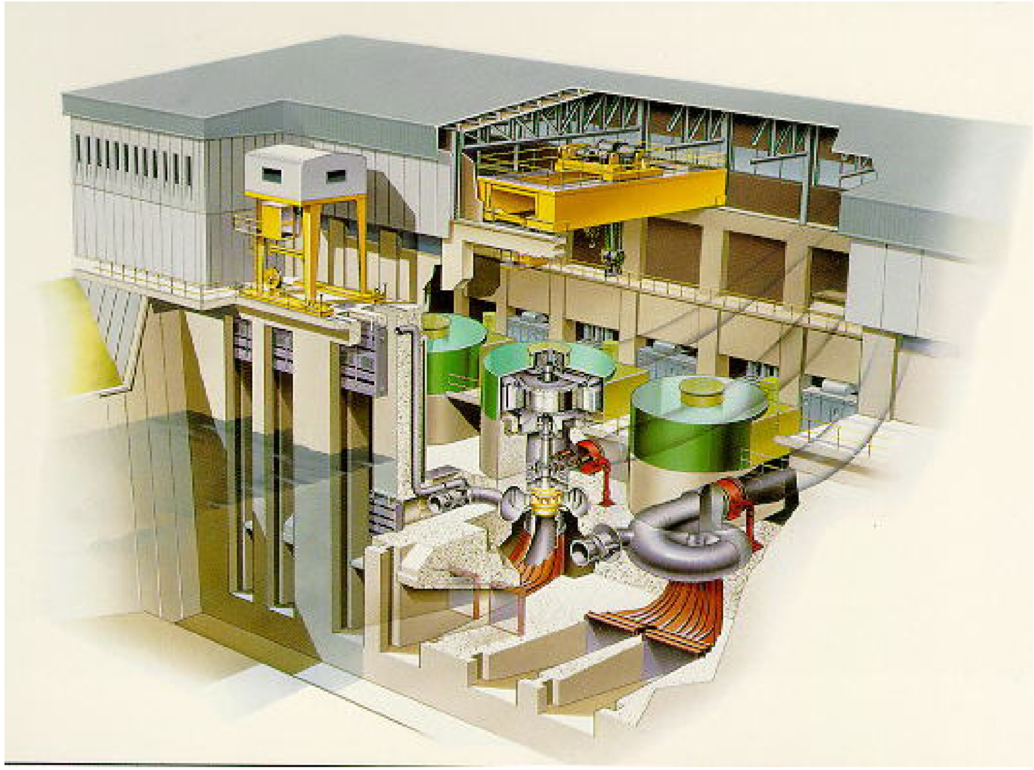
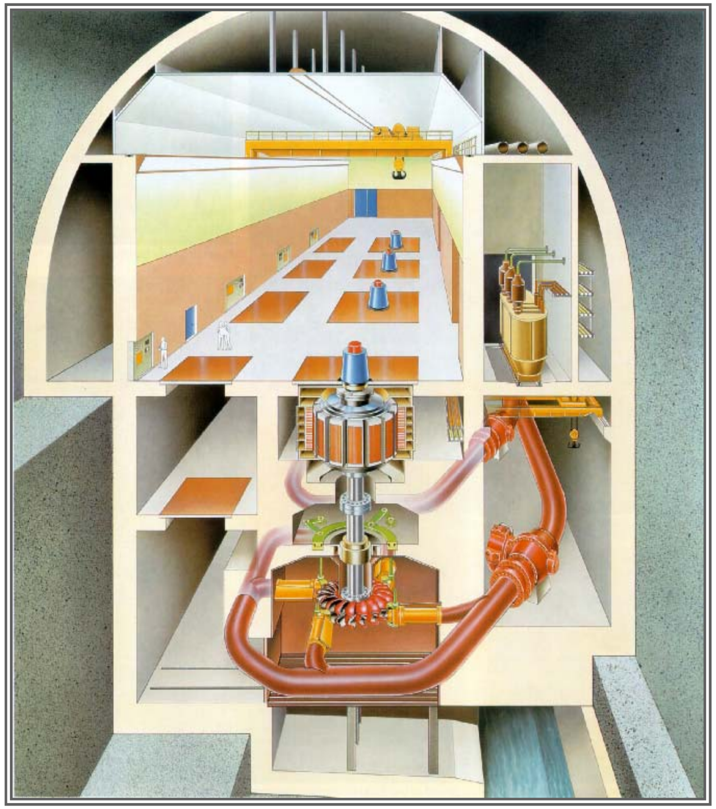
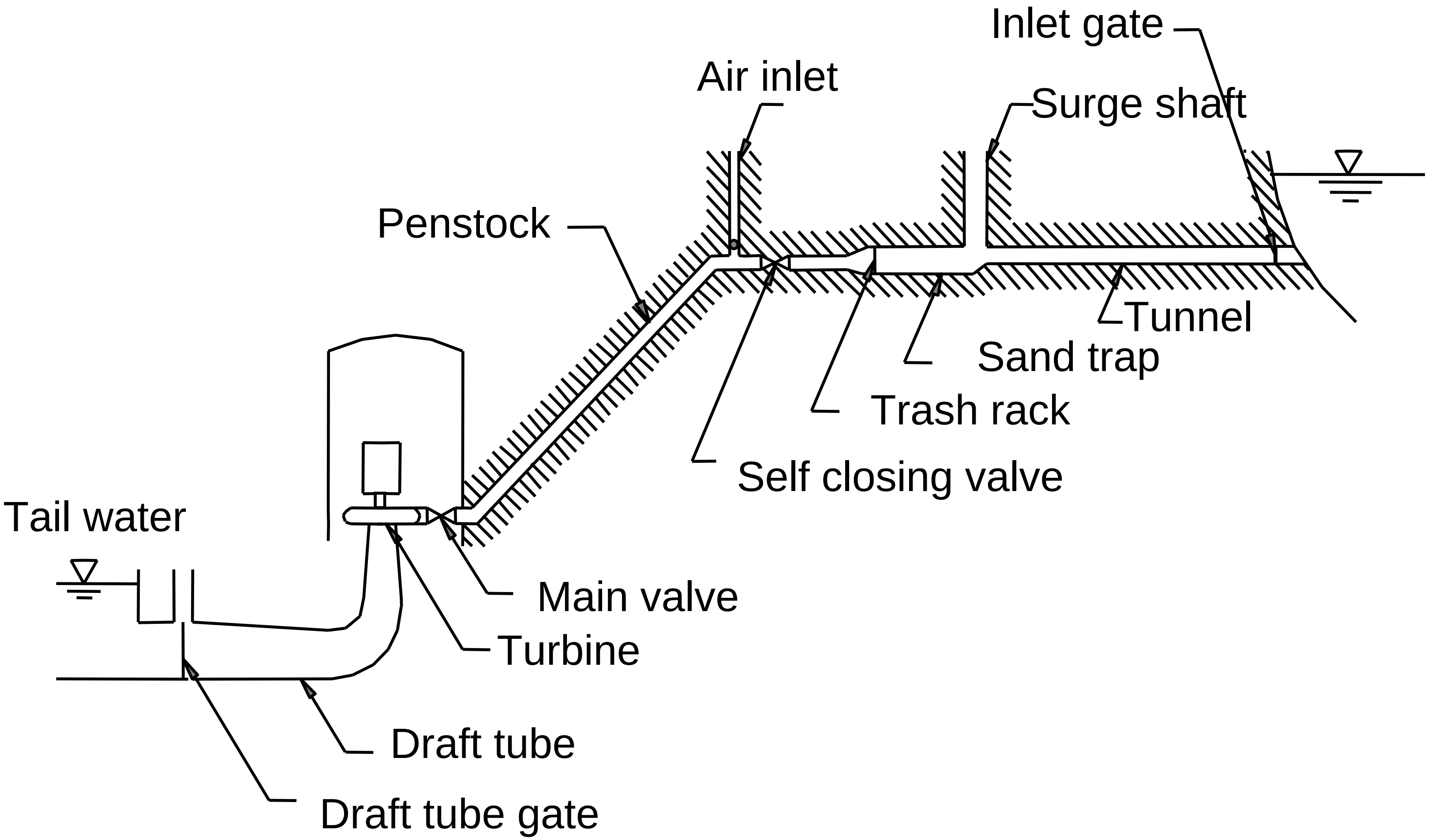
Hydro power plants

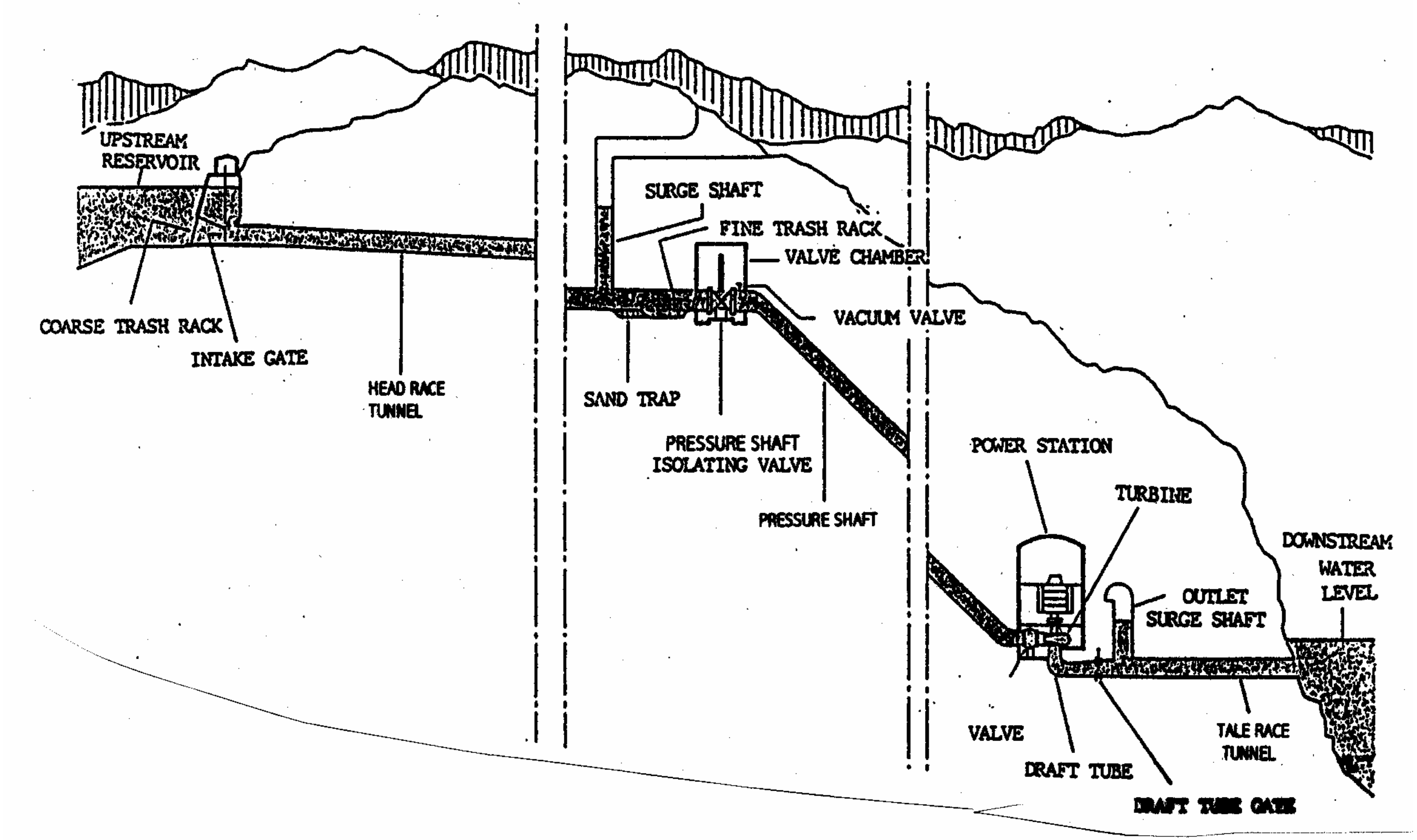




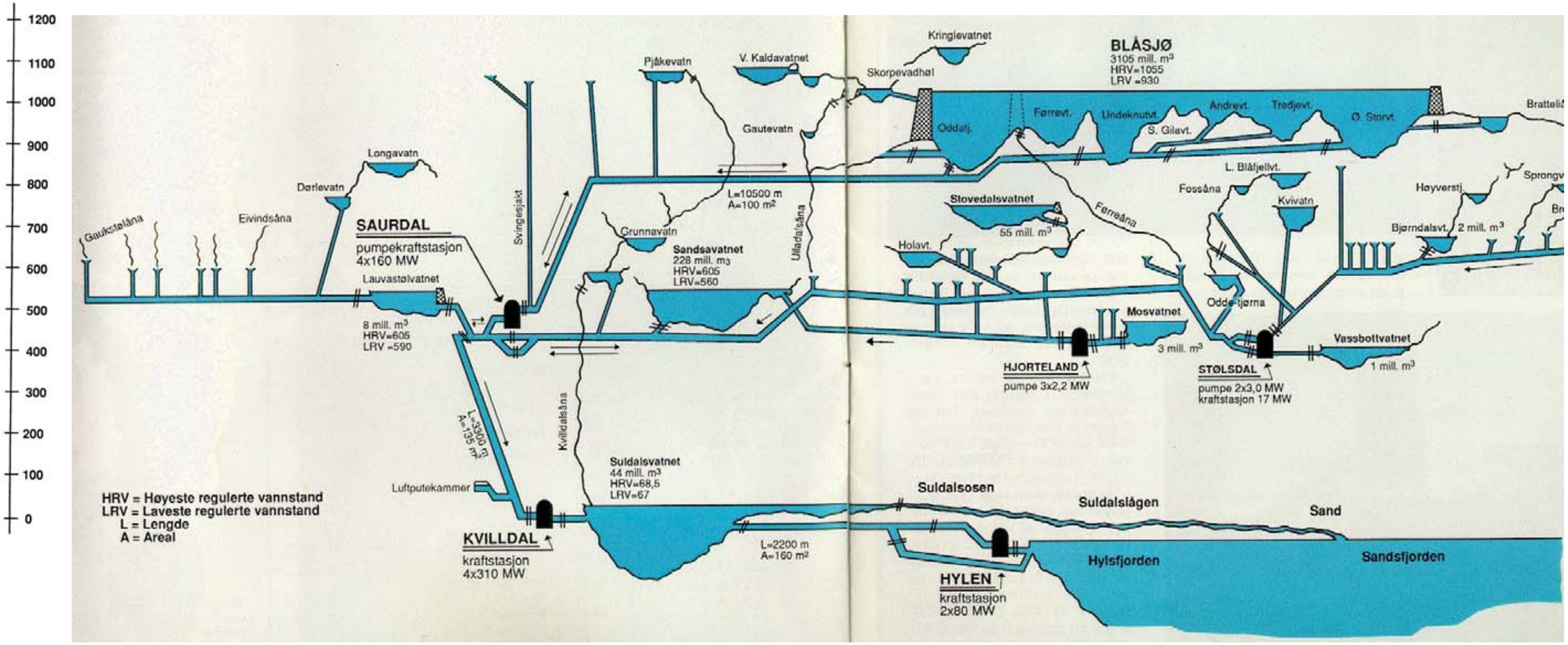
Hydro power plants



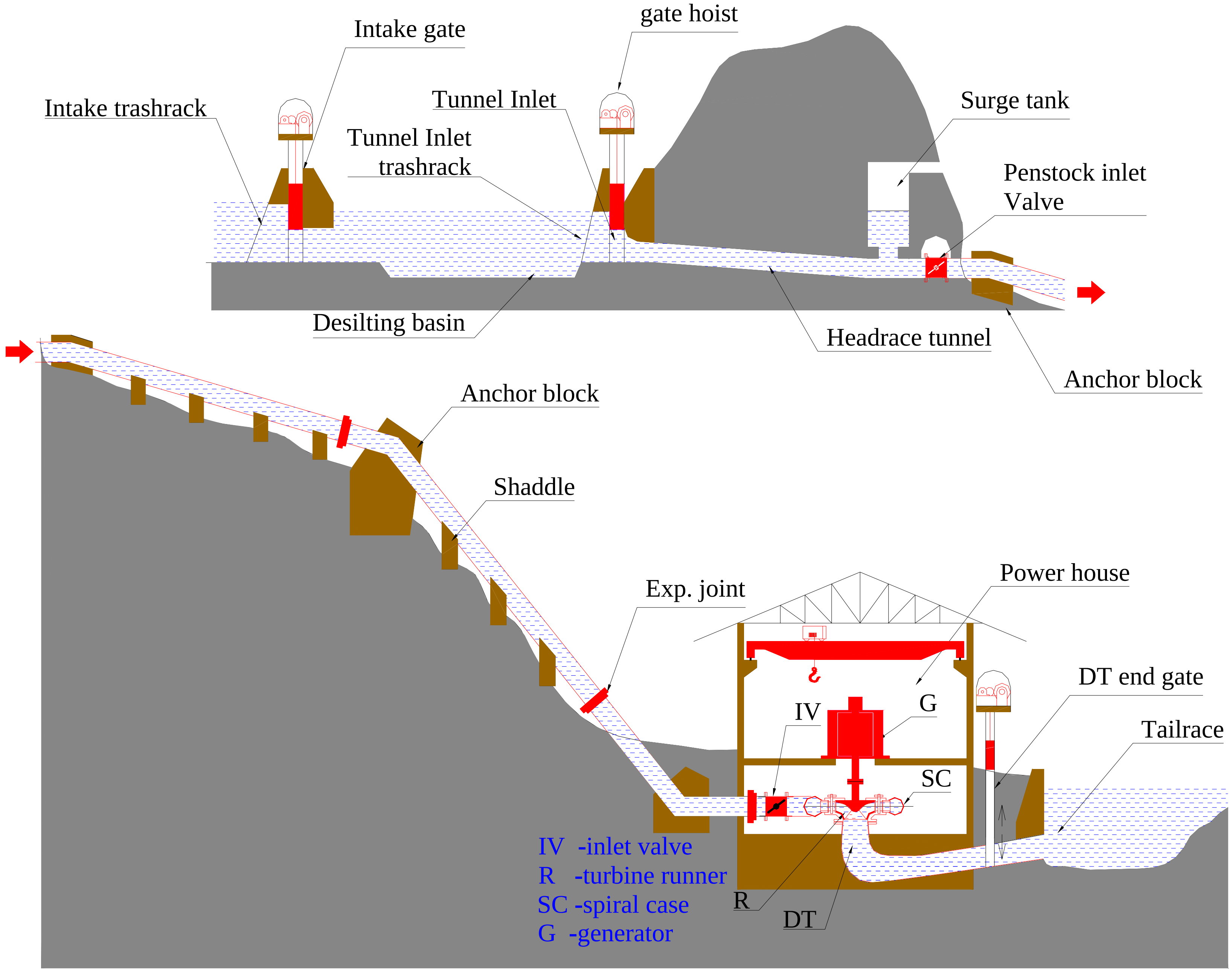
The principle the water conduits of a traditional high head power plant



Ulla- Førre

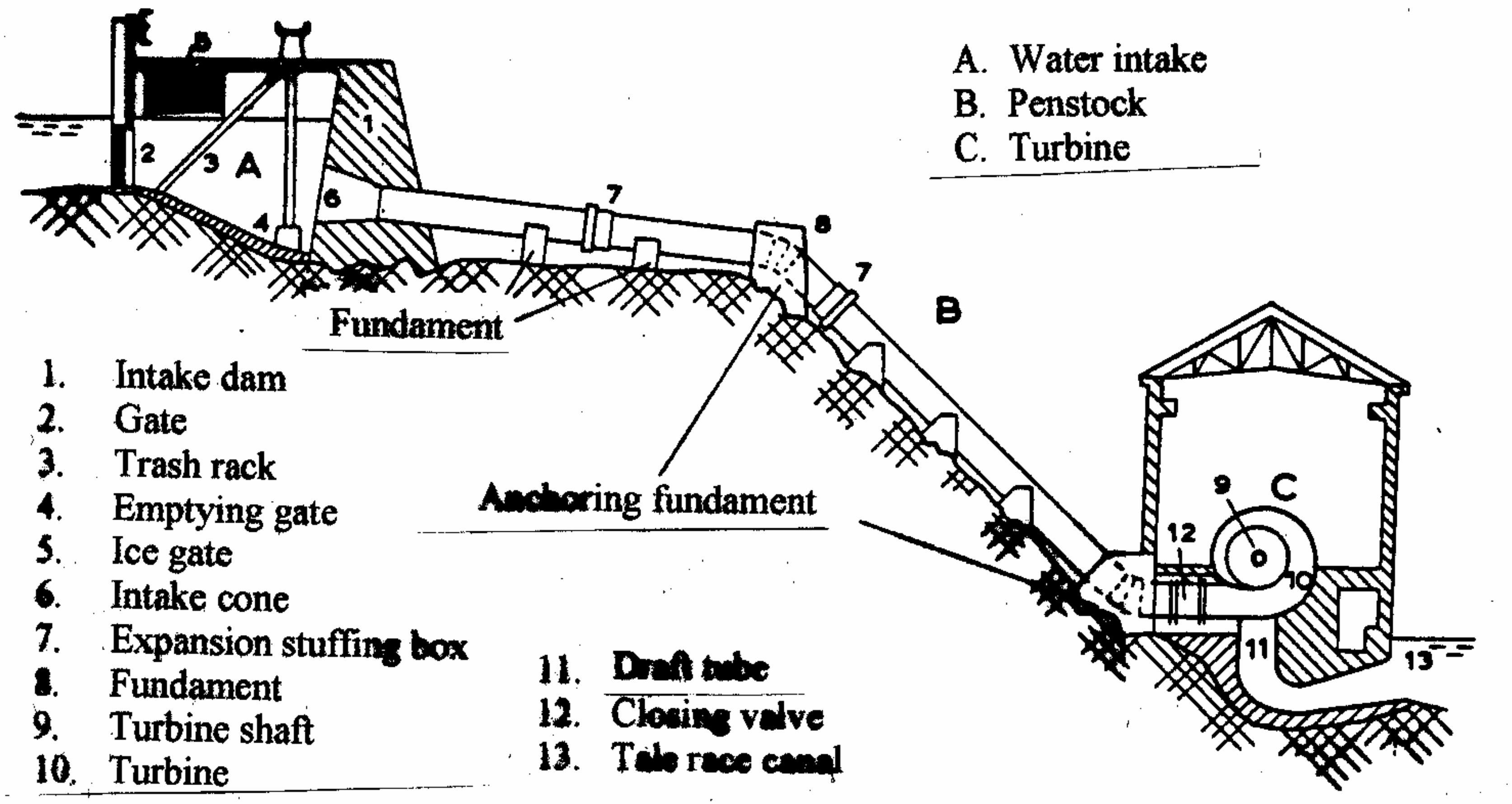


Original figur ved Statkraft Vestlandsverkene

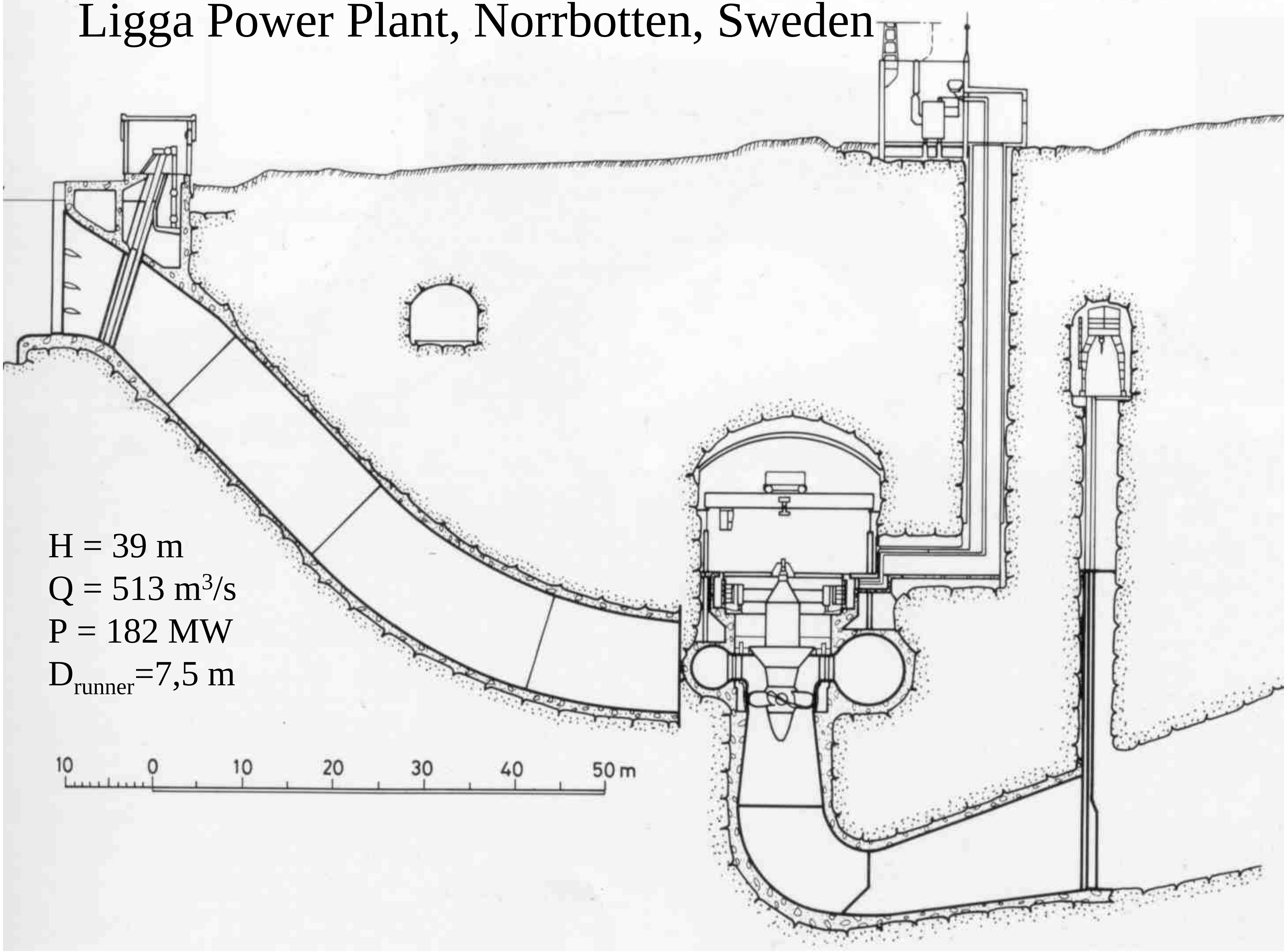


Typical Power House with Francis Turbine

Arrangement of a small hydropower plant

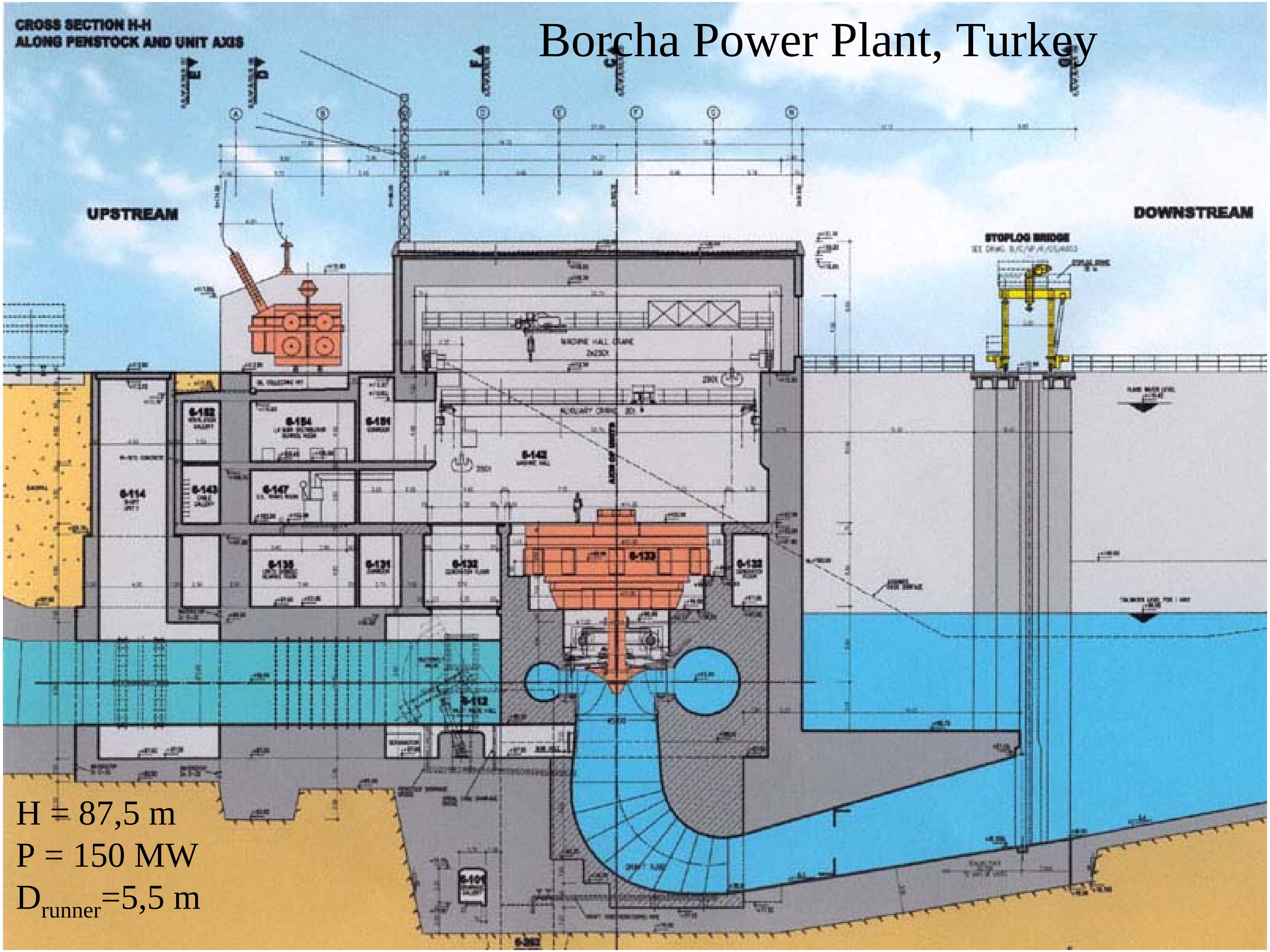


Ligga Power Plant, Norrbotten, Sweden



$H = 39$ m
$Q = 513\ m^3/s$
$P = 182$ MW
D_{runner}=7,5 m

Borcha Power Plant, Turkey



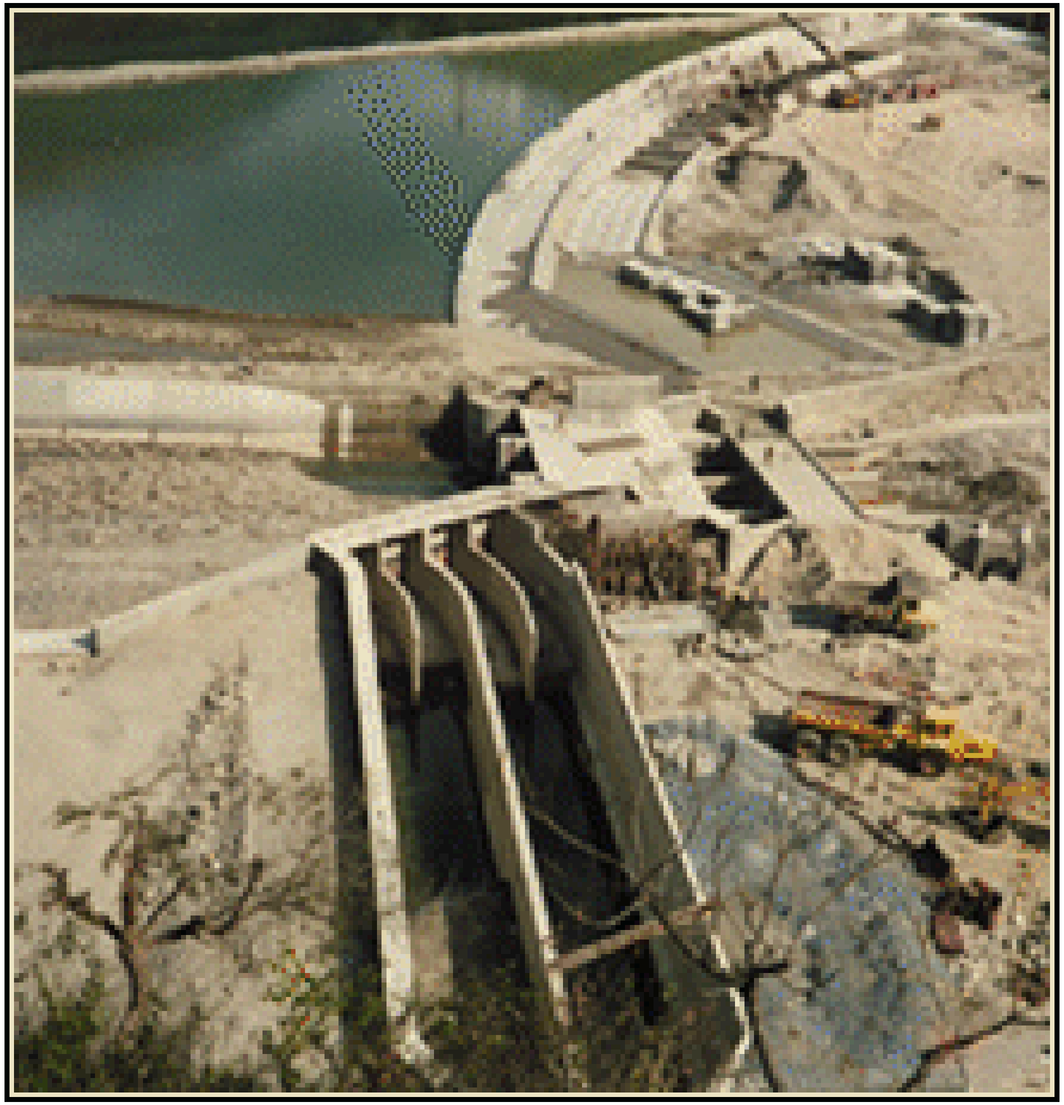
H = 87,5 m

P = 150 MW

D_{runner}=5,5 m

Water intake

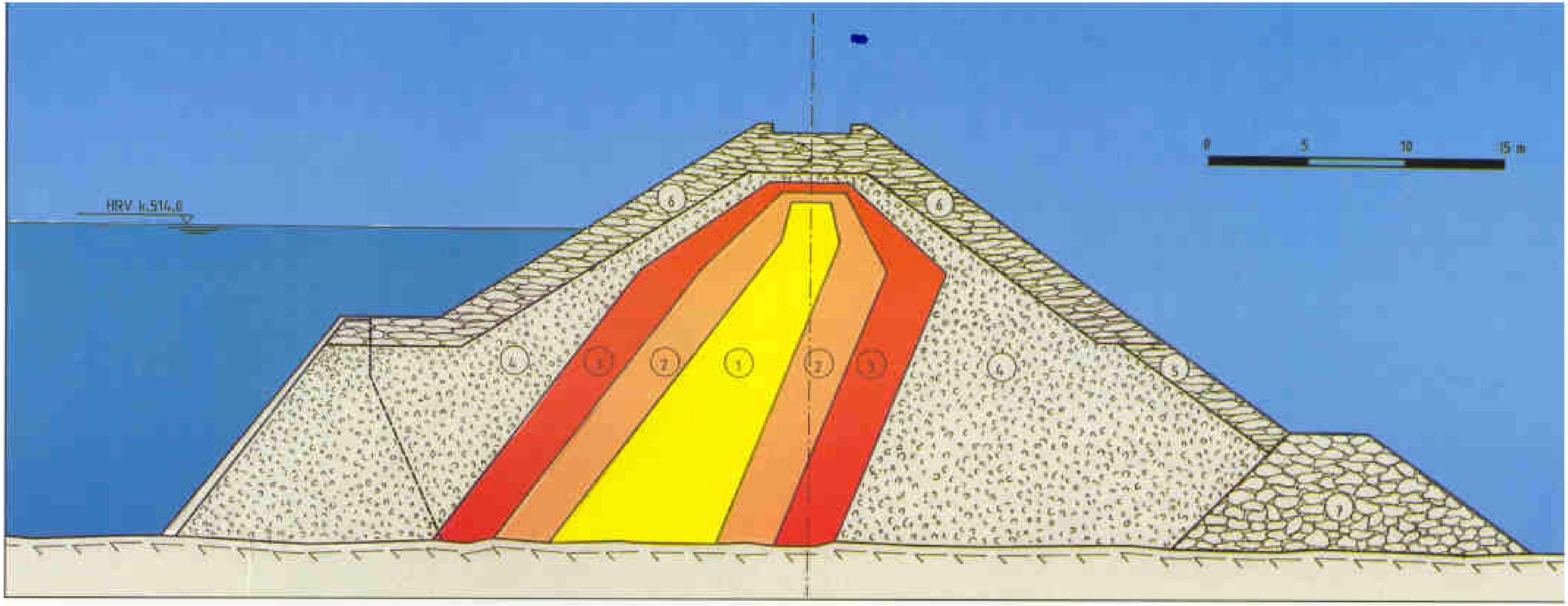
- Dam
- Coarse trash rack
- Intake gate
- Sediment settling basement



Dams

- Rockfill dams
- Pilar og platedammer
- Hvelvdammer

Rock-fill dams



1. Core	Moraine, crushed soft rock, concrete, asphalt
2. Filter zone	Sandy gravel
3. Transition zone	Fine blasted rock
4. Supporting shell	Blasted rock

Slab concrete dam

Arc dam

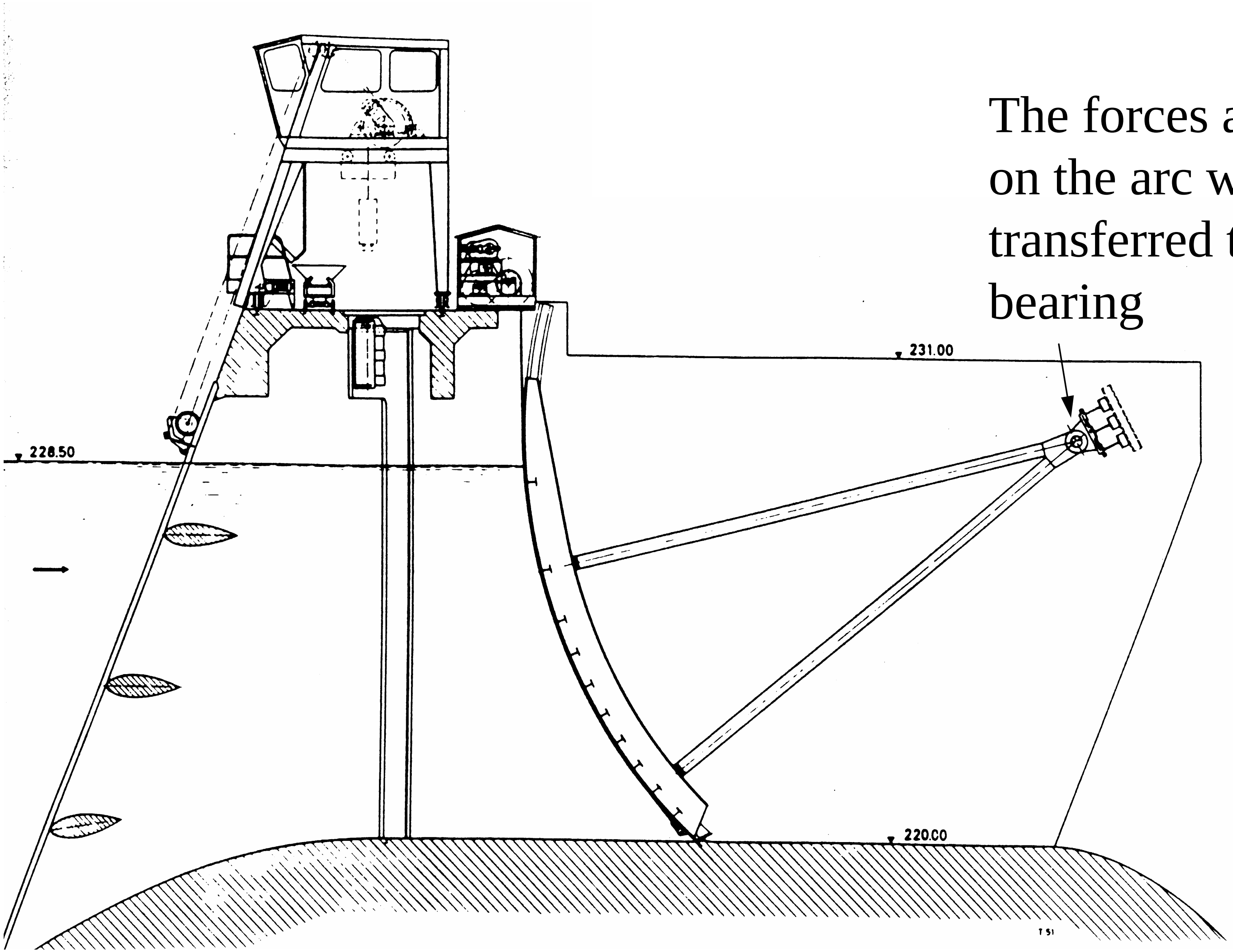
Gates in Hydro Power Plants

Types of Gates

- Radial Gates
- Wheel Gates
- Slide Gates
- Flap Gates
- Rubber Gates

Radial Gates at Älvkarleby, Sweden

Radial Gate



The forces acting on the arc will be transferred to the bearing

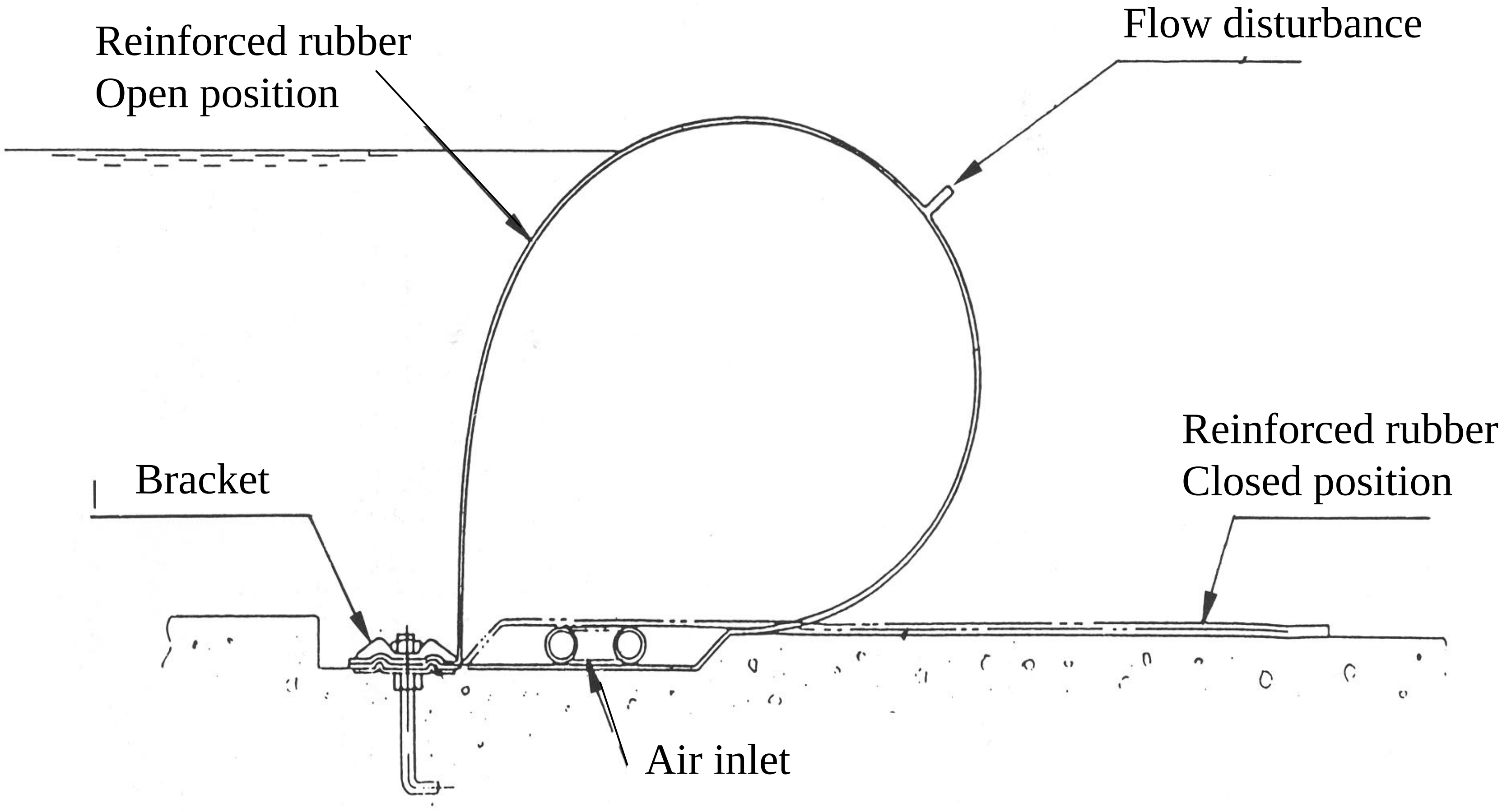
Slide Gate

2004.04.23

Jhimruk Power Plant, Nepal

Flap Gate

Rubber gate



Reinforced rubber
Open position

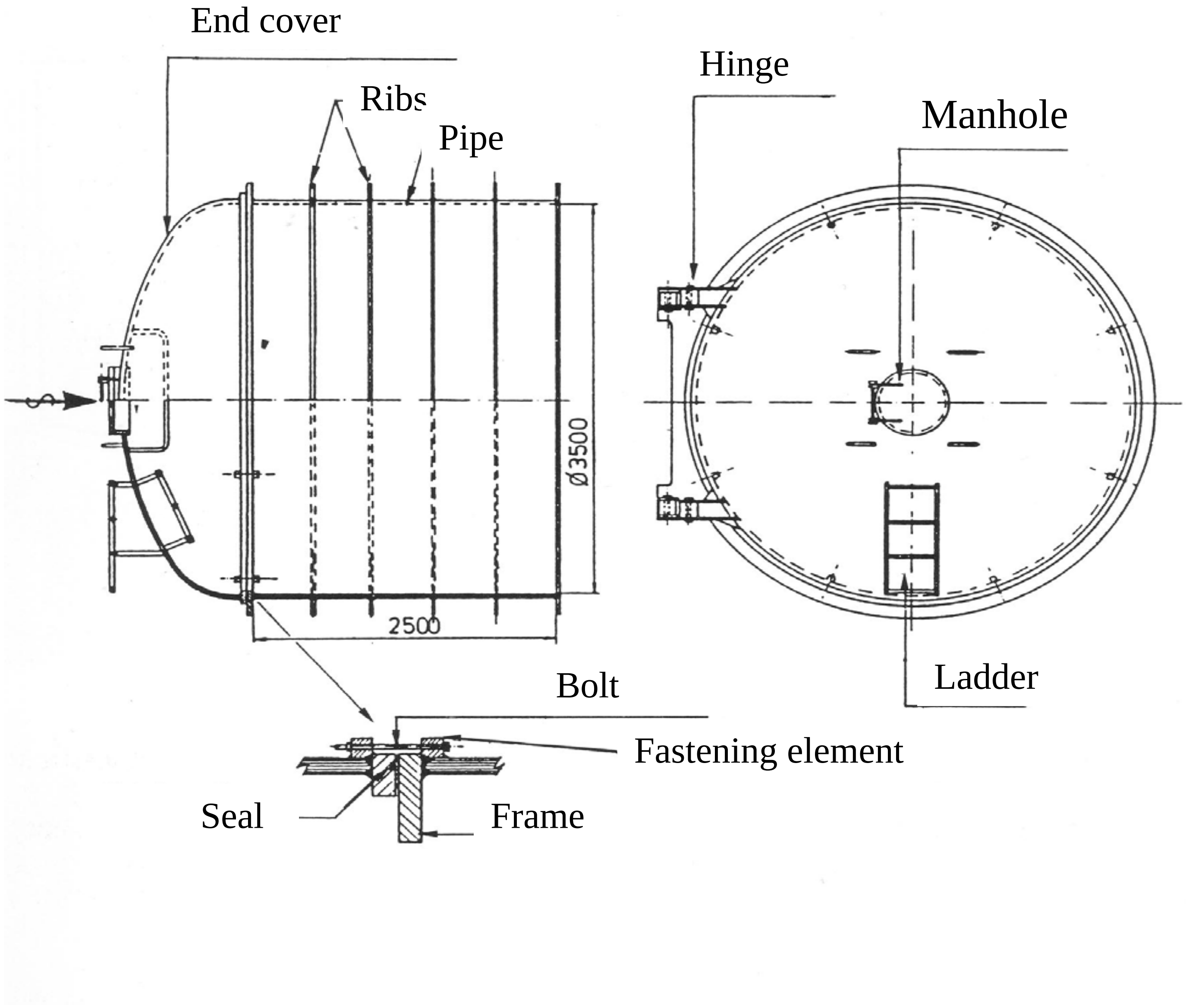
Flow disturbance

Bracket

Reinforced rubber
Closed position

Air inlet

Circular gate



Circular gate

Jhimruk Power Plant, Nepal

Trash Racks

Panauti Power Plant, Nepal

Theun Hinboun Power Plant

Laos

Gravfoss

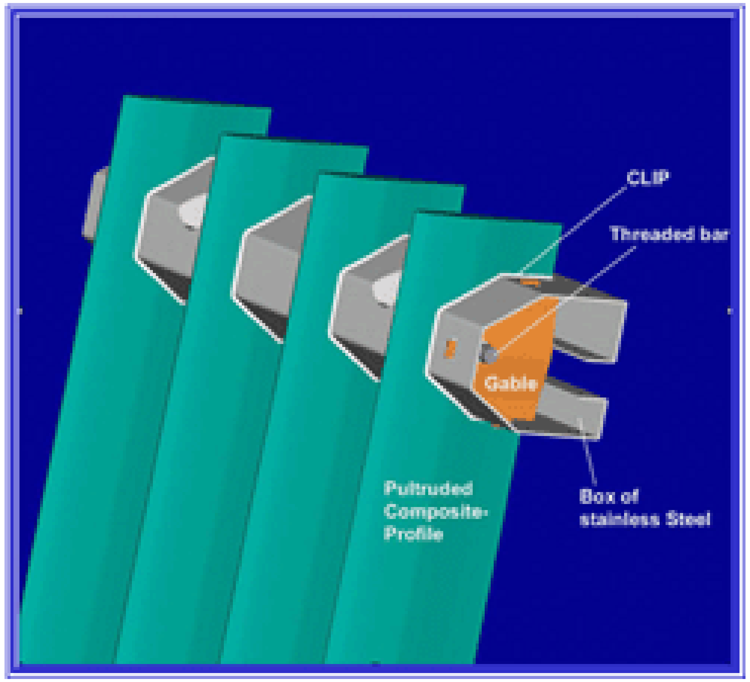
Power Plant
Norway

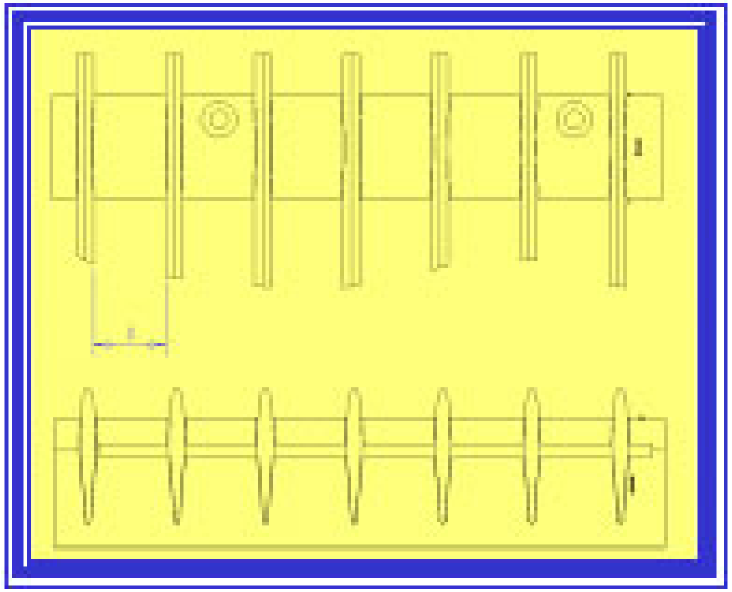
Trash Rack size:
Width: 12 meter
Height: 13 meter

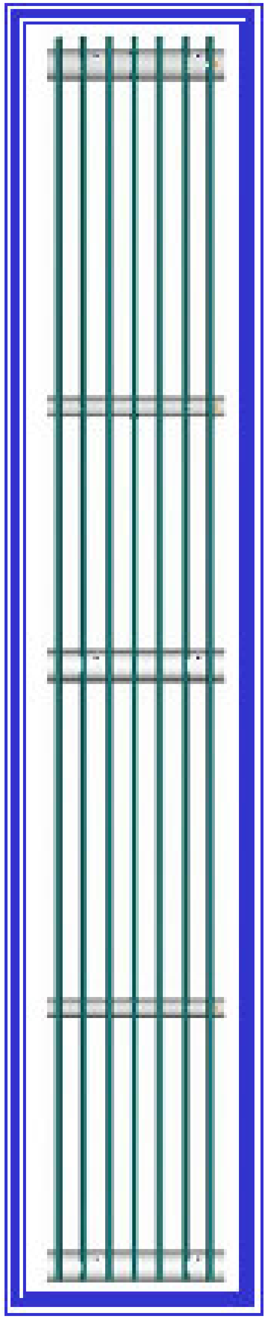
Stainless Steel

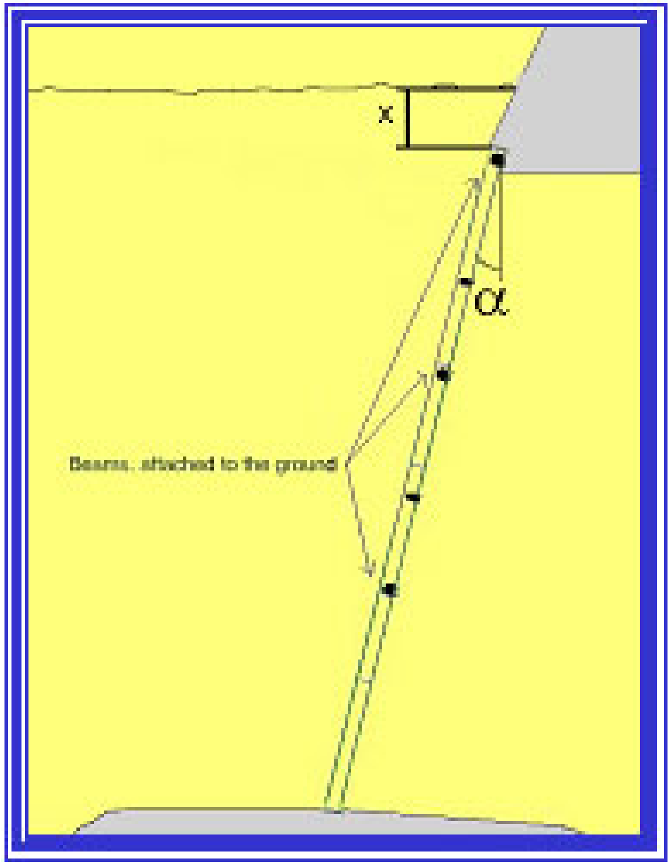
CompRack

Trash Rack delivered
by VA-Tech









Cleaning the trash rack


Centrale de Ryburg-Schwörstadt : modèle G, râteau à grappins, grue hydrauliqu

Pipes

- Materials
- Calculation of the change of length due to the change of the temperature
- Calculation of the head loss
- Calculation of maximum pressure
  - Static pressure
  - Water hammer
- Calculation of the pipe thickness
- Calculation of the economical correct diameter
- Calculation of the forces acting on the anchors

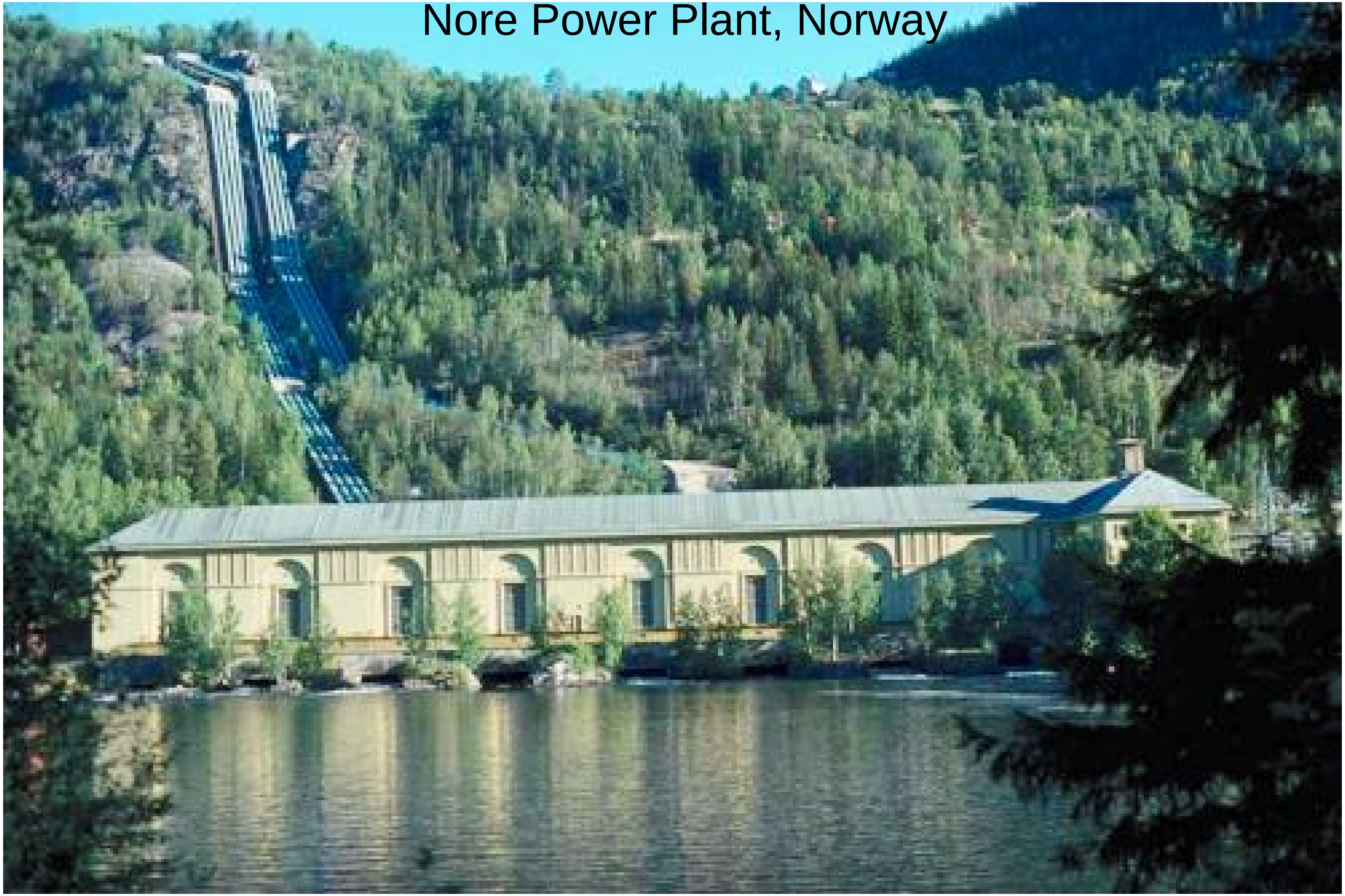
Materials

- Steel
- Polyethylene, PE
- Glass-fibre reinforced Unsaturated Polyesterplastic , GUP
- Wood
- Concrete

Materials

Material	Max. Diameter	Max. Pressure	Max. Stresses
	[m]	[m]	[MPa]
Steel, St.37			150
Steel, St.42			190
Steel, St.52			206
PE	~ 1,0	160	5
GUP	2,4 Max. p = 160 m.	320 Max. D: 1,4 m.	
Wood	~5	80	
Concrete	~5	~ 400	

Steel pipes in penstock



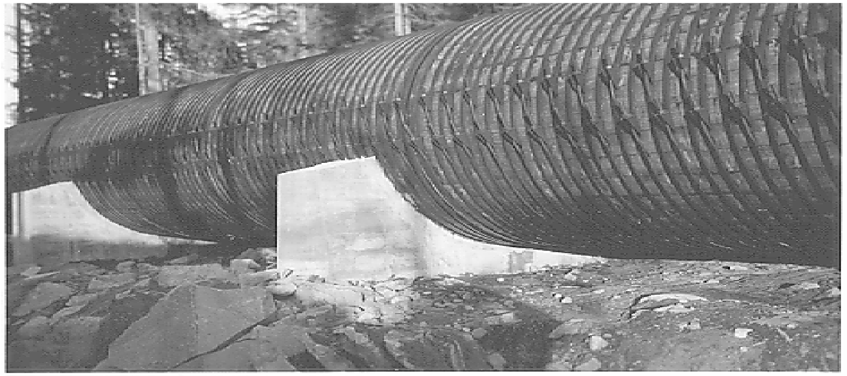
Nore Power Plant, Norway

GUP-Pipe

Raubergfossen Power Plant, Norway

Wood Pipes

Breivikbotn Power Plant, Norway



Øvre Porsa Power Plant, Norway

Calculation of the change of length due to the change of the temperature

$$\Delta L = \alpha \cdot \Delta T \cdot L$$

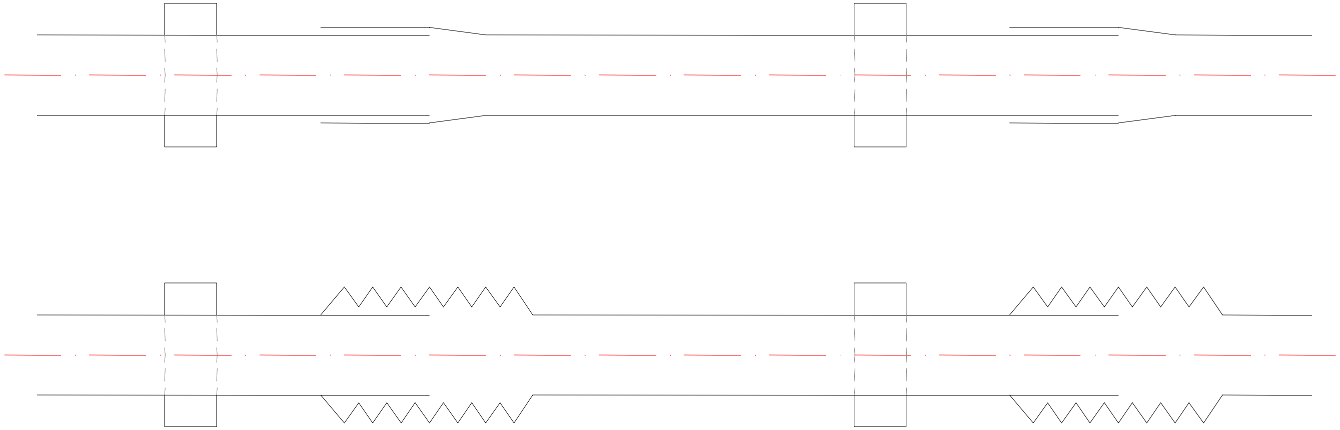
Where:

ΔL = Change of length [m]

L = Length [m]

α = Coefficient of thermal expansion [m/^{o}C m]

ΔT = Change of temperature [^{o}C]



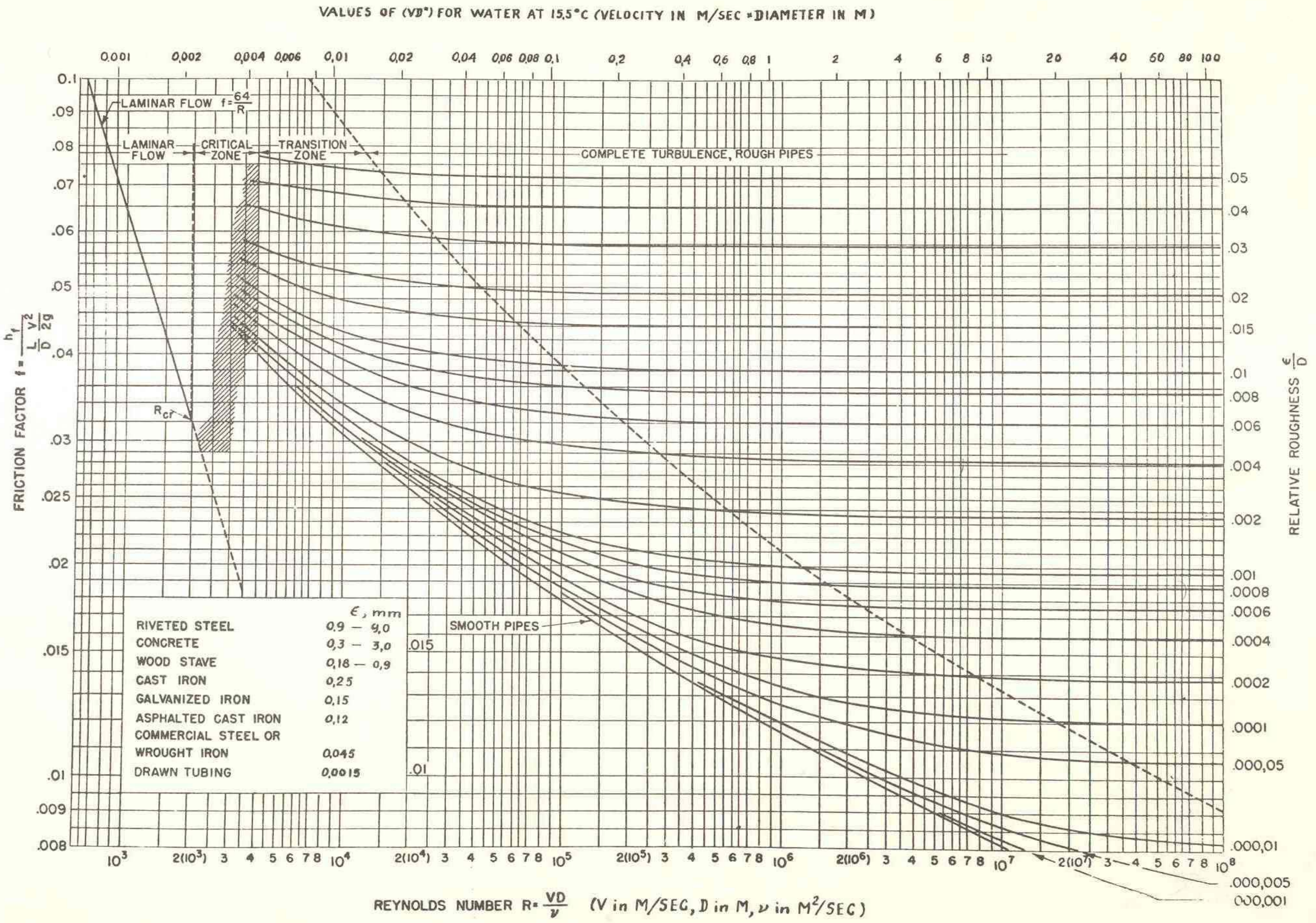
Calculation of the head loss

$$h_f = f \cdot \frac{L}{D} \cdot \frac{c^2}{2 \cdot g}$$

Where:

h_f = Head loss [m]
f = Friction factor [-]
L = Length of pipe [m]
D = Diameter of the pipe [m]
c = Water velocity [m/s]
g = Gravity [m/s^2]

MOODY DIAGRAM



	ε, mm
RIVETED STEEL	0,9 — 9,0
CONCRETE	0,3 — 3,0
WOOD STAVE	0,18 — 0,9
CAST IRON	0,25
GALVANIZED IRON	0,15
ASPHALTED CAST IRON	0,12
COMMERCIAL STEEL OR WROUGHT IRON	0,045
DRAWN TUBING	0,0015

Example

Calculation of the head loss

Power Plant data:

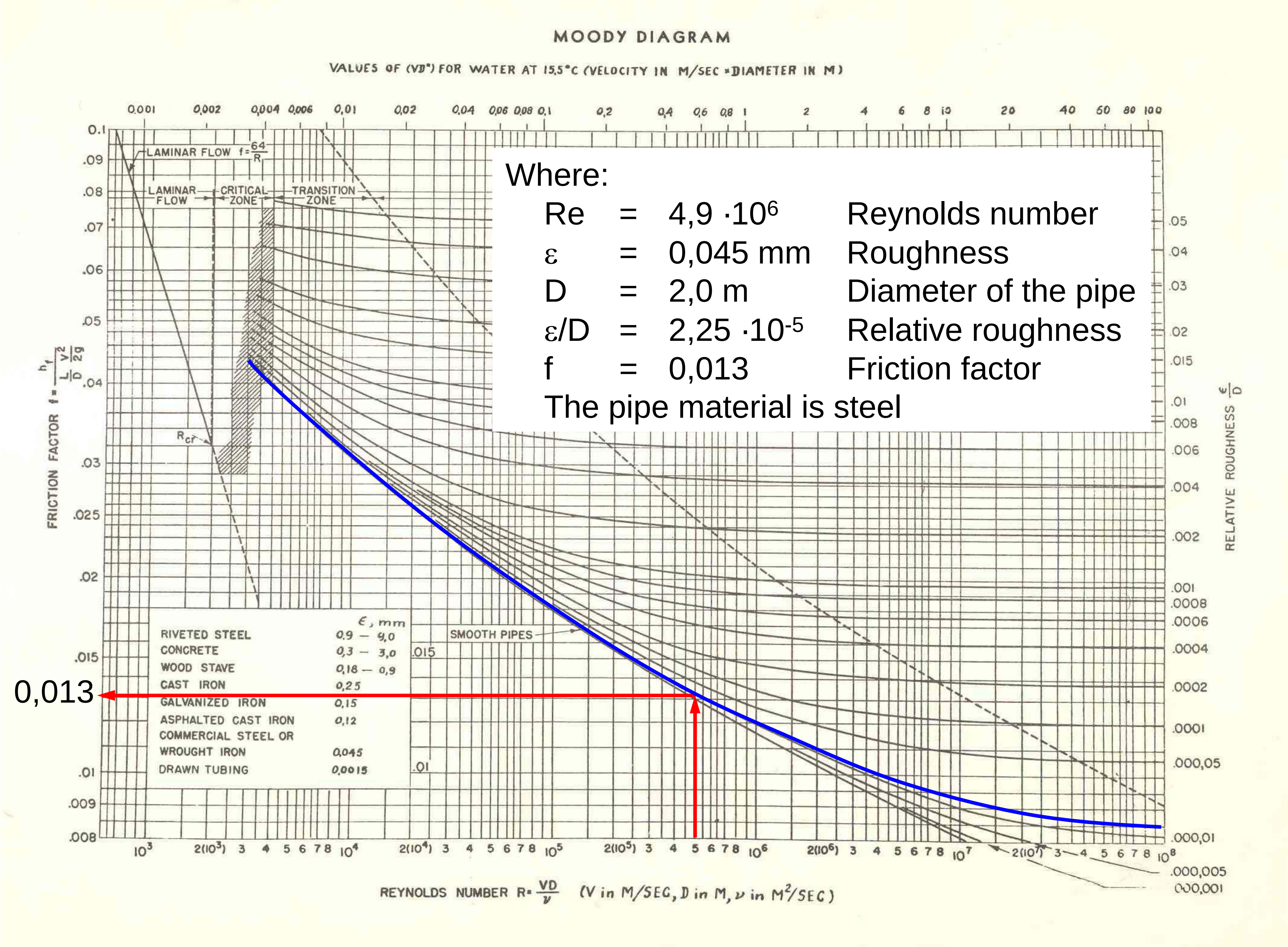
H = 100 m Head
Q = 10 m^3/s Flow Rate
L = 1000 m Length of pipe
D = 2,0 m Diameter of the pipe
The pipe material is steel

$$h_f = f \cdot \frac{L}{D} \cdot \frac{c^2}{2 \cdot g}$$

$$\mathrm{Re} = \frac{c \cdot D}{\upsilon}$$

Where:

c = 3,2 m/s Water velocity
ν = $1{,}308 \cdot 10^{-6}$ m^2/s Kinetic viscosity
Re = $4{,}9 \cdot 10^6$ Reynolds number



	ε, mm
RIVETED STEEL	0,9 — 9,0
CONCRETE	0,3 — 3,0
WOOD STAVE	0,18 — 0,9
CAST IRON	0,25
GALVANIZED IRON	0,15
ASPHALTED CAST IRON	0,12
COMMERCIAL STEEL OR WROUGHT IRON	0,045
DRAWN TUBING	0,0015

Where:

Re = $4{,}9 \cdot 10^6$ Reynolds number
ε = 0,045 mm Roughness
D = 2,0 m Diameter of the pipe
ε/D = $2{,}25 \cdot 10^{-5}$ Relative roughness
f = 0,013 Friction factor
The pipe material is steel

Example

Calculation of the head loss

Power Plant data:

H = 100 m Head
Q = 10 m^3/s Flow Rate
L = 1000 m Length of pipe
D = 2,0 m Diameter of the pipe
The pipe material is steel

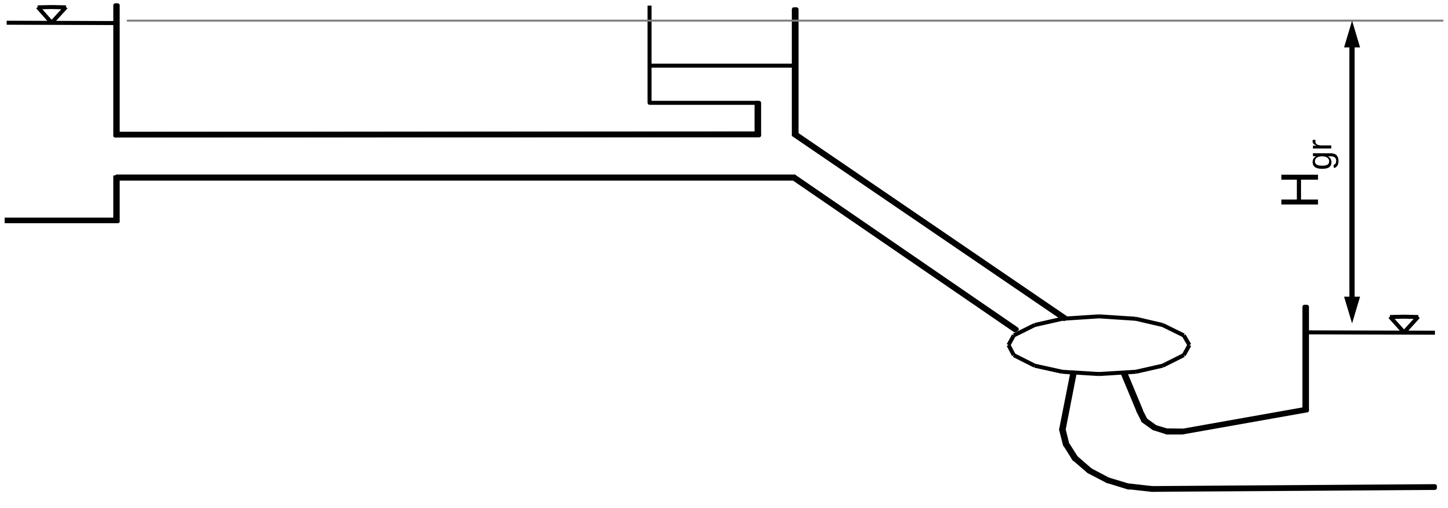
$$h_f = f\cdot\frac{L}{D}\cdot\frac{c^2}{2\cdot g} = 0{,}013\cdot\frac{1000}{2}\cdot\frac{3{,}2^2}{2\cdot 9{,}82} = 3{,}4\ \mathrm{m}$$

Where:

f = 0,013 Friction factor
c = 3,2 m/s Water velocity
g = 9,82 m/s^2 Gravity

Calculation of maximum pressure

- Static head, H_{gr} (Gross Head)
- Water hammer, Δh_{wh}
- Deflection between pipe supports
- Friction in the axial direction

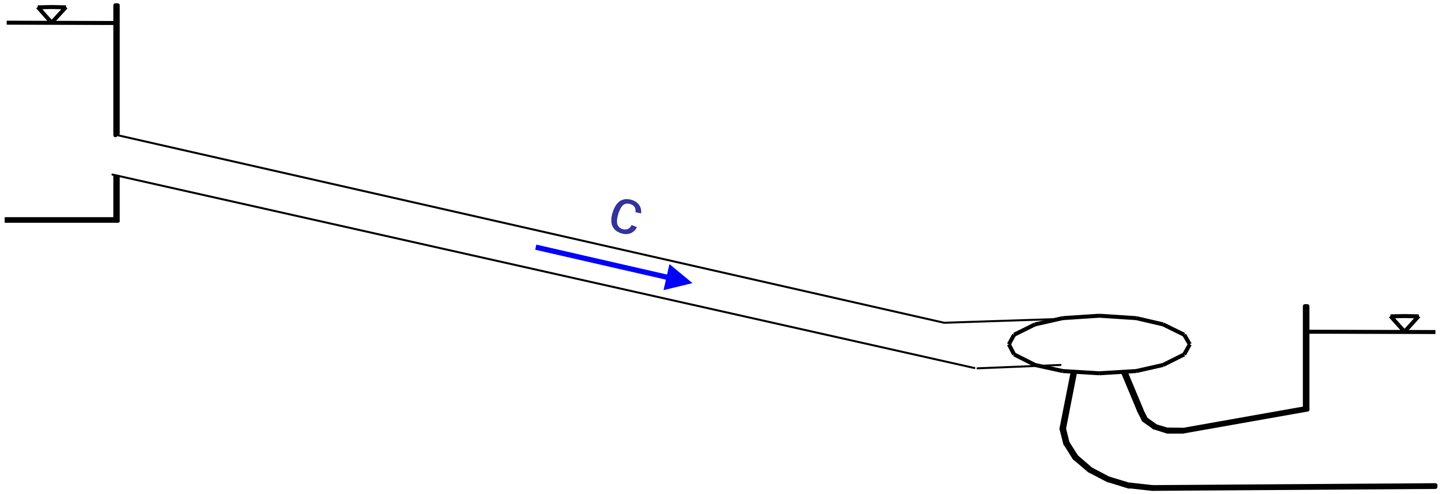


Maximum pressure rise due to the Water Hammer

$$\Delta h_{wh} = \frac{a \cdot c_{max}}{g} \qquad \text{IF} \quad T_C << \frac{2 \cdot L}{a}$$

Jowkowsky

Δh_{wh} = Pressure rise due to water hammer [mWC]
a = Speed of sound in the penstock [m/s]
c_{max} = maximum velocity [m/s]
g = gravity [m/s^2]



Example

Jowkowsky

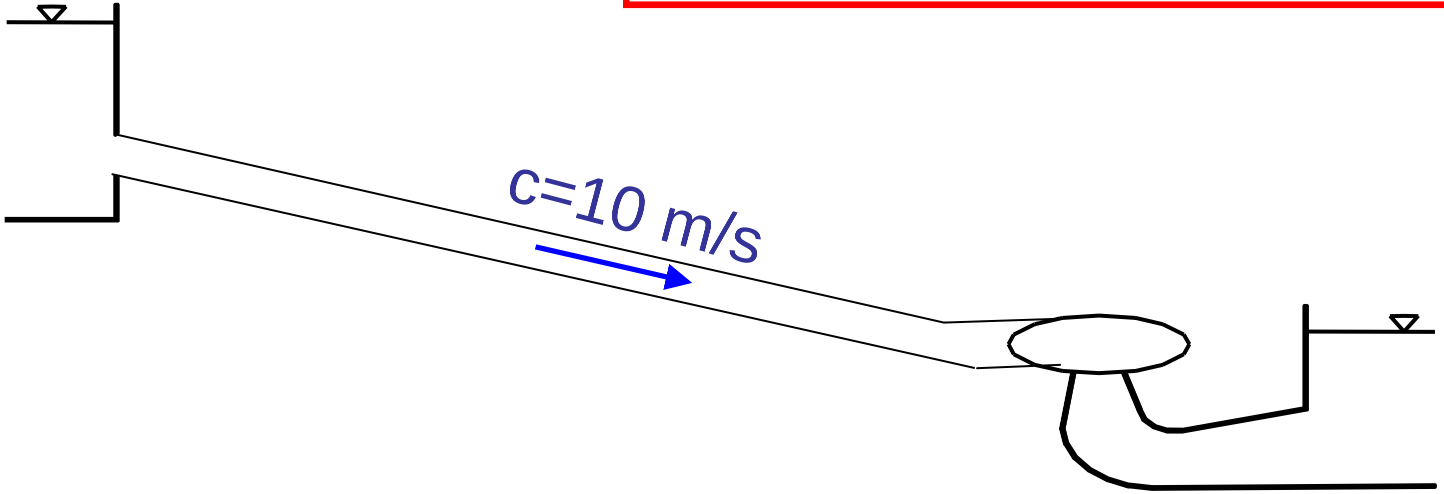
$a = 1000\ [\text{m/s}]$

$c_{max} = 10\ [\text{m/s}]$

$g = 9{,}81\ [\text{m/s}^2]$

$$T_C << \frac{2 \cdot L}{a}$$

$$\boxed{\Delta h_{wh} = \frac{a \cdot c_{max}}{g} = 1020\ \text{m}}$$

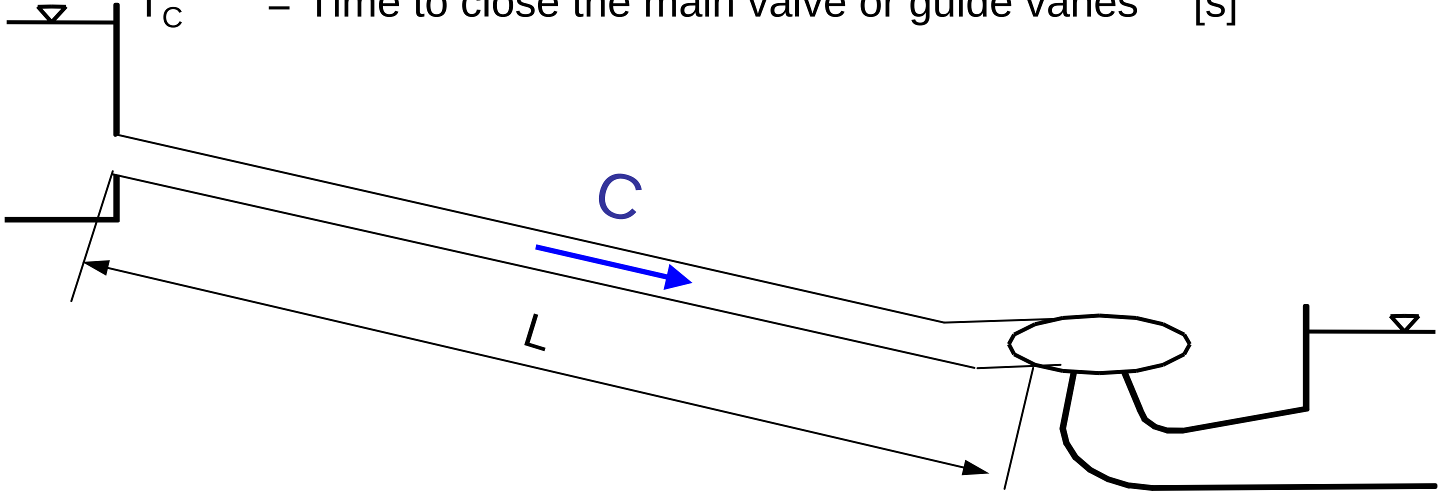


Maximum pressure rise due to the Water Hammer

$$\Delta h_{wh} = \frac{a \cdot c_{max}}{g} \cdot \frac{{}^{2 \cdot L}/_{a}}{T_C} = \frac{c_{max} \cdot 2 \cdot L}{g \cdot T_C} \qquad \text{IF} \quad T_C \geq \frac{2 \cdot L}{a}$$

Where:

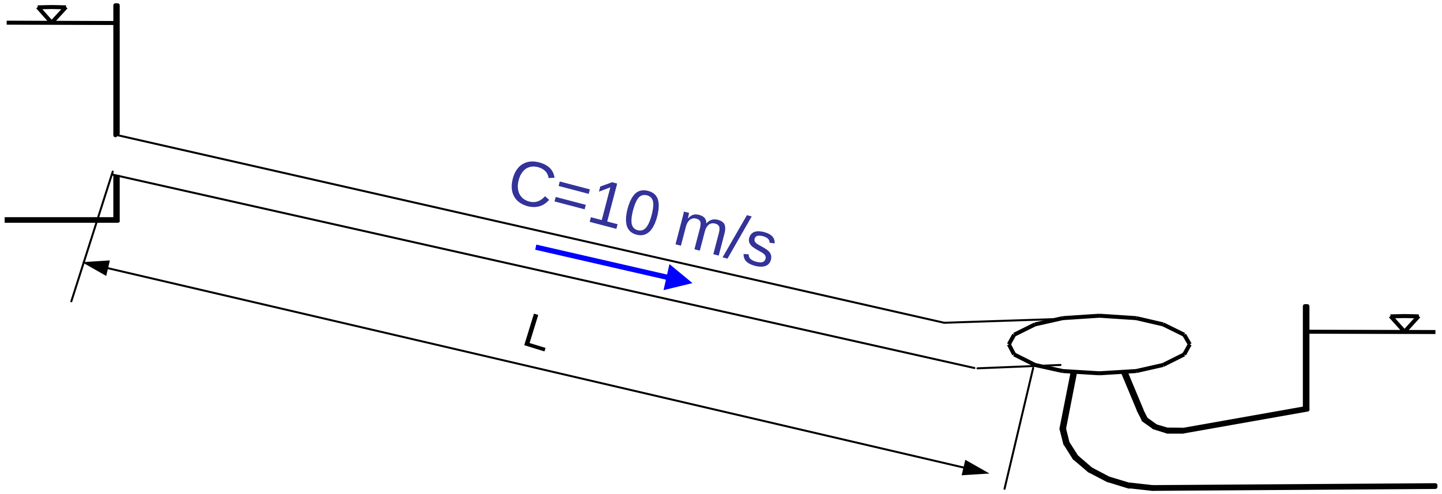
Δh_{wh} = Pressure rise due to water hammer [mWC]
a = Speed of sound in the penstock [m/s]
c_{max} = maximum velocity [m/s]
g = gravity [m/s^2]
L = Length [m]
T_C = Time to close the main valve or guide vanes [s]



Example

L	=	300	[m]
T_C	=	10	[s]
c_{max}	=	10	[m/s]
g	=	9,81	[m/s^2]

$$\boxed{\Delta h_{wh} = \frac{c_{max} \cdot 2 \cdot L}{g \cdot T_C} = 61\,\mathrm{m}}$$



Calculation of the pipe thickness

$$L \cdot D_i \cdot p \cdot C_s = 2 \cdot \sigma_t \cdot L \cdot t$$

$$\Downarrow$$

$$\sigma_t = \frac{p \cdot r_i \cdot C_s}{t}$$

$$p = \rho \cdot g \cdot \left(H_{gr} + h_{wh}\right)$$

- Based on:
  - – Material properties
  - – Pressure from:
    - Water hammer
    - Static head

Where:

L = Length of the pipe [m]

D_i = Inner diameter of the pipe [m]

p = Pressure inside the pipe [Pa

σ_t = Stresses in the pipe material [Pa]

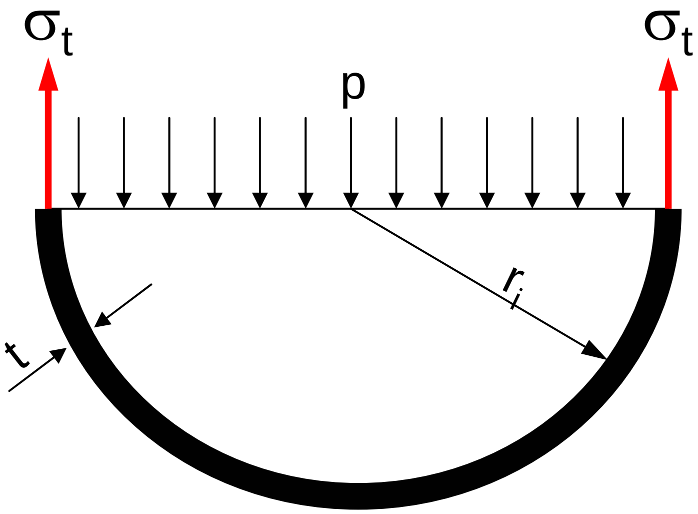
t = Thickness of the pipe [m]

C_s = Coefficient of safety [-]

ρ = Density of the water [kg/m^3]

H_{gr} = Gross Head [m]

Δh_{wh} = Pressure rise due to water hammer [m]



Example

Calculation of the pipe thickness

$$L \cdot D_i \cdot p \cdot C_s = 2 \cdot \sigma_t \cdot L \cdot t$$

$$\Downarrow$$

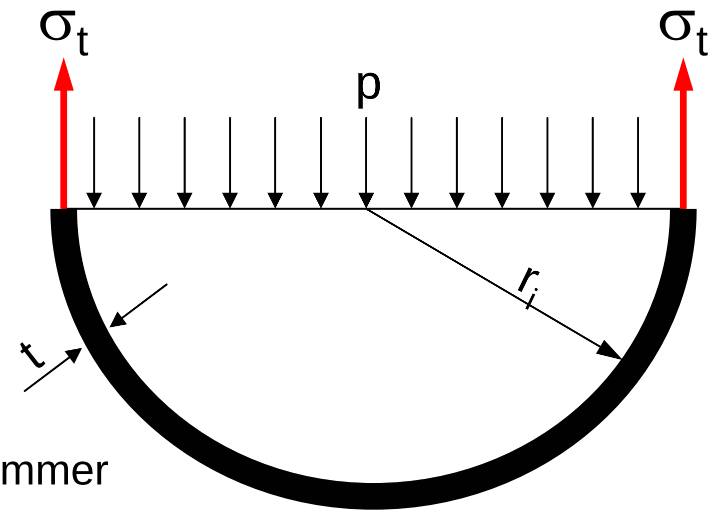
$$\boxed{t = \frac{p \cdot r_i \cdot C_s}{\sigma_t} = 0{,}009\ \mathrm{m}}$$

$$p = \rho \cdot g \cdot \left(H_{gr} + h_{wh}\right) = 1{,}57\ \mathrm{MPa}$$

- Based on:
  - Material properties
  - Pressure from:
    - Water hammer
    - Static head

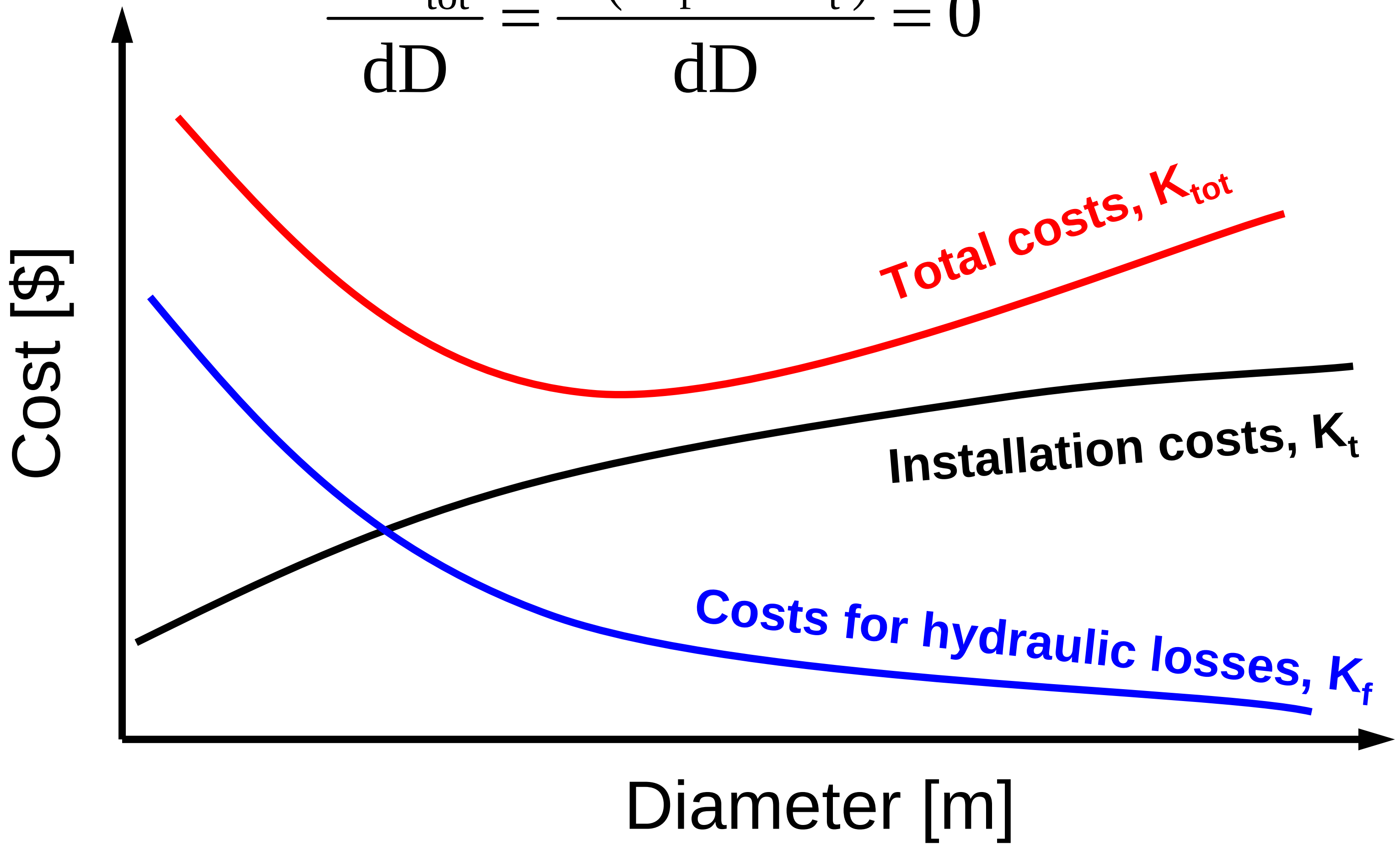
Where:

L	=	0,001 m	Length of the pipe
D_i	=	2,0 m	Inner diameter of the pipe
σ_t	=	206 MPa	Stresses in the pipe material
ρ	=	1000 kg/m^3	Density of the water
C_s	=	1,2	Coefficient of safety
H_{gr}	=	100 m	Gross Head
Δh_{wh}	=	61 m	Pressure rise due to water hammer



Calculation of the economical correct diameter of the pipe

$$\frac{dK_{tot}}{dD} = \frac{d(K_f + K_t)}{dD} = 0$$



Example

Calculation of the economical correct diameter of the pipe

Hydraulic Losses

Power Plant data:

H = 100 m Head
Q = 10 m^3/s Flow Rate
η_{plant} = 85 % Plant efficiency
L = 1000 m Length of pipe

$$P_{Loss} = \rho \cdot g \cdot Q \cdot h_f = \rho \cdot g \cdot Q \cdot f \frac{L}{2 \cdot r} \cdot \frac{Q^2}{2 \cdot g \cdot \pi^2 \cdot r^4} = \frac{C_2}{r^5}$$

Where:

P_{Loss} = Loss of power due to the head loss [W]
ρ = Density of the water [kg/m^3]
g = gravity [m/s^2]
Q = Flow rate [m^3/s]
h_f = Head loss [m]
f = Friction factor [-]
L = Length of pipe [m]
r = Radius of the pipe [m]
C_2 = Calculation coefficient

Example

Calculation of the economical correct diameter of the pipe

Cost of the Hydraulic Losses per year

$$K_f = P_{Loss} \cdot T \cdot kWh_{price} = \frac{C_2}{r^5} \cdot T \cdot kWh_{price}$$

Where:

K_f = Cost for the hydraulic losses [€]

P_{Loss} = Loss of power due to the head loss [W]

T = Energy production time [h/year]

kWh_{price} = Energy price [€/kWh]

r = Radius of the pipe [m]

C_2 = Calculation coefficient

Example

Calculation of the economical correct diameter of the pipe
Present value of the Hydraulic Losses per year

$$K_f = \frac{C_2}{r^5} \cdot T \cdot kWh_{price}$$

Where:

K_f = Cost for the hydraulic losses [€]
T = Energy production time [h/year]
kWh_{price} = Energy price [€/kWh]
r = Radius of the pipe [m]
C_2 = Calculation coefficient

Present value for 20 year of operation:

$$K_{f\ pv} = \sum_{i=1}^{n} \frac{K_f}{(1+I)^i}$$

Where:

$K_{f\ pv}$ = Present value of the hydraulic losses [€]
n = Lifetime, (Number of year) [-]
I = Interest rate [-]

Example

Calculation of the economical correct diameter of the pipe

Cost for the Pipe Material

$$m = \rho_m \cdot V = \rho_m \cdot 2 \cdot \pi \cdot r \cdot t \cdot L = \rho_m \cdot 2 \cdot \pi \cdot r \cdot \frac{p \cdot r}{\sigma} \cdot L = C_1 \cdot r^2$$

$$K_t = M \cdot m = M \cdot C_1 \cdot r^2$$

Where:

m = Mass of the pipe [kg]
ρ_m = Density of the material [kg/m³]
V = Volume of material [m³]
r = Radius of pipe [m]
L = Length of pipe [m]
p = Pressure in the pipe [MPa]
σ = Maximum stress [MPa]
C_1 = Calculation coefficient
K_t = Installation costs [€]
M = Cost for the material [€/kg]

NB:
This is a simplification because no other component then the pipe is calculated

Example

Calculation of the economical correct diameter of the pipe

- Installation Costs:
  - Pipes
  - Maintenance
  - Interests
  - Etc.

Example

Calculation of the economical correct diameter of the pipe

$$K_{f\ pv} = \sum_{i=1}^{n} \frac{\frac{C_2}{r^5} \cdot T \cdot kWh_{price}}{(1+I)^i} \qquad K_t = M \cdot C_1 \cdot r^2$$

$$\frac{d(K_t + K_f)}{dr} = 2 \cdot M \cdot C \cdot r - \frac{5}{r^6} \cdot \sum_{i=1}^{n} \frac{C_2 \cdot T \cdot kWh_{price}}{(1+I)^i} = 0$$

Where:

K_f = Cost for the hydraulic losses [€]
K_t = Installation costs [€]
T = Energy production time [h/year]
kWh_{price} = Energy price [€/kWh]
r = Radius of the pipe [m]
C_1 = Calculation coefficient
C_2 = Calculation coefficient
M = Cost for the material [€/kg]
n = Lifetime, (Number of year) [-]
I = Interest rate [-]

Example

Calculation of the economical correct diameter of the pipe

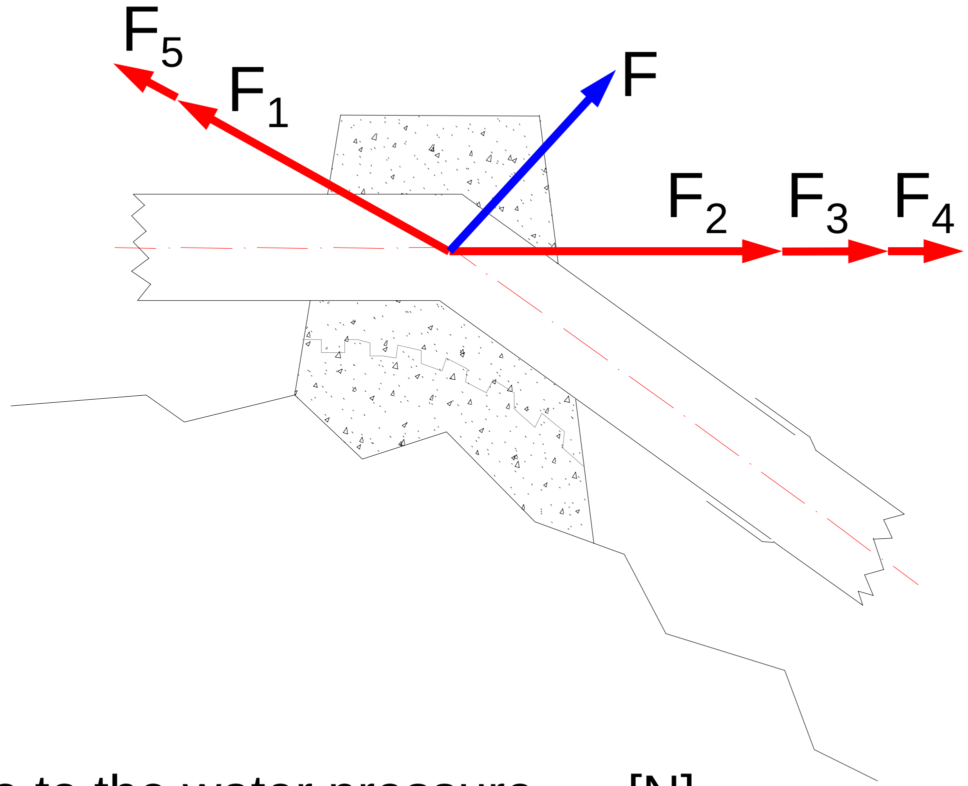
$$\frac{d\left(K_t + K_f\right)}{dr} = 2 \cdot M \cdot C \cdot r - \frac{5}{r^6} \cdot \sum_{i=1}^{n} \frac{C_2 \cdot T \cdot kWh_{price}}{\left(1 + I\right)^i} = 0$$

$$\Downarrow$$

$$r = \sqrt[7]{\frac{5}{2} \cdot \sum_{i=1}^{n} \frac{C_2 \cdot T \cdot kWh_{price}}{M \cdot C \cdot \left(1 + I\right)^i}}$$

Calculation of the forces acting on the anchors

Calculation of the forces acting on the anchors



F_1 = Force due to the water pressure [N]

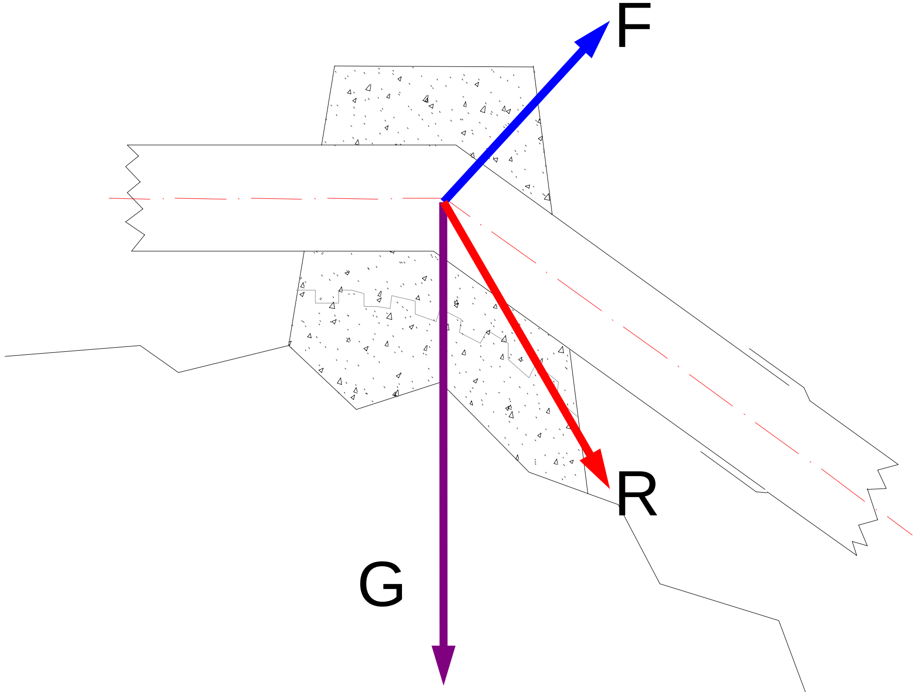
F_2 = Force due to the water pressure [N]

F_3 = Friction force due to the pillars upstream the anchor [N]

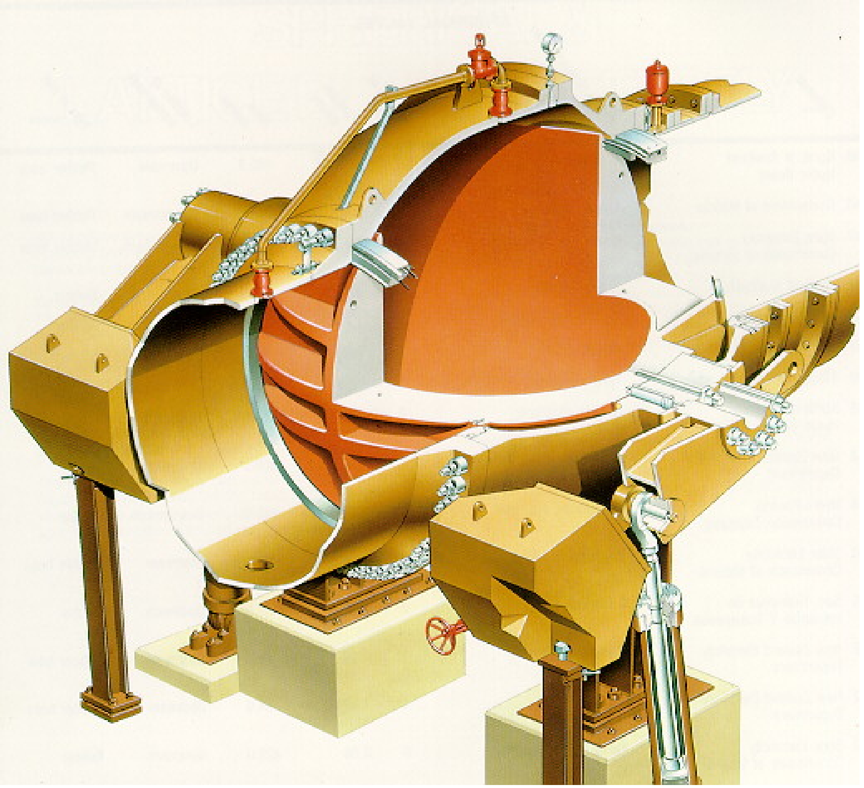
F_4 = Friction force due to the expansion joint upstream the anchor [N]

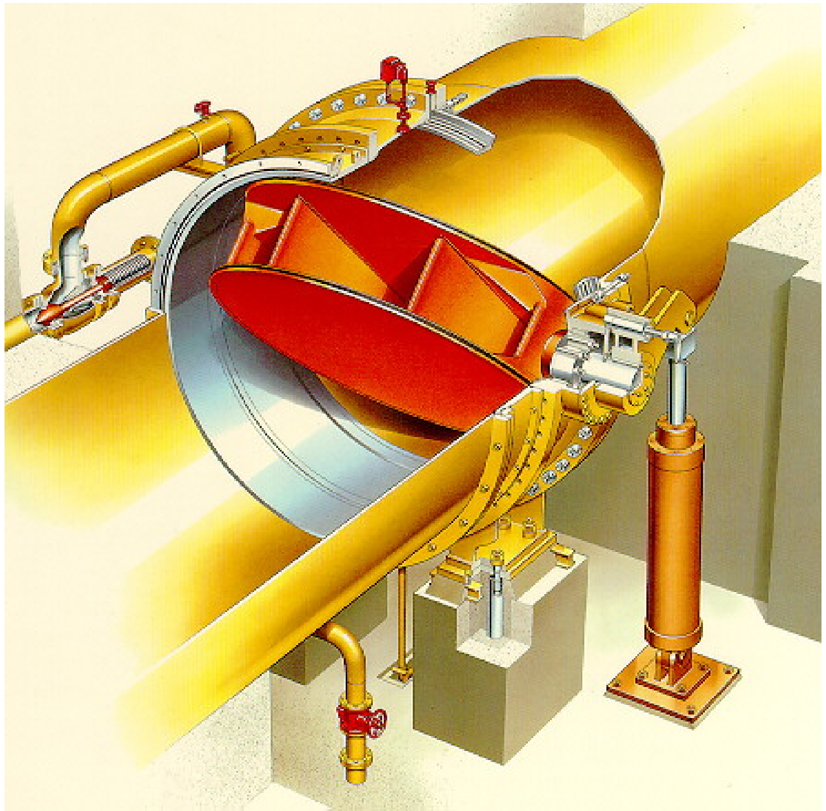
F_5 = Friction force due to the expansion joint downstream the anchor [N]

Calculation of the forces acting on the anchors



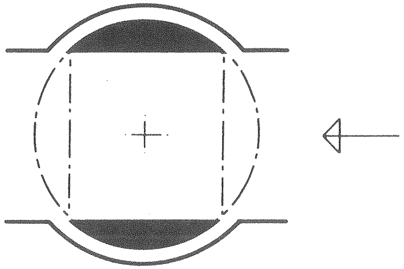
Valves



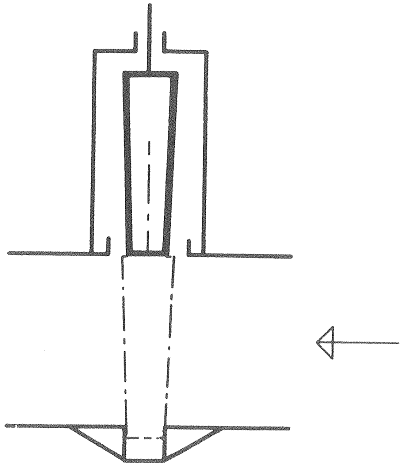


Principle drawings of valves

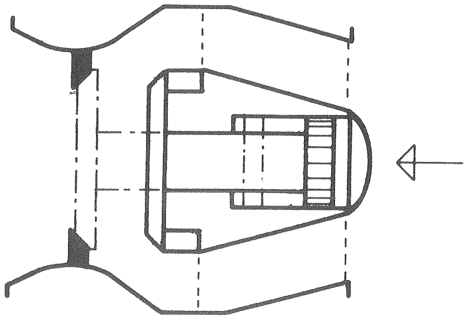
Open position ———
Closed position —·—·—



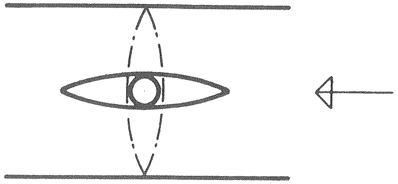
Spherical valve



Gate valve

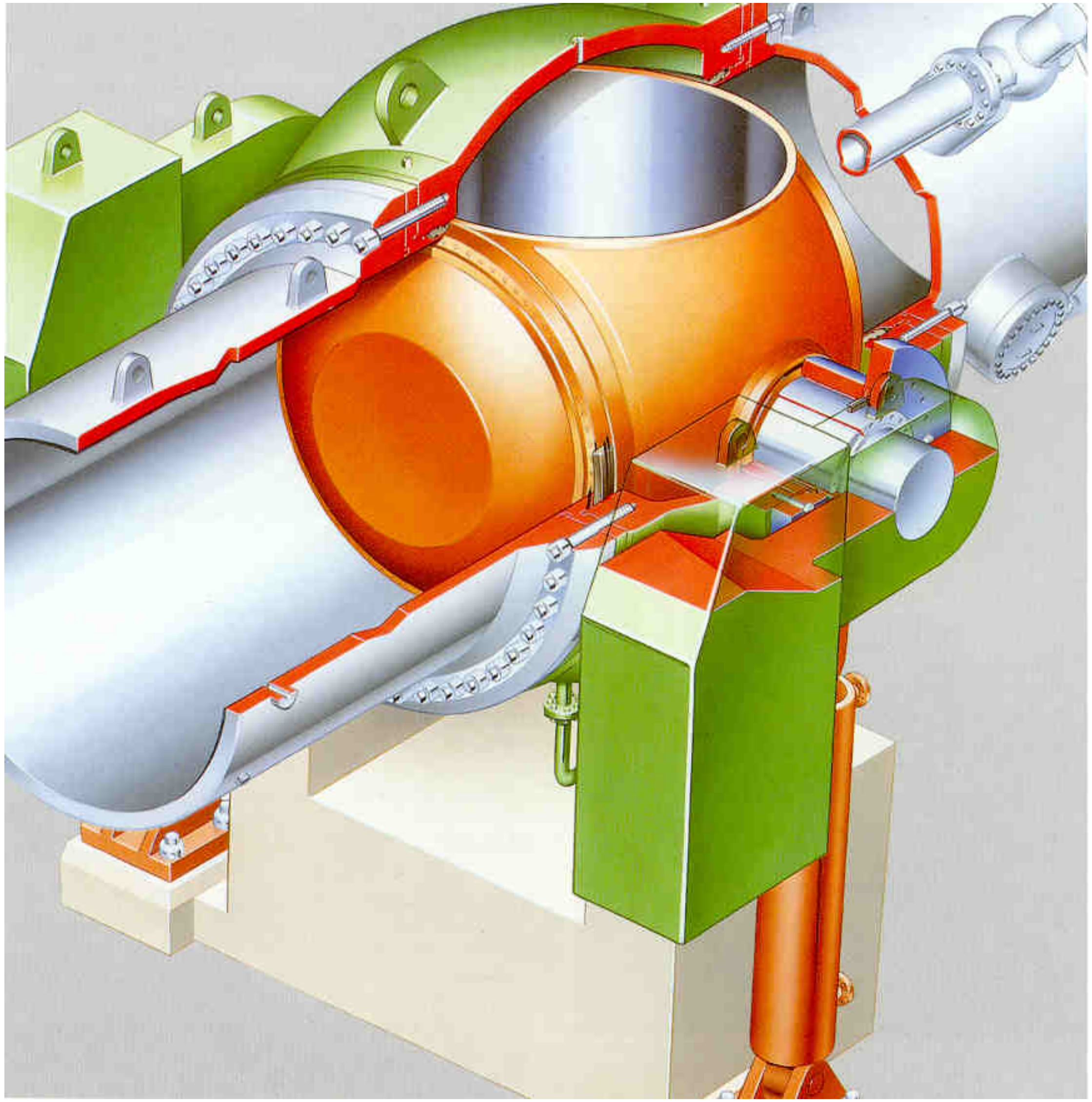


Hollow-jet valve

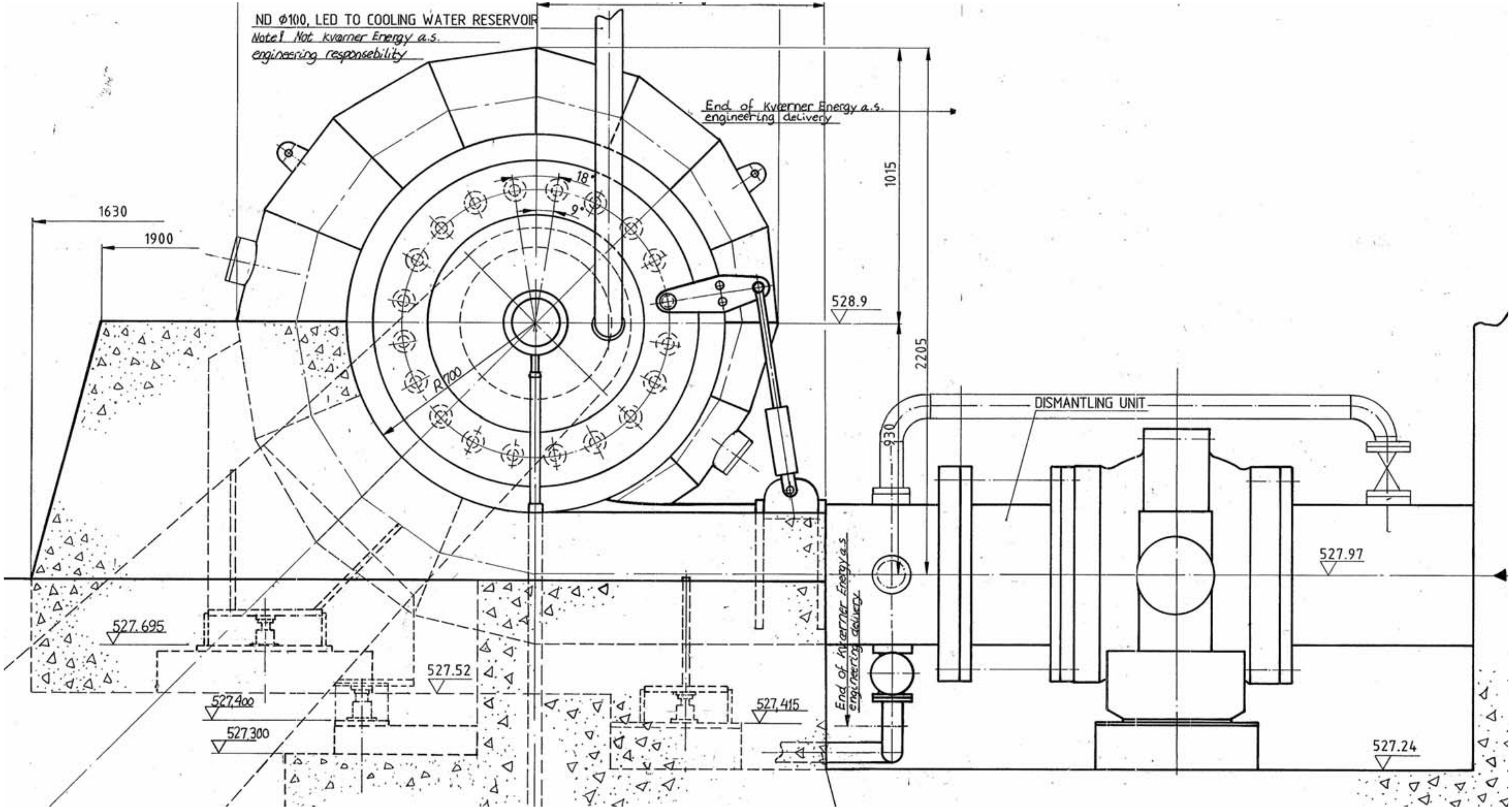


Butterfly valve

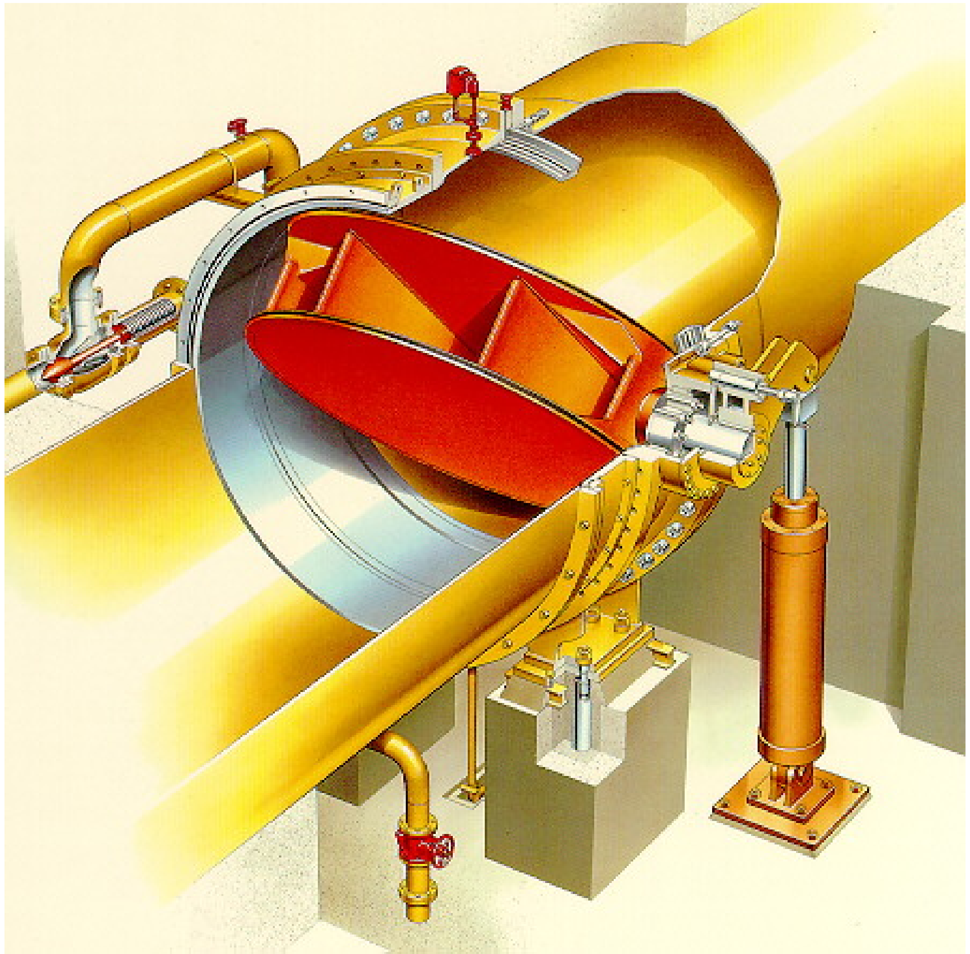
Spherical valve



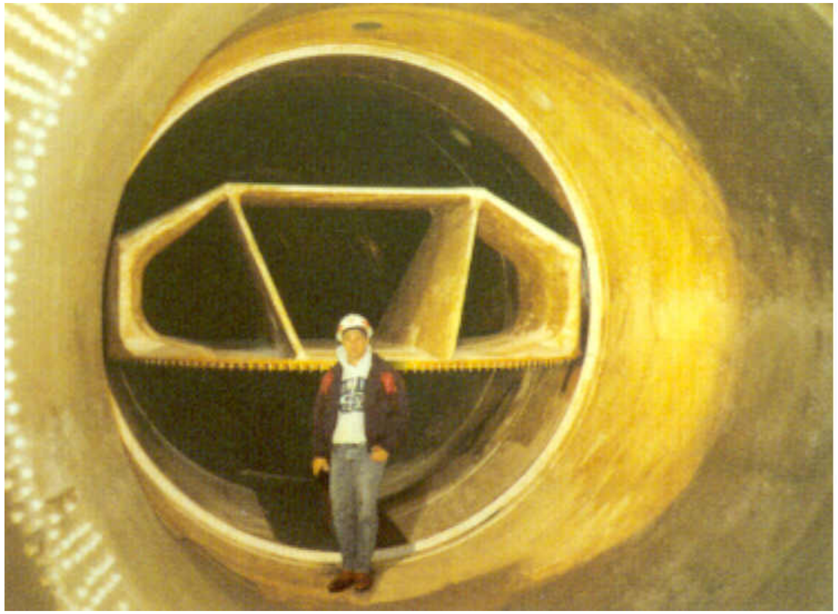
Bypass system

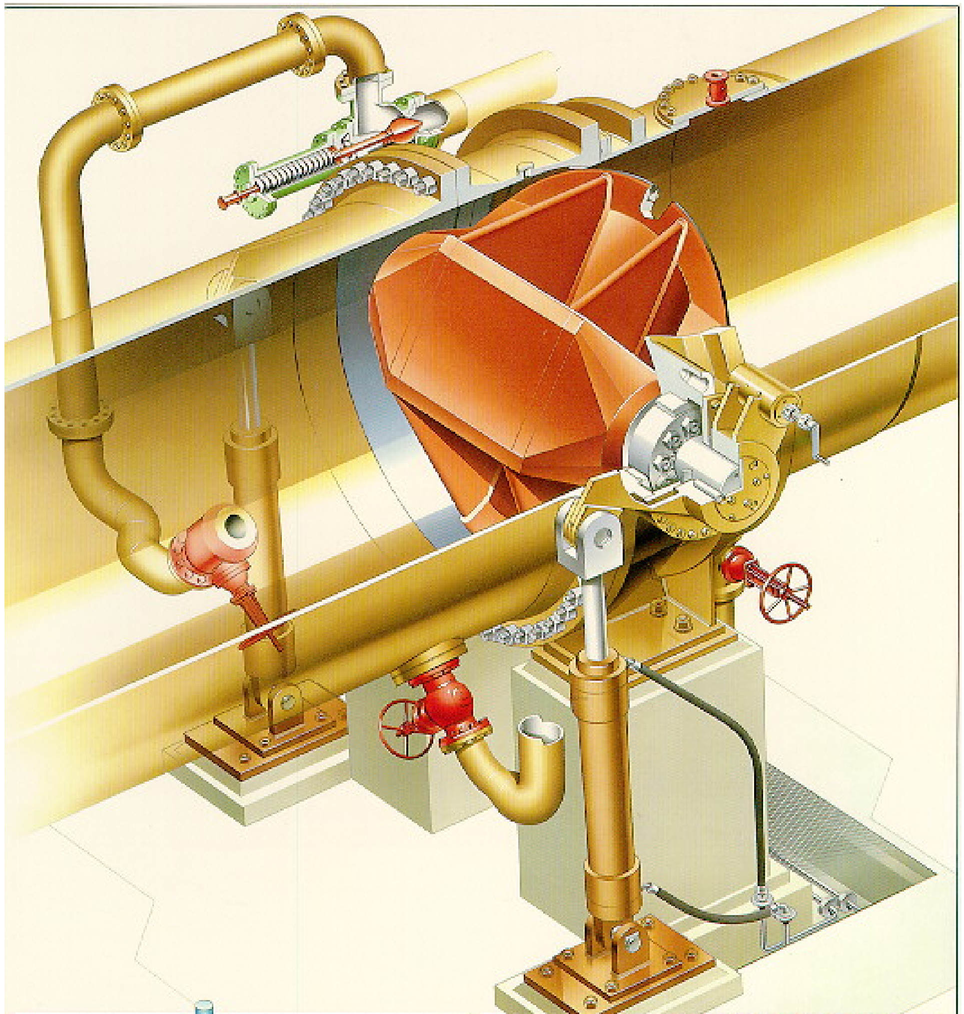


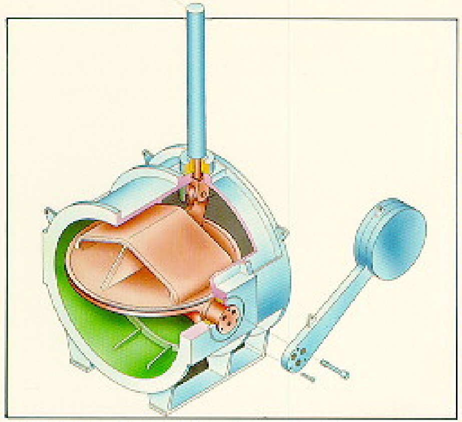
Butterfly valve



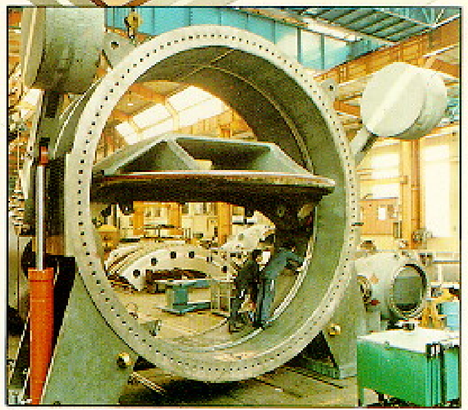
Butterfly valve





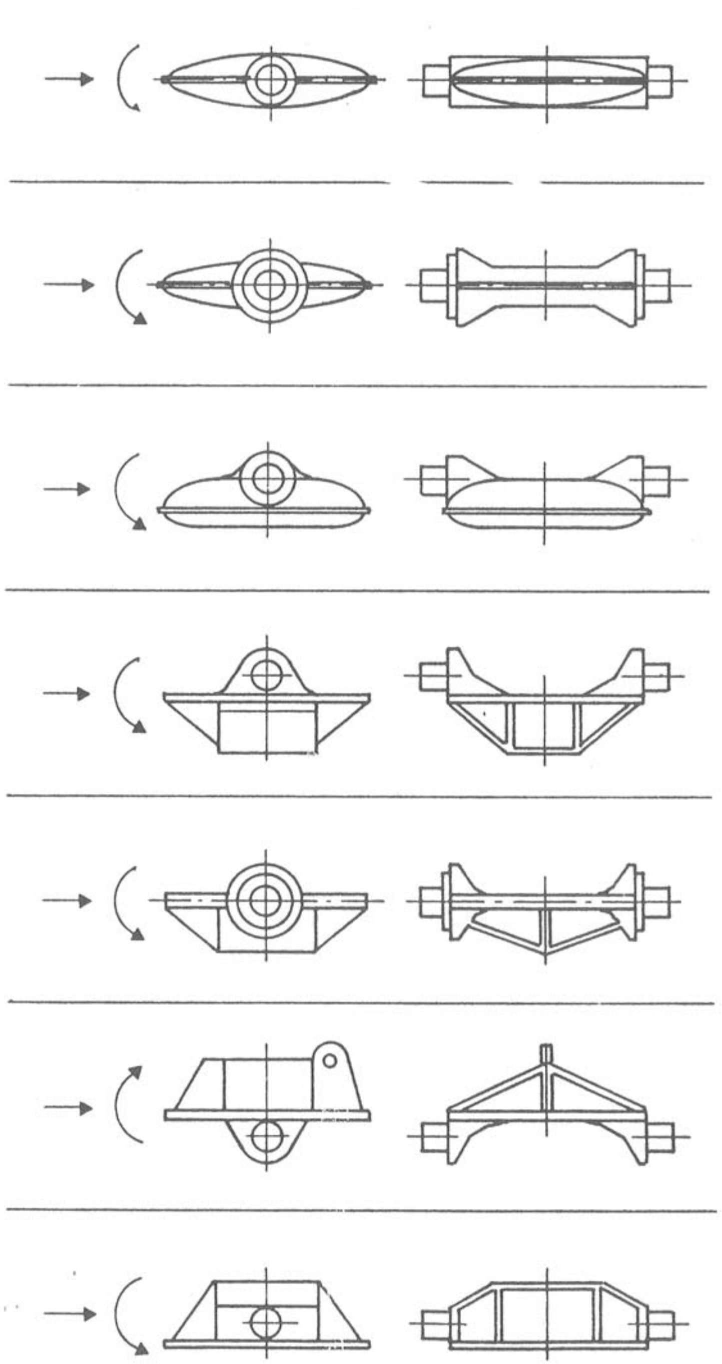


Lattice blade butterfly valve with blade mounted cylinder

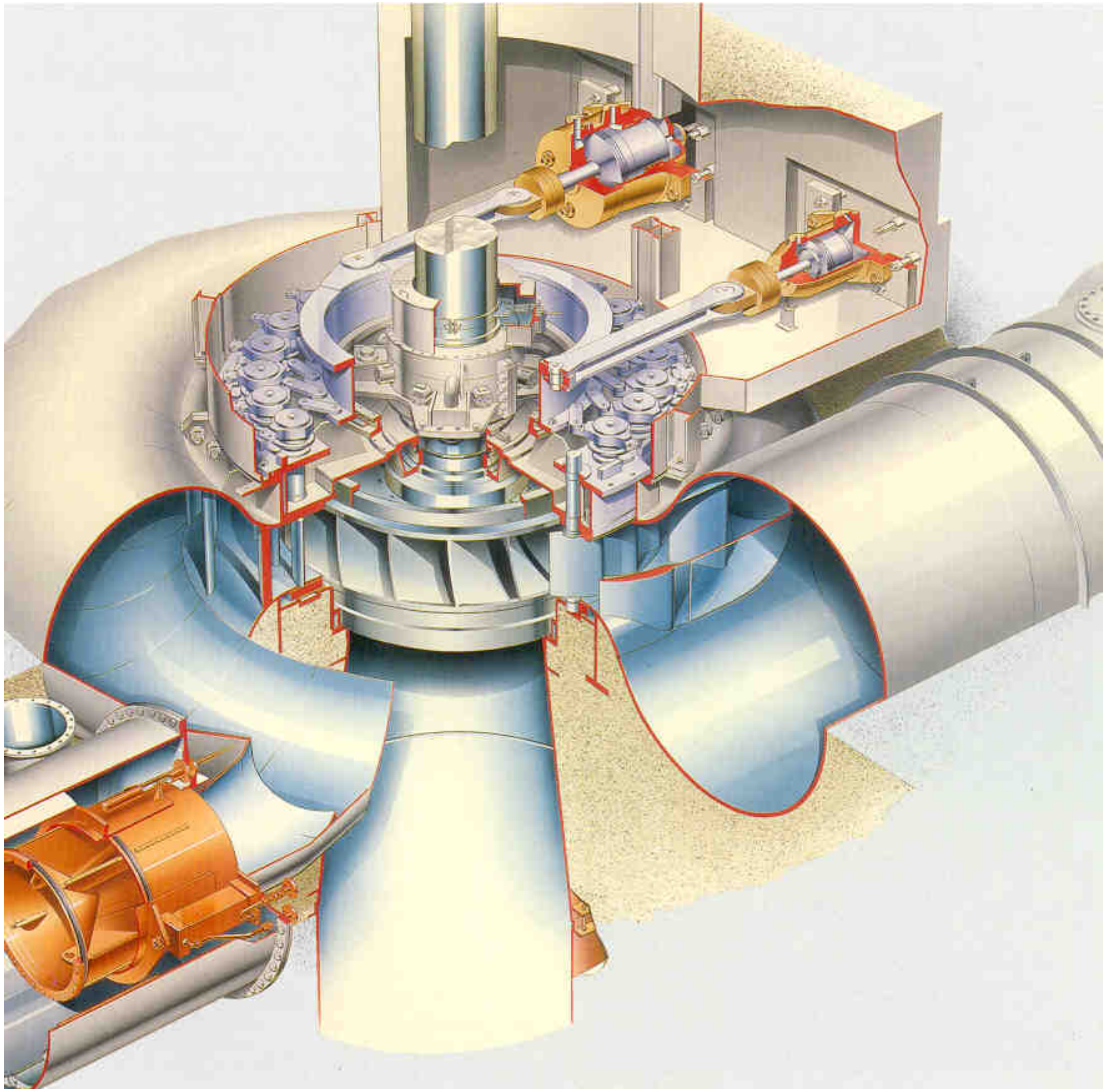


Turbine inlet valve, Steinsloss, Norway

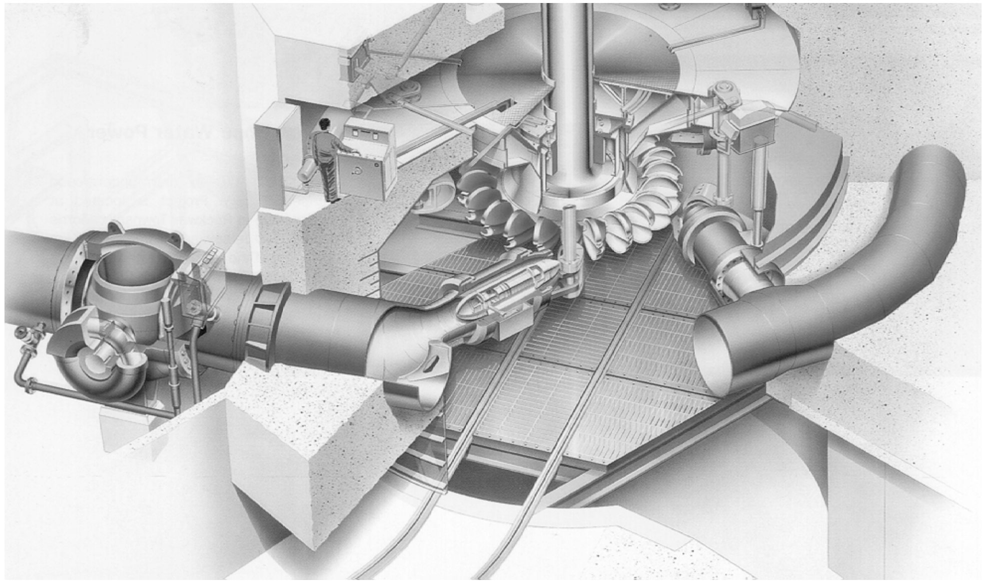
Butterfly valve disk types



Hollow-jet Valve



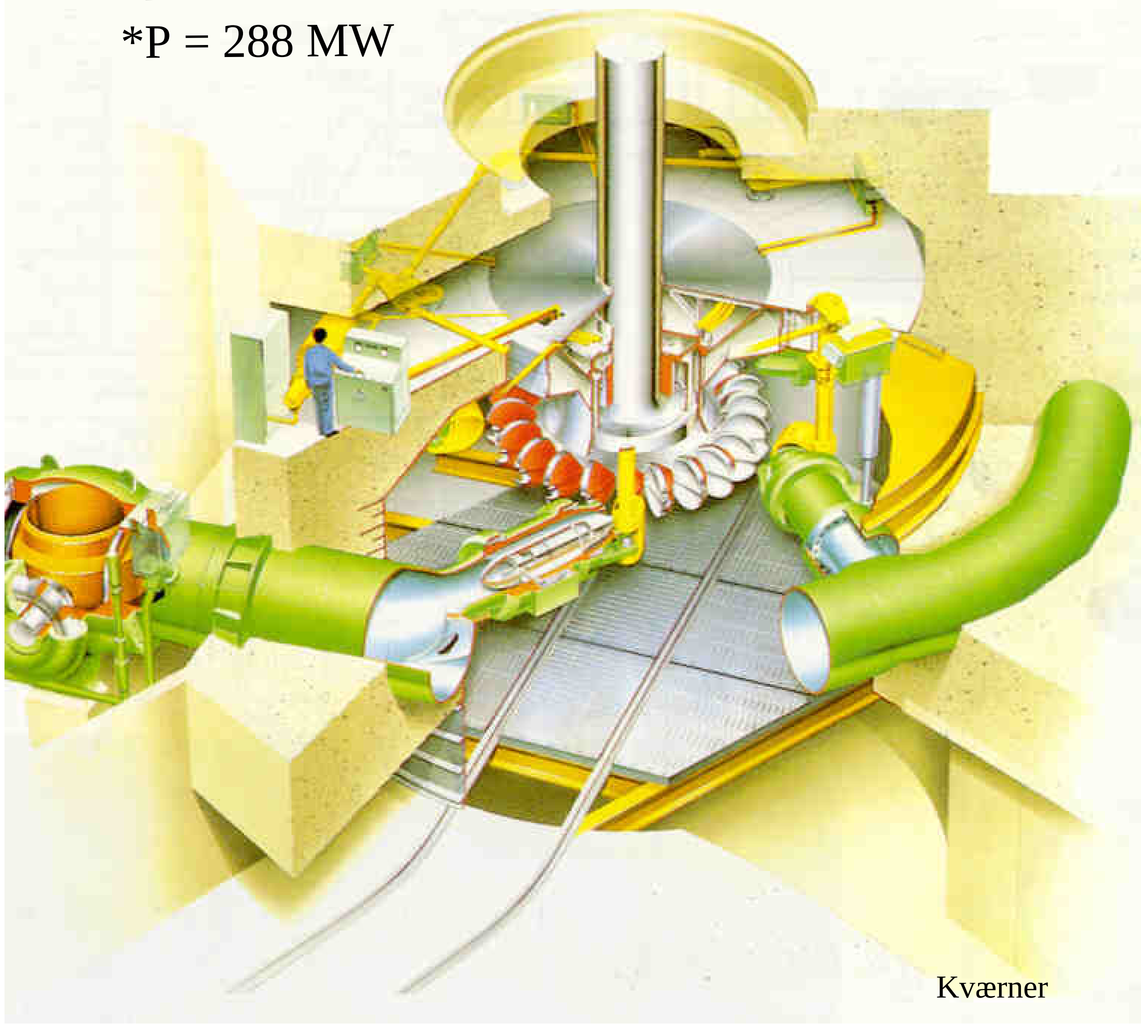
Pelton turbines



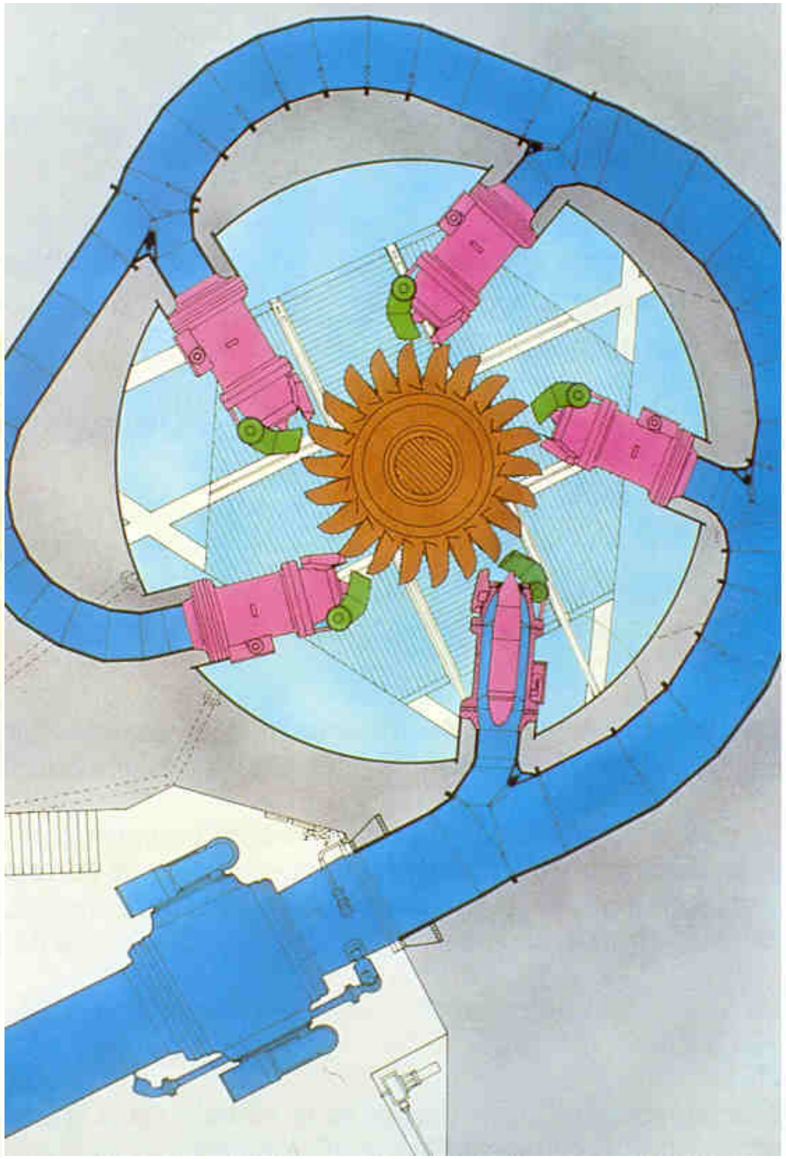
- Large heads (from 100 meter to 1800 meter)
- Relatively small flow rate
- Maximum of 6 nozzles
- Good efficiency over a vide range

Jostedal, Norway

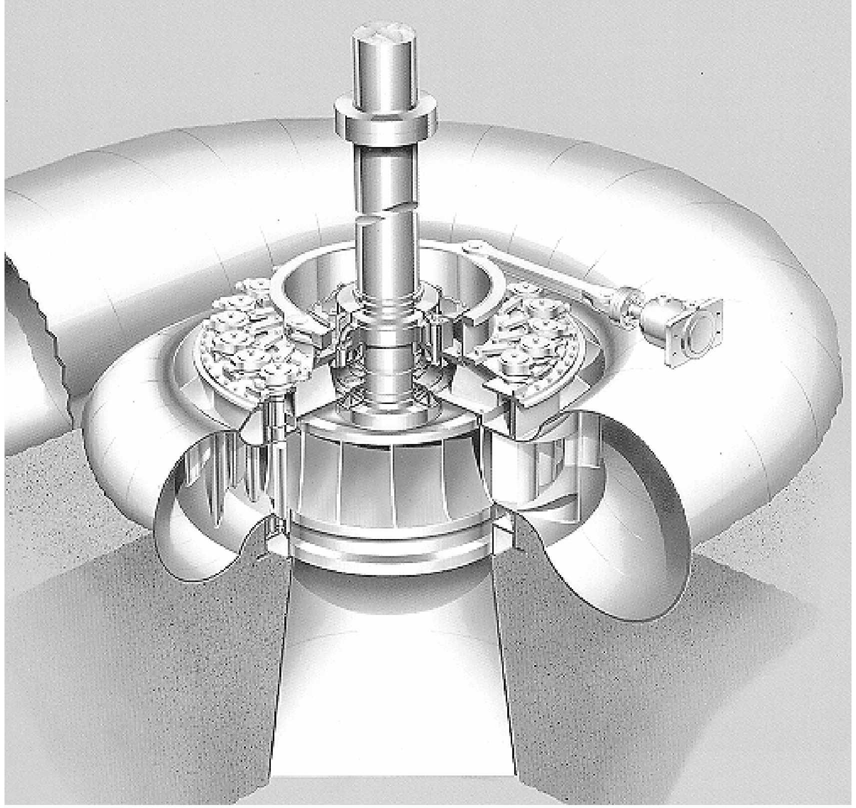
*Q = 28,5 m^3/s
*H = 1130 m
*P = 288 MW



Kværner

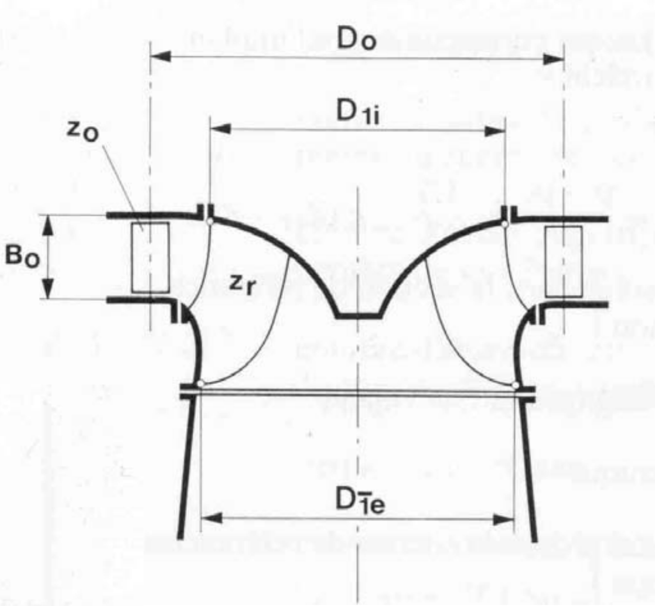


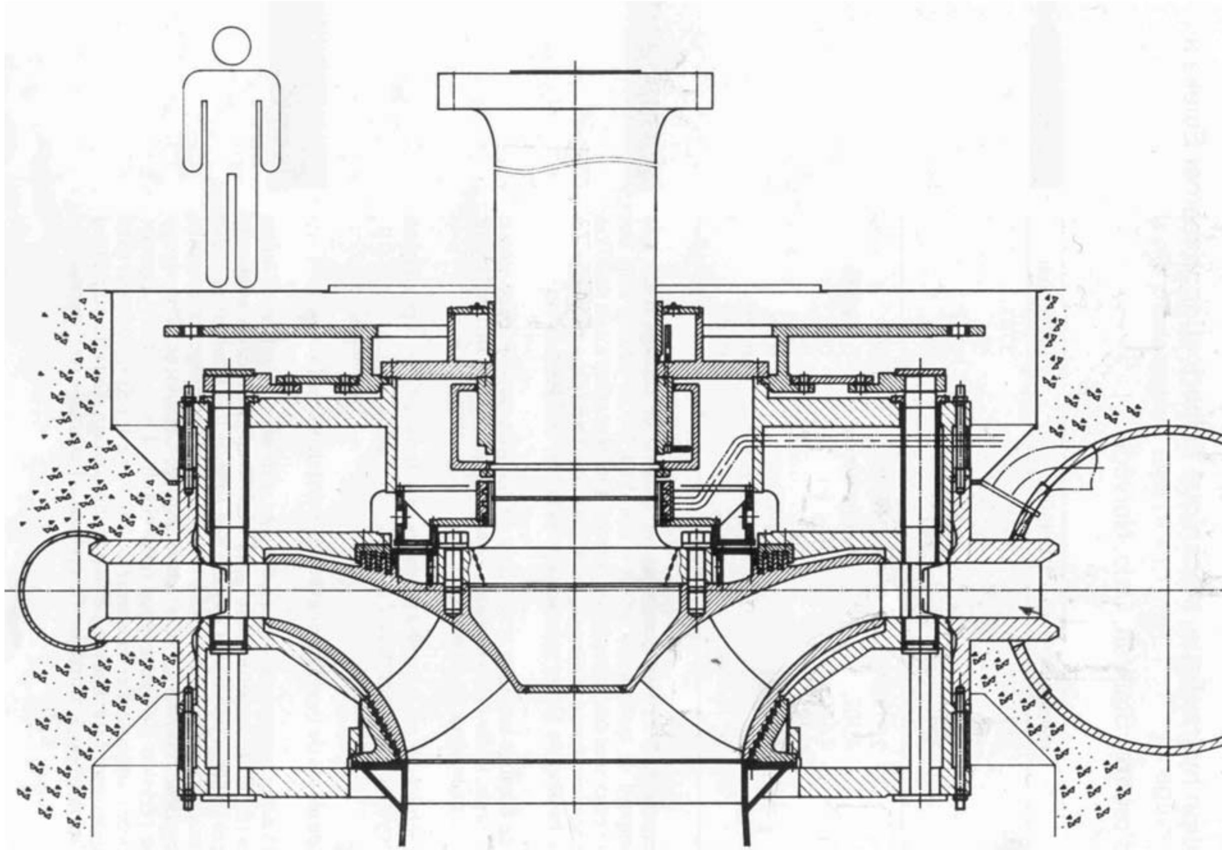
Francis turbines



- Heads between 15 and 700 meter
- Medium Flow Rates
- Good efficiency η=0.96 for modern machines

SVARTISEN





P = 350 MW

H = 543 m

Q* = 71,5 m^3/S

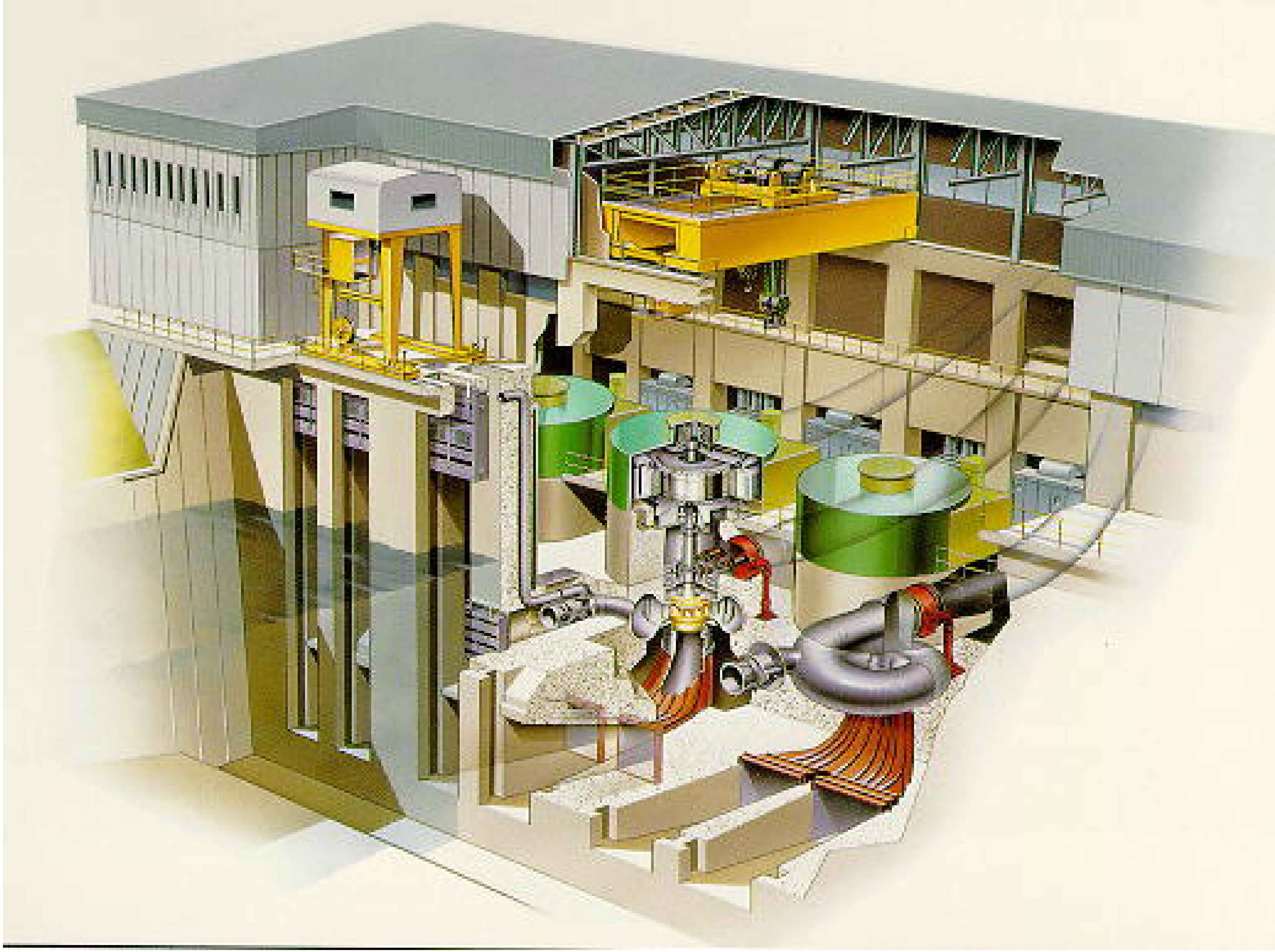
D_0 = 4,86 m

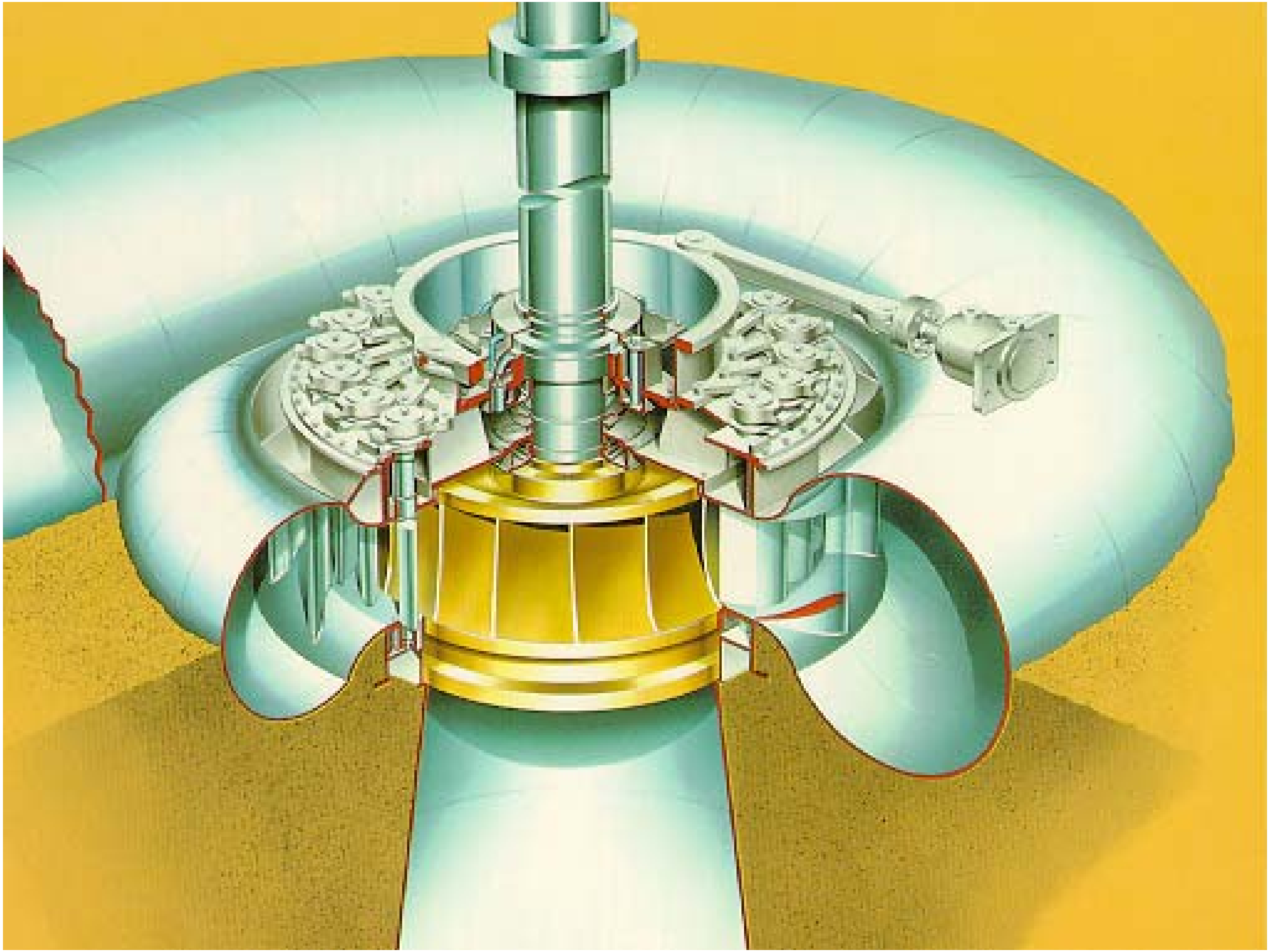
D_1 = 4,31m

D_2 = 2,35 m

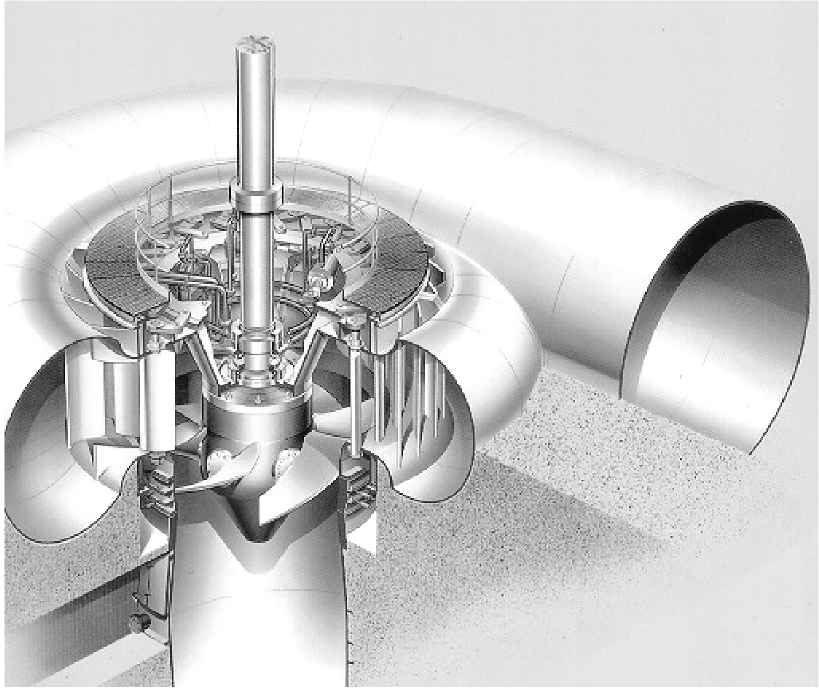
B_0 = 0,28 m

n = 333 rpm





Kaplan turbines



- Low head (from 70 meter and down to 5 meter)
- Large flow rates
- The runner vanes can be governed
- Good efficiency over a vide range