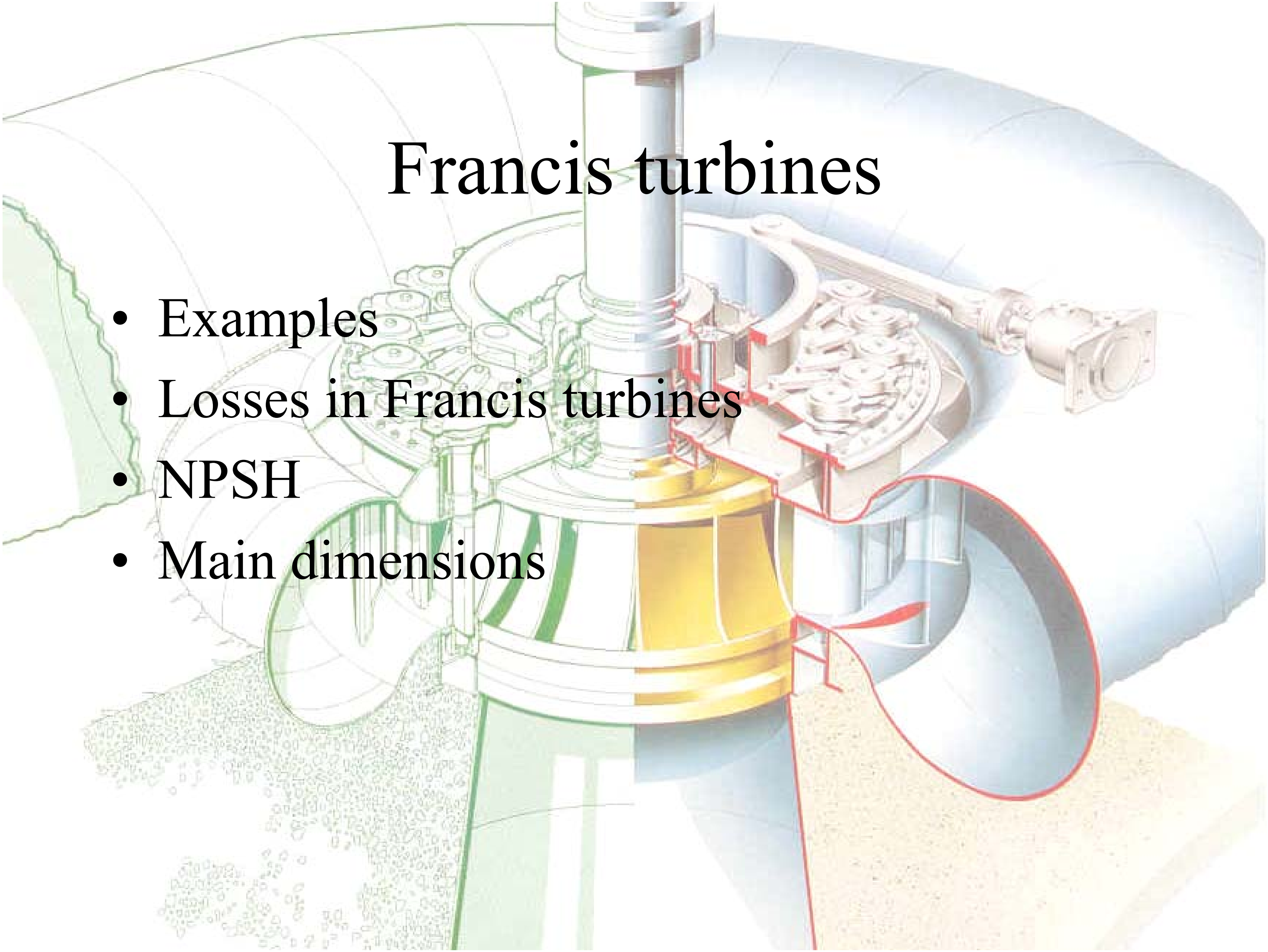
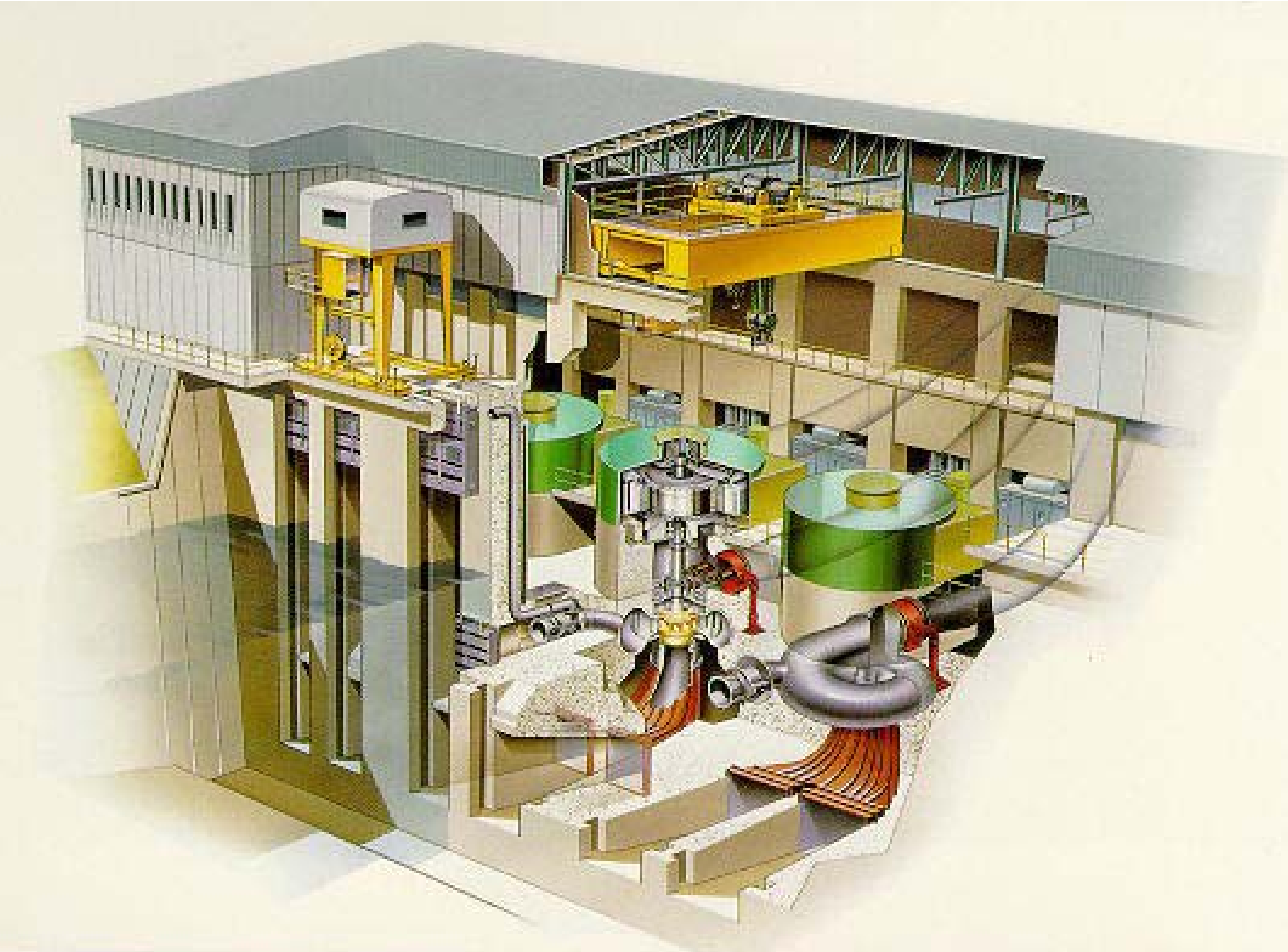
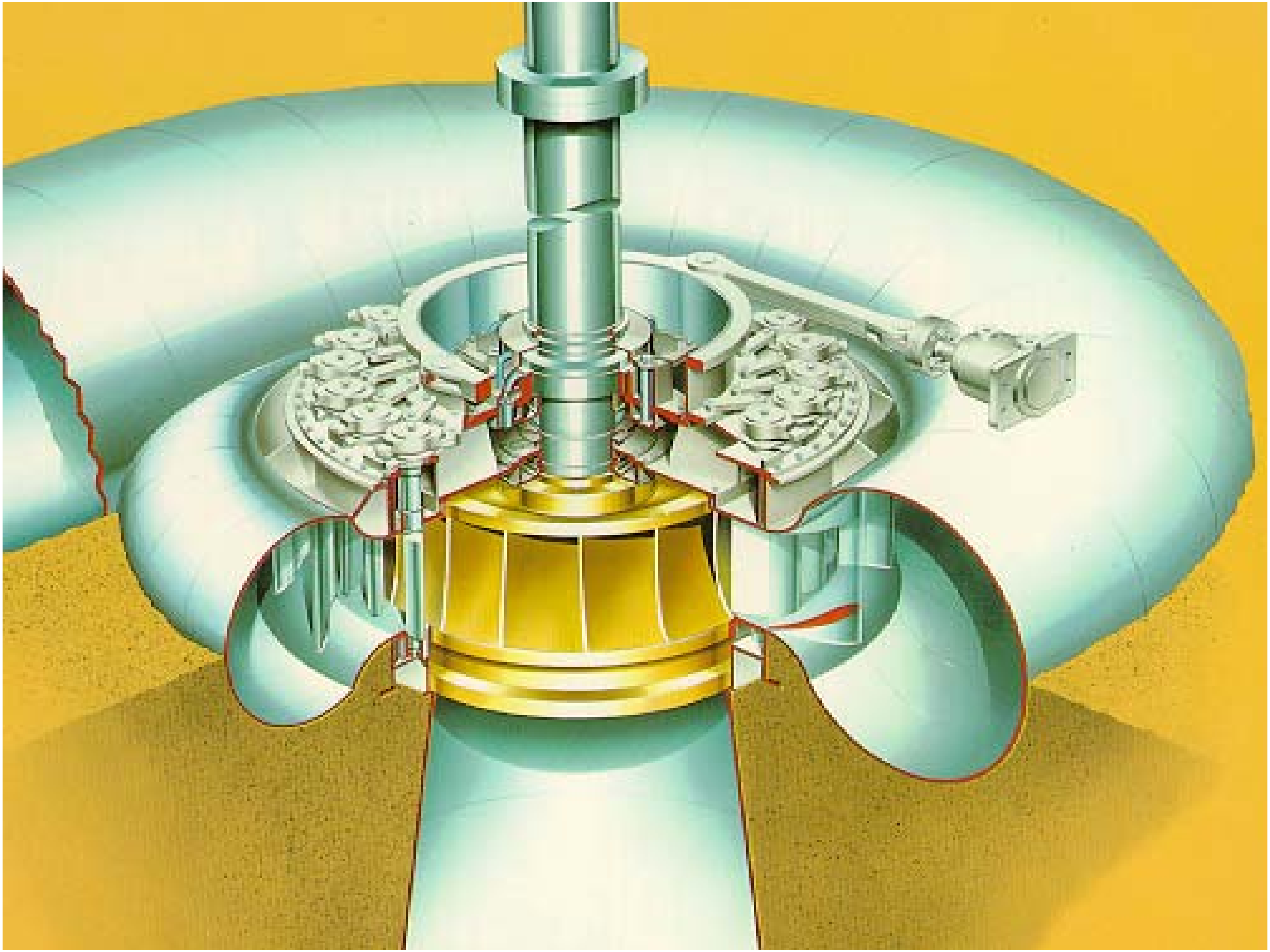
Francis turbines

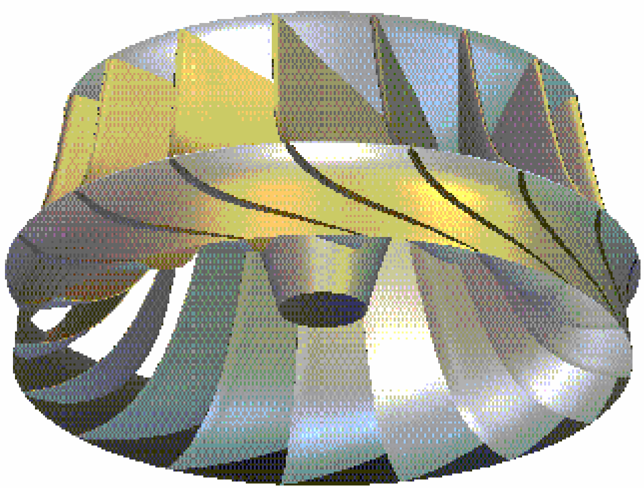
- Examples
- Losses in Francis turbines
- NPSH
- Main dimensions



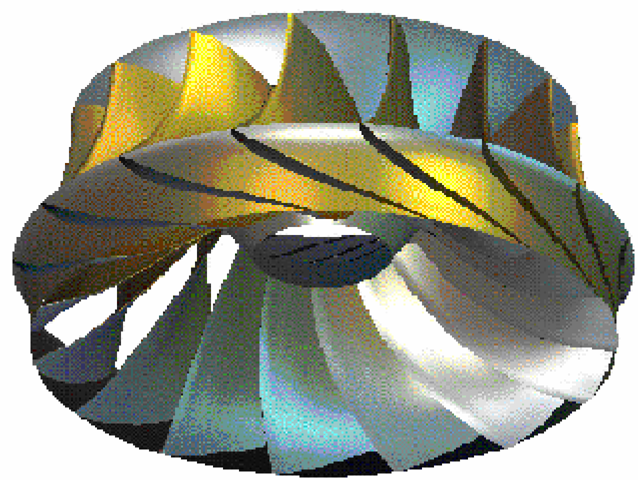




Traditional runner



X blade runner



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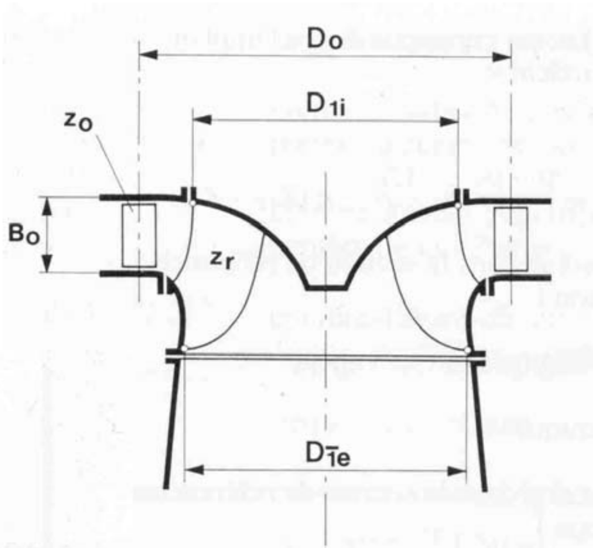
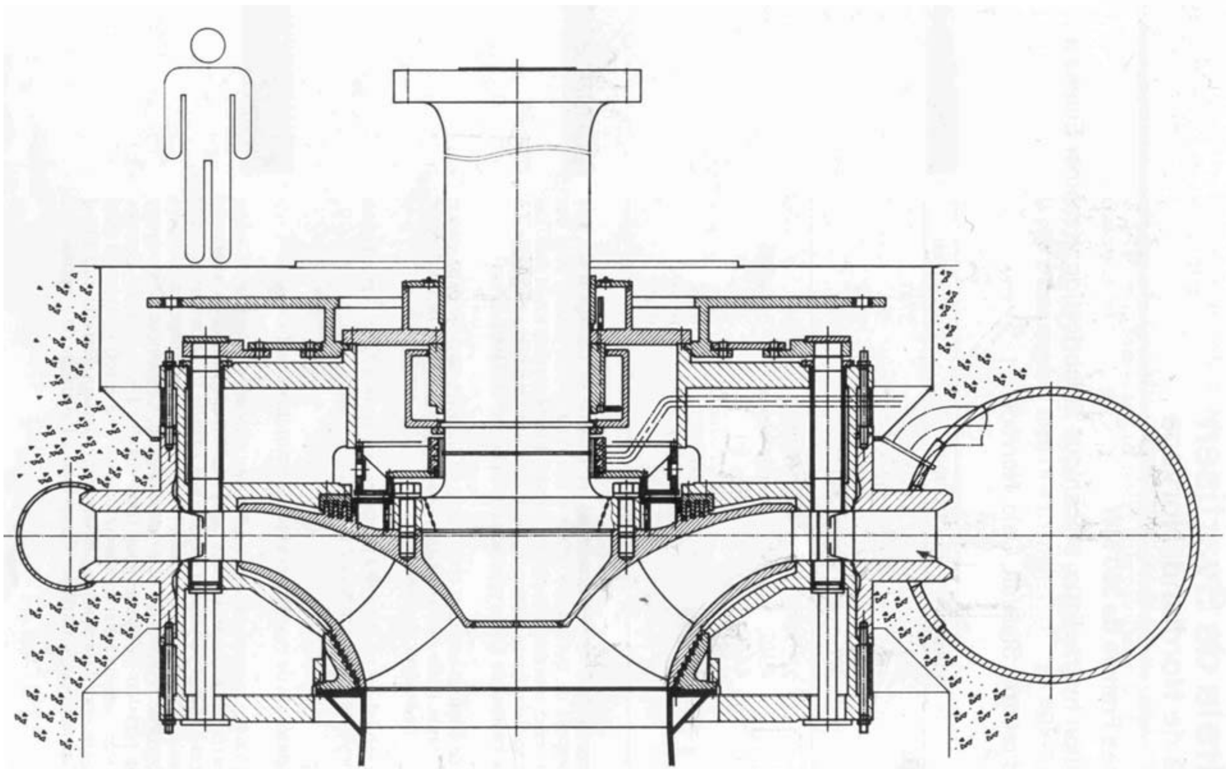




$P = 350\ MW$

$H = 543\ m$

$Q^* = 71{,}5\ m^3/S$

$D_0 = 4{,}86\ m$

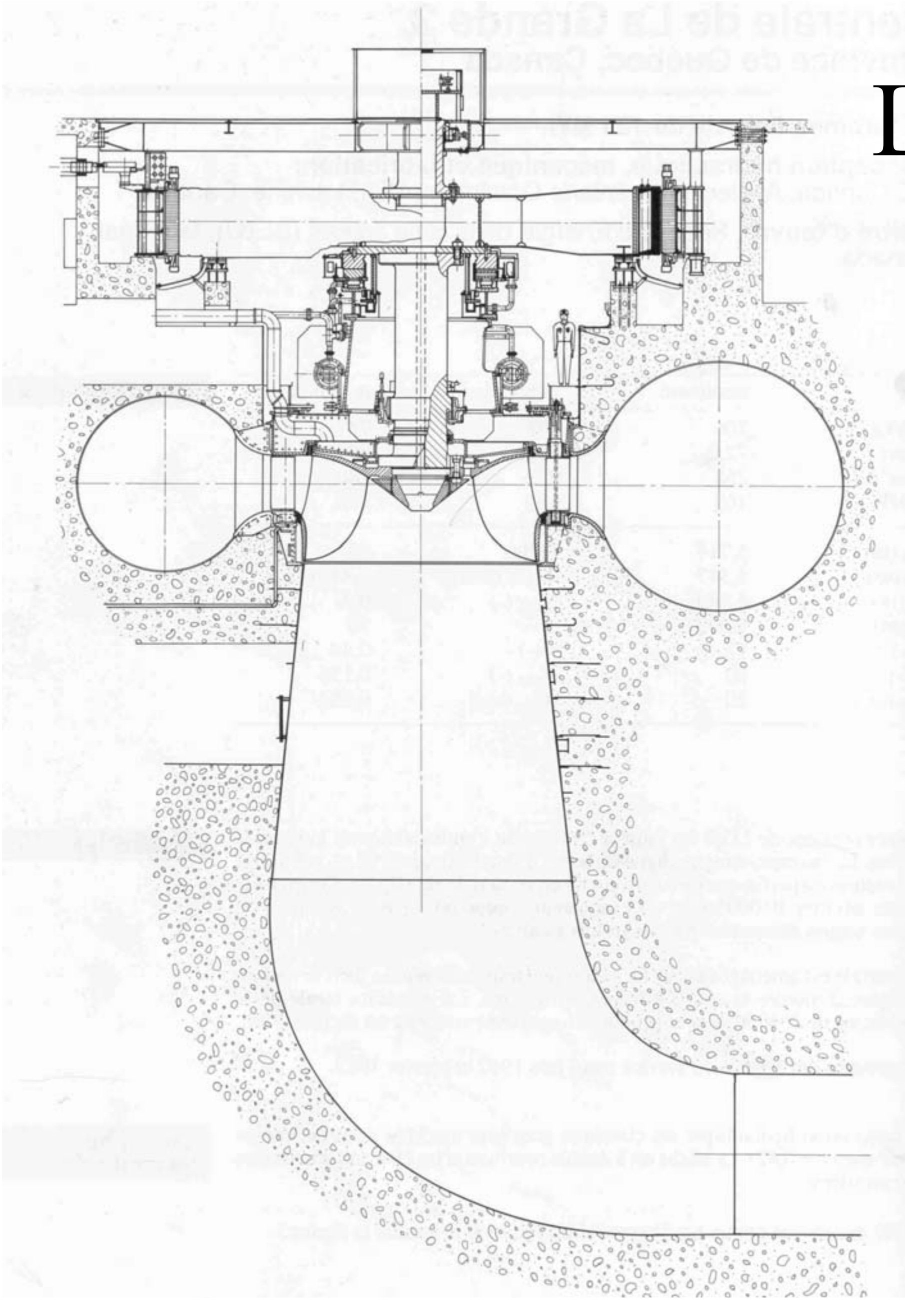
$D_1 = 4{,}31 m$

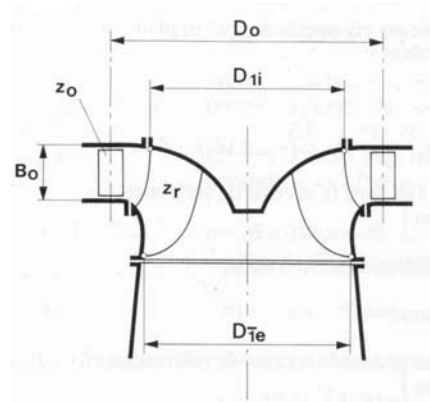
$D_2 = 2{,}35\ m$

$B_0 = 0{,}28\ m$

$n = 333\ rpm$

La Grande, Canada





P = 169 MW

H = 72 m

Q = 265 m^3/s

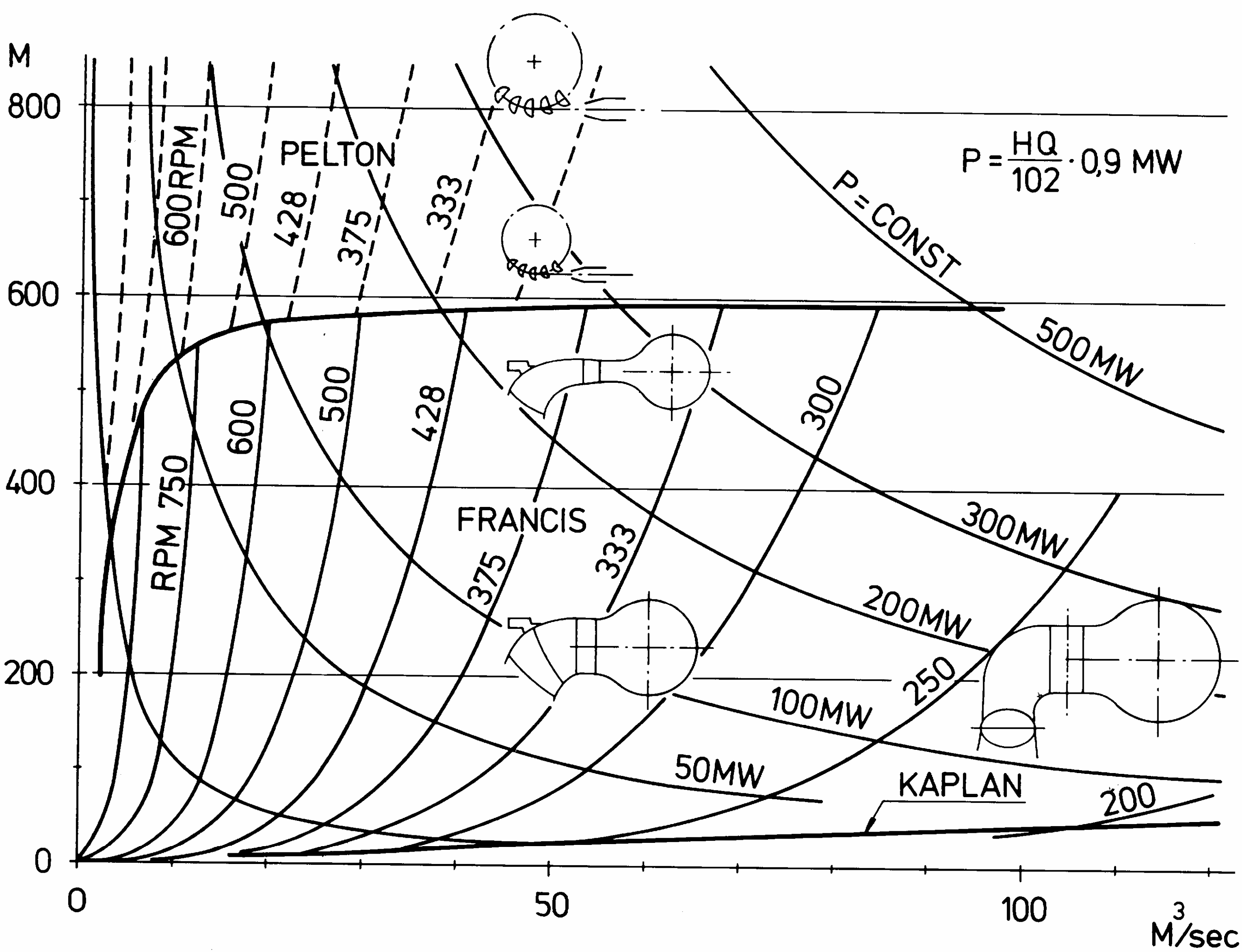
D_0 = 6,68 m

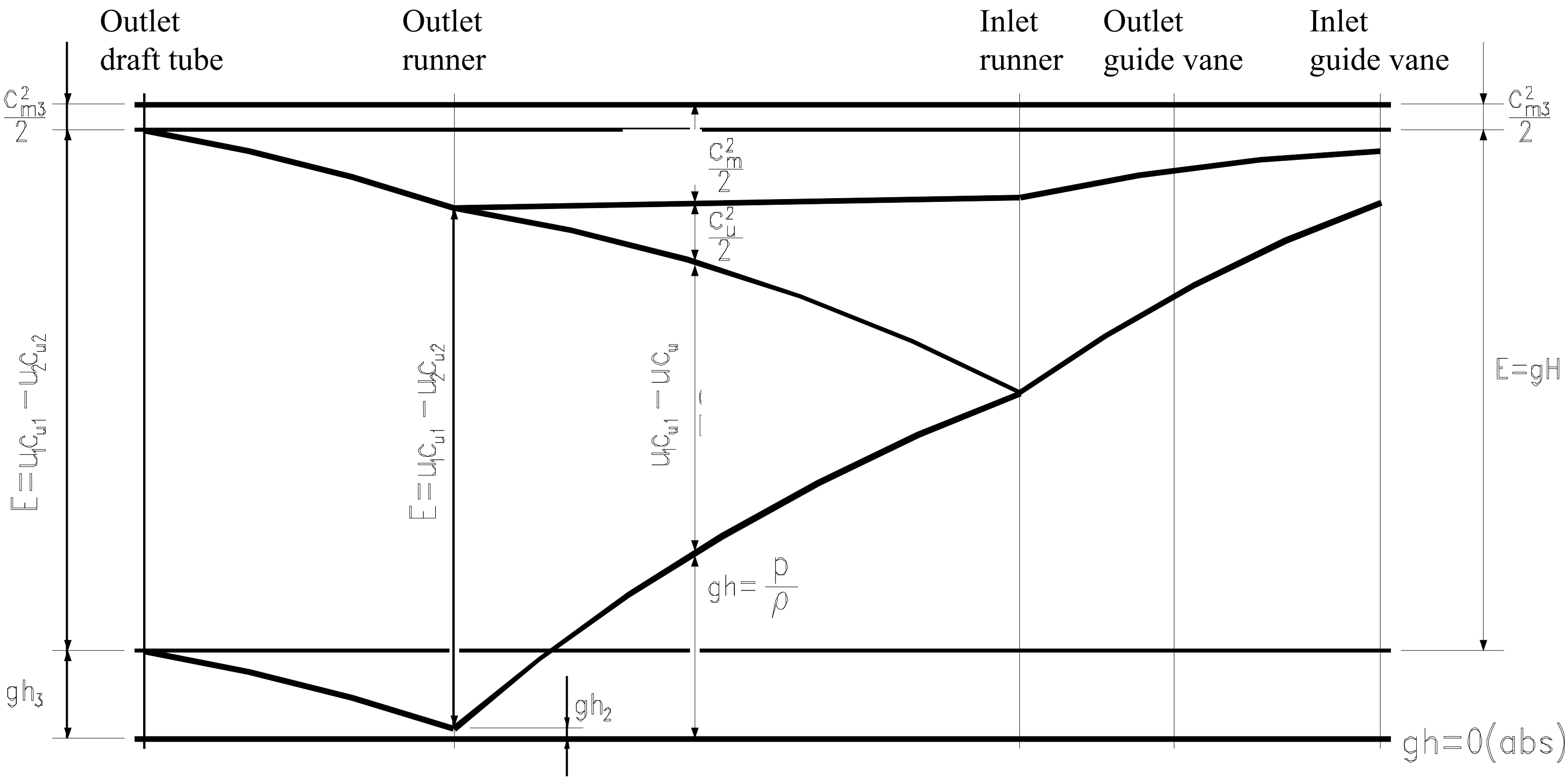
D_{1e} = 5,71m

D_{1i} = 2,35 m

B_0 = 1,4 m

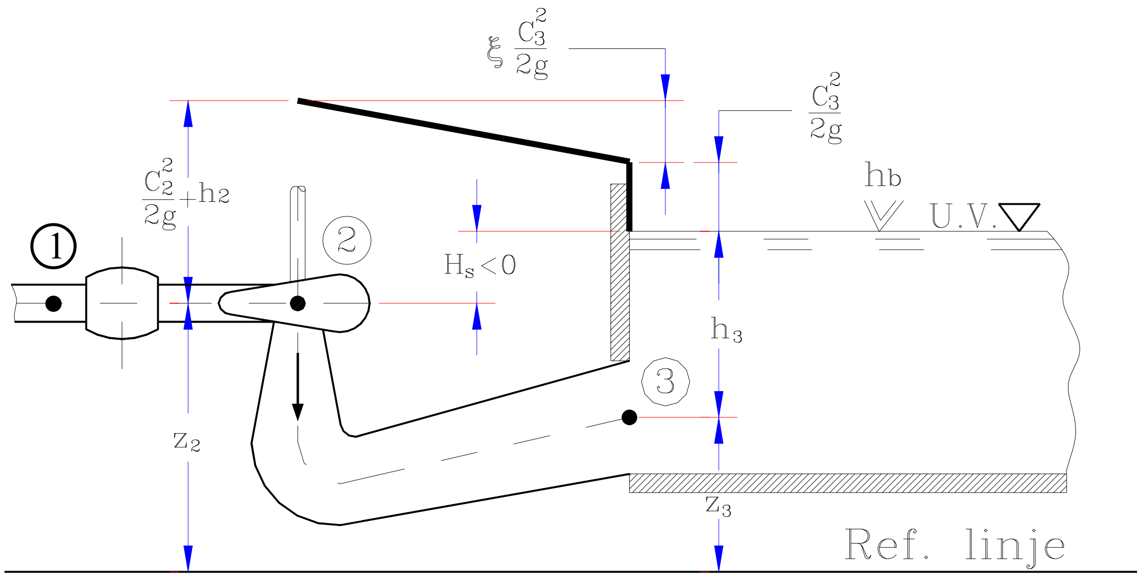
n = 112,5 rpm


M
800
600
400
200
0
0
50
100
M3/sec
PELTON
600RPM
500
428
375
333
P = CONST
P = HQ/102 · 0,9 MW
500MW
300MW
200MW
100MW
50MW
FRANCIS
RPM 750
600
500
428
375
333
300
250
200
KAPLAN

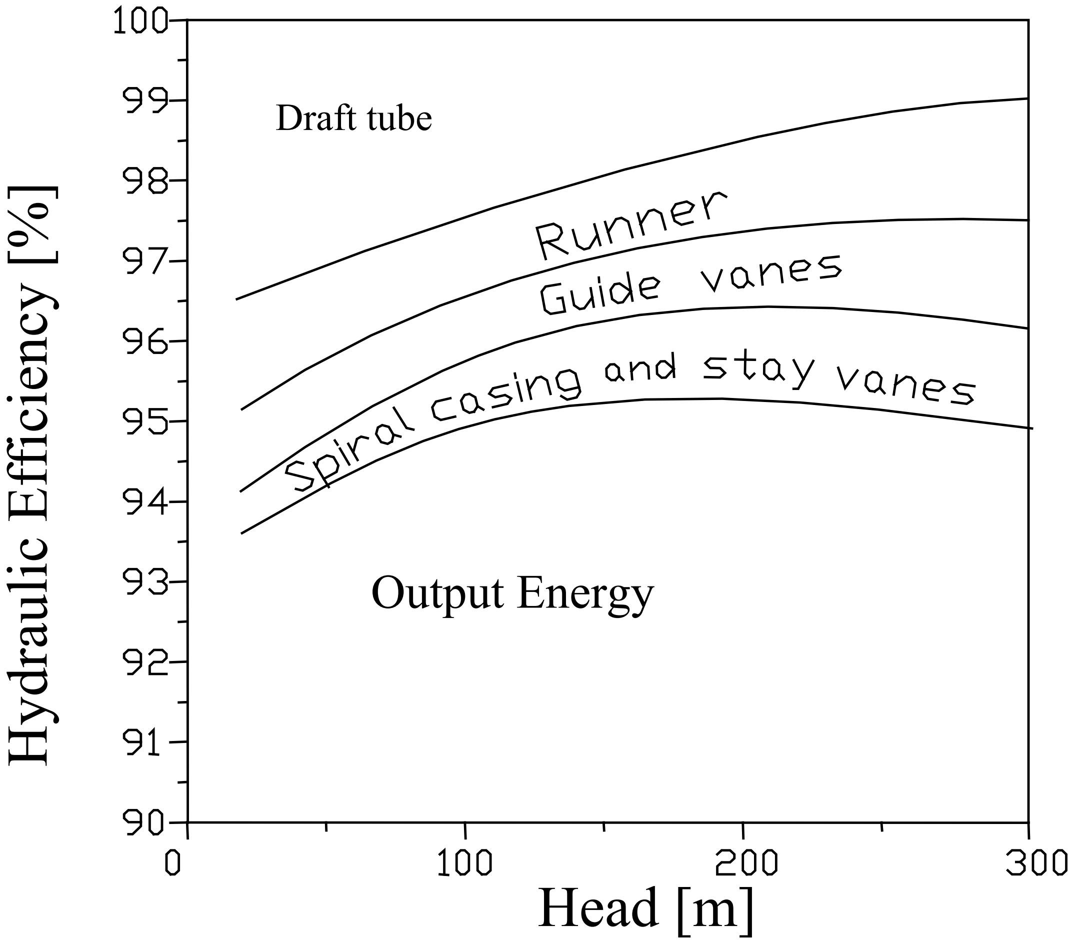

Outlet draft tube
Outlet runner
Inlet runner
Outlet guide vane
Inlet guide vane
$\frac{c_{m3}^2}{2}$
$\frac{c_m^2}{2}$
$\frac{c_u^2}{2}$
$E = u_1c_{u1} - u_2c_{u2}$
$u_1c_{u1} - uc_u$
$E=gH$
$gh = \frac{p}{\rho}$
gh_3
gh_2
$gh=0(abs)$

Hydraulic efficiency

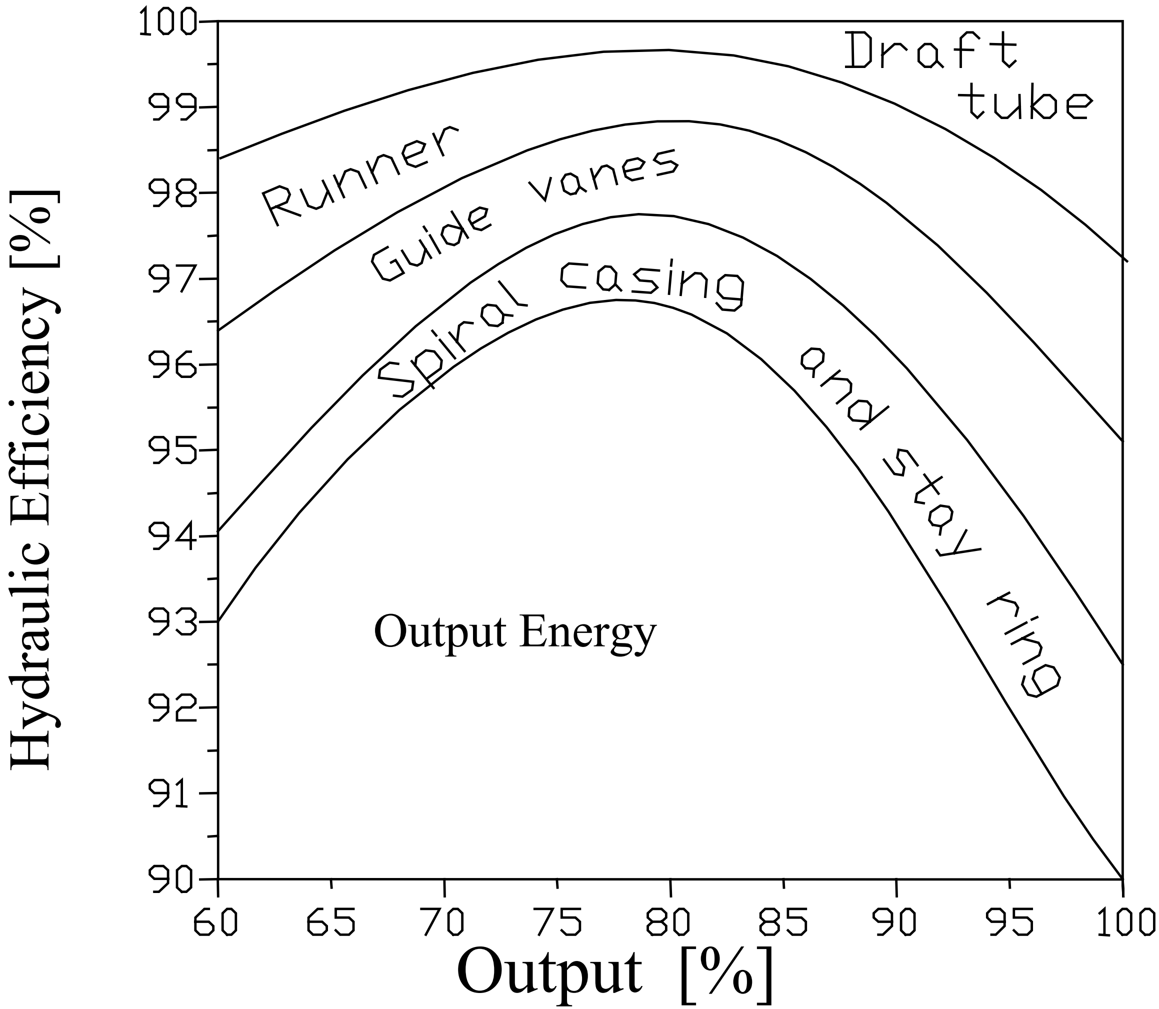
$$\eta_h = \frac{c_{1u}\cdot u_1 - c_{2u}\cdot u_2}{g\cdot H_n} = \frac{\left(g\cdot h_1 + \frac{c_1^2}{2} + z_1\right) - \left(g\cdot h_3 + \frac{c_3^2}{2} + z_3\right) - \text{losses}}{\left(g\cdot h_1 + \frac{c_1^2}{2} + z_1\right) - \left(g\cdot h_3 + \frac{c_3^2}{2} + z_3\right)}$$



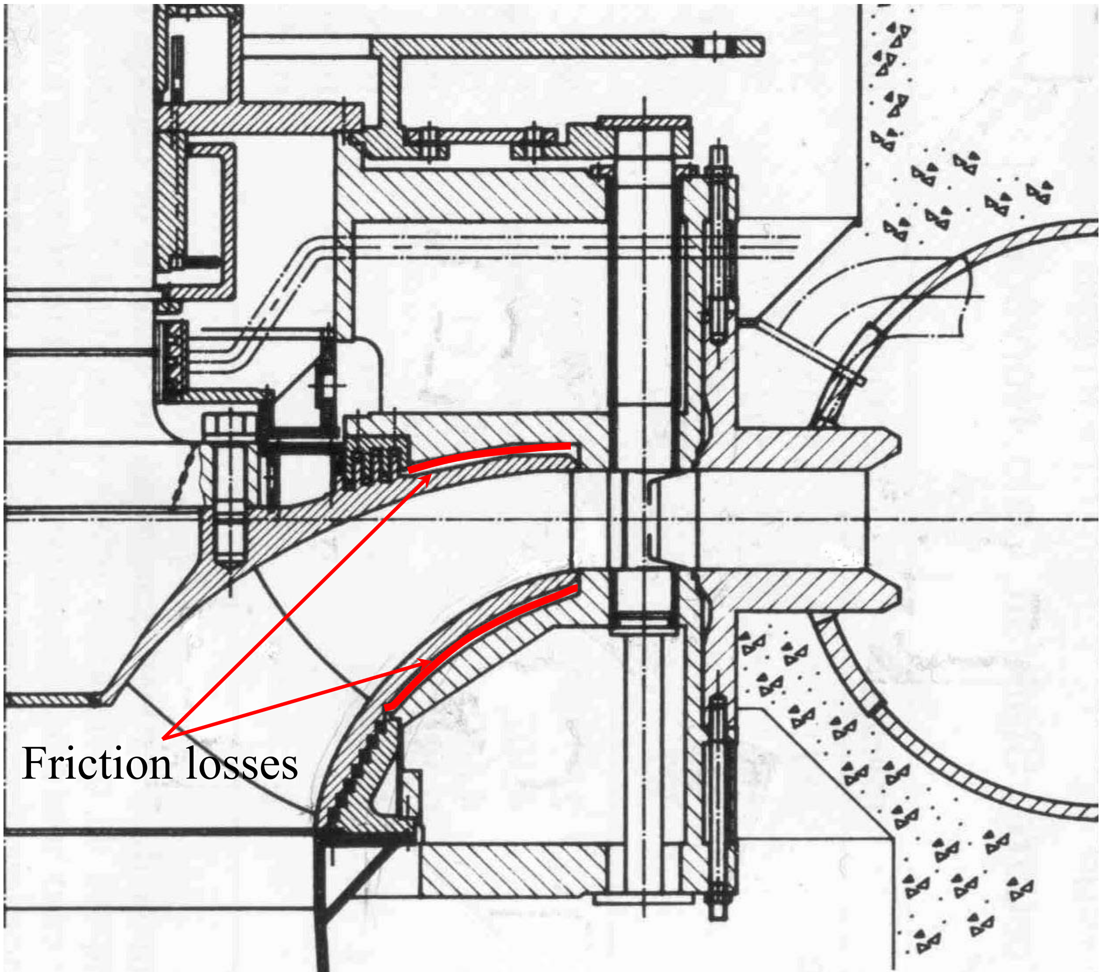
Losses in Francis Turbines



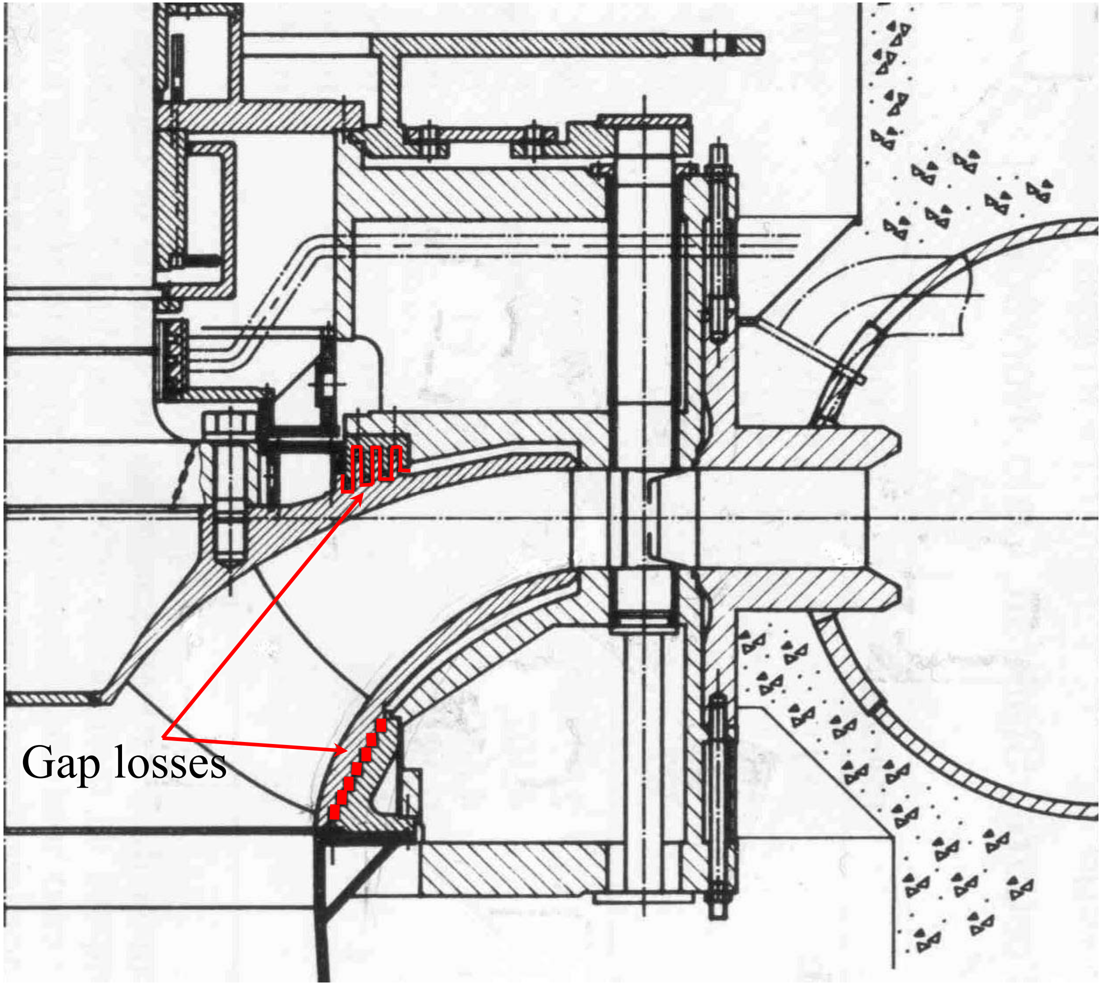
Losses in Francis Turbines

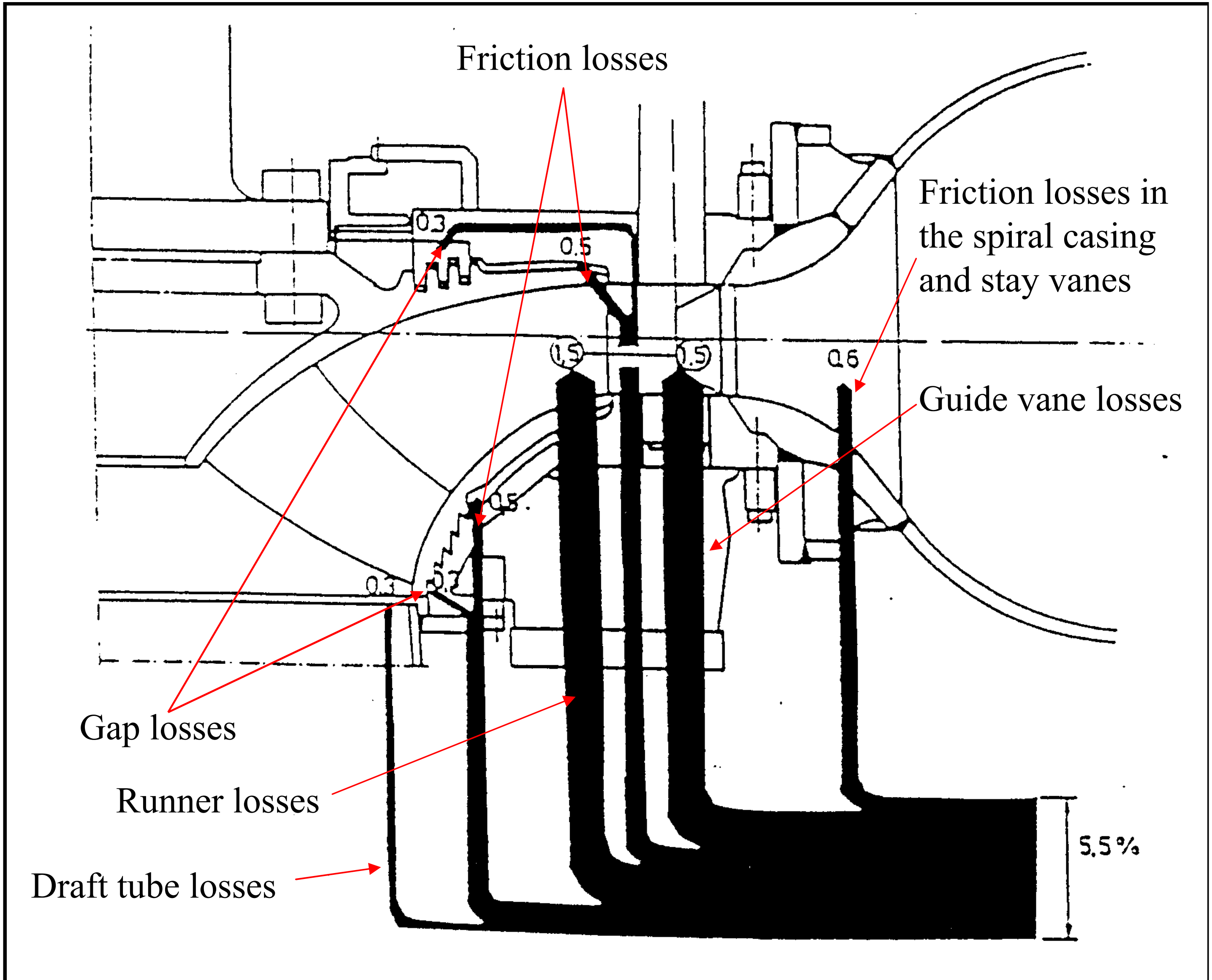


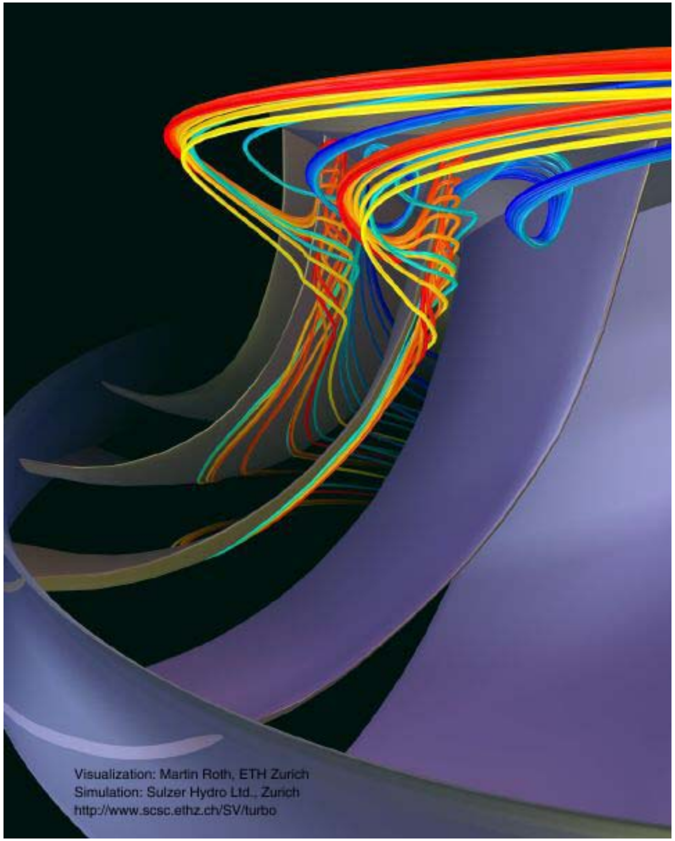
Friction losses between runner and covers

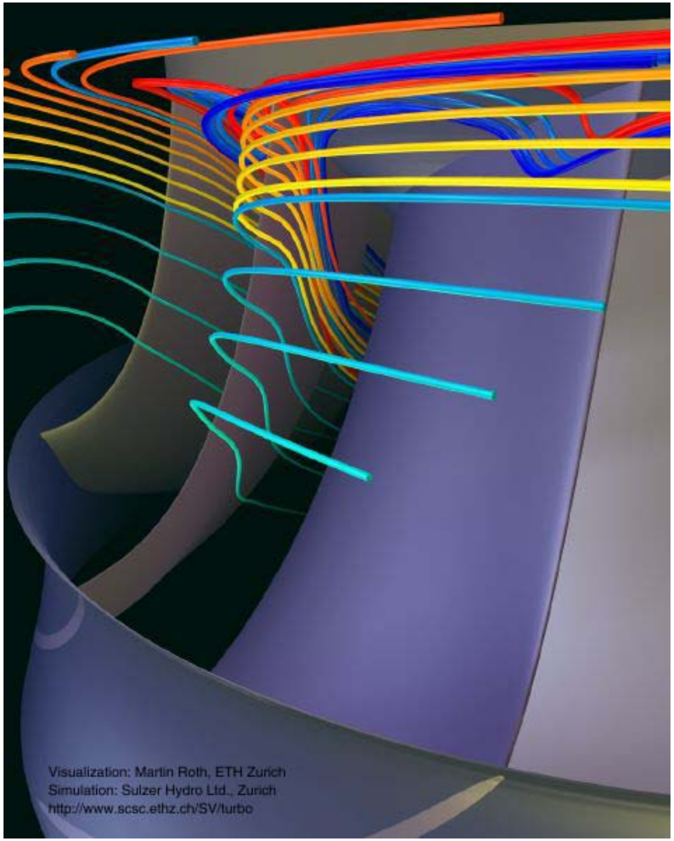


Gap losses




Friction losses
Friction losses in the spiral casing and stay vanes
Guide vane losses
Gap losses
Runner losses
Draft tube losses
0.3
0.5
1.5
1.5
0.6
0.5
0.3
5.5 %


Visualization: Martin Roth, ETH Zurich
Simulation: Sulzer Hydro Ltd., Zurich
http://www.scsc.ethz.ch/SV/turbo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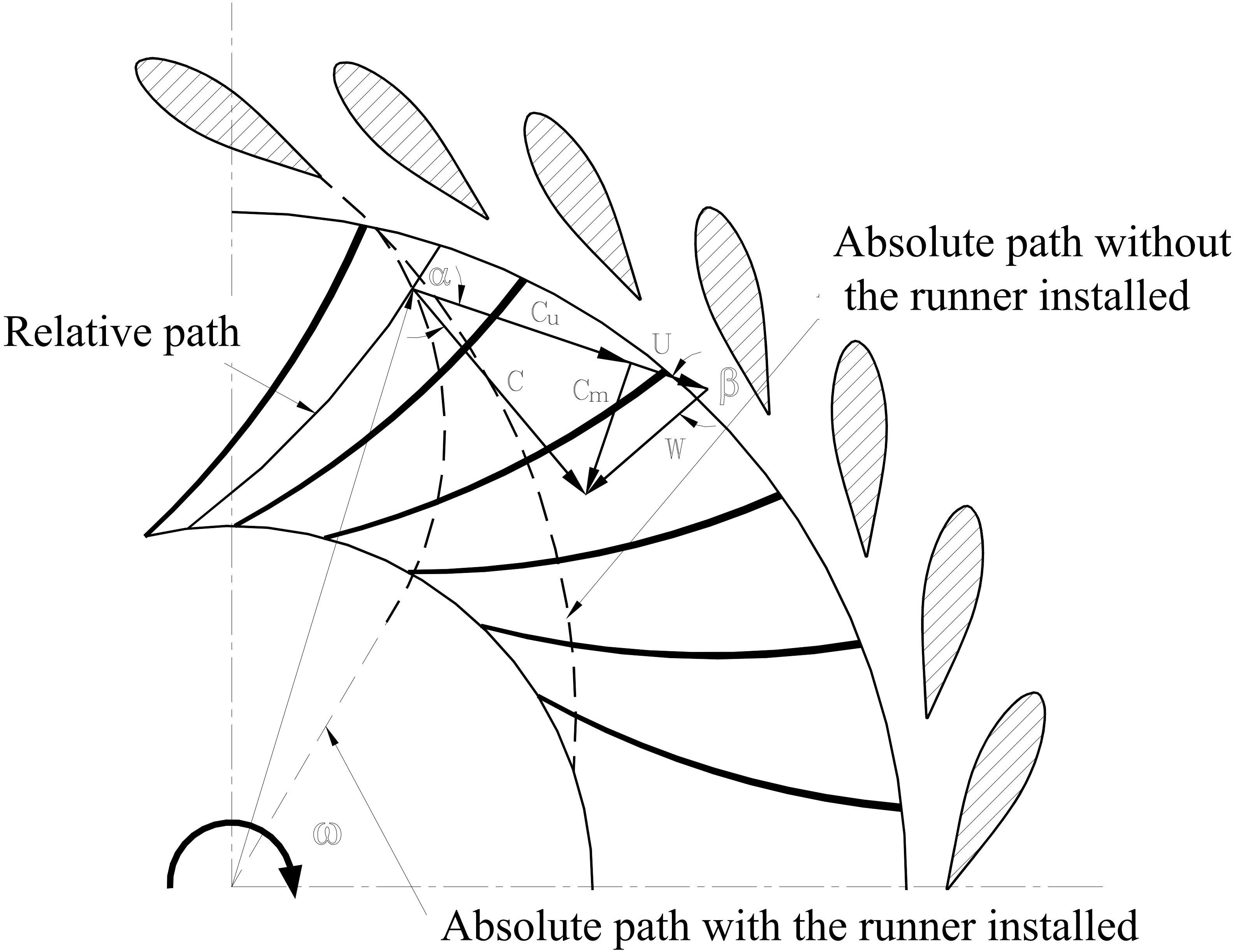
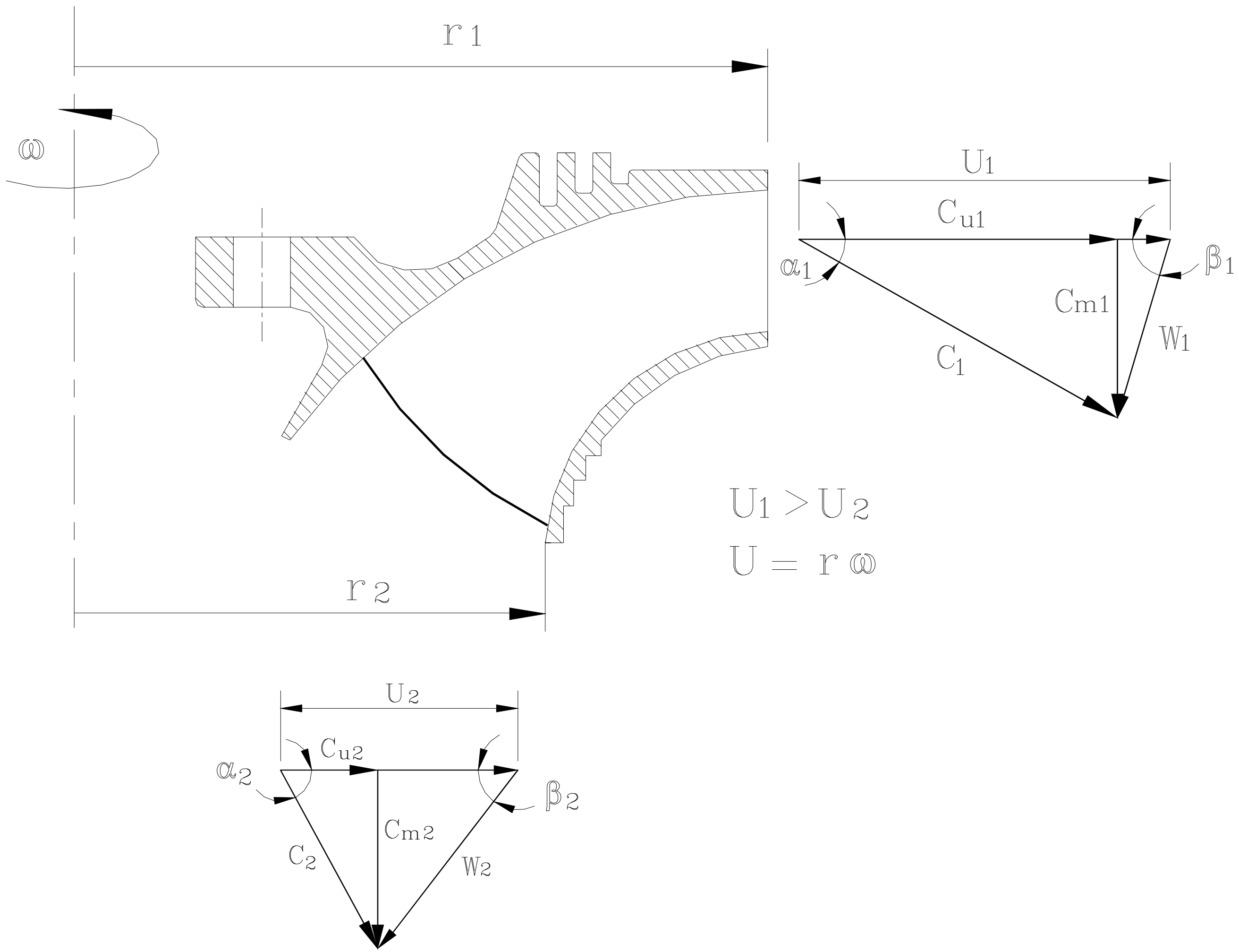

Absolute path without the runner installed
Relative path
α
Cu
U
C
Cm
β
W
ω
Absolute path with the runner installed

Velocity triangles



Net Positive Suction Head, NPSH

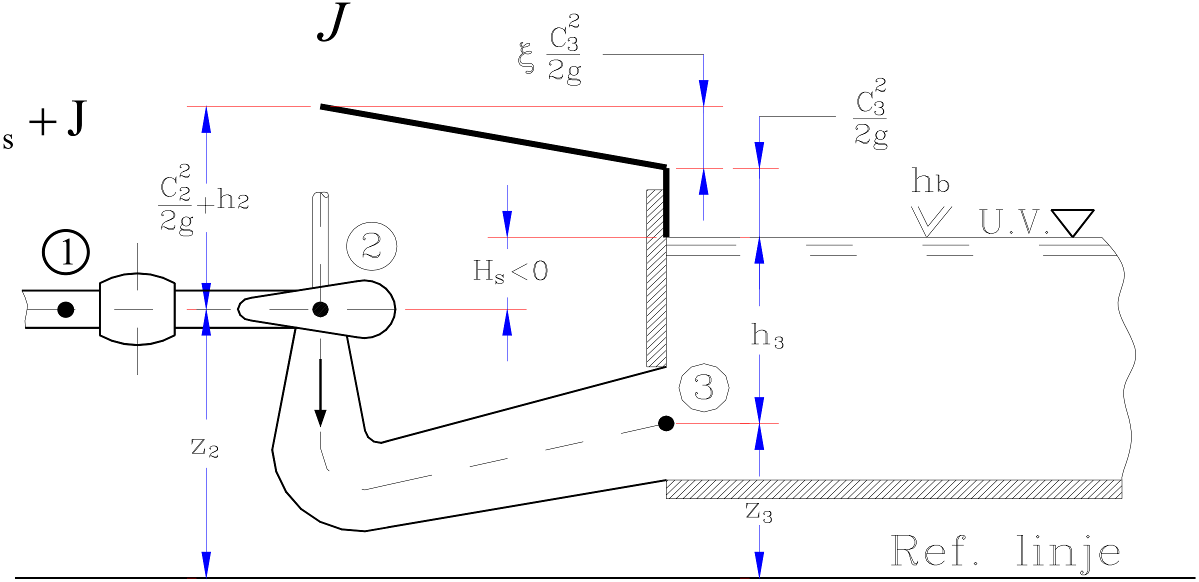
$$h_2 + \frac{c_2^2}{2\cdot g} + z_2 \quad = \quad h_b + h_3 + \frac{c_3^2}{2\cdot g} + z_3 + \zeta\cdot\frac{c_3^2}{2\cdot g}$$

$$h_2 = h_b + h_2^{'}$$

$$-H_s = h_3 + \frac{c_3^2}{2\cdot g} + z_3 - z_2$$

$$h_2 + \frac{c_2^2}{2\cdot g} + z_2 \quad = \quad h_b - H_s + z_2 + \underbrace{\zeta\cdot\frac{c_3^2}{2\cdot g}}_{J}$$

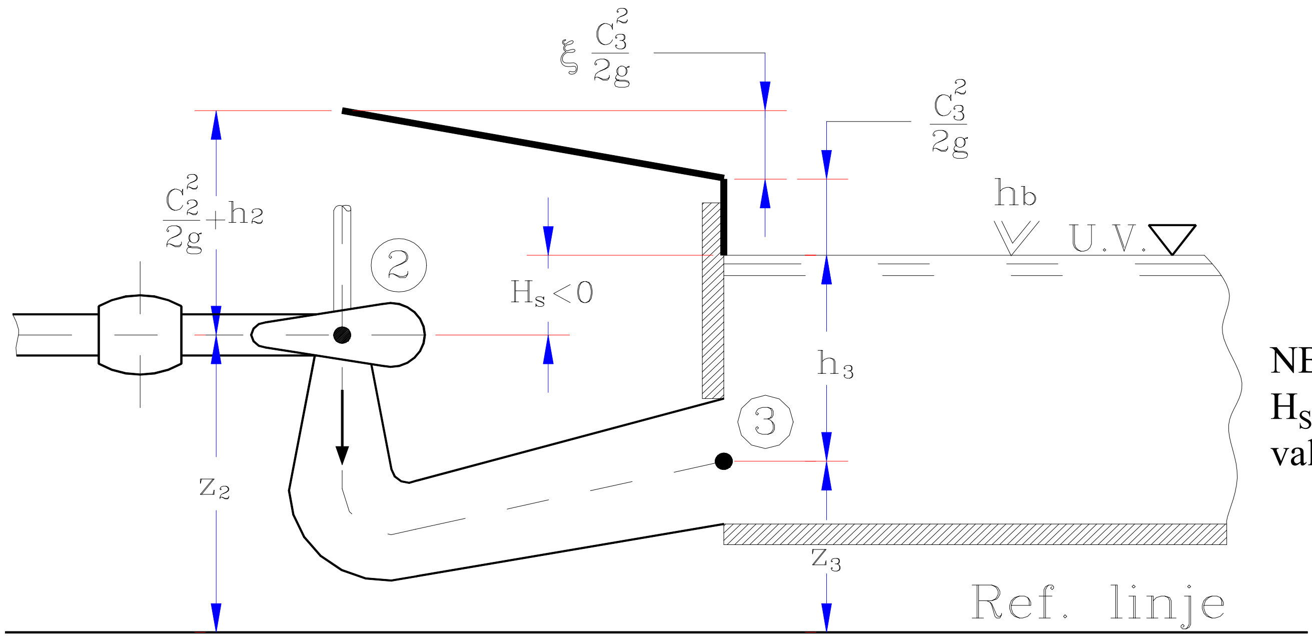
$$h_2 + \frac{c_2^2}{2\cdot g} \quad = \quad h_b - H_s + J$$



NPSH

$$h_2 = h_b - H_s - \underbrace{\left(\frac{c_2^2}{2 \cdot g} - J\right)}_{NPSH} > h_{va}$$

$$\mathrm{NPSH} = h_b - h_2 - H_s$$



NB:
H_S has a negative value in this figure.

NPSH required

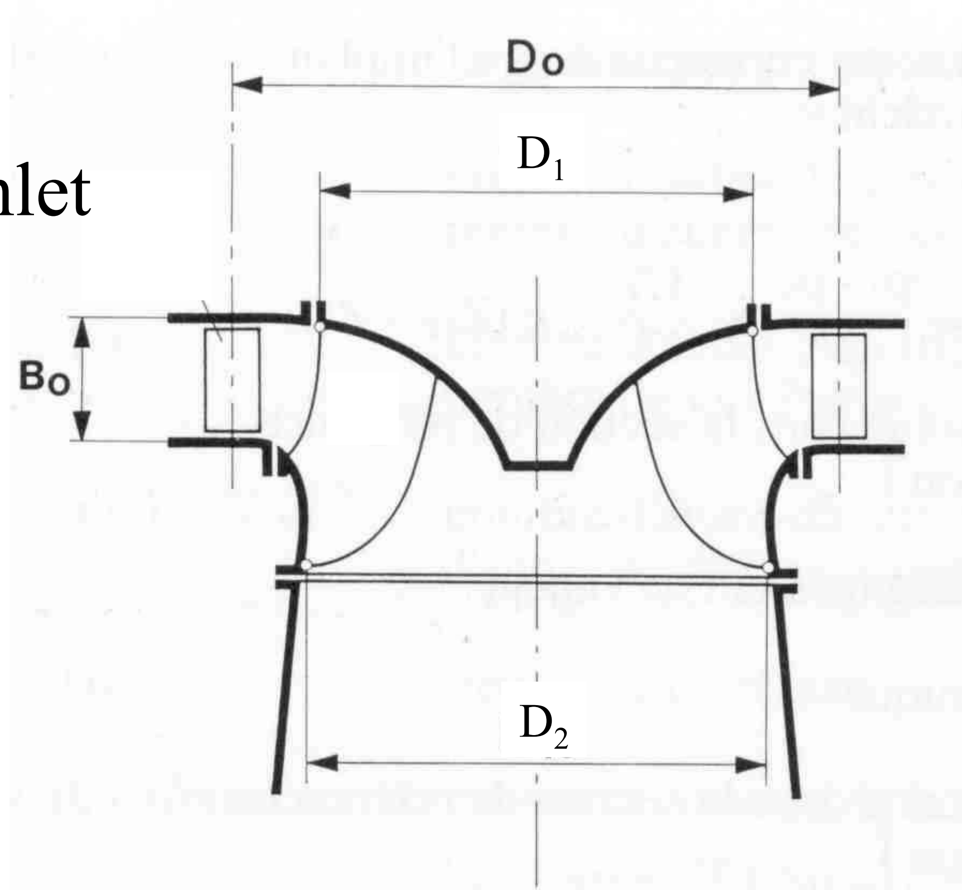
$$\mathrm{NPSH_R} \quad < \quad \mathrm{h_b - h_{va} - H_s} \quad = \quad \mathrm{NPSH_A}$$

$$NPSH_R = a \cdot \frac{c_{m2}^2}{2 \cdot g} + b \cdot \frac{u_2^2}{2 \cdot g}$$

	Turbines	Pumps
a	$1.05 < a < 1.15$	$1.6 < a < 2.0$
b	$0.05 < b < 0.15$	$0.2 < b < 0.25$

Main dimensions

- Dimensions of the outlet
- Speed
- Dimensions of the inlet



Dimensions of the outlet

We assume $c_{u2} = 0$ and choose β_2 and u_2 from $NPSH_R$:

$$NPSH_R = a \cdot \frac{c_{m2}^2}{2 \cdot g} + b \cdot \frac{u_2^2}{2 \cdot g} = \frac{a \cdot \left(u_2 \cdot \tan \beta_2\right)^2 + b \cdot u_2^2}{2 \cdot g}$$

$13^o < \beta_2 < 22^o$ (Lowest value for highest head)

$35 < u_2 < 43$ m/s (Highest value for highest head)

$1{,}05 < a < 1{,}15$

$0{,}05 < b < 0{,}15$

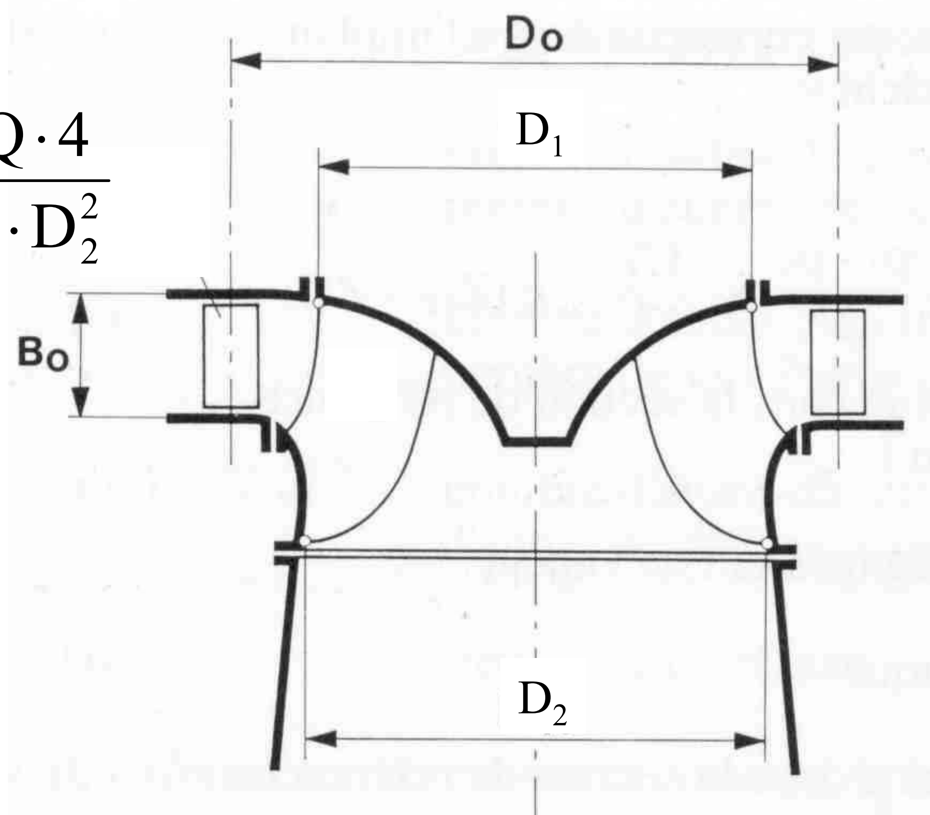
Diameter at the outlet

$$c_{m2} = u_2 \tan\beta_2$$

Connection between $c_{m2}$and choose D_2 :

$$Q = \pi \cdot \frac{D_2^2}{4} \cdot c_{m2} \quad \Rightarrow \quad c_{m2} = \frac{Q \cdot 4}{\pi \cdot D_2^2}$$

$$\Rightarrow \quad D_2 = \sqrt{\frac{4 \cdot Q}{\pi \cdot c_{m2}}}$$



Speed

Connection between n and choose u_2 :

$$u_2 = \frac{\pi \cdot D_2 \cdot n}{60} \quad \Rightarrow \quad \boxed{n = \frac{u_2 \cdot 60}{\pi \cdot D_2}}$$

Correction of the speed

The speed of the generator is given from the number of poles and the net frequency

$$n = \frac{3000}{z_p} \quad \text{for} \quad f = 50\text{Hz}$$

Example

Given data:

Flow rate $Q = 71.5\ m^3/s$

Head $H = 543\ m$

We choose:

$a = 1,10$

$b = 0,10$

$\beta_2 = 22^o$

$u_2 = 40\ m/s$

$$NPSH_R = \frac{1,1 \cdot \left(40 \cdot \tan 22^\circ\right)^2 + 0,1 \cdot 40^2}{2 \cdot g} = 22,8\ m$$

Find D_2 from:

$$D_2 = \sqrt{\frac{4 \cdot Q}{\pi \cdot c_{m2}}} = \sqrt{\frac{4 \cdot Q}{\pi \cdot u_2 \cdot \tan \beta_2}}$$

$$\mathrm{D}_2 = \sqrt{\frac{4 \cdot 71{,}5}{\pi \cdot 40 \cdot \tan 22^\circ}} = 2.37\mathrm{m}$$

Find speed from:

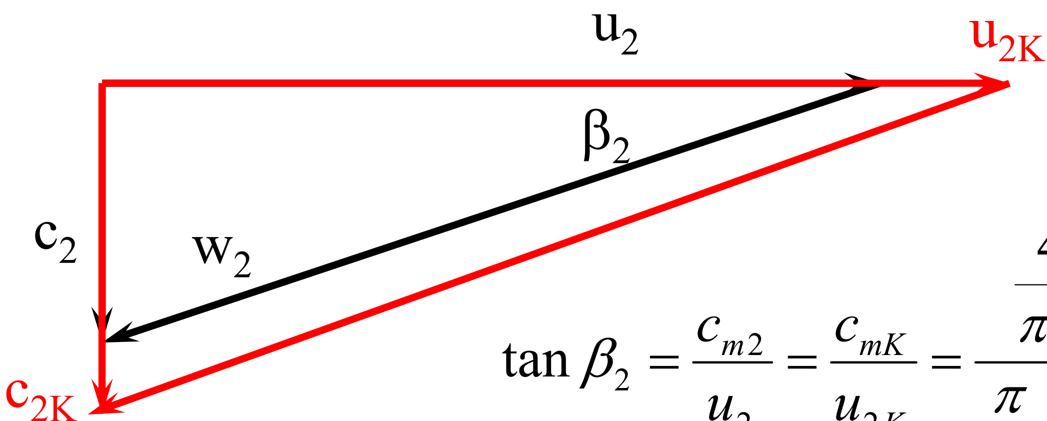
$$n = \frac{u_2 \cdot 60}{\pi \cdot D_2} = \frac{40 \cdot 60}{\pi \cdot 2.37} = 322\ rpm$$

Correct the speed with synchronic speed:

$$z_p = \frac{3000}{n} = 9.3$$

$$\text{choose } z_p = 9 \quad \Rightarrow \quad n_K = \frac{3000}{9} = \boxed{333 \text{ rpm}}$$

We keep the velocity triangle at the outlet:



$$\tan\beta_2 = \frac{c_{m2}}{u_2} = \frac{c_{mK}}{u_{2K}} = \frac{\dfrac{4\cdot Q}{\pi\cdot D_2^2}}{\dfrac{\pi}{60}\cdot n\cdot D_2} = \frac{\dfrac{4\cdot Q}{\pi\cdot D_{2\,K}^2}}{\dfrac{\pi}{60}\cdot n_K\cdot D_{2K}}$$

$$\Downarrow$$

$$n_K\cdot D_{2K}^3 = n\cdot D_2^3$$

$$\Downarrow$$

$$D_{2K} = \sqrt[3]{\frac{n\cdot D_2^3}{n_K}} = 2.373\cdot\sqrt[3]{\frac{322}{333}} = \underline{\underline{2.35m}}$$

Dimensions of the inlet

$$\eta_h = \frac{u_1 \cdot c_{u1} - u_2 \cdot c_{u2}}{g \cdot H} = 2 \cdot \left(\underline{u}_1 \cdot \underline{c}_{u1} - \underline{u}_2 \cdot \underline{c}_{u2} \right)$$

At best efficiency point, $\underline{c}_{u2} = 0$

$$\eta_h \approx 0{,}96 = \frac{u_1 \cdot c_{u1}}{g \cdot H} = 2 \cdot \underline{u}_1 \cdot \underline{c}_{u1}$$

$$\underline{c}_{u1} = \frac{\eta_h}{2 \cdot \underline{u}_1} = \frac{0{,}96}{2 \cdot \underline{u}_1}$$

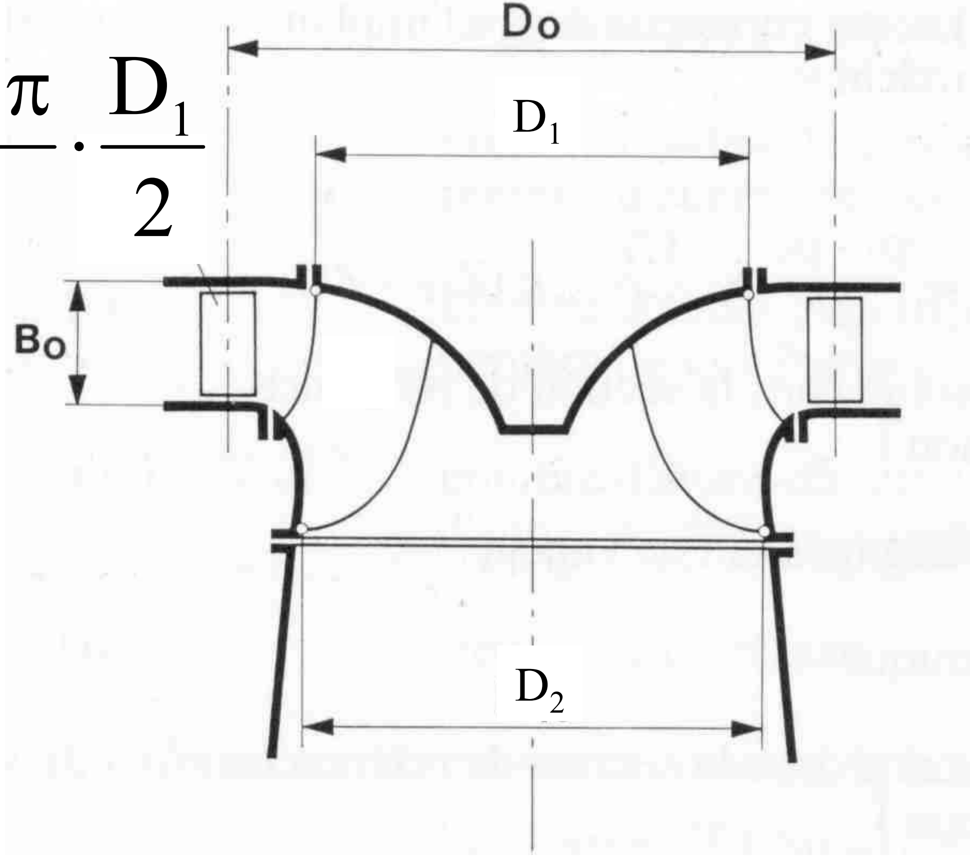
Diameter at the inlet

We choose: $0{,}7 < \underline{u}_1 < 0{,}75$

$$u_1 = \omega \cdot \frac{D_1}{2} = \frac{n \cdot 2 \cdot \pi}{60} \cdot \frac{D_1}{2}$$

$\Downarrow$

$$D_1 = \frac{u_1 \cdot 60}{n \cdot \pi}$$



Height of the inlet

Continuity gives:

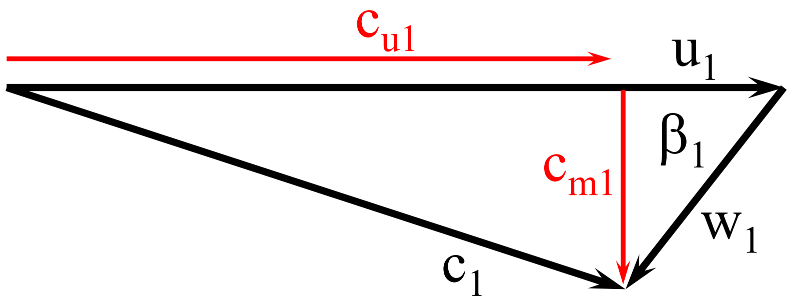
$$c_{m1} \cdot A_1 = c_{m2} \cdot A_2$$

We choose: $c_{m2} = 1{,}1 \cdot c_{m1}$

$$B_1 \cdot D_1 \cdot \pi = \frac{1.1 \cdot \pi \cdot D_2^2}{4}$$

$$B_1 = B_0$$

Inlet angle



$$\tan \beta_1 = \frac{c_{m1}}{u_1 - c_{u1}}$$

Example continues

Given data:

Flow rate	$Q = 71.5\ m^3/s$
Head	$H = 543\ m$

We choose:

$\eta_h = 0{,}96$

$\underline{u}_1 = 0{,}728$

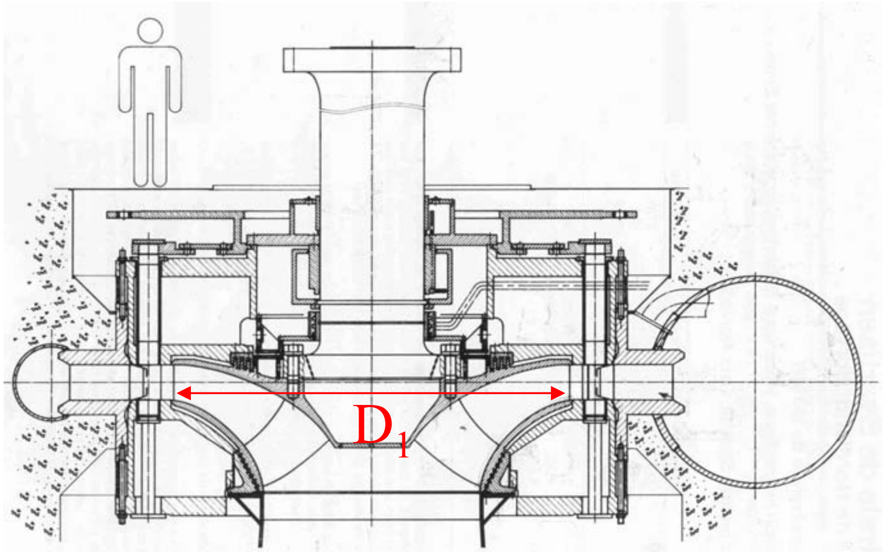
$\underline{c}_{u2} = 0$

$$\eta_h = 2 \cdot \underline{u}_1 \cdot \underline{c}_{u1} \quad \Rightarrow \quad \underline{c}_{u1} = \frac{\eta_h}{2 \cdot \underline{u}_1} = \frac{0.96}{2 \cdot 0{,}728} = 0{,}66$$

Diameter at the inlet

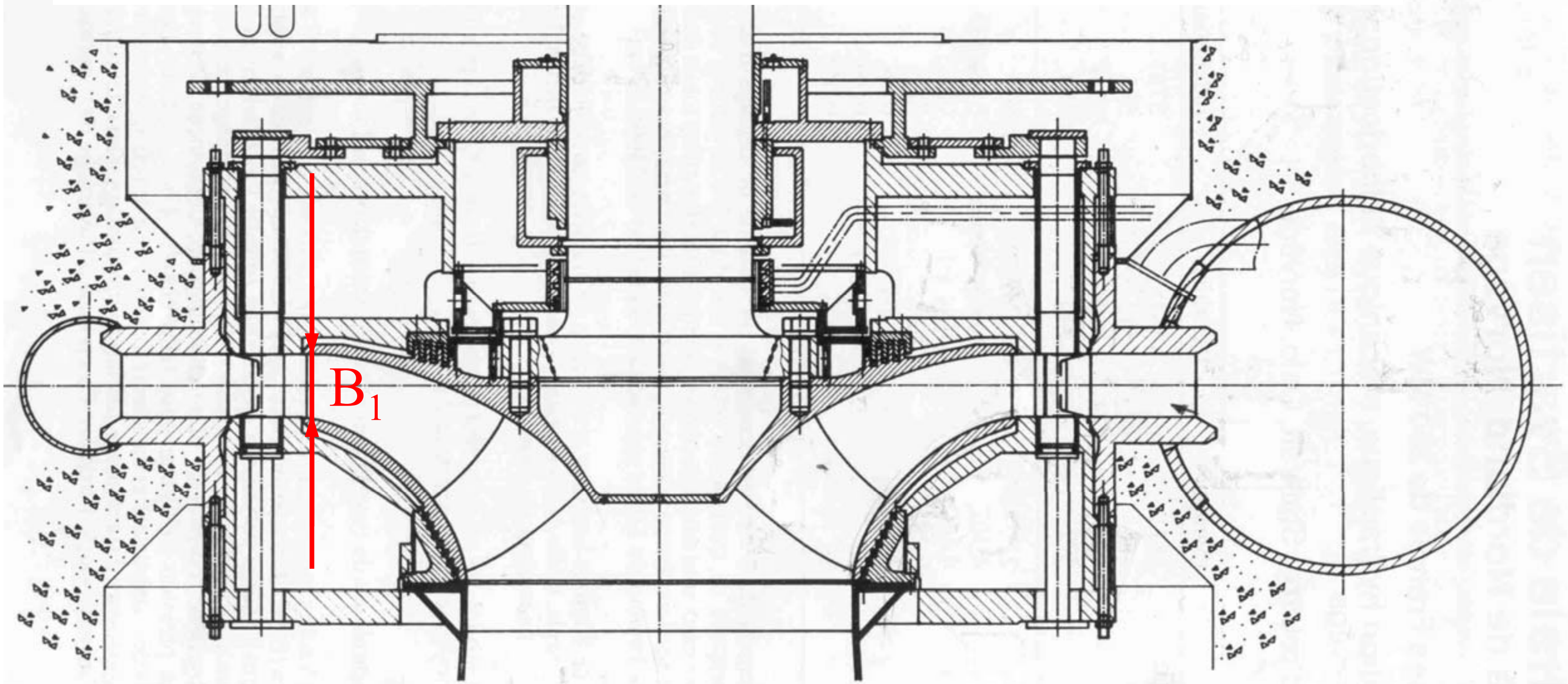
$$u_1 = \underline{u}_1 \cdot \sqrt{2 \cdot g \cdot h} = 0{,}728 \cdot \sqrt{2 \cdot 9{,}81 \cdot 543} = 75{,}15\, m/s$$

$$D_1 = \frac{u_1 \cdot 60}{n \cdot \pi} = \frac{75{,}15 \cdot 60}{333 \cdot \pi} = 4{,}31\, m$$

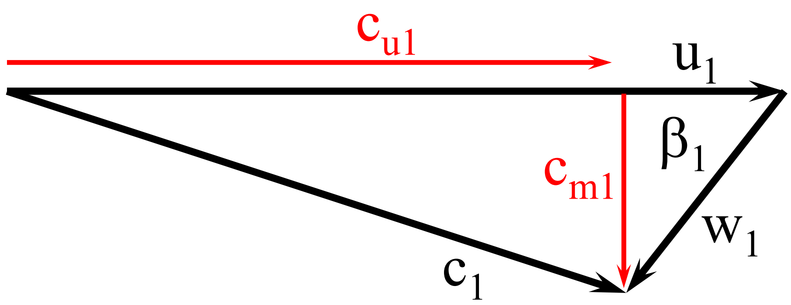


Height of the inlet

$$B_1 = \frac{1{,}1 \cdot \pi \cdot D_2^2}{4 \cdot D_1 \cdot \pi} = \frac{1{,}1 \cdot 2.35^2}{4 \cdot 4{,}31} = 0{,}35\ m$$



Inlet angle



$$c_{m1} = \frac{c_{m2}}{1{,}1} = \frac{\sin\beta_2 \cdot u_2}{1{,}1} = \frac{\sin 22^\circ \cdot 40{,}9\,{}^{m}\!/\!{}_{s}}{1{,}1} = 13{,}9\,{}^{m}\!/\!{}_{s}$$

$$\underline{c}_{m1} = \frac{c_{m1}}{\sqrt{2\cdot g\cdot h}} = \frac{13{,}9}{\sqrt{2\cdot 9{,}81\cdot 543}} = 0{,}135$$

$$\beta_1 = \arctan\left(\frac{\underline{c}_{m1}}{\underline{u}_1 - \underline{c}_{u1}}\right) = \arctan\left(\frac{0{,}135}{0{,}728 - 0{,}659}\right) = 62.9^\circ$$

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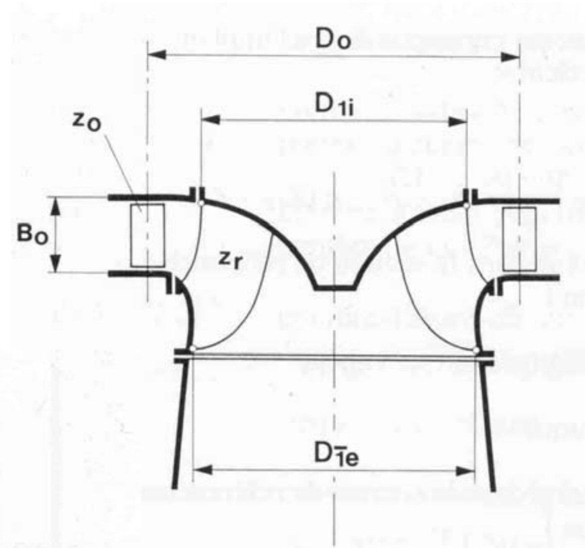

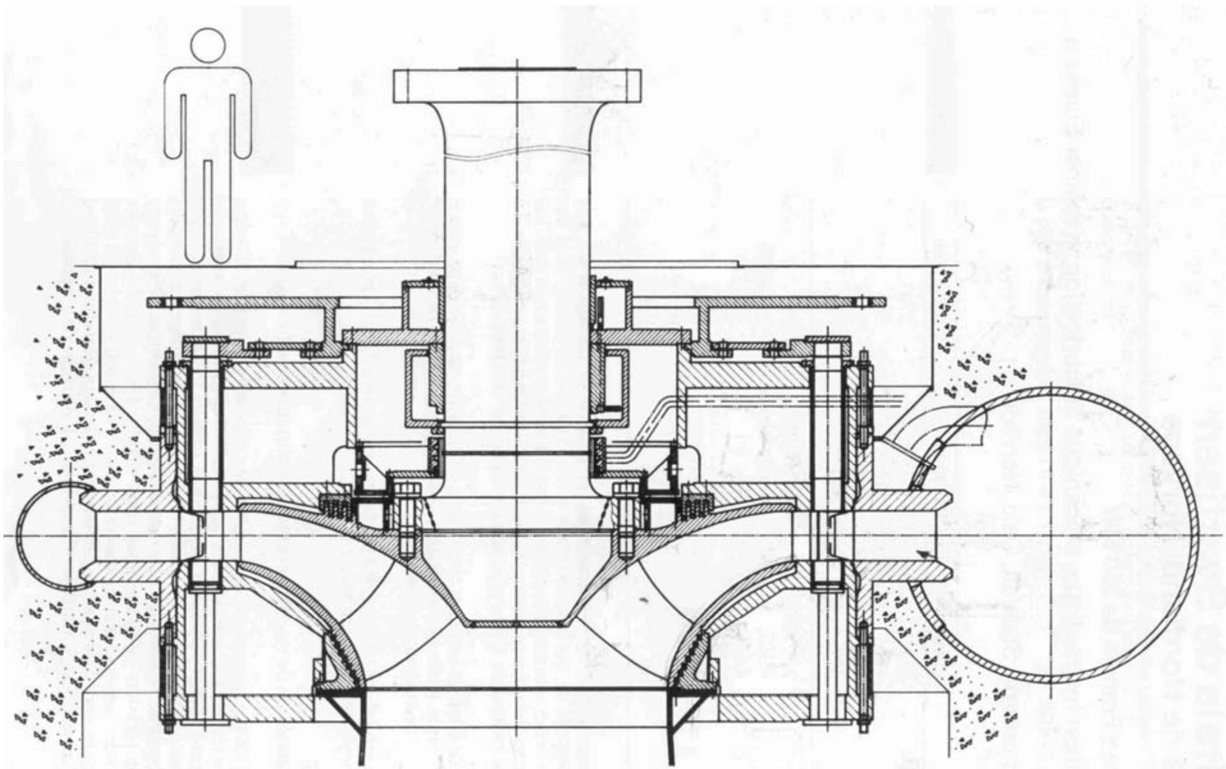

P = 350 MW
H = 543 m
Q* = 71,5 m^3/S
D_0 = 4,86 m
D_1 = 4,31m
D_2 = 2,35 m
B_0 = 0,28 m
n = 333 rpm