Proceedings World Geothermal Congress 2015
Melbourne, Australia, 19-25 April 2015

Discharge Testing of Magma Well IDDP-1

Kristján EINARSSON, Karl E. SVEINSSON, Kristinn INGASON, Vilhjálmur KRISTJÁNSSON, Sveinbjörn HÓLMGEIRSSON

Landsvirkjun, Háaleitisbraut 68, 103 Reykjavík, Iceland

kristjan.einarsson@landsvirkjun.is

Keywords: IDDP, Magma, Krafla, Iceland

ABSTRACT

Well IDDP-1 in Krafla, Iceland, was the first well drilled in the Icelandic Deep Drilling Project (IDDP). The target depth of 4000-5000m was not achieved as the well was drilled into magma at a depth of 2100m and further drilling was not possible. The well was completed with a cemented 9 5/8" production casing to 1950 m and a 9 5/8" slotted liner from 1950 m to 2072 m depth. The well was flow tested from March 2010 to July 2012. The well proved to be very powerful with max flow rate of 40-50 kg/s at 40-80 bar wellhead pressure and max temperature of 450°C at 140 bar wellhead pressure which is the highest recorded temperature for a flowing geothermal well. The super-heated steam from the well contained hydrogen chloride and dissolved silica which caused corrosion and erosion to casing and surface equipment. To address the different challenges which emerged during the flow testing period, several modifications were needed to the wellhead and flow line. Continuous monitoring of the well was required to ensure the integrity of surface equipment and area and personnel safety and a HSE program was specially adapted to the situation. Lessons learned from the IDDP-1 flow testing form the basis for well, wellhead and flow line designs for future magma-enhanced geothermal wells.

1. INTRODUCTION

The main purpose of the Icelandic Deep Drilling Project (IDDP) is to find out if it is economically feasible to extract energy out of hydrothermal systems at supercritical conditions. The project is a consortium of three of the leading energy companies in Iceland (Landsvirkjun, HS Orka, Orkuveita Reykjavíkur) together with the Icelandic Energy Authority (OS). The industrial and scientific partners in the project are Alcoa (2007), Statoil (2008), ICDP (2001) and US NSF (2005) for coring and scientific studies.

The first well drilled in the IDDP is IDDP-1 in Krafla, NE Iceland, completed in 2009. The aim was to drill a 4-5 km deep well possibly into a 400-600°C (752-1112°F) supercritical hydrous fluid system. However, at a depth of around 2100m magma was encountered, and despite two sidetracks, further drilling was not possible. The final depth of the well was 2104m.

Although the goal to drill a 4-5km deep well was not achieved, temperature conditions at the bottom of the well were nonetheless of great interest to the IDDP due to the proximity of magma (>900°C). After drilling completion, the well was cooled extensively and allowed to heat up slowly. The initial flow test began in March 2010 and continued with several modifications to the wellhead and flow discharge equipment until July 2012, when both the wellhead master valves failed.

IDDP-1 proved to be both an extremely powerful and difficult well to control. Maximum flow was in the range of 40 – 50 kg/s of superheated steam with an enthalpy of around 3200 kJ/kg. The fluid was highly corrosive. Erosion of wellhead equipment was also an initial problem. Due to failure of flow control valves at maximum flow conditions, the flow was restricted to 7-12 kg/s to conduct research on the fluid. During this phase of the project, the well flowed continuously with short repair intervals from September 2011 to July 2012, when the well was quenched due to failure of master valves. During this phase the WHP was maintained at ~ 140 bar and WH temperature was fairly constant at around 450°C. To our knowledge, these are among the most extreme conditions of any flowing geothermal well to date.

Although the project did not achieve its original aims it nonetheless proved to be a valuable milestone in the quest for more powerful geothermal wells. Many lessons from IDDP-1 are now incorporated into the planning of the next IDDP well. But there are also technical issues yet to be fully answered. Chief among them is to identify suitable valves for these extreme conditions and whether casing design and material selection should be revised.

2. DISCHARGE HISTORY

The discharge of the well was executed in phases during a more than two year period. Every new phase introduced minor to major changes in wellhead discharge pipeline from the previous phase (i.e. from restricted to full flow and back to restricted flow in the final phase). The flow was controlled with series of orifices in each phase. An overview of the discharge history of IDDP-1 is presented in Table 1.

Table 1: History of Well IDDP-1

Discharge Phase	Date	Arrangement	P [bar]	T [°C]	h [kJ/kg]	m [kg/s]	Remarks
I	Mar 22-31, 2010	Figure 1	70 – 120	285 – 325	2700 (?)	30 (?)	Two phase flow
II	May 11 – Aug 24, 2010	Figure 4	20	210 – 380	2700 – 3200	30	Superheated from May 18, erosion
III	May 17, May 25, 2011	Figure 7	55-70	340-390	3030-3130	>50(?)	Extreme vibration
IV	Aug 9 – 11, 2011	Figure 10	40 – 80	320 – 380	3000 – 3100	42 - 48	Failure of ø12" valve, debris from down-hole block orifice
V	Sep 28, 2011 – July 24, 2012	Figure 13	138 – 142	380 - 440	3000 – 3150	7 – 12	Restricted flow, SiO_2 precipitation

The first discharge took place on the 22nd of March in 2010, and prior to that, the well had been heating up since August 2009. The initial flow testing was performed in order to ensure that the well would flow and to gather fluid information. The well discharged in two phase flow for about 10 days, and it was estimated that the flow was nearly 30 kg/s. The fluid did not become superheated during this time. The arrangement at the well head and the discharge system is shown in Fig.1. Result of temperature and pressure measurements can be seen in Fig. 2 and evaluated enthalpy in Figure 3.

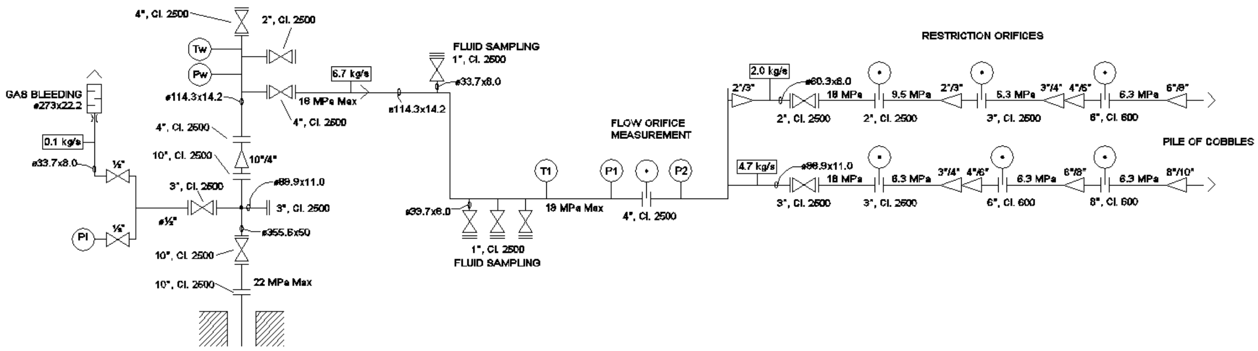

Figure 1: Phase I, initial arrangement of discharge wellhead through DN100 pipeline

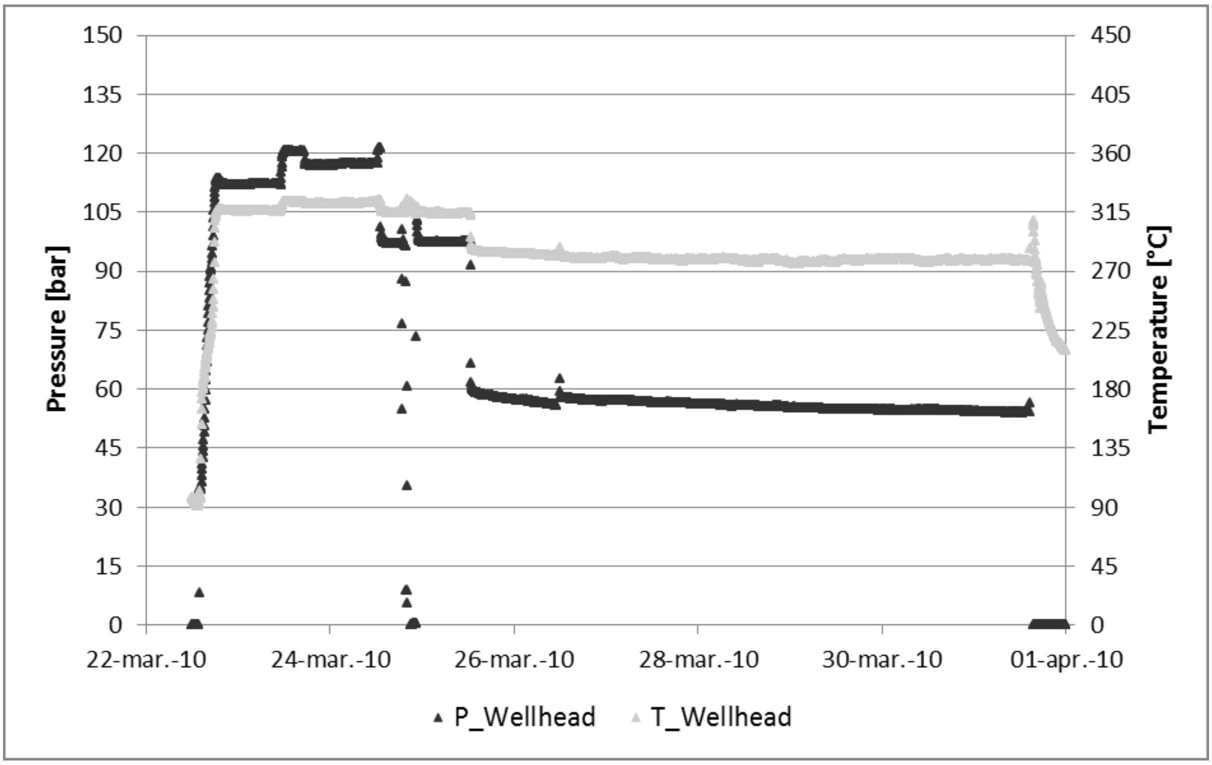

Figure 2: Results of measurements in Phase I

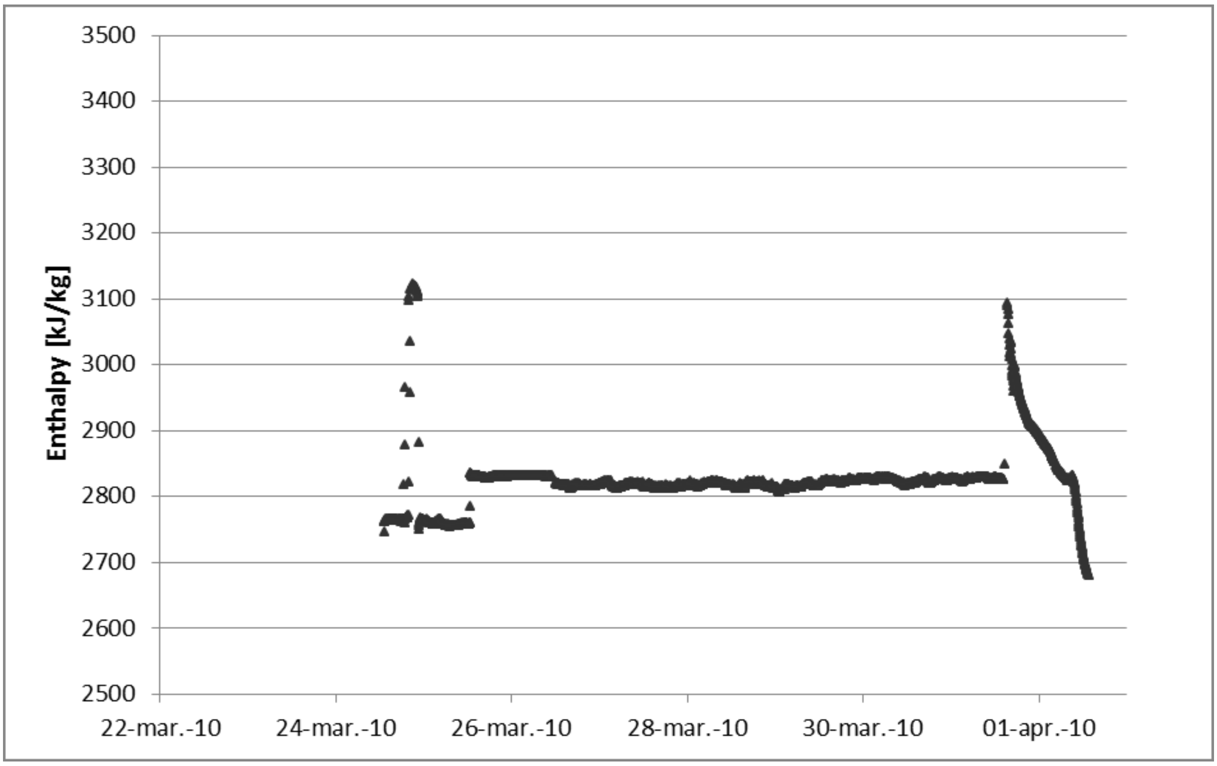

Figure 3: Enthalpy evaluated from measurements in Phase I

In phase II, it was decided to discharge the well at full flow and changes were made to the discharge line accordingly, as indicated in Fig.4. The well discharged for about 3 months during the summer of 2010 and proved to be very powerful, discharging approximately 30 kg/s of superheated steam having an enthalpy of close to 3200 kJ/kg as can be seen in Fig. 6. Temperature and pressure measured during this time are shown in Fig. 5 and evaluated enthalpy in Fig. 6.

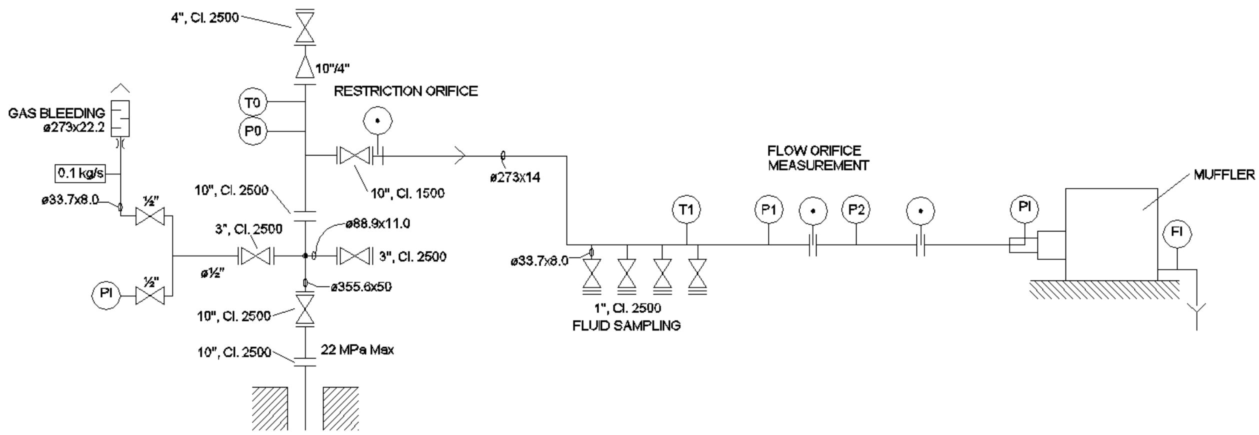

Figure 4: Discharge system in Phase II.

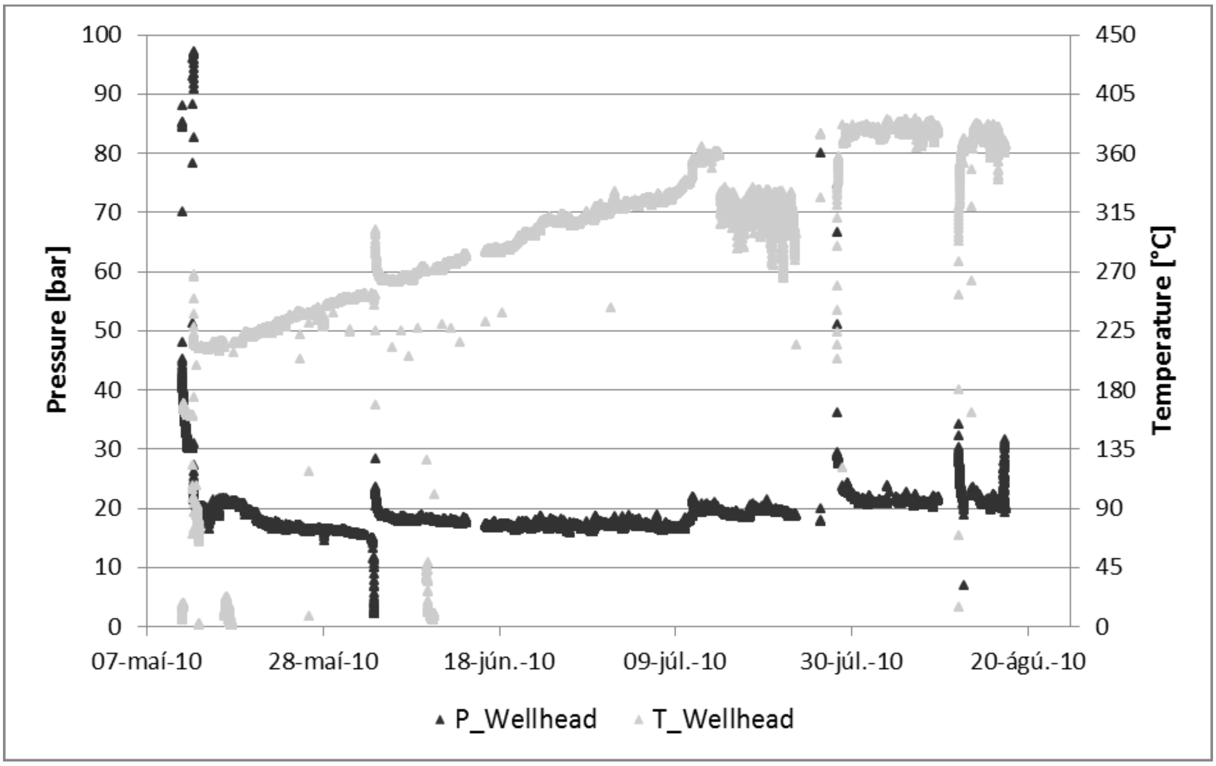

Figure 5: Results of measurement in Phase II

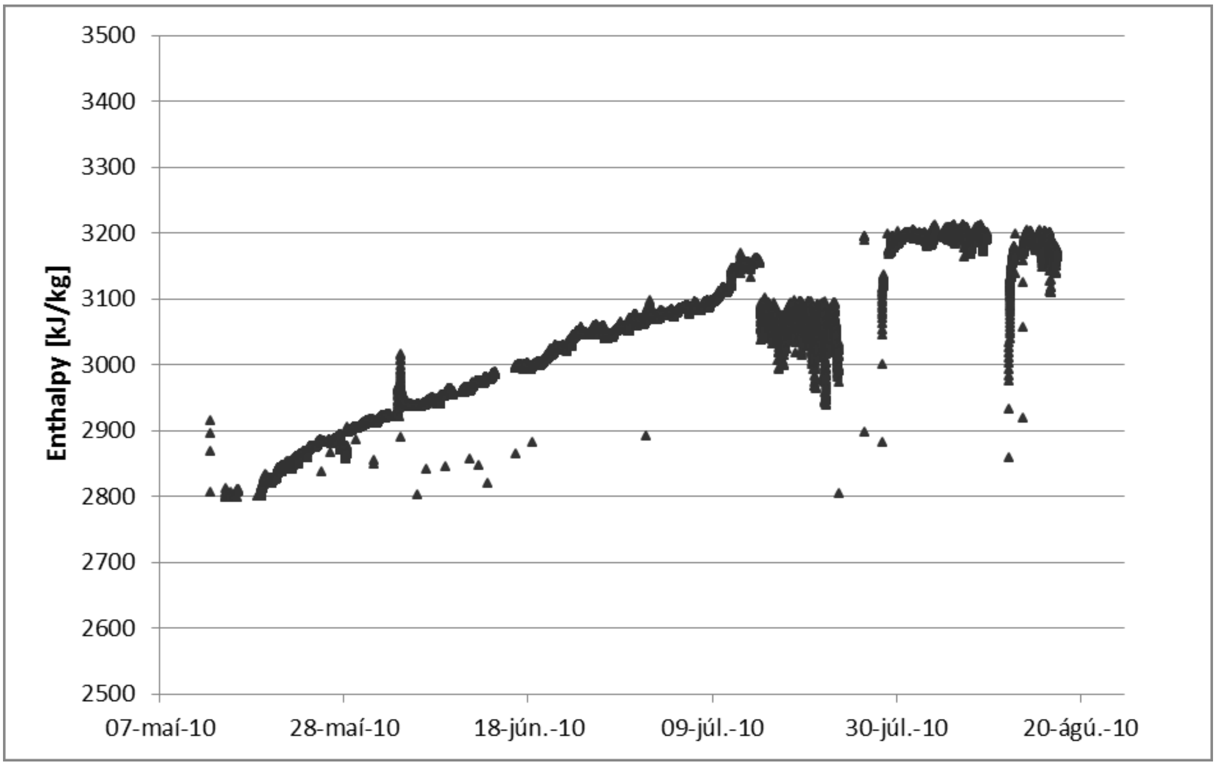

Figure 6: Enthalpy evaluated from measurement in Phase II

Phase III consisted of two short discharges that took place on May 17 and May 25 in 2011. The discharge system had been redesigned to keep steam velocity and well head pressure manageable, Fig. 7. Surprisingly, the well discharged at an estimated flow of about 50 kg/s on both occasions. Intense vibration during these discharges resulted in damage of pipelines and equipment. The most likely source of the vibration was the orifice controlling the flow from the well head where the flow was critical. Measurements taken during the discharge are shown in Figures 8 and 9.

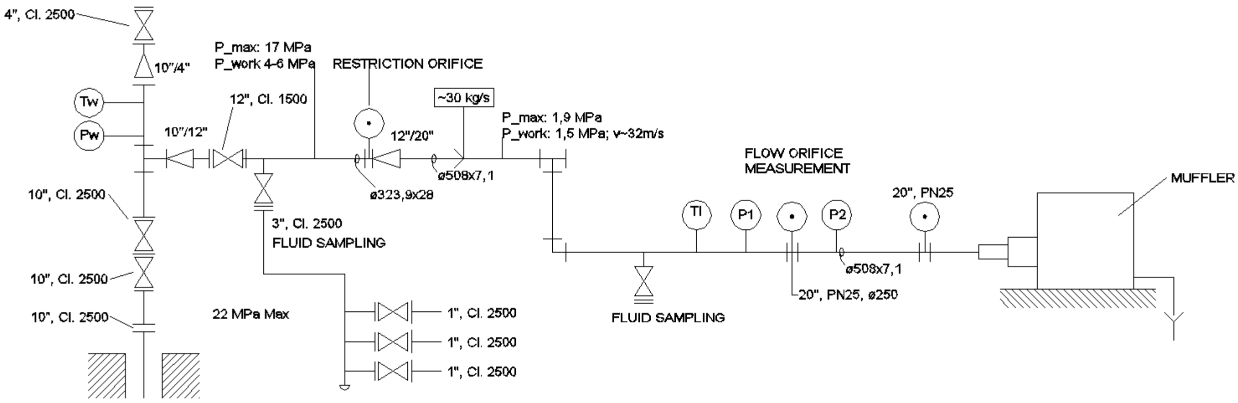

Figure 7: Discharge system in Phase III

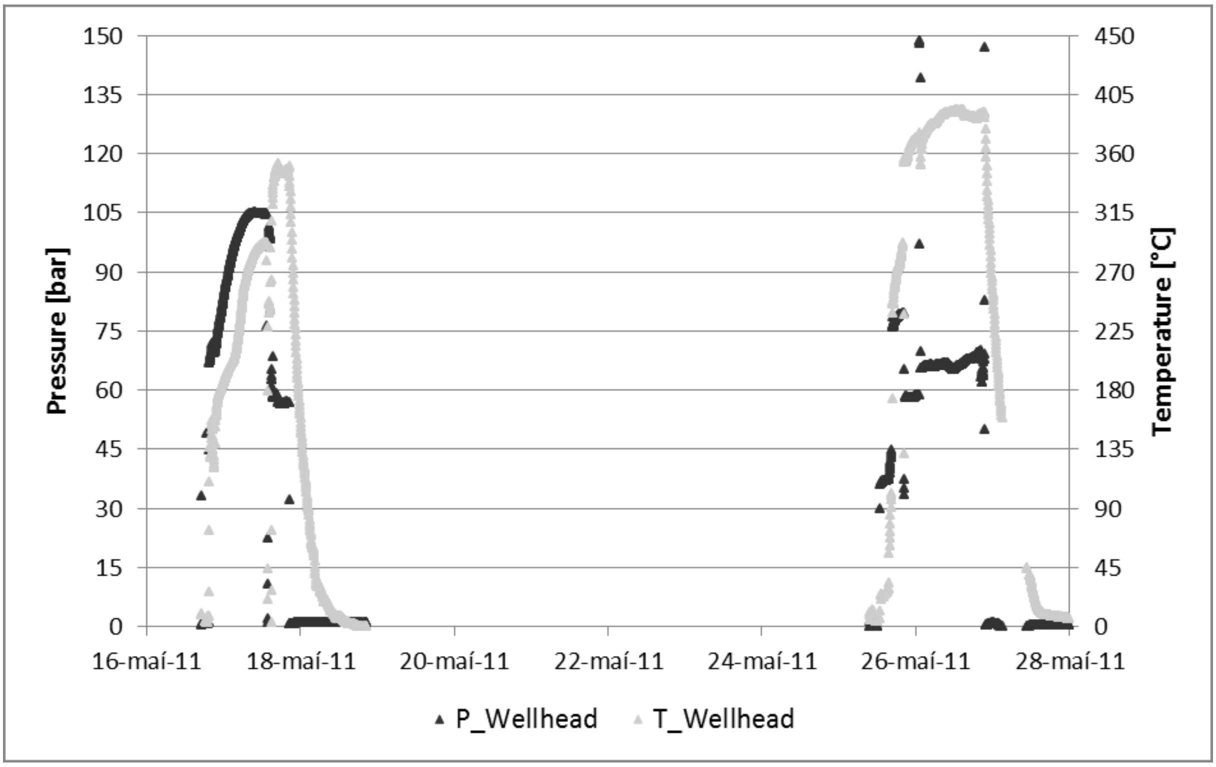

Figure 8: Result of measurement during the discharge in Phase III

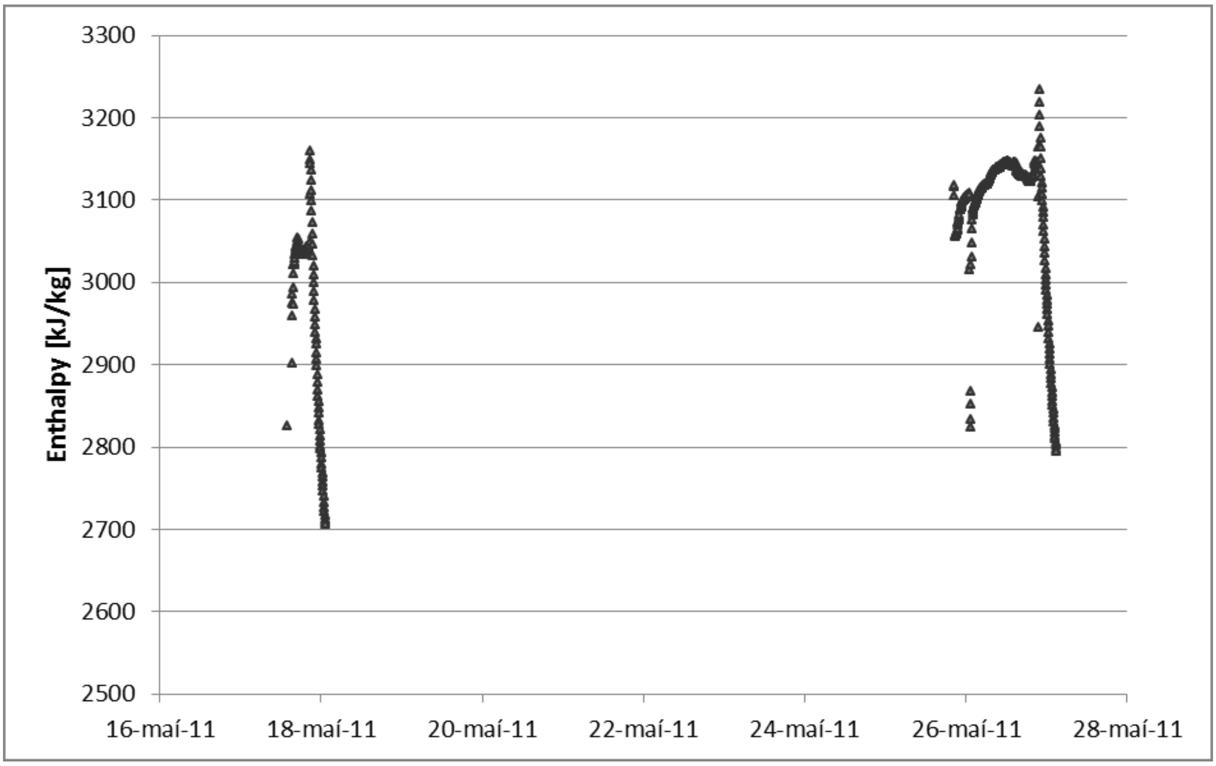

Figure 9: Enthalpy evaluated from temperature and pressure measurements in Phase III

During phases I-III it was necessary to shut for the flow (shut the well in) during maintenance or for other service. Repeated heating and cooling of the well casing was therefore inevitable. Another load factor on the casing was acid condensate. To eliminate the need to completely shut the well in a secondary discharge line was installed prior to start of phase IV, Fig. 10.

Discharge of Phase IV started on August 11 and lasted for 2 days (Figures 11 and 12). It revealed problems of discharging the well at full flow as the steam carried debris and corrosion residue from the sacrificial casing which resulted in clogged orifices and damaged valves.

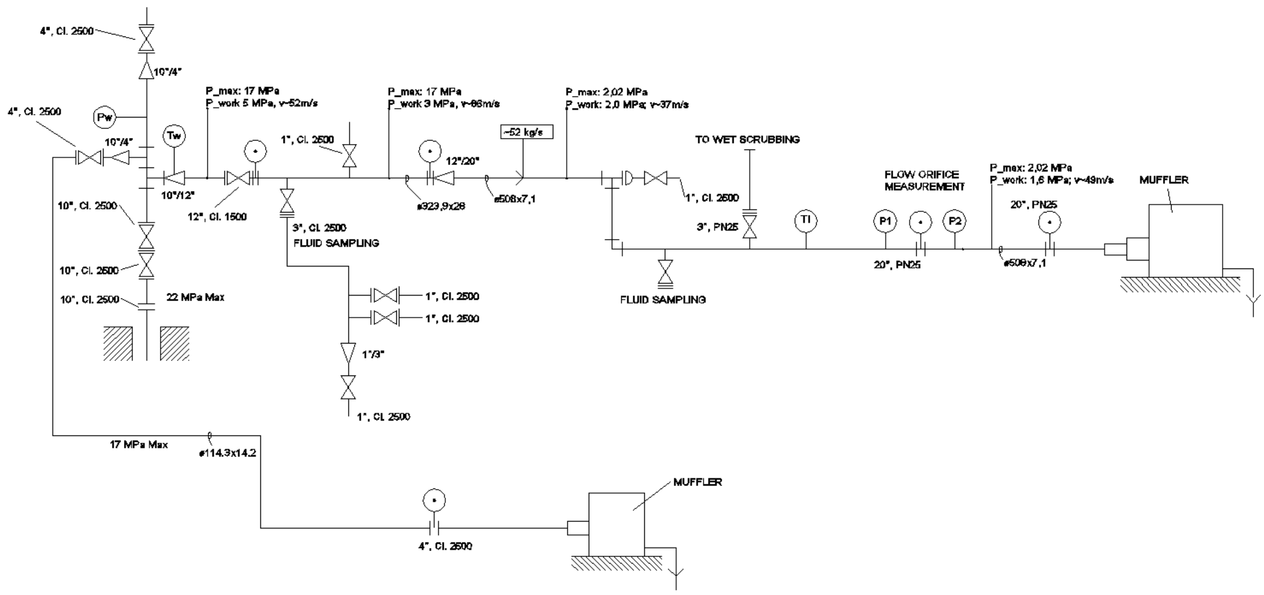

Figure 10: Discharge system in Phase IV

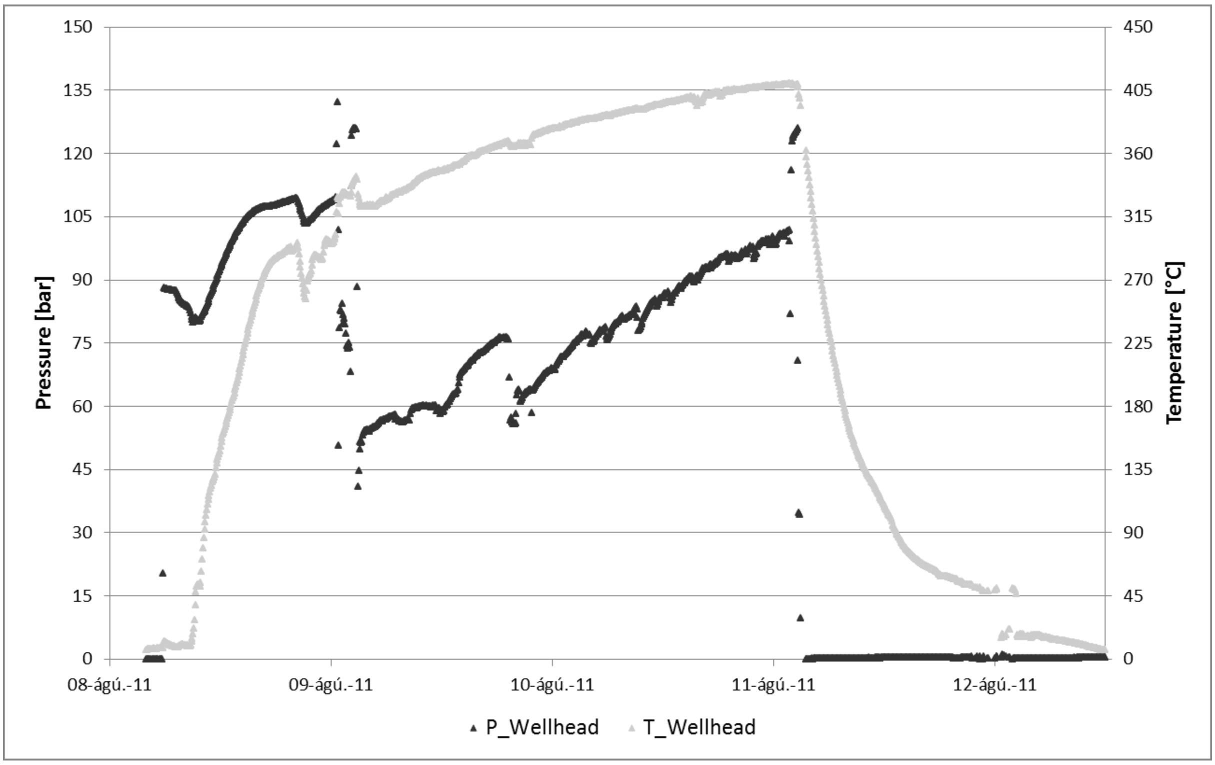

Figure 11: Result of measurements in Phase IV. Rising pressure during discharge indicates blockage in the first orifice due to debris

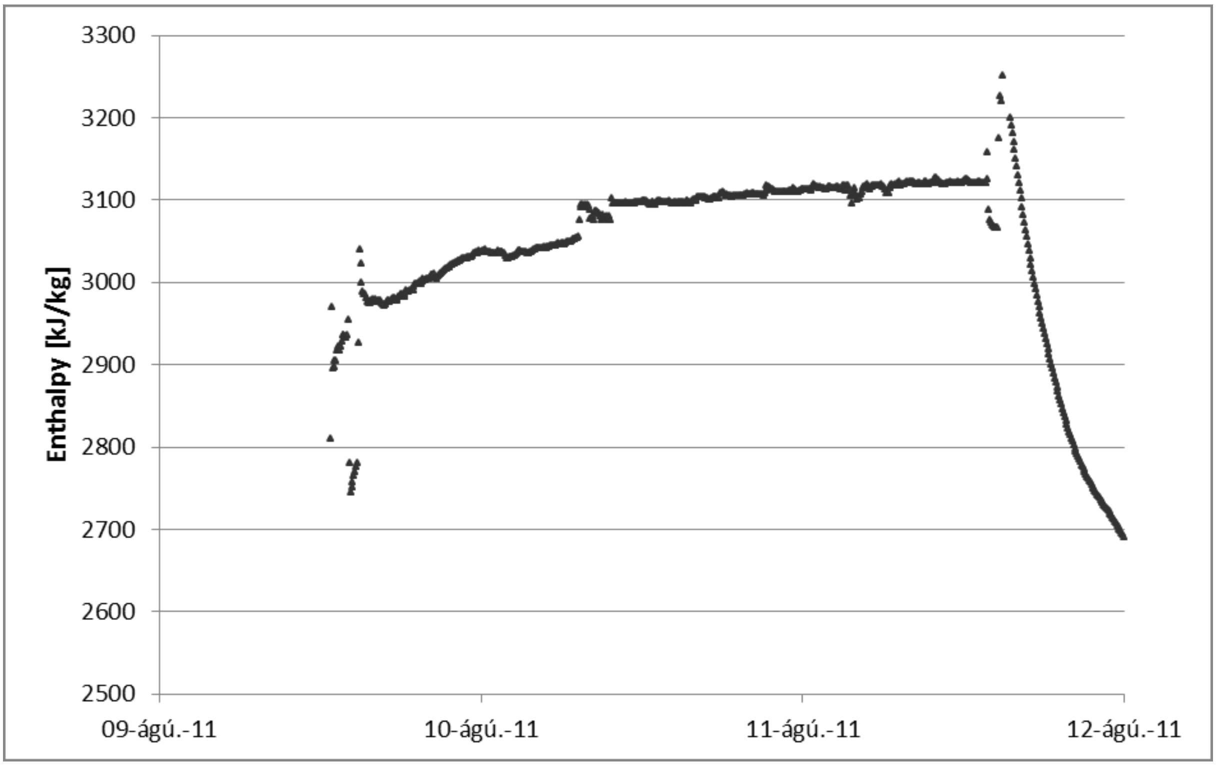

Figure 12: Enthalpy evaluated from temperature and pressure measurements in Phase IV.

Consequently a decision was made to restrict the flow to 8 – 12 kg/s for the next phase, Fig. 13. Size of valves used for discharge was reduced. Discharge of Phase V started in late September of 2011. Initial problems due to silica scaling in orifices were overcome and eventually led to the longest continuous discharge of the IDDP-1 well or for about 10 months. Results of measurement during the discharge of Phase V are shown in Figure 14 and 15.

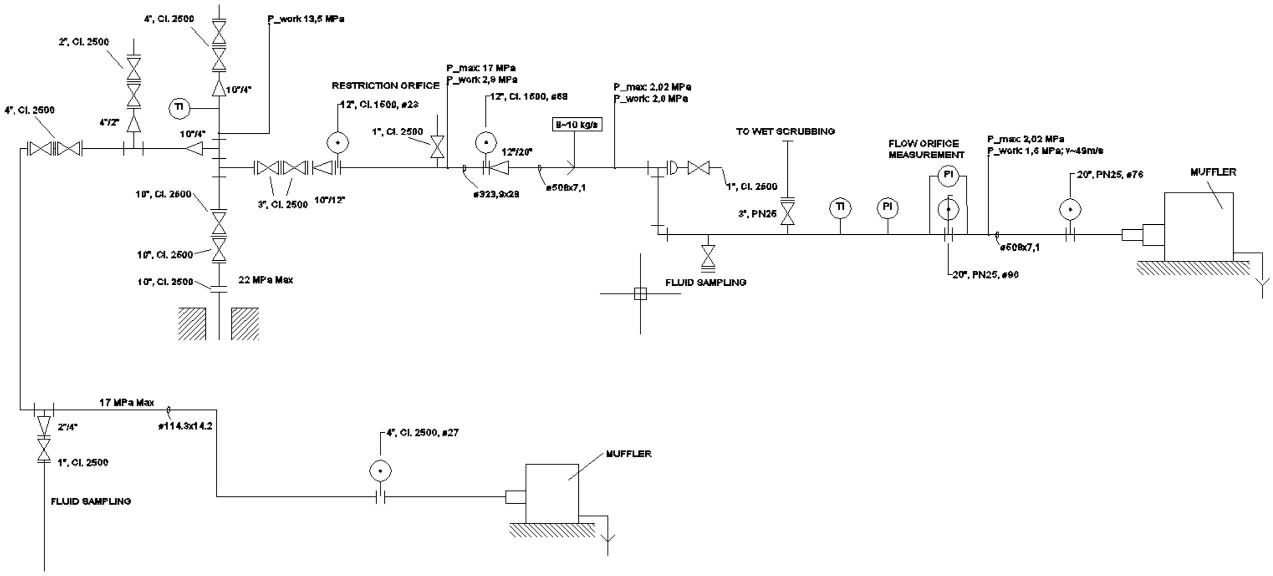

Figure 13: Discharge system in Phase V

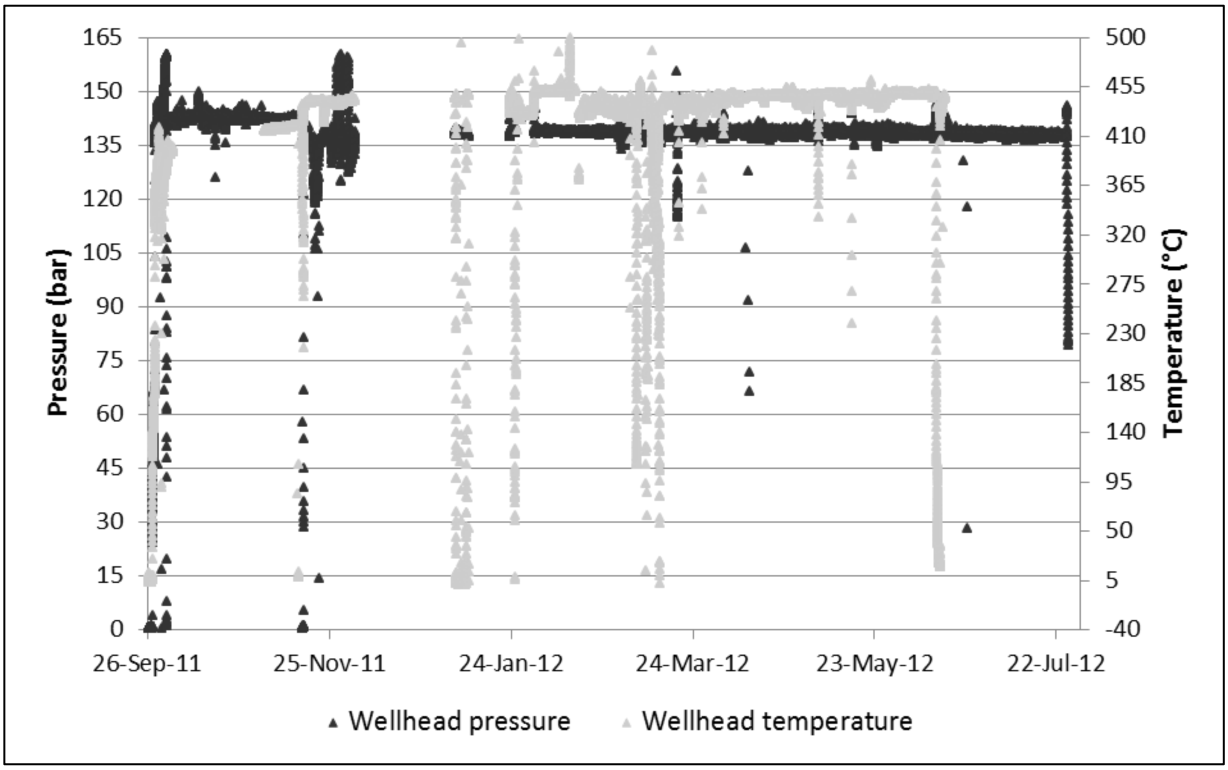

Figure 14: Result of measurements in Phase V. Absence of temperature measurements is caused by faulty sensor.

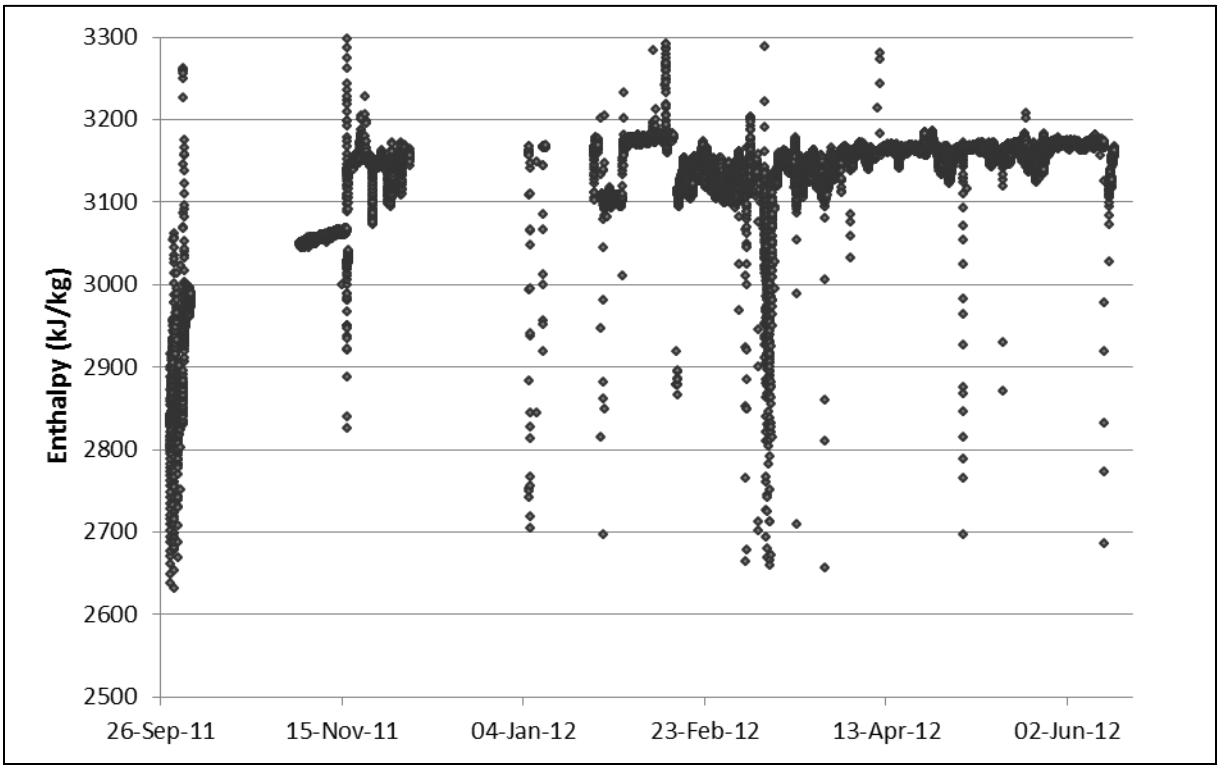

Figure 15: Enthalpy evaluated from temperature and pressure measurements in Phase V.

Work was in progress to utilize the well for power production when a failure in wellhead equipment led to the need to kill the well with water injection in late July 2012.

During the discharge in 2011, the flow of steam was measured at different well head pressure. From these measurements the well characteristics have been evaluated as presented in Figure 16. The rise or height of the well head was monitored regularly throughout the entire discharge history. The results of these measurements are presented in Figure 17.

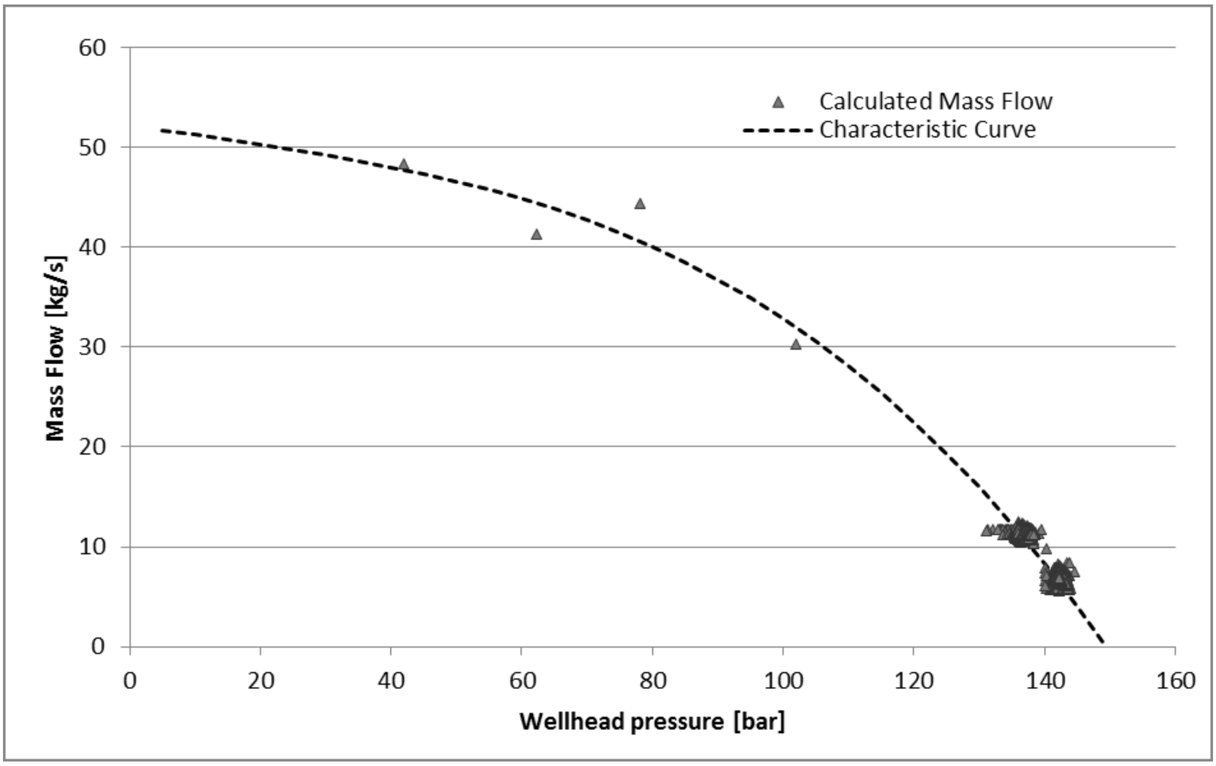

Figure 16: Characteristic curve for IDDP-1 derived from measurements during the various discharges in 2011.

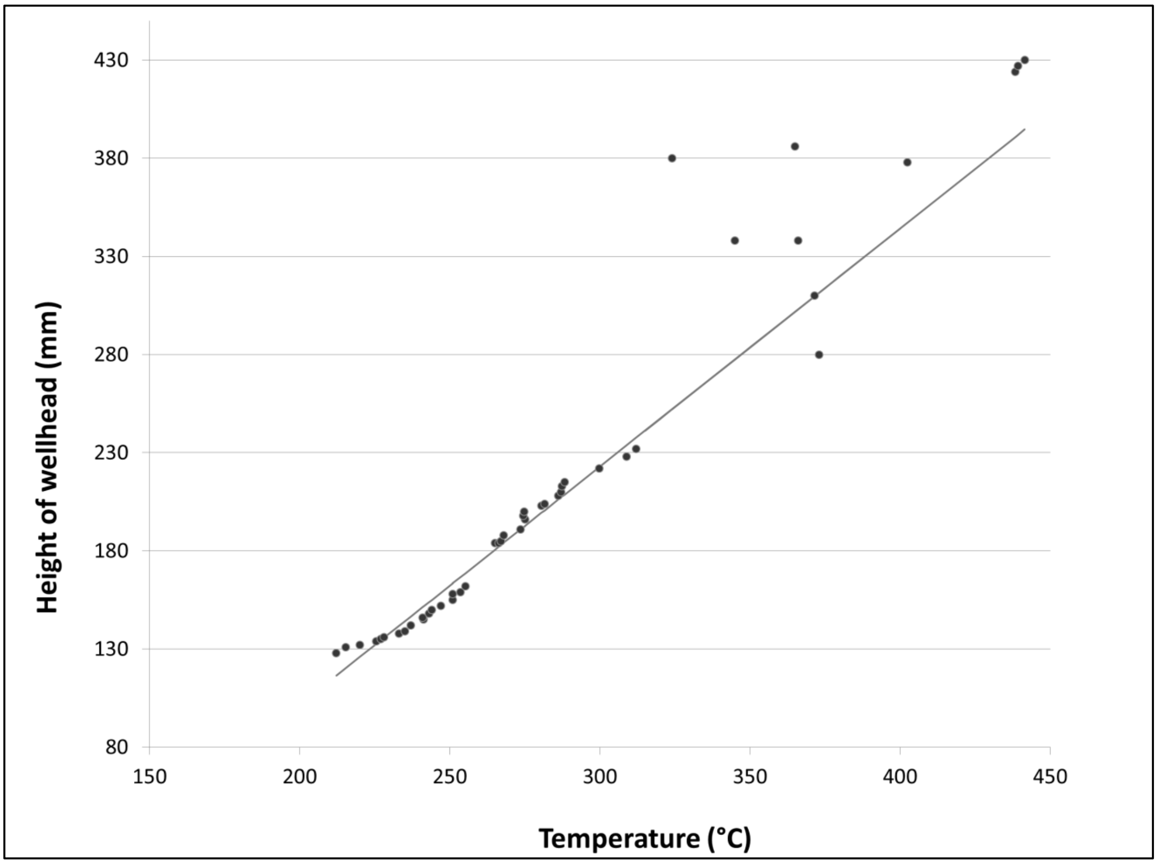

Figure 17: Rise of well head vs. well head temperature.

3. OPERATION AND MONITORING DURING DISCHARGE

3.1 Master Valves

During early discharge testing in Phase II from May to August 2010, it was reported by the on-site operators that unusually high forces were required to close the main valve. The valve is a Cl1500 expanding gate type with Cl2500 flanges. To increase safety of the well it was decided to add an identical valve on top of the master valve for further discharge testing, Phase III, IV and V. Similar problems were reported for the upper valve as was earlier reported for the original lower master valve. Eventually both valves failed during a maintenance stop in July 2012. The valve stem broke on both valves close to the gate seat. The operational history of the valves is given in Table 2.

Table 2: Operational history of master valves.

IDDP-1 - master valves, operational history					
Expanding gate valve 10" class 1500 with class 2500 flanges.					
		Lower valve		Upper valve	
Date	Operation	Opening	Closing	Opening	Closing
6/7 2009	The lower master valve installed on well, tested and left in open positioin.	2	1		
16/3 2010	Lower valve closed		1		
18/3 2010	Valve opened	1			
22/3 2010	Initial discharge of the well				
12/4 2010	Lower valve closed		1		
7/5 2010	Lower valve opened	1			
26/7 2010	Lower valve closed		1		
28/7 2010	Lower valve opened	1			
9/8 2010	Lower valve closed		1		
11/8 2010	Lower valve opened	1			
24/8 2010	Lower valve closed		1		
9/5 2011	The upper master valve installed			1	1
11/5 2011	Both valves opened	1		1	
17/5 2011	Well shut in with upper valve, in flow condition				1
25/5 2011	Upper valve opened			1	
26/5 2011	Upper valve closed				1
26/5 2011	Well shut in with lower valve, in flow condition		1		
4/8 2011	Both valves operated for IKS inspector (Garner)	1	1	1	1
9/8 2011	Both valves opened	1		1	
11/8 2011	Well shut in with upper valve, in flow condition		1		1
27/9 2011	Both valves opened	1		1	
1/10 2011	Upper valve closed due to minor leakage, opened again			1	1
2/10 2011	Upper valve closed due to minor leakage, opened again			1	1
21/10 2011	Upper valve closed due to minor leakage, opened again			1	1
25/7 2012	Both valve malfunctioned, well choked				
Total		10	9	9	8

3.2 Flow Control Valves

All flow control valves were of the expanding gate type. The Phase I discharge piping was 4" with a 4" valve splitting into two discharge legs 3" and 2" with valves of same size. These valves were Cl2500 and operated successfully during the discharge testing. For the Phase 2 discharge testing, the main valve was a 10" Cl1500. This valve was subject to heavy erosion caused by dissolved silica in the steam flow due to the low well head pressure of 20 bar. For the Phase III and IV discharge testing a 12" Cl1500 valve was used. During opening of the valve dirt from the well entered the valve housing and seized up the valve. The valve was removed, cleaned and re-installed. However, the problem persisted and it was decided to operate the well on smaller valves. The Phase V discharge piping and valves were 4" and 3" respectively on the two discharge legs. Operation of small 2", 3" and 4" valves was satisfactory considering the extreme conditions.

3.3 Sampling valves

The sampling valves specified for the discharge piping are 1” Cl2500 ball valves. These valves were located on the discharge piping and were thus on a lower pressure than the well head. These valves operated successfully if care was taken to operate them regularly. Otherwise, there was the possibility of the valve seizing up.

3.4 Pressure Measurement

Continuous pressure measurement on well head was through a ½” valve into closed probe well with Setra type sensor connected to a Campbell data logger. For manual pressure measurements a digital pressure sensor was used through a separate ½” valve. Valves for pressure measurement had to be replaced on a regular basis.

3.5 Temperature Measurements

Well head temperature measurements were through a type Rtd Pt100 temperature sensor inserted in a SS316 housing into the stream on the well head. Erosion of the SS housing became a problem during the Phase II discharge testing, Fig. 18. Once temperature logging failed the housing was replaced with an identical one. Different protective housings for the temperature probe were later tried, including a ceramic housing and an Inconel housing with Stellite coating. The ceramic one was identified as a possible alternative to counter the effects of erosion. However, it broke early on probably due to solids entrained with the steam. The Inconel housing was used in the later stages on discharge testing and proved quite robust. For temperature measurements on discharge piping a Type K thermocouple was inserted into a stainless steel housing into the steam flow. Indirect temperature measurements were also used and calibrated using in-flow measurements. The type used was a type K thermocouple on the exterior of the discharge piping and well head.

Figure 18: Eroded temperature sensor housing.

3.6 Risk Assessment

A comprehensive risk assessment was done for the discharge testing of the well. Risks not identified initially were later incorporated into the risk assessment. These included problems encountered with operating the main valve leading to the decision to have two identical master valves in series. After the Phase III and IV discharge testing it was also decided that all flow valves should be in pairs, one manually operated and the other with hydraulic ram. The hydraulic ram valves could be operated faster than the manual ones preventing the gates from eroding, while the valves were being operated. This was also a considerable safety improvement allowing operators to open and close the well from a distance, Fig. 19.

Figure 19: Flow control valves in pair, one with handwheel, the other with hydraulic ram.

3.7 Monitoring

Well head and discharge piping pressure and temperature were monitored continuously during the various discharge periods. Real time data was collected through a Campbell data logger and made accessible through an online webpage set up for the project. In addition a cell phone alarm was provided for the on-site operators should pressure change abruptly on the well head or discharge piping. The well was visually inspected daily from 2010 onward until the well was closed. The monitoring allowed for quick response (<20 minutes) to leaks on the well head and discharge piping.

4. LESSONS LEARNED

During the discharge history of IDDP-1, various problem were encountered. The design conditions at well head turned out to be challenging due to high pressure, temperature, corrosion and erosion. Operating the well at high flow may cause erosion at the well head, and debris from down-hole is likely to cause problems in the well head equipment.

Orifices prove to be adequate for controlling the flow but must be designed with potential vibration and scaling in mind. Acid concentrated condensate has contributed to leaks in nozzles and cold dead ends of the well head, revealing the importance for insulation as well as material selection. Stainless steel 309 cladding of carbon steel in valves has proven to be successful.

Valves of various sizes and pressure ratings were used through the discharge history. Operation of valves at the well head has been difficult and more difficult for larger valves. The valves are of expanding gate type, the same design as has been used successfully for a long time as master valves on high enthalpy wells in Iceland. The corrosive and erosive properties of the steam have caused difficulties, but the high temperature seems to also contribute to the problem, even though the valves are rated for higher pressure and temperature than exist at the IDDP-1 well head. The high forces required to operate the master valves is most likely due to debris trapped between the gate and the segment which resulted in high forces required to operate the valve. Another valve design may therefore be more adequate.

Future design of the discharge system for IDDP-1 will be based on the experience gained during the discharging of the well 2010 - 2012. The well will discharge through smaller valves in parallel rather than one large valve. Valves will be installed in series, one for normal operation and the other as spare and for sealing. Alternative valve designs will be looked into. Orifices will be designed to have adequate pressure drop with respect to both vibration and scaling. The insulation of the well head and discharge system will be improved to ensure there is no condensation of steam, and corrosion resistant material will be used where condensation cannot be prevented.

REFERENCES

Hólmgeirsson, S., Guðmundsson, Á., Pálsson, B., Bóasson, H.Á., Ingason, K., Þórhallsson, S.: Drilling Operation of the First Iceland Deep Drilling Well, *Proceedings*, World Geothermal Conference. Bali Indonesia (2010).

Ingason, K., Kristjansson, V., Einarsson, K.: Design and Development of the Discharge System of IDDP-1, *Geothermics,* 49, (2014), 58-65.

Hauksson, T., Markússon, S., Einarsson, K., Karlsdóttir, S.N., Einarsson, A., Möller, A., Sigmarsson, Þ.: Pilot testing of Handling the Fluids from the IDDP-1 Exploratory Geothermal well, Krafla, N.E. Iceland, *Geothermics*, 49 (2014), 76-82.

Einarsson, K., Pálsson, B., Guðmundsson, Á., Hólmgeirsson, S., Ingason, K., Matthíasson, J., Hauksson, T., Ármannsson, H.: Acid Wells in the Krafla Geothermal Field, *Proceedings*, World Geothermal Conference. Bali Indonesia (2010).