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Review and evaluation of Archimedes screw pump design guidance

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Water Resources

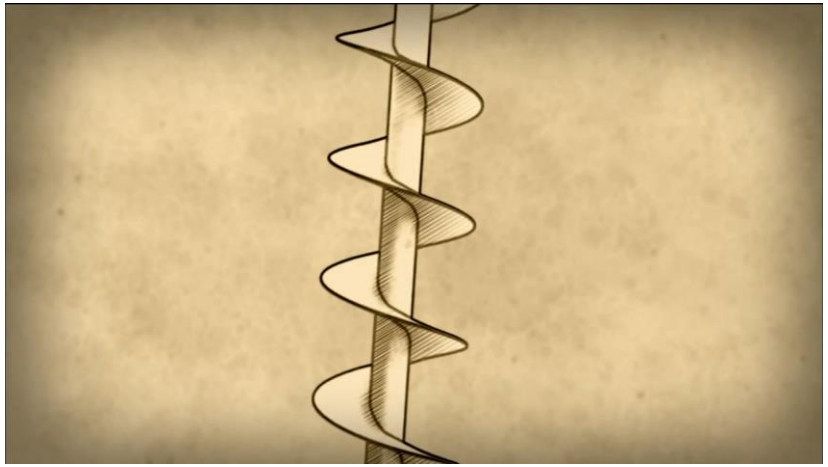
Mechanical

Environmental

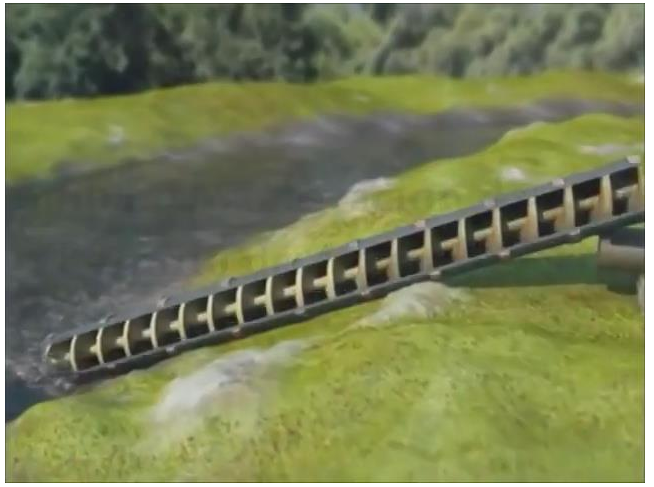
1. Introduction

1. Background

- Archimedes screws are an ancient pumping technology
- Named after Archimedes of Syracuse (~287-212 BCE)
- Evidence suggests it was used during reign of King Sennacherib (704-681 BCE) of the Neo-Assyrian Empire
- Trap water between blades as screw rotates due to an applied torque
- Water translates along axis of rotation



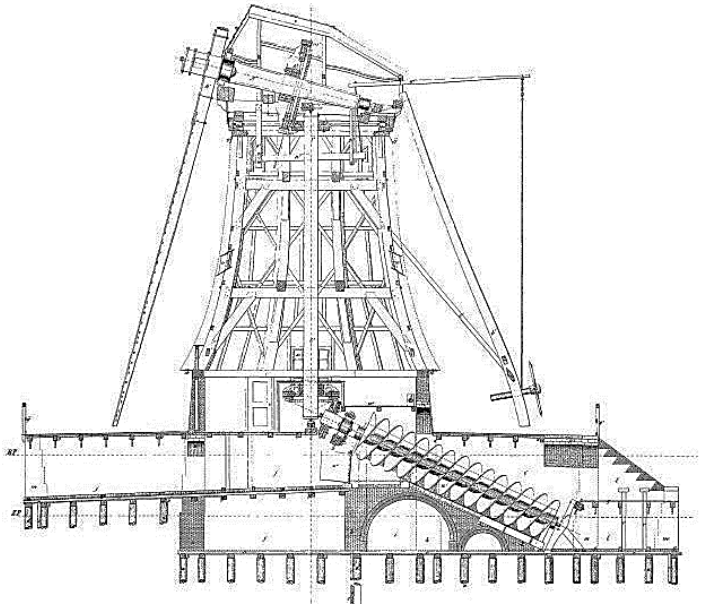
PBS (2014), *Secrets of the dead: Archimedes' screw and the Hanging Gardens of Babylon* [https://www.youtube.com/watch?v=NhNEB_mWvBw&ab_channel=PBS].



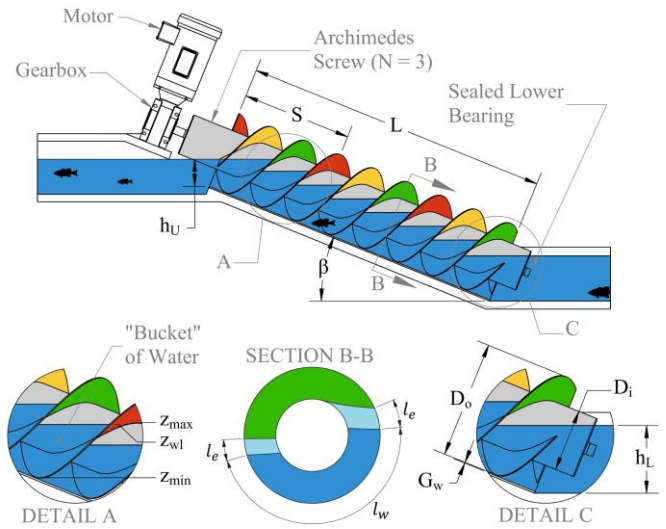
Adriana Tub (2016), *Tornillo de arquimedes* [https://www.youtube.com/watch?v=A_mZ6ekbJtw&ab_channel=AdrianaTub].

1. Background

- Archimedes screws have been designed as pumps for millennia
- Design is largely empirical or heuristic
- No extensive studies of the effects of scaling design parameters in published literature
- We have performed a comprehensive review of the literature



https://www.notechmagazine.com/2012/10/building-plans-of-dutch-industrial-windmills-1850.html



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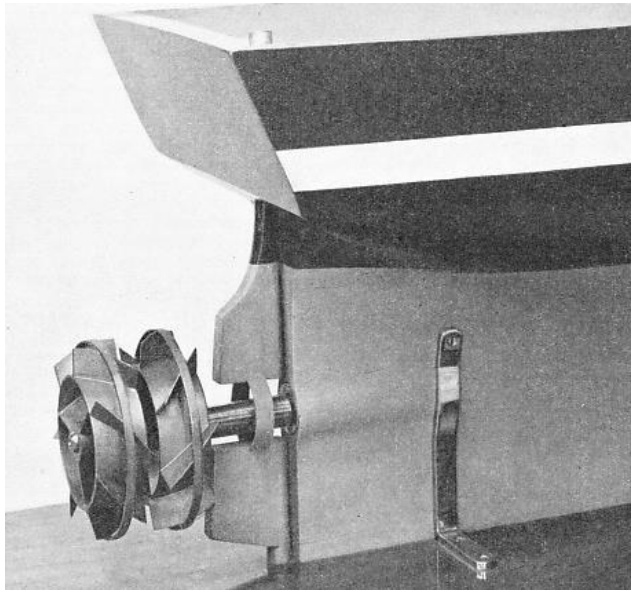
2. Historical Context

2. Historical Context

- Used for irrigation in:
  - Neo-Assyrian Empire of Sennacherib (c. 704-681 BCE) for irrigation
  - The Nile Delta by Archimedes of Syracuse (c. 287 BCE)
- Used for ship drainage in:
  - Hiero II's Kingdom of Syracuse by Archimedes (c. 280s BCE)
- Used for draining mines in:
  - The Roman Empire (c. 27 BCE to 400s CE)
  - Visigothic Iberia (c. 400s to 711 CE)
  - Al-Andalus Caliphates (711 – 1212 CE)

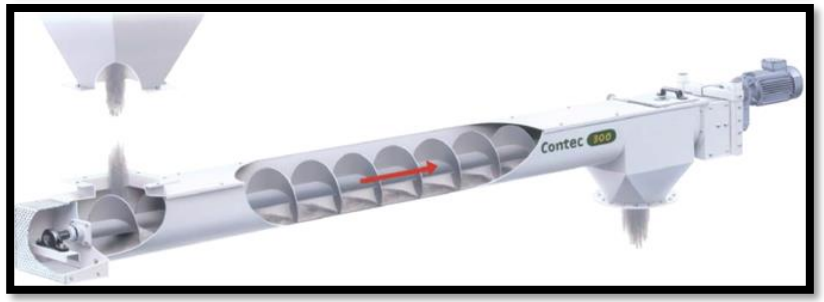
2. Historical Context

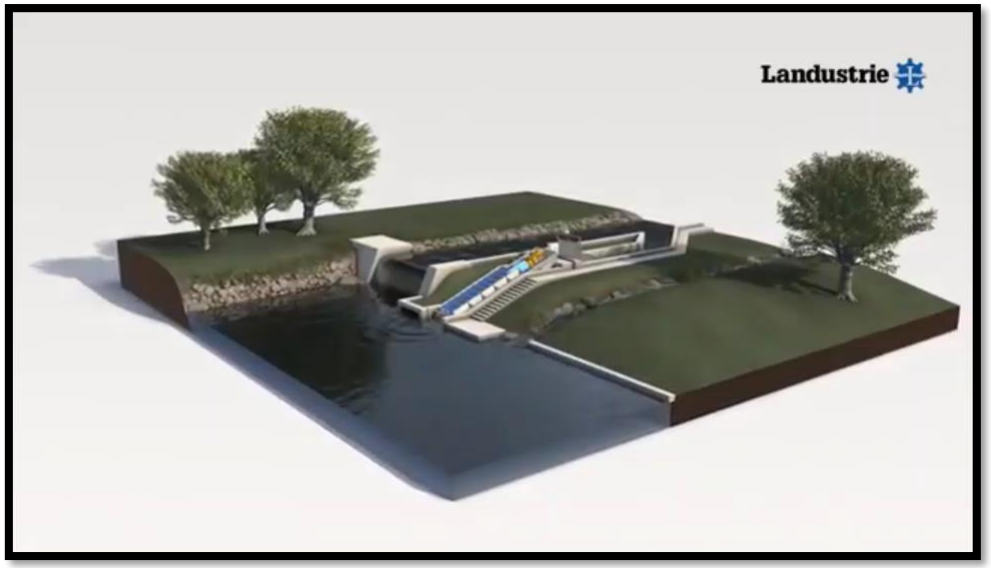
- Used for land drainage/reclamation in:
  - Dutch Golden Age (c. 1500s to 1600s CE)
- Used for ship propulsion in:
  - (Possibly) Hiero II's Kingdom of Syracuse by Archimedes (c. 280s BCE)
  - Austria by Josef Ressel (1829 CE)
  - England by Francis Smith (1839 CE)



2. Historical Context

- Modern implementations include:
  - Water and wastewater pump
  - Conveyor for grains
  - Fish ladder
  - Drive mechanism for amphibious vehicles
  - Injector in plastic moulding
  - Heart valve replacements
  - Hydropower generation





3. Design Details and Modelling

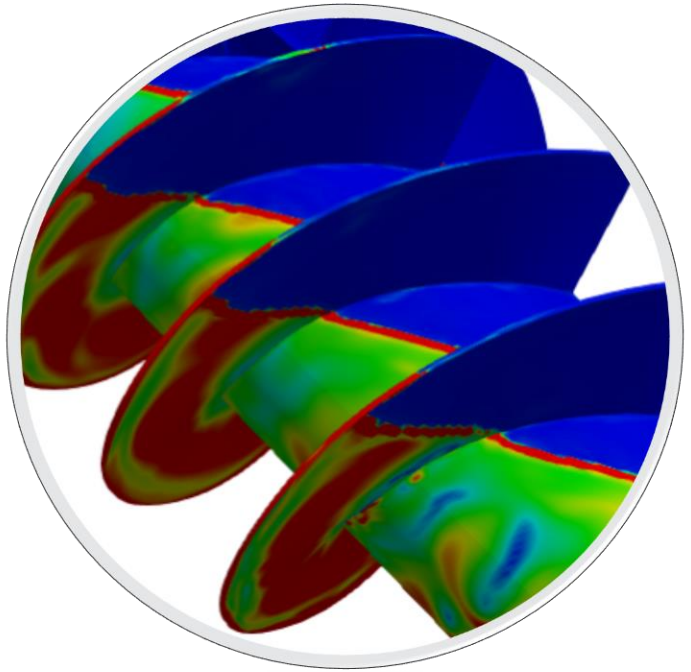
3.1. Flow Rate (Q)

3.2. Screw Size (D_o, D_i, and S)

3.3. Number of Blades (N)

3.4. Inclination Angle (β)

3.5. Water Levels (h_U and h_L)

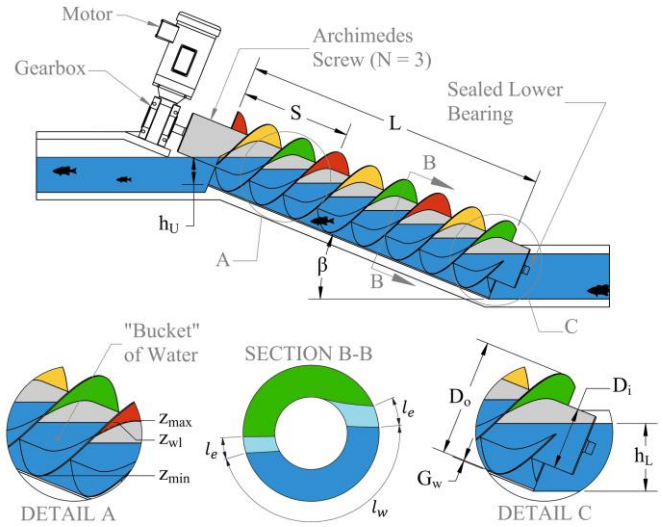


3.1. Flow Rate (Q)

- Largest Archimedes screw pump (ASP) station has 4 parallel screws, each with a discharge capacity of $Q \approx 4.2$ m^3/s
- Largest Archimedes screw **generator** (ASG) powerplant has a screw that converts electricity from Q ≈ 14.5 m3/s
- Many pumping stations use multiple, parallel screw pumps
- Muysken (1932) estimated flow with:

$$Q = q \cdot \Omega \cdot D_O^3$$

Variable	Description
Q	Flow Rate (m^3/s)
q	Dimensionless Flow Parameter (-)
Ω	Rotation Speed (rev/min)
D_o	Outer Diameter (m)



3.1. Flow Rate (Q)

- Muysken (1932) corrected estimates to:

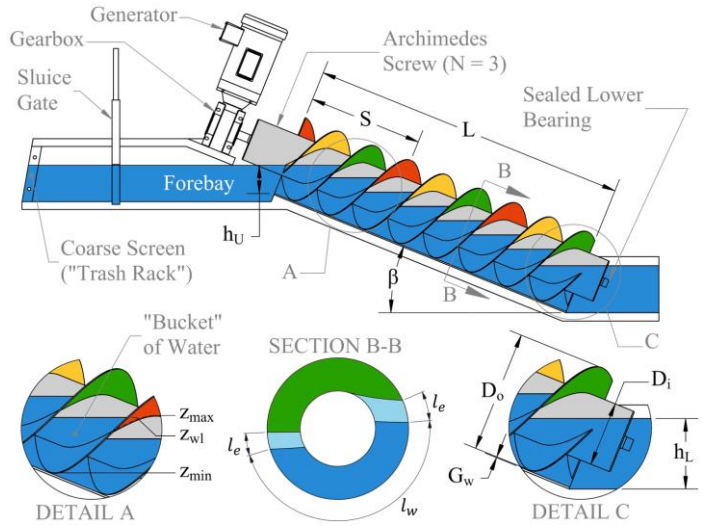
$$Q = 1.15 \cdot q \cdot \Omega \cdot D_O^3$$

- Small gap exists between blade tips and trough which introduces a "gap leakage flow" (Q_g)

$$Q_g = 2.5 \cdot G_w \cdot D_o \cdot \sqrt{D_o}$$

- Gap leakage cannot be measured in operating screws
  - Used a "validated" CFD model to measure in ASGs

Variable	Description
Q_g	Gap Leakage Rate (m^3/s)
G_w	Gap Width (m)
D_o	Outer Diameter (m)



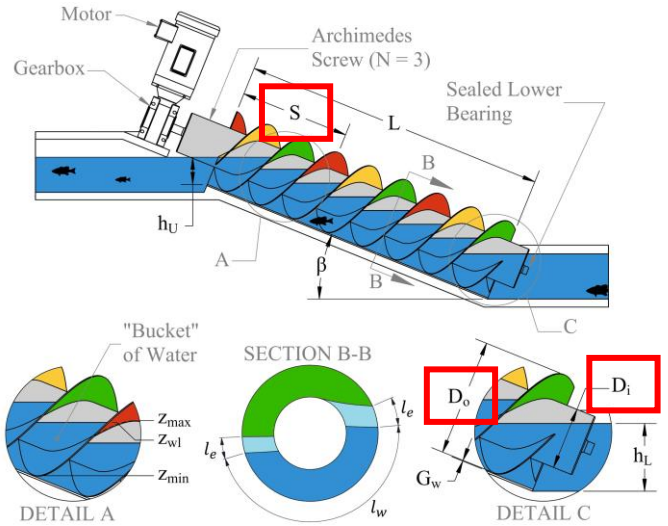
3.2. Screw Size (D_o, D_i, and S)

- State-of-the-art guideline is from 1932:

$$D_o = \sqrt[3]{\frac{Q}{q \cdot \Omega}}$$

- Do not apply correction factor of 1.15
  - We want screw to be robust and over-deliver flow instead of under-deliver

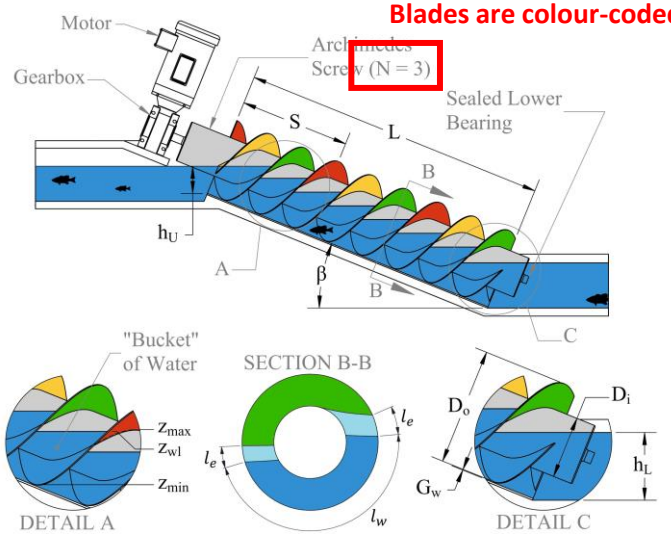
- Optimal design ratios (Rorres, 2000):
  - Diameter ratio = $\delta = \frac{D_i}{D_o} \approx 0.54$
  - Pitch ratio = $\sigma = \frac{S}{D_o} \approx 1$



3.3. Number of Blades (*N*)

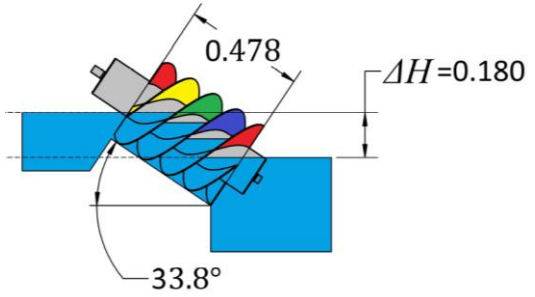
- In a hydraulically idealized world, more blades = more efficient
  - In practice, friction effects make this a balance
- Most modern screws have 3 or 4 blades.
  - Nagel and Radlik (1988) suggest screw's have 2 or 3 blades
  - ASGs shown to be optimal with 3 or 4 blades
  - Muysken (1932) almost exclusively analysed 3-bladed screws

Blades are colour-coded

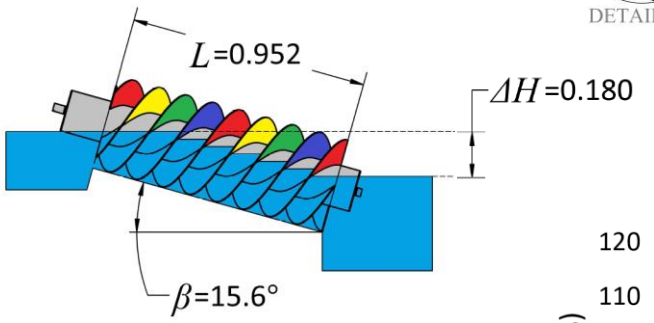


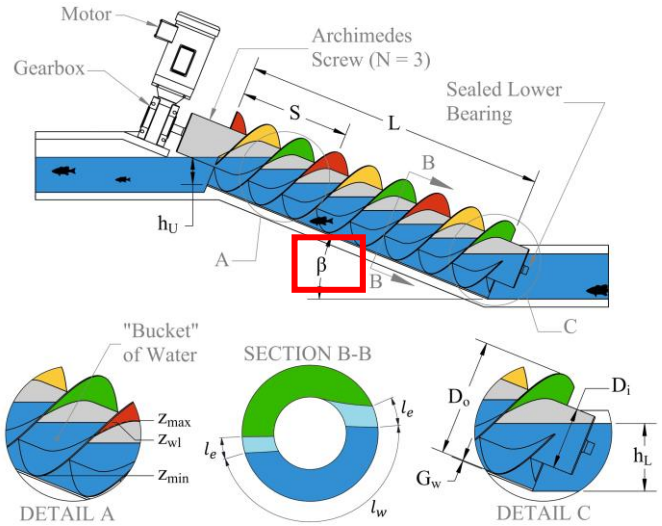
3.4. Inclination Angle (β)

- Steep screws have shorter lengths
  - Less friction loss
  - Less bucket volume
    - Must turn at proportionally higher rotation speeds
  - Less expensive

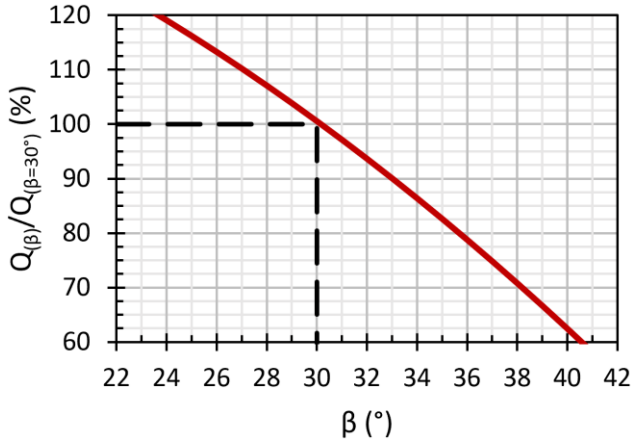


- Shallow-inclined screws are longer
  - More friction
  - More bucket volume
    - Can turn at lower speeds and are generally more mechanically efficient
  - More expensive





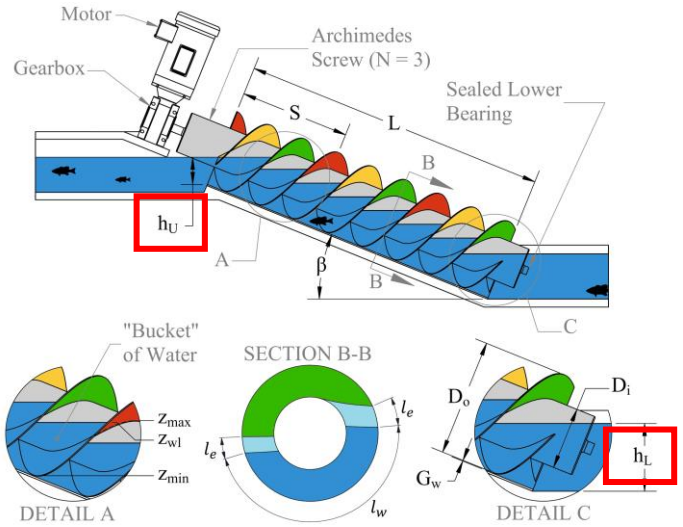
- Muysken (1932) suggests screw pumps for dewatering should operate around β = 26°



3.5. Water Levels (h_U and h_L)

- In wastewater, upper water level is often set to h_U = 0 m
- Optimal lower water level (h'_L) is screw-specific
  - It is usually set so the lower end of screw is submerged about 75%, or $\psi_L = 0.75$

$$\psi_L = \frac{D_o + D_i}{2D_o}\sqrt{1 - \left(\frac{S\tan\beta}{\pi D_i}\right)^2}$$



About 75% Submerged [Near Optimal]

Over 100% Submerged [Not Optimal]

4. Conclusions

4. Conclusions

- The “state-of-the-art” is outdated
  - Lacks accuracy, lots of room for improvement
- More data is necessary for development of more accurate models
- Flow and leakage rates, hydraulic losses, and geometric optimization is underway

4. Conclusions

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Thank you all very much for your time.

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