton air cooled chiller provided to meet the 100-ton heat load. There are six (6) 20-ton CRAH Units to distribute the cooling around the targeted cooling area. It is worth noting that each pump would need to be sized to handle the design flow on its own.

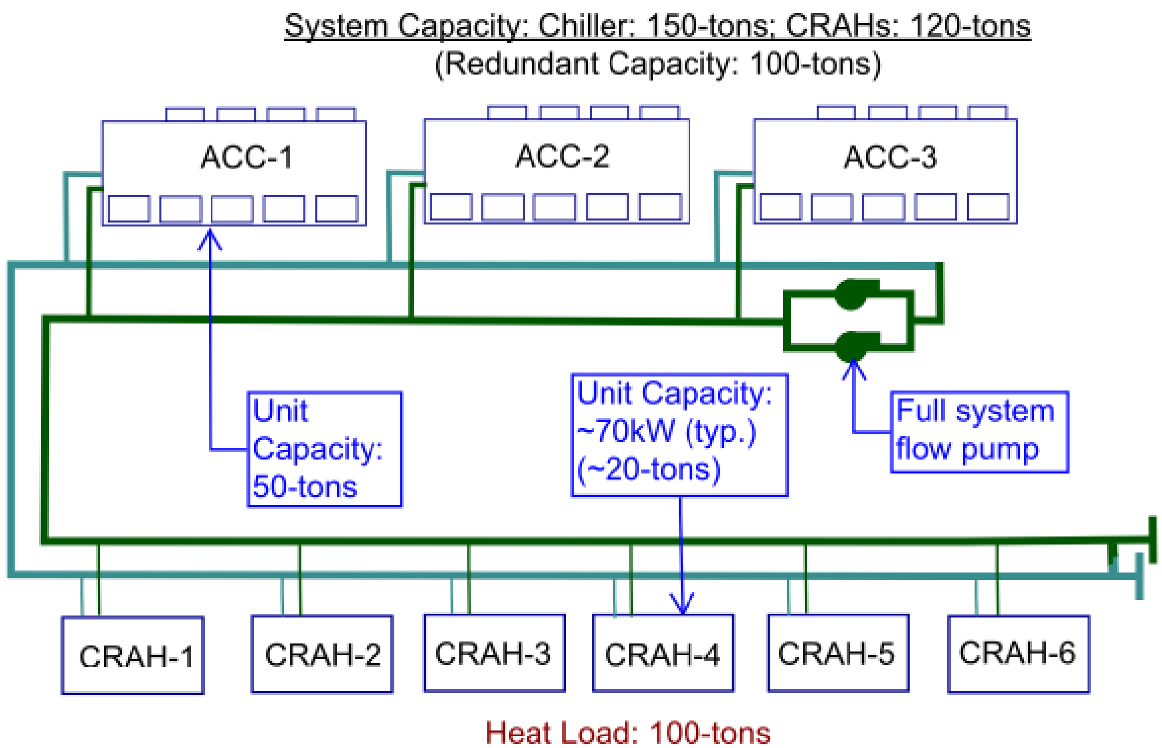


Figure F-21A
(A flow diagram of an N+1 chilled water system)

The chilled water systems shown above are adequate for most non-mission critical designs. It would also be described as being installed "on a header/manifold". A header based chilled water system (including one with N+1 redundancy) is exposed to system downtime if a portion of the piping loop has a failure or requires maintenance. On a non-mission critical system, maintenance can be done off hours, perhaps at night when the office building (as an example) is closed.

Figure F-21B depicts a sample scenario where a length of pipe needs to be replaced, and due to the maintenance, several CRAH units will not be able to have the required chilled water circulation during the repair. Therefore the equipment redundancy provided was not adequately beneficial to the mission (assuming the need to avoid downtime) without significant temporary cost.

It is worth mentioning that this N+1 equipment configuration as shown is slightly different from Figure F-21A in that the N+1 pump redundancy is provided by three (3) smaller pumps where two (2) are adequate to provide the required flow.

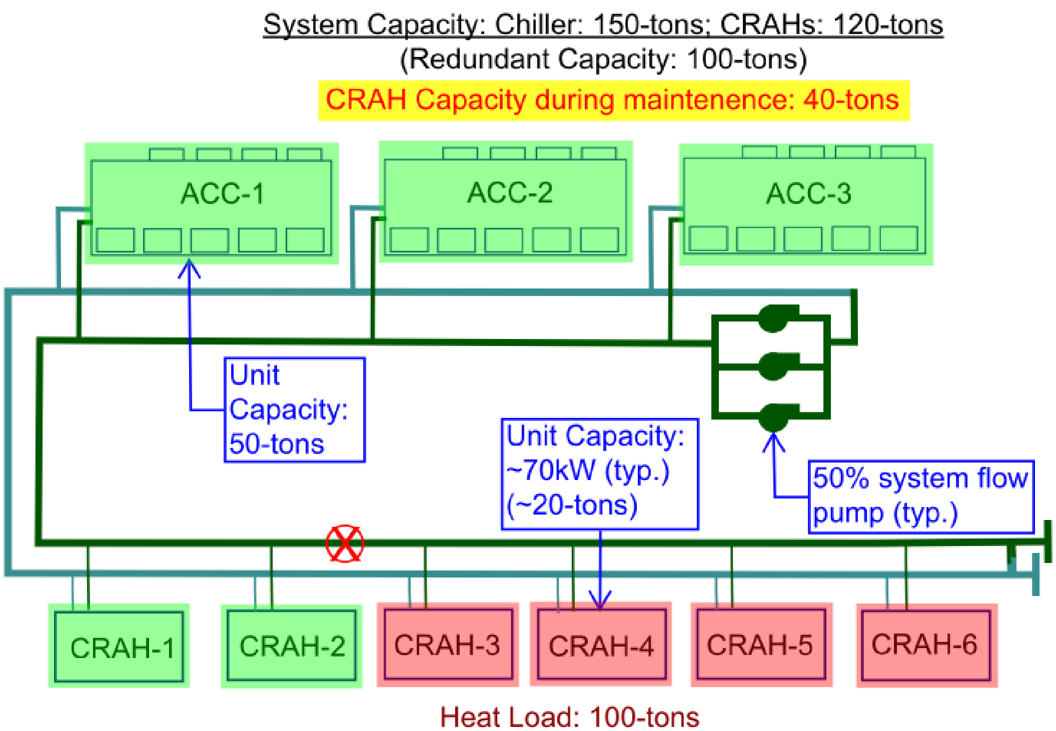


Figure F-21B
(A flow diagram of an N+1 chilled water system with downtime due to a pipe repair)

System Maintainability & Resiliency (Chilled Water System Loops):

One simple way to reduce the risk identified above is to design a “looped” system. This is not to be confused with the fact that even the water of a system with a header manifold circulates in a basic supply-return loop. The loops being referred to in a looped system refer to the fact that both the supply lines and the return lines are looped. This allows the water to flow in both directions to each piece of equipment if needed.

Figure F-22A shows a simple primary loop design which allows the piping to be maintained without the loss of any more than one piece of equipment. It is worth identifying that "isolation valves" are shown which allow sections to be isolated between equipment.

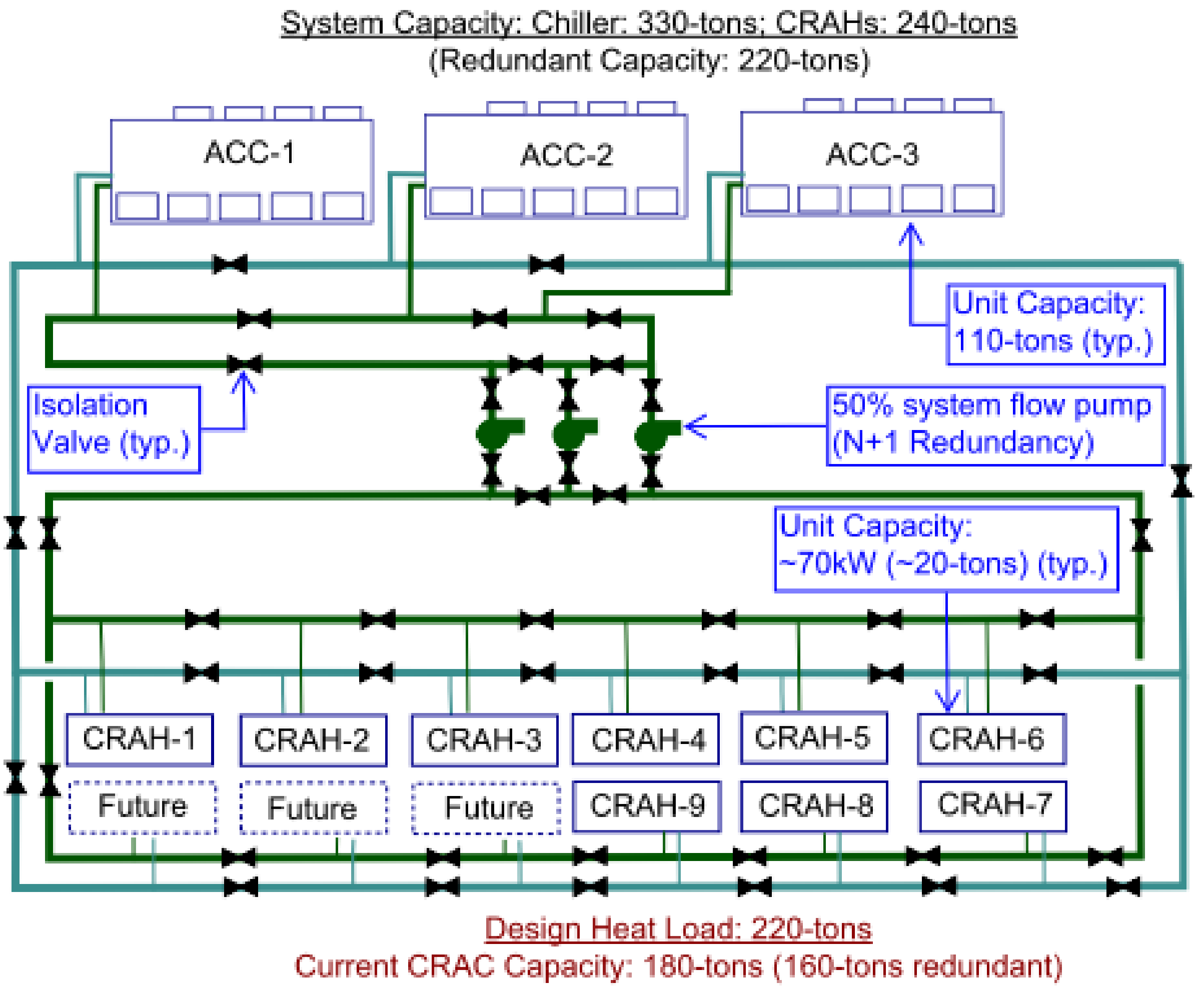


Figure F-22A
(A flow diagram of an N+1 chilled water system with supply and return loops and isolation valves)

As is attempted to be illustrated in Figure F-22B, a loss of any section of pipe will not impact the system as there is redundancy in the equipment, and chilled water can flow in both directions up to the isolation valves, supplying the needed chilled water to meet the load.

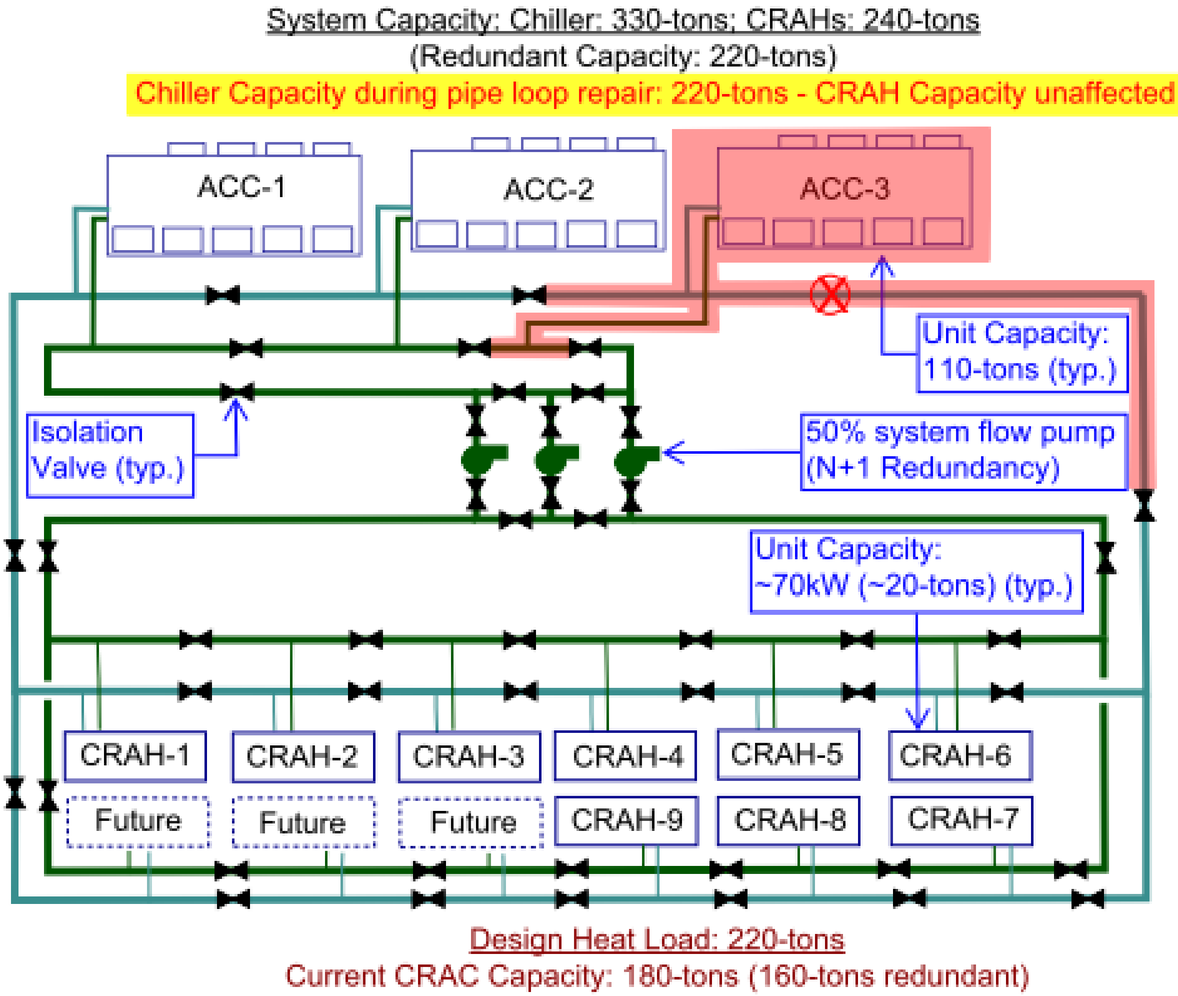


Figure F-22B
(A flow diagram of an N+1 looped chilled water system Showing the limit of planned maintenance to a system)

It is worth noting that a catastrophic failure to a section of pipe in a looped system is unlikely but still a potential risk to downtime. A catastrophic failure will take the systems down, then the failure can likely be isolated and the system restored in a relatively short order. “Relatively short order” is in comparison to a catastrophic failure of a header manifold system, which could take weeks or months to recover from a catastrophic failure. A looped system recovery would likely be able to be restored in hours or days.

2N Systems (Chilled Water Systems)

2N is the term in this course used to describe **system** redundancy. This system configuration provides additional fault tolerance and will accomplish the mission of redundancy, reliability and maintainability to an entire system if desired. The business drivers behind why one would choose this strategy are also many and will not be discussed.

There are several ways to approach a 2N design. One way is with redundant mechanical plants. Figure F-23A shows an example of a complete 2N system configuration. In this example, there are two (2) totally redundant mechanical plants with dual circuit CRAH units provided (which are fed from each plant).

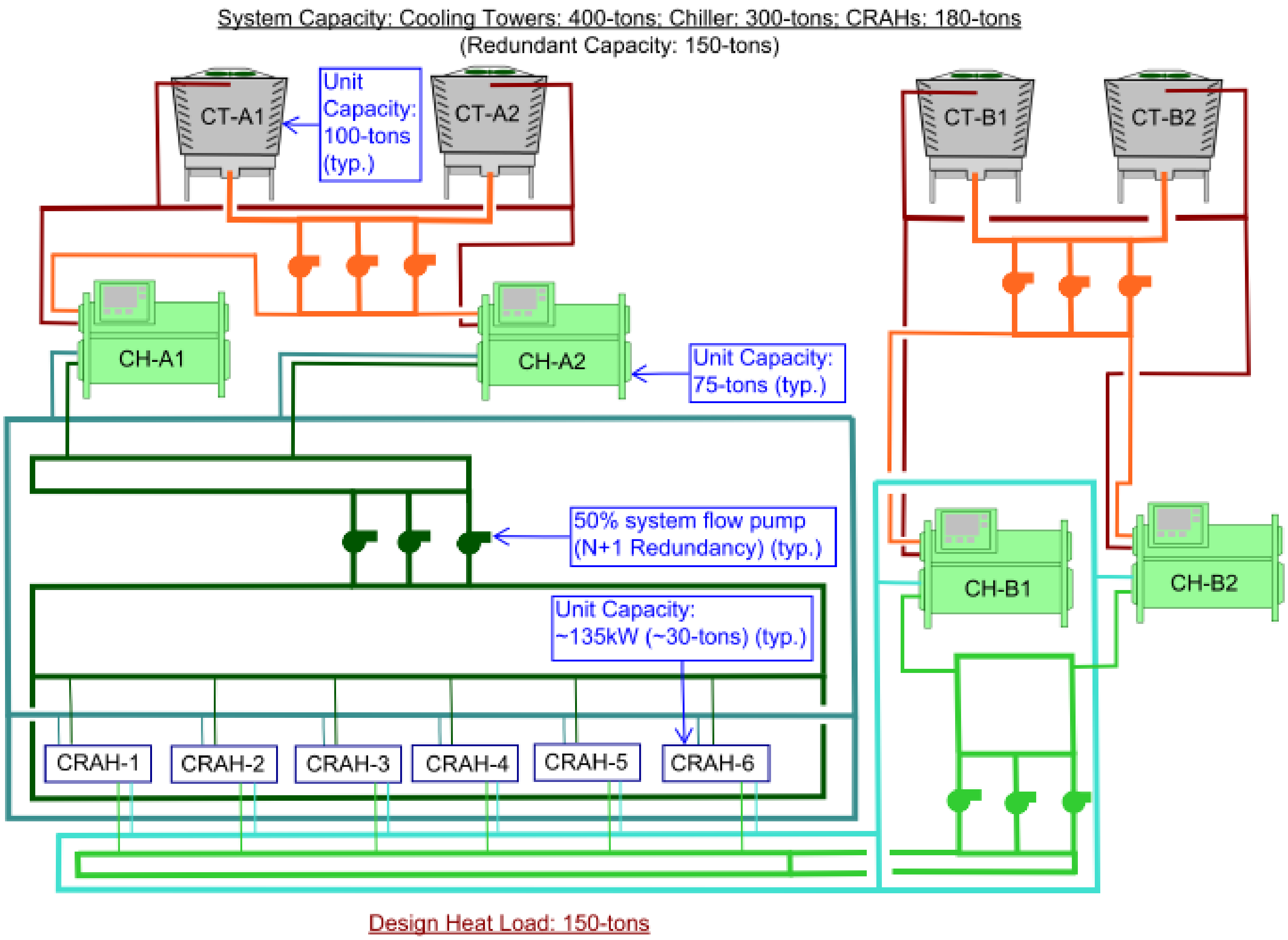


Figure F-23A
(A single line of a "2N" system – water cooled chiller based systems with chillers, pumps, cooling towers, and dual circuit CRAH units)

It is worth noting in the above example that the CRAH units are provided N+1. In order to provide a 2N CRAH scenario, there would be ten (10) CRAH Units, each dual fed from each mechanical plant.

Figure F-23B shows how the design load would be met by one plant even if the other plant has been taken out of service for maintenance or major overhaul.

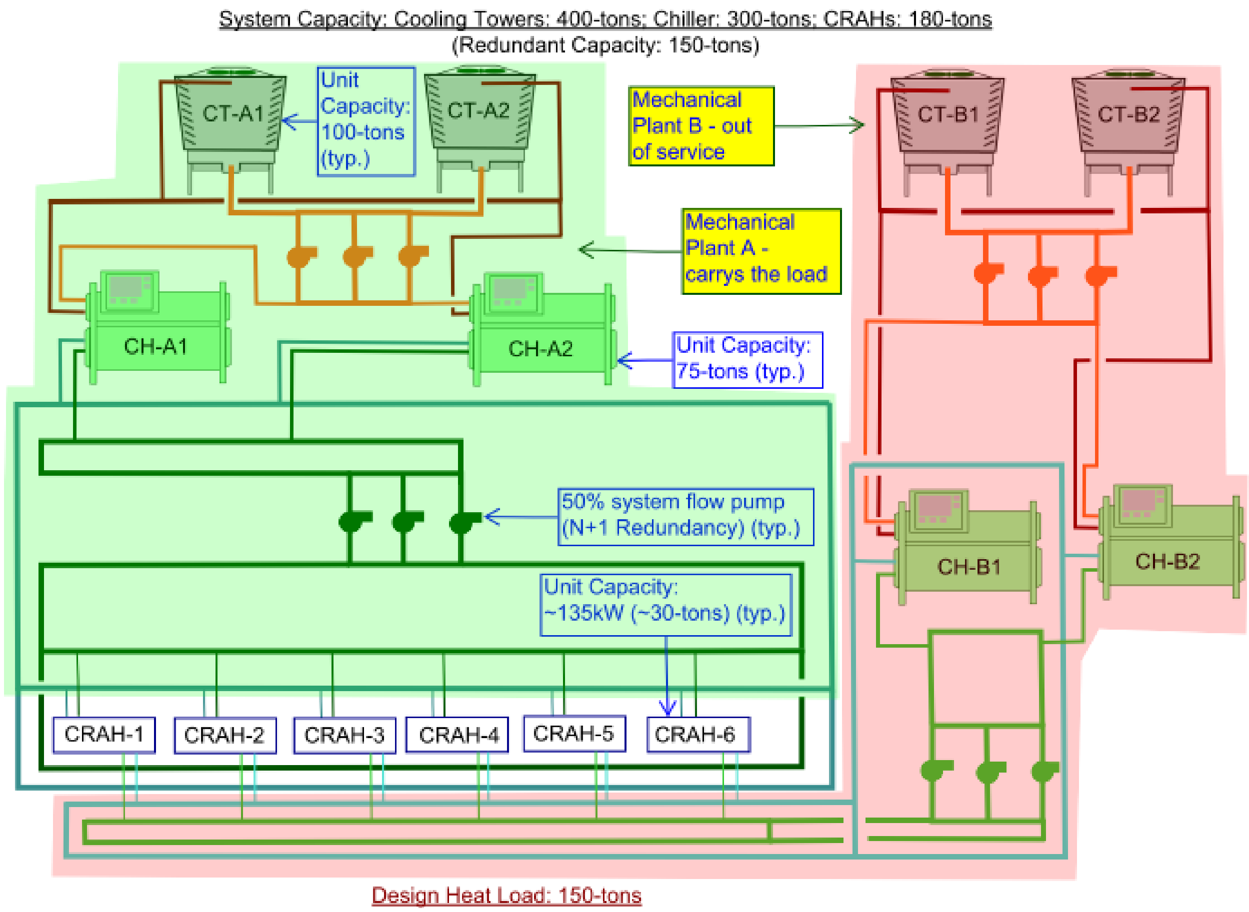


Figure F-23B
(A single line of a "2N" chilled water system – with one plant out of service)

2N+1 Scenarios

2N+1 is generally a phrase that describes an extremely redundant, fault tolerant, and maintainable system. A major reason to consider a 2N+1 system is in order to provide redundancy during maintenance scenario. One can imagine a 2N+1 scenario by combining the concepts of Figures 22A and 23A. In such a scenario there would be a third chiller and cooling tower on each system (i.e. for each mechanical plant, A and B).

This sort of scenario, while feasible, begins to get extremely costly from a constructability and budgeting standpoint and as was covered in *Reliability in Mission Critical Applications - Part I*, there are options that can minimize the need for this even if this degree of maintainability is desired. For example, each plant can be equipped with temporary chiller connections, and rental chillers can be obtained for the duration of a planned maintenance initiative.

There are many configurations available that an experienced design engineer can use to value engineer, cut back, and/or save the owner money; depending on the budget availability. Of course the best way to decide what is best for a facility is to know the business needs of the enterprise and engage a qualified engineer with experience in mission critical reliability design.

Dual Source Scenarios

The last scenarios that will be discussed in this course was alluded to above in the equipment section regarding dual source CRAC/CRAH units. This section will discuss the "dual source scenario" in two ways. The first will be referred to as a "Hybrid 2N" CRAH/CRAC scenario where the load is covered by CRAC Units and CRAH units. This is reflected in Figure F-24

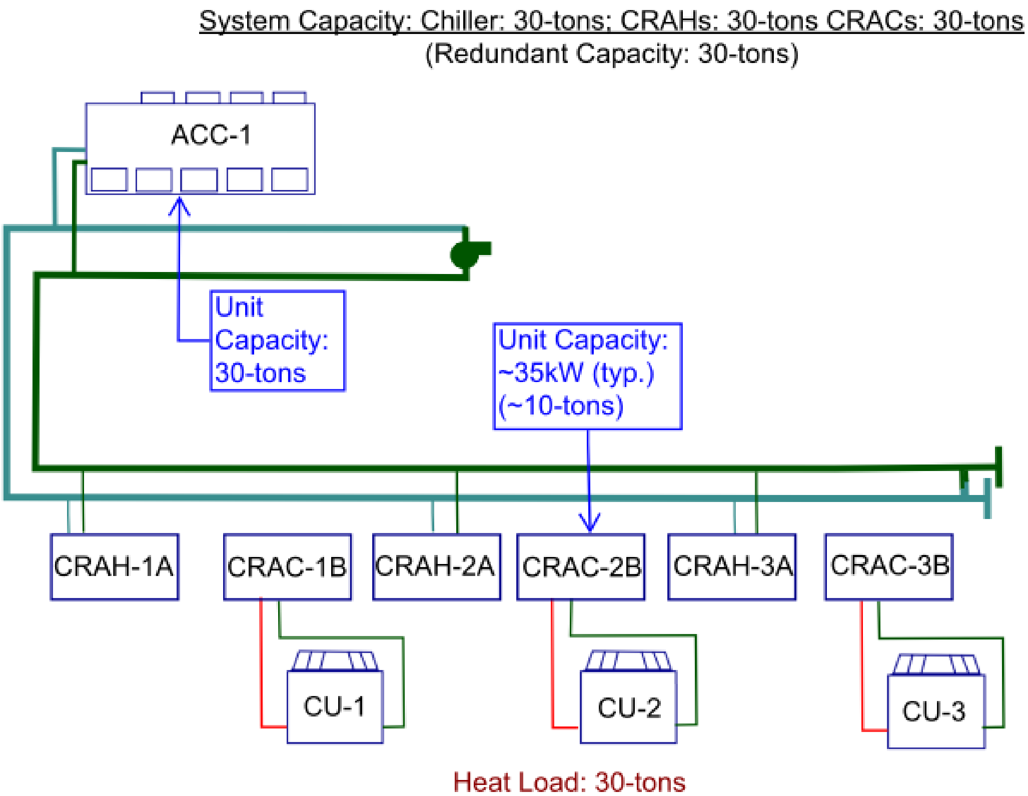


Figure F-24
(A single line of a "Hybrid 2N" design)

As can be seen, the load is covered by different types of equipment in two different ways. There is a series of Dx equipment and a non-looped chilled water system with a header manifold.

The other hybrid solution considered is utilizing "dual source" air conditioning units. The units are sized and rated to provide a certain capacity under both a chilled water circuit and a Dx circuit. Typically these units function "either/or", and do not run on both the chilled water and Dx circuits at the same time.

While these units can be used in any scenario, a very wise use of them is when there is a campus or shared chilled water source that may be unreliable, or only available partially throughout the year. In this strategy, the facility can run normally and take advantage of the efficiency related to the larger mechanical plant, but in the "emergency" scenario, the Dx circuits can take over and provide the needed cooling. Figure F-25 shows a single line of a system that is taking advantage of dual source CRAC units.

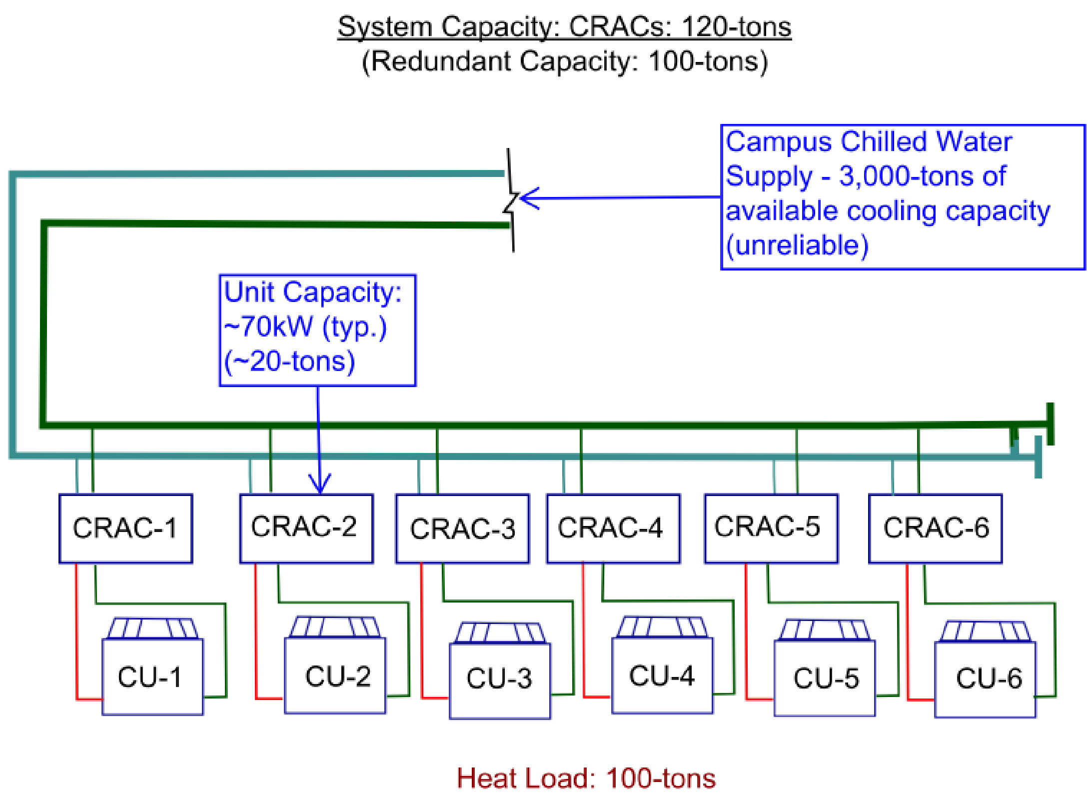


Figure F-25
(A single line of a system utilizing "dual source" CRAC units)

G. Summary and Conclusion

This course provided a continuation of the study of mission critical reliability started in the previous course, *Reliability in Mission Critical Systems – Part 1*. In this case, reliability was considered associated with the mechanical systems supporting mission critical applications, most specifically in computer rooms. The student of this course should be able to have knowledgeable conversations regarding reliability, redundancy, fault tolerance and maintainability of mission critical systems as well as a working knowledge of some of the most common components that these systems consist of.

Additionally the student should have a better understanding of the refrigeration cycle and should be able to understand where the refrigeration cycle occurs within various types of mechanical systems.

Reliability is an important topic for any engineer and facilities manager to be familiar with, especially as relates to the degree they are required to design, manage, or expected to comment on mission critical systems.