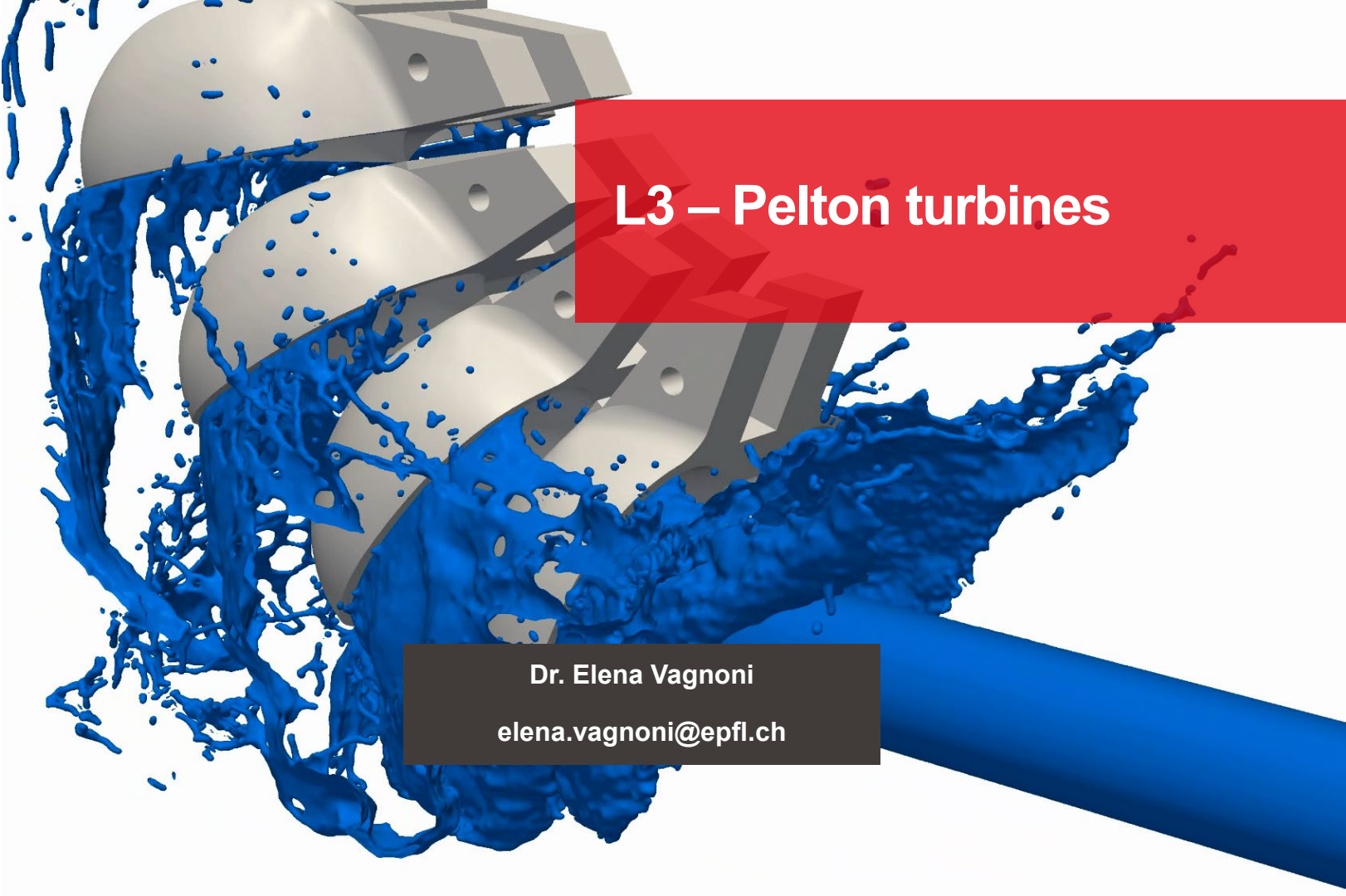


A 3D simulation of a Pelton turbine bucket, shown in a light gray color, is the central focus. It is surrounded by a dynamic splash of blue liquid, representing water, which is captured in mid-motion. The background is a solid white. A red rectangular banner is positioned in the upper right, and a dark gray rectangular box is in the lower center, both containing text.

L3 – Pelton turbines

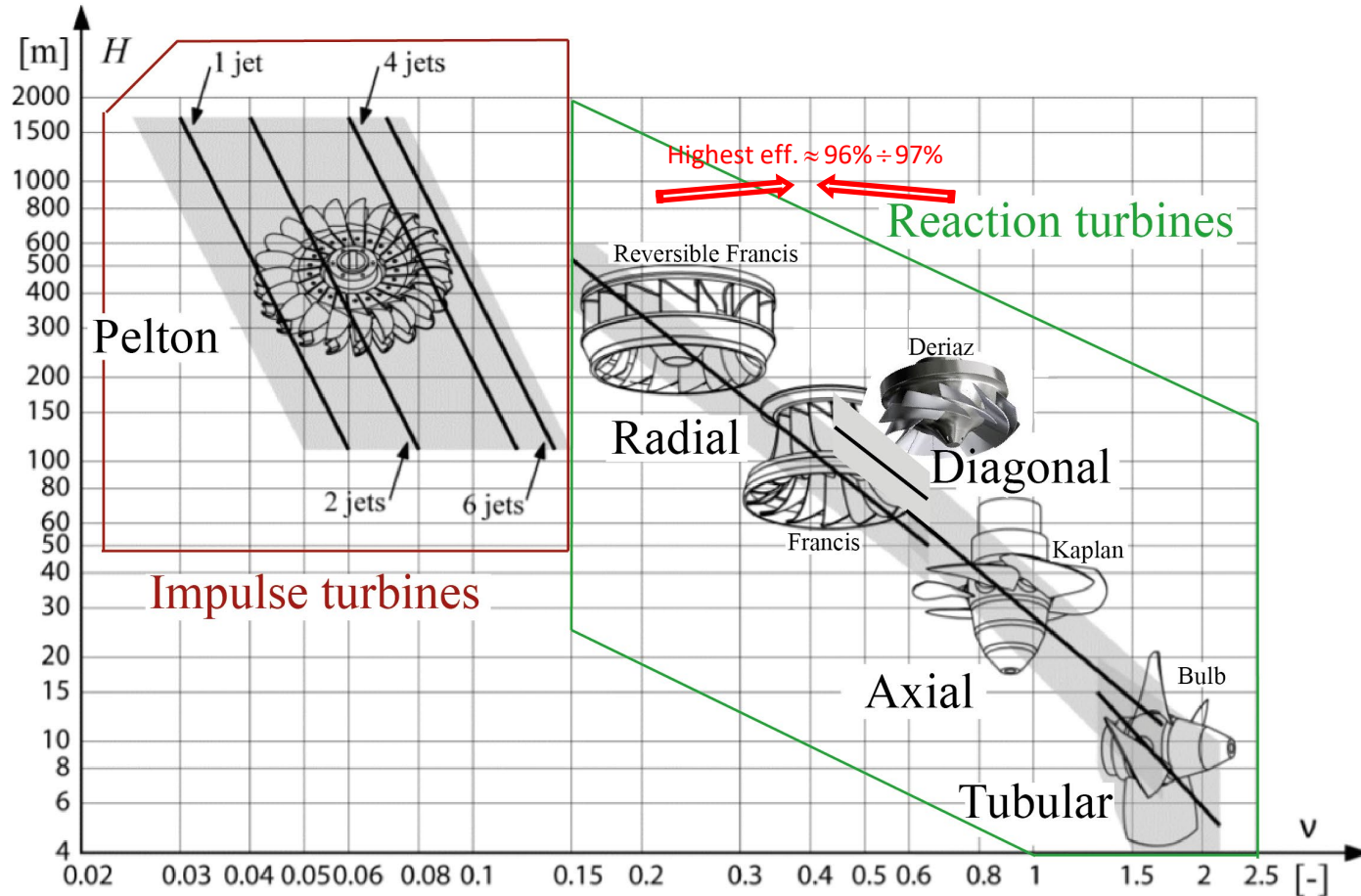
Dr. Elena Vagnoni

elena.vagnoni@epfl.ch

Topics of the lecture

- Historical Background
- Operating Principle
- Special Issues
- Bieudron Power Station

From L2: Classification of Hydraulic



Head = H (m)

Discharge = Q ($\text{m}^3 \cdot \text{s}^{-1}$)

Speed = N (min^{-1})

$$v = 2^{\frac{1}{4}} \pi^{\frac{1}{2}} \times n \times \frac{Q^{\frac{1}{2}}}{E^{\frac{3}{4}}}$$

From L2: Classification of Hydraulic Runners

Runner/impeller specific energy transfer

- Transferred Specific Energy

$$gH_1 - gH_{\bar{1}} = E_t \pm E_{rb} \quad (\text{J} \cdot \text{kg}^{-1})$$

- Specific Energy

$$gH = \frac{p}{\rho} + gZ + \frac{C^2}{2} \quad (\text{J} \cdot \text{kg}^{-1})$$

- Specific Energy Balance:

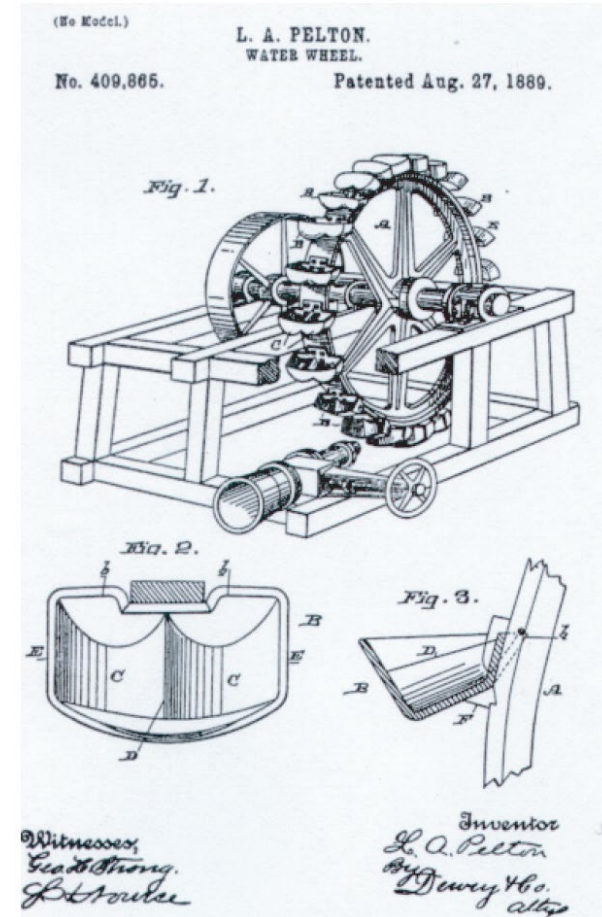
$$E_t = \underbrace{\left(\frac{p_1}{\rho} - \frac{p_{\bar{1}}}{\rho} \right)}_{\text{Displacement}} + \underbrace{\left(\frac{C_1^2}{2} - \frac{C_{\bar{1}}^2}{2} \right)}_{\text{Impulse}} + \underbrace{\left[gZ_1 - gZ_{\bar{1}} \right]}_{\text{Water Wheel}} \pm \underbrace{E_{rb}}_{\text{Loss}} \quad (\text{J} \cdot \text{kg}^{-1})$$

Reaction

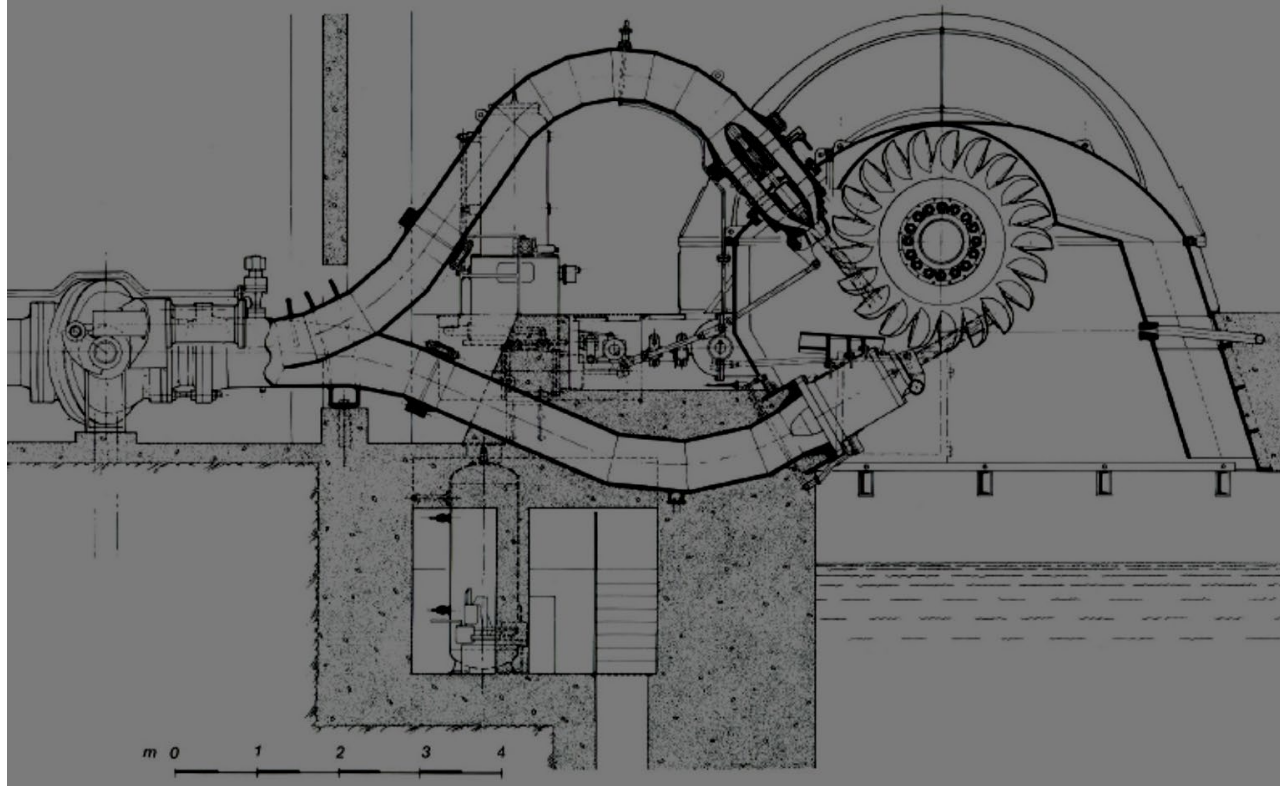


Splitter Bucket Invention by Lester A. Pelton (1831-1908)

- Impulse Turbine
- Head (300 m - 2'000 m)
- Unit Power up to 420 MW
- Efficiency up to 92%
- 1-6 injectors
- Horizontal or Vertical shaft



Horizontal Shaft

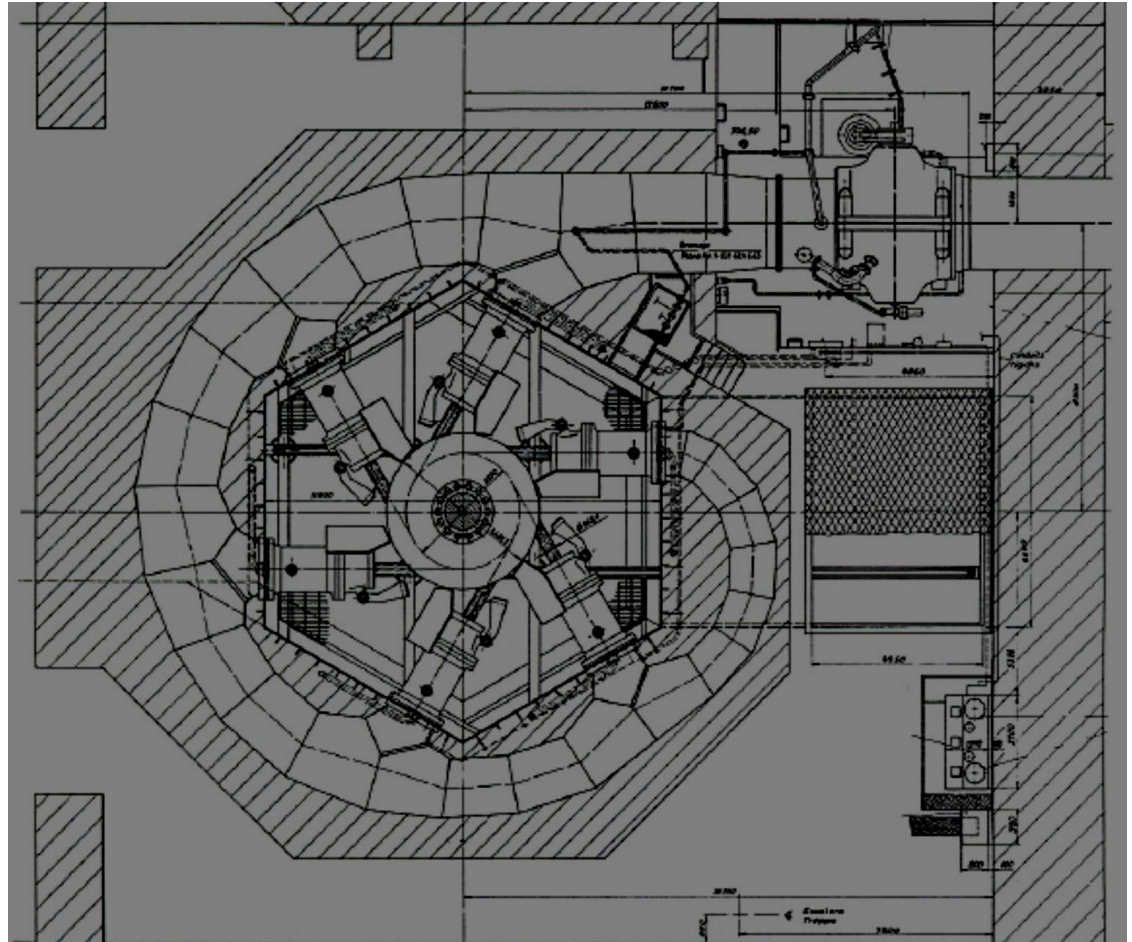


Naturno (IT)

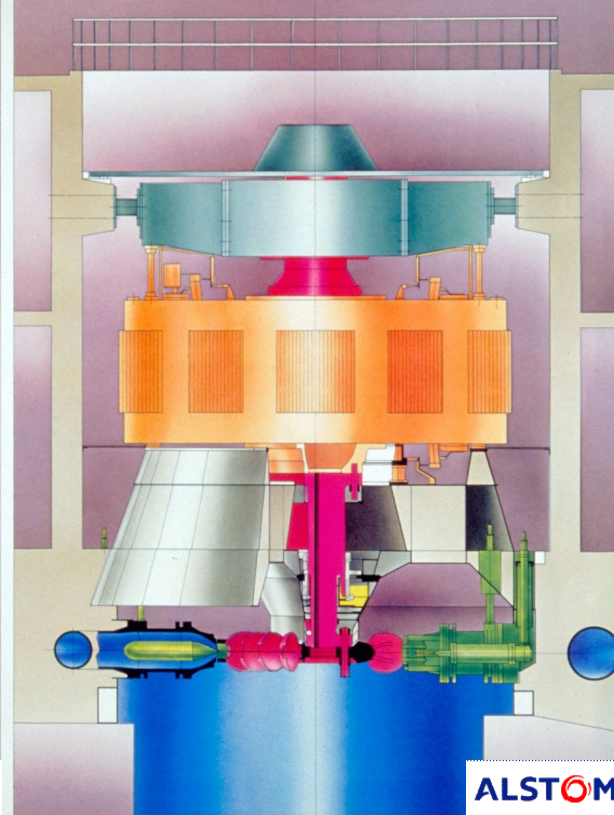
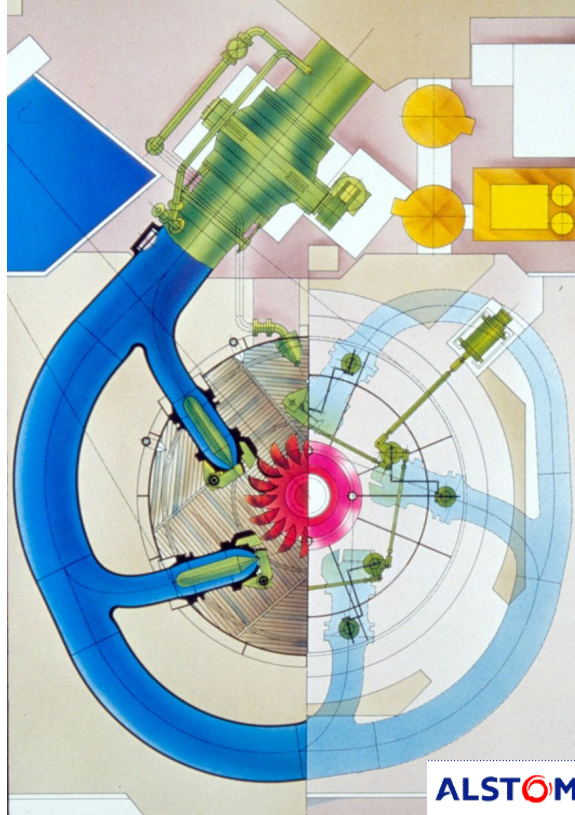
2 x 2 jets, 600 min^{-1} , 1'088 m, $5.77 \text{ m}^3/\text{s}$, 55 MW, $D_1 = 2.26 \text{ m}$,
 $D_o = 0.21 \text{ m}$, $D_2 = 0.22 \text{ m}$, $B = 0.53 \text{ m}$, $z_b = 21$.

EPFL Vertical Shaft

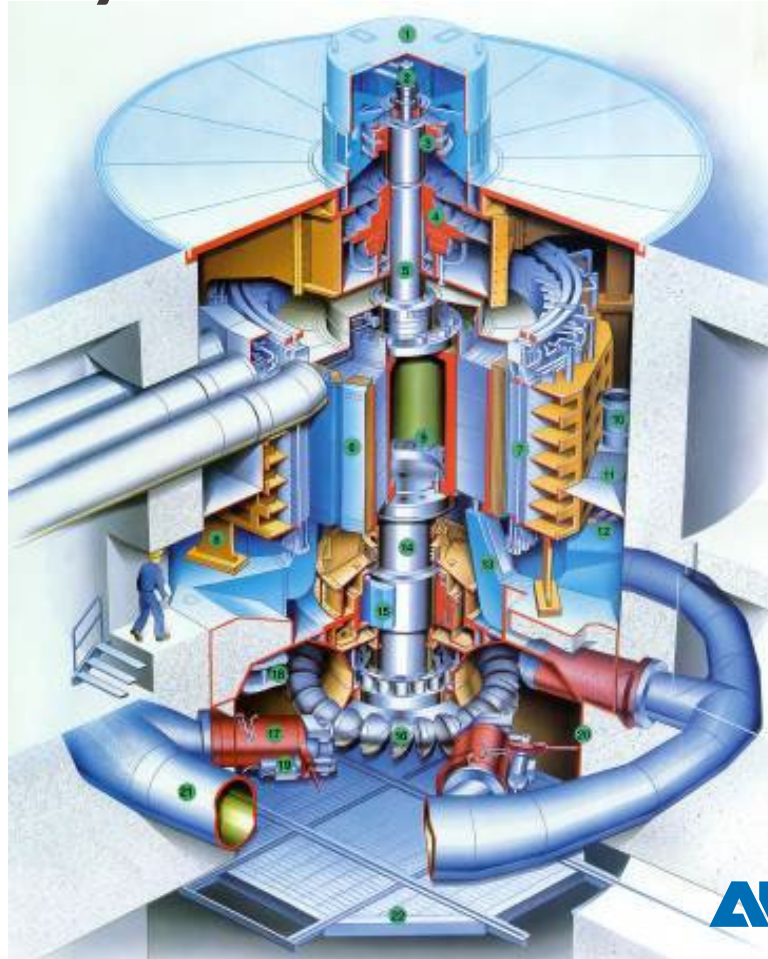
San Agaton (VE)
6 jets, 225 min^{-1} , 350 m, $49.76 \text{ m}^3/\text{s}$, 153 MW,
 $D_1 = 3.33 \text{ m}$, $D_o = 0.464 \text{ m}$, $D_2 = 0.365 \text{ m}$, $B = 1.11 \text{ m}$,
 $z_b = 20$.



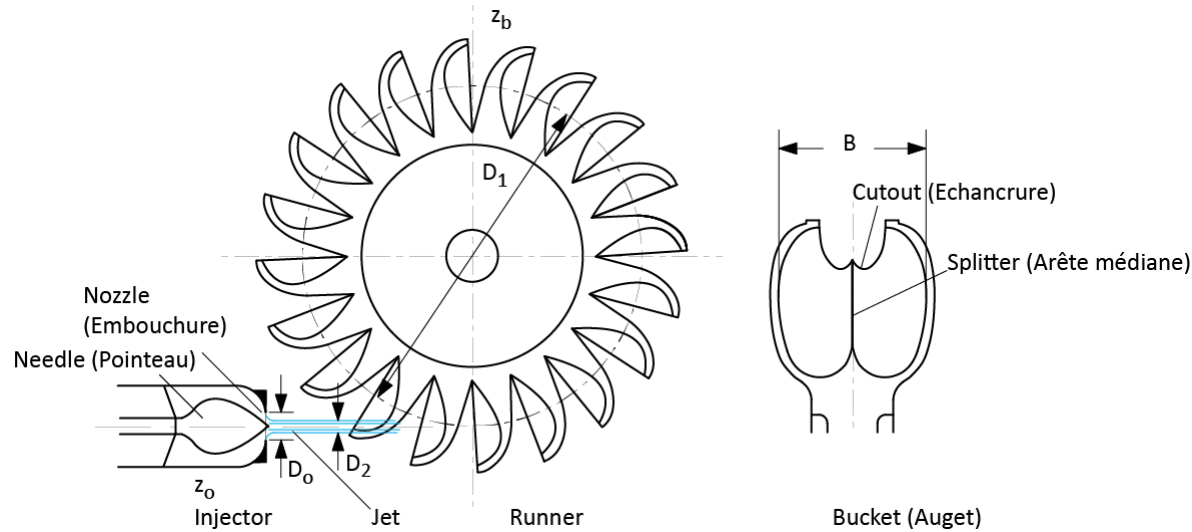
Pelton Turbine Layout



Pelton Unit Layout



Operating Principle for Impulse Turbines



$$E_t = \underbrace{\left(\frac{p_1}{\rho} - \frac{p_{\bar{1}}}{\rho} \right)}_{\text{Displacement}} + \underbrace{\left(\frac{c_1^2}{2} - \frac{c_{\bar{1}}^2}{2} \right)}_{\text{Impulse}} + \underbrace{\left[gZ_1 - gZ_{\bar{1}} \right]}_{\text{Water Wheel}} \pm \underbrace{E_{rb}}_{\text{Loss}} \quad (\text{J} \cdot \text{kg}^{-1})$$

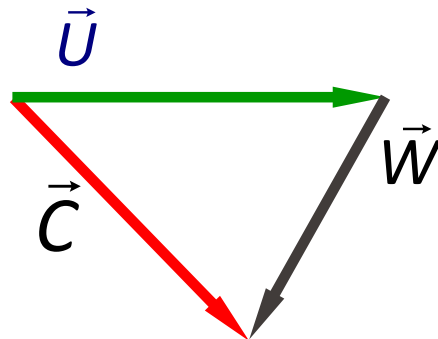
~~Reaction~~

Operating Principle for Impulse Turbines

Specific Energy Balance

$$E_t = \frac{C_1^2}{2} - \frac{C_2^2}{2} - E_{rb}$$

$$= \frac{(\vec{W}_1 + \vec{U}_1)^2}{2} - \frac{(\vec{W}_2 + \vec{U}_2)^2}{2} - E_{rb}$$



- Absolute Flow Velocity

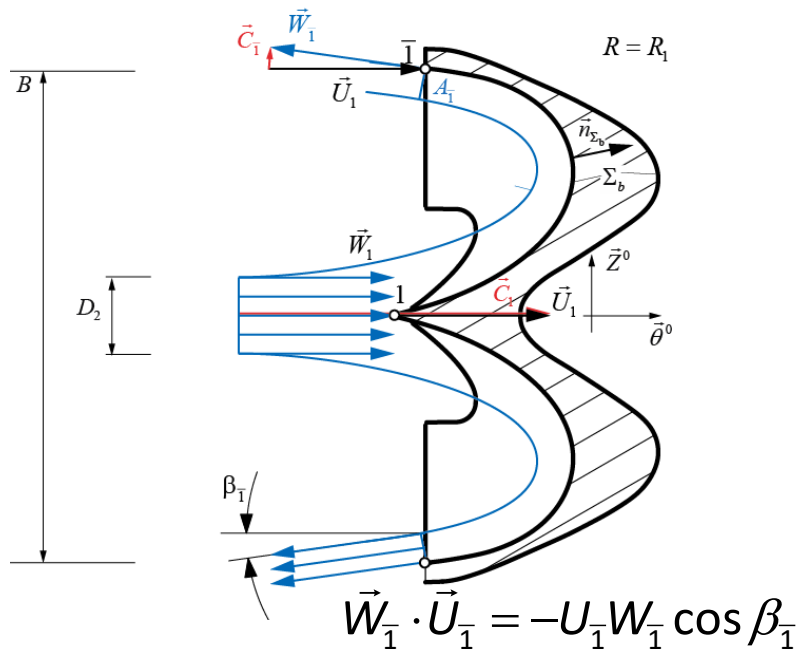
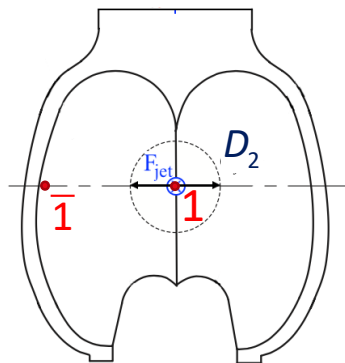
$$\vec{C} = \vec{U} + \vec{W}$$

- Rotating Velocity $\vec{U} = \vec{\omega} \times \vec{X}$
 $= \omega R$

- Relative Flow Velocity

$$\vec{W} = \vec{C} - \vec{U}$$

Operating Principle for Impulse Turbines



Hypothesis: no specific energy losses between the bucket inlet and outlet (the fluid loses no energy in its path through the bucket): $W_1^2 = W_2^2$

$$\begin{aligned}
 E_t &= \frac{(\vec{W}_1 + \vec{U}_1)^2}{2} - \frac{(\vec{W}_2 + \vec{U}_2)^2}{2} - E_{rb} = \frac{\cancel{W_1^2} + 2\vec{W}_1 \cdot \vec{U}_1 + \cancel{U_1^2}}{2} - \frac{\cancel{W_2^2} + 2\vec{W}_2 \cdot \vec{U}_2 + \cancel{U_2^2}}{2} - E_{rb} = \\
 &= W_1 U_1 + \cos \beta_1 W_1 U_1 - E_{rb} = (1 + \cos \beta_1)(C_1 - U_1)U_1 - E_{rb}
 \end{aligned}$$

Operating Principle for Impulse Turbines

- Maximum specific energy

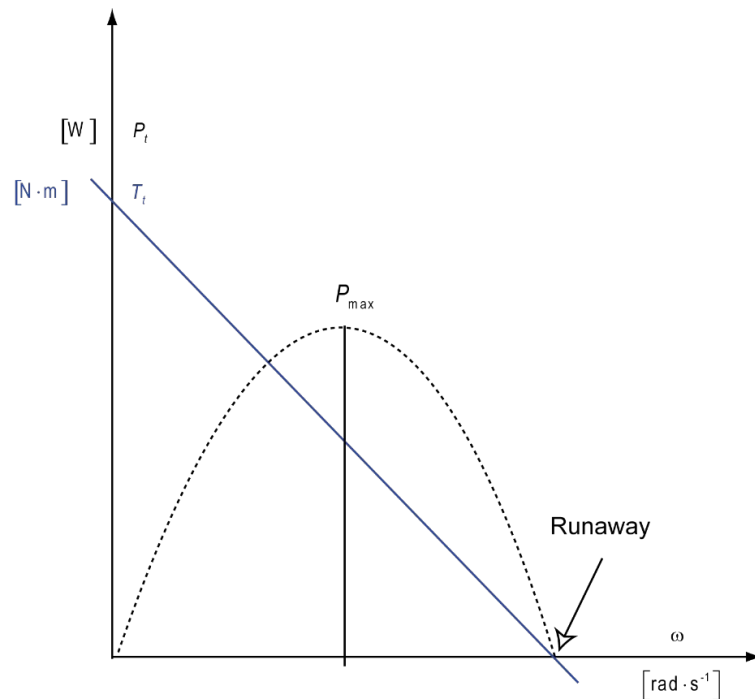
$$E_t = (1 + \cos \beta_1)(C_1 - U_1)U_1 - E_{rb}$$

$$\left. \begin{array}{l} \beta_1 = 0 \\ U_1 = \frac{C_1}{2} \end{array} \right\} \Rightarrow E_t^{\max} = \frac{C_1^2}{2} - E_{rb}$$

- Maximum Power

$$P = \rho \frac{\pi D_2^2}{4} (1 + \cos \beta_1)(C_1 - U_1)U_1 C_1$$

$$\left. \begin{array}{l} \beta_1 = 0 \\ U_1 = \frac{C_1}{2} \end{array} \right\} \Rightarrow P^{\max} = \rho \frac{\pi D_2^2}{4} \frac{C_1^3}{2}$$



Needle Stroke

- Energy Balance

$$E = gH = g(Z_B - Z_{\bar{B}}) - \sum gH_r$$

$$gH_B - gH_2 = g(Z_B - Z_2) + \cancel{\frac{p_B - p_2}{\rho}} + \cancel{\frac{C_B^2}{2}} - \frac{C_2^2}{2} = \sum gH_r = \sum_{B \rightarrow I} E_r + \underbrace{e_r \cdot E}_{\substack{\% \text{ Specific Energy} \\ \text{Lost in the nozzle}}}$$

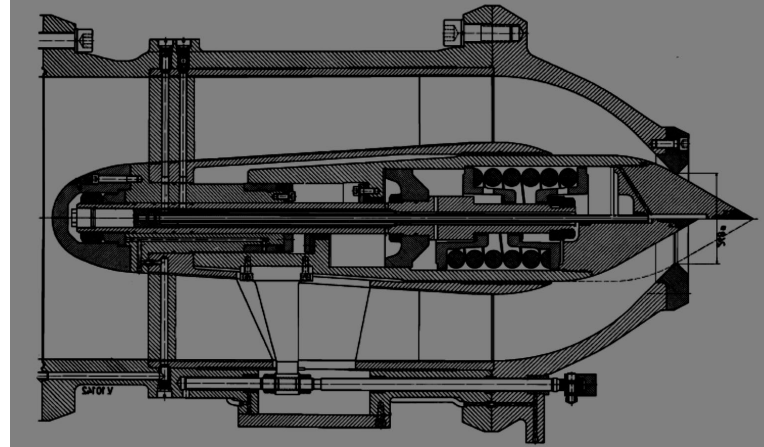
$$E = \frac{C_2^2}{2} + \sum_i E_{r_i} \quad (\text{J} \cdot \text{kg}^{-1}) \Rightarrow C_2 = \sqrt{2E(1 - e_r)}$$

- Discharge

$$Q = z_o A_2 C_2 = z_o \frac{\pi D_2^2}{4} C_2 = z_o \frac{\pi D_2^2}{4} \sqrt{2E(1 - e_r)}$$

- Power

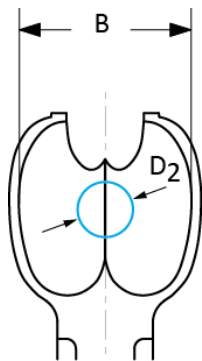
$$P = z_o \rho \frac{\pi D_2^2}{4} \frac{(2E(1 - e_r))^{\frac{3}{2}}}{2}$$



Jet Specific Speed

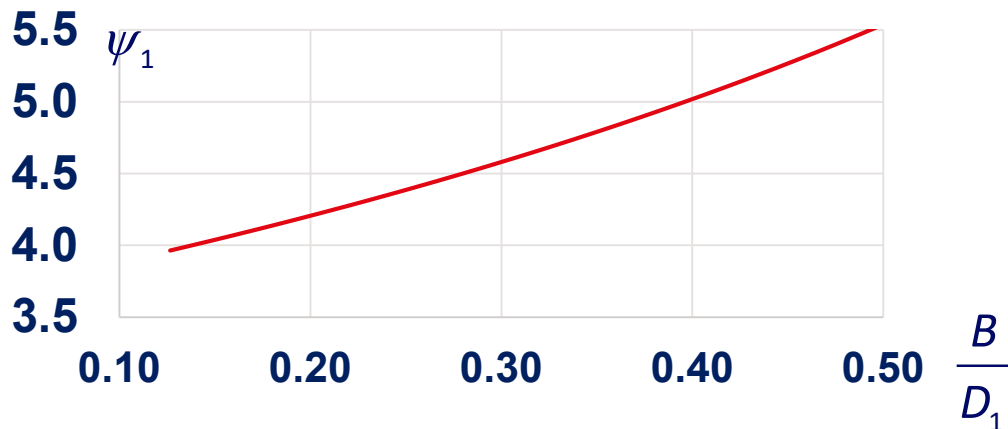
- Jet Discharge $\frac{Q}{z_o} = \frac{\pi D_2^2}{4} \sqrt{(1-e_r)2E}$
- Specific Speed
$$\begin{aligned} v_o &= \frac{\sqrt{\pi}}{30} \frac{N}{(2E)^{3/4}} \frac{\sqrt{\pi} D_2}{2} (1-e_r)^{1/4} (2E)^{1/4} \\ &= \frac{\pi}{60} (1-e_r)^{1/4} \frac{N D_2}{\sqrt{2E}} \end{aligned}$$
- Optimum Speed $U_1 = \frac{C_2}{2} \Leftrightarrow \frac{\pi}{30} N \frac{D_1}{2} = \frac{\sqrt{2E(1-e_r)}}{2}$

Jet Specific Speed



$$D_2 \approx \frac{B}{3 \div 3.4} \quad v_o = \frac{(1-e_r)^{\frac{3}{4}}}{2} \frac{D_2}{D_1} \quad \psi_1 \left(\frac{B}{D_1} \right) = \frac{3.6}{1 - 0.735 \times \frac{B}{D_1}}$$

$$= \frac{(1-e_r)^{\frac{3}{4}}}{2(3 \div 3.4)} \frac{B}{D_1}$$



Pelton Specific Issues

Silt Erosion



Pelton Specific Issues

Silt Erosion: Hardcoating



- Bucket



- Needle

Successfully mitigating silt erosion

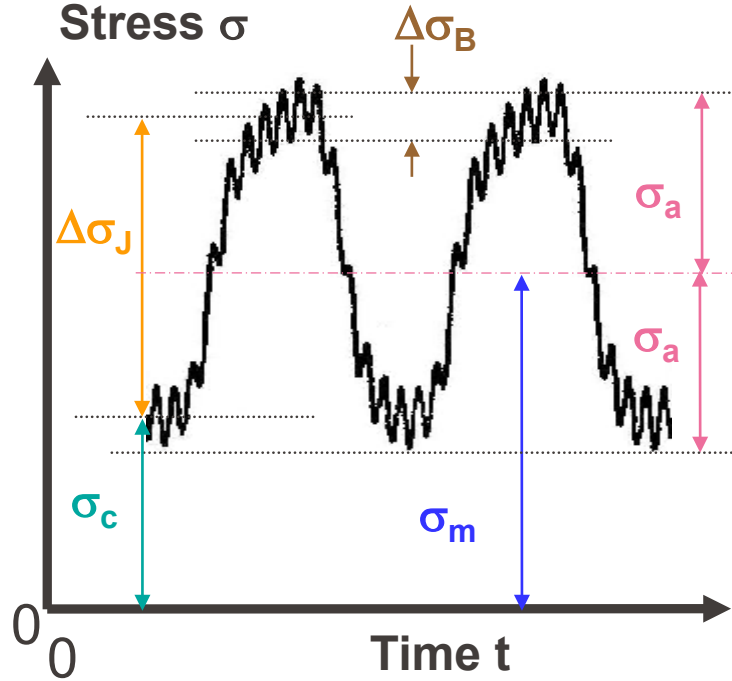


- Uncoated after 4'000 h



- SXH70-coated after 3'000 h

Pelton Special Issues: Dynamic Loading

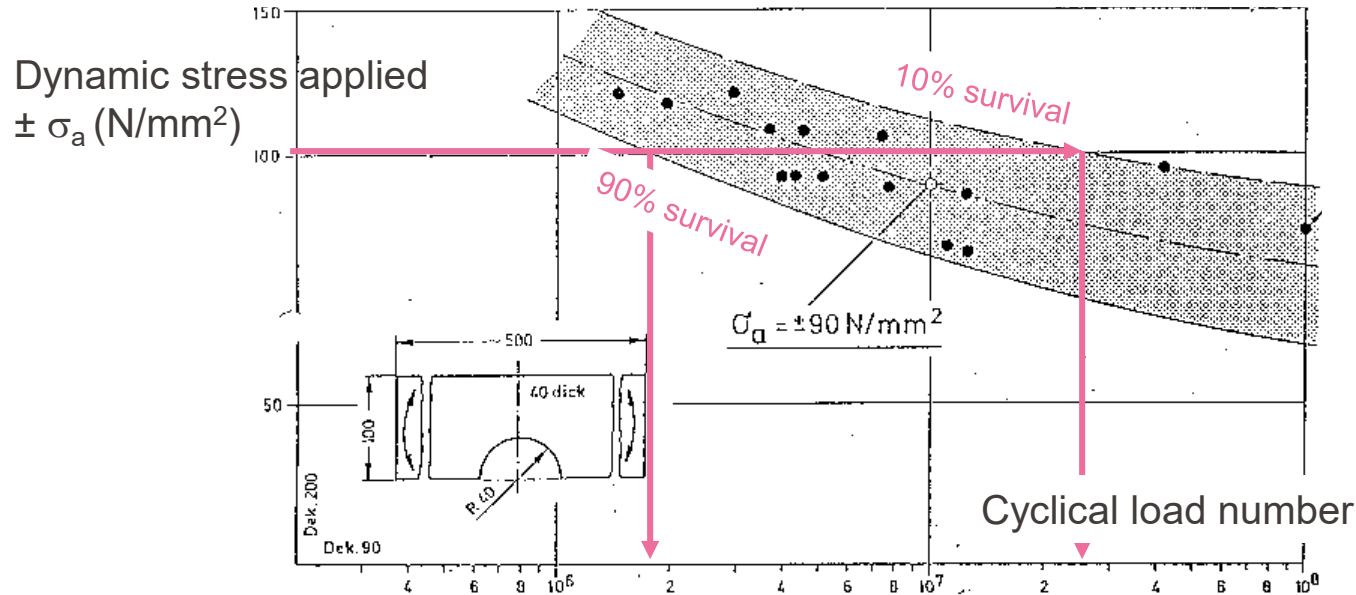


- $\Delta\sigma_J$ jet deviation
- $\Delta\sigma_B$ bucket vibration (5 to 10 MPa)
- σ_c Centrifugal stress
- σ_a Dynamic stress <30 MPa for EDF, based on statistics $\Rightarrow$ Life time
- σ_m Mean stress

Sellrain Silz runner measurement: 6 jets, 262 MW, 1'233 m Head

Typical WÖHLER curve for Fatigue damage

$$R = \frac{\sigma_{\min}}{\sigma_{\max}} = \frac{\sigma_m - \sigma_a}{\sigma_m + \sigma_a}$$

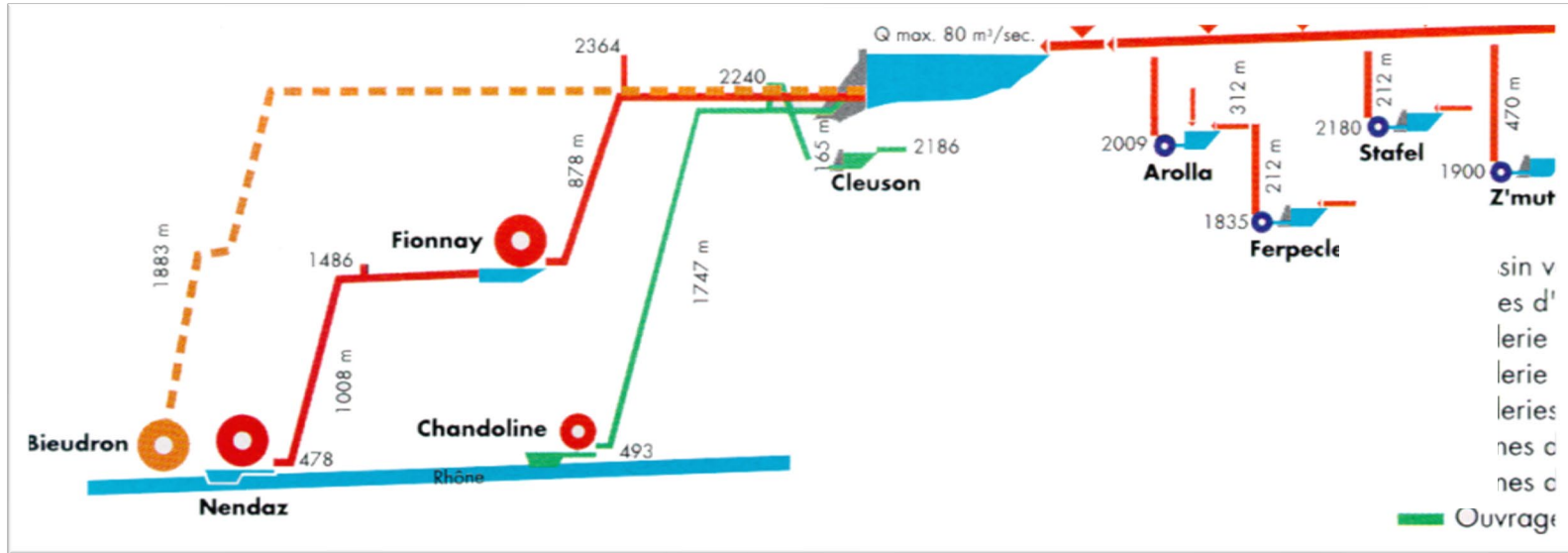


- Samples for different steels of Pelton runners, in wet atmosphere (curves not saturating)

Grande Dixence Hydropower Scheme



Grande Dixence Hydropower Scheme

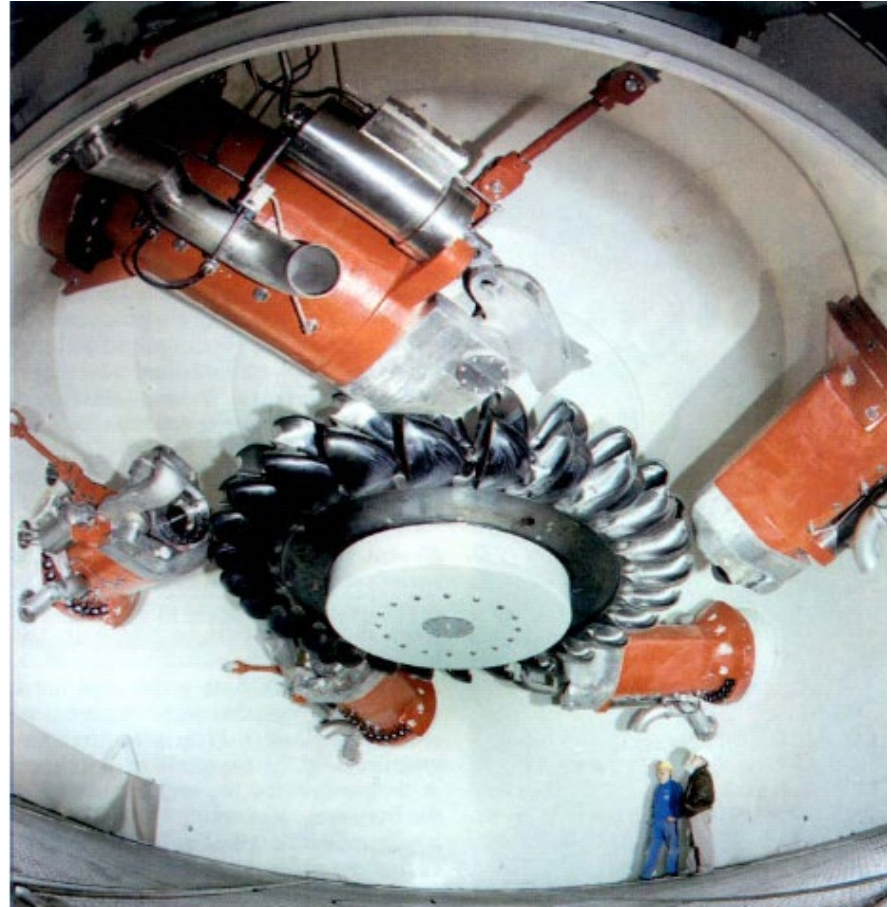


- Generating Power Station: Seasonal Operation
 - 1'269 MW Bieudron
 - 685 MW Nendaz-Fionnay
 - 100 MW Chandoline
- Collecting Water from 35 Glaciers
 - 170 MW Pumping Power

1'269 MW Bieudron Power Plant

3 Pelton Turbines

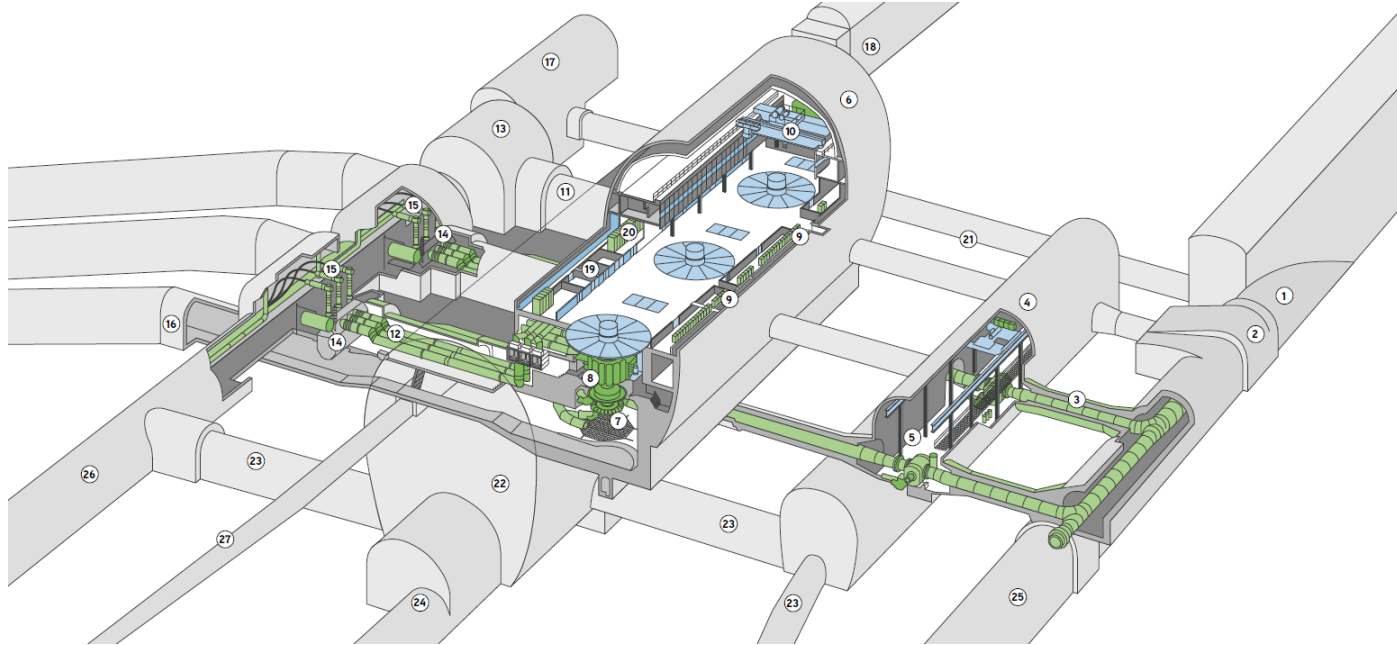
- 500 MVA Generators
 - 428.5 min^{-1}
 - 14 poles, 35.7 MVA/pole
 - Water Cooled
- 423 MW Pelton Turbines, 5 injectors
 - 1'883 mWC Head
 - $25 \text{ m}^3/\text{s}$ Discharge
 - $D_1 = 3.993 \text{ m}$
 - ~28 t Runner Mass



1'269 MW Bieudron Power Plant

3 Pelton Turbines

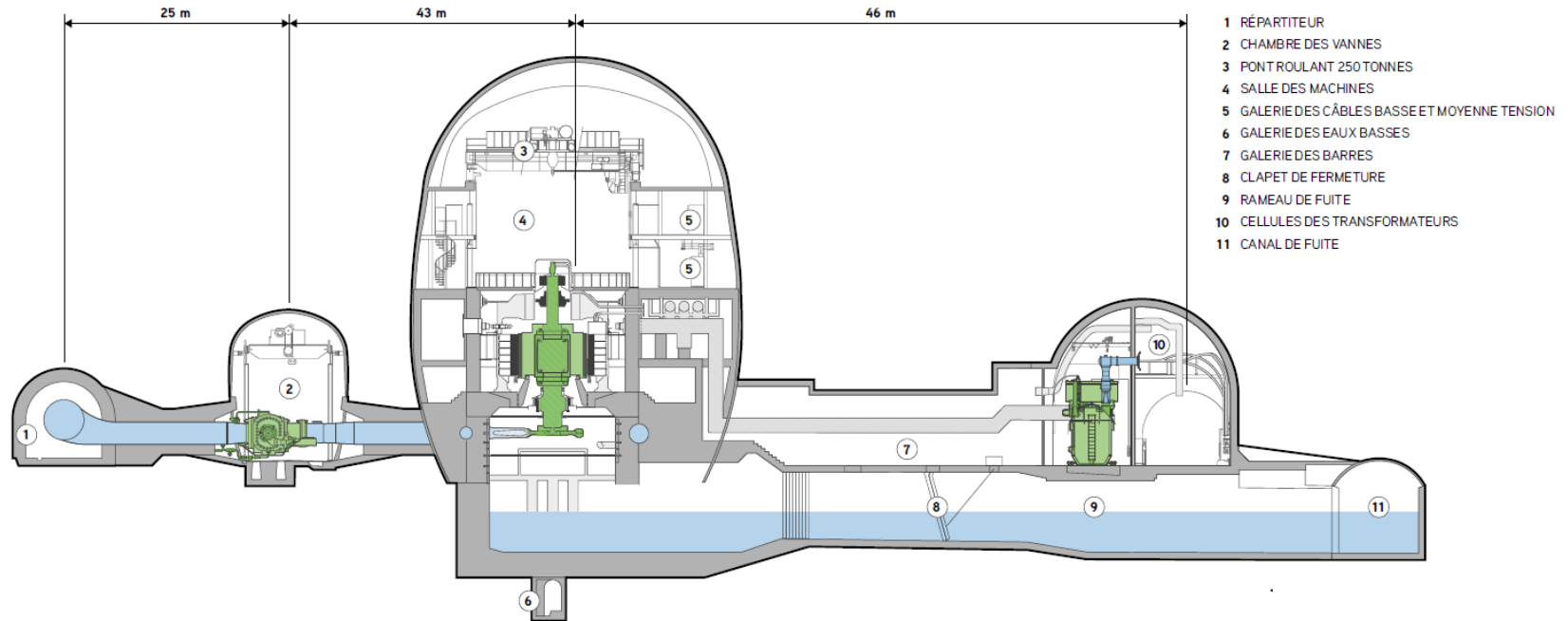
Underground Power House



1'269 MW Bieudron Power Plant

3 Pelton Turbines

Power House Cut View



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