Evergreen Nuclear

Saturday, August 27, 2011

A Primer on How A Pressurized Water Reactor Shuts Down

My motivation for this layman's primer is to correct the misstatements of what actually goes on when an operating Pressurized Water Reactor Shuts Down as a result of either a suddenly occurring event such as an earthquake or because of an impending severe storm such as a hurricane. There are two types of shutdowns to be considered: (1) one in which an event such as earthquake or loss of offsite power occurs and the unit automatically trips, and (2) one in which station procedures recognizing a deteriorating weather situation (as an example) takes a slower path to shutdown. I will discuss both of these cases. I will discuss the equivalent case for an operating Boiling Water Reactor in a separate blog.

Safety Considerations

The key difference between a nuclear power plant and a coal fired thermal power plant is that after a unit trip the nuclear heat source continues to produce heat. When a coal fired power plant is tripped: the blower fans and fuel supply is cut off quickly stops generation of new heat. The heat that remains is a result of the hot tubes in the boiler needing to cool down and this is accomplished by continuing to supply feedwater to the boiler. A nuclear power plant on the other hand continues to generate decay heat. This is a well known and well understood phenomenon and is characterized by design standards such: ANSI/ANS Std. 5.1 [Reference 1]. A graph of how decay heat drops off with time (dotted line) is shown in the figure below.

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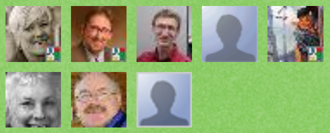

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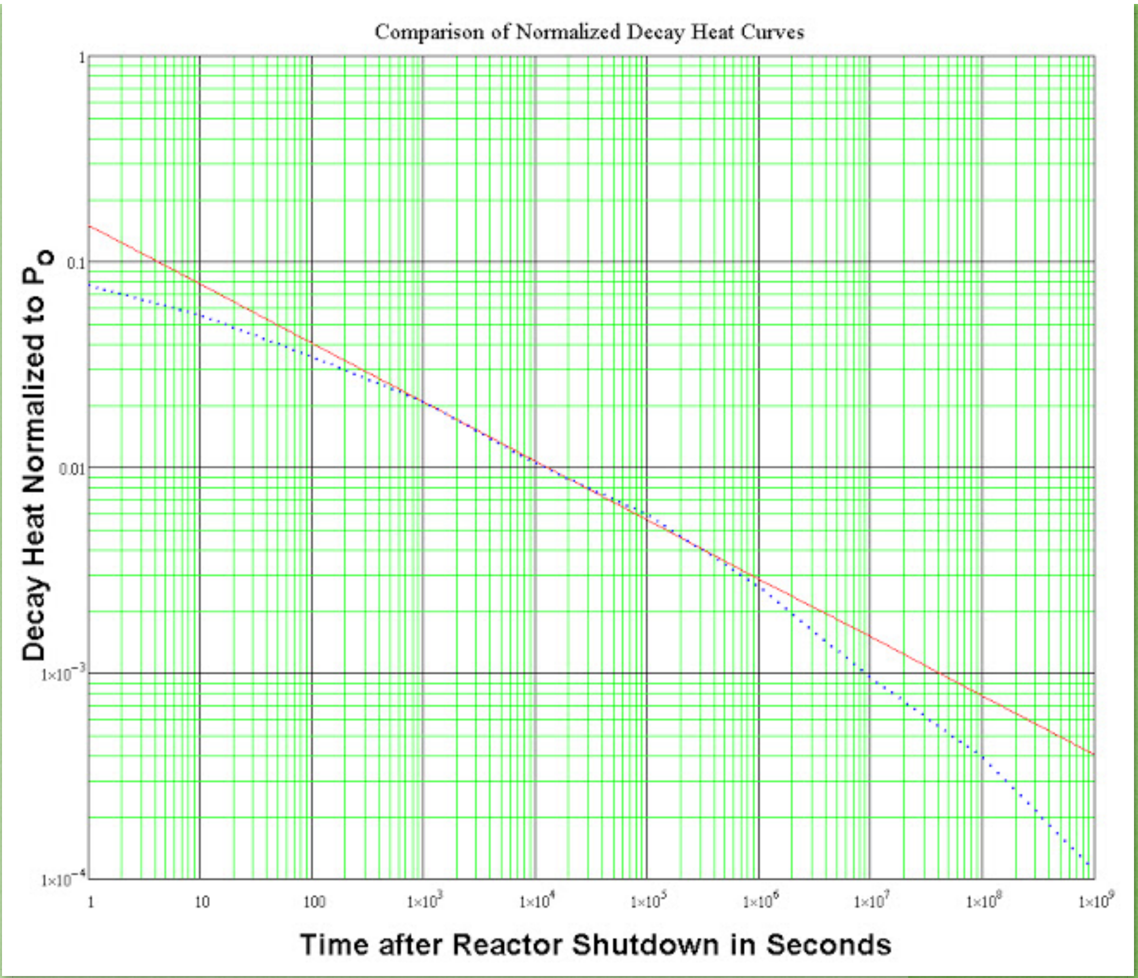
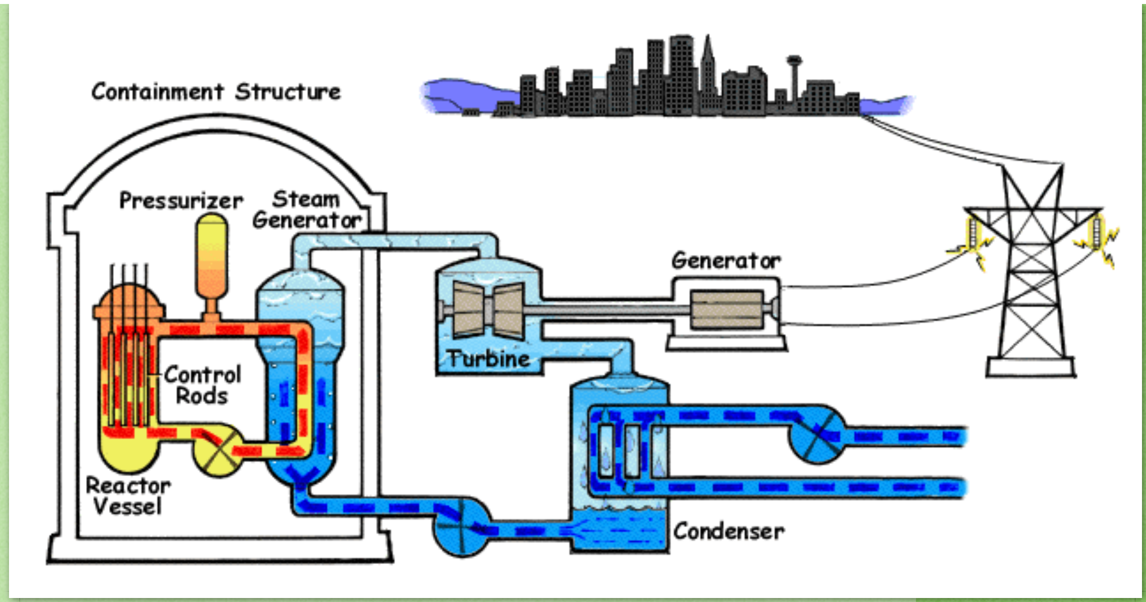


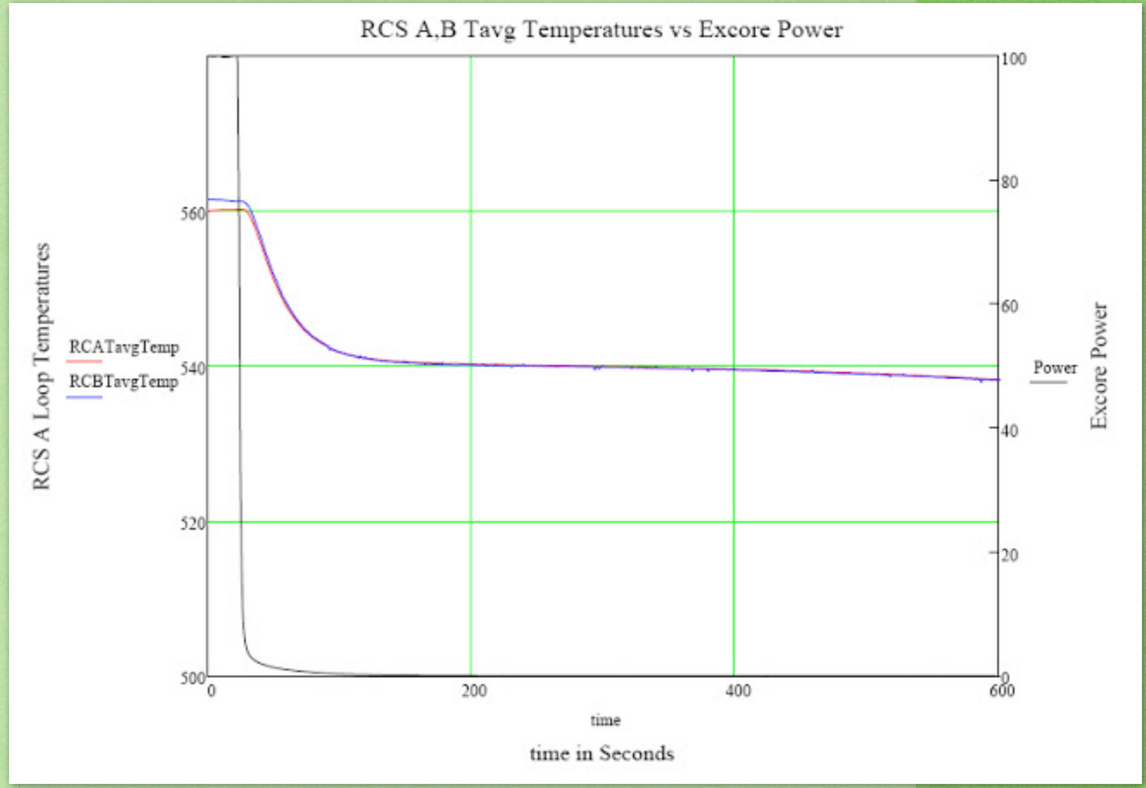
The dotted lines are taken directly from the standard. One second after a reactor trips, the standard assumes the heat is at 8% of the original power output. So if we had a reactor generating 1000MegaWatts of heat at one second after trip it is putting out 80 MegaWatts. At 100 seconds the heat has dropped to ~3.5% (or like 35MegaWatts) and so forth. As in the case of the coal fired boiler - after a unit trip there are is a lot of very hot metal which need to be cooled down as well (e.g. piping, steam turbines, etc). All of this requires continuous addition of water.

Plant Trip from Full Power with Offsite Power Available

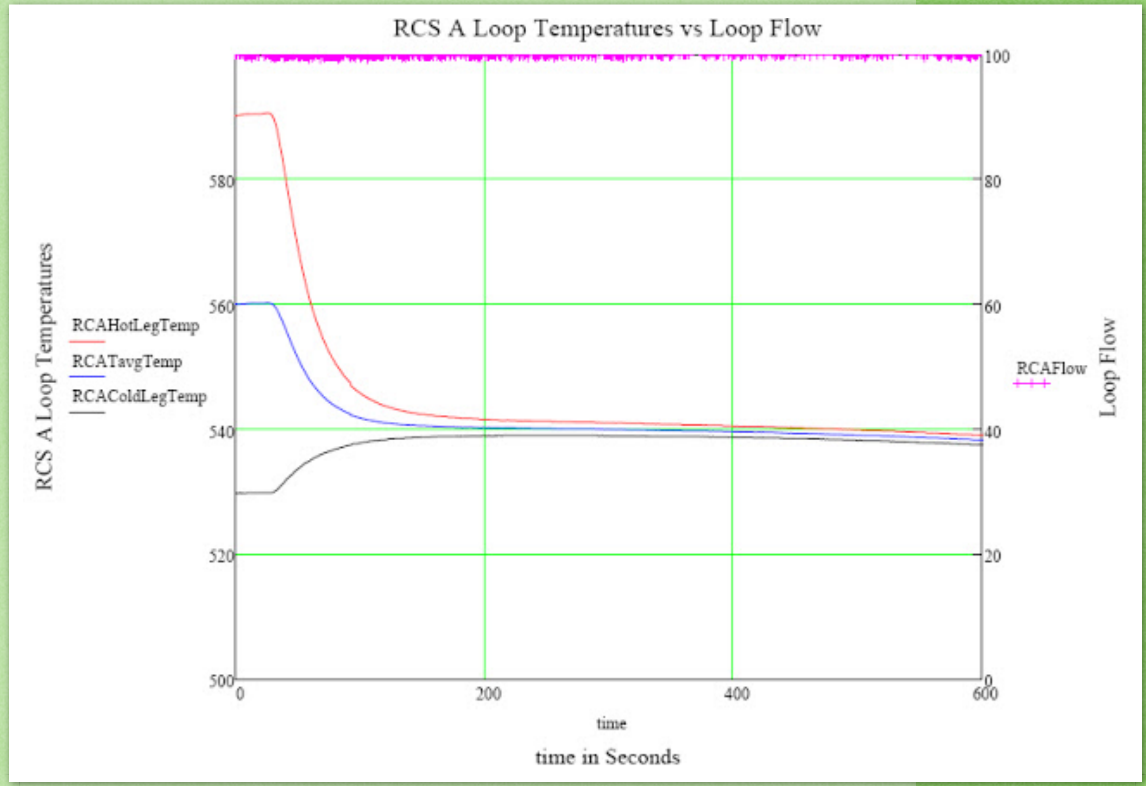
When a pressurized water reactor (see figure below) is operating at full power one would find: hot steam is being produced at nominally 900-1000 pounds per square inch or "psi" by boiling water in the steam generators. The source of heat in the steam generators is hotter water, typically 580-600F pumped to the steam generators from the reactor by reactor coolant pumps that take the water from the colder side of the steam generators.



Depending on the size and rating of the reactor plant, water coming into the reactor enters at above 500F and is heated in the reactor and heads for the steam generators. There are two main sources of heat to the water: heat transferred from the reactor (depending on the rating of the unit several hundreds to thousands of MegaWatts) and heat added to the water by the functioning of the reactor coolant pumps (which can be several MegaWatts). When a unit trips from full power, the control rods are inserted in 1-2 seconds and the reactor transitions from heat directly from fissioning to decay heat plus reactor coolant pump heat. The figures below are taken from a actual full power plant trip as recorded by the unit's plant data logging computer..



When the measured neutron "flux" power (scale on the right) abruptly drops - the actual time when the reactor trip occurred - the measured temperatures at the cold and hot sides start to approach each other. The difference between the upper and lower temperature is proportional to the decay heat and heat added by the reactor coolant pumps.



The immediate actions by a well trained crew of operators in the control room would be to announce over the plant address system that the reactor had tripped and then they begin their immediate reviews to confirm that: all control rods have fully inserted, that the turbine has tripped and main generator disconnected, that electrical buses needed to power equipment is energized, and that pressures, water levels and temperatures are trending the way that is expected and that there is no need for operating emergency cooling systems. Equipment operators in the plant will typically walk to their pre-defined post-unit-trip duty stations and make further adjustments on equipment in the turbine building. The normal preferred pathway from this point on would be to continue to generate steam in the steam generators - send it directly to the main condenser - cool the steam and feed it back to the steam generators. After about 10 minutes in this condition, the control room staff would actually hold a meeting to discuss what caused the trip, any out of tolerance conditions observed by the operators, or indications that are not as expected, and where to proceed from this point based upon their written procedures. The options include to continue to remain on steam generator cooling (which we call *hot standby*) or proceed to cold shutdown - meaning the primary coolant system in further cooled down to temperatures where heat is removed by a special set of heat exchangers called a residual heat removal system.

Plant Trip from Full Power with Loss of Offsite Power

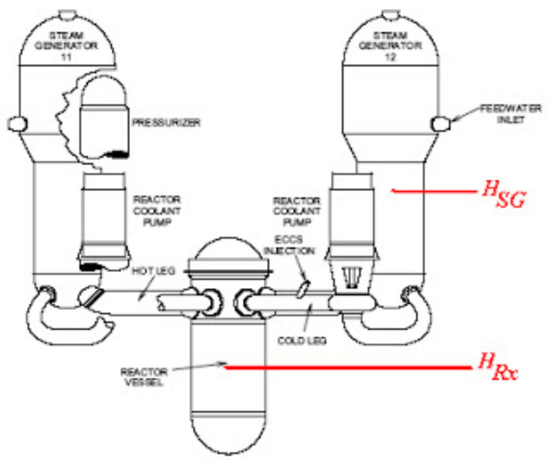
In a plant trip from full power without offsite power (like recently occurred at the

North Anna plant following the earthquake in Mineral Virginia last week) the response by the control room operators would essentially be the same. The initial steps are in fact identical. Typically they would experience a momentary dimming of control room lighting while emergency diesel generators kicked in. They would announce a plant trip, confirm the control rods are inserted, that the turbine and main generator have tripped, and evaluate the status of incoming electrical connections.

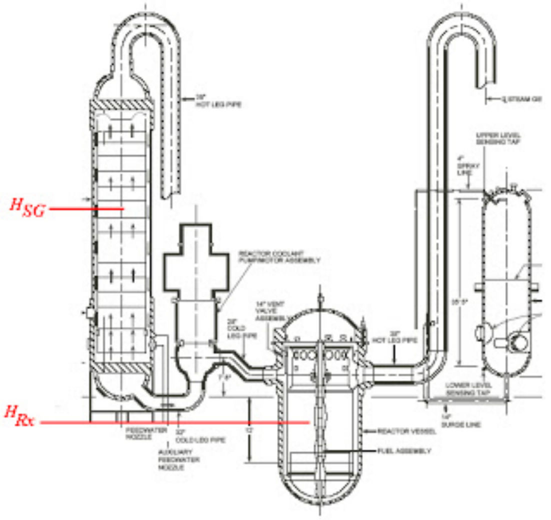
There are several key differences in what equipment would be used to remove post-trip decay heat. All *non-essential electrical buses are de-energized* when there is a loss of offsite power. Emergency diesel generators have started and essential pumps, motors and loads such as battery chargers are reloaded automatically to the diesels. The main condenser unit - which is *not a safety system* and is *not powered by emergency diesel generators* - and all of its associated pumps and heat exchangers are just sitting there and not available to remove decay heat from the steam generators. Additionally the main reactor coolant pumps which are not safety related de-energize and spin down. While this implies no forced coolant flow -- it also means a rapid elimination of the several MegaWatts of pump heat added to the system - leaving only the decay heat from the reactor. Initially, there is considerable momentum of water circulating in the coolant system to carry away the decay heat from the reactor.

So, after this point: ***How is the heat transported from the reactor to the steam generators?***

The answer is ***natural circulation***. Pressurized Water Reactors (both those with U-tubes, and those with straight tubes) are designed with relatively large vertical elevations in mind that allow hot water to rise - as the coolant flows up through the reactor to the steam generator. As the water cools - via transferring heat in the steam generators through boiling water on the steam side it becomes colder and denser. The denser, heavier water wants to flow downwards to the lowest point in the coolant system -- which in this case is the bottom of the reactor vessel. I show two elevations drawings for common nuclear power plant designs below. The points being highlighted are the "thermal centers" in the steam generator (***Hsg***) and the reactor (***Hrx***). The thermal center is the point in the closed loop of the coolant system where the mid-range coolant temperature -- which we call ***Tavg*** is physically located. As long as: ***Hsg*** is elevated above ***Hrx*** water is naturally circulated to remove decay heat *without any moving parts in the primary coolant system.*

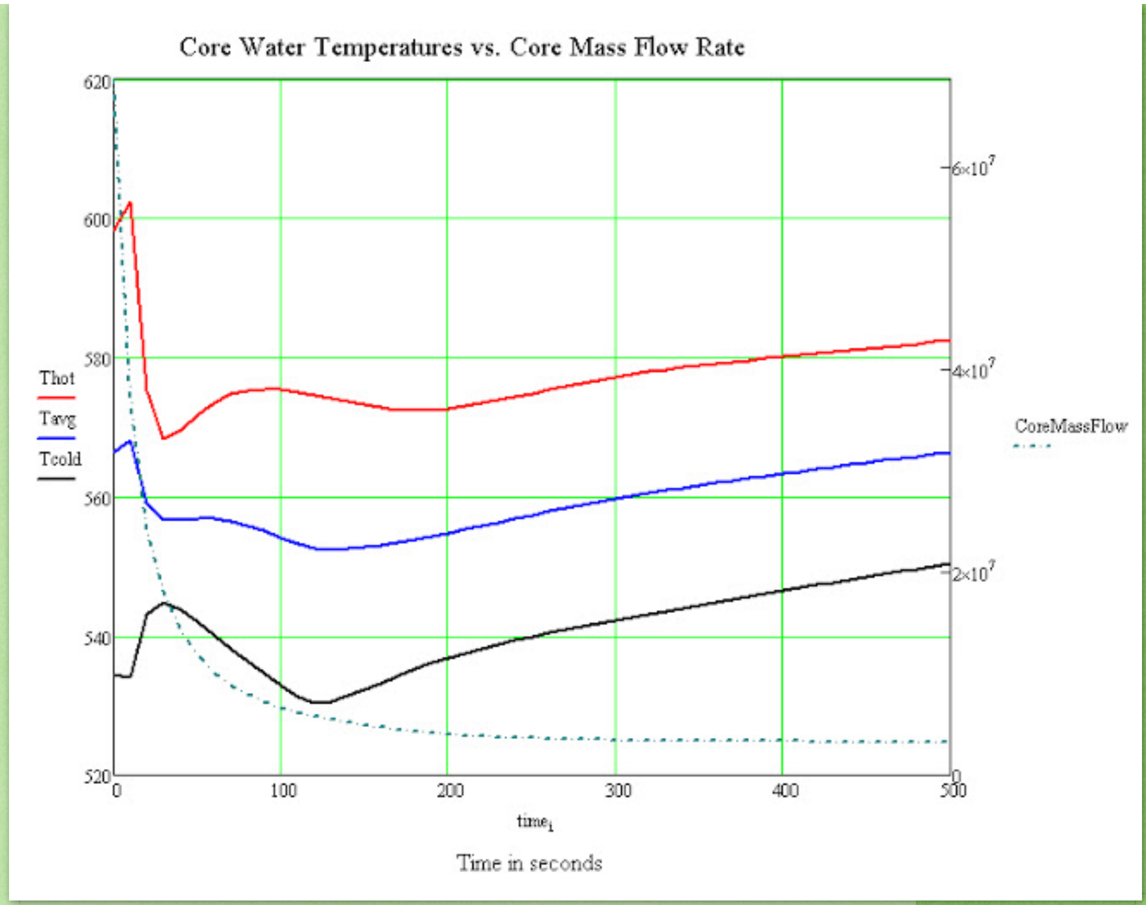


CE 2-Loop Nuclear Steam Supply System

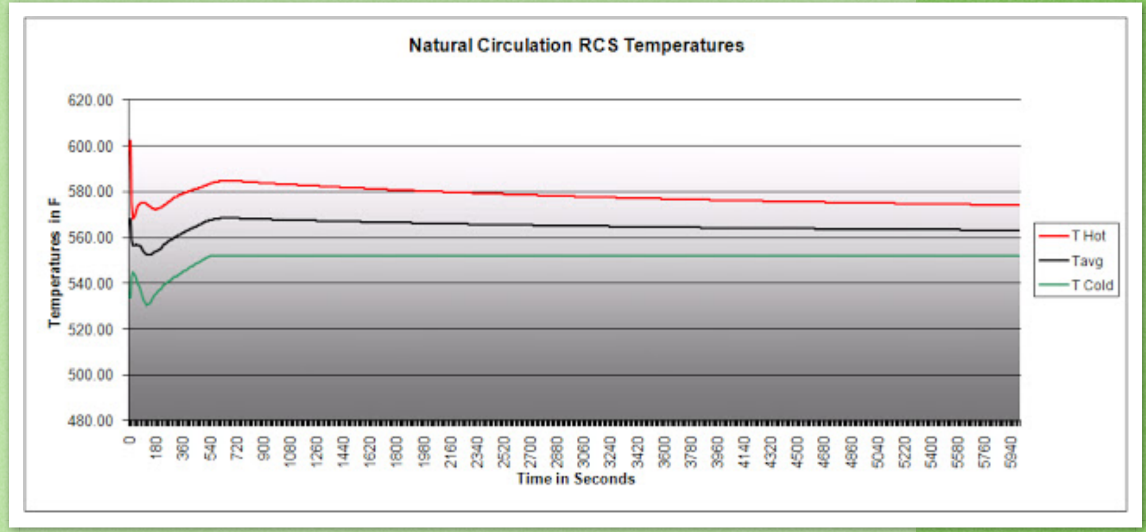


B&W 2-Loop Nuclear Steam Supply System

So - hotter less dense water rises in the reactor core, and colder denser water wants to fall downwards - as long as heat is being removed in the steam generators. I show below a trend plot below from an actual trip with loss of offsite power.



In the first few hundred seconds, what we see is the rapid drop off of forced primary flow provided by the pumps -- but it doesn't go to "zero" because natural circulation kicks in and provides 4-5% normal flow. As the decay heat from the reactor core starts to drop off, the heat added to the water drops off and this naturally slows down the rate of water flow. The figure below shows what the temperature trend looked like over a significantly longer time scale as the plant entered a stable long term natural circulation cooling..

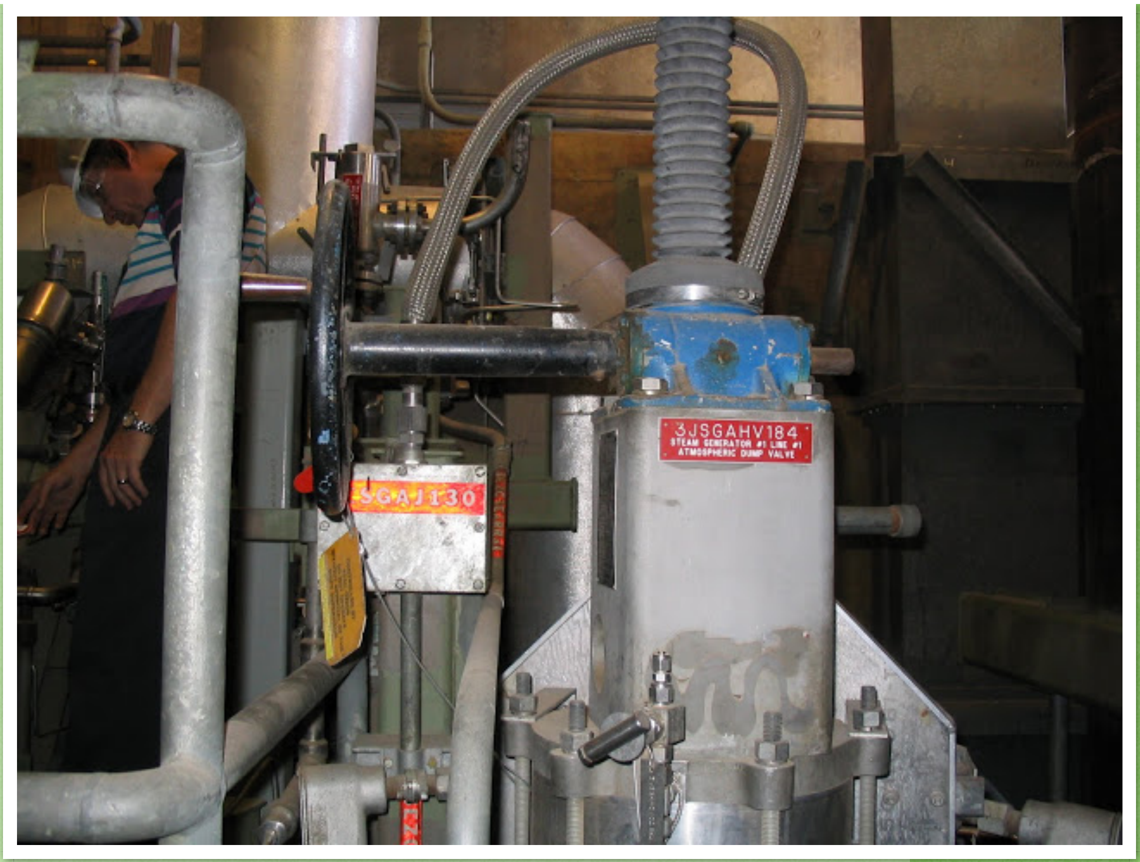


I have previously mentioned that it is important to keep water flowing to the steam generators and steam flowing out of them.

Getting water into the steam generator is accomplished by what we call an ***auxiliary feedwater (AFW) pump system***. Depending on the design, this can be a combination of one (or two) electrically driven AFW pumps and a diverse steam driven AFW pump. Typically only one of these is needed and operators would keep only one feeding the system and shutdown (or secure) the others to keep them in reserve and to prevent them from overfilling the steam generator. The electric driven AFW pump(s) would be powered by a diesel. The steam driven pump is powered by a small portion of the steam generated by the steam generators. This is kind of a "*play as you go*" operation - the higher the decay heat load the higher the steaming rate - the lower the decay heat to lower the steaming rate. These pumps take suction from a safety related water storage tank (or in many designs several tanks) with enough water to last typically a day. If this tank should become depleted operators have that whole day to align to an alternate water source such as a small diesel fire water pump using well water, river water, or even ocean water.

(Photo of a steam driven, Terry Turbine, auxiliary feedwater pump with Woodward Governor)

Getting steam out of the steam generators is accomplished by venting the steam to the atmosphere either by manually opening an atmospheric dump valve or letting the steam pressure naturally rise to the point where a steam generator relief valve operates. Venting to the atmosphere is necessary because - recall: the main condenser is unavailable due to lack of power for running pumps. Venting to the atmosphere is simple and straight forward but it results in continuous depletion of water supplies and this is the main reason for large water storage tanks and the ability to make up to those tanks with alternate water sources such as fire water.



(photo of the pneumatic controls on a steam generator atmospheric dump valve)

Throughout the cool-down (or until offsite power is restored), electrical power would be provided by redundant diesel generators typically rated at 4-5MegaWatts and about the size of a locomotive engine. These units provide all necessary power to run electric AFW pumps (if operators chose to run an electric pump), power other essential cooling water pumps to cool pump bearings, run safety related room cooling, and keep the redundant batteries powered so that the control room instruments remain powered and operable. To keep the diesels running all that is required is fuel oil and some form of engine cooling. Some plants have water cooled diesels others have air cooled diesels. Fuel oil is stored in a smaller quantity for immediate operational needs in what is called a *day tank* and over longer periods would be replenished by a fuel oil transfer pump from a much larger supply tank.

With the plant temperatures stabilized - typically in about 10-20 minutes - the control room operators would make contact with outside dispatchers to determine the source of the loss of offsite power and when it was likely that offsite power connections would be restored. From this information the crew meeting would be held and following plant procedures, decisions would be made on whether to remain in hot standby or to proceed to cold shutdown.

What is Different if the Plant has Advanced Warning?
A Hurricane like we are experiencing this weekend on the east coast is an example of an external event which has many hours of advanced warning. The typical issues that might warrant a shutdown of the plant before the hurricane reaches the plant could include the likelihood of storm related damage to the main switch-yard or

incoming electrical transmission system. High winds and debris (tree branches, etc.) can knock down transmission lines. Hurricanes have been known to transport large amounts of salt on to high voltage electrical insulators causing transmission lines to electrically short-circuit to transmission tower metal and then to ground. Hurricanes have also been known to tear up the seaweed and kelp from the ocean bed and cause clogging of intake structures - and this could result in reduced water flows to the diesel (if it isn't air cooled) or to other heat exchangers needed to support operation of essential systems. Utilities and the people who operate nuclear power plants know of these potential challenges and have specific emergency operating procedures to deal with external events with long lead times. The general idea behind these procedures is to reduce power ahead of time (thus starting off with a ***lower decay heat level***) and making use of their largest single heat removal system available to them -- namely: the ***main condenser***. Because the condenser is relatively large, it is possible to quickly cooldown the steam generators and reactor coolant system while not discharging steam to the atmosphere. This means the water in the storage tanks for the AFW pumps remains at a maximum inventory level for as long as possible. [I would point out that nuclear power plants also have written procedures covering advance warning of tornadoes and high winds. Although these scenarios may have only 10 minutes advance warning these would also be addressed by rapidly reducing power.]

Typical utility procedures in the event on an oncoming hurricane (where there could be an extended loss of offsite power) would include:

- reducing overall power output levels several hours before the storm arrives
- topping off the reserve diesel fuel oil tanks
- securing from any non-essential maintenance activities that might leave the plant vulnerable in a loss of offsite power situation
- doing a walk-down of plant areas to remove or secure outside equipment or supplies in the plant yards that might become a missile hurled at plant equipment by hurricane force winds
- installing temporary flooding protection to doorways leading into plant buildings
- calling in and stationing additional plant equipment operators in specific areas that might need additional monitoring during a hurricane.

It is thus not surprising that given decades of coping with actual hurricanes, tornadoes, earthquakes, continuous operator training (roughly a week every five weeks involving classroom refresher training and simulator drills on what to do), well written procedures and guidance -- that US nuclear power plants know how to cope with severe weather and other natural disasters. When I read in the *main street media* that nuclear power plant operators don't know how to deal with such situations and that further improvements are urgently needed because a theoretical physicist thinks we just "*dodged a bullet*"..... I have only one word to say, and that is:

" ***B@!!$'t*** "

References

[1} Decay Heat Power in Light Water Reactors, ANSI/ANS Std. 5.1-2005, issued by the American Nuclear Society.

Posted by Dr. John H. Bickel at 3:24 PM

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alliedelectricals E February 22, 2013 at 2:50 AM

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Andrew Collins April 18, 2014 at 8:47 PM

You have given some graphs and images posted in your blog.I have read the above information and provided the some points that is energetic and mind blowing.You have mentioned that how liquid cooling helps to cool the system?

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