Hydraulic Modeling of Air-Entraining Vortex Formation During Flow Withdrawal from Water Storage Tanks

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Abstract

In response to recent U.S. Nuclear Regulatory Commission (NRC) Component Design Bases Inspection (CBDI) issues, many US nuclear power stations have been required to demonstrate that minimum submergence requirements were properly determined for flow withdrawal from various safety related storage tanks. In many cases, the licensees failed to consider a vortex allowance, or applied an inappropriate vortex methodology.

For Duke Energy's McGuire Station, a Refueling Water Storage Tank (RWST) model was constructed using a geometric scale of 1:4.073. Testing included transient water level conditions simulating the field 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 nozzle in the model (prototype submergences of 4 to 20.3 ft). Results showed that with no return flow, 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. Based on the 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. The scale model testing showed that the critical submergences for initiation of air-entraining vortices were much lower than those predicted by Hydraulic Institute guidelines.

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. These corrective actions were required to addresses issues identified during Nuclear Regulatory Commission (NRC) safety system design and performance capability inspections. In 2006, the NRC sent an information notice [1] to nuclear plant operators outlining several events associated with recent inspections involving the possible entrainment of air into the Emergency Core Cooling System (ECCS) and Containment Spray Systems (CSS). One of the examples cited was a licensee who had not selected the correct method for calculating the onset of air entrainment due to vortex formation. Tanks of interest are typically associated with a critical component of the 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 (CST).

Generic flow modeling studies [2] addressing vortexing and air entrainment in pump suction lines have been utilized to develop empirical equations to estimate submergence requirements to minimize 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.

For site-specific applications, physical hydraulic models are useful tools to evaluate the potential for air entrainment due to vortexing over a range of operating flows and water levels, including transient operating conditions. Additionally, 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 otherwise attainable while avoiding vortexing and associated air entrainment phenomena. Over the past several years, a number of hydraulic model studies of water storage tanks have been performed to address the aforementioned issues. Most recently, studies have been conducted for the D.C Cook [3], McGuire, Catawba and Oconee nuclear power plants. The studies require observation and documentation of approach flow patterns, classification of vortices, and can include measurement of inlet losses and quantification of swirling flow in the suction pipes.

The recent work builds upon research in vortex formation, vortex suppressor design, and scale effects on vortex phenomena in Froude scale models [4], including generic testing to determine flow characteristics in ECCS containment sumps which was used to revise NRC regulatory guidelines [5] [6].

It should be noted that numeric modeling techniques, such as Computational Fluid Dynamics (CFD) can be used to study many flow related problems. These models are useful tools for predicting the flow patterns within hydraulic structures and typically offer the advantage that the geometry can be quickly modified to study extensive design modifications more economically than similar changes to a physical model. While CFD models offer cost and schedule advantages over physical models, they are not yet capable 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. The use of physical models to evaluate the potential for air entrainment due to vortex formation in pump intake structures, as an example, is well documented [4][7] and widely accepted.

Duke Energy's McGuire Power Station desired to perform scale model testing to proactively address one of the generic issues identified by the NRC in their 2006 informational notice. The primary objective of the detailed physical model study was to demonstrate that their original methodology for determining minimum water level in their RWST was 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).

Nomenclature

BWST	Borated Water Storage Tanks
CDBI	Component Design Bases Inspection
CFD	Computational Fluid Dynamics
CSS	Containment Spray System
CST	Condensate Storage Tank
ECCS	Emergency Core Cooling System
Fr	Froude number
g	Gravitational acceleration
gpm	Gallons per minute
ID	Internal diameter
L	Length scale: average intake diameter (elliptical intake geometry)
NRC	U.S. Nuclear Regulatory Commission
RCIC	Reactor Core Isolation Cooling
RWST	Refueling Water Storage Tank
V	Velocity scale: average velocity at the intake
μ	Dynamic viscosity
ρ	Density
σ	Surface tension

Modeling Objectives

Scaled hydraulic models are routinely used throughout various industries to accurately determine hydraulic conditions and identify minimum submergence requirements (to avoid air entrainment) for site specific intake configurations. Additionally physical models can be reliably used to derive remedial modifications, such as vortex suppressors, which may allow for lower submergence requirements without air entrainment.

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

Model Scaling

Models involving a free surface are constructed and operated using Froude number similarity since the flow process is controlled by gravity and inertial forces. The Froude Number is defined as

By keeping *Fr* constant, the flow patterns in a scaled geometry will be identical to those in the plant, provided that any 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. Past studies [7][8] have shown that model inlet Reynolds numbers should be above $3X10^4$ to avoid viscous effects, and model Weber numbers [9] should be above 120 to avoid surface tension effects. 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.

Model Description

Figures 1 and 2 show a drawing and photo of the model of the RWST at McGuire Station, respectively. A model scale of 1:4.073 was chosen, which allowed for the use of commercially available plexiglass pipes as well as a common tank model to be used for multiple Duke Energy projects. The actual tank is circular with a diameter of approximately 40 ft at the bottom. The suction nozzle is 24" schedule 10 (23.5" ID). The pipe slants at 45 degrees and the entrance, which is 12" above the tank bottom, is elliptical. The suction flow varies depending on the operating cases. The model tank had an I.D. of 9.813 ft and was 6 ft deep. The tank was fitted with a removable floor and had a finished depth of approximately 5.5 ft which allowed simulation of water levels corresponding to as high as 22.4 ft in the plant. However, only lower water levels were tested, as air-entrainment due to air-drawing vortices or other anticipated conditions are likely to occur only at lower water levels. Downstream piping geometry just outside the tank is unlikely to influence the flow patterns at the suction nozzle entrance, if a straight pipe of approximately 5 pipe diameters is available immediately

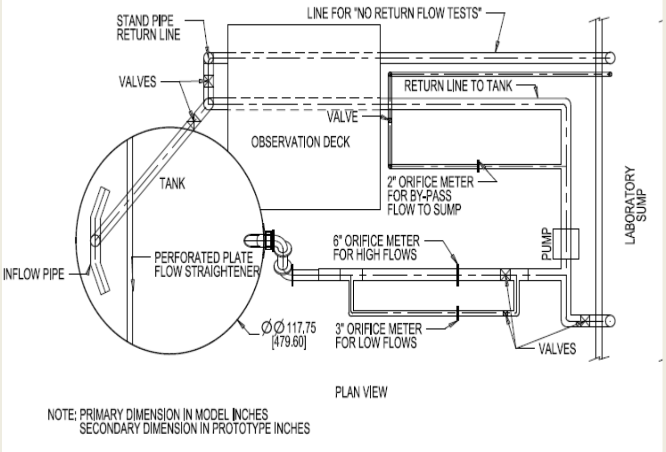

Figure 1: Schematic of laboratory model and piping.

after the suction pipe exits the tank. In this case, the 24 inch outlet pipe geometry within the tank and outside the tank, including the horizontal piping, the two 90 degree bends and the 45 degree inclined spacer between the bends was simulated in the model. The model suction piping close to the tank was fabricated using clear acrylic pipe to provide for visual observations of air entrainment, as shown in Figure 3.

Figure 2: Photo of laboratory tank exterior and model piping.

The model was provided with a flow loop which could function as a full, partially closed, or open loop. The flow loop included a laboratory sump as a reservoir for optional return flow. With a closed flow loop, transient water level tests could be conducted with full or partial return flow to the tank. Partial return flow would control the rate of water level drop by drawing water from the tank and returning part of the flow to the tank and sending the remainder to the laboratory sump. For closed flow loop tests, the flow was returned to the tank opposite to the intake with a sparger manifold and perforated plate flow distributor (Figure 1) provided to avoid any skewed approach flow to the suction nozzles.

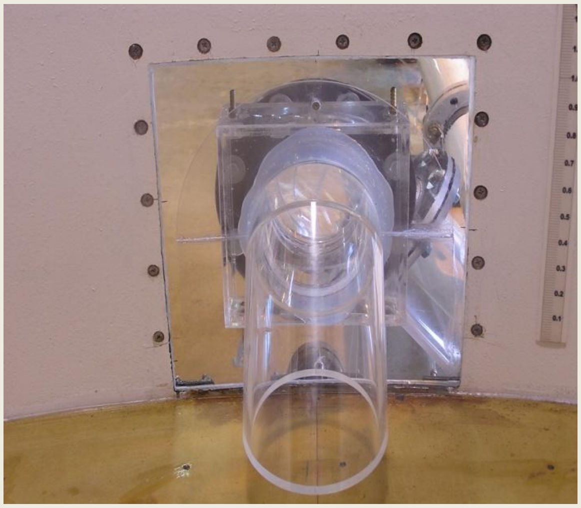

Figure 3: Acrylic model suction pipe.

Calibrated orifice flow meters were used for flow measurements. Separate flow meters were provided for lower flows (up to approximately 150 gpm model), higher flows (above 150 gpm model) and the return flow to the sump for partially closed loop tests. A tap located on the side wall of the model RWST was used to read water levels in the tank with a differential pressure transducer, one side of which was connected to a known fixed water column.

A rectangular acrylic viewing box (seen in the center of Figure 3) enclosed the outlet pipe and was filled with water. The nearly identical refractive index of water and acrylic enables the compensation for visual distortion due to the curvature of the pipe. This method provided a good viewing and videotaping location for air bubble identification.

Test Program

Test No.	Prototype Flow (gpm)	Scaled Model Flow (gpm)	Flow Returned to Tank (gpm)	Initial Water Level (in)
1	1600	47.79	0	20
2	2800	83.63	0	36
3	8250	246.42	0	36
4	9850	294.21	0	60
5	19700	588.41	0	60
6	1600	47.79	24.31	12
7	2800	83.63	60.15	12
8	8250	246.42	222.94	12
9	9850	294.21	270.73	12
10	19700	588.41	564.93	12

Table 1: Test matrix for scaled RWST at McGuire Station.

Water level was measured from the bottom of the suction nozzle. Tests for selected operating conditions were conducted at scaled flow and submergences. The matrix of conditions studied is shown in Table 1. For each flow of interest, the water level was allowed to drop at the scaled rate corresponding to that in the field (as governed by the flow until the onset of air entrainment was identified for that flow). As the water level dropped, a simultaneous record of flow and water level versus time was logged and the onset of air entrainment was observed and recorded with a video camera. Simultaneously, additional video cameras recorded the onset of air bubble ingestion into the suction pipe as observed through the acrylic section. Free surface vortices were classified from type 1 to type 6 (See Figure 4). Of particular interest for studies such as these are air drawing vortices (types 5 and 6). Air may also be ingested into the suction pipe due to local draw-down of the water surface as the water level approaches the suction nozzle entrance.

Results and Discussion

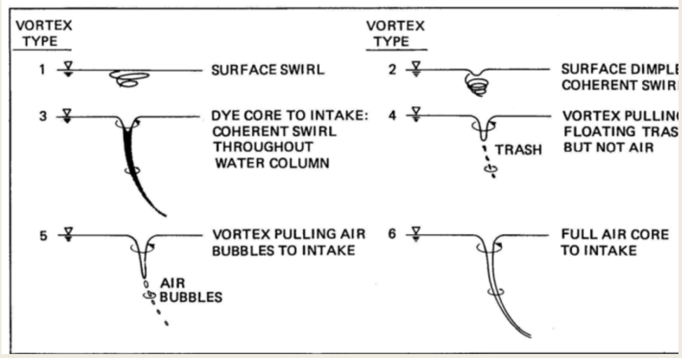

Figure 4: Alden surface vortex classification.

A summary of the test results is shown in Table 2. As mentioned previously, the test matrix consisted of 5 tests with no return flow to the tank and 5 tests with partial return flow. Tests 6 through 10 in the matrix are tests with partial return flow and constitute transient water level tests with a specified water level drop of about 1/2" per minute. Tests for McGuire covered specified flows from 1,600 to 19,700 gpm (prototype) and the initial water depths tested covered initial submergences corresponding to about 4 to 20.3 ft (prototype) above the suction nozzle entrance in the plant.

For tests with no return flow (Tests 1 through 5) and prototype flows of approximately 1,600, 2,800, 8,250, 9,850 and 19,700 gpm, the submergence at the onset of air entrainment was 0.049, 0.102, 0.318, 0.326, and 0.705 ft prototype, respectively.

For tests with partial return flow (Tests 6 through 10) and prototype flows of approximately 1,600, 2,800, 8,250, 9,850 and 19,700 gpm, the submergence at the onset of air entrainment was 0.045, 0.094, 0.261, 0.310, and 2.851 ft prototype, respectively. Tests with return flow showed results similar to those without return flow, except for the 19,700 gpm conditions. This suggests that the partial return to the tank may have affected the approach patterns at higher flows resulting in stronger air drawing vortices. Tests with return flow were expected to give more conservative results even though they may not be a true representation of the field conditions due to the change in approach flow conditions.

Test No.	Prototype Flow (gpm)	Initial Water Level (in)	Submergence at Onset of Air Entrainment (Prototype ft)	Submergence Requirement Based on HIS (Prototype ft)
1	1600	20	0.049	2.85
2	2800	36	0.102	3.23
3	8250	36	0.318	5.00
4	9850	60	0.326	5.52
4r	9850	36	0.305	5.52
5	19700	60	0.705	8.70
6	1600	12	0.045	2.85
7	2800	12	0.094	3.23
8	8250	12	0.261	5.00
9	9850	12	0.310	5.52
10	19700	12	2.851	8.70

Table 2: Test results with submergence at air entrainment onset extrapolated to full prototype scale.

Test 4r was a repeat of test 4, but with a lower initial water level. Test 4 with an initial water level of 60 inches showed an air entrainment onset submergence of 0.326 ft prototype compared to 0.305 ft prototype for Test 4r, which had an initial water level of 36 inches. This comparison provides an indication of the repeatability of the results and the dependence on the initial water level.

For each test, the air entrainment onset submergence was far below the Hydraulic Institute guideline [10] (the last column in Table 2), indicating the conservatism in that method.

Based on the test results, it was determined that a vortex suppression device was not required, as the expected water levels during operation would be higher than those indicated for onset of air entrainment for a given flow.

Summary

In order to address NRC concerns about minimum storage tank levels proactively, Duke Energy's McGuire Power Station contracted a physical model study of their RWST. Various flow rates with and without recirculation were studied in order to investigate the onset of air entraining vortices relative to previously computed minimum water level values.

The results of the testing confirmed that the operation of the RWST was conservative and that a vortex suppression device was not required. 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 were associated with reduced outage time and resource requirements

Physical model studies of tank draw-down vortex formation have been shown to be a valuable tool in addressing related regulatory concerns.

References

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