How Nuclear Plant Operators Are Evaluating the Potential for Vortex Formation and Air Entrainment in Water Storage Tanks

Andrew Johansson & Mahadevan Padmanabhan, PhD, PE, Alden Research Laboratory

Introduction

Over the past several years many US Nuclear Power Stations have been required to take corrective action to address the potential for air entrainment due to vortex formation associated with flow withdrawal from certain types of water storage tanks. The corrective actions were required to address issues identified during Nuclear Regulatory Commission (NRC) safety system design and performance capability inspections (see sidebar). Tanks of interest are typically associated with a critical component of the emergency core cooling system (ECCS) and can include, but are not limited to, Refueling Water Storage Tanks (RWSTs), Borated Water Storage Tanks (BWSTs), Reactor Core Isolation Cooling (RCIC) Tanks and Condensate Storage Tanks (CSTs). NRC inspection activities have identified several instances in which tank vortex allowances were not properly considered, or were based on an inappropriate vortex methodology.

Generic flow modeling studies[i] addressing vortexing and air entrainment in pump suction lines have been utilized to develop empirical equations to estimate submergence requirements, minimizing the potential for air-drawing vortices. These studies consider a wide variety of tank geometries and suction configurations operating under steady conditions (flow and submergence). It is well known and documented, however, that site-specific geometry of the suction pipe, including floor and wall clearances, approach flow patterns and transient (dropping water levels) conditions, have a profound influence on vortex formation. As such, it is difficult to reliably and defensibly apply the data available in the literature to each specific installation and associated set of operating conditions.

While numerical modeling techniques, such as Computational Fluid Dynamics (CFD,) can be used to study many flow related problems, they are unable to address air entrainment in storage tanks. CFD can predict the flow patterns within thermal hydraulic structures and typically offer the advantage that the geometry can be quickly modified to study design modifications. It is not yet capable, however, of reliably predicting the persistence and strength of free surface vortices (their unsteadiness and whether they are air-drawing or not) and quantifying the volume of air entrainment. Determining the potential for air entrainment due to vortex formation requires a physical hydraulic model. The accuracy of this method for pump intake structures is well documented and widely accepted[ii,iii,iv].

Physical Hydraulic Modeling and Air Entrainment

For site-specific applications under regulatory scrutiny, physical hydraulic models are useful tools to evaluate the potential for air entrainment due to vortex formation over a range of operating flows and water levels, including transient operating conditions. Additionally, scaled physical modeling can be used to derive modifications, such as vortex suppressors, which allow tanks to be drawn down to water levels lower than that attainable without these structures installed. Over the past several years, a number of nuclear power plants have used hydraulic model studies of their water storage tanks to address the aforementioned issues. These include D.C Cook[v], McGuire, Catawba and Oconee nuclear power plants. Studies involving vortex formation have also been conducted for cooling water intakes, reactor containment sumps, and other specialized intake facilities. All of the aforementioned intake studies required observation and documentation of approach flow patterns, classification of vortices, measurement of inlet losses and quantification of swirling flow in the suction pipes.

How it works

Typical objectives of water storage tank draw down tests include: (1) identification of the water level at the onset of air entrainment, (2) classification of vortex severities at intermediate draw-down water levels and (3) derivation of vortex suppression devices.

U.S. NRC Safety Inspections

The U.S. Nuclear Regulatory Commission oversight process for operating reactors includes an evaluation of plant performance by analyzing inspection findings and performance indicators (PIs) reported by the licensee. Resident inspectors monitor licensee activities continuously in accordance with the baseline inspection program. Regional inspection specialists conduct inspections of each plant in their region periodically, and, as needed, regional inspectors conduct special inspections of those plants that require increased attention, having exceeded established thresholds during routine inspections.

The Component Design Bases Inspection is one of twenty-three attachments to the inspection procedure for the reactor safety strategic performance area. It is here that operational inspection of most water storage tanks would be covered. The goal of this inspection is to verify the initial design and subsequent modifications, monitoring of the capability of the selected components and operator actions to perform their design bases functions.

Additionally, the NRC put out an Information Notice during September of 2006 (NRC IN 2006-21) that summarized recent inspection findings in which some plants had not properly accounted for vortex allowances for the Emergency Core Cooling System (ECCS). One specific example included a plant which had improperly calculated the onset of vortex induced air entrainment for a storage tank.
(Source: http://www.nrc.gov/reactors/operating/oversight.html)

Figure 1. Photo of a typical model setup

Models involving a free surface are constructed and operated using Froude number similarity since the flow process is controlled by gravity and inertial forces. By keeping the Froude number (, where V is velocity, g the acceleration of gravity, and L the characteristic length) constant, the flow patterns in a scaled geometry will be identical to that in the plant, if viscous and surface tension effects are negligible. When the same fluid is used in the scaled model, it is impossible to keep all relevant dimensionless numbers identical from plant to sub-scale. Therefore, in a tank draw-down study evaluating the formation of vortices, it is important to select a reasonably large geometric scale to achieve large Reynolds ($\rho VL/\mu$) and Weber ($\rho V^2L/\sigma$) numbers so as to minimize viscous and surface tension scale effects, respectively, thereby accurately reproducing the flow pattern in the vicinity of the suction. The model scale must, however, be small enough to avoid prohibitive study costs. In general, geometric scales vary from 1:2 to 1:5 for nuclear tank draw-down models.

A model of the tank and outlet piping of interest are constructed to the geometric scale based on the considerations described above. The suction pipe geometry including the corresponding floor and wall clearance and any bends or fittings which may influence the flow patterns at the outlet suction are also modeled. The model suction piping close to the tank should be fabricated using clear acrylic pipe to provide for visual observations of any air entrainment. Other tank internal details (representing significant obstructions to the flow) which may influence the flow patterns in the vicinity of the suction should also be included.

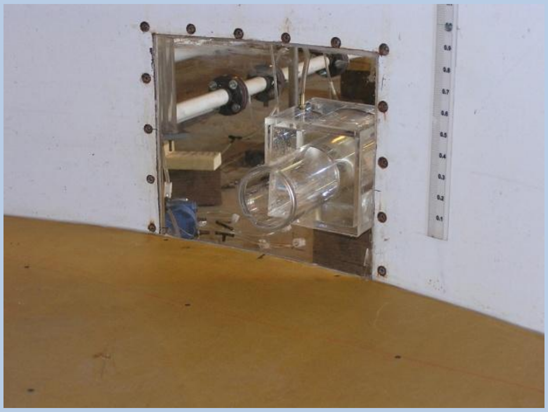

Figure 2. Photo of a typical model suction pipe

The model setup includes piping to withdraw the appropriate flow from the modeled tank at the specified rate and to provide flow into the tank, if necessary. The model is instrumented to measure flow and water levels which are recorded using a computerized data acquisition system. The onset of air entrainment is recorded using multiple video cameras synchronized to the data acquisition system.

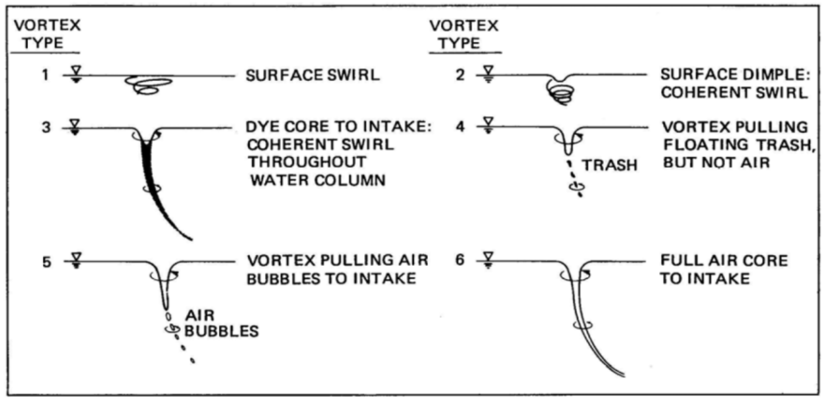

Figure 3. Alden classification of free surface vortices

Test programs

Test programs and matrices are generally customized to specific requirements of the subject study. Tests for selected operating conditions are conducted at scaled flow and submergences. For flows of interest, the water level is allowed to drop at the rate corresponding to that in the field (as governed by the flow until the onset of air entrainment is identified for that flow). As the water level drops, a simultaneous record of flow and water level versus time is logged and the onset of air entrainment is observed and recorded with a video camera. Simultaneously, additional video cameras record the onset of air bubble ingestion into the suction pipe as observed through the acrylic section of the suction pipe. Free surface vortices are classified from type 1 to type 6 (See Figure 3). Of particular interest for studies such as these are air drawing vortices (type 5 and 6). Air may also be ingested into the suction pipe due to local draw down of the water surface as water levels approach suction nozzle entrance.

Upon completion of initial testing, results are then evaluated to determine the need for modifications such as vortex suppressors which would allow for additional water level draw-down. With modifications installed, testing is repeated to determine the effectiveness of various devices in suppressing objectionable vortices and air entrainment.

A case in point: Duke Energy's McGuire Station

Duke Energy's McGuire Nuclear Power Station is located in Huntersville, North Carolina. McGuire desired to perform scale model testing to proactively address the generic issues identified by the NRC 2006 informational notice. The primary objective of the scale model testing was to demonstrate that their original RWST vortex allowance had been conservative. The performance of a detailed physical model study could also provide additional ECCS sump inventory margin in the event of a Loss of Coolant Accident (LOCA), and determine whether or not a vortex suppression device would be necessary for the RWST. A model was constructed using a geometric scale of 1:4.073. Testing included transient water level conditions simulating the field operation for selected flows (corresponding to prototype flows of 1,600 to 19,700 gpm) and water levels giving submergences of 1 to 5 ft above the suction nozzles in the model (prototype submergences of 4 to 20.3 ft). Results showed that the submergence at the onset of air entrainment ranged from 0.049 to 0.705 ft prototype for flows ranging from 1,600 to 19,700 gpm prototype, respectively. Onset occurred at water levels far below Hydraulic Institute guidelines for all cases. Based on these test results, it was determined that a vortex suppression device was not required for the McGuire RWST, as the expected water levels during operation would be higher than those indicated for onset of air entrainment for a given flow. In addition to sparing Duke Energy the modest materials and engineering costs of such a device (approximately $50,000 per unit), the more appreciable savings was associated with reduced outage time and resources.

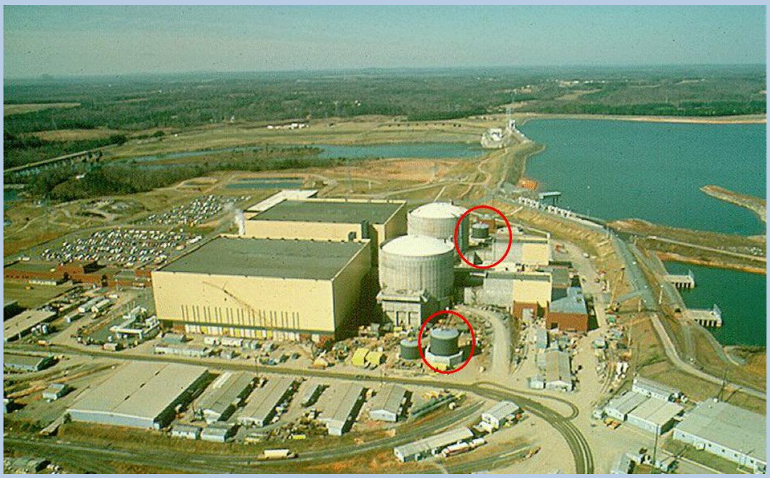

Figure 4. McGuire Nuclear Power Station. RWST's are circled in red. Photo courtesy of North Carolina Division of Water Resources

Summary

Several US Nuclear Power Stations have been required to take corrective action to address the potential for vortex induced air entrainment associated with flow withdrawal from certain types of water storage tanks. Although some guidance exists in the literature to estimate vortex formation and air entrainment under steady-state operating conditions, the potential for the phenomena under transient water level draw down conditions is not well understood. Further, the potential for occurrence under these transient conditions is strongly influenced by inlet suction geometry and orientation, the presence or absence of vortex suppression devices, and the proximity of obstructions inside the tank to the suction pipe inlet. A scaled physical model test program can demonstrate whether current vortex allowances are conservative and, if not, what mitigation measures are likely to resolve the problem.

Andrew Johansson is the Director of Hydraulic and Numeric Modeling at Alden Research Laboratory. He has more than 15 years of experience in providing supervision of hydraulic and air model studies as well as computational modeling. He has directed studies of pumping and storage tanks at nuclear power plants, fossil power plants, and waste water treatment plants. He is on the intake design committee of the Hydraulic Institute (HI).

Dr. Mahadevan Padmanabhan, P.E. has over 30 years of fluid mechanics and hydraulics engineering experience solving a wide spectrum of both closed conduit and free surface flow problems. He is a senior consultant and former principal at Alden Research Laboratory. He has published widely on nuclear power plant thermal hydraulics, and performed generic testing to determine flow characteristics in emergency core cooling system (ECCS) containment sumps (NUREG/CR-2758), data from which was subsequently used to revise the NRC regulatory guidelines.

About Alden Research Laboratory: Founded in 1894, Alden is the oldest continuously operating hydraulic laboratory in the United States and one of the oldest in the world. Alden has been a recognized leader in the field of fluid dynamics research and development with a focus on the energy and environmental industries. The current Alden organization consists of engineers, scientists, biologists, and support staff in five specialty areas: Hydraulic Modeling and Consulting, Environmental and Engineering Services, Gas Flow Systems Engineering, Flow Meter Calibration, and Field Services. http://www.aldenlab.com/

[i] Harleman, D.R.F., Morgan, R.L. & Purple, R.A. 1959. "Selective withdrawal from a vertically stratified fluid," 8th Congress of the International Association for Hydraulic Research, August 24 – 29, Montreal, Canada.

[ii] Daggett, L. & Keulegan, G.H., "Similitude in free-surface vortex formations," *J. of the Hydraulics Division, ASCE*, November, 1974.

[iii] Padmanabhan, M. & Hecker, G.E., 1984. "Scale effects in pump sump models," *ASCE J. Hyd. Eng.* **110**, N. 11, November, 1984

[iv] Hydraulic Institute Standards, American National Standard for Pump Intake Design, ANSI/HI 9.8-1998.

[v] JPGC2001/PWR-19010, "Air Entrainment in a Partially Filled Horizontal Pump Suction Line," June 2001.