



— BUREAU OF —
RECLAMATION

Final Report No. ST-2025-23062

Improved Air Vent Sizing Methods for Emergency Gates

Research and Development Office

Science and Technology

Research Program



REPORT DOCUMENTATION PAGE				Form Approved OMB No. 0704-0188	
The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing the burden, to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number. PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.					
1. REPORT DATE (DD-MM-YYYY) 09-30-2025		2. REPORT TYPE Research		3. DATES COVERED (From - To) 2022 - 2025	
4. TITLE AND SUBTITLE Improved Air Vent Sizing Methods for Emergency Gates				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER 1541 (S&T)	
6. AUTHOR(S) Joseph Wright, PE, Hydraulic Engineer				5d. PROJECT ID NUMBER Final Report ST-2025-23062	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Hydraulic Investigations and Laboratory Services Group Technical Services Center Bureau of Reclamation U.S. Department of the Interior Denver Federal Center PO Box 25007, Denver, CO 80225-0007				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Science and Technology Program Research and Development Office Bureau of Reclamation U.S. Department of the Interior Denver Federal Center PO Box 25007, Denver, CO 80225-0007				10. SPONSOR/MONITOR'S ACRONYM(S) Reclamation	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S) (if applicable)	
12. DISTRIBUTION/AVAILABILITY STATEMENT Final Report may be downloaded from https://www.usbr.gov/research/projects/index.html					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT Penstock structures on Reclamation dams provide regulated flow to powerplants and outlet channels using gates or valves on their downstream end. Guard gates, typically located on the upstream end of the penstock, are an important feature for filling, dewatering, and other operations. They also provide a measure of redundancy for isolating or shutting down equipment in emergency situations when the primary shutdown equipment is disabled. An important feature during emergency shutdowns is the air vent system that prevents extreme negative pressures in the penstock. This report concatenates four case studies that assess air vent sizing at Reclamation facilities during unbalanced guard gate closures. This report also presents guidance that can be used for assessing similar facilities.					
15. SUBJECT TERMS Emergency Gate Closure, Unbalanced Gate Closure, Penstock Failure, Air Venting					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES 82	19a. NAME OF RESPONSIBLE PERSON Joseph Wright
a. REPORT U	b. ABSTRACT U	c. THIS PAGE U			19b. TELEPHONE NUMBER (Include area code) 303-445-2463

Mission Statements

The U.S. Department of the Interior protects and manages the Nation's natural resources and cultural heritage; provides scientific and other information about those resources; honors its trust responsibilities or special commitments to American Indians, Alaska Natives, Native Hawaiians, and affiliated Island Communities.

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

Disclaimer

Information in this report may not be used for advertising or promotional purchases. The data and findings should not be construed as an endorsement of any product or firm by the Bureau of Reclamation, Department of Interior, or Federal Government. The products evaluated in the report were evaluated for purposes specific to the Bureau of Reclamation mission. Reclamation gives no warranties or guarantees, expressed or implied, for the products evaluated in this report, including merchantability or fitness for a particular purpose.

Acknowledgements

The Science and Technology Program, Bureau of Reclamation, sponsored this research. This report wishes to acknowledge Bryan Heiner and Joseph Kubistcheck for their work on compiling much of the information used for this report and Tony Wahl for his comprehensive review of the HFVENT computer program.

Cover Image – Photograph showing a collapsed penstock at Folsom Dam, California (Mortensen / Bureau of Reclamation, 2017).

Improved Air Vent Sizing Methods for Emergency Gates

Final Report No. ST-2025-23062

Prepared by:

**Technical Service Center
Joseph Wright, Hydraulic Engineer**

Peer Review

Bureau of Reclamation Research and Development Office Science and Technology Research Program

Final Report ST-2025-23062

Improved Air Vent Sizing Methods for Emergency Gates

Prepared by: Joseph Wright, PE

Hydraulic Engineer, Technical Services Center, Hydraulic Investigations and Laboratory Services Group, 86-68560

Peer review by: Josh Mortensen, PE

Hydraulic Engineer, Technical Services Center, Hydraulic Investigations and Laboratory Services Group, 86-68560

This document has been reviewed under the Research and Development Office Discretionary peer review process, consistent with Reclamation Policy CMP P14. It does not represent and should not be construed to represent the Bureau of Reclamation's determination, concurrence, or policy.

Acronyms and Abbreviations

Reclamation	Bureau of Reclamation
CFD	computational fluid dynamic
ft ³ /s	cubic foot per second
FORTTRAN	Formula Translation (computer programming language)
ft	foot/feet
ft/s	foot per second
ft/s ²	foot per second squared
HFVENT	Hydraulic Falling water and Venting (computer program
lb/ft ³	pounds per cubic foot
psig	pounds per square inch gauge
N/A	not available; not applicable
TSC	Technical Service Center
WSEL	water surface elevation

Symbols

Δ	change
%	percent
Σ	summation

Contents

	Page
Executive Summary	ES-1
1.0 Introduction.....	1
2.0 Reclamation Case Studies.....	1
2.1. Helena Valley Pumping Plant.....	1
2.2. Green Mountain Powerplant	3
2.3. Clear Creek Dam Outlet Works.....	5
2.4. Glendo Dam Powerplant.....	9
3.0 Air Demand Assessment.....	10
3.1. Maximum Allowable Air Flow (Upper Threshold).....	10
3.1.1. Calculate the Collapse Pressure (First Step).....	11
3.1.2. Calculate the Maximum Allowable Air Flow (Second Step)	11
3.2. Estimate Air Demand During Gate Closure	12
3.2.1. Numerical Modeling	12
4.0 HFVENT.FOR.....	14
5.0 Conclusions and Recommendations	15
5.1. Conclusions.....	15
5.2. Recommendations.....	15
6.0 References.....	19

Tables

1.—Summary of variations for each un-balanced gate closure simulation conducted for the Clear Creek Outlet Works air demand analysis.	7
--	---

Figures

1.—Chart showing the comparison between numerical modeling results and measurements taken from a physical model for Green Mountain powerplant (Mortensen 2016).....	4
2.—Photograph of the Clear Creek scaled physical model showing the square shaped gate leaf upstream of the penstock (looking downstream; Kubitschek 2022).	6
3.—Photograph of the Clear Creek scaled physical model showing the round shaped gate leaf upstream of the penstock (looking downstream; Kubitschek 2022).	6
4.—Chart showing the effects various initial discharge conditions have on the air demand.	7
5.—Chart showing the air demand when the initial flow condition is 320 ft ³ /s for conditions when the tailwater is free or submerged.....	8
6.—Chart showing the effects of air venting from various closure rates of the upstream guard gate.	8
7.—Chart showing the effects from various gate leaf geometries tested for two different vent pipe diameters.....	9

Appendix

A Notes on HFVENT.FOR (unedited compliation by Tony Wahl)

Executive Summary

Penstock structures on Bureau of Reclamation dams provide regulated flow to powerplants and outlet channels using gates or valves on their downstream end. Guard gates, located on the upstream end of the penstock, are an important feature for filling, dewatering, and other operations. They also provide a measure of redundancy for isolating or shutting down equipment in emergency situations when the primary shutdown equipment is disabled. In emergencies, these gates are closed under unbalanced pressure conditions with upstream pressure driven by the water level of the reservoir. Closing these gates under these conditions requires suitable air venting downstream to ensure smooth operation and prevent excessively low pressures from damaging the connecting conduit. For some cases, these excessively low pressures can collapse the downstream conduit resulting in system failure if the venting cannot accommodate the air demand during a gate closure. Although many facilities have structural features that prevent collapse failure, such as support rings or encasing downstream conduit in concrete, facilities lacking such prevention measures require greater effort to determine an optimal air vent. Reclamation has limited guidance for analyzing air-water flow through a penstock during a gate closure as summarized in Engineering Monograph No. 41 (EM-41; Falvey 1980).

This report summarizes methods presented in four case studies conducted at Reclamation facilities for assessing air vents during an unbalanced guard gate closure. These case studies can be used as guidance for assessing air venting during emergency unbalanced guard gate closures at similar facilities. The case studies presented include the following Reclamation facilities:

1. Helena Valley Pumping Plant
2. Green Mountain Power Plant
3. Clear Creek Dam Outlet Works
4. Glendo Dam Powerplant

The information compiled from these case studies presents both analytical and numerical modeling concepts. This report presents an outline approach for estimating a design threshold for venting during an emergency closure and calculating the maximum air flow, or air demand, through a vent to satisfy this threshold. While numerical code was not updated or developed during this study, the outline presents numerical concepts needed for further developing a numerical model.

Finally, this report presents a detailed assessment of the HFVENT (Hydraulic Falling water and Venting) computer program developed for EM-41. HFVENT is a numerical model that computes a transient air-water surface through a penstock during an unbalanced gate closure. Although specifically tailored for Morrow Point Dam, EM-41 presents the source code for HFVENT with the intent for others to modify and use to analyze other facilities (Falvey 1980). Applying this code for other facilities, however, became impractical for analysts who were limited by their

understanding of the EM-41 FORTRAN¹. The information presented in this assessment can be used to develop an updated computer program that can be used for current and future air venting analyses.

¹ FORTRAN is a computer programming language named from the abbreviation “Formula Translation.”

1.0 Introduction

Penstock structures on Reclamation dams provide regulated flow to powerplants and outlet channels using gates or valves on their downstream end². Guard gates, located on the upstream end of the penstock, are an important feature for filling, dewatering, and other operations³. They also provide a measure of redundancy for isolating or shutting down equipment in emergency situations when the primary shutdown equipment is disabled. Closing these gates requires suitable air venting to ensure smooth operation and prevent excessively low pressures from damaging the connecting downstream conduit. This air demand⁴ is driven by multiple factors including the turbulent mixing of air and water in high velocity flow from the gate, the air-entraining behavior of a hydraulic jump forming in the downstream conduit, and the change in volume of the conduit as it is rapidly drained during gate closure. Failure to allow for high air flows into the conduit results in excessively low pressures that can cause operational issues such as irregular gate closure or vibration, cavitation, and added stress to structural components.

For larger conduits, these excessively low pressures can collapse and fail the conduit. Although many facilities have structural features that prevent collapse failure, such as encasing downstream conduit in concrete, facilities where the air vent size is marginal or that lack structural integrity may require a higher level of modeling and analysis to determine an appropriate air vent size. While Reclamation has provided some guidance for analyzing air-water flow through a penstock during a gate closure, summarized in Engineering Monograph No. 41 (Falvey 1980), robust analytical and numerical tools for air vent sizing are lacking. This document concatenates recent Reclamation air demand studies to provide applicable guidance for similar studies.

2.0 Reclamation Case Studies

Reclamation has recently conducted air venting studies for Helena Valley pumping plant (Kubitschek 2014), Green Mountain powerplant (Mortensen 2016), Clear Creek outlet works (Kubitschek 2022), and Glendo Dam powerplant (Kubitschek 2024). Although conducted independently, these studies follow a common pattern for assessing the air demand during an emergency gate closure and offer guidance for current and future studies.

2.1. Helena Valley Pumping Plant

In 2014, Reclamation conducted an analysis to estimate the air demand required to prevent a penstock collapse during an unbalanced penstock guard gate closure at Helena Valley pumping

² The regulating gates or valves on the downstream end of a penstock (or outlet works) are referred herein as “regulating” gates.

³ Gates or valves on the upstream end of a penstock (or outlet works) as referred herein as “guard” gates.

⁴ Unless explicitly stated, the term “air demand” will imply the maximum volumetric air flow during an unbalanced gate closure.

plant (referred herein as the 2014 study). This study used an analytical approach to determine the amount of pressure drop needed to collapse the penstock, or the collapse pressure (Kubitschek 2014).

$$P_c = 5.02 \times 10^7 (t/D)^3 \quad (1)$$

Where:

- P_c is the collapse pressure (in psi)
- t is the thickness of the penstock typically in inches)
- D is the diameter of the penstock (same units as t)

The penstock downstream from the guard gate has a diameter of 156.5 inches and a thickness of 0.5 inches. The small ratio of thickness to diameter makes this penstock susceptible to collapse for internal pressures at or below 1.6 psi. Because the collapse pressure was significantly below atmospheric pressure (approximately 14.7 psi at sea level), the air vent for the guard gate must be able to accommodate air flow resulting from an internal pressure of 1.6 psi. This air flow capacity was calculated using the following equation:

$$Q_{a,max} = A_v \sqrt{2g \left[\frac{(144 (in^2/ft^2)^{P_c/\gamma} + \Delta Z)}{\sum K_s + f(L/D)} \right]} \quad (2)$$

Where:

- $Q_{a,max}$ is the maximum allowable air flow (ft³/s)
- P_c is the collapse pressure (psig)
- ΔZ is the change in elevation from upstream to downstream (feet)
- $\sum K_s$, is the summation coefficient for minor energy losses through the vent
- f is the Darcy-Weisbach frictional loss coefficient through the vent pipe
- D is the vent pipe diameter (typically in feet)
- L is the vent pipe length (same unit as D)
- g is gravitational acceleration (32.2 ft/s²)
- γ is the density of air (lb/ft³)

The 2014 study calculated an air vent capacity of 340 ft³/s using equation 2. This means that the air demand during an unbalanced closure of the guard gate cannot exceed 340 ft³/s if the allowable pressure drop across the vent is to remain less than 1.6 psi. Using this upper air flow threshold was established, the 2014 study used a hybrid approach to numerically model transient flow conditions through the penstock during a simulated guard gate closure. This approach used a transient method of characteristics finite difference model to compute the transient pressure downstream of the guard gate incrementally during closing. When the computed pressure head in the penstock drops below the top of the penstock (resulting in a hydraulic jump just downstream of the guard gate), a quasi-steady-state method is used to compute the transient air-water flow until the penstock is fully drained after the guard gate is fully closed. This quasi-steady-state calculates air demand for steady-state conditions at incremental gate openings until the gate comes to full closure and all water is evacuated from the penstock. The steady state condition

calculates air demand as the summation of air entrained into the hydraulic jump and the volumetric change of displaced air in the penstock as the hydraulic jump moves downstream. The ratio of entrained air into the hydraulic jump to water flowing through the gate opening can be computed as a function of the Froude number calculated from the jet flow velocity under the gate and the effective supercritical depth upstream of the hydraulic jump. This ratio can be used to solve the air entrainment into the hydraulic jump using the following equation (Kalinske and Robertson 1943):

$$Q_a = Q_w[0.0066(Fr - 1)^{1.4}] \quad (3)$$

Where:

Q_a is the air flow (ft³/s)

Q_w is the incremental discharge (ft³/s)

Fr is the Froude number

The Froude number, Fr , is calculated as follows:

$$Fr = \frac{U}{\sqrt{gd_e}} \quad (4)$$

Where:

U is the incremental mean jet velocity under the gate (ft/s)

d_e is the effective water depth at the gate (ft)

The total air demand is the summation of the air entrained into the hydraulic jump and the displaced air in the penstock as the hydraulic jump moves downstream during guard gate closing. The 2014 study accounted for the displaced air conservatively by assuming that at each time step during venting, the discharge through downstream, fixed regulating gate is driven by a fixed head in the penstock. The artificial difference between the inflow and outflow calculated under such conditions is assumed to be the incremental volumetric flow and added to the entrained air flow into the hydraulic jump to get total air demand (Kubitschek 2014). Details for this calculation are not presented in this report.

If the maximum airflow computed from this quasi-steady state method remains below the air flow threshold computed from the collapse pressure, the design is considered suitable (Kubitschek 2014). If it is greater than the threshold, the air vent size is increased to reduce the pressure drop across the vent to keep the internal pressure above the collapse pressure of the pipe.

2.2. Green Mountain Powerplant

In 2016, Reclamation conducted an analysis of the existing air vents for the two power plant penstocks at Green Mountain Powerplant for an emergency gate closure (referred herein as the 2016 study; Mortensen 2016). Like the 2014 study, this study checked the collapse pressure of the penstock. The penstock has a wall thickness of 0.6135inch and a diameter of 102inch, resulting in a collapse pressure of 10.9 psi. Atmospheric pressure at Green Mountain was

estimated to be 10.85 psi using its centerline elevation of 7,708 ft and the collapse of the penstock was determined to be not possible. Given that collapse is not possible, the 2016 study based its air vent assessment on its ability to provide sufficient air for smooth operation of the guard gates during an unbalanced closure, preventing choked air flow through the vent. Prevention of choked air flow is ensured by maintaining an internal to atmospheric pressure ratio greater than 0.528 (Falvey 1980).

The 2016 study used both a numerical model and a physical model to estimate the air demand during an emergency gate closure. The physical model was constructed in Technical Service Center's Hydraulics Laboratory for a concurrent research project funded by the Science and Technology program (Mortensen 2017). The numerical model followed a similar "hybrid" approach as the 2014 Study, however the incremental volume of displaced air due to the downstream movement of the hydraulic jump was calculated using an empirically determined hydraulic jump velocity (Mortenson 2016). The mechanism for this movement is documented in a 2017 Bureau of Reclamation report (Mortensen 2017). The results from both the physical and numerical model show reasonable agreement for both the onset of air flow with respect to gate position and the maximum air flow during venting (figure 1; Mortensen 2016).

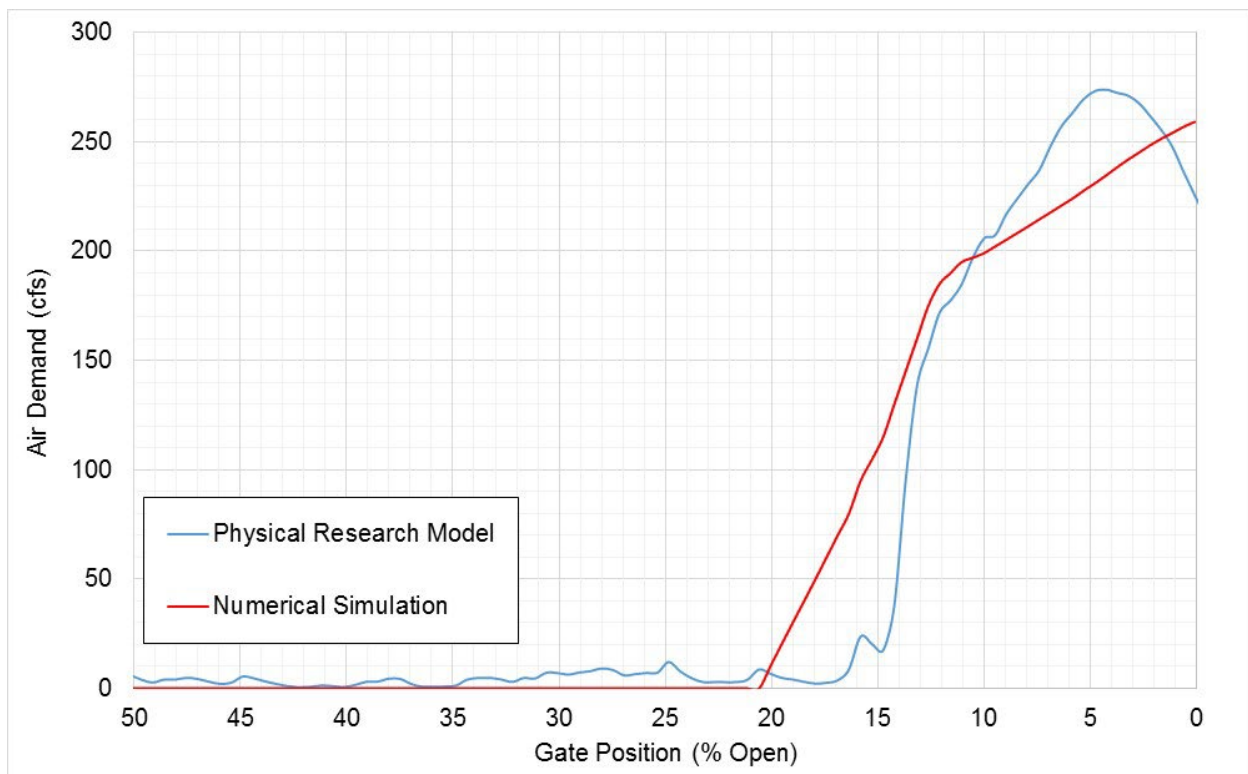


Figure 1.—Chart showing the comparison between numerical modeling results and measurements taken from a physical model for Green Mountain powerplant (Mortensen 2016).

Pressure loss calculations showed that the air demand of 270 ft³/s will produce an internal pressure of 5.78 psi and concluded that the air vent is suitable because the ratio of internal pressure to atmospheric pressure is greater than 0.528.

Calculations for flow of compressible fluids, such as air, indicate that if this ratio is above 0.528, the air flow will not become choked and continue to be controlled by the pressure differential across the vent in a stable condition (Mortensen 2016).

2.3. Clear Creek Dam Outlet Works

In 2022 Reclamation conducted an analysis to determine the air demand and vent capacity for existing outlet works vents at Clear Creek Dam during an emergency gate closure (referred herein as the 2022 Study; Kubitschek 2022). Like the 2014 and 2016 Studies, the 2022 Study calculated a collapse pressure for the outlet works pipe and used this pressure for establishing a maximum allowable air flow through the vent. Unlike the previous studies, the calculated collapse pressure 36-inch outlet works pipe was calculated to be 16.8 psi, greater than atmospheric pressure and is physically unable to collapse. This is common for smaller pipes having larger wall thickness to diameter ratios. The air vent assessment in this case was based on the entrance velocity of air entering the vent. Nonetheless, the 2022 study estimated the air demand during an upstream guard gate closure using both a physical and numerical model. The numerical modeling followed the same method presented in the 2014 Study, which conservatively calculated the incremental displaced air volume as the hydraulic jump moves downstream during gate closure. Agreement between the physical and numerical models, however, was less than satisfactory resulting in the 2022 Study only recommending results from the physical model for the air vent analysis (Kubitschek 2014).

The 2016 Study used a 1:12 scaled physical model of the outlet works for Clear Creek Dam to measure air demand during an emergency gate closure. The physical modeling effort is uniquely important because the analysis included variations in geometry, hydraulic conditions, and operation of the outlet works and vent during a gate closure. Specifically, the 2022 Study investigated the effects from two gate leaf geometries (figure 2 and figure 3), four reservoir water surface elevations (WSEL), and three gate closure rates. Variations in the WSEL were achieved by setting an initial steady-state outflow with the gate fully opened and translating this outflow to a WSEL using an established relationship (Reclamation, 2014). Upon reaching a steady-state flow condition for a given initial flow condition, the model used a stepper motor actuator to control the gate position and simulate a gate closure. The 2022 Study, however, does not specify how the WSEL in the model reservoir was maintained during this gate closure. The 2022 Study presents ten variations which include four variations of WSEL, and two variations (each) of the tailwater condition, gate speed, vent pipe diameter, and outlet works gate geometry (table 1; Kubitschek 2022). Results from these variations are presented in figure 4 through figure 7.



Figure 2.—Photograph of the Clear Creek scaled physical model showing the square shaped gate leaf upstream of the penstock (looking downstream; Kubitschek 2022).



Figure 3.—Photograph of the Clear Creek scaled physical model showing the round shaped gate leaf upstream of the penstock (looking downstream; Kubitschek 2022).

Table 1.—Summary of variations for each un-balanced gate closure simulation conducted for the Clear Creek Outlet Works air demand analysis.

*Initial Outflow (prototype, ft ³ /s)	Tailwater Condition	Gate Speed	Vent Diameter (prototype, inches)	Outlet Works Gate Leaf Geometry
320	Submerged	Normal	4.5	Flat
280	Submerged	Normal	4.5	Flat
240	Submerged	Normal	4.5	Flat
200	Submerged	Normal	4.5	Flat
320	Free	Normal	4.5	Flat
320	Submerged	Slow	4.5	Flat
320	Submerged	Fast	4.5	Flat
320	Submerged	Normal	4.5	Curved
320	Submerged	Normal	3.375	Flat
320	Submerged	Normal	3.375	Curved

* Initial outflow is the steady-state outflow with the gate fully open.

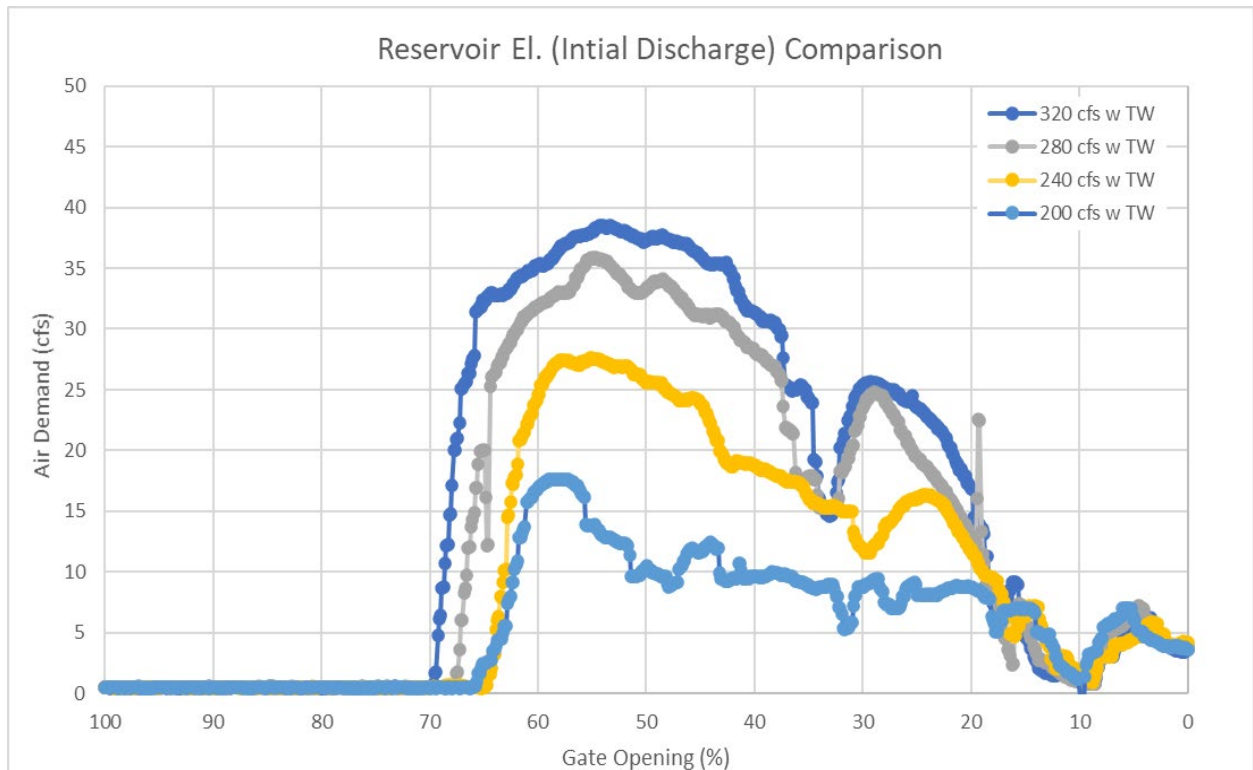


Figure 4.—Chart showing the effects various initial discharge conditions have on the air demand. The chart shows the air demand decreases when the initial discharge decreases (Kubitschek 2022).

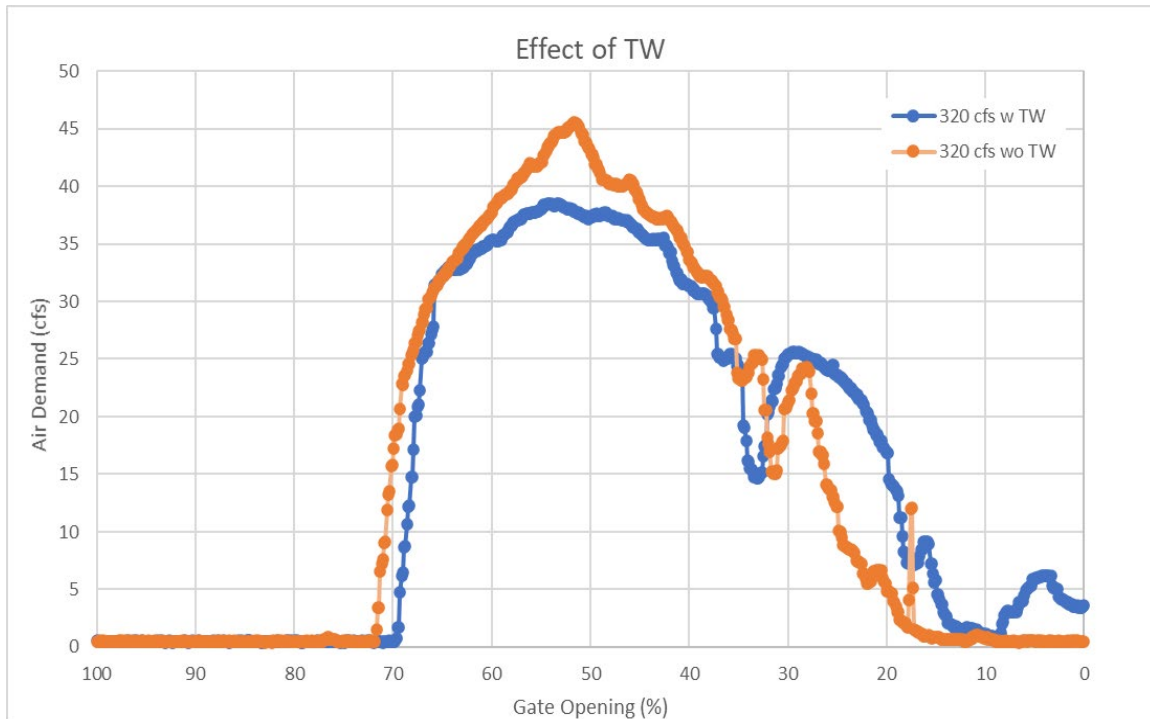


Figure 5.—Chart showing the air demand when the initial flow condition is 320 ft³/s for conditions when the tailwater is free or submerged. The chart shows that the air demand is slightly higher with free flow discharge (Kubitschek 2022).

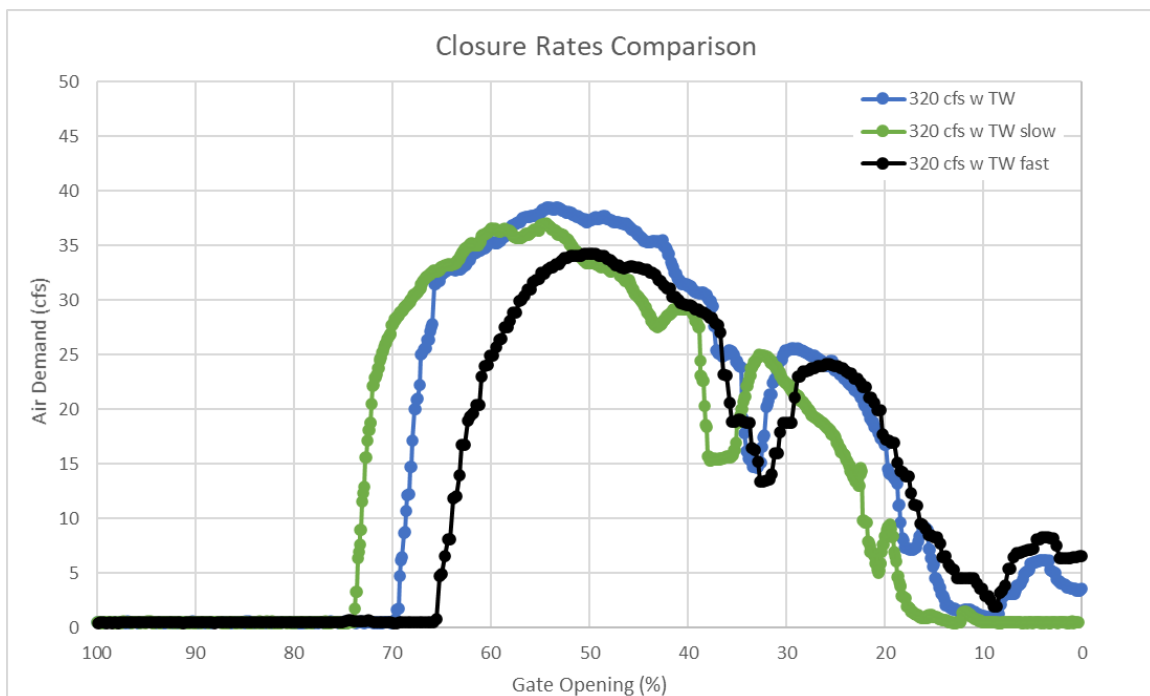


Figure 6.—Chart showing the effects of air venting from various closure rates of the upstream guard gate. The chart shows that air venting occurs sooner at higher percentage gate openings as the closure rate decreases (Kubitschek 2022).

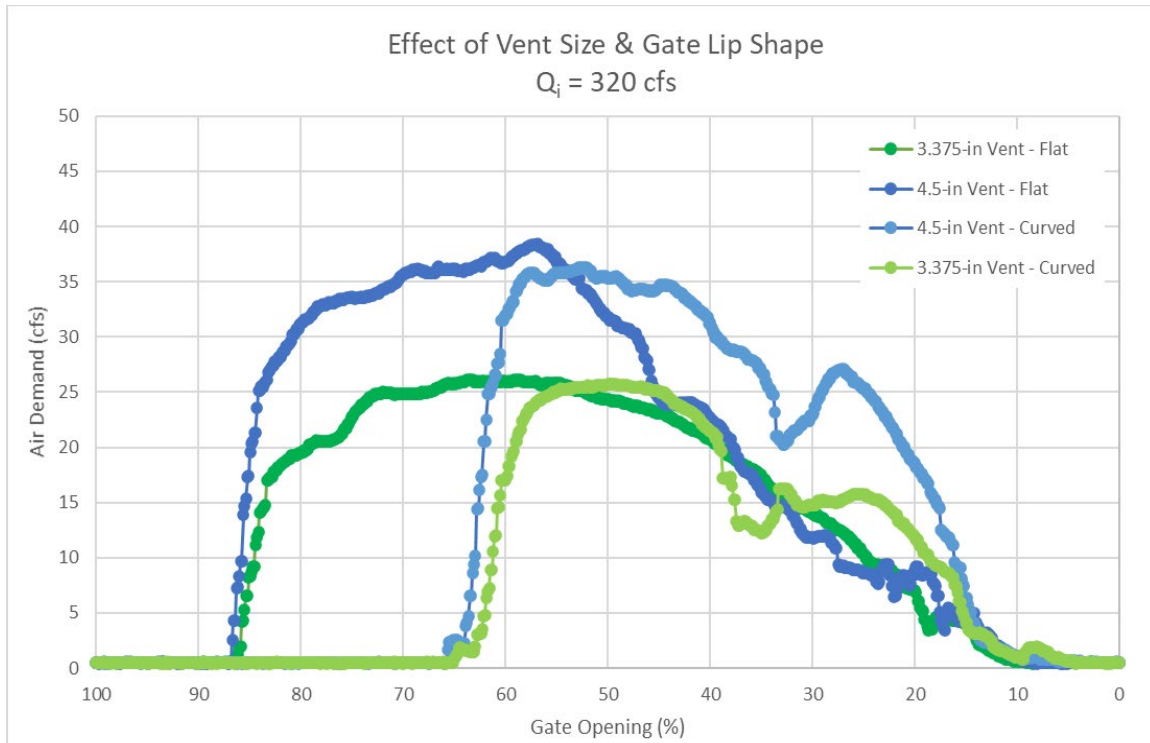


Figure 7.—Chart showing the effects from various gate leaf geometries tested for two different vent pipe diameters. The chart shows a significant increase in air volume for a flat gate leaf compared to that of a curved gate leaf. The air demand for both geometries remains approximately the same; however, the increase air volume is due to the air venting for the flat leaf occurring much sooner than the curved leaf. The chart suggests the timing for the venting depends on the leaf geometry and not vent diameter (Kubitschek 2022).

2.4. Glendo Dam Powerplant

In 2024 Reclamation’s Hydraulics Laboratory assessed the air demand at Glendo Dam during the emergency closure of the fixed-wheel gate on the powerplant penstock (referred herein as the 2024 Study; Kubitschek 2024). This assessment was mostly qualitative, presenting calculations based on approximate assumptions.

The 2024 Study used two methods for assessing air demand:

1. The air demand can be described from the amount of air entrained into a hydraulic jump that occurs at a discrete gate opening.
2. The air demand can be described as the amount needed to achieve the maximum possible air-water ratio of 0.245 as depicted in figure 24 of EM-41 (Falvey 1980) for 25 percent of the design capacity of the fixed-wheel gate.

Both methods of assessment yield feasible air demands, however, the more conservative estimate derived from using the maximum possible air-water ratio was used to justify modifying the air vent openings to accommodate higher air flow.

The 2024 Study cites that uncertainties associated with the complexity of the flow conditions through the penstock and fixed wheel gate require a more detailed analysis to address (Kubitschek 2024).

3.0 Air Demand Assessment

Each of the four case studies presented in section 2.0 calculates the air flow through an existing (or proposed) vent for comparison against a design threshold.

A general approach, derived from these case studies, can be described using the following steps:

1. Determine an upper threshold for allowable air flow in the penstock downstream of the gate. EM-41 presents various design criteria and considerations that can be used for this determination. Design considerations, presented in this report, include the following phenomena occurring during an unbalanced guard gate closure:
 - a. Excessively low internal pressure collapsing the penstock (Helena Valley Pumping Plant)
 - b. Choked air flow through the vent if the penstock has an internal to atmospheric pressure ratio greater than 0.53 (Green Mountain Powerplant)
 - c. High air vent intake velocities exceeding a threshold of 100 ft/s are considered unsafe for operators (Clear Creek Outlet Works and Glendo Powerplant)
2. Estimate the air demand during an emergency closure. Although this air demand can be approximated explicitly, numerical and physical models may reduce uncertainty of the air demand estimation as well as provide a time series of air flow and hydraulic conditions within the conduit throughout the full gate closure.
3. Determine if the vent size and configuration is suitable by comparing the air demand to the allowable maximum air flow.

3.1. Maximum Allowable Air Flow (Upper Threshold)

If feasible, the maximum allowable air flow through a penstock (or pipe) should be calculated empirically. This calculation often begins with determining the collapse pressure. If collapse is determined not possible under full vacuum conditions based on this calculation, other factors should be considered for determining a suitable design threshold. Such factors might include maintaining an internal to atmospheric ratio large enough to prevent air choking or maintaining air intake velocities below an acceptable threshold. Nonetheless, a suitable performance

threshold needs to be established before the air vent can be properly evaluated during an unbalanced guard gate closure. Section 3.1.1 presents this first step using collapse pressure as an example.

3.1.1. Calculate the Collapse Pressure (First Step)

The collapse pressure should be calculated to determine whether it is a critical design factor. If the collapse pressure is greater than atmospheric pressure, collapse is unable to occur. Otherwise, the analyst should consider other factors such as concrete encasement before deciding how the collapse pressure will be used for analysis.

The penstock's collapse pressure, P_c (psig), is minimum gauge pressure inside a penstock before collapsing. The collapse pressure is generally calculated using the following relationship:

$$P_c = \frac{2E}{1-\nu^2} \left(\frac{t}{D} \right)^3 \quad (5)$$

Where:

- E is the Modulus of Elasticity of the penstock (psi)
- ν is Poisson's ratio of penstock
- t is the thickness penstock wall (typically in inches)
- D is the diameter of the penstock (same unit as t)

The Reclamation case studies presented in this report use a lumped value of 5.02×10^7 psi for $\frac{2E}{1-\nu^2}$ as recommended by the American Water Works Association for steel penstocks (AWWA 2004).

$$P_c = 5.02 \times 10^7 \left(\frac{t}{D} \right)^3 \quad (6)$$

3.1.2. Calculate the Maximum Allowable Air Flow (Second Step)

The air velocity through a vent pipe can be calculated by expressing Bernoulli's equation as a function of pressure and elevation.

$$V_a = \left[2g \frac{144 \left(\frac{P_{atm} - P_{in}}{\gamma} \right) + \Delta Z}{\sum K_s + f(L/D)} \right]^{1/2} \quad (7)$$

Where:

- V_a is the velocity of air in the vent pipe
- $P_{atm} - P_{in}$ is the gage pressure inside the air vent (psig)
- ΔZ is the change in elevation from upstream to downstream (feet)
- $\sum K_s$, is the summation coefficient for minor energy losses through the vent
- f is the Darcy-Weisbach frictional loss coefficient through the vent pipe

D is the vent pipe diameter (typically in feet)
 L is the vent pipe length (same unit as D)
 g is gravitational acceleration (32.2 ft/s²)
 γ is the density of air (lb/ft³)

The gage pressure inside the vent pipe, $P_{atm} - P_{in}$, can effectively be substituted with the collapse pressure, P_c if collapse is possible. If not, the minimum allowable pressure in the pipe based on another threshold. Multiplying equation 7 by the cross-sectional area of the vent pipe results in the following equation:

$$Q_a = A_v \left[2g \frac{144 \left(\frac{P_c}{\gamma} \right) + \Delta Z}{\sum K_s + f(L/D)} \right]^{1/2} \quad (8)$$

Where Q_a is the maximum allowable air flow through the vent before collapsing the penstock from excessive low internal pressure.

3.2. Estimate Air Demand During Gate Closure

Estimating the actual air flow through a gate vent during an un-balanced closure can be a difficult process often requiring a numerical model to compute the transient flow conditions. Such transient flow models often use the method of characteristics to build a one-dimensional finite-difference model to solve hydraulic conditions at discretized locations along the downstream penstock (Wylie and Streeter 1983). The computer program, HFVENT is a FORTRAN program, presented in EM-41, that uses a method of characteristics model to simulate an entire un-balanced gate closure. HFVENT uses special algorithms to account for the air demand from the hydraulic jump as it moves downstream during closure (Falvey 1980). The institutional knowledge of using HFVENT (amongst other similar FORTRAN programs) has diminished in Reclamation, prompting recent air demand studies to develop their own numerical modeling solutions for transient flow conditions. These solutions use a “hybrid” approach that combines a transient flow model with a quasi-steady state model for computing the air demand.

The air demand for some gated-penstock systems cannot be confidently resolved using a numerical model alone due to complex issues. Such issues might include complex geometry of the gated-penstock system, complex hydraulic conditions during an un-balanced gate closure, or complex gate operations. When necessary, Reclamation also uses scaled physical hydraulic models to estimate air demand during simulated un-balanced gate closures. These estimates are often considered alongside numerical modeling estimates allowing the analyst to reasonably justify an air vent design with increased confidence.

3.2.1. Numerical Modeling

The numerical modeling approach presented in the case studies is a hybrid combination of two numerical methods for computing transient flow (except for the Glendo Dam Powerplant 2024 Study).

3.2.1.1. First – Compute Transient Flow through Penstock Gate

The first method computes the gate position at which the pressure head drops below the top of the downstream penstock during a simulated gate closure. Although simplifying assumptions can be made to calculate this value explicitly, a time-stepped approach is preferred for more accurate results. The characteristic method is one such time-stepped approach that can easily be implemented as a one-dimensional forward-time-centered space finite difference model (Wylie and Streeter 1982). Initial conditions assume the gate is fully open and the immediate downstream pressure in the penstock is equal to the reservoir water surface elevation (minus minor losses). As the gate closes, flow through the gate is empirically calculated, often using an established relationship for the gate geometry. This flow is used as an upstream boundary condition to compute the pressure at discrete intervals along the downstream penstock. Numerous algorithms developed for computing transient flow in pipes are publicly available online in a variety of programming languages.

3.2.1.2. Second – Compute Air Demand in Penstock

Air flowing into the penstock is assumed to be the sum of the entrained air into the hydraulic jump (Q_a) and the increased volume of air in the penstock as the hydraulic jump moves downstream ($Q_{a,v}$).

$$\text{Total Air Demand} = Q_a + Q_{a,v} \quad (9)$$

Although some methods of modeling transient flow can be used entirely for a simulated gate closure, such models are more complex and require additional effort and resources often unavailable or outside of the project budget. These also include three-dimensional computational fluid dynamic (CFD) models.

The case studies presented in Section 2.0 use a quasi-steady-state approach for computing air demand using empirical equations for the guard gate positions that produced open channel flow conditions downstream. As the gate continues to close and air is drawn into the penstock, the flow through the gate opening is calculated empirically as before in the first method (section 3.1.1). Flow under the gate is then used to calculate the Froude number immediately upstream of the hydraulic jump in the penstock, as presented in equation 4, as a function of the air velocity, U , and depth of water immediately upstream of the hydraulic jump, d_e . The jet velocity issuing through the gate, U , can be approximated as follows:

$$U = \frac{Q_w}{A_g} \quad (10)$$

Where:

Q_w is the incremental discharge under the gate (ft^3/s)
 A_g is the incremental area of the gate opening (ft^2)

The volumetric flowrate of air, Q_a , due to entrainment into the hydraulic jump can be estimated empirically using the following equation (Kalinske and Robertson 1943):

$$Q_a = Q_w[0.0066(Fr - 1)^{1.4}] \quad (11)$$

The increased volume of air in the penstock as the hydraulic jump moves downstream requires knowing where the hydraulic jump occurs. The case study for Green Mountain Powerplant uses a simplified approach outlined in HL Report 2017-11 that explicitly calculates the velocity of a hydraulic jump, V_{hj} , as it moves downstream during an un-balanced gate closure (Mortensen 2017).

$$V_{hj} = \frac{35.465[T_r]^{-0.704}Q_i}{D_p^2} \quad (12)$$

$$T_r = \frac{T_c Q_i}{D_p^3} \quad (13)$$

Where:

D_p is the inside diameter of the pipe (feet)

Q_i is the steady state water discharge when the gate begins to close (ft³/s)

T_c is the time to fully close the gate (s)

4.0 HFVENT.FOR

The original FORTRAN program developed for Morrow Point Dam and presented in HYD-584 and found in the data file F-734 (Falvey 1968). The program was later improved and documented by Dr. Henry Falvey, who presented an updated version of the program as HFVENT in EM-41 (Reclamation 1980). A note in the data file references some of the improvements were based on 1973 field measurements of the gate chamber air pressure and air inlet velocity during a penstock emergency gate closure test at Morrow Point Dam (PAP-297; Dexter 1973). HFVENT uses the method of characteristics to solve a falling water surface immediately downstream of a closing gate followed by a penstock. The program accounts for the air demand using specialized algorithms developed using assumed air-entrainment/air-water flow conditions (Falvey 1980).

Tony Wahl from Technical Service Center's Hydraulic Investigations and Laboratory Services Group documented the existing HFVENT program. The HFVENT FORTRAN code, presented in EM-41, was digitized using Optical Character Recognition (OCR) and compiled into a Microsoft Windows 10 executable using the GNU FORTRAN compiler. Once compiled, the simulated emergency gate closure at Morrow Point, as presented in EM-41, was recreated using a digitized input file taken from report's appendix. Unfortunately, the executable would not run to full completion due to numerical convergence errors. Although many of these errors were corrected in the FORTRAN code, a suitable program for air demand analysis has yet to be released by Reclamation. Notes from Tony Wahl's effort are included in the appendix of this report (Wahl 2025).

5.0 Conclusions and Recommendations

5.1. Conclusions

This report is intended to be used as a general guideline for air demand studies at facilities like those presented in the four Reclamation case studies. This report is not intended to be used as a design standard for air vent sizing but rather presents an outline that can be used for analyzing the air demand requirement for unbalanced guard gate closures for reservoir outlet works, penstocks, and piping systems in powerplants, and pumping plants. The level of analysis depends on the complexity of the gated penstock system and the air venting system. Although simplified solutions may work for air demands that can easily be accommodated with a vent design, such solutions are often driven by design costs – especially for less complex systems.

The “hybrid” approach for numerically computing transient flow conditions assumes a hydraulic jump forms in the penstock downstream of the gate when the pressure head is below the top of the crown of the conduit. When this happens, the air demand is the combination of air entrained into the hydraulic jump and the displacement of water due to downstream movement of the hydraulic jump. The quasi-steady state approach presented in this report may be suitable for a design analysis, however, there is a lot of uncertainty surrounding the air entrainment equations presented in this report. This uncertainty is also noted in EM-41 (Falvey 1980) and HL Report 2017-11 (Mortensen 2017).

The air vent design criteria this report presents only represents four Reclamation case studies and is not a complete list of criteria and considerations. Considerations may include smooth gate operations, stable air flow conditions within the vent system, personnel safety, and noise. EM-41 provides guidance velocity thresholds for a variety of situations (Falvey 1980).

5.2. Recommendations

This report is an attempt to improve methods for sizing air vents based on air demand during an unbalanced (emergency) gate closure. Although this report offers guidance for similar air vent assessments, Reclamation currently does not have explicit design guidelines.

This report recommends the following steps towards achieving such guidelines:

1. Develop a plan for collecting standardized measurements of the hydraulic conditions during an unbalanced gate closure at various Reclamation facilities. Ideally, all data are directly relatable, however, realistically, some translation will be needed to relate measurements from various facilities. This standardization will be needed to minimize bias when investigating trends and effects. If possible, during an unbalanced gate closure, measurements should sample the pressure in penstock immediately downstream of the gate if possible, flow through the penstock, closing gate position, and air flow into the vent. This plan also needs to list specific facility parameters and measurements needed for analyzing air demand. Most of these parameters and measurements are documented in

as-built drawings and standing operating procedures, however, deficiencies in this documentation may need to be addressed in this plan.

2. Implement the plan for collecting these standardized measurements to develop a database that can be used for investigating how they affect air demand during an unbalanced gate closure. Many facilities conduct routine, emergency gate closure tests, presenting an opportunity for measuring relevant hydraulic conditions during the test. Scaled physical models developed for analyzing air demand can also be included in this data collection effort.
3. Develop a computational model that can easily be implemented in a computer application by designers and analysts. Such application should be well documented and adaptable to a variety of penstock configurations. The application should also be maintained for use on current and future computer operating systems.

In preparation for developing an adaptable computer application, Reclamation should begin collecting a consistent set of measurements of the transient air-water conditions during unbalanced gate closures. Preferably these measurements can be taken during routine testing of emergency gate closures at Reclamation facilities, however, these measurements can also come from physical model studies. Analyzing such a dataset might reveal relationships amongst the transient measurements and the system parameters that can be used to develop a generalized numerical modeling approach. Building such a dataset requires a consistent approach for data collection during these un-balanced gate closures. Ideally, these measurements should include (at minimum) the following samples during a gate closure: WSEL, tailwater elevation, air flow through the vent, gate position, and gate discharge throughout the closure event.

Site specific information collected during unbalanced guard gate closures for a variety of penstock variations should also include geometric attributes that may affect air demand. A large, standard set of data can be used to isolate a particular attribute's effect. Such information can be compiled into design standards and used to achieve desirable outcomes.

All the numerical models presented in this report were uniquely developed for a site-specific air demand assessment. Although HFVENT is presented as a template for application for other facilities, Reclamation lacks the institutional knowledge needed to do so. Furthermore, Reclamation lacks site specific information needed for developing a robust, adaptable computer model for estimating volumetric air flow for a variety of penstock configurations. Numerical estimates of transient air-water flow have large uncertainties due to a current lack of understanding in mathematically describing such a process. This lack of understanding can be reduced by collecting physical data during unbalanced gate closures. Such data can be collected on-site during routine, emergency guard gate closure tests or collected from a scaled physical model during a simulated unbalanced guard gate closure.

Recent advances in three-dimensional computational fluid dynamic (CFD) modeling offer a detailed numerical approach for computing air demand during un-balanced gate closures. While CFD models can better capture the geometry and material properties needed to compute transient water flow, such models still use numerical methods for simulating fluid flow and air entrainment and require verification and validation. Despite this shortcoming in CFD models, a calibrated CFD model can offer insight into the effect of air entrainment. If a physical model is needed to satisfy the accuracy needed for a particular analysis, an accompanying CFD model is recommended (provided resources are available). This CFD model can be substituted for the numerical modeling approach presented in section 3.1.2.

6.0 References

- American Water Works Association. 2004. *M11, Steel Pipe: A Guide for Design and Installation*. 4th ed. Denver, Colorado: American Water Works Association.
- Dexter, R. 1973. Morrow Point Dam Emergency Closure Test. PAP-297. Bureau of Reclamation, Denver, Colorado.
- Falvey, H.T 1968. Air Vent Computations, Morrow Point Dam, Colorado River Storage Project. HYD-584. Bureau of Reclamation, Denver, Colorado.
- . 1980. Air-Flow in Hydraulic Structures. Engineering Monograph No. 41. Bureau of Reclamation, Denver, Colorado.
- Kalinske, A., and J. Robertson. 1943. Closed-Conduit Flow. *Transactions of the American Society of Civil Engineers* 108: 1435–1447.
- Kubitschek, J.P. 2014. Penstock Air Vent Analysis for Helena Valley Pumping Plant. PAP-1085. Bureau of Reclamation, Denver, Colorado.
- . 2022. Air Vent Analysis for 36-in Outlets at Clear Creek Dam. Draft Technical Memorandum. Bureau of Reclamation, Denver, Colorado.
- . 2024. Glendo Fixed Wheel Gate Air Vent Size Assessment. Draft Technical Memorandum. Bureau of Reclamation, Denver, Colorado.
- Mortensen, J.D. 2016. Penstock Air Vent Analysis for Green Mountain Powerplant. PAP-1158. Bureau of Reclamation, Denver, Colorado.
- . 2017. Air Vent Analysis for Penstocks and Low-Level Outlets. Hydraulic Laboratory Report No. 2017-11. Bureau of Reclamation, Denver, Colorado.
- Wahl, T. 2025. Bureau of Reclamation Technical Service Center, Denver, Colorado, personal communication.
- Wylie, E.B., and V.L. Streeter. 1983. Fluid Transients. FEB Press, Ann Arbor, Michigan.

Appendix A

Notes on HFVENT.FOR (unedited compilation by Tony Wahl)

Appendix A: Observations on HFVENT

The HFVENT computer program was developed and improved by Dr. Henry Falvey over a period of several years and was documented in two publications, HYD-584 (1968) and Engineering Monograph 41 (EM-41; 1980). Both publications apply it to the problem of modeling air demand during emergency gate closure at Morrow Point Dam, although the example cases in the two publications are for different reservoir conditions and gate closure rates. The programs were written in early fixed-format FORTRAN and existed only as card decks which have not survived to the present day. Applications of the program to air demand problems at Grand Coulee Third Powerplant have also been found in data file F-734, along with a run for Morrow Point that was performed after the publication of HYD-584 (circa 1969). Each of the runs in F-734 includes an associated program listing, and the code exhibits some improvements over the original in HYD-584, but not all the improvements contained in the EM-41 version. Some of the input data for these various program runs are undocumented, and the input data embedded in the programs do not fully match the field-test conditions.

The original HYD-584 code incorporated site-specific geometric details as numerical constants (not as named variables). The F-734 codes have site-specific geometric details coded as variables, but in many ways the algorithms are very similar to those in the HYD-584 code. There are some unspecified improvements to the algorithms in the F-734 versions compared to the HYD-584 version, and a note in the data file from Dr. Falvey to Bob Dexter indicates that the results in F-734 should correspond more closely to field results from Morrow Point. PAP-297 contains measurements of gate chamber air pressure and air inlet velocity for the Morrow Point field test, and there is also one hand-generated plot made by Bob Dexter on 11/13/1973 that shows water pressure below the gate chamber during the Morrow Point field test. That plot shows prototype and computer-modeled pressures at the end of the gate chamber with a note about a potential timing discrepancy in the prototype data. Comparison of the field data plots in PAP-297 to modern-day runs of the EM-41 program have some discrepancies; air inlet velocities are underpredicted and the gate chamber pressure drops a little more than was observed in the field. Some questions are unresolved about this field test and about the Morrow Point application in general, as PAP-297 reports the gate to be 17-ft high (in the text of the report), while all drawings show the gate to be 16.07 ft high x 13.5 ft wide. The computer code listings in F-734 define the gate height as 16.43 ft and area as 222.13 ft² (implied width = 13.52 ft). The computer code in HYD-584 also shows the gate area to be 222.13 ft², but the gate height cannot be readily located in the code as a separate variable or constant. The runs of the F-734 computer code did not use the actual reservoir head from the field test, so comparisons between it and field test results are somewhat qualitative. Also, it is not known which turbine/penstock unit was used for the field test (No. 1, which is on the left at the reservoir but feeds the right-hand turbine in the powerhouse, or No. 2 which feeds the left-hand turbine). They do have different air vent system geometries and different penstock profiles and alignments.

The Morrow Point model runs in HYD-584 and F-734 all assumed a friction factor $FRICT=0.93$. Subsequent investigation of the air vent system geometries for Morrow Point suggested $FRICT=2.14$ and $FRICT=4.65$ for penstocks 1 and 2, respectively. The larger values are driven mostly by consideration for losses caused by mitered 90° bends in the air ducts. Using these values with the other input data given for HYD-584, the maximum air inlet velocities drop from 63 m/s ($FRICT=0.93$) at time $t=62.5$ s to 60 m/s and 55 m/s, respectively. For comparison, the maximum air inlet velocity in the F-734 program run was 58.4 m/s (191.5 ft/s) at 62 s. Unfortunately, applying $FRICT=2.14$ to a program run that matches the conditions described for the PAP-297 field test case causes the program to halt with an error stating that vapor pressure occurs in the gate chamber after about 12 seconds, but the data leading up to the time of the calculation halt do not suggest that this is about to happen, so it seems likely that this is an unresolved numerical instability of the code. Setting $FRICT=4.65$ also produces a vapor pressure error after about 24 seconds of simulation time. With these input parameters it seems like the velocity of the water surface in the penstock and gate chamber is blowing up at some point.

Further improvements of the code appear to have occurred between the time of F-734 and the subsequent publication of the program listing in EM-41. The latest version of the program in EM-41 incorporated improved modeling of some aspects of the problem, most specifically the possibility for a submerged hydraulic jump on the downstream side of the closing gate (feature described in the text of EM-41, but not specifically located in the code) and the possibility for different modes of turbine operation during gate closure (constant speed or varying speed, i.e., uncontrolled). The program was also made more general, with the ability to operate in English or metric units and with site-specific details provided through initial variable assignments that are well commented in the code. Two site-specific details appear in the functions FUNCT1 and FUNCT3: an equation for the gate discharge coefficient and a formula for computing the length of the water column in the penstock as a function of the falling water surface elevation. For the discharge coefficient, the same equation was used in both the Morrow Point and Grand Coulee III applications of the program, so apparently this function may apply universally to the class of gates installed at these two dams. Equations related to the compressible air flow in the vent system are contained in subroutine AMACH, and these might require some site-specific adjustments for other applications, although again they appear to be the same in all existing versions of the programs. One other notable difference is that the EM-41 version of the program uses a different implementation of the Taylor series integration correction procedure in subroutines DE2 and DE1.

The program source code from EM-41 (1980) was scanned and converted to text using Optical Character Recognition (OCR) to recreate the source code. The code was recompiled using the modern, open-source GNU FORTRAN compiler (g77). Extensive testing and careful checking of the code was needed to eliminate typographical errors introduced during the scanning/OCR process. During this checking process, the following issues were noted in the previous codes and documentation:

- SUBROUTINE Q – In the EM-41 version of the program, the equation for QR in the case of $JFIRST \geq 7$ has the signs reversed on the term $(PGC-PTOHD*PATM)$ when compared to the similar equation in the HYD-584 program listing. The HYD-584 equation seems correct, since the gate chamber pressure should be subtracted from the

reservoir head to obtain net head across the gate. However, further confusion is created by the text of the HYD-584 report. It again reverses the signs when the equations are discussed in the report (eq. 1b), and there is also confusion regarding whether the correct equations are being associated with free and submerged flow. Eq. 1a in the HYD-584 report is described as being for submerged flow but has a net-head formulation with an undefined P_R term being subtracted from the reservoir head, but does not show up at all in subroutine Q, and Eq. 1b is described as being a free flow equation, but also has a net-head formulation, except that the gate chamber pressure is inexplicably added to the reservoir head. For now, I have kept the signs as shown in the EM-41 program listing. (The Grand Coulee listings in F-734 use the same signs as the EM-41 listing). In limited testing on the Morrow Point case, this section of code never actually executed.

- Figure III-4 (EM-41) – The y-intercept of the air volume curve is shown as ELC1 but should be GCLP. As implemented in the code, ELC1 is the elevation at which the air volume curve sharply changes slope. The correct equation for air volume when the water surface is in the upper portion of the penstock should be $AVOL=(GCLP-WS)*VOLC1$. Also, the VOLC1 and VOLC2 variables are areas in m^2 or ft^2 , not volumes. They are the approximate water surfaces areas where the water level is in the upper and lower penstock zones, respectively.
- The HYD-584 version of the code contains an error in subroutine DE2. The line that computes $B2=RKY(K)+AP2/2$. should have the AP2 replaced with AL2. This line of code is correct in the later F-734 and EM-41 versions of HFVENT. A test was run in which this bug was recreated, and the effect was negligible. The DE2 routine still produced essentially the same results, presumably due to the robustness of the Runge-Kutta scheme with the Taylor series integration correction procedure.
- The EM-41 code fails to declare variable MACH as REAL, causing the EQ(MACH) function in subroutine AMACH to incorrectly compile with MACH assumed to be an integer (the FORTRAN default for variables beginning with 'M'). MACH is declared REAL in the HYD-584 and F-734 programs. Either the compiler used for the EM-41 program was more forgiving, or this error was corrected but not shown in the program listing, since the program fails utterly if MACH is an integer.
- Code in subroutines DE2 and DE1 is meant to save the maximum value of the integration errors (output in variables DX and DY) and potentially employ simplified solution techniques when the integration errors are too large was miswritten in the EM-41 program so that the saved integration errors were always zero. This code was modified to correctly save the integration errors and compare them to the ACURAC variable. (The EM-41 code defined the ACURAC variable so that the integration error test could be made units-independent, but the variable was unused). The integration errors still seem to be very small in most cases and are usually reported as effectively zero. In limited testing, the situation this code was meant to handle occurred very rarely.
- The TMAX variable does not work as described in the EM-41 code comments for all possible settings of DELT. The code as published in EM-41 runs for a simulation time of 80 seconds even though $TMAX=40$.

- COMMON blocks in some subroutines reassigned the variable name used to index time increments (J) and then used J for simple loop counting in the subroutines. This was not causing problems, but it is a poor programming practice that makes the code difficult to decipher. These COMMON blocks and routines were changed to make variable names match in all COMMON blocks and use J as an index only in the main program. A few subroutines now use JJ where they previously used J. (COMMON blocks are forbidden in modern FORTRAN because of the debugging problems they can create).
- Problems were found with the MOON loop solver in subroutine AMACH. Following the call to NEWX, a line to save the newly calculated function value C1 in variable C2 was missing, so the routine was always attempting to make its next best estimate prediction of the solution point based on the initial value of C2=-0.01. This error was corrected and the NEWX routine was subsequently replaced with a better solver.
- The program was found to have significant difficulty reliably converging in the AMACH subroutine that iteratively solves for the Mach number at the air vent. Four different iterative loops (including the MOON loop mentioned above) all were calling the NEWX routine which employed a crude marching process to approach the solution. This routine was replaced with a NEWTON subroutine that employs a Newton's method-type solver. The Newton's method solver was initially written to use directly calculated derivatives of the EQ(MACH) function where possible, but this solver was overly sensitive and prone to diverge irretrievably from the desired solution in some cases. Ultimately, the routine was written to make a numerical approximation of the derivative using function values at two nearby points and to use a purposefully relaxed estimation process to gradually work its way toward a solution. As the process approaches the solution, the relaxation is gradually reduced so that a more exact estimate can be made. With appropriately small time steps (DELT) this routine seemed to be more reliable than the NEWX method, although there are still scenarios in which convergence can be difficult to achieve. The convergence routine for the main loop in AMACH (which solves for M1I) was also modified to save the "best" guess of all those tried, since it was found that the relation between M1I guesses and the calculated pressure error (the test parameter for evaluating convergence) was not always well behaved.
- Problems were found in the FUNCT3 function with the formulas and code used to compute the surface area of the falling water surface in the penstock. The HYD-584 program did not include this calculation, but the F-734 and EM-41 programs both contain this code or its equivalent:

```

7 IF (WS.GE.GCLP) GOTO 8
PL= WS-PENLEN
SURAR= CF*SIN( (GCLP-WS) /PER)
IF (SURAR.LE.CAREA) SURAR= CAREA
8 IF (ABS (GCLP-WS) .LE.DP/4.) SURAR= AREAP
VWS= (AREAP*BC-QRTST) /SURAR

```

Several problems are present here. First, the formula for SURAR is missing a factor of 2π , which is necessary because the FORTRAN SIN function accepts an angle in radians as input. The correct formula is shown on Figure III-5 in EM-41, but the FORTRAN code in EM-41 (and in the programs contained in F-734) uses the incorrect equation. The correct equation is:

$$\text{SURAR} = \text{CF} * \text{SIN} (2 * \text{PI} * (\text{GCLP} - \text{WS}) / \text{PER})$$

The second problem occurs when GCLP-WS exceeds PER (the period for the SIN function). The SIN function is meant to only apply when GCLP-WS is less than PER/2 (see figure III-5 in EM-41), but the code never checks to see if that condition has been exceeded. When PER is exceeded, the SIN function will again cause SURAR to exceed CAREA. Finally, the check at label “8” limits the water surface area to the penstock cross-sectional area, AREAP (why not CAREA?) but only if the water surface WS is $\pm 1/4$ penstock diameter above or below the bottom of the gate chamber (GCLP). The reason for this is not apparent. For even lower water surfaces this will not apply and the check for SURAR.LE.CAREA will not limit the water surface area to CAREA as intended, since the SIN function will be causing SURAR to be greater than CAREA again. It should also be noted that the case of WS.GE.GCLP should never occur, since FUNCT3 is only called when the water surface has dropped below the bottom of the gate chamber. Correct code to implement the water surface area function as described in EM-41 is:

```

7 IF (WS.GE.GCLP) SURAR=AD (this probably never applies)
IF (WS.GE.GCLP) GOTO 8
PL= WS-PENLEN
SURAR= CF*SIN(2.*PI*(GCLP-WS)/PER)
IF (SURAR.LE.CAREA) SURAR= CAREA
IF (GCLP-WS.GE.PER/2.) SURAR=CAREA
8 VWS= (AREAP*BC-QRTST) /SURAR

```

Subsequent testing showed that fixing these problems had a small effect when the EM-41 Morrow Point scenario was run and an almost negligible effect for the HYD-584 Morrow Point scenario. The effect of the surface area adjustment is apparently very minor in comparison to other factors in the equations being solved.

- One additional issue was noted while examining this section of code. The calculation of the length of the water column in the penstock, PL, is site-specific, and the formulas used to calculate it have varied in the different programs.

HYD-584	$PL = 1.14 * WS - 7652.08 = 1.14(WS - 6712.35)$
F-734	$PL = WS - 6615.75$

EM-41 (metric)	$PL = WS - \text{PENLEN} = WS - 2016.48 \text{ m}$ $PL = WS - 6615.75 \text{ ft}$
----------------	--

The length of a full penstock is defined in all the programs to be 471 ft for Morrow Point, and the formulas used in F-734 and EM-41 reduce the penstock length from that value by 1 ft for each 1 ft drop in water surface, implying that the penstock is vertical. However, the upper penstock is horizontal and the lower penstock is inclined at about 67.5° for the Morrow Point case. The formulas in F-734 and EM-41 do not account for the horizontal section, the bend, or the slope of the lower section. The formula used in HYD-584 appears to attempt to account for the slope of the lower section of the penstock, but does so in a way that creates a discontinuity, since the penstock length when the penstock just begins to drain ($WS = \text{GCLP} = 7086.78 \text{ ft}$) is calculated to be only 427 ft. A more complex penstock length calculation might be warranted, but there will always be a challenge to compute a realistic effective length when the water surface is within the horizontal sections at the top and bottom of the penstock. Since the exact location of a hydraulic jump is not predicted by the program, any estimate of the effective penstock length will be crude at best. In the Grand Coulee III applications of the program, a more complicated site-specific function for the penstock length is used and is programmed as an inline function within the FUNCT3 routine. It is important to be aware that this site-specific function must be developed for each application and must be added to the program in the FUNCT3 routine. Note that subsequent testing of alternative PL equations for the Morrow Point full-reservoir case (i.e., HYD-584) showed negligible effect, except that any discontinuity in the penstock length function seems to create difficulties with numerical convergence as the water surface drops out of the gate chamber. Also, it was noted that the two penstocks at Morrow Point Dam each have unique geometries (as do the air vent ducts). Nothing in the HYD-584 or EM-41 documents states explicitly which penstock system was modeled.

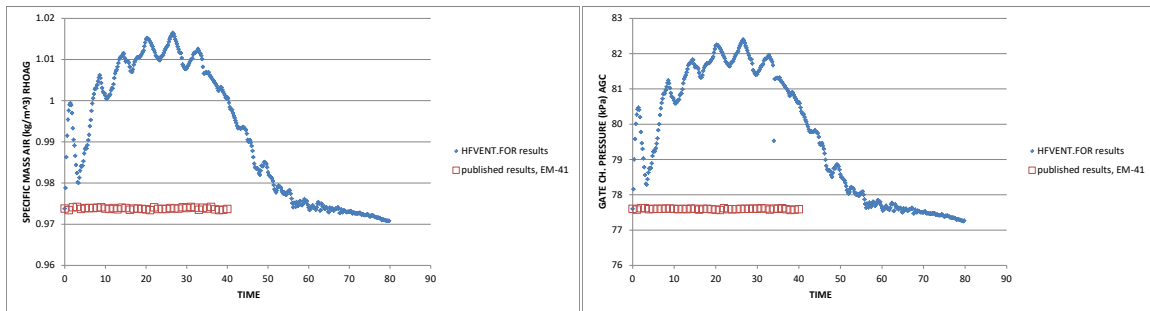
- One final issue was noted with the formulas used to calculate the vapor pressure head of water. The formulas are reasonably accurate up to a water temperature of about 80 degrees Fahrenheit ($^\circ\text{F}$) (about 25 degrees Celsius [$^\circ\text{C}$]) but then diverge rapidly from handbook values. New fourth-order polynomial equations were developed that are accurate from 0–100 $^\circ\text{C}$. This change has negligible impact for all the scenarios to which the program has been applied.

To test the resurrected code, it was applied to the example cases given in EM-41 and HYD-584. The solver improvements discussed above were made, but no changes were made to the FUNCT3 routines for calculating SURAR and PL, since the objective was to compare the resurrected program to the original program runs. Spreadsheets were set up to enable graphical comparison of the previously published program output and that obtained from the resurrected program.

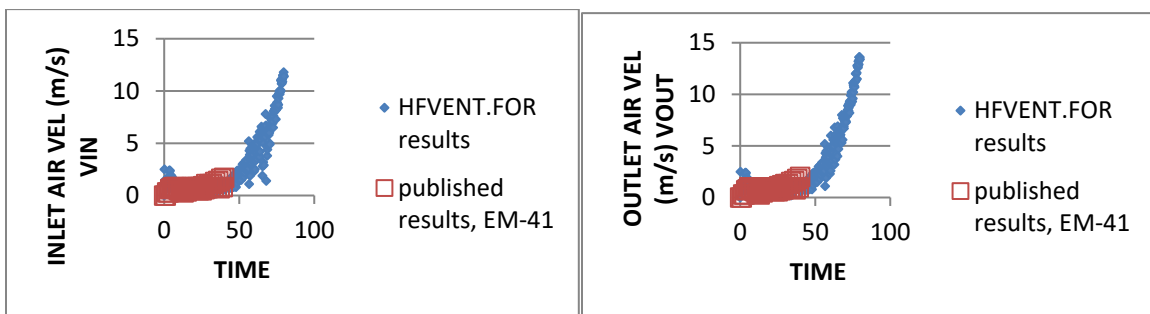
The application to the EM-41 case produced reasonable agreement, but not exact reproduction of the EM-41 results. This included runs in which the exact code as printed in EM-41 was used (with none of the issues described above addressed). These runs failed to converge in subroutine AMACH. To get the EM-41 simulation to run reliably, the improvements described above were made and the time increment for calculations was reduced from 1.0 to 0.2 seconds.

Unfortunately, EM-41 provides only 40 seconds of printed output (output was presumably truncated to save space in the publication), and the most interesting part of the simulation (increasing air vent flow rates) occurs at time 50 seconds and beyond. This case also is not a dramatic one, as the gate closing rate is relatively slow and the initial conditions are not at maximum turbine output. Notable discrepancies in the output include:

- The specific mass of air and gate chamber pressure deviate significantly in the simulation from the initial conditions, but the published output shows these variables to be nearly static.
- Inlet and outlet air velocities exhibit more random fluctuation than the published results but are generally similar.

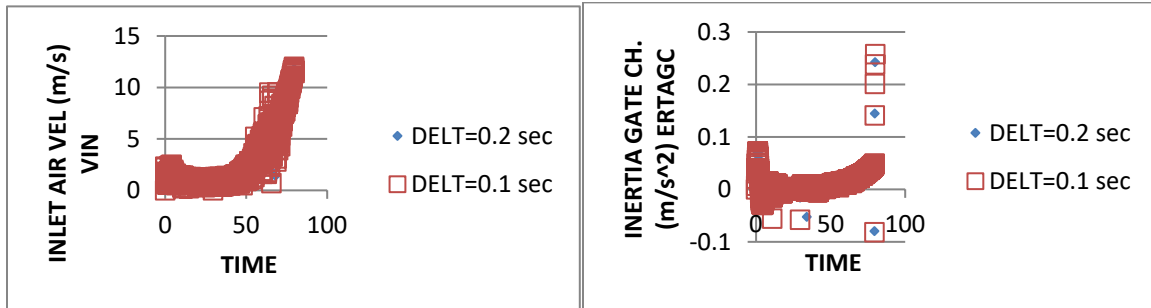


Deviation of specific mass of air. The differences appear dramatic on this scale but are actually relatively small.



A test run was made in which the time increment for calculations was further reduced to DELT=0.1 sec.

The results did not change dramatically, but pseudo-random periodic oscillation of some of the output parameters seemed to diminish further with smaller time steps. This suggests that the solution is still sensitive to some numerical convergence errors at $\Delta T = 0.2$ sec.

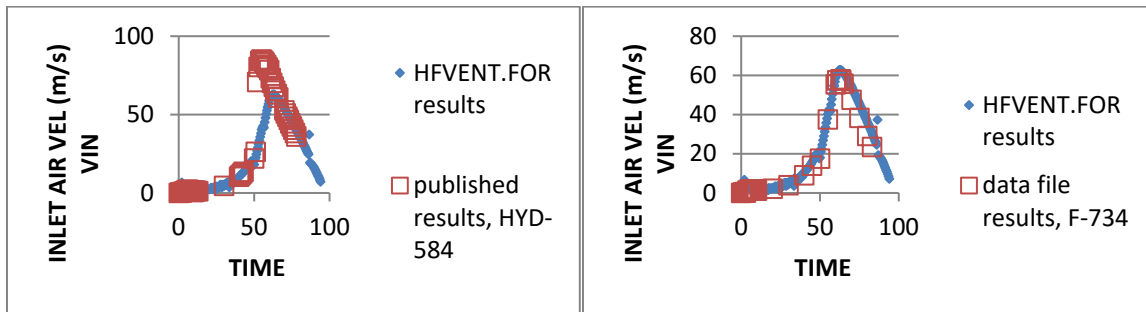


Because the EM-41 published output did not provide a fully satisfactory test case (truncated output, lack of interesting air flow conditions), the program was also run with the HYD-584 example conditions (maximum reservoir and faster gate closing rate, with turbine speed uncontrolled). This offered a greater chance to compare output, since the HYD-584 output includes Mach numbers at the inlet and exit of the air vent and inertial terms in the gate chamber ($ERTAGC = FUNCT2$) and penstock ($ENRTAP = FUNCT1$ or $FUNCT3$). Highlights of the comparison of these results include:

- Minor deviations in discharge from the gate chamber and penstock pressure,
- About 25 percent more air demand when the water surface enters the penstock, with air inlet velocities peaking at 85 m/s, versus 63 m/s in the published results.
 - A subsequent comparison to the printed output from 1969 in the F-734 data file shows much closer agreement of air flow rates.
- Mach numbers higher at the air vent inlet and outlet, consistent with the greater air demand.
 - Again, there is much closer agreement when the results are compared to the 1969 Morrow Point runs in data file F-734.
- Inertial terms that are dramatically different from those in the published HYD-584 and F-734 results (opposite in sign in the gate chamber and opposite in sign and of significantly greater magnitude in the penstock). These differences may be due to EM-41's fundamental changes in the momentum equation being applied to the gate chamber and penstock.

A better comparison for the results of the HYD-584 example case (maximum reservoir and fast gate closing rate, with turbine speed uncontrolled) is the output provided in data file F-734. Notes in this data file suggest that program improvements were made after HYD-584 was published and that the results in F-734 were much closer to observed field performance. Presumably, these program improvements were carried forward into the EM-41 version of the

program. Indeed, this comparison showed that the EM-41 program produces results that closely match the F-734 output.



Note closer agreement of results to F-734 output than to HYD-584 output.

Grand Coulee III Application

It would be desirable to verify that the resurrected EM-41 program produces results consistent with the analysis of Grand Coulee III contained in data file F-734. Most of the necessary input data can be obtained from the program output and program listings in F-734.

Wicket Gate	Air Vent	Turbine TLOSS	Starting Reservoir Elev., ft (RES)
11°	Two 4.0-ft x 4.5-ft (final design)	164	1287.68
15°		93	1285.92
20°		58	1283.47
11°	Two 3.0-ft x 4.5-ft	164	1287.68
15°		93	1285.92
20°		58	1283.47
26°		40	1280.56
34°		30	1277.45

Fixed input parameters for all Grand Coulee III runs are:

- NSPEED=0
- HMOTOR=N/A
- GCR=100./180. (180 second closing time)
- PATM=14.20 psi
- FRICT=0.93 (???? see below)
- TW=958 ft
- UGCLGC=1208.5 ft
- ZP=1120 ft
- TGC=1295.08 ft
- AU=204 ft²
- AD=68.09 ft²
- AG=1261.5 ft²
- NVENTS=2
- VOLC1=4998 ft²
- VOLC2=1758 ft²
- ELC1=1119.12 ft
- ELC2=1235.34 ft
- PL=483.41 ft
- PL(WS)=483.41-SQRT(ABS(1160-WS)/0.00127)
- DP=40 ft
- SO=43.5 ft
- HYDDIA=2.54*4=10.16 ft
- CF=6360 ft²
- PER=80 ft
- CAREA=1758 ft²

A couple of issues arise:

- The F-734 programs used HYDRAD, whereas the EM-41 program uses HYDDIA (for the lower gate chamber). HYDDIA is typically defined as $4A/P$, where A and P are the flow area and wetted perimeter, respectively, so $HYDDIA=4*HYDRAD$. This variable is used in FUNCT2, and the formulas used to compute FUNCT2 are significantly different in the EM-41 program from those used in the F-734 and HYD-584 programs, so it is not immediately obvious that it is equivalent to set $HYDDIA=4*HYDRAD$. Unfortunately, EM-41 documentation does not explicitly say how HYDDIA should be determined. The Morrow Point applications of the program use $HYDRAD=1.19$ ft (F-734) and $HYDDIA=1.41$ m (EM-41). These are slightly different from $HYDDIA=4*HYDRAD$, since $4*1.19 = 4.76$ ft = 1.45 m, not 1.41 m. Presumably in the later EM-41 use of the program there was new information about the exact size of the gate chamber.

- Although most input parameters are coded into the program directly, a separate data input card was meant to provide values of DELT, PATM, SPWTA, AVENT, FRICT, GCR, PGCINC, and MINC for each run. These data values are not reported in data file F-734, so there is not definite knowledge of exactly what input data led to the output provided in the data file. However, the SPWTA variable is not used in the EM-41 program and values of PGCINC and MINC are the tolerances for numerical convergence, which generally have fixed values. The values of DELT (calculation time step), PATM (atmospheric pressure), AVENT (vent area), and GCR (gate closing rate) can be easily found or deduced from the output. The one variable that cannot be readily determined is FRICT, the value of the incompressible friction factor for air flow in the duct zone (fL/D). For the Morrow Point case the programs were always run with $FRICT=0.93$, but the individual values of f , L , and D were not documented and the method for separately estimating f was not described. It may have been estimated by a straightforward use of the Moody diagram for steady air flow in the duct, or alternately there is some discussion of friction factors in HYD-584 (equations 29-31), but it is not immediately clear how this applies. For the Grand Coulee III case, drawings of the air vent system were initially not available, so for initial runs, FRICT was set equal to 0.93, the same value used for Morrow Point.

Using $DELT=0.05$ sec, the program was run for the eight cases previously listed, with the following results:

Wicket Gate	Air Vent	F-734		EM-41 Program Result	
		Max Air Inlet Velocity (ft/s)	Time of Maximum (s)	Max Air Inlet Velocity (ft/s)	Time of Maximum (s)
11° *	Two	258.7	185	239.5	186
15°	4.0-ft x 4.5-ft (final design)	289	183	274	182.8
20°		284.7	180	267.6	180.8
11° **	Two 3.0-ft x 4.5-ft	346.2	185	308.1*	187.8
15°		387.5	184	345.1	184
20°		381.8	181	340.5	181.4
26°		339.3	175	309.9	173.7
34° ***		319.4	145	282.7	144
		304.3	165	282.5	162.6

* The 11° gate opening with 4 x 4.5-ft air vent was run with $DELT=0.005$ s.

** The 11° gate opening with 3 x 4.5-ft air vent was run with $DELT=0.02$ s to avoid numerical convergence problems.

*** The 34° case experiences a double peak.

To test the sensitivity of results to the FRICT variable, the 20° case with two 3 x 4.5-ft air vents was run with $FRICT=0.93$, $FRICT=4$, and $FRICT = 0.1$. Maximum air inlet velocities were 340.5 ft/s, 262.8 ft/s, and 379.9 ft/s, respectively. This demonstrates that results are sensitive to this variable and more accurate results might be obtained with further investigation to determine the proper value for the Grand Coulee III case. Subsequently, drawings of the Grand Coulee air vents were obtained and a steady-flow analysis suggested that $FRICT=0.056$ was a reasonable

value. Using this parameter, the peak air flow velocity at the inlet is predicted to be 386.4 ft/s at 181.1 s, slightly larger than the F-734 result.

Re-running each of the cases with best estimates of FRICT produces the following results:

Wicket Gate	Air Vent	F-734		EM-41 Program Result	
		Max Air Inlet Velocity (ft/s)	Time of Maximum (s)	Max Air Inlet Velocity (ft/s)	Time of Maximum (s)
11° *	Two	258.7	185	251.1	184.88
15°	4.0-ft x 4.5-ft	289	183	294.9	182.3
20°	(final design)	284.7	180	287.4	180.75
11° **	Two 3.0-ft x 4.5-ft	346.2	185	336.6*	186.36
15°		387.5	184	393.9	183.3
20°		381.8	181	386.4	181.1
26°		339.3	175	340.7	174.0
34° ***		319.4	145	308.7	144.1
		304.3	165	304.2	163.1

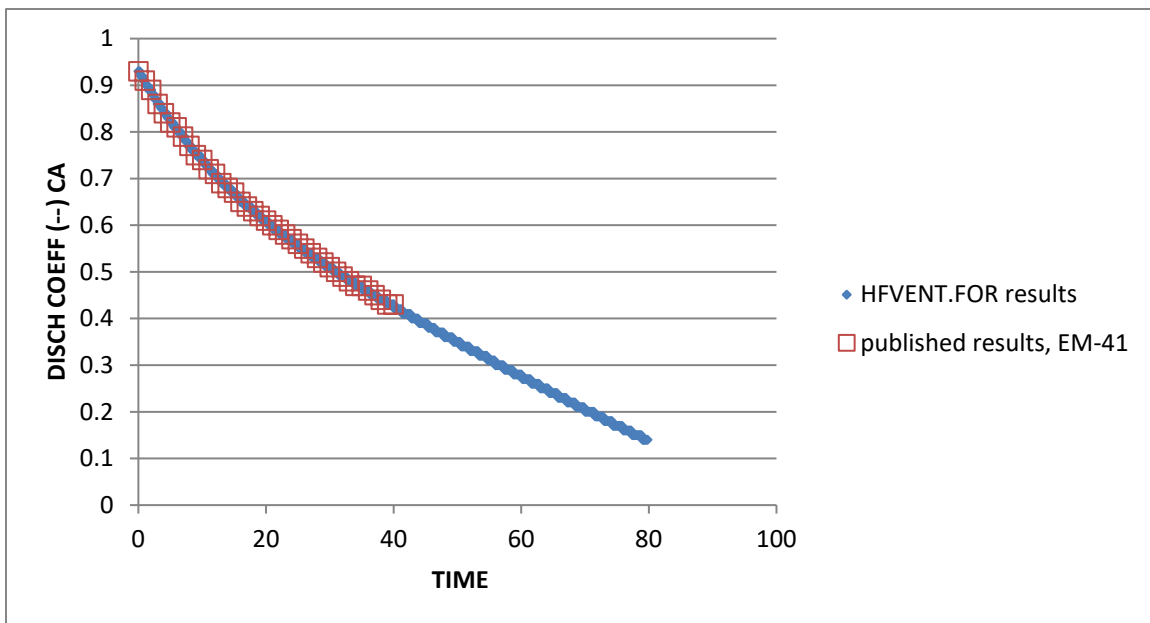
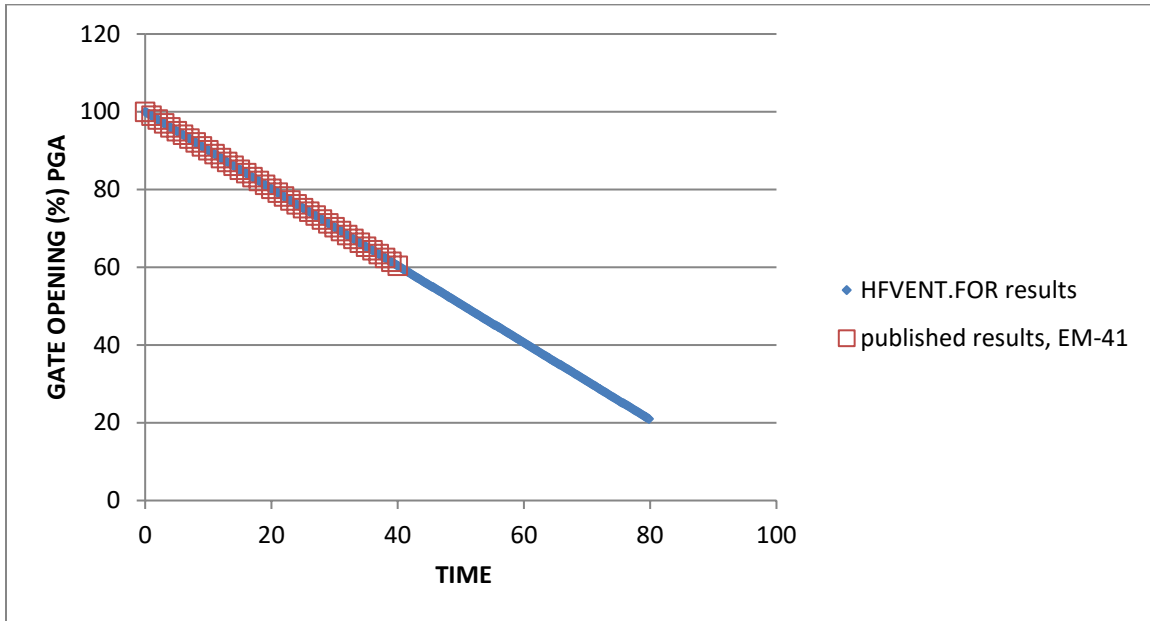
Overall, the results are very encouraging. Maximum air inlet velocities and the timing of the maximum air demand are very close, and although F-734 results were not plotted, from a cursory inspection the general character of the air demand versus time curve seems similar.

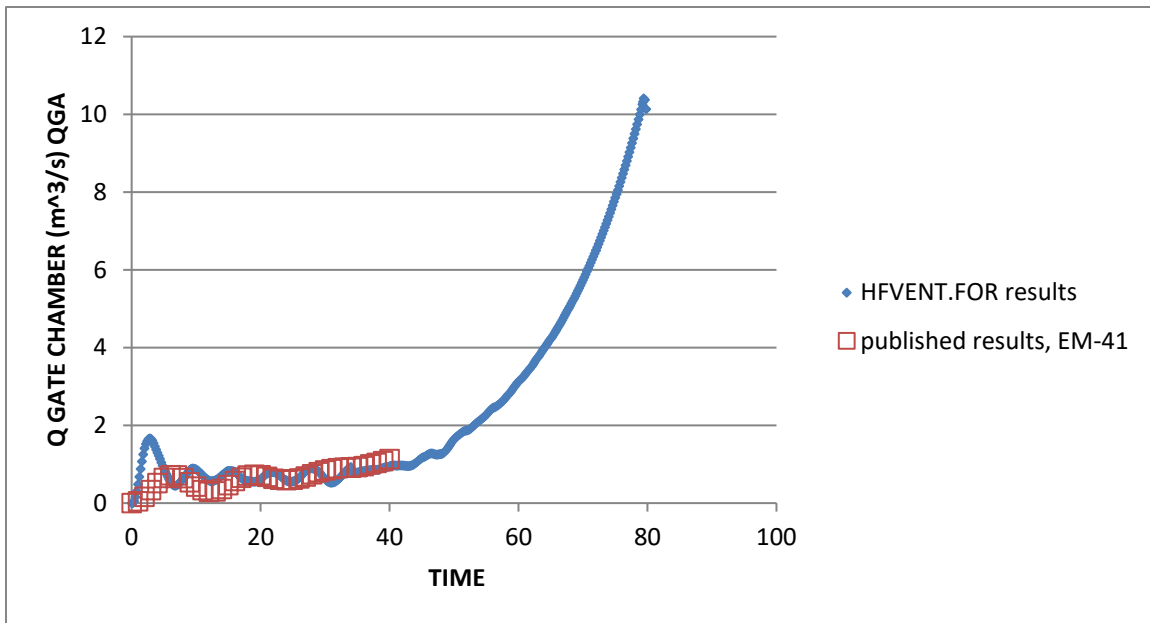
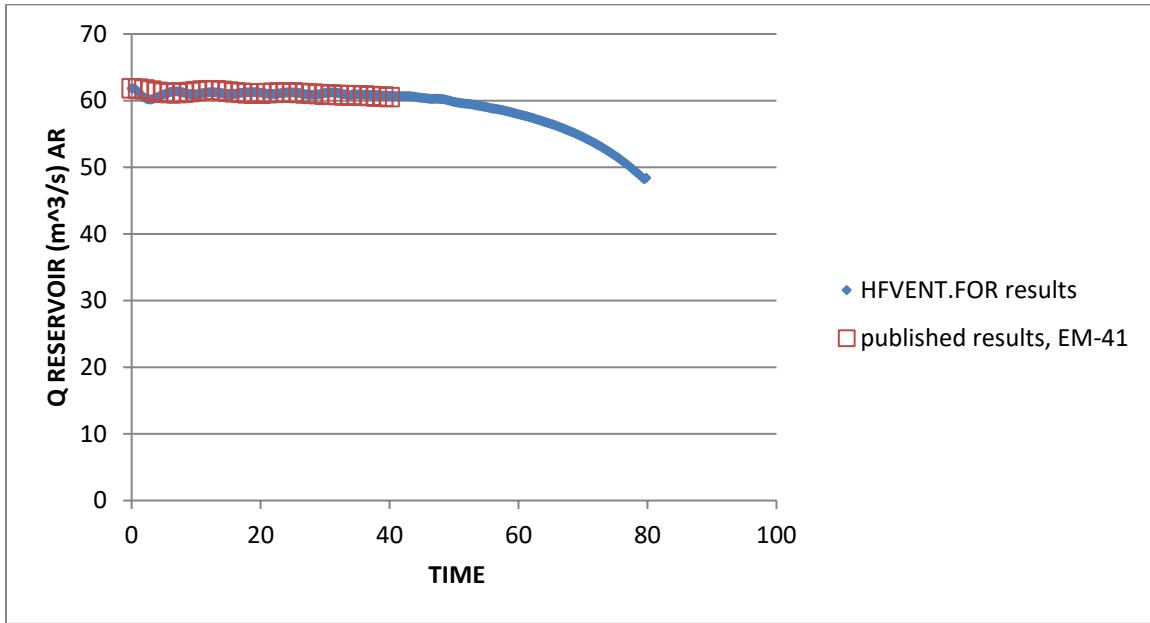
The one troubling aspect of the EM-41 program is the need to use shorter time steps and still occasional problems achieving convergence, even with the use of small time steps.

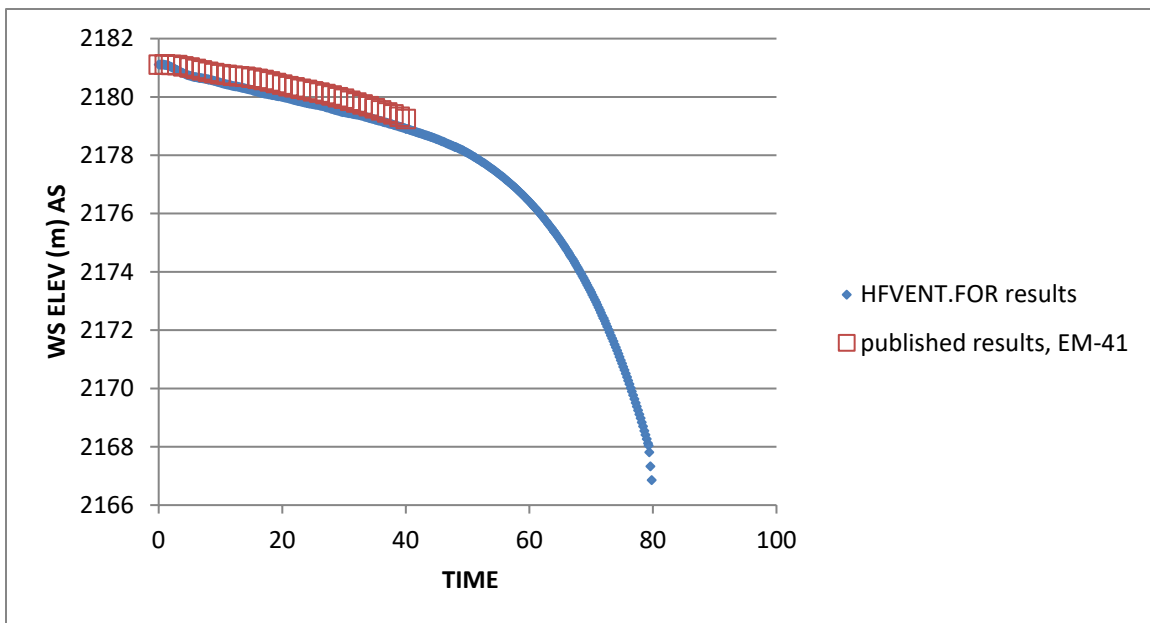
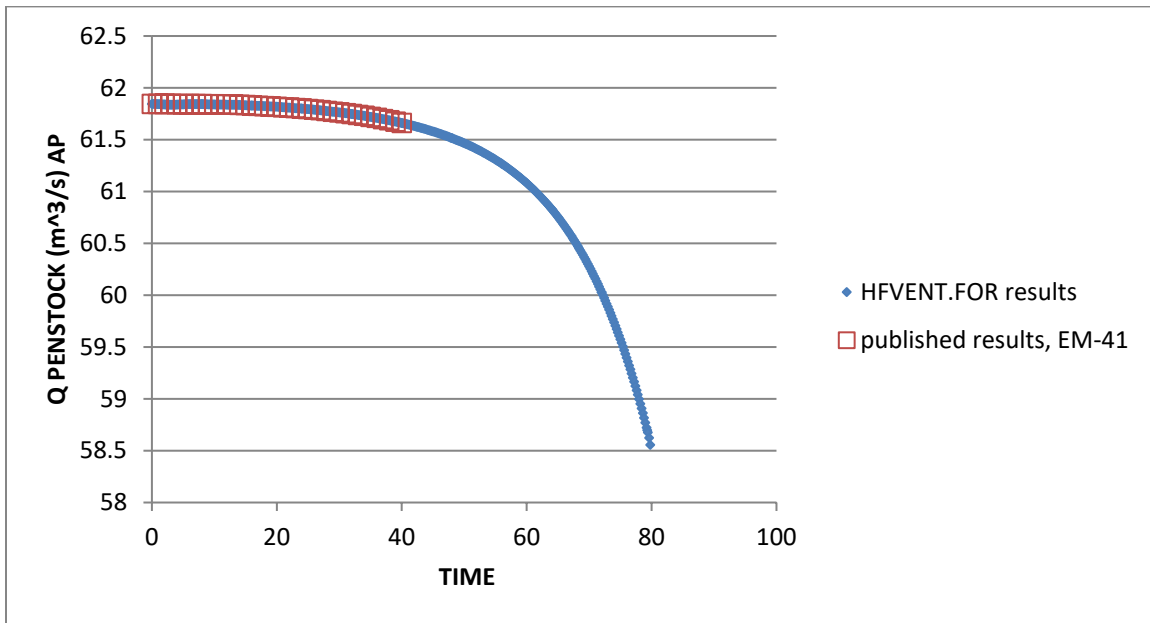
Comparison to EM-41 Published Output

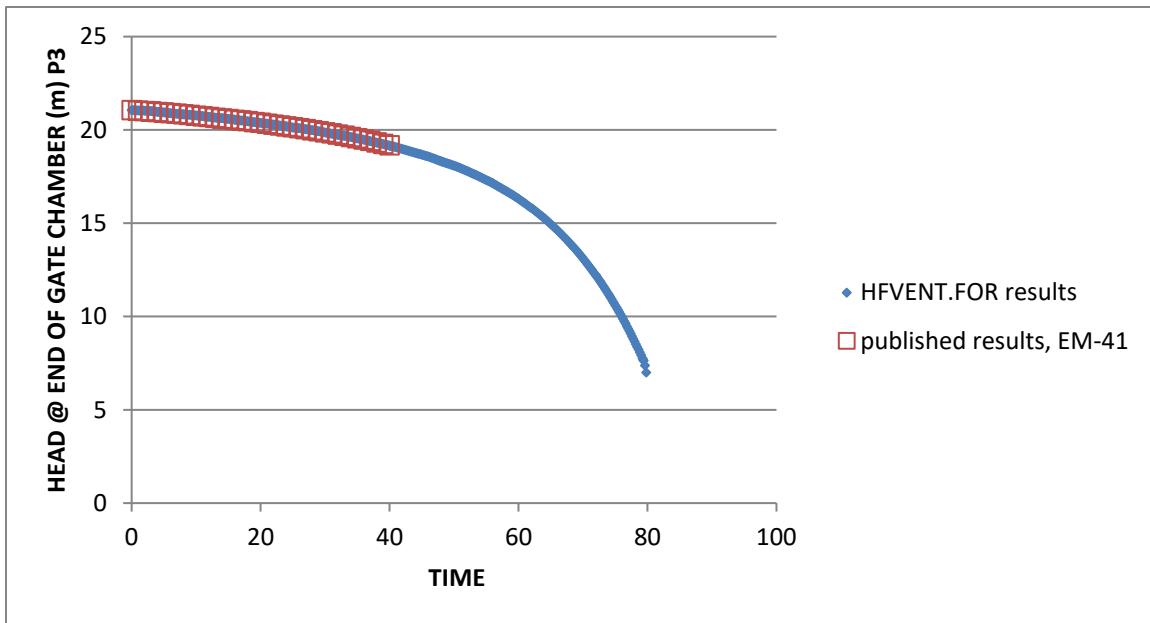
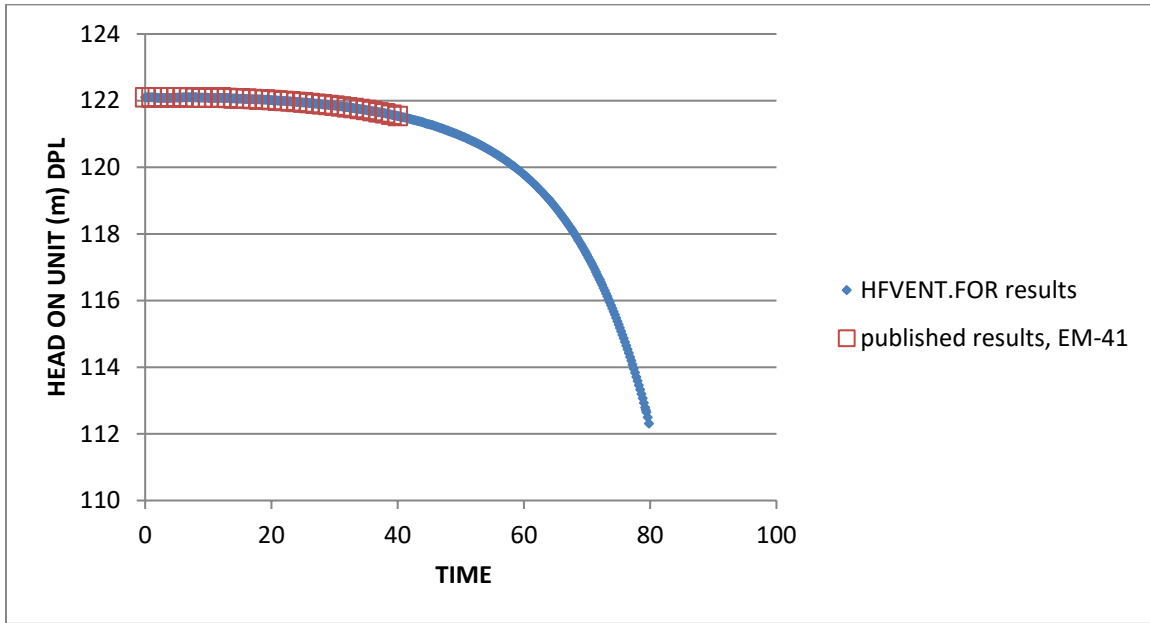
Notable input data:

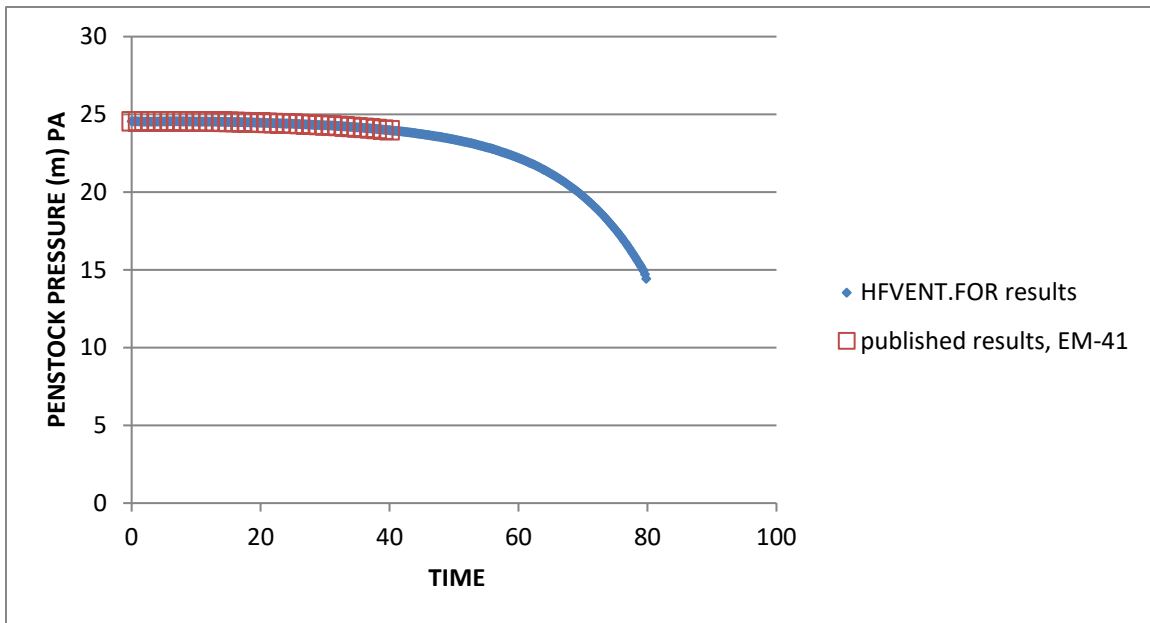
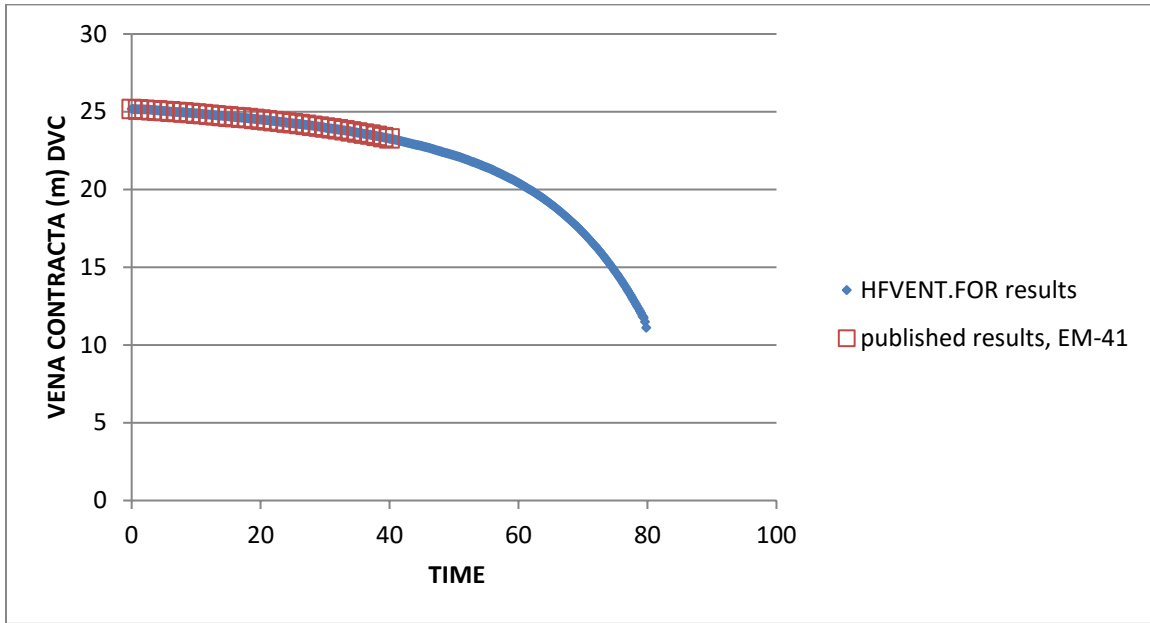
- DELT=0.2
- TLOSS=111.2
- NSPEED=1
- HMOTOR=27.5
- GCR=0.9901 (101 second closing time)
- PATM=77.6 kPa (11.255 psi)
- FRICT=0.93
- RES=2181.64 m (7157.61 ft)
- TW=2059.23 m (6756.00 ft)
- UGCLGC=2168.04 m (7112.99 ft)
- ZP=2155.93 m (7073.26 ft)
- TGC=2183.89 m (7164.99 ft)
- AU=13.80 m²
- AD=4.33 m²
- AG=20.64 m²
- AVENT=0.766 m²
- NVENTS=1
- VOLC1=46.16 m²
- VOLC2=13.3 m²
- ELC1=2155.93 m (7073.26 ft)
- ELC2=2170.21 m (7120.11 ft)
- PL=143.56 m (471 ft)
- PENLEN=2016.48 m (6615.75 ft)
- DP=4.12 m
- SO=5.01 m
- HYDDIA=1.41 m
- CF=48.83 m²
- PER=8.23 m
- CAREA=13.5 m²

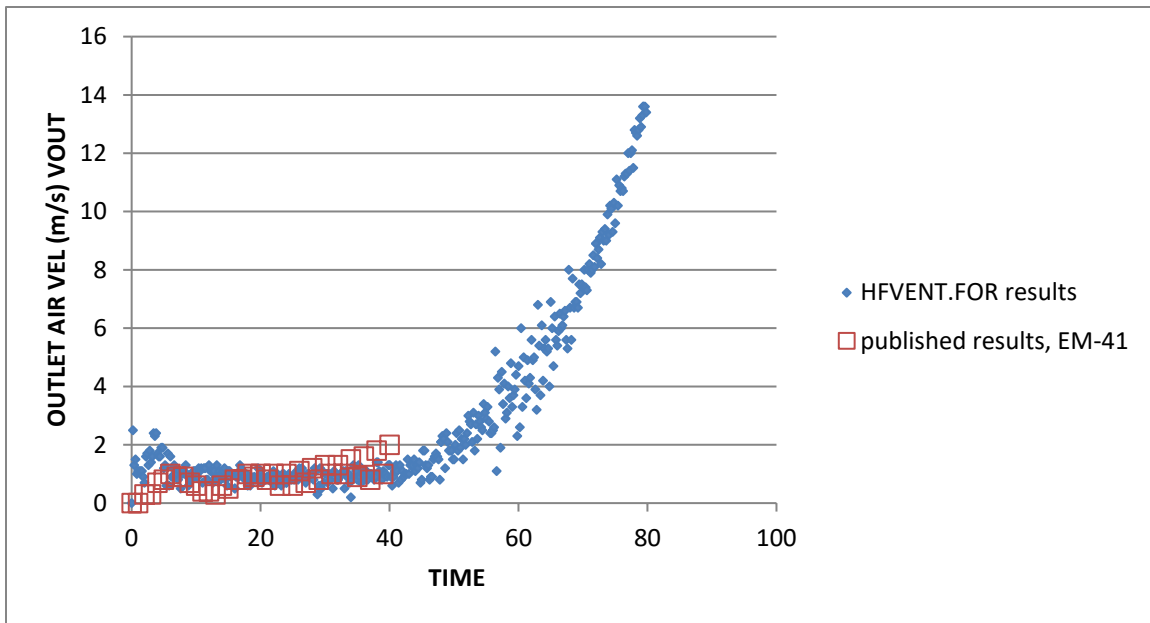
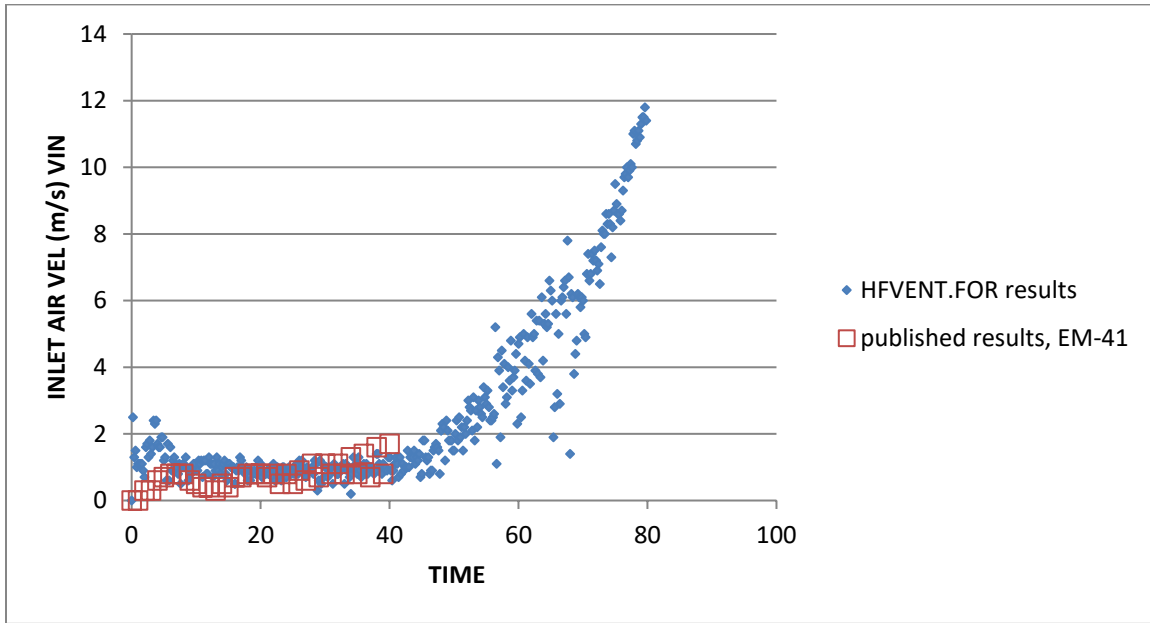


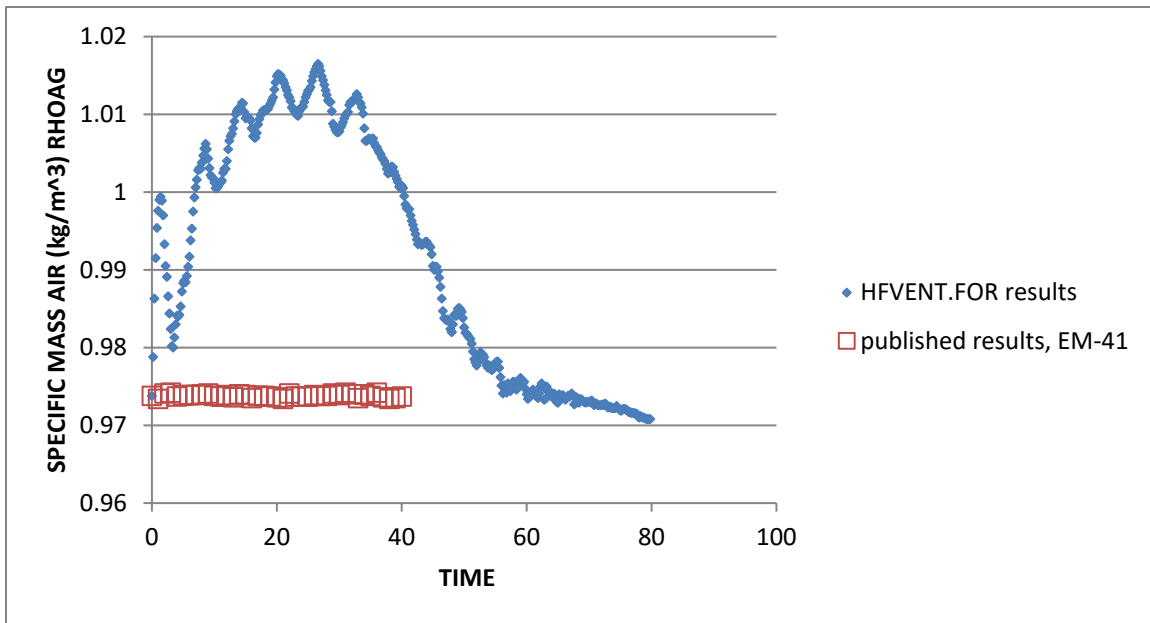
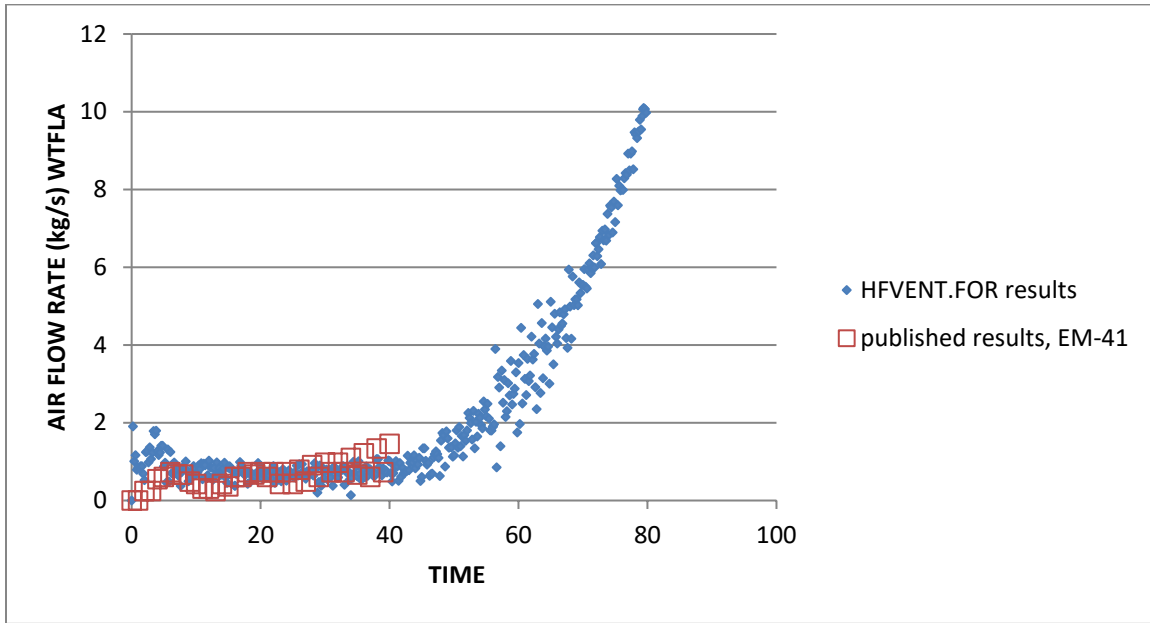


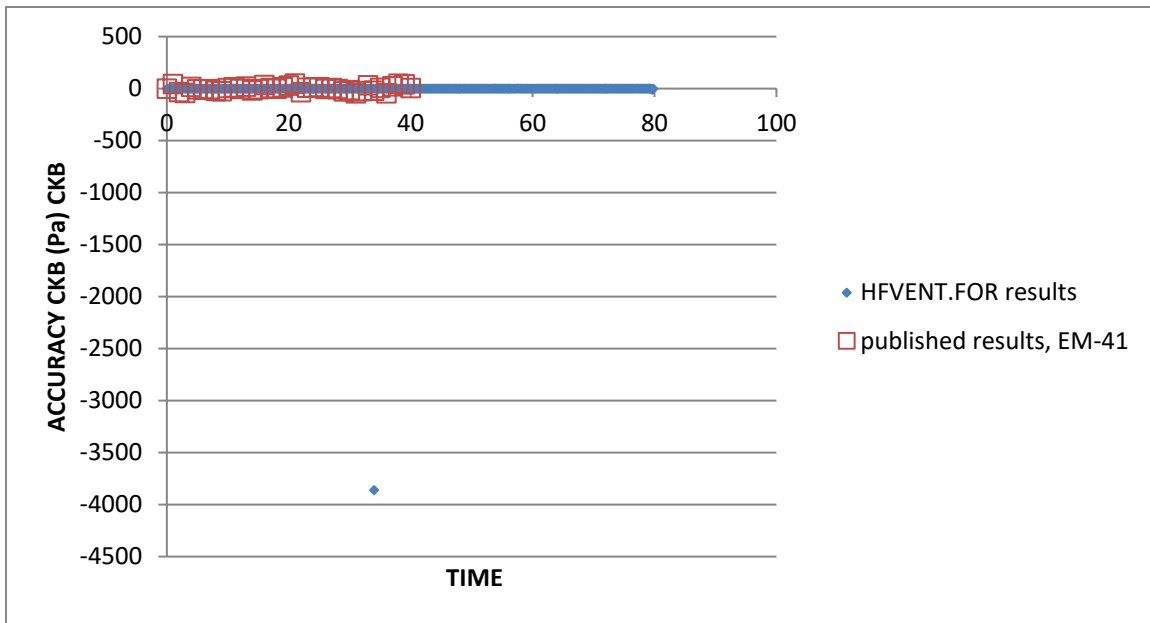
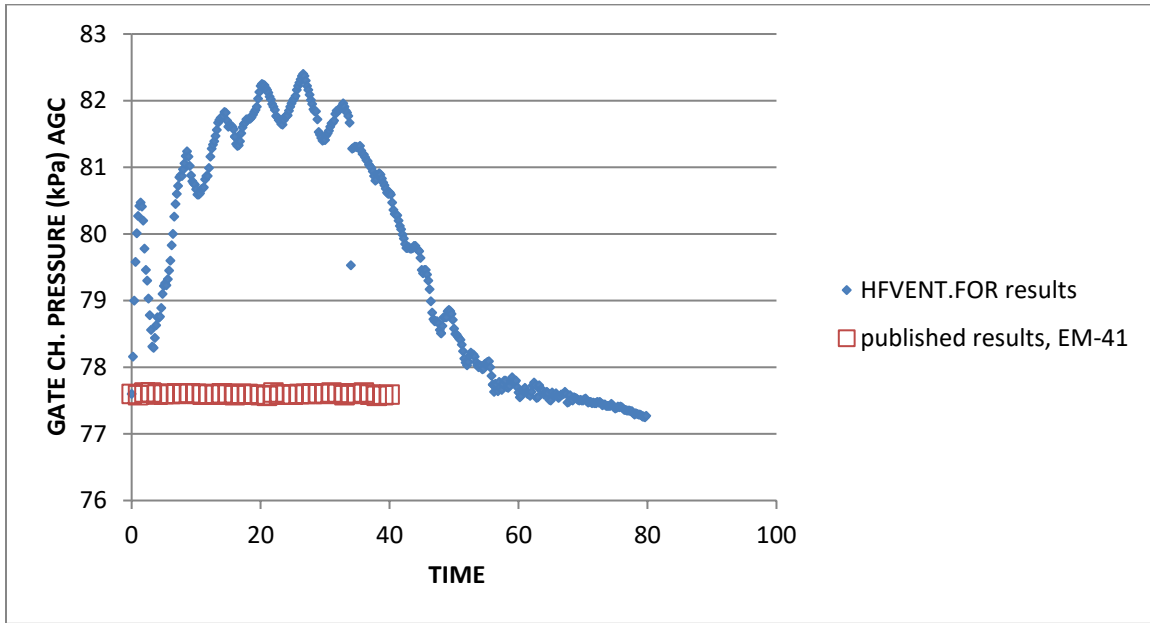




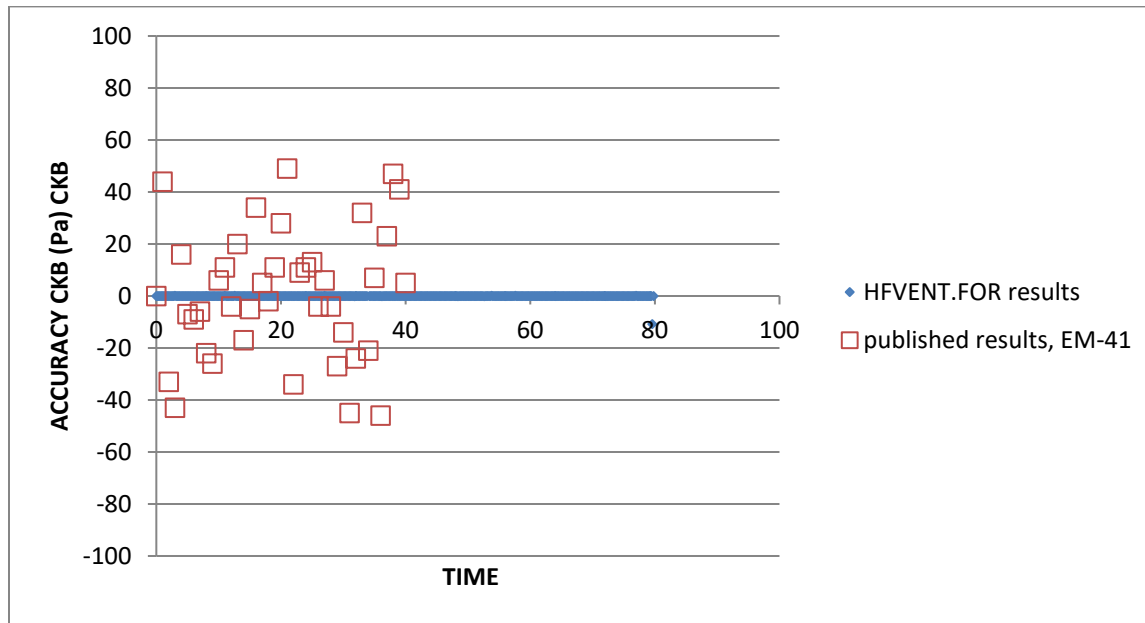


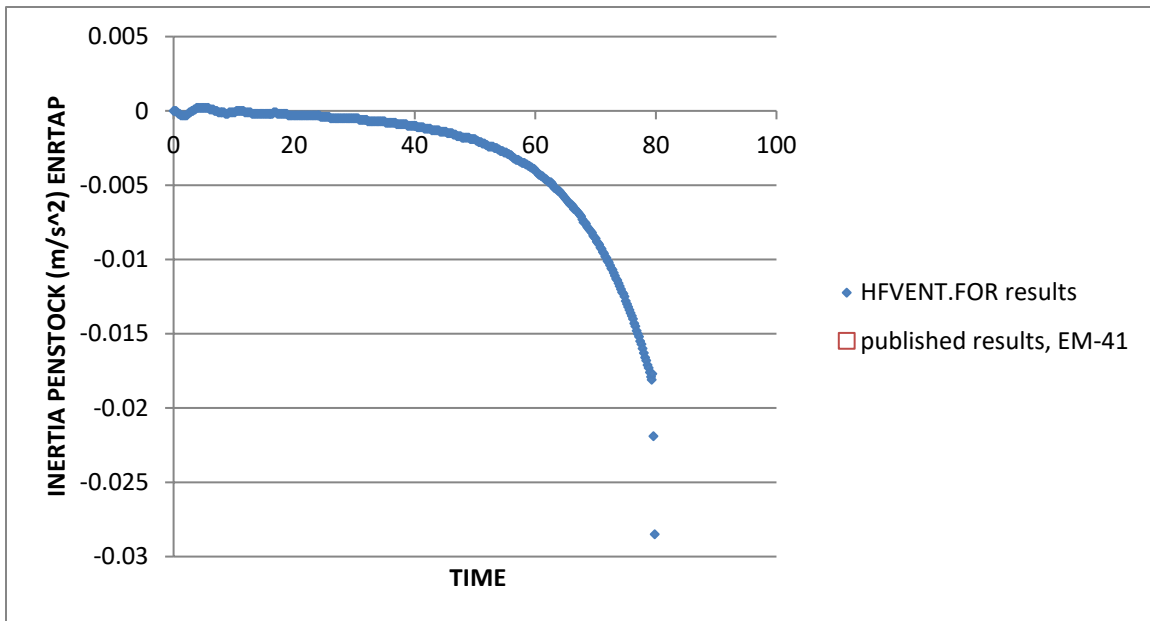
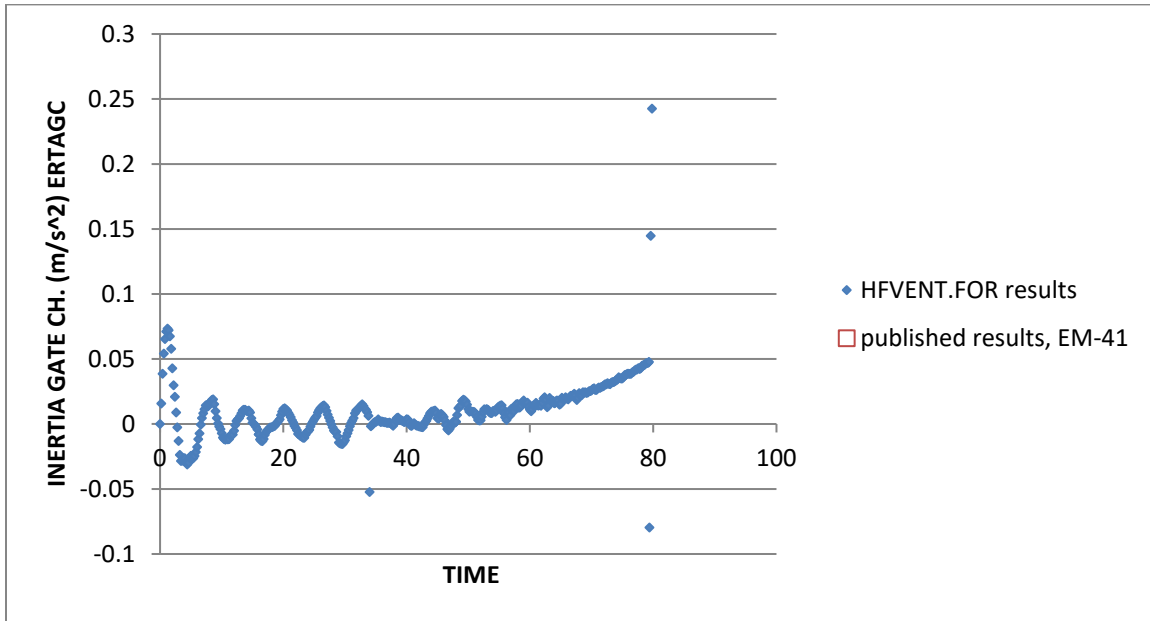




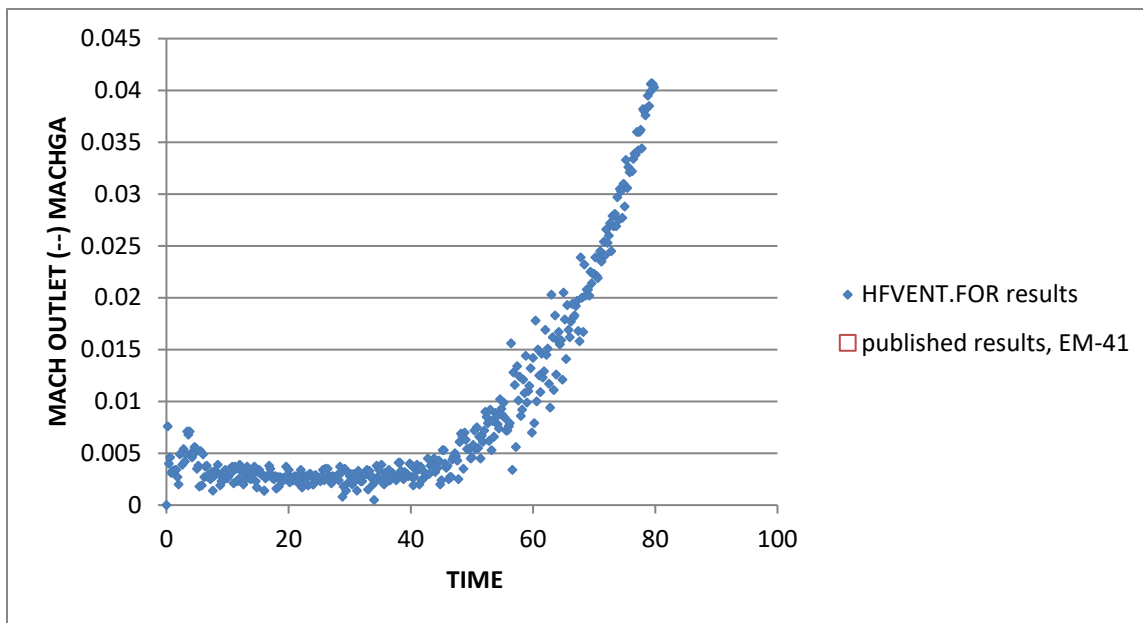
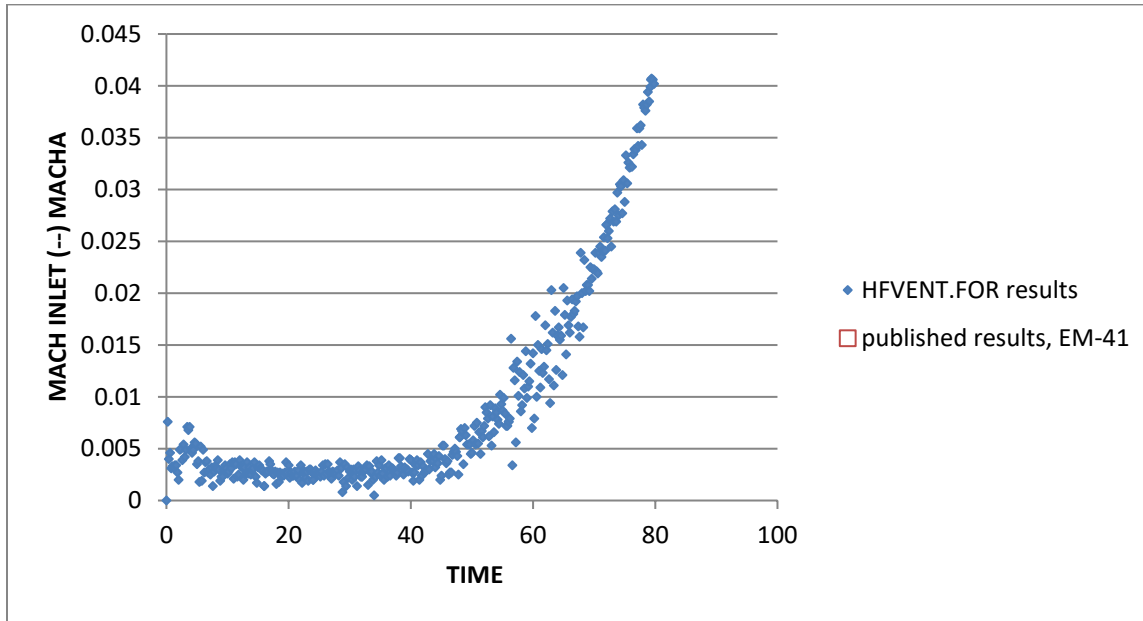


One time step failed to converge...The specific mass of air seems to occur because the gate chamber is pressurizing during the first 50 seconds of the simulation, but why is this occurring? It seems to suggest that something is not in equilibrium at the start, but what?





No data available for comparison on these parameters, as inertia values were not published in EM-41.

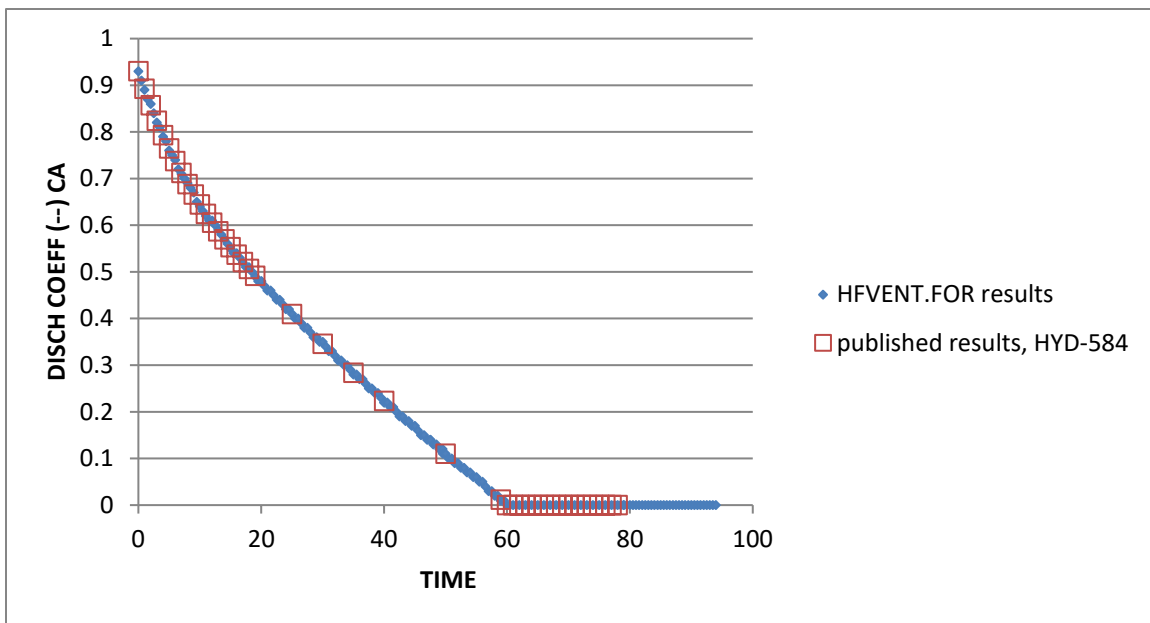
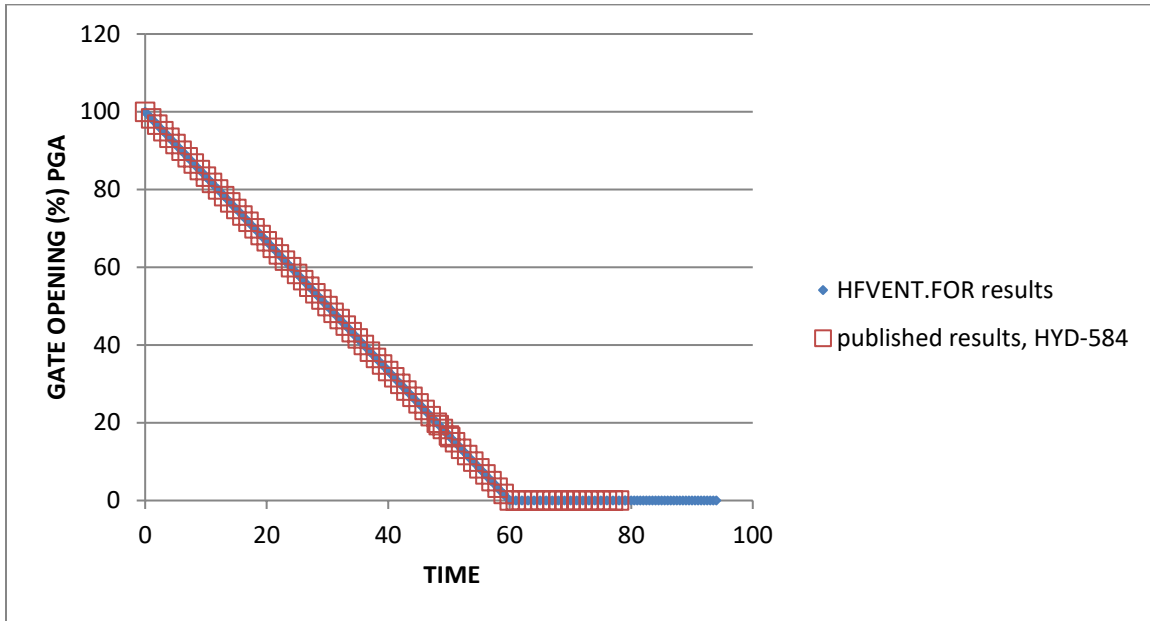


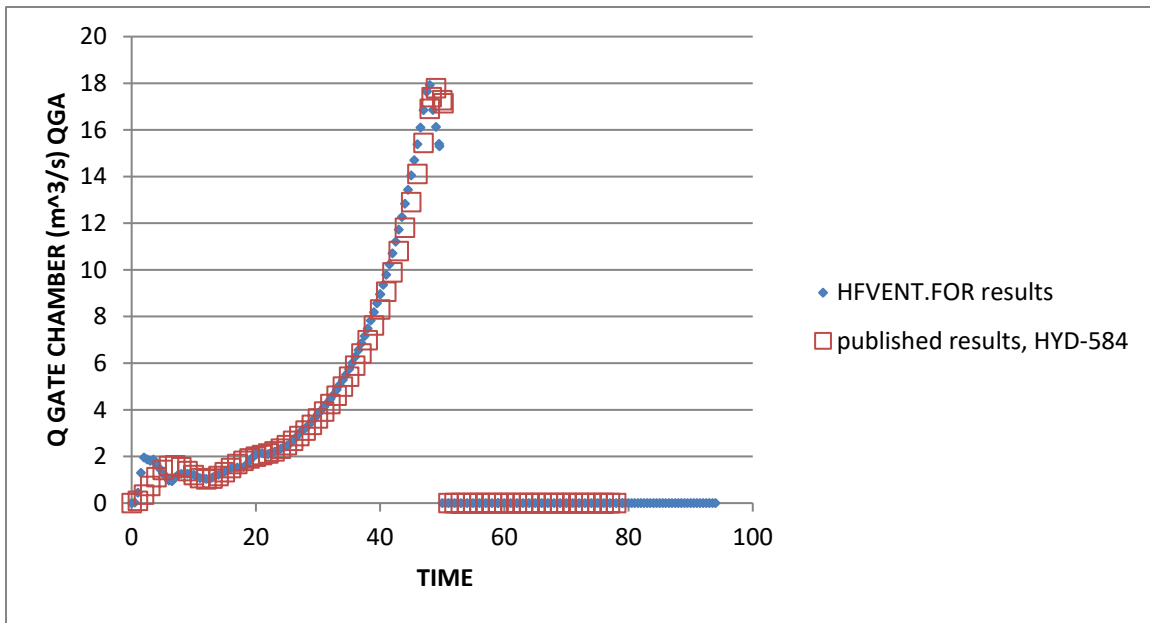
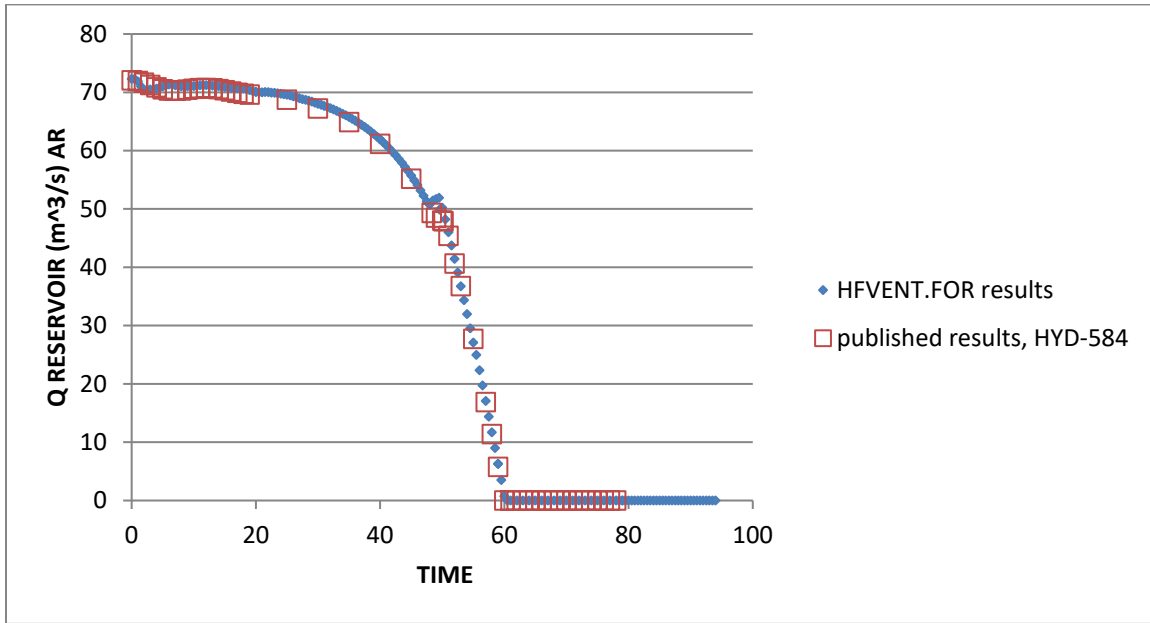
No data available for comparison on these parameters, as Mach numbers were not published in EM-41.

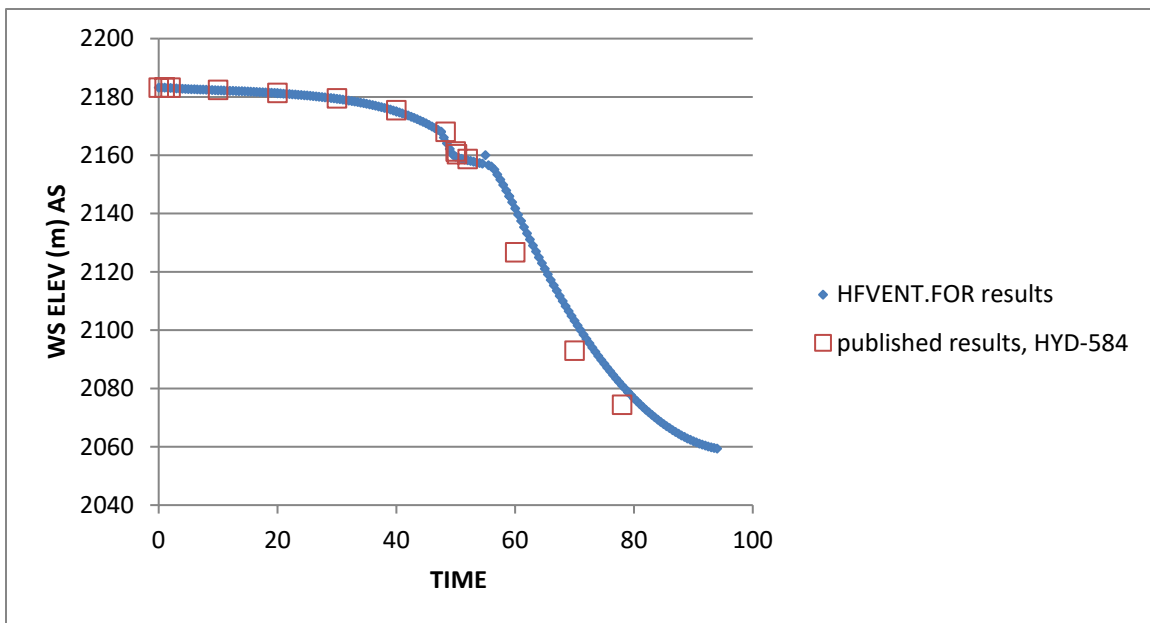
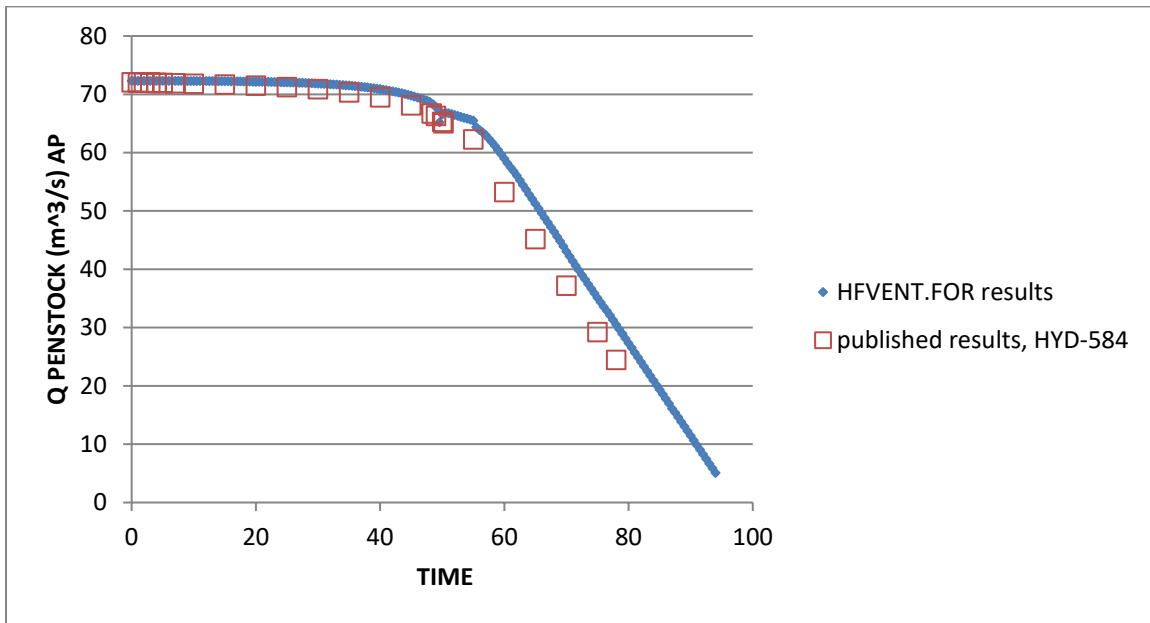
Comparison to HYD-584 published output

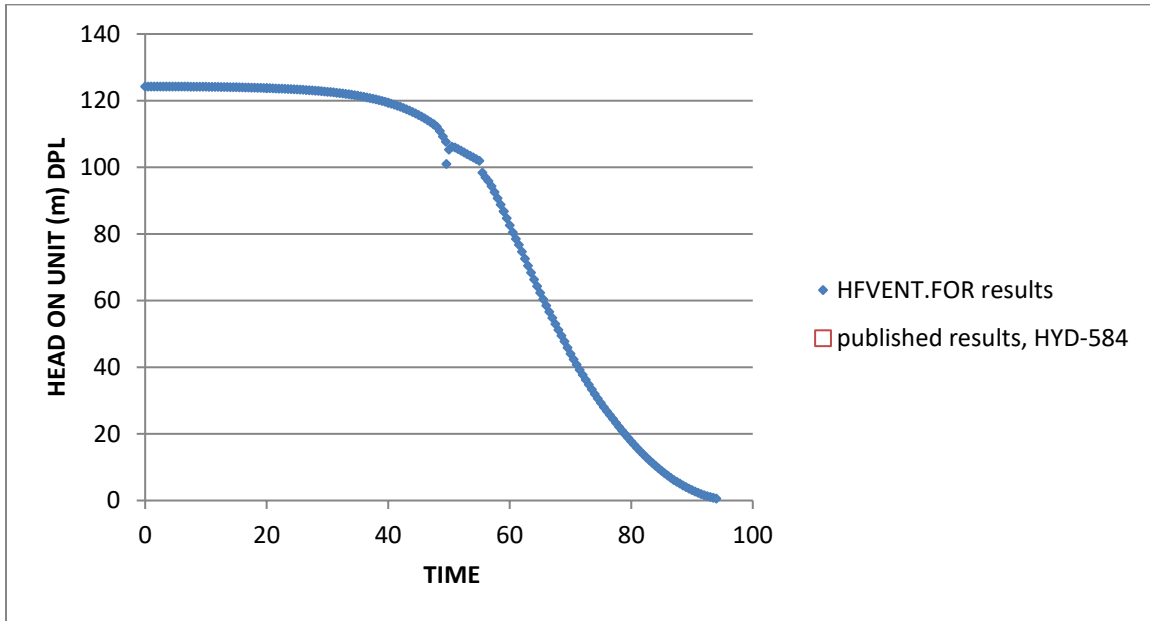
Notable input data (differences from EM-41 case highlighted in **bold**):

- DELT=0.2
- **TLOSS=82.75**
- **NSPEED=0**
- **HMOTOR= N/A when NSPEED=0**
- **GCR=100./60. (60 second closing time)**
- PATM= 77.6 kPa (11.255 psi)
- FRICT=0.93
- **RES=2183.89 m (7165.00 ft)**
- TW=2059.23 m (6756.00 ft) (the HYD-584 and F-734 programs did not include any consideration for tailwater effects)
- UGCLGC=2168.04 m (7112.99 ft)
- ZP=2155.93 m (7073.26 ft)
- TGC=2183.89 m (7164.99 ft)
- AU=13.80 m²
- AD=4.33 m²
- AG=20.64 m²
- AVENT=0.766 m²
- NVENTS=1
- VOLC1=46.16 m²
- VOLC2=13.3 m²
- ELC1=2155.93 m (7073.26 ft)
- ELC2=2170.21 m (7120.11 ft)
- PL=143.56 m (471 ft)
- PENLEN=2016.48 m (6615.75 ft) (Note that HYD-584 and F-734 programs modeled penstock length adjustment in a different way)
- DP=4.12 m (13.52 ft)
- SO=5.01 m (16.44 ft)
- HYDDIA=1.41 m (4.63 ft)
- CF=48.83 m² (525.6 ft²)
- PER=8.23 m (27 ft)
- CAREA=13.5 m² (145.31 ft²)

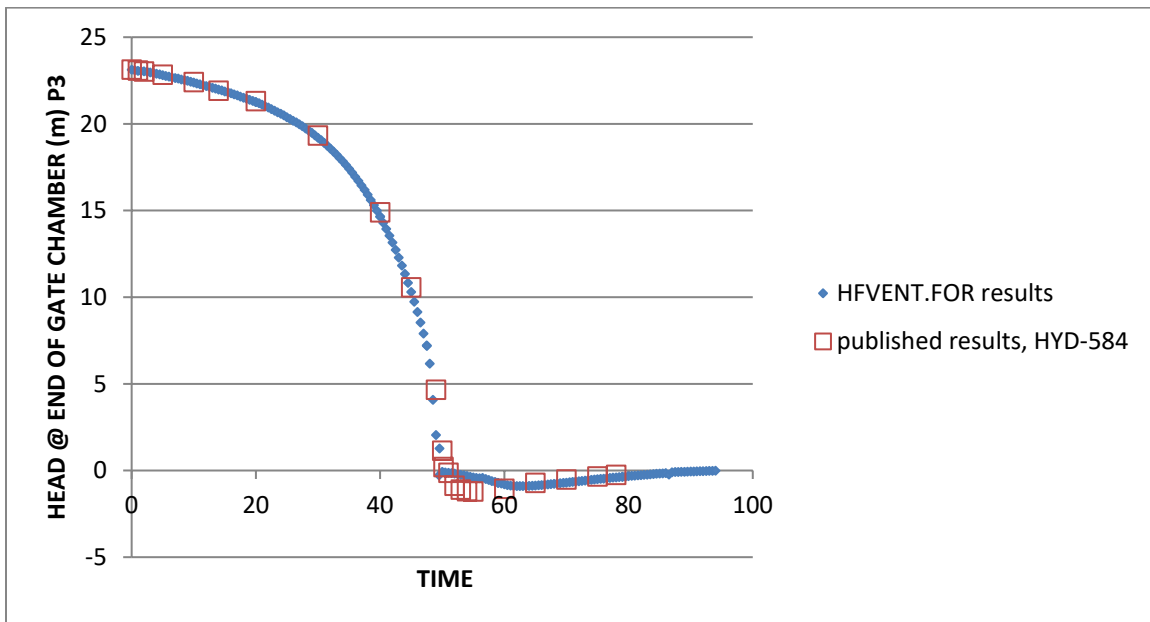


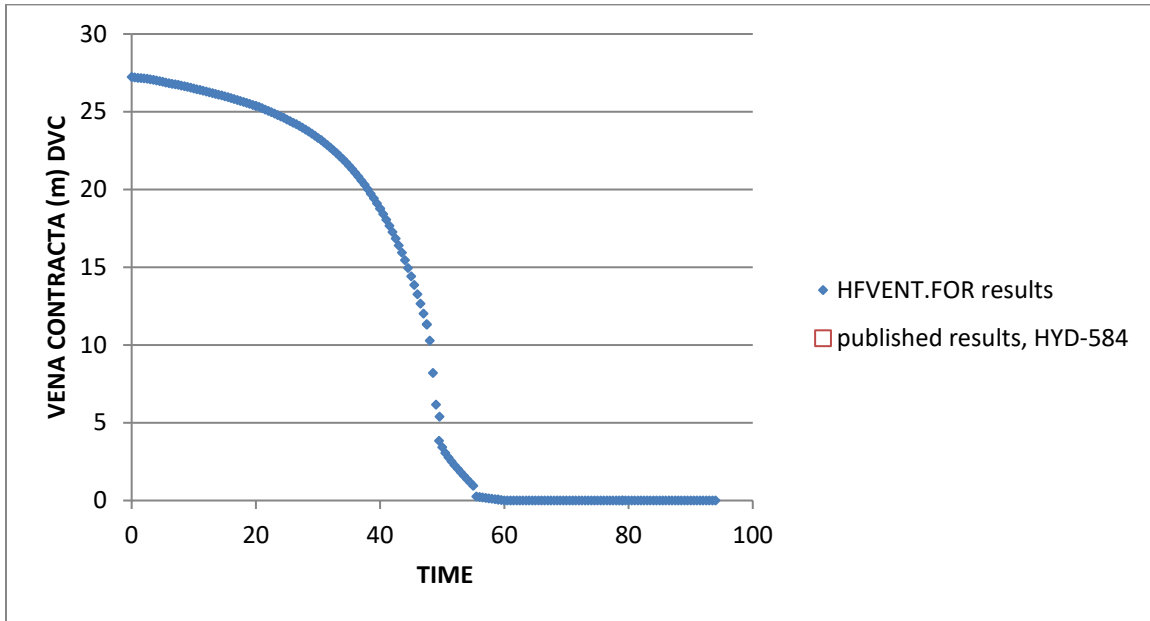




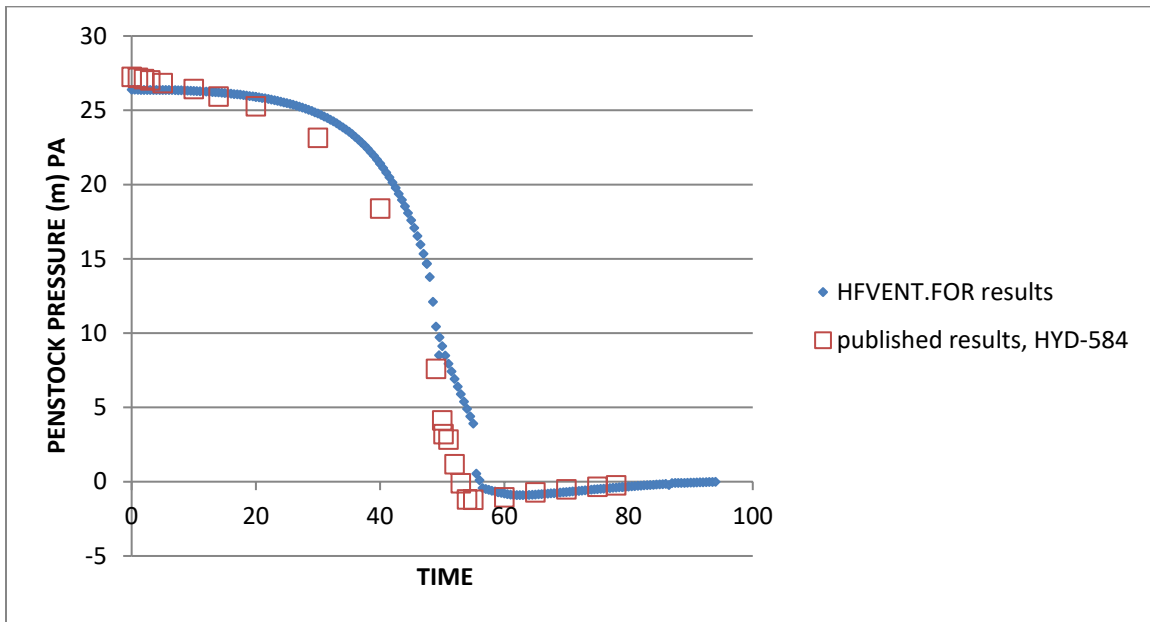


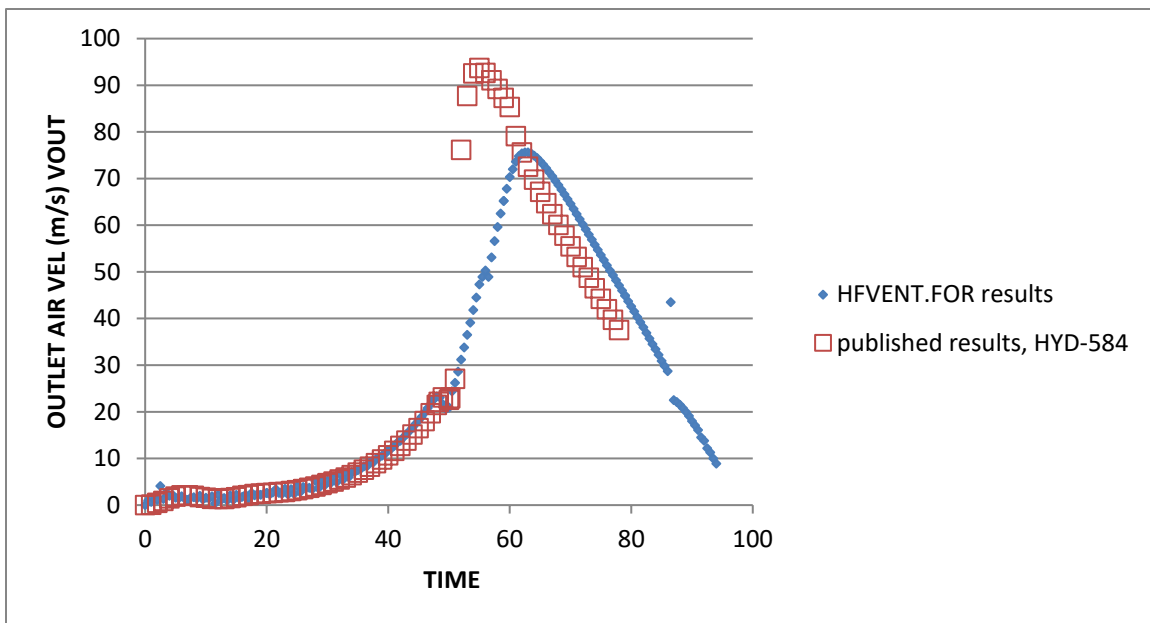
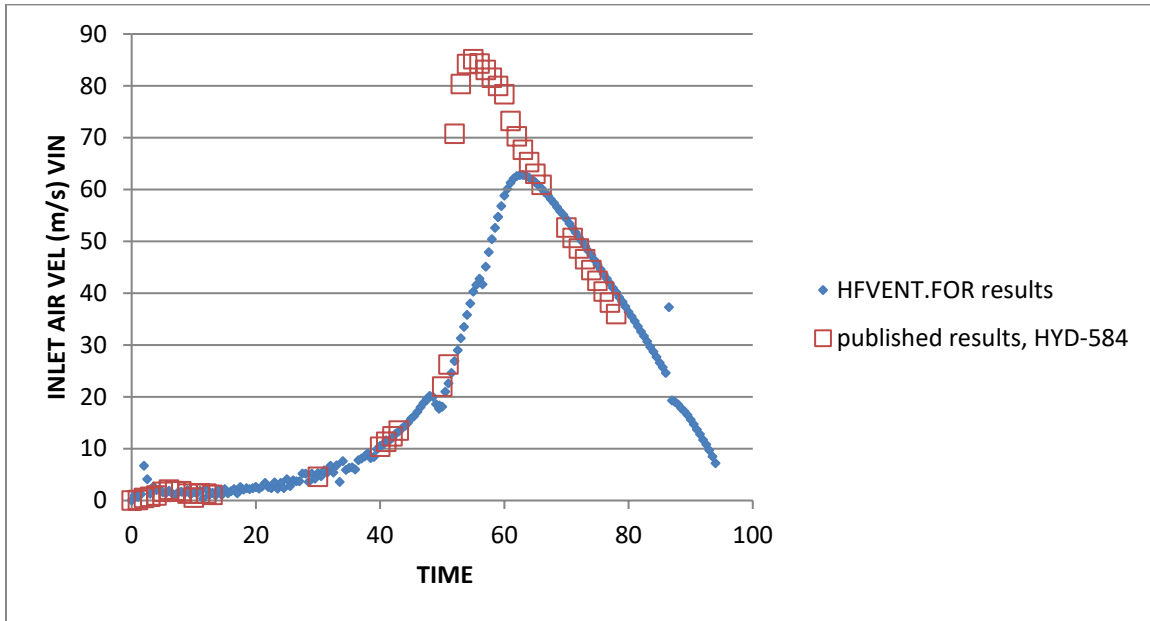
Head on unit was not included in HYD-584 output

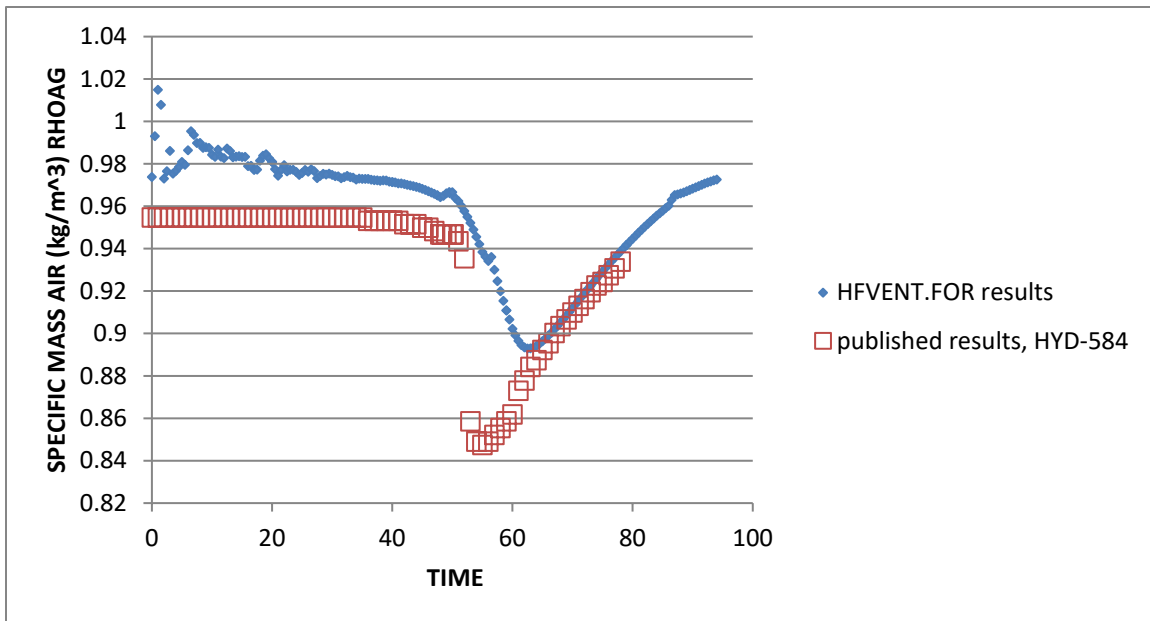
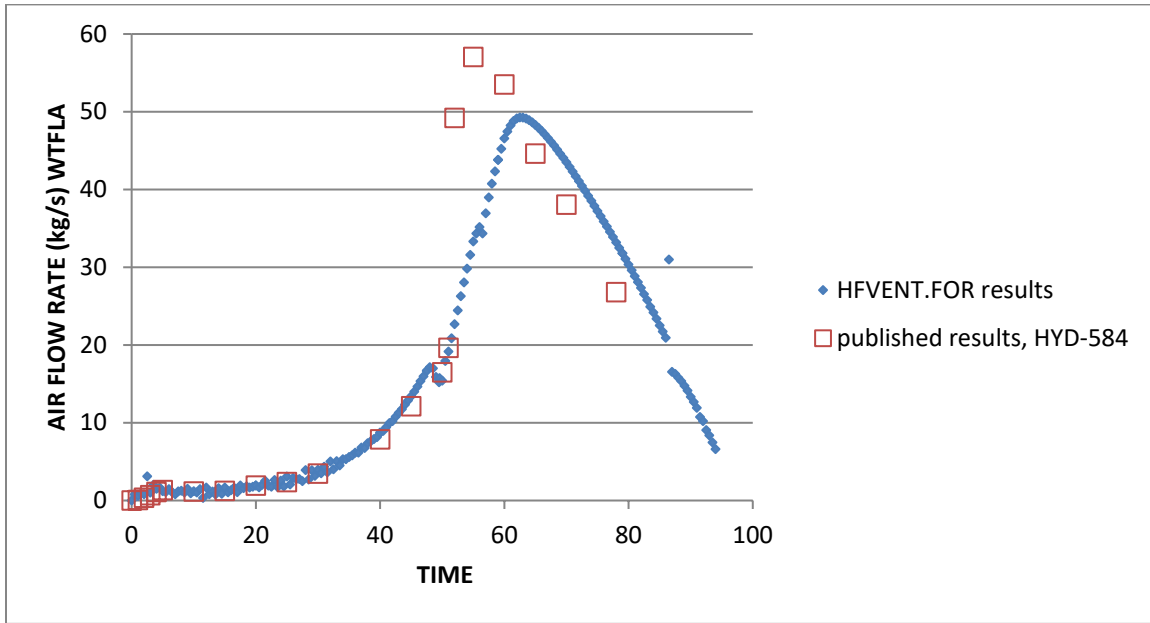


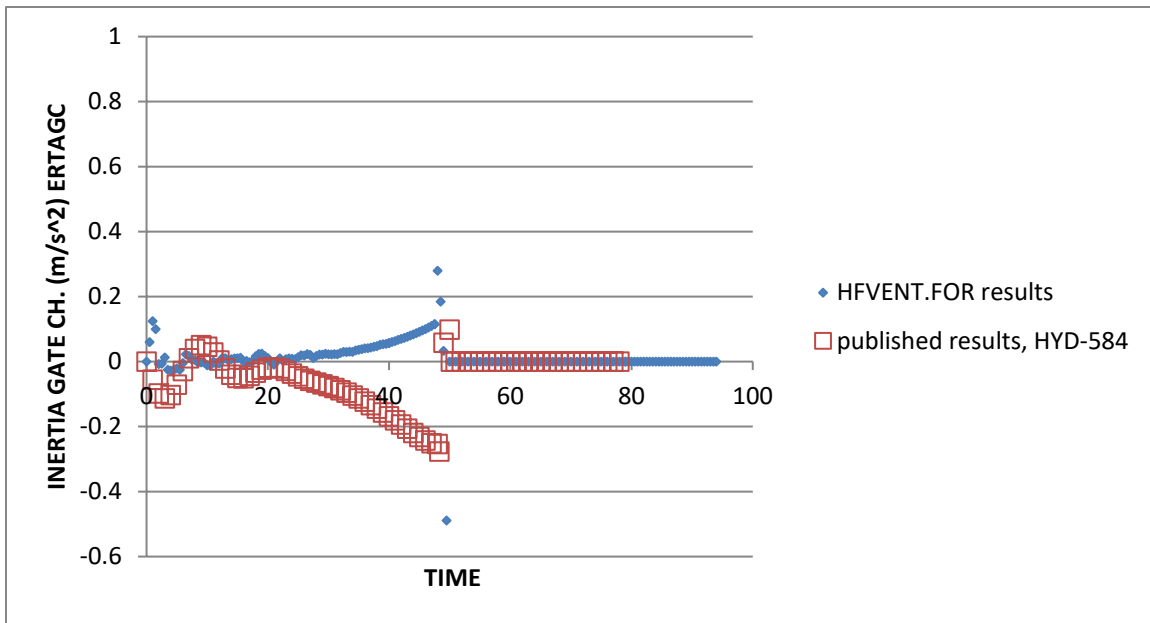
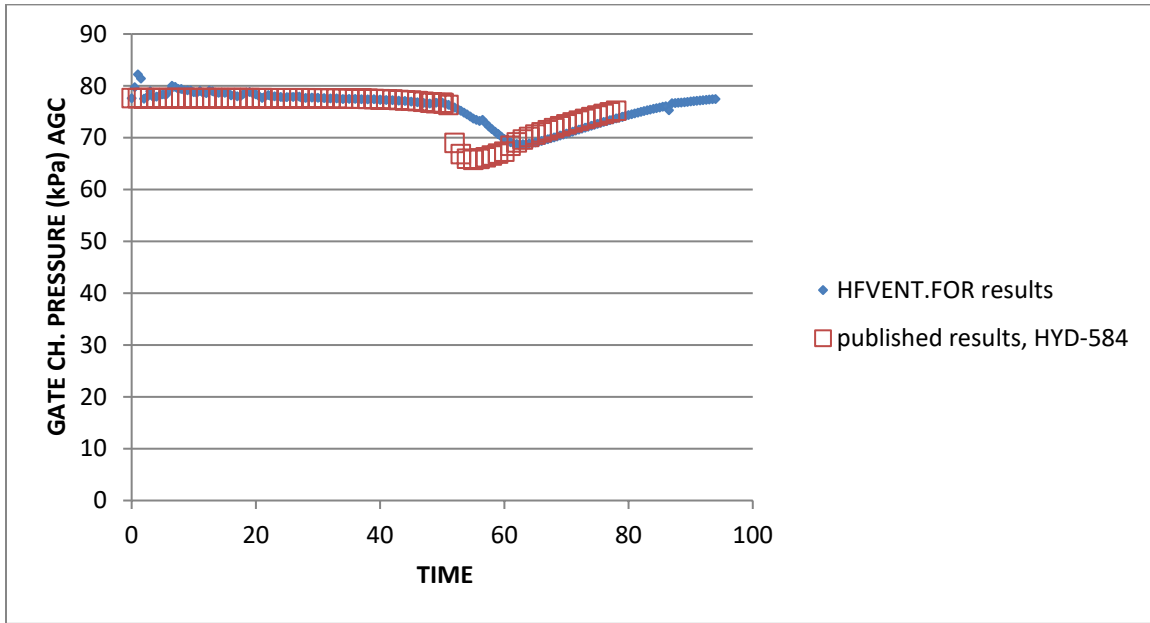


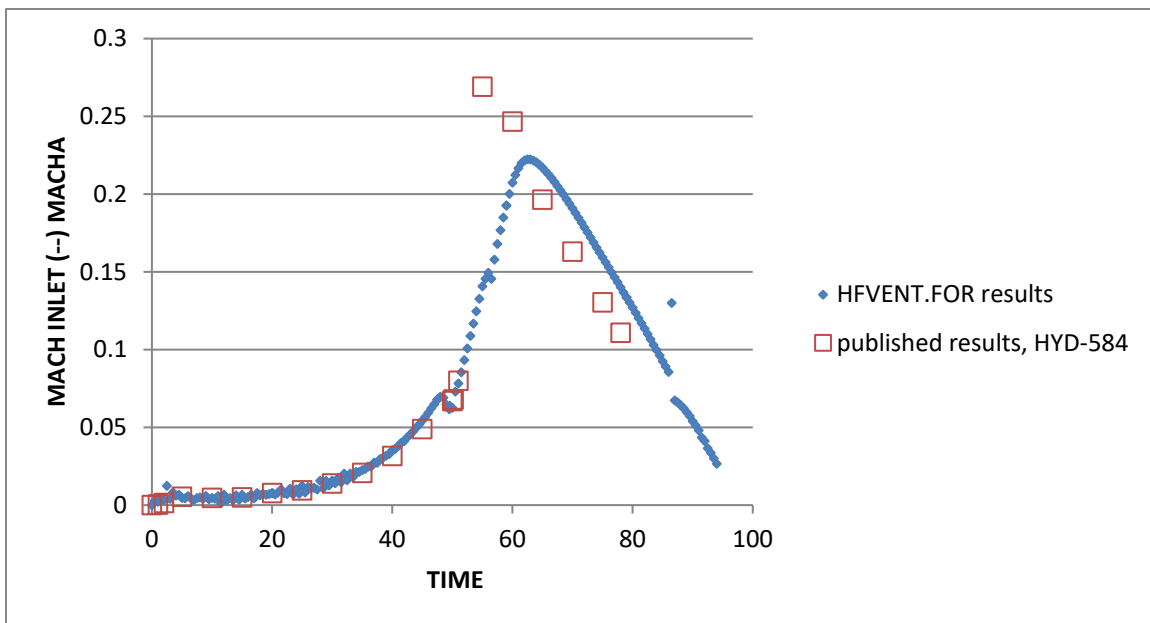
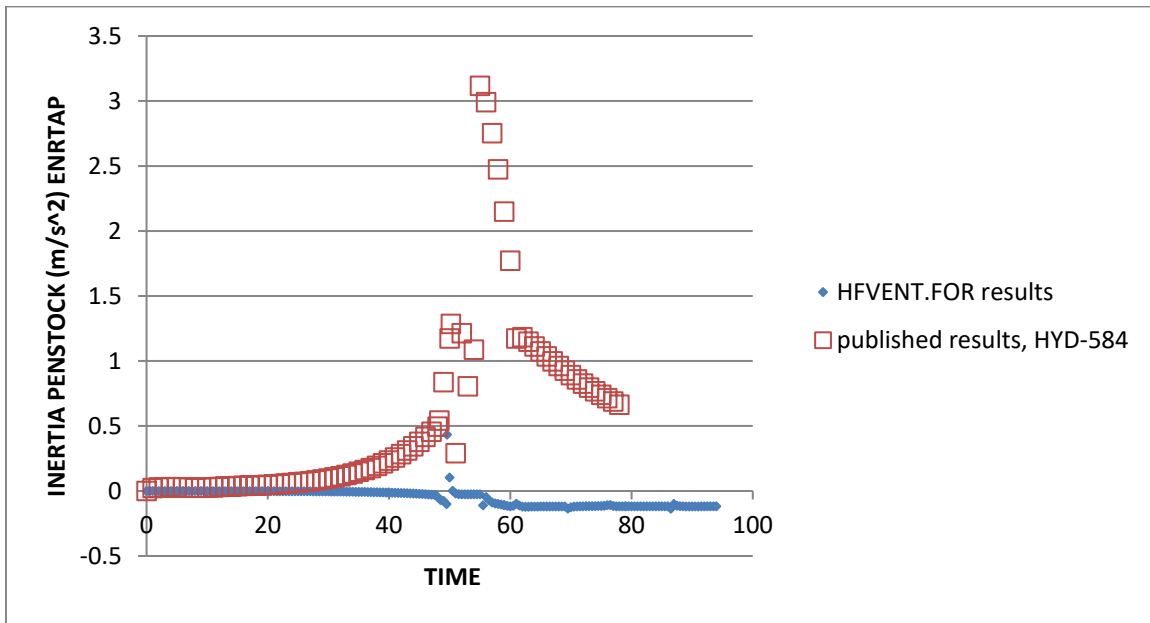
Vena contracta pressure was not included in HYD-584 output.

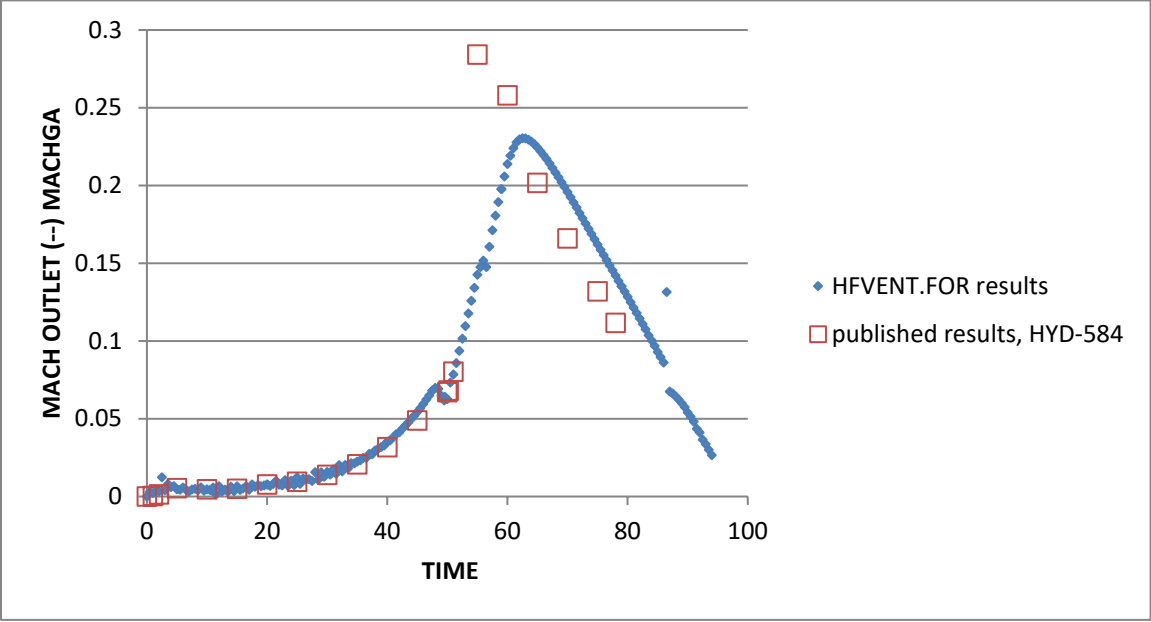












Comparison to F-734 output

Notable input data (differences from EM-41 case highlighted in **bold**). These input data are the same as used in Appendix B:

- DELT=0.2
- **TLOSS=82.75**
- **NSPEED=0**
- **HMOTOR= N/A when NSPEED=0**
- **GCR=100./60. (60 second closing time)**
- PATM= 77.6 kPa (11.255 psi)
- FRICT=0.93
- **RES=2183.89 m (7165.00 ft)**
- TW=2059.23 m (6756.00 ft) (the HYD-584 and F-734 programs did not include any consideration for tailwater effects)
- UGCLGC=2168.04 m (7112.99 ft)
- ZP=2155.93 m (7073.26 ft)
- TGC=2183.89 m (7164.99 ft)
- AU=13.80 m²
- AD=4.33 m²
- AG=20.64 m²
- AVENT=0.766 m²
- NVENTS=1
- VOLC1=46.16 m²
- VOLC2=13.3 m²
- ELC1=2155.93 m (7073.26 ft)
- ELC2=2170.21 m (7120.11 ft)
- PL=143.56 m (471 ft)
- PENLEN=2016.48 m (6615.75 ft) (Note that HYD-584 and F-734 programs modeled penstock length adjustment in a different way)
- DP=4.12 m (13.52 ft)
- SO=5.01 m (16.44 ft)
- HYDDIA=1.41 m (4.63 ft)
- CF=48.83 m² (525.6 ft²)
- PER=8.23 m (27 ft)
- CAREA=13.5 m² (145.31 ft²)

