OLD LESSONS APPLIED TO MODERN SEPARATOR STATION DESIGN

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ABSTRACT

Wairakei development was enabled by the development of effective two-phase separators and valuable early research on two-phase flow. The basic separator technology continues in use to the present day, in many cases upscaled, with centralised separator stations. There have been some refinements to outlet controls and some change in proportions. However, there may be some fundamental lessons that have been forgotten along the way. This paper skims over early and more recent research, then looks at the design and performance of a separator station on the Ulubelu geothermal field in Indonesia, designed and constructed by international experts, that in fact is similar to many centralised separator stations around the world. Performance is compromised by forgotten lessons. The paper looks at inlet and outlet conditions, and finally considers some possible solutions to performance loss.

1. EARLY WAIRAKEI-ORIENTATED RESEARCH

1.1 Background

When Wairakei research and development began in the early 1950s, geothermal development faced fundamental questions around two-phase flow and effective phase separation. Unlike Lardarello in Italy, Wairakei had wells that discharged a mixture of steam and brine. A clean dry steam supply was needed for the station turbines.

The New Zealand Government had partnered with a British company Merz and McLellan, partly because of the interest in developing a heavy water plant at Wairakei, though this nuclear component was dropped late in the design stage (after initial turbine orders had been placed).

Merz and McLellan had an engineer (Basil Wood) who was their separator expert. He considered the cyclone separators used in Brown Boveri Velox boilers (as found in the State Hydro Electric Department's Evans Bay coal-fired station in Wellington), scrubber-separators (but wrote them off due to difficulty of inspection and modification) (Wood, 1954), tried an in-line separator (which failed) then proceeded with a prototype top outlet cyclone separator design with internal baffles (which worked to an extent but was unnecessarily complicated).

The New Zealand Government needed to ensure that an effective two-phase separation solution was found so proceeded with independent studies. Starting in 1955, the Dominion Laboratory of the New Zealand Department of Scientific and Industrial Research employed a number of scientists and engineers to study two-phase flow in pipes, and to study phase separation. They used a combination of Perspex models with air-water mixtures and a geothermal test rig on well WK9 at Wairakei (Figure 1). These early two-phase research pioneers included Willem Stuiver assisted by Gordon Dawson who assembled the model (Stuiver 1955, Dawson 1991) in the Physical Laboratory, then Gordon Maskill-Smith and Yuan Hoe (with these two chemical engineers generally cooperating in joint research papers) in the Chemical Engineering Laboratory.

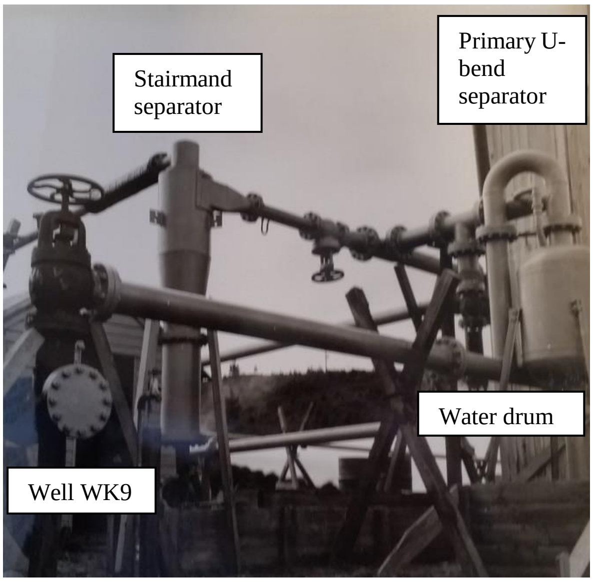

Figure 1: The original WK9 test rig – Well WK9 left foreground, primary U-bend separator on the right with brine to a water drum and remaining two-phase mix passing to a top outlet Stairmand high efficiency cyclone separator (actually a dust separator) on the left (from Maskill-Smith and Hoe, March 1956).

Internationally, two-phase flow concepts were in their infancy. A horizontal flow regime map had been published by Baker the previous year (Baker, 1954). This Baker Chart continues in use to the present day, especially in the oil and gas industry. Stuiver designed the Dominion Laboratory air-water test rig to cover most of the expected flow regimes (Figure 2). A test rig was thought necessary because expected Reynolds numbers for Wairakei were between one and two orders of magnitude greater than published literature (Stuiver, 1955).

The Dominion Laboratory Perspex rig tested a number of configurations, including flow regimes and pressure loss in straight pipe and in 90 and 180^o bends, efficiency of T-junctions as separators (with branch offtake at the bottom of the pipe to form the basis for steam drain pot design), efficiency of U-bend separators, and then tested some bottom outlet cyclone separator designs.

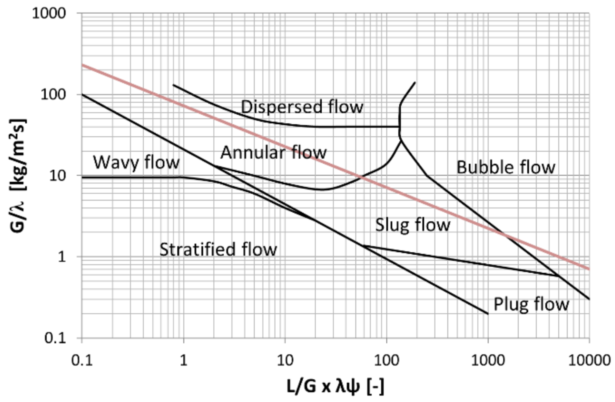

Figure 2: Baker Chart (metric version) plotting regimes against axes of superficial gas velocity (converted to equivalent properties of air) and a ratio of superficial liquid and gas velocities (converted to equivalent properties of water and air). The area to the left of the red line is the approximate operating range of Stuiver's test rig. (based on Stuiver, June 1955)

Figure 3: An image from the test of a U-Bend separator. Note that incoming water (vertical right) in annular flow regime continues straight at the corner until it hits the opposite wall. The focused stream of water then flattens and spreads out under the effects of centrifugal force, which actually directs significant quantities of water into the outlet pipe of the separator. Note the thick film after the U-bend which may be explained by Azzopardi's "film-stopping" mechanism (Maskill-Smith and Hoe, 1956).

The Dominion Laboratory rig was useful, especially in allowing flow visualization. However, as wells became available in both Wairakei and Kawerau geothermal fields it became possible to undertake flow testing in the field under actual conditions. The New Zealand Ministry of Works then tested various separator configurations including U-bend separators, Wood's in-line separator, Wood's top outlet cyclone separator and their own bottom outlet cyclone separator.

The following results are shown for U-bend separator efficiency tests as they represent a special case of a T-junction separator, which is discussed in more detail later in this paper.

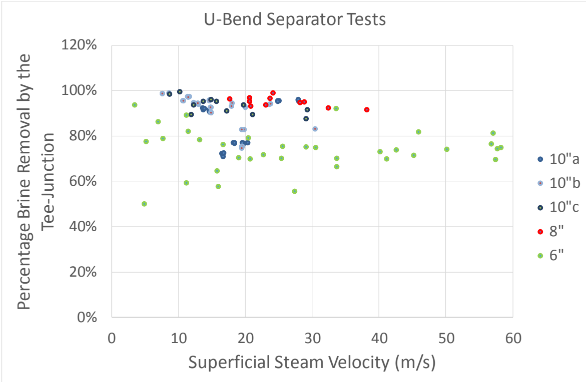

Figure 4: Field test results for U-bend separators based on 6", 8" and 10" diameter pipes (based on data in Fooks, 1954).

The 6" U-bends were linked directly to a water drum which may have allowed a backfeed of brine into the offtake line resulting in removal of only around 75% of all brine. However the later tests on 8" and 10" U-bends had provision to vent the waste brine more directly resulting in typical efficiency of water removal closer to 95%.

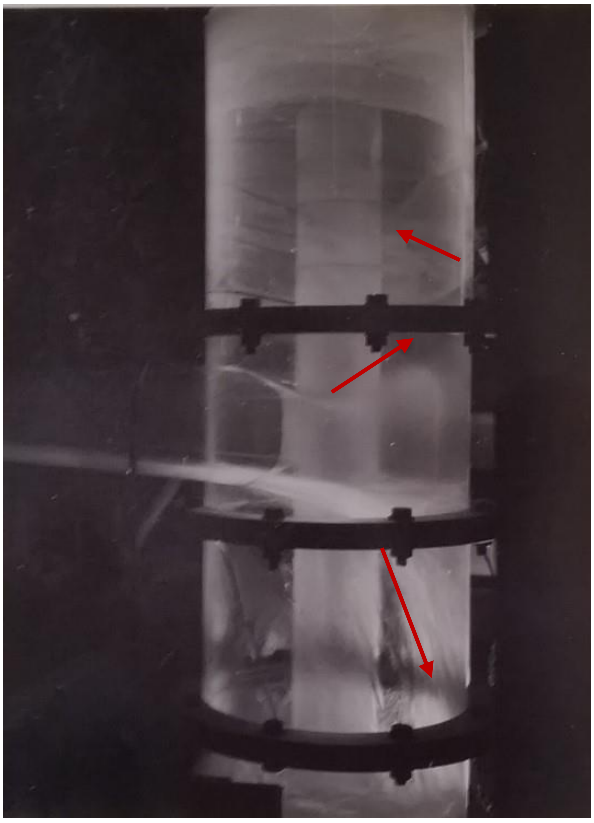

Figure 5: An image of bottom outlet cyclone separator tests showing water falling under the effect of gravity, while some is given upward momentum through the effects of centrifugal force – potentially up to 100 G-force (Maskill-Smith and Hoe, 1958).

The Ministry of Works test facilities became the focus of research. When Pieter Bangma published the results of the Ministry of Works tests on bottom outlet separators at the United Nations Conference on New Sources of Energy in Rome in 1961 (Bangma, 1961), this design became the master template that enabled global development of wet fields for geothermal development (but subsequently was modified by Lazalde-Crabtree (1984)). Note that Bangma's original test separator continues in use to the present day, now supplying steam to the Ohaaki kilns.

Many years later, additional research was undertaken on a Wairakei test rig, initially by Roger Harrison (Harrison, 1975) and then by Hagen Hole and "KC" Lee (then a station assistant engineer) under the supervision of Professor Derek Freeston (University of Auckland) (Freeston et al, 1983).

It was Harrison who popularised the use of the Mandhane Chart as the preferred means of anticipating flow regime for horizontal pipes in geothermal systems, although the Baker Chart continues in use for other applications and in other geographical regions.

The flow regimes are affected by fluid properties (e.g. through the effects of pressure). However, the following chart shows anticipated flow regimes for a steam-water mix at 8 and 15 bara covering a reasonable operating range. The red lines show the approximate flow regime transitions based on the Baker Chart.

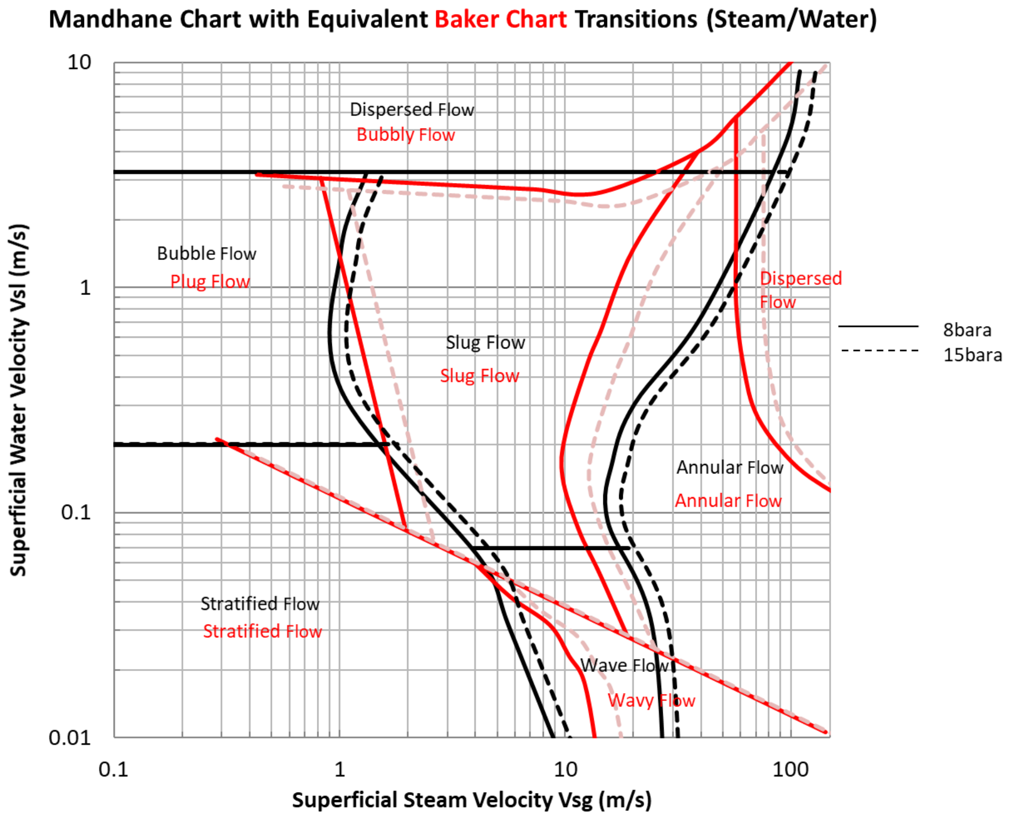

Figure 6: A combined Mandhane (black lines) and Baker (red lines) flow regime chart for steam/water mix on Mandhane chart axes.

In terms of design conditions for steamfield above ground systems, it is preferable for pipes to be sized to avoid slug flow, because of potential impact on pipe supports. Pipes are commonly designed for annular flow but near the slug flow boundary to help manage pressure drop associated higher velocities and long pipelines. However, the pipe leading in to the separator may be designed for slug flow (at least according to Mandhane) to avoid excessive steam velocities which could lead to separator breakdown (i.e. separator inefficiency associated with carryover of brine).

There is still considerable uncertainty about what actual flow regime will exist in large diameter pipes. For large straight pipes, gravity will obviously play a role such that the thickness of the annulus for annular flow will be greater at the bottom of the pipe than at the top. The Mandhane and Baker Charts are in disagreement in the critical area where many geothermal engineers design their systems (with Vsg in the range 20 – 60 m/s). From the steady sound made by fluid travelling in these pipes (more consistent with annular flow than slug flow), it appears that the Baker chart may be more accurate in this range.

1.2 Central Separator Stations

For Wairakei, Merz and McLellan had been particularly averse to centralised separator stations. There were uncertainties about the transmission of two-phase fluid and about the performance of the separators, but their greater concern seemed to be about corrosion risk from the flashed steam. This concern led them to select multiple steam mains to the power station utilizing the largest available seamless pipe to minimize corrosion risk to welds (Haldane and Armstead, 1962). A "pilot hot water station" (a form of centralised separator station) was commissioned at Wairakei between A and B Stations in July 1963 but was abandoned in April 1964 due to supply issues with connected wells (White and Chambefort, 2016). A number of flash plants (regional separators) were installed in 1973/4 once confidence in the design and performance at Wairakei had been established, building on the experience of the pilot hot water system. The triple flash arrangement for Wairakei then immediately lifted utilisation efficiency from about 8% to over 9% (Thain and White, 1993).

Centralised separator stations had been considered before then. In 1957, Bechtel was proceeding with design for a development at Kawerau. While this field was predominantly intended to be for a direct heat supply for Tasman Pulp and Paper Company Limited, Bechtel did develop a geothermal power station concept, with two 10MW condensing sets largely located outdoors. Figure 7 from their concept report includes a centralised separator just outside the power station. This was a top-outlet separator about 3.5 m in diameter and 10.5 m high, including insulation (Fletcher-Bechtel-Raymond, 1957).

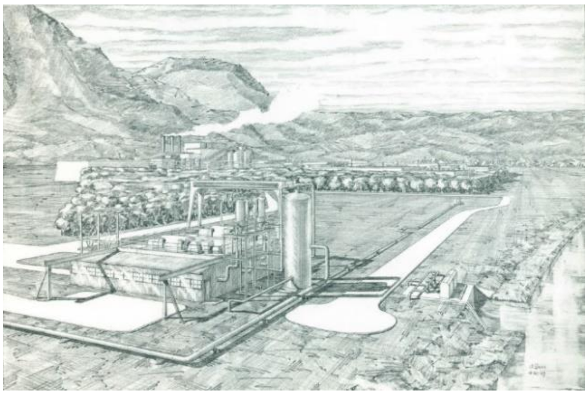

Figure 7: Proposed 20 MW Kawerau Condensing Station showing a central separator. (Source: 1957 Fletcher-Bechtel-Raymond report)

Centralised separators are now a common feature of geothermal developments world-wide (see examples in Figures 8 and 9). While these may have a single separator performing 100% duty, very often there are two or three separators at each separator station. They are manifolded through the two-phase lines, the outlet steam lines and the outlet brine lines. The separators may have integral water tanks or water tanks can be separate. Although a spiral inlet design was shown to be superior by Bangma in his 1961 paper, some of these continue to have tangential inlets.

Figure 8: Two banks of three separators with integral water tanks for Wayang Windu units 1 and 2, each separator rated at 40 MWe. (Source: Purnanto and Purwakusumah, 2015)

Figure 9: Flashplant 16 supplying Te Mihi Power Station on the Wairakei field, each separator is rated at 55 MWe (Source: Harwood, Koorey and Mann, 2015)

1.3 Some Kawerau Experience

The following experience is referenced with a view to upcoming discussion of Ulubelu separator station performance.

While cyclone separators or scrubbers are needed to deliver steam of adequate dryness for electricity generation, direct heat applications do not have the same dryness requirement. The Kawerau geothermal field was initially developed to supply steam to a pulp and paper mill. In practice, most of the supply is through cyclone separators which enables some steam to be used in electricity generation plant within the system. More recently the complexity of supply networks at Kawerau has increased with multiple generating plants on the field, all taking advantage of cyclone separation.

However, in the 1980's a greenhouse was developed on the field with a requirement for steam. The annual value of steam sales to this plant was particularly low and could not justify the installation of a dedicated separator, while the plant was too distant from other steam lines to justify connection to already separated steam. The KA21/27 two-phase line passed close to the greenhouse site. The choice was made to simply take a small tee off the top of the two-phase line (which experienced annular flow regime). Essentially, it was confirmed that the T-junction acted as a separator, and the supply of steam to the greenhouse was of adequate dryness.

Another experience related to the performance of the KA21/27 Separator Station itself. This separator station is located closer to the mill and consists of two separators beside each other. Rather than have flow split evenly at a common manifold, the two-phase line essentially passed in front of the two separators with the first separator receiving its mix of fluid from the side-arm of a T-junction. There was indirect evidence that this first separator did not receive sufficient brine to enable a water seal beyond the separator so that some steam was being lost to the adjacent silencer. The T-junction was acting as a primary separator.

1.4 Some External Research on T-Junctions as Two-Phase Separators

Two-phase flow research generally happens with a view to applications outside of geothermal development, with oil and gas applications being a particular focus.

Much research has been directed at the effects of T-junctions as partial phase separators, particularly over the last 35 years (Baker 2003). One centre for this study was the University of Nottingham under Professor Barry Azzopardi (died 2017).

Key parameters defining dimensions and flow properties at T-junctions are shown in Figure 10 with most items self-explanatory: "x" is the quality of the stream, which in the geothermal case is percentage of steam in brine or brine in steam, "$\dot{M}$" is mass flow, "Δp" is pressure drop, "D" is diameter and β, θ and ϕ are angles.

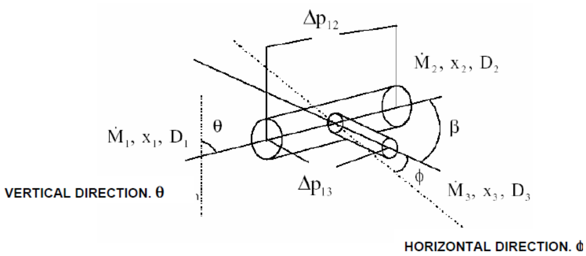

Figure 10: Parameters involved in T-junction definitions (Baker 2003).

The dominant forces that affect phase split at a T-junction are

- Gravity, which will act predominantly on the liquid phase and will oppose any displacement in the side-arm if angled upwards. Note that centrifugal force as was evident in the U-bend separator can be thought of as a variant on gravity.
- Inertia, in which the liquid will travel along the pipe with much higher axial momentum than the gas due to its higher density. This has the effect of forcing liquid to continue along the pipe, bypassing the entrance to the side-arm. If the side-arm is of reduced diameter the effect will be more pronounced since the liquid will have less time to be influenced by gravity.
- Pressure, in which there is pressure loss between the inlet and side-arm but recovery into the run, this being a Bernoulli effect from reduced velocity in the run.

Much of the research has focused on stratified, slug and annular flow as these are the most relevant to industry (stratified and slug flow being most relevant to oil and gas applications). Some conclusions:

- Flow regime has a significant influence.
- Inclination of the run makes little difference to performance
- A reduced side-arm diameter reduces the liquid take-off for a fixed gas take-off (but main pipe diameters for research purposes have been in the diameter range of 25-130 mm)
- Inclination of the side-arm can make a difference as most liquid will be in the bottom of the pipe even for annular flow
- Inserts into the run at the side-arm can affect phase separation

Barry Azzopardi has specifically looked at split of horizontal annular flow at a T-junction (Roberts et al 1997). This theoretical split was tested with vertical side-arms and main pipe diameters in the range 32-38mm.

Part of the theory looked at the thickness and flow rate of the film that would be passing across the side-arm offtake. For the small sizes of pipe considered (32mm diameter), the film thickness at the top of the pipe could be an order of magnitude less than the thickness at the bottom, and similarly the velocity at the top of the pipe could be an order of magnitude less than at the bottom. This effect could be increased by larger diameters such that the mass flow (thickness x velocity x sector length x density) of liquid at the bottom of a pipe could be 100 times or more that of mass flow near the top. An offtake near the top of the pipe would be exposed to this smaller mass flow for which only a fraction would actually be entrained into the side-arm.

Azzopardi noticed a feature called "film stop" (which may be evident in Figure 3 of this report downstream of the Tee in the U-bend separator) which can occur due to the film reacting to pressure increase along the pipe due to Bernoulli effects after velocity in the run is decreased by the offtake (Roberts et al 1997). However, film stop is not thought to play a role in the later discussion on Ulubelu.

2. ULUBELU GEOTHERMAL DEVELOPMENT, INDONESIA

2.1 Background

Indonesia is pressing ahead with rapid geothermal development. In 2018, installed capacity across the country reached 2000 MWe now making Indonesia the second largest generator of geothermal electricity in the world. Ambitions are to reach 5000 MWe by 2025.

Within Indonesia, Pertamina Geothermal Energy (PGE) is one of the largest geothermal developers. If the capacity associated with Joint Operation Contracts is ignored, then PGE has developed steamfields delivering steam to 402 MWe of generation at Kamojang, Lahendong, Sibayak and Ulubelu (units 1&2), and another 340 MWe of total projects (steamfield and stations) at Kamojang (unit 5), Tompaso (known as Lahendong units 5&6), Ulubelu (units 3&4), Karaha (unit 1) and Lumut Balai (unit 1 with unit 2 of 55 MWe to be commissioned later this year). With over 700MWe of generation, PGE is now one of the largest geothermal electricity generators in the world.

The Ulubelu geothermal field in Sumatra demonstrates PGE's desire for total field development. While PGE has had responsibility for all drilling on the field and for all steamfield above ground systems, the first 110 MWe station commissioned in 2012 was developed by the State Electricity Company (PLN) while the second 110 MWe station was developed as a total project by PGE with units commissioned in 2016 and 2017. Because commissioning is recent, there are a number of performance issues still to be sorted, particularly the performance of the central separator. A number of design aspects of this central separator were covered in a previous paper (Mubarok and Zarrouk, 2016).

There have been unrelated issues with the total steam supply across all units which PGE is addressing through makeup drilling, attempted well stimulation programs, and increased physical separation of injection and production areas to avoid cool returns. While Ulubelu 1 & 2 stations can be fully loaded, Ulubelu 3 & 4 generation has hovered between 80 MWe mean output with a peak of around 90 MWe.

2.2 Ulubelu Separator Station

Units 3 & 4 are supplied with steam from a single central separator station that has three conventional cyclone separators with integral water tanks.

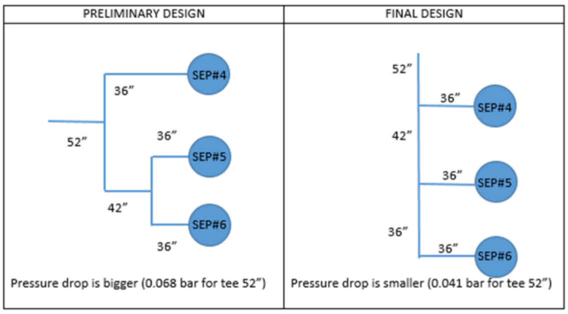

Figure 11: Comparison of original and final designs for separator inlet pipe configuration to minimise pressure drop (Source: PGE, 2017).

The key elements of the design are as follows:

- Central separation station comprises three separator vessels, each designed for a nominal steam flow of 350 t/h (50 MW equivalent power production)
- All three separators operate at a common pressure set point (to get 7.27 barg at the station scrubber inlet)
- The brine level in the separator is maintained by a modulating level control valve (LCV)
- Brine is discharged to the gravity flow brine reinjection pipeline through the LCV, modulating as per the water level set points inside the brine drum
- A pneumatically operated emergency brine dump valve (EDV) is provided for each separator to discharge brine to a common atmospheric flash tank (AFT) in case the brine level in the water drum is too high and prevents separator flooding.
- The whole system is followed by a scrubber line then station scrubber.

An overview of the separator station is shown in Figures 12 and 13. At first sight, this is a conventional central separator station, for which no unexpected behavior is expected.

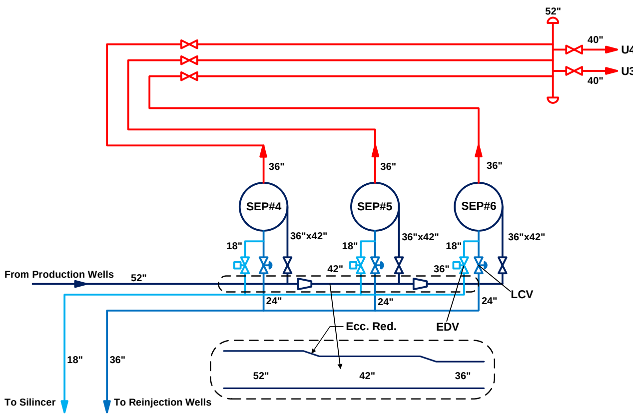

Figure 12: Overview of Ulubelu 3&4 separator station (Source: PGE, 2017)

Figure 13: Overview of Unit 3&4 Central Separator station. Ulubelu 1&2 Power Station can be seen above the separator station while Ulubelu 3&4 Power Station can be seen to the right. (Source: PGE, 2017).

However, problems have occurred as follows:

- Separator 4 behaves as though its inlet is throttled
- Separator 4 water level is low such that there may be steam loss through the brine line to the separator (now thought unlikely)
- Separator 5 water level is high and surging, such that the flow to the separator must be highly throttled to avoid the risk of separator flooding
- Separator 6 appears to take the most brine and has a high but stable water level, but is approaching its design limit
- The overall separation efficiency of the separator station prior to the scrubbing line and scrubber is only 99.6%.

When it is further considered that the power station has a 30% shortfall in steam supply, and that this shortfall will be rectified in 2019, then PGE faces critical issues with this separator station performance, still in its warranty period.

Assessed operating and design conditions are shown in Table 1 and on the modified Mandhane Chart in Figure 14.

Table 1: Summary of key assessed operating data

Item	Separator 4	Separator 5	Separator 6
2-phase main internal dia (mm)	1292	1038	885
T-junction arrangement	52"x36"	42"x36"	36"
Separator inlet diameter (mm)	1038		
Line Pressure (bara)	8.74		
Steam flow (t/h)	105	124	317
Brine flow (t/h)	0	841	2149

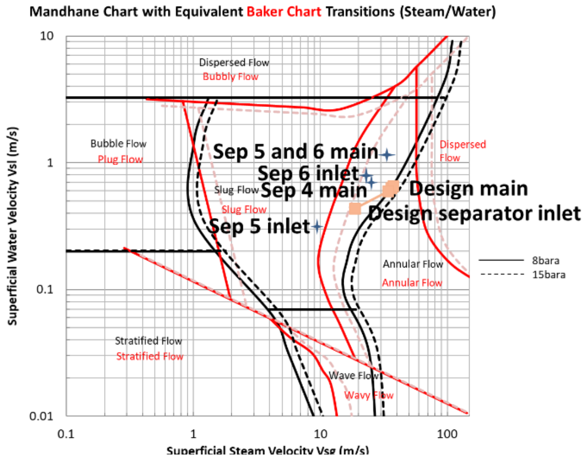

Figure 14: Current operating conditions compared with design conditions shown on the previously presented combined Mandhane/Baker Chart.

Separator 4 problems appear to result from issues around T-junction off-take through annular flow. Any T-junction in a two-phase line acts as a partial separator. This was one of the early findings of Maskill-Smith and Hoe, and more recently by Professor Barry Azzopardi. An attempt to sample the fluid on the inlet pipe to the separator failed to identify any brine component. In that case, the flow regime may be steam only or possibly stratified or wavy flow. The presence of a brine level in the integral water vessel is surprising, unless it is backfed from the reinjection system. If the observed brine level is real it will at least prevent loss of steam into the reinjection system.

Momentum will drive most liquid on through the two-phase main so that only a small fraction has an opportunity to pass into the separator offtake line through the T-junction. Assuming that water is flowing in a thin annulus at the offtake pipe, then this annulus must split at the offtake. It is speculated that a relatively narrow split of this annulus acts as a type of orifice which then throttles flow into this line. The steam flow through Separator 4 is slightly less than that through Separator 5 for which the inlet valve is 80% closed.

The surging behavior of Separator 5 may in part be due to it operating in the slug flow regime according to both Baker and Mandhane. It was initially thought that surging behaviour could be due to the reducer in the two-phase main deflecting brine upwards towards the offtake line near the top of the main. However, eccentric reducers were used such that the bottom of the pipe, where the brine annulus is expected to be thicker due to effects of gravity, was retained at the same level. The large quantity of brine may partly be a backfeed through the reinjection system. However, some may be a function of the previous Separator 4 offtake. The annulus at the Separator 4 offtake would detach from the pipe wall at the offtake then start to fall under gravity. If any of this brine impacts on the reducing section of the two-phase main then it could both be broken up and lose forward momentum allowing steam to entrain it into Separator 5.

Due to the momentum of the brine and straight two-phase main arrangement, Separator 6 must be taking the bulk of brine flow and would do so even if steam flow from the individual separators was equal. This is further reinforced by the bulk of brine flow being in the bottom of the main so having no opportunity to flow into the off-takes in the upper part of the pipe.

In hindsight, behavior of annular flow was not adequately accounted for in the redesign of the pipe network prior to the separator station. While pressure loss may have been reduced by the implemented arrangement, separator performance was highly compromised. A series of bifurcations as per the original design would have been preferable as a means to split two-phase flow more evenly.

Another issue with the separator station is the apparent overall low efficiency of separation (though this may be a function of sampling method). The steam flow for Separator 6 at 317 t/h is significantly below the limit of 350 t/h suggested by the manufacturers (although that limit may be exceeded when total flow through the separator station is boosted to match the station's 110 MW capacity). However a factor that may have been overlooked here is that separator efficiency also drops off at low inlet velocities of the order of 10m/s (Awerbuch et al 1983), as experienced here for Separators 4 and 5. In any case, impacts on turbines are avoided by the presence of a station scrubber.

2.3 Solutions

PGE has engaged in a brainstorming session on potential solutions.

One of the challenges for any rectification is that it should minimize Ulubelu 3&4 station shutdown. Currently a series of unit (rather than station) shutdowns are planned, so a full station shutdown would represent a major financial loss. An additional two-week station shutdown is worth US$3 million in lost revenue.

Failure to rectify the problem, especially after PGE has completed its drilling programme would leave station generation at around 90 MWe which will lead to around US$13 million per year of lost revenue.

For comparison, a totally new separator station of similar size would cost approximately US$4 million.

PGE's brainstorming identified several partial or complete solutions to the problems identified. These could include:

- protrusions into the two-phase main (either a pipe extension or a bow splitter just upstream of the first offtake) for Separator 4 (so that the line would not be throttled by the annulus, and possibly to reduce brine entering Separator 5);
- a partial duct in the vicinity of Separator 5 offtake (to prevent excess brine being sprayed into the offtake);
- addition of a fourth separator in spare space for final connection in a short shutdown (assuming the possibility that some separators may remain throttled so additional capacity can be handled);
- possibility of constructing piping of the correct configuration in parallel with existing pipework ready for final connection in a short shutdown, then later removal of existing pipework;
- full replacement of the separator station on adjacent land based on original piping design, with final connection in a short shutdown.

Concerns about separator flooding could be alleviated by a second brine offtake from the integral water tank diagonally opposite the existing offtake.

It is noted that some of the solutions may lead to new problems associated with steam loss to the reinjection system if there is insufficient brine to form a seal at the separator brine exit.

There may be other solutions, and for now resolution is the responsibility of the EPC contractor.

3. CONCLUSIONS

There is disagreement on the likely flow regime, especially in the common superficial steam velocity ranges of design for geothermal developments.

Early and recent lessons about the use of T-junctions as partial separators need to be reviewed and taken into account during two-phase flow design.

Annular flow can have a throttling effect at T-junctions for the offtake flow.

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