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SUBJECT: TECHNICAL CONSIDERATIONS FOR REASONABLY ASSURING EMERGENCY CORE COOLING, DECAY HEAT REMOVAL, AND CONTAINMENT SPRAY SYSTEMS OPERABILITY

Overview

Nuclear power plant designers recognized that gas accumulation in the subject systems could cause water hammer, gas binding in pumps, and inadvertent relief valve actuation that may damage pumps, valves, piping, and supports with a resulting loss of system operability. Consequently, these systems are equipped with vents, and some of the subject systems have keep-full systems that are intended to avoid these problems by maintaining them full of water. However, as summarized in NRC Generic Letter (GL) 2007-XX, “Managing Gas Intrusion in Emergency Core Cooling, Decay Heat Removal, and Containment Spray Systems,” the history of gas accumulation in the subject systems has shown that the subject systems, as designed and maintained, have been exposed to gas accumulations sufficient to cause potential or actual loss of operability. This memorandum provides operating experience insights that the NRC staff has gained in its reviews that should be considered in addressing actions that are necessary on a plant-specific basis to comply with applicable regulatory requirements.

The root causes of gas accumulation include poor designs, licensees failing to properly fill and vent the system following drain-down or maintenance, ineffective controls on gas accumulation during operation and, in some cases, unanticipated problems with keep-full systems. System designs allow various means of gas introduction and accumulation.

The objective of gas control measures are to limit the volume of gas accumulation to a quantity that does not jeopardize system operability. An acceptable volume depends on a variety of factors including, but not necessarily limited to, the location, the type of pump, the net positive suction head (NPSH) margin, the gas volume fraction at the pump impeller, and the flow rate. A gas volume downstream of an emergency core cooling system (ECCS) pump that would not cause a loss of system function might cause a pump failure if located upstream of the pump.

This memorandum addresses the following six topics:

(1) sources of gas
(2) gas accumulation locations
(3) determination of gas quantity
(4) water hammer and acceptable gas quantity
(5) pump operation and acceptable gas quantity
(6) control of gas

(1) Sources of Gas

Gas may result from the following:

- leakage from accumulators;
- leakage from the reactor coolant system (RCS);
- outgassing of dissolved gas because of a pressure reduction;
- draining, system realignments, incorrect maintenance procedures, and failure to follow procedures;
- failure of level instruments to indicate correct level;
- leakage through test header valves;
- leakage through faulty vent system components when local pressure is less than the nominal downstream pressure;
- temperatures at or above saturation temperature; and
- vortexing in suction sources or gas introduced from suction sources.

Gas in discharge piping can be an indicator of potential backleakage from high-pressure sources such as accumulators or the RCS, and the gas may have moved into the pumps and the pump suction piping. Such gas may have flowed through multiple closed in-series valves. For this reason, it is important to reassess gas accumulation conditions following system operations and valve manipulations. In addition, many plants have a dozen or more test valves that connect to a common header and provide multiple potential leak paths. For example, the gas accumulation rates at Sequoyah Nuclear Plant were significantly reduced in 2002 by test header valve maintenance and, at Indian Point Energy Center Unit 2, the test header provided a leakage pathway into both high-pressure injection (HPI) lines in January 2005.

Some pressurized-water reactors (PWRs) have experienced gas accumulation due to outgassing in charging pump bypass orifices. Installing multiple-stage orifices (such as 22 orifices in series) essentially eliminated the problem.

(2) Gas Accumulation Locations

Gas can accumulate in the following locations:

- in high points in pipe runs, including elevation variation in nominally horizontal pipes;
- under closed valves;
- in decay heat removal (DHR) system heat exchanger U-tubes;
- in horizontal pipe diameter transitions that introduce traps at the top of the larger pipe;
- in tees where gas in flowing water can pass into a stagnant pipe where it accumulates;
- in valve bonnets
- in pump casings; and
- in piping when the temperature is at or above the saturation temperature.

Some locations, such as tees, horizontal pipes, and valve bonnets are commonly overlooked. Gas accumulation due to separation of liquid and gas at a tee has caused significant problems. In some PWRs, gas accumulates under the isolation valve in the crossover piping between the DHR pump discharge to the suction of the HPI pumps where there are no vents. The crossover piping is especially vulnerable because system testing usually does not involve flow through that location and licensees may not have correctly determined the acceptable gas volume.

Gas accumulation can be exacerbated by failure to adequately determine actual system high points and failure to have vents where gas accumulates. For example, plant isometric drawings often indicate that a length of pipe is horizontal, but an in-plant examination will reveal that the pipe is sloped, sometimes by several inches. This is an important consideration for vent locations and for using ultrasonic testing (UT) to determine gas volume.

(3) Determination of Gas Quantity

The most common methods to determine gas quantity in the subject systems are to measure the volume of gas released through vents or to determine the gas volume by UT.

Hard-piped vents might exhaust at a remote location or into a vent manifold where it is impossible to determine whether any gas was released. Closed systems may have sight glasses for observing bubbles. When the flow rate is adequate to force the gas from the high point down through the vent line to a clean sight glass, and the venting period is long enough for the gas to have traveled through the sight glass, personnel can tell if all gas has been removed. However, it is difficult to accurately determine the volume of gas removed. In some cases, vent flow is passed into a test header with a flow meter, but this method of determining gas quantity has generally been found to be unsatisfactory. Vents consisting of a valve with a removable blind flange immediately downstream of the valve allow the effluent to be observed and are often used in conjunction with other means to determine the vented volume. Procedures should cover venting and post-venting actions.

Several conditions may effect the accuracy of a vented volume determination. In some locations, venting changes the pressure, and a volume estimate based on venting time may therefore be in error because the venting rate is not constant. In some cases, opening and closing or repositioning the throttle valve during venting may affect timing. Gas and water vapor released from the liquid during depressurization may also affect volume determinations. Saturated water vapor will superheat when pressure decreases and will condense if exposed to a temperature below the saturation temperature. Saturated water may boil during venting when pressure is decreased. These conditions may result in a misleading assessment of gas quantity if the behavior is not recognized.

Other methods of determining gas volume are available. UT can provide accurate gas volumes regardless of vent locations. A known volume of water can be injected into an isolated section of piping (or a heat exchanger) and the void can then be calculated from the known pressures and injected volume. Another method is to record DHR system flow rate behavior immediately following pump start to estimate gas volume in the DHR system discharge piping. NRC Special Inspection Report 50-400/02-06 stated that this method is useful in determining whether the DHR heat exchangers are void free. This has been used at Sequoyah. When a DHR pump was started for testing with the DHR system configured for injection into the RCS, the flow rate indicated on a local gauge immediately downstream of the DHR pump should increase approximately linearly for the first 8 seconds as the minimum flow line flow control valve opens and should then level off at approximately 550 gallons per minute (gpm) if there is no gas volume downstream of the pump. In this case, there is no actual injection since the RCS pressure is higher than the DHR system pump discharge pressure and the flow is through the minimum flow line. With gas present, the flow rate typically increases more rapidly to a value greater than approximately 550 gpm and then decreases to approximately 550 gpm within roughly 20 seconds.

(4) Water Hammer and Acceptable Gas Quantity

A principal water-hammer concern is the sudden pressure increase in the pump discharge piping and associated components when systems are put into service. Another concern is pressurization of the DHR system when it is initially connected to the RCS when the RCS pressure is near the DHR system relief valve set pressure. A small pressure perturbation because of a minor water hammer can open DHR system relief valves, which then might fail to close. The relief valve reseating pressure could be less than the RCS pressure, which complicates recovery. Therefore, it is particularly important to initiate DHR system operation by a process that minimizes the potential to cause a pressure pulse. However, application of such techniques must be carefully considered if used for performing surveillances to assess operability. During testing, any proceduralized deviation from normal system operation must be evaluated for the potential to cause unacceptable preconditioning. If the ECCS must start and operate under accident conditions without benefit of pressure-pulse-reducing techniques, then it should be tested in a manner that demonstrates it is capable of doing so without those techniques.

(5) Pump Operation and Acceptable Gas Quantity

The amount of gas that can be ingested without a significant impact on pump operability and reliability is not well established. It is known to depend on pump design, gas dispersion, and flow rate. The presence of gas is undesirable because gas may initiate a long-term failure mechanism such as shaft fatigue, wear ring degradation, bearing wear, or seal wear. Unfortunately, a no-gas condition cannot be assured in practice, and the operational goal should be to minimize the amount of gas consistent with the requirement that operability must be reasonably assured.

A single-stage pump, such as a DHR system pump with significant clearances between moving parts, can often withstand a large slug of gas that completely stops flow, and the pump may be restored to operation when the gas is removed. However, in some cases, physical pump failure has occurred after ingesting gas. A similar condition with a multistage pump that has close tolerances between moving parts, such as the multi-stage pumps used in the ECCS, will likely cause permanent damage.

All pumps will exhibit a loss of developed head when exposed to gas at the pump impeller. The following general conclusions appear reasonable for single-stage pumps that are operating at close to rated flow rate:

- Less than about 0.5 to 1 percent gas by volume at the impeller does not have a significant effect on pump head.
- Pump head may be degraded with 1 to 2 percent gas by volume.
- Some pumps will fail to provide significant head at 5 percent gas by volume.
- Most pumps will fail to provide significant head at 10 percent gas by volume.

However, these percentages are a function of flow rate. With respect to developed head, NUREG/CR-2792[1] states that expert opinions on the level of gas ingestion giving negligible degradation ranged from 1 to 3 percent. These experts generally agreed that for flow rates less than 50 percent at best efficiency, the presence of gas might cause gas binding that would not occur at full flow in some pump designs. The experts apparently agreed that gas in the suction lines increased NPSH requirements, but no quantitative data were found. NUREG/CR-2792 also identified a problem that does not appear to be widely recognized. At reduced flow rates with gas ingestion rates that are not normally a problem, gas can accumulate with time and the pump can eventually become gas bound. According to NUREG/CR-2792, this is possible with less than 2 percent gas by volume at low flow rates. Gas binding because of this effect is a potential concern since ECCS pumps are often operated at low flow rates when the gas volume passing through the pump may be at a maximum.

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[1] Kamath, P. S., et al., "An Assessment of Residual Heat Removal and Containment Spray Pump Performance Under Air and Debris Ingesting Conditions," Creare, Inc., NUREG/CR-2792.

There is some evidence that a multistage pump can tolerate a higher fraction of incoming gas than a single-stage pump without completely losing developed head. This characteristic is attributed to compression of the gas in the early stages so that later stages are exposed to a lower void fraction and consequently continue to develop head. However, this is only true if the flow rate remains a substantial fraction of the best-efficiency flow rate. A significantly reduced flow rate may result in pump damage that makes the pump non-functional. For example, in large break loss-of-coolant accidents (LOCAs) where there is little backpressure, the high-pressure ECCS pumps may continue to function with a substantial void fraction at the first stage impeller, but the high backpressure associated with small LOCAs could cause pump damage at the same void fraction.

There is concern that more than 5 percent gas passing through a multistage pump may result in impeller load imbalance that could bend the shaft or initiate shaft cracks, although this did not occur in tests conducted by Palo Verde Nuclear Generating Station in 2004, where flow rates remained high. If such damage occurred, it is not clear how long the pump would continue to operate. Moreover, such damage may not be evident from developed head tests or pump vibration observation. On the other hand, a few cubic feet of finely dispersed 2 percent gas by volume, although undesirable in a multistage pump, would probably not cause immediately evident pump damage if the exposure time was short, pump flow rate remained high, and the exposure did not occur repeatedly.

These considerations lead to the conclusion that the commonly used limit of 5 percent gas into a multi-stage pump is reasonable only if a substantial flow rate can be assured. For low flow rates, it may be a nonconservative limit.

(6) Control of Gas

Venting for a fixed time at what are perceived as local high points is often performed to satisfy TS (surveillance requirements) SRs to assure that gas accumulation in the ECCS and DHR system will not jeopardize operation. However, the SR is intended to reasonably assure that gas will not accumulate in sufficient quantity to jeopardize operability before the next surveillance, and the vented volume should be consistent with that extrapolation. Since TSs do not explicitly describe the venting process and a standard does not exist, the effectiveness of venting is indeterminate in many circumstances. Venting is sometimes performed where the effluent cannot be directly observed. The venting times are sometimes specified, but they may be too short for an unexpectedly large gas accumulation. In such cases, effective corrective actions may include modifying vents to accommodate direct observation and to provide procedures keyed to the observed venting results.

Some licensees fail to record observations or to follow up when venting indicates a potential gas concern. This may be due to inadequate procedures. The failure to follow up on this condition reflects a lack of appreciation of the potential consequence of operating the system with excessive gas present. Further, it may not provide reasonable assurance that the system will remain operable until the next surveillance. As mentioned earlier, damage can result from system operation with excessive gas. That damage may only reveal itself upon further testing or analysis, or during an actual demand. Similar considerations apply to UT measurements of gas volume where, for example, the NRC staff has observed testing methods that were conducted without applicable procedures.

High points do not always have installed vents, and vents in long, nominally horizontal pipes might not be completely effective in eliminating gas. Licensees have also found vents that were supposed to be installed at a high point but were actually installed at a different location. Where high points are not vented, the important questions are whether the licensee is aware of the potential problems and whether the licensee's controls and practices sufficiently reflect this awareness. For example, where vents are not installed at high points, UT measurements can provide an excellent check for gas, and a high flow rate may be useful to assure gas has been swept from high points.

Hydrogen is sometimes vented and ignition may be a concern if the area to which the hydrogen is vented is small and not well ventilated. The source of the gas to be vented should be determined and, if the gas is hydrogen, steps to monitor and control the effluent should be considered.

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