Lessons Learned from the Rotokawa Condensation Induced Water Hammer Incident

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ABSTRACT

This paper details the conditions that can lead to Condensation Induced Water Hammer (CIWH) and seeks to raise awareness for the potential catastrophic nature of these events and the major impact they can have in terms of Health and Safety and how this risk can be managed during the design phase of a project as well as during normal operation.

The sequence of events that led to the CIWH incident that occurred at Mercury's Rotokawa site is presented including the key lessons learned related to plant design, human behaviour, and operational processes, as well as the corrective actions that were taken.

1. INTRODUCTION

1.1 Rotokawa Upgrade project

In July 2021, a process safety incident occurred at Mercury's Rotokawa Geothermal Generation site. At the time of the incident, an upgrade project was being executed to rebalance and optimise generation of the Rotokawa (RKA) and Ngā Awa Pūrua (NAP) geothermal power stations.

The upgrade included the installation of two new steam field separators, (McLellan and Koorey, 2021). The upstream 'H-Line separator' allows a higher enthalpy geothermal fluid, i.e. a mixture of steam and brine, being delivered to NAP while diverting the lower enthalpy geothermal fluid, i.e. predominantly brine, to RKA. The downstream 'RKA separator', operating at a lower pressure, separates the incoming flashing brine into steam and brine. With the implementation of the upgrade project, due to the lower enthalpy of the geothermal fluid, the total brine flow to RKA increased.

A new brine dump pond was installed and one of the binary cycle power generation units, Ormat Energy Converter (OEC) unit 21, 'OEC21', was converted from running on a mix of steam and brine to 100% brine. The hot brine bypass control valve, that allows hot brine to bypass the OEC units towards reinjection, was enlarged as well. In addition, acid dosing facilities had been installed to control the pH of the brine.

Figure 1: Scope of the Rotokawa Upgrade Project

1.2 Water hammer types, mechanisms and potential consequences in geothermal steam and brine systems

Based on the work by Kirsner (1999, 2012), Harms (2006), Paffel (2008), Rizaldy and Zarrouk (2016), Koorey (2019) and TLV (2024), the following two phenomena can be identified that can cause damage to geothermal fluid transmission systems and steam and brine systems. It should be noted that in different industries, applications or context, different terminology is used for ultimately the same (or a close to similar) phenomenon. Some of the terms that can / are being used interchangeably, have been included.

- Slug flow (sometimes referred to as 'steam-flow-driven water hammer' or 'differential shock'). When a slug of water seals the cross section of a pipe, the slug is being propelled by the flowing steam at the corresponding steam velocity which is often more than 10 times the velocity of the liquid. When the rapidly moving water slug hits a stationary object, for instance a tee or elbow, the exchange of momentum creates a pressure increase at the location of impact.

- Condensation Induced Water Hammer (CIWH) (sometimes referred to as 'steam hammer', 'steam induced water hammer' (in a predominantly water environment), 'condensate induced water hammer' (in a predominantly steam environment) or 'thermal shock'). See figure 2. When an isolated pocket of steam comes in contact with subcooled water, it will rapidly condense, leaving behind a low-pressure void with a pressure equal to the vapour pressure of the subcooled water. As the subcooled water rushes in to fill the low-pressure void, its collision causes a pressure wave that travels through the water-filled portion of the pipe.

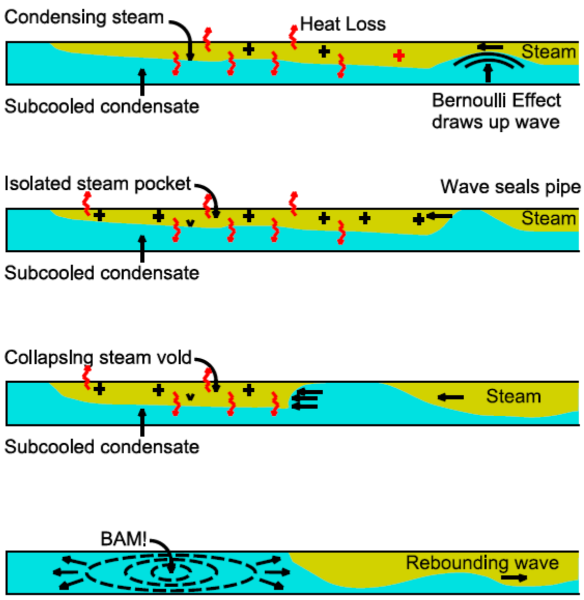

Figure 2: Condensation Induced Water Hammer in a horizontal pipe, Kirsner (1999), Koorey (2019)

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For the remainder of this paper, the author will refer to either 'slug flow' or 'CIWH'.

The impact of slug flow when it hits a stationary object like a tee or elbow, can be movement of the piping to the extent that it can drop from its supports or potential damage to the piping supports. Continuous occurrences of slug flow can potentially cause fatigue that can reduce pipe strength or damage to welded connections and or piping supports.

Compared to slug flow, the overpressure due to CIWH can be more severe. Continuous, minor occurrences of CIWH can lead to a similar impact as slug flow, i.e. pipe movement, fatigue, damage to welded connections and or piping supports. However, severe CIWH cases can generate overpressures exceeding 100 bar, which is far beyond the typical system design pressure, and can lead to catastrophic failure of piping or equipment and the uncontrolled release of hot geothermal fluid which can potentially cause serious harm to people including fatality. It is important to identify and manage CIWH risks during the design phase of a project as well as the operational phase.

CIWH events continue to happen within the New Zealand Geothermal power generation industry. Examples of CIWH occurrences in New Zealand over the last 25 years were presented by Koorey (2019). Sharing of the lessons learned from CIWH and other process safety incidents and near misses can help prevent these types of incidents from reoccurring in the geothermal industry and is the main driver for writing this paper.

2. SEQUENCE OF EVENTS

The following describes the sequence of events that took place on July 7th, 2021, that ultimately led to a CIWH incident at Mercury's Rotokawa site.

2.1 Before the incident

The RKA station is operated remotely from the NAP control room. Geothermal fluid from the RKA steam field is separated into steam and brine in the RKA separator that operates at ~25 barg. The steam is sent to a back pressure steam turbine to generate power. The hot brine is sent to binary cycle power generating units OEC1 and OEC21, that use n-pentane as a motive fluid to generate power.

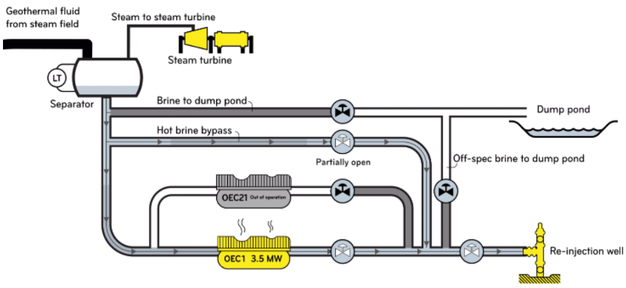

Figure 3: Situation before the incident

On the morning of the incident, OEC1 was in operation and brine was flowing through it towards the reinjection well. The hot brine bypass control valve was partially open to control the level in the separator. After the new enlarged hot brine bypass had been first taken into operation, less severe occurrences of CIWH had been observed but these were assessed as not requiring immediate action. OEC21 was out of operation while being converted as part of the upgrade project.

2.2 Control system switch over

Since the new acid dosing facilities had not been commissioned yet, a temporary force had been put in place in the primary control system by means of a so-called symbolic variable, to override the off-spec brine control during the commissioning and initial operating phase of the project. In the absence of acid dosing, the pH of the brine would be too high, and the off-spec brine control would, should a force not have been put in place, automatically close the reinjection well control valve and interrupt normal operation.

At 9:26 am, a control system malfunction triggered the automatic switch over from the primary to the backup control system. The temporary force that had been put in place in the primary control system, did not transfer to the backup control system. Without the force, the backup control system caused the brine reinjection well control valve to close, and reinjection flow to stop.

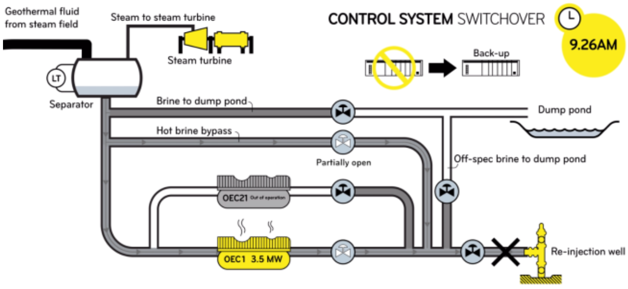

Figure 4: Control system switch over

2.3 High separator level

Due to there being no outlet for the brine, the separator level started to rise. At 9:29 am, the hot brine bypass automatically opened to full capacity in response to the high separator level but was not able to pass any flow due to the brine reinjection well control valve being closed.

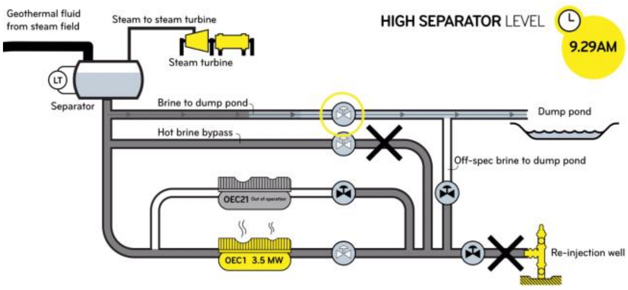

Figure 5: High separator level

Eventually, the control system automatically opened the brine dump valve to the brine dump pond to control the level in the separator.

2.4 Brine temperature at OEC1 outlet drops

At 9:40 am, the brine temperature at the OEC1 outlet had dropped from approximately 130 °C to 55°C due to continued vaporisation of cold pentane whilst there was no brine flow.

Generation dropped to zero MW while the unit stayed in generation mode.

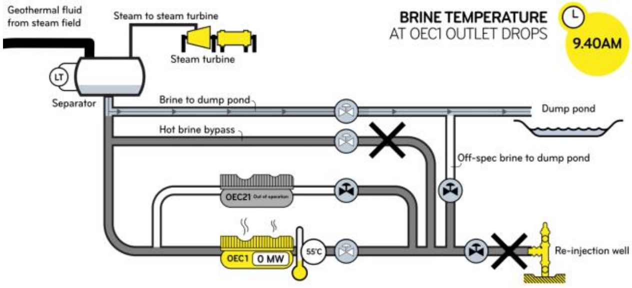

Figure 6: Brine temperature at OEC1 outlet drops

2.5 Attempt to reestablish brine flow resulting in CIWH

At 9:45 am, the operators in the control room attempted to reestablish brine flow by manually opening the reinjection well control valve, which opened briefly to 10% before the control system automatically overrode this due to the off-spec brine detection and immediately closed the reinjection control valve again.

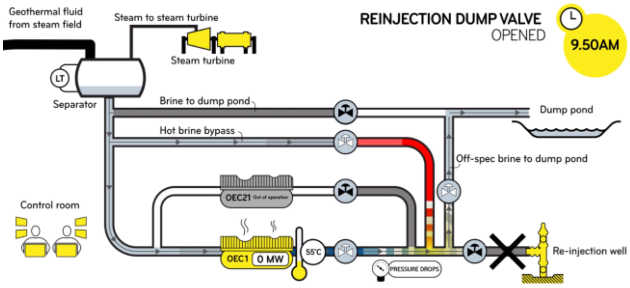

Figure 7: Attempt to reestablish brine flow resulting in CIWH

At 9:50 am, the operators in the control room manually opened the reinjection dump valve to the brine dump pond to reestablish brine flow. As a result, the reinjection back pressure started to drop from initially 24 barg to approximately 12 barg.

The lower reinjection back pressure caused the incoming hot brine from the hot brine bypass to flash and generate > 90 vol.% of steam. With the OEC1 control valve initially briefly shut (not shown in figure 7), the piping section between the hot brine bypass mixing point and the off-spec brine dump valves filled with predominantly steam. Subsequently, the OEC1 control valve opened and introduced cold brine into the steam filled section of the pipe. The mixing of the subcooled brine flow from OEC1 with the steam led to CIWH near the location of the hot brine bypass tie-in point.

2.6 Loss of containment of steam and emergency response

At 10:13 am, the ongoing CIWH eventually led to loss of containment of steam and a large steam leak was visible on the CCTV.

At 10:20 am, severe hammering and steam discharge was observed and reported by contractor personnel working on site. Mercury staff went across to Rotokawa to investigate and confirmed the ongoing steam leak and reported this back to the control room.

At 10:36 am, the operators in the control room activated the evacuation alarms and at 10:47 am the area was evacuated, and the station was shut down.

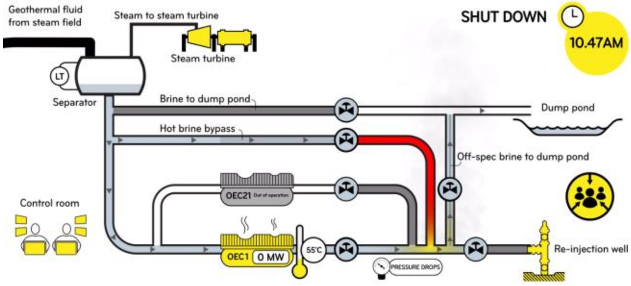

Figure 8: Loss of containment of steam and emergency response

No one was harmed but there was the potential for serious harm had someone been in the vicinity.

2.7 After the incident - damage assessment

Once the station was shut down and the steam leak stopped, it was possible to assess the damage that had occurred in close proximity, i.e. within 3-5 meters, of the hot brine bypass tie-in point:

- A small-bore pipe connection had ruptured and opened.
- The OEC21 isolation valve gearbox had come apart allowing the valve stem and gate to be lifted. This valve acted as the single isolation between the operational steam field and the project work being carried out at OEC21. As a result, the isolation between the operational steam field and the OEC21 construction area was breached.
- A pressure instrument tubing connection had come loose.

Figure 10: Ruptured small-bore connection

Figure 11: Damaged isolation valve

Figure 12: Loose pressure instrument tubing connection

3. INCIDENT INVESTIGATION AND LESSONS LEARNED

The incident was reported, and an internal investigation was initiated immediately after the incident. The investigation identified contributing factors and root causes in relation to Plant Design, Human Behaviour and Operational Processes.

3.1 Plant design

During the plant design phase of the Rotokawa Upgrade Project, the HAZOP design review identified three scenarios that could potentially lead to CIWH, pipe damage and loss of containment of hot geothermal fluid:

- Spurious opening of the hot brine bypass control valve
- Low reinjection back pressure
- Loss of the separator level

The potential Health and Safety impact in relation to loss of containment of hot geothermal fluid was assessed as 'Major' meaning 'potential fatality'. There was a recommendation to carry out a separate Risk Assessment to manage this risk.

During the HAZOP review action close-out, the credibility of CIWH potentially leading to a fatality was questioned based on the following beliefs:

- In the past, before the upgrade project modifications, CIWH had occurred due to bypassing of hot brine during normal operation, but this had not resulted in equipment damage or catastrophic failure.
- CIWH was considered a cold start-up risk only, which could be managed by Standard Operating Procedures.

Based on these beliefs, the consequence of CIWH was reassessed as having no potential Health and Safety impact, and therefore the separate Risk Assessment was deemed no longer necessary. No further mitigations in relation to plant design were put in place at this point.

In hindsight, the close-out of the HAZOP design review action items should have been more diligent, with the following lessons learned:

- Additional safeguards to protect against the identified CIWH scenarios should have been put in place.
- It is important to not rely on past experience and procedures to assess and manage CIWH risks.
- Instead of allowing 100% bypassing of the hot brine flow, the capacity of the hot brine bypass control valve should have been limited to allow hot brine bypassing to a maximum of around 10-20% of the total brine flow into a cold stream that provides sufficient heat sink, i.e. the cold brine stream coming from OEC1 and OEC21 which is equivalent to the remaining 80-90% of the total brine flow. See section 4.1 for more details.

3.2 Human behaviour

Based on the observations during the design phase of the project and the initial operating phase when the station was returned to service (with the exception of OEC21), the investigation concluded that elements of human behaviour had contributed to the incident. The findings can be summarised by the following lessons learned:

- It is crucial that people involved in the design and operation of geothermal plants have a proper understanding of the CIWH mechanism and its potential consequence of catastrophic failure and serious harm or fatality.
- The occurrence and associated risk of CIWH in geothermal operations should not be normalised.
- Potential risks should not be reclassified as having a lower impact based on past experience. (Remember: if it hasn't happened before it does not mean it cannot happen in the future!)

- Standard Operating Procedures should not be overly relied upon to manage process safety risks.

- The previous, less severe, occurrences of CIWH during the commissioning of the new enlarged hot brine bypass should have been interpreted as weak signals and warning signs that a higher-risk incident could follow.

3.3 Operational processes

In addition, the nature and timing of some of the actions during the sequence of events on the day of the incident, and the breached isolation between the running station and the OEC21 construction area, highlighted weaknesses in some of the operational processes that contributed to the incident, with the following lessons learned:

- Operations teams need to be comprehensively trained on new functionality that is being introduced as part of projects or plant changes.

- It is important that only essential people are present on-site during commissioning and start-up. When, after proper risk assessment, people are allowed to continue to work on site there should be a plan in place on how to establish two-way communication and how to initiate a site evacuation.

- Instead of relying on one valve acting as a single isolation, a more robust isolation method such as air gapping, a spade isolation or a double block and bleed isolation should have been applied.

- The fact that symbolic variables, in this case used for the temporary forcing of the off-spec brine control, are not part of the variables that are automatically transferred between primary and backup control systems, turned out to be specific to the brand of the control system and is not common across most brands of control systems. Control technicians should be made aware of this.

- Site evacuation and station shut down should have been initiated without hesitation upon the detection of loss of containment of steam on the CCTV system. Initiating further investigation and confirmation in the field instead of immediate site evacuation and station shutdown, leads to unnecessary delay and potentially puts people at risk.

4. CORRECTIVE ACTIONS

Since the Rotokawa CIWH incident, there has been a concentrated effort to improve the awareness and processes to better manage the risks of CIWH across Mercury's geothermal generation sites.

4.1 Redesign

HAZOP/LOPA techniques were used to redesign the Rotokawa hot brine bypass system and install additional hardware barriers, to prevent a similar CIWH event from reoccurring. During the redesign, as a precaution, bypassing of hot brine had been deferred until the following improvements were made:

- A smaller hot brine bypass control valve with a capacity limited to 20% of the total brine flow was installed. As per Kirsner (2012), this ensures that the ratio of the condensing capacity of the cold brine flow to the heating capacity of the incoming steam flow (due to the flashing brine), the so-called $R_{c/s}$, is >1. See also equation (1) below. If $R_{c/s}$ is >1, and there is good mixing between the two streams, (the mixing tee is equipped with an insert, consisting of an internal elbow and diffuser pipe), all steam will be condensed as it enters the flowing cold brine, and no steam bubbles will remain to collapse. When mixing hot flashing brine into subcooled brine, it is good practice to include some margin and keep $R_{c/s} > 1.4$, to compensate for imperfect mixing. After the redesign, the actual $R_{c/s}$ is > 4. Note: the CIWH incident at RKA was an example of a transition from $R_{c/s} < 1$ (a predominantly steam filled system) to $R_{c/s} > 1$ (due to the introduction of cold brine into the steam filled system). This type of transition is a guarantee for CIWH to occur and should be avoided.

- The hot brine bypass control valve was relocated to a high point which enables a vertical entry of the hot brine bypass line into the brine reinjection line. This approach minimises horizontal dead legs that could potentially accumulate cold brine.

- Instrumented Protective Functions were put in place that will shut down hot brine bypassing in the case of:

    a. Loss of heat sink, which means loss of cold brine flow from either or both brine units.

    b. Low brine reinjection back pressure.

    c. Inadvertent opening of the hot brine bypass control valve.

- An online vibration monitoring sensor was installed downstream of the mixing point between the hot brine bypass and the brine reinjection line.

$R_{c/s}$ in the above is defined as follows:

$$R_{c/s} = \left|\frac{Condensing\ capacity\ of\ the\ condensate\ flow}{Heating\ capacity\ of\ the\ steam\ flow}\right|$$

$$= \left|\frac{m_c c_p \Delta T_{below\ saturation\ temp}}{m_s h_{fg}}\right| \quad (1)$$

Where:
m_c = mass flow of the subcooled condensate in kg/s
m_s = mass flow of the flash steam in kg/s
c_p = heat capacity of water/brine in kJ/kg·°C
$\Delta T_{below\ saturation\ temp}$ = degrees subcooling below the saturation temperature in °C
h_{fg} = enthalpy of vaporisation, water/steam in kJ/kg

4.2 Human behaviour and operational processes

A customised training program and targeted face-to-face presentations and workshops have been rolled out across Mercury's geothermal generation team to:

- Address the normalisation of CIWH risks and encourage reporting of CIWH occurrences.

- Improve the identification and management of CIWH risks.

- Strengthen the operational processes related to safe isolation standards, emergency response and standard operating procedures.

5. CONCLUSION

Sharing of lessons learned from CIWH and other process safety incidents and near misses within the New Zealand geothermal industry can help prevent these incidents from reoccurring.

CIWH risks should not be normalised and weak signals of less severe CIWH occurrences should be reported and acted upon.

In order to identify and manage CIWH risks during the design phase as well as the normal operating phase, it is important that the mechanism that leads to CIWH is understood by operational staff and engineers and that its potential consequence of catastrophic failure and fatality is acknowledged so that proper controls can be put in place.

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