May 9, 2013

MEMORANDUM TO: Christopher P. Jackson, Chief
Reactor Systems Branch
Division of Safety Systems
Office of Nuclear Reactor Regulation

FROM: Warren C. Lyon, Sr. Reactor Systems Engineer ***/RA/***
Reactor Systems Branch
Division of Safety Systems
Office of Nuclear Reactor Regulation

SUBJECT: MEETING MINUTES COVERING THE APRIL 18, 2013 CLOSED MEETING TO DISCUSS GAS INTRUSION DUE TO VORTEXING

LOCATION: Westinghouse Rockville Office
12300 Twinbrook Pkwy
Rockville, MD 20852

SUMMARY

The subject meeting was held as announced in the Agencywide Documents Access and Management System (ADAMS) Accession No. ML13098A046. Technical discussions covered the preliminary Nuclear Regulatory Commission (NRC) staff approach to treatment of vortexing and industry expert information. The principal conclusions from the meeting were:

(1) The NRC preference of no incipient vortexing to reasonably ensure that systems that are important to safety in currently licensed nuclear power plants is overly conservative and cannot always be achieved without impractical hardware modifications. For example, industry representatives provided information to illustrate where the reactor coolant system water level required to support residual heat removal operation would potentially prevent maintenance and the water available in tanks would not be sufficient to support operation with recirculation from containment emergency sumps. Discussion then focused on how potential vortexing could be addressed while reasonably ensuring system operability and while consistent with the current licensing bases. Warren Lyon (NRC) committed to examine the new information with the objective of achieving an approach to vortexing that addresses the identified concerns while satisfying NRC safety requirements.

(2) Industry participants committed to examine existing test information with the objective of providing as much information to the NRC as possible without releasing proprietary information. Information that could be released would be provided as a follow up to the meeting.

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301-415-2897

(3) All participants agreed that the meeting was valuable as a step to closing the long-standing issue where licensees and NRC inspectors used various, sometimes contradictory, approaches to addressing vortexing issues.

DISCUSSION[1]

The following summarizes the meeting presentations and discussions:

(1) Amber Vincent, Westinghouse Office - Westinghouse Office Safety Brief

(2) Introductions – Each participant identified her / his affiliation and background.

(3) Meeting Kick-off– Warren Lyon / Anderson Lin

- NRC – Warren Lyon

The NRC is working on a NUREG that covers vortexing that, when a draft is completed and reviewed within NRC, will be issued for public comment prior to finalization. The public comment period will probably be 90 days. The NRC desirable outcome from this meeting is to obtain data that is accessible to the industry as a result of plant specific testing which can be used to strengthen the NUREG basis. The data can be submitted to NRC via such means as an email to Warren Lyon who will place the email in a publically available section of ADAMS. If the source of the data is not to be identified because, for example, the source may reveal sensitive plant-specific information, it can be provided to Anderson Lin who will transmit it to Warren Lyon without revealing the source.

- Industry – Anderson Lin

Based on concerns from the draft NUREG, the meeting will be divided into two sections:

a. Mid-Loop[2]
   i. Pacific Gas and Electric mid-loop event
   ii. Westinghouse Owners Group (WOG) mid-loop test
   iii. Palo Verde mid-loop tests at Arizona State University (ASU)
   iv. Dominion tests of switchover from injection to cold leg recirculation
   v. Open discussion

b. Tank vortex testing
   i. Alden Research Laboratory (ARL) discussion of vortexing criteria
   ii. ARL presentation of summary of tank tests

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[1] Extensive notes were provided by Steve Swantner and are used in the Discussion.
[2] Mid-loop is defined as operation when the water level in a pressurized water reactor hot leg is below the top of the hot leg where it joins the reactor vessel.

(4) Anderson Lin - Loss of Core Cooling During RCS Mid-Loop on April 10, 1987, that Resulted in Residual Heat Removal Pump Cavitation

- Residual heat removal system (RHRS) common suction line contains inverted loop seal which rises above mid-loop (loop centerline is 107' plant elevation; and bottom of RHR pipe internal diameter at top of inverted loop seal is 106'-11")
- RHRS was initially operating at 3000 gpm (Froude number = 1) and reactor coolant system (RCS) level was between 107'-0" and 107'-8"
- An RCS drain valve was inadvertently opened (2043)
- RHR pump (RHRP) 2-2 started cavitating and was isolated
- RHRP 2-1 was started and also cavitated (2123)
- RHRP venting initiated
- Diagnosis of Event
    - o RCS started boiling
    - o RCS water level dropped to 106'-6" (inverted loop seal was drained)
    - o RHR pump operation drained suction pipe between the loop seal and pump suction
    - o Loss of RHR was due to this piping layout issue, and was not directly related to a vortex issue

- There are practical operating concerns that may preclude limiting the RHR flow to a value that would preclude air entrainment
    - o Boron dilution (minimum flow for mixing)
    - o Core differential temperature (ΔT) mechanical design limits
    - o RHRS flow throttle valve cavitation limits

(5) Steve Swantner - WOG Pressurized Water Reactor RHR Operating Limits

- Testing conducted in 1987 as part of WOG investigations
- Results documented in Westinghouse document WCAP-11916
- Geometric scale was 7:29 set by model of hot leg
- Same geometric scale was used to scale RHR intake pipe
- Four off-take angles tested: 0°, 45°, 60°, and 90°
- Three RHR off-take to RCS hot leg diameter ratios: 0.18, 0.32 and 0.39
- Conductivity based void fraction meter used to measure air ingestion
- Vortex formation and subsequent air ingestion was very sporadic
- Critical submergence was established such that average air ingestion rate during test was 1% by volume and maximum instantaneous air ingestion rate was 3% by volume
- Relevant dimensionless parameters:
    - o s/d (Ratio of critical submergence to RHR off-take diameter)
    - o Froude number based on RHR intake pipe diameter (d) and flow velocity

- Critical submergence was measured relative to top of RHR nozzle flow area at the connection to the hot leg

- s/d was correlated as a function of Froude number
    - Power Law relation was best fit, s/d = $a\,Fr^{b}$
- Correlation was validated with in-situ test at Seabrook
- Seabrook RCS levels were measured at both active and inactive cross-over legs
- Level in active hot leg at RHR nozzle would be lower than either level as measured at active or inactive cross-over leg
- RHR pump noise was used as the criterion to stop test
- Operating experience indicates that pump noise occurs prior to suction pressure fluctuations or pump motor current oscillations
- Plant was able to operate at or below WCAP-11916 limits

(6) Steve Swantner for Jeff Brown – Palo Verde Nuclear Generation Station Test Program to Address Gas Entrainment in Side-branching Pipes from a Common Header

- Preliminary test data demonstrates the conservatisms associated with WCAP 11916
- A scaled flow loop (3:1) was constructed from Palo Verde Nuclear Generation Station (PVNGS) geometry
- Testing and selection of flow conditions based on Froude Number scaling
- Void fraction limited to 2% and was determined by time averaged impedance measurements
- Three branch line orientations tested (0^{o}, 45^{o}, 90^{o} from horizontal)
- Three off-take to header diameter ratios tested (0.250, 0.4375, 0.750)
- Test data for 0.25 aspect ratio and 45° off-take angle matched (or was below) WCAP-11916 correlation for 45° off-take with aspect ratio between 0.32 and 0.39
    - The WCAP-11916 correlation for an aspect ratio of 0.18 at 45° requires significantly more submergence that the correlation for 0.32 and 0.39
    - This indicates the actual change is somewhere between 0.25 and 0.18
    - This is significant since some plants have an aspect ratio of ~ 0.24 with an angle of 45°
- Test data for 0.4375 aspect ratio and 0° off-take angle requires less submergence than the WCAP-11916 correlation for 0° off-take
- Test data for 0.4375 aspect ratio and 45° off-take angle requires less submergence than the WCAP-11916 correlation for 45° off-take with aspect ratio between 0.32 and 0.39
- Test data for 0.4375 aspect ratio and 90° off-take angle is consistent with the WCAP-11916 correlation for 90° off-take with aspect ratio between 0.32 and 0.39
- Allowing for differences in the aspect ratios established in WCAP 11916, these results suggest that the WCAP correlations are reasonable and conservative

(7) Ed Shore - Kewaunee Gas Intrusion

- Event summary: 7700 cubic inches of air trapped in safety injection (SI) pipe
- Dominion tried to model using Purdue test, waterfall method, vortex models, and NRC Temporary Instruction (TI)-2525/177 methods
- Models were not successful since Froude number was very low (~0.3)
- Plant isolates one SI pump at 37% refueling water storage tank (RWST) level and the second at 4% level
- At lower flow rates (Froude number < 0.1) more significant transport occurred near end of test as the void expanded into downcomers
- Gas traps in the system can significantly reduce transport; a significant portion of the transported gas was trapped in a vertical off-take in the downstream piping
- Purdue methods provided conservative results for high flow rate tests
- Waterfall and vortex combined analytical results were relatively close to test results at design flow, but it doesn't appear that either of these phenomenon duplicated the observed condition
- The limiting case for gas transport was at neither extreme of tested flow rates but occurred somewhere in the middle
- Due to short lengths of pipe, flow was never fully developed
- Downcomer incline appeared to result in a significant level of swirl
- Downcomer water volume/level during expansion was lowest at lower flow rates and highest at high flow rate

(8) Stuart Cain - ARL presentation of Pipeline Air Entrainment Study

- Air entrainment in auxiliary feedwater system at highpoint in pump suction was studied
- Flow rate varied from 7600 l/m to 60,500 l/m
- A full scale model was built
- Since the pipe size was large (36 inches) view ports were used to monitor air movement
- Transported air was extracted in accumulator prior to flow discharge
- Portion of air was transported under transient conditions

(9) Anderson Lin - Wrap up of morning session

- WCAP-11916 has been used for 25 years
- Pressurized Water Reactor Owners Group has made training videos available
- Plant tests and other tests indicate WCAP data are conservative
- Therefore, adequate tools are available
- Recommend that NUREG endorse existing WCAP rather than propose new correlation

(10) Actions from morning session

- Will Westinghouse release training videos to public domain?
- Will Arizona Power Service release ASU test data?
- Will Dominion release Kewaunee information?

(11) Anderson Lin - Tank Vortexing

- Volume control tank (VCT) to RWST
  - o Increasing VCT level would limit surge capacity of tank and gas absorption functions of VCT
  - o Therefore, it is not feasible to increase water volume for operating reasons
  - o Pump Roadmap Report results indicate charging pumps are tolerant to small gas volumetric rates

- RWST to Sump
  - o RWST is credited for accident analysis and sump screen submergence
  - o RWST has large cross-sectional area
  - o Imposing a large (9') minimum submergence makes a large amount of water unavailable
  - o Therefore, it is not feasible to accommodate this type of submergence

- What air ingestion is acceptable?
  - o 0%, 1%, 2%?

- NRC clarification – Warren clarified that he agrees increasing the critical submergence level to 9' may not be practical, but the 9' criterion was to be used as a preliminary check that would indicate that further consideration of vortexing effects was not necessary. It was not a criterion that had to be met. Further, incorporation of a vortex suppression device may eliminate the concern.

(12) Andy Johansson - Vortexing and Air Withdrawal Evaluations for Storage Tanks using Physical Hydraulic Model studies

- Computational fluid dynamics modeling cannot be used and cannot deal with sporadic nature of vortex formation
- Bubble size and rise velocity are scalable but are prototypic, therefore initiation and extent of air bubble withdrawal into the suction nozzle from jet impingement is not conservative in model.
- Tanks tested with several different types of outlets
  - o horizontal,
  - o vertical,
  - o outlet flush with tank wall,
  - o outlet pipe penetrates tank wall (re-entrant),
    - ▪ entrance is straight pipe
    - ▪ entrance is angled downwards (elbow and miter)
  - o with and without vortex suppressors

- All tests were transient; that is the tank drawdown rate was modeled

- Some of the tests incorporated return flow to the tank
- Some of the tests had multiple outlets
- In general each configuration was tested over a range of flow rates
- The data was from about 20 separate tests representing different customers and applications
- Vortices were categorized as types 1-6 (See Figure 1)
- Critical submergence is defined as types 5 or 6 (i.e., air ingestion)
- Critical submergence is defined as distance above the outlet centerline
- Three figures were presented which compared the test data (s/d as function of Froude Number, Fr) with three common correlations
    - Harleman Equation
        - $\frac{s}{d} = \sqrt{\frac{Fr}{2.05}}$
    - Reddy-Pickford (RP) Equation
        - $\frac{s}{d} = 1.5 + Fr$
    - Hydraulic Institute (HI) Equation
        - $\frac{s}{d} = 1 + 2.3Fr$
- The first figure[3] depicted data from tests without return flow to the tank
- The second figure depicted data from tests with return flow to the tank
- The third figure was both sets of data
- Observations
    - All data falls below HI correlation
    - All but a few data points fall below the RP correlation
    - Tanks without return flow are near Harleman Equation
        - Harleman Equation is conservative for Fr $\geq$ 2
        - Harleman Equation best estimate equation for Fr $\geq$ 1
        - Harleman Equation appears non-conservative for Fr < 1
        - All test data were bounded by s/d = 2
    - Tanks with return flow lie between Harleman and Reddy Pickford
- Comments from presenter relative to results
    - Tanks draw down much more rapidly than the reservoirs used to develop the HI correlation. Longer times allow flow patterns to set up which can contribute to vortex formation. This may be why HI requires such a high submergence
    - In general, it is not possible to state whether return flow will increase or decrease the required submergence; this depends on several factors, such as the angle of return, the height of the return, its location relative to the outlet, etc.
    - Caution should be exercised when viewing results for Fr > 2 as all of the data came from one configuration

[3] The figures were not retained by NRC and are not provided in these meeting minutes.

- Questions raised by Figures
  - The Harleman equation was developed for a vertical outlet; therefore, the submergence would be defined as water level above outlet; if this definition was adopted, would the Harleman equation become conservative, or at least conservative in all cases for Fr $\geq$ 0.5 or 1.0?

Enclosures:
1. List of Attendees
2. Warren Lyon (NRC) Presentation

cc w/encls: Attendees
Sheldon Stuchell
Jonathan Rowley

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ADAMS Accession No. ML13129A089

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DATE	05/09/2013

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Attendance at April 18, 2013 Vortex Meeting

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Joshua Miller	NRC	301-415-8398	Joshua.miller@nrc.gov
Participants by telephone			
Chris Brenner	Exelon		
Kent Frederick	First Energy		
Jeff Brown	Arizona Public Service		

Enclosure 1

WARREN LYON PRESENTATION

Overview of Vortex NUREG and NRC's Objective for this Meeting

- Objective: Obtain information to support a NUREG that is as informative and complete as is practical.
- Information that is included in the NUREG must be publically available.
- Information to be considered for inclusion in the NUREG can be included in publically available meeting minutes or emailed to warren.lyon@nrc.gov who will place the email and attachments in publically available section of ADAMS.
- We can discuss proprietary information but we cannot retain it unless accompanied by an affidavit. Such information may be useful to ensure the NUREG is accurate.

NUREG Status

- 75 page draft. Will be provided for review before final is issued.
- Does not include identified test information that has not been provided to NRC as publically available.
- Has not been independently assessed.
- Addresses vortexing in PWR hot leg to RHR connections, tanks, and sumps.
- Does not include vortexing at other locations such as at tees or elbows in headers for lack of data.

Vorticies

- The vortex of concern is generally a hydraulic phenomenon that is observed in the vicinity of an exit pipe from a source that has a larger hydraulic diameter such as a larger pipe, a tank, or a sump.
- Vortex types can range from a surface dimple to a full air core into the exit pipe.
- Vortex behavior may be intermittent. Operation may continue for minutes without a vortex and then one may form.
- Vortex behavior may be affected by upstream conditions. Small changes in upstream hardware or flow perturbations may affect vortex behavior.

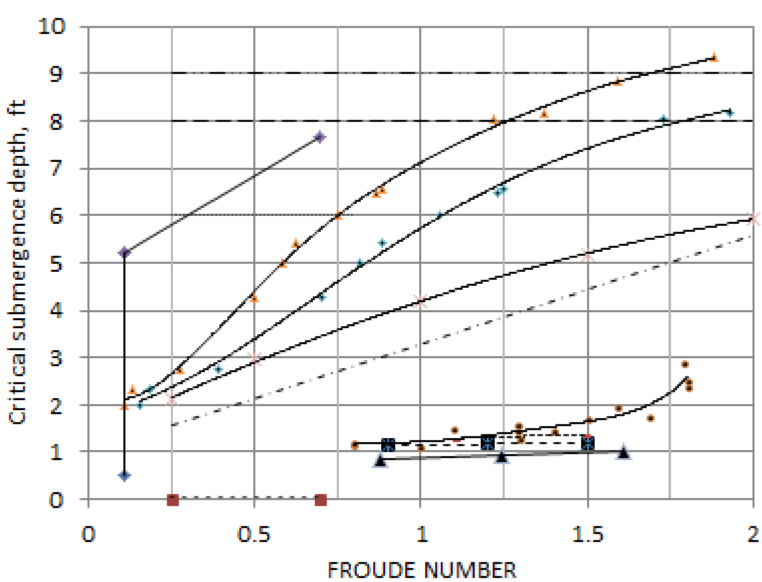
Vortices (continued)

- We have found no theoretical treatments that predict vortex behavior that are acceptable for nuclear power plant analysis.
- All vortex predictions must be based on acceptable tests.
- Many tests provide the minimum allowable level to prevent a vortex concern based on allowing air into the exit pipe.
- We presently require no vortexing of any kind and no gas into the exit pipe unless acceptable justification for different criteria is provided.

Present NRC confirmatory criteria

- Not a concern if water depth above an exit pipe is greater than 9 feet.
- Not a concern if exit Froude number ≤ 0.25 and water depth is at least one exit pipe diameter above exit pipe flow area.
- Have developed correlation to predict PWR hot leg water level that reasonably ensures vortexing will not occur at RHR pipe connection.

Critical submergence summary (from draft NUREG that summarizes configurations where data were found)



NRC confirmatory PWR Hot Leg Vortex Correlation

$$H/D = a\,N_{FR} + b$$

H = distance from top of RHR pipe flow area where it is attached to hot leg to water level, D = RHR pipe diameter, N_{FR} = Froude number = $V / (D\,g)^{1/2}$, V = *liquid velocity based on* $\pi D^2 / 4$*, g = gravitational constant*

Plant	*a*	*b*
W 4-loop	0.478	0.086
Prairie Island, Kewaunee	0.255	1.98
Point Beach	0.478	0.212
Ginna	0.528	1.201
Others, bottom (90º) hot leg connection	0.528	1.021
Others, 60º hot leg connection	0.472	0.349

Comparison of NRC Equation to Data Including 45 Degree Plant Data From WCAP-11916 Rev 0 (ML12006A164)