# Asymmetric sudden enlargement energy dissipater in Jökulsá Tunnel of the Kárahnjúkar HEP in Iceland

**Porbergur S. Leifsson** Verkís hf. Ármúli 4. IS-108 Reykjavik Iceland Arnoldo Baumann Pöyry Energy Ltd. Hardturmstrasse. 161. CH-8037 Zurich Switzerland

# Introduction

The 690 MW capacity, 600 m gross head Kárahnjúkar Hydroelectric Scheme, constructed and owned by Landsvirkjun, was commissioned and put into service in November 2007.

The Project is characterized by the uncommon dimensions of its underground power waterways. They consist of a nearly 40 km long Headrace Tunnel to supply water from the large Hálslón Reservoir and a second tunnel, the 13,3 km long Jökulsá Tunnel acts as a diversion tunnel from the small Ufsarlón Pond to the Headrace Tunnel. The connection point of the tunnels is close to the midpoint of the Headrace Tunnel at the Jökulsá Valve Chamber, where a butterfly valve is installed so the Jökulsá Tunnel can be closed off from the Headrace Tunnel. Due to large hydraulic head variations in the Hálslón Reservoir and through the Headrace Tunnel in contrast to the almost constant head at the secondary intake at Ufsarlón Pond the Jökulsá Tunnel can experience both pressurized flow and free surface flow depending on the elevation of Hálslón Reservoir and the diversion and plant discharge. This is a rather uncommon feature of a power waterway.

When open, the Jökulsá Tunnel acts as a very efficient extra surge tunnel to the Headrace system. A reverse flow can thus be obtained in the tunnel during load variations and always when the station trips. Then water flows from the Headrace Tunnel back into the Jökulsá Tunnel and in some cases all the way up to the Ufsarlón Pond. In some cases this discharge can become extensive and higher than can be tolerated by the butterfly valve at the connection between the two tunnels. This large reverse flow had therefore to be reduced while keeping good and efficient flow conditions during normal flow. The selected solution, that was rather unusual, consisted of introducing an asymmetric energy dissipater in the Jökulsá Tunnel at the beginning of the steel lined section of the conduit just upstream of the valve in the Jökulsá Valve Chamber. This energy dissipater would cause large local headlosses in reverse flow conditions, and thus reduce the maximum reverse flow, but much smaller headlosses in normal flow conditions.

The paper describes the problem and the reasons for the large reverse flow and the effect of increased local headloss. It discusses the possible alternative solutions and the reason for the selected one. The static and transient calculations for the selected solutions are shown, explained and discussed as well as the setup, execution and results of the Hydraulic Model Tests. The construction, installation and experience made with the dissipater is also discussed.

## 1. Project layout

## 1.1 General

The Kárahnjúkar Hydroelectric Project is located in the eastern part of Iceland to the north of the Vatnajökull glacier (Europe's largest glacier), some 40-100 km southwest of Egilsstaðir, the nearest town. The Project includes a total of four reservoirs and ponds in the Jökulsá á Dal and the Jökulsá í Fljótsdal catchment areas. The Owner is Landsvirkjun, the National Power Company of Iceland. The main storage reservoir and the only reservoir in the Jökulsá á Dal catchment area is Hálslón Reservoir retained by the almost 200 m high Kárahnjúkar Dam and by two smaller saddle dams in adjacent valleys. The operational level is 550 to 625 m a.s.l, although in most years the reservoir will most likely only go down to between 590 and 570 m a.s.l.

Water from the Hálslón Reservoir is conveyed from the Hálslón Intake through a 40 km long mainly unlined Headrace Tunnel to a valve chamber and from there, through two vertical steel lined, 400 m high, Penstocks to an underground Powerhouse located in the Fljótsdalur valley, housing six Francis turbines. From the Powerhouse water is diverted through the 1,35 km long Tailrace Tunnel and the ensuing Tailrace Canal to the river Jökulsá í Fljótsdalur at a normal elevation of 26 m a.s.l. (see *Fig*ure 1).

A secondary diversion, the Ufsarveita Diversion, conveys water from the Ufsarlón Pond, retained by the Ufsarstífla Dam located on the river Jökulsá í Fljótsdal, through the Jökulsá Tunnel and into the Headrace Tunnel. Additionally several adjacent rivers will be diverted into Ufsarlón Pond using a series of tunnels and dams.

Main waterways			
Installed capacity (6 units, 115 MW each) 690			
Annual energy production	4,8	TWh	
Gross head	600	m	
Total headloss in waterways at rated discharge	78,7	m	
Rated discharge	144	m <sup>3</sup> /s	
Volume of Kárahnjúkar dam (max height 198 m)	$8,4*10^{6}$	m <sup>3</sup>	
Hálslón Reservoir live storage (57 km <sup>2</sup> )	$2085*10^{6}$	$m^3$	
Average flow to Hálslón	114	$m^3/s$	
Headrace Tunnel TBM diameter (L=35,4 km)	7,2-7,6	m	
Headrace Tunnel D&B diameter (L= 4,2 km)	7,2-8,0	m	
Height of Pressure Shaft $(2xD=3,4 m)$	418	m	
Length of Miðfell Surge Tunnel (D=4,5 and 5,0 m)	1,7	km	
Height of Hólsufs Surge Shaft (D= 5,0 m) 200		m	
Ufsarveita Diversion (Jökulsá Tunnel)			
Rated discharge	90	m³/s	
Average flow into Ufsarlón pond	32,4	m³/s	
Jökulsá Tunnel (TBM diameter, L=8,8 km) 7,		m	
Jökulsá Tunnel (D&B diameter, L=4,5 km) 6,0		m	
Slope of free surface flow in Jökulsá Tunnel 1,23 & 1,30		%	
Jökulsá Valve Chamber Valve diameter	3,4	m	
Orifice minimum diameter 2,1		m	

Some of the key figures of the project are as listed in Table 1

Table 1 Some of Kárahnjúkar project key figures

With a total gross head of about 600 m, the installed Powerhouse capacity is rated at 690 MW with power generation capability of about 4800 GWh/year. The construction of the project started in the spring of 2003. Most of the generated power will be used by the Alcoa aluminium smelter located in Reyðarfjörður. The design of the project was performed by the Kárahnjúkar Engineering Joint Venture (KEJV) consisting of VST Ltd and Rafteikning (now Verkis), Pöyry (formerly Electrowatt), MWH and Almenna Verkfræðistofan.

#### 1.2 Headrace Tunnel

*Figure 1* shows a schematic longitudinal section through the waterways. The 40 km long, mainly unlined, Headrace Tunnel was mainly excavated by Tunnel Boring Machine techniques (TBM) with diameters of 7,2 m and 7,6 m downstream of the connection point of Jökulsá Tunnel. The water is conveyed through the Headrace Tunnel to the Pressure Shaft Valve Chamber.

The Headrace Tunnel was excavated by three TBM machines always working in ascending directions from the three adits (Adit 1, 2 and 3, See *Figure 1*) resulting in high points along the tunnel route that had to be de-aerated by air-vents to the ground surface being higher than the highest hydraulic grade line.

#### 1.3 Surge facilities

The extensive waterways create enormous mass surges as a response to rapid discharge variations at the power station. The Miðfell Surge Tunnel, about 1,7 km long, sloping 12 to 16 % from horizontal was constructed at the downstream end of the Headrace Tunnel just upstream of the Pressure Shaft Valve Chamber. The surge tunnel had to be long and gently sloping to reach high enough ground surface elevation, as due to the local topographical conditions a conventional vertical surge shaft would have required construction of a high concrete surge tower, neither acceptable for economical nor environmental reasons. The large horizontal area of the water surface in the sloping tunnel provided an efficient volume for mass surge damping. The main drawback of this long sloping surge tunnel is the delayed reflection of waterhammer waves from the distant water surface and therefore not protecting sufficiently the upstream part of the headrace from the undesirable propagation of water hammer pressures. This lead to the decision to add the 5 m diameter vertical Hólsufs Surge Shaft some 2,7 km upstream of the surge tunnel where the ground surface elevation is the highest close to the main surge tunnel. At this location only a limited overflow of water occurs in special cases when the station has to come to instantaneous complete stop (station trip). The shaft is equipped with a throttle and provides a shielding effect from waterhammer waves in

the Headrace Tunnel upstream. It is one of the special features of the project that was discussed and explained in Ref .[3] at the HYDRO2006 conference.



*Figure 1* Schematic longitudinal section through the waterways, and a plan on the inserted picture (vertical scale extended 20 times)

#### 1.4 Jökulsá Tunnel

A second tunnel, the 13,3 km long Jökulsá Tunnel is a diversion tunnel from the small Ufsarlón Pond to the Headrace Tunnel. A longitudinal section is shown on *Figure* 2. The Ufsarlón Pond captures water from a smaller mainly unregulated glacier river Jökulsá in Fljótsdalur. The spillway crest level of Ufsarlón Pond is the same as that of Hálslón Reservoir or 625 m a.s.l. but the minimum operating level is on the other hand only 3 m lower or 622 m a.s.l. The water enters through the gate controlled Ufsarlón Intake and the first 3 km are designed as an inverted siphon to cross a lateral valley. A hydraulic control is set at elevation 608 m a.s.l at the downstream end of the siphon. Downstream of the hydraulic control the tunnel slopes gently towards the connection point to the Headrace Tunnel at elevation 460 m a.s.l. The first 1,5 km downstream of the siphon are, as the siphon, excavated by drill and blast technique (D&B) and are D shaped with a width and a height of 6,0 m. The remaining 8,8 km are excavated by a TBM machine with a 7,2 m wide diameter. The slope of the D&B section downstream of the hydraulic control is generally about 0,5% and the slope of the TBM section is 1,21% and 1,30% for the upper most part and 2,85% for the tunnel invert lower than 520 m a.s.l at elevations where free surface flow is never expected in the tunnel.



Figure 2 Longitudinal profile of the Jökulsá Tunnel (vertical scale enlarged 10 times)

The Jökulsá Tunnel is closed off from the Headrace Tunnel by a butterfly valve at the Jökulsá Valve Chamber. This made it possible to take the powerstation into operation almost a year before the Jökulsá Tunnel was finished in October 2008. For the convenience of the contractor he used the same TBM machine (D=7,2 m) to excavate the

Jökulsá Tunnel as he used for the Headrace Tunnel making the TBM part of the tunnel much wider than the optimum diameter of about 5,5 m that would have been required for an optimized hydraulic design.

Due to mass surges in the Jökulsá Tunnel a short (ca. 100 m) surge tunnel ending in an open surge canal was installed at the hydraulic control point at 608 m a.s.l. This Jökulsá Surge Tunnel was also useful as an airvent and as a construction and inspection adit.

Due to the large variation in hydraulic head at the connection point to the Headrace Tunnel, the Jökulsá Tunnel can experience both free surface flow and fully pressurized flow as explained further in chapter 2. The gentle slope of the tunnel is used to dissipate the excess head by friction in the free surface flow while keeping the flow velocity and air entrainment within acceptable limits.

#### 1.5 Jökulsá Valve Chamber

The Jökulsá Tunnel is separated from the Headrace Tunnel by a butterfly valve located at the Jökulsá Valve Chamber. The Valve Chamber is located at the connection point of Jökulsá Tunnel, Headrace Tunnel, Adit 2 and construction branches as can be seen on *Figure 3*. The connection point is close to the midpoint of the Headrace Tunnel or at a 23,4 km distance from the Power Intake and 16,1 km from the Pressure Shaft Valve Chamber and the Surge Tunnel downstream.



*Figure 3 Jökulsá Valve Chamber (JVC) located at the connection point of Jökulsá Tunnel, Headrace Tunnel, Adit 2 and construction branches.* 

This closure valve was necessary as the Jökulsá Tunnel was not finished when the Headrace Tunnel was taken into operation. The closure of the Jökulsá Tunnel is also required to empty the Jökulsá Tunnel for inspection while the station is running. This is especially important to check the tunnel for possible damages due to the high water velocity and energy dissipation in the Jökulsá Tunnel.

The Jökulsá Valve Chamber can be accessed through one of the constructions adits, Adit 2. A plan and a section through the Butterfly Valve and adjacent steel lining and the Energy Dissipater are shown on *Figure 4*.

Downstream of the Jökulsá Valve Chamber the steel lined section enlarges gradually from 3,4 m to 5 m diameter and after that suddenly to a 5 m long 6 m diameter circular concrete lined tunnel until finally the section changes to the final tunnel section of 7,2 m horseshoe shape.



Figure 4 Plan and section through the Jökulsá Valve Chamber and adjacent steel lined concrete plugs including the Energy Dissipater.

The butterfly valve is able to shut off flow in either direction. The two DN250 by-pass lines are used to equalise pressure on both sides of the valve before opening. DN250 air release and vacuum valves are furnished on each side of the butterfly valve. "Clamp on" acoustic flow meters are installed on the pipe just upstream of the valve.

## 1.6 Asymmetric sudden enlargement energy dissipater

The Energy Dissipater consists of (in flow direction from downstream to upstream during normal flow), a 8,2 m long gradually contracting section from the 3,4 m diameter valve pipe to the 1,5 m long throat section with a diameter of 2,1 m ending in a rounded spherically shaped bellmouth or trumpet like section with 0,5 meter radius and discharges into the ca. 17 m long concrete lined circular section with 6,0 m diameter (the sudden enlargement). The details of the steel lining in the bellmouth section are shown on *Figure 5*. Due to difficulty in manufacturing the spherically shaped bellmouth, it was made from 24 segments of flat plates bended and welded together. This was not considered to influence the hydraulic performance of the section.

The throat diameter is designed to give the headloss required for reverse flow. The gradual contraction is actually designed as efficient optimal diffuser for normal flow. The bellmouth inlet radius is also designed for providing minimum headlosses for normal flow without reducing the energy dissipation for reverse flow.

The ca. 15 m long section from upstream of the throat to the left Jökulsá construction branches is fully concrete lined with circular section of 6 m diameter. The concrete lining extends further 2 m into the construction branches at the centreline as can be seen in *Figure 3*. The construction branches are left open and the tunnel upstream is only protected by 200 mm shotcrete with wire mesh at the corners and a few meters in each direction.

The dissipated energy in the dissipater can be up to 30 MW. This high energy dissipation justifies the choice of an internal steel lining and the provision of a vibrating resistant reinforced concrete structure anchored into the rock formation.



Figure 5 The steel lining in the bellmouth section from the 2,1 m diameter throat to the 6,0 m sudden enlargement.

## 2. Static and dynamic hydraulic of the headrace system

The headlosses in the Headrace Tunnel amount to 46 m upstream of the connection point to the Jökulsá Tunnel and to 23 m downstream for the design discharge of 144 m<sup>3</sup>/s and no flow in the Jökulsá Tunnel. The hydraulic head at the connection point is always governed by the waterlevel in the Hálslón Reservoir and can vary according to following extreme limits for normal operation:

Theoretical minimum level Practical minimum level Maximum level 504 m a.s.l (Hálslón level 550 m a.s.l and no flow in Jökulsá Tunnel)
524 m a.s.l (Hálslón level 570 m a.s.l and no flow in Jökulsá Tunnel)
620 m a.s.l (Hálslón level 625 m a.s.l and full flow in Jökulsá Tunnel)

The headlosses in the Jökulsá Tunnel are estimated to 23 m if the tunnel is flowing at full capacity (90  $m^3/s$ ) in normal flow direction, thereof 12 m in the D&B section, 7 m in the TBM section and 5 m in the Energy Dissipater and Jökulsá Valve Chamber. The Jökulsá Tunnel can therefore both have fully pressurised flow and free surface flow depending on the head at the connection point. The free surface flow can exist all the way from the hydraulic control point at 608 m a.s.l down to 524 m a.s.l or for about 7 km of tunnel length for little flow in Jökulsá Tunnel. If Jökulsá Tunnel is running at maximum discharge of 90 m<sup>3</sup>/s, the practical minimum level of pressurized flow is around 575 m a.s.l (for Hálslón Reservoir level of 570 m a.s.l). If, on the other hand, the Hálslón Reservoir is at an elevation higher than ca. 600 m a.s.l, and the discharge in Jökulsá Tunnel is large, a fully pressurised flow will exist all the way in the Jökulsá Tunnel and the maximum capacity of the Jökulsá Tunnel is limited down to 50 m<sup>3</sup>/s for full reservoir and average station flow.

The free surface flow in the Jökulsá Tunnel is used to dissipate the excess energy in the flow from the hydraulic point at 608 m a.s.l down to the pressurised flow level. The energy is dissipated by friction in the uniform free surface flow in the gently sloping tunnel. In the D&B section the longitudinal slope is 0,5% and the free surface flow is subcritical, and the maximum water velocity is moderate or less than 5,0 m/s.To cope with the large variation in hydraulic head and adjust to the existing longitudinal profile and topography the TBM section had to slope up to 1,3%. This created a supercritical flow with velocities up to 7 m/s. When the supercritical flow meets the pressurized flow a hydraulic jump is created with associated air entrainment. The hydraulic jump can be located anywhere in the ca. 5 km long supercritical flow TBM tunnel section. The high velocity supercritical flow and the energy dissipation in the hydraulic jump create high erosion load on the mainly unlined tunnel. This rather special feature of a pressure tunnel has been detailed and discussed in a paper at the HYDRO2007 conference Ref. [2].

In normal operation conditions the Jökulsá Tunnel acts as an extra surge tunnel to the Headrace Tunnel system. A reverse flow is obtained in the tunnel when the station trips and water is pushed from the Headrace Tunnel back into the Jökulsá Tunnel and in some cases all the way up to the Ufsarlón Pond. The horizontal free surface area of the Jökulsá Tunnel is about 3 200 m<sup>2</sup> due to the gentle slope and the large diameter. This is more then 20 times larger than the horizontal area of the Miðfell Surge Tunnel. During surges the water surface in the Jökulsá Tunnel rises therefore much slower than the pressure in the Headrace Tunnel at the connection point. The head difference between the Headrace Tunnel and the Jökulsá Tunnel increases therefore steadily and the reverse flow could

become extensive and could in many cases exceed the maximum normal design flow of the tunnel by up to 90%, i.e. to  $170 \text{ m}^3$ /s. Being such a high discharge, much in excess of the permissible value for the butterfly valve, counter measures had to be looked for.

The reverse flow in Jökulsá Tunnel due to station trips increases with decreasing initial flow in Jökulsá Tunnel. There are at least 3 reasons for this:

- 1. If there is any discharge from the Ufsarlón Pond it helps filling up the empty space in the free surface flow section of the Jökulsá Tunnel and will thus reduce the pressure difference between the two tunnels during surges.
- 2. More discharge in Jökulsá Tunnel means that the boundary between the free surface flow and pressurised flow in the Jökulsá Tunnel is at higher elevations as less discharge is coming from the Hálslón Reservoir. The distance from the Headrace Tunnel to the free surface flow in Jökulsá Tunnel is thus longer for more discharge in Jökulsá Tunnel.
- 3. More discharge in Jökulsá Tunnel means less discharge in the long Headrace Tunnel and therefore less volume of surging mass and therefore less surge elevation and thus less reverse flow.

The maximum reverse flow increases also with decreasing Hálslón Reservoir level as the distance to the free surface level in Jökulsá Tunnel is shorter than if Hálslón Reservoir is at higher elevations.

## 3. Reduction of the reverse flow

## **3.1** Possible alternative solutions

The reduction of the reverse flow has to be designed in such a way as not to restrict the reverse flow to much less than the accepted max. reverse flow for the butterfly valve of  $100 \text{ m}^3$ /s. This not to reduce excessively the surge tunnel effect of the Jökulsá Tunnel during mass surges. On the other hand any solution should affect the normal operating conditions only in a very limited way.

For the above reasons a solution with a one-way check valve is not feasible. Also a normal throttling, acting in both directions is not acceptable.

Since the butterfly valve is designed only for operation in fully open or closed position, alternatives with partial openings during backflow by limitation of the closing angle are likewise not feasible. The butterfly valve could in any case not withstand such strong forces and turbulences.

All the above calls for a solution without movable elements creating first and foremost a large headloss in the reverse flow direction. This goal can be reached with a sudden enlargement in the backflow direction. The solution is described in ch. 3.2.

#### **3.2** The selected solution

A sudden enlargement in a discharge conduit is known to be an efficient way of dissipating energy. This concept was used and the shape optimized so as to give as little headloss in the normal flow direction as practical. Generally the headloss for sudden enlargement can be computed by the well known formula:

Headloss in sudden enlargement:  $\Delta H = (V_t - V_a)^2 / (2g)$ 

Where  $\Delta H$  is the headloss in m, V<sub>t</sub> is the water velocity in the throat and V<sub>a</sub> the velocity in the enlarged section and g is acceleration of gravity.

Transient calculations of the mass surges showed that with additional local headlosses of some 30 to 35 m for reverse flow, the reverse flow maximum discharge could be limited to approximately the permissible values for the butterfly valve of 100 m<sup>3</sup>/s. The results of the above formula are presented in *Figure 6*. The figure shows how effective it is to reduce the throat diameter for increased headlosses. For example a throat diameter of 1,6 m would create 100 m headloss.

A compromise between the required headlosses and the acceptable maximum discharge for normal flow led to the selection of a 2,1 m throat diameter. The maximum velocity of 26 m/s for maximum normal flow is quite high even for a steel lined section but considered acceptable as that high discharge is only experienced for few days each year on the average (less than a week).



Figure 6 Relationship between throat diameter and headloss for reverse flow and maximum velocity for normal flow

An example of the effect of the energy dissipater is shown in *Table 2*. The table shows the maximum return flow according to a complete trip of the station from full flow, with no flow from Jökulsá Tunnel, for some calculated and selected cases. The table clearly illustrates the reducing effect of the dissipater. The final throat diameter was selected to 2,1 m and therewith the maximum reverse flow was reduced down to close to 100 m<sup>3</sup>/s for almost all possible cases.

Hálslón Res.level	Maximum reverse flow in m <sup>3</sup> /s			
m a.s.l	Without energy dissipater	With energy dissipater (d=2,25m)	With energy dissipater (d=2,10m)	
625	145	100		
580	170	115	104*	

Table 2 Maximum reverse flow with and without the energy dissipater(\*calculated for Hálslón Reservoir at 570 m a.s.l)

*Figure 7* shows a time plot of the reverse flow and waterlevel in Jökulsá Tunnel during station trip with and without the energy dissipater. The damping effect of the energy dissipater is clearly detectable.



Figure 7 Example of backflow into Jökulsá Tunnel (green line and right side ordinate) with and without the energy dissipater. No initial flow in Jökulsá Tunnel and complete stop of station from full load (Q=144 m<sup>3</sup>/s) and full Hálslón Reservoir (625 m a.s.l)

The preferred location of the dissipater from an economic point of view seems to be as close as possible to the Jökulsá Valve Chamber. Then the orifice construction would mainly replace part of the normal concrete embedded steel lining upstream of the butterfly valve.

# 4. Hydraulic model test and a hydraulic evaluation

A sudden enlargement energy dissipater is a rather uncommon or even unique feature for flow in two directions inside a waterway. The anticipated discharge and energy dissipation is also relatively high so the design and the performance was studied in a 1/20 scale Hydraulic Model at the Laboratoire de Constructions Hydrauliques (LCH) in Lausanne, Switzerland Ref. [1]. The objective of the model test was to determine the efficiency and operational safety. The headloss calculations as well as several other design assumptions were verified in the model. The model gave also information on the characteristic localized flow turbulences, the cavitation potential and the forces acting on the solid boundaries both for reverse and normal flow conditions. The model consisted of the sections shown in *Figure 4* with appropriate upstream and downstream lengths.

## 4.1 Headloss

The main design aim of the Energy Dissipater is to limit as much as possible the headlosses in normal operation conditions and to achieve the desired level of head losses under reverse flow conditions. *Figure 8* clearly demonstrated the almost 6 times higher headlosses in the reverse flow direction compared to the normal flow direction. The figure also shows a good agreement between the theoretical calculated headlosses and the measured ones.



Figure 8 Measured and calculated headlosses through the modelled section for normal and reverse flow

## 4.2 Localized flow turbulences

The reverse flow expanding jet diffusion upstream of the throat is the most critical design item due to the high velocity and energy diffusion. *Figure 9* (from Ref. [1]) shows the evaluation of the velocity profile as measured by Ultrasonic Doppler Velocity Profile (Metflow SA, UVP-DUO).



Figure 9 Axial velocity measurements with UVP along a vertical diameter at different distance from the 2.1 m diameter throat for Q=90 m3/s.

The figure shows very high velocities in the middle of the enlarged duct close to the orifice with a reverse flow close to the outer edge. The flow is on the other hand rather uniform at ca. 22 m distance from the orifice. Dynamic pressure measurements also showed clearly that the jet influence zone is limited to the first 20 m from the orifice. The potential damage to the concrete lined tunnel walls due to high turbulence level and pressure variation is thus limited to within 20 m closest to the throat. This also compares well with the classical jet diffusion theory. The left branch tunnel centreline is at approximately 19 m distance from the dissipater and the concrete lining was terminated at the branch and the tunnel branches left open as the extra space was assumed to be beneficial for the flow stabilisation and energy dissipation.

#### 4.3 Risk of cavitation

The average velocity in the throat for a 100 m<sup>3</sup>/s discharge is about 29 m/s. The velocity head ( $v^2/(2g)$ ) is therefore up to 42 m. As the velocity head in the enlarged section upstream of the throat is insignificant the hydraulic pressure in normal flow conditions reduces by this amount by entering the throat. A severe cavitation condition might therefore easily be created depending on the prevailing total pressure. The risk of cavitation was evaluated by indexes according to two formulas:

Quintela Index  $\sigma = \frac{p_{\vec{\sigma}} - p_{\vec{v}}}{\rho * \frac{V^2}{2}}$  and Falvey index  $K = \frac{Hd - Hv}{Ht - Hd}$ 

where  $p_e$  is the pressure and V the velocity in the throat  $p_v$  the water vapour pressure and  $\rho$  the density, Hd is the pressure head downstream of the contraction, Ht the total head (pressure plus velocity) upstream of the contraction and Hv the water vapour pressure expressed in head relative to atmospheric pressure.

An incipient cavitation is assumed to be possible for  $\sigma < 0,6$  and for K < 0,2

The risk of cavitation was studied by use of the above indexes and sensitivity analysis performed based on results of the model test both for normal and reverse flow. The cavitation was most likely to happen in normal flow conditions according to the Quintela Index. A sensitivity analysis of this case is shown in *Figure 10*.



Figure 10 Cavitation index for normal flow according to Quintela index  $\sigma$  as a function of discharge and head in the Headrace Tunnel downstream of the Jökulsá Valve Chamber

On *Figure 10* calculations of cavitation index according to Quintela Index  $\sigma$  are done for various combinations of waterlevel in the Headrace Tunnel just downstream of the Jökulsá Valve Chamber and discharge in Jökulsá Tunnel from 80 m<sup>3</sup>/s up to more than 110 m<sup>3</sup>/s. According to those calculations cavitation is only likely to happen if the discharge is higher than 85 m<sup>3</sup>/s and the waterlevel is lower than 500 m a.s.l and for discharges above 100 m<sup>3</sup>/s if the waterlevel is lower than 520 m a.s.l. The green dotted line on the figure shows that those combinations of head and discharge are impossible for steady normal operation. Fortunately the higher the discharge in the Jökulsá Tunnel the higher is the head at the tunnel junction. Cavitation risk is therefore not likely as the incipient cavitation limit (black horizontal line on *Figure 10*) is always considerably lower than the green dotted line

During transient conditions (mass surges) the relation between the waterlevel and the discharge can be different than the one obtained from the steady state conditions. The maximum discharge can become higher than during steady state or even up to  $100 \text{ m}^3$ /s. However it is not likely that the waterlevel will at the same time be as low as in the steady state case, and even if this would happen it would be infrequent and only for a very limited time.

## 5. Construction and experience

The dissipater was executed as planned. It was installed and taken into operation in October 2008. Now almost 2 years later (July 2010) it has experienced a total of 3 complete station trips, indeed much fewer than expected. The last trip occurred in August 2009 and that was before the final hydraulic data measurements and high frequency collection system were fully installed in the Jökulsá Tunnel and the Valve Chamber and connected to the stations monitoring system. A detailed analysis of the system has therefore not been completed yet, but the dissipater seems to function as expected just as the whole Kárahnjúkar Project that has had a very successful operation for its startup and the first 3 years. The Jökulsá Tunnel has not yet been emptied completely so the dissipater and the tunnel lining upstream has not been inspected, but that will be done within next couple of years.

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#### The Authors

**Porbergur S. Leifsson** graduated in Civil Engineering from the University of Iceland in 1980, and with M.Sc degree from Colorado State University 1982, specializing in hydraulic and hydrology. He worked as a consulting engineer for Almenna Consulting Engineers in Iceland 1982-2002 and for VST/VERKÍS since 2002, notably in the field of hydropower developments and hydraulic engineering. He is a member of the Icelandic National Committee on Large Dams (ISCOLD) and the Icelandic Society for Operational Research. He was a Member of the Hydraulics Team within the Kárahnjúkar Engineering Joint Venture (KEJV) and participated in most of the hydraulic tasks in the design of that project. He is currently the main hydraulic designer of HEP for VERKIS working i.e. on HEP projects in Greenland (Sisimuit and Ilulissat) and Búðalháls and future HEP projects in Lower-Þjórsá river in Iceland.

**Arnoldo Baumann** graduated in Civil Engineering from Swiss Federal Institute of Technology, Zurich, Switzerland in 1969. His special field of professional experience is hydraulics. Since 1970 he is working with Pöyry Energy AG, where he is in charge of design of hydraulic structures (intakes, outlets, spillways, energy dissipaters) and hydropower schemes (headrace and power tunnels, surge tanks, penstocks, tailrace structures). He is an expert in the analysis of transient conditions in hydropower waterways, cooling systems and water-supply systems and has supervised and organized hydraulic model tests in various countries. He is member of the Swiss National Committee on Large Dams (SNCOLD) and the Swiss Society of Water Management. He was Member of the Hydraulics Team within the Kárahnjúkar Engineering Joint Venture (KEJV) and accompanied all the hydraulic model tests connected with the power waterways.