LOST IN THE JUNGLE – A REVIEW OF THE STILL-RADICAL GEOTHERMAL DEVELOPMENT AT KIABUKWA, DR CONGO

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ABSTRACT

In 1951, tin miners in what was then Belgian Congo needed electricity for their plant, but faced cost and logistic challenges around bringing fuel to site. There was a 91°C large flow hot spring near the site so they sought engineering help to develop this. This request would still be thought of as a development challenge today, especially in a tropical environment, even with the present availability of binary cycle technology. The resulting 250kW Kiabukwa geothermal station, which ran for several years before Wairakei, was developed in this purely commercial context.

This paper reviews the still-radical solutions employed by the English designer/manufacturer in this largely forgotten pioneering project, particularly its use of sub-atmospheric flash technology.

1. CONTEXT

This paper had its origins in a house move when long-forgotten articles surfaced for refiling. The particular article was "Power from natural hot water" published in Power & Works Engineering, January, 1953 which described the 1953 Kiabukwa development with photos of the main plant undergoing trials in Belliss & Morcom Ltd works. Kiabukwa is occasionally mentioned in papers with an African context, but it is sometimes incorrectly described as binary cycle plant, presumably on the incorrect assumption that this is the only technology that could use temperatures as low as 91°C.

Early Belgian authors recognised the value of the development (Rollet 1957), but also that replicability opportunities would be limited (Clerfaÿt 1960). Ronald DiPippo briefly covered Kiabukwa plant design in a general review of the evolution of geothermal power plants (DiPippo, 2015). Kiabukwa was a true pioneering geothermal plant.

The instigator of the Kiabukwa project was a Belgian company, the Société d'Exploitation et de Recherches Minières au Katanga (shortened to Sermikat). Sermikat planned to establish a tin mine in Kiabukwa, Belgian Congo (now Democratic Republic of the Congo), (see Figure 1). There was a great distance to fuel supplies (which raises questions about what fuel was needed for mining equipment) so the company investigated use of the hot spring at the location. Clerfaÿt (1961) makes it clear that power options were limited by the relatively short planned life of the mine, so that drilling as at Larderello in Italy or Wairakei in New Zealand would have been unattractive. Thus interest was in simply making use of the 91°C spring

Figure 1: Location of Kiabukwa in DR Congo. Note that it sits outside the African Rift Valley [Source: Google Maps]

As would still be the case today, Sermikat struggled to find any company willing to design and build a power station using such a resource, but in 1951 Belliss & Morcom Ltd was contracted.

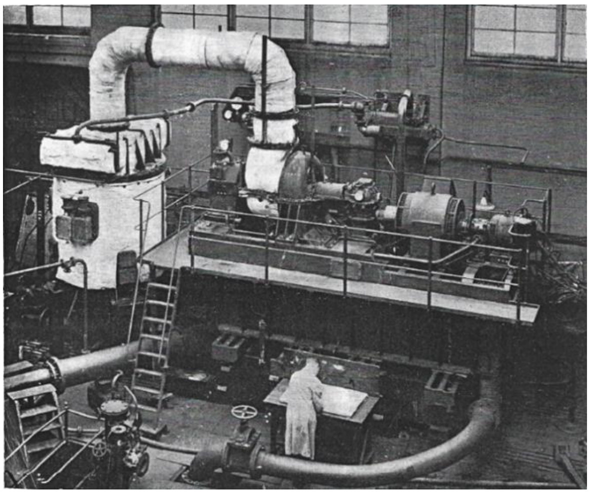

Figure 2: View of the main Kiabukwa plant during trials at Belliss and Morcom's works. Evaporator capped with the superheater is on the left, turbine, gearbox and alternator are fixed on top of the condenser, air pump is mounted on the wall behind the alternator [Source: Power & Works Engineering 1953]

Belliss & Morcom Ltd was an English manufacturer established 90 years prior to this. They had been early pioneers of steam-powered electricity generation in the 1880s. By 1887 they were powering British navy torpedo gunships. A draughtsman developed a means of forced lubrication of bearings in 1891. In 1907 the company built a first experimental double-decker bus for London. By World War I, the company was producing a range of engines, condensing plant, air compressors, fan engines and pumping engines. After World War II, the company developed its steel works. A second geothermal development for them after Kiabukwa was the reciprocating steam engine used for site power at Wairakei prior to construction of the main plant. As a rule, the company seems to be associated with innovation and quality, at one time in the 1990s being under Rolls Royce.

2. RESOURCES AT HAND

Geothermal resources across the Democratic Republic of the Congo are still poorly researched. It is possible that first surveys in the Kiabukwa area were carried out by Bas-Katanga Engineers in 1911 backed up in 1949 by further research with a specific view to supporting mine development (Makuku 2019). Specific details have not been found.

Clerfaÿt reported in 1960 that the springs did not appear to have a volcanic connection and that it was thought the springs were due to deep circulation in an otherwise normal 30ºC/km geothermal gradient environment.

Based on the Power & Works Engineering article, the hot water was described as "of very good quality, containing no acidity and very little hardness". There was a "reasonably constant supply of water" with about 139 t/h at 91ºC but if the natural overflow level of the spring was lowered by a meter or so then flow could be increased to 243 t/h at 93ºC. By any standards, this is a large and very hot spring. For design purposes, the lower flow was considered normal operation while the higher flow was considered an "overload" situation, with the turbo-alternator having a normal output of 220 kW and overload output of 275 kW.

A cold water reservoir was available about 200 m from the hot springs and about 6 m above the power station site for cooling purposes. This was typically at 24ºC with a usual water flow of 576 t/h available outside the dry season depending on rainfall. To help manage dry season risk, Belliss and Morcom had an upper and lower reservoir constructed. The upper reservoir had a surface area of 2276 m^2 while the lower reservoir had a surface area of 6782 m^2. The area allowed heat loss. If the upper reservoir was about 2 m deep (actual details are unknown) then it could have stored water for 8 hours of operation. The lower reservoir could have been shallower with emphasis on heat loss, a depth of about 0.7 m allowing for 8 hours of storage. In the dry season, a closed loop system could be brought in to play with water pumped from the lower reservoir to the upper reservoir or to a "mechanical cooler" before return to the condenser. One innovative feature of these cooling ponds was the ability (in some modes of operation) to shift the timing of pumping back up to the top reservoir to low electricity demand periods i.e. they could shape parasitic load to maximise available generation at peak demand times. Because of the head between the reservoirs, the transfer pump motors were probably sized between 20 and 60 kW. At the time of design, it was expected that electricity demand would drop to 150 kW through 16 hours of the day from the 220 kW or higher at the peak of the day, though in practice demand never reached these levels. DiPippo (2015) described this as a type of "hybrid geothermal/pumped-storage" system.

3. PLANT DESCRIPTION

The plant included venturi nozzles discharging into an "evaporator (or flash-steam generator)" to allow sub-atmospheric flash, coupled with a steam superheater fed by a small auxiliary biomass boiler. After the flashed steam passed through the three stage turbine it was condensed in a shell and tube condenser that also formed the turbo-alternator bedplate. Any air leakage or residual gas from the brine was extracted from the condenser with a two-stage steam jet ejector for which steam was sourced from the auxiliary boiler. The discharge from the second stage ejector was fed through the superheater then to waste. A high condenser vacuum was maintained through a barometric leg formed in an 11.7 m deep tail well with two submersible pumps to remove hot discharge water to waste.

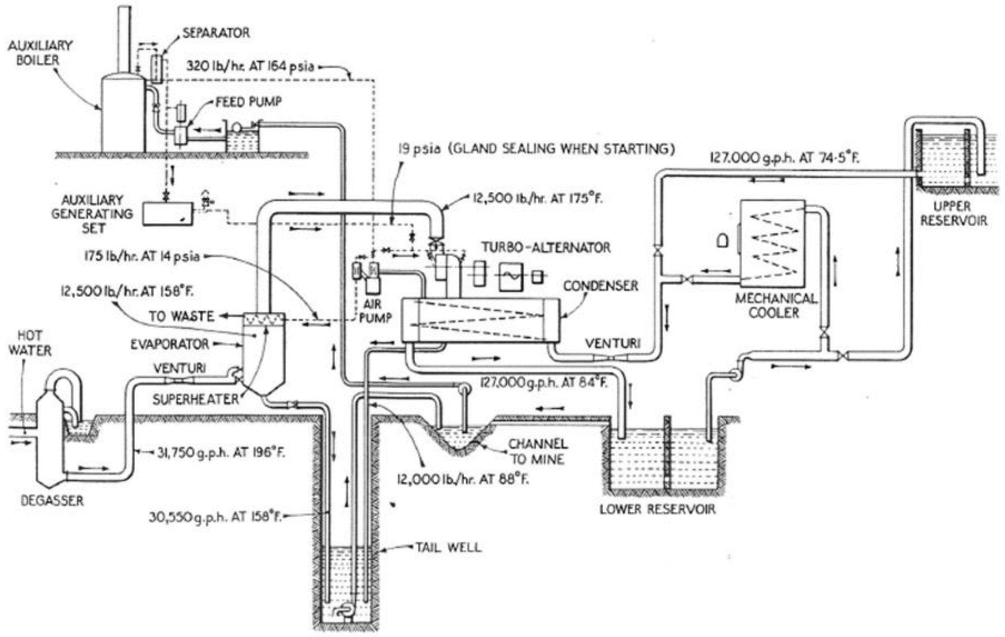

Figure 3: Process flow diagram for Kiabukwa [Source: Power & Works Engineering, 1953]

The innovative features here are the venturi nozzles feeding into a vacuum vessel acting as a sub-atmospheric evaporator. When fluid flows through a constricting venturi, its speed increases in the constriction and, from Bernoulli's principle, pressure decreases. If this pressure is suitably low then steam can flash off hot water. After passing through the constriction, the velocity profile within the expanded section of the venturi still contains a core of higher velocity fluid so that pressure is still lower than the inlet condition. Simple application of the principle shows that flashing of 91°C water can be induced if the ratio of inlet diameter to constriction diameter is greater than 2.3 (or for 50°C if the ratio is greater than 3).

The flash-steam generator contained two rows of venturi nozzles. The lower level of sixteen nozzles was associated with normal operation and fitted with manual controls because of the intention to baseload this operation. The upper level of twelve nozzles was for the overload operation and had automatically controlled valves with a feedback loop linked to the pressure drop across the turbine governor valve.

The following data illustrates the operation of the flash-steam generator. Under normal operation with a 220 kW turbo-alternator output, inlet temperature was 91°C associated with an enthalpy of 381.5 kJ/kg. In the flash-steam generator the pressure was 0.31 ba (4 ½ psia) for which saturation temperature was 69.9°C, liquid enthalpy was 292.5 kJ/kg and heat of vaporisation was 2333.6 kJ/kg. This suggests a dryness of 0.0381 so an inflow of 139 t/h of hot water would generate 5.31 t/h of steam. In practice 5.67 t/h of steam left the superheater so an extra 0.36 t/h is unaccounted for. Some of this could have been entrainment of mist but it is likely that actual vacuum was not accurately recorded. A vacuum of 0.29 ba (4 ¼ psia) would have generated about this steam flow.

The superheater was supplied with 79 kg/h of steam at 0.97 ba pressure from the biomass boiler, which then discharged to waste after the superheater. Most energy would have transferred as this steam condensed, equating to a heat transfer of just under 50 kW. If this heat was simply used to reflash water vapour rather than provide superheat, then it could reflash just under 0.08 t/h i.e. a negligible amount. As superheat was achieved it appears that entrained mist was minimal.

For the overload situation, for which the turbo-alternator was limited to a 275 kW output, a 75% increase in brine flow at slightly higher temperature resulted in a 27% increase in steam flow. Examining this in more detail, under overload operation, inlet temperature was 93°C associated with an enthalpy of 390.8 kJ/kg. The paper was silent on vacuum pressure at these conditions so assuming the same vacuum was maintained implies a dryness of 0.0421 so an inflow of 243 t/h of hot water would generate 10.22 t/h of steam. In practice only 6.89 t/h was generated, so it is likely that the vacuum was compromised, rising to a value near 0.43 ba. The turbine throttle valve would have backpressured the system to avoid overload.

Given the low inlet temperature it is no surprise that of the nearly 139 t/h of hot water supplied under normal operation, 133 t/h was rejected.

The superheater added further energy. The energy for the superheater came from an auxiliary boiler, normally fuelled by dry soft-wood logs sourced from the forest, though it could also burn site refuse. This boiler served purposes of providing steam for the air ejectors, gland steam for the turbine at startup, and could power a startup generator. The steam from the second stage air ejector fed the superheater. The design steam flow to the superheater was only 79 kg/h at a pressure of 0.97 bara and 98.6°C much of which exhausted to waste, leaving geothermal-sourced flash steam to do most of the work. The superheater would have added about 50 kW of heat to the steam flow bringing total energy delivered to the turbine of 4166 kW. So the end contribution of biomass was negligible in terms of energy balance (though useful in terms of providing higher pressure steam for ejectors and for glands at startup) and Kiabukwa can be thought of as a geothermal operation rather than hybrid geothermal-biomass.

Under normal operation the turbo-alternator could be expected to produce 220 kW while 275 kW could be produced in overload operation. Given the recorded flows, this suggests a turbine conversion efficiency of 65%. While modern units might have efficiencies closer to 85%, efficiencies as low as 60% have been observed (Wahl 1977). In Kiabukwa design, it is likely that efficiency was sacrificed for robustness for this radical application in a remote location. However, if the concept is taken up again, then higher efficiency turbines could conceivably be used.

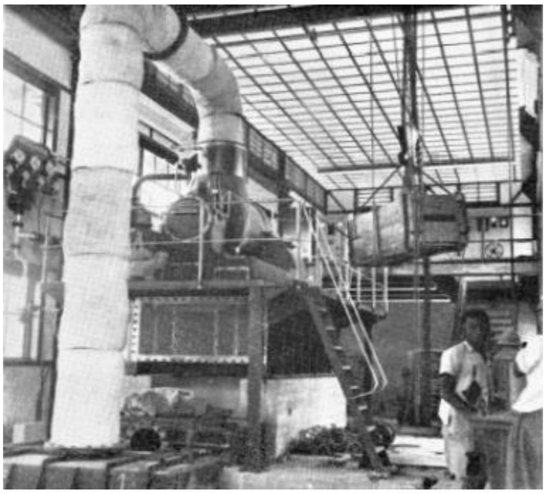

Figure 4: View inside Kiabukwa station, probably during construction since pipes are partly lagged and large loads are being moved by crane [Source: Omenda 2019]

In contrast to most current condenser designs, Kiabukwa did not use a direct contact condenser. A high vacuum was developed in a shell and tube condenser, with steam vented into the shell while the cooling water made three passes through the shell in brass tubes. Total cooling water flow was 479 t/h at about 24°C to cool the 5.67 t/h of flashed steam. A vacuum of 0.045 ba was created, so that condensate left the condenser at 31°C while cooling water left the condenser at 29°C. It is not recorded why a direct contact condenser was not used. In the dry season when cooling fluid was recirculated then the addition of condensate to the total flow could have been useful.

In practice, the steam condensate went into a deep barometric leg and was subsequently pumped out to a mine discharge. Some of the mixed condensate and rejected brine formed a makeup feed for the biomass auxiliary boiler.

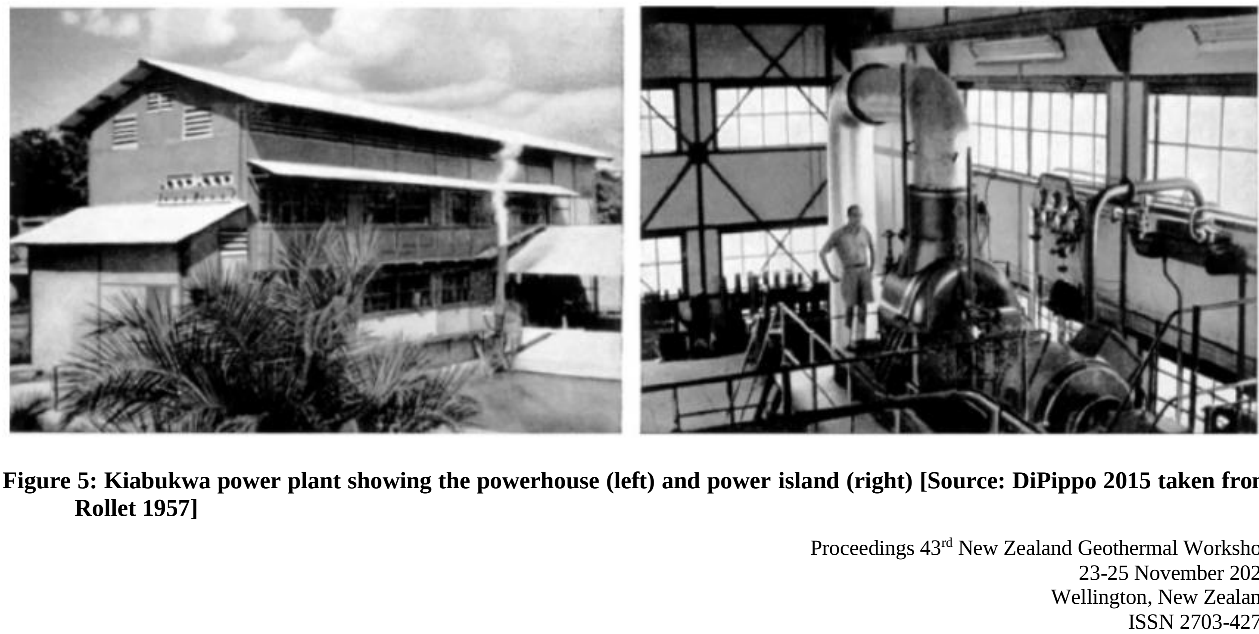

Figure 5: Kiabukwa power plant showing the powerhouse (left) and power island (right) [Source: DiPippo 2015 taken from Rollet 1957]

It appears the project was fortuitous with the nature of the spring water. Chemical composition of the spring is not available. However, trials located in New Zealand privately by Bechtel at Kawerau in 1957 (Fletcher-Bechtel-Raymond 1957) mainly focused on steam condensates and by the government at Wairakei in the 1950s showed that alloys of copper were not suitable for general geothermal environments, particularly where hydrogen sulphide gas was present. This knowledge largely post-dated design and would not have been available to Belliss and Morcom, who may have drawn on their marine experience in selection of materials. Consequently, copper and its alloys played an important role in the design of the plant. They did include a degasser at the exit of the pool which supplied the hot water which may have helped.

Hot-water nozzles were stainless steel. A conical copper baffle was fitted about the nozzles to restrict the height of spray, while a further baffle may have been located below the superheater. The steel superheater included brass tubes fixed into brass tube plates. The turbine had cast-iron casings. The gate-type governor valve was of cast-bronze and actuated by the governor gear. All three stages of the turbine had manganese-bronze rotor blades machined from stampings and rolled brass-strip stator blades. Carbon ring glands on the turbine rotor were used to exclude air ingress. The condenser was of rectangular welded-steel construction containing brass tubes secured to brass tube plates by brass ferrules with cast-iron water boxes and end covers. The two-stage steam-jet ejectors had stainless-steel jets, bronze throats and steel strainers above the jets.

As far as is known, there were no particular issues with material selection in the operation of the plant.

Clerfaÿt noted that maintenance effort seemed slightly less than comparable thermal power plant. Routine maintenance operations included condenser cleaning and seal renewals and could be undertaken in a 3- or 4-week general maintenance period. No major repairs had been required in six years of service.

4. OVERALL PERFORMANCE

A calculation of thermal power into the system compared with (gross) electrical power output shows a resource conversion efficiency of 1.5%. In future with more efficient turbines, this could be raised to 2.0%. At first sight this appears to be poor compared with typical net efficiencies of 10 to 18% for geothermal energy conversion, but performance for any technology would be limited by these very low operating temperatures.

As a cross check, the Chena plant in Alaska operates at more extreme conditions than Kiabukwa with a supply temperature of 74°C and total flow of 117t/h to generate a net output of 210kW (Chena Power Company 2007) so has a resource conversion efficiency of 2.1% but is helped by the cool alpine conditions in terms of its sink temperature.

The following graph plots this simple conversion efficiency against an effective source temperature, which is taken as the equivalent saturation temperature if the enthalpy was that of saturated water. Kiabukwa is located at the extreme end of this broad span of data.

The graph takes the analysis one step further to look at a potential performance curve on a similar net basis for modern sub-atmospheric flash plant with the following parameters:

- Flash temperature picked as half of the effective source temperature and vacuum temperature as a crude optimisation (Tarigan 1979)
- Standard direct contact condensers and cooling towers generating a vacuum of 0.08ba
- No superheat
- External source of steam for air ejectors
- Modern turbogenerators achieving 85% efficiency
- Parasitic load of 5.5% equivalent to normal flash technology (possibly an underestimate given that wells are also likely to be pumped, though would be an appropriate assumption if developers were considering using collected brine destined for reinjection).

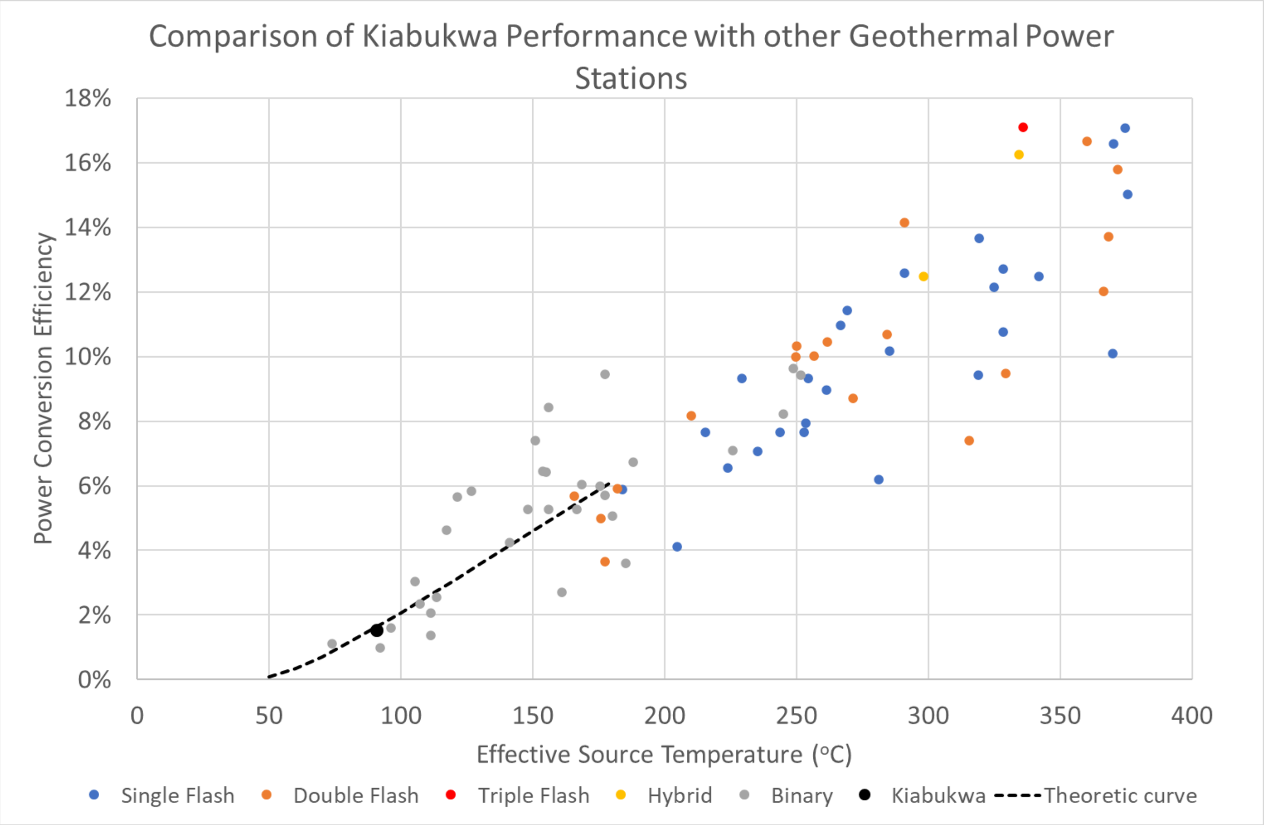

Figure 6: Comparison between Kiabukwa sub-atmospheric flash performance and a range of other technologies and developments [Source: data adapted from Moon and Zarrouk 2012]

A conclusion is that the use of nozzles and sub-atmospheric flash plant has the ability to stretch the competing range of operating conditions for steam turbines down to and below temperature supply conditions currently achieved by binary cycle plant. It will be up to manufacturers of these potentially competing technologies to ensure their plant is commercially competitive.

The author is aware of one project where serious study was given thirty years ago to sub-atmospheric flash as an alternative to binary cycle plant to make use of brine that was otherwise being injected. Various manufacturers were identified who could design and build the plant. However, on balance, the choice was made in favour of binary cycle plant.

5. FINAL STATE OF THE KIABUKWA PROJECT

Clerfaÿt reported in 1960 that the project had been running for six years without significant difficulties, although plant output was only 1,000,000 kWh per year (i.e. a mean output of 125 kW allowing for a one month annual shutdown), fully satisfying the demand from the mine. So, the plant was limited in output by the actual load of the mine rather than any performance limitation of the plant itself.

His report also contained advice on the need to baseload plant. However that may relate to the design of the nozzle controls. For low loads (and the plant typically operated at about half of its design load) the nozzle controls were hand-operated, whereas automatic control of the upper nozzles came into play for the overload operation. The throttle valve at the turbine could also be used but that would mean raising the pressure in the flash separator which could have had undesirable effects. With future plant design it is advisable to ensure automated control through all venturi nozzles.

Clerfaÿt also suggested that the plant was partly selected with the relatively short life of the mine in mind i.e. the intention was to abandon it eventually. How long until abandonment took place is unclear. DiPippo suggested that the mine and plant shut down in 1960 when the country plunged into civil war following independence. The previous Force Publique led successionist struggles in the province of Katanga (where Kiabukwa was located) and South Kasai in the months following the 1960 independence. There have been continuing international and local conflicts over the last sixty years in this mineral-rich area so that prior to COVID-19 the area including Kiabukwa was covered by a "Do Not Travel" advisory note. It may be several years before geothermal specialists can revisit the area.

A number of people claimed to have seen Kiabukwa station, but photographs have not been found for this report.

6. CONCLUSIONS

Kiabukwa sub-atmospheric flash plant was developed prior to most other flash developments and outside the common geothermal circles. This embedded plant faced a lower than design load, then its operation was curtailed by civil war over sixty years ago. It now sits largely forgotten in the DR Congo jungle.

But the plant worked and showed that flash operation with steam turbines could be applied over the full range of available temperatures, potentially below the extreme low temperatures recently achieved by binary cycle plant.

Both technologies can compete in this low temperature market.

REFERENCES

______: Power from natural hot water. *Power & Works Engineering, January, 1953* pp 13-17 (January 1953)

Chena Power Company: *400kW Geothermal Power Plant at Chena Hot Springs, Alaska*. Final Project report prepared for the Alaska Energy Authority. (February 2007)

Clerfaÿt, A: *Le développement énergétique du Congo Belge et du Ruanda-Urundi.* Académie Royale des Sciences D'Outre-Mer – Mémoires. (1960)

DiPippo, R.: Geothermal power plants: Evolution and performance assessments. *Geothermics Vol 53, January 2015, pp 291-307* (January 2015)

Fletcher-Bechtel-Raymond: *Completion Report – Geothermal Steam Research and Development Program for Tasman Pulp and Paper Company Limited*. (1957)

Makuku, L.: Inventory of geothermal sources in the DRC and their development plan for the electrification of local areas. Case of the eastern part of the DRC. *IOP Conf. Series: Earth and Environmental Science* 249 012016 (2019)

Moon, H. and Zarrouk, S.J.: Efficiency of Geothermal Power Plants: A Worldwide Review. *New Zealand Geothermal Workshop 2012 Proceedings.* (November 2012)

Omenda, P.: *Geothermal Outlook in East Africa: Perspectives for Geothermal Development.* IRENA – IGA Presentation (2018)

Rollet, A.: Centrale géothermique de Kiabukwa: Leçons tirées de quatre années d'exploitation (Kiabukwa geothermal power plant: lessons learned from four years of operation) *Bulletin des Séances III(6), 1246-1262, Académie Royale des Sciences Coloniales (Nouvelle série).* (1957)

Tarigan, G.: *Thermodynamics of Geothermal Plant – Optimisation Studies.* Geothermal Institute Report 79.22 (1979)

Wahl, E.F.: *Geothermal energy utilization*. (1977)

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