Presented at "Short Course on Geothermal Drilling, Resource Development and Power Plants",
organized by UNU-GTP and LaGeo, in Santa Tecla, El Salvador, January 16-22, 2011.

UNITED NATIONS UNIVERSITY
GEOTHERMAL TRAINING PROGRAMME

LaGeo S.A. de C.V.

ENVIRONMENTAL MONITORING OF GEOTHERMAL POWER PLANTS IN OPERATION

Ingimar G. Haraldsson
United Nations University Geothermal Training Programme
Orkustofnun, Grensasvegi 9, 108 Reykjavik
ICELAND
ingimar.haraldsson@os.is

ABSTRACT

During the operation phase of geothermal power plants, environmental engineers and scientist are entrusted with the task of monitoring their impacts on the environment. With a well designed monitoring plan, they are kept informed of the conditions of the system which they are responsible for maintaining and a sound environmental management plan helps ensure that the monitoring is carried out in an effective manner within the boundaries of their observation space, in accordance with regulation and best practices. As is the case with the power plant engineer, the environmental engineer should strive to apply preventive measures, to ensure continued sustenance of the natural environment.

1. INTRODUCTION

As all other anthropic projects, geothermal power plants interact with their surrounding environment in various ways over the course of their lifetime. They thus become a part of the complex planetary environment without any obvious demarcated boundaries. The impacts can vary in nature, severity and scope over the different phases of development, which according to Steingrímsson (2009) consist of a preliminary study, an appraisal study, project design and construction, commissioning and operation, and finally shutdown and abandonment.

Early impacts during surface exploration are usually minimal, but they become gradually more pronounced as the project moves through exploratory drilling and on to the appraisal study phase (Figure 1). The greatest impacts are brought about during the design and construction phase, when the local environment in the geothermal field and at the power plant site may change significantly with the clearing of land and the construction of man-made structures, when wells are being flow tested and the economic and social effects of the power plant are felt most profoundly in the neighboring communities. After commissioning, the power plant usually falls into a rather steady interaction with the environment if maintenance and operation activities are carried out according to best practices. This interaction finally stops when the plant is shut down and abandoned, although there will be lingering local effects, depending on the reversibility of impacts and the degree of restoration.

The intent of this paper is to present a broad overview of environmental monitoring of geothermal power plants in operation and to examine to a limited extent the role of environmental engineers and scientists in that context. To that end, a somewhat broad philosophical approach is taken at the outset, but specific potential environmental concerns are addressed in more detail in a table in Appendix I.

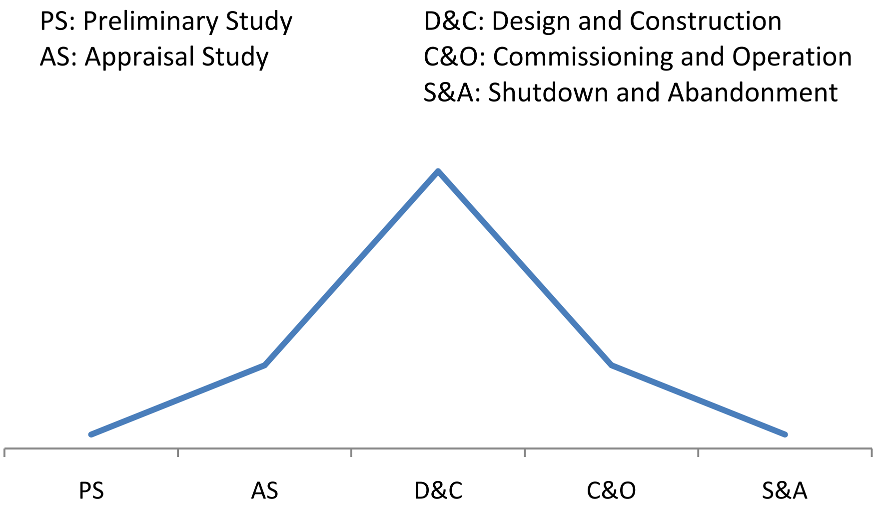

FIGURE 1: Hypothetical relative degrees of the environmental impacts of the different phases of geothermal power plant development

2. GEOTHERMAL POWER PLANTS IN THE ENVIRONMENT

Geothermal power plants in operation cannot be viewed as isolated systems. They rely upon high enthalpy geothermal fluids that may draw their heat content from rocks several kilometers beneath the surface of the earth – heat that may have been locked in the deep interior of the planet since its formation around 4.5 billion years ago or released from radioactive heavy elements that captured and locked away some of the tremendous energy of supernovae long before the formation of the solar system. The plants process these fluids and re-emit them to the environment in different states and compositions: water and dissolved substances are reinjected or discharged to the surface and steam and noncondensable gases are emitted to the atmosphere, where they may be advected and dispersed over long distances while undergoing chemical reactions with other atmospheric components. One of these gases is CO_2, which has an estimated 200 years combined lifetime in the atmosphere, biosphere, and upper ocean (Seinfeld and Pandis, 1998). Over this period, it can contribute to radiative forcing of the climate and acidification of the oceans. Geothermal power plants therefore interact with the environment over vast distance and time scales.

Geothermal power plants need cooling fluids to discard waste heat to the environment. These can be fresh or salt water that makes a one-time pass through a condenser, carrying the waste heat into a nearby river, lake or ocean. The cooling fluid can also be water that carries waste heat into the environment in latent form through an evaporative process in a cooling tower or air that cools a dry condenser. The first method increases the temperature of the receiving river, lake or ocean, which may affect the biosphere, the second increases the temperature and humidity of the local atmosphere and the third increases the temperature of the local atmosphere.

In addition to geothermal fluids and cooling fluids, a geothermal power plant in operation needs to discard various substances, materials and equipment and new ones are required for maintenance purposes. A pump made by workers in China may be bought for maintenance in a power plant in El Salvador, Iceland or Kenya, and transformer oil or cooling water treatment chemicals may likewise be shipped between continents. Last, but not least, geothermal power plants may provide electricity to the public and industry on a country-wide scale and hot water to district heating systems on a municipal scale, thereby affecting the social and economic fabric in these spaces. It is thus clear that geothermal power plants in operation affect the environment and socio-economic sphere near and far.

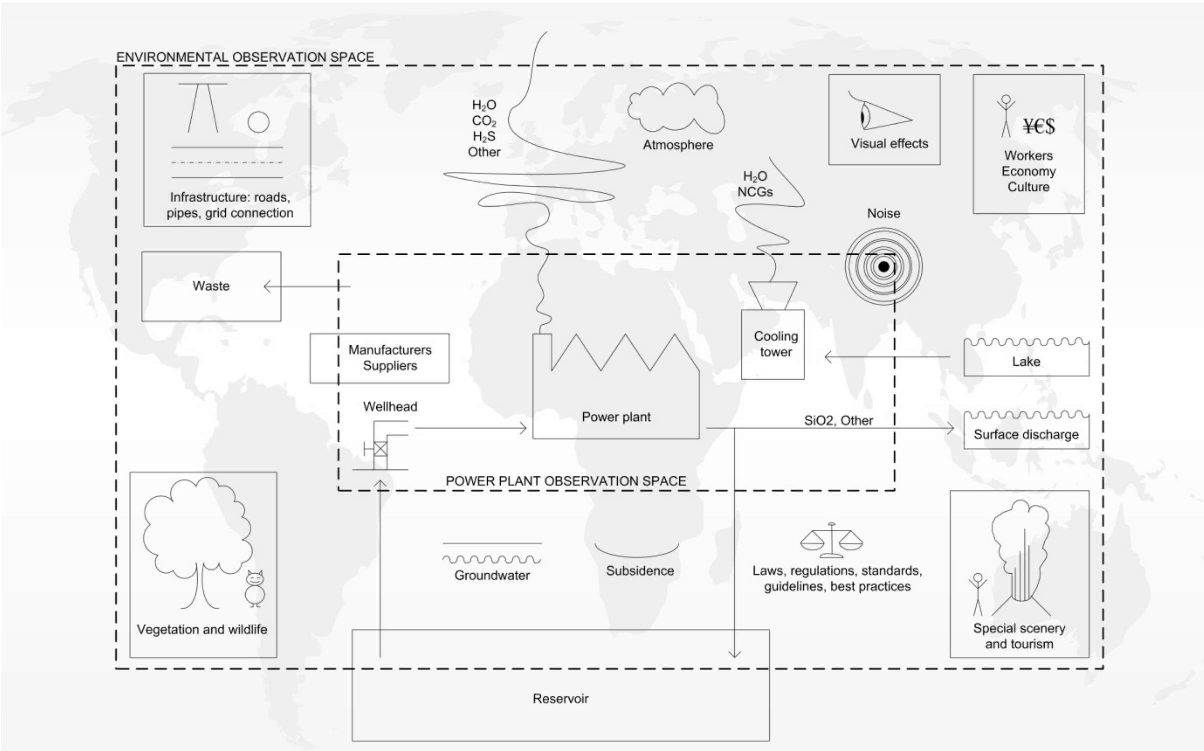

FIGURE 2: A simple presentation of one possible demarcation of the environmental and power plant observation spaces

A common practice in environmental engineering, fluid mechanics and thermodynamics is the application of control volumes to systems of interest. They can range from the infinitesimal to the very large depending on the problem at hand and are used for simplification to draw an arbitrary border between the system of choice and its surroundings. The goal is usually to bundle the various processes of the system within the control volume together without regard to the details of system components. The interaction of such systems with the surrounding environment can be evaluated on the basis of mass, energy or information exchange through the imaginary borders of the control volume.

One way of selecting the control volume, or observation space, of a geothermal power plant is to imagine the borders as consisting of the land surface and the borders of man-made structures and equipment, or perhaps extending them below the surface to the casings of wells (Figure 2). This may be the preferred observation space of power plant engineers who are concerned with daily operations and maintenance of their power plants. In order to keep the plants in optimum shape for future operations, they may apply preventive maintenance philosophies within this space, since the key to reliable operation is constant monitoring and condition-based maintenance (Thorolfsson, 2010). In such an observation space, the environment may be a concern primarily as an outside agent of influence on the system of relevance (the power plant), as weather conditions and the chemistry of surrounding fluids may detrimentally affect equipment and materials.

The environmental engineer may take the stance of looking at a bounded or unbounded observation space surrounding the power plant to look at the effects of the plant on the environment. In this case, the power plant has become the outside agent of influence on the system of relevance, which is the environment, often extended to the socio-economic sphere. The environmental engineer is concerned with sustaining the environment, so that it is passed on to the future in the same or better shape than at present. As one synonym of the verb to „sustain“ is to „maintain“, the goals of the power plant engineer who seeks to maintain his system in optimum working condition is analogous to that of the environmental engineer who seeks to sustain the system which he or she is responsible for monitoring.

In this respect, it is important to note that the environmental engineer may choose to look at details or overall effects within the observation space. An example is the clearing of a patch of land and the associated loss of vegetation and wildlife, which may or may not be considered acceptable depending on the scarcity of the affected flora and fauna and the magnitude of the effects, but which may possibly be compensated for by restoring another patch of land to similar conditions. Therefore sustained balance of the system on a predetermined scale is sometimes what should be sought rather than simply keeping individual small scale parts of the system in sustained condition.

While arbitrary compartmentalization into observation spaces can be useful, it should be remembered that the power plant and its surrounding environment can also be viewed as a single system of interacting parts and perhaps such an approach is most fit.

3. INTERACTION WITH THE ENVIRONMENT

The interaction between geothermal power plants and the surrounding environment can be divided into the impacts of the power plants on the environment and the impacts of the environment on the power plants. Kristmannsdóttir and Ármannsson (2003) have classified the former into the following categories:

- Surface disturbances;
- Physical effects of fluid withdrawal;
- Noise;
- Thermal effects;
- Chemical pollution;
- Biological effects; and
- Impact on (protected) natural features.

Surface disturbances include the clearing of land, changes in landscape and the introduction of man-made structures where none existed before. Physical effects of fluid withdrawal include subsidence, lowering of the groundwater table and induced seismicity as earth layers consolidate due to the removal of fluids from matrix pore spaces or when increased pressure due to injection causes the relief of accumulated geological stresses. Thermal effects include elevated temperatures of rivers, lakes and groundwater due to thermal fluid discharges and changes in cloud formation and local weather due to steam emissions. Chemical pollution can be caused by steam and non-condensible gas emissions to the atmosphere and the discharge of brine to surface or subsurface water bodies. All of these have the potential of impacting wildlife, vegetation and the socio-economic sphere around a geothermal power plant, as well as altering natural features for the short term or permanently. Monitoring and controlling sources and their impacts is therefore of utmost importance.

On the other hand, the impacts of the environment on geothermal power plants include:

- The application of external dynamic forces to power plant structures. These include seismic forces changing over short time scales and deforming forces that may change over much longer time scales due to subsidence. Wind (hurricanes), floods, snow and ice are also examples of dynamic environmental forces that may follow a seasonal pattern and affect power plant structures.
- Degradation of equipment and materials due to environmental chemistry. These effects include corrosion and scaling.

All of these effects need to be monitored to maintain and sustain the power plant and its environment.

4. ENVIRONMENTAL MONITORING

The goal of environmental monitoring is to keep the environmental engineer informed of the conditions of the system which he/she is responsible for maintaining. Ideally, information about all possible factors of concern should be available at all times to give instantaneous snapshots of the system when needed. The environmental engineer, however, does not have the same elaborate monitoring and control system at his/her disposal as the power plant engineer, where the most important parameters of power plant operations are constantly monitored and recorded, and can be viewed on a display in a central location. While such frequent information may be obtained by chemical, meteorological and seismic sensors in the environment, the environmental engineer will in most cases have to make his/her own observations and measurements. As this can be costly, it is important to design a well structured monitoring program that fulfills the demands of regulations and best practices, while minimizing cost. Quality of data should be emphasized over quantity, since data volume by itself is not an indicator of meaningful information, but rather the context in which the data is collected and how it is related to processes of interest.

In 1999, the World Bank Group (WBG) listed the common components of a pollution monitoring program in the following manner:

> The elements of a monitoring plan normally include selection of the parameters of concern; the method of collection and handling of samples (specifying the location, the frequency, type, and quantity of samples, and sampling equipment); sample analysis (or, alternatively, on-line monitoring); and a format for reporting the results.

While pollution monitoring is essentially the monitoring of various chemical species and other potentially harmful agents (such as particulate matter) in the environment and unmistakably important in the context of geothermal power plants, it is only a part of a thorough and well rounded geothermal environmental monitoring program. The WBG description is therefore not complete in the context of geothermal power plants, but can nevertheless serve as a basis that can be extended to the other factors of concern to design a sound environmental monitoring program.

According to the WBG (1999), "an environmental management system is a structured program of continuous environmental improvement that follows procedures drawn from established business management practices". One such system is the ISO 14000 series, which helps delineate well organized management programs. As it provides structure more than content, it leaves the responsibility of identifying environmental concerns to the users of the system. The ISO 14001 environmental management system has for example been implemented by Instituto Costarricense de Electricidad for the Miravalles power plant in Costa Rica and has allowed continuous improvement in controlling the environmental impacts of the power plant (Guido-Sequeira, 2010).

In order to clarify the goals of monitoring and establish the content of an environmental management plan, it can be helpful to keep the following basic questions in mind:

1. *What* aspects need to be monitored?
2. *Why* are they a concern?
3. *Where* should the monitoring take place?
4. *How* should monitoring and analysis be carried out?
5. *When* is monitoring needed?

An attempt is made to answer these questions for some issues of concern in a table in Appendix I, roughly following the categorization of Kristmannsdóttir and Ármannsson. The table is intended as an aid or a checklist for environmental monitoring of geothermal power plants in operation and the issues addressed cover various environmental aspects that are of concern in disparate countries. As concerns may differ between countries, it is probable that the table is not relevant in its entirety to any one power plant. It is certainly not exhaustive and is meant to evolve as new concerns and information may be brought to light.

While environmental monitoring programs can be designed meticulously, they are meaningless without references to compare observations against, and these mainly take two forms:

- The natural state before alteration; and
- Laws, regulations, standards, codes, guidelines, and best practices.

5. BASELINE ESTABLISHMENT

It is necessary to know the natural state of the environment before it is changed by exploration, testing or utilization. Baseline data collection involves collecting background information for this purpose on the physical, chemical, biological, social and economic settings in the vicinity of a proposed geothermal power plant and is usually carried out as part of scoping or an environmental impact assessment. The information may be obtained from secondary sources or gathered through measurements, field samplings, surveys, interviews and consultations (Achieng Ogola, 2009). A well established baseline allows the environmental engineer to assess how significantly specific environmental conditions deviate from the natural state during the power plant operation phase and to what extent they are caused by the plant.

6. THE ROLE OF LAWS, REGULATIONS, STANDARDS, CODES, GUIDELINES AND BEST PRACTICES

Most countries have established specific laws that address the environment, and environmental regulations may be issued by relevant ministries. The particular aspects addressed and the detail in which they are covered can however vary from country to country. Power plant designers and operators may be obliged to follow certain standards, norms and codes that may be relevant to the environment, and financing institutions may condition the financing of projects to the observation of environmental guidelines that they have established. Companies and developers can also decide on their own accord to follow best practices without being obliged to do so by outside parties.

Environmental laws are important in channeling and placing constraints on human interaction with nature. Governmental and municipal regulations are an extension of the law, which may address specific topics in more detail than the laws themselves and dictate limits, such as the allowable concentration of pollutants in the environment. They may also provide a framework for the development of geothermal resources and address issues as diverse as planning, the acquisition of land, the application of concessions, exploration, exploitation, rights, permits, performance guarantees, taxation, general procedures and obligations of actors.

Engineers may be constrained by standards and codes in their design work that are pertinent to the environment. Civil engineers who design concrete containment structures for conveying, storing or treating liquid or solid wastes may for example have to take account of specific codes in structural design and materials selection in order to ensure that those wastes will not find their way into the environment.

A provision in the International Development and Finance Act of 1989, known as the Pelosi Amendment, requires the World Bank and all the regional multilateral development banks to review the potential environmental impacts of development projects for which they provide funding and to make these environmental assessments publicly available (BIC, 2010). This provision and the establishment of stringent guidelines within development banks has helped ensure that the environmental impacts of projects financed by these entities are within acceptable limits.

Additionally, such guidelines have had spillover effects on various other bodies. A case in point is noted by Arévalo (2009), who reports that "in the 1980's, the Latin American Energy Organization (OLADE) under the auspices of the Inter-American Development Bank (IDB) established a guideline for the development of geothermal projects for the countries in the region". She further notes that "the application of the OLADE guidelines in the region helped raise awareness in countries where geothermal resources are explored".

Health guidelines are important to the environmental engineer as they often provide advice on maximum allowable concentrations of particular pollutants over a set time period. Such guidelines are issued by national agencies or international organizations such as the World Health Organization (WHO) and are often specific to the fluid medium carrying the pollutants, such as the atmosphere or water bodies. One of the tasks of the environmental engineer is to assess measured concentrations against such guidelines and to devise mitigation schemes if they are surpassed.

7. ENVIRONMENTAL ENGINEERING AND MITIGATION

It is important that environmental considerations be taken into account from the very first stages of geothermal resources development and that these considerations are noted in the design of a power plant. To this end, it is important to start gathering environmental baseline information as soon as possible and that an environmental impact assessment be carried out – the results of which will be of use in the power plant design. If environmental constraints are likely to be broken based upon available information about the geothermal fluid properties and composition and initial proposals for utilization, it is the task of the environmental engineer to devise schemes to prevent such scenarios from unfolding. A geothermal power plant that is well designed with regard to the environment and well managed is not likely to cause environmental harm. However, as regulations and guidelines may change and conditions become more stringent with time, the environmental engineer must keep abreast of developments in the regulatory sphere that may increase environmental demands on a power plant, even if the operation remains in a steady phase.

8. CONCLUSION

During the operation phase of geothermal power plants, environmental engineers and scientist are entrusted with the task of monitoring their impacts on the environment. With a well designed monitoring plan, they are kept informed of the conditions of the system which they are responsible for maintaining, and a sound management plan helps ensure that the monitoring is carried out in an effective manner. It is important to monitor both the sources of potential problems and their effects. The role of the environmental engineer is to ensure the maintenance of the system within the boundaries of the chosen observation space, in accordance with laws, regulations, standards, guidelines and best practices. If problems arise, countering or mitigative measures should be taken in order to deal with them. As is the case with the power plant engineer, the environmental engineer should strive to apply preventive measures to ensure continued sustenance of the system within the relevant observation space and to collaborate with colleagues of other disciplines to attain the necessary goals.

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APPENDIX I: Potential environmental concerns in the operation of geothermal power plants

Category	What to monitor (Concern)	Why monitor (Risks)	Where to monitor (Location)	How to monitor (Method)	When to monitor (Frequency)	Guides / Limits	Mitigation options/Alternatives
Surface disturbances	**Clearing of land**	• Can destroy vegetation and wildlife habitat • Can lead to soil erosion and changes in runoff • Can cause displeasing scars in vegetation	In the vicinity of power plant where new wells, roads or other constructions may be built.	• Be involved in the design and decision phase • Conduct baseline studies on the affected land • Observe impacts during and after construction phase	• During clearance • During and after construction phase until balance (equilibrium) is attained.	• Permits may be needed • EIA may be needed • Local community considerations	• Select areas where effects on vegetation and wildlife will be minimal (well pad locations, road paths) • Minimize affected area (e.g. by drilling deviated wells from a single well pad).
	Changes in landscape	• Can lead to landslides • Can contribute to erosion • Can cause displeasing scars	In the vicinity of power plant where new civil works may be undertaken.	• Carry out necessary geotechnical studies and assess env. impacts • Be involved in the design and decision phase • Monitor execution of civil works • Photograph before, during and after changes	During civil works until land has been formed according to plans and surplus rocks and soil disposed of appropriately.	• Permits may be needed • EIA may be needed • Local community considerations	• Minimize changes • Take account of the surrounding environment • Avoid sharp unnatural boarders • Introduce vegetation if appropriate
	New construction / structures	• Can affect vegetation and wildlife • Can lead to changes in runoff • Can be accompanied by polluting activities • Changed view	Where construction activity takes place.	• Be involved in the design and decision phase • Monitor execution of civil works and effects on the environment	During civil works until the construction has been finished according to plans.	• May need permits • EIA may be needed • Local community considerations • Accepted construction practices should be followed	• Minimize affected area • Follow accepted construction practices • Ensure proper drainage design • Avoid unsound materials and toxic substances (handle according to HSE stipulations if needed)
	Untidiness	Can degrade views	• At power plant • At new construction sites	Visual inspection / photographing	• Once a year? • During new construction activities	• Company standards • Community opinions	Tidy up

Category	What to monitor (Concern)	Why monitor (Risks)	Where to monitor (Location)	How to monitor (Method)	When to monitor (Frequency)	Guides / Limits	Mitigation options/Alternatives
Surface disturbances	**Altered hydrology: runoff and drainage**	• Can contribute to flooding • Can cause erosion	• Constructed areas • Drainage system • Receiving channels and streams	• Visual inspection • Runoff volume and sediment concentration measurements if necessary	During rainy season.	• Company standards • Community opinions	• Good initial drainage design is important: will reduce need for monitoring • Improved drainage design if necessary • Appropriate vegetation to inhibit erosion
	Soil instabilities and landslides	• Can cause loss of human life • Can cause destruction of wildlife and vegetation • Can cause destruction of human-made structures • Can cause long-term or permanent scars in vegetation and landscape	• At new construction sites (e.g. well pads) in sloping terrain where soil stability is circumspect • At operational sites if considered necessary	Establishment of slope stability using accepted shear & compaction tests, penetration tests, and other in situ tests, with due consideration of structural loads, earthquake loads, saturation /seepage, stratification, slip surface, vegetation etc.	• Before new construction or changes in landscape (new well pads, roads, buildings) • When there is reason to believe that changed conditions will affect stability, e.g. changes in land use or vegetative cover, sustained erosion etc.	• Company standards • Sound engineering judgment	• Distribution of load • Change of soil • Compaction • Retaining walls • Vegetation
	Erosion	Leads to degradation of soil and vegetative cover.	In geothermal field / power plant area.	Visual inspection, photography, erosion pins etc.	As needed, particularly during periods of erosive stresses, e.g. rainy season or dry and windy season.	• Company standards • Sound engineering judgment	• Effective drainage design • Changes in vegetative cover
	Effluent lagoons / Evaporation ponds	• Can pollute groundwater • Changes in surface area: can encroach on surrounding land or shrink to leave a barren desert of mineral deposits • Changes in volume capacity due to deposition	• Monitor borders for changes • Monitor surface area • Monitor rate and accumulation of precipitation and deposition	• Inspection of border landmarks • Aerial photography / comparisons over time • Collection of accumulated sedimentation over specific time interval (collector vessel) • Measurement of sedimentation thickness	• Quarterly to annual inspection of borders • Annual aerial photography • Collection of sedimentation and thickness measurements according to needs	• Permits from regulating authorities • Company standards • Community considerations	• Avoid altogether by reinjection • If unavoidable or preferred for balneology, maintain design/authorized surface area by reinjection or, if considered acceptable, by channeling to a large water body (ocean)

Category	What to monitor (Concern)	Why monitor (Risks)	Where to monitor (Location)	How to monitor (Method)	When to monitor (Frequency)	Guides / Limits	Mitigation options/Alternatives
Physical effects of fluid withdrawal	**Subsidence**	• Can cause deformation or cracking of structures (pipelines, roads, concrete channels, well casings) • Can cause cracks or fissures in ground • Can cause changes in landscape and water bodies • Can cause an irretrievable loss of pore spaces	In geothermal field above and around production zone – extend monitoring area if needed.	• Establish benchmarks • Carry out releveling surveys on the marks	According to assessment in each field.	• Regulations / permits • Company guidelines • Community considerations	Avoid reservoir pressure decline by reinjection.
	Changes in ground water table	• Can affect surface water bodies and springs • Can affect groundwater wells • Can affect the vadose zone and water availability to vegetation (positively or negatively)	• Surface water bodies in geothermal field (surface area) • Spring activity • Water level in groundwater wells	• Aerial or ground-based photography of surface water bodies / Inspection of border landmarks • Measure spring flow • Measure water level in wells	According to need (annually?)	• Regulations / permits • Company guidelines • Community considerations	Reinjection
	Micro-seismicity	• Small but perceivable earthquakes (>M2) can cause concern among local residents	Geothermal field	Application of seismometers / seismometer arrays	Continuous	• Limits of detection by local population • Building codes	• Design reinjection programs to minimize micro-seismicity • Inform and cooperate with local population to reduce unnecessary concerns

Category	What to monitor (Concern)	Why monitor (Risks)	Where to monitor (Location)	How to monitor (Method)	When to monitor (Frequency)	Guides / Limits	Mitigation options/Alternatives
Noise	**Noise level (dBA)**	• Risk of hearing impairment of workers • Nuisance to residents near power plant • Nuisance to tourists • Nuisance to wildlife	• In areas of concern: well pads during drilling and flow tests, within power plant boundaries • At boundaries of significance, e.g. at lease boundary or power plant fence • Near equipment during normal operation: cooling towers, turbine and generator, switch yards / substation, gas extraction system, pumps, control valves and other flow restrictions	• Certified sound level meters	• As needed: e.g. quarterly or once a year during normal operations if previous measurements have proved well within limits, but more frequently if previous measurements have been near limits or during atypical operations, such as during borehole flow testing or during periods of additional construction • Note: sound levels from equipment may change as they age or operate out of design conditions	• EU daily 8 hr exposure limit values for workers (time weighted average, with protection): 87 dBA and 200 Pa (EU, 2003) • OSHA daily 8 hr permissible exposure (over 1 s or less, with protection): 90 dBA (OSHAa) • Kenya OHS 8 hr average noise level limit (regardless of protection): 85 dBa (Kubo, 2003) • US Bureau of Land Management: max 65 dBA at 0.5 miles from source or lease boundary if closer (Kagel et al., 2007)	• Minimize duration of flow tests • Time noisy scheduled events during daylight hours • Use wellhead silencers • Use sound barriers: by introducing vegetation (trees), modifying landscape or constructing other man made barriers (e.g. walls) • Use insulation where applicable (e.g. on buildings housing noisy equipment) • Use ear muffs • See (Hunt1, 1998)

Category	What to monitor (Concern)		Why monitor (Risks)	Where to monitor (Location)	How to monitor (Method)	When to monitor (Frequency)	Guides / Limits	Mitigation options/Alternatives
Thermal effects	Atmosphere (fogging)		Fogging: diminishes visibility and can contribute to corrosion	• At site • Around cooling towers	• Visual scan • Hydrometer or hygrometer if necessary	• Visual scan during temperature low (nighttime or early morning) • Fog conditions may follow an annual as well as a daily cycle	• Probably none	• Dry cooling tower • Once through cooling (river, lake or ocean water)
	Surface water (temperature)	River	• Can affect aquatic life downstream of discharge point(s) • Can cause visible mist above river under right conditions (water temperature vs. air temperature and humidity)	• At discharge point(s) • Downstream of discharge point(s)	• Thermometer • Other temperature measurement devices	• Depends on situation: the magnitude and extent of temperature changes and the sensitivity of aquatic life to those changes	• Regulations / permits • Good practices • Community considerations	• Dry cooling tower • Wet cooling tower (water recycling) • Diffuse discharge (several discharge points): contributes to quicker mixing and reduces total volume of local high Ts • Discharge into turbulent river segments: contributes to quick mixing and minimizes volume of local high Ts
		Lake	• Can affect aquatic life around discharge point(s) • Can cause visible mist above lake around discharge point(s) or de-icing in winter	• At discharge point(s) • In appropriate volume(s) around discharge point(s)	• Thermometer • Other temperature measurement devices	• Depends on situation: magnitude and extent of temperature changes and sensitivity of aquatic life to those changes	• Regulations / permits • Good practices • Community considerations	• Dry cooling tower • Wet cooling tower • Diffuse discharge (several discharge points): contributes to quicker mixing (diffusion / dispersion) and reduces total volume of local high Ts
		Ocean	Can affect marine life around discharge point(s) (positively or negatively)	• At discharge point(s) • In appropriate volume(s) around discharge point(s)	• Thermometer • Other temperature measurement devices	• Depends on situation: magnitude and extent of temperature changes, sensitivity of marine life to those changes, importance / uniqueness of local marine life	• Regulations / permits • Good practices • Community considerations	• Reinjection • Dry cooling tower • Wet cooling tower • Diffuse discharge (several discharge points): contributes to quicker mixing and reduces total volume of local high Ts
	Groundwater		Can affect vegetation (roots) and microbial activity (positively or negatively)	At and around discharge / injection points	Temperature measurements in wells	As need or interest may dictate	Probably none	• Reinjection below ground water layer • Discharge to surface water bodies • Dry cooling tower • Wet cooling tower

Category	What to monitor (Concern)		Why monitor (Risks)	Where to monitor (Location)	How to monitor (Method)	When to monitor (Frequency)	Guides / Limits	Mitigation options/Alternatives
Pollutants, trace elements and wastes	Steam	**Gas ratio**	NCG ratio: NCGs reduce the efficiency of power generation	At sources (wells)	• Gas collecting bottle[*] • Weighing*	• At least annually	None	• Limited (use wells with a low NCG ratio)
		H_2S : Hydrogen Sulfide	• Toxicity (high concentration) • Odor nuisance (low concentration) • Causes corrosion of various metals and alloys, such as aluminum, copper, steel and silver	• At sources (wells, steam vents, condenser ejection system etc.) • In power plant area • In machine hall and control room • In neighboring residential areas	• Sampling of sources (wells): condensate and gas mixed with base, which is titrated to yield concentration* • Portable detectors and analyzers for concentrations in ambient air • Fixed sensors in power plant area that feed into control system	• At least annually at sources (wells) • Measurements with portable sensor as needed (quarterly?) • Continuously by fixed sensors	• 0.011 mg/m^3: odor threshold • 5-29 mg/m^3: eye irritation • >140 mg/m^3: olfactory paralysis • >700 mg/m^3: death • 150 $\mu g/m^3$: 24 hour average guideline set by WHO • 50 $\mu g/m^3$: 24 hour average limit set by Icelandic regulation • 43 $\mu g/m^3$: 1 hour average standard set by USEPA-California regulation • See for example (Franco, 2010)	Downstream of turbine-generator (Padilla, 2007): • Stretford process • LO-CAT process • SulFerox process • THIOPAQ process • Fe-Cl hybrid process • Claus process – Amine/Claus • Selectox process • Wet gas sulphuric acid process (WSA) • XERGY process • AMIS process Upstream of turbine-generator (Franco, 2010): • Caustic scrubbing • Caustic scrubbing with H_2O_2 • Caustic scrubbing with $FeSO_4$
		CO_2 : Carbon Dioxide	Greenhouse gas	At sources (wells) and in condensate	• Sampling: condensate and gas mixed with base* • Titration*	• At least annually	• International agreements of state • Obligations under clean development mechanism (CDM)	• Limited • Capture and sell • Fixation into deep rock formations (Sigurdardottir et al., 2010)
		CH_4 : Methane	Greenhouse gas	At sources	• Sampling: gas collected over base* • Gas analyzer used to yield concentration*	• At least annually	• International agreements of state • Obligations under CDM	• Limited: probably not warranted due to low concentration • Burning to yield CO_2
		H_2 : Hydrogen N_2 : Nitrogen O_2 : Oxygen Ar : Argon	For information about fluid composition and reservoir geochemistry	At sources	• Sampling: gas collected over base* • Gas analyzer used to yield concentration*	• Annually	None	Not warranted

[*] (Gudmundsson and Hauksson, 2005)

Category	What to monitor (Concern)		Why monitor (Risks)	Where to monitor (Location)	How to monitor (Method)	When to monitor (Frequency)	Guides / Limits	Mitigation options
Pollutants, trace elements and wastes	Steam	**B : Boron**	• Boron compounds can result in respiratory irritation (IPCS, 1998) • Has not been found in dangerous conc. in geoth. gas, but needs to be watched (Ármannsson and Kristmannsdóttir, 1993)	At sources		As needed		
		Hg : Mercury	• Mercury vapor can cause effects in the central and peripheral nervous systems, lungs, kidneys, skin and eyes. It is mutagenic and affects the immune system. • Mercury can accumulate in sediments and organisms • Has not been found in dangerous conc. in geoth. gas, but needs to be watched (Ármannsson and Kristmannsdóttir, 1993)	At sources	Mercury vapor monitor	• Annually?	• OSHA permissible exposure limit: 0.1 mg/m^3 (ceiling) • NIOSH recommended exposure limit: 0.05 mg/m^3 (time weighted average for 8 hr workday, 40 hr workweek) • ACGIH threshold limit value: 0.025 mg/m^3 (TWA for 8 hr workday, 40 hr workweek • See (OSHAb, 2010)	
		Rn : Radon	• For information about reservoir characteristics • Carcinogen: can cause lung cancer if inhaled in high enough concentration due to ionizing radiation • Has not been found in dangerous conc. in geoth. gas, but needs to be watched (Ármannsson and Kristmannsdóttir, 1993)	• At sources • In confined spaces and at low points where the dense gas may accumulate (seepage through cracks into basements is possible)	Radon gas detector	• As needed (due to low concentrations, regular monitoring may not be necessary)	4 pCi/L in homes (EPA, 2009)	• Sealing pathways • Venting
		NH_3 : Ammonia	• Corrosive to the eyes, skin and lungs • Flammable over a conc. range • Has not been found in dangerous conc. in geoth. gas, but needs to be watched. • Danger of accidental releases from Kalina power cycles.	At sources	• Handheld detectors • Nessler's solution • Olfaction	As needed (regular monitoring may not be necessary)	Ontario Ministry of Environment: 100 µg/m^3 ambient air quality criterion (24 hr average)	

Category	What to monitor (Concern)		Why monitor (Risks)	Where to monitor (Location)	How to monitor (Method)	When to monitor (Frequency)	Guides / Limits	Mitigation options/Alter-natives
Pollutants, trace elements and wastes	**Water**	**Temp.**	• To determine thermodynamic state at time and place of sampling • To determine energy content (enthalpy) of reinjected fluid • To determine potential thermal effects if released into the environment	• At chemical sampling locations (same each time) • At any point of discharge to the environment	Thermometer, thermistors etc.	• Annually? • More frequently at points of constant discharge to the environment	N/A	N/A
		pH	• For geochemical studies • To determine impact if discharged into the environment • To determine corrosiveness and scaling potential	• At sources (wells) • At other chemical sampling locations of interest	• Sample collected in an air-tight glass bottle* • Analyzed with a pH meter*	• Annually? • More frequently if needed		• Reinjection to reservoir to avoid environmental impact • Alter pH with an acid or base to reduce corrosiveness or scaling potential
		CO_2 : Carbon Dioxide	• Greenhouse gas: important to measure water concentration to get a full account of fluid CO_2 content • Acidic gas: dissolves in water to form carbonic acid	At sources	• Sample collected in an air-tight glass bottle* • Acid-base titration*	Annually?		Reinjection
		H_2S : Hydrogen Sulfide	• To get full account of fluid H_2S content • An acid that dissociates to very limited extent below pH=5 • Anti-corrosive as it reacts with O_2	At sources	• Sample collected in an air-tight glass bottle* • Titration with $HgAc_2$*	Annually?	• No information on oral toxicity (WHO, 2003b)	N/A
		Conductivity	Geochemical studies	At sources	• Sample collected in an air-tight glass bottle* • Conductivity meter*	Annually?	N/A	N/A
		Suspended Solids (SS)	• Geochemical studies • Deposition • Erosion	At sources	• Sample collected in a plastic bottle* • Filtration and weighing*	Annually?	N/A	N/A

Category	What to monitor (Concern)		Why monitor (Risks)	Where to monitor (Location)	How to monitor (Method)	When to monitor (Frequency)	Guides / Limits	Mitigation options/Alter-natives
Pollutants, trace elements and wastes	Water	**SiO_2 : Silica (Quartz, Cristobalite)**	• Reservoir conditions: geothermometer and mixing models • Scaling potential in pipes and conduits • Deposition in environment when discharged to surface water bodies (e.g. Blue Lagoon)	• At sources • In groundwater and/or surface water in power plant surroundings	• Collection of diluted sample (1:9)* • Color analysis*	• Semi-annually? • Annually?	• Silica solubility • Polymerization and deposition rates • Established by calculations and experimentation • See for example (Thorhallsson, 2006) and (Padilla et al., 2005)	• Tempera-ture control (design restrictions on cooling) • Scaling inhibitors
		Total Dissolved Solids (TDS)	Geochemical studies	At sources	• Collection of filtrated sample (0,45 µm)* • Drying and weighing*	Annually?	N/A	N/A
		Cl : Chlorine / Chloride	• Reservoir conditions: mixing models • Contribution to corrosion (chloride stress corrosion)	• At sources • In groundwater and/or surface water in power plant surroundings	• Collection of filtrated sample (0,45 µm)* • Acidified with 0,5% HNO_3* • Titration*	Annually?	N/A	N/A
		F : Fluorine / Fluoride	• Geochemical studies • Potential impacts when discharged to surface water bodies: • Fluoride can accumulate in plants (Miller et al., 1999) • Sustained exposure to high concentrations can cause dental and skeletal fluorosis (WHO, 2004b)	• At sources • In groundwater and/or surface water in power plant surroundings	• Collection of filtrated sample (0,45 µm)* • Acidified with 0,5% HNO_3* • Detection by ion-selective electrode*	Annually?	Guideline value of 1.5 mg/l set by WHO for fluoride in drinking water (WHO, 2004b)	• Reinjection • Mixing / dilution
		SO_4 : Sulfate	Geochemical studies	• At sources • In groundwater and/or surface water in power plant surroundings	• Collection of filtrated sample (0,45 µm)* • Precipitation with $ZnAc_2$* • Titration*	• Semi-annually? • Annually?	N/A	N/A
		Na : Sodium Mg : Magnesium K : Potassium Ca – Calcium Fe – Iron	• Reservoir conditions: Na/K and Na-K-Ca geothermometers. Also: Na/Li, Li/Mg K/Mg and Na-K-Mg (Arnórsson, 2000) • $CaCO_3$ is a common scale in geothermal systems, primarily found in wells at and above boiling point (Thorhallsson, 2006)	• At sources • In groundwater and/or surface water in power plant surroundings	• Collection of filtrated sample (0,45 µm)* • Acidified with 0,5% HNO_3* • Inductively coupled plasma mass spectrometry (ICP-MS) / Atomic absorption spectroscopy (AAS)*	• Semi-annually? • Annually?	N/A	N/A

Category	What to monitor (Concern)		Why monitor (Risks)	Where to monitor (Location)	How to monitor (Method)	When to monitor (Frequency)	Guides / Limits	Mitigation options/Alter-natives
Pollutants, trace elements and wastes	Water	**B : Boron**	• Harmful to most plants (Kristmannsdóttir and Ármannsson, 2003) • Concerns on decreased fetal weight during pregnancy when ingested (WHO, 2009)	• At sources • In groundwater and/or surface water in power plant surroundings	• Collection of filtrated sample (0,45 μm)* • Acidified with 0,5% HNO_3* • ICP-MS*	Annually?	Conservative guideline value of 2.4 mg/l set by WHO for Boron in drinking water (WHO, 2009)	• Reinjection • Mixing / dilution
Pollutants, trace elements and wastes	Water	**Al : Aluminum**	• Can have toxic effects on fish (Ármannsson and Ólafsson, 2005) • Some studies have suggested the possibility of association of Alzheimer disease with aluminum in water, but other studies have not confirmed this (WHO, 2010)	• At sources • In groundwater and/or surface water in power plant surroundings	• Collection of filtrated sample (0,45 μm)* • Acidified with 0,5% HNO_3* • ICP-MS*	• Semi-annually? • Annually?	• Health-based value of 0.9 mg/l suggested by WHO for aluminum in drinking water • Practicable levels of 0.1-0.2 mg/l obtainable in water treatment facilities • See (WHO, 2010)	• Reinjection • Mixing / dilution
Pollutants, trace elements and wastes	Water	**Mn : Manganese**	An essential element, but inadequate intake or overexposure can lead to neurological effects (WHO, 2004c)	• At sources • In groundwater and/or surface water in power plant surroundings	• Collection of filtrated sample (0,45 μm)* • Acidified with 0,5% HNO_3* • ICP-MS*	• Semi-annually? • Annually?	Health-based guideline value of 0.4 mg/l suggested by WHO for manganese in drinking water	• Reinjection • Mixing / dilution
Pollutants, trace elements and wastes	Water	**As : Arsenic**	Long-term exposure to arsenic in drinking-water is causally related to increased risks of cancer in the skin, lungs, bladder and kidney, as well as other skin changes such as hyperkeratosis and pigmentation changes (IPCS, 2001)	• At sources • In groundwater and/or surface water in power plant surroundings	• Collection of filtrated sample (0,45 μm)* • Acidified with 0,5% HNO_3* • ICP-MS*	• Semi-annually? • Annually?	Provisional guideline value of 10 μg/l set by WHO for arsenic in drinking water (WHO, 2003a)	• Reinjection • Mixing / dilution
Pollutants, trace elements and wastes	Water	**Cd : Cadmium**	• There is some evidence that cadmium is carcinogenic by the inhalation route, but no evidence of carcinogenicity by the oral route and no clear evidence that cadmium is genotoxic • With chronic oral exposure, the kidney appears to be the most sensitive organ (WHO, 2004a)	• At sources • In groundwater and/or surface water in power plant surroundings	• Collection of filtrated sample (0,45 μm)* • Acidified with 0,5% HNO_3* • ICP-MS*	• Semi-annually? • Annually?	Guideline value of 3 μg/l set by WHO for cadmium in drinking water (WHO, 2004a)	• Reinjection • Mixing / dilution

Category	What to monitor (Concern)		Why monitor (Risks)	Where to monitor (Location)	How to monitor (Method)	When to monitor (Frequency)	Guides / Limits	Mitigation options/Alter-natives
Pollutants, trace elements and wastes	Water	**Hg : Mercury**	• Can cause neurological and renal disturbances • Pregnant women and nursing mothers likely to be at greater risk from methyl-mercury (WHO, 2005)	• At sources • In groundwater and/or surface water in power plant surroundings	• Collection of filtrated sample (0,45 µm)* • Acidified with 0,5% HNO_3* • ICP-MS*	• Semi-annually? • Annually?	Guideline value of 6 µg/l set by WHO for inorganic mercury in drinking water (WHO, 2005)	• Reinjection • Mixing / dilution
		Pb : Lead	• A cumulative general poison • Pregnant women, fetuses, infants and young children most susceptible • Effects on central nervous system particularly serious (WHO, 2003c)	• At sources • In groundwater and/or surface water in power plant surroundings	• Collection of filtrated sample (0,45 µm)* • Acidified with 0,5% HNO_3* • ICP-MS*	• Semi-annually? • Annually?	Guideline value of 10 µg/l set by WHO for lead in drinking water based on infant tolerance, being the most sensitive subgroup of the population (WHO, 2003c)	• Reinjection • Mixing / dilution
		NH_3 : Ammonia	• Can occur in harmful concentrations (Kristmannsdóttir and Ármannsson, 2003) • Can have adverse effects on aquatic life	• At sources • In groundwater and/or surface water in power plant surroundings		As needed (due to low concentrations and limited effects, monitoring may not be necessary)	EPA 1985 Aquatic Life Criteria Guidelines: freshwater concentration based on chronic criterion (function of T and pH)	• Reinjection • Mixing / dilution
		S, Si, Ba, Co, Cr, Cu, Mo, Ni, P, Sr, Zn	• Geochemical studies • Trace elements	• At sources • In groundwater and/or surface water in power plant surroundings	• Collection of filtrated sample (0,45 µm)* • Acidified with 0,5% HNO_3* • ICP-MS*	• Semi-annually? • Annually? • Less often?	These species are generally not of great concern for environmental or human health	• Reinjection • Mixing / dilution
		^2H : Deuterium ^{18}O :Oxygen-18	• Origin and age of geothermal water • Reservoir boiling, mixing, tracing • Isotope geothermometers • See for example (Arnórsson, 2000)	At sources (wells)	• Sample collection* • Mass spectrometry (MS)*	Annually?	N/A	N/A

Category	What to monitor (Concern)		Why monitor (Risks)	Where to monitor (Location)	How to monitor (Method)	When to monitor (Frequency)	Guides / Limits	Mitigation options/Alter-natives
Pollutants, trace elements and wastes	**Power plant substances and wastes: solids and liquids**	**Spent materials, containers etc.**	• Potential pollutants (soil and groundwater, surface water, atmosphere) • Potential visual distraction if not disposed of properly	• At power plant • At disposal sites	• Require description of constituents when procured (asbestos, PCBs, heavy metals, material remnants in containers) • Ensure proper disposal in accordance with constituents	• When procured • When to be disposed of	In accordance with the materials / substances of concern	Procure materials that can be easily disposed of when possible
		Failed or outdated equipment	• Mechanical and electrical equipment may need to be replaced • Potential pollutants • Potential visual distraction if not disposed of properly	• At power plant • At disposal sites	• Require description of constituents when procured • Ensure proper disposal in accordance with constituents	• When procured • When to be disposed of	In accordance with the materials / substances of concern	Procure equipment that can be easily disposed when possible
		Process fluids: isobutane, isopentane, ammonia-water	• Pollutants • Flammable	• At power plant • At storage sites	• Control system sensors • Hand held sensors • Infrared camera where leaks are suspected • Olfaction	• Upon arrival to power plant or storage site • During filling / re-filling of system cycle • During regular operation • During emptying of system cycle	MSDS / Standards: flammability, toxicity, danger of asphyxia	Handle in accordance with set procedures
		Chemicals: biocides, corrosion & scaling inhibitors	• Potentially harmful to human health • Potential environmental pollutants (soil, groundwater and surface water)	At storage and handling sites	• Visual inspection / observation • Observation of cooling tower blow-down water disposal: sampling if necessary	During handling	Material Safety Data Sheets (MSDS)	• Procure chemicals that pose the least threat • Handle in accordance with set procedures
		Oils (lubricants and coolants)	Potential pollutants (soil, groundwater and surface water)	• At storage and handling sites • At equipment sites (e.g. turbo-generator and transformers)	• Visual inspection / observation • Equipment sensors (e.g. oil pressure)	• Upon arrival to storage site • During filling of equipment • During regular operation • During emptying of equipment • Upon disposal of spent oil	Regulations	• Handle in accordance with set procedures • Build containment structures / oil traps with fire safety measures
		Garbage	Potential pollution / nuisance	• At power plant • At disposal sites	Visual observation			
		Waste water and sewage	Potential microbial pollution	At power plant	Inspection of waste water and sewage systems	As needed	Regulations	

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Biological effects	**Vegetation (flora)**	**Diversity** (species)	To observe and record changes in biodiversity level	In the power plant impact zone	Visual inspection / surveying	As needed (may be stipulated in an EIA)	Environmental Impact Assessment	Depends on the nature of the impact and the source
		Density	• To observe and record changes • To spot trends	In the power plant impact zone	Visual inspection / photography	As needed	Environmental Impact Assessment	
	Wildlife (fauna)	**Diversity** (species)	To observe and record changes in biodiversity level	In the power plant impact zone	Visual inspection / surveying	As needed (may be stipulated in an EIA)	Environmental Impact Assessment	Depends on the nature of the impact and the source
		Density	• To observe and record changes • To spot trends	In the power plant impact zone	Visual inspection / surveying	As needed	Environmental Impact Assessment	
	Micro-organisms	**Diversity** (species)	To observe and record changes in geothermal micro-organism diversity as a result of changed habitat	In natural geothermal surface manifestations	Sampling and analysis	As needed	Environmental Impact Assessment	
		Density	• To observe and record changes • To spot trends	In natural geothermal surface manifestations	Sampling and analysis	As needed	Environmental Impact Assessment	
	Water intake structures		• Aquatic organisms can be drawn into cooling water intake structures • Make certain that protective schemes are maintained and working as planned	• Intake structure • Fish handling and return system • Barrier net • Screens • Filters • Other barriers	Visual inspection	As needed (may be seasonal)		• Thorough research and planning on the location of the intake structure(s) • Seasonal shutdowns • Flow reduction • Fish handling and return system • Barrier net • Screens • Filters • Other barriers

Category	What to monitor (Concern)	Why monitor (Risks)	Where to monitor (Location)	How to monitor (Method)	When to monitor (Frequency)	Guides / Limits	Mitigation options/Alternatives
Socio-economic effects	Special scenery / Uniqueness	• Society may agree on the preservation of unique places • Most important during EIA and planning phase, but changes during the operation phase of a power plant can also affect scenery (e.g. new well pads, steam columns from new wells, cooling tower plumes, new pipelines, roads, buildings, transmission lines, and other structures	Where new structures are planned	Observation	At the planning phase for new structures	• Environmental Impact Assessment? • Nature Conservation Laws?	• Hiding new structures: laying pipes or cables underground, selecting surface pipe routes along paths of low visibility from surroundings, constructing mounds to hide structures • Designing buildings to fall into landscape • Minimize well blowing • Use hybrid cooling towers to minimize plumes
	Tourist industry	• Geothermal power plants may affect tourism positively or negatively • May allow easier access to remote areas • Power plants can themselves become a source of attraction • Tourism can affect local economy and culture, place stress on flora, fauna and delicate natural features • May be important to watch and manage	• In the areas around the power plant • In areas that have opened up to tourism due to power plant, e.g. because of improved or new roads • Special need to monitor effects on delicate natural features, such as geothermal surface manifestations or geologic features • Towns in the vicinity of the power plant	Observation	• As needed • Tourism may follow seasonal trends	• Environmental Impact Assessment? • Nature Conservation Laws?	• Direct and manage tourism: build walkways in delicate areas and restrict traffic outside them • Charge access fees at delicate areas • Employ personnel to direct, manage and inform tourists • Restrict access

Category	What to monitor (Concern)	Why monitor (Risks)	Where to monitor (Location)	How to monitor (Method)	When to monitor (Frequency)	Guides / Limits	Mitigation options/Alternatives
Socio-economic effects	**Local economy / Employment**	• Power plants may bring local jobs for operation, maintenance and services • Effects on equality and culture • Increased tourism can affect local economy and present job opportunities (Arévalo, 1998)	• Community in the vicinity of the power plant	• Official employment data • Polls • Interviews with employees and employers • Company listings • Tax revenue	• During initial period of power plant operation • During plant changes or enlargements that may call for workers • Periodically over the operational lifetime of plant if needed		
	Cultural preservation	• Increased tourism and job opportunities may place transformational pressure on the local culture • This is especially relevant if the area was inaccessible prior to the power plant construction, if tourism increases and/or if the plant brings significant economic changes to the local society	• Community in the vicinity of the power plant	• Observation of traditional customs, habits, dress, speech etc. • Polls • Interviews	• During initial period of power plant operation • Periodically over the operational lifetime of the plant if needed		• Supporting education about cultural values to increase awareness • Supporting cultural events
	Public opinion	• Public opinion can be of great importance to power plant owners/operators • Mutual benefits of the power plant owners and the local community can help maintain positive attitude • Positive public attitude is conducive to a constructive operational environment	• Local community	• Polls • Interviews	• During initial period of power plant operation • Periodically over the operational lifetime of the plant if needed		• Power companies can help to construct positive public opinion by actively engaging with the community and sharing benefits