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# STIMULATION OF WELL SN-12 IN THE SELTJARNARNES LOW-TEMPERATURE FIELD IN SW-ICELAND

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## ABSTRACT

*Well SN-12 in the Seltjarnarnes low-temperature field in SW-Iceland was drilled to a depth of 2714 m in the fall of 1994. The well appeared to be almost non-productive at the end of drilling. A comprehensive ten day stimulation program was, therefore, initiated. The program involved, firstly, high-pressure wellhead injection and, secondly, high-pressure injection below a packer placed at 1412 m depth. After about twelve hours of wellhead stimulation the pressure dropped suddenly, indicating that the well had been stimulated. At the same time the water level response increased suddenly in two near-by monitoring wells. During the second stimulation phase (packer at 1412 m) the well appeared to be stimulated even further. The well eventually produced about 35 l/s with a drawdown of roughly 60 m, and the stimulation had increased the yield of the well by a factor of nearly 60. Thus well SN-12, which appeared to be almost non-productive at the completion of drilling, had turned into a good production well. It is believed that during the stimulation some previously closed fractures, or interbed contacts, reopened connecting well SN-12 to the main fracture system of the geothermal reservoir.*

## INTRODUCTION

The Seltjarnarnes geothermal field is located within the town of Seltjarnarnes, which is a small suburb to the west of Reykjavík, the capital city of Iceland (Figure 1). The field has been exploited since 1970 and the hot water used for space heating of the town (pop. 4,500). It is a typical low temperature field, with reservoir temperatures ranging from 80°C to over 140°C at 2700 m depth (Tulinius et al., 1987). Drilling in the area started in 1965 and at the end of 1995 twelve wells had been drilled; four production wells, three monitoring wells and five shallow thermal gradient wells (Table 1). The average yearly production has been around 30 l/s since 1991, when the tariff system for space heating was changed from a maximum flow rate system to one based on the energy consumed (Kristmannsdóttir et al., 1995). Before that the average production was around 45 l/s. In 1986 a conceptual model was developed for the Seltjarnarnes geothermal system, followed by a numerical modeling study (Tulinius et al., 1987). In 1994 a second numerical model was developed for the system (Vatnaskil Consulting Engineers, 1994).

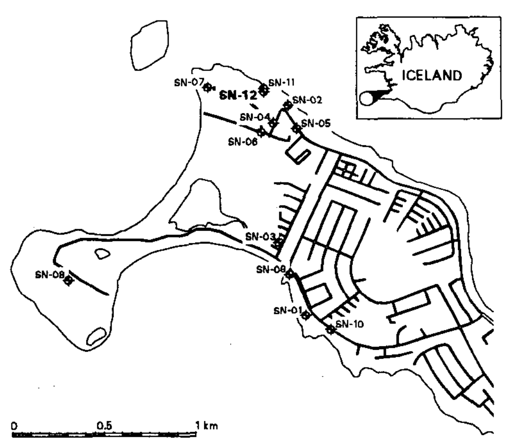


**Figure 1.** *Location of wells in the Seltjarnarnes low-temperature field.*

During the production history of the system the salinity of the produced fluid has slowly increased, due to sea-water infiltration, from about 500 ppm of total dissolved solids to about 3000 - 4000 ppm (Kristmannsdóttir, 1986; Kristmannsdóttir et al., 1995). Because of the high salinity the hot water is mostly used indirectly, i.e. through heat exchangers.

The Seltjarnarnes reservoir rocks are of Quaternary age, 1.8 - 2.8 Ma., dipping towards the southeast. The subsurface rocks may be divided into 8 groups of basaltic lavas and hyaloclastites interbedded by a few sedimentary interbeds and igneous intrusions, the latter increasing in frequency with increasing depth (Tómasson et al. 1977, Tulinius et al., 1987).

The Seltjarnarnes geothermal system consists of 3 - 4 different aquifers, with different temperatures and salinity. Mixing of water from the different feed-zones, within a well, causes calcium carbonate supersaturation of the water. This supersaturation is highest when the colder water from shallow feed-zones mixes with hotter water from the deeper ones. The scaling potential increases with increasing temperature difference between feed-zones. The supersaturation has increased with time and is now at a level where scaling is known to have occurred in other geothermal installations in Iceland.

**Table 1.** *Wells drilled in the Seltjarnarnes field.*

| Well | Drilled | Depth (m) | Type |
|---|---|---|---|
| SN-1 | 1967 | 1282 | Monit. well |
| SN-2 | 1965 | 856 | Monit. well |
| SN-3 | 1970 | 1715 | Monit. well |
| *SN-4* | *1972* | *2025* | *Prod. well* |
| *SN-5* | *1981* | *2207* | *Prod. well* |
| *SN-6* | *1985* | *2701* | *Prod. well* |
| SN-7 | 1994 | 154 | Expl. well |
| SN-8 | 1994 | 153 | Expl. well |
| SN-9 | 1994 | 132 | Expl. well |
| SN-10 | 1994 | 132 | Expl. well |
| SN-11 | 1994 | 145 | Expl. well |
| *SN-12* | *1994* | *2714* | *Prod. well* |

A new production well (SN-12) was drilled in the Seltjarnarnes field in the fall of 1994. The well appeared to be almost non productive at the end of drilling. A comprehensive stimulation program was, therefore, conducted. This paper describes the stimulation of well SN-12, which involved both high-pressure wellhead injection and high-pressure injection below a downhole packer. The paper also describes the results of three production tests carried out prior to and following the stimulation program as well as discussing the results of the stimulation (Axelsson et al., 1994).

Stimulation of geothermal wells, by high-pressure injection, started in the late sixties in Iceland. These operations were so successful that this method was used at the completion of numerous wells during the seventies. A peak in the number of stimulations was reached around 1980, but during the eighties stimulations became less frequent. Three production wells in the Seltjarnarnes field were stimulated during this period. Recently stimulation programs at the end of drilling have again become more frequent (Tómasson and Thorsteinsson, 1975 and 1978; Tómasson et al., 1995).

## DRILLING OF WELL SN-12

Well SN-12 was drilled during the summer and fall of 1994. The purpose was, firstly, to drill a well producing only from the deeper and hotter feed-zones, by casing off the most shallow aquifer. Thus the scaling potential would be reduced as well as the total mass extraction from the field. Secondly, the purpose was to drill a back-up well and to ensure enough hot water for the district heating system during cold periods. Prior to the drilling of well SN-12 five shallow exploration wells were drilled in the area to aid in the location of the new well.

Well SN-12 was cased with a 10 3/4" casing down to a depth of 791 m, to case off the shallower feed-zones. The other production wells are cased to depths of less than 400 m. Drilling of the production part of the well started at the end of August. The final depth of 2712 m was reached on the 7th of October after 45 days of drilling. No serious difficulties occurred during drilling of the approximately 2000 m long production part.

Only minor circulation losses occurred during the drilling of the production part of well SN-12. This was believed to be partly because the well was drilled with a minimum drillstring load, which resulted in very fine drill cuttings clogging the feed-zones intersected. An one hour air-lift test, carried out at the completion of drilling of the well, yielded less than 1.5 l/s with a 150 m water level draw down. In addition, water could only be injected at a very low rate into the well at the end of drilling. It was, therefore, decided to attempt to stimulate the well.

It should be mentioned that during drilling of the other production wells in the Seltjarnarnes field, minor circulation losses were detected. Yet, they were not quite as poorly productive as well SN-12 appeared to be. These wells were improved significantly by stimulation programs at the end of drilling.

The operations carried out during the ten day stimulation program for well SN-12 are listed in Table 2. The stimulation program involved two main phases. Firstly, high-pressure wellhead injection and, secondly, high-pressure injection below a packer at 1412 m depth. In addition the stimulation program involved a few air-lift production tests, step-rate injection tests and cleaning of the well. During the stimulation program a lot of data were collected, which will be discussed in the following two chapters.

## THE STIMULATION PROGRAM

Before the actual stimulation work started, well SN-12 was tested by an one hour air-lift test through the drillstring. In this test the well only yielded 1.5 l/s with a draw-down of 14.8 bars. Based on the pressure build-up following the test, the transmissivity was estimated to be only of the order of $T = 10^{-10} m^3/Pa{\cdot}s$. Originally the plan was to use air-lifting to clean drill cuttings from feed-zones intersected by the well, but the test indicated that this would not be possible.

The first stimulation phase involved wellhead injection of cold water. Two pumps, belonging to the drill rig, had the capacity to inject about 60 l/s, for this purpose. However, only 40 l/s of water were available at the drill site. To achieve the optimum effect on the well, the water containers of the drill rig were used as storage tanks and 60 l/s injected for several one hour periods, each followed by a 30 min break, during which the containers were refilled. Thus the maximum possible wellhead- and downhole pressures were attained.

This first phase started briefly on the 10th of October (Table 2), but had to be discontinued, due to technical problems, until just after 4 p.m. the following day. The injection procedure described above was continued until about 4 a.m. the next morning, when one of the pumps broke down. The wellhead pressure during this period is shown in Figure 2, where it may be seen that a maximum wellhead pressure of 76 bars was attained. Only minor pressure losses are expected in the 10 3/4" casing. At the end of the pumping period prior to the one when the pump broke down, the wellhead pressure dropped suddenly, indicating that the well had in fact been stimulated. This appears to have been a very sudden break-through, rather than a gradual stimulation.

**Table 2.** *Operations during the stimulation of well SN-12 in October 1994.*

| Date | Operation |
|---|---|
| Oct. 10th | One hr. air-lift test |
| | Short wellhead injection |
| Oct. 11-12 | *High-pressure wellhead injection* |
| Oct. 12th | Temperature and caliper logging |
| Oct. 13th | Cleaning of a collapse in well |
| | Step-rate wellhead injection |
| Oct. 14th | Unsuccessful injection below packer |
| Oct. 15-16 | Weekend break |
| Oct. 17th | *High-pressure injection below packer* |
| | Temperature logging |
| Oct. 18th | Step-rate air-lift testing |
| Oct. 19th | Air-lift testing, cont. |
| | Temperature logging |
| | Step-rate wellhead injection |
| | Cleaning of the well |
| Oct. 20th | Air-lift testing |
| | Temperature logging |
| | Final cleaning of the well |

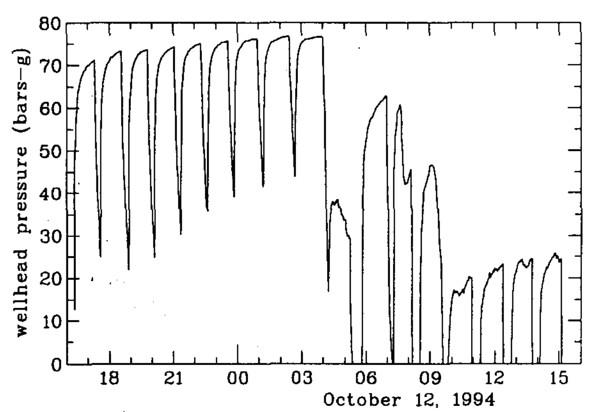


**Figure 2.** *Wellhead pressure during the wellhead injection phase of the stimulation of well SN-12.*

During the stimulation program the water levels in two nearby wells, SN-2 and SN-6 (see Figure 1), were recorded continuously. These data are presented in Figure 3 where the waterlevel variations due to the different operation can clearly be seen, in addition to tidal variations. Greater variations in well SN-6 than in well SN-2 result from the fact that well SN-2 is only 856 m deep, while well SN-6 is about 2700 m. At the moment when well SN-12 appeared to be suddenly stimulated, the amplitude of the waterlevel variations in wells SN-6 and SN-2 also increased suddenly (Figure 4). The average water level amplitude in well SN-6 increased from 0.36 m to 2.15 m, which is an increase by a factor of six. The amplitude was relatively constant before and after the break-through, respectively. Almost no water level oscillations could be seen in well SN-2 prior to the break-through, whereas the average amplitude after the stimulation was about 0.28 m. It should be mentioned that the measurement resolution was much better for well SN-6 than well SN-2.

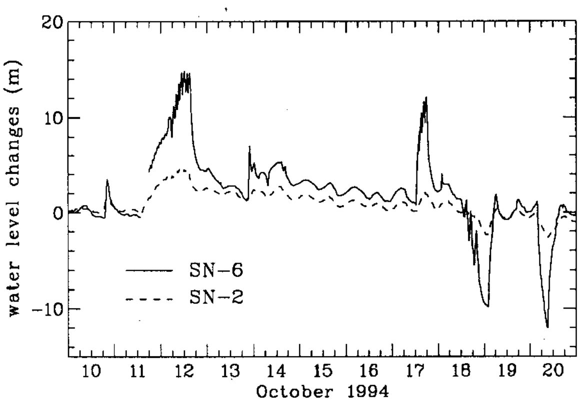


**Figure 3.** *Water levels in wells SN-2 and SN-6 during the stimulation of well SN-12.*

The water level data from wells SN-2 and SN-6 support strongly the assertion that the stimulation appears to have been a very sudden break-through, rather than a gradual increase in permeability. It is believed that this involved the reopening of fractures, or interbed contacts, connecting well SN-12 to the main fracture system of the geothermal reservoir, by removal of alteration minerals, rather than the removal of drill cuttings clogging the feed-zones intersected by the well. It should be mentioned that the gradual stimulation of the well during other stages probably resulted from the removal of drill cuttings.

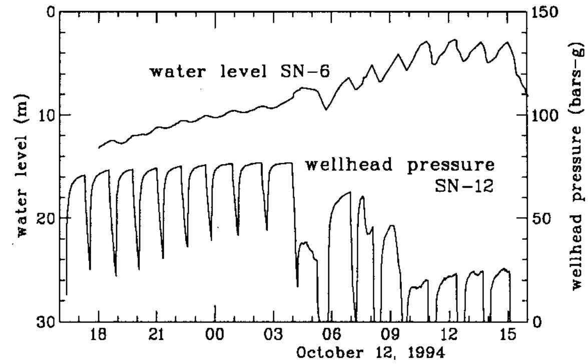


**Figure 4.** *Water level in well SN-6 and wellhead pressure of well SN-12 during the wellhead injection phase.*

The wellhead injection continued for about another 12 hrs. After the pump had been repaired (at about 6:00 a.m.), and the injection increased again to 60 l/s, the wellhead pressure continued to decrease (Figure 2). At about 8 a.m. the pressure dropped suddenly by about 18 bars and at about 10 a.m. the wellhead pressure was down to 23 bars, having reached as high as 76 bars before the break-through. This indicated that the well had been stimulated even further. At the end of this injection phase the pressure started to increase again, and it became evident that the well had collapsed. Therefore, the wellhead injection was terminated and the well temperature and caliper logged in order to determine the depth of the collapse. This concluded the first main phase of the stimulation program.

During the logging an obstruction was found at 2040 m depth. Consequently the drill was used to clean the well. This only took about one day. Minor obstructions were encountered at depths of 2400 m and 2600 m. This operation was concluded at a depth of 2603 m.

To evaluate the success of the stimulation, well SN-12 was briefly tested by injecting water at three different flow rates into the well (step-rate injection test) and monitoring the pressure changes in the well. Each step lasted for about 1 hr. Based on this test the characteristic curve for the well, at that time, was:

$$\Delta p = 0.38 \times Q - 0.0074 \times Q^2 \quad (1)$$

where Δp is the pressure drawdown in bars and Q the flow rate in l/s. The transmissivity was estimated to be of the order T = $10^{-8} m^3/Pa{\cdot}s$, or about 100 times greater than at the end of drilling. This test indicated, however, somewhat lower injectivity than at the end of the wellhead stimulation, most likely because some feed-zones had become clogged by drill-cuttings during the cleaning operation.

The second main phase of the stimulation program involved high-pressure injection below a packer located at depth in well SN-12 (Table 2). This was done to stimulate the lower part of the well further and to clean out feed-zones clogged by drill-cuttings. The depth for the packer, around 1400 m, was chosen on the basis of the available temperature logs from the well (Figure 5), which indicated the existence of feed-zones at the depths of approximately 1070 m, 1250 m, 1600 m and just below 2000 m depth. The 2000 m feed-zone appeared to be by far the biggest. On the basis of caliper logs and borehole lithology the interval between 1250 and 1400 m appeared to be an ideal location for the packer.

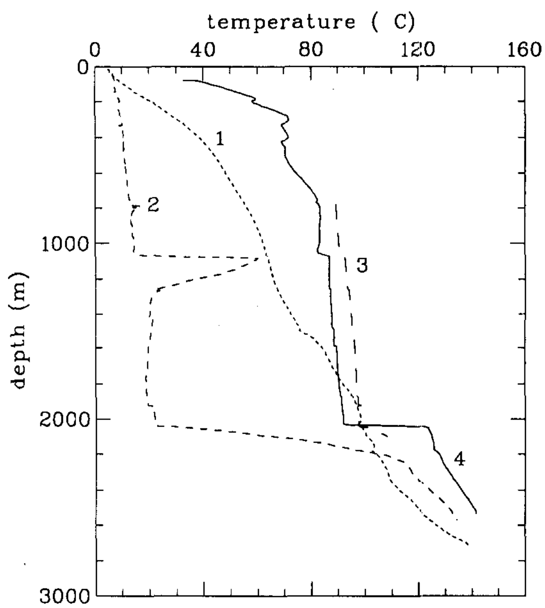


**Figure 5.** *Temperature logs from well SN-12. (1) Prior to the stimulation program (08/10/94), (2) after injection below packer at 1412 m (17/10/94), (3) during final production test (20/10/94) and (4) three months after drilling (27/01/95).*

After a weekend break the stimulation program continued on Monday the 17th of October. The packer was placed at a depth of 1412 m and inflated. Consequently 58 - 59 l/s were injected below the packer during four one hour intervals, each followed by a 20 min break. The wellhead pressure during this operation is shown in Figure 6. The wellhead pressure almost reached 130 bars at the beginning, but after less than an hour it was down to 90 bars and down to 85 bars at the end of this phase. Taking the pressure loss in the drill string into account the pressure below the packer went from about 85 bars at the beginning down to 40 bars. This apparent stimulation is believed to be due to the removal of drill cuttings clogging feed-zones, below 1412 m depth, rather than a sudden break-through as is believed to have occurred in the earlier stimulation phase. This concluded the second main phase of the stimulation program.

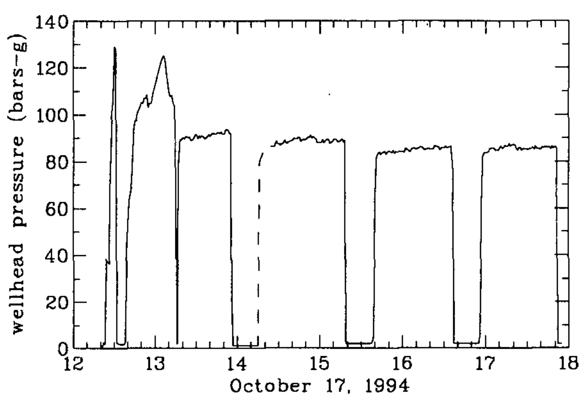


**Figure 6.** *Wellhead pressure during injection below a packer at 1412 m depth in well SN-12.*

## PRODUCTION TESTING OF WELL SN-12

In addition to the brief air-lift test at the end of drilling and the step-rate injection test on the 13th of October, well SN-12 was thoroughly tested at the conclusion of the stimulation program (Table 2). This was done to estimate the production potential of the well. Firstly, the well was tested by air-lifting through the drill-string for about ten hours on the 18th and 19th of October. This test was done in four steps, with the drill string at different depths. The flow-rate varied between steps, from 12 l/s up to almost 30 l/s. The down-hole pressure was measured during the test, and the pressure drawdown varied from about 1.5 bars to almost 6 bars. Thus it was clear that the productivity of the well had improved drastically. The results of this test are presented in Figure 7, which shows the pressure draw-down vs. flow-rate about one hour into each step. At the time the characteristic curve for the well was given by:

$$\Delta p = 0.083 \times Q - 0.0036 \times Q^2 \qquad (2)$$

where $\Delta p$ is the pressure drawdown in bars and Q the flow rate in l/s.

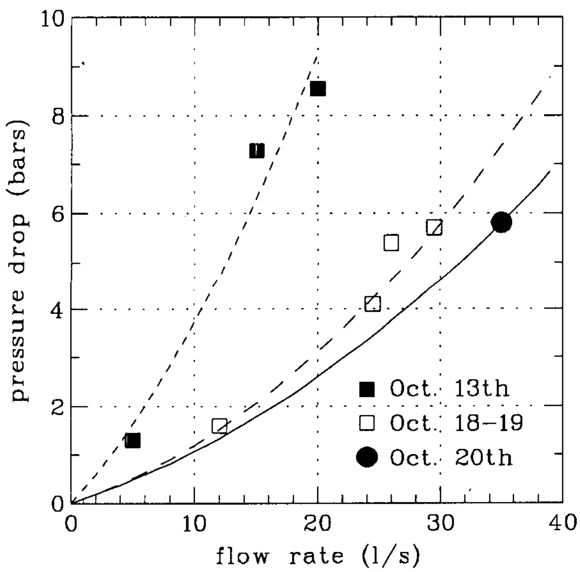


**Figure 7.** *Results of production testing of well SN-12. Symbols show observed data one hour into each step while lines show calculated output characteristics.*

A temperature log (see Figure 5) measured after this test showed that the well had collapsed again, this time at a depth of 2033 m. A short injection test (Table 2) also indicated a drastic drop in injectivity. Therefore, it was obvious that a feed-zone at a depth of 2040 m was the main feed-zone of the well. Following this the collapse was cleaned out and a second drill string air-lift test performed. This was a one step test, which took about 5.5 hrs. The results of the test are presented in Figure 7. They indicated that the productivity of the well had increased further following the cleaning. It is believed that this increase is due to reduced turbulence losses at the main feed-zone (the second term in equations (1), (2) and (3)), and that the well had collapsed because of material falling into the well from this zone. The well eventually produced about 35 l/s with a draw-down of roughly 60 m. Comparing this result with the results of the first air-lift test, indicates that the stimulation had increased the yield of the well by a factor of nearly 60. The characteristic curve for well SN-12, fully stimulated, is given by:

$$\Delta p = 0.083 \times Q - 0.0024 \times Q^2 \qquad (3)$$

where $\Delta p$ is again the pressure drawdown in bars and Q the flow rate in l/s.

Water level data were collected in wells SN-2 and SN-6 during the whole stimulation program, as mentioned earlier (Figure 3). The interference observed in well SN-6 during the final air-lift testing of well SN-12 was analyzed to estimate the hydrological properties of the Seltjarnarnes reservoir. The observed and simulated interference data are presented in Figure 8. The transmissivity was estimated to equal $T = 6.3 \times 10^{-8} m^3/Pa \cdot s$, and the storage coefficient to be $S = 3.5 \times 10^{-9} m^3/Pa$. This corresponds to a permeability thickness of 15 Dm. The transmissivity may be compared to older estimates which are in the range of $3.2 \times 10^{-8} m^3/Pa \cdot s$ to $40 \times 10^{-8} m^3/Pa \cdot s$ (Tulinius et al., 1987). The storage coefficient is small, which indicates that the permeability is limited to a thin fracture-zone, perhaps of the order of 50 - 100 m.

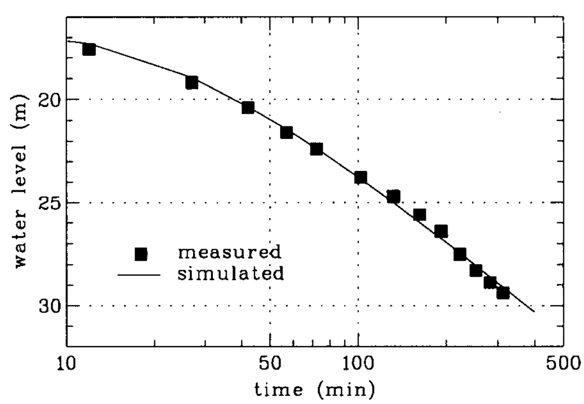


**Figure 8.** *Observed and simulated interference in well SN-6 during the final air-lift testing of well SN-12.*

The estimated hydrological properties, along with equation (3), were finally used to predict the draw-down in well SN-12 after 1 - 2 weeks of production from the well. The results are presented in Figure 9.

To estimate the depth to the water level in the well, on the basis of this figure, one must add the draw-down to the water level in the system at the corresponding time. During the winters of 1993 and 1994 the system water level was always above about 50 m. Therefore, the well may be expected to yield up to 37 l/s, during the next winters, with a pump at a depth of 150 m. These results were confirmed by a one week production test, conducted about a year after drilling of the well.

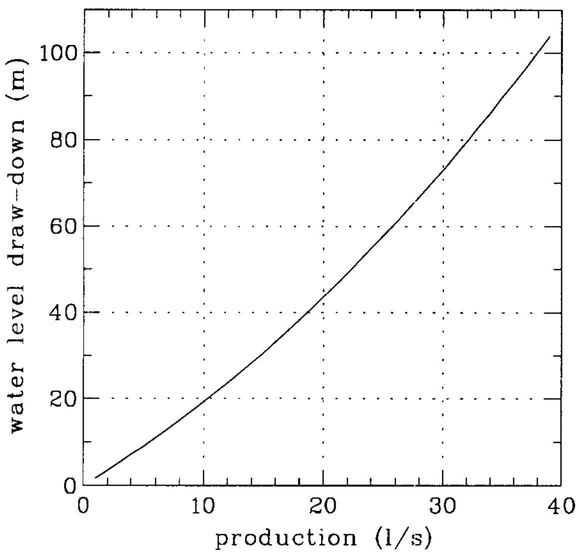


**Figure 9.** *Predicted water level draw-down in well SN-12 as a function of production. The figure applies after 1 - 2 weeks of production.*

Twenty temperature logs are available from well SN-12. A few selected examples are presented in Figure 5. Several aquifers can be seen in these logs and the aquifer at 2040 m depth is the most pronounced. At the time of the last measurement, performed three months after the end of drilling, the bottom hole temperature was above 140°C and the temperature of the 2040 m aquifer was about 125°C. The smaller feed-zone at 1070 - 1080 m appears to have a temperature of 85 - 95°C. There is clearly a down-flow in the well, from this feed-zone down to the one at 2040 m depth.

## CONCLUSIONS

Well SN-12 in the Seltjarnarnes field in SW-Iceland appeared to be almost non-productive at the completion of drilling. A comprehensive stimulation program, described in this paper, turned the well into a good production well. The main conclusions of this work are the following:

- The productivity of the well increased by a factor of almost 60 during the stimulation.
- The main feed-zone of the well is at a depth of 2040 m, possibly with a temperature of about 125 - 130°C. A smaller feed-zone at 1070 - 1080 m has a temperature of 85 - 95°C.
- The well collapsed three times during the stimulation program. Each time the obstructions were located close to the main feed-zone and easily cleaned out by the drill.
- Based on the interference between wells SN-12 and SN-6, the transmissivity of the Seltjarnarnes reservoir is estimated to equal $T = 6.3\times10^{-8} m^3/Pa{\cdot}s$. The permeability appears to be limited to a thin layer or zone.
- The well is expected to yield up to 37 l/s, during the next winters, with a pump at a depth of 150 m.

Well SN-12 has been produced continuously since the 20th of November 1995. The production has been 26 l/s on the average with a draw-down of about 50 m. The water temperature has been rising slowly, having reached 107°C by the second week of January 1996. This is somewhat lower than anticipated prior to drilling, but the temperature is still rising. Therefore, it is not clear at the present time whether all the goals of drilling the well have been achieved.

Finally it should be emphasized that stimulation programs, similar to the one described here, used to be a part of most geothermal drilling operations in Iceland. During the last decade such programs have, however, been scarce. The success of the stimulation of well SN-12 has increased the interest in stimulation work, and will hopefully make stimulation programs again an integral part of geothermal drilling in the future, in Iceland and elsewhere.


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