Simplified Equation for Gas Transport To Pumps

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Anderson Lin / Diablo Canyon Power Plant
Steve Swantner / Westinghouse
What Factors Could Result In Gas Generation?

- Temperature
- Pressure
PWROG Projects

Void Transport
(WCAP-16631 for 6” & 8”)
On Going 4” & 12” @ Purdue
- Static Pressure
- Buoyancy
- Breaks down
- Transport Buffers
- Scaling of models

Water Hammer
- Pressure Pulsation
  (OG-08-315)
  - Pipe Hangers
  - Relief Valves
- Hot Recirc. & Containment Spray
  (OG-08-292)

Non-Condensable Gas into the Reactor Vessel
(OG-08-293)
- ECCS Delay
- LOCA & Non-LOCA Qualitative Evaluation

Pump Interim Gas Ingestion Tolerance Criteria
(V-EC-1866)
- Steady State & Transient Void Limits
- Types of Pumps
- Peak / Average Void Fraction
- Momentary TDH Degradation
- NPSHR vs. NPSHA
Gas Transport vs. Flow Rate

Observation 1: Higher flow results in higher void fraction (over a shorter duration) being transported
Test Loop at Purdue: Video Locations

Top Horizontal

Top Vertical

Bottom Vertical

Bottom Horizontal
Gas Transport vs. Flow Rate

Observation 2: Larger initial void volume results in larger void Fraction being transported.
Identify Critical Parameters

- Observations:
  - Higher flow $\Rightarrow$ Higher Void
  - Larger initial void volume $\Rightarrow$ Higher Void

- Minimizing Void Transport to The Pump
  - Identify the maximum flow rate
  - Limit the allowable initial void
### Simplified Equation vs. APC Criteria

<table>
<thead>
<tr>
<th></th>
<th>BWR Typical Pumps</th>
<th>PWR Typical Pumps</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>% $\frac{Q}{Q_{BEP}}$</td>
<td>Single Stage (WDF)</td>
</tr>
<tr>
<td>Steady State Operation</td>
<td>40%-120%</td>
<td>2%</td>
</tr>
<tr>
<td>&gt; 20 seconds</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Steady State Operation</td>
<td>&lt; 40% or &gt; 120%</td>
<td>1%</td>
</tr>
<tr>
<td>(see Note)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transient Operation</td>
<td>70%-120%</td>
<td>10%</td>
</tr>
<tr>
<td>≤ 5 seconds</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transient Operation</td>
<td>&lt; 70% or &gt; 120%</td>
<td>5%</td>
</tr>
<tr>
<td>(see Note)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transient Operation</td>
<td>70%-120%</td>
<td>5%</td>
</tr>
<tr>
<td>≤ 20 seconds</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transient Operation</td>
<td>&lt; 70% or &gt; 120%</td>
<td>5%</td>
</tr>
<tr>
<td>≤ 20 seconds</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Note:** Further review by the respective Owner’s Groups may determine that criteria for pump operation below 70% BEP may not be required, as the conditions are bounded by the set of criteria for the 70%-120% BEP range.
Gas Transport vs. Flow Rate

Limit the allowable initial void

Simplified Equation To Limit The Initial Void
(Easy For Plant Implementation)

\[ V_{allowable} = Q_{max} \times \alpha \times \Delta t \times \left( \frac{P_p}{P_1} \right) \]

\[ V_{allowable} \]: Determines the Void Fraction

( If \( \alpha \times \Delta t = 0 \) \( \Rightarrow \) No void at all )

What are the appropriate \( \alpha \) & \( \Delta t \) \( \rightarrow \) Gas Volume?
Void Impact To the Pump

Pump Performance Considerations
- Relies on “incompressible” water to do work
  - Higher Void Fraction (less working fluid) \(\Rightarrow\) Less TDH

- Void expands as it approaches the eye of the impeller
  - \(P_{total} = \text{Constant} = P_{\text{Static}} + P_{\frac{1}{2}} \rho V^2 = P_{\text{local}} + P_{\text{kinetic}}\)
  - As \(P_{\text{kinetic}}\) increases, \(P_{\text{local}}\) decreases \(\Rightarrow\) Void Vol. Increases

- \(P_{\text{local}} \gg P_{\text{vapor}}\) \(\Rightarrow\) Issue is not NPSHr (cavitation) but a flow passage issue

- **Void Fraction To The Pump Must Be Limited**
Figure 9. Two-phase flow pump torque and pressure distribution versus suction void fraction.
Continuous Pump Test Curve

(At least 3 test data points for a test curve)

Ref: NUREG / CR 2792  Atmospheric Suction Pressure
Continuous Pump Test Curve

(At least 3 test data points for a test curve)

Figure 3-11. AIR/WATER HEAD CHARACTERISTICS AT 50 PSIG SUCTION PRESSURE FROM STEFANOFF [14]

Ref: NUREG / CR 2792  50 psig Suction Pressure
Figure 3-9. Effect of number of stages on air/water performance from Florjancic [32].

Ref: NUREG / CR 2792
Void Impact To the Pump

- A Small, Limited Void Should Be Tolerable
  - Pump Curve Typically Breaks Down After 20% - 40% void
  - Available Pump Tests Suggest Void Tolerance to 10% - 20% (based on the available suction pressure)
    - Effect Is a Continuous Degradation of the Pump Curve
    - The Pump Will Continue to Operate (No Gas Binding)
Void Impact To the Pump

- A Small, Limited Void May Be Tolerable
  - Pump Curve Typically Breaks Down After 20% - 40% Void
  - Available Pump Tests Suggest Void Tolerance Between 10% - 20% (based on the available suction pressure)

- Simplified Equation
  \[ V_{allowable} = Q_{max} \times \alpha \times \Delta t \times \left( \frac{P_p}{P_1} \right) \]

- Simplified Equation ➔ Conservative Volume
  - No Continuous Void Source in the ECCS
  - Void Passage Through Pump Is A Momentary Condition
  - ECCS Pumps have High Suction Pressure
    - Injection phase ➔ full RWST static head
    - Recirc. Phase ➔ Static head + containment P – screen \( \Delta P \)
Peak Void from the 6” Loop Test
Peak Void from the 12” Loop Test
Identify the Maximum Flow Rate

<table>
<thead>
<tr>
<th>ECCS Pumps</th>
<th>Suction ID (inch)</th>
<th>Q-max (gpm)</th>
<th>Fr -max</th>
</tr>
</thead>
<tbody>
<tr>
<td>CCP</td>
<td>6.357”</td>
<td>560</td>
<td>1.37</td>
</tr>
<tr>
<td>SIP</td>
<td>6.357”</td>
<td>670</td>
<td>1.64</td>
</tr>
<tr>
<td>HPSI</td>
<td>10.25”</td>
<td>1410</td>
<td>1.05</td>
</tr>
<tr>
<td>RHRP</td>
<td>12.25”</td>
<td>4500</td>
<td>2.14</td>
</tr>
<tr>
<td>LPSI</td>
<td>18”</td>
<td>5500</td>
<td>1.00</td>
</tr>
</tbody>
</table>
Figure 6
6 inch 5% initial void fraction RIMP2 (11% initial void & Fr=1.9)

70% ≤ BEP ≤ 120%
10% for 5 Seconds

BEP < 70% or > 120%
4.8 gallon Total Void Volume

Most Limiting
Simplified Allowable Void Equation

- Static Void $\leq 5\%$ for smaller pipes, $\leq 2\%$ for larger pipes

$$V_{\text{allowable}} = Q_{\text{max}} \times \alpha \times \Delta t \times \left( \frac{P_p}{P_1} \right)$$

<table>
<thead>
<tr>
<th>Pipe ID</th>
<th>$\alpha$</th>
<th>$\Delta t$</th>
<th>X-Section (Static Conditions)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$&lt; 12''$</td>
<td>10%</td>
<td>5 second</td>
<td>$\leq 5%$</td>
</tr>
<tr>
<td>$\geq 12''$</td>
<td>2%</td>
<td>20 second</td>
<td>$\leq 2%$</td>
</tr>
</tbody>
</table>
Examples of Allowable Void From The Simplified Equation

- Static Void ≤ 5% for smaller pipes, ≤ 2% for larger pipes
- \( V_{\text{allowable}} = Q_{\text{max}} \times \alpha \times \Delta t \times \left( \frac{P_p}{P_1} \right) \)

<table>
<thead>
<tr>
<th>Pumps</th>
<th>( Q_{\text{max}} )</th>
<th>( \alpha )</th>
<th>( \Delta t )</th>
<th>( V_{\text{allowable}} )</th>
<th>X-Section</th>
</tr>
</thead>
<tbody>
<tr>
<td>CCPs</td>
<td>560</td>
<td>10%</td>
<td>5 second</td>
<td>4.67 gal</td>
<td>≤ 5%</td>
</tr>
<tr>
<td>SIPs</td>
<td>670</td>
<td>10%</td>
<td>5 second</td>
<td>5.58 gal</td>
<td>≤ 5%</td>
</tr>
<tr>
<td>RHRPs</td>
<td>4500</td>
<td>2%</td>
<td>20 second</td>
<td>30 gal</td>
<td>≤ 2%</td>
</tr>
<tr>
<td>HPSI</td>
<td>1800</td>
<td>10%</td>
<td>5 second</td>
<td>12 gal</td>
<td>≤ 5%</td>
</tr>
<tr>
<td>LPSI</td>
<td>5500</td>
<td>2%</td>
<td>20 seconds</td>
<td>36 gal</td>
<td>≤ 2%</td>
</tr>
</tbody>
</table>

Purdue -8 psig: 5% → 4.8 gal & 10% → 9.7 gal
Treatment of the Simplified Equation

- Supply Headers with Takeoffs
  - Calculate allowable volume for each individual pump suction
  - Apply smallest of the allowable branch line limits to the header
- Vertical pipe volume $> 4 \times$ Void volume
- Allowable void accounts for static pressure change between high point and pump suction
  - Elevation change must be $\geq 10$ feet
Advantages of the Simplified Equation

- Simplified Equation is Conservative
  - Limits The Allowable Void Volume
  - Allowable Void volumes < Purdue Tested
  - Not Likely To Gas Bind The Pump
  - Provides Reasonable Basis for Pump “Operability”
  - Reasonable Engineering Judgment
  - Enveloped by DSS / APC Void Criteria
  - Supported by the Purdue Test Data

- Easily Implemented In ECCS Surveillance Acceptance Criteria
  - Simple Method to Define Allowable Void Volume