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Flammable Gas Safety When Handling Geothermal Non-Condensable Gas

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ABSTRACT

Non-condensable gas (NCG) from geothermal power plants often contains CO_2, H_2S, H_2, N_2, NH_3, CH_4, and other trace species. Reinjection of gas species from binary geothermal power plants is well known and widely operated without major complexity or safety concerns. However, if the geothermal plant uses a condensing steam turbine, as is the case for the geothermal power plants operated by Landsvirkjun, then oxygen from atmospheric air ingress may also be present due to the vacuum conditions in the main condenser and gas extraction systems (GESs). The presence of oxygen in the NCG raises significant safety concerns. If enough air leaks into the NCG or is allowed to flow into the NCG from other sources, then it can become an explosive gas mixture, and a deflagration or explosion could occur in the gas removal or downstream systems. Special care must be given when removing CO_2 and/or H_2S from the NCG, because as CO_2 and H_2S are removed the remaining species (e.g., H_2, CH_4, N_2, and O_2) are concentrated in the residual gas stream. Any NCG processing scheme must ensure that dangerous concentrations of fuels (e.g. H_2) and oxidants (e.g. O_2) are avoided, and this requirement can significantly reduce the amount of CO_2 and H_2S that can safely be removed. This paper explains the primary sources of oxygen ingress in geothermal power plants and further, gives some perspective of oxygen concentrations and instruments that have been investigated to reliably measure and limit oxygen concentrations. The paper also reviews the authors' experience with explosions or deflagrations that are known to have occurred, explains in more detail why this safety issue exists for condensing steam turbines, and reviews why the issue generally does not exist for binary systems and back-pressure turbines. Further, the paper i) defines flammability terms, ii) illustrates where those safety issues exist in a geothermal power plant, and iii) discusses solutions for those issues. A primary goal of the paper is to raise awareness of this safety issue and highlight the importance of designing gas handling systems tailored to the specific needs of each geothermal power plant.

1. Introduction

Geothermal power plants generate electricity by expanding steam extracted from an underground geothermal reservoir through a steam turbine. In many cases, the steam turbine expands the steam to vacuum conditions, and the steam is condensed under vacuum. There are always other gases mixed in with the steam that do not condense at these operating conditions; these are referred to as non-condensable gases (NCG). NCG often includes carbon dioxide (CO_2), hydrogen sulfide (H_2S), hydrogen (H_2), ammonia (NH_3), methane (CH_4), and nitrogen (N_2), along with other trace gas species.

The vacuum conditions in the turbine, condenser, and gas extraction system (GES) can pull atmospheric air into the system through seals and leaks. The air introduces nitrogen and oxygen to the process. When the air mixes with the NCG, the resulting mixture can potentially have enough oxygen and flammable species to support combustion reactions, which can lead to a deflagration, explosion, and/or fire inside of the piping and equipment, possibly resulting in injuries, damage to equipment, and/or long-term unplanned plant outages.

This paper provides a brief overview of the terms and definitions associated with flammability, known incidents in geothermal power plants that have been caused by fires, explosions, or deflagrations inside of equipment, and mitigation measures that geothermal power plant designers and operators can take to reduce the potential of explosive gas mixtures forming inside of the process equipment.

NCG varies significantly by region, specific plant, and over time. For example, Landsvirkjun operates three geothermal power plants in Northeast Iceland: Krafla, Theistareykir, and Bjarnarflag. Despite being in the same region, the chemical composition of the geothermal fluids varies significantly between the fields and even between individual wells within the same field. Landsvirkjun has observed that these chemical compositions can change over time, particularly in response to volcanic and seismic activity. Additionally, each plant is designed differently, which may result in different conditions for gas existing the GES.

Looking ahead, Landsvirkjun plans to develop new geothermal plants and has a goal to return NCG back into the geothermal system within a closed-loop to the extent possible. This goal would be effective for reducing the emissions of CO_2, H_2S, methane, etc., to the atmosphere. In the handling and/or reinjection of NCG, the flammability of the gases leaving the GES becomes particularly important and must be taken into consideration in the design of the systems downstream of the GES.

This paper contributes to global collaboration within the IEA-Geothermal Consortium, aiming to foster knowledge exchange and innovation within the geothermal sector as part of corporate social responsibility. By identifying barriers to reinjecting geothermal gases under various conditions, particularly concerning flammability, and openly sharing this information, we can advance our understanding. Additionally, by comparing methodologies and data sources from different countries, we can further enhance our knowledge and prevent repetitive errors.

2. Flammability Terms and Definitions

A combustion reaction requires three different elements: a fuel, an oxidizer, and an ignition source. The most common oxidant is oxygen and the most common ignition source is heat, so the reaction is commonly represented as the "fire triangle" which is shown below in Figure 1.

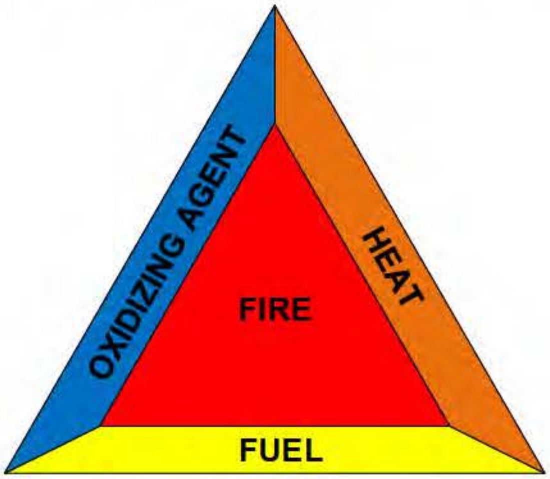


Figure 1: Fire Triangle for Combustion Reactions.

Figure 1 is a simplification in some important ways. Most notably, the relative amounts of fuel and oxygen present in the mixture are important, as described by the following definitions:

- Lower Flammability Limit (LFL) - The LFL of a gas species (or mixture of species) is the minimum fraction of a flammable gas (or gas mixture) required for the gas to burn when mixed with air. LFL and Lower Explosive Limit (LEL) are used interchangeably (Crowl & Louvar, 1990).
- Upper Flammability Limit (UFL) – The UFL of a gas species (or mixture of species) is the maximum fraction of a flammable gas (or gas mixture) that can be present for the gas to burn when mixed with air. UFL and Upper Explosive Limit (UEL) are used interchangeably (Crowl & Louvar, 1990).
- Limiting Oxygen Concentration (LOC) – The LOC is the minimum fraction of oxygen in a gas mixture required for a combustion reaction to generate enough energy to heat the entire mixture of gases (including the inerts) to the extent required for the self-propagation of a flame. Other terms such as Minimum Oxygen/Oxidant Concentration or Minimum Oxygen for Combustion (MOC) may also be used (Crowl & Louvar, 1990).
- Explosive Gas Mixture –As used here, an explosive gas mixture is a gas in which a mixture of fuels and oxygen are already present such that the gas only needs an ignition source to burn, deflagrate, or explode. (Note, in other documents or references, different terminology is sometimes used, such as a 'flammable gas mixture'.),

A given gas mixture is only an explosive gas mixture when several different conditions (which are directly influenced by temperature and pressure) are met:

1. The fraction of flammable gas in the mixed gas is above the LFL.
2. The fraction of flammable gas in the mixed gas is below the UFL.
3. The amount of oxygen in the gas mixture is above the LOC.

When the above three conditions are true, the gas mixture is an explosive gas mixture and only requires an ignition source (heat in the figure above). While heat is one possible ignition source, there are others, such as static discharges and sparks, that can provide enough energy to initiate a fire or explosion. In NCG handling systems (and chemical processes in general) there are numerous possible ignition sources, so most processes operate to either exclude oxygen from flammable gases or exclude flammable gases from equipment where oxygen is present.

Different flammable gases have different LFL, UFL, and LOC values and mixtures of gases have LFL, UFL, and LOC values that are different than their individual components. A mixture's LFL, UFL, and LOC values will be impacted by the presence of inert diluent gases like CO_2 and N_2 (Piggott, et.al., 2021). In general, inert species tend to reduce the concentration ranges at which a gas may be flammable by diluting the mixture itself, lowering the relative concentration of fuels and oxidants in the mixture.

3. Flammable Gas Locations in Geothermal Power Plants

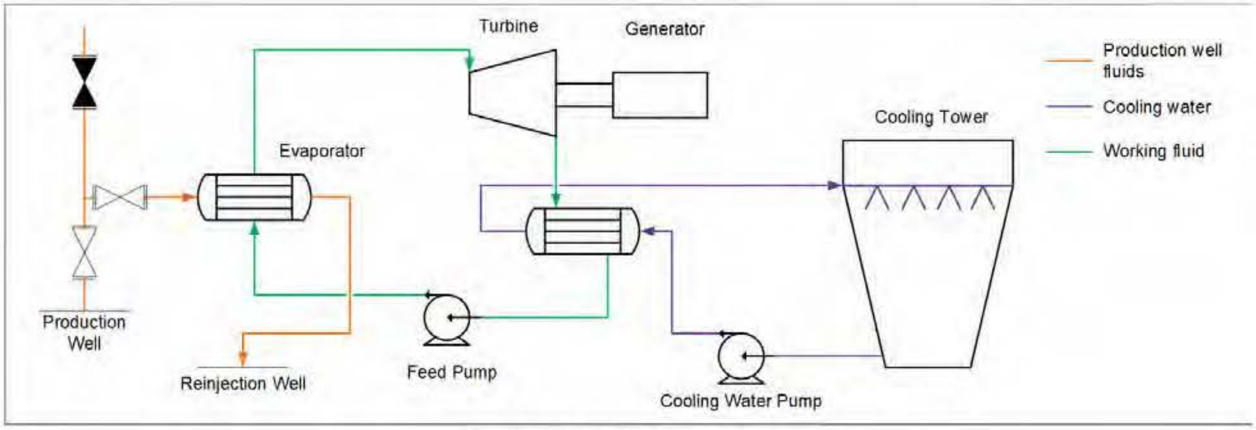
The composition of geothermal fluids varies greatly by geological region and by individual reservoirs, directly influencing the resulting composition of the NCG. Management of the NCG in the process can significantly impact plant safety, particularly with respect to flammability, but also with respect to the health hazards associated with some species, such as H_2S. In general, geothermal power plants that produce a separate NCG stream and operate under vacuum where air from the atmosphere can leak into the system ("air ingress") have the potential to form an explosive gas mixture. Typically, oxygen will not be present in meaningful concentration in geothermal reservoirs, and any oxygen present in the NCG is generally due to atmospheric air ingress.

3.1 Flammability Risk for Different Types of Geothermal Power Plants

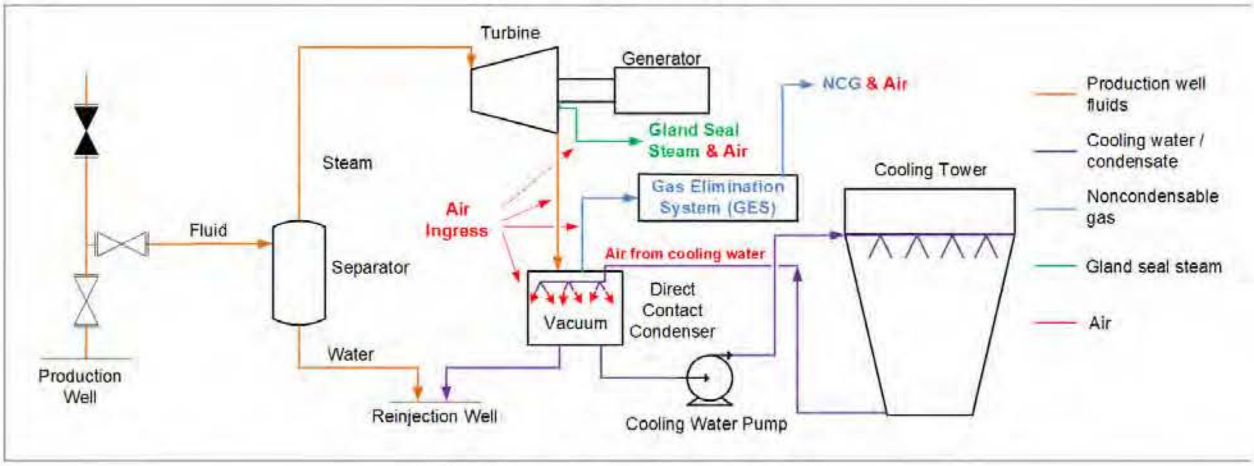
Figure 2 shows schematics of binary and flash-type geothermal power plants. Binary plants are generally applied on lower temperature geothermal resources (100°C to 200°C) (Verkis, 2014). The geothermal fluid is a single liquid phase of hot water that is pumped from the well to the evaporator heat exchanger, where it transfers heat to and vaporizes a working fluid (e.g., isobutane, isopentane, etc.). The vaporized working fluid passes through the expansion turbine to produce electricity. The vapor is then cooled and condensed in an air-cooled or water-cooled condenser heat exchanger.

In the binary plant shown in the figure, the pressure of the hot geothermal water is kept high enough that i) there is no steam phase, only a liquid water phase, and ii) any light species (NCGs) remain dissolved in the hot water and do not form a separate gas phase in the system. The geothermal fluids are reinjected. In this type of system a GES, is not required. Other binary plants may utilize condensing steam from the geothermal formation, but in this case the GES may operate under pressure and not vacuum, eliminating the potential for air ingress. In general, binary plants do not operate under vacuum, so air ingress will not normally occur.

Likewise, back-pressure units (not shown in Figure 2) typically do not have issues with air ingress. Back-pressure units are typically smaller geothermal power plants used when the geothermal field produces significant amounts of steam (as opposed to just hot water). In this type of unit, the steam is expanded through a turbine to produce electricity, and the exhaust steam is not condensed but instead released to the atmosphere. There is no condenser, and the NCGs stay mixed with the steam after the turbine. Since this type of system does not operate under vacuum, the risk of air ingress is effectively eliminated.



Typical Binary Power Plant



Typical Flash Power Plant with DCC

Figure 2: Schematics of Simplified Binary Type and Flash Type Geothermal Power Plants.

Flash-type units are typically used when the geothermal fluid has a significant amount of both steam and hot water. In the flash example in Figure 2, geothermal fluid entering the separator is a two-phase mixture of hot liquid water and steam. The liquid water is removed from the steam in a steam separator and mist eliminator. The steam from the separator is used directly as the working fluid that passes through the turbine to generate electricity. In most flash-type plants, the steam is condensed at vacuum conditions at the exit of the turbine. (Condensing at vacuum conditions greatly increases the power produced per unit of geothermal fluid, more efficiently using the steam.) After the steam passes through the turbine, separate condensate and NCG phases are formed within the condenser. NCG is pulled from the condenser by ejectors or mechanical vacuum pumps (the GES).

Air from the atmosphere can leak into the vacuum portion of the system. In practice, some air ingress is unavoidable, even with a well-maintained system. Air ingress can be due to equipment leaks in the turbine, condensers, and vacuum-generation equipment (jets and/or pumps), and their associated piping. In particular, turbine shaft gland sealing steam systems usually have some air ingress, and if the gland steam leak-off vent is combined with the NCG, the air content of the NCG can increase significantly.

The type of condenser also plays a significant role in air ingress. In a direct contact condenser (DCC) (Figure 2), cooling water, saturated with air in the cooling tower, is directly contacted with the steam in the condenser. A portion of the dissolved air will be stripped from the cooling water and become part of the NCG. In some cases, the NCG that exits the GES may contain on the order of 10-15 vol% air (2-3% oxygen) as a result of the use of the DCC. If the gland seal steam is combined with the NCG from a DCC, the ensuing oxygen content can be significantly higher. For example, one geothermal power plant observed 6% oxygen in this combined stream, but only 2.5% when the gland seal steam was segregated.

Many flash-type geothermal power plants have indirect condensers, also called surface condensers. In a surface condenser, the cooling water passes through heat exchange tubes in the condenser, and the cooling water does not come into direct contact with the condensing steam. Because of this, the NCG exiting the GES from a surface condenser at a flash-type plant will typically have less air, on the order of 5 vol% (~1 vol% oxygen).

The presence of air in the NCG exiting the GES can cause problems. For example, if the NCG is to be reinjected with the brine and steam condensate back into the ground, the presence of air makes it more difficult to completely dissolve the NCG into the water phase for injection. The oxygen in the air can also increase corrosion of pipes and equipment, cause elemental sulfur formation (via reaction with hydrogen sulfide), cause scaling / plugging, and introduce the possible formation of an explosive gas mixture.

(Note that dry-steam plants are similar to flash plants, except that the geothermal fluid is essentially 100% steam. For the purposes of this paper, the conclusions that apply to flash-type plants also generally apply to dry-steam plants.)

Given the above, one might ask 'why not always use binary plants, since binary plants have a natural advantage in that they do not have the problems associated with air ingress?' The answer has to do with efficient use of the geothermal resource. When the geothermal resource is capable of producing significant steam, binary plants are less efficient and do not produce as much power as condensing steam turbine plants (like a flash plant). Flash plants use steam directly to drive the turbine, while binary plants use a secondary fluid and a heat exchanger that have thermal inefficiencies. In some cases, a binary plant may produce on the order of half the power as a plant with a condensing steam turbine supplied with the same amount of steam (Collie, 1978). Consequently, flash plants with condensing steam turbine units use the geothermal resource more efficiently and are preferred for long-term applications when the geothermal field can supply a high volume of steam; even though this type of plant is susceptible to air ingress it is generally manageable.

3.2 Example Geothermal Power Plant with DCC and Contaminant Control

This paper focuses on condensing steam turbine plants equipped with DCCs, but the conclusions presented apply to surface condenser plants as well. Figure 3 shows a general overview of a geothermal power plant utilizing DCC with both H_2S abatement and CO_2 removal systems.

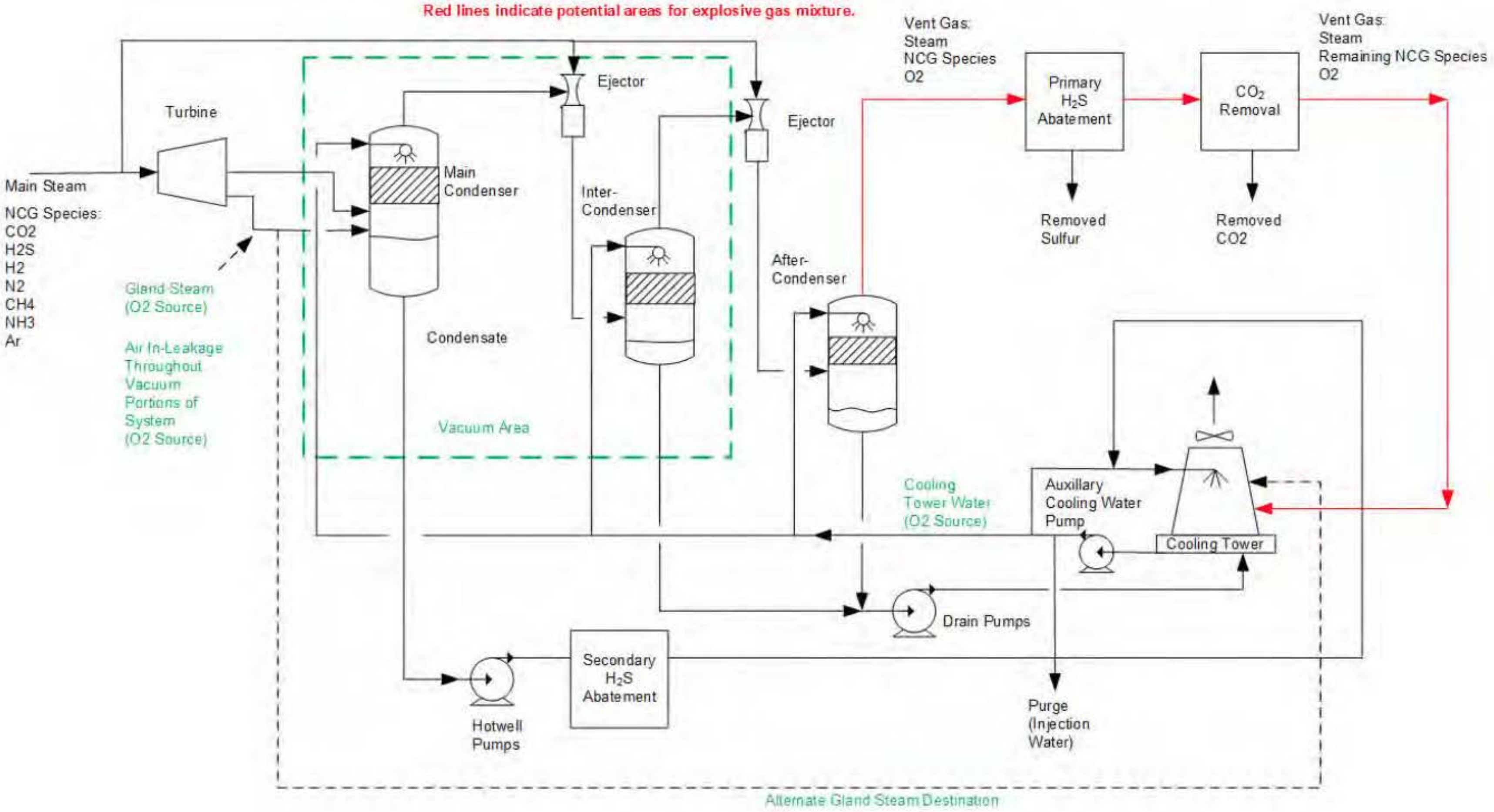


Figure 3: Example Geothermal Power Plant with H_2S Abatement and CO_2 Removal.

The NCG from the main condenser is drawn off by vacuum ejectors, vacuum pumps or a hybrid system (the GES) for atmospheric release. In Figure 3, the ejectors discharge sequentially into an inter-condenser and after-condenser to condense additional steam and increase the pressure of the NCG to just above atmospheric. The condensate (water phase) from all the condensers is sent to the cooling tower for recirculation to the condenser and/or reinjection. Turbine seal gland steam is sometimes routed to one of the condensers, combined with the NCG pipe to the cooling towers or may be handled separately.

The condensate and/or NCG may need to be treated to remove H_2S and other species that may be present (mercury, VOC, etc.). In some geothermal power plants with DCCs, the removal of H_2S from both the NCG (primary abatement) and the condensate (secondary abatement) may be required, particularly when there is ammonia present.

If only primary abatement is required (typically systems that do not have ammonia or those that use surface condensers), the H_2S can be removed with burn-and-scrub technology, liquid redox processes, and pressurized water scrubbing, among others as documented in the literature (Mamrosh, McIntush, Beitler, Markússon, & Einarsson, 2012) (Benn, McIntush, Beitler, Mamrosh, & Hileman, 2010) (McIntush, Mamrosh, Beitler, & Kitz, 2017) (Rodriguez, Harvey, & Asbjornsson, 2014).

The NCG may be further treated to remove CO_2, which may be disposed of by reinjection / sequestration or purified for use as a product. In geothermal areas utilizing the resource for electricity generation, reinjection / sequestration of CO_2 may be the preferred option since it is simple compared to isolating and purifying a CO_2 product, and because making a CO_2 product is not related to the central business of power production (Energy Sector Management Assistance Program, 2015). In some areas, including some in Iceland, the abundance of water sources enables the economic use of the water as a solvent to dissolve CO_2 from the NCG, with the CO_2-loaded water then injected. Also, the geochemistry in the subsurface in some areas allows dissolved CO_2 to react with basalts and other minerals to form solid carbonates that permanently sequester the CO_2 (Matter, et al., 2011). H_2S dissolved in water can potentially also react with minerals to be permanently sequestered (Clark, et al., 2020).

If NCG is treated for CO_2 and/or H_2S removal, the remaining species – some of which are flammable constituents – will become more concentrated in the residue gas. If oxygen is also present an explosive gas mixture may form. Thus, CO_2 and H_2S removal systems need to be carefully designed to mitigate this risk.

4. Known Issues in Geothermal Power Plants

The authors are aware of multiple fires, deflagrations, and explosions in the geothermal power industry associated with NCG handling. The potential for such events at geothermal plants in California has been documented (Farison, Garcia & Benn, 2022), and, at least one event in Iceland was disclosed publicly. Many of these incidents have occurred in the NCG without any CO_2 removal, indicating that even before the removal of CO_2 and H_2S, there is potential risk of producing an explosive gas mixture in the NCG in some cases. At one geothermal power plant that uses a surface condenser, a fire occurred within the NCG system that resulted in significant damage. The fire was most likely caused by air ingress from the gland steam leak-off from one of the turbines that had been combined with the NCG stream leaving the turbine's main condenser (Iceland Geothermal Conference, 2024).

Routing the gland steam/air leak-off into the main condenser has the potential to result in excessive ingress of air into the NCG. To reduce this risk, these streams should be isolated from one another so that i) the gland steam leak-off stream (with its typically high air content) remains lean in flammable gases and ii) the NCG from the condensing steam remains lean in oxygen. At the plant where the NCG fire occurred, the company plans to implement a system where oxygen measurements can be made on individual turbines to help them assess the location of air ingress (from leaks or other sources) in the future (Iceland Geothermal Conference, 2024).

In the authors' experience, the focus of geothermal operators is generally not on the condenser and GES in terms of safety of the NCG composition, but rather mechanical operational efficiency of those systems, with a broader focus on the electricity generation. For that reason, it is rare to have extensive instrumentation on the NCG discharge system. Energy companies often realize this limited understanding of the NCG system functionality and effects when beginning to design a gas handling system for future purposes. Thus, operators may not have a good understanding of what is going on inside the NCG piping and equipment at all times, and an explosive gas mixture may exist in the NCG piping before operators are aware of the hazard. Frequent analysis of the NCG composition and reliable instantaneous measurement of the oxygen fraction in a facility's NCG can be used to provide operators with real-time awareness of air ingress problems.

Changes to operations at geothermal power plants can also impact the composition and flammability of the NCG. For example, some geothermal power plants implement water injection into the reservoir to replace the steam that has been withdrawn. It has been reported that over the years, as water has been injected into the reservoir, the amount of NCG in the steam has decreased and the NCG composition has changed to contain more flammable components (more H_2 and less CO_2) than original conditions (Piggott, et.al., 2021). Other locations show differing trends, and these changes may not always be predictable. For cases where NCG content of steam decreases over time, the oxygen concentration in the NCG can increase, because the rate of air ingress into the plant system typically remains essentially constant.

Other specific issues related to burn-and-scrub units are listed below.

- Burn Back: For cases in which the NCG flowrate decreases over time the velocity of the gas entering the burner may become lower than the flame velocity and the flame can travel backward into the feed gas line (e.g., burn back). Burner modifications may need to be considered with additional safety devices installed to minimize the risk (Piggott, et.al., 2021).

- Burner Startup: After a shutdown, the burner should be re-lit with caution. Air leakage into the condenser may cause the vent gas composition to enter a combustible or explosive range. If this occurs, the presence of an ignition source could trigger a fire or explosion in the piping upstream of the burner (Farison, Garcia & Benn, 2022).

- Use of Chelated Iron: Another flammability-related concern relates to the use of chelated iron in the secondary abatement system. It has been proposed that iron may be carried over by entrainment into the NCG piping. Once in the NCG piping, the iron may react with H_2S

or elemental sulfur to form pyrophoric iron sulfides (Clark & Dowling, 2016). The iron sulfides may form a layer with other solid material. Theoretically, fluctuations in gas flows during startup or other events may be enough to break up the solid material and expose the pyrophoric iron sulfide to the oxygen in the NCG, providing an ignition source (Piggott, et.al., 2021).

If an incident occurs, it may be difficult to determine the root cause. The concentrations of the NCG can vary throughout the system, depending on operating conditions, flow rates, and leaks, making it hard to identify where a flammable mixture first formed. Further, as noted above, the typical lack of instrumentation in the NCG system may not allow for extensive troubleshooting. Leaks can also originate from buried pipe, steam traps, or other points that are not easily recognizable.

These examples demonstrate the importance of monitoring the NCG for flammability and designing the plant with appropriate safety devices and controls to mitigate the issue and ensure safe operation.

5. Flammability Estimation

Because NCG may contain both fuels (e.g., hydrogen, methane) and oxygen, the potential for a gas mixture to be in the "flammability envelope" must be carefully considered. A gas mixture in its flammability envelope contains fuels and oxygen in appropriate amounts such that all that is required for the mixture to burn, deflagrate, or explode is an ignition source. The flammability envelope for a mixture of flammable gases is typically defined by its upper and lower flammability limits (UFL and LFL), as described in Section 2. For geothermal NCG (contained in the pipes and processing systems prior to release to the atmosphere), the oxygen content is typically (but not always) relatively low, but adding oxygen-containing gases to the NCG, such as the gland steam/air leak-off stream can increase the oxygen concentration of the gas enough to put the gas mixture in the flammability envelope.

In the process design of gas handling systems, the formation of gas mixtures in, or near, the flammability envelope should always be avoided. Careful process design and redundant safety features are essential for gas mixtures that may approach the flammability envelope. The flammability envelope for many pure gases is well documented. However, when mixtures of flammable gases are present and diluted by inert gases (e.g., CO_2) and air, determining flammability properties becomes more complex.

Most flammability analyses focus on the release of a flammable gas mixture to the ambient air; these analyses determine the relative amounts of the released gas and the air that may result in a flammable gas mixture. Although that issue may also be important in geothermal power plants in the event of NCG being released inadvertently to the atmosphere, this paper is concerned with the flammability properties of the NCG inside the process equipment and pipes.

The standard and most trusted method of determining the flammability properties of complex gas mixtures involves conducting experiments in a laboratory with a company specializing in the analytical determination of flammability envelopes. However, there are also predictive calculation methods, such as the one outlined in a Bureau of Mines (BoM) publication (Coward & Jones, 1952). In this method, the air content of the gas is mathematically separated from the mixture as the "air" component and the remaining gas is referred to as the "fuel plus inerts". The UFL and LFL of the "fuel plus inerts" is then estimated separately and compared with the actual concentration of "fuel plus inerts" in the gas mixture.

The UFL and LFL of the "fuel plus inerts" composition is estimated via the BoM method by resolving the composition into a set of binary pseudo-mixtures of a flammable component and an inert component (e.g., a binary pseudo-mixture of H_2 and CO_2), and then using graphs of UFL and LFL for the binary mixtures to determine the UFL and LFL for the specific ratios of the pseudo-mixtures. The UFL and LFL of the mixture are then calculated using Le Chatelier's rule.

For cases in which the gas already contains oxygen, the limiting oxygen concentration (LOC) of the gas can also be considered. This is the minimum concentration of oxygen that can (but doesn't necessarily) result in the gas mixture being in the explosive region. Using the fuel-only data, a method outlined in NFPA 69 (National Fire Protection Association, 2019 Edition) can be used to estimate the LOC of the fuel mixture from pure component data. If the gas mixture has an oxygen content above the LOC, then it will be an explosive gas mixture if the fuel in it is also above the LFL and below the UFL.

Another factor to consider in the assessment of flammability hazards is the impact of pressure and temperature on the flammability parameters. Published UFL, LFL, and LOC are typically measured at ambient temperature and pressure; however, pressure and temperature can affect these quantities. Increasing temperature generally expands the flammability range as the LFL decreases and the UFL increases. Increasing pressure tends to raise the UFL, but the LFL is mostly not impacted (Crowl, 2012). The LOC generally decreases with an increase in initial temperature, so at higher temperatures, a lower oxygen concentration is sufficient for the mixture to become flammable. Likewise, as initial pressure increases, the LOC also tends to decrease (Zabetakis, 1965).

However, as shown in Figure 4, there are anomalies to these trends for certain components, such as hydrogen, which is often a constituent of NCG and may become highly concentrated during CO_2 recovery. The graph shows that the LFL actually increases with pressure, which is atypical of most flammable hydrocarbons. Also, the UFL decreases until a pressure of about 20 bara and then increases again.

Due to the uncertainty in the flammability estimates for UFL, LFL, and LOC, it is common to apply safety margins to the estimates. Table 1 shows a summary of some safety margins found in the literature.

LOC safety factors are most logically employed when the gas mixture contains little or no inert species, when the composition of the gas mixture is subject to large changes, and/or the LFL and UFL of the gas mixture cannot readily be evaluated. For gas mixtures containing large concentrations of inert gases, the LOC may be an overly-conservative estimate of the flammability hazard. The LOC can be evaluated as a first, conservative estimate, but the LFL and UFL safety factors may provide the most reliable estimate for flammability hazards of inert-containing gases.

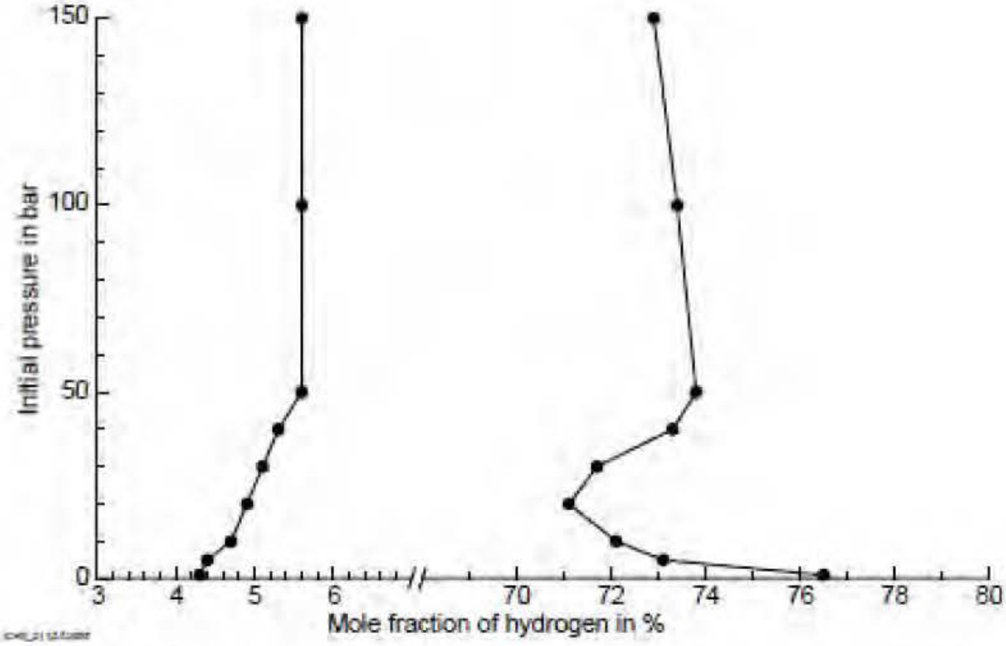


Figure 4: Influence of the Initial Pressure on the Explosive Limits of Hydrogen-Air Mixtures Measured at Room Temperature (copied from (Schroeder & Holtappels, 2005)).

Table 1. Flammability Targets.

Flammability Parameter	**Safety Margin**
Limiting Oxygen Concentration (Cunliffe, 2001)	
Maximum permissible oxygen concentration (MPOC)	Two percentage points below LOC, for example: LOC = 6% MPOC = 6% - 2% = 4%
If the plant is not continuously monitored	operate at <60% of LOC
If LOC is < 5%	operate <40% of LOC
Lower Flammability Limit (National Fire Protection Association, 2019 Edition) (Zlochower & Green, 2021)	
General fuel concentration	operate < 25% of LEL
For gaseous systems with automated in-line sensors and controls	operate < 60% of LEL
Upper Flammability Limit (US Code of Federal Regulations)	
Inerting vent gases in the maritime industry	operate > 170% of UFL
	operate 10 percentage points higher, for example: UFL = 39% UFL + 10% = 49%

6. Mitigation Measures

6.1 Prevent Explosive Gas Mixtures

The concentration of oxygen in NCG is a parameter that is relatively easy to continuously monitor, it can be an indication of changes in the NCG system, and it can indicate the potential presence of a flammable mixture.

In Section 4, the common routes of air ingress to the NCG were summarized. The sources of air ingress vary greatly between plants, and are dependent upon the design, with the use of DCC or surface condensers being an important factor. Air ingress from the DCC may in some cases provide over half of the O_2 found in the NCG. For a plant already equipped with a DCC, it is unlikely to be economical to consider replacing the DCC with a surface condenser, and other options would be considered to reduce oxygen concentration.

Gland steam leak-off mixed with the NCG and leaks in vacuum equipment and piping are two other major sources of air ingress. Choosing alternate handling methods for gland steam leak-off would be a primary consideration for some plants. Fixing leaks in the vacuum systems is another way of reducing air ingress.

A systematic leak detection procedure should be developed to inspect all parts of the GES from the condenser through to the exit of the final stage of ejectors or vacuum pumps. A geothermal power plant in Iceland that uses surface condensers conducted an in-depth leak detection program by using a sound detection device and smoke pen. The high-frequency sound leak detection device was positioned near the main components of the GES. When the front-mounted sensor detects a leak, the operator hears the leak indirectly through a headset. The smoke pen operates by igniting a non-toxic smoke emitting wick into a pen-style holder. The smoke pen generates a thin, visible stream of smoke that flows with air currents making it easy to see if the smoke drifts away or is pulled inward to the process, indicating air ingress taking place through a leak. Loose bolts on flanges were tightened, and flange gaskets were replaced as needed. Steel spiral wound gaskets are typically used as they form a better seal than rubber gaskets. Some of the flange packings were also replaced. The power plant used a real-time, fiber-optic oxygen sensor to determine the oxygen content at various points in the GES during and after leak inspection. The plant noted that the majority of the air ingress was from the GES rather than the main condenser. Oxygen levels were reduced from 1.1 vol% to as low as 0.67 vol% in some cases (Stefánsdóttir & Emilsson, 2023).

Oxygen concentration in the NCG also varies with electricity generation. Figure 5 shows a graph of the oxygen concentration in the NCG and the electricity generated at the time of sampling for the same power plant referenced in the previous paragraph. The figure shows that at lower operating rates the oxygen concentration is approximately 2 to 4 times higher than at full load. Air ingress due to leaks remains relatively constant while the amount of NCG increases with the additional steam required to produce more power. The variability in oxygen content with power load should be considered when assessing flammability concerns across the operating spectrum of the power plant.

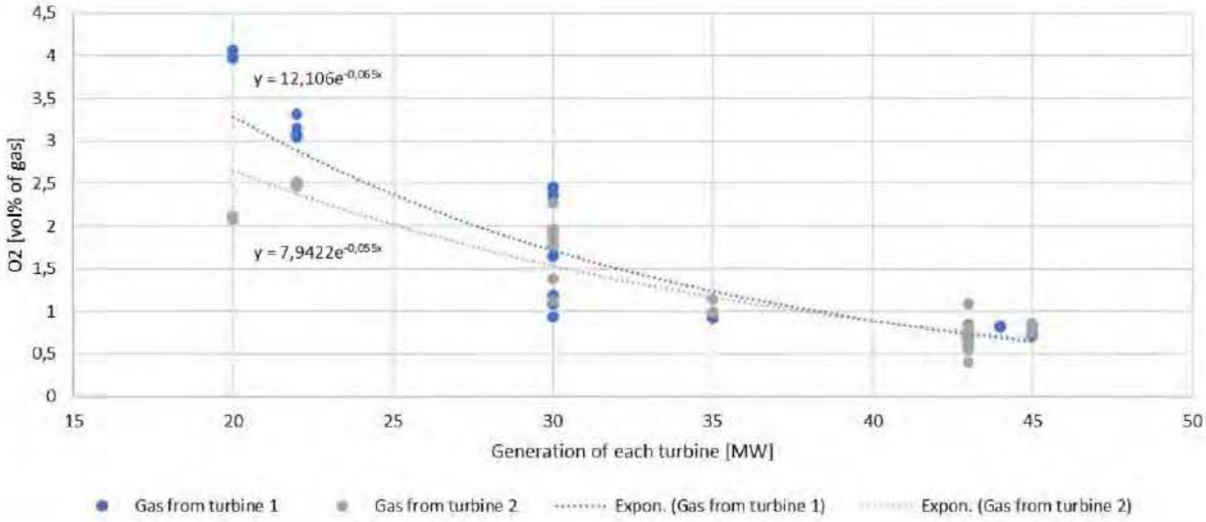


Figure 5. Oxygen Concentration as a Function of Generated Electricity (copied from (Stefánsdóttir & Emilsson, 2023).

In addition to fixing leaks at the plant, other changes that could be considered to lower the oxygen content of the NCG include:

- Replacing the DCC with a surface condenser to eliminate the oxygen ingress to the NCG caused by contact with the cooling tower water.
- Deaerating the cooling water after the cooling tower and before the DCC.
- Controlling the cooling water flow rate to the condenser to avoid using more than necessary.
- Diluting the NCG with an inert gas such as CO_2 recovered and recycled from the NCG, nitrogen, steam bypassed around the final condenser, or flue gas recycled from an H_2S abatement incinerator among others.

6.2 Special Situations that Concentrate Fuel and Oxygen

Some power plants remove H_2S and CO_2 from the NCG for reinjection, sequestration, or other use. As the H_2S and CO_2 are removed, the remaining species (e.g., fuels and O_2) are concentrated in the residue gas and can become an explosive gas mixture. This is demonstrated in the example in Figure 6 below, which shows the UFL of the NCG as a function of the percent of the CO_2 that is removed (or recovered) from the NCG. As CO_2 is removed from the NCG, the concentration of flammable species (mostly H_2 in this case) and oxygen both become higher. The increase in flammable content of the residue gas increases the UFL as CO_2 is removed. Because oxygen (and nitrogen) also become more concentrated as CO_2 is removed, the "fuel+inert" fraction of the gas becomes lower as CO_2 is removed. The result is that as CO_2 is removed from the NCG the UFL and the fraction of "fuel+inert" become closer, and ultimately cross.

The graph shows that below approximately 85% CO_2 removal, the fuel+inert concentration of the residual gas is safely above the UFL plus a 10% safety factor. Between 85% and 97% CO_2 recovery, the fuel+inert concentration is in the safety factor range. Above 97% CO_2 recovery, the gas is in the flammable region (i.e., is an explosive gas mixture). Understanding how the flammability of the residue gas changes with CO_2 recovery is crucial for defining safe operating limits for CO_2-removal processes.

This graph is based on a single oxygen concentration in the feed NCG. If the air ingress changes, the "fuel+inert" curve will shift. With more air ingress, less CO_2 recovery can be done before the residue gas enters the flammability envelope.

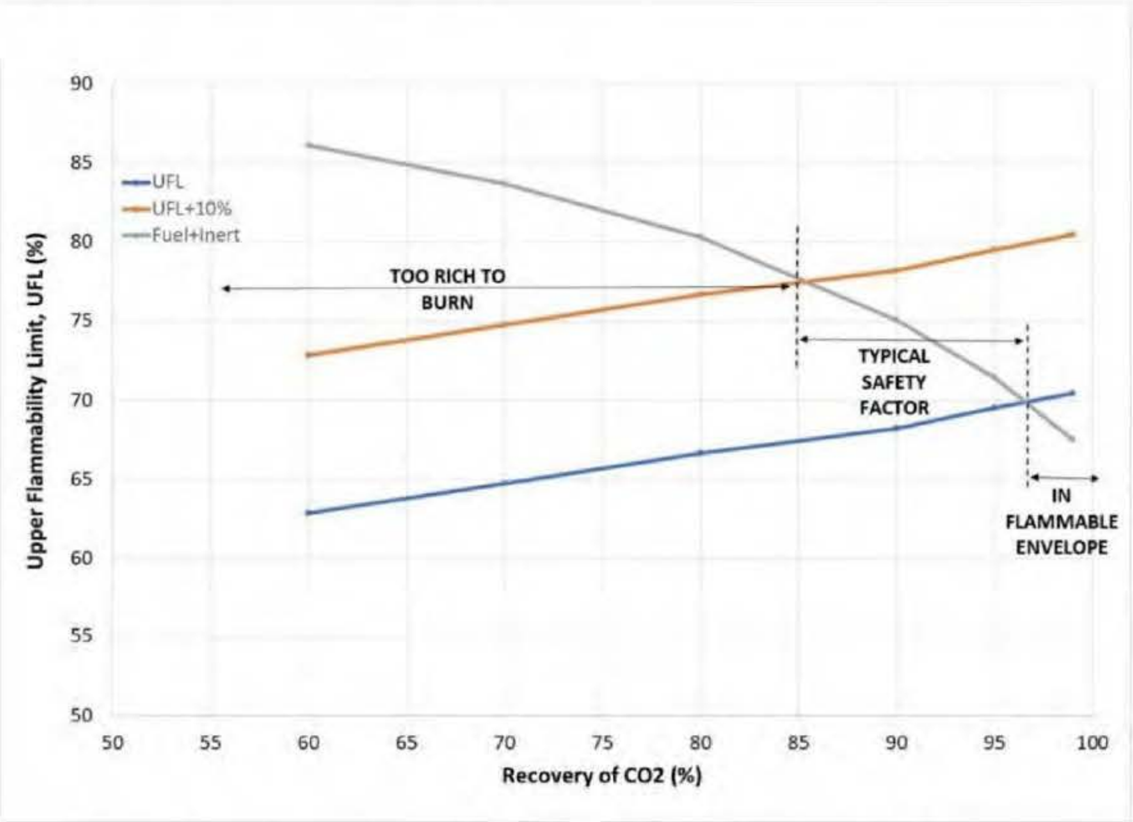


Figure 6: Upper Flammability Limit in Residue Gas as a Function of CO_2 Recovery.

In some cases, changes to operating conditions can be made to keep the NCG and/or residue gas from becoming a flammable mixture. For example, if a pressurized water scrubber is used to remove CO_2 and H_2S from the NCG, the flow rate of water to the scrubber could be lowered to leave more CO_2 in the residual gas. In other cases, new equipment can be incorporated in the design such as a pre-absorber to contact the water and NCG stream upstream of the main absorption column to absorb the bulk of the CO_2 and H_2S into the water phase. The pre-absorber concept manages the flammable species at the beginning of the processing scheme, making it easier to make a safe gas product low in oxygen for sequestration or utilization later in the processing scheme (Olafsdottir, et. al., 2023).

6.3 Avoid Ignition Sources

If there is the potential for an explosive gas mixture, measures should be taken to avoid the presence of ignition sources. Potential sources of ignition include static electric discharge from the movement of debris or dust in the vent gas, friction from movement of valves, or other sources.

In plants that use burn-and-scrub technology for primary H_2S abatement, the incinerator itself can be an ignition source, along with combustion air blowers. Safety equipment (e.g., hydraulic barriers and/or flame arrestors) must be installed to prevent propagation of the flame upstream. Keeping adequate velocities in gas supply pipes to the burner is also important to prevent flame back-propagation ('burn back').

As discussed in Section 4, there is also the concern of pyrophoric iron sulfide potentially being in the vent gas piping at plants with DCCs, particularly where iron chelate is used for secondary H_2S abatement. Methods may need to be put in place to safely remove and/or inert such material.

6.4 Safety Devices

The NCG vent gas system, including H_2S abatement and CO_2 recovery, must be designed to stay under flammability limits. Online measurements of gas flammability (e.g., LFL/UFL detectors) and oxygen concentrations detectors may be warranted. These measurements could be used to trigger addition of an inert diluting gas or changes to operating conditions to bring the NCG or residue gas back into a nonflammable regime or shut down the process.

If the risk of an explosion cannot be eliminated, then measures should be taken to mitigate its effects. Some process equipment can be designed to be resistant to explosion pressure, or designed to safely vent explosive pressures. Explosion pressure vents, like rupture discs or explosion vents, may need to be incorporated in the design of certain equipment, and the authors know such vents to have been used in some geothermal power plant systems. It is also important to isolate the explosion by including rapid isolation valves and flame arrestors in the design. Piping should also be made of material that can withstand a deflagration.

Areas of the process can be divided into different zones according to the likelihood of a flammable or explosive gas environment being present. Gas mixtures in the explosive range are sometimes defined as Zone 0, and managing such gases typically requires multiple redundant safety features and intrinsically safe equipment as documented in the literature (Davies & Heidermann, 2013).

6.5 Training

Another way to address flammability concerns is to ensure that the geothermal operating staff are properly trained on the potential hazards and means to avoid them. The operators need to understand the flammable properties of NCG, identify risk areas, know the importance of immediately addressing leaks / air ingress, and know how to respond to hazardous operating scenarios. Operating procedures should clearly identify safe ways to operate the power plant during routine operation as well as during startup and shutdown when there may be transient flammability conditions.

7. Conclusions

The primary goal of this paper was to raise awareness of the potential for flammability issues when handling geothermal non-condensable gas. Power plants that condense steam and form a separate NCG stream while operating under vacuum (flash and dry-steam type plants) use the geothermal resource most efficiently, but they can form an explosive gas mixture due to air ingress from leaks. Plants that operate with a direct contact condensers also have an added source of oxygen that is stripped from the cooling tower water. As demonstrated with an example of a known fire, gland steam leak-off should not be routed to non-condensable gas piping because it often contains a high concentration of air. Methods for estimating the flammability of the non-condensable gas were presented and safety margins to the lower flammability limit, upper flammability limit, and limiting oxygen concentration found in the literature were summarized. Mitigation measures to prevent explosive gas mixtures, avoid ignition sources, and utilize safety devices were also reviewed.

In conclusion, Landsvirkjun's efforts in operating and developing geothermal power plants in Northeast Iceland highlight the importance of understanding and managing the varying chemical compositions of geothermal fluids for different power plant designs. Through global collaboration with Trimeric and within the IEA-Geothermal Consortium, Landsvirkjun aims to foster knowledge exchange and innovation, addressing barriers to reinjecting geothermal gases and enhancing our methodologies. By sharing insights and comparing data internationally, the geothermal sector can advance and contribute to sustainable energy solutions worldwide with minimal gas emissions to the atmosphere.

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