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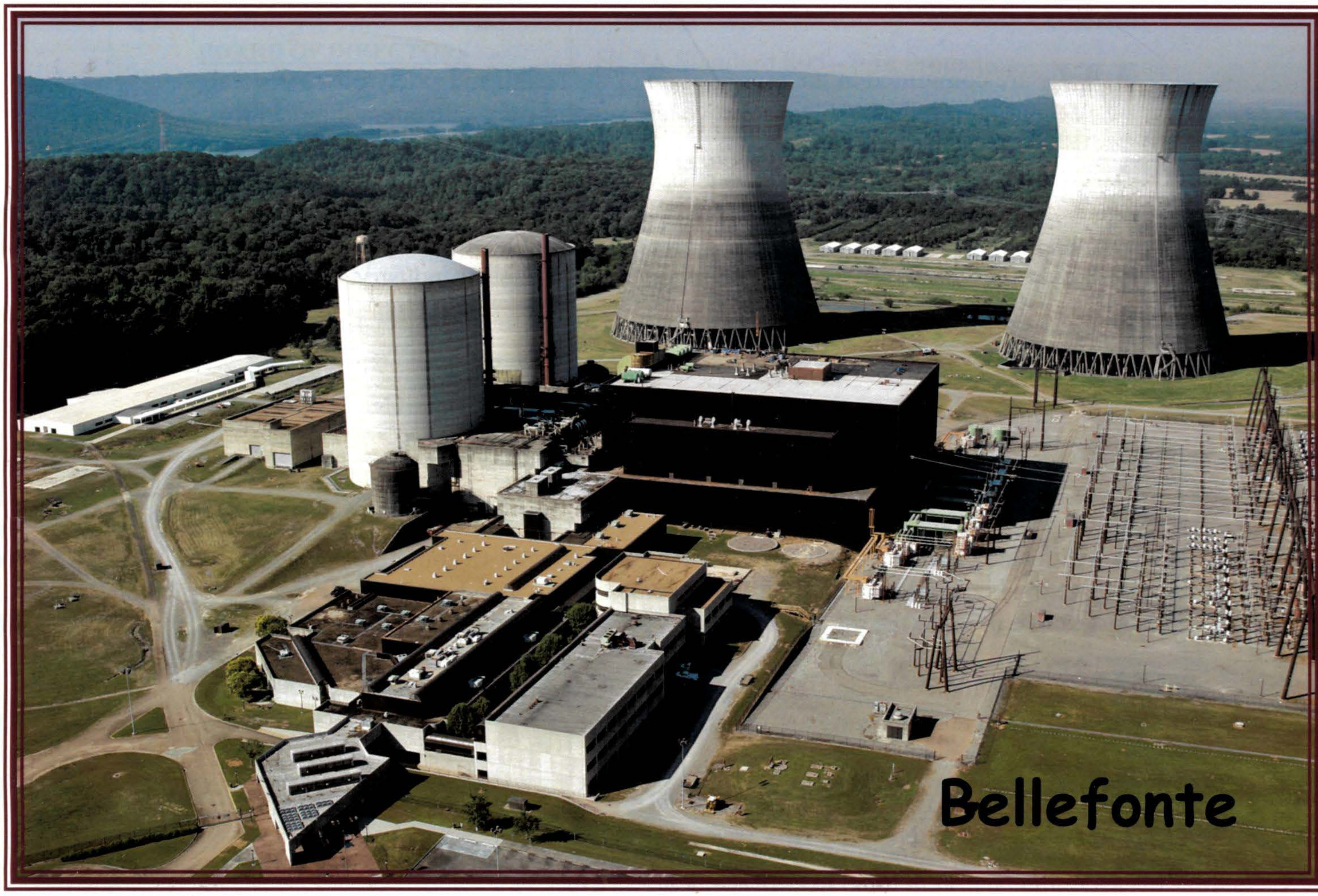

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ON THE COVER:

TVA's Bellefonte Nuclear Power Plant is scheduled to be online between 2018 and 2020.

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Analysis of the October 21, 2003 Passive Reactor Shutdown at Callaway Plant

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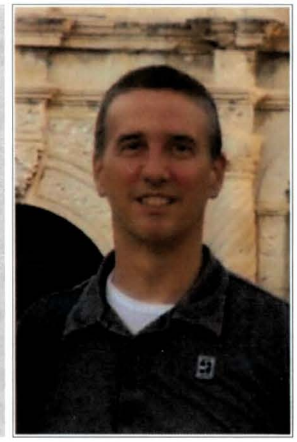

Abstract: *At Callaway Plant on October 21, 2003, while attempting to stabilize reactor power during a forced de-rate, Xenon-135 buildup caused average reactor coolant temperature to lower at ~0.4°F/min for a 25 minute period, resulting in an automatic isolation of the letdown system on low pressurizer water level and operation of the reactor below the Minimum Temperature for Critical Operation. After manually tripping the turbine-generator to assist in temperature recovery, the reactor passively shut down due to a sharp 4°F rise in average coolant temperature. For the next 110 minutes the operators performed secondary and tertiary plant shutdown activities while relying on an informal estimation that Xenon-135 levels were sufficient to prevent the reactor from inadvertently restarting. The passive reactor shutdown was not documented until it was uncovered 40 months later, and it was not shared with the Institute of Nuclear Power Operations following the request which accompanied SOER 07-1. The incident highlights the pitfalls associated with attempting to maintain a commercial pressurized water reactor critical during MODE 2-Descending and demonstrates how concepts tested on the NRC Generic Fundamentals Exam apply to actual reactor operation. The incident also highlights some non-conservative reactivity management practices which must be avoided by Professional Reactor Operators.*

This article describes the events leading up to and immediately following a passive reactor shutdown which occurred at Ameren Corporation's nuclear plant in Callaway County, MO on October 21, 2003. An assessment of the NRC's response to the incident is included along with key "lessons to be learned." Details of the incident were first publically released by the Union of Concerned Scientists (UCS) in a 2010 issue brief[1] titled *2003 Segmented Shutdown at Callaway*, and then, in 2011, the US Nuclear Regulatory Commission (NRC) partially covered the incident as part of Information Notice 2011-02, *Operator Performance Issues Involving Reactivity Management at Nuclear Power Plants.*[2]

Also discussed in the article are:

- The manner by which the effect of Xenon-135 buildup can be masked by other passive reactivity insertions during a plant transient.
- The effect operation near the Non-Fission Heat Rate has on Temperature-Reactivity feedback.
- The challenges facing the operator during low power operation due to human factoring of control board instruments.

(Continued on next page)

[1] http://www.ucsusa.org/nuclear_power/nuclear_power_risk/safety/2003-segmented-shutdown-at-callaway.html
[2] http://pbadupws.nrc.gov/docs/ML1018/ML101810282.pdf

REACTOR DYNAMICS REFRESHER

Passive Response to Reactivity Changes
Commercial Pressurized Water Reactors (PWRs) in the United States are designed to passively respond to changes in reactivity. They do this through two primary methods:[3]

1. A negative power coefficient of reactivity
2. A negative Moderator Temperature Coefficient of reactivity (-MTC)

Item 1 is a required safety feature of all US Commercial designs: a negative power coefficient of reactivity ensures that an uncontrolled rise in reactor power will result in a negative insertion of reactivity, thereby limiting the power rise.

Item 2 is normally present throughout the fuel cycle at most PWRs; however, some plants do permit a slight +MTC during a limited window of their fuel cycle. October 21, 2003 was late in fuel cycle 13 for Callaway Plant and a –MTC was present so discussions in this article assume a –MTC.

The combined result of items 1 and 2 is that, on a US commercial PWR, power is inherently stable. That is, the reactor "wants" to stay at a steady power and resists power increases and decreases.

Response to a reactivity insertion with steady state steam demand: When negative reactivity ($\Delta\rho$) is inserted (e.g. insertion of control rods, addition of boron, buildup of Xenon-135) while the steam demand (i.e. turbine-generator loading) is held constant, reactor power will decrease slightly. Because of the negative power coefficient of reactivity, positive reactivity is passively inserted as power lowers, dampening the negative reactivity insertion. With steam demand unchanged, the new lower power will cause a negative power mismatch to develop.[4] This negative power mismatch will cause temperature to lower. Due to the –MTC, as temperature lowers positive reactivity is passively inserted, which further dampens the negative reactivity insertion. Temperature will continue to lower as long as there is a negative power mismatch. Eventually, enough positive reactivity will be inserted by the temperature drop to result in a net increase in reactivity. This point is called the point of power "turning." At this point, reactor power will start to rise and the magnitude of the negative power mismatch will lower, dampening the temperature drop.

Once reactor power rises above steam demand, there will be a positive power mismatch which will now cause temperature to rise. The rising temperature will insert negative reactivity, causing reactor power to lower. These passive feedback processes will continue until, eventually, reactor power again matches steam demand and there is no power mismatch to drive temperature. At this point, temperature will be lower than it was prior to the negative reactivity insertion. Mathematically, the change in temperature is: $\Delta T = \Delta\rho/(-MTC)$.

The reactor will passively respond to a positive insertion of reactivity in a similar manner, resulting in the reactor operating at a higher temperature than prior to the reactivity insertion.

The response of the reactor described in the paragraphs above is called "Temperature-Reactivity feedback." Temperature-Reactivity feedback consists of two things:

1. The passive response of the average reactor coolant temperature (T_{avg}) to the power mismatch induced by the change in reactivity.
2. The passive counter insertion of reactivity due to the temperature response, which continues until power turns and re-approaches steam demand.

So, without any operator action, US commercial PWRs passively respond to reactivity changes in a manner that eventually results in the same steady state power at a new temperature. This generic fundamental is demonstrated later in this article by

[3]Since Callaway Plant is a PWR, the reactivity coefficient due to voids is not discussed in this article.
[4]Power mismatch is the difference between steam demand and reactor power.

the way the reactor at Callaway Plant responded to Xenon-135 buildup when the turbine-generator loading was kept constant from 09:36 to 10:03 (see Figure 1 on next page).

Passive response to a change in steam demand (for a PWR): When the steam demanded by the turbine is lowered, a negative power mismatch will result, causing temperature to rise. The rising temperature will insert negative reactivity, causing reactor power to lower. The lowering reactor power will result in a lowering of the power mismatch, dampening the temperature rise. As long as there is a positive power mismatch, temperature will continue to rise. The negative reactivity insertion from rising temperature will continue until reactor power falls below steam demand resulting in a negative power mismatch which thereby causes temperature to lower. The lowering temperature will insert positive reactivity, causing power to turn and approach steam demand. Reactor power will eventually become steady at the new steam demand level. Due to the negative power coefficient of reactivity, the lower power level will have resulted in a passive positive reactivity insertion. Temperature will passively respond to this positive reactivity insertion by steadying out at a higher level and thus inducing a negative reactivity insertion which cancels out the power defect.[5]

A pressurized water reactor will respond similarly to an increase in steam demand.

The response of the reactor described in the paragraphs above is characterized as "reactor power follows steam demand."

Without any operator action, US PWRs passively respond to steam demand changes in a manner that eventually results in reactor power matching steam demand at a new temperature. This generic fundamental is demonstrated later in this article by the way the reactor at Callaway Plant responded to the lowering of turbine-generator loading between 10:03 and 10:10 (see Figure 1).

The Effect of Decay Heat

Following the initial criticality of the fuel cycle, some level of decay heat is always present. The amount of decay heat present is determined by the reactor's power history. At 100% rated power, decay heat typically accounts for 7% of the power being generated in the core. During a down power, decay heat accounts for a slightly larger percentage of reactor power than at steady state power. This is because the longer lived fission product daughters which were produced at 100% power are exerting a disproportional influence on the decay heat spectrum than they normally would at a steady state power level. This influence is not easily noticed in MODE 1.[6] However, as reactor power nears MODE 2,[7] the effects of decay heat become substantial.

The Non-Fission Heat Rate: The Non-Fission Heat Rate (NFHR) is the power produced by the reactor plant from sources other than fission. Although there are other contributors to the NFHR besides decay heat (e.g. friction heat from the Reactor Coolant Pumps), this article is primarily concerned with the effect of decay heat. The NFHR is about 7% of rated power when the reactor is operating at 100% power. The contribution of short-lived fission product daughters to the NFHR is roughly proportional to the fission rate so it lowers proportionally to reactor power. However, the change in the population of long-lived fission product daughters lags the change in fission rate as the reactor is down powered. As the fission rate falls to zero, there is still a substantial amount of heat being generated by the long lived fission product daughters. This NFHR varies with power history, but, following a 10%/hour shutdown of the reactor, the half-life spectrum of the remaining daughters is long enough that the NFHR is relatively constant when measured in hours (i.e. it lowers by just a few percent every hour).

(Continued on next page)

[5]power defect is the term for the reactivity inserted from a change in reactor power level.

[6]MODE 1 refers to the state of operating the reactor at power (5% to 100% rated reactor power).

[7]MODE 2 refers to the transition state between the reactor being solidly in the power range (i.e. beyond the point at which the NFHR exerts any substantial influence) and the reactor being shutdown (i.e. definitively subcritical as indicated by calculating K_{eff} to be less than 0.99). The reactor enters MODE 2-Descending when reactor power lowers below 5% rated power.

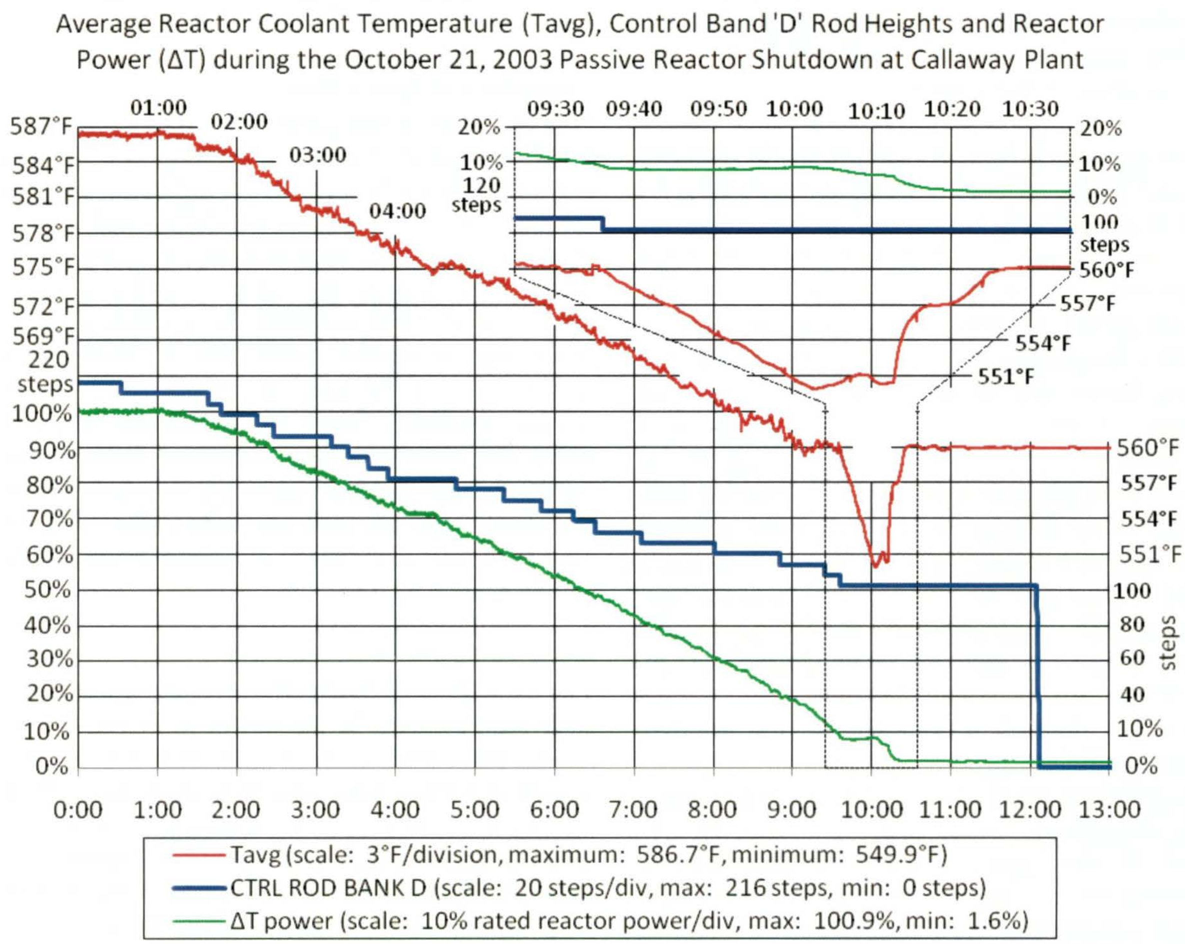

Figure 1: Plot of Average Coolant Temperature (T_{avg}), Primary Calorimetric power (ΔT) and Control Bank 'D' rod heights during the October 21, 2003 down power and passive reactor shutdown. Note the severe temperature transient which began at 09:36. Turbine first stage steam pressure data indicates that the operators stopped lowering turbine-generator loading at 09:36 with reactor power at 9%. Over the next three minutes, negative reactivity due to Xenon-135 caused power to continue to lower another 1%. The power mismatch between the steam demanded by the turbine throttle setpoint and the power being produced by fission caused T_{avg} to immediately begin to lower, thereby inserting positive reactivity which countered the negative reactivity being inserted by the continual buildup of Xenon-135. Around 09:39 the positive reactivity being inserted by the lowering temperature matched the negative reactivity being inserted by Xenon -135 causing reactor power (as indicated by core ΔT) to stabilize at approximately 8%. With a 1% power mismatch present, over the next twenty minutes T_{avg} continued to steadily lower and thereby counteract the continual buildup of xenon. Shortly after 10:00 the crew again began to lower turbine-generator loading in response to the Shift Manager's decision to take the turbine off-line following the letdown isolation. The renewed lowering of generator loading caused steam demand to lower below fission power and thereby allowed T_{avg} to temporarily recover slightly. During this time period (10:03 to 10:09), the negative reactivity being inserted by Xenon-135 was now being counteracted by the positive reactivity being inserted by the load decrease (the plant had a negative power coefficient of reactivity). Generator loading was again stabilized around 10:09 causing T_{avg} to resume falling, which is the expected passive response of the reactor plant to Xenon-135 buildup. The operators failed to grasp the reactor dynamics behind the transient and assumed the 10°F drop in T_{avg} was being caused by malfunctioning steam line and turbine drain valves (which had coincidentally been placed in service at about the same time the temperature transient began).

By the time the reactor at Callaway Plant passively shut down on October 21, 2003, the NFHR was 1.75% of rated reactor power. About half of this was due to RCP pump heat.

The Point of Adding Heat: The NFHR determines the reactor's Point of Adding Heat (POAH). The POAH is the amount of fission power needed to noticeably affect reactor power. During a reactor startup, the POAH is the point at which raising reactor power (as measured by the nuclear instruments[8]) will noticeably affect total power (as measured by the calorimetric Instruments[9]). The POAH is significant during a reactor startup because it is the point at which Temperature-Reactivity feedback starts to occur: once reactor power ascends above the POAH, it becomes difficult for the reactor operator to pull control rods to produce a set Start Up Rate (SUR) because as positive reactivity is actively inserted with the control rods the resultant reactor power increase causes temperature to rise and thereby feed back negative reactivity which lowers the SUR. Prior to reaching the POAH, the reactor operator uses the control rods to actively control reactivity. Beyond the POAH, the control rods are used to actively control average coolant temperature via the passive response that temperature has to manual reactivity changes.

On a shutdown, the POAH cannot be recognized until the reactor is already below it. During a shutdown, the POAH is the point at which lowering fission power (as indicated by the Intermediate Range Nuclear Instruments) has no effect on total power. This generic fundamental is demonstrated on Figure 4 by the way the ΔT trace steadies out at 1.75% while the IRNI trace continues to lower.

EVENT NARRATIVE DESCRIPTION

Cause of the Forced De-Rate

At 07:21 on October 20, 2003 a safety-related inverter (NN11) failed, causing the unit to enter a 24-hour Technical Specification (T/S 3.8.7.A) to either repair the failed inverter or begin a plant shutdown.

At 00:37 on October 21, 2003, after repair attempts by Electrical Maintenance, the operators placed the inverter in service for a retest. The inverter failed its retest and at 01:00 the operators began down powering the reactor at 10%/hour in preparation for a reactor shutdown.

By 07:21 reactor power was just below 40% with the inverter still unrepaired so the unit entered the 6-hour Technical Specification (T/S 3.8.7.B) to either repair the failed inverter or shut down the reactor.

Entry into Off-Normal Procedure for *Loss of Safety-Related Instrument Power*

At 08:21 the inverter was again placed in service for a retest. The inverter failed its retest and the crew responded by performing the off-normal procedure for a "Loss of Safety Related Instrument Power." By 08:36 the control room operators had completed their actions, but the off-normal procedure could not be closed until an equipment operator could become available to perform an alignment check of some valves in the Auxiliary Feedwater system. This alignment check was not completed until 11:34, resulting in the off-normal procedure remaining open until 11:37. Although this off-normal procedure administratively remaining open should not, in and of itself, have caused a problem, for unexplained reasons the operators claim they could not perform the step in the Reactor Shutdown procedure for inserting the control banks until this off-normal procedure had been exited (see discussion in the "Safety and PI&R Concerns" section).

Xenon-135 induced Cooldown

At 09:36 the unit was at 9% power and the operators discontinued down powering the turbine-generator. It is not clear why this occurred, but since they were 2½ hours ahead of schedule it is likely they intended to hold power at ~10% while

[8] There are three sets of nuclear instruments (the power range, intermediate range and source range). The nuclear instruments measure fission rate by detecting stray neutrons produced by fission.

[9] There are two sets of calorimetric instruments at Callaway Plant: ΔT instruments (primary calorimetric calculated from the temperature rise across the core) and thermal output computer points (calculated from a secondary calorimetric).

further troubleshooting occurred on the failed inverter.

Also around 09:36 the operators cycled the Group B turbine drains. One of the switches for the drains was not indicating properly, requiring the operators to locally observe the operation of the thirteen valves controlled by the malfunctioning switch.

By 09:36, the 10%/hour downpower which had been occurring for the past 8½ hours was causing a significant Xenon-135 transient. The constant build up of xenon was inserting negative reactivity at a significant rate; however, prior to 09:36 it was having little effect on reactor plant parameters. The build up of xenon went largely unnoticed because, although significant, it was not great enough to overcome the large amounts of positive reactivity being inserted by the 10%/hour lowering of reactor power and the 3°F/hour lowering of reactor coolant temperature. In fact, prior to 09:36 the operators were occasionally having to actively insert negative reactivity because the positive reactivity being passively inserted from the down power/cool down was slightly greater than the negative reactivity being passively inserted by xenon. Through 09:36, 114 inward steps of rod movement and 220 gallons of boron were required to keep temperature lowering at the desired rate (the boron additions were done during the first 2½ hours of the downpower, when the rate of xenon buildup was still low; see Figure 1 for the control rod movements).

When the crew ceased lowering turbine-generator load at 09:36, positive reactivity was no longer being passively inserted from the downpower. However, since Xenon-135 was still building up, negative reactivity was still being passively inserted. The crew did not have a detailed Reactivity Management Plan[10] and, because of their experiences during the past three hours,[11] failed to recognize that, with the downpower no longer occurring, they needed to actively insert positive reactivity to keep average coolant temperature stable.

Starting at 09:36, average reactor coolant temperature (T_{avg}) began to lower at about 22°F/hr. With Xenon-135 continuing to insert negative reactivity, the reactor would occasionally become slightly subcritical causing power to lower below steam demand. With power less than steam demand, T_{avg} lowered slightly. Due to the -MTC, the lowering T_{avg} inserted positive reactivity and caused the reactor to return to a critical state. In this manner, the reactor passively remained critical (i.e. passively overcame the negative reactivity being inserted by Xenon-135) by responding to the buildup of xenon with a lowering of T_{avg}.

The crew mistakenly believed that malfunctioning turbine drains were causing the drop in T_{avg}, so instead of aggressively inserting positive reactivity (e.g. by diluting boron or withdrawing rods), they coordinated with equipment operators in the turbine building to troubleshoot the turbine drains. The only positive reactivity actively inserted the entire day was a 360 gallon add of water to the Volume Control Tank which occurred between 09:47 and 10:00.

Letdown Isolation

By 10:00 T_{avg} had lowered 9°F and the letdown system automatically isolated on low pressurizer water level. Also by 10:00, the crew recognized that T_{avg} had fallen below 551°F, the Minimum Temperature for Critical Operations (MTCO) at Callaway Plant. To assist in recovering temperature, the Shift Manager directed that the turbine be taken off-line.

Manual Turbine Trip and MODE 2 Entry

After the letdown isolation, the operators began lowering turbine-generator loading in preparation for removing the turbine from service. This caused a positive power mismatch which tempo-

[10]Those with access to proprietary documents from the World Association of Nuclear Operators should see the recommendations contained in WANO SOER 2007-1, *Reactivity Management*, for expectations regarding Reactivity Management Plans.

[11]In the 3 hours since relieving the watch at 06:30 the crew had needed to insert control rods 30 steps in order to keep Tavg lowering at the programmed rate. No active insertions of positive reactivity had been required to overcome Xenon-135.

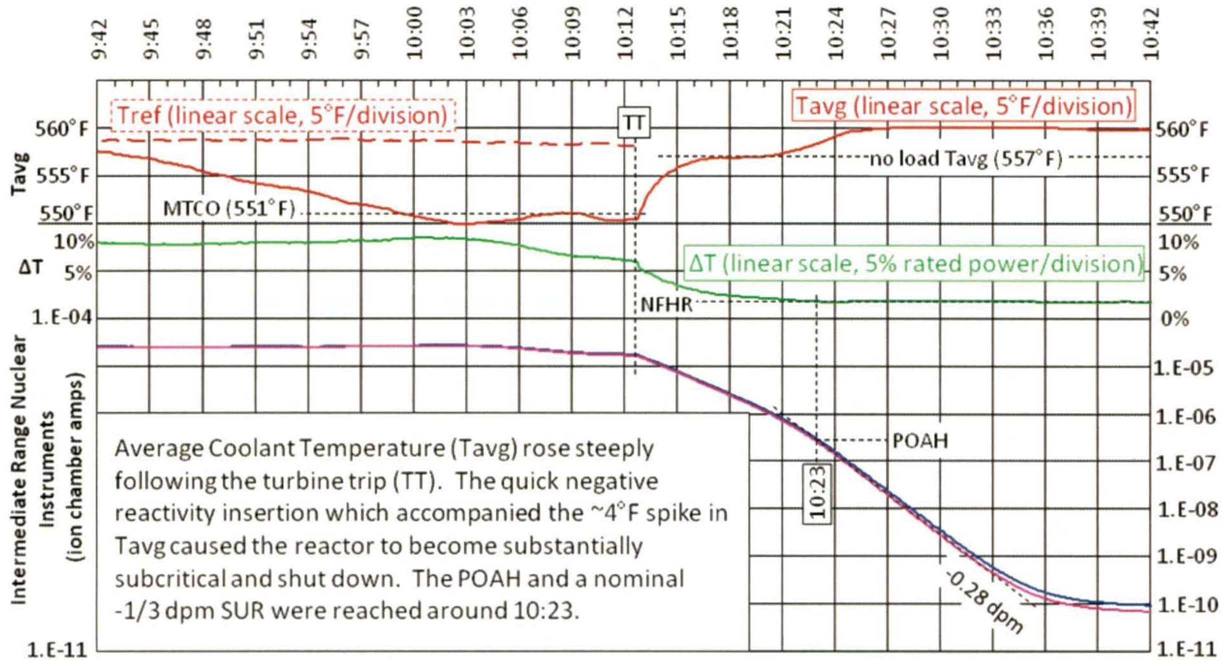

Figure 2: Plot of Average Coolant Temperature (T_{avg}), Primary Calorimetric power (ΔT) and Intermediate Nuclear Instrument currents (IRNI) on October 21, 2003. The sharp rise in T_{avg} was caused by the power mismatch resulting from manually tripping the turbine at 6% power and 550.4°F with the steam dumps set at 1092 psig (557°F). The negative reactivity inserted by this temperature rise caused the reactor to passively shut down. The leveling out of the ΔT trace at 10:23 indicated the Point of Adding Heat. The leveling out of the IRNI traces at 10:39 indicates entry into the source range. See Figure 3 for plant evolutions occurring during this time frame.

rarily caused T_{avg} to stop lowering (the minimum T_{avg} occurring at 10:03 in Figures 1 and 2 corresponds to the lowering of turbine load below reactor power). Between 10:03 and 10:09 the negative reactivity being inserted by xenon was addressed with power defect instead of temperature defect.

At 10:12:35 the operators manually tripped the turbine-generator with reactor power just under 6% and T_{avg} at 550.4°F. Prior to tripping the turbine, the operators had, per their procedure, set the condenser steam dumps to open at 1092 psig (which corresponds to 557°F, the "no-load" average coolant temperature at Callaway Plant). However, because of the confusion resulting from the temperature transient and automatic letdown isolation, the crew missed the procedure step to "*Hold Reactor Power constant by transferring load to the condenser steam dumps while reducing Turbine Load. This will prevent inadvertent entry into Mode 2 when the Turbine is tripped.*"

Within 30 seconds of tripping the main turbine, reactor power lowered below 5% and the operators declared MODE 2.

Rapid Rise in T_{avg} and Passive Shutdown

With the condenser steam dumps set to modulate at 1092 psig, upon tripping the turbine there was no steam demand until T_{avg} rose to 557°F (corresponding to a steam pressure of 1092 psig). With the reactor initially around 6% power and with no steam demand, T_{avg} rose rapidly: 1°F within the first 20 seconds, 2.5°F in the first minute, 4°F in the first two minutes, and the full 6.6°F rise (corresponding to 557°F) within five minutes. The sharp insertion of negative reactivity resulting from this temperature rise caused the reactor to passively shut down, as indicated by the Start Up Rate (SUR) data. When the turbine was tripped at 10:12:35, SUR was -0.01 decades per minute (dpm); by 10:18 SUR was -0.16 dpm – a change of 1600%.

(Continued on next page)

As the reactor neared the Non-Fission Heat Rate (1.75% rated reactor power for this shutdown), temperature-reactivity feedback was lost (see Figure 4 on page 20); that is, lowering reactor power would no longer feed back positive reactivity via lowering temperature. Thus, without a manual insertion of positive reactivity, power would continue to lower into the source range.

At 10:13, the ΔT instruments had indicated 5.17% and the Intermediate Range Nuclear Instruments (IRNIs) had indicated 1.52E-5 ion chamber amps (ica). By 10:18, ΔT instruments indicated 2.4% and the IRNIs indicated 2.43E-6 ica. So in the time it took total power (as indicated by core ΔT) to lower to ½ its initial value, fission power (as indicated by IRNI currents) lowered to 1/6 its initial value. This is further indication the fission reaction had shut down and the Non-Fission Heat Rate was raising/maintaining reactor coolant temperature.

Response to the Passive Shutdown

While the reactor was passively shutting down, the operators were performing the off-normal procedure for "Loss of Letdown" (which had been entered at 10:00). At 10:18, a 75 gpm letdown orifice was placed in service and the crew exited the off-normal procedure. By this point (10:18), had they recognized the reactor was shut down, it

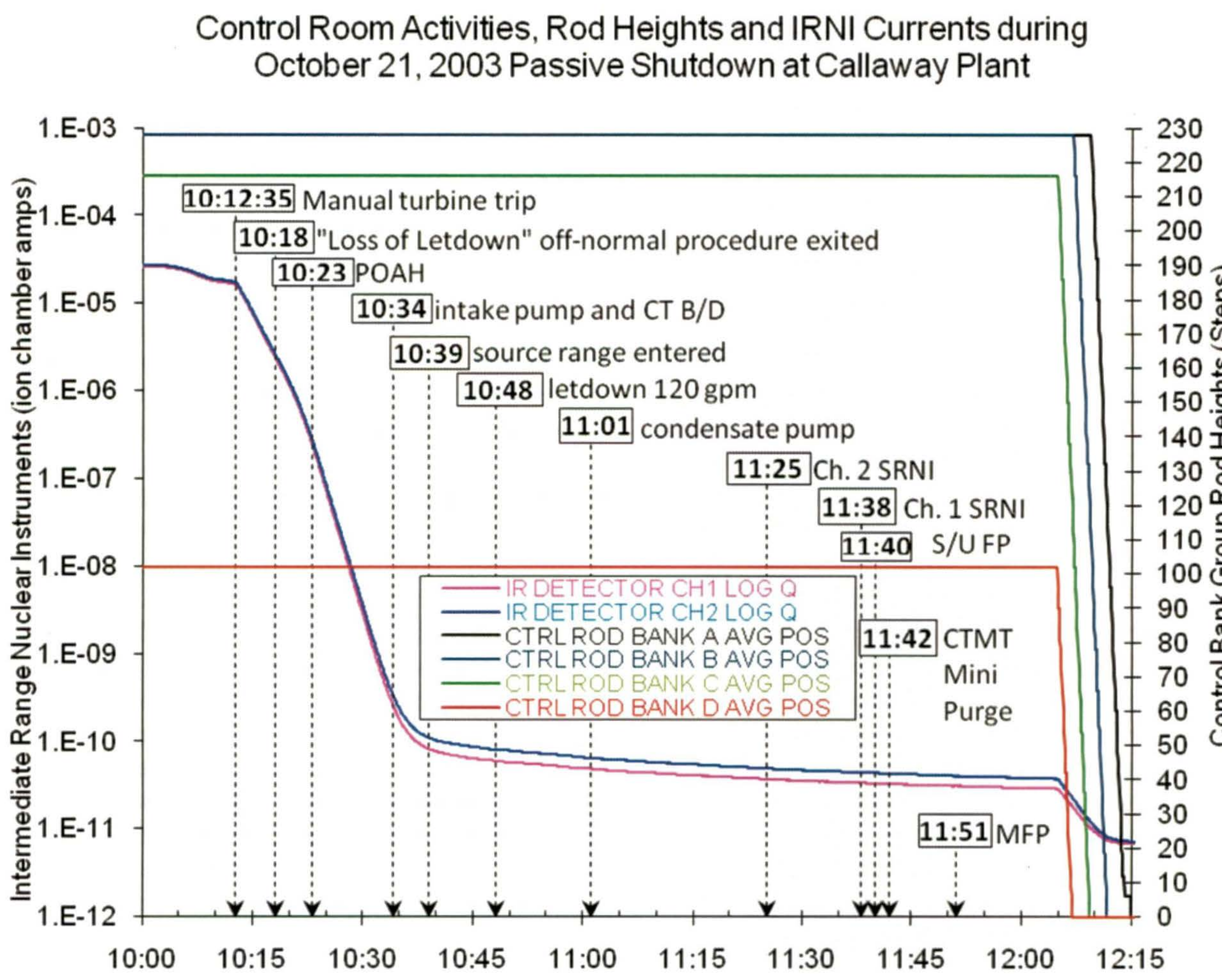

Figure 3: Plot of Control Bank rod heights and Intermediate Range (IRNI) currents on October 21, 2003. The reactor passively shut down shortly after the turbine was manually tripped at 10:13 and reached the source range about 26 minutes later. A nominal -1/3 dpm SUR developed as power fell below the POAH. The slight drop in reactor power from 10:39 to 12:05 was caused by a lowering of subcritical multiplication resulting from the continued buildup of Xenon-135. The operators began inserting the control banks at 12:05 and completed at 12:15.

was already too late to prudently try to recover criticality.

After exiting the off-normal procedure for "Loss of Letdown" the Control Room Supervisor assigned the Reactor Operator the task of raising letdown flow to 120 gpm by placing the 45 gpm orifice in service per the normal operating procedure. It is unclear why this task was prioritized over actively controlling core reactivity (i.e. over inserting the control banks to ensure the reactor remained shutdown). This task involves multiple manipulations of charging system components and took 30 minutes to complete; in comparison, manually driving in the control banks takes 10 minutes.

As reactor power was decaying through five decades of power to reach the source range, licensed Reactor Operators were assigned to place Cooling Tower Blowdown in service and to secure the second of three intake pumps (cooling Tower Blowdown had been secured a couple of hours earlier to support Chemistry surveillances and the intake pump was secured because two pumps were no longer needed due to the forced de-rate causing evaporation rate to lower). These tasks were both logged complete at 10:34. It is unclear why these tasks were prioritized over inserting the control banks.

Operation in the Source Range

At 10:39, reactor power entered the source range, as evident on Figure 3 (page 18) by the IRNI currents stabilizing. As at most reactor plants, the Source Range Nuclear Instruments (SRNIs) at Callaway remain de-energized until bistables on the IRNIs validate reactor power is in the source range. Because the control rods were still at their last critical rod heights, there was more subcritical multiplication than is normally present when these IRNI bistables are calibrated. As a result, the SRNIs did not energize upon initially entering the source range. It took 45 minutes of additional Xenon-135 buildup to lower subcritical multiplication to the point at which the first SRNI channel was able to automatically energize.

At 11:01 a licensed operator was assigned to secure the second of three condensate pumps. It is unclear why, while in the source range with no SRNIs energized and with the control rods still at their last critical rod heights, the licensed operators prioritized manipulation of the condensate system over inserting the control banks.

To some (e.g. this author) the crew's actions indicate that they were unaware the reactor had passively shut down. That is, the most reasonable explanation for the crew "prioritizing" ancillary tasks[12] over deliberate control of the nuclear fission reaction is that for 67 minutes they failed to recognize the reactor had shut down.[13]

At 11:25 the channel 2 SRNI energized. Since a Main Control Board alarm annunciates whenever a SRNI channel energizes, it can be confidently assumed that at 11:25 the crew was aware they were in the source range. At 11:38 the channel 1 SRNI energized. *(Continued on next page)*

[12]For example: placing an extra 45 gpm letdown orifice in service, placing Cooling Tower Blowdown in service, securing unnecessary intake and condensate pumps. Although optimizing water chemistry of the primary plant and cooling tower is important and although minimizing "house" electric loads by securing large and no longer needed pumps is important, these tasks are "ancillary" with regard to the primary focus of the reactor shutdown procedure: inserting the control banks to definitively ensure the reactor is in a shutdown condition and will remain in that state regardless of passive (e.g. xenon decay) or unexpected (e.g. inadvertent dilutions or cooldowns) changes in core reactivity.

[13]It should be noted here that the crew has consistently asserted that prior to manually tripping the turbine they were aware the reactor would passively shut down once steam demand was removed. This assertion amounts to the crew deliberately allowing the reactor to passively shut down while they performed the ancillary items mentioned in note 12. The author of this article believes that, if true, this amounts to incompetence. That is, it is incompetent for an NRC licensed operator to prioritize ancillary tasks over deliberately controlling the reactor, and it is incompetent to deliberately rely on passive measures to shut down the reactor when active means (e.g. rods and boron) are available. Since the US NRC has refused to question the operators' assertions, at this point the question remains unresolved as to whether or not, prior to the SRNIs energizing, the operators were aware the reactor had passively shut down. Although the Institute of Nuclear Power Operations (INPO) is aware of the discrepancies surrounding the October 21, 2003 shutdown, INPO has similarly declined to evaluate the claims made by the operators; since INPO must rely on Ameren to voluntarily report the incident, INPO has stated that it is in no position to conduct its own assessment. For those interested, the claims of the operators are summarized in enclosure 2 to NRC ADAMS document ML110140104 and are analyzed in detail in ADAMS document ML102640674.

At 11:40 a licensed operator placed the motor driven Start Up Feed pump (S/U FP) in service in preparation for securing the second of two turbine driven Main Feed pumps (MFPs). At 11:42 a Reactor Operator initiated a Containment Mini-Purge. At 11:51 the final MFP was secured. It is unclear why these tasks were prioritized over inserting the control banks.

From 12:05 to 12:15 the Reactor Operator inserted the control banks. Control bank insertion was not completed until over two hours after the 4°F temperature spike which caused the passive reactor shutdown.

HUMAN PERFORMANCE ASPECTS

Xenon-135 Cooldown

The temperature transient which significantly contributed to the confusion that resulted in the passive reactor shutdown was a result of the operators failing to account for Xenon-135 when they stopped the turbine downpower at 09:36. Although operators might well understand the physics of Xenon-135, applying this knowledge while conducting a busy forced de-rate and while being distracted by equipment malfunctions is much more difficult than applying this knowledge while taking a Generic Fundamentals Exam. Two possible solutions to aid the operators in adequately assessing xenon are to have readily available Operating Experience (OpE) listed on procedure-specific pre-job brief forms and to require Reactor Engineering to prepare detailed Reactivity Management Plans for forced de-rates.

Challenges of MODE 2-Descending

Due to the degradation of Temperature-Reactivity feedback which occurs in MODE 2-Descending (see Figure 4, below), if there is a need to remain

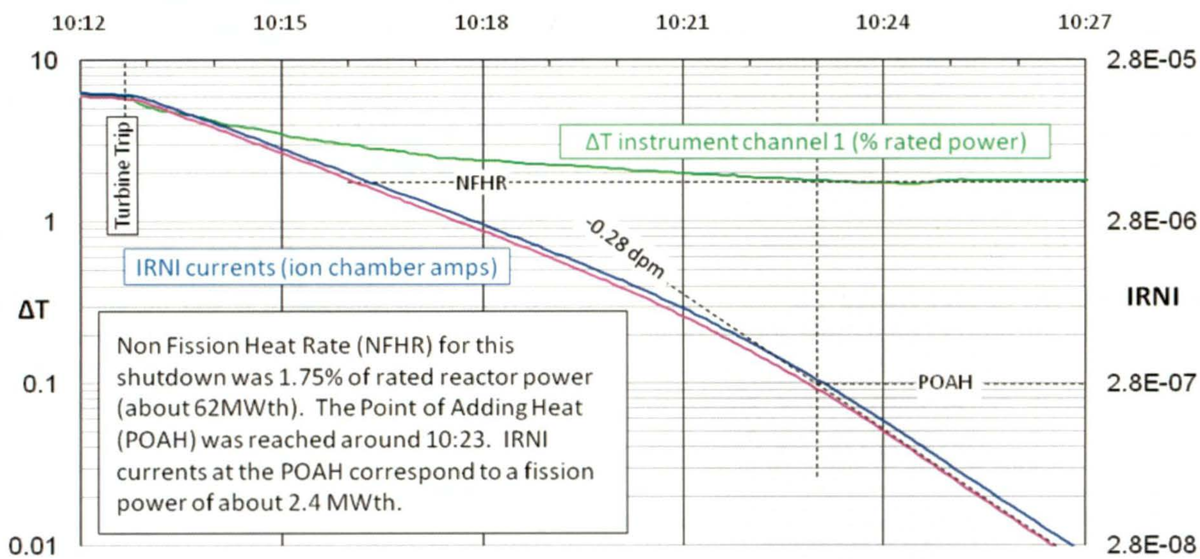

Figure 4: Logarithmic plots of Total Power (as represented by ΔT instrument readings) and fission power (as represented by Intermediate Range Nuclear Instrument currents). Starting around 5% rated reactor power, as fission power lowers exponentially, total power asymptotically approaches the Non-Fission Heat Rate (NFHR). The mismatch between fission power and total power has a strong impact on Temperature-Reactivity feedback causing it to degrade upon entry into MODE 2-Descending and causing it to completely disappear at the Point of Adding Heat (POAH). Although temperature continues to directly affect reactivity as the NFHR is approached, Temperature-Reactivity is lost because falling fission power from a negative reactivity insertion does not immediately affect temperature since non-fission heat sources "buffer" temperature from dramatically lowering.

critical at low powers then the reactor should remain in low MODE 1 (i.e. greater than 5% power).

Because of the Temperature-Reactivity feedback afforded in MODE 1, operators can rely on temperature to passively respond to reactivity changes. Near the Non-Fission Heat Rate (i.e. in MODE 2) the operator must directly respond to reactivity changes (e.g. xenon buildup) with active reactivity manipulations (e.g. rods or boron/water). Whereas it is not very difficult to maintain temperature through the active insertion of reactivity, it can be extremely difficult to actively respond to reactivity changes directly (while at the same time ensuring the reactor neither exceeds 5% power nor drops below the POAH).

In 2007 Callaway Plant's procedures were changed to minimize sustained operations in MODE 2-Descending. On April 13 and 14, 2009 Callaway Plant successfully performed turbine control valve repairs while maintaining the reactor critical in low MODE 1. Based on their past experience with low power operations, it is unlikely that they would have successfully remained critical during the turbine control valve repairs had they attempted these repairs in MODE 2-Descending. By prudently conducting the turbine repairs in MODE 1, Callaway Plant learned from its past mistakes and set its operators up for success.

Recognizing the Passive Shutdown

Although the operators claim otherwise, it appears that for 67 minutes (from 10:18 to 11:25) they failed to realize the reactor was shutdown. Whether or not the operators were aware of the passive shutdown as it was occurring, it is still worth exploring some of the "human factors" pitfalls associated with attempting to maintain MODE 2-Descending.

There are no adequate instruments for indicating fission power when attempting to maintain MODE 2-Descending. Due to decay heat and other non-fission heat sources, both primary calorimetric (e.g. ΔT instruments) and secondary calorimetric instrumentation are poor indicators of fission power in MODE 2. Due to cold-leg shielding and decay gammas, Power Range Nuclear Instruments (PRNIs) do not accurately reflect fission power and will continue to read ~1% rated reactor power even after the reactor has entered the source range.

The only accurate indications of fission power in MODE 2-Descending are the IRNIs; however, these instruments are human factored for conducting reactor startups and not for maintaining MODE 2. Because of the significant range of these instruments (i.e. 10 decades of power) they have substantial calibration errors. These errors have little effect on the operator as long as the operator is using these instruments to detect CHANGES in fission power and not as an absolute measure of fission power. For this reason, these instruments are intentionally scaled in ion chamber amps instead of percent rated power. That is, the calibration errors prevent these instruments from accurately indicating absolute power levels so they were intentionally "human factored" to use units which are not easily converted into percent rated power or into MWth, thus discouraging the operator from using them while attempting to maintain discrete power bands. Attempting to use the IRNIs to maintain a power band from the POAH to 5% is unwise. Furthermore, although recognizing when the Point of Adding Heat has been attained during a power ascension is straight forward, during a downpower it is impossible to recognize the POAH until fission power is substantially below it.

See References 2 and 6 for more details on technical Lessons Learned.

SAFETY AND PI&R CONCERNS

No PI&R effort in 2003

For unknown reasons the passive reactor shutdown was not documented in the plant's corrective action program in 2003. The failure of the crew to document the passive reactor shutdown resulted in the organization failing to perform adequate Problem Identification & Resolution (PI&R). That is, without a condition report documenting either the xenon induced letdown isolation or the inadvertent passive reactor shutdown, the organization was unaware that it had an event which it could analyze for "problems" needing "resolution." The purpose of writing a condition report is not to "turn yourself in for making errors," it is to provide the organization a record of the known (or perceived) facts so that these facts can be analyzed for potential "problems" (e.g. inadequate procedural guidance, operator knowledge weaknesses, unrealistic management expectations, etc.) and these problems can then be analyzed for "resolutions" (e.g. improved guidance).

There are some (e.g. this author) who believe that on October 21, 2003 the crew was "set up for failure." The general operating procedure for conducting the down power and reactor shutdown was poorly structured. The procedure assumed that in order to stop the down power the operators needed to do nothing more than delay continuing in the procedure. The procedure made no recognition that the actions the operators needed to take for "holding" power during a xenon transient were different than the actions needed for "reducing" power. The procedure did not take into account the limitations of the operator's control equipment (i.e. the degradation of Temperature-Reactivity feedback) and monitoring equipment (i.e. affect the NFHR and decay gammas have on total power meters) in MODE 2-Descending. Management expectations were unrealistic; it was unrealistic to expect the crew, with procedural guidance written for a continuous (i.e. "non-segmented") shutdown, to be able to hold power at 10% power during the severe xenon transient which is induced from an aggressive 9 hour downpower at 10%/hour. However, since the October 21, 2003 passive reactor shutdown was not documented until it was accidentally uncovered 40 months after the fact, these gross procedural deficiencies and unrealistic management expectations went uncorrected until 2007.

On June 17, 2005 a similar passive reactor shutdown occurred during a forced de-rate for a failed power supply in an Engineered Safeguards Feature (ESF) cabinet. During this de-rate, the reactor passively shut down due to a 2°F spike in T_{avg} which occurred upon manually tripping the main turbine. The shutdown occurred two minutes prior to the failed power supply being successfully retested and 54 minutes prior to the expiration of the shutdown action of the Technical Specification. That is, since the broken equipment was successfully repaired prior to the planned shutdown time, had the reactor not passively shut down the crew could have immediately returned to power. Instead, resultant delays in returning to power following the inadvertent passive shutdown cost the utility 31 hours of lost generation. Like the 2003 passive shutdown, the 2005 passive shutdown was not documented until it, too, was accidently uncovered in February 2007. Had the October 21, 2003 passive reactor shutdown been evaluated by the utility's Problem Identification & Resolution process, it is likely the 2005 passive reactor shutdown would never have occurred.

Although the inadvertent passive shutdown of a commercial PWR might seem like a commercial concern vice a safety concern, failing to recognize it can readily jeopardize reactor safety. In February 2005, the operators of a reactor in Virginia were attempting to maintain the reactor in MODE 2-Descending while repairs were being conducted on the secondary plant. The reactor passively shut down and the operators failed to notice it. Two hours later, the reactor inadvertently restarted following a manual positive reactivity addition which was conducted by operators who had failed to recognize the reactor had entered the source range. Like the October 2003 passive reactor shutdown at Callaway Plant, the operators failed to document the event. Unlike the Callaway incident, when the incident in Virginia was brought to the attention of plant management, an investigation was performed and the results were reported to the Institute of Nuclear Power Operations and shared with the industry via a Significant Event Notification.

Sharing OpE with INPO

Both the October 21, 2003 and June 17, 2005 passive reactor shutdowns were accidently uncovered in February 2007 during a review of critical parameter data from past shutdowns to support a major revision to the Reactor Shutdown Procedure.

The two shutdowns were documented along with seven other shutdowns in Callaway Action Request 200701278, *Analysis of Past Reactor Shutdowns – RF15 Preparation Concerns*. In their

August 10, 2007 cover letter distributing WANO SOER 07-01, *Reactivity Management*, INPO requested that their member utilities "*provide information on similar occurrences and solutions at their plants*." For unexplained reasons, Ameren determined that neither the October 2003 nor the June 2005 passive reactor shutdowns were worthy of sharing with the industry. Since no INPO SEN concerning the October 2003 passive shutdown has been released since the NRC's issuance of IN 2011-02, it appears that INPO agrees with Ameren's decision that a passive reactor shutdown resulting in a two hour delay in inserting control banks does not meet the threshold for a Significant Event Notification. In the absence of a detailed INPO document on the incident, interested nuclear professionals should review the issue brief released by the Union of Concerned Scientists (see Reference 2).

Informally Relying on Xenon-135

One of the more troubling aspects of the operators' claim that they were consciously aware the reactor had passively shut down is that this claim amounts to informally relying on Xenon-135 to prevent the reactor from inadvertently restarting.

Several times during the downpower, the operators performed a "Xenon Prediction." A Xenon Prediction estimates Xenon-135 levels based on projected power history, and it is used as a tool to assist the operators in maintaining the reactor critical. A Xenon Prediction is very different from a Shutdown Margin Calculation. Although there are times when a Shutdown Margin Calculation will rely on Xenon-135 for Shutdown Margin (SDM), when this is done it is based on actual power history. Another major difference between the two calculations is their uses: a SDM calculation is used to ensure the reactor will not inadvertently return to criticality during postulated positive reactivity additions (e.g. inadvertent dilutions, inadvertent cool downs, etc.) whereas a Xenon Prediction assumes no failures and is used to estimate the amount of negative reactivity which must be overcome to maintain the reactor critical. Since a SDM calculation was not completed on October 21, 2003 until forty minutes after the control banks had been inserted, the crew, for the 106 minutes they claim they knew the reactor was shutdown (10:18 to 12:04) yet were still retaining the rods at their last critical rod heights, inexplicably relied on an informal estimate that Xenon-135 levels were large enough to prevent an inadvertent restart. Following the Shift Technical Advisor's calculation of Shutdown Margin (at 12:49), the crew added over 3600 gallons of boron in order to meet the required SDM.

Since Xenon-135 is a radioactive isotope with a half-life of 9.2 hours, a reactor requiring Xenon-135 to maintain it subcritical will eventually return to power. Although the physics of Iodine-135 and Xenon-135 are well understood, informally relying on estimations when formal calculations are available is contrary to the principles of conservative reactor operation. If there is a commercial reason to rely on Xenon-135 to maintain Shutdown Margin, a formal SDM calculation should be performed and reviewed PRIOR to relying on Xenon-135 to maintain the reactor shut down.

Operating Beyond Procedure Guidance

In 2007 the US NRC investigated the October 21, 2003 passive reactor shutdown. Although they issued non-cited violations (NCVs) for the operators failing to make a log entry documenting operation below the MTCO and for the operators failing to document the passive shutdown with a condition report, the NRC found no problems regarding the two hour delay in the insertion of the control rods. Concerning this delay, the NRC stated, "*The inspector's review of the operating procedures did not find any timeliness guidance on performing the steps to insert the control rods.*"

It is unclear why the NRC inspector expected the Reactor Shutdown procedure to contain "*timeliness guidance on performing the steps to insert the control rods.*" Like the normal (i.e. non-faulted) reactor shutdown procedures at all US commercial reactors, Callaway Plant's Reactor Shutdown procedure contained no provisions for intentionally allowing the reactor to passively shut down. Per the procedure, the only way to shut down the reactor was to manually insert the control banks. Since the procedure inherently assumes it is followed, and since the procedure requires the control banks be manually inserted to effect the shutdown, then it would be nonsensical for the procedure to contain "*timeliness guidance on performing the steps to insert the control rods*." That is, since the reactor is shut down by manually inserting the control banks, it would not make sense for the procedure to dictate a time frame for inserting the control banks FOLLOWING a passive reactor shutdown.

Nonetheless, the NRC has thus far maintained its 2007 position that no violations occurred other than the two NCVs concerning the lack of a log entry and condition report. In Information Notice 2011-02 the NRC specifically avoided addressing whether or not they believed the operators were aware of the passive reactor shutdown prior to the first SRNI channel energizing. [Note: The author of this article was a reviewer for IN 2011-02 and is the owner of the initial block which has a "Non-Concur" in it on the routing page. For those interested, the Non-Concurrence Form, which includes the NRC's response, can be found in the NRC's public ADAMS library as ML110420293.]

Note that it is the opinion of this author it is not a procedure violation to unknowingly allow the reactor to passively shut down. Operating a large commercial PWR at low power during an aggressive xenon transient is not an easy task; combined with the challenges already mentioned above (e.g. loss of Temperature-Reactivity feedback, physical limitations of calorimetric indications of "fission" power near the NFHR, poor procedural guidance, lack of a detailed Reactivity Management Plan, equipment malfunctions) it should not be surprising to any NRC licensed operator that the crew failed to perform flawlessly. Although most operators would like to think that it would never take them 67 minutes to recognize the reactor had shut down, most do recognize that, given the wrong set of circumstances, any operator is capable of making a mistake such as this. It is not a procedure violation to fail to recognize a passive reactor shutdown, it is a human performance error and no more. And it is not a procedure violation to, due to a human performance error, find oneself in circumstances not expected by the procedure. When this occurs, the proper response is to use one's training and experience to place the plant in an analyzed condition (e.g. if the plant has passively shut down, then manually insert the control banks). Note that failing to recognize a passive shutdown as it is occurring is very different from recognizing the reactor is passively shutting down and then intentionally prioritizing other actions above the deliberate control of reactivity.

Whether or not the NRC chooses to address it, intentionally allowing a large commercial reactor plant to passively shut down constitutes a fundamental misunderstanding of the principles of conservative reactor plant operations. As discussed above, US commercial PWRs "want" to be critical and "want" to match steam demand. The inherent passive response of the reactor as xenon decays is to eventually return to criticality and to match steam demand. As soon as it is noted that the reactor has passively shut down, and as long as active means to control the nuclear fission reaction are available, they should be used to ensure the reactor is taken to, and remains in, a shutdown condition.

Loss of Safety Related Instrument Power

During the investigation of the October 21, 2003 passive reactor shutdown, the Shift Manager indicated that the biggest delay in inserting the control banks was the fact that the crew was still performing the off-normal procedure for the "Loss of Safety-Related Instrument Power" which had been entered at 08:21 but was not exited until 11:37. Since all the control room actions were completed by 08:36 (an hour before the temperature transient which led to the passive reactor shutdown), it is unclear exactly how this off normal procedure delayed the insertion of the control banks during the hour following the turbine trip. Nonetheless, for unstated reasons the NRC has decided to take the operators at their word and not question how the performance of this procedure inhibited the insertion of the control banks yet did not inhibit the operators from placing the 45 gpm letdown orifice in service, placing Cooling Tower Blowdown in service, lowering intake flow, or manipulating the feed and condensate systems. Those interested in this topic should consult References 4, 5 and/or 6, cited on page 26.

(Continued on next page)

Operation without SRNIs

The reactor entered the source range at 10:39; yet, no Source Range Nuclear Instrument (SRNI) energized for another 45 minutes (11:25).

Each SRNI at Callaway Plant is powered through a contact on its channel's associated IRNI. This contact automatically closes at 5E-11 ica. Because of the subcritical multiplication afforded by the control banks still being at their last critical rod heights, both channels of IRNIs were reading greater than 5E-11 ica when the reactor first entered the source range. It took 45 minutes of additional Xenon-135 buildup for the channel 2 IRNI to lower below 5E-11 ica and 59 minutes for channel 1.

The SRNIs can also be manually energized once the PRNI signal has lowered below 10% rated reactor power. Had they, prior to 11:25, recognized they were in the source range, the operators could have manually energized either or both SRNIs. The fact that they did not do this is one of many indications to this author that, prior to the SRNIs automatically energizing at 11:25, the operators were unaware they were in the source range[14].

The SRNIs add significant defense in depth during operation in the source range by providing:

- start up rate indication;
- an audible count rate which quickly alerts the operator to rising reactivity;
- a meter indication better suited for monitoring power in the source range than the more broadly ranged IRNI meters;
- an automatic high flux reactor trip which is set about 5 decades earlier than the IRNI high flux trip; and
- a signal to the Boron Dilution and Mitigation System (BDMS) which causes an automatic swap over of charging pump suctions from the Volume Control Tank to the Refueling Water Storage Tank (RWST) in the event that source range counts increase by 70% in a rolling 10 minute period (since the RWST is borated to ~2500 ppm, this BDMS circuit provides protection against inadvertent reactivity additions caused by xenon-135 decay, inadvertent dilutions, and inadvertent cooldowns).

Although the Technical Specifications for Callaway Plant permit operation in the source range with the SRNIs de-energized, this is so a reactor start up can be performed.[15] During a reactor startup, administrative controls[16] are in place which mitigate the loss of safety margin from blocking the automatic safety circuits driven by the SRNIs. The designers of Callaway Plant never intended for the plant to be operated in the source range with the control rods at their critical rod heights and with none of the SRNI driven automatic protections in place. Although the NRC is technically correct in stating that this condition did not violate the plant's licensing requirements, there is more to ensuring reactor safety than enforcing a verbatim interpretation of the Technical Specifications; not all conditions can be exactly defined by the Technical Specifications and a competent professional reactor operator should be able to discern when the plant is in a condition in which the designer never intended.

(Continued on next page)

[14]Note that from 10:23 to 11:25 all indications other than the IRNIs were steadily indicating the plant was low in the power range: the PRNIs were reading ~1% rated power, the ΔT instruments were reading 1.75% power and the secondary calorimetric computer points were reading 62 MWth. In order to realize they were in the source range the operators would have either had to note the IRNI readings or question why they had not needed to add positive reactivity to account for xenon buildup. With regard to noting the IRNI readings, because of their units (ion chamber amps) and their scaling (logarithmic) the operators do not normally use these instruments while at power. With regard to questioning why they had not needed to dilute or pull rods to make up for xenon, understanding the reactor dynamics of Iodine/Xenon was a weakness of this crew as demonstrated by their response to the 9°F temperature drop which occurred from 09:36 to 10:00.

[15]It is impossible to do a successful reactor startup without blocking the SRNI flux trip and BDMS; therefore, once the IRNI signal reaches 1E-10 ica during a reactor startup, the operators are permitted to de-energized the SRNIs (which by then have had all their protective functions blocked).

[16]For example: a Reactor Engineer present in the control room, an Estimated Critical Position has been calculated, the crew is intently performing a procedure which warns them to "expect criticality at any time," etc.

CONCLUSIONS

There is much to be learned from the October 21, 2003 passive shutdown at Callaway Plant. The incident highlights a number of issues: the manner by which NRC licensed operators might fail to appreciate the magnitude of the effect xenon is having on core reactivity while that effect is being masked by power defect, the need for specific and thoughtful procedural guidance for stabilizing the reactor at low power levels following a down-power, the challenge that loss of Temperature-Reactivity feedback poses to the operator as the NFHR is approached, the manner in which an operator focusing on calorimetric instruments while at low power might fail to recognize fission power lowering below the Point of Adding Heat, and the importance of documenting incidents in the corrective action process. For PWR trainers/operators, data from the incident provide practical demonstrations of many of the "generic fundamentals" of reactor dynamics. No analysis of the incident has been done by INPO and the NRC's analysis in Information Notice 2011-02 is not very thorough; those interested in a deeper analysis of the details of the incident are encouraged to review the references at the end of this article.

DISCLAIMER

The views expressed in this article are those of the author and in no way reflect the position of the US Nuclear Regulatory Commission or the Professional Reactor Operator Society.

To participate in an online analysis of this incident, send an email to: RCSOTP_16_ReactivityControl-subscribe@yahoogroups.com (anonymous participation is accommodated).

Anyone wishing additional information on this incident is encouraged to contact me at: LSCriscione@hotmail.com (573) 230-3959

REFERENCES

1. US Nuclear Regulatory Commission, Information Notice 2011-02, *Operator Performance Issues Involving Reactivity Management at Nuclear Power Plants*, January 31, 2011.
2. Union of Concerned Scientists, Issue Brief 20101100, *2003 Segmented Shutdown at Callaway*, November 2010.
3. Non-Concurrence on NRC Information Notice 2011-02, Operator Performance Issues Involving Reactivity Management At Nuclear Power Plants (ADAMS #ML110420293).
4. September 17, 2010 letter from L. Criscione to William Borchardt (ADAMS #ML102640674).
5. April 27, 2010 letter from Lawrence Criscione to William Borchardt (ADAMS #ML101200401).
6. April 30, 2010 letter from Lawrence Criscione to William Borchardt (ADAMS #ML101230100).
7. G2010059/EDATS: OEDO-2010-0775 – Petition Closure Letter to Lawrence S. Criscione Related to Requested Action Under 10CFR 2.206 Regarding October 21, 2003 Event at Callaway Plant, Unit 1 (TAC No. ME4721), ADAMS #ML110140104, January 19, 2011.

Note from the Author

In my opinion, this is an important piece of Operating Experience which is only available through PROS. The event was never submitted to INPO and, although the NRC included it in an Information Notice, most of the significant Lessons Learned from the incident were not addressed. More than anything, the event is an example of: (1) licensed reactor operators being "set up for failure" by impractical operating practices and expectations and (2) the importance of honestly reporting events and accurately analyzing them so that future reactor operators (both at the plant and throughout the industry) do not fall victim to the same poor practices and knowledge gaps.