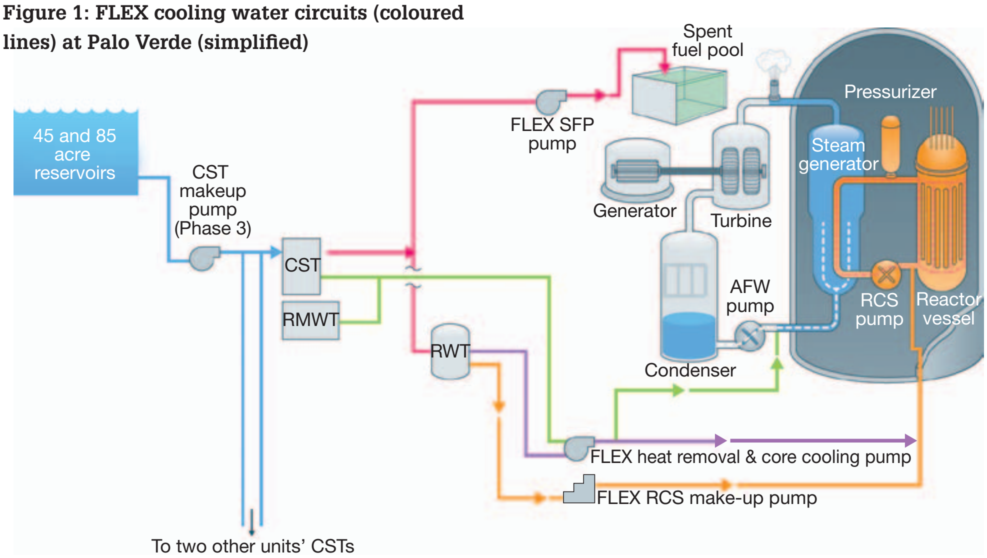
The impact of FLEX on outage risk

Palo Verde has developed a plan for post-Fukushima modifications following US industry guidance. It found these changes generated extra outage safety and performance benefits. By Mike Powell, Kevin Graham and Jeff Taylor

Figure 1: FLEX cooling water circuits (coloured lines) at Palo Verde (simplified)



Following the Fukushima Daiichi accident, the US Nuclear Regulatory Commission (NRC) issued order ES-12-049 [1] requiring nuclear plants in the US to implement mitigation strategies to cope with a beyond-design-basis external event.

The event is assumed to result in an extended loss of all AC power and loss of access to the ultimate heat sink for all units on the site, with no expectation of either returning. The initial phase requires installed equipment and on-site resources to be used to maintain or restore cooling capability for the core, containment and spent fuel pool (SFP). The transition phase requires the use of portable onsite equipment to provide sufficient cooling for these functions. The final phase requires the use of offsite resources to sustain these functions indefinitely.

The US commercial nuclear industry, working through the Nuclear Energy Institute (NEI), developed guidance for flexible and diverse strategies (hereafter referred to as FLEX) that would address the NRC order. NEI 12-06 [2] was developed and discussed with the NRC over several months, and after several drafts and many public meetings, was eventually approved by the NRC as Interim Staff Guidance (JLD-ISG-2012-01) [3] on 29 August 2012. Operating licence holders had to submit an "overall integrated plan" on how they would comply with the NRC order and guidance by 28 February 2013. They were then required to complete full implementation of the order within two refuelling cycles following submittal of their plan, or by 31 December 2016, whichever came first (see also 'Developing the FLEX plan', April 2013, pp. 21-3).

Palo Verde nuclear station is a three-unit site 50 miles west of Phoenix, Arizona, operated by Arizona Public Service Company (APS). All three units are two-loop Combustion Engineering System 80® designs, which are licensed for 60 years and will operate well past 2040. APS must implement the new requirements. Based on the outage schedules, Unit 1 will be the first to achieve full compliance, in the third quarter of 2014, Unit 3 will be compliant in the first quarter of 2015 and Unit 2 will be compliant by third quarter 2015.

APS completed the baseline coping capability in the engineering phase and established conceptual modifications (typical for PWRs) to comply with the FLEX order. To comply with the order and to provide diversity and defence-in-depth, a primary and alternate means of accomplishing each function is needed.

Modifications were made to:

- The auxiliary feedwater system (AFW), to allow for primary and alternate steam generator injection with a FLEX pump (right-hand green line in Figure 1, above)
- The high pressure safety injection (HPSI) system, to allow for primary and alternate reactor coolant system (RCS) makeup with a FLEX pump (yellow line above). If steam generators are not available (for example during an outage) the HPSI modification also would allow the SG injection FLEX pump to inject into the RCS (purple line)
- Two new seismically-qualified pipes (primary and alternate) discharging into the spent fuel pool for makeup with a FLEX pump (red line above)
- The 480V Class 1E load centres, to install primary and alternate FLEX junction boxes to allow for FLEX generator hookup
- The 4160V Class 1E switchgear, to install primary and alternate FLEX connection (disconnects) to allow for FLEX generator hookup
- A variety of tanks to allow suction and refilling of the condensate storage tank (CST) and the refuelling water tank (RWT).

In accordance with NEI 12-06, the FLEX strategies were designed assuming the reactor is at power, but the diverse and flexible approach to the strategies allows them to be implemented in essentially all plant states. While the FLEX strategies were not specifically designed for outage conditions (with the exception of RCS makeup (orange line above), which was designed to support core cooling during an outage), providing multiple connection points does help provide redundancy when installed plant equipment is out of service during an outage.

During at-power conditions, the portable equipment cannot be credited for recovery during the initial phase of the event (which lasts 36 hours at APS). However, during an outage, the FLEX portable equipment can be pre-deployed as long as it is within the allowed out-of-service time of the equipment as defined in NEI 12-06. This approach has been confirmed by an NRC-approved NEI position paper on the use of FLEX equipment in shutdown modes [4].

Using a combination of the FLEX modifications and the pre-deployment allowance, APS has made significant enhancements to reduce the outage risk profile and outage time. The following is a review of some of these approaches.

Palo Verde approach to managing outage risk

At Palo Verde, outage risk is communicated in terms of risk management action level (RMAL). From NUMARC 93-03 [5], risk management is accomplished by defining action levels and using risk management actions. These actions are specific to a given maintenance activity and vary depending on the magnitude and duration of the risk impact, the nature of the activity and other factors.

RMAL is a risk scale that provides a tool for station management to monitor and manage nuclear risk. By law [6] risk assessment must be performed for maintenance activities prior to performing the task. Having a scale is an excellent way for management to evaluate the risk level of the proposed activity in combination with other maintenance activities by reviewing the schedule and changing it if necessary.

The outage scale (shutdown risk) is a qualitative method based on managing safety functions via defence-in-depth. The latter refers to:

- Providing systems, structures and components to back up shutdown safety functions using redundant, alternate or diverse methods
- Scheduling outage activities in a manner that optimises safety system availability
- Providing administrative controls that support or supplement the above elements.

Determination of the RMAL is based solely on the available mitigating equipment. The shutdown RMAL does not convey relative differences in plant risk due to plant operating state and time after shutdown. For example, the plant risk is greater with all mitigating equipment available at lowered pressuriser level then it is with all mitigating equipment available when pressuriser level is normal. But the defence-in-depth model concludes that both plant operating states have the same number of layers of safety.

The safety function RMAL value is based on N+1 criteria, where "N" is the safety-significant control needed to meet the safety function, and colour-coded as follows:

- Green RMAL N+2
- Yellow RMAL N+1
- Orange RMAL N
- Red 0 safety function success paths available

Although "N" meets the safety function, it lacks defence-in-depth and is an undesirable risk level, so it constitutes an orange RMAL. The minimum acceptable defence-in-depth is N+1, and this constitutes a yellow RMAL.

As a general philosophy, the Palo Verde expectation is to maintain green RMAL conditions. If a non-green condition cannot be avoided by rescheduling activities, work that affects the risk shall be completed as quickly as possible.

Spent fuel pool: reducing outage risk

From NUMARC 93-03, the following safety functions must be addressed for shutdown conditions:

- Decay heat removal capability
- Inventory control
- Power availability
- Reactivity control
- Primary and secondary containment issues

When the fuel is off-loaded from the core to the spent fuel pool during an outage, these functions are shifted from the coolant system to the pool. At Palo Verde, the RMAL requirements apply to the spent fuel pool in the following conditions: when the refuel pool and spent fuel pool are connected (the PCNV118 and SFP transfer gate are both open), such as during core off-load or reload; when the core is fully off-loaded to the spent fuel pool; or when the spent fuel pool's heat load is greater than 3.69 MW. In any of these conditions, Palo Verde requires at least N+2 success paths to be available for normal-risk activities, and N+3 success paths for high-risk activities, for the SFP RMAL to be green.

Since the spent fuel pool is one of the three focus areas of the mitigating strategies order, APS has put strategies in place to provide

Figure 2: Phase 3 FLEX pump for Palo Verde

a redundant means of filling it if an event were to occur. Two pathways transfer water from the condensate storage tank through a portable FLEX pump (Figure 1). A review of this FLEX strategy found that pre-deploying the portable FLEX pump during an outage and making the connections adds redundancy to the spent fuel pool makeup system (a critical system during a refuelling outage).

The normal SFP inventory control safety function defence-in-depth is maintained by condensate transfer pumps that take suction from the condensate storage tank. Thus, if there is any work on the tank in an outage both success paths would be lost, and the plant would be in an orange RMAL. Alternatively, the core offloading would need to be delayed until the condensate storage tank work is complete, which adds outage time. Employing the FLEX pumps to draw from an alternate tank and crediting them as success paths allows Palo Verde to remain green while working on the tank without delaying core offload — a significant benefit that is obtained at no additional cost.

In addition to the inventory function, FLEX also adds defence-in-depth to spent fuel pool cooling. At Palo Verde some classic shutdown risks — and others related to design discrepancies — require both spent fuel pool cooling pumps to be available during an outage. Over the past few outages Palo Verde provided temporary power to the cooling pumps to compensate for the loss of availability due to scheduled electrical bus work. Part of the planned FLEX effort will allow Palo Verde to use a portable FLEX 480V generator to "backfeed" either cooling pump, thereby maintaining the safety function. This allows electrical work to be performed during the outage, while maintaining the spent fuel pool RMALs as green, without bringing in additional temporary power.

Figure 3: Revised spent fuel pool cooling electrics

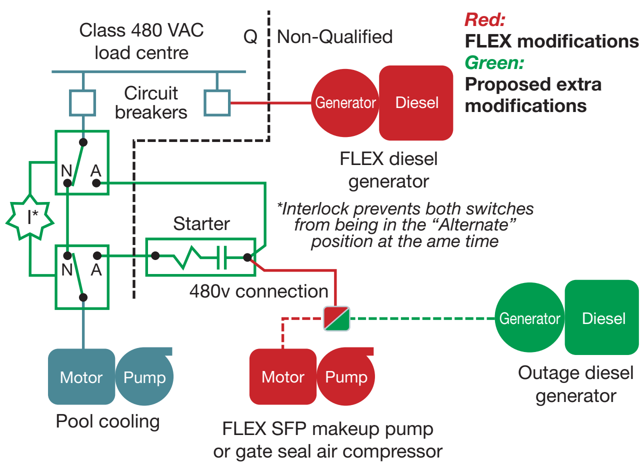
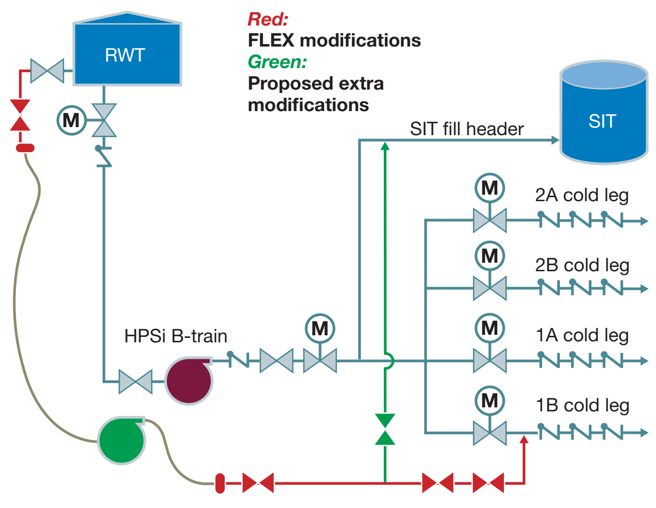


Figure 4: FLEX mods and proposed alternative to fill SIT in outage



Avoiding the use of safety-critical equipment in maintenance

The high-pressure safety injection pump at Palo Verde is a key safety component that is used to provide high-pressure coolant system makeup in the event of an accident. However, this pump is also used during an outage for normal maintenance activities such as refilling the accumulators, also known as safety injection tanks (SIT, see Figure 4, above), as well as providing high pressure for check-valve testing. The original plant design only allows the B-train safety injection pump to perform these activities, and the in-service testing data on the B pump in each unit showed greater wear than the A-train pump. Using the B pump for normal maintenance activities is something that has always been a concern of the plant operations department, so when the FLEX modifications were reviewed by operations and the outage team, several opportunities were identified.

One of the FLEX modifications is the coolant system primary makeup connection. This flow path uses the proposed connections from the existing refuelling water tank (RWT) drain valve through a portable pump connecting, via a Storz fitting, to permanently-installed piping. This ties into the safety injection piping downstream of HPSI injection valves to supply borated water to the RCS (orange line in Figure 1). By adding a connection from the FLEX piping into the safety injection tank fill and drain header, and by pre-deploying the FLEX portable low-pressure/moderate-flow pump, this modification — in conjunction with the pre-deployment of the pump — can now be used to fill the four safety injection tanks during an outage, rather than using the HPSI B pump. The plan is depicted in Figure 4. APS is also considering using a high-pressure FLEX pump in hot standby (at the back end of the outage) as the hydro test pump (instead of the HPSI pump). Not only will these changes eliminate the need to use a safety component for normal maintenance activities, but they will also increase the outage maintenance scheduling window for the B-train HPSI pump.

Improving boration capabilities to reduce outage time

An improvement being considered is adding a portable boric acid storage tank (BAST) as a suction source for the FLEX RCS makeup pump using the primary RCS FLEX injection path. Palo Verde is designed with three positive displacement charging pumps, which are used to borate and maintain RCS inventory during the cooldown at the beginning of the outage. Because of limited flow from the pumps, the initial cooldown is limited to 70° F (21° C) per hour, although the plant technical specifications allow for 100° F per hour. By deploying a FLEX pump at the beginning of the outage for RCS makeup, the full cooldown rate can be utilised, which will reduce the outage duration.

Injecting the higher-concentration borated water from the BAST also reduces the time to reach the refuelling boron requirement of 3,000 ppm specified in core operating limits. Palo Verde has two reactor coolant pumps in service until the specified boron concentration is achieved.

With the current outage plan (charging pumps only) it takes about 19 hours to reach 3,000 ppm boron in the coolant system. In the current outage template, at 13 hours into the outage the station starts the coolant cleanup by injecting hydrogen peroxide into the system to induce a crud burst. Because the pumps are still in service, the crud from the fuel is transported throughout the coolant system and all the water in the system has to be cleaned. If the coolant could be borated to >3,000 ppm prior to the hydrogen peroxide injection, the utility could secure the pumps before injecting hydrogen peroxide and inducing an in-core crud burst, therefore limiting crud mobilisation and reducing the volume of water to be cleaned. Cleanup time is directly proportional to the volume of radioactive water and the purification flow rate, so an in-core crud burst would reduce the amount of time needed to reach the chemistry limit (0.05 microCuries/ml). That reduces dose and allows maintenance windows to open sooner. An earlier start for maintenance improves resource levelling and balancing and, in some cases, could shorten outage duration.

The BAST also provides margin to the back-end hot shutdown refuelling water tank minimum water level requirement. Currently, Palo Verde stores and transfers water from various canals and pits to meet this requirement. There have been outages where the plant was very close to having to batch the tank to achieve minimum level. This involves dissolving boric acid to make borated water in the Chemical Volume and Control System, a time-consuming task that challenges outage duration. The BAST, which is not yet designed but in theory will be about 35,000 gallons, will provide about 5% refuelling water tank margin. APS is working with Westinghouse to design a portable BAST that meets these functions. ■

References

[1] US NRC Order EA-12-049, "Issuance of Order to Modify Licenses with Regard to Requirements for Mitigation Strategies for Beyond-Design-Basis External Events", March 12, 2012. [ADAMS Accession No.: ML 1205A736]

[2] NEI 12-06, Rev. 0, "Diverse and Flexible Coping Strategies (FLEX) Implementation Guide," August 2012.

[3] NRC JLD-ISG-2012-01, Rev. 0, "Compliance with Order EA-12-049, Order Modifying Licenses with Regard to Requirements for Mitigation Strategies for Beyond-Design-Basis External Events," August 2012.

[4] Nuclear Energy Institute (NEI) "Position Paper: Shutdown/ Refueling Modes", September 18, 2013. [ADAMS Accession No.: ML13273A514]

[5] NUMARC 93-03, "Industry Guideline for Monitoring the Effectiveness of Maintenance at Nuclear Power Plants", Revision 4A, April 2011. [ADAMS Accession No.: ML11116A198]

[6] US 10CFR50.65, "Requirements for monitoring the effectiveness of maintenance at nuclear power plants"

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