# Pentane Evacuation for Binary Plants

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## ABSTRACT

Mercury owns and operates several Ormat binary plants located in the North Island of New Zealand. For each site n-Pentane is the motive fluid and its flammable nature presents challenges with respect to maintenance activities on pentane plants. Until recently Mercury has relied on specialized contractors or flooding vessels with water to enable hot work such as welding to take place on pentane equipment. With large binary units this approach is not always practical and for the past two years Mercury have undertaken significant research and planning to enable the safe evacuation of pentane plant.

A key focus for the project has been to assess and reduce risks associated with the evacuation procedure. With guidance from Ormat and collaboration with other New Zealand pentane site operators Mercury have established a guideline for evacuation of pentane plants. The approach taken uses a combination of nitrogen purging and evacuation techniques to remove pentane from a unit. A key piece of equipment designed and fabricated by Mercury is a portable pentane evacuation skid for use at any of their pentane sites. This paper discusses the effectiveness of the pentane evacuation, lessons learned along with Mercury's plans to improve pentane safety in their plants.

## 1. INTRODUCTION

### 1.1 Ngatamariki Geothermal Power Station

This paper focuses on the journey undertaken for pentane evacuations at the Ngatamariki Geothermal Power Station (Ngatamariki). Ngatamariki (pictured in Figure 1) is located approximately 20km northeast of Taupo, New Zealand. The power plant was commissioned in 2013 and exports 82 MW of electricity to the national grid. Ormat Technologies Inc. designed and constructed the binary plant which consists of four identical units. Each unit runs using a combination of geothermal steam and brine. The binary fluid used in the organic Rankine cycle process is n-Pentane.

### 1.2 Pentane Evacuations at Ngatamariki

Between May 2019 and March 2020 Mercury have undertaken three pentane evacuations at their Ngatamariki plant. Each time the evacuations were to enable turbine maintenance. A significant amount of research, engineering design and planning was undertaken in the lead up to the first outage in May 2019.

**Figure 1: An aerial view of the Ngatamariki Power Station**

### 1.3 Pentane as a Motive Fluid

Most binary geothermal plants in New Zealand and in fact globally use pentane as the working fluid. The main downside of using pentane is that it is a flammable hydrocarbon meaning that precautions during operation and maintenance are necessary to prevent ignition.

n-Pentane which is used at Ngatamariki boils at approximately 37°C. Pentane is heavier than air and will therefore collect at low points. The lower explosion limit (LEL) for n-pentane is 1.5%vol. To complete hotwork safely on a Pentane system the Pentane needs to be removed to well below its flammability limit.

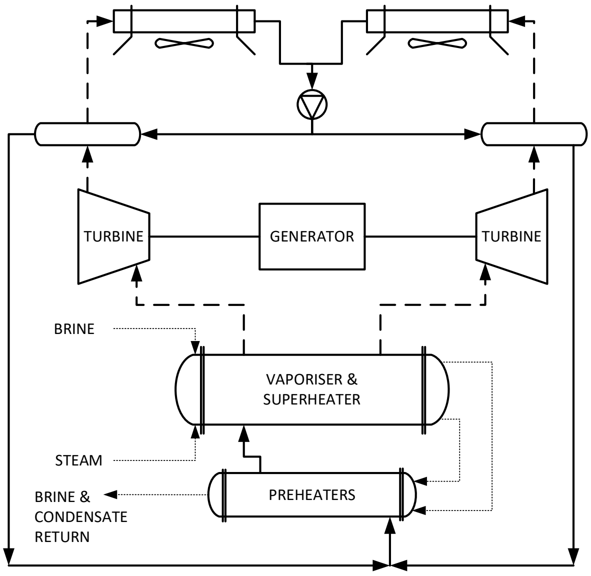


**Figure 2: A simple Process Flow Diagram (PFD) of the Ngatamariki binary process**

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## 2. PLANNING AND PREPARATION

### 2.1 The Need for Pentane Evacuations

Mercury has a mandate to continuously improve health and safety and maintenance practices and has over the past few years focused on integrating process safety within the organisation. This identified the need to develop the ability to effectively remove pentane from binary units and subsequent workstreams were initiated.

There are three key drivers to remove pentane from a unit,

1) Reduce personnel exposure to pentane during maintenance activities
2) Lower the risk of pentane ignition during maintenance activities
3) Safely perform traditional hot work e.g. welding for plant refurbishments

Mercury practice strict and well adhered to ignition control practices under their 'Pentane Rules' and pentane evacuations give another option to further manage risk for maintenance activities.

For activities generating a spark or flame, the target pentane concentration is <5% of the LEL to avoid risk of ignition (from welding or other ignition sources). In the past, Mercury has relied on specialized contractors or flooding vessels with water to achieve this e.g. during heat exchanger replacements. The Ngatamariki plant is newer and significantly larger than Mercury's other, older binary plant assets which were built circa 2000. With large binary units this approach is not always practical. Key dimensions and volumes for the Ngatamariki plant are given in Table 1. Photos of one of the Ngatamariki binary units can be found in Figure 3.

Further to this, valves and flanges are kept to a minimum to limit pressure drop and maximize power generation. This gives few options to isolate parts of a unit into more manageable volumes. On the Ngatamariki plant, (refer to Figure 2. for a Process Flow Diagram, PFD) valves that could potentially be used to isolate sections of plant are located around the feed pumps, and on the turbine inlet and turbine bypass. This, along with a lack in confidence that the valves will give a tight seal means a complete evacuation of the entire unit was the initial approach taken.

**Table 1: Key dimensions of the Ngatamariki binary units**

| | |
|---|---|
| Number of Units | 4 |
| MW | ~21 MWnet |
| Total unit volume | ~1000 $m^3$ |
| Pentane volume | ~150$m^3$ |
| Diameter of turbine exhaust | 1400 NPS |
| Total On-Site Storage | 100$m^3$ |

### 2.2 Planning and Preparation

Mercury kicked off a workstream to develop improved methods to remove pentane from a binary unit in 2018. Procedures were developed over several months at first focusing on one Ngatamariki unit. Options to remove pentane vapour were quickly narrowed down to a combination of nitrogen purging and drawing a vacuum to evaporate residual liquid pentane.

**Figure 3: Photos of an OEC at the Ngatamariki Power Plant from top left: Turbines, Turbine Exhaust Piping, Feed Pumps; and Heat Exchangers**

In 2018 representatives from Mercury and Contact Energy Ltd travelled to Nevada, US to observe a pentane evacuation at one of Ormat Technologies Inc. owned and operated facilities. This trip greatly increased confidence in the process and further helped refine procedures.

## 3. PENTANE EVACUATIONS

### 3.1 Procedure Development

The procedure consisted of the following steps,

1) Draining the unit of liquid pentane
2) Pulling a vacuum on the unit to evaporate remaining pentane
3) Break vacuum with nitrogen
4) Repeat evacuation cycle (several times)
5) Break with air
6) Handover for Maintenance

After each evacuation, the procedures were further updated and refined considering lessons learned. This template procedure has been able to be rolled out at each of the Mercury binary plant sites. By taking this baseline procedure and tweaking it slightly for each specific unit Mercury were able to leverage off design, risk reviews and HAZOPs. to ensure a consistent approach is adhered to across all sites and units.

### 3.2 Draining

Two options are available to transfer pentane from a binary unit to the storage tanks, using either:

1) pneumatic transfer pumps
2) nitrogen pressure

Pneumatic transfer pumps are used in normal operation to move pentane around the site to/from storage tanks and the OEC (Ormat Energy Converter) units. With large pentane volumes and low net positive suction head (NPSH), available, (due to low unit pressure and/or warm pentane) this transfer operations can take extended periods of time.

To speed up this transfer process the evacuation procedure uses nitrogen pressure to ‘push’ out liquid pentane from the unit. This approach has the following advantages:

1) Reduces transfer time
2) Decreases pentane handling by limiting hose connections and disconnections.
3) Allows blowing through and sweeping of lines to further clear liquid pentane; and
4) Takes advantage of already having nitrogen on site (to break vacuum)

For each evacuation, a liquid nitrogen vaporizer unit was used to provide nitrogen in quantities to allow multiple fills of the unit at pressure. Figure 4 below shows a nitrogen vaporizer skid being used at Ngatamariki.

**Figure 4: Liquid nitrogen supply and vaporiser in use at Rotokawa Power Station**

A key lesson from Mercury’s first evacuation at Ngatamariki was that extra care and attention is required to drain the unit. The large size of the units meant that the low points inherently contain a lot of pentane and any unnecessary pentane left in the system increases evacuation times and subsequent pentane loss.

It was noted that nitrogen vortexing occurs as the pentane levels reduce prior to the unit being completely drained. To avoid a false ‘empty’ reading each drain is checked at least four times. Reducing flows by throttling drain valves to limit vortices is also carried out.

Years of operating experience have shown pentane in a shutdown unit has the habit of ‘shifting’ around within a unit. This is primarily due to changes in ambient temperature resulting in the pentane to shift phase and move to different locations. This further increases the importance of returning to each drain location several time.

Of note was the effect of the heat exchanger baffles, which increased draining times. Once the bulk liquid pentane in the exchangers is drained there remains significant volumes of pentane trapped between vertical (and horizontal) baffles. The draining of this liquid is then through the v-notch drain (refer Figure 5) which significantly adds to draining times and increases the risk of excess pentane being left in the system.

The diameter of the Ngatamariki heat exchanger is 2000mm, therefore with a drain hole of 20mm the amount of liquid held up in these low points can be significant.

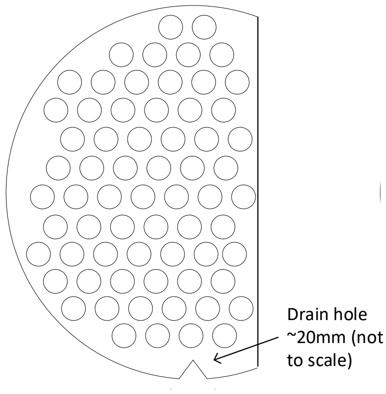


**Figure 5: Sketch of a heat exchanger baffles assembly showing drain notch.**

### 3.3 Pentane Evacuation Skid

Mercury designed and built two Pentane Evacuation Skids to undertake pentane evacuations, refer Figure 6 and Figure 7. The pumps are skid mounted and portable to allow movement between Mercury sites as required.

Two oil-lubricated rotary vane vacuum pumps were procured from Busch NZ Ltd. The model selected was the RA0603 Model (ATEX) and is nominally rated at 500m$^3$/h and 50mbara. A rotary vane type vacuum pump was selected due to its robustness, simplicity for maintenance as well as its ability to generate high vacuum pressures.

**Figure 6: Pentane Evacuation Skids in storage at Ngatamariki**

**Figure 7: Pentane Evacuation Skid at Ngatamariki**

The pumps are mounted on skids which included a suction knock out pot, instrumentation for pump protection, pressure monitoring and a pneumatic shut off valve. This has allowed the pumps to run as an unattended operation. A bypass line was included in the design to allow de-pressuring of the OEC unit. Figure 8 below shows a PFD of the Pentane Evacuation Skid.

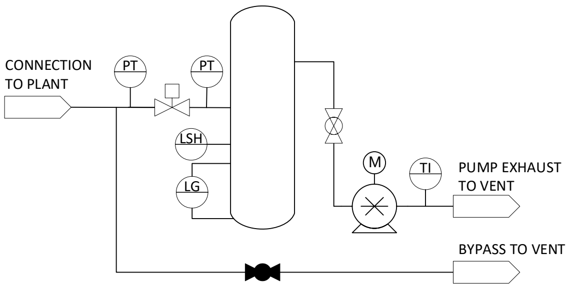


**Figure 8: Process Flow Diagram of Pentane Evacuation Skid.**

### 3.4 Evacuation Times

The Pentane Evacuation Skids have performed very well for ten evacuations across Mercury binary sites. At Ngatamariki, to decrease outage times, both pumps are used in parallel. A theoretical pump down time can be calculated using the following equation,

$$t_{vapour} = \frac{V}{Q} ln \frac{P_0}{P_1} \qquad (1)$$

$$t_{liquid} = \frac{m_L RT}{V_L M P_v} \qquad (2)$$

$$t = t_{vapour} + t_{liquid} \qquad (3)$$

*Where,*

| | |
|---|---|
| $m_L$ | *Mass of Liquid, kg* |
| $M$ | *Molecular Weight, kg/mol* |
| $P_1$ | *Initial Pressure, mbara* |
| $P_0$ | *End Pressure, mbara* |
| $P_v$ | *Vapour Pressure* |
| $Q$ | *Volumetric Flowrate, $m^3/s$* |
| $R$ | *Gas Constant, $m^3Pa/K/mol$* |
| $T$ | *Temperature, K* |
| $t$ | *Total Evacuation Time, w* |
| $t_{vapour}$ | *Evacuation Time for Vapour, s* |
| $t_{liquid}$ | *Evacuation Time for Liquid, s* |
| $V$ | *System Volume, $m^3$* |
| $V_L$ | *Liquid Volume, $m^3$* |

A theoretical pump down-time for a Ngatamariki unit evacuated to 50 mbara is 3 hours, equation (1). This does not consider the time to evaporate any liquid pentane. Assuming liquid left in the low points is 5m$^3$ this adds an additional 4 hours, equation (2) of evacuation time. This gives a theoretical pump down time of 7 hours. Equation (2) assumes the ideal gas law applies, no heat transfer limitations and a nominal ambient temperature.

The first practical evacuation cycle took approximately 12 hours to reach 50 mbara compared to a theoretical time of 7 hours (see Figure 9). Although not as pronounced as the theoretical curve there are definite regions of flattening of the pressure trend indicating that liquid is being evaporated. Broad assumptions made for the theoretical pressure trend of ideal gas behavior and ignoring heat transfer effects, contribute to the discrepancy between actual and theoretical predictions.

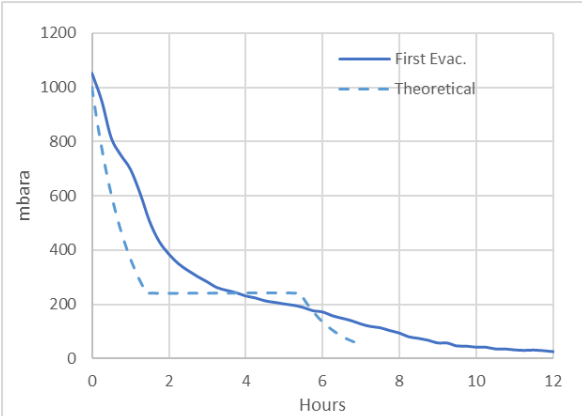


**Figure 9: Pressure trends for the first evacuation cycle in Ngatamariki OEC02 unit evacuation performed in January 2020.**

After the first evacuation, all the residual pentane liquid has been evaporated. For the third evacuation, there is very good agreement with theoretical and actual pressure trends for the unit as indicated in Figure 10.

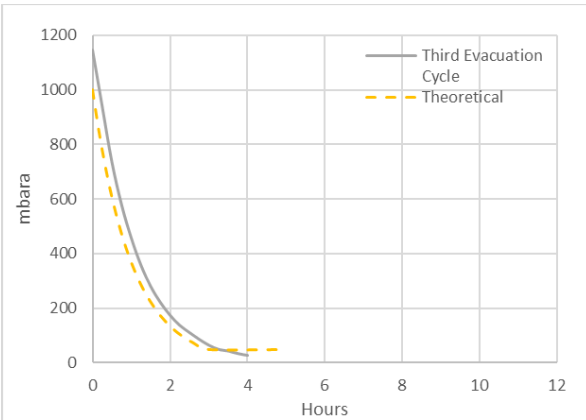


**Figure 10: Pressure trends for the second and third evacuation cycles in Ngatamariki OEC02 unit evacuation performed in January 2020.**

### 3.4 Vacuum Pump Exhaust

The vacuum pump exhaust was directed to vent above the Condenser. To help with dispersion, the vent was directed above a fan which was left running. The pentane vapour exits the vacuum pump at around 80°C. During the design period it was anticipated that the exhaust would not cool sufficiently and thus all the pentane exhaust would be vented to the top of the condenser. This however was not the case and especially overnight (with low ambient temperatures) significant quantities of pentane condensed in the exhaust piping.

This condensed pentane caused issues with recovery and safely transferring it back to the storage tanks. From this key lesson Mercury designed and built a collection pot to connect to the vacuum pump exhaust line (Figure 11 and Figure 12). This collection pot allowed for safe and effective recovery of condensed pentane from the vacuum pump exhaust.

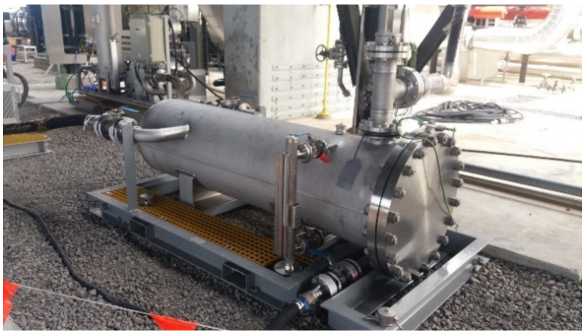

**Figure 11: Vacuum pump exhaust collection vessel allows condensed pentane in the vacuum pump exhaust line to be safely recovered.**

**Figure 12: Pentane Evacuation Skid and Exhaust collection vessel installed at Rotokawa Power Plant OEC01 unit.**

### 3.5 Evacuation Results

Pentane concentrations after evacuation cycles have been measured at trace levels. At Ngatamariki transient low levels (<50% LEL) of pentane have been measured in certain areas of the plant. To date there has not been a need to weld at the Ngatamariki plant and as such additional measures have not been required to further reduce pentane.

Experience has found trace amounts of pentane (less than 50% LEL) in heat exchangers and feed pump cans can easily be reduced to 0% LEL by opening the unit to atmosphere and allowing small amounts of pentane to disperse/vent to atmosphere. Isolating the feed pumps has also been done to ensure any residual pentane does not migrate to other parts of the unit. These additional measures have allowed welding work to be carried out safely at Mercury's other binary sites.

## 4. PENTANE STORAGE

Ngatamariki has two 50m$^3$ pentane storage tanks on site giving a total storage capacity for the site of 100m$^3$. Each unit has approximately 150m$^3$ of pentane leaving 50-70m$^3$ of surplus pentane requiring additional, temporary storage.

Several options have been considered for temporary storage including storing pentane on site in isotanks. However, after further investigation it became apparent that to comply with Major Hazard Facility and Hazardous Substance legislation, significant infrastructure would be required. Namely, a fireproof bund and possible upgrade of firefighting facilities. Design and building of this infrastructure could not be met within the timeframes of these initial outages.

This led Mercury to engage a transport company to transport the pentane in isotanks and store it at their storage facility in Auckland. This increased the complexity of the operation in the form of tanker logistics, load in and load out procedures and an increase in pentane handling.

This lack of storage is common to all of Mercury binary plant sites. The storing of pentane offsite is viewed as a temporary solution only and several workstreams are underway to assess onsite storage options. This includes:

1) Additional or replacement pentane storage tanks and
2) A purpose-built laydown area for temporary storage of pentane in isotanks.

## 5. ISOLATIONS

Generally, Ormat binary units are not designed with an abundance of isolation valves in the system; this is primarily to reduce pressure drop and to ensure power output is maximized. As a result, this provides limited opportunities to isolate the plant into smaller sections to complete smaller evacuation activities.

For the second and third evacuations at Ngatamariki, trials to isolate parts of the plant were conducted. For the second evacuation, the Feed Pumps were isolated. For the third evacuation, the Feed Pumps and the Heat Exchangers were isolated from the system. Although these evacuations were successful, concern remains around the leak tightness of these valves. These mitigations alone would not be relied upon if welding activities were required to take place.

## 6. DIFFERENCES FOR SMALLER BINARY UNITS

The Mercury owned and operated Rotokawa Power Plant consists of older and much smaller units than Ngatamariki. On average, a Rotokawa OEC unit volume and pentane inventory are 25-33% of a Ngatamariki unit. The small nature of these units provides flexibility. For certain maintenance activities, pentane evacuations have been completed with several nitrogen bottle packs and a single evacuation cycle. This means the additional cost and/or time for liquid nitrogen and a vaporiser is greatly reduced. The approach has proven quite effective for maintenance activities. If welding activities were required, more nitrogen would be needed, and as a result a liquid nitrogen vaporiser would be used.

## 7. CONCLUSION

Mercury's development of procedures and the design and build of two vacuum pumps skids has greatly improved their capability to manage and safely handle pentane at their binary power plants.

A core team of people has worked together to develop an evacuation methodology which has ensured consistency and continual improvemnet of evacuation procedures. These evacuation procedures have been rolled out accross all sites and is now 'business as usual' for Mercucy.

A key lesson learnt has been to apply increased focus to draining of liquid pentane from the unit prior to evacuating to minimise pentane losses and evacuation times. The Pentane Evacuation Skids built to evacuate a unit have proved sucessful and with the more recent addition of the exhaust collection pot, more pentane can be safely recovered.

A lack of pentane storage on site still remains a challenge which Mercury seek to remedy with ongoing workstreams.

## 8. IMPROVEMENTS AND FUTURE PLANS

A lack of onsite pentane storage remains one of the biggest challenges for Mercury and this is a current focus for improving pentane evacuations. With a focus on reducing cost and plant outage time, solutions for nitrogen supply are also being discussed.

Looking further ahead, at what are possibly aspirational goals, equipment, and techniques for complete pentane recovery (zero emissions) would be the ultimate goal. Achieving this however will likely be driven by increased pentane costs and/or changes to regulation.

Still in early stages of development are nonflammable refrigerants suitable for use in geothermal binary plants. These fluids could replace the need for pentane entirely. However, design and methods for extraction and recovery of what will likely be a costly fluid will no doubt be an integral part of power plant design.

## 9. ACKNOWLEDGEMENTS

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