Filling and Pressurizing of the Headrace Tunnel for the Kárahnjúkar HEP in Iceland

Introduction

The 690 MW capacity, 600 m gross head Kárahnjúkar Hydroelectric Scheme, commissioned and put into service in November 2007 by Landsvirkjun (National Power Company of Iceland), harnesses water from two glacial rivers originating in the large Vatnajökull Glacier. The nearly 40 km long Headrace Tunnel supplies water from the Háslón Reservoir to six Francis turbines in the Powerhouse, with a design discharge of 144 m³/s, and was filled and pressurized in October 2007. A secondary diversion using the 13.3 km long Jökulsá Tunnel, connected to the Headrace Tunnel, was put into service in October of 2008.

Difficult tunnel conditions, due to heavy groundwater inflows and to locally unstable rock conditions, were encountered during excavation of the Headrace Tunnel. The resulting delays required acceleration of the filling, pressurizing and commissioning of the Headrace Tunnel. This was achieved by filling the Headrace Tunnel in two stages. First the penstocks and lower section of the tunnel were filled using the groundwater inflow, and water stored in the lower tunnel behind a temporary cofferdam in the tunnel was used to commence wet testing of several turbine units while finishing work continued in the upper section of the tunnel. Following completion of the tunnel finishing work, the remainder of the tunnel was filled and pressurized in a second stage.

Filling and pressurizing in the second stage were accomplished using gate equipment installed at the Háslón Power Intake. Háslón Reservoir was already at full supply level prior to tunnel filling. Due to the hydraulic head difference across the gates of 95 m special procedures had to be worked out using the gate equipment, in order to safely fill the tunnel. For tunnel filling, nozzles were installed in the bulkhead gates and filling was carried out using the wheel gates for on-off control.

After filling of the tunnel itself was concluded, pressurization was achieved by controlled filling of the surge tunnel, surge shaft and gate shafts. As these volumes were relatively small, compared to the filling rate, there was a real risk of pressurizing the tunnel too rapidly. An additional complication was the expected leakage from the tunnel required to recharge the groundwater aquifer, which made control of pressurization more difficult. Pressurization was accomplished by a controlled, very small opening of the wheel gates, with gate opening increments typically on the order of 5 mm. After pressurization to the Háslón Reservoir water level, a final leakage test was carried out and the gates were fully opened allowing the hydropower scheme to begin operations.

Since initial turbine wet-testing had already been carried out, the first unit of the Powerplant was able to begin commercial operations two days after the completed Headrace Tunnel pressurization. Full power availability was achieved three weeks later.

1. Project Overview

The Kárahnjúkar Hydroelectric Project is located in the eastern part of Iceland to the north of the Vatnajökull 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 (National Power Company of Iceland).
The main storage reservoir and the only reservoir in the Jökulsá á Dal catchment area is Háslón Reservoir, with 2085 Gl live storage. Háslón Reservoir is retained by the 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.

Water from the Háslón Reservoir is conveyed from the Háslón Intake through a 40 km long mainly unlined Headrace Tunnel to a valve chamber and from there, through two vertical steel lined Pressure Shaft 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. 1).

Fig. 1: Longitudinal schematic of Waterways

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.

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 and the first unit started commercial operation 2 November, 2007 with full power availability achieved on 23 November, 2007. The Ufsarveita Diversion was taken into operation in October 2008. Most of the generated power will be used by the Alcoa aluminum smelter located in Reydarfjordur.

Design of the Headrace Tunnel was performed by Pöyry (formerly Electrowatt) under the Kárahnjúkar Engineering Joint Venture (KEJV) consisting also of VST Ltd and Rafeikning (now Verkis), MWH and Almenna Verkfræðistofan.
2. Situation During Finishing Work for Headrace Tunnel

The tight construction schedule for excavation of the Headrace Tunnel was challenged over the course of construction by initial delays in adit construction and TBM move-in, by difficulties faced by the contractor in completing tunnel rock support concurrently with TBM boring, and by the effort required to overcome difficult geological conditions in several locations.

Most of the 40 km long Headrace Tunnel was excavated by 3 tunnel boring machines (TBM's) of 7.2 - 7.6 m diameter. All 3 TBM's encountered difficulties and their advances were slowed significantly by heavy water inflows (TBM 3), multiple faults with heavily fractured rock and heavy water inflows (TBM 2) and by weak sedimentary layers (TBM 1). Fig. 1 indicates the location of the TBM drives.

The upstream TBM 3 bore was stopped prematurely due to the heavy water inflows and the TBM was turned around to bore downstream towards TBM 2 leaving the remaining approx. 1 km tunnel section to be completed by drill and blast excavation (D&B). To accelerate the D&B excavation, an additional adit (Adit 4) was constructed adjacent to the saddle dam just east of the Kárahnjúkar Dam, recovering several months of construction time.

TBM 1 progress was initially slow due to the weak sedimentary layers, but broke through first after some 15 km of boring on September 9, 2006.

TBM 2 was delayed around 6 months due to tectonic fault zones and heavy water inflow which could to some extent be mitigated by lengthening the TBM 3 downstream drive. The last breakthrough was by TBM 3 on December 5, 2006.

Impoundment of Hálslón Reservoir started in September 2006 on schedule as planned. During early 2007 finishing work in the Headrace Tunnel between the Power Intake Gates and the Pressure Shafts was ongoing along the entire 40 km length of the tunnel.

Two 220 kV transmission lines between the Powerplant and the smelter with a link to the existing 132 kV national grid were commissioned in January/February 2007.

To make initial start-up power available on time to the aluminum smelter it was decided to operate the generator of Unit 1 of the Powerstation without water as a synchro-condenser. This was made possible by installing appropriate additional electronic converter equipment for start-up of Unit 1 from the grid. The generator was decoupled from the turbine shaft. With these arrangements for the Unit 1 generator the weak electrical network on the east coast of Iceland was stabilized, transmission capacity was increased and voltage regulation was provided. This allowed start-up of the aluminum smelter on time in April 2007 from the national grid with an initial supply of up to 100 MW.

By April 2007 delays and slippage of the construction schedule for completion of Headrace Tunnel finishing were threatening to delay start-up activities for the aluminum smelter. The finishing works inside the tunnel, including completion of rock support, concrete structures, utility removal and cleaning became time critical for project completion and great efforts had to be made in order to speed up these works. Apart from an increase in the workforce, additional rail equipment and tunnel equipment for finishing work as well as incentive payments and increased working times were used by the contractor to mitigate the delays. Additional delay recovery was achieved by modifying designs to facilitate accelerated finishing, by using air vents as drop shafts for concrete delivery and by using the surge tunnel and surge shaft during finishing work as additional access. By doing all of this the delays could be mitigated considerably.

However, continued slippage of the construction schedule due also to the difficulty of accessing the long tunnels for finishing work and the challenges of organizing and supervising tunnel completion with finishing work ongoing along 40 km of tunnel made further acceleration measures necessary. In addition to accelerating the tunnel finishing work in the tunnels wherever possible, it became necessary to shorten the testing and commissioning period for turbine/generator Units 2-6. The underground Powerhouse construction as well as the Pressure Shaft steel lining and installation of electro-mechanical equipment were essentially on schedule.

3. Concept for Two-Stage Filling of Headrace Tunnel

Shortening of the testing period for the turbine/generator Units was achieved by a decision in April 2007 to fill the Headrace Tunnel in two stages. The lower 15 km of tunnel downstream of Adit 2 would be finished first and filled using the groundwater inflows into the tunnel between the TBM 2 / TBM 3 breakthrough and the Pressure Shafts, which at that time were approx. 800 l/s in total (see Fig. 2). Several units would then be wet-tested at speed, no-load conditions at a somewhat reduced water head (450 m instead of 600 m static water head). It was anticipated that 2-3 weeks of testing time for each of the generating units could be saved using this procedure.
In order to use the water inflows upstream of Adit 2 for filling the lower tunnel, it was necessary to divert water flowing out of the upper tunnel section into the lower tunnel. This could be done by using Rock Trap 2 as a pump sump, installing a cofferdam within the Headrace Tunnel just downstream of Adit 2, and pumping water from the pump sump across the cofferdam into the lower tunnel (see Fig. 3).

Following filling of the lower section of the Headrace Tunnel, finishing work in the remaining tunnel would be completed, and the remaining tunnel filled and pressurized.

The preparations for two-stage filling of the Headrace Tunnel required extensive risk assessment and contingency planning, as well as careful planning of the execution, to ensure the safety of all personnel working in the tunnel.

4. Headrace Tunnel Filling Plan

Planning for the filling of the Headrace Tunnel included numerous aspects:
- final walkthrough inspections of all tunnel sections and approval as ready for filling,
- closure of adits and temporary drainage pipes used for construction,
- assessments of expected leakage into rock mass during pressurizing,
- determination of filling rates and pressurizing rates,
- filling and pressurization sequences,
- operation of Intake Gates during filling and pressurizing,
- leakage monitoring during filling and pressurizing.
A Filling Manual was prepared to provide details of the required filling procedures, including responsibilities and monitoring requirements. Detailed checklists were prepared for the walkthrough tunnel inspections carried out during finishing and as final inspections.

The Filling Manual detailed procedures for the closure of each adit. Due to the heavy water inflow encountered in many sections of the tunnel, extensive dewatering facilities were in use, including a drainage tunnel at Adit 1, temporary drainage pipes through several plugs and dewatering pumps at numerous locations along the tunnel. Careful sequencing was required for removal of pumps, closure of drainage pipes, closure of bulkhead doors at adit plugs and grouting of temporary drainage pipes.

Following excavation the water inflows did naturally reduce somewhat over time, but although a large amount of grouting was carried out to reduce water inflow, approximately 2 m$^3$/s of groundwater were still flowing into the 40 km Headrace Tunnel during finishing work. Groundwater monitoring using instrumented boreholes showed substantial groundwater drawdown in some locations and it was expected that initial leakage from the tunnel would be high following pressurizing due to aquifer discharge. As most of the Headrace Tunnel is below a plateau, with groundwater levels at or above Háslón Reservoir water levels, long term leakage was however expected to be very low. Various analytical calculations carried out (e.g. Schleiss and Johannesson, "Erstfüllung von durchlässigen Druckstollen und Druckschächten") indicated that higher leakage would occur immediately following a pressurizing increment, decreasing over time to lower leakage rates. The relationship between filling rate and pressure increase in the tunnel is difficult to predict due the great uncertainty in the quantity of leakage from the tunnel for recharging of the surrounding aquifers. However the analysis showed that the flow rate needed to be controllable between 1 and 10 m$^3$/s.

A conservative filling rate of 10 m/day was chosen for Headrace Tunnel (HRT) filling and pressurization. This was due partly to the expected large leakage and the difficulty of controlling tunnel pressurization when large leakage occurs. The main concern was however potential hydraulic jacking where the Headrace Tunnel crosses several valleys in the upper section with minimum rock cover.

The filling and pressurization sequence was (refer to Fig. 1 and 2):

- Filling of Pressure Shafts and HRT downstream of Adit 2 to EL 466 m using groundwater inflow (Stage 1)
- Turbine wet-testing using water stored in HRT downstream of Adit 2
- Filling of HRT adjacent to Adit 3 up to culmination adjacent to breakthrough of TBM 2 / TBM 3 at EL 508 m (Stage 2)
- Filling of HRT upstream of Adit 2 to culmination adjacent to breakthrough of TBM 2 / TBM 3 (Stage 2)
- Filling of HRT to Adit 4 level at EL 528 m (Stage 2)
- Filling of HRT to crown of Power Intake Gate Chamber at EL 540 (Stage 2)
- Pressurizing of HRT by filling of Surge Tunnel, Surge Shaft and Gate Shafts to EL 625 m (Stage 2).

Stage 2 filling and pressurization was done through the Hálslón Power Intake. Initial project planning foresaw the first filling and pressurizing of the HRT with Háslón Reservoir at low level (around EL 550 m a.s.l.). Due to the delays in finishing of the HRT, filling and pressurization would take place with Háslón Reservoir full (EL 625 m a.s.l.). This required revising the procedures for gate operations. It should also be noted that future filling of the Headrace Tunnel will be done through the Jökulsá Tunnel, which includes facilities for this purpose.

A Gate Chamber with floor elevation at 530 m a.s.l. (see Fig. 4), located just downstream of the Háslón Power Intake, provides twin bulkheads (sliding gates W$^*$H$^*$=2.05$^*$6.5) and twin wheel gates (W$^*$H$^*$=2.05$^*$6.5). Since the wheel gates are suspended in an approx. 80 m long series of stem extensions, the gates do not precisely follow the movement of the hydraulic cylinders. It was roughly estimated that a gate might jump up to 20 mm at the start of movement since the static friction must be compensated by elongation of the stem extensions before the gate moves. This opening step would cause about a 2 m$^3$/s increase in discharge, which is much too large for controlled filling. Opening the wheel gates under the very high hydraulic head of 95 m could also create cavitation damage to the concrete due to the high flow speed downstream of the gate when there is no or little backwater pressure. This led to a rather unique design with the installation of 10 pipes of 200 mm diameter through the bulkhead gate panels. The pipes can be closed with blind flanges at the downstream end, but by replacing the blind flange with four 100 mm and four 120 mm orifices (as nozzles) a total discharge of 2 m$^3$/s could be obtained during filling at full reservoir water level. Different discharge capacities could be obtained if necessary by closing both wheel gates and lifting the bulkhead panels to the surface to change the nozzle configuration, which was however not necessary. The water flow from Háslón reservoir into the HRT during filling could be switched on and off by opening and closing the wheel gates.

The control of the gate opening and the verification of the gate opening had to be checked thoroughly before the filling process started and the initial gate opening for filling was planned with this in mind.

The pressurization of the tunnel takes place between about EL 540 and 625 m a.s.l. (Hálslón full supply level). In that region only the surge tunnel and shaft as well as the gate shaft are being filled. These features have a
combined horizontal water surface of about 170 m². To achieve a pressurization rate of 10 m/day, only about 30 l/s are needed for the filling of the shafts and tunnel volume. Small deviations in filling rates would cause large increase or decrease in the HRT pressure. This required elaborate procedures for gate operation.

For pressurization higher intake flow rates were required due to expected leakages as explained above. The bulkhead nozzles can be used until the required flow rate exceeds their capacity, which of course reduces as the tunnel pressure increases. Then one or both wheel gates must be cracked to achieve the desired filling rate. As the Gate Chamber would be submerged, no erosion of the concrete structure by water jetting through the cracked gate was expected. Continuous monitoring of the pressure in the tunnel and frequent regulation of the gate opening is required.

![Fig 4: Schematic drawing of Power Intake Gates](image)

Requirements for leakage monitoring during filling and pressurizing were detailed for the plugs and adjacent adits as well as for valley crossings along the upper HRT. The monitoring requirements included warning and alarm limits at locations where leakage could be expected.
5. HRT Filling and Pressurizing

Walkthrough tunnel inspections were carried out, first as pre-inspection, and then following completion of all identified punch items, as final inspections. Tunnel cleaning was carried out using high pressure water flushing with a maximum of 10 liters per tunnel meter of sediments and rock fragments allowed to remain in the tunnel. After approval of a tunnel section as ready for filling, the adjacent adit could be closed.

The planned cofferdam downstream of Adit 2 (see Fig. 2 and 3) was erected, pumping facilities from the adjacent rock trap were installed and the water flowing out of the upper tunnel section of Adit 2 was diverted into the rock trap. Adit 1 and the adjacent drainage tunnel were closed on 28 July, 2007 and the twin vertical Pressure Shafts as well as the lower 15 km of the Headrace Tunnel were filled using groundwater inflows.

Finishing work continued in the remaining 25 km of Headrace Tunnel, downstream of the closed Power Intake Gates and upstream of the cofferdam impounding water in the lower third of the Headrace Tunnel. During this period, wet-testing of Units 2, 3 and 5 was carried out at speed, no-load conditions.

Adit 2 was closed on 13 October, 2007 (Fig. 5) following final tunnel inspection and removal of the cofferdam together with the associated pumping facilities. Although a significant amount of fine silt had accumulated immediately downstream of the cofferdam, gradation testing confirmed this to be very fine (< 100 micron) and it was decided that this could be left in the tunnel to be later eroded and discharged through the turbines. The tunnel low point adjacent to Adit 2 was then filled using groundwater inflow.

On 16 October, 2007 Adit 3 was closed and filling of the Headrace Tunnel through the Power Intake commenced on the next day. Interestingly, Hálsión Reservoir began spilling at the same time. Filling was done as planned using the bulkhead nozzles and was initiated by raising the wheel gates. Due to problems initially encountered with the electronic control systems, the wheel gates were controlled manually using the hydraulic equipment. During use of the bulkhead nozzles for filling, the wheel gates were always fully opened.

Raising the wheel gates also gave the start-up team an opportunity to begin testing gate procedures for the later pressurization phase. A laser distance meter was fixed to the first stem extension of both wheel gates close to the dogging facility at the top of the gate shaft (see Fig. 4). All gate movements were registered carefully. After familiarization with the wheel gate movements by manual hydraulic control, it was found possible to minimize gate jumping occurring during opening. Due to slack in the stem extensions and due to elastic stretching of the stem extension an initial hydraulic piston movement of 100 mm (±10 mm) was required before the gate opened. Gate opening could be determined audibly by the flowing water as well as by a drop in the hydraulic pressure following the gate jump. Following familiarization, an initial gate opening of 5 - 10 mm could be achieved, calculated by orifice curves prepared for the filling process and verified by the observed rate of tunnel pressurization. During additional gate opening it was found possible to minimize the gate jumping to a few mm and the opening could be controlled to within approx. 2 mm. After the initial gate opening (cracking) it was important that all further gate movements were for progressive gate opening (i.e. no gate closure movement).
Prior to the closure of Adit 4 on 19 October, 2007 a final inspection of the Gate Chamber was carried out. No damage to the concrete due to the filling nozzles during the filling of the Headrace Tunnel was observed. Filling to El 540 m a.s.l. continued using the bulkhead nozzles.

At El 540 m a.s.l. filling of the Headrace Tunnel was completed and pressurization began. This was accomplished using the bulkhead nozzles up to El 553 m a.s.l. and afterward by removing the bulkheads (Fig. 6) and using the gate cracking procedures described above. Initially one wheel gate was cracked to achieve the desired filling rate. The initial cracking was estimated to be 7 mm and was increased to 15 mm after 6 hours. A leakage test of the Headrace Tunnel was conducted at El 555 m a.s.l. by closing the Intake Gates and indicated tunnel leakage of 1.1 m$^3$/s, which was substantially less than expected. Pressurization continued with the flow rate controlled by wheel gate cracking, initially with one wheel gate and then with both wheel gates after a water level of 600 m a.s.l. was reached in the Gate Shafts. The gates were progressively opened to maintain a discharge of 30 l/s plus leakage. The Headrace Tunnel water pressure development is shown in Fig. 7, together with gate openings and leakage rates.

As is indicated by Fig. 7, after each additional gate opening an initial faster pressure rise was followed by a slower and relatively constant rise. The initial faster pressure rise observed implies a short time lag before the tunnel leakage increases to correspond to the additional pressure.

Due to the inertia of the 40 km long water column, extreme care had to be taken, since an abrupt gate opening would have caused a sudden pressure rise at the upstream end of the tunnel. The planned filling and pressurization rate of 10 m/day could be maintained quite well. This was partly helped by the fact that the maximum leakage during pressurizing was less than had been expected. The competence and care of the mechanical staff with the gate operations contributed greatly to the successful filling and pressurization.

Pressurizing was completed on 31 October, 2007. A leakage test of the Headrace Tunnel was conducted approx. 6 hours after completing pressurizing, by closing the Intake Gates, and indicated tunnel leakage of 1.1 m$^3$/s.

Each generating unit was successively brought on line and tested at full power after completion of Headrace Tunnel filling and pressurizing. The two-stage filling methodology followed brought about a substantial advancement of full power production from the Kárahnjúkar plant. In spite of the severe delays in tunnel completion, the first unit started commercial operation 2 November 2007, with full power availability achieved on 23 November, 2007 and full power production reached in the spring of 2008. Full power availability was thus achieved close to the original project schedule of October 2007.
Minor leakage at the adit plugs was observed following pressurization. At the plugs, leakage through and around the plugs varied between 1 - 4 l/s. Additional contact grouting and grouting repair of minor concrete cracking in the plugs (which was largely expected due to increased concrete lift heights and reduced waiting times before grouting to accelerate plug construction) generally reduced the leakage to around 1 l/s, which was considered acceptable. Additional consolidation grouting was required adjacent to the Adit 1 plug, in order to reduce the water draining through the Pressure Shafts Valve Chamber.

Surface leakage at the three valley crossings along the upper Headrace Tunnel was observed, with total leakage of around 200 - 300 l/s at full Hálsólón Reservoir level. Suitable drainage measures were carried out and the leakage zones were checked against geological records, indicating that most of the leakage occurred through open joints crossing the Headrace Tunnel, which had not been grouted or only partially grouted to reduce water inflows during construction. Turbidity measurements showed that the sediment load was generally less than that in Hálsólón Reservoir, indicating that no internal erosion of the rock mass was occurring and that sealing of the rock mass through the sediments should over time reduce the surface leakage. At a reservoir elevation of 590 m a.s.l. in early summer of 2008 the leakage was very small.

6. Experience to Date

The Kárahnjúkar powerplant has been fully operational since November 2007 and no problems have been observed with operation of the Headrace Tunnel. The Jökulsá Tunnel was filled and put into operation in October 2008.

The Authors

Joseph J Kaelin graduated with a Sc.M. degree in Civil Engineering from the Massachusetts Institute of Technology in 1986. He is a senior tunnel engineer at Pöyry Infra Ltd. and as a Lead Engineer for the Kárahnjúkar Engineering Joint Venture (KEJV) was responsible for the design and construction monitoring of the power waterways for the the Kárahnjúkar Hydroelectric Project.

Sveinn I Ólafsson graduated with M.Sc. degree in Mechanical Engineering from Washington State University in 1982. He is now the managing director of Verkis Consulting engineers. He has been involved in all types of mechanical design as well as overall design of several hydro power plants. Sveinn was the Lead Mechanical Engineer and Deputy Project Manager for the Kárahnjúkar Engineering Joint Venture (KEJV), the designer of the Kárahnjúkar Hydroelectric Project.

Þorbergur S Leifsson graduated with M.Sc. degree in Civil Engineering from Colorado State University in 1981. He is a hydraulic engineer at Verkis hf. He participated in the hydraulic design of the power waterways of the Kárahnjúkar HEP and in the planning and execution of the tunnel filling and pressurizing.

Fig. 7: Headrace Tunnel pressurization as recorded in Powerhouse control room for the final 6 days