Chapter 10

ENVIRONMENTAL IMPACTS AND MITIGATION

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1. Introduction to Environmental Issues in Geothermal Development

1.1. Outline

Since the early days of geothermal development the attitude of the Public towards World's natural resources, in general, and energy sources, in particular, has changed drasticcally. Not only does it address the aware-ness of the exhaustible nature of the resource but also of the interactions of the production, distribution and use chain with the environment at large.

Hence, resource management policies, aimed at optimised exploitation strategies, in compliance with technical feasibility, economic viability and environmental safety requirements, should become the rule. These concerns raise growing interest in the perspective of sustainable development of alternative, preferably renewable, sources, deemed less polluting as highlighted by the debate on global warming, climatic changes and the relevant recommendations of recent World Environmental Summits (Kyoto Protocol, Johannesburg Sustainability Statement).

Geothermal energy should therefore conform to a complex, often stringent, environmental regulatory framework otherwise it would lose any credibility whatsoever, at a stage of its development where it needs to gain social acceptance and upgrade its image. As a matter of fact, although regarded as environmentally friendly, geothermal energy exhibits a number of sensitive attributes and related impacts (toxic gases, heavy metals, land subsidence, induced seismicity…), which, if not carefully handled, may cause serious short-comings.

Actually, there are several counter examples, where these impacts have been either clearly overlooked or readily ignored, leading to severe disputes with the authorities and, in several cases, to project abandonment.

Summing up, careful attention ought to be paid, during project preparation, commissioning and start up phases, to a clear assessment of the initial environmental status and to identifying and quantifying all possible, actual and potential, effects on the environment in order to secure adequate monitoring, remedial and mitigation protocols.

Worth mentioning here is that a thorough environmental impact assessment is a key issue to project commissioning and public acceptance.

Environmental issues are summarised In the global approach displayed in fig.1.

The diagram identifies the impacts on the physical media-land/soil, water, air, built areas- of the source mechanisms involved in the early exploration/development (expro, acronym of exploration/production) and ultimate plant/ equipment operation stages relating to power generation and direct heat uses.

These impacts and processes will be briefly described and mitigation/remedial procedures and legal/ institutional/social implications discussed in fine.

1.2. Preliminary Surface and sub-Surface Investigations

This early reconnaissance stage, which includes (i) geological, hydro-geological, geochemical sampling/ mapping, (ii) geophysical surveys and, occasionally, (iii) shallow slim-hole drillings, does not significantly impact the environment.

Only may geophysical (mainly seismics and MTs) and shallow drilling campaigns cause temporary disturbances when removing vegetation and accommodating site accesses and works facilities.

In any case public information and involvement is recommended if not formally required.

Exploration and Development Drilling

Exploratory drilling ventures currently mobilise heavy rig equipments (150-350 t hook load capacities). The rig force and its environment needs to level off (flat terrain) the drilling pad over an average 0.5 ha acreage, unless otherwise dictated by adverse steep topographies.

It elsewhere requires to construct access roads, drilling pads, water supply lines, refuse pits and waste disposal/processing infrastructures.

Hence, deep drilling and well testing operations address the sensitive impacts listed below.

. land disturbance (occupation landscape modification)
. waste (solid, liquid) disposal and

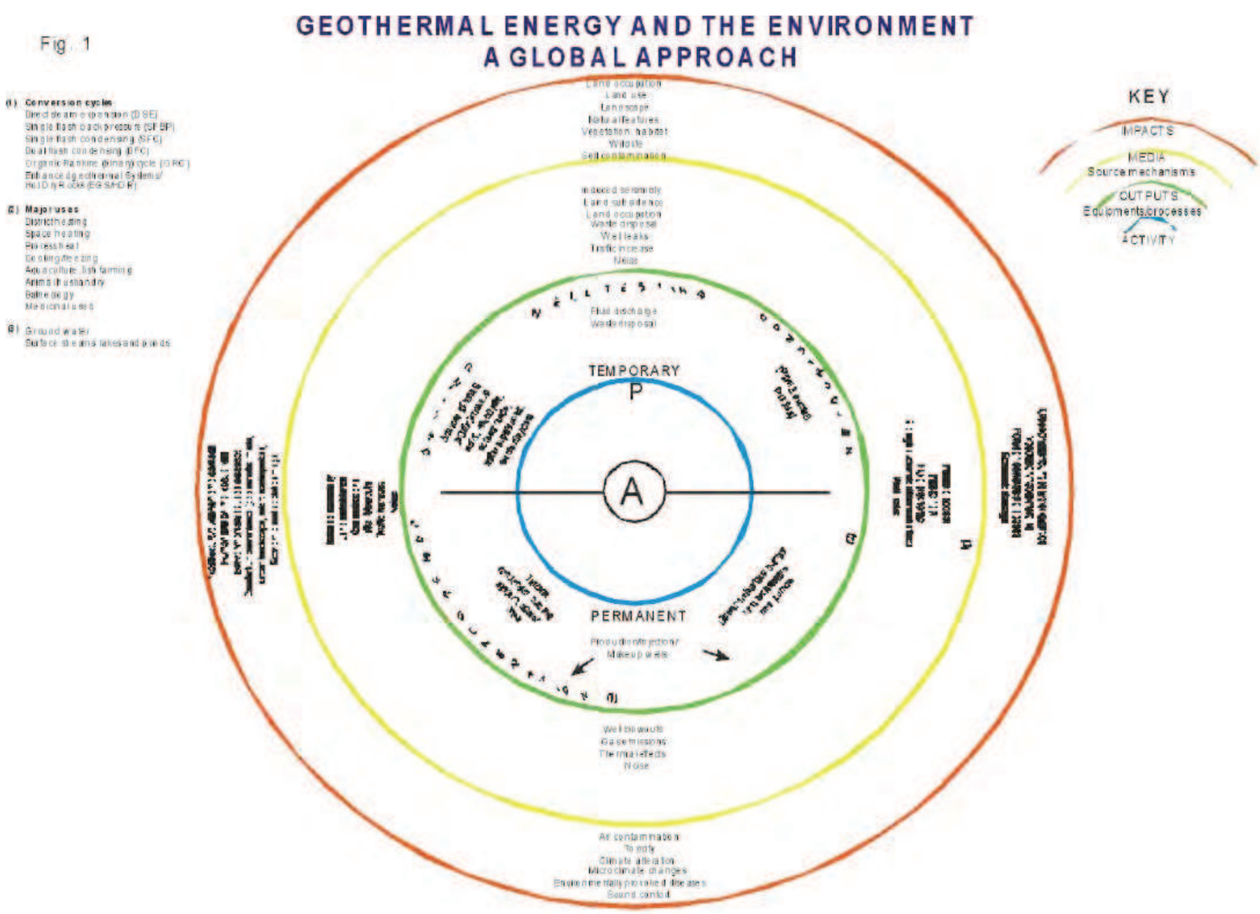

Fig.10.1. Geothermal Energy and the Environment – A Global Approach

fluid (water, gases) discharge
- noise
- traffic increase
- natural features, vegetation, habitat, wildlife
- workers safety and health
- social effects

These impacts affect further drilling of step out, production/injection and make up wells, at a likely lesser extent though, thanks to the infrastructures (re use) and experience inheritated from previous exploration stages.

Noteworthy is that impact mitigation can be reasonably expected from recent technological improvements (compact rig environments, top drive, electrically powered draworks and pumps, mud and solid treatments, waste processing and gas abatement lines…).

Drilling and testing operations have to comply with mining and environmental regulations in force, whose formats vary country wise, and fulfil due licensing/permitting/ authorisation requirements. In most, if not in all, instances a thorough environmental impact report is to be issued together with the application to the relevant authority.

1.4. Exploitation

Given a minimum twenty year life expectation, the exploitation segment of a geothermal development project is, structurally, the most demanding as to environmental impact and mitigation concerns.

Depending on the enthalpy of the geothermal source, two energy uses are contemplated, power and heat respectively and, within these categories, the size of the exploitation scheme (say 50 vs 5 MWe–power- and 10 vs 1 MWt–heat) will be discussed owing to contrasted environmental implications.

- *Power generation*

Sources above 180°C are, broadly speeking, deemed eligible to single and dual flash condensing con version cycles provided they can supply a ca 50 MWe plant capacity (assuming a 10 t steam load/MWe and 50°C condensing temperature).

Within the 120-180°C temperature range, binary cycles (either Organic Rankine or Kalina) are the rule. Plant capacities stand in general between 5 and 20 MWe.

Direct steam expansion (either condensing or non condensing back pressure) cycles, associated with the occurrence of dry steam deposits re-mains the exception (only five fields recorded to date).

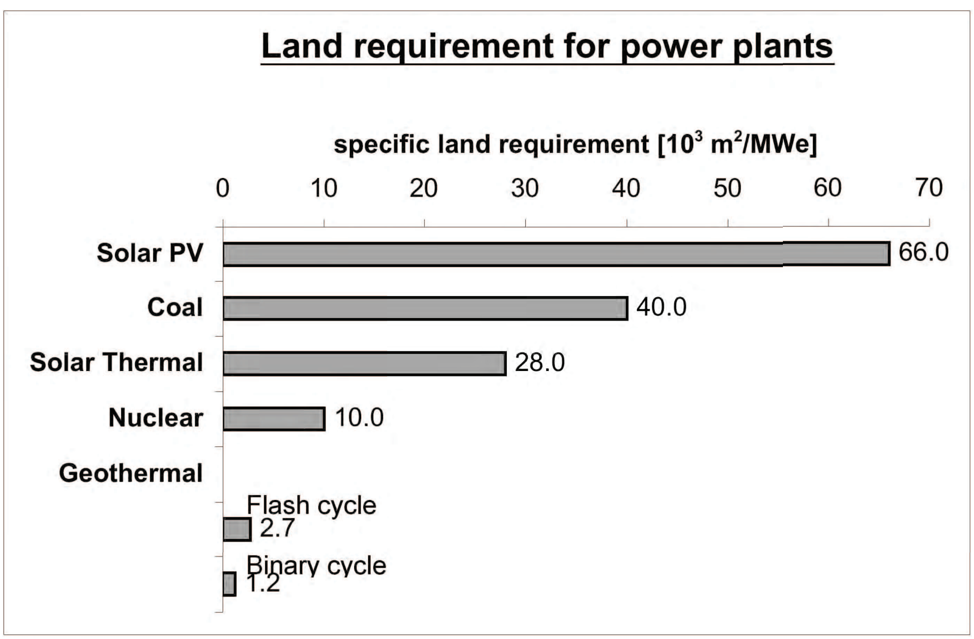

Fig.10.2: Comparison of land use for different power generation technologies.
(Di Pippo, 1991; modified by Rybach, 2005)

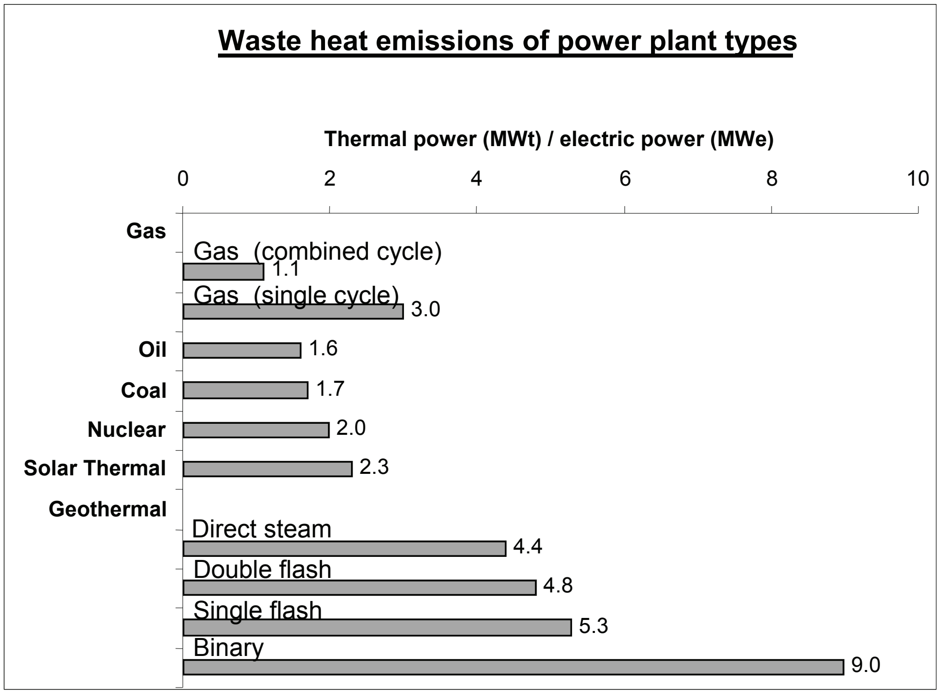

Fig.10.3.: Waste heat (MWt) per unit electric capacity (MWe) of geothermal power generation cycles compared to competing renewable and fossil fuel fired generation processes (Di Pippo, 1991; quoted by Rybach, 2005)

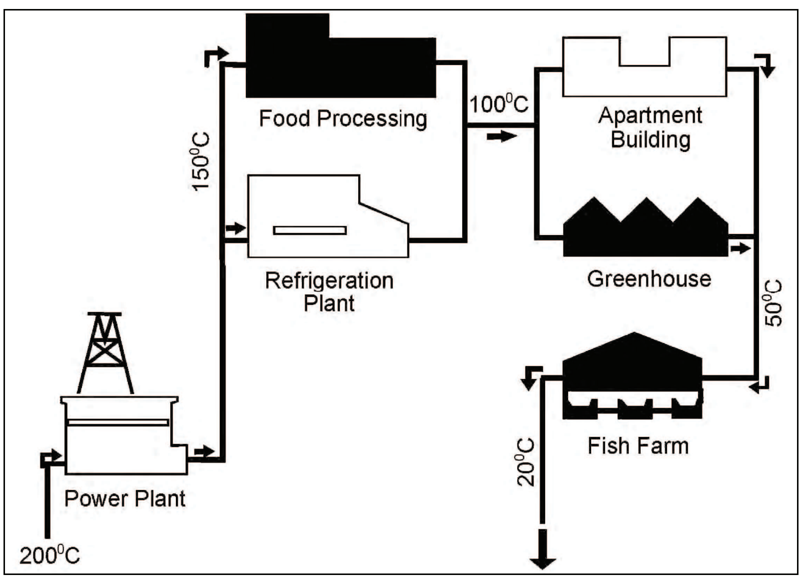

Fig.10.4.: Schematic flow diagram of a cascading sequence. (Rybach, 2005)

At this stage, the decisive ad-vantage, with respect to greenhouse gas emissions, for geothermal electricity over fossil fuel generated power, illustrated in table 1 comparative figures, ought to be readily emphasized.

A distinctive attribute of geoelectric under-takings, evidenced in fig. 2 is their compact plant design and subsequent limited land requirements as compared to fossil fuel (coal) nuclear and solar plants.

Table 10.1. Greenhouse gas emissions (CO2 equivalent) for fossil fuel fined and renewable energy power generation systems.

Source \ Pollutant	CO_2	SO_x	NO_x	PM
Coal	994	4.7	2	1
Oil	758	5.5	1.8	
Natural Gas	550	0.1	1.3	0.07
Geothermal			0	0
Flash cycle	27	0.16		
Binary cycle	0	0		

On the other hand, waste heat from geothermal power plants stands significantly higher than for fossil fuel, nuclear and solar thermal fired plants (fig. 3), a factor in favour of CHP and downstream cascading sequences of the type illustrated in fig. 4.

Direct Uses

Low grade heat exploitation displays a wide range of uses incompassing, among others, individual ground source heat pumps (a fast growing application), space/greenhouse heating, fish farming, process heat, district heating and absorption cooling.

Implementation of large district heating grids (rated 5 to 15 MWt) such as in the Paris suburban areas, can compare, all things being equal, to geoelectric plants and thus comply with most of the impacts listed in table 2.

However, given the sensitive urban environments, illustrated the aerial view of drilling works shown in fig.5, in which they take place, attention should be drawn to the following specific features.

- well inspection : casing integrites need to be checked periodically via wireline logs (multi arm caliper, ultra-sonic tools), leak off (pressure, tracer) tests and chemical monitoring ;
- casing protection : inhibition of corrosion/scaling/bacterial shortcomings is achieved by means of down-hole chemical injection lines set in production wells ;
- blow outs (overpressure self flowing wells). Intervention within a maximum 6 hour delay of an emergency, blow out control unit (well head and high capacity pumps) enables to reduce the impact of such unpredictible events;
- well workovers. The waste pro-cessing line described in fig. 6 acco-modates fluid degassing, filtering and cooling functions, thus avoiding the conventional refuse pits used in the past.

2. Chemical Impacts

They address the emissions of sensitive contaminant species, either in liquid or gaseous phases, to surface / subsurface waters and to the atmosphere during operation of power and heat plant facilities

However, the potential impacts on surrounding soils cannot be readily discarded, neither overlooked. Actually, the fallout of these emissions on soil and subsoil compositions, via spreading infiltration and capillary processes, ought to be assessed prior to plant start up and soil samples be collected and analysed is order to assess the initial soil chemical status.

Unless otherwise dictated, chemical impact stated for geo-power uses are assumed transferable, at a lesser magnitude though, to geoheat applications.

2.1. Impact on Water Quality

Contamination of surface and subsurface waters occurs as a result of waste fluid (separated water, steam condensates) discharge, disposal and (re) injection. Discharge into a nearby stream or pond will affect straightforwardly the environment at large (aquatic life, irrigated cultures, cattle, inhabitants,…) and indirectly exposed soils and ground water by seepage of discharged/ disposed waste fluids.

Occasionally, remedial injection of the cooled brine may turn into a damage whenever induced by well leaks and migration of solution gases.

Table 10.2. Large Scale (≥ 50 MWe) Geoelectric Development Projects. Summary of Candidate Impacts. Damage and Remedial Actions (Adapted from L. Rybach)

IMPACT	DAMAGE	RISK/OCCUR-RENCE LEVEL	REMEDIAL
Land/Soil	. Vegetation loss	M	. Cluster well pads
Occupation	. Erosion	L	. Revegetation
	. Ownership transfer	H	. Compensation
Water with			
drawal	. hydrological (watershed)changes	L	. Minimise withdrawals recycling
. Surface	. stream diversion	M	. Small dam storage
waters	. Pressure depletion/water		. Optimised reservoir manage-
	table drawdown	M-H	ment (multiwell production)
			injection arrays
. Groundwater	. Modifications of natural shows		. Injection of heat dep-
/geothermal	(spring recession,vanishing of	M	leted brine
reservoir	steam/gas vents, fumarolles etc		
	…)		
	. Corrosion/scaling	M-H	Chemical inhibition (optimum
			discharge)
	. Land subsidence	M-H	. Location of wells away
			from existing phreatic
	. Saline intrusion / sea	L-M	eruption craters
	water encroachment		. Avoid cultivated areas
	. Induced seismicity	L	unless systematic (re)
	. Agricultural impact	L	injection practice (cf. Im-
	(capillary zone)	L	perial Valley of Southern
	. Phreatic eruptions		California
	. Blow outs	L	. Blow out control
	. Reservoir cooling / prod-	M-H	Optimum design of P/I well
	uction well shortcircuiting		arrays
	. Well / reservoir plugging	M-H	
. Water (heat	(internal particles entrainment		. Sustainable reservoir
depleted	. Scaling		management
brine) injec-	. Induced seismicity	M-H	. Particle filtering, sand
tion		M	control, well completion
			. Chemical inhibition
			. (micro) seismic monito-
			ring/event prediction
			. Information of the public
. waste (brine,	. Biological	M	. Waste processing
condensate,	. Chemical	M-H	. Statement of toxic species
suspended	. Thermal	H	. Injection of processed
solids)			brine and condensate
disposal			. Effluent cooling
			. Storage, removal, drill-
			ing fluids and cuttings
. Atmospheric	. Biological	M	. Toxic gas abatement
emissions	. Chemical	M	(H_2S scrubbing)
	. Haze (heat) and mists	M-H	. Processing/fixing of non
	(condensing)	L	condensable gaser ven-
	. Air heating	L-M	tilation
	. Odd smells	L	. Blow out control
	. Blow outs		equipment
. Noise	. Disturbance to human/	L	. Sound proof facilities
	animal		(muflers, silencers)
	. Impaired hearingi	L	. Electric drive

Fig.10.5. Aerial view of a drilling site in the Paris suburban area
(GPC and Sedco-Forex, 1995)

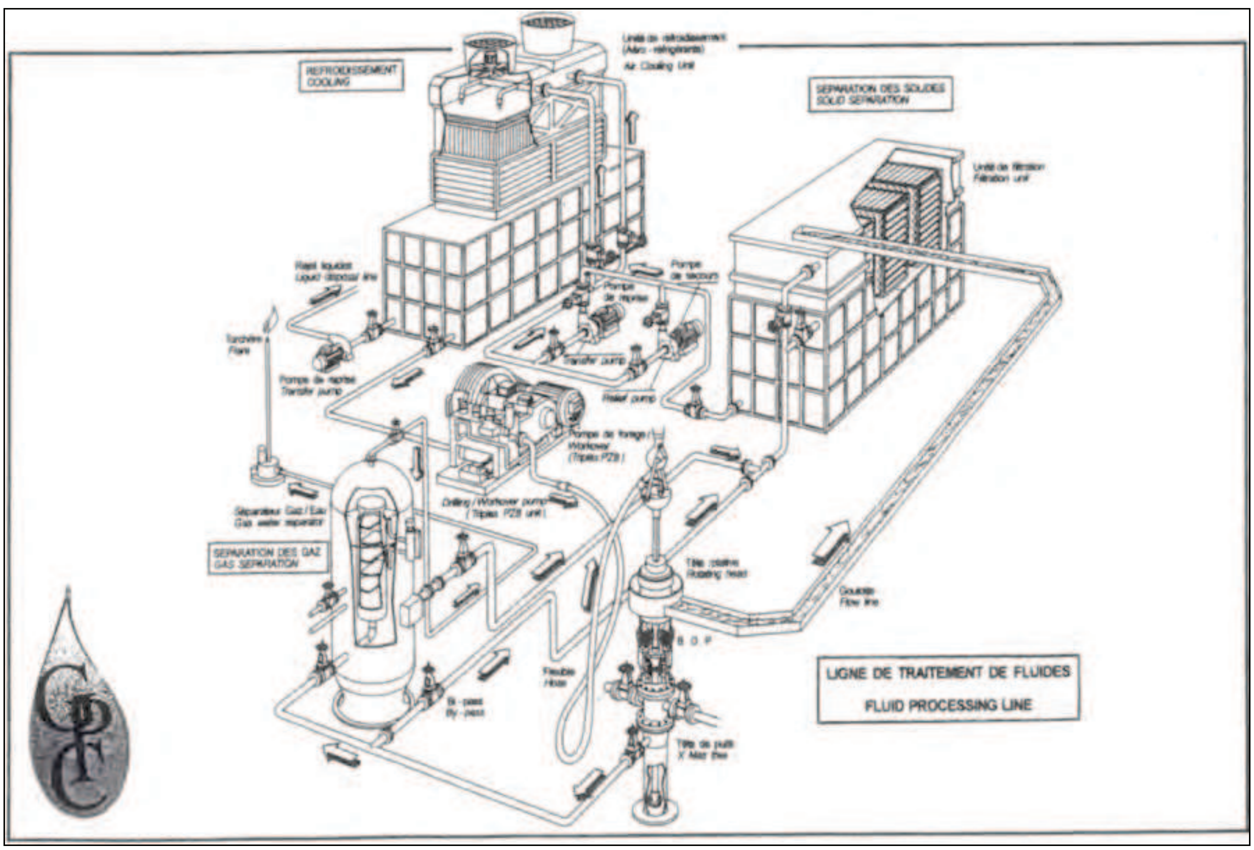

Fig.10.6. Workover waste fluid processing line (Ungemach, 2005)

Table 10.3. Contaminant concentrations (*) in waste bore water discharges from selected high enthalpy geothermal fields (Source Brown, 2005)

	H_2S	NH_3	H_3BO_3	Hg	As	Li
Salton Sea (USA)	16	386	2,231	6.0	12	215
Cerro Prieto (Mex)	0.16	127	109	0.05	2.3	
Wairakei (NZ)	1.7	0.20	172	0.12	4.7	14
Ohaaki (NZ)	1.0	2.1	276	0.05	8.1	11.7
Haveragerdi (Iceland)	7.3	0.1	3.4		0.0	0.3
Typical river water	<0.1	0.04	0.05	0.00004	0.002	0.003

Table 10.4. Water quality impacts. Summary of contaminant conservation and speciation processes

Con-tami-nant	Native fluid (wellbore)	Separated water discharge	Separa-ted steam dis-charge	Steam conden-sate	Surface water	Sediment	Impacted medium	Com-ments
Li	LI^+	Li^+			Li^+			
B	H_3BO_3	H_3BO_3			H_3BO_3			pH < 9
B	H_3BO_3	H^+, $H_2BO_3^-$			H^+, H_2BO_3			pH > 9
As	H_3AsO_3	H_3AsO_3 $H_2AsO_4^-$, $HAsO_4$			H_3AsO_3, $H_2AsO_4^-$, $HAsO_4^=$, $As(CH_3)_3$	$H_2AsO_4^-$	Aquatic plant (H_3AsO_3)	
Hg	Hg	Hg	Hg	Hg	Hg, $HgCl_2$, Hg^{++}, Hg_2^{++}	Hg, HgS	Aquatic life Hg (CH_3)	
H_2S	H_2S	H_2S, HS-	H_2S	H_2S, HS^-, S	H_2S, HS^-, $SO_4^=$, HSO_3^-, $S_2O_3^=$	$SO_4^=$, FeS		Solids in conden-sates
NH_3	NH_3	NH_3,NH_4^+	NH_3	NH_3, NH_4^+	N_2, NH_3, NH_4^+, NO_3^-			N_2 cycle in surface waters and sedi-ments

Not to be overlooked are the potential contaminating sources related to the storage of chemical (scale / corrosion) inhibitors, biocides, fuels, lubricants and drilling fluids which deserve due impact assessments and remedial procedures.

. *Composition of fluid discharges*

Major contaminants consist of lithium (Li), boric acid (H_3BO_3), arsenic (As), mercury (Hg), hydrogen sulphide (H_2S) and ammonia (NH_3). Minor, elements such as antimony (Sb), thallium (Th), silver (Ag), tellurium (Te) copper (Cu) and selenium (Se) may be encountered occasionally at trace concentrations.

Concentrations of the most volatile elements (H_2S and Hg) are higher in the steam condensate whereas the lesser volatile ones (Li, As, H_3, BO_3) are more concentrated in the water phase. Concentrations of these major contaminants on selected geothermal fields are displayed in table 3. Earlier mentioned, miror trace elements often lead to exotic scale species as a result of H_2S escape further to flashing in the wellbore and brine cooling (Brown, 2005).

. ***Contaminant behaviour in the receiving environment***

As stressed by Brown (2005), the same contaminant may react differently with the environment, depending on its either conservative (chemically passive) or dissociated (chemically active) form. The latter speciation results from air exposure and oxidising and boron remains passive, unless pH exceeds 9, in which case the source boric acid H_3BO_3 gets dissociated into H^+ and H_2BO_3. The oxidising reduction and complexing processes involved in the production sequences are portrayed in table 4.Arsenic, mercury and sulphur undergo complex speciation processes discussed by Brown (2005), summarised here under.

Arsenic, once the separated water has been exposed to air, will be present as arsenate ion, H_2AsO_4 or its dissociated $HAsO_4^=$ form. It may also be methylated as $As(CH_3)_3$. Arsenic is absorbed by plants (replacing phosphate as nutrient) as inorganic As.

Mercury, initially under metal form will, after oxidising, be complexed by halogen ions to form stable salts ($HgCl_2$ for instance). It can also be methylated as $HgCH_3^+$ ions and fixed by aquatic life organisms.

Sulphur exists in the geothermal fluid in H_2S form, a known toxic contaminant which can be either reduced in HS^- ions or oxidised in thio-sulfate ($S_2O_3^=$), sulphite (HSO_3^-) and, ultimately, sulphate ($SO_4^=$) ions. Total H_2S concentrations include both H_2S proper and HS^-ions. Note that, whenever the geothermal fluid pressure is depleted below bubble point pressure, the initially dissolved gaseous H_2S will escape to atmosphere.

Nitrogen can undergo a number of oxidised states. In the separated water it will be present as ammonium ion NH_4^+. Exposure to air and oxygen rich waters will cause oxidation and, when discharged into surface waters, will get involved in the biochemical nitrogen cycle and appear under N_2, NH_3, NH_4^+, NO_2^- and NO_3 forms and also as organic compounds (amino acids, amines, proteins etc…).

Removal of contaminant species can be achieved by means of either physical (adsorption) or chemical (precipitation) processes. For instance, clay and oxide surfaces can absorb As, B and Hg and organic matter likewise. Note, however, that these adsorbed elements may be released whenever the chemical environment changes or bacterial activity occurs (the latter can lead to reducing the adsorbed Hg into methylmercury).

Heavy metals may be fixed by sulphur and precipitated, under suitable (oxygen free – anaerobic and solubility – supersaturation) conditions, into sulphides such as pyrite-FeS – and cinnabar – HgS. Volatile elements (NH_4, H_2S, Hg) can be vented to atmosphere as earlier mentioned for H_2S.

. ***Toxicity and environmental effects***

Disposal and discharge of toxic liquid contaminants are likely to damage the environment with respect to aquatic life, irrigated crops, stock watering and human consumption of exposed watered stock and crops. These, actual and potential, damage sources are listed in table 5 and their effects outlined herein after.

. *Boric acid.* Excess Boron contents may affect foliage depending on crop and soil types. Humans and stock can be sensitive to high boron concentrations in water supply, causing stock weight losses and human gastro-intestinal problems.

. *Arsenic*. Generally speaking, As is regarded a poison to life as a whole, at concentrations however seldomly encountered in natural settings. Aquatic vegetation often concentrates inorganic arsenic, which, accumulated, may become toxic towards human and crop consumption.

Unless extensively used in irrigation, which is seldomly, if ever, the case, arsenic does not significantly affect crops with the exception of some losses in crop outputs.

There is evidence of occurrence of arsenic enriched ground water as a result of host rock leaching which may provoke skin cancer. Important to note is that arsenic is easily removed (via adsorption processes) from waters eligible to drinking uses.

Hydrogen sulphide. It does not represent a danger when dissolved in water, only draw-back associated with off smells.

Solution H_2S however can be harmful to aquatic life at large as a result of its ability to capture dissolved oxygen. Toxic effects other-wise decrease with increasing pHs.

. *Ammonia.* Dissolved ammonia is not a dangerous contaminant unless oxidised into nitrate causing undesirable disturbance in aquatic plant growth, either limitation or proliferation and, ultimately, water entrophication.

Hence its effects on human health stock and crops are minimum. Only may excessive oxygen reduction endanger fish life.

Note also that decreasing pHs favour formation of non toxic ammonium.

. *Miscellaneous.* Those deal chiefly with salinity and temperature effects.

Saline waters reduce irrigation efficiency especially when adequate drainage facilities are lacking. Many vegetable and fruit varieties do not accommodate excess sodium and chloride contents which elsewhere impact aquatic life.

Table 10.5. Potential effects of selected contaminants on surface waters (adapted from Brown. 2005)

CONTAMINANT	HUMANS	STOCK	CROPS	AQUATIC LIFE	COMMENTS
H_3BO_3	Gastro intestinal disease	Weight loss	Toxic	None	Crop damage dependant of type and soils
As	High toxicity	Highly toxic	Chlorophyl destruction	High toxicity to fish and invertebrate	Accumulated by aquatic plants
Hg	High toxicity	Toxic-tissue accumulation	Mushrooms (accumulation)	High toxicity critical to for fishes	Contamination through food Bioaccumulation (aquatic life)
H_2S	None. Unpleasant odour	None. Unpleasant odour	Questionable	High toxicity	Non harmful at low concentrations for humans and stocks toxicity and acidity impacts unknown for crop
NH_3			Positive (Nutrient)	Hight toxicity (fish) positive for vegetables (nutrient)	Unpleasant smell/taste for humans and stock
NaCl (TDS)	Unpleasant taste (water, food) cardio vascular impact	Weight loss. Unpleasant taste	toxic	Toxicity to fresh water habitats	Crop and aquatic life sensitive to osmotic changes

High salinity water is not drinkable by humans and animals ; whenever tolerated by stock it may result in weight loss and subsequent productivity decrease (milk, eggs, meat…)

Hot water discharge in surface streams can be damaging to aquatic life and particularity to fish under low flow (recession) conditions, as a consequence of excess temperature rises. The later will also induce reduction in dissolved oxygen.

- ***Mitigation and remedial procedures***

Waste water treatment is the recommended policy in reducing the effects on the environment of the most critical toxic contaminants such as heavy metals. Protection of sensitive, terrestrial and aquatic, ecosystems.
and of biodiversity should be a dominant concern which, in several countries, is reflected in ad-hoc guide lines, standards and environmental and water regulations.

Mitigation and remediation procedures of the most potentially dangerous contaminants are two fold, wastes (re)injection or processing respectively.

(re)Injection, preferably into the sour-ce reservoir, of the heat depleted brine and steam condensates is, obviously, the most satisfactory. As a matter of fact, it avoids disposing the waste in the surface natural media, a fully secured objective provided the receiving piping and wellbore materials are adequately designed.

The waste treatment option addresses adsorption, flocculation or ultrafiltration processes to remove, among other toxic contaminants, heavy metals. Actually, these processes are quite similar to those handled routinely in drinking water treatment facilities.

- ***Drinking water protection***

Table 6 summarises the threshold figures, set for the aforementioned contaminants, known as water quality guidelines issued by the United Nations (WHO) and US and Canadian agencies which are the nucleus of most national water quality standards.

Note that the drastic value recomended by WHO for arsenic has been guided by its recent identification as a candidate carcinogen agent.

These criteria, according to Brown (2005), assume a two liters daily absorption by a human, 60 kg in weight. The definition of these standards is based on human exposure observation and tests carried out on animals. Brown (2005) elsewhere stresses that a great extrapolation prevails within the "tolerable daily intake and lifetime exposure" gap.

In some instances (Cl, H_2S, NH_3), values refer to odour and taste comfort concerns rather than to proper health protection standards.

- ***Aquatic life protection***

This key issue, regarding protection of ecosystems and biodiversity, is documented in US, Canadian, Australian and New Zealander issued "water quality guidelines".

The guiding criteria, specific to aquatic life, are two fold (i) upper threshold values i.e. maximum concentrations under which sensitive species remain unaffected, and (ii) contaminant concentrations ranging between "chronic" (4 day average concentration single Ph / temperature ranges respectively range of Li contents set for various soil and crop types exposure over 3 years) and "acute" criteria (1 hour average concentration single exposure over 3 years).

Critical contaminant contents are analysed on acidised (pH≤ 2), non filtered (a condition often deemed overprotective), water samples.

An in depth review of aquatic life protection protocols may be found in Brown (2005).

- ***Stock watering and irrigation***

Drinking standards are transferable so far to irrigated crops and livestock watering unless otherwise specified by country specific food requirements.

Nevertheless, upper limits are usually agreedwith respect to sensitive contamination concentrations. As a livestock is concerned, such standards need to be adjusted to body weights and relevant daily water consumptions.

2.2 Impacts on Air Quality

Atmospheric emissions occur through well discharge during drilling/testing/workover phases and gas exhaust (steam- geopower and dissolved gases-geoheat) during plant operation.

Table 7 (Barbier, 1997 ; Rybach, 2005) shows that non condensable gas/water ratios in steam can vary from 310^{-3} to 510^{-2} (wt/wt), i.e. concentration ranges between 3 and 50 g/kg. CO_2 and H_2S are the major constituants, other gases (NH_3, CH_4, H_2, B, Rn…) being present as trace elements.

Table 10.6. Guidelines for geothermal contaminant concentrations in fresh water (mg/kg). (from K. Brown, 2005)

	WHO(1993) Drinking water	**USEPA(1986) Aquatic life Chronic criteria**	**CCREM(1991)** ***Aquatic life***	**USEPA (1972) Stock**	**CCREM (1991) Irrigation**
As	0.01	0.19	0.05	0.20	0.1-2.0[3]
B	0.3	0.75[1]		5.0	0.5-6.0[3]
Li					0.075-2.5[3]
Hg	0.001	0.000012	0.0001	0.01	
H2S	0.05	0.002			
NH3	1.5	0.08-2.5[2]	0.08-2.5[2]		
Cl	250				100-700
Na					500-3500

Acronyms :

WHO : World Health Organisation

USEPA : US Environmental Protection Agency

CCREM : Canadian Council of Resource and Environment Ministers

limit set to protect crops (2) NH3 thresholds set for 9-30°C and 6.5-0°C

Table 8 displays the composition of the dissolved gaseous phase on selected geothermal district heating wells in the Paris area. Here, CH_4, CO_2 and N_2 are the dominant constituents but, as elsewhere discussed, H_2S, although present in limited amounts, represents a major contaminantowing to its toxicity and corrosion impact in acid CO_2-H_2S aqueous environments.

With respect to green house gases (GHG) it should be mentioned that geothermal power plants release no NOx gases and that CO_2 emissions remains signifycantly lower (one half of natural gas and one quarter of coal/oil emissions in average) than for fossil fuel fired power plants.

Note also that the closed circuit design inherent to binary (ORC) powerplant and district heating doublets practically eliminates any gaseous emissions whatsoever out of acci-dental events (blowouts, leaks).

- ***Contaminant behaviour in the receiving environments***

Dispersion (or accumulation) into and removal from the atmosphere of gas emissions are specific to the site (topography weather conditions, plant/process design) and to the chemistry/stability of the gas.

Physical effects can be appraised by mathematical models used in atmospheric science/air pollution (plume dispersion) and Industrial design of exhaust/cooling facilities.

Table 10.7. Steam composition at various geothermal localities (after Barbier, 1997)

Constituents (g/kg)	**The Geysers USA** (*)	**Larderello Italy** (*)	**Matsukawa Japan** (*)	**Wairakei New Zealand** (**)	**Cerro Prieto Mexico** (**)
H_2O	995.9	953.2	986.3	997.5	984.3
CO_2	3.3	45.2	12.4	2.3	14.1
H_2S	0.2	0.8	1.2	0.1	1.5
NH_3	0.2	0.2			0.1
$CH_4 + H_2$	0.2	0.3			
Others (B, Rn…)	0.2	0.3	0.1	0.1	
GWR (wt/wt)	0.004	0.05	0.014	0.003	0.016

(*) field vapour dominated (**) liquid dominated field

Table 10.8. Typical solution gas compositions (% mol) on selected Paris Basin Geothermal District Heating Wells (source GPC)

Well / Solution Gas	PWA	PWB	PWC	PWD(*)
CO_2	14	8	9	51
H_2S	0.1	0.15	0.1	1
N_2	53	37	34	25
CH_4	30	44	50	20
C_2H_6	2	4	3	2
Others(**)	1	7	4	1
GLR (voi/voi)	0.11	0.12	0.16	0.25

(*) bottomhole (1880 m) sample (**) mainly C_3H_8, ic4, ic5, nc4, nc5

Gas solubility and local climate may influence contaminant accumulation and removal depending upon the gas-water interactions (rain, fog) involved. Brown (2005) highlights in this respect the contrasted behaviours of gaseous ammonia and mercury vapour. For instance ammonia is easily leached due to its, high solubility in water whereas, instead, weakly soluble mercury will remain for long periods in the atmosphere and therefore spread over wide areas.

H_2S is another example of chemical modifications leading ultimately to less or non toxic species. Oxydising by rain droplets, will, as previously mentioned, form thiosulfate, sulphite and sulphate ions. In neutral or alkaline pH environments, H_2S can get dissociated into HS^- and H^+ ions less toxic than gaseous H_2S.

There can be, further to capture and entrainment of contaminants by rain and fog, secondary effects of gas emissions on soils, surface/ ground water, vegetation, crops and livestock.

- ***Toxicity and environmental effects***

CO_2 (the most abundant), H_2S, vapour mercury, ammonia and boron (as boric acid H_3BO_3) are the most sensitive toxic gases.

CO_2, H_2S and Hg are poorly soluble in water and therefore non condensable, which, if not extracted (via compressors) will be discharged to atmosphere and incidentally penalise both the efficiencies and economics of the power production cycle.

B (H_3BO_3) and NH_3 are more soluble in water and eligible to some condensing. As a result they will lesser affect gas exhaust.

CO_2, H_2S and Hg being volatile gases, especially CO_2, will be transferred after separation to the vapour phase.

Less volatile B (H_3BO_3), NH_3 and As constituents will either remain in the separated brine (case of As) or migrate (B, NH_3) to the steam phase, particularly in dry steam fields where no separation process is needed.

CO_2 and H_2S are, on the other hand, "heavy" gases lowly miscible with air, which can accumulate in low lying areas, which can occasionally provide serious casualties to the population whenever blowouts occur on wells located on topographic tops.

It should be noted that natural surface manifestations (fumaroles, steam/gas vents and pools, sulphur springs…) can, occasionally, exceed plant generated emissions.

The most critical species exhibit the following toxic attributes.

CO_2, a colour and odourless gas, severely endangers human health as a consequence of pH changes in blood. When inhaled at 5 % (wt) concentration in air it causes breathlessness and dizziness ; at 10 % (wt), unconsciousness and suffocation at lethal stage. Critical exposures are set at 10 000 ppm/10 min. Reduction of GHG emissions should, sooner or later become a more serious environmental concern to geothermal operators.

H_2S is an acute toxic agent. Its lethal concentrations and exposures are signifycantly lower than those specified for CO2. Presence of H2S is signed by its characteristic "rotten egg smelling" detectable at very low contents (less than 1 ppm). At 0.5-10 ppm eye stinging appears, above 500 ppm, suffocation. Critical exposures are set, by industry and competent authorities, to ca 20-30 ppm/10 min. Most frequent complaints from the public address odd smells, a precursory sign which may be misleading as much as alerting; as a matter of fact high concentrations are odourless and lethal. Concerned industries and health agencies issue relevant safety recommendations in H2S environments. Brown (2005) stresses that, despite several secondary (oxyamines, sulphite, sulphate) foot prints, no geothermal acid rain sourcing by H_2S emissions has been yet evidenced.

Toxicity of Hg vapour, although poorly documented in the geothermal literature, is a sensitive matter. Its low concentrations in geo-thermal steam is counterbalanced by long residence times, as a result of its low water solubility, thus influencing widespread acreages, which highlight the importance of Hg fluxes. Large proportions (up to 80 %) of inhaled gaseous Hg are fixed by human organisms, a retention capacity significantly higher than for ingested Hg (ca 10 %). Last but not least, secondary effects are non trivial, owing to its bio-accumulation properties in the food chain and downstream animal and vegetal contamination. Ultimately, prolonged exposure may lead to ireparable, non reversible, damage to the central nervous system.

Ammonia, in addition to its characteristic, unpleasant, odour is a toxic gas which can affect human physiology.

Boron (boric acid) toxicity is generally considered as low. However secondary effects of boron gaseous/steam discharge on contamination of exposed surface waters and soils can be expected.

- ***Mitigation and remedial procedures***

They should, by all means, comply with air quality guidelines issued by the WHO (see table 9) and HSE for protection of public (WHO) and occupation health (HSE) respectively. Brown (2005) comments on the differences between WHO and HSE criteria which lie in exposure times. Typically, HSE would recommend not to exceed 10-20 ppm over 10 minutes for H_2S exposure against 0.13 ppm vs 24 hours set by WHO. Clearly, the HSE recommendation should apply to protection of working (well, plant) personnel, directly exposed to closeby H_2S emissions, whereas WHO would consider instead more remote, diffuse, exposures.

Note, the large mercury exposure time which reflects the accumulative capacity of this constituent. Worth mentioning elsewhere is that these, widespread disseminated, "standards" refer to the sole effects on (and protection of) humans of contaminated air breathing. In so stating they assume these effects (and protective guidelines) extrapolable to livestock and wildlife. Neither do they account for indirect, secondary, effects on surface water, soils, vegetation and crops.

Environmental concerns, while serviceing and operating plant and well facilities address sensitive gas monitoring protocols and toxic gas abatement processes. As regards monitoring, it is mandatory that, prior to project implementation and plant start up, a thorough initial environmental assessment of soil, water and air status be completed to avoid undue future disputes.

Abatement of sensitive toxic gases, chiefly H_2S, requires adequate efficient and economic stripping / scrubbing methods abundantly documented in literature (Brown, 2005 ; Rybach, 2005).

Secondary by products can be recovered from condensed steam among which sulphur, ammonia and boron. The latter, actually, has long been the main, if not the sole, chemical output of the Larderello steam field before on-line power commercial development.

Direct uses of low grade geothermal heat call upon specific mitigation/remedial procedures. On Paris Basin geothermal district heating wells, produced, in self flowing mode below bubble point pressure, the degassing/abatement line described in fig. 7 was designed in order to accommodate, via combustion (hidden flare), emissions of dissolved CH_4 and H_2S. In Slovakia (Kosice district heating scheme) abundant dissolved CO_2 emissions could be countered by production of, pellet packaged, calcium carbonate.

Impacts on the Physical Environment

Those concern chiefly natural features, land subsidence and induced seismicity issu-es.

3.1. Natural features

Any geothermal development modifies the environment. This fatal issue applies essentially to geopower undertakings, often located in exotic hydrothermal environments of outstanding interest and beauty.

These matters, delicate to appraise and quantify, deserve a ranking procedure in order to classify preservation priorities.

The classifications formatted by New Zealand authorities includes the categories listed below (Brown, 2005).

. Category A. Areas containing unique and outstanding hydrothermal features that need to be entirely preserved ;

. Category B. Areas with a selection of outstanding thermal features, to be protec-ted subject to category C specifications

. Category C. Areas already irreversibly altered or those containing no recognised unique geological or geophysical features. Lowest priority preservation.

The foregoing could valuably feature a regulatory framework for protecting land-scape aesthetics and hydrothermal unique attributes.

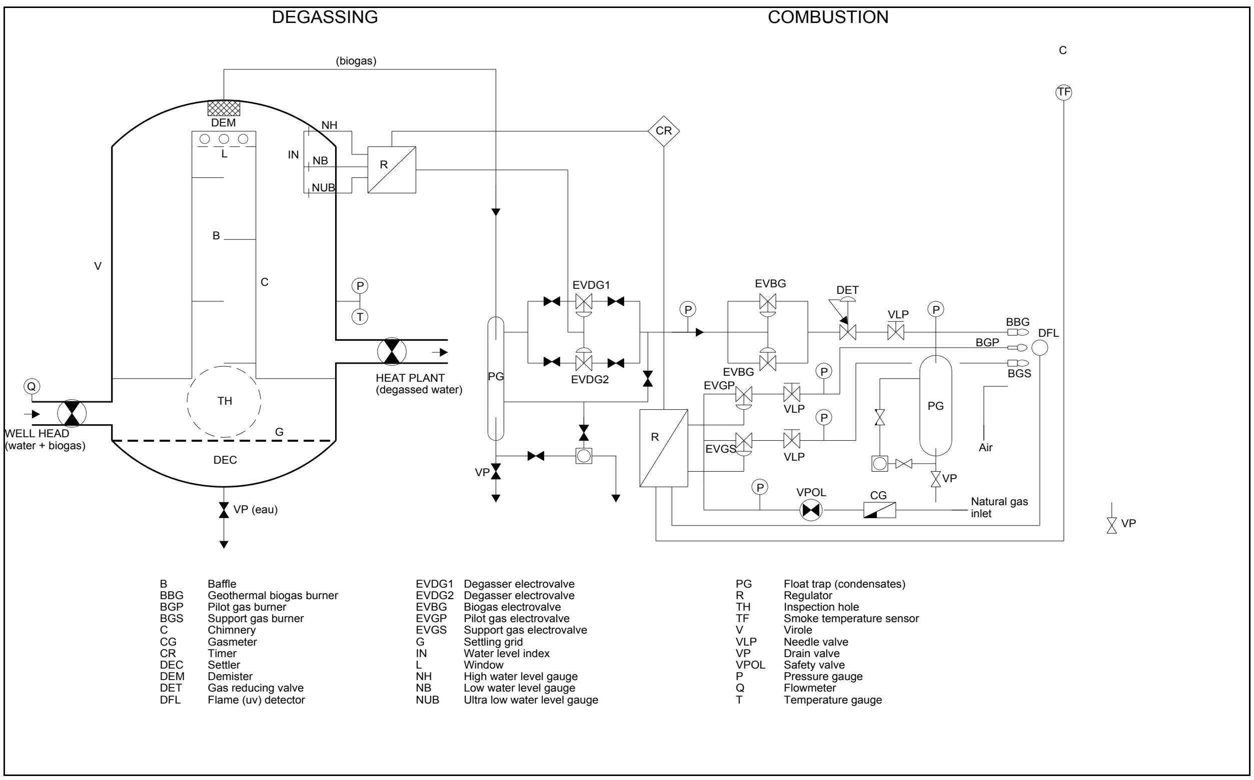

Fig.10.7. Geothermal biogas Degassing / Burning line schematics (GPC)

3.2. Land subsidence

Land subsidence is a consequence of underground fluid abstraction, long expe-rienced and well documented in ground-water, hydrocarbon and geothermal pro-duction. As the fluid is withdrawn from the reservoir the pore pressure decreases, thus increasing the load of the overlying rocks and terrains, causing them eventually to sink, a process illustrated in fig. 10 (note incidentally that subsidence persists where-as reservoir pressure had stabilised). This vertical movement is generally associated with lateral displacements trending radially, with decreasing magnitudes, from the maximum subsidence, a combination likely to damage the surrounding wells and facilities as mentioned by Brown (2005) in New Zealand.

Subsidence has been reported on several high enthalpy fields, Wairakei (Allis, 1990) and Broadlands (New Zealand), Cerro Prieto (Mexico) and the Geysers (Northern Califor-nia) (Mossop and Segall, 1997), with varying degrees of severity, depending on the nature of the rock and its porosity pattern. A hard rock with a low porosity will be lesser affected than a high porosity soft rock. Subsidence may also be influenced by the in situ fluid state, either dry steam or pressurised liquid, the latter inducing, seemingly, higher subsidence rates. In this respect, the Wairakei field exhibits (fig. 8) the highest ever recorded, rates (0.2 m/yr in average maximum 0.45 m/yr, total amplitude up to 10 m). Wairakei is an interesting well surveyed case study. Here, subsidence had been monitored prior to exploitation and estimated at ca 5 mm/yr, a figure reflecting a tectonically active setting. Further surveying showed that the highest, exploitation provoked, rates do not correspond to the producing areas but to preferential connecting paths with the geothermal reservoir instead (Brown, 2005).

The foregoing definitely emphasize the need for thorough monitoring of land movements, by geodetic measurements, prior to and during production.

Injection of the waste fluid seems the best remediation so far. As a matter of fact, in the Imperial Valley of Southern California, an extensively irrigated farmland, geothermal operators were imposed to restrict land movements to no more than 20 mm, an objective successfully achieved via brine injection into the source reservoir.

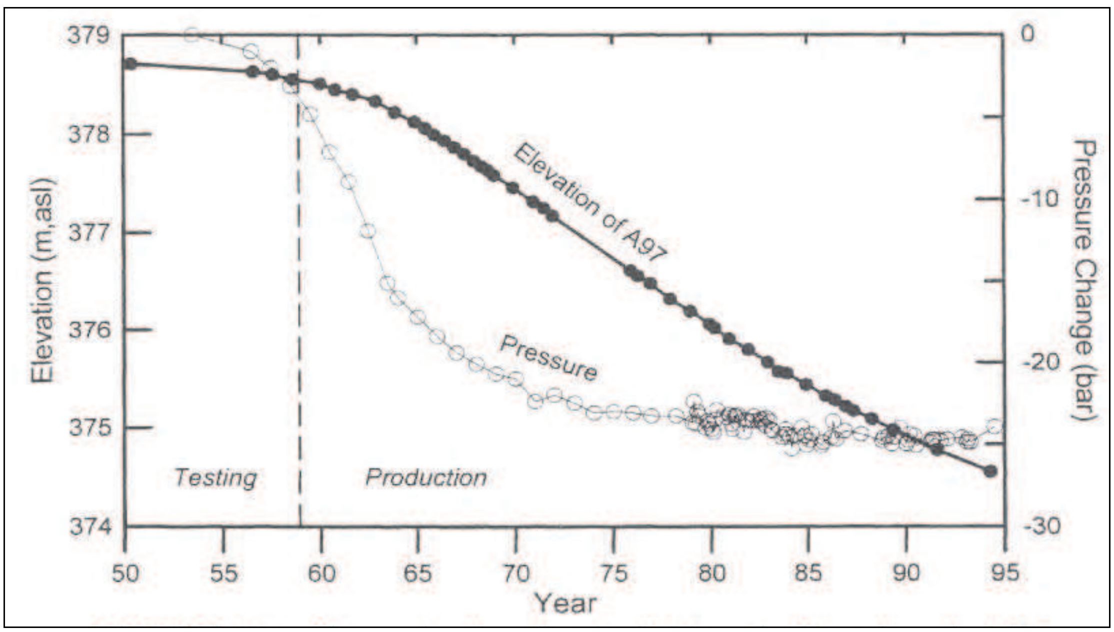

Fig.10.8. Surface elevation changes correlated with fluid pore pressures. Wairakei Field, New Zealand (Rybach, 2005)

3.3. Induced seismicity

Benefits expected from injection practice may be offset by induced seismic events. Injection increases pore pressure, therefore modifying the local stress field, eventually triggering small earthquakes. This poroelastic source mechanism requires high tectonic stresses to allow for deformations induced by relatively small changes in pore pressure. Actually microseismic induced events recorded on major, long exploited, geothermal fields (The Geysers, Larderello, Wairakei among others) occur in tectonic, seismically active, fractured zones known to host high enthalpy reservoirs. In The Geysers field, where a large city waste water injection scheme is being implemented, events of magnitude 4 on the Richter scale have been recorded. The low magnitude of induced events (The Geysers case could be regarded as an exception owing to the size of the injection programme) could be attributed to the local impact of injection associated with a damper effect of reservoir fractures, avoiding excess strain to develop (Bromley, quoted by Ryback, 2005).

Note that fluid withdrawal (and pressure depletion) generates, alongside earlier commented land subsidence, induced microseismicity. Poroelastic stressing and seismicity induced by hydrocarbon and geothermal production have been investigated by Segall et al. (1994) and Segall and Fitzgerald (1998). In the Lacq gas field, there has been evidence that the stress and deformation patterns induced by gas extraction conform to a simple linear poroelastic model, providing reliable estimates of land subsidence and microearthquake predictions (Segall et al, 1994).

Thermal stimulation by cold water injection, known as thermal stress cracking, aimed at enhancing well productivities and injective-ties, may provoke detectable microseismic events.

Within the scope of well/reservoir stimulation, the hot dry rock (HDR) concept of heat mining has provided useful clues on induced seismicity issues. HDR reservoirs, rebaptised enhanced geothermal systems (EGS), require the build-up of a large, deep seated, heat exchanger, achieved by interconnecting two or more wells using hydraulic fracturing technology. The stimulated, preferably self propped, rock volume should reconcile a high hydraulic conductivity connection with long reservoir life, the so called HDR paradox. Experiments, con-ducted on the Soultz European EGS site, evidenced, further to hydraulic fracturing, a strong microseismic activity culminating with events nearing magnitude 3, sensed by the local population (Baria et al, 2004). Worth mentioning in this respect is that, some thirty years earlier, a magnitude 5, natural seism was recorded in that, tectonically active graben environment. Furthermore, induced microseismicity validated fracture mapping and reservoir assessments, based on hydromechanical simulations correlating hydra-ulic diffusivity of a randomly fractured reser-voir with shear driven fracturing (Bruel, 2005).

On the other hand, once the desired heat exchange area is completed, it could be reasonably assumed that no undue seismic event be artificially induced during exploitation of the system.

Noteworthy is that water injection induced microseisms is likely to favour release of stresses which otherwise would accumulate and, ultimately, lead to devastating earthquakes.

Summing up, sound microseismic monitoring protocols are required to assess natural and induced seismic status.

4. Legal, Institutional and Social Implications

4.1. Legal and institutional

It has been previously mentioned that environmental regulations, although they share common concerns and principles, vary country wise. In countries enjoying a relevant geo-thermal development legislation, the normal application/commissionning/startup procedure includes the following steps (i) environmental impact survey, (ii) prefeasibility/feasibility analysis, (iii) land occupation/construction/exploitation permits (leases), and (iv) monitoring protocols. Operators have also to comply with additional specific water protection, clean air, health and safety regulations. References of selected national legislation are given in table 10 These regulatory frameworks are perfectible. First, concerned authorities should seek harmonisation between countries, a task in which the EU could act as a driving force. Second, environmental regulations should stick more closely to the energy source rather than focusing on its sole effects. In this respect, the French Mining Code relates the mining activity to all connected impact areas and hazards i.e. the Environmental Code, Water Act, Classified Industrial Hazards etc… In so doing the geothermal energy source is regarded as a mineral and its development as a mine (see ad hoc decrees in table 10). This seems indeed a satisfactory legal scheme. In other countries instead, geothermal sources are subject to the water law. Some countries consider ground source heat pumps as part of the renewable energy sector, others not.

Institutional matters may also address the various financial and fiscal incentives set by the states or international institutions to support RES development. These incentives consist of guaranteed take over prices for power from RES, tax credits, green certificates, various subsidies (most often from regional authorities), etc… They reflect the growing interest of the Public to environmental-global warning, GHG emission and economic – oil price rises – concerns.

4.2. Social

Acceptance by the local communities of any geothermal development project is a key issue. Whenever overlooked or readily ignored there are examples where the hostility of the population stopped the project at either startup or exploitation stages.

Project operators should therefore focus on gaining public acceptance by communication transparency, away from remote bureaucratic decisions.

All consequences on the local ecosystems natural features and habitats alongside expected socio-economic benefits (job creat-ion, royalties…) and externalities, the pros and the cons, need to be disclosed in the form of an impact assessment review and adequately publicised.

Rybach (2005) insists on the necessity of attracting the participation of the population to the management of their resources, a consensus which is indispensable to accompany project development and achievement.

Socio-economic advantages of large scale development schemes result in financial assets (mining royalty, taxes), employment opportunities and stimulation of parallel activities downstream from the reclamed energy source.

5. Conclusions. Recommendations

Geothermal energy is most often granted the label of a clean and environmentally friendly energy source. This perception occurs in a context of greater awareness of the public and institutional bodies to environmental, clean air/clear water, issues. Therefore, the greatest attention should be paid by the geothermal community in meeting the requirements of an increasingly demanding environ-mental legislation.

This requires a dynamic approach to the interactions between the energy production, distribution and use chain and the environment at large, addressing the following priorities.

(i) a clear and non ambiguous legal definition of the resource, enabling to regulate its use – power, heat – and development. The legislator should specify under which regime geothermal energy fits in, either mineral resource/mining or groundwater/ water rights. An adequately formulated mining law, appended to the existing legal framework, seems a reasonable compromise. It would ease also the concession/lease licensing process and fiscal regime applicable to private and public operators. Note also that the foregoing would enable bridging the gap between an, essentially protective, environmental legislation and an alternative energy source eligible to, environmentally safe, sustainable development. Directives addressing Power and Heat production from RES issued by international

Table 10.9. Legislations relevant to geothermal development (after Brown and Rybach)

Country	Environmental legislation	Specific geothermal legislation
USA	National Environment Policy Act	Geothermal Resources Operational Orders
The Philippines	Presidential Decree 1586 (Environmental Impact System)	Presidential Decree 1442 (Exploration and Development of Geothermal Resources)
New Zealand	Resource Management Act	Code of Practice for Deep Geothermal Wells
Italy	EEC Directive 85/337 (Environmental Impact Assessment)	Decree of President of the Republic 395/91 (Geothermal Exploration and Development)
France	Mining code Art. 79	Decrees 77-620 (exploration) and 74.498 (exploitation)

institutions would represent an important support ;
(ii) harmonisation and standardisation of existing, geothermally relevant, environmental legislations and regulations. Actions pioneered along this line by the EU have already demonstrated a rewarding impact ;
(iii) supportive public programmes combining specific incentives-takeover tariffs, -green certificates, tax credits low interest loans, mining risks guarantees - to promote geothermal heat and power project development.
(iv) last but not least, social acceptance. Gaining the support of local populations is of utmost importance to secure any project implementation and operation. Hence, all pertinent information, including a thorough impact assessment analysis and local environment initial status, should be disclosed, via appropriate communication, and a consensus reached accordingly.

Would these prerequisites be fulfilled, geothermal energy has a good chance.

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