GRC Transactions, Vol. 48, 2024

Well Control Considerations for a Global Geothermal Industry: A Historical Review and an Assessment of Current and Future Requirements

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Keywords

Well control, blowout, geothermal

ABSTRACT

Geothermal well blowouts pose a significant financial and reputational risk to companies exploring for or developing geothermal energy resources. The potential catastrophic impact of a major geothermal blowout can tarnish in the arena of public opinion the recent gains of the geothermal renaissance that the nascent and fast-growing global geothermal industry is experiencing.

Given the increasing geological and geographical distribution of geothermal projects, the introduction of new well architectures and advanced drilling technologies and the drive towards hotter supercritical geothermal reservoirs to achieve greater global energy contribution and scale, a comprehensive assessment of the well control and blowout contingency considerations unique to the geothermal industry is needed.

With this in mind, a thorough historical review of available well-control-related information, publication and events will be conducted. This will provide a solid foundation for the determination of the current and future well control risks and blowout contingency requirements of the geothermal industry. The paper also intends to cover the issues involved with the direct application of conventional oil and gas well control techniques and methods in the geothermal industry and to raise relevant concerns about what the geothermal industry is doing and identify possible pitfalls in the direction that the industry is headed.

1. Introduction

Geothermal formations are comprised of reservoirs of hot water that naturally occur or are man-made at varying temperatures and depths below the earth's surface. As defined by Naturally occurring geothermal formations (with heat, water, permeability) that have historically been developed for heating and electricity generation purposes are usually classified as of the hydrothermal type (US Department of Energy, Office of Energy Efficiency and Renewable Energy, 2024), but other types such as geopressured-geothermal systems, which contain water with somewhat elevated temperatures and with pressures well above hydrostatic for their depth, as well as magmatic systems, with temperature ranging from 600°C to 1400°C also exist. Man-made geothermal systems usually target Hot Dry Rock (HDR) geothermal resources, with ideal temperatures from 200°C to 350°C, and are usually referred to as enhanced geothermal systems (EGS) or advanced geothermal systems (AGS) or advanced closed loop (ACL), depending on the technologies being used to develop the resource. Rock types are typically granite, granodiorite, quartzite, greywacke, basalt, or volcanic tuffs but geothermal reservoirs in sedimentary rock types are also possible.

Because geothermal formations are usually under pressured (pore pressure less than fluid pressure in a full wellbore), influx into the wellbore is rare. Geothermal well control considerations, as described by Wild Well Control (2024), are primarily due to these two causes for loss of control:

- An unexpectedly hot formation is encountered at a shallow depth where the annulus pressure is insufficient to keep the drilling fluid or the formation fluid from flashing to steam.
- Lost circulation causes the fluid level and the pressure in the wellbore to suddenly fall far enough for the same thing to happen.

If complete control is not lost, simply pumping cold water into the wellbore can usually kill the well.

Like in oil and gas drilling settings, the apparatus that controls a geothermal kick and potential outflow at the wellhead is called the blowout preventer (BOP) or blowout prevention equipment (BOPE). According to the Handbook of Best Practices for Geothermal Drilling published by Sandia National Laboratories, the geothermal BOP stack comprises five types of device to shut off the wellbore and prevent fluid flow out of it: rotating control devices (RCD) or rotating heads, annular preventers, pipe rams, blind rams, and shear rams. The basic function of each is to shut off the wellbore, but they operate in slightly different ways. Below the BOP stack, there is a drilling spool with two valved lines (called the choke and kill lines) connected to the drilling spool so that fluids can be either released from or pumped into the wellbore as part of the well-control process. (Finger & Blankenship, 2010) (Weatherford, 2024)

Compared to the sedimentary formations of most oil/gas reservoirs, hydrothermal geothermal formations are, by definition:

- Hot (production intervals from 160°C to above 300°C)
- Often hard (240+ MPa compressive strength), abrasive (quartz content above 50%)
- Highly fractured (fracture apertures of centimeters)
- Under pressured
- Often contain corrosive fluids
- Some formation fluids have very high solids content [total dissolved solids (TDS) in some brines it can be above 250,000 ppm]

Purba et al. highlight that the fundamental differences between petroleum and geothermal environment systems lie in reservoir and fluid temperatures, rock permeability and pressure and the heterogeneity of the rock-forming systems. (Purba, et al., 2022).

Purba et al. also emphasizes that the generalization of well control methods and blowout preventer (BOP) designs between petroleum and geothermal can be dangerous because generally well control methods and equipment in the petroleum industry are designed to anticipate pressure. It adds that geothermal is likely to face a well control situation that is influenced by temperature, and that the availability of a continuous supply of cold water, the ability and reliability of the pump on the rig, and an adequate BOP temperature rating are the main factors that must be considered.

Finger and Blankenship (2010) highlight that though pressures in geothermal drilling are almost always lower than those encountered in oil and gas drilling, the key to control is having adequate casing setting depths, which will permit shutting the well if a kick is detected in the early stages. They warn that unexpected steam flow in a permeable formation that is not completely sealed by casing is particularly dangerous; because steam can begin to flow up the outside of the previous casing string ("underground blowout") and eventually destroy the casing's integrity and often causes loss of the drill rig.

The geothermal well control incidents in the following section highlight these hazards and emphasizes the fact that geothermal well blowouts pose a significant financial and reputational risk to companies exploring for or developing geothermal energy resources. Though most of the well control case studies featured in this paper are from historical geothermal development projects involving hydrothermal resources, the risks involved and lessons learned will have a high degree of applicability to the new technologies being tested or piloted involving enhanced and advanced geothermal systems (EGS / AGS / ACL) that are receiving a lot of recent attention from the global energy community.

Adaptations that might be required from a well control standpoint to accommodate these new geothermal technologies and methods that have the potential to bring geothermal anywhere and everywhere are presented in the section following the case studies.

2. Geothermal Well Control Incidents and Statistics

With the rapidly evolving and expanding geothermal energy industry future in mind, a historical review of publicly available well-control-related information, publication and events was conducted as part this paper. It is intended to provide a solid foundation for the determination of the current and future well control risks and blowout contingency requirements of the geothermal industry.

So in terms of risk, how does geothermal energy systems compare to other energy sources and which what is the level of risk involved with well blowouts? A paper published on "Comparative accident risk assessment with focus on deep geothermal energy systems in the Organization for Economic Co-operation and Development (OECD) countries" provides some insights on the matter. The paper concludes that the drilling and stimulation phases of deep geothermal energy development are considered the riskier due to the potential of blowouts or release of drilling muds and stimulation fluids during these operations. Within the drilling phase, blowout accident risk is significantly higher than the transportation, storage and use of caustic soda. In both the stimulation phase and drilling phase of geothermal operation blowouts are among the highest risks. This is related to the fact that if a blowout happens the effect can be catastrophic not only for the deep geothermal project itself, but for the workers in the area. It is interesting to note that blowouts in the drilling phase are higher with respect to the stimulation phase. This could be possibly due to the fact that during a stimulation phase the bore should have been stabilized in terms of pressures, while during the drilling phase, kicks from different gasses, i.e. natural gas, hydrogen sulfide, could still happen in an unpredictable way, leading to an increased risk. (Spada, Sutra, & Burgherr, 2021)

It is interesting to note that the study also developed and compared deep geothermal cases (best and worst) against fossil, hydrogen and selected renewable technologies, in terms of expected accident risk. The lowest fatality rate, i.e., expected risk, was found for the deep geothermal energy best case. The deep geothermal energy worst case is similar to wind offshore and performs better than the fossil, hydrogen, hydropower and biogas energy chains. In contrast, in terms of extreme accident risk, maximum consequences, i.e., extreme risk, for both deep geothermal energy scenarios were similarly low as for other renewables, implying that they are substantially less prone to high-consequence events than fossil, hydrogen, and hydropower energy chains.

Going further into the details of geothermal well blowout incidents and risks, the table below lists down by country and by approximate year the instances of the same available in published literature and in the worldwide web, using the search terms “blowout” or “well control” in the publication title or in the Internet or AI Chatbot search query. Snippets of the incidents found (in chronological order) are provided in the paper but the complete list of sources (including links to available geothermal blowout videos) are also provided in the References section.

Table 1. Geothermal Well Control Incidents by Location and Year (tallied from incidents with publicly available information cited in this paper)

	Country								
Year	**HUN**	**IND**	**IDN**	**JPN**	**NZL**	**PHP**	**TUR**	**USA**	**Total**
1958					1				1
1960					2				2
1976								1	1
1983								2	2
1989								1	1
1991				1				1	2
2003						1			1
2010	1			1			1		3
2014						1			1
2016			3						3
2018			1						1
2019			1						1
2020			1						1
2022		1							1
2023				1					1
Total	1	1	6	3	3	2	1	5	22

Legend: Complete Country Names: HUN – Hungary; IND – India; IDN – Indonesia; JPN – Japan; NZL – New Zealand; PHP – Philippines; TRK – Turkey; USA – United States of America.

2.1 New Zealand – 1958 and 1960

This article published in the Geothermics journal describes three blowouts that have occurred in Wairakei: at bore WK26 which blew out early in 1960, at bore WK204 later the same year, and bore WK201, which happened in 1958. The paper mentions that the location of two of these is still marked by large craters (WK201, 204), while the situation at the third (WK26) was recovered and there is now little evidence of the events that took place. None of the blowouts resulted in loss of life, but all provided learning experiences and had a substantial influence on subsequent geothermal drilling practices at Wairakei and elsewhere in New Zealand. (Bolton, Hunt, King, & Thompson, 2009)

A Ministry of Works video on WK204, the 'Rogue Bore' of the Wairakei Geothermal Field has been uploaded by user DamageIncNZ and is available on YouTube, the link to which is provided in the References. (DamageIncNZ, 2015)

2.2 USA - California - 1976

The effects of the blowout of Union Oil Company geothermal well "G.D.C." 65-28 are described, photographed, and diagrammed in this paper. Attempts to control the well are also described. This well, like over 50 percent of the wells drilled at The Geysers, was sited on a Quaternary landslide, according to the authors, and an attempt was made to determine whether or not the well blew out as a result of renewed movements on the old slide. (Bacon, 1976)

2.3 USA – California - 1983

This paper describes the drilling of a relief well Thermal 15 in the Thermal Shallow Reservoir in the Geysers, which was drilled in November, 1983, to a total depth of 700 feet. A steam entry encountered at 490 feet was found to communicate with the high permeability upflow zone of the Thermal Shallow Reservoir. A low-flowrate, higher-pressure steam entry at 600 feet was not detected while drilling but was indicated during a subsequent spinner survey. The pressure, flowrate, and enthalpy of the five wells completed in the upflow zone, including the Thermal 4 blowout, were monitored and recorded over a four month period before, during and after Thermal 15 was drilled. It was found that the Thermal 4 blowout communicates with the upper flow zone of the Thermal Shallow Reservoir, the Thermal 4 flowrate is controlled by the shallow reservoir pressure, and the high permeability of the upflow zone allows such strong interference effects that three of the four commercial production wells will maximize production from this reservoir. (Mogen & Maney, 1985)

2.4 USA - Utah - 1983

This GRC Transactions paper describes the capping of a geothermal blowout near Cove Fort, Utah. The blowout occurred on October 24, 1983, and was considered uncontrollable after four days of attempts by the drilling crew to cool and cement the well. Well control specialists arrived on October 29th, 1983 to establish procedures for containment of the blowout. Upon arrival to the rig site, it was estimated that the flow rate through the 20" conductor casing was 800 ft/sec, with an estimated minimum of 100 ppm hydrogen sulfide. Attempts had been made to measure the temperature of the 97% steam and $H2S$ mixture, with the result being the destruction of a 400 F temperature probe. Steam temperature was estimated to be between 400°F and 600°F. The initial step, in order to control the well, was the removal of the drilling rig, followed by putting in place surface casing support for the installation of blowout prevention equipment. Wellbore stability was then established followed by the cementing and plugging of the well. (Gray & Gass, 1984)

2.5 USA - Nevada - 1989

This publication focuses on Ormat's 14-6 well that blew out near Fallon, Nevada, on January 1989. The well was drilled using the same drilling program followed on other field wells. However, an unexpected fault caused severe lost circulation, and eventually, the well blew out. The nature of the problems required a combination of surface and subsurface well control techniques. Time was important because the well was flowing 5,000 gpm of 350°F geothermally heated water. (Adams & Thomson, 1989)

2.6 USA - Hawaii - 1991

In June 1991, a high-pressure high-temperature geothermal well, KS-8, being drilled by the Puna Geothermal Venture located in Hawaii kicked and unloaded at 3,476 ft (1,059 m). This well was estimated to have a possible bottomhole temperature of 650°F (343°C) and a reservoir pressure approaching 2,300 psi (15,858 kPa). (Rickard, et al., 1995)

After the well blew out, Hawaii state officials ordered a halt to all drilling. The incident routed 75 people from their homes on the island of Hawaii. The state Department of Health and the county ordered the company to stop drilling while the incident was investigated. (Essoyan, 1991)

Immediate attempts to kill the well were unsuccessful, and the long process of well control was started. Several attempts to kill the well over the next 2 weeks were unsuccessful. The volume of water required to cool the well necessitated drilling a water well. Specialists in the area of well control began transporting snubbing equipment and personnel to Hawaii and their snubbing operation was critical in the final kill operation. (Rickard, et al., 1995)

2.7 Philippines - 2003

This paper describes a blowout that occurred on PNOC-EDC Well 5R-12D, which was drilled as a reinjection well in pad 5R4 of the Malitbog sector to augment the injection capacity of the 231 MW Malitbog Visayan Geothermal Power Corporation (VGPC) power plant. The well was spudded on July 19, 2003 and its 610 mm surface casing was set at 110m. Drilling of the 533 mm hole proceeded normally until partial and subsequently total circulation loss (TLC) was encountered, and blind drilling using water was performed until 450 m. After pullout of the string to 106 m, the well kicked. The annular preventer was closed while the excess pressure was bled off through the bleed line. Water was then pumped through the string at 37 li/s but apparently this was insufficient to quench the well. After a few minutes, steam was noticed coming up in the cellar area. Additional water was pumped in the annulus through the connected cementing lines at 26 li/s. The steam discharge intensified, forming a mushroom-like cloud that rose some 50 m above the well, and thereafter, spewing mud, soil and rocks. A crater structure soon developed around the concrete cellar area that made the whole rig fall on its side after 8 hours of continuous and uncontrolled discharge. (Herras, Caranto, & Palma, 2004)

Another paper on a related topic documents how PNOC-EDC drilled Well 5R-13D, the first geothermal relief well in the Philippines. Well 5R-13D is probably the only relief well in the geothermal industry drilled using a single shot directional survey system. This well was designed to relieve the pressure of the uncompleted Well 5R-12D that blew out and toppled down the drilling rig on top of it after encountering a shallow pressurized two-phase zone at 450m estimated at about 4 MPa. Early completion of Well 5R-13D was very important to control the environmental, social and economic impact brought about by the continuous discharge. In spite of the various drilling constraints like the proximity of the drilling pad against the main geologic fault prompting a revised welltrack, the non-utilization of MWD tools and time constraints, Well 5R-13D successfully intersected and quenched Well 5R-12D. As an added bonus, the completion test results suggest that this well can even be utilized as a production well. To fully seal off the formerly discharging Well 5R-12D at surface, a series of cement plugs were set through its cut-off casing. (Jumawan, Mendita, Aguilar, Belista, & Retuya, 2005)

2.8 Hungary - 2010

This paper describes the existence of a high temperature and highly over-pressured geothermal reservoir that was proven during a steam blowout in Fabiansebestyen, South-eastern Hungary. The pressure balance of the drilling mud broke down during an incorrect drilling operation. An intensive inflow took place from a fractured dolomite reservoir at 3880m depth. The pressure of the reservoir was 73.1 MPa, its temperature was 199.6°C. The abrupt pressure increase pushed the drill collar to the blowout preventer, seriously damaging the safety valve. The blowout displaced the mud from the borehole and in a very short time it developed into a steam blowout. The blowout held constant for 46 days until staff succeeded in sealing the well. The mathematical model of the blowout is also presented in the paper. (Toth, 2010)

2.9 Japan - 2010

The Onikobe single-flash steam turbine geothermal power plant in Japan has been supplying electricity to the grid for 36 years. Numerous natural geothermal manifestations were present in the field prior to development. New fumaroles accompanied by hot liquid discharges spontaneously appeared near Well 128 on 8 September 2010. The new features were monitored carefully – the manifestations intensified abruptly on 8 October, and engulfed Well 128 the same day. The fumaroles continued to grow until a large scale steam explosion occurred on 17 October 2010. A crater-lake formed and the Well 128 wellhead became submerged in hot water. After the steam explosion, steam and water continued flowing from the crater-lake. Fluid sampling was performed using a radio-controlled helicopter, and results of the chemical analysis of the fluid showed that the fluid in the crater was identical to production well 128 fluid. This suggests that Well 128 was damaged by the steam explosion incident, and that the residual flow from the crater-lake afterwards could be due to a casing failure in Well 128. This paper describes the sequence of crater-lake events and relief well drilling which finally succeeded in killing and plugging Well 128. (Takizawa, et al., 2013)

2.10 Turkey - 2010

Alasehir is the most important geothermal site in western part of Turkey. Many geothermal wells have been drilled in Alasehir Plain to produce the geothermal fluid from the deep reservoir in the last 10 years. A blowout accident happened during a geothermal well drilling operation in Alasehir Plain, and significant amount of geothermal fluid surfaced out along the fault zone in three locations. When drilling string entered the reservoir rock about 1000 m, blowout occurred. As the well head preventer system was closed because of the blowout, high-pressure fluid surfaced out along the fault zone cutting the Neogene formation. In order to understand the geothermal fluid effects on groundwater chemistry, physical and chemical compositions of local cold groundwater were monitored from May 2012 to September 2014 in the study area. The geothermal fluid was found to be of Na–HCO3 water type, and especially, arsenic and boron concentrations reached levels as high as 3 and 127 mg/L, respectively. The concentrations of arsenic and boron in the geothermal fluid and groundwater exceeded the maximum allowable limits given in the national and international standards for drinking water quality. (Rabet, Simsek, Baba, & Murathan, 2016) Another related study by Timur intended to determine contaminated area in Alesehir by using magnetic susceptibility measurements for the surface and VLF-R method for underground layers. (Timur, 2013)

2.11 USA - Nevada - 2010

This news article mentioned that a legislative audit in Nevada mentioned that there was a 2010 incident where geothermal fluids and steam temporarily flowed uncontrollably on the surface. No one was hurt during the incident. The audit also provided information on oil and geothermal production in Nevada. In 2012, 2.4 million megawatt hours of electricity were provided by Nevada geothermal wells, mostly found in Churchill and Washoe counties, enough to power 219,000 homes. (Vogel, 2014)

2.12 USA - California - 2014

This news article reported that an Ormat geothermal well north of Brawley blew out in May 2014. It was described as a blown well head at the Ormat geothermal plant north of Brawley and it was still shooting into the air uncontrolled when the article was published by the local news outlet. It did not appear that anyone was injured. (Imperial Valley Press, 2014)

2.13 Indonesia - 2016

This technical paper documents capping job activities in three geothermal wells that were done successfully in Indonesia, at a PT. Pertamina Geothermal Energy (PGE) location in Cluster-A Hululais Field. A landslide in Bukit Beriti 2 km away from the location of Hululais-A had damaged three production wells that broke all of the wellheads. In order to prevent more severe effects, immediate and effective well control action was taken. Before the capping job was conducted, clearing work was done, and an appropriate well control method was then selected based on the actual condition of each well, before the capping job was successfully carried out using the BOP method. (Toni, et al., 2017)

2.14 Indonesia - 2018-2019

Wayang Windu geothermal field in Indonesia completed a drilling campaign in 2020 in order to maintain full generation of unit 1 and unit 2 at 277 MW. Four new makeup wells were drilled from two different pads, MBA pad and MBD pad, with two wells drilled in each pad. Two of the four wells drilled had well control events that occurred in different wells and pads. The sequence of well control events were recorded and documented clearly from initial condition until well is safely secured, through combination of down hole pressure and temperature sensors installed in Measure While Drilling (MWD) tool as well as surface pressure, temperature and flow sensors installed in surface line. Some of takeaways from well control events are as follows: (1) In total losses condition, well control events can be grouped into two conditions, steam flow from above and below the head liquid column; (2) Steam flow from above the head liquid column may occur due to the hydrostatic column drops below steam feed zone that allows saturation condition to occur and fluids flashing into steam; (3) Steam flow from below the head liquid column may occur due to the wellbore hydrostatic pressure drops significantly that leads to an underbalanced condition relative to the formation pressure. This allows hot fluid circulation from deeper depth and flashing at surface; (4) Continuous water supply is safeguard for well control risk and water supply shall be tested prior to spud in and maintain back up water storage full all the time. (Souvanir, Putra, & Darmawan, 2021)

2.15 Indonesia - 2020

This news article from ThinkGeoEnergy mentions that PT Medco Energi has shared details on a recent well steam kick out at its Blawan Ijen geothermal project in East Java, Indonesia. The incident occured on April 24, 2020 and has since been contained and the well is under control again. PT Medco Cahaya Geothermal (MCG) is a joint venture company between of PT Medco Power Indonesia and PT Ormat Geothermal Power informed that there has been a steam kick during the drilling of IJN 6-1 well at IJEN PLTP project located in Blawan Ijen, East Java. This steam kick occurred during the time of drilling at IJN 6-1 entering a shallow depth high temperature steam reservoir at 630 m.The BOP functioned properly during the incident, however due to the increase of the pressure and temperature of the well, steam flowed to the surface. AS of publication, MCG is still working to manage the steam kick and stabilizing the well by pumping heavy drilling mud and it is expected the situation will be stabilized soon. The incident has been reported and coordinated with the related government body, local authorities and socialized with local communities. (Richter, 2020)

2.16 India 2022

This news article by the DownToEarth website mentions that the Oil and Natural Gas Corporation Energy Centre (OECT) and the Iceland Geosurvey (ISOR), which have signed a memorandum of understanding (MoU) for developing a geothermal plant in Puga, Ladakh, have termed a recent accident at the site as a ‘freak incident’ and that they have also said the geothermal fluid that leaked from the ground and flowed into the Puga nullah, a tributary of the Indus, was benign. (Patil, 2022)

The article also mentions that Ravi, the director-general of OECT, told media in Leh August 31, 2022 that the team at the site had encountered a shallow reservoir at a high temperature of 120-130 degrees Celsius while drilling between August 4 and 9. The team immediately stopped the drilling at a depth of 39 metres depth. Further drilling required cooling the shallow reservoir. Due to heavy rain on August 16, the power supply from the grid needed for cooling failed. There was a delay of 20 minutes in restoring the power supply and this is when a blowout occurred. The ONGC has now closed the borehole and is all set to conduct further exploratory drilling at a different location on the same 5 hectares of land in the Puga hot spring area that has been granted wildlife clearance by the state board for wildlife. (Patil, 2022)

A video of a ground report by ThePrint's Simrin Sirur & Praveen Jain tracks the Ladakh renewable energy project's challenges & prospects. The link to the video is provided in References. (ThePrint, 2022)

2.17 Japan 2023

This news article from Kyodo News mentions that four people have so far complained of illness in a town near Hokkaido's Niseko mountain resort after steam erupted during drilling for a geothermal energy development project, Mitsui Oil Exploration Co. said. Hydrogen sulfide at the site in Rankoshi and a high level of arsenic in water collected in a nearby area were detected. Mitsui Oil began drilling on June 25 to survey the potential resource, and the steam erupted four days later. According to the company and the town, the arsenic level detected from the nearby water was 1,590 times higher than the standard for drinking water and 318 times higher than that for water for agricultural use. Mitsui Oil has been disposing of water accumulated at the site of the steam eruption by dumping it in an area approximately 500 meters away from a pond known for being a tourist site, according to a company official. At a press conference in Rankoshi, Mitsui Oil President Hidenori Harada stated that the Hokkaido government has instructed the company to cease dumping water outside the site. However, it is expected to take approximately two weeks to construct a pipeline that will redirect the accumulated water to a well about 1 kilometer away. (Kyodo News, 2023) (Kombrink, 2023)

3. Well Control Considerations for Future Geothermal Development

Given the increasing geological and geographical distribution of geothermal projects, the introduction of new well architectures and advanced drilling technologies and the drive towards hotter supercritical geothermal reservoirs to achieve greater global energy contribution and scale, an assessment of the well control and blowout contingency considerations unique to the geothermal industry is needed.

3.1 Hydrothermal

3.1.1 BOPE for Mining Drilling Equipment Used Geothermal Drilling Operations

All drilling operations inside the geothermal environment, including mining drilling, have the same risk on the well control side. Well control equipment is normally not required in mineral/mining drilling exploration, but for some mineral coring operation that intersect a geothermal area, high temperature of water/steam and/or gases could be encountered during the drilling operation. Irwansyah et al (2021) stipulates that in order to safely conduct drilling, we need to consider the use of well control equipment for mineral/mining drilling operations in geothermal areas. For the application of the geothermal well control to mining drilling operations, the mining well schematic should be modified. There are two additional sections that have to be drilled with 9-1/2” and 6-1/2” IADC bits. Those additional sections will support the installation of a 7-1/16” diverter, thus ensuring the safety of the mining drilling operation. Then the mining drilling can be continued for the rest of the section by installing IPI (inflatable packer). (Irwansyah, Gilang, Augustino, Adityatama, & Wiharlan, 2021)

3.1.2 Kick Detection and Temperature Management

The Sandia Handbook of Best Practices for Geothermal Drilling mentions that better methods for inflow and returns metering are available, and if well control is expected to be an issue, these methods should be investigated. Other indicators of impending flow from the well are the influx of gas, rapid rise in the temperature of returning fluids and encountering rapid drilling, particularly if associated with a loss of returns. It adds that as in many contexts, prevention of a problem is more efficient than a cure and a number of methods are available to estimate the wellbore temperature profile and warn that a problem may be near: comparison of drilling fluid inflow and outflow temperatures; maximum-reading thermometers either run just above the bit or lowered through the drill pipe on a wireline; or onboard logging tools that can transmit temperature data in real time, as it is always important to know as much as possible about the downhole environment. (Finger & Blankenship, 2010) Technologies for early kick detection and inflow and returns flow and temperature measurement have already been partly deployed in geothermal settings through managed pressure drilling (MPD) methods. (Weatherford, 2024)

3.2 Enhanced and Advanced Geothermal Systems

3.2.1 BOPE for Big-Bore Wells

Deeper and hotter plays and requirements for bigger wellbores to be able to increase the commercial viability of geothermal development projects. Well architectures associated with new geothermal technologies are increasingly requiring larger BOP equipment to be able to deliver the volumes of steam required while drilling fewer wells for their projects. However, BOP systems available in inventory that are mostly geared towards oil and gas applications do not usually go as large as those that are required by the geothermal big-bore designs (17-1/2" or larger), thereby possibly putting a constraint on implementing future EGS / AGS / ACL projects because of the very limited number of larger BOP systems available, unless more of these BOP systems will be manufactured by BOP systems providers.

3.3 Oil and Gas Well Conversion to Geothermal

3.3.1 Well Control Considerations for Both Geothermal / Oil & Gas

Finger and Blankenship (2010) mention that there are geothermal fields (such as Cooper Basin, in South Australia) in which hydrocarbon resources are also found and that this, of course, means that well control procedures and equipment must be capable of handing the somewhat different characteristics of both drilling environments. With the advent of "geothermal everywhere", and initiatives to be able to convert legacy oil and gas assets into geothermal systems, especially in existing petroleum basins, it is important that both the geothermal and oil and gas aspects of well control be properly taken into consideration when planning operations in these hybrid environments.

3.4 Supercritical Geothermal Systems

3.4.1 BOPE Elastomer Seals Good For 260°C

The Sandia Handbook of Best Practices for Geothermal Drilling states that though there will usually be detailed local regulatory requirements for the BOPE the critical factors are to make sure that the BOP pressure rating is adequate and that all the elastomer seals in the equipment are qualified for high temperature. It mentions that most BOPE are dressed with the normal temperature rubbers, which have a working temperature limit of 121°C, because of the high cost and limited availability of high temperature BOP rubbers. It adds that even dressing the BOP's with high temperature rubbers may not provide adequate safety, as they have a working temperature limit of 177°C and as pressures increase when circulating out a high temperature kick, even these higher temperatures can be exceeded. For this reason, a cooling line should be connected below the pipe rams to pump cool water down through the inside of the BOP and out the choke line during a kill operation, if the temperature might exceed the working temperature of the BOPE. (Finger & Blankenship, 2010)

The high temperature capability of elastomeric sealing elements used in ram type blowout preventers was being addressed by a research project described in a paper by Parker (1995) that require that they must be capable of operating in steam and brine up to 500°F (260°C). Typical well drilling equipment used for oil and gas drilling is designed to operate up to 250°F and under special conditions up to 350°F. The paper reports on the final phase of a joint development project in which high temperature elastomers were tested in ram type BOPs under geothermal conditions. Tests were conducted at ENECs Secolo #1 geothermal well near Larderello, Italy in the period from November 1990 to April 1991. The final phase testing demonstrated improved high temperature elastomer compounds and specially designed ram packer plates would permit operation at 425°F and 1800 psi for significantly longer periods of time than the test goal of 54 hours. (Parker, 1995)

4. Conclusion

The incident case studies and considerations for future development highlight that geothermal well control can be a complex topic, but it is clearly critical to a successful geothermal drilling operation so a holistic approach to well control should be adopted. As such, well-control engineering and procedures and risk management should be part of well planning, so that the proper casing design is developed during the planning stage. Careful planning, modeling and execution of geothermal projects should also comprise a robust well control contingency plan. Sound engineering, multi-disciplinary engineering design, and analysis will ensure a successful outcome. It is essential that proper well control preparations be established and crews will be familiar with them when drilling begins so that rig crews be trained to react quickly and appropriately to an unexpected event that might jeopardize the well.

Given the rapidly increasing volume of geothermal wells being drilled globally of the natural and man-made reservoir type as well as the intention of geothermal operating companies to drill larger, deeper and hotter wells to improve the commercial viability of geothermal energy, it is important that the industry be made aware of the potential catastrophic impact of a major geothermal blowout and mitigate against or prepare for it. Failure to do so might squander the immense gains of the global renaissance that the resurgent and expanding geothermal industry is experiencing.

REFERENCES

Adams, N., & Thomson, J. (1989, June 1). How a geothermal blowout was controlled. *Environmental Science, Engineering, Geology*.

Bacon, C. F. (1976, January 1). Blowout of a geothermal well. The Geysers Geothermal Field, Sonoma County, California. *Calif. Geol.*

Bolton, R. S., Hunt, T. M., King, T. R., & Thompson, G. E. (2009, March). Dramatic incidents during drilling at Wairakei Geothermal Field, New Zealand. *Geothermics, 38*(1), 40-47. doi:https://doi.org/10.1016/j.geothermics.2008.12.002

DamageIncNZ. (2015, June 7). *Wairakei Rogue Bore WK204 Well Blowout.* Retrieved August 19, 2024, from YouTube: https://youtu.be/ZfhXgIm-mMs?si=ZhagSxslzAMpWqcb

Essoyan, S. (1991, June 15). *Blowout Shuts Geothermal Unit in Hawaii.* Retrieved August 19, 2024, from Los Angeles Times: https://www.latimes.com/archives/la-xpm-1991-06-15-mn-503-story.html

Finger, J., & Blankenship, D. (2010). *Handbook of Best Practices for Geothermal Drilling.* Albuquerque: Sandia National Laboratories.

Gray, J., & Gass, D. W. (1984). Capping of a Geothermal Blowout. *Geothermal Resources Council, Transaction. 8.* Geothermal Resources Council.

Herras, E. B., Caranto, J. A., & Palma, R. R. (2004). A Geoscientific Approach in the Design and Success of the First Relief Well at the Leyte Geothermal Production Field. *Geothermal Resources Council Transactions. 28.* Geothermal Resources Council.

Imperial Valley Press. (2014, May 1). *Brawley geothermal well blows, still not under control.* Retrieved August 19, 2024, from Imperial Valley Press Online: https://www.ivpressonline.com/quicknews/brawley-geothermal-well-blows-still-not-under-control/article_93bd5aa8-d186-11e3-8fd1-0017a43b2370.html

Irwansyah, D., Gilang, R., Augustino, V., Adityatama, D., & Wiharlan, H. (2021). Geothermal Well Control Equipment Application for Mining Drilling in Geothermal Environment. *Proceedings 43rd New Zealand Geothermal Workshop.* Wellington, New Zealand.

Jumawan, J. E., Mendita, F. E., Aguilar, M. Z., Belista, B. B., & Retuya, R. E. (2005). The Philippines' First Geothermal Relief Well. *Proceedings World Geothermal Congress 2005.* Antalya, Turkey: World Geothermal Congress.

Kombrink, H. (2023, June 30). *A geothermal blowout in Japan*. Retrieved August 19, 2024, from GEOExpro: https://geoexpro.com/a-geothermal-blowout-in-japan/

Kyodo News. (2023, July 8). *4 complain of illness after steam eruption near Hokkaido's Niseko*. Retrieved August 19, 2024, from Kyodo News: https://english.kyodonews.net/news/2023/07/414284ea9955-4-complain-of-illness-after-steam-eruption-near-hokkaidos-niseko.html#:~:text=Four%20people%20have%20so%20far%20complained%20of%20illness,water%20collected%20in%20a%20nearby%20area%20were%20detected.

Mogen, P., & Maney, J. (1985). The Thermal 15 Relief Well and Production Performance of the Thermal Shallow Reservoir. *Proceedings, Tenth Workshop on Geothermal Reservoir Engineering.* Stanford, California, USA: Stanford University.

Parker, B. G. (1995). Development of Geothermal Capable Elastomers for Use in Ram Type Blowout Preventers Phase IV Testing at Geothermal Wellsite. *Geothermal Resources Council Transactions. 19.* Geothermal Resources Council.

Patil, N. (2022, September 02). *'Freak incident': ONGC, ISOR downplay geothermal fluid discharge into Ladakh's Puga nullah.* Retrieved August 19, 2024, from DownToEarth: https://www.downtoearth.org.in/pollution/-freak-incident-ongc-isor-downplay-geothermal-fluid-discharge-into-ladakh-s-puga-nullah-

84703#:~:text=Due%20to%20heavy%20rain%20on%20August%2016%2C%20the,threw%20up%20muck%20from%20the%20geothermal%20drill%20hole.

Purba, D., Adityatama, D. W., Fadhillah, F. R., Al-Asyari, M., Gumelar, P., Gunawan, A., & Nugraha, R. P. (2022). A Discussion on Petroleum and Geothermal Subsurface Characteristic Differences and Its Impact to Well Control Methods During Drilling. *Proceedings, 47th Workshop on Geothermal Reservoir Engineering.* Stanford, California: Stanford University.

Rabet, R. S., Simsek, C., Baba, A., & Murathan, A. (2016, December 31). Blowout mechanism of Alasehir (Turkey) geothermal field and its effects on groundwater chemistry. *Environmental Earth Sciences, 76*.

Richter, A. (2020, May 3). *Steam kick from geothermal exploration well at Blawan Ijen geothermal project.* Retrieved August 19, 2024, from ThikGeoenergy: https://www.thinkgeoenergy.com/steam-kick-from-geothermal-exploration-well-at-blawan-ijen-geothermal-project/

Rickard, B., Livesay, B., Teplow, B., Winters, S., Evanoff, J., & Howard, W. (1995). Control of Well KS-8 in the Kilauea Lower East Rift Zone. *World Geothermal Congress.* Florence, Italy: World Geothermal Congress.

Souvanir, T., Putra, R. B., & Darmawan, D. (2021). Example Case of Geothermal Well Control Event. *Proceedings World Geothermal Congress 2020+1.* Reykjavik, Iceland: World Geothermal Congress.

Spada, M., Sutra, E., & Burgherr, P. (2021). Comparative accident risk assessment with focus on deep geothermal energy systems in the Organization for Economic Co-operation and Development (OECD) countries. *Geothermics, 95*. doi:https://doi.org/10.1016/j.geothermics.2021.102142

Takizawa, K., Iwasaki, O., Todaka, N., Shimizu, I., Tezuka, S., & Nakanishi, S. (2013). Geothermal Relief Well at the Onikobe Geothermal Power Station. *GRC Transactions. 37.* GRC.

ThePrint. (2022, September 8). *After 'freak incident' it's full steam ahead for India's 1st geothermal power project in Ladakh.* Retrieved August 19, 2024, from YouTube: https://www.youtube.com/watch?v=fuMvVxiQ76U

Timur, E. (2013). Determination of the contaminated area after the blowouts in Alasehir (Manisa/Turkey) Geothermal Area using geophysical methods. *EGU General Assembly 2013.* Vienna.

Toni, A., Irawan, T., Prasetyo, A. D., Andika, F. A., Prasetyo, I. M., & Saputra, M. B. (2017). Success Story Handling the Blowout of Three Wells in Hululais Geothermal Field with Capping Method. *GRC Transaction. 41.* GRC.

Toth, A. (2010). Steam Blowout from an Over Pressured Geothermal Reservoir in Hungary. *GRC Transactions* (pp. 211-214). Geothermal Resources Council.

US Department of Energy, Office of Energy Efficiency and Renewable Energy. (2024). *Geothermal Basics*. Retrieved from US Department of Energy, Office of Energy Efficiency and Renewable Energy: https://www.energy.gov/eere/geothermal/geothermal-basics

Vogel, E. (2014, January 7). *Audit: Nevada inspects oil, geothermal wells infrequently.* Retrieved August 19, 2024, from Las Vegas Review - Journal Capital Bureau: https://www.reviewjournal.com/news/audit-nevada-inspects-oil-geothermal-wells-infrequently/

Weatherford. (2024). *Geothermal Energy Solutions*. Retrieved from Weatherford: https://www.weatherford.com/new-energy-solutions/geothermal-energy-solutions/

Weatherford. (2024). *Rotating Control Devices*. Retrieved from Weatherford: https://www.weatherford.com/products-and-services/drilling-and-evaluation/managed-pressure-drilling/rotating-control-devices/

Wild Well Control. (2024). *Geothermal*. Retrieved August 19, 2024, from Wild Well Control: https://www.wildwell.com/ccus/geothermal