L3 – High head generating units

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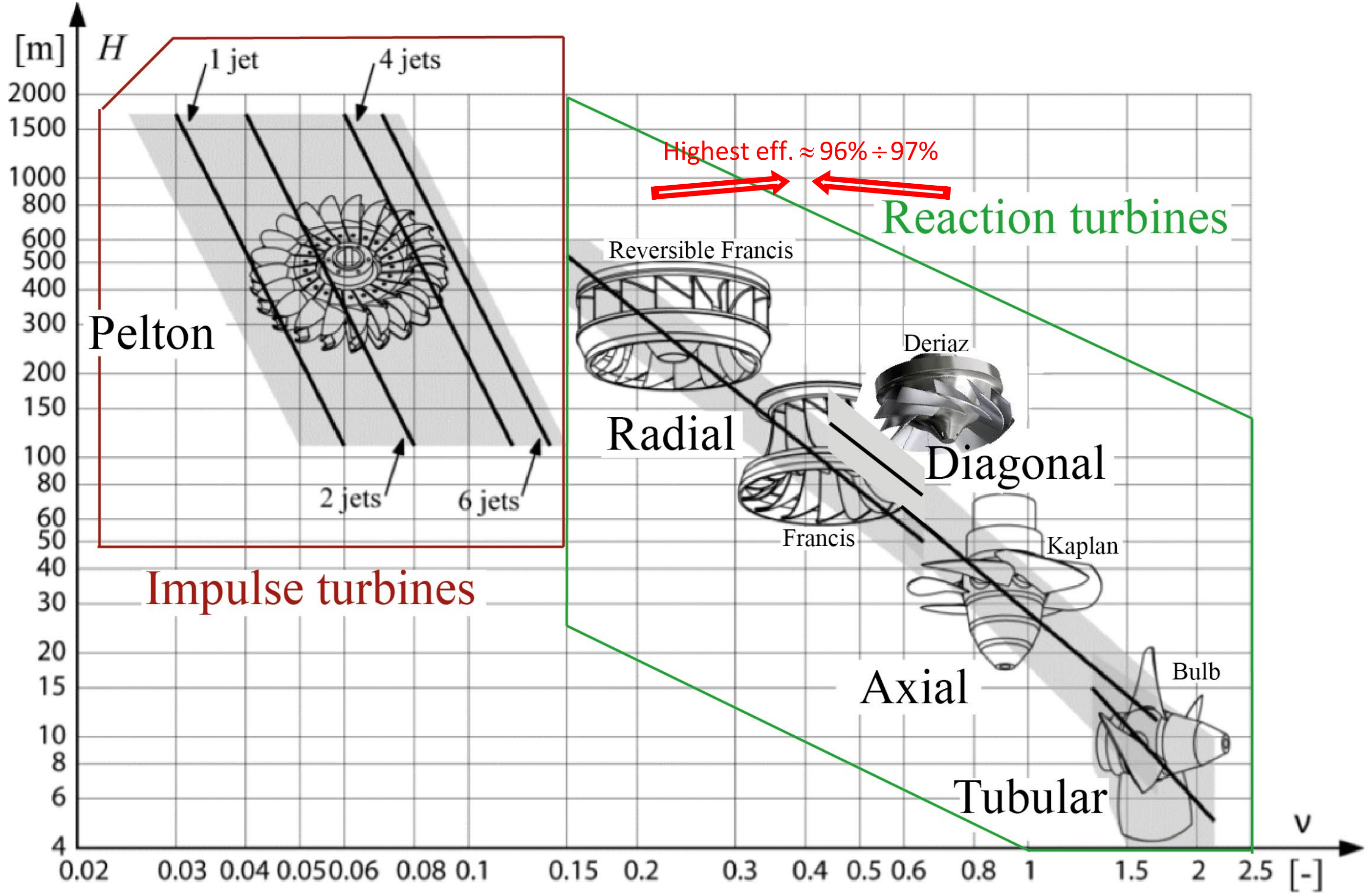
Topics of the lecture

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

From L2: Classification of Hydraulic



Highest eff. ≈ 96% ÷ 97%

$\text{Head} = H \quad (\text{m})$

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

$\text{Speed} = N \quad (\text{min}^{-1})$

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

From L2: Classification of Hydraulic Runners

Runner/impeller specific energy transfer

- Transferred Specific Energy

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

- Specific Energy

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

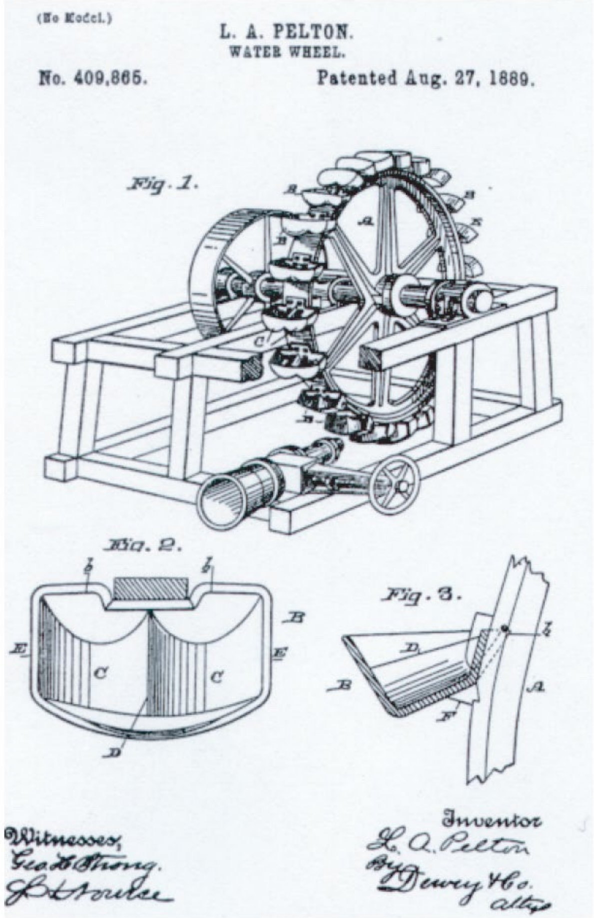
- Specific Energy Balance:

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

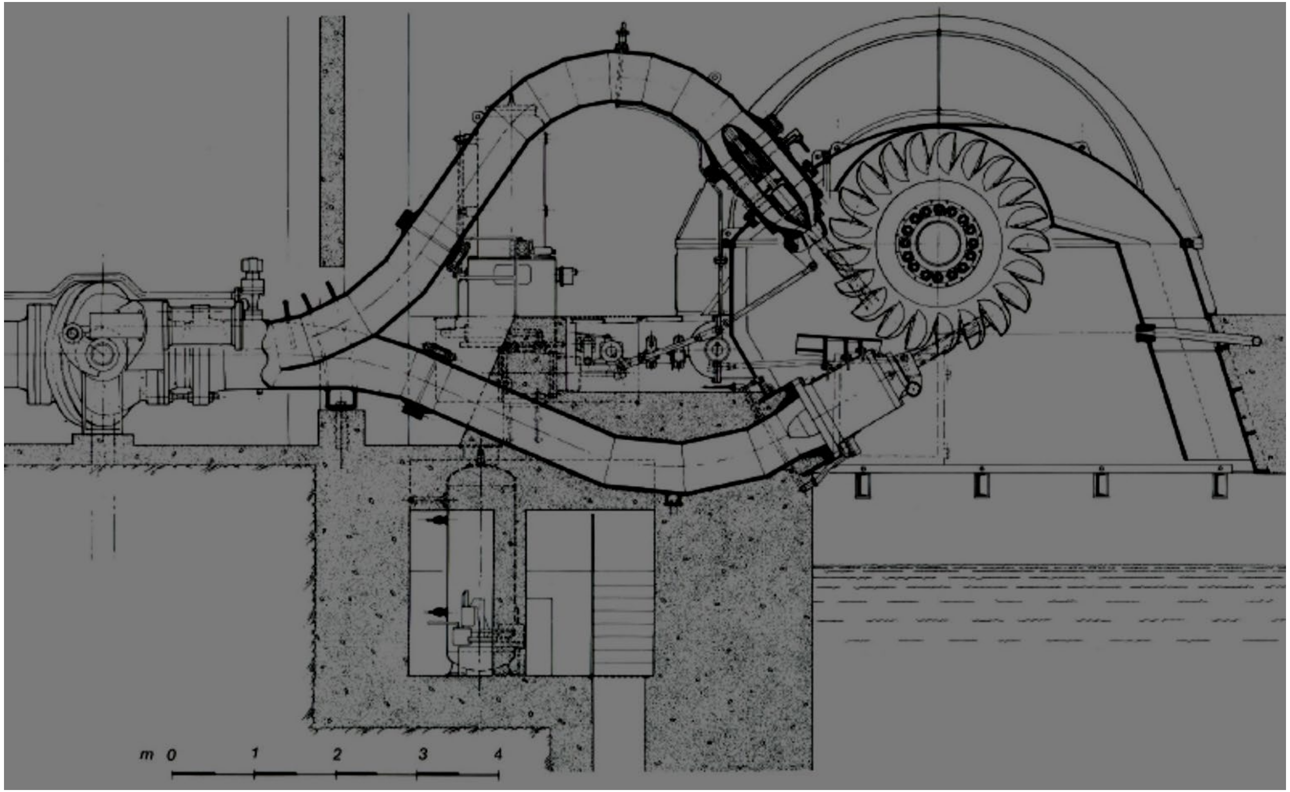
$$\left(\mathrm{J\cdot kg^{-1}}\right)$$

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

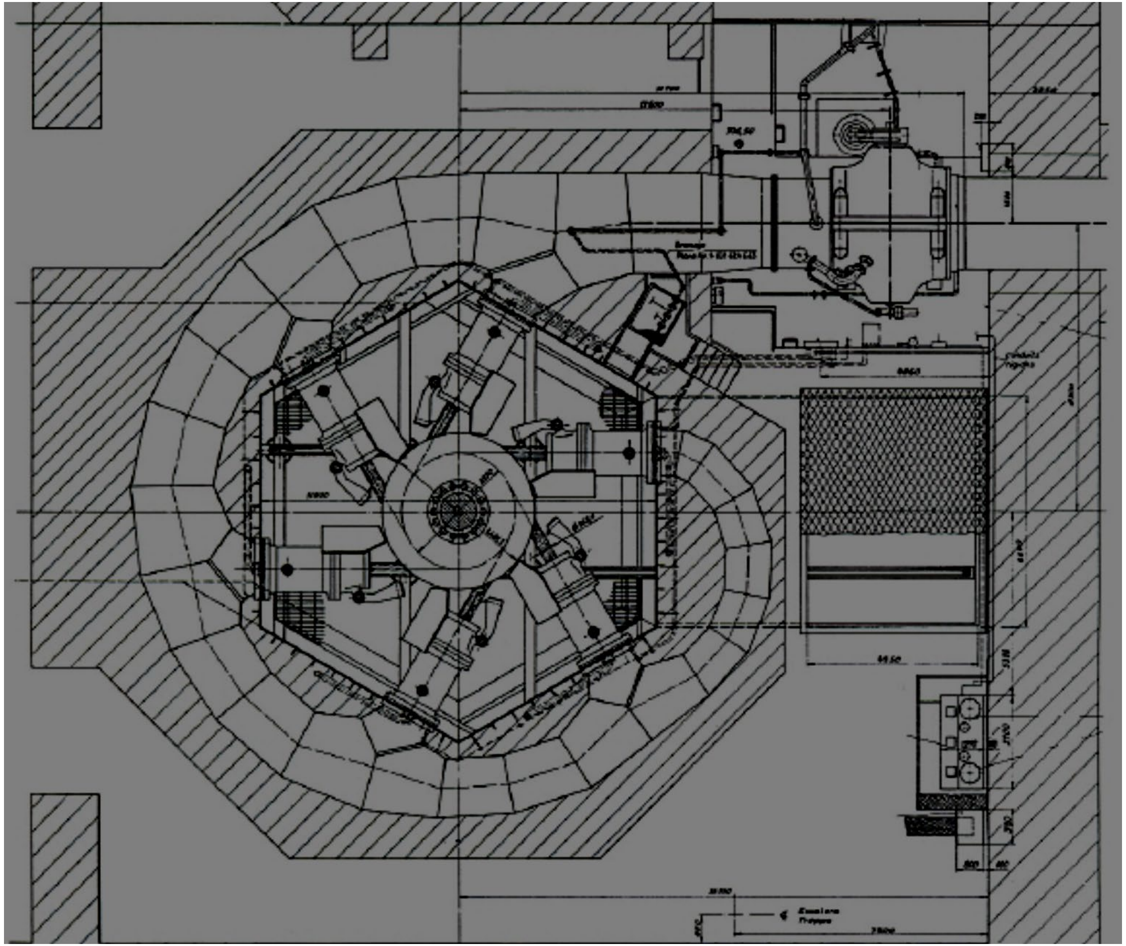


Horizontal Shaft



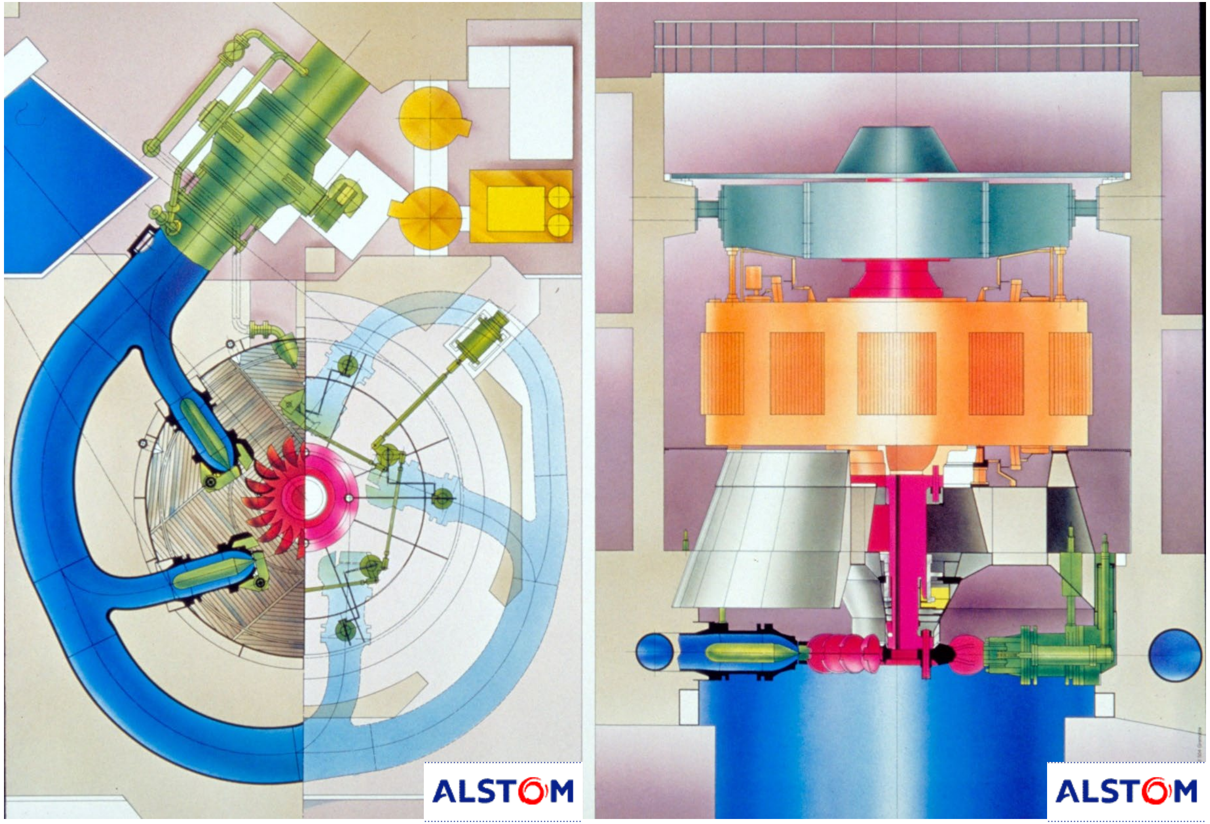
Naturno (IT)
2 x 2 jets, 600 min^{-1} , 1'088 m, 5.77 m^3/s, 55 MW, D_1 = 2.26 m, D_o = 0.21 m, D_2 = 0.22 m, B = 0.53 m, z_b = 21.

Vertical Shaft

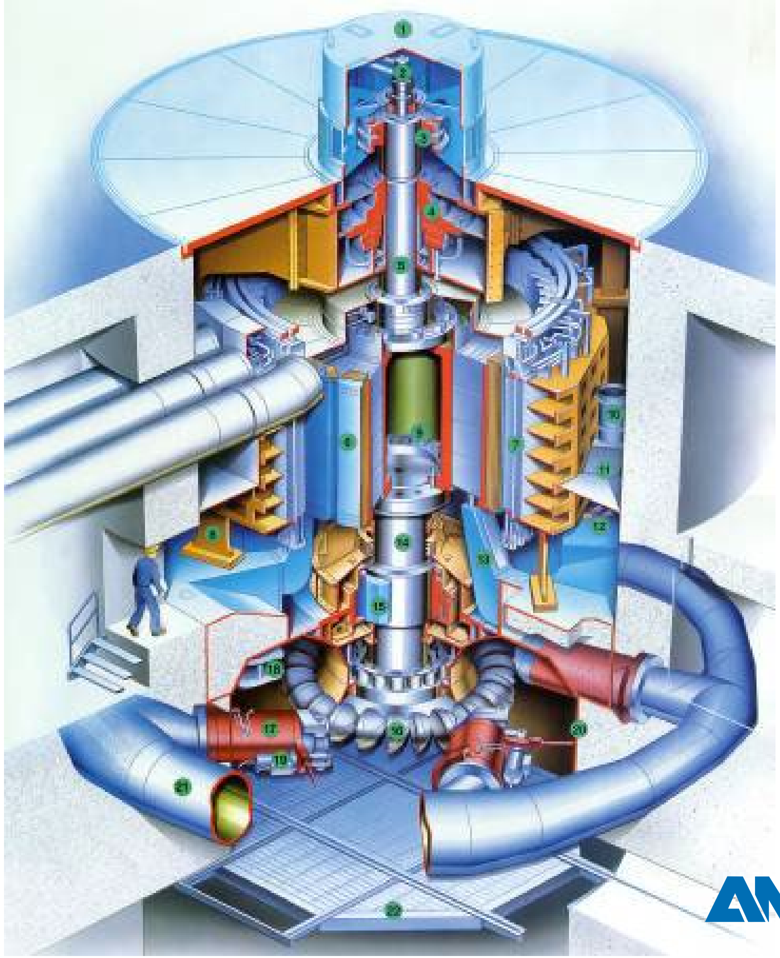


San Agaton (VE)
6 jets, 225 min^{-1} , 350 m, 49.76 m^3/s, 153 MW,
D_1 = 3.33 m, D_o = 0.464 m, D_2 = 0.365 m, B = 1.11 m,
z_b = 20.

Pelton Turbine Layout

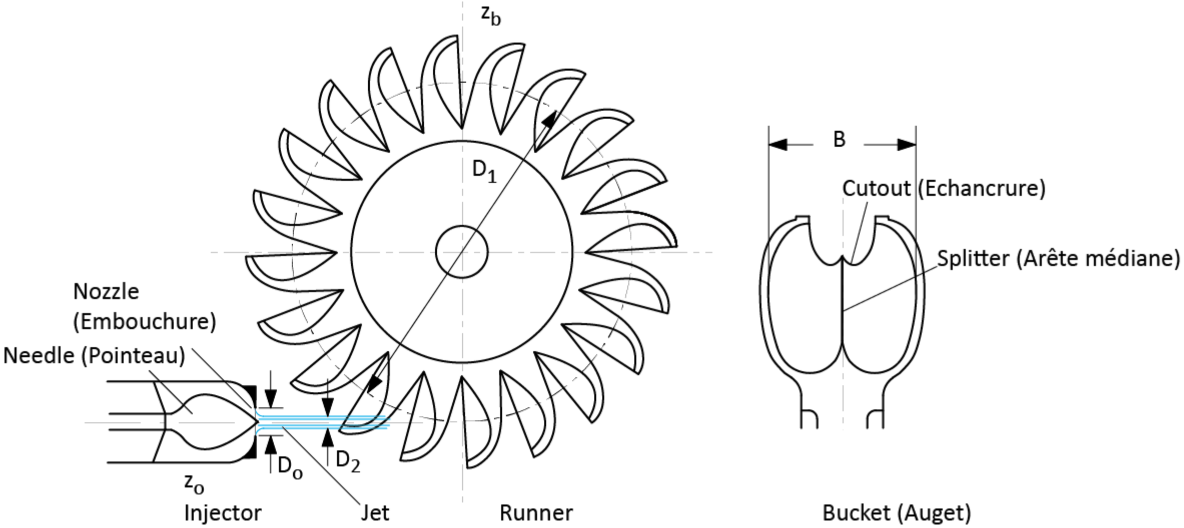


Pelton Unit Layout



ANDRITZ Hydro

Operating Principle for Impulse Turbines



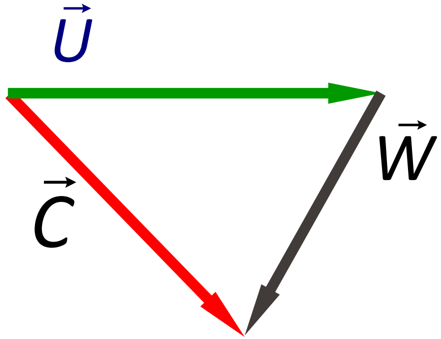
$$E_t = \overbrace{\underbrace{\cancel{\left(\frac{p_1}{\rho}-\frac{p_{\bar{1}}}{\rho}\right)}}_{\text{\sout{Displacement}}} + \underbrace{\left(\frac{C_1^2}{2}-\frac{C_{\bar{1}}^2}{2}\right)}_{\text{Impulse}}}^{\text{\sout{Reaction}}} + \underbrace{\cancel{\left[gZ_1 - gZ_{\bar{1}}\right]}}_{\text{\sout{Water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

Operating Principle for Impulse Turbines

Specific Energy Balance

$$E_t = \frac{C_1^2}{2} - \frac{C_{\bar{1}}^2}{2} - E_{rb}$$

$$= \frac{\left(\vec{W}_1 + \vec{U}_1\right)^2}{2} - \frac{\left(\vec{W}_{\bar{1}} + \vec{U}_{\bar{1}}\right)^2}{2} - E_{rb}$$



- Absolute Flow Velocity

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

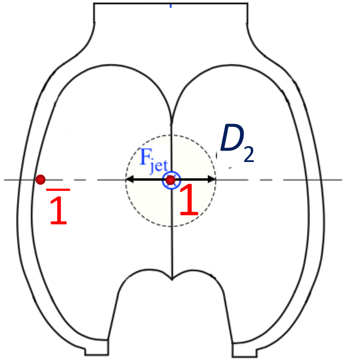
- Rotating Velocity $\vec{U} = \vec{\omega} \times \vec{X}$

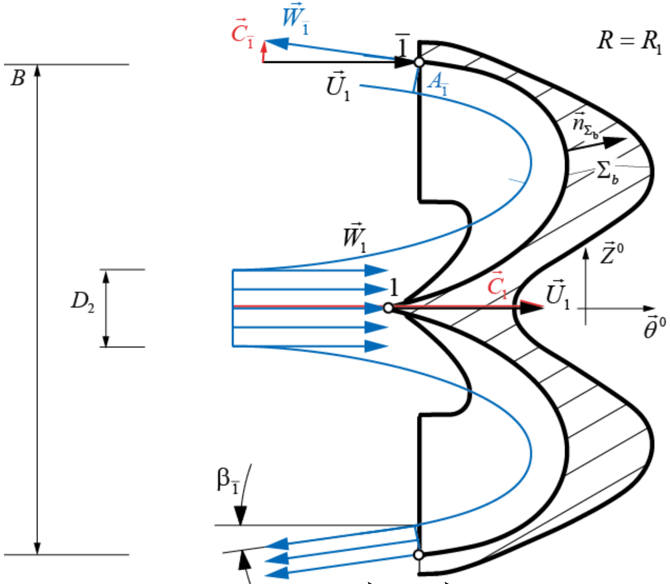
  $$= \omega R$$

- 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): $W_1^2 = W_{\bar{1}}^2$

$$\vec{W}_{\bar{1}} \cdot \vec{U}_{\bar{1}} = -U_{\bar{1}} W_{\bar{1}} \cos\beta_{\bar{1}}$$

$$E_t = \frac{\left(\vec{W}_1 + \vec{U}_1\right)^2}{2} - \frac{\left(\vec{W}_{\bar{1}} + \vec{U}_{\bar{1}}\right)^2}{2} - E_{rb} = \frac{\cancel{W_1^2} + 2\vec{W}_1 \cdot \vec{U}_1 + \cancel{U_1^2}}{2} - \frac{\cancel{W_{\bar{1}}^2} + 2\vec{W}_{\bar{1}} \cdot \vec{U}_{\bar{1}} + \cancel{U_{\bar{1}}^2}}{2} - E_{rb} =$$

$$= W_1 U_1 + \cos\beta_{\bar{1}} W_{\bar{1}} U_1 - E_{rb} = \left(1 + \cos\beta_{\bar{1}}\right)\left(C_1 - U_1\right) U_1 - E_{rb}$$

Operating Principle for Impulse Turbines

- Maximum specific energy

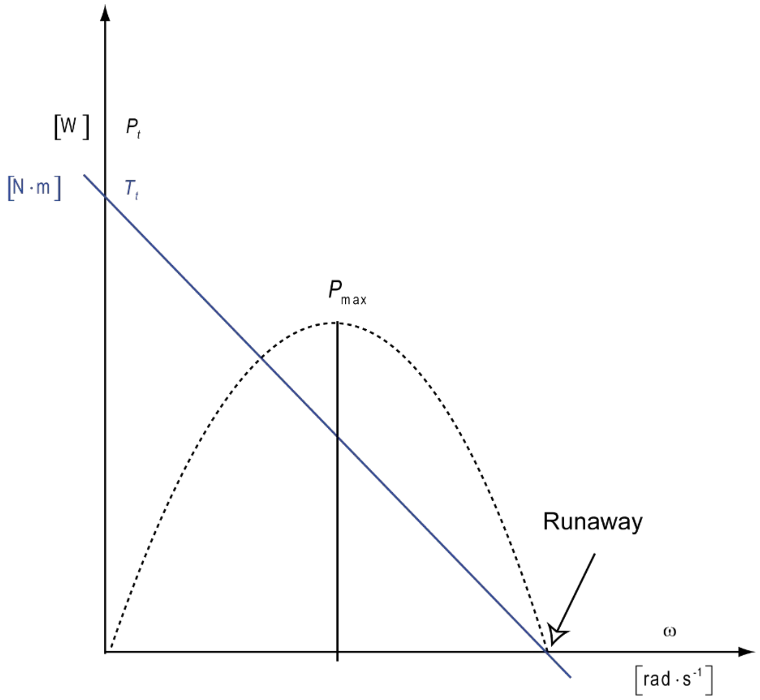
$$E_t = \left(1 + \cos\beta_{\bar{1}}\right)\left(C_1 - U_1\right)U_1 - E_{rb}$$

$$\left.\begin{aligned} \beta_{\bar{1}} &= 0 \\ U_1 &= \frac{C_1}{2} \end{aligned}\right\} \Rightarrow E_t^{\max} = \frac{C_1^2}{2} - E_{rb}$$

- Maximum Power

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

$$\left.\begin{aligned} \beta_{\bar{1}} &= 0 \\ U_1 &= \frac{C_1}{2} \end{aligned}\right\} \Rightarrow P^{\max} = \rho\frac{\pi D_2^2}{4}\frac{C_1^3}{2}$$



Needle Stroke

- **Energy Balance**

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

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

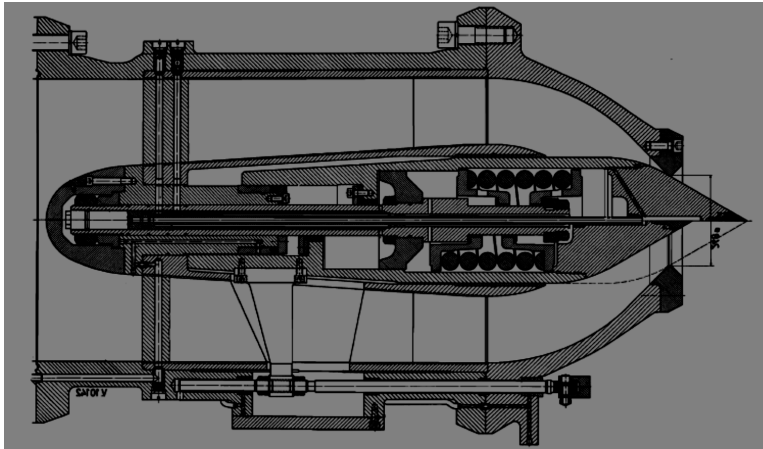
$$E = \frac{C_2^2}{2} + \sum_i E_{r_i} \quad \left(\mathrm{J\cdot kg^{-1}}\right) \Rightarrow C_2 = \sqrt{2E(1-e_r)}$$

- **Discharge**

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

- **Power**

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



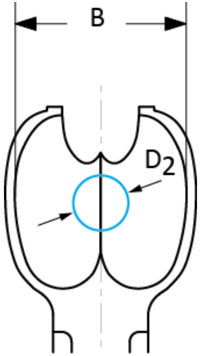
Jet Specific Speed

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

- Specific Speed $$\nu_o = \frac{\sqrt{\pi}}{30}\frac{N}{(2E)^{3/4}}\frac{\sqrt{\pi}D_2}{2}(1-e_r)^{1/4}(2E)^{1/4}$$
$$= \frac{\pi}{60}(1-e_r)^{1/4}\frac{ND_2}{\sqrt{2E}}$$

- 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

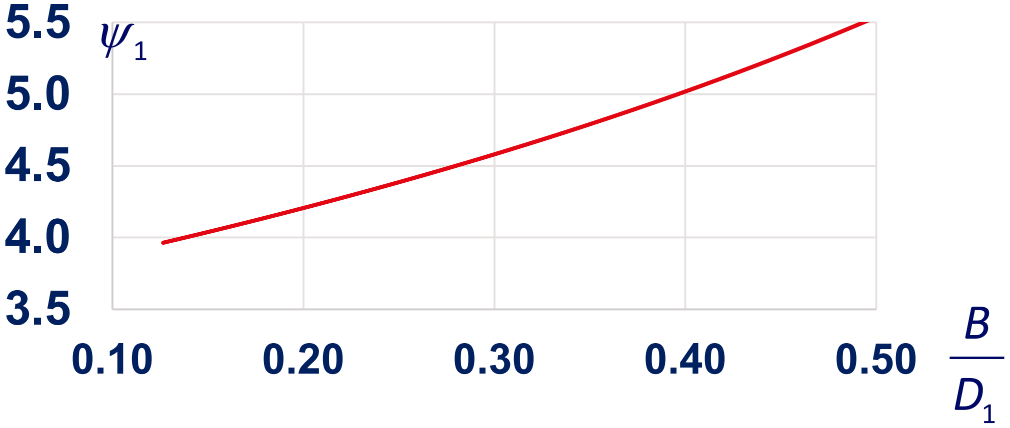


$$D_2 \approx \frac{B}{3 \div 3.4}$$

$$\nu_o = \frac{\left(1-e_r\right)^{\frac{3}{4}}}{2}\frac{D_2}{D_1}$$

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

$$\psi_1\left(\frac{B}{D_1}\right) = \frac{3.6}{1-0.735\times\frac{B}{D_1}}$$



Pelton Specific Issues
Silt Erosion

Pelton Specific Issues
Silt Erosion: Hardcoating

- Bucket

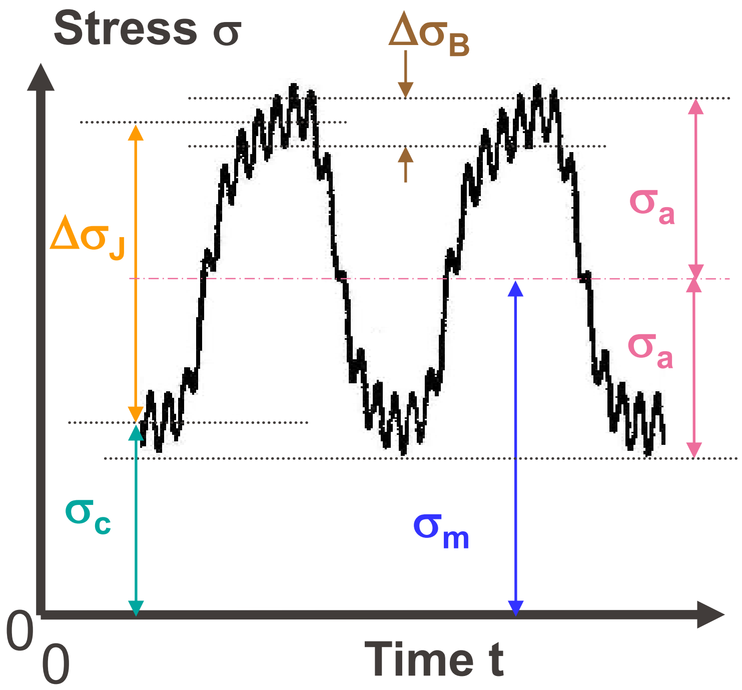
- Needle

Successfully mitigating silt erosion

- Uncoated after 4'000 h

- SXH70-coated after 3'000 h

Pelton Special Issues: Dynamic Loading

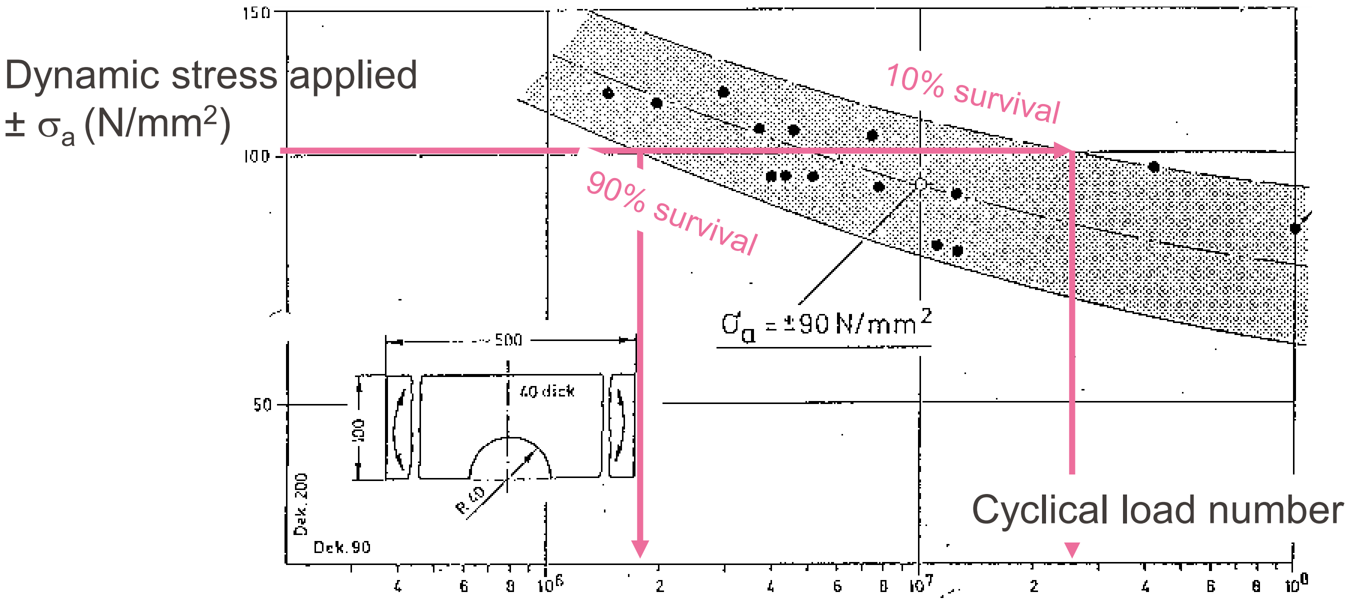


- $\Delta\sigma_J$ jet deviation
- $\Delta\sigma_B$ bucket vibration (5 to 10 MPa)
- σ_c Centrifugal stress
- σ_a Dynamic stress <30 MPa for EDF, based on statistics ⇒ Life time
- σ_m Mean stress

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

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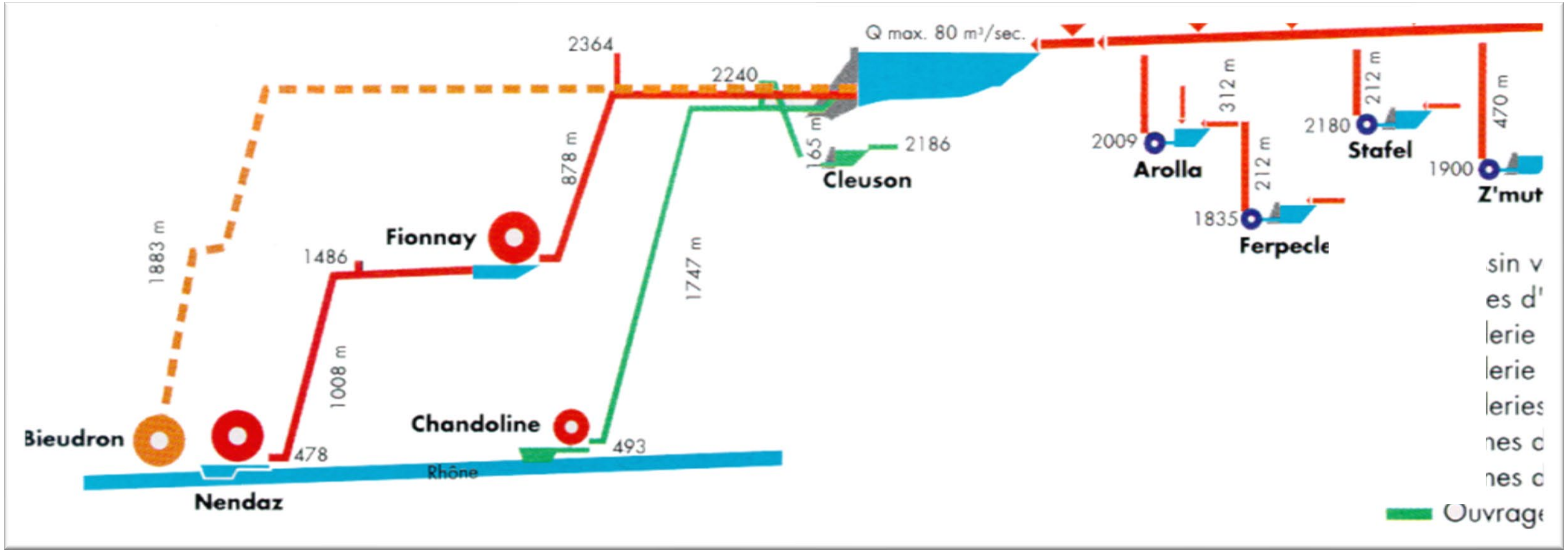
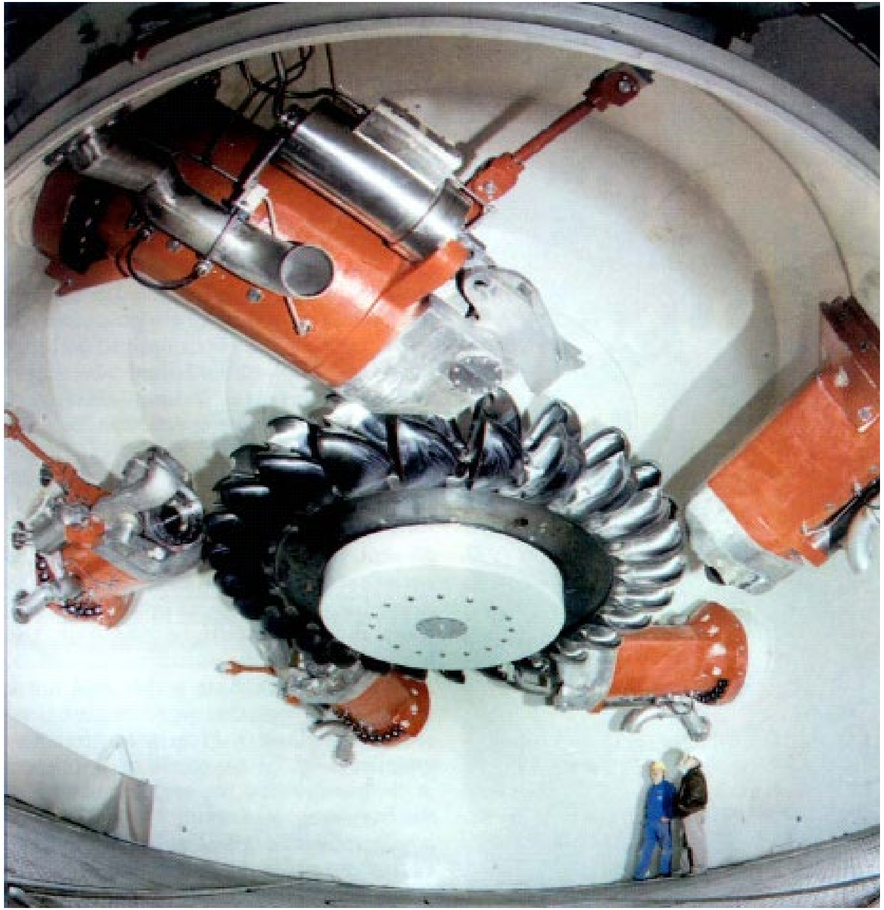
Grande Dixence Hydropower Scheme



- 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

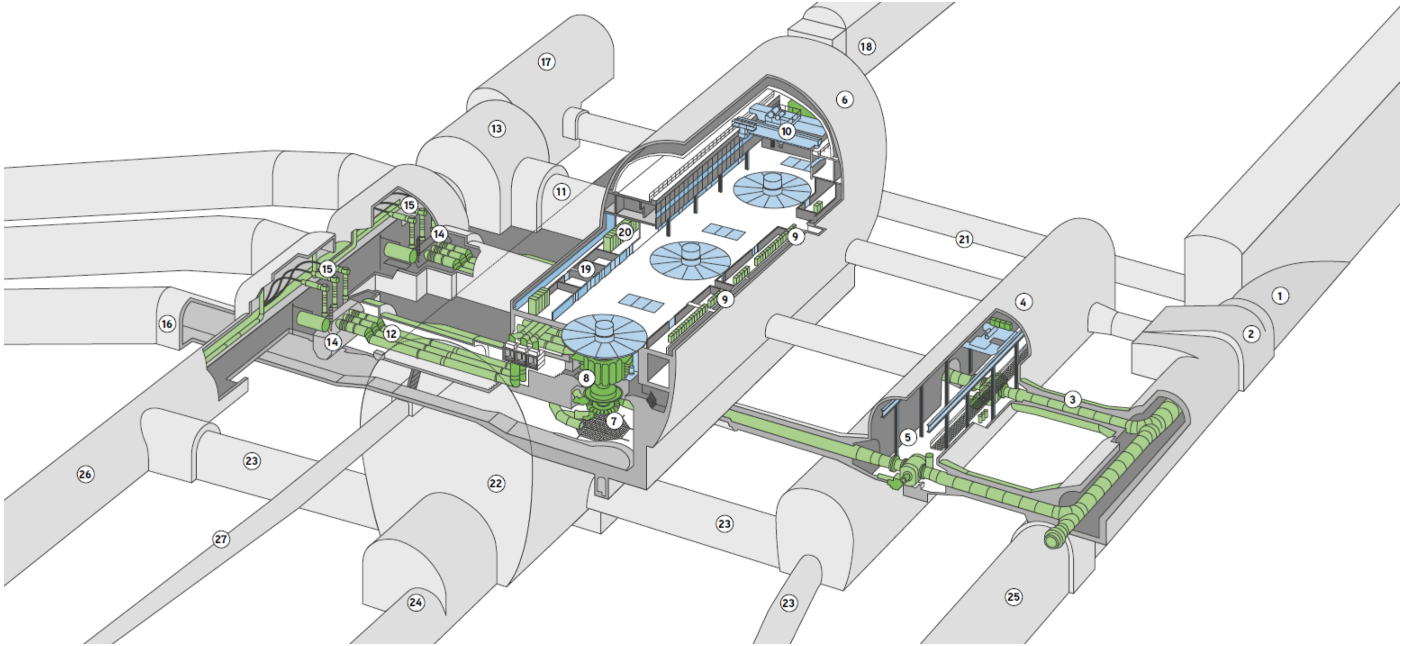
1'269 MW Bieudron Power Plant
3 Pelton Turbines

- 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 m^3/s Discharge
  - D1 = 3.993 m
  - ~28 t Runner Mass



1'269 MW Bieudron Power Plant
3 Pelton Turbines

Underground Power House



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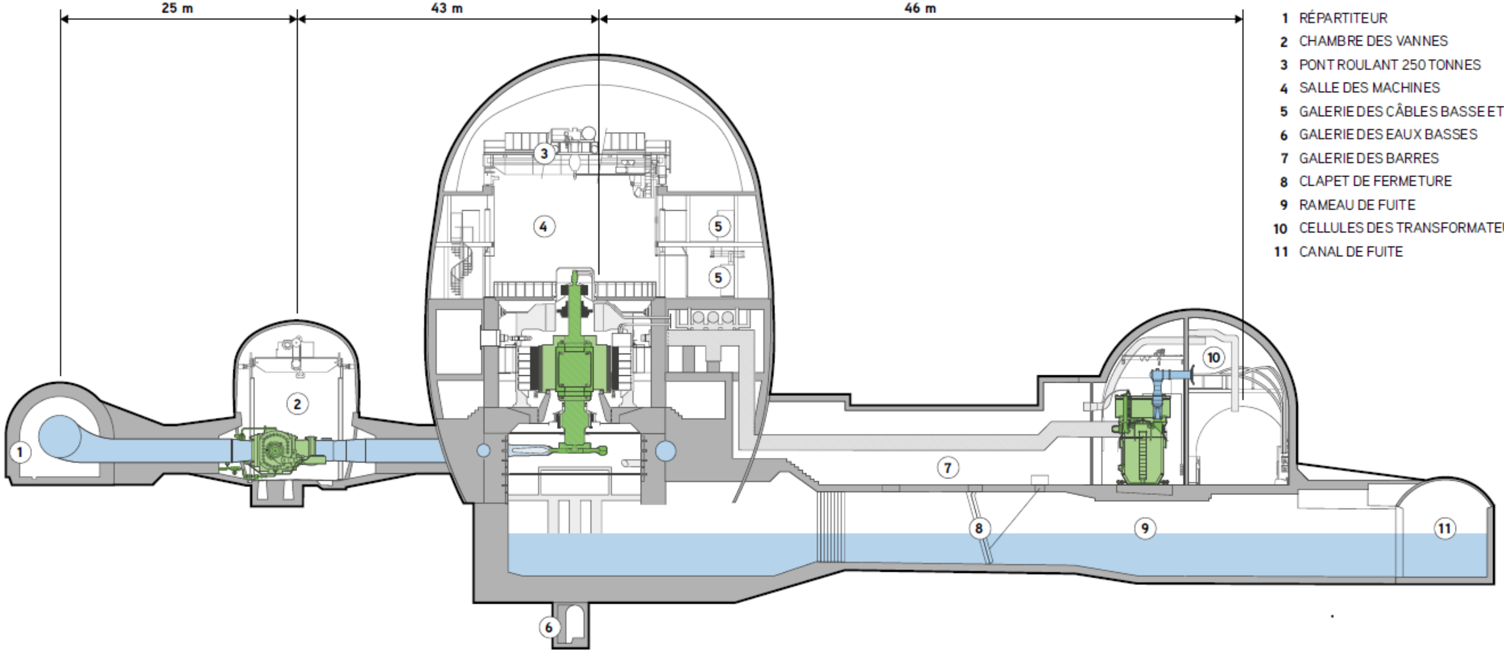
1'269 MW Bieudron Power Plant
3 Pelton Turbines

Power House Cut View



1 RÉPARTITEUR
2 CHAMBRE DES VANNES
3 PONT ROULANT 250 TONNES
4 SALLE DES MACHINES
5 GALERIE DES CÂBLES BASSE ET MOYENNE TENSION
6 GALERIE DES EAUX BASSES
7 GALERIE DES BARRES
8 CLAPET DE FERMETURE
9 RAMEAU DE FUITE
10 CELLULES DES TRANSFORMATEURS
11 CANAL DE FUITE

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