Compliance and operational safety of geothermal power plants

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Keywords: certification process, safety inspections, national and international standards, acoustic emission testing

ABSTRACT

The European Single Market comprises the 28 EU Member States plus Norway, Iceland, Lichtenstein and Switzerland. Geothermal plants placed on this market must fulfil the requirements of various directives as well as application standards and codes.

TÜV SÜD has a long track record of certification of products to ensure their compliance with the relevant directives and recognised international standards. TÜV SÜD's experts have developed a guideline which covers all phases of the certification process for above-ground geothermal plants in line with official licensing.

The first part of this paper describes this certification process, which has been successfully applied to several geothermal power plants in Germany so far. A detailed outline of the following steps is provided: hazard identification and risk assessment, assessment of the safety concept, production control, validation and declaration of conformity. Related subject-specific topics in the certification process include pressure hazards (Pressure Equipment Directive), explosion hazards (ATEX Directives), groundwater protection (Water Resources Act in Germany), emissions (Seveso-III Directive) and functional safety (IEC 61508).

If all certification requirements are fulfilled, the manufacturer receives a final assessment report and is allowed to place the plant on the market. Ownership of the plant passes to the operating company, who can then proceed to place the plant into service. Responsibility for compliance with the industrial safety and health regulations applicable in the respective country also remains with the operating company.

The second part of the paper is dedicated to this responsibility. It describes the permits and inspections required prior to commissioning and the periodic inspections during the service life of the plant, focusing on customised inspection and test plans with detailed scopes and methods of inspections developed for the respective plant.

1. INTRODUCTION

In general, there are two approaches to build a geothermal plant:

A) The operating company orders equipment and assemblies from various manufacturers and assembles them. This approach leads to different boundary conditions, which must be considered in a risk analysis. In this case, the operating company is responsible for the safety concept of the built assembly, which is approved within the scope of national start-up testing by a third party such as TÜV SÜD.

B) The operating company orders a completed assembly or unit from a single manufacturer. In this case, the manufacturer develops, and is fully responsible for the safety concept of the assembly, which is approved through a CE declaration of conformity issued by a notified body such as TÜV SÜD. Start-up testing covers only the operating and installation conditions on site at the location of the plant.

According to the experience of TÜV SÜD with geothermal power plants in Germany, approach A is more common than approach B. However, approach B can be more interesting for the operating company. As an example, TÜV SÜD was involved in the application of approach B for the geothermal power plant in Sauerlach. In this case, the safety concept of the full plant was under the responsibility of the single manufacturer. This limits the risks linked with having multiple interfaces between different assemblies and often guarantee a quicker and simpler execution of the later steps in the certification process.

Affixing of the CE marking to products is the responsibility of the products’ manufacturers or authorised dealers. The standardised CE marking confirms that a product satisfies the legal requirements of the EU and the product-safety requirements and conforms to the legal minimum requirements at the time when it is placed on the market. Declarations of conformity are based on various EU Directives, including the Pressure Equipment Directive (PED) but also the Machinery Directive and the ATEX Directive. Other binding EU Directives include the Low Voltage Directive 2014/35/EU and the EMC Directive 2014/30/EU. However, implementation of the PED is most important as it is the key directive for certification.

EU Directives define legally binding minimum standards within the European Economic Area and must be transposed into national law.

The basic challenge consists in assembling a host of different components that are in conformity with EU law into assemblies, and ultimately complex geothermal systems and plants. To form an assembly, the individual items of pressure equipment must fulfil the following criteria: They must be connected and compatible, and function in a manner such that they can achieve the established overall objectives and be taken into operation. For this purpose these devices must be integrated into a functional whole, together with all parts required to ensure the safety of the assembly, and the assembly as a whole must undergo conformity assessment.

In many cases individual components are sourced globally, assembled far from the place of installation, and then delivered as finished assemblies. Such an approach requires special attention to, and detailed review of, the technical documentation and the relevant declarations of conformity.

This in turn involves numerous technical challenges. Do all components really fit together? What interactions need to be taken into consideration? Have the correct measures been taken to ensure the safety of the system/plant as a functional unit (assembly)? [1] As an example, a geothermal plant comprises various pressure devices, including pressure vessels, valves, control valves, safety valves and piping systems. Under the Pressure Equipment Directive (PED 2014/68/EU), assessment of the entire assembly must be performed, taking into account the individual components and their interactions. After all, experience has shown interfaces to be particularly prone to faults and defects. The safety concept, assembly and functional safety devices of the assembly must be inspected in detail. This is indispensable for final assessment of the assembly and issue of a certificate of conformity.

2. APPROVAL OF CONCEPT

The equipment must be designed for all relevant conditions and demands (e.g. high pressures and temperatures, corrosive thermal water and mechanical demands). Critical risks occur regularly in the course of a geothermal project and need to be managed. Manufacturers wishing to save time and prevent critical and costly project delays need to rely exclusively on equipment with CE declaration of conformity. The operating company must establish detailed and accurate technical specifications. To order the correct type of equipment, the operating company must have in-depth familiarity with the relevant EU Directives and Regulations, such as the PED (2014/68/EU) and the ATEX Directive (2014/34/EU), etc. Responsibility for the equipment rests with the manufacturer, but is transferred to the buyer upon purchase of the equipment. The buyer is responsible for operating the equipment in line with the national regulations. The equipment manufacturers generate safety concepts for their parts or assemblies, which take into account the technical specifications of the area, in which the part or assembly will be operated, and its limits (e.g. temperature, pressure, flow rates, fluid properties).

2.1 Hazard identification

There are various approaches to risk analysis, including risk-identification and assessment methods. Risk-identification methods include checklists, matrix methods, FMEA, operating fault analysis, what-if analysis and HAZOP studies (guide words). Risk-assessment methods are quantitative methods, such as probability of failure, event tree analysis, and semi-quantitative methods like LOPA, IEC DIN EN 61511 (risk graph). The HAZOP method and the semi-quantitative methods have proved to be the best approaches for geothermal plants [2].

A HAZOP (HAZard and OPerability) study is an established systematic procedure to assess the design of a plant as well as its process and safety concept. While not a legal requirement, HAZOP analysis is referenced in technical guidelines and standards. The method uses a set of pre-defined guide words to identify weaknesses in the safety concept. It is a tool used for the systematic identification of root causes and the resulting consequences. After this has been done, the HAZOP team lists and assesses the existing safeguards to make sure they are sufficient for ensuring the safety of the plant. The method is very effective at identifying critical interfaces and possible hazards or malfunctions in operation. The HAZOP study not only identifies risks and develops strategies for risk prevention; it also results in adequate documentation. The HAZOP results are documented in a record by the HAZOP secretary, also referred to as a HAZOP scribe. Open issues are documented in a list of recommendations or action plan. This approach minimises the probability that safety-relevant points are ignored or forgotten. In view of the above, it makes good sense to use the HAZOP method at an early stage – where possible, in the planning phase of a geothermal plant or system. However, the analysis can also be applied in other phases of a geothermal project as basic, design, as-built and layout HAZOP. It is even applicable to contracts, negotiations with insurance companies and approval procedures. In the latter case, HAZOP assists with the definition of the relevant standards, technical guidelines, laws and operation-specific requirements, with precise wording and precise supply and performance specifications being of critical importance.

HAZOP studies are conducted by a team of interdisciplinary experts headed by an experienced HAZOP facilitator, also referred to as HAZOP chairman. External HAZOP facilitators offer impartiality and independence. Their professional approach is generally recognised by stakeholders, interested parties and authorities. HAZOP documentation sets out the technical safety concept and may facilitate the assessment required for the declaration of conformity and national start-up testing.

2.2 Assessment of the safety concept

According to the Pressure Equipment Directive 2014/68/EU, the safety concept applied to pressure equipment or an assembly must be reviewed. The assembly must fulfil the essential safety requirements (ESR) of Annex I, PED, referenced in Article 14 (6) lit. c. Assessment of the assembly as specified in Article 14 (6) lit. c must be systematically performed by a notified body in accordance with CABF PED/SPVD 2014-06-17 "Principles for the Assessment of Assemblies", clause 6 (global conformity assessment), and must verify that the safety concept adequately covers all pressure-initiated hazards. The following criteria must be fulfilled in addition:

- Each item of pressure equipment must be evaluated as specified in Art 14 (6) lit. a) PED
- All interfaces of the assembly must be referenced in P&IDs
- All parameters relevant for the assembly and specified in the instruction manual and the P&IDs must be verified
- The list of pressure vessels and their designs and protection devices must be reviewed
- Specifications of safety valves must be evaluated
- The pressure equipment of the assembly must be designed for the relevant pressures and temperatures and for the fluids with which it will come into contact
- An adequate level of protection of the pressure devices must be ensured
- Operating instructions must be provided

The assessment must be summarised in a report covering the design examination of the assembly's safety concept.

3. CERTIFICATION PROCESS ACCORDING TO THE PRESSURE EQUIPEMENT DIRECTIVE

3.1 Individual items of pressure equipment and integration of components

Each individual pressure device is subject to verification to ensure that its design is suitable for withstanding hazards caused by pressure, temperature and contact fluid etc. The main steps of verification are design examination (office) and final assessment (on-site in the factory). The notified body pays particular attention to examining the content of the technical documentation, assessing the materials, verifying the qualifications of welders and checking the results of non-destructive testing and strength calculations. The notified body must also verify that the product is in conformity with the design (main content). If verification is successful, the notified body issues a certificate of conformity for the individual item of pressure equipment, as specified in Article 14 (6) lit a) PED.

Assessment of the integration of the various components of the assembly and of the resulting interactions is then addressed in Art. 14 (6) b), which forms the basis of the Mechanical Interaction Report for assemblies excluding the issue of functional safety. The entire process thus comprises three steps: In step 1, each item of pressure equipment is usually assessed directly at the manufacturing site. Step 2 comprises assessment of the mechanical assembly (interactions) and step 3 then refers to the assessment of the functional safety of the assembly.

3.2 Functional safety

Crucial factors regarding functional safety are the verification of suitability and the integration and combination of all items of equipment for the intended use. Functional safety is based on hazard analysis, process description, piping and instrumentation diagrams (P&IDs) and general arrangement drawings. Conformity assessment of the integration of the various components of the assembly must fulfil the requirements determined by the highest category of pressure equipment (other than that applicable to safety valves). Again, the key steps are design examination and final assessment. The interactions of all items of pressure equipment implemented must be verified for the intended use of the assembly as a whole. The notified body produces a report summarising the results of the assessment of the integration of various components of the assembly.

The key standard for functional safety is the IEC 61508 standard, which is applicable across all industries and covers the entire safety life cycle. Sector-specific standards based on the IEC 61508 framework are the IEC 61511 standard for the process-industry sector and the IEC 62061 for the manufacturing sector and machinery. IEC standard 61511 sets out practices in the engineering of safety instrumented systems (SIS) which ensure the safety of industrial processes. The safety integrity level (SIL) is a measure of the safety performance required from such a system if applied in hazardous operations. The report by the notified body also addresses the SIL of safety-related sub-systems such as programmable logic controllers (PLCs).

3.3 Production control

Every pressure-bearing part of an assembly must be inspected both during and after production. As far as geothermal plants are concerned, this mainly refers to piping. Items of pressure equipment placed on the market are generally identified by CE marking, which means their design, materials, manufacturing and testing are in compliance with the relevant EU requirements and standards. On top of the above, manufacturers of geothermal plants must prepare technical documentation as evidence of compliance with these requirements. The following documents must be reviewed for compliance with the approved design: general description of the pressure vessel, technical drawings (piping isometric drawings), results of calculations and examinations and the technical or manufacturing schedule. This applies to pressure vessels (EN 13445), but also and in particular to pipes (EN 13480).

According to the standards, all welding activities must be performed by qualified staff. The qualification processes to be applied depend on the material to be welded. The qualifications required for ferritic and austenitic steels are outlined in EN 287-1 / EN ISO 9606-1, while the qualifications for welding of aluminium are specified in EN ISO 9606-2. Welding Procedure Specifications (WPS) in accordance with EN ISO 15609 must be prepared for all welds between pressure-retaining parts and between attachments to pressure-retaining parts which are performed in the factory and on site. Welds, materials, wall thickness, temperature and welding methods also form the basis for defining the scope of non-destructive testing in line with the applicable specification (e.g. EN 13480, EN 13445, AD-2000).

Final assessment of pressure equipment must include a test for pressure containment. This test normally takes the form of a hydrostatic pressure test. Where such a test is harmful or impractical, other tests of a recognised value are also possible. Any additional measures required for these tests must be applied before the tests are carried out. Pneumatic tests, for example, require compressible fluids. In this context, special consideration must be given to the following factors:

- During the test, the highest practicable standards of safety must be maintained and steps must be taken to ensure that only personnel involved in the testing can access the area;
- If testing is not performed in a special room, the immediate vicinity of the test area must be cordoned off and warning signs used to highlight the danger zone and prohibited area;
- Resistance of the materials to fast fracture must be ensured and brittle fracture (at least 25°C above impact temperature required) must be avoided by all means
- The extent of remote monitoring during the test.

The local authorities of the EU Member State in question may have to be informed before a pneumatic pressure test is performed.

3.4 Final assessment and placing on the market

Verification of the effectiveness of safety concepts, mechanical interactions and the safety-related PLC must be provided on site. They are central elements of the final safety assessment, and thus of central importance for the final assessment report of an assembly. If all the above requirements are fulfilled, a certificate of conformity according to the Pressure Equipment Directive can be issued for the assembly.

According to the PED, the following documents must be submitted: Operating instructions, declarations of conformity and CE markings of the items of pressure equipment included in the assembly. The documentation pertaining to the items of pressure equipment must be retained for a minimum period of ten years.

The requirements and descriptions outlined above show that use of assemblies differs significantly from the use of individual items of pressure equipment. An assembly certified according to Art. 14 (6) lit. c) PED has already been tested for the effectiveness of its safety devices and found to be in conformity. If entire assemblies are placed on the market, the responsibility rests with the manufacturers of these assemblies. Only the conditions of installation and assembly according to the German Ordinance on Industrial Safety and Health (BetrSichV) will be inspected on site. By contrast, if manufacturers of geothermal plants purchase single items of pressure equipment they are the ones responsible for the safety concept, the interaction between the individual pressure equipment and the effectiveness of the safety devices. As soon as hot commissioning according to BetrSichV is performed, i.e. as soon as the plant is energised, the risk passes in both cases to the operating company or the employer respectively.

4. ADDITIONAL REGULATIONS BEYOND THE PRESSURE EQUIPMENT DIRECTIVE

In addition to the requirements imposed by the Pressure Equipment Directive (stresses, pressure and temperature) described in the previous section, additional regulations are also relevant for the approval and licensing of a geothermal plant. These regulations are discussed below.

4.1 Emissions

One of these regulations is the Industrial Emissions Directive (2010/75/EU) or IED, which is the main EU instrument for regulating pollutant emissions caused by industrial installations. Noise emissions, too, must be in conformity with the national standards. Hazardous fluids as defined in the Seveso-III Directive, including butane or flammable refrigerants, are used in geothermal plants. Whether a plant falls under the scope of the above directive depends on whether the quantities of these hazardous substances exceed the threshold values defined in Appendix 1 of the Seveso-III Directive. If the Seveso-III Directive is applicable, additional requirements must be fulfilled.

4.2 Explosion protection

Taking the example of Germany, council Directive 2014/34/EU has been transposed into national law by the eleventh Ordinance on the Product Safety Act and the Explosion Protection Ordinance (11. ProdSV). Directive 1999/92/EC of the European Parliament and of the Council of 16 December 1999 ("ATEX 137") was transposed into national law by the Ordinance on Industrial Safety and Health (BetrSichV), which includes technical rules for operational safety and explosion protection. In line with the above, testing for explosion protection according to BetrSichV is mandatory and verifies the explosion safety of systems in potentially explosive atmospheres. Testing of explosion protection (including fire-protection measures) of installations, that are subject to approval, covers filling systems and storage systems (over 10,000 litres). The explosion-protection document according to the German Ordinance on Hazardous Substances (GefStoffV) of 2015 must address the following points in particular:

1. The identification and evaluation of explosion hazards;

2. The implementation of adequate precautions to achieve the explosion-protection objectives (presentation of an explosion-protection concept);

3. The zoning in accordance with Annex I, point 1.7 (zone classification);

4. The areas for which explosion protection measures have been established in accordance with Section 11 (special protective measures against physico-chemical effects and fire and explosion hazards) and Annex I, no. 1 (minimum requirements);

5. The method of implementation of the requirements according to Section 15 (cooperation of different companies), and

6. The tests and explosion-protection tests that must be carried out in accordance with Section 7 (Testing of the function and effectiveness of protection measures) and Annex 2, Section 3 of the Ordinance on Industrial Safety and Health (BetrSichV) respectively.

4.3 Water protection

Installations for the storage, filling, production and treatment of water-polluting substances and installations for the use of substances hazardous to water in geothermal plants must be constructed, maintained, operated and decommissioned in such a way that no negative impact on the aquatic environment need be expected. This also applies to piping systems within the boundaries of a geothermal plant, which are accessories to systems for handling substances hazardous to water or for connecting systems that are closely related in terms of space and operation.

As a universal rule, the two-barrier principle, which prevents releases into the environment, is required for the safe storage of hazardous materials. “Two barriers” means that there is an interstitial space between two walls that can be monitored. The inner wall is considered the first, the outer wall the second barrier.

The operating company must have the whole geothermal plant inspected by authorised experts. In Germany this must be done before commissioning, after major system modifications and at least every five years. In water-protection areas as defined in section 51 (1) of the Water Resources Act, inspections must be performed at least every two and a half years. Inspections are also mandatory before restarting a system that has been shut down for more than a year, or if inspections are ordered based on concerns regarding water pollution. An inspection is also required when the system is shut down.

5. INSPECTIONS ACCORDING TO THE ORDINANCE ON INDUSTRIAL SAFETY AND HEALTH

Beyond the safe placing on the market of equipment and assemblies of a geothermal plant tested and certified by notified bodies, safe operation of these items of equipment and assemblies must also be ensured. To this end, the authorised inspection agencies carry out inspections prior to commissioning as well as periodic inspections during operation.

In Germany, the use of work equipment is regulated by the Ordinance on Industrial Safety and Health (BetrSichV). Aspects that must generally be ensured in all facilities are plant integrity, health and safety measures and protection of third parties and the environment. To ensure this level of protection, pressure equipment is classified in categories according to the ascending level of hazard. Classification depends on fluid group, fluid volume and fluid pressure as set forth in the PED [3].

All pressure devices that involve a certain hazard potential must be inspected by a third party. These devices must be inspected by pressure-vessel experts for compliance with the BetrSichV, both before they are taken into service and at regular intervals afterwards. Other EU Member States have similar regulations with approximately equivalent requirements

5.1 Commissioning

According to Section 15 of the BetrSichV, all items of pressure equipment, for which regular inspection is mandatory, must be inspected before they are placed into service. The inspection verifies that assembly has been performed correctly and that the mode of operation is in compliance with the rules and regulations. This generally involves comparison with the manufacturer's specifications. The experience shows that the more thorough and detailed these specifications, the faster and easier the inspection before commissioning into service. In ideal cases, the inspection involves no more than verification of the assembly and document review.

5.2 Periodic inspections

Each item of the pressure system for which inspection is mandatory must be inspected at regular intervals. In Germany, these statutory inspection intervals are defined during commissioning by the operating company and the authorised inspection agency. The maximum intervals permitted by the German Ordinance on Industrial Safety and Health (BetrSichV) are five years for internal inspection of the pressure-containing walls of a vessel and ten years for the strength test. Internal inspection is generally performed in the form of visual testing, while the strength test generally involves a hydrostatic pressure test. Under the German Ordinance on Industrial Safety and Health, operating companies are also allowed to use test methods other than the standard methods outlined above, provided they establish an inspection concept and have this concept approved by the competent authorised inspection agency. Within the scope of this concept, the operating companies are free to choose other test methods.

6. TEST PLAN

6.1 Inspection concept and scope

An individual inspection concept must be established for every single plant. This is a duty of the operating company. In case of identical plants, the scope of inspection may also be identical. Generally, the inspection concept includes different test methods for each item of pressure equipment. The method that is used is at the discretion of the operating company. Within certain limits, the test methods used can change from one periodic inspection to the next. Use is generally made of the following non-destructive test methods: visual testing, ultrasonic testing, radiographic testing or acoustic emission testing.

The planned inspection scope should cover the entire pressure equipment. However, depending on the test method chosen, 100 per cent coverage of every item of pressure equipment (vessels, pipes, etc.) may not always be possible. In this case, the operating company must identify the parts that are exposed to the highest stress and thus most likely to suffer damage. This practice is generally applied to piping, but may also become necessary for other pressure devices, such as in cases involving ultrasonic testing. The aim, however, is to find an integrated test method that can be applied to as many parts as possible.

6.2 Example of acoustic emission testing

Acoustic emission testing (AT) is one example of a highly efficient test method. Virtually every technical process emits sounds. Acoustic emissions can be caused by explosions, friction, impacts, leakage, crack initiation and growth. Acoustic emission measurement is normally performed at frequencies between 75 kHz and 350 kHz to separate the detected signals from the surrounding sounds at low frequencies (e.g. machinery noise) and avoid high frequencies which have high attenuation. As a general rule, the smaller a particle, the higher its eigenfrequency. Micro-cracks, for example, cause crystallites to vibrate at frequencies in a range from several KHz to several MHz (see Figure 1)

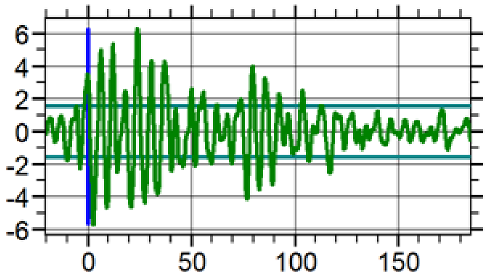

Figure 1: sampled transient acoustic signal, x-axis: time in µs, y-axis: tension in µV

Unlike classic non-destructive-testing (NDT) methods, AT is a dynamic testing method. In other words, the part to be tested must be exposed to stress, which could be mechanical, thermal or corrosive. If this stress causes a critical state, the part will emit an elastic transient wave. The process causing the release of elastic energy is irreversible and cannot be reproduced. Depending on the attenuation of the acoustic emission, the method is an integrated test method, requiring only a few sensors to monitor even large-scale devices.

Contrary to other NDT methods, AT can only detect active defects. When applied to in-operation periodic inspections, acoustic emission testing will only detect defects caused during the last period of service. Discontinuities produced in manufacturing which do not impact on vessel integrity are inactive, and therefore do not show up in AT. If possible, the stress needed for performing the test should be increased while the equipment is in service and operated with fluid [4].

In 2018 TÜV SÜD applied acoustic emission testing for the periodic inspection of three geothermal power plants (Sauerlach, Dürrnhaar, Kirchstockach). For example, acoustic emission was used to inspect the working fluid storage tanks. The storage tanks did not have to be emptied for the purpose of the inspection and could be tested under the pressure of the working fluid itself. It was confirmed that AT enables a comprehensive evaluation of the pressure equipment in geothermal power plants. The preparations of the tests could happen, while the plants were still running. The time to equip the plants with sensors and the testing time were also limited in comparison with other testing methods. This results in shorter maintenance downtime.

7. CONCLUSION

This paper first described the guideline developed by TÜV SÜD for the certification of geothermal power plants, based on the experience gathered in multiple power plants in Germany. In the second part, the inspection prior to commissioning and the development of an inspection plan, including the application of innovative testing methods, were discussed.

During the description of the full compliance and operational safety process, several key learning of TÜV SÜD could be highlighted. Firstly, the ordering of a geothermal power plant as a completed assembly from a single manufacturer certification is advantageous for the operator, as it results in less risks related to interfaces between different assemblies and enable a simpler execution of the downstream certification process. Secondly, the HAZOP method has proven to be the most adequate for the identification of operational risk in a geothermal power plant. However, it should happen early in the project, if possible already in the design phase. Last but not least, experiences made with acoustic emission testing in geothermal power plants show that the use of this test method in regular inspections can result in reduced maintenance downtime.

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