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MODULAR DEVELOPMENT OF THE NESJAVELLIR POWER PLANT FOR FLEXIBILITY

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ABSTRACT

In late 1986 Hitaveita Reykjavikur, nowadays Orkuveita Reykjavikur, decided to harness the high temperature geothermal field at Nesjavellir. This field is located some 30 km east of Reykjavik; see Figure 1. The Nesjavellir plant was intended to supply the city of Reykjavik and the annexing communities both with hot water for space heating and electricity for at least a period of 30 years and reach a fully developed capacity of about 100 MW_e in electric and 300 MW_t in thermal power. The plant will be expanded in harmony with increase in demand for heat and electricity. During this 30 years period the geothermal field is expected to change over time. According to reservoir modelling studies, the production fluid enthalpies will decrease gradually in the future. To achieve optimal thermal efficiency and flexibility during this development, both the process and the buildings are designed modular. The first stage of the plant was commissioned in 1990, with a thermal output of 100 MW_t using the geothermal steam. The geothermal water was at the same time used in a pilot module to achieve operational experience with the Nesjavellir geothermal water. In 1994 the second stage of the power plant was commissioned, adding equipment to boost the output to 150 MW_t. In late 1998, electricity generation started. Two condensing steam turbine-generator units produce now 60 MW_e. The cooling water from the condensers is heated further in geothermal water heat exchangers, to suit the district heating requirements. This paper describes the development of the plant, the design philosophy and the experienced gathered during the 10 years of operation.

1. INTRODUCTION

The city of Reykjavik started using geothermal energy for heating of houses in 1930. The use of geothermal water grew rapidly and in 1976 all houses within the city and surroundings were heated by geothermal energy. Reykjavik and surroundings have been rapidly growing and the demand for energy, both electric and thermal, has been increasing. The district heating systems of this area now provides hot water to a population of 170,000 people or about 60% of the population of Iceland. The low temperature geothermal resources within Reykjavik are limited and further geothermal development was needed in the eighties to meet the market demand. These leads to the exploration of the Nesjavellir field some 30 km east of Reykjavik; see Figure 1. In late 1986 the drilling of a total of 18 wells were successfully completed (Gunnarsson *et al.,* 1992).

2. THE NATURE OF THE GEOTHERMAL RESOURCES

The planning and design of the Nesjavellir plant started in 1986, after the period of successful drilling. Information on the nature of the geothermal resources was relatively good and extensive. In addition, a pilot plant had been operating for several years, to determine the basic parameters for the utilisation of the resources. The pilot plant included running of a small electric generating plant and different kinds of heat exchangers, especially for the purpose of finding the best way of extracting the heat from the geothermal water.

Until the exploitation of the Nesjavellir geothermal field started, Reykjavik used the low temperature water directly in the district heating system. The chemistry of the high temperature geothermal water in Nesjavellir however made the direct use of the water impossible. Therefore, heating of fresh water had to be applied.

The character of the geothermal steam was considered to be good and no problems were foreseen in utilising the steam in turbines or in heat exchangers. The geothermal water contained silica (SiO_2, approx. 850 ppm) and the pilot plant findings indicated problems related to scaling. The technique of using fluidised bed heat exchangers was adopted and planned to be included in the plant at later stages of the development.

The enthalpy of the fluid varied greatly from one well to another, in the range from 1200 kJ/kg up to 2500 kJ/kg. Model studies of the reservoir indicated that exploitation of the field would result in increased water fraction from the wells due to lower enthalpy in the long run (Bodvarsson 1993).

3. DEVELOPMENT OF THE ENERGY MARKET

The average temperature in Reykjavik is 5°C; the coldest month is January at 0°C and the warmest is July at 11°C. Therefore, the load factor of the district heating system is high, some 5000 hours. That is ideal for a geothermal source, which has a high investment and a low running cost. Since 1976 all houses in Reykjavik and in the five adjacent communities have been heated by geothermal energy. The population in the area is increasing and the heated volume in buildings increases by 2-3% per year. The thermal load increased proportionally, except during the last 10 years, when the increase in heated buildings was counteracted by improvement in the customer's heat utilisation; see Figure 2. The heat load demand is expected to increase by 1.5% per year. The increase of the thermal load will be met by increased thermal power generation at Nesjavellir. According to the above prognosis, the load will increase by 10 MW_t per annum. The electricity market was characterised in the years 1990 to 1995 by low demand and availability of low cost energy. Since then, the industrial demand has increased considerably. Figure 3 shows the capacity of the Nesjavellir plant in the past and the expected development in the future.

The growth of the market for electric energy and hot water is, as described above, not in harmony, so that flexible development and construction of the plant is of great importance. Flexibility between electricity and heat production is also important for the economy, efficiency and environmental reasons.

4. DESIGN STRATEGY

The design strategy for the Nesjavellir plant has been based on the following:

- The nature of the geothermal resources
- The energy market trends, demand and prices
- The general policy of the city of Reykjavik

The two first points are discussed in previous chapters. The general policy of the city of Reykjavik, which perhaps goes without saying, refers to utilising geothermal energy instead of other form of energy resources. This is an environmentally friendly way of utilising energy, as the geothermal energy is a clean and renewable energy source. Furthermore, the policy included offering low energy prices in the long run.

The strategy developed had to include all possibilities in the market development. When starting the design of the first construction stage, there was only market for 100 MW_t. There was a surplus of electric power in the national grid and no need for generation of electricity. However, it was considered only a matter of time when the electric power production would start and when additional thermal power would be needed; therefore, flexibility had to be adopted.

The expected development of the mean enthalpy for the wells connected to the power plant is shown in Figure 4. To keep initial investment low, high enthalpy wells were chosen for the first stage of the plant and the main emphasis laid on utilising the energy from the steam.

On the other hand the process design strategy had to take into account the decrease in enthalpy over the lifetime of the power plant. Thus, more separated geothermal water would be available in the later stages of development. By using steam for the first stage of the plant, time was gained to test heat exchangers using the separated geothermal water to heat fresh water. The results of these equipment tests are described in Kjartansson (2000). Tests showed that conventional shell and tube heat exchanger could be used, if the scaling behaviour of the separated geothermal water is considered, especially in the equipment design.

As described above, a forecast of the market development for hot water was difficult when the first stage of the plant went into operation. Modular expansion of the power plant at Nesjavellir postpones investments and leads to lower cost of the produced energy.

The Nesjavellir plant is an important production unit for the district heating system and reliability is one point of concern when choosing the capacity of the production modules. Electricity on the other hand can be generated in other plants if there is an emergency situation.

The above design consideration led to the following main design premises:

- The plant will be built in modular units and units will be added as the market demand increases.
- The maximum capacity of each hot water production module shall be 50 MW.
- The plant layout shall allow easy addition of further production modules.
- Hot water production will have priority over electric production.

4.1 Layout planning

The overall plan for the plant focused on one centralised plant, instead of several units distributed over the area. The main powerhouse was located in the middle of the Nesjavellir valley, taking into account the elevation compared to the location of the production wells. Geotechnical consideration of the lava formations in this area led to only few locations where suitable foundation for buildings was found. The site layout was finally determined be the geothermal fluid supply system. The location of most of the future production wells was quite well determined and the separator station was placed centrally to these wells, some 450 m away from the main powerhouse. To avoid boiling in the pipeline for the separated geothermal water from the separator station to the main powerhouse, the elevation of the site chosen for the separator station is about 10 m higher than that of the main powerhouse. Two-phase pipelines connect the wells to the separator station. The longest pipelines are up to two kilometres long (Ballzus *et al*., 1992).

To meet the development of the plant and the steam supply system, a preliminary layout of the connection of all production wells was made during the design phase of the first stage. All routes were planned and the sizing took into consideration the future development. The individual systems were considered not to change over period of time, only the capacity would change by adding further production modules.

The main powerhouse consists of a service building and machine halls, as shown in Figure 5. The service building houses all common equipment of the plant, such as control systems, high and low voltage distribution, compressors and facilities for the staff. The upper floor is open for guests visiting the plant from where the equipment in the machine halls can be overviewed. Annexing to the service building are the turbine hall and the hot water production hall, which house the main power production equipment such as turbine generator units, condensers, heat exchangers, deaerators and main pumps. These machine halls can be extended to house additional equipment, as shown in Figure 5.

4.2 Process planning

It was evident from the beginning that the Nesjavellir plant would be built in several stages, with the first stage of 100 MW_t. To fit the process into the future planning, the process for fully developed plant was designed for 400 MW_t and 80 MW_e (Gunnarsson *et al.*, 1992). Ballzus *et al.* (2000) describe in detail the process design as it is now in the plant.

It is interesting to compare the initial planned fully developed plant process to the existing one, which is based on the first 10 years of operating experience and development. At present, the fully developed plant is planned to be 300 MW_t and 106 MW_e. In all basic principles the process is unchanged; however, the use of separated geothermal water plays a bigger role in the heating than originally anticipated.

5. PLANT SUBSYSTEMS AND MODULES

The geothermal plant consists of the following five subsystems, all of which have a certain function:

- Cold water supply
- Geothermal steam and water supply
- Electricity production and preheating of the cold water
- Hot water production for district heating
- Transmission of the electricity and hot water to the consumer

The producing subsystems are designed modular in the size corresponding to 25 to 50 MW_t to achieve flexibility during development of the plant in stages.

6. PLANT DEVELOPMENT

The development of the Nesjavellir geothermal power plant is today divided into six stages: The first three stages are completed and commissioned, the fourth stage is ongoing and the fifth is in the early planning phase. Figure 5 shows the development of the main powerhouse and the individual building stages up to today.

6.1 1st stage 100 MW_t power plant

The first stage only involved production of thermal power. The plant made use of geothermal steam, as only high enthalpy wells were connected. The power plant had a production capacity of 600 l/s of 80°C water. The basis for the decision was relatively low costs and reliability in process design.

The process for extracting heat from the geothermal water was not yet determined. The pilot plant findings indicated that fluidised bed heat exchangers would be suitable equipment. However, the heat exchangers had not been proven in full scale and therefore it was decided to test them further in larger scale to gain operational experience with this type of heat exchangers.

The preparation for the construction of the first stage started in 1986 and was commissioned in 1990. The time for commissioning was set according to market situation.

6.2 2nd stage, expansion to 150 MW_t

Soon after the first stage was commissioned, it became evident that additional thermal power would be needed for the market. Still, the situation in the electric market was unchanged, i.e. surplus of power. Therefore, it was decided to increase the thermal power by 50 MW_t, i.e. to produce 900 l/s of 80°C water.

The 2nd stage was completed and commissioned in 1994.

Due to decreasing enthalpy of the geothermal water the importance of establishing a reliable technique to extract heat from the water became more important than before. The testing of conventional shell and tube heat exchangers became successful and an acceptable cooling of the separated geothermal water was proven with minimum scaling.

6.3 3rd stage, expansion to 200 MW_t and addition of 60 MW_e

The third stage of development was commissioned in October 1998. The nominal installed capacity of the plant is 200 MW_t and 60 MW_e. The thermal power plant produces 1150 l/s at a condenser pressure of 0.35 bar_a. During low thermal load, the condenser pressure is lowered to 0.2 bar_a to minimise the energy extracted from the geothermal resource.

The utilisation of the geothermal fluid is now such that geothermal steam is used for generating electricity and the condensation heat is used for preheating cold fresh water. The final heating takes place in heat exchangers where geothermal water is used as a heat source, see Ballzus *et al.* (2000).

Additional wells were connected with a fluid of relatively lower enthalpy and consequently there was more geothermal water available. The heat extracted from the geothermal water therefore played larger role than before.

The operating experience of using conventional shell and tube heat exchangers for the geothermal water is quite excellent.

6.4 4th stage, addition of 30 MW_e to 90 MW_e and 200 MW_t

Orkuveita Reykjavikur decided in September 1999 to install a third 30 MW_e condensing unit. Commissioning is planned in June 2001. This unit will be operated at part load of 16 MW_e, until further research of the geothermal field shows that the field can sustain a higher long-term load. Exploratory drilling has already started on the south border of the Nesjavellir production field, to find out if the field is larger than known today. If confirmed, new wells have to be connected to the steam supply system, and a new main steam supply line from the separator station to the power plant has to be built. The construction period for this stage will be about 16 month.

6.5 5th stage, addition of 100 MW_t to 90 MW_e and 300 MW_t

The fully developed plant is expected to reach a capacity of 90 MW_e and 300 MW_t in the year 2010. Further development in thermal capacity is not expected due to safety considerations. The importance of the Nesjavellir plant for the district heating system would then be that great that damages to the plant, e.g. due to volcanic activities, would lead to considerable shortage of hot water for the district heating in the Reykjavik area.

6.6 6[th] stage, expansion to 106 MW_e and 300 MW_t

If the enthalpy of the geothermal fluid decreases, as expected, and the available geothermal separated water increases consequently, a potential might be to utilise the excess geothermal water for an additional 16 MW_e in a binary cycle system.

7. FUTURE DEVELOPMENT

When the above six construction stages are completed, it is believed that the geothermal resources at Nesjavellir are nearly fully utilised. Further exploratory work will be carried out especially focusing on the production monitoring and reservoir prediction, to see if further production increase is feasible.

8. CONCLUSION

The Nesjavellir geothermal power plant has been successfully developed into one of the biggest geothermal power plant in the world. It is built to meet both markets for electric and thermal power. The experience, so far, has been quite excellent and the development of the plant has been able to meet the development of the market.

Technically, the modular planning has been quite successful. On the other hand, it is difficult to say if the original modular development plan for the plant has lived up to expectations concerning economical goals. Considering economy it is a fact that the price of hot water for heating in Reykjavik has not been raised during the period of the Nesjavellir plant's development.

The price of electricity in Reykjavik is still unaffected by the competitive energy production cost of the Nesjavellir plant, but the council of Reykjavik has declared that the price will be lowered in the long run as a result of the Nesjavellir geothermal power plant. Therefore, the plant's development has been successful.

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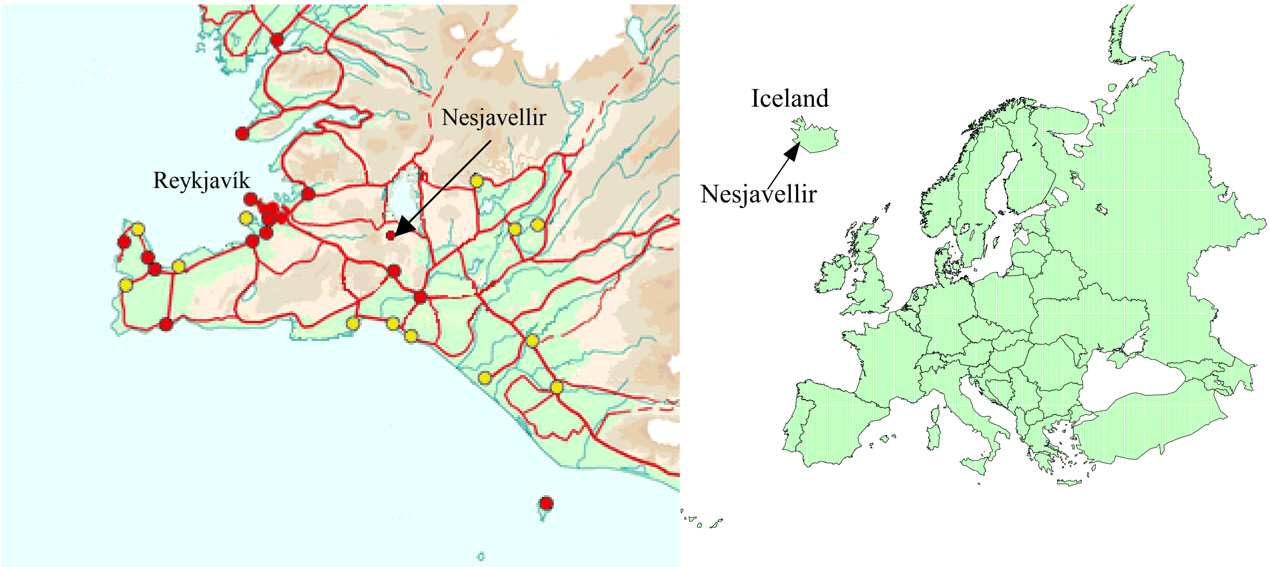

Figure 1. Maps

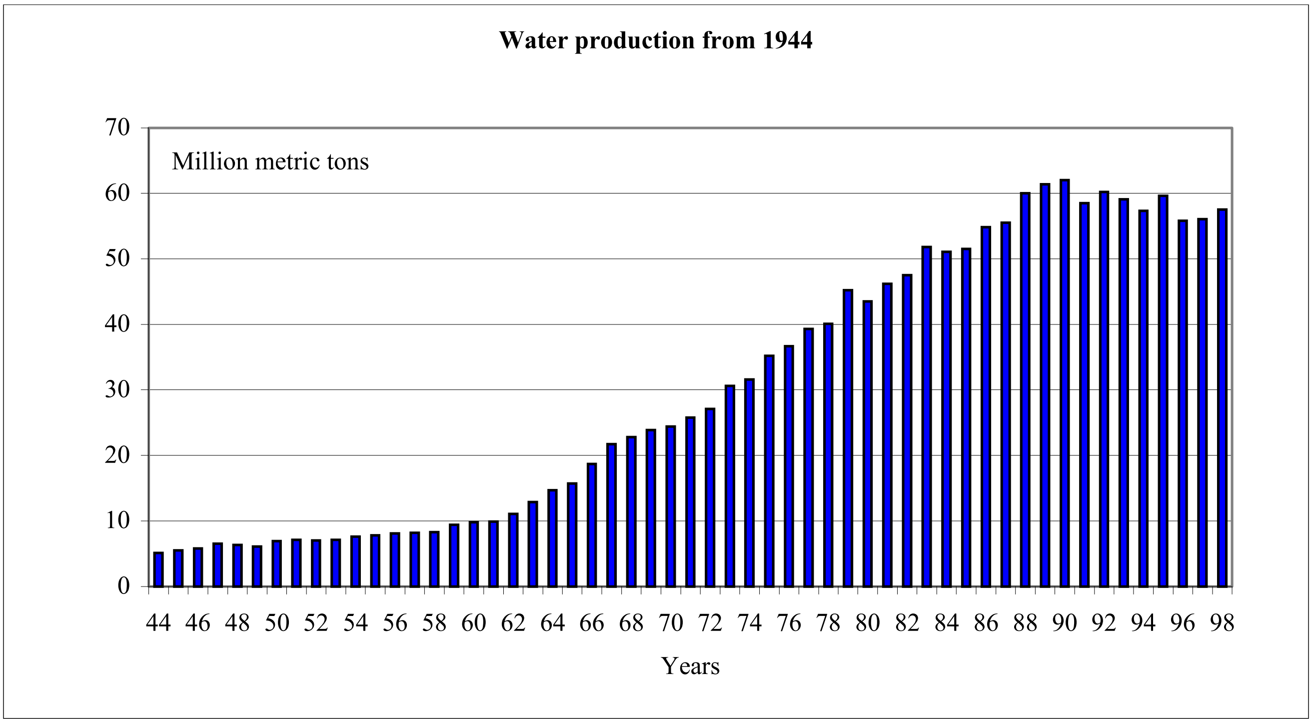

Figure 2. Water production from 1944 to 1998

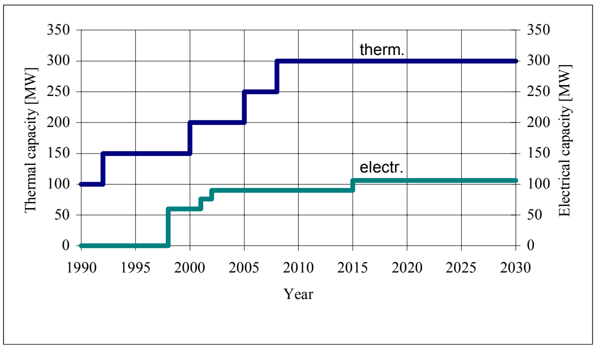

Figure 3. Thermal and electrical capacity of the plant

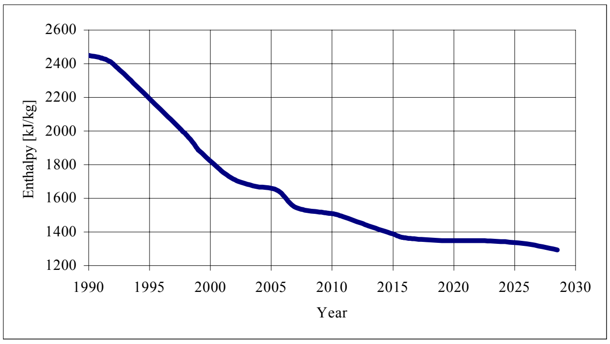

Figure 4. Mean well enthalpy observed and predicted

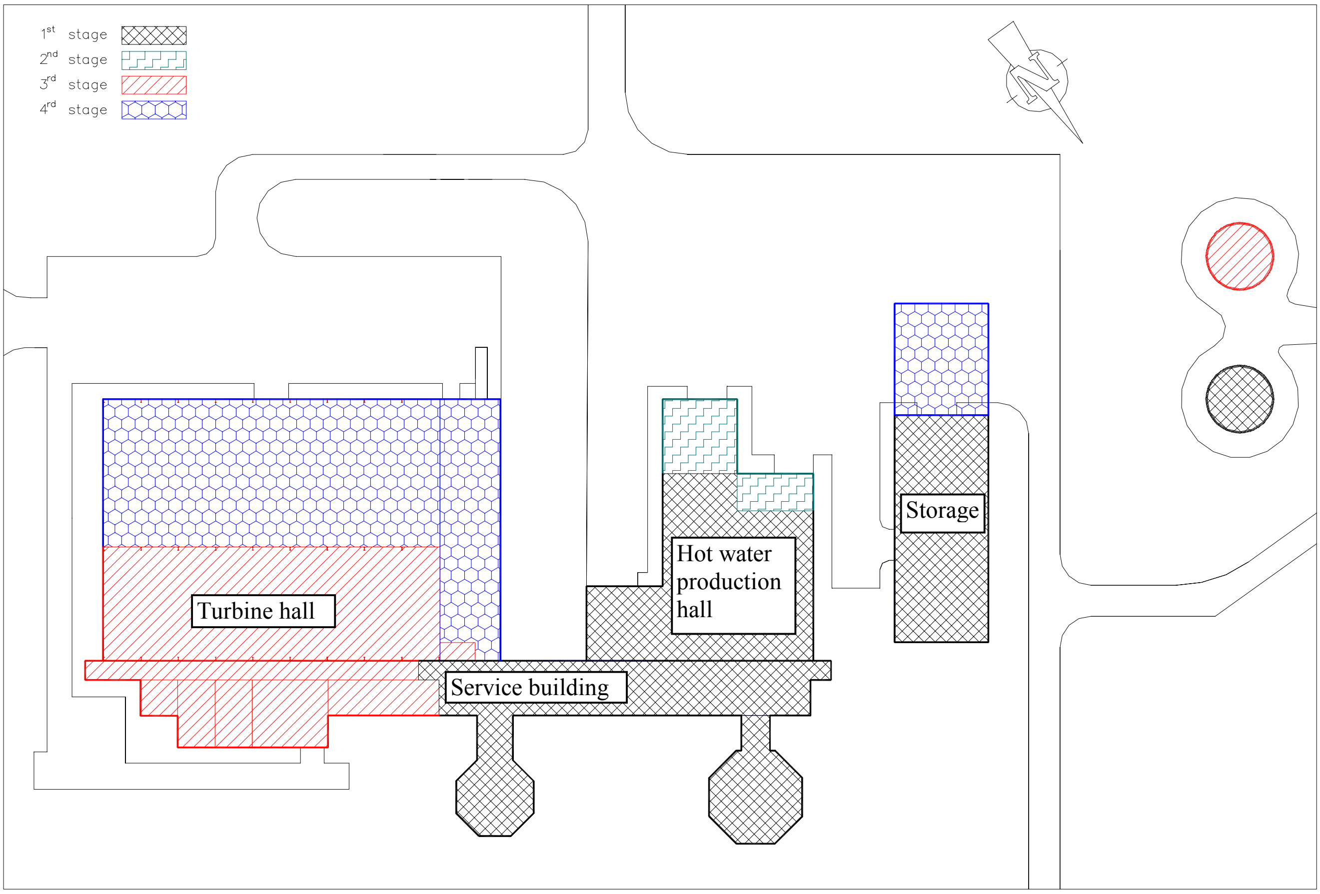

Figure 5. Layout of the power station (status 1999/2000)